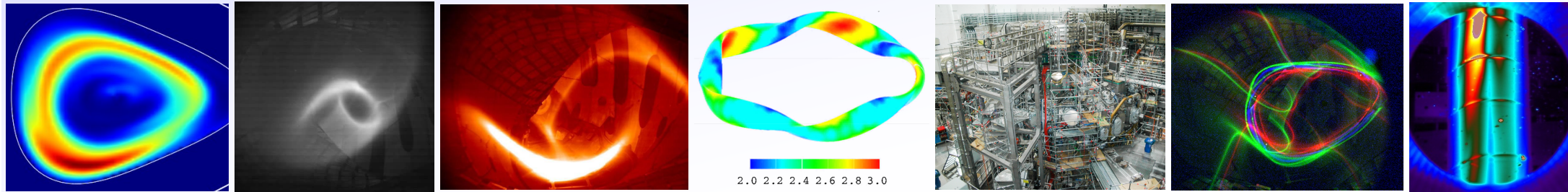


Wendelstein 7-X: Highlights from the first operational phase of a new optimised Stellarator.



Presented by Oliver Ford on behalf of the W7-X team and collaboration partners:

A. Adnan¹, A. Alonso⁶, T. Andreeva¹, J. Baldzuhn¹, T. Barbui⁷, M. Beurskens¹, W. Biel², C. Biedermann¹, B. Blackwell¹⁸, H. S. Bosch¹, S. Bozhenkov¹, R. Brakel¹, T. Bräuer¹, B. Brotas de Carvalho³, R. Burhenn¹, B. Buttenschön¹, A. Cappa⁶, G. Cseh⁴, A. Czarnecka⁵, A. Dinklage¹, A. Dzikowicka¹⁹, F. Effenberg⁷, M. Ender¹, V. Erckmann¹, T. Estrada⁶, O. Ford¹, T. Fornal⁵, G. Fuchert¹, J. Geiger¹, O. Grulke¹, J. H. Harris¹³, H. J. Hartfuß¹, D. Hartmann¹, D. Hathiraman¹, M. Hirsch¹, U. Höfel¹, S. Jabłoński⁵, M. W. Jakubowski¹, J. Kaczmarczyk⁵, T. Klinger¹, S. Klose¹, J. Knauer¹, G. Kocsis⁴, Ralf König¹, P. Kornejew¹, A. Krämer-Flecken², N. Krawczyk⁵, T. Kremeyer⁷, M. Krychowiak, I. Książek¹⁴, M. Kubkowska⁵, A. Langenberg¹, H. P. Laqua¹, M. Laux¹, S. Lazerson¹⁰, Y. Liang², A. Lorenz¹, A. O. Marchuk², S. Marsen¹, V. Moncada⁸, D. Naujoks¹, H. Neilson¹⁰, O. Neubauer², U. Neuner¹, H. Niemann¹, J. W. Oosterbeek⁹, M. Otte¹, N. Pablant¹⁰, E. Pasch¹, T. S. Pedersen¹, F. Pisano¹⁵, K. Rahbarnia¹, L. Ryc⁵, O. Schmitz⁷, S. Schmuck¹⁶, W. Schneider¹, T. Schröder¹, H. Schuhmacher¹¹, B. Schweer², B. Standley¹, T. Stange¹, L. Stephey⁷, J. Svensson¹, T. Szabolics⁴, T. Szepesi⁴, H. Thomsen¹, J.-M. Travere⁸, H. Trimino Mora¹, H. Tsuchiya¹⁷, G. M. Weir¹, U. Wenzel¹, A. Werner¹, B. Wiegel¹¹, T. Windisch¹, R. Wolf¹, G. A. Wurden¹², D. Zhang¹, A. Zimbal¹¹, S. Zoletnik⁴ and the W7-X Team

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⁶Laboratorio Nacional de Fusión, CIEMAT, Avenida Complutense, Madrid, Spain

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¹⁴Opole University, Opole, Poland

¹⁵University of Cagliari, Cagliari, Italy

¹⁶Culham Science Centre, Abingdon, OX14 3DB, United Kingdom

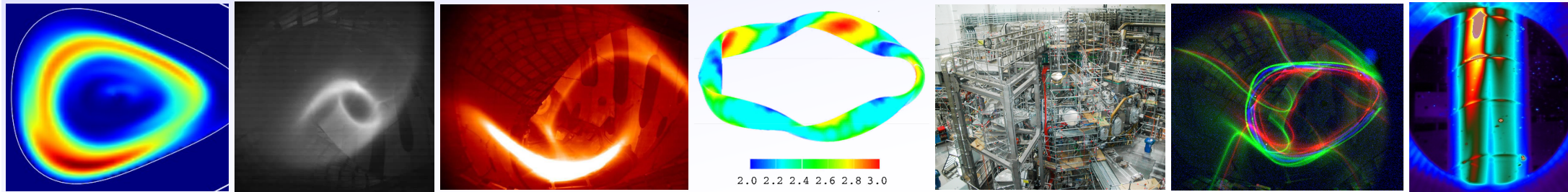
¹⁷NIFS National Institute for Fusion Science, Toki, Japan

¹⁸Australian National University, Canberra, Australia

¹⁹University of Szczecin, Poland



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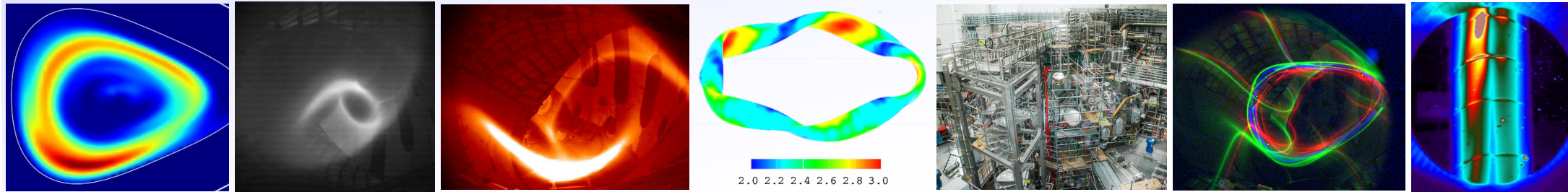
US Contributors



THE UNIVERSITY
of
WISCONSIN
MADISON



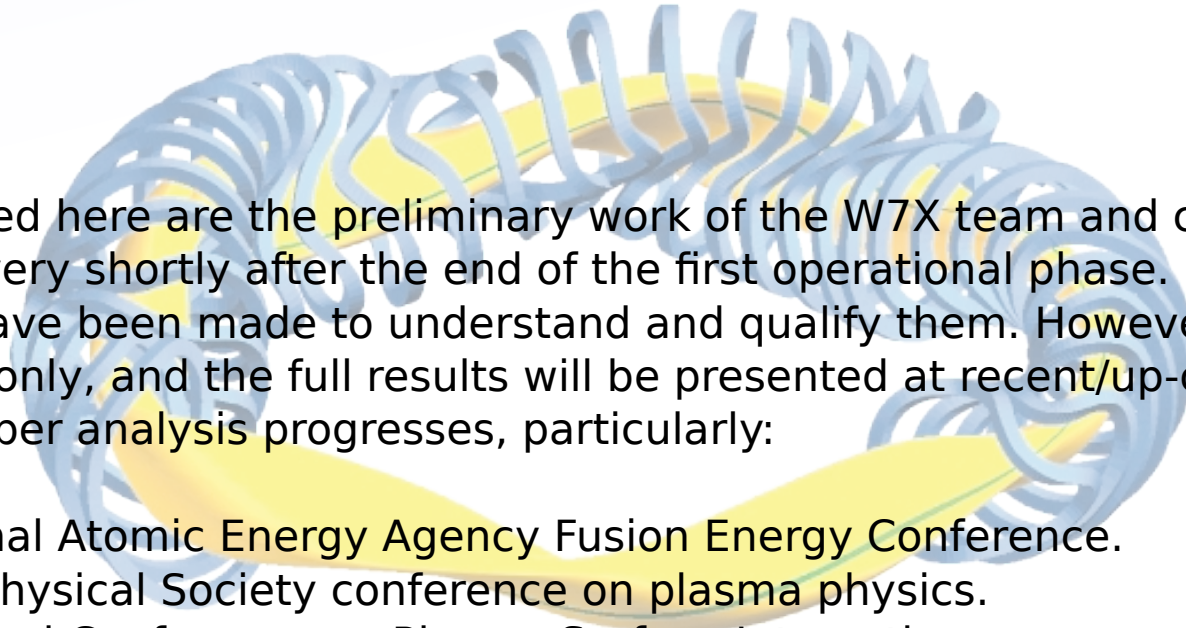
Wendelstein 7-X: Highlights from the first operational phase of a new optimised Stellarator.



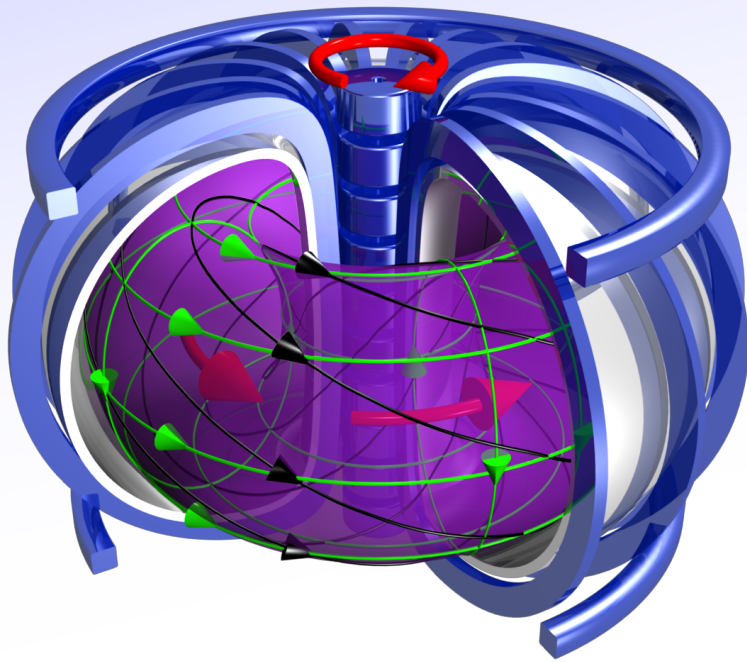
Disclaimer....

The results presented here are the preliminary work of the W7X team and collaboration partners analysed very shortly after the end of the first operational phase. Despite very little time, best efforts have been made to understand and qualify them. However, they should be taken as indicative only, and the full results will be presented at recent/up-coming conferences as deeper analysis progresses, particularly:

- 26th International Atomic Energy Agency Fusion Energy Conference.
- 43rd European Physical Society conference on plasma physics.
- 22nd International Conference on Plasma Surface Interactions.
- 58th Annual Meeting of the APS Division of Plasma Physics.

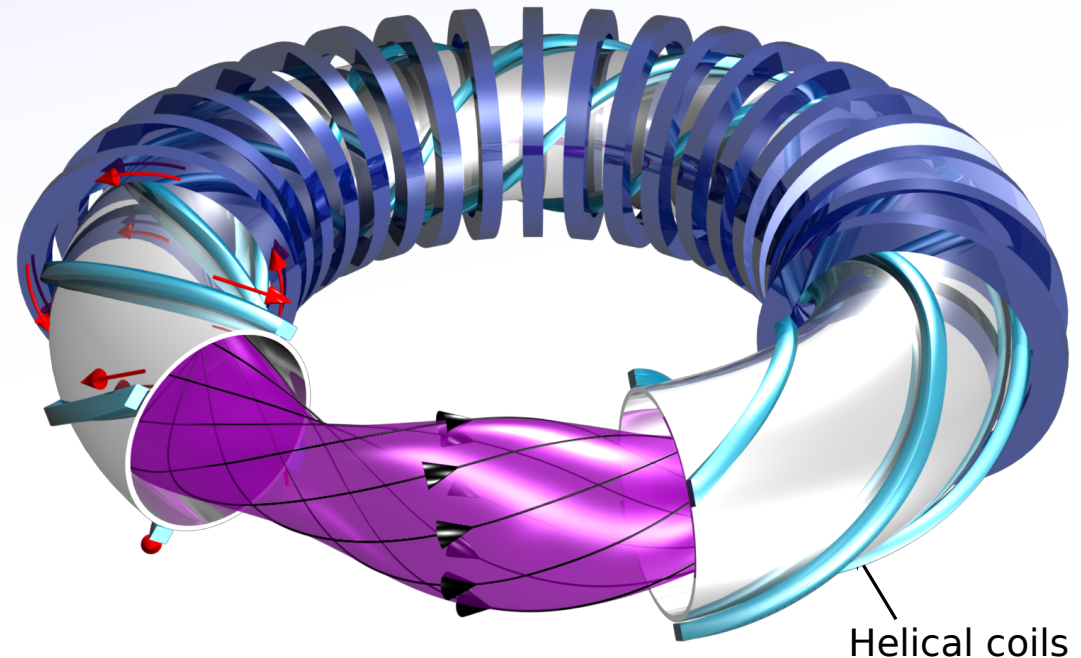


Tokamaks and Stellarators



Tokamak

- Helical field created by toroidal field and toroidal current in the plasma.
- + Good confinement.
- + Simpler construction - axisymmetric.
 - Pulsed driven transformer.
 - Current instabilities and disruptions.

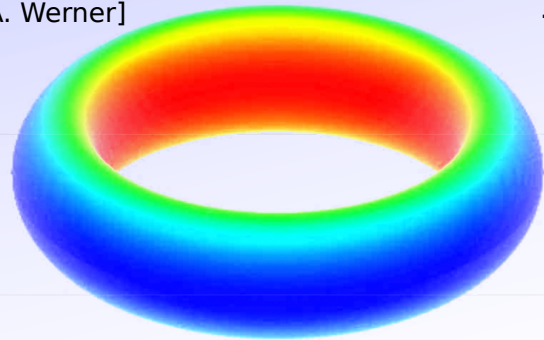


Stellarator (Classical)

- Helical field created externally by coils.
- Classically poor confinement.
- Complex construction - 3D.
 - + Inherently steady state.
 - + No current instabilities or disruptions.
 - + Higher densities.

Stellarator Optimisation

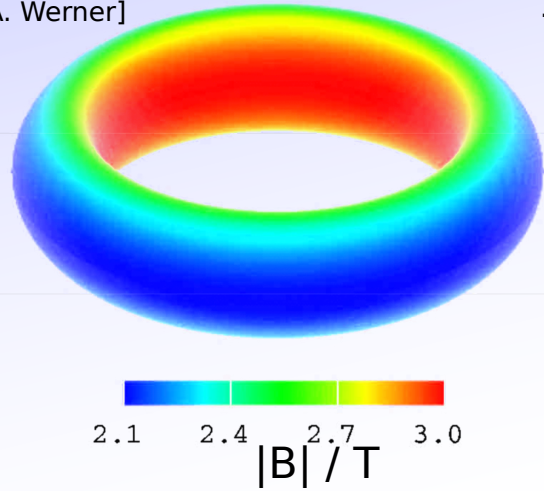
[A. Werner]



Tokamak:
Trapped particles precess
toroidally because $|B|$ is axi-
symmetric.

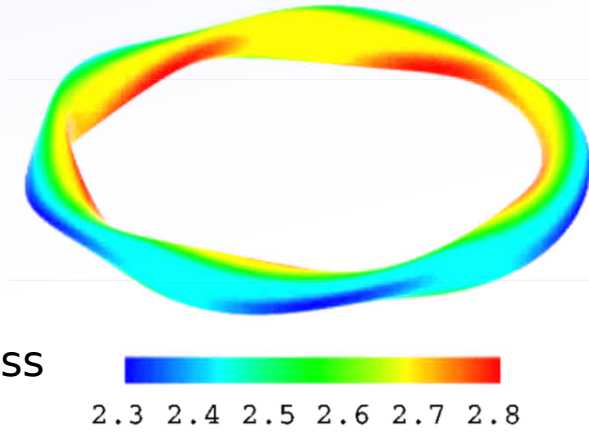
Stellarator Optimisation

[A. Werner]



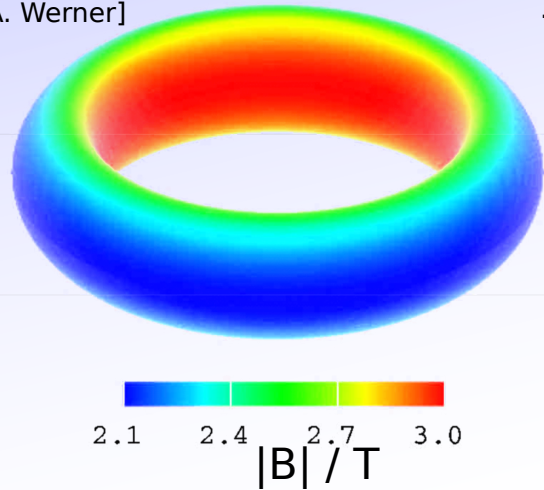
Tokamak:
Trapped particles precess
toroidally because $|B|$ is axi-
symmetric.

Classical Stellarator:
Poor neoclassical
confinement due to loss
of trapped particles.



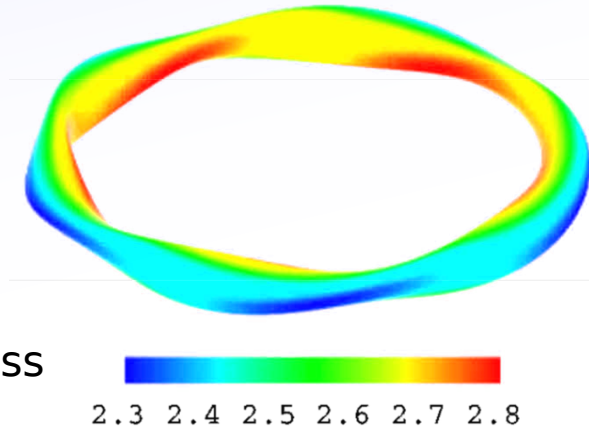
Stellarator Optimisation

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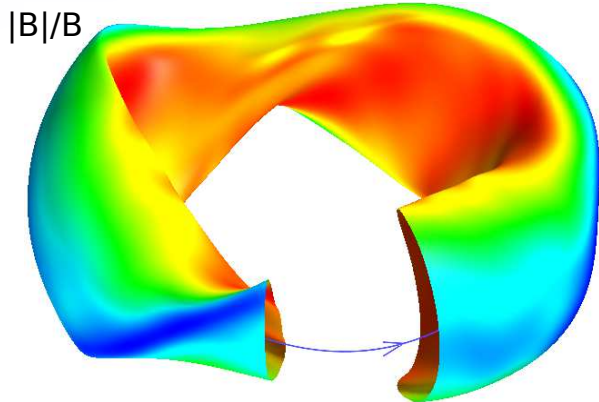


Tokamak:
Trapped particles precess toroidally because $|B|$ is axis-symmetric.

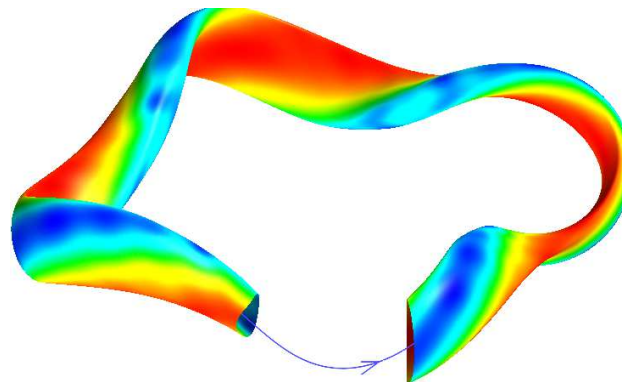
Classical Stellarator:
Poor neoclassical confinement due to loss of trapped particles.



Optimised Stellarator: Create a field with a quasi-symmetry of $|B|$ in some direction:



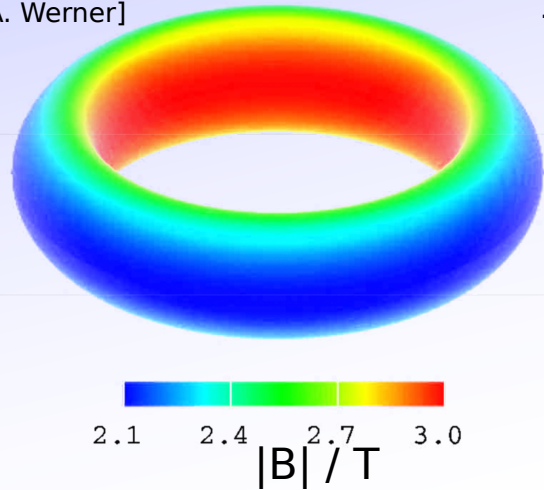
Quasi-axisymmetric
(NCSX: National Compact Stellarator Experiment)



Quasi-helically symmetric:
(HSX: Helically Symmetric Experiment)

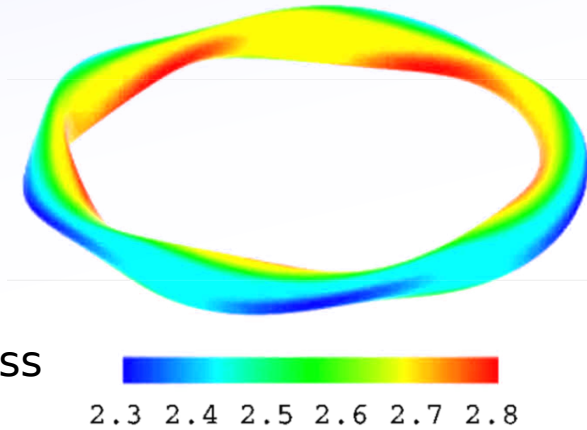
Stellarator Optimisation

[A. Werner]

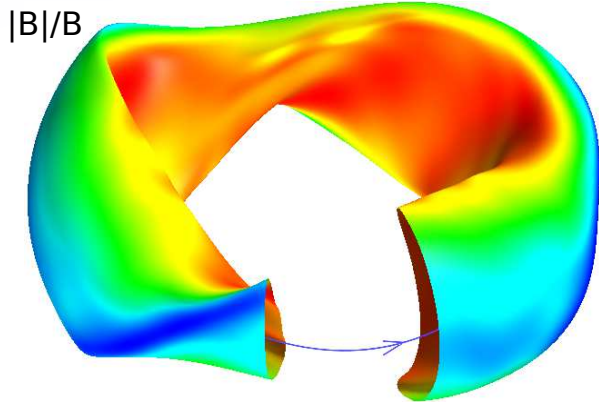


Tokamak:
Trapped particles precess toroidally because $|B|$ is axis-symmetric.

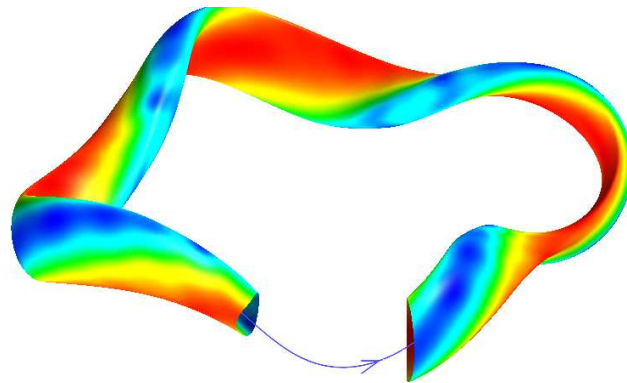
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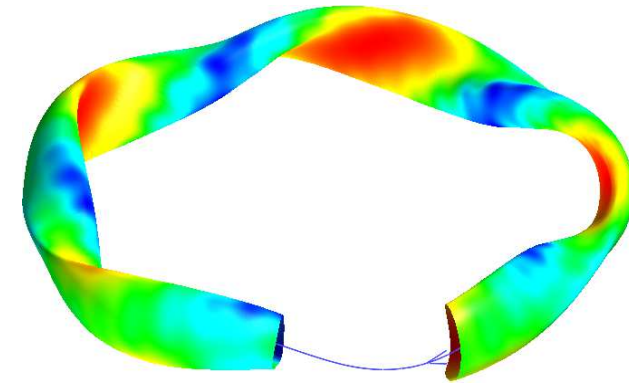
Optimised Stellarator: Create a field with a quasi-symmetry of $|B|$ in some direction:



Quasi-axisymmetric
(NCSX: National Compact Stellarator Experiment)

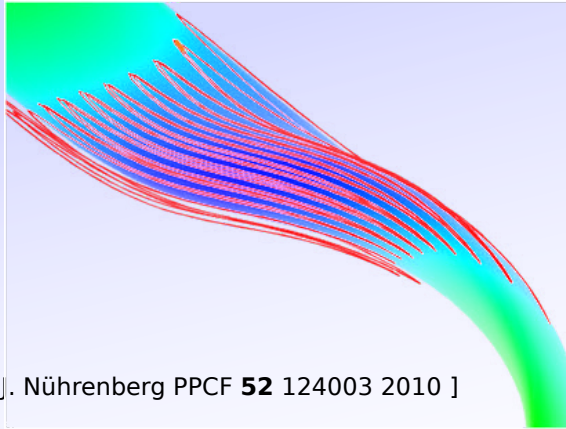


Quasi-helically symmetric:
(HSX: Helically Symmetric Experiment)

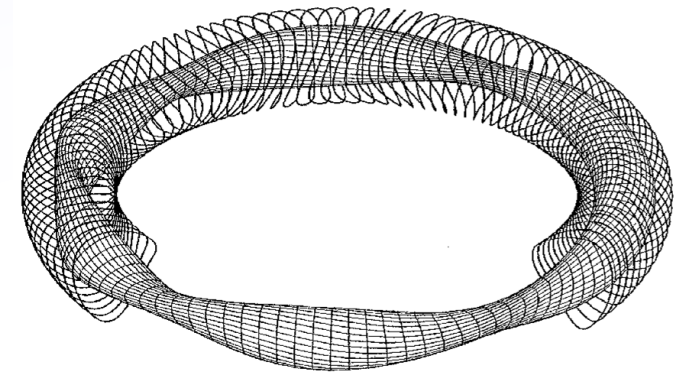


Quasi-isodynamic:
Mixed symmetry chosen to minimise bootstrap current.
(Wendelstein 7-X)

Stellarator Optimisation



W7X: At high β ($\sim 5\%$), trapped particles should precess \sim poloidally, remaining confined (in one module).

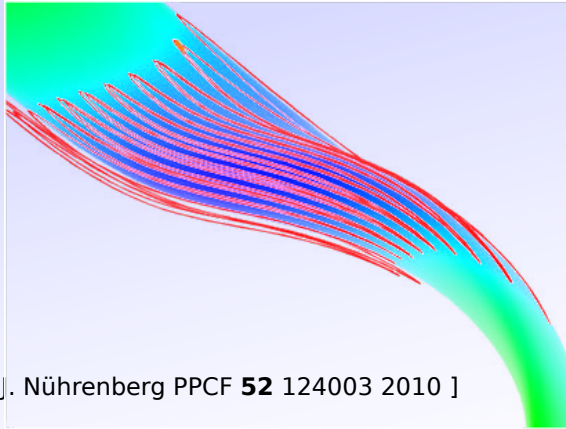


[J. Nührenberg PPCF **52** 124003 2010]

Optimisation of W7-X:

1. Feasible modular coils (no toroidal conductors)
2. Good, nested magnetic surfaces
3. Good finite- β equilibria
4. Good MHD stability
5. Small neoclassical transport
6. Small bootstrap current
7. Good confinement of fast particles

Stellarator Optimisation



W7X: At high β ($\sim 5\%$), trapped particles should precess \sim poloidally, remaining confined (in one module).

[J. Nührenberg PPCF **52** 124003 2010]

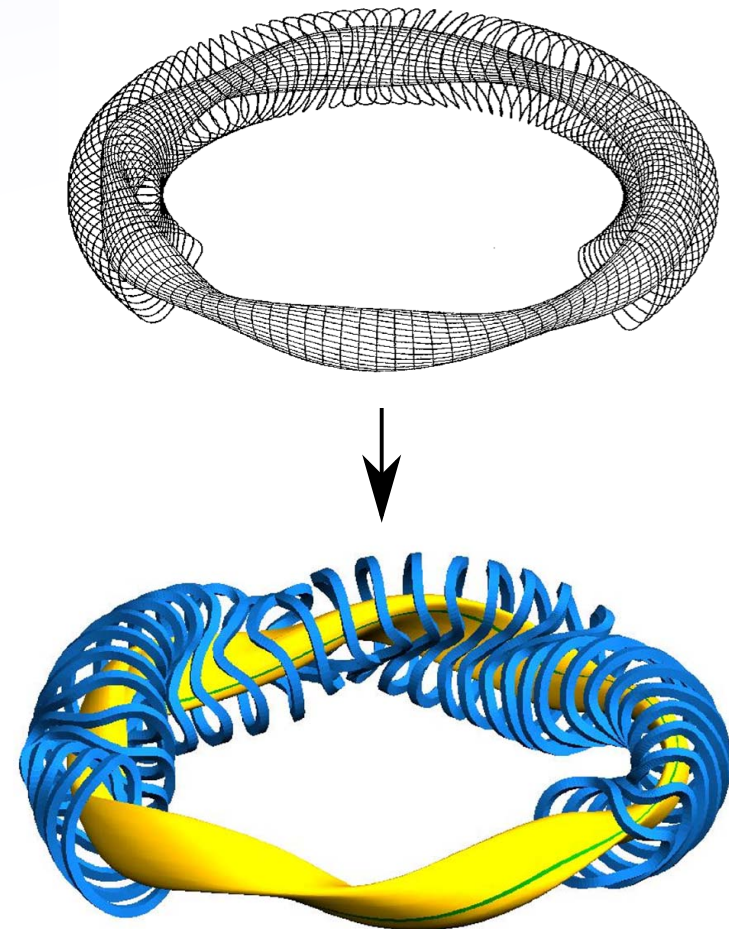
Optimisation of W7-X:

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2. Good, nested magnetic surfaces
3. Good finite- β equilibria
4. Good MHD stability
5. Small neoclassical transport
6. Small bootstrap current
7. Good confinement of fast particles

--> Feasible but still complex coil design,
required precision much higher than a Tokamak.
Can such a coil set be built?

Missions:

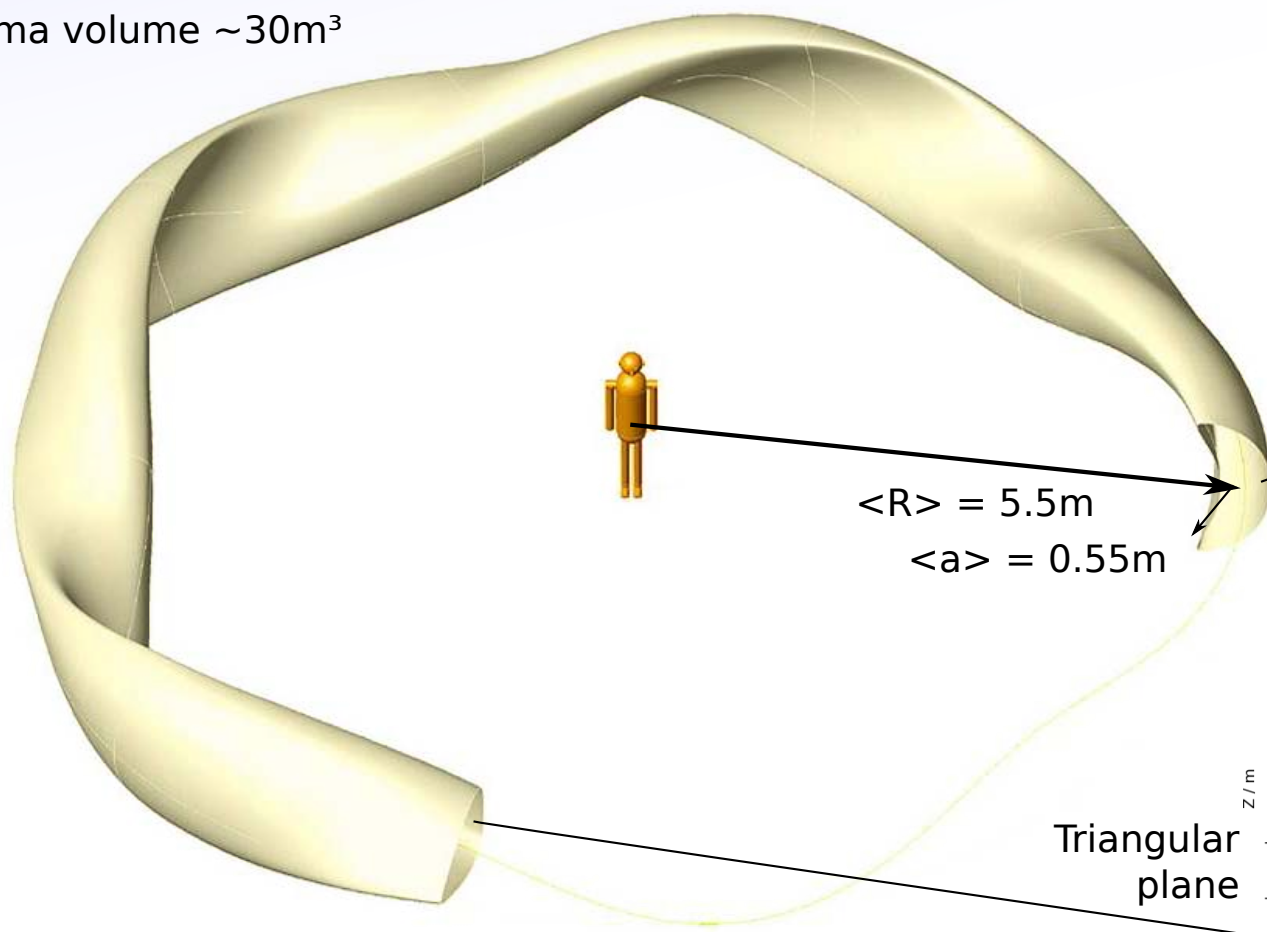
- Build Wendelstein 7-X to the required precision.
- Verify construction by showing good vacuum flux surfaces.
- Confirm optimisation of neoclassical confinement - is it at Tokamak level?
- Show sufficient confinement of fast-ions.
- Demonstrate steady-state operation at a relevant plasma β .



W7-X Construction

Steady-state operation requires steady-state coils --> Super-conducting --> Even more complexity!
After a lot of R&D, the final design of W7-X was complete:

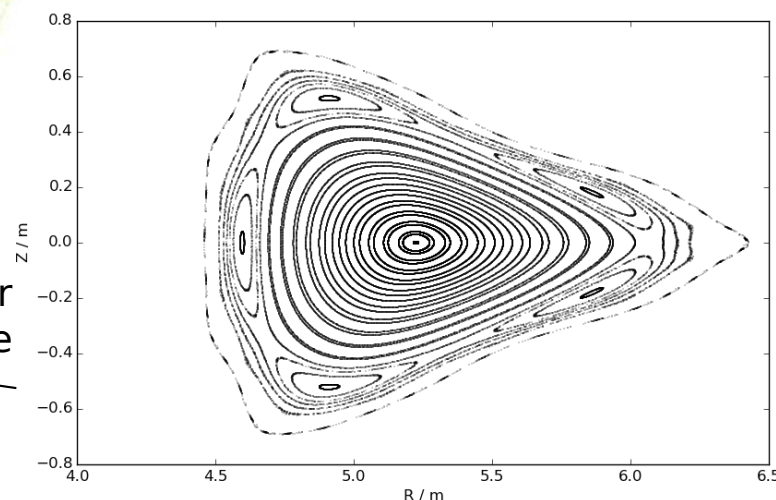
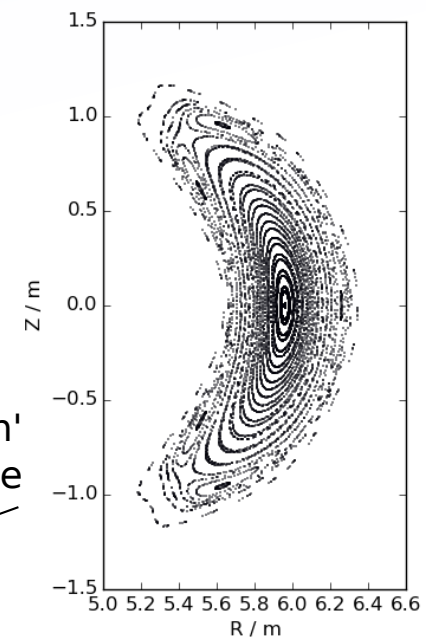
Plasma volume $\sim 30\text{m}^3$



$\langle R \rangle = 5.5\text{m}$
 $\langle a \rangle = 0.55\text{m}$

'Bean'
plane

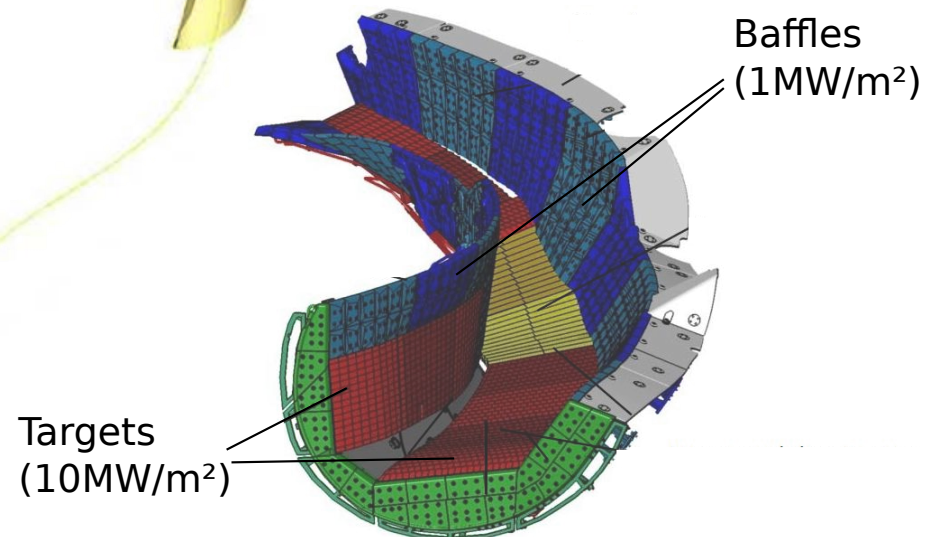
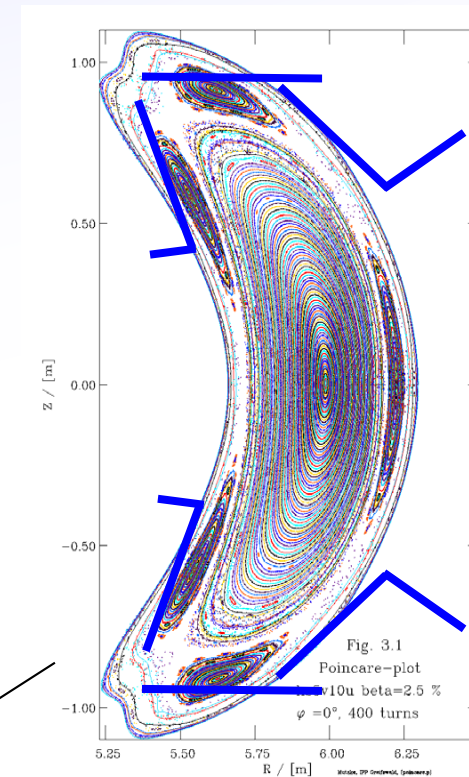
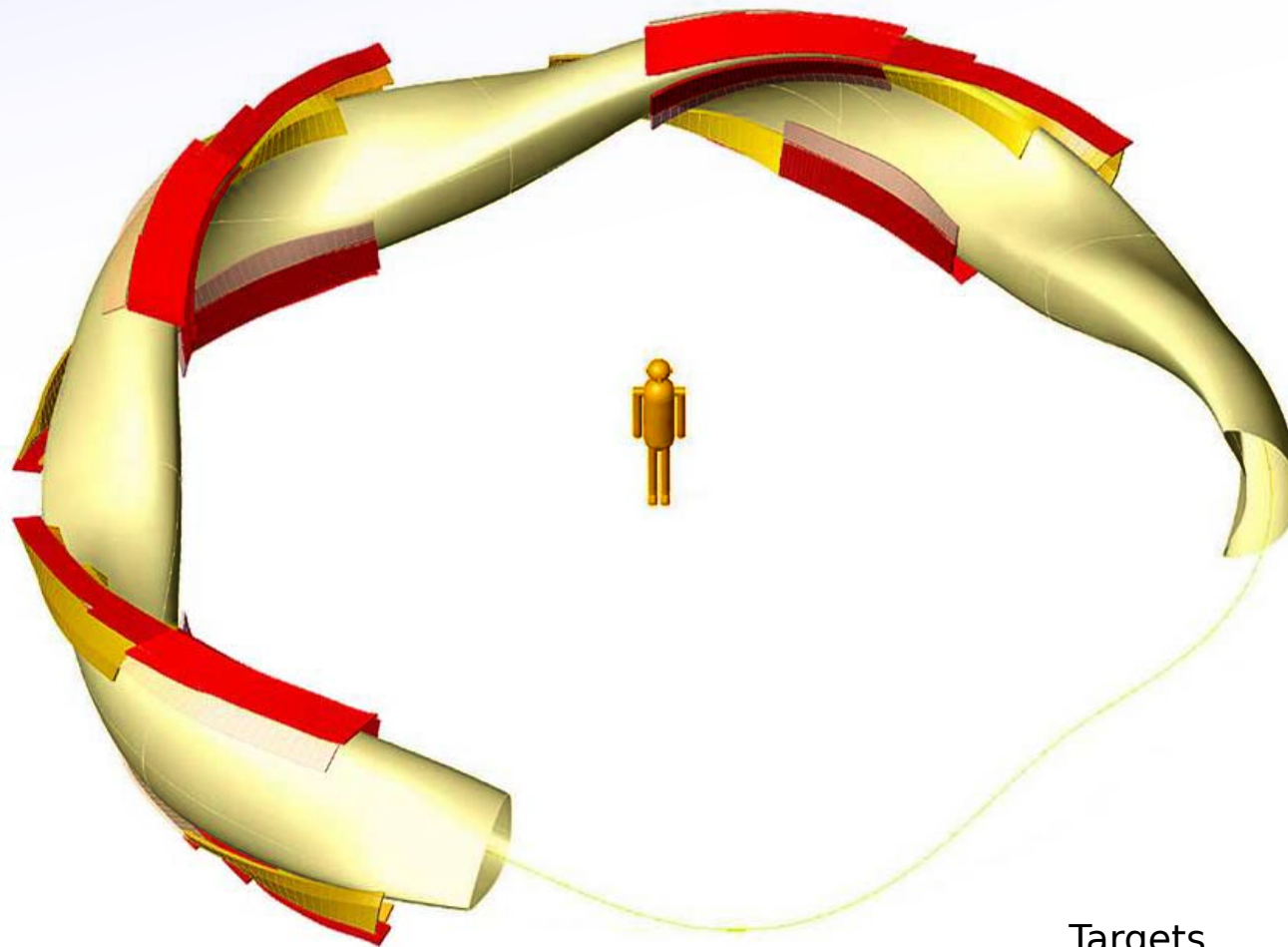
Triangular
plane



W7-X Construction

Island Divertor:

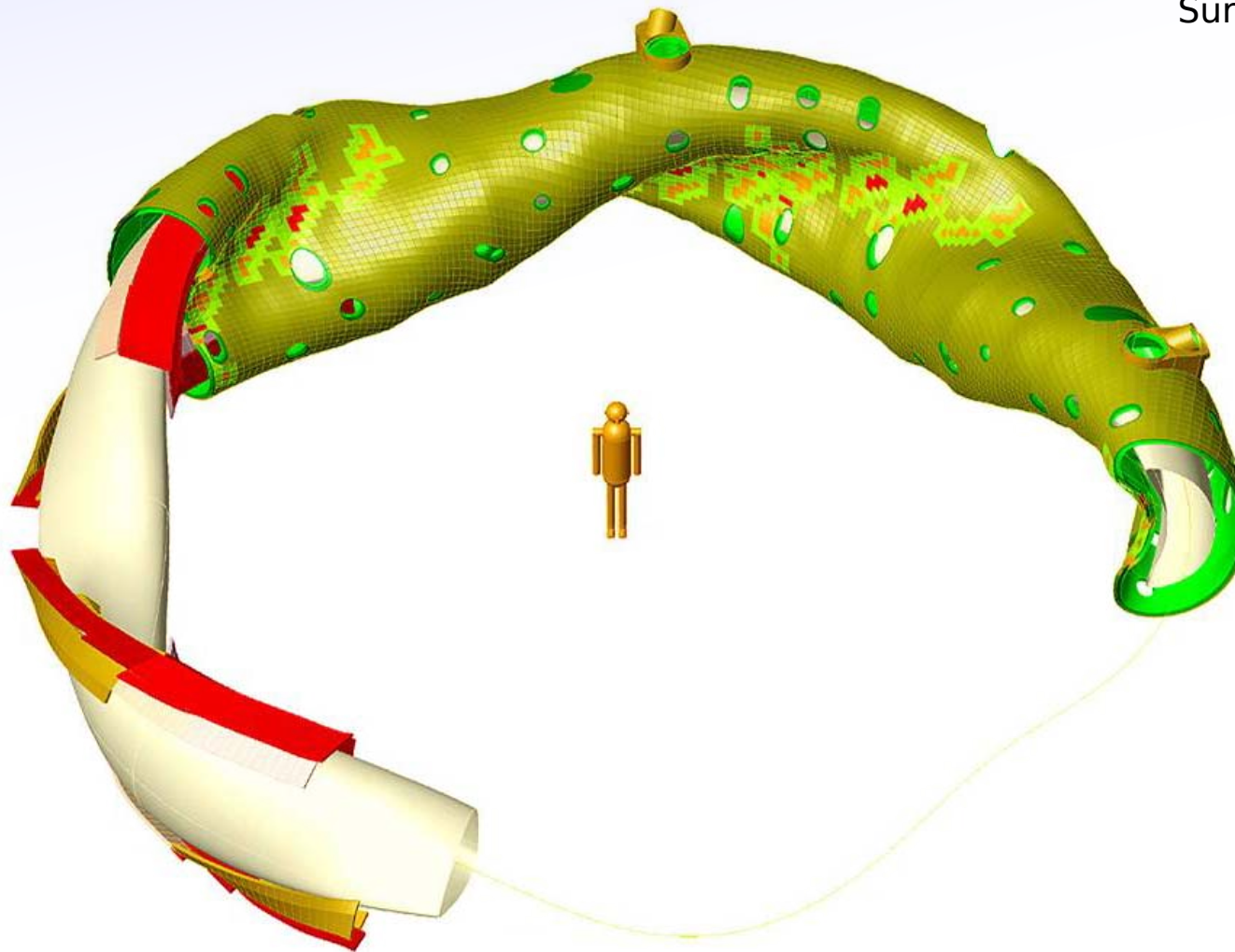
Island chain at plasma edge functions like a Tokamak divertor to bring highest heat-loads to special target plates, away from the plasma edge.



W7-X Construction

Vacuum Vessel

Vacuum Vessel:
Volume: 84m^3
Surface area: $\sim 200\text{m}^2$



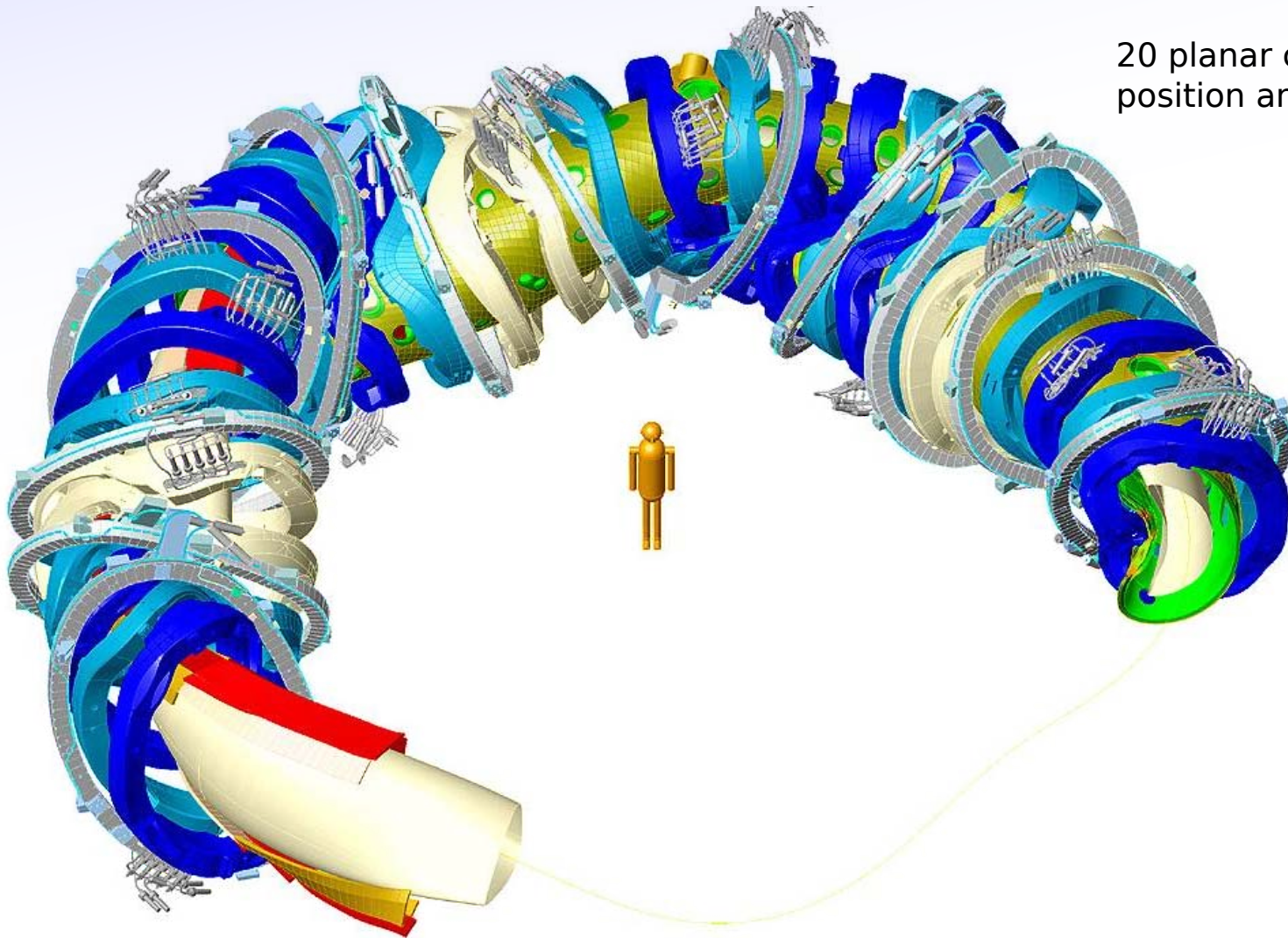
W7-X Construction

Magnetic Coils

Super-conducting coils:

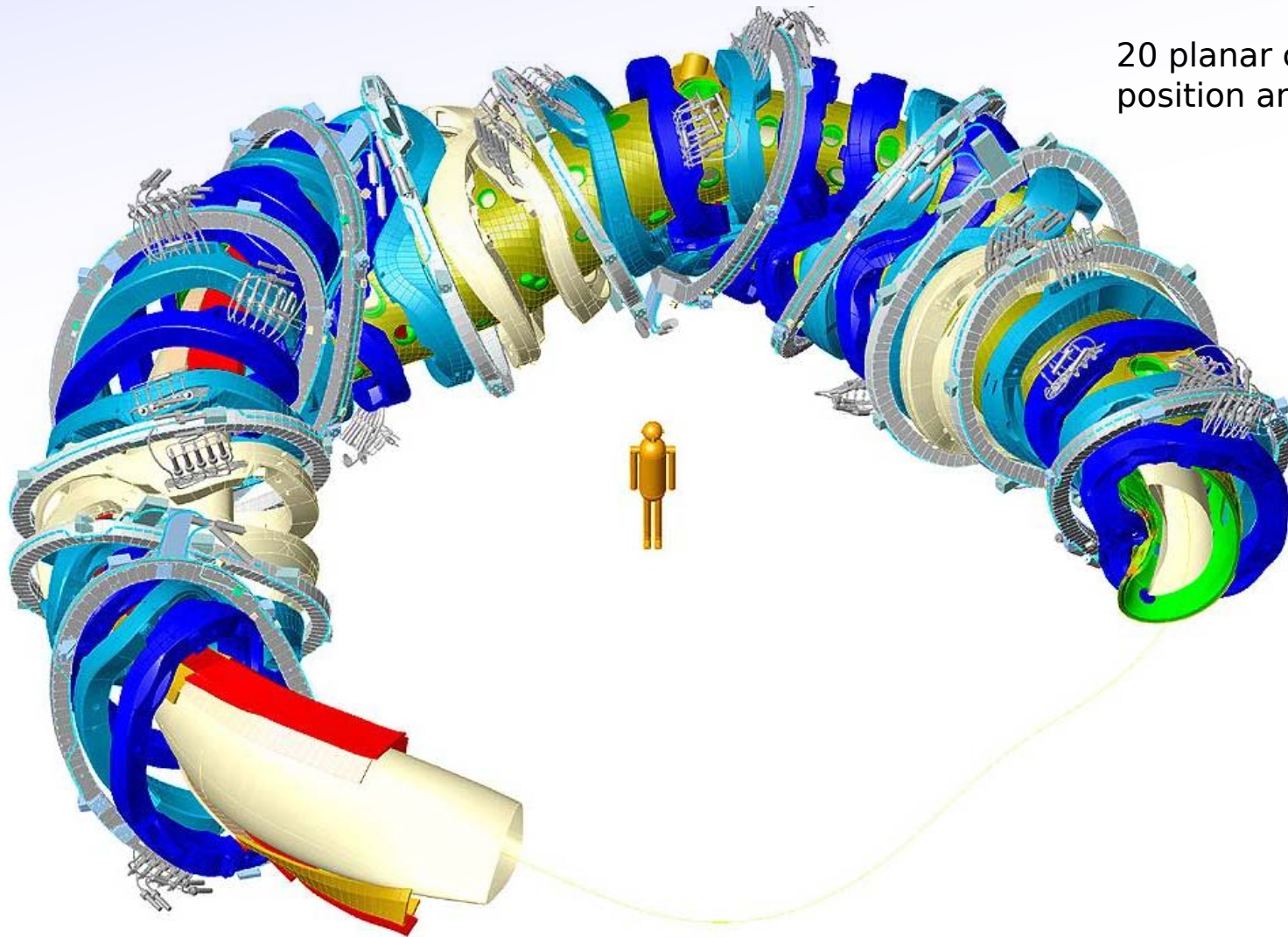
50 complex non planar coils create the standard optimised magnetic configuration.

20 planar coils allow adjustment of plasma position and rotational transform.



W7-X Construction

Magnetic Coils



Super-conducting coils:

50 complex non planar coils create the standard optimised magnetic configuration.

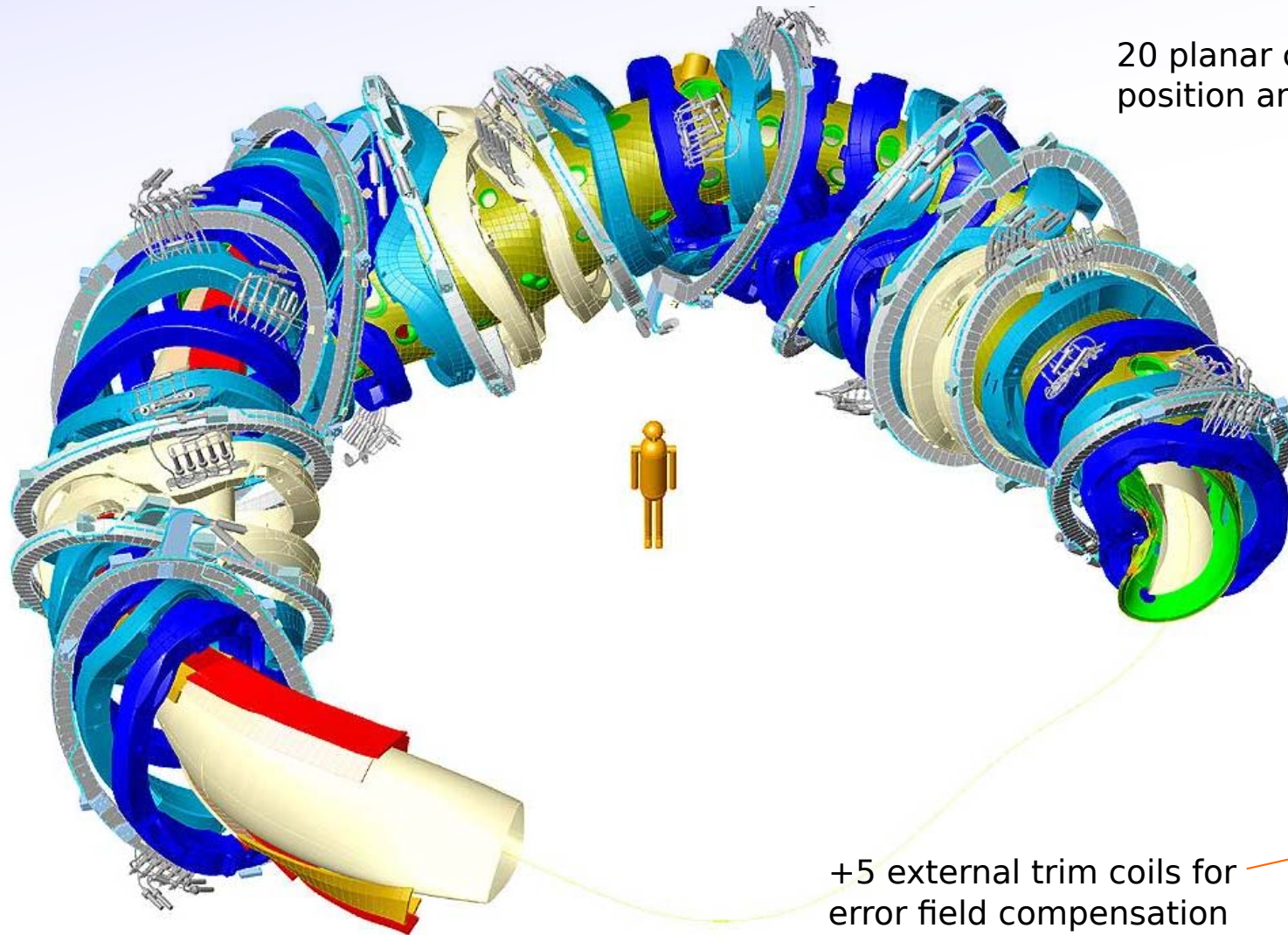
20 planar coils allow adjustment of plasma position and rotational transform.

Non-superconducting coils:

10 control/sweep coils for modifying the edge and moving the divertor strike points.

W7-X Construction

Magnetic Coils



Super-conducting coils:

50 complex non planar coils create the standard optimised magnetic configuration.

20 planar coils allow adjustment of plasma position and rotational transform.

Non-superconducting coils:

10 control/sweep coils for modifying the edge and moving the divertor strike points.

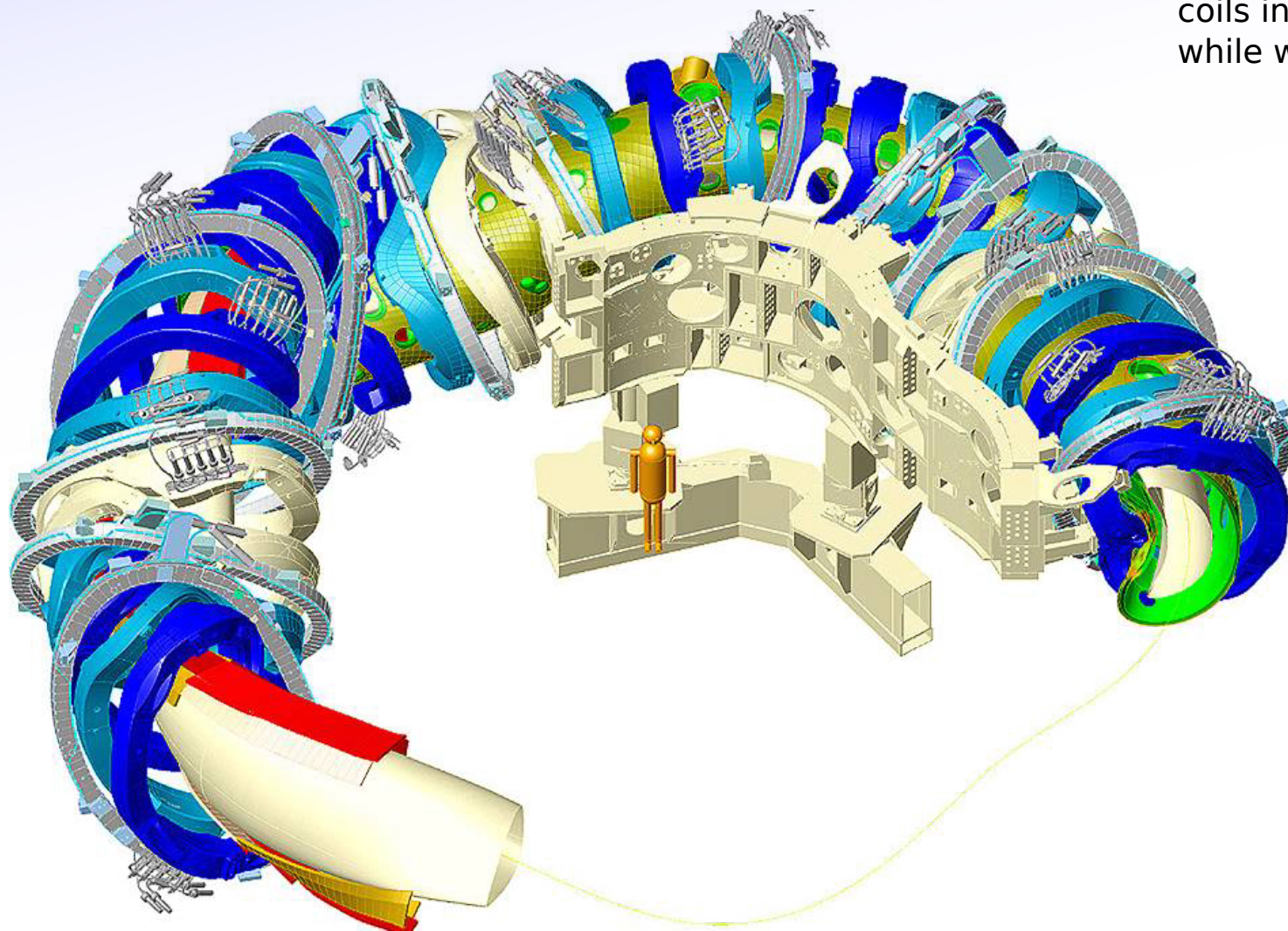
+5 external trim coils for error field compensation and plasma positioning (provided by PPPL)



W7-X Construction

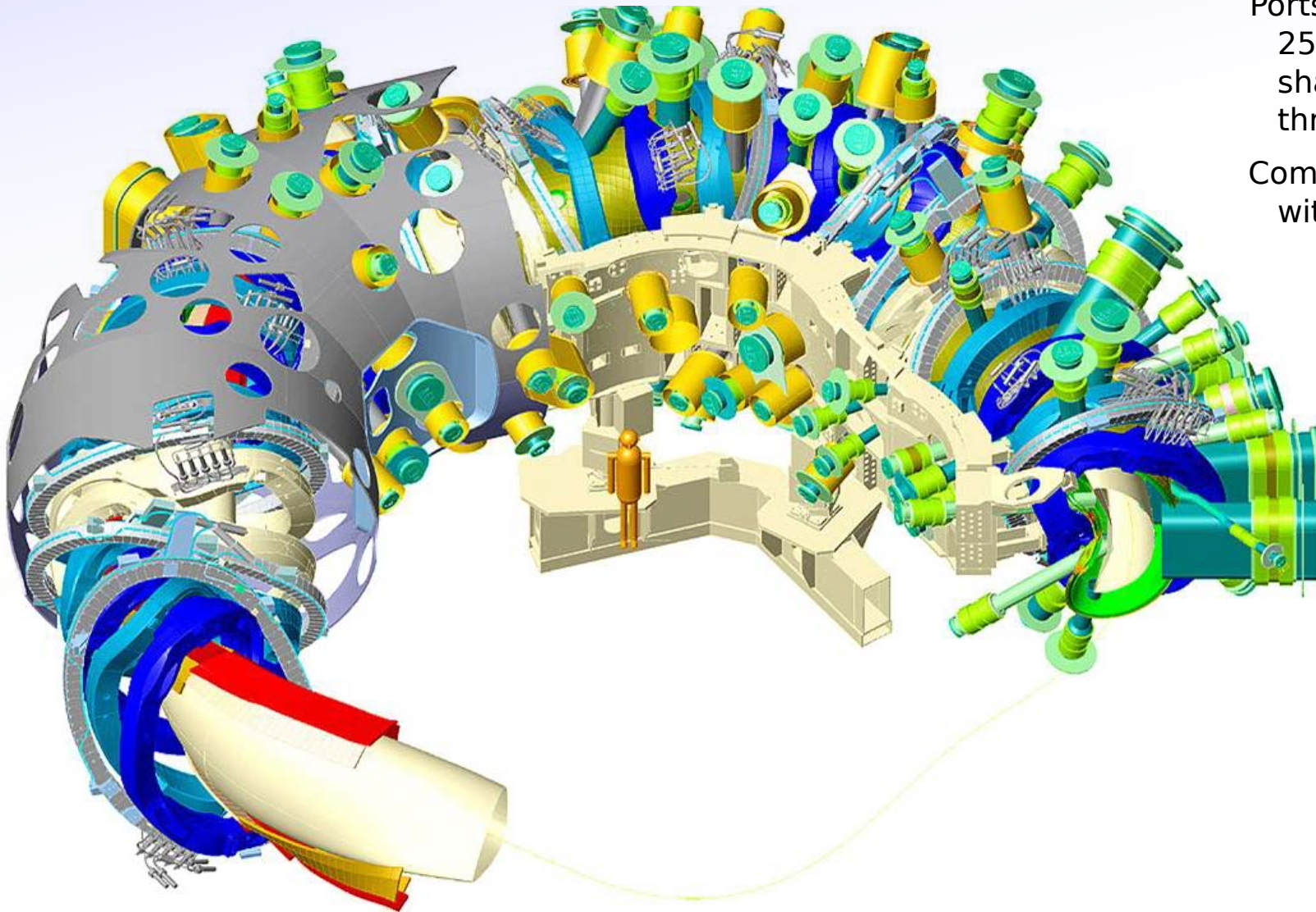
Support structure:

Support structure required to support coils in position to \sim mm precision while withstanding \sim 100t forces.



W7-X Construction

Ports and Cryostat



Cryostat:

Liquid helium cooling for all superconducting coils.

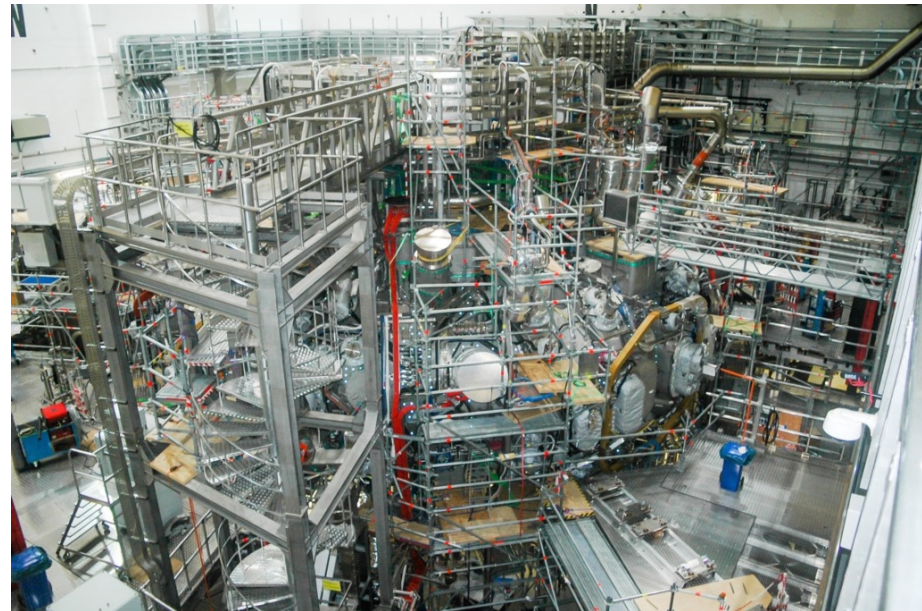
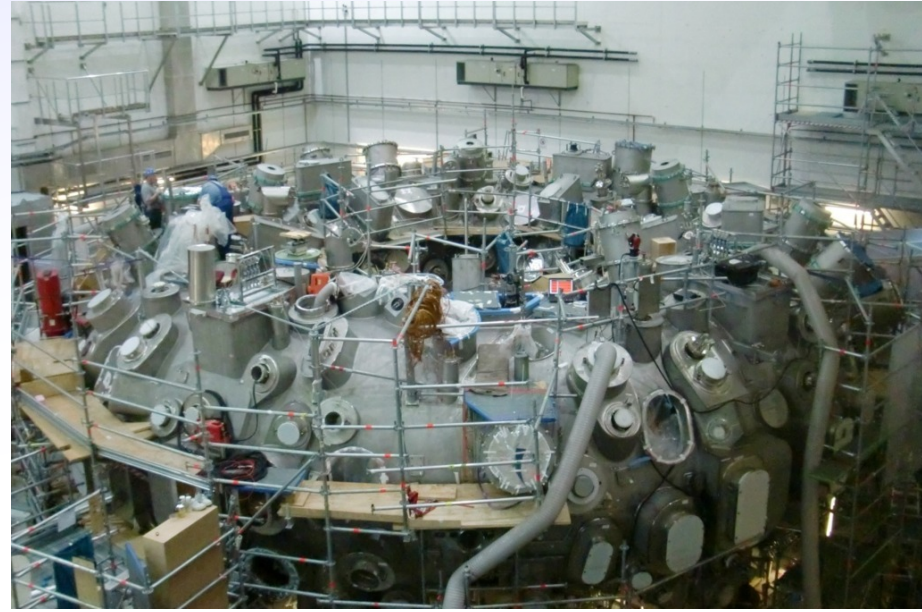
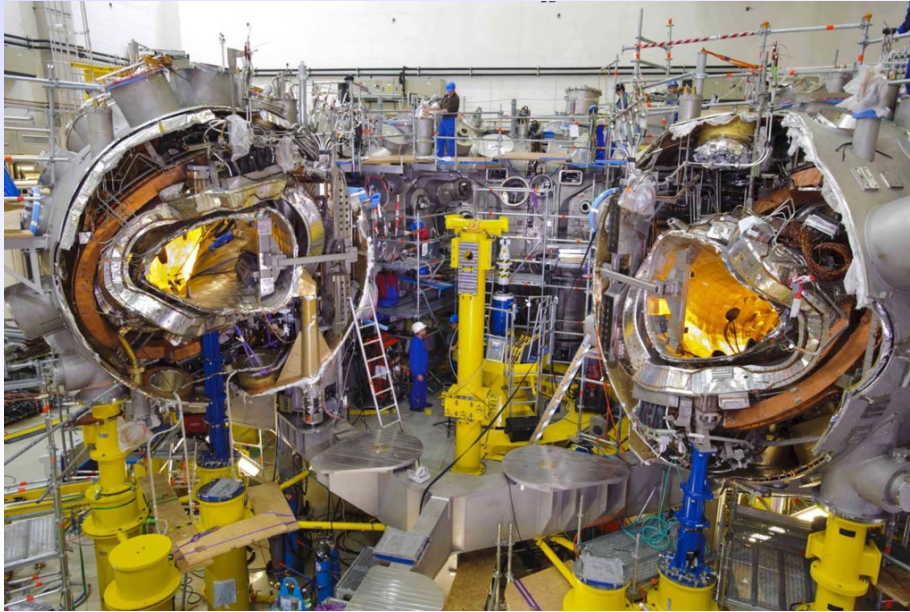
Ports:

253 ports of wide range of shapes and sizes for feed-throughs and diagnostics.

Complete construction 735t with 435t cold mass.

W7-X Construction

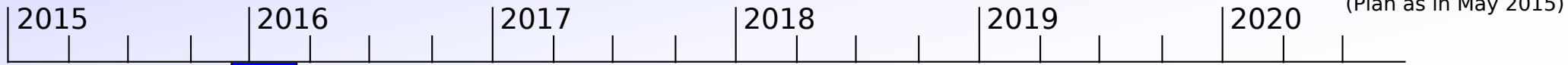
Construction was completed by 2013.



✓ Build Wendelstein 7-X to the required precision.

W7-X Operational Phases

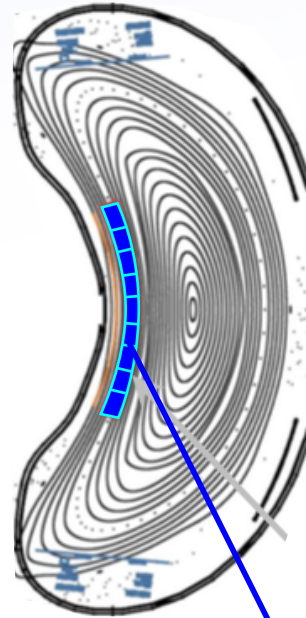
- Steady-state operation is a long term goal. 10MW/m² 'high heat flux' divertor will take longer to construct.



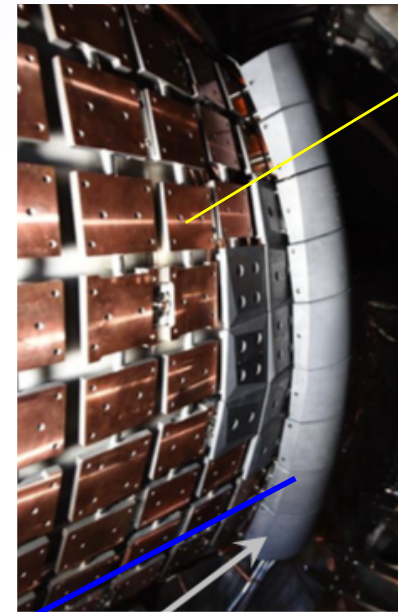
OP1.1

OP1.1: Limiter phase

- 5 Graphite inboard limiters.
- No tiles protecting the inner wall.
- Pulse energy restricted to 2MJ (planned).
- Very limited diagnostic and heating systems.



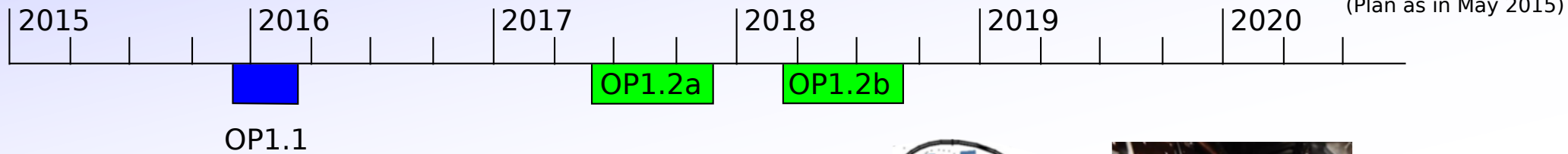
Poloidal Limiter



Unprotected copper mounting points

W7-X Operational Phases

- Steady-state operation is a long term goal. 10MW/m² 'high heat flux' divertor will take longer to construct.

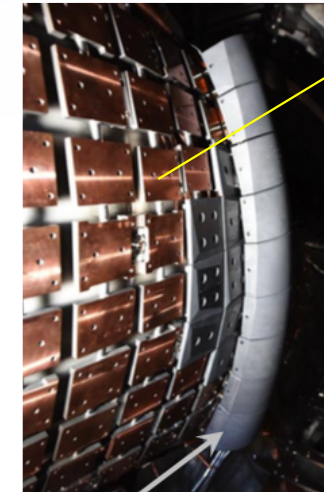
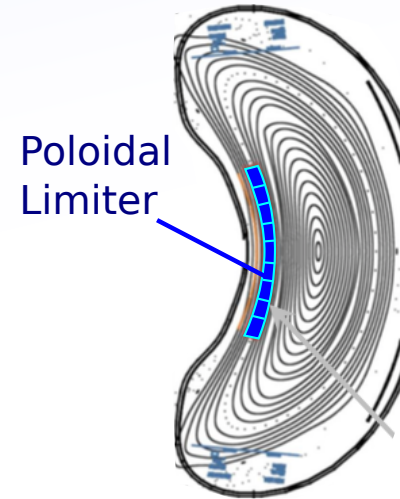


OP1.1: Limiter phase

- 5 Graphite inboard limiters.
- No tiles protecting the inner wall.
- Pulse energy restricted to 2MJ (planned).
- Very limited diagnostic and heating systems.

OP1.2: Test divertor phase.

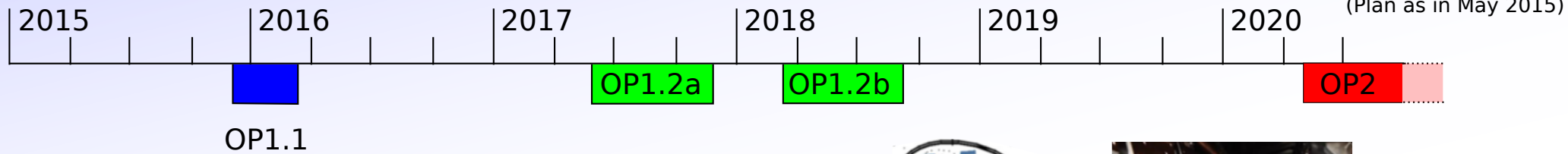
- Inertially cooled 'test' divertor unit (TDU)
- Water cooled heat shield tiles and panels.
- Pulse energy up to 80MJ, 10 seconds. Max power 10MW.
- Many more diagnostic systems
- NBI heating.



OP1.2: Test Divertor Unit

W7-X Operational Phases

- Steady-state operation is a long term goal. 10MW/m² 'high heat flux' divertor will take longer to construct.



OP1.1: Limiter phase

- 5 Graphite inboard limiters.
- No tiles protecting the inner wall.
- Pulse energy restricted to 2MJ (planned).
- Very limited diagnostic and heating systems.

OP1.2: Test divertor phase.

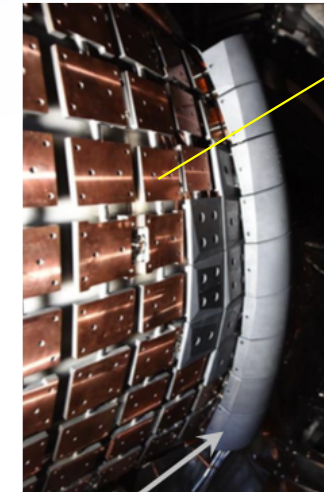
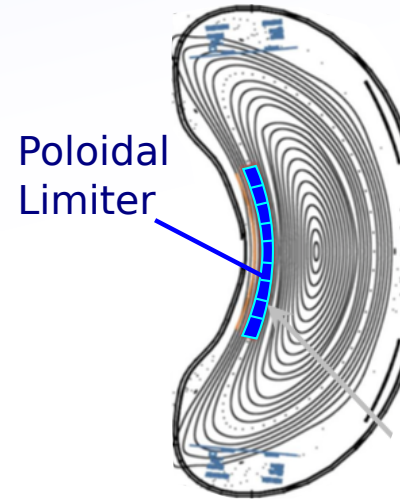
- Inertially cooled 'test' divertor unit (TDU)
- Water cooled heat shield tiles and panels.
- Pulse energy up to 80MJ, 10 seconds. Max power 10MW.
- Many more diagnostic systems
- NBI heating.

OP2: Steady-state phase.

- Actively cooled high heat flux (HHF) divertor.
- All wall components water cooled.
- 10MW for up to 30 minutes, 20MW pulsed.
- Full steady-state capable diagnostics suite.

???: Future phases

- Tungsten wall??



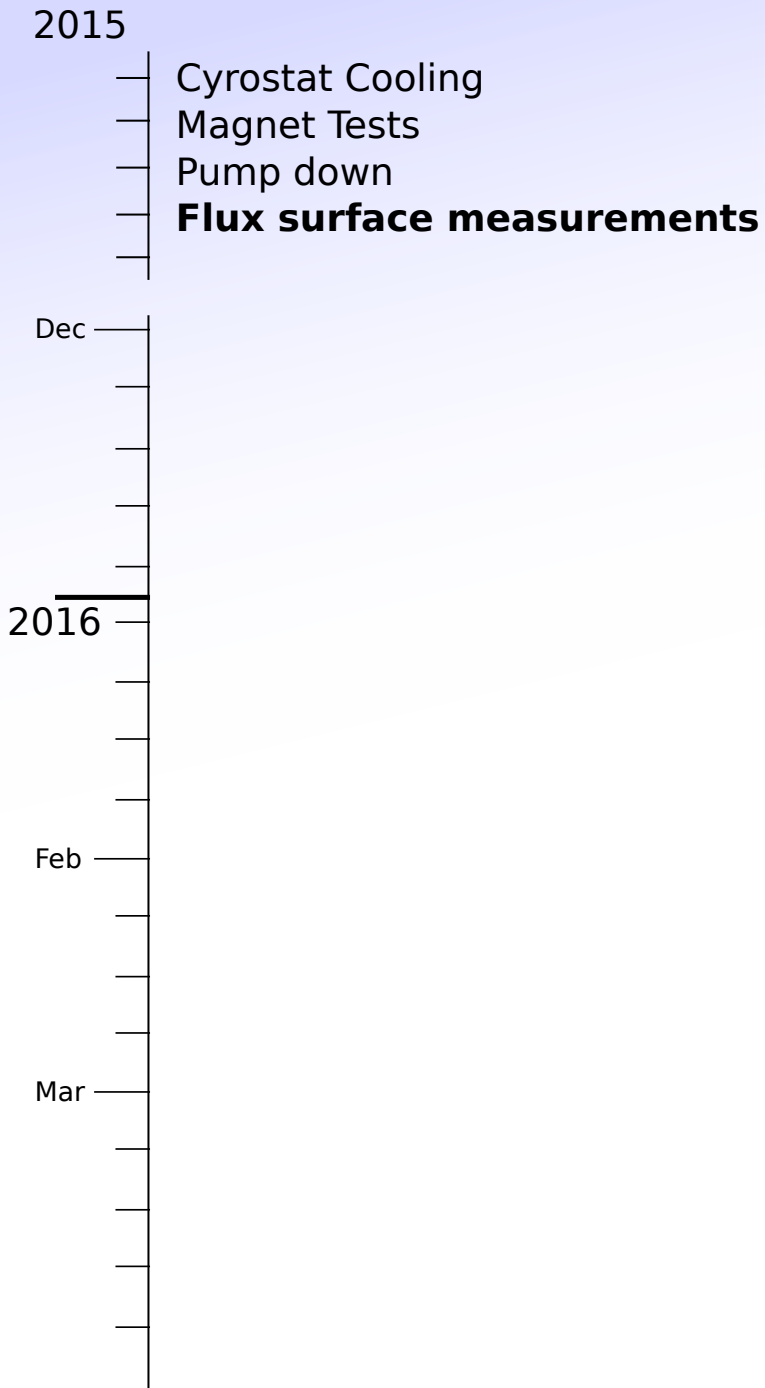
OP1.2: Test Divertor Unit

OP2: High Heat Flux divertor



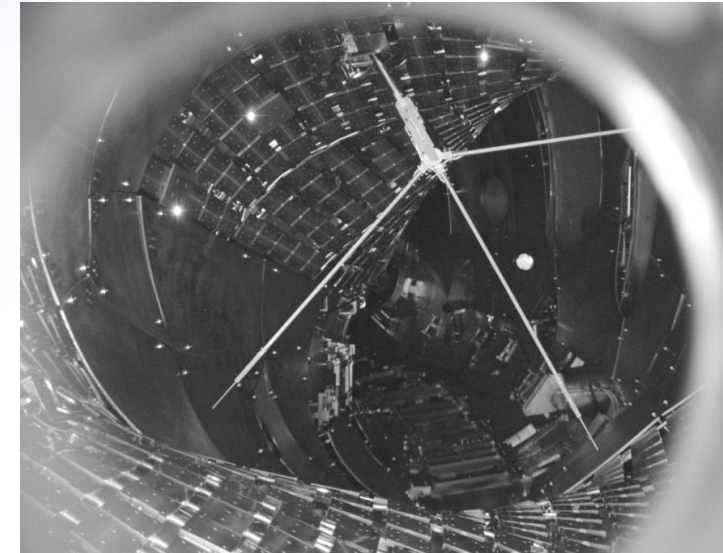
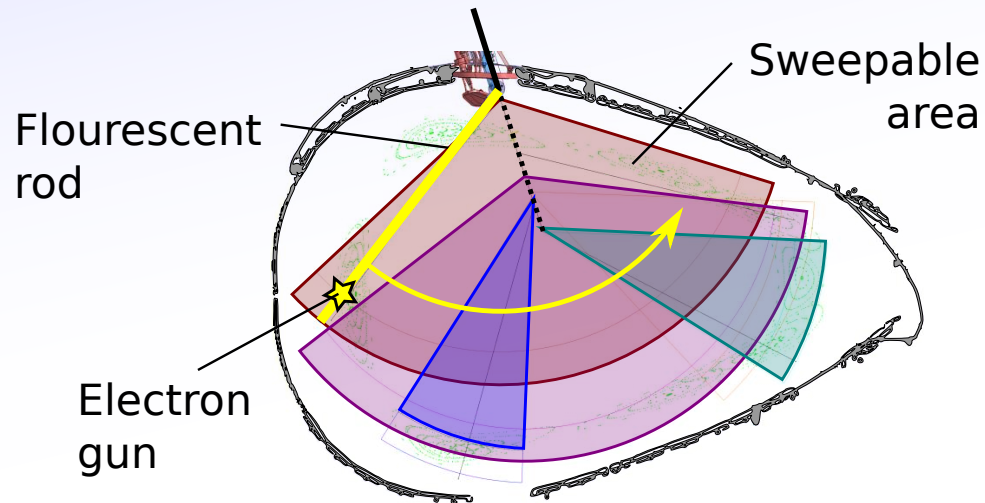


Start-up: Timeline



Flux surfaces

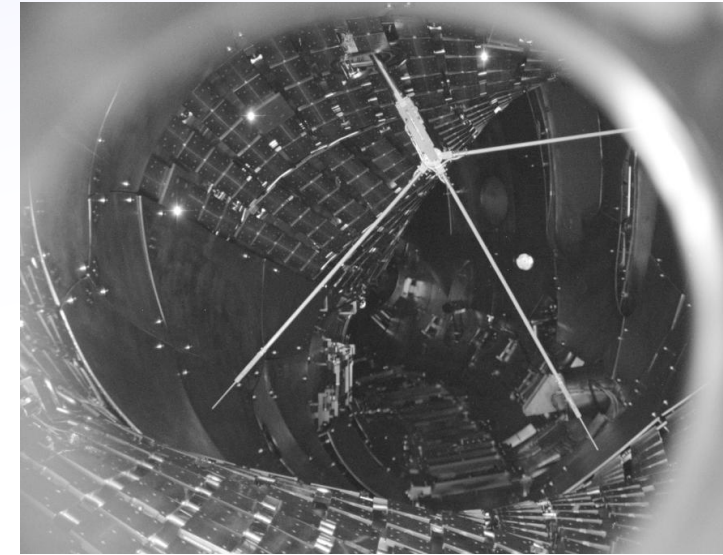
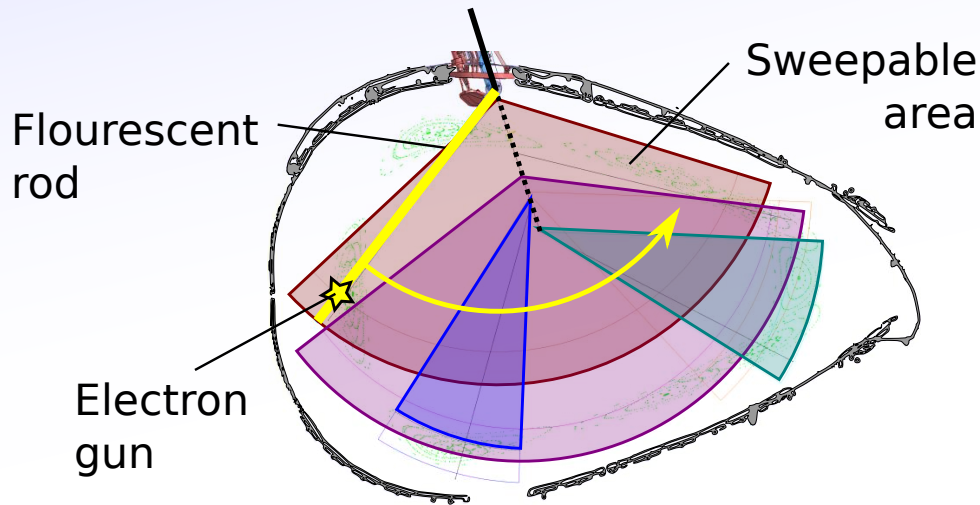
- 2x 90cm retractable fluorescent rods, with an electron gun near the tip.
- Rods extend into the vessel and sweep the poloidal plane.
- Electrons follow field lines until they interact with the rod or background gas.
- Electron interaction viewed by video cameras.



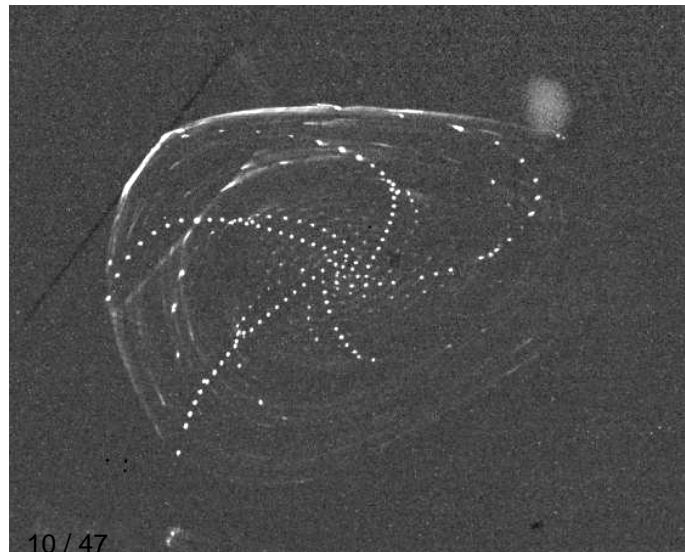
Video system viewing
the manipulator.

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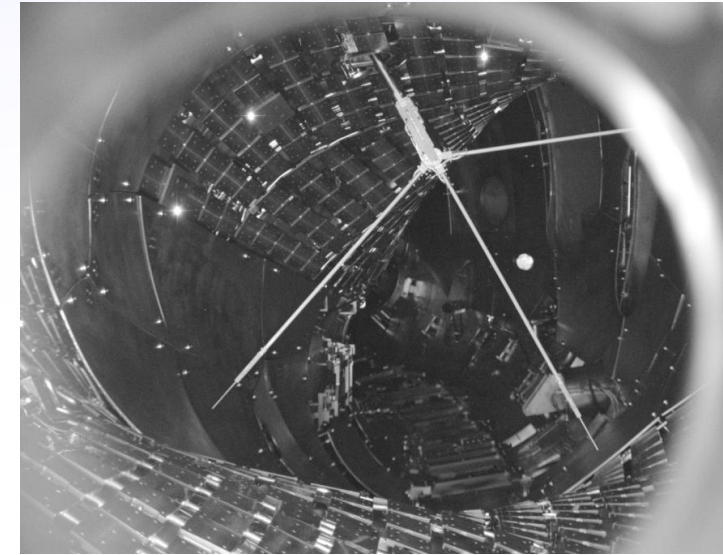
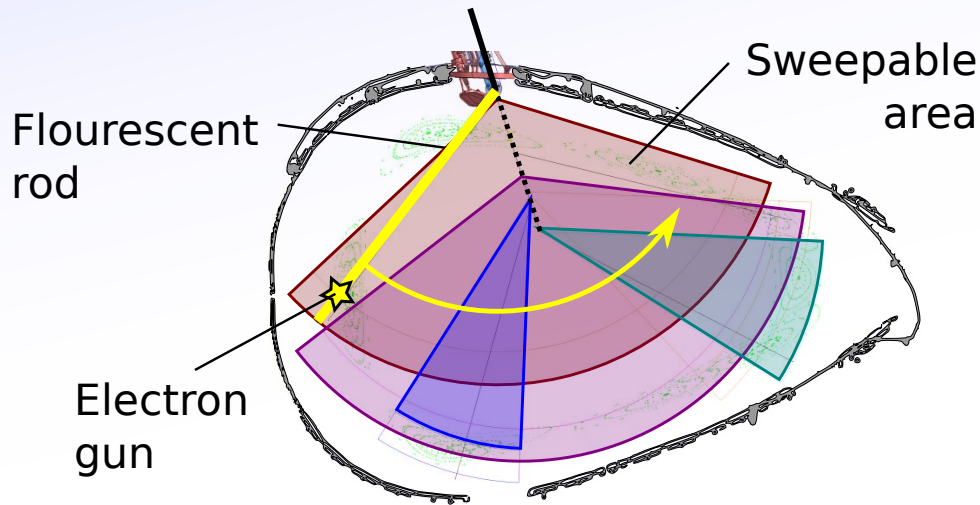
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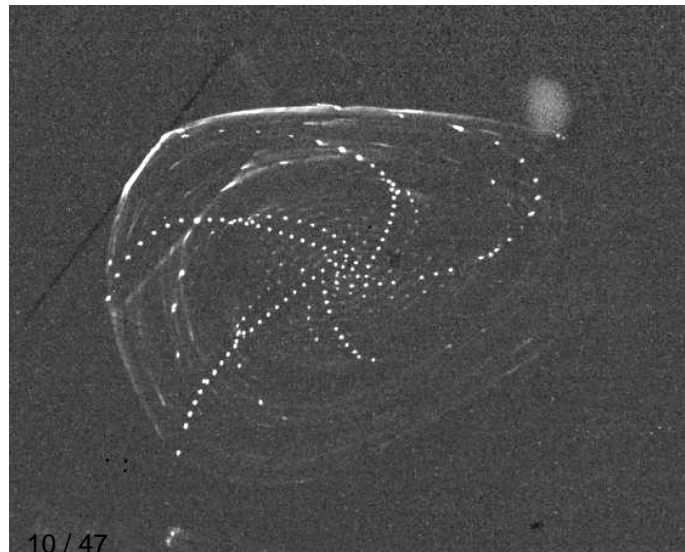
← Typical scan of OP1.1 surfaces using flourescent rod. Confirms good, symmetric, non-disturbed flux surfaces for $0.4T < B < 2.5T$.

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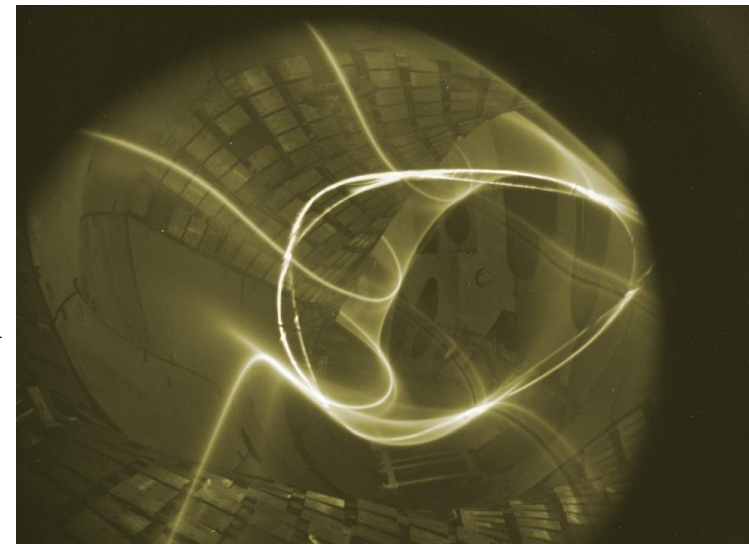


Video system viewing the manipulator.



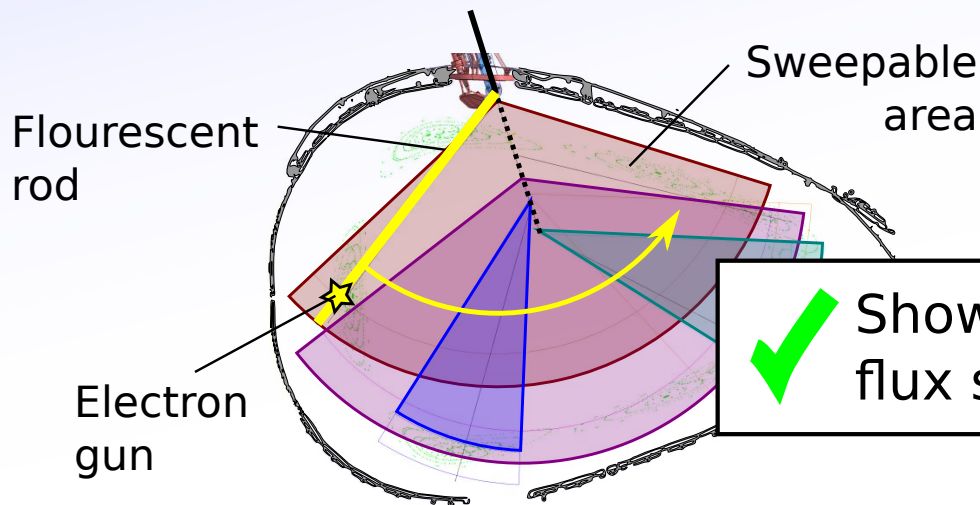
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5/6 Island chain with fluorescent rod and background gas. Islands have expected position, orientation and symmetry. →

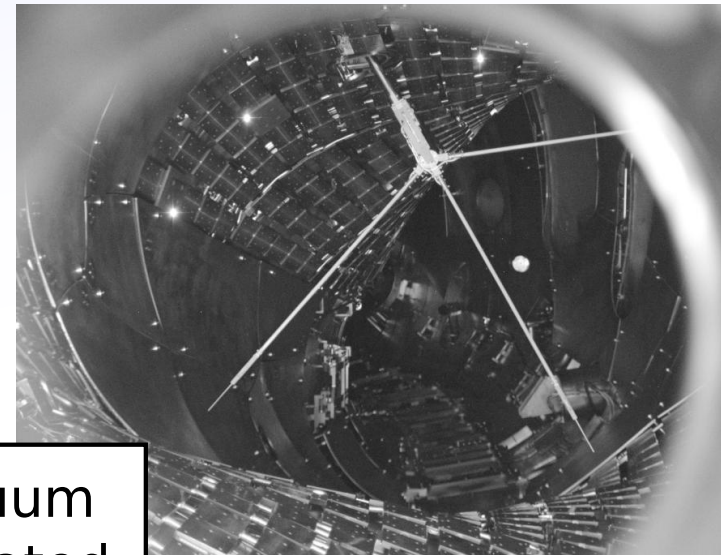


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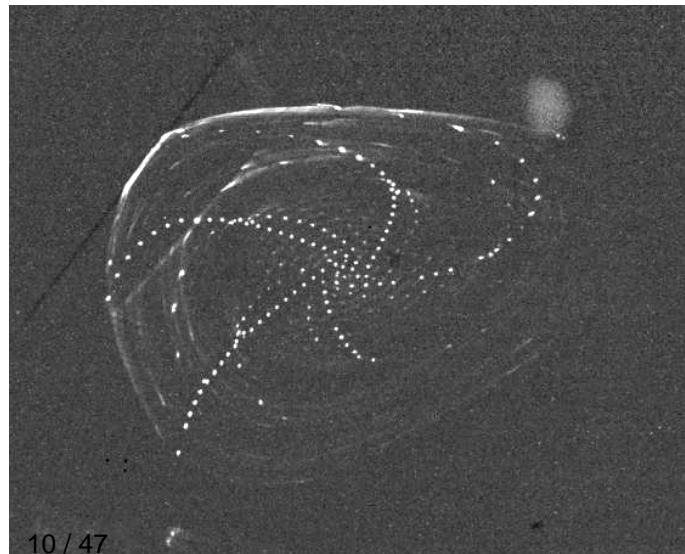
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✓ Show that good vacuum flux surfaces are created.

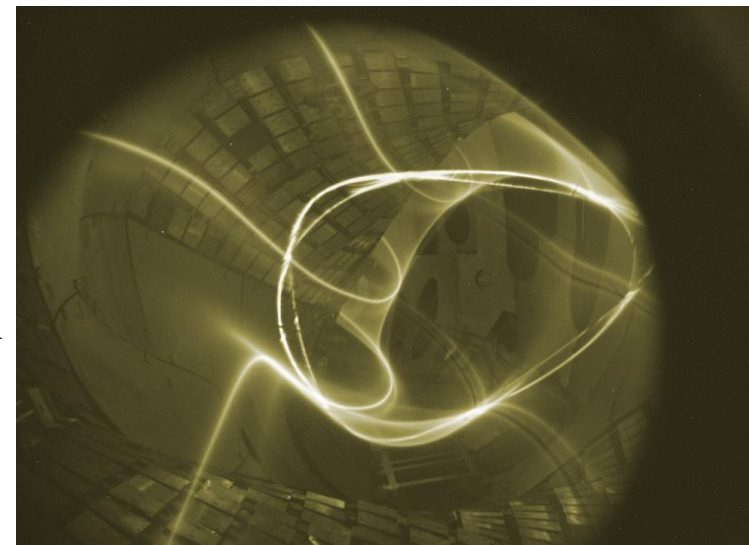


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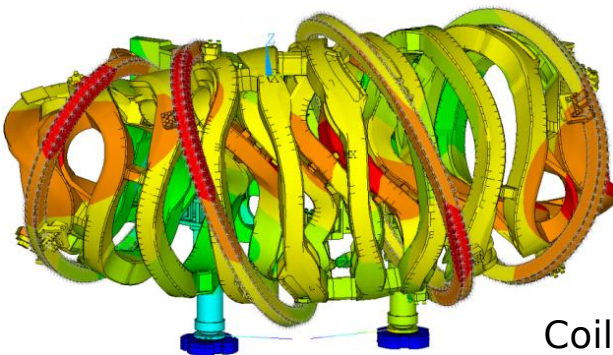
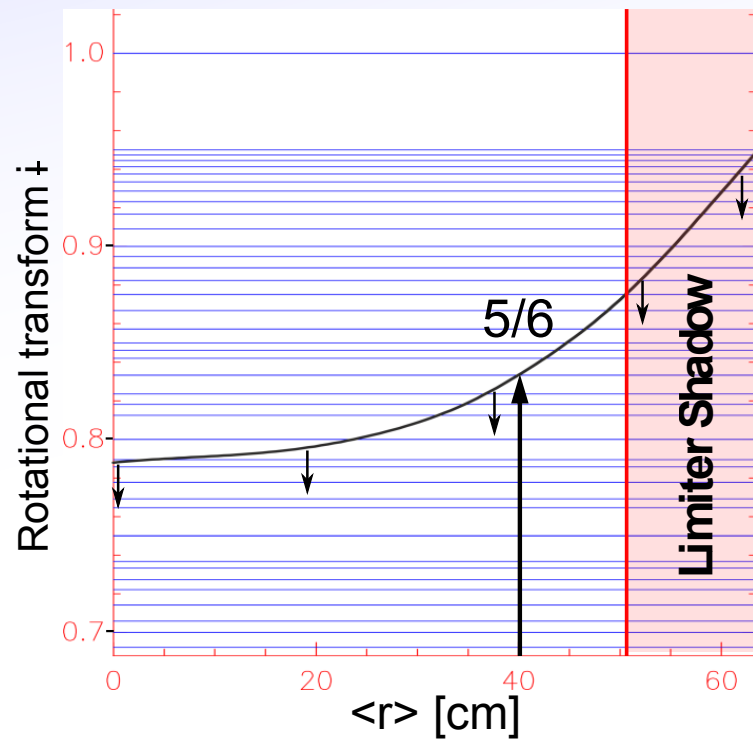
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Flux surfaces: Rotational Transform changes

Change of $|B|$ should not change flux surfaces, but...

- Predicted deformation of the coils at 2.5T by up to 10mm. (FEM calculations)
- Deformation leads to a decrease of the rotational transform

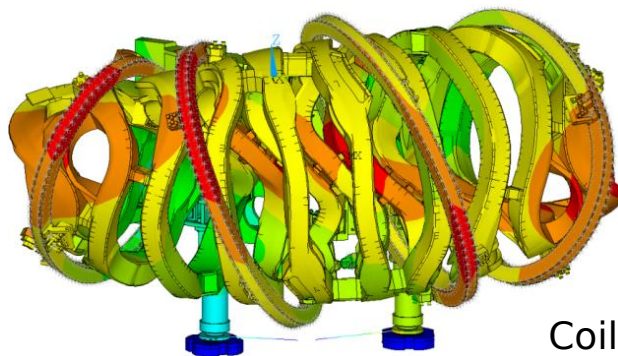
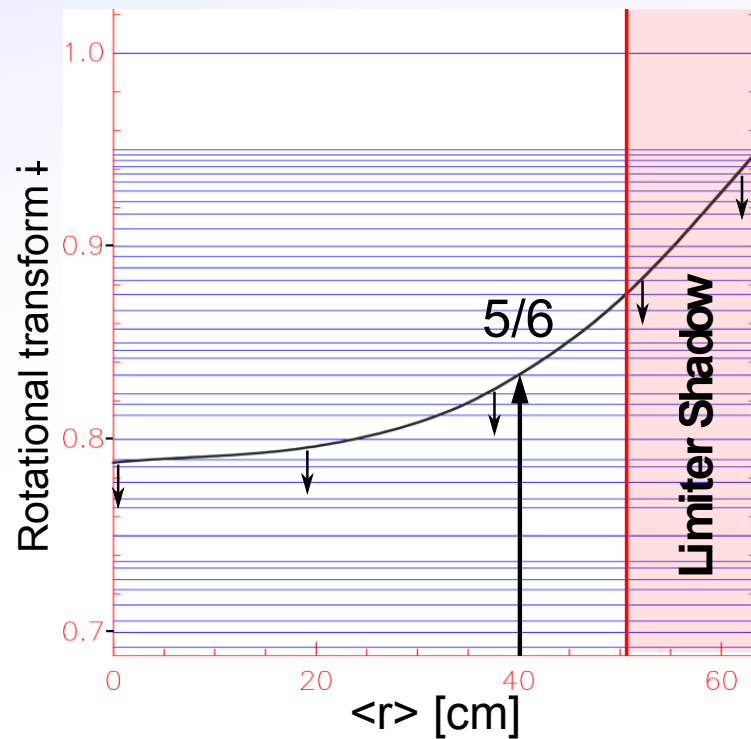


Coil stress/deformation [V. Bykov]

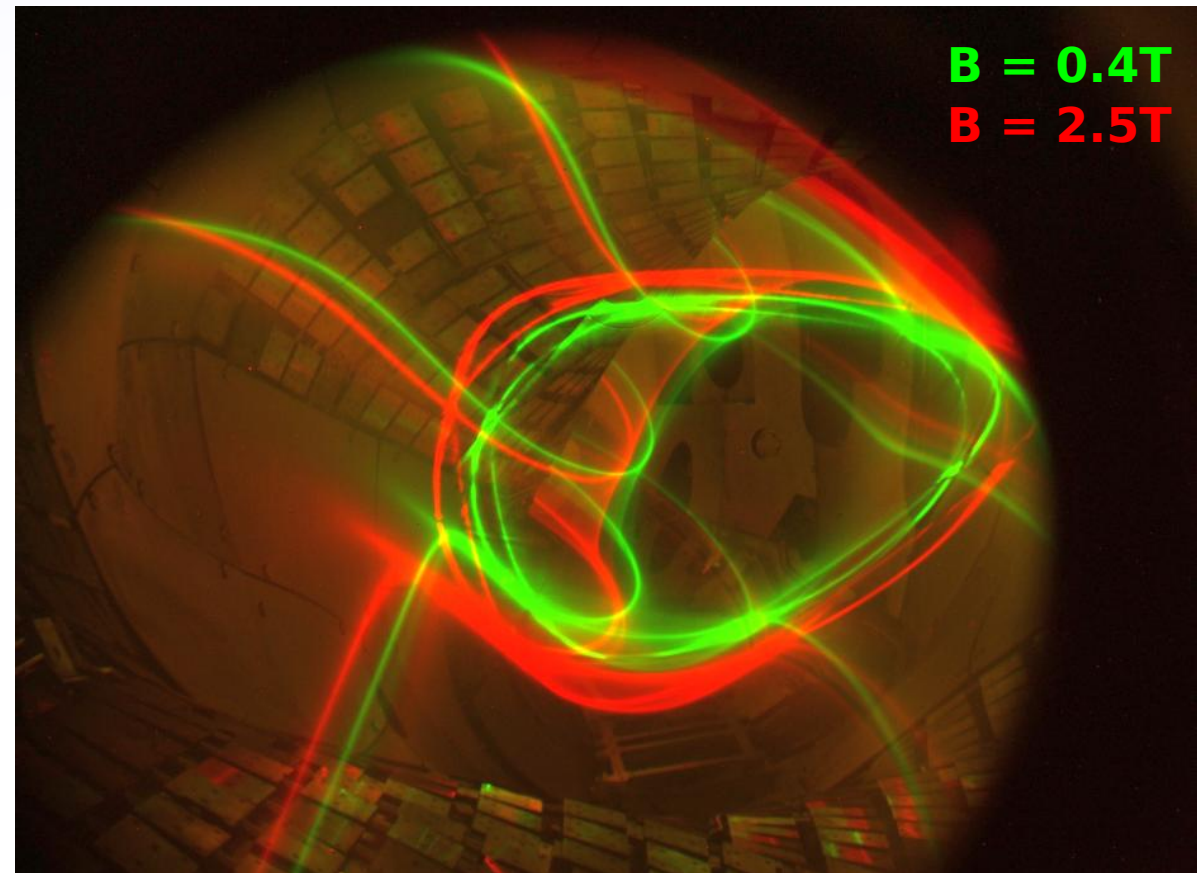
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- Predicted deformation of the coils at 2.5T by up to 10mm. (FEM calculations)
- Deformation leads to a decrease of the rotational transform and movement of the 5/6 islands.
- Seen clearly with the flux surface measurements.
- Coil currents are adapted to correct for this.

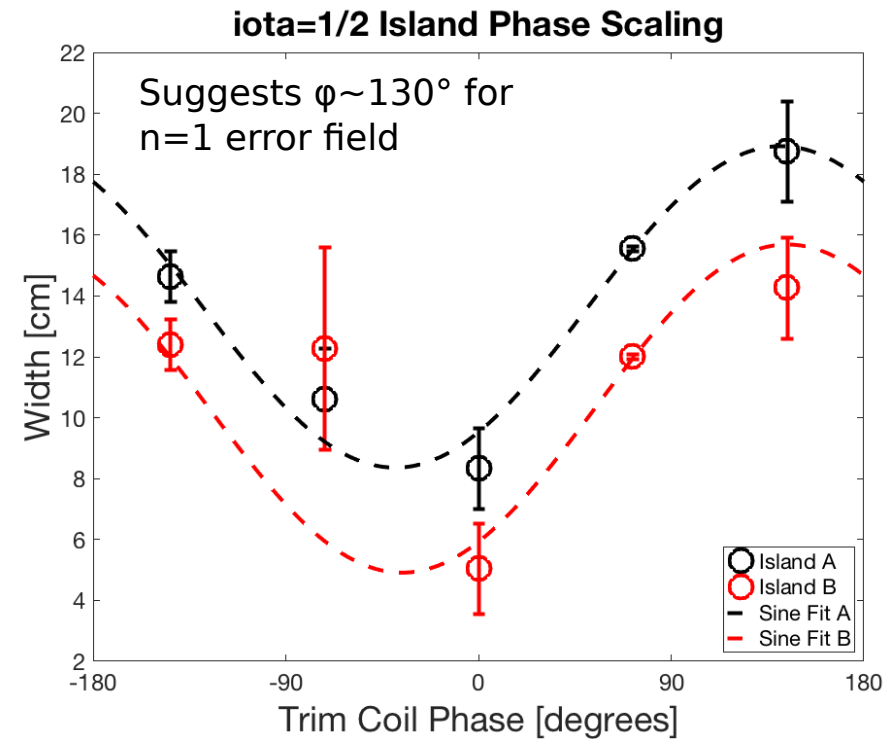
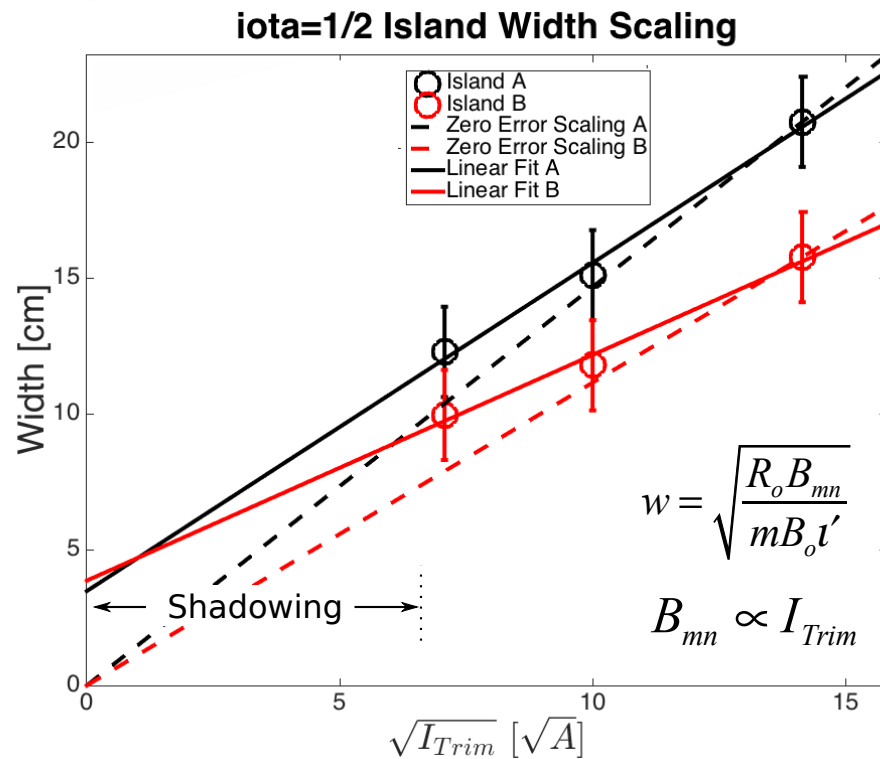
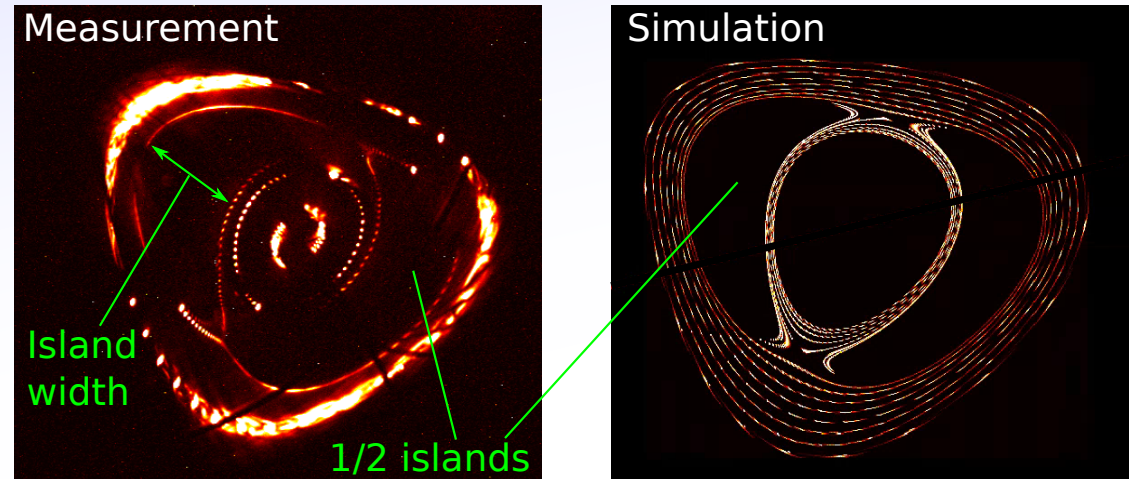


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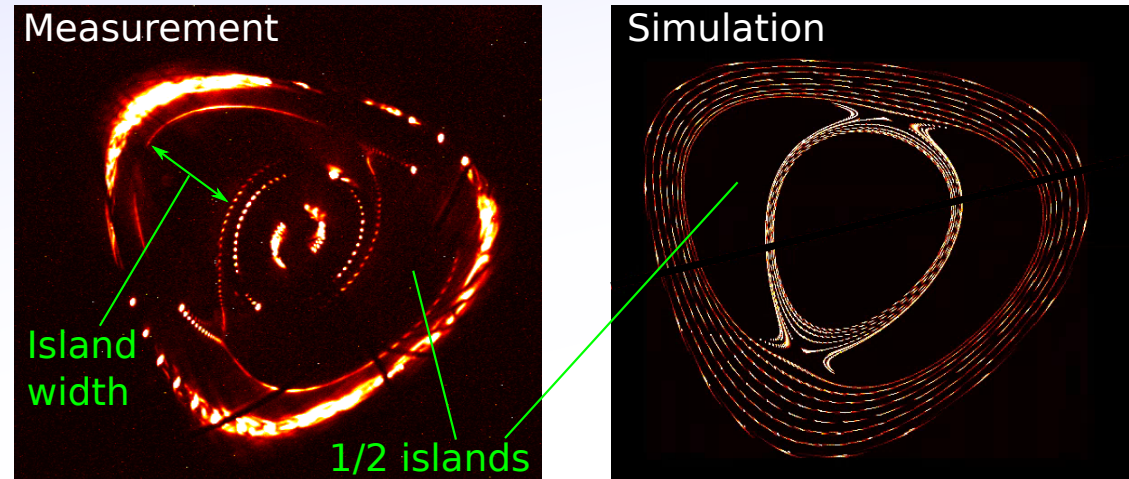
Flux surfaces: Error Fields

- Developed magnetic field configuration with $\iota = 1/2$ at \sim mid radius.
- Apply $n=1$ perturbation using PPPL trim coils.
- Scan phase and amplitude of perturbing field and examine width of 1/2 island from flux surface measurement.

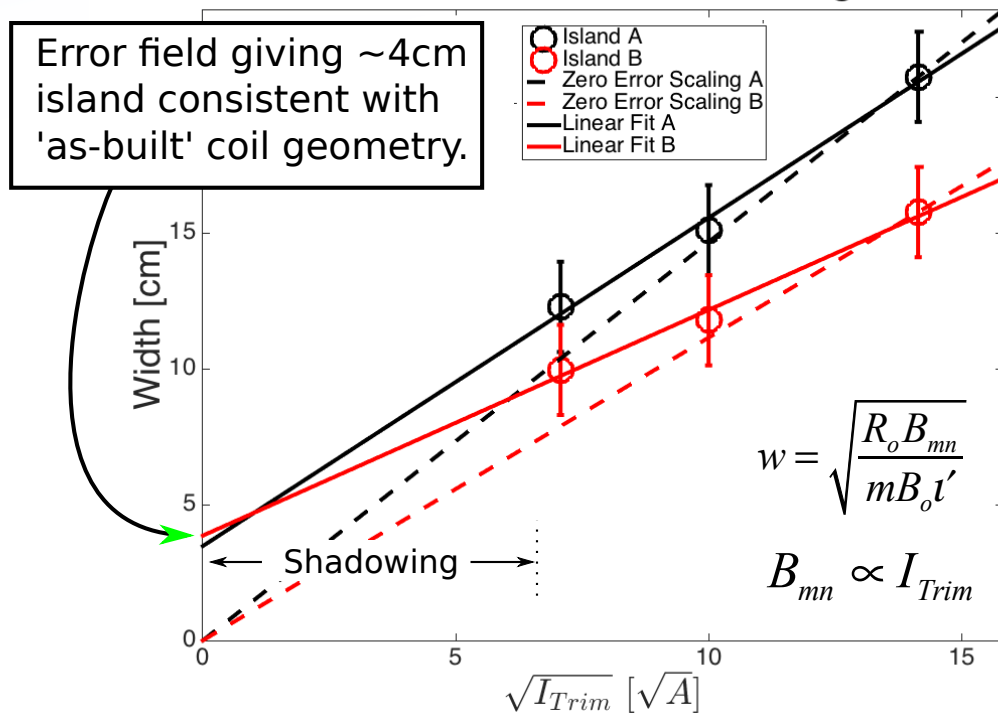


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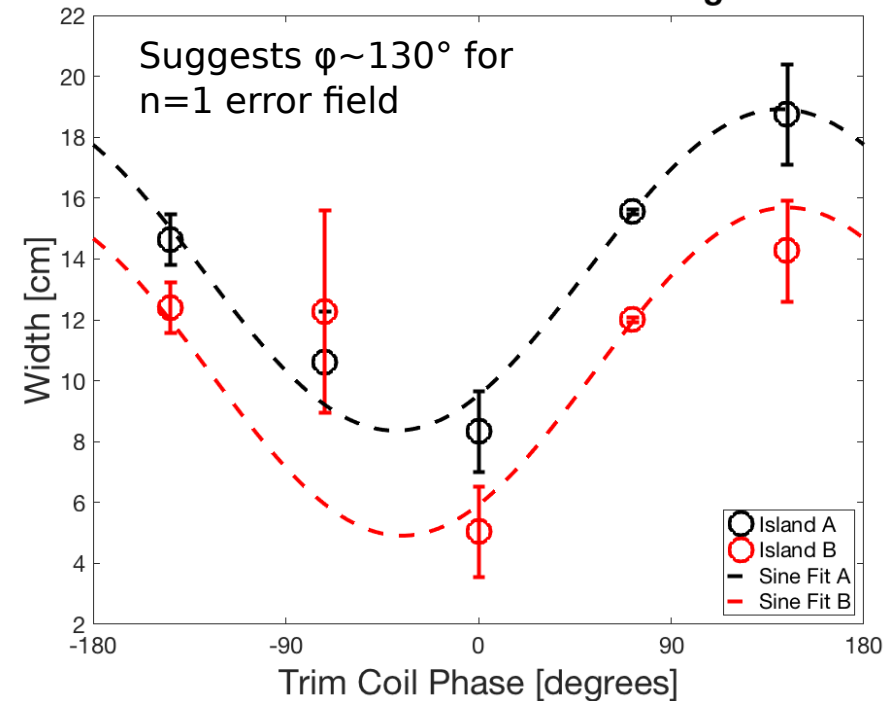
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$\iota = 1/2$ Island Width Scaling



$\iota = 1/2$ Island Phase Scaling





Start-up: Timeline

2015

- Cyrostat Cooling
- Magnet Tests
- Pump down
- Flux surface measurements
- 14th August: Vessel baking to 150°C

Dec

2016

Feb

Mar

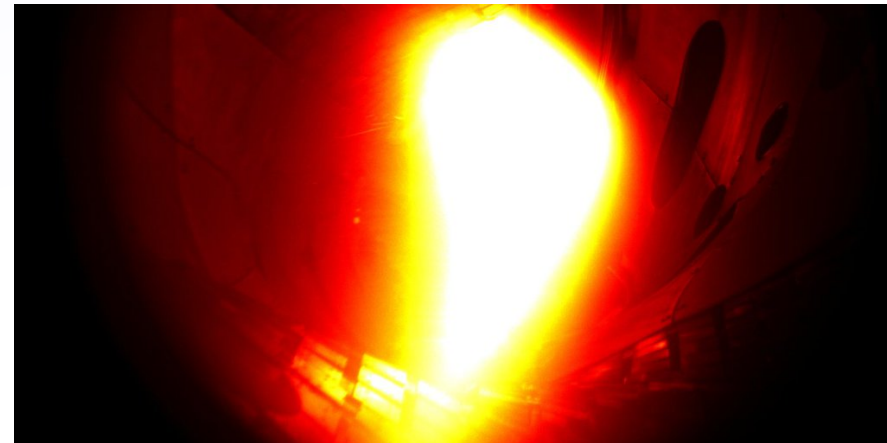
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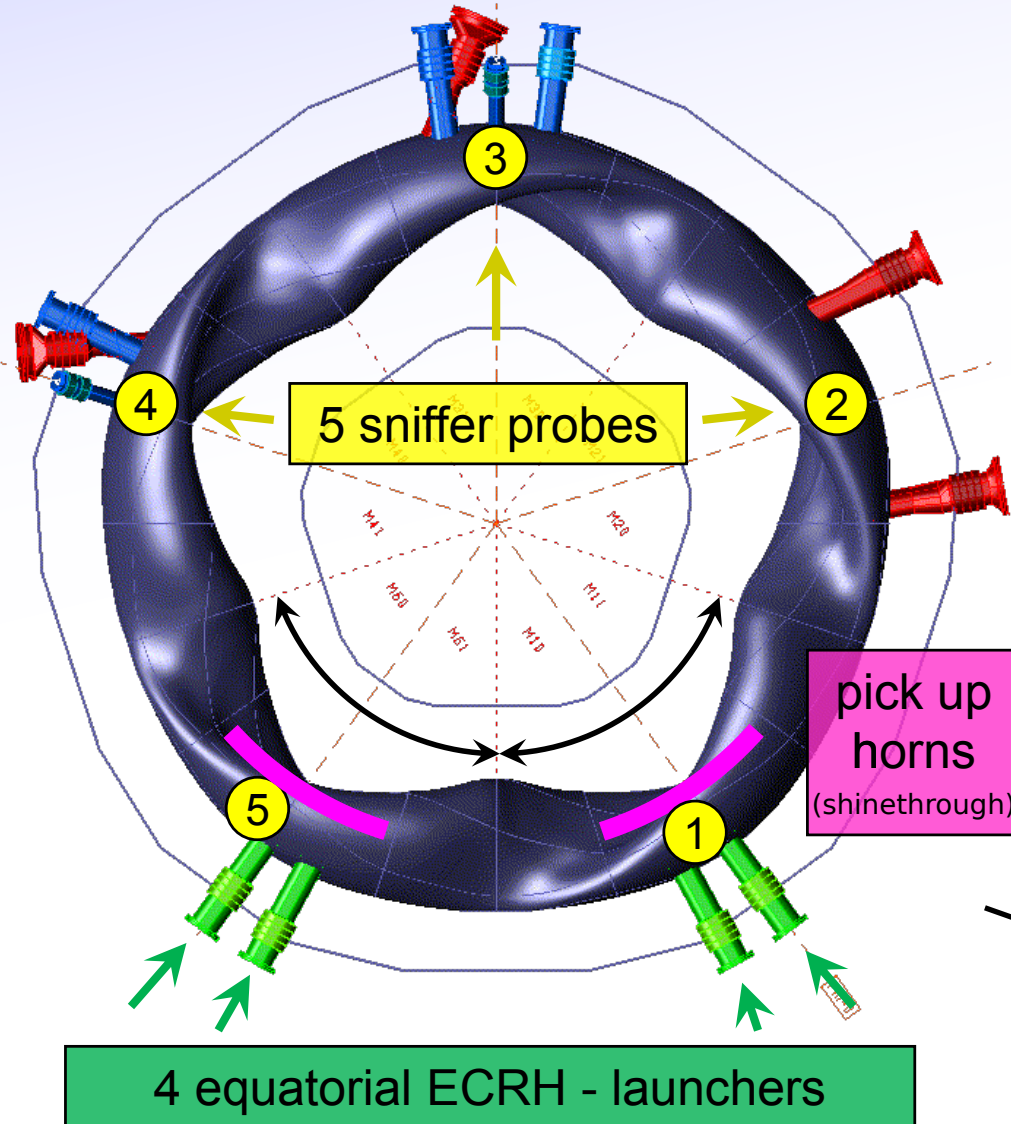
2016

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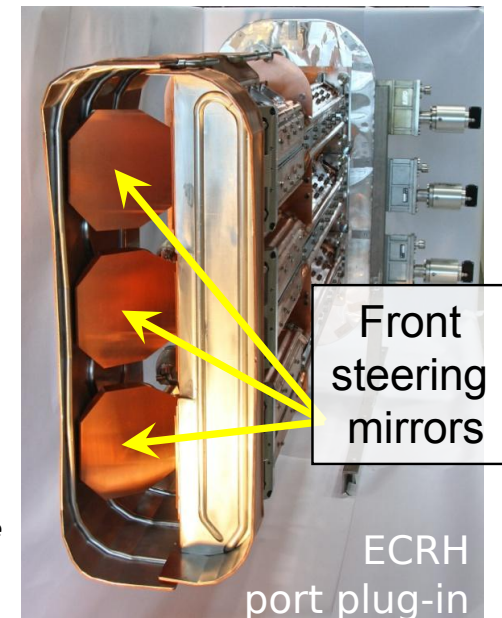
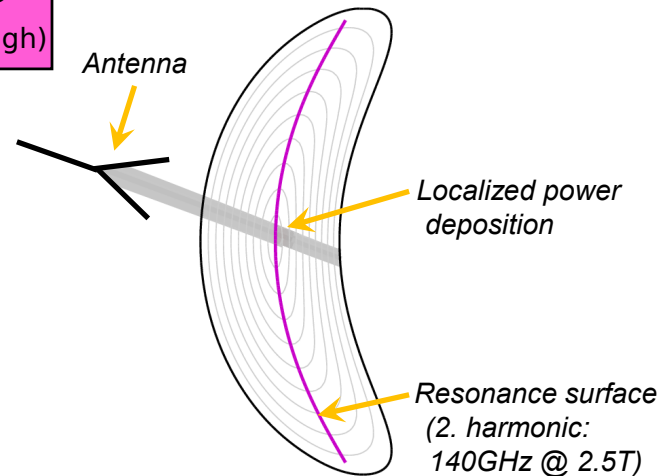
W7X ECRH Heating

Electron Cyclotron Resonance Heating will be the primary plasma heating for W7X in steady-state (10MW for 30min).



Capabilities:

- 6 Gyrotrons giving 4MW in OP1.1.
- Modulation up to at least 1kHz.
- Polarisation fully variable.
- Steady-state operation up to 30mins.
- Steerable mirrors:
 - Poloidally: $\pm 30^\circ$ (off-axis heating)
 - Toroidally: $-15 - +30^\circ$ (current drive)
- X2 mode heating ($n_e < 1.2 \times 10^{20} \text{ m}^{-3}$)
- O2 mode heating up to $2.4 \times 10^{20} \text{ m}^{-3}$
(was not planned for OP1.1)



W7X Video Diagnostics

Tangential view of the whole plasma vessel from 10 ports:

7x EDICAM (CMOS, up to 50kHz)

- Standard plasma observation

2x PixelFly (CCD, long exposures)

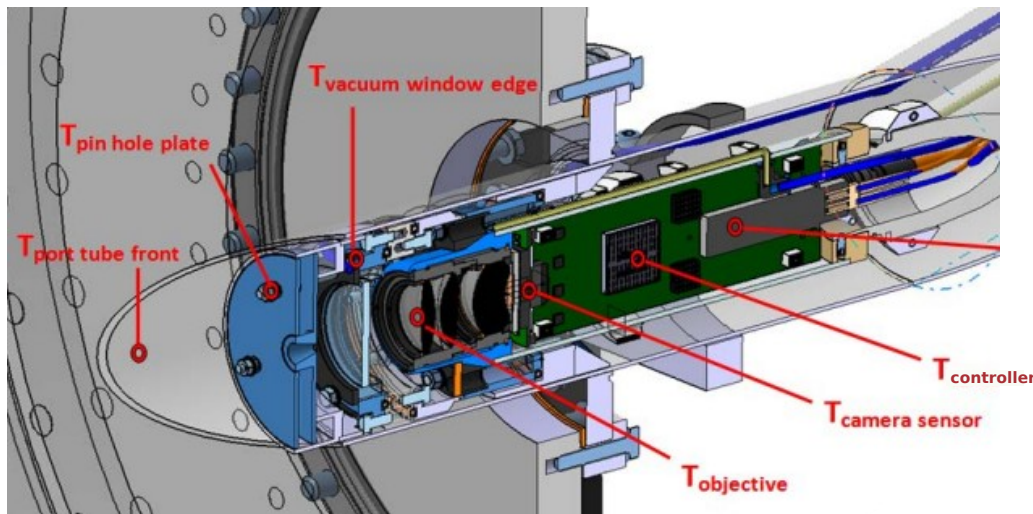
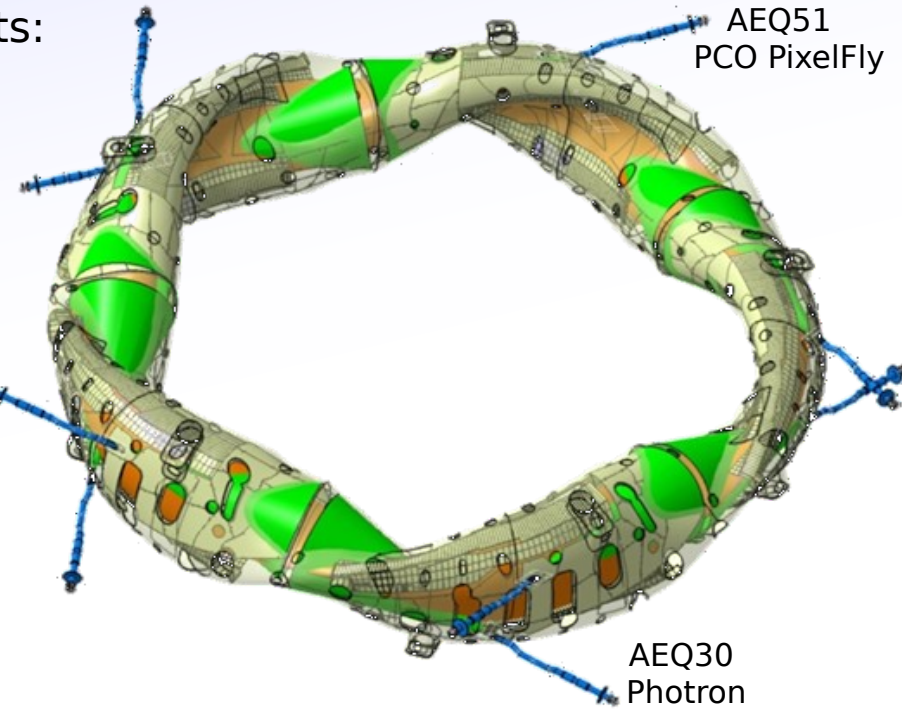
- Flux surface measurements

1x Photron (CMOS, up to 1MHz) + image guide

- Turbulence, fast events

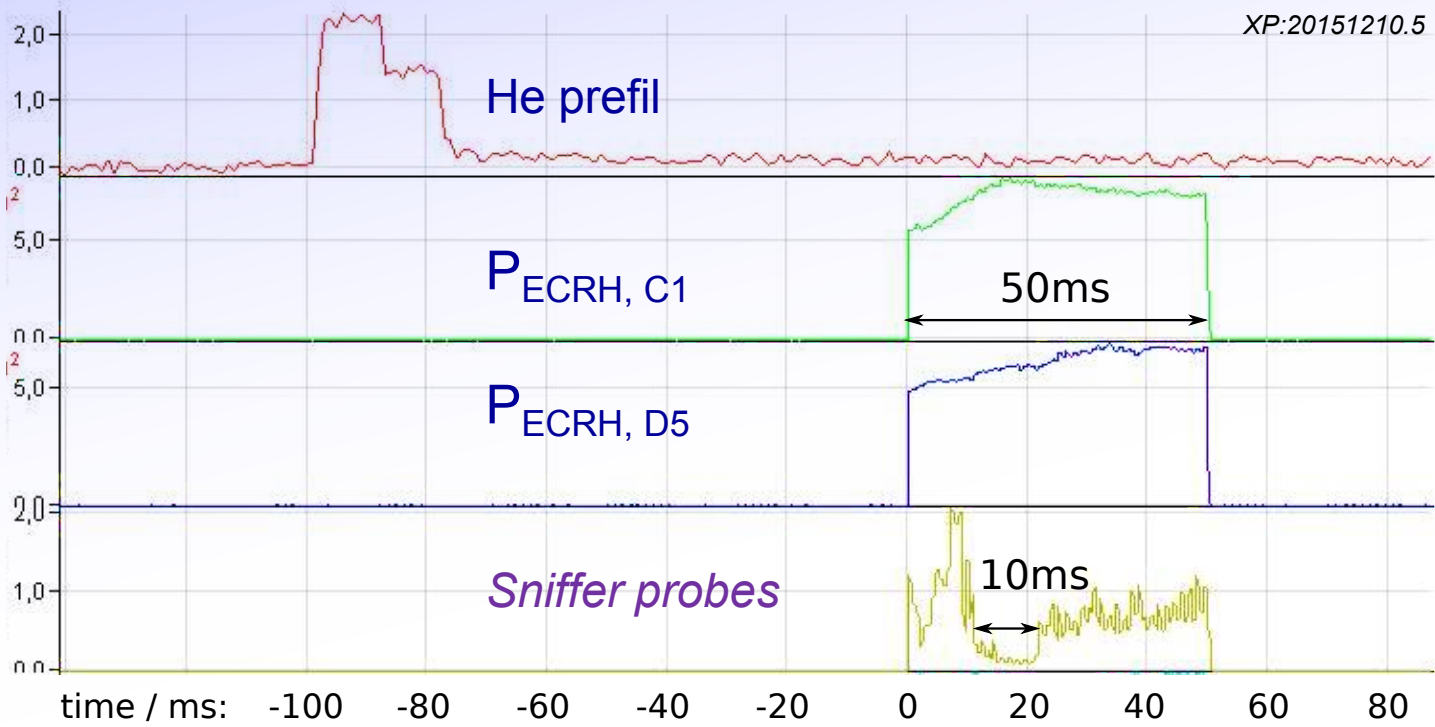
Good spatial resolution: 2mm @ 7m

Variable exposure 10 μ s to 10s



- Water cooled steady state capable front end.
- Other cameras or image guides can be docked from outside machine.

W7X First Plasma



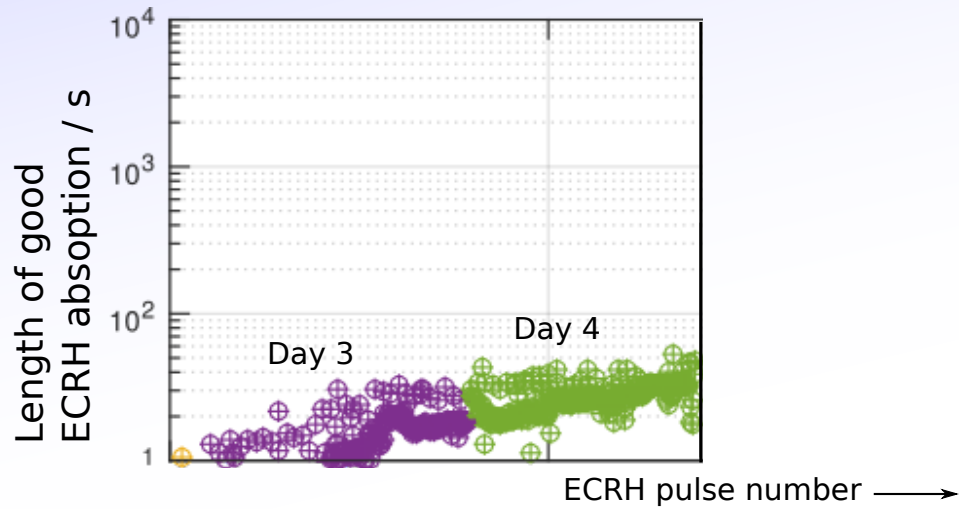
First helium plasma very short:

- No preceding wall conditioning except baking.
- 50ms ECRH heating, but only 10ms absorption.
- Small plasma in vessel centre.
- Pulse length limited by outgassing and radiation.



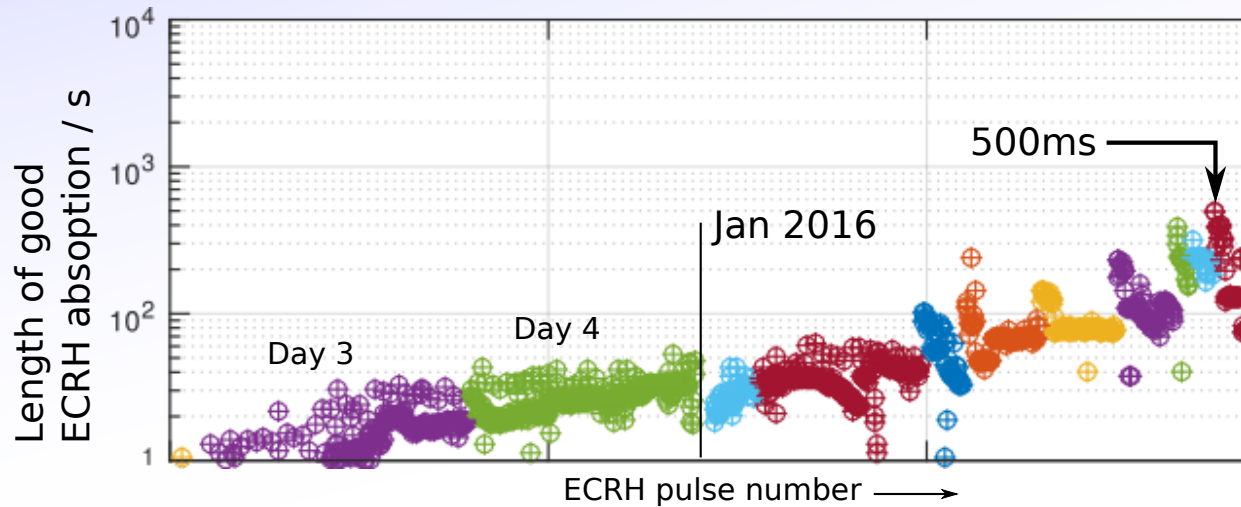
Start-up: Conditioning: Helium

- Started with Helium plasmas for easier breakdown.
- Plasmas improved slowly.
- Chains of repeated ECRH discharges to heat and drive outgassing from the walls.



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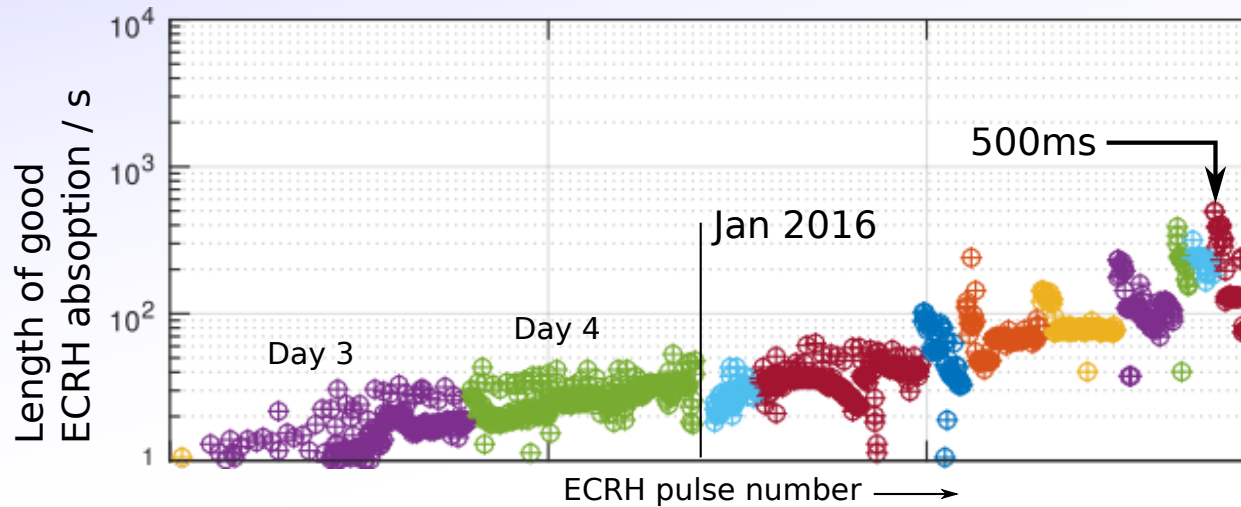


After the Christmas break...

- He glow discharges dramatically increased performance for the first few shots of each day.
- Performance deteriorated through the course of each day.
- Best plasma parameters achieved:
 $T_e \sim 8 \text{ keV}$, $T_i \sim 1.5 \text{ keV}$, $n_e \sim 3 \times 10^{19} \text{ m}^{-3}$

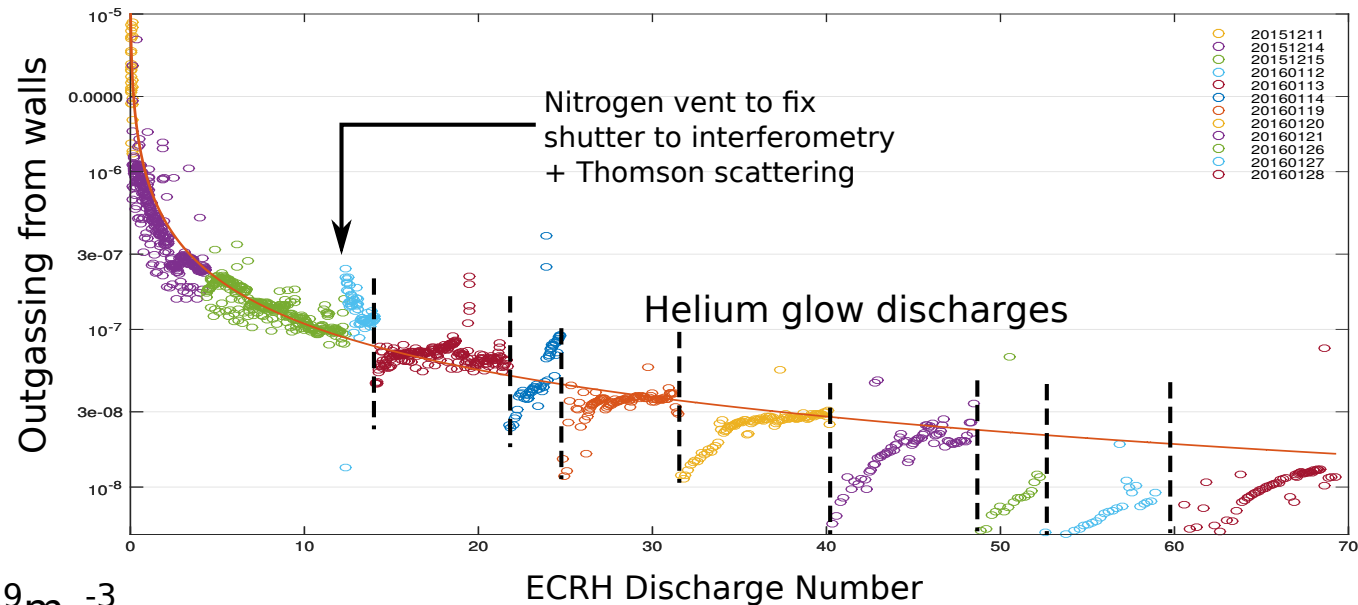
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ECRH Wall Conditioning

2016

12th Jan: Helium glow discharges available.

Improved conditioning

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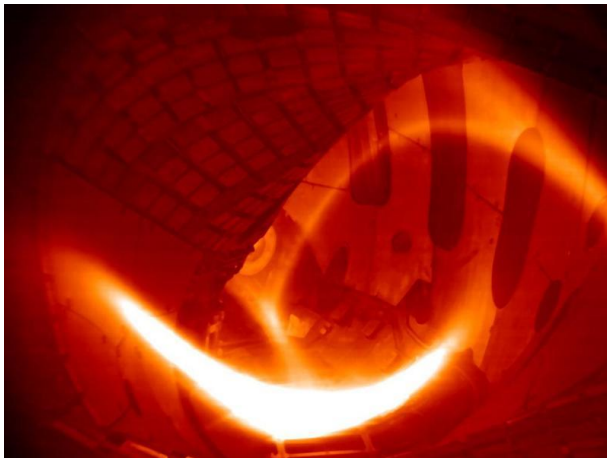
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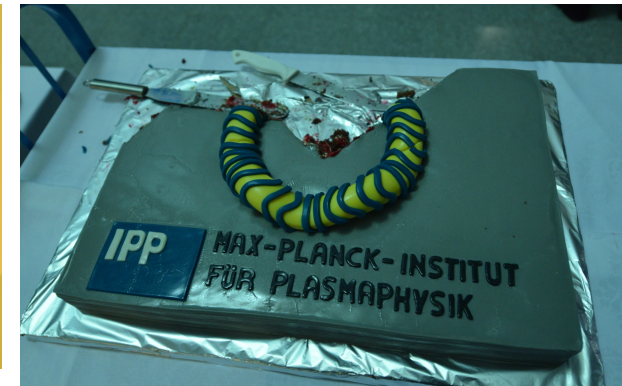
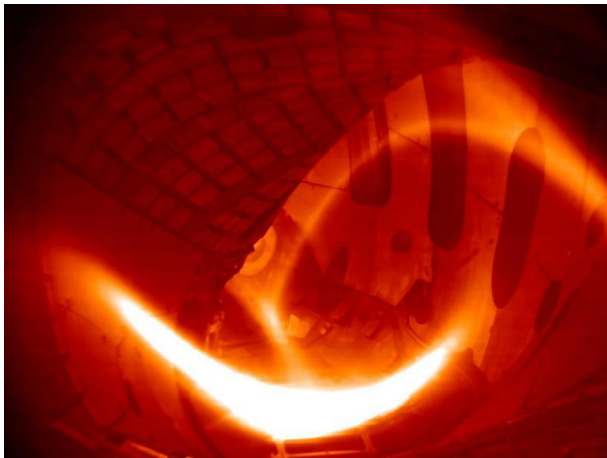
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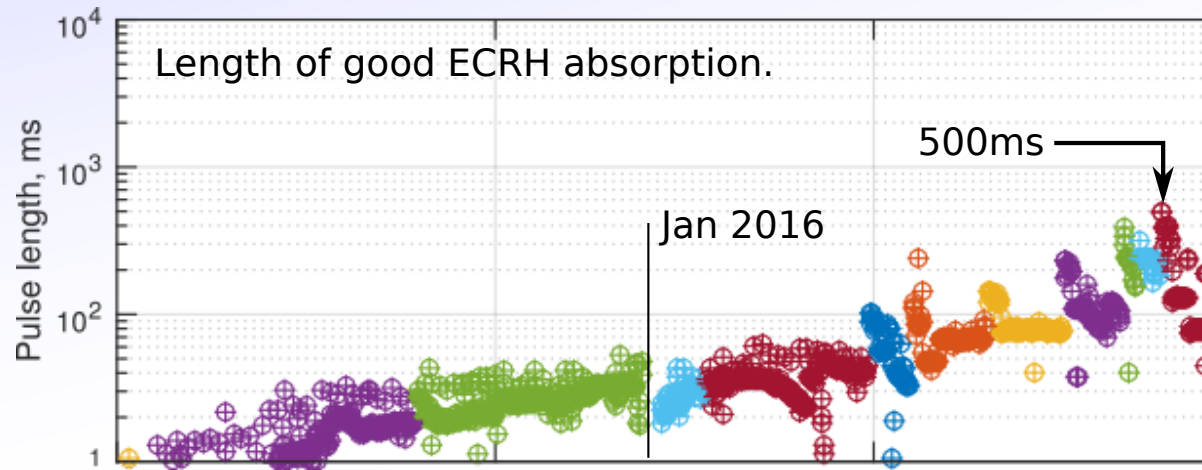
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Mar



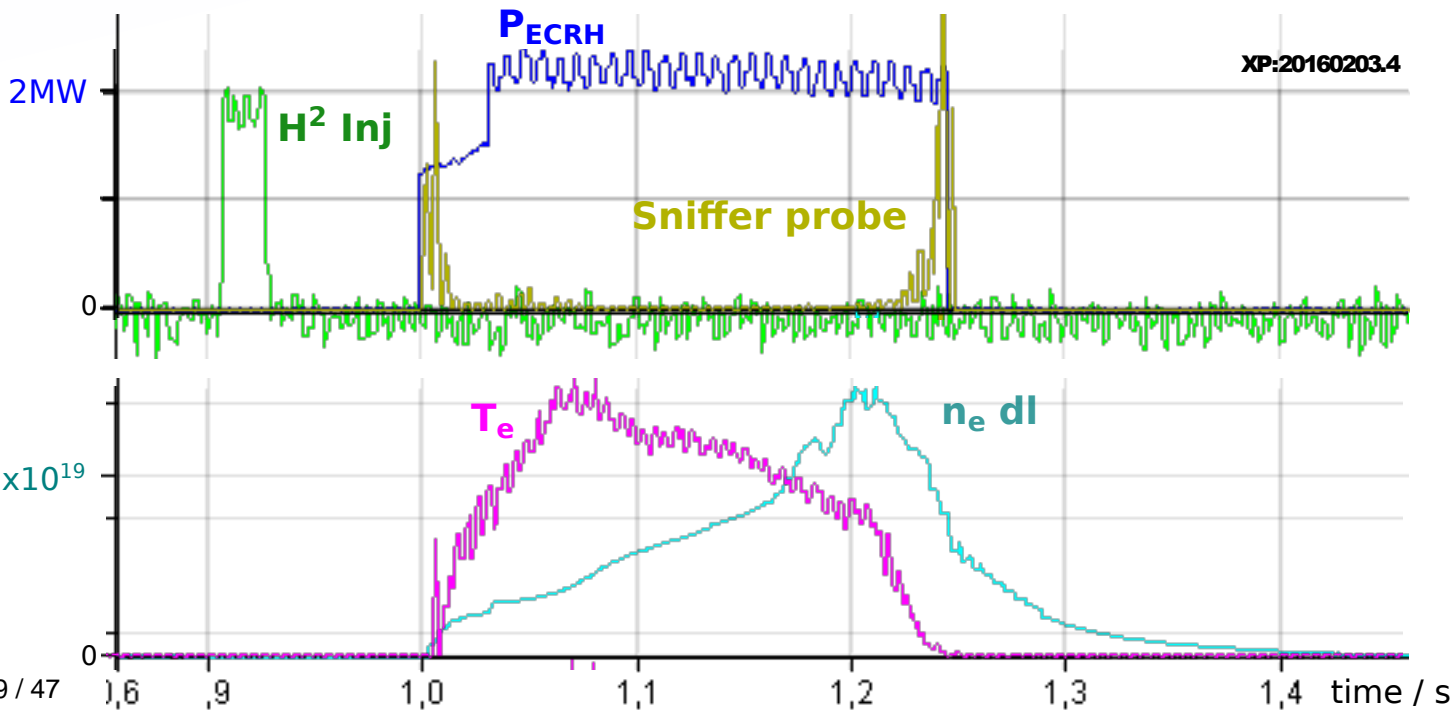
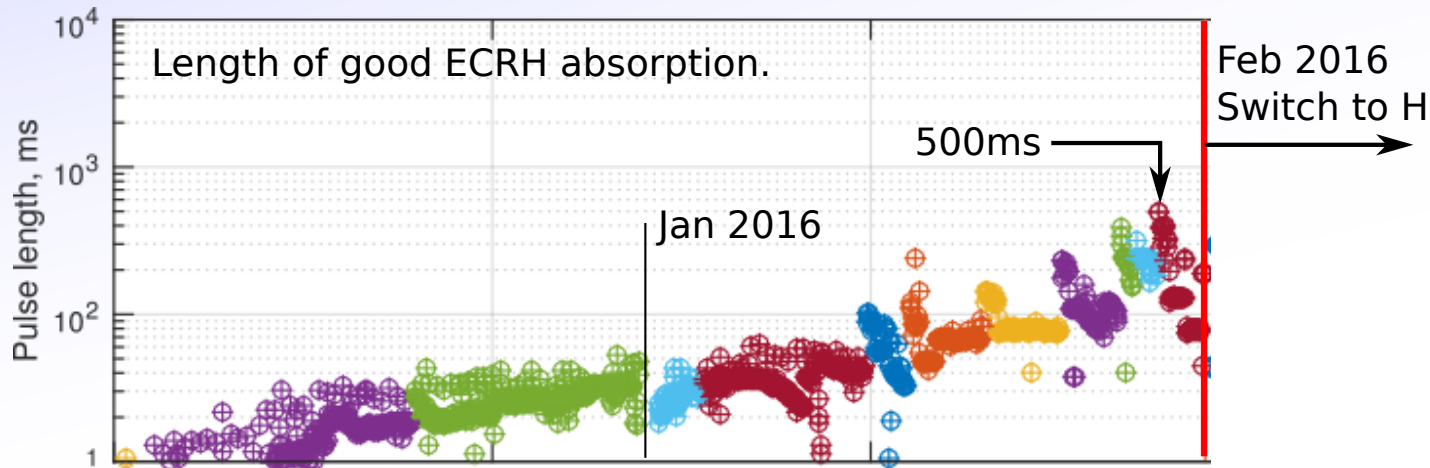
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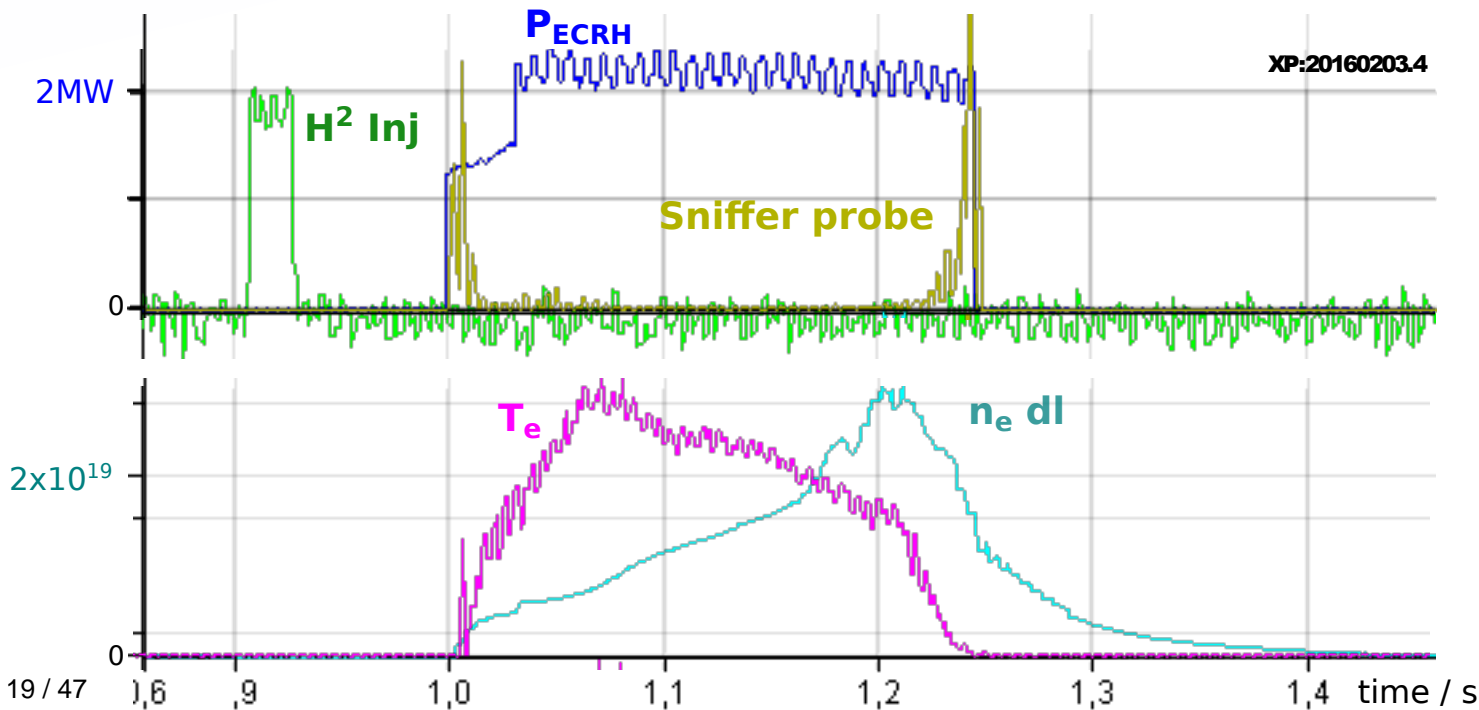
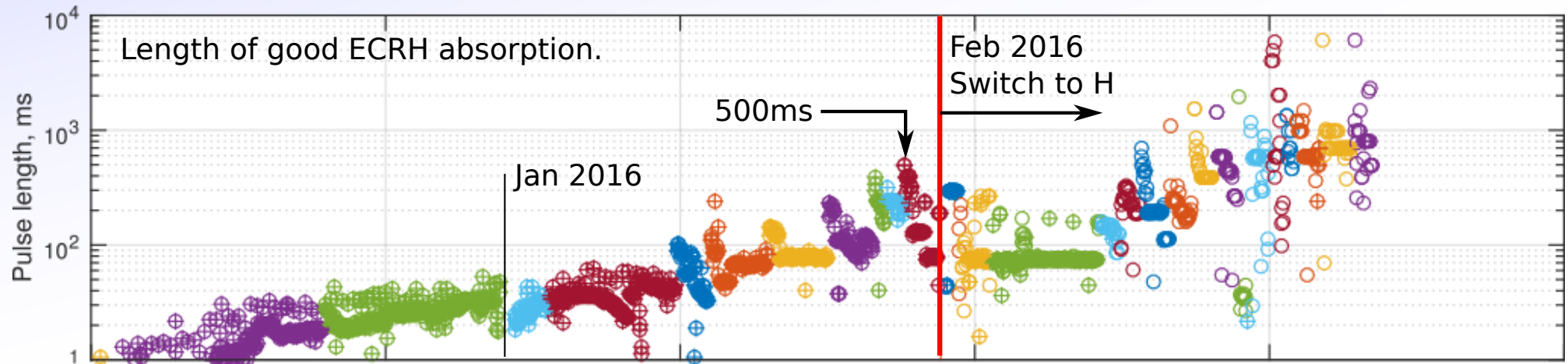
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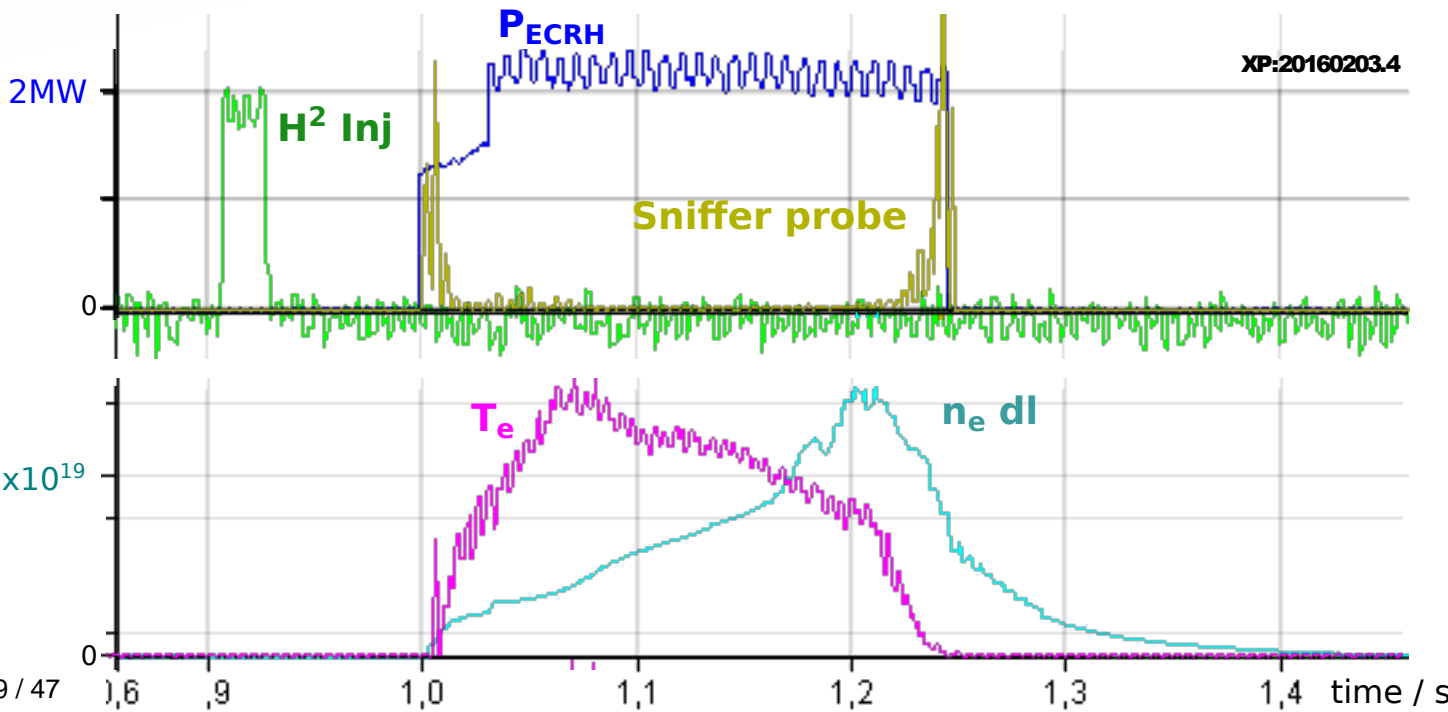
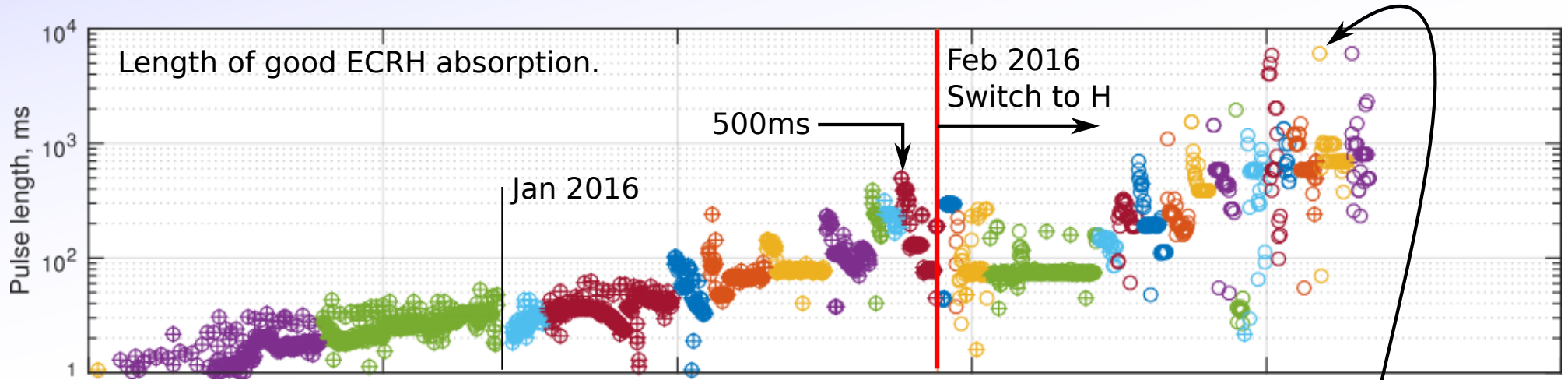
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6 seconds!
OP1.1 Expectation was < 1s

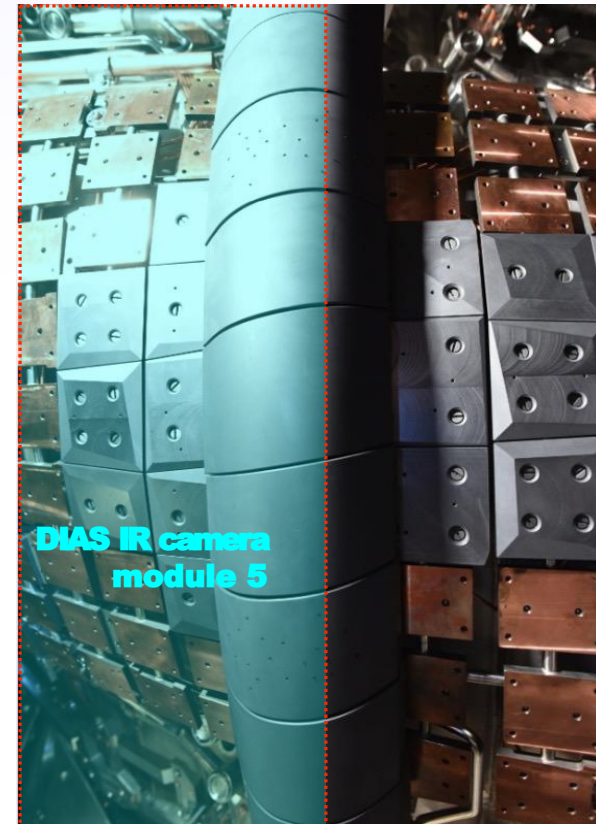
Limiter Observation Diagnostics

- Total plasma energy initially limited to 2MJ to avoid damage to limiters.
- Several diagnostics to monitor the limiters:



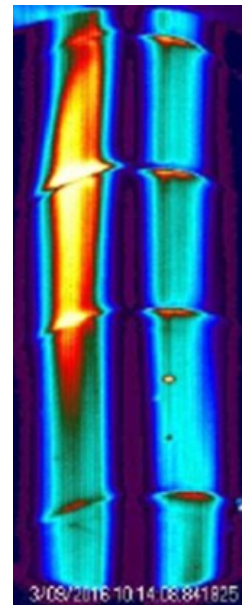
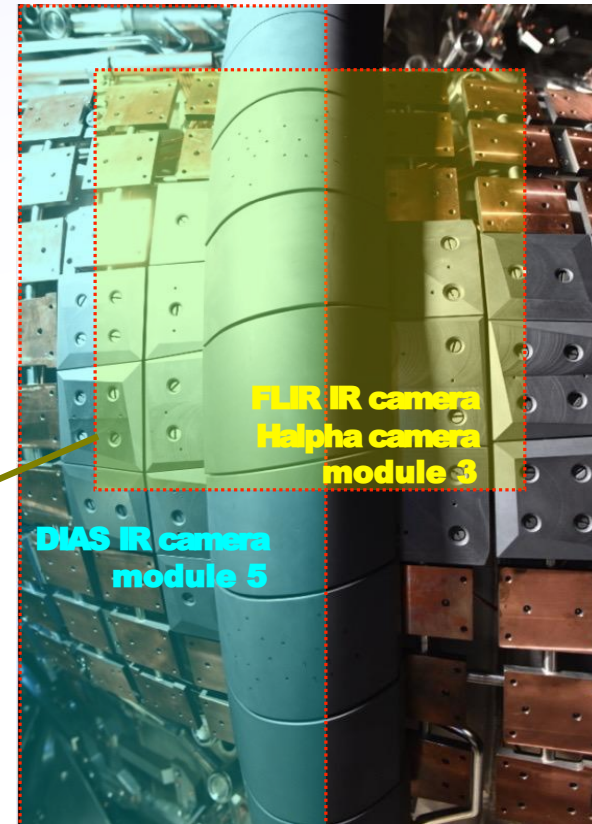
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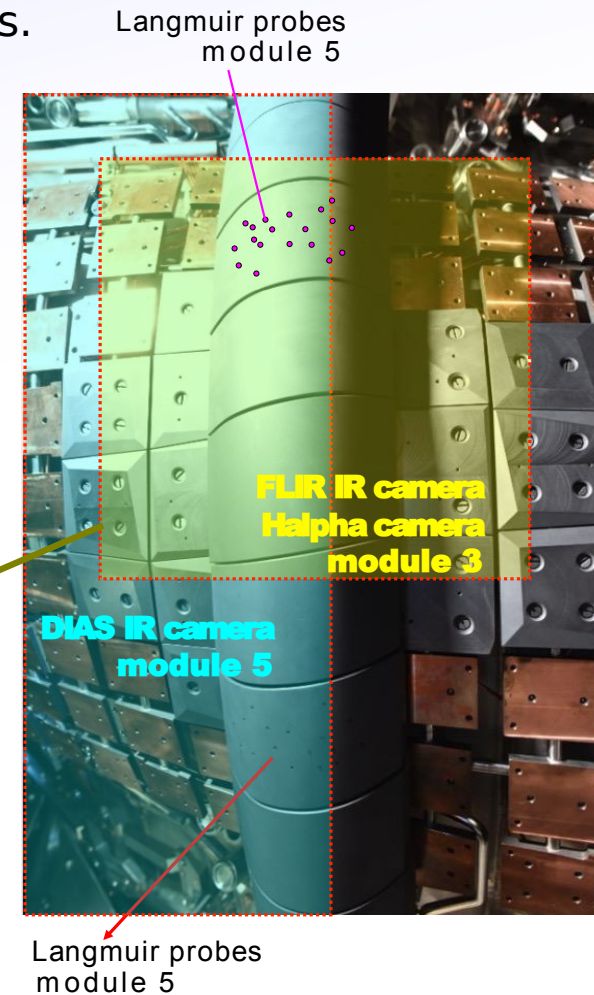
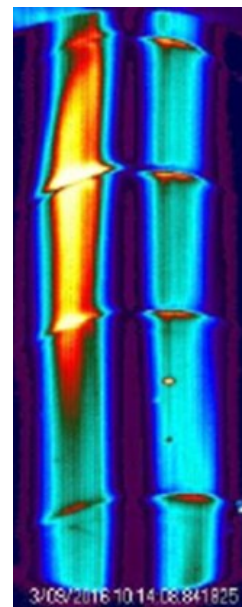
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Generally, power loads to the limiters were unexpectedly low.
In the first plasmas, the bulk temperature rose by only a few degrees.

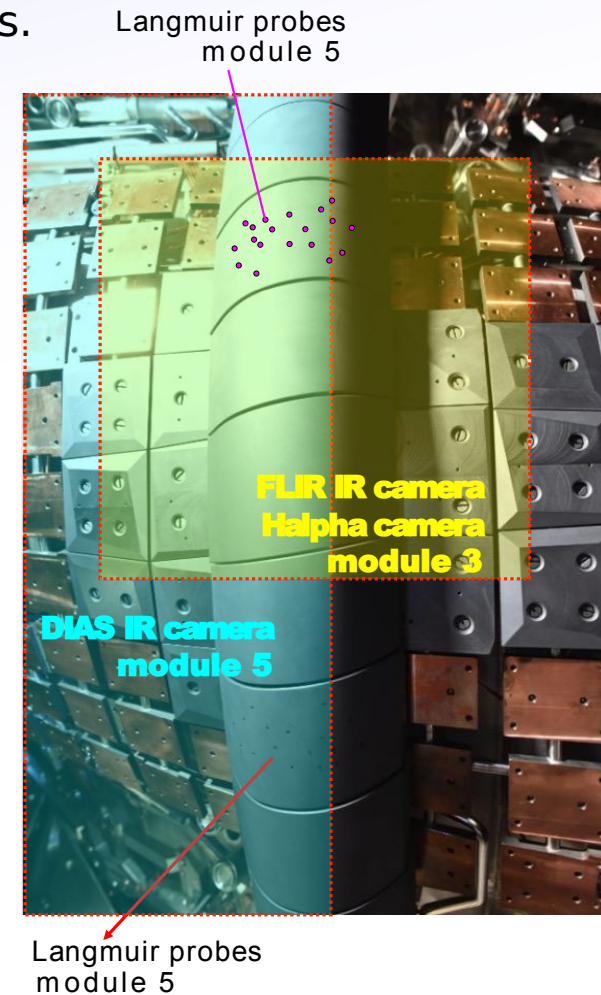


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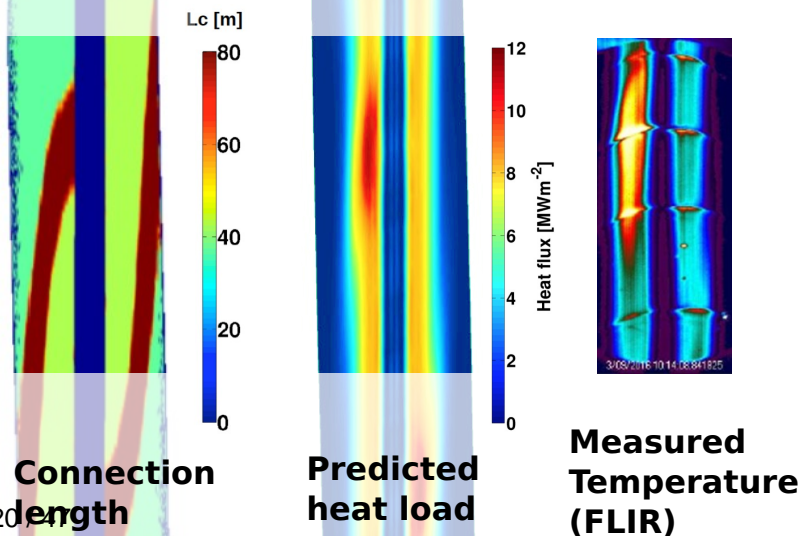
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(Later in OP1.1): Power flux patterns to limiters matched qualitatively that predicted from EMC3-EIRENE, including with changes to magnetic configuration:



OP1.1 standard configuration.

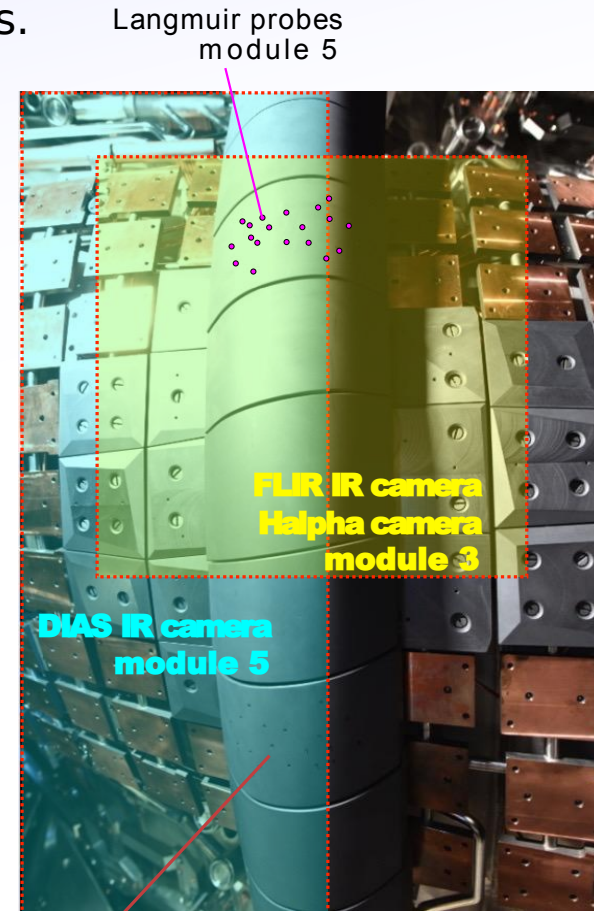


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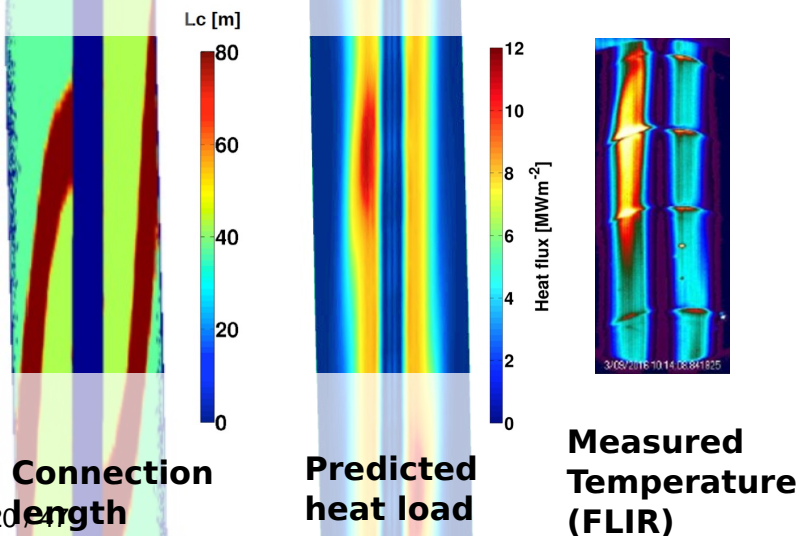
Generally, power loads to the limiters were unexpectedly low. In the first plasmas, the bulk temperature rose by only a few degrees.

(Later in OP1.1): Power flux patterns to limiters matched qualitatively that predicted from EMC3-EIRENE, including with changes to magnetic configuration:

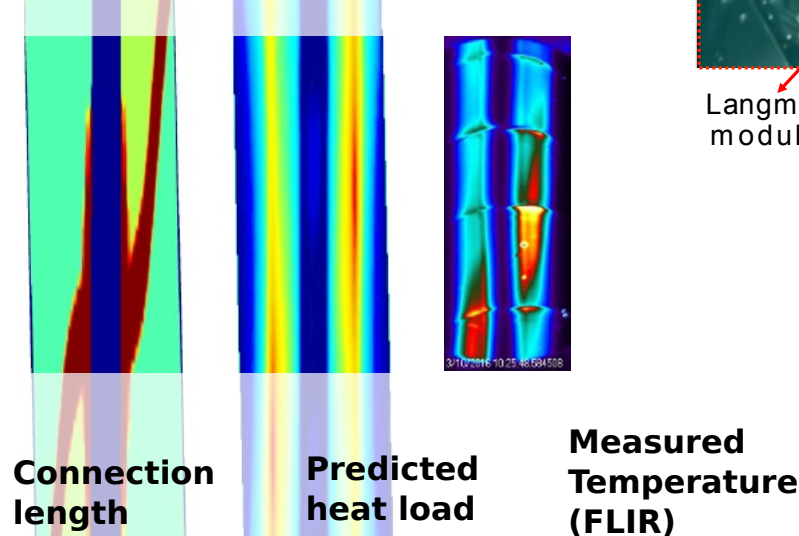


Langmuir probes module 5

OP1.1 standard configuration.



OP1.1 increased iota.

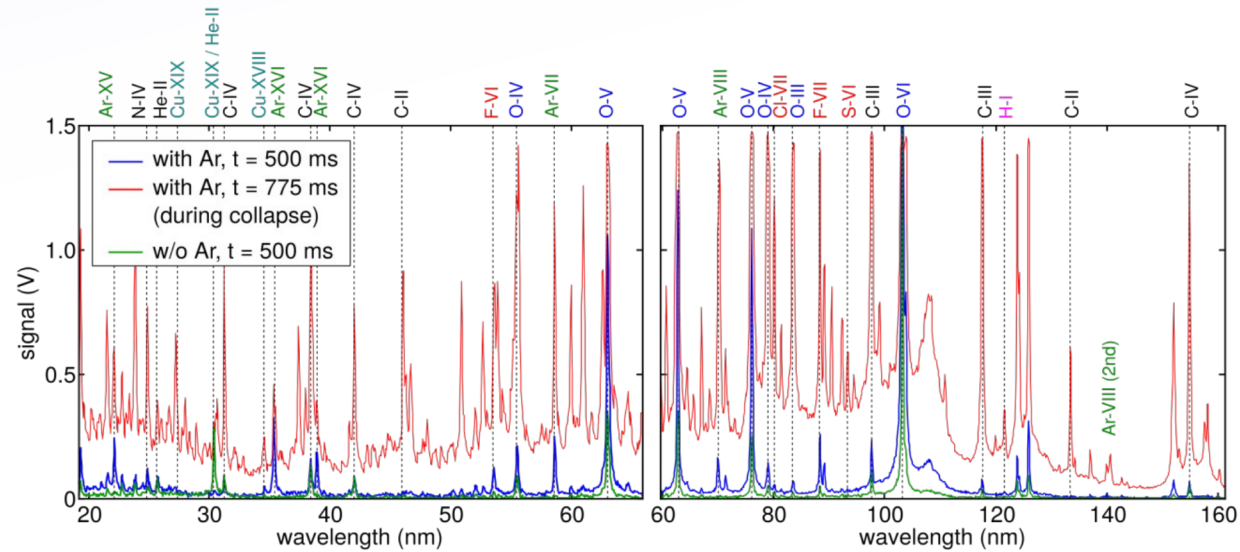
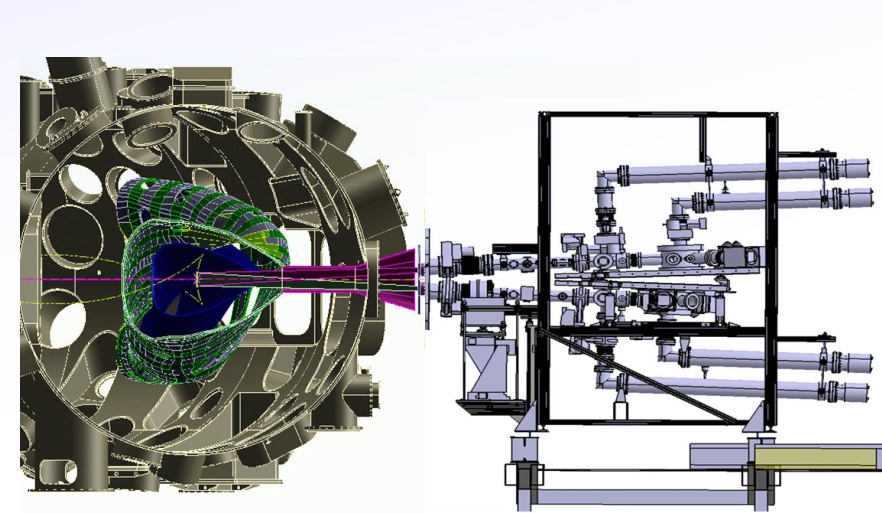


Impurity Content

- Most of the input power was radiated by impurities before reaching the limiters.

HEXOS VUV-Spectrometer (High Efficiency eXtreme ultraviolet Overview Spectrometer):

- 2.5 - 160nm (20-160nm available in OP1.1)
- High spectral and temporal resolution.
- Observes the expected Oxygen, Carbon and puffed Nitrogen, Neon, Argon etc
- Also sees Chlorine and Sulfur, but no significant Copper (from unprotected heat shield mounts)

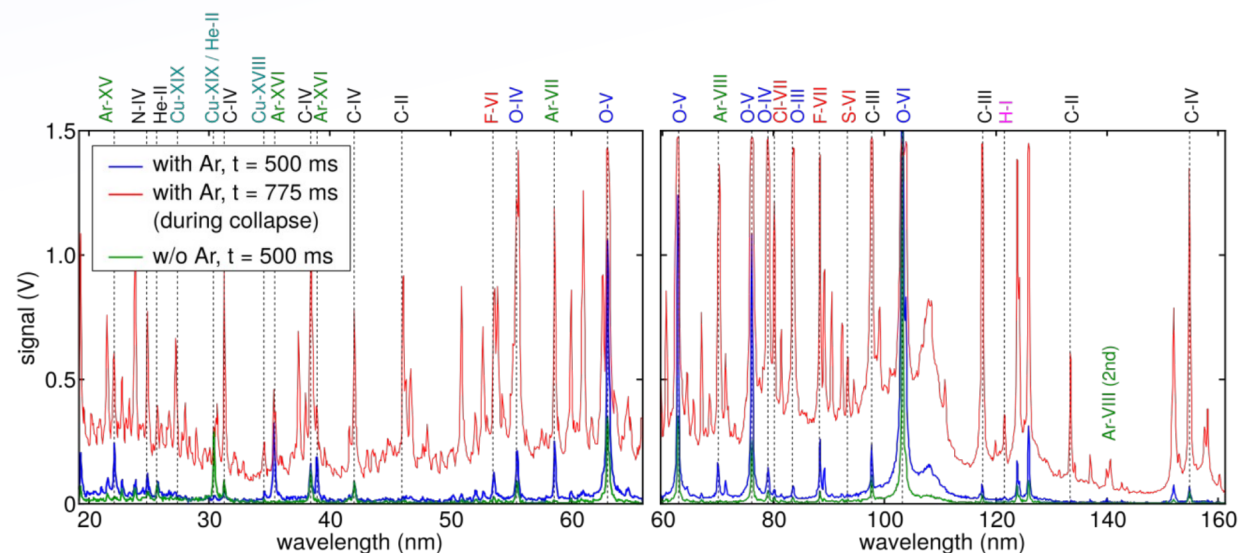
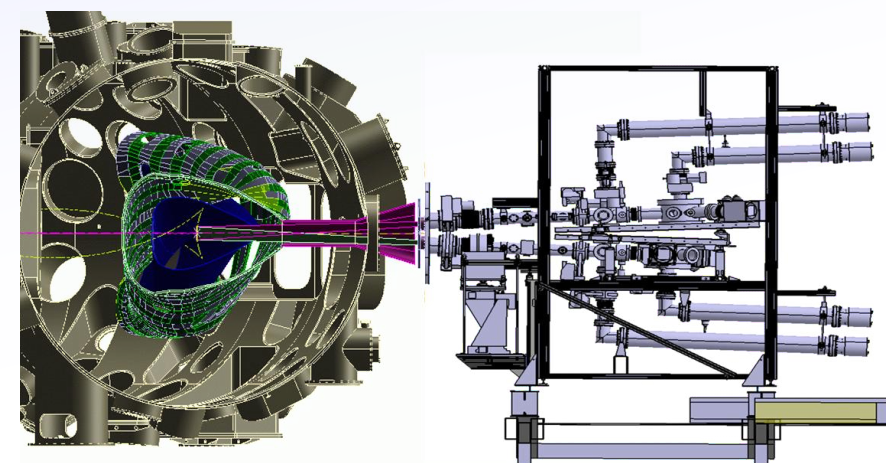


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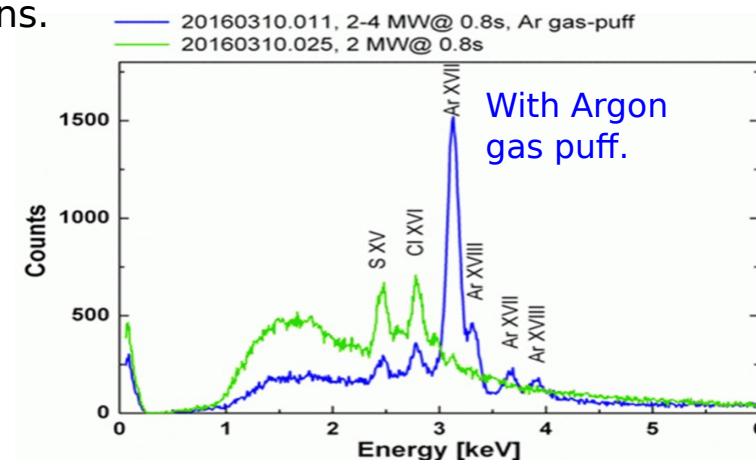
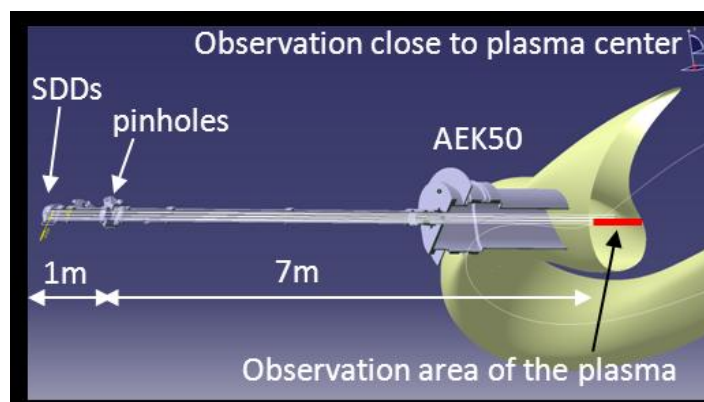
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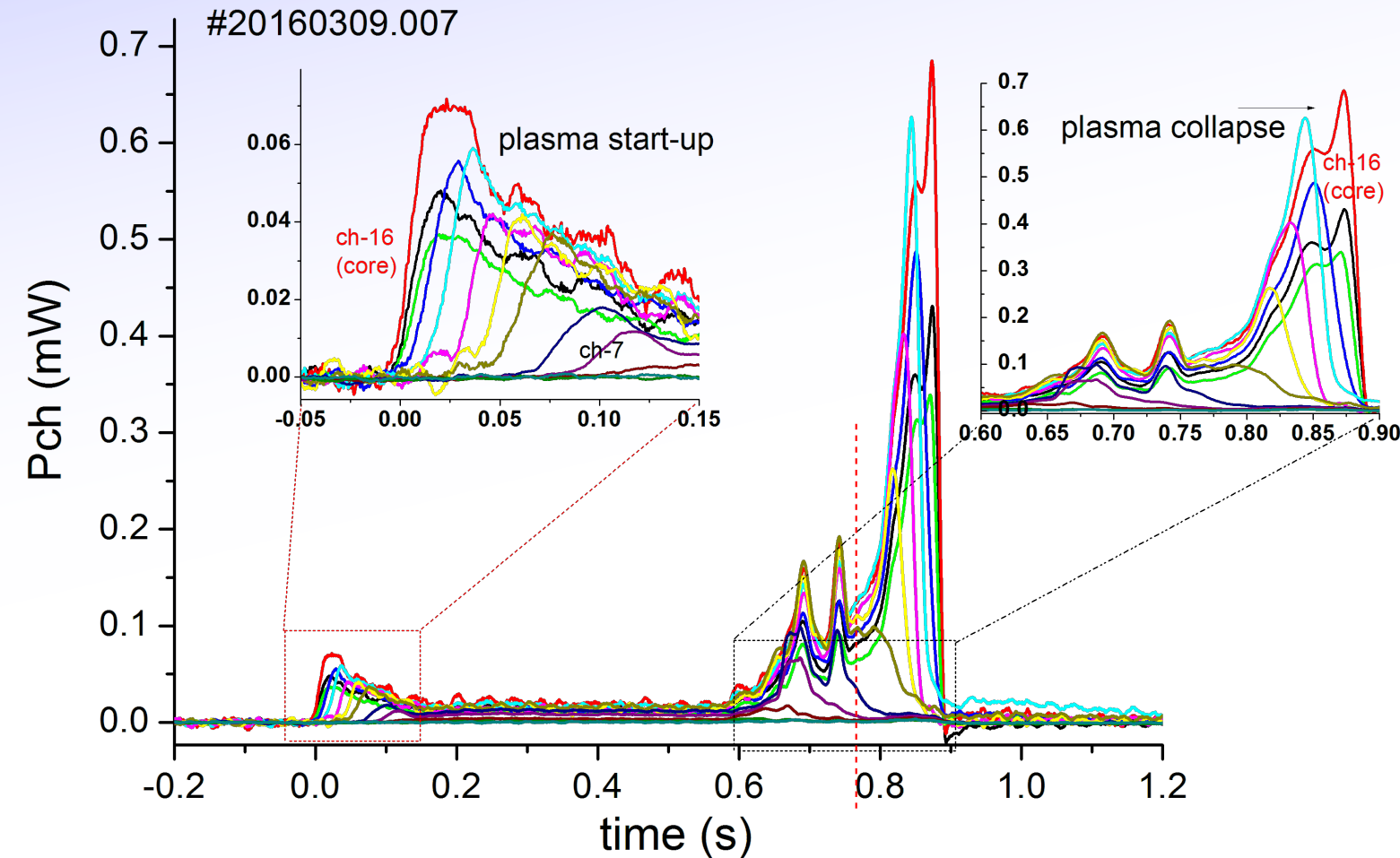
- X-Ray Pulse Height Analysis (PHA): Core medium to high-Z impurity ions.

- Single line of sight
- Sulfur and Chlorine detected.



Impurity Content

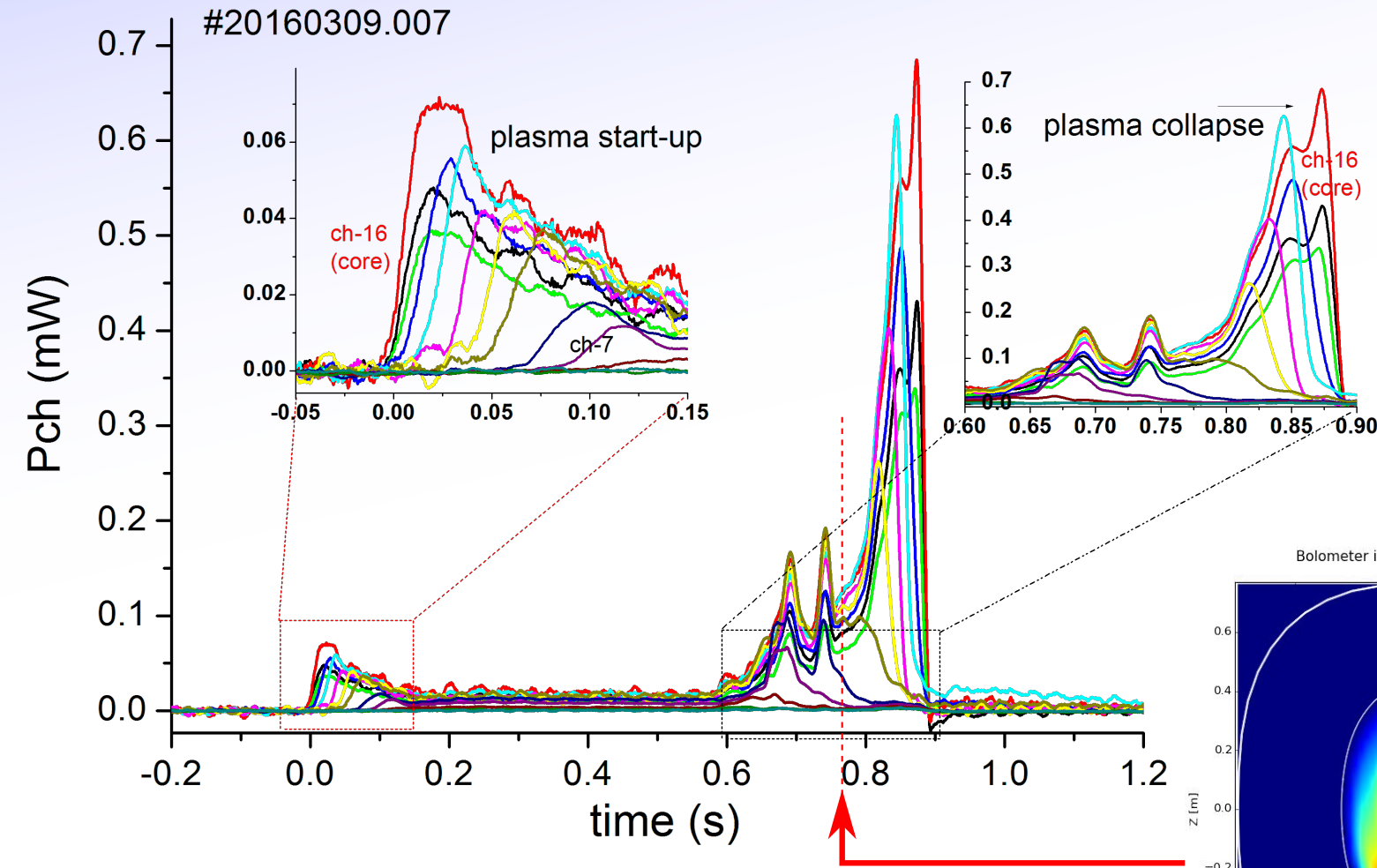
- Bolometry shows strong edge impurity radiation, especially at end of discharge.



- Confirms pulse length is limited by impurity influx
in most cases, except at the very beginning of the day.

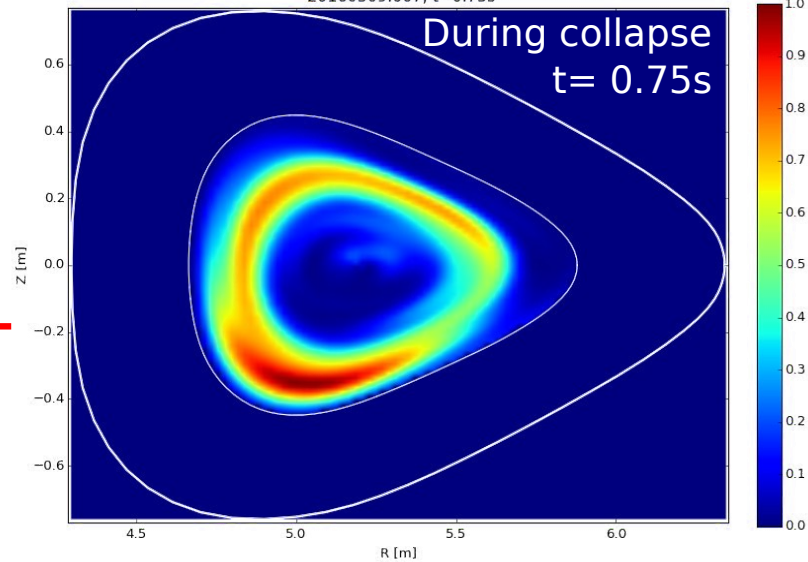
Impurity Content

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Bolometer inversion Minerva using Gaussian Process Tomography
20160309.007, t=0.75s

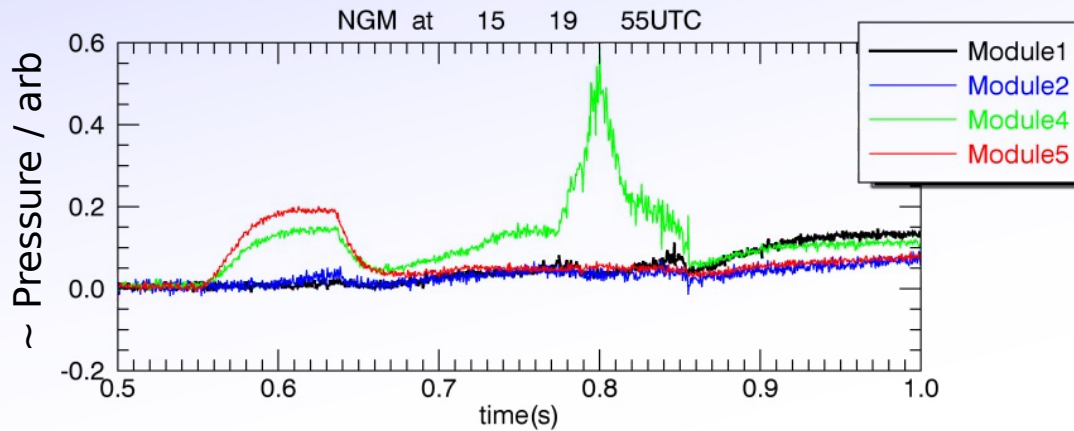


Bayesian Gaussian Process Tomography
[Minerva]

[U. Wenzel, M. Jakubowski,
G. Wurden, S. Lazerson]

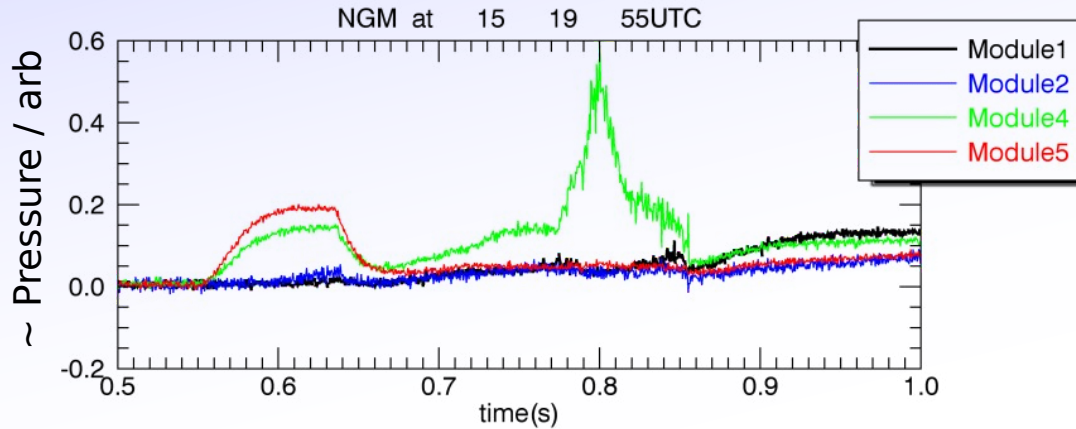
(A)symmetrisation: outgassing

- Neutral gas manometers installed in each module: 1kHz continuous data acquisition.
- High pressure event seen in module 4, often limiting discharge length.

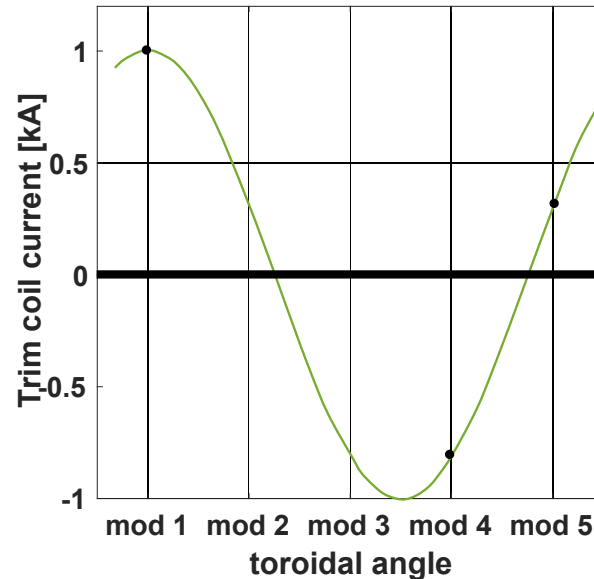
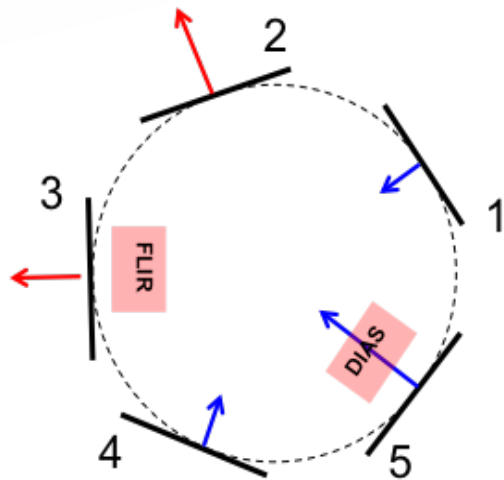


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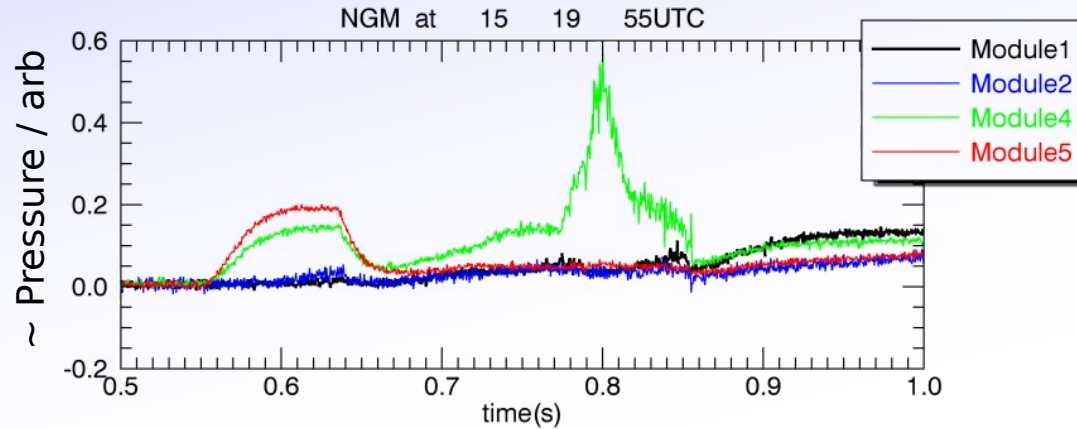


Possible to symmetrise pressures with $n/m=1/1$ perturbation using trim coils.

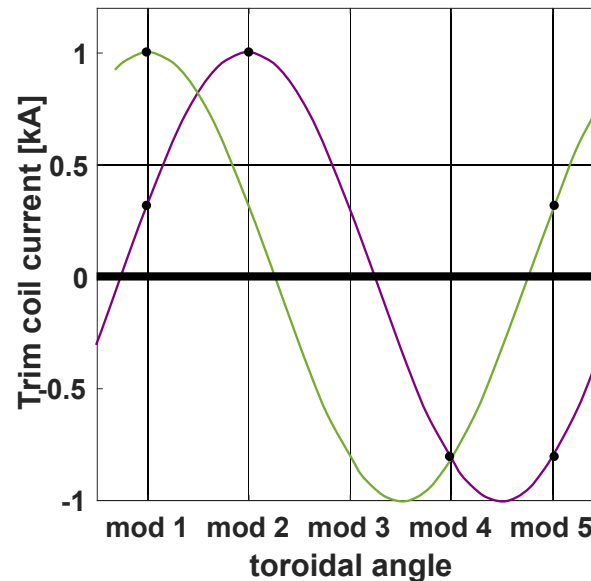
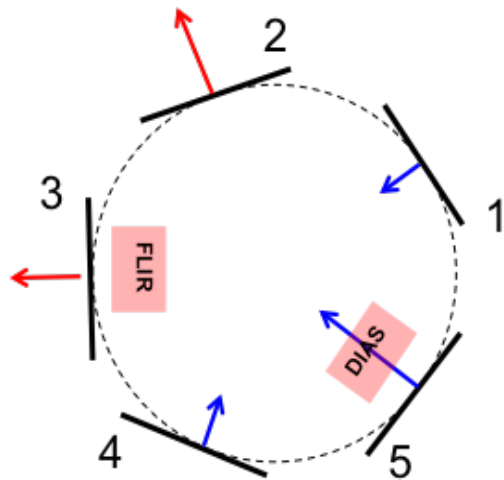


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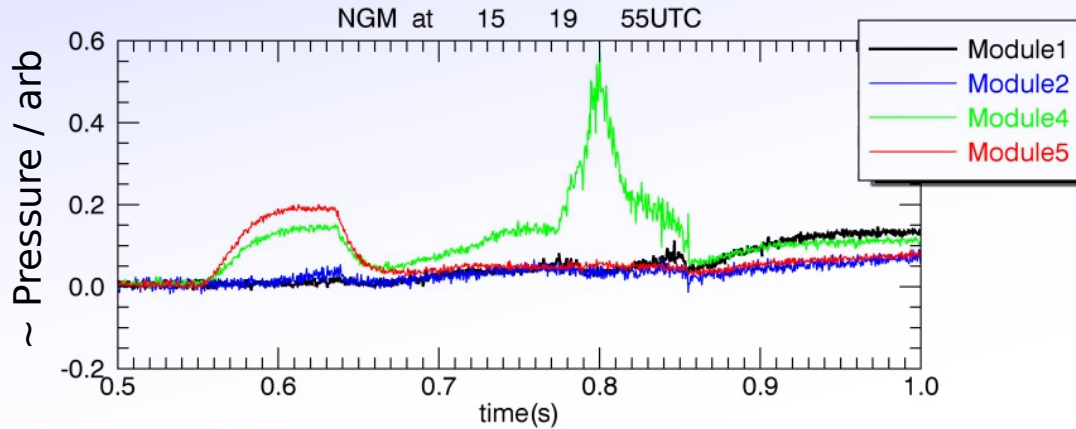


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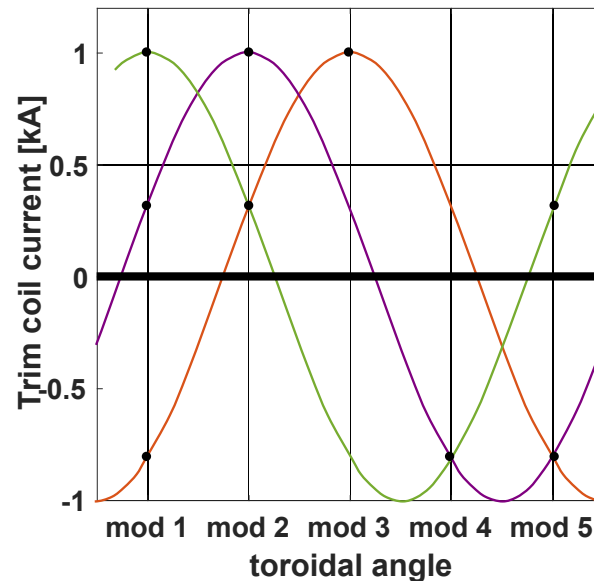
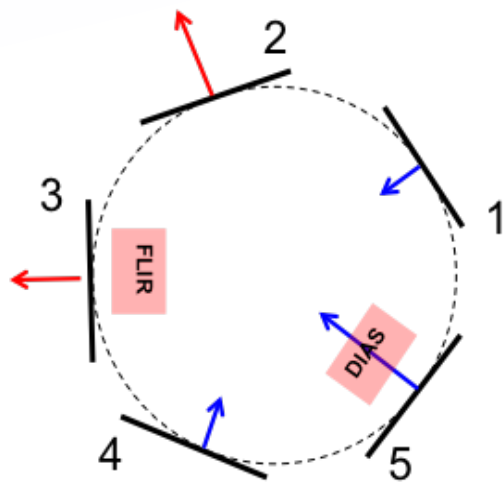


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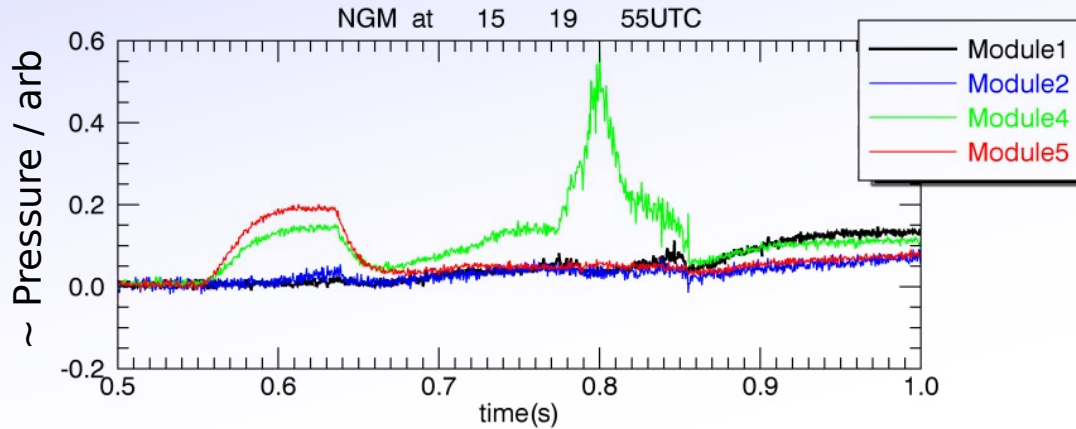


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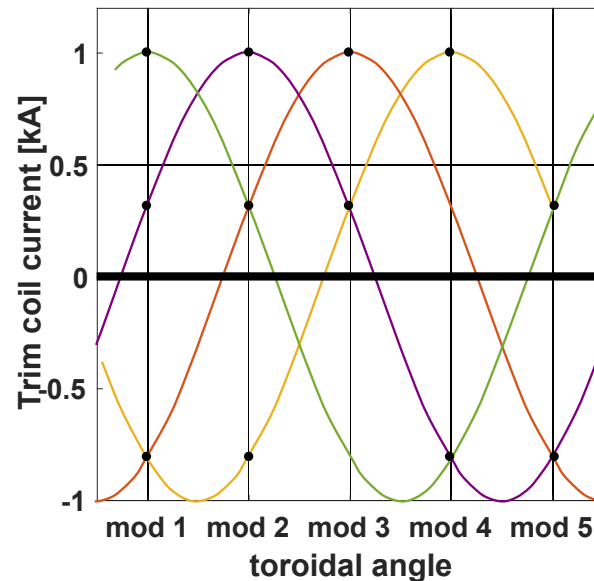
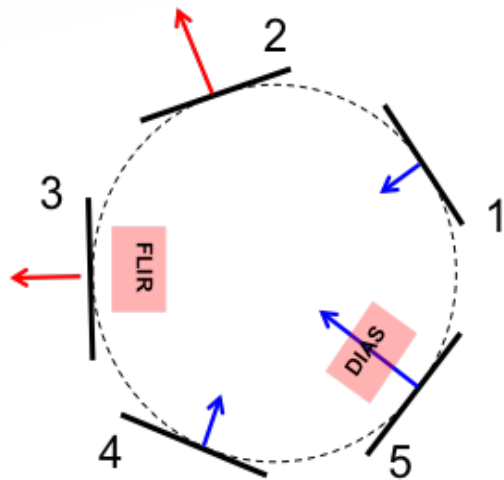


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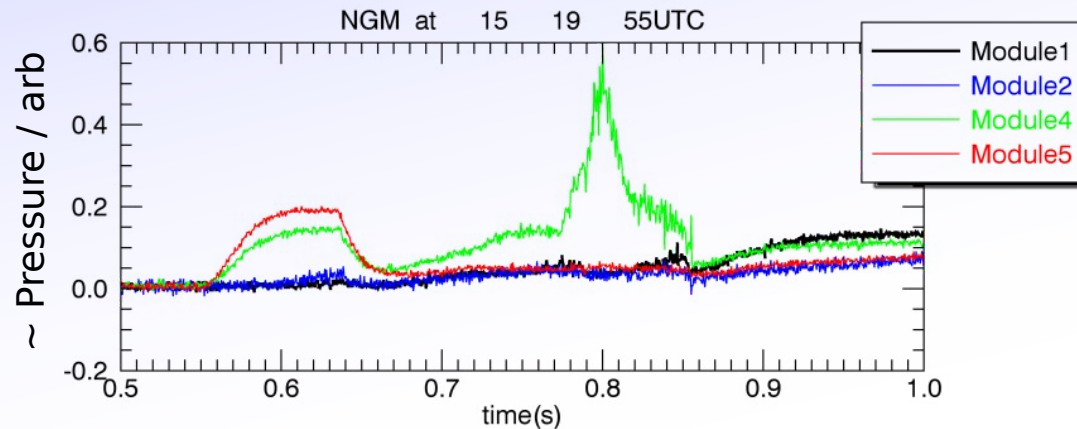


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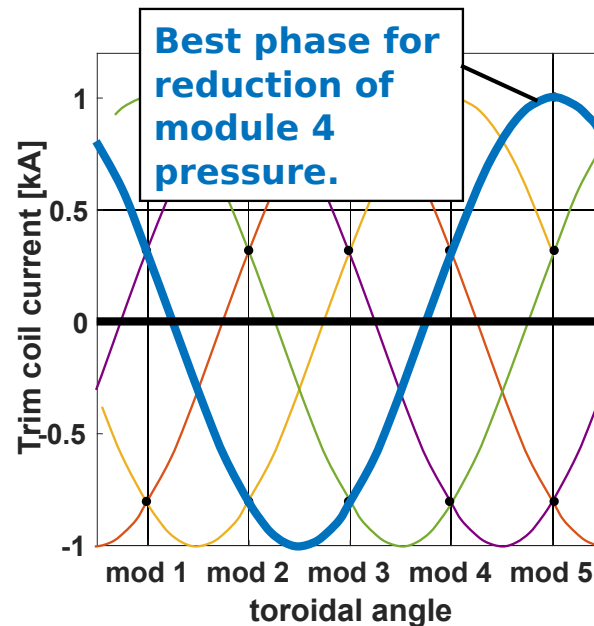
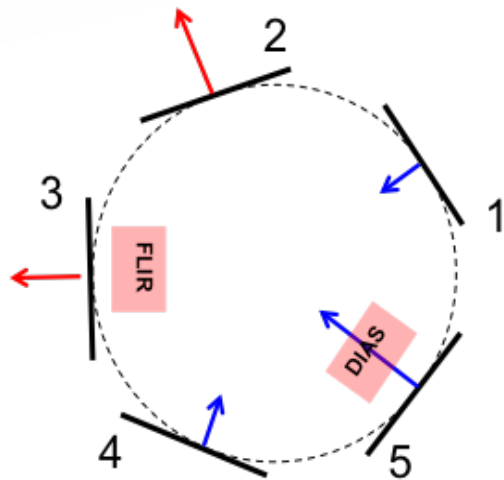


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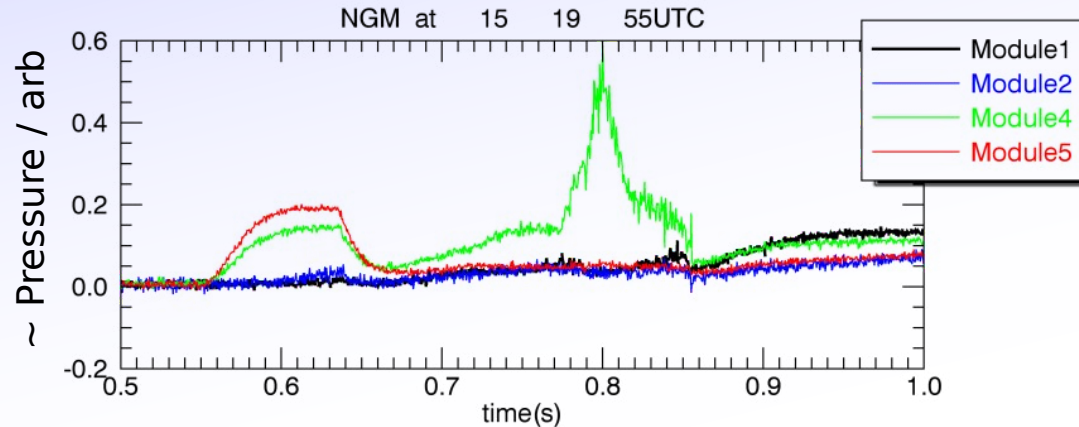


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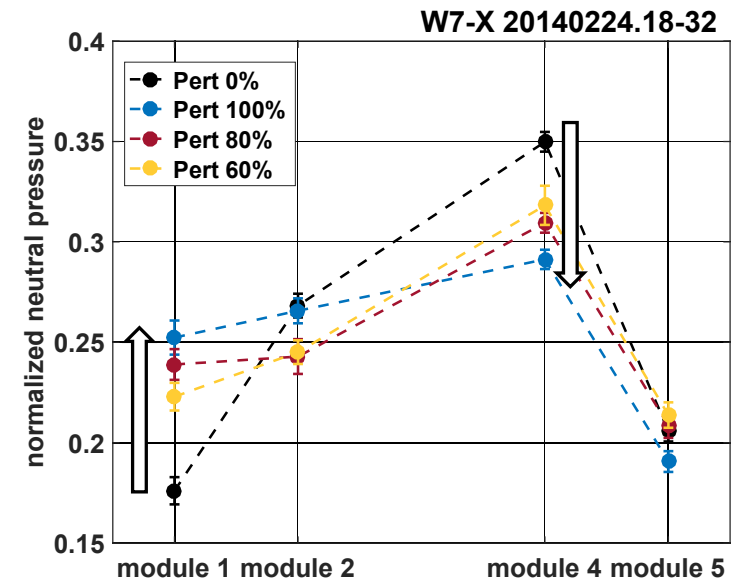
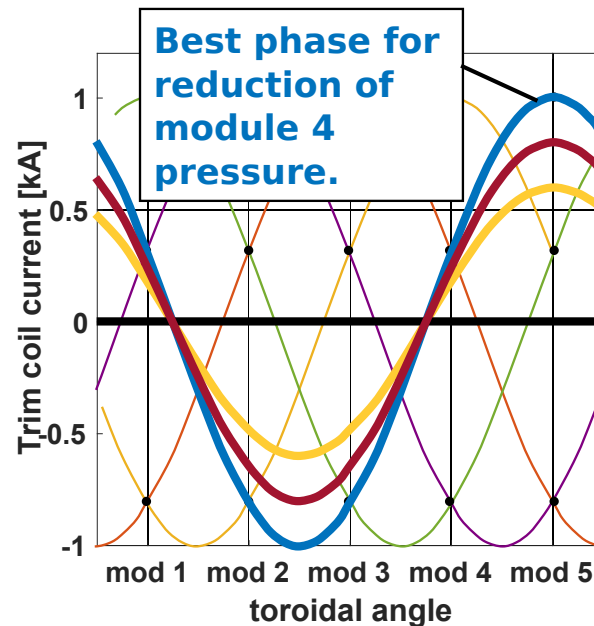
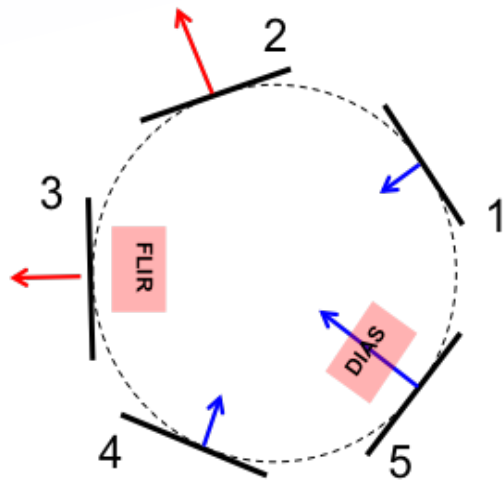


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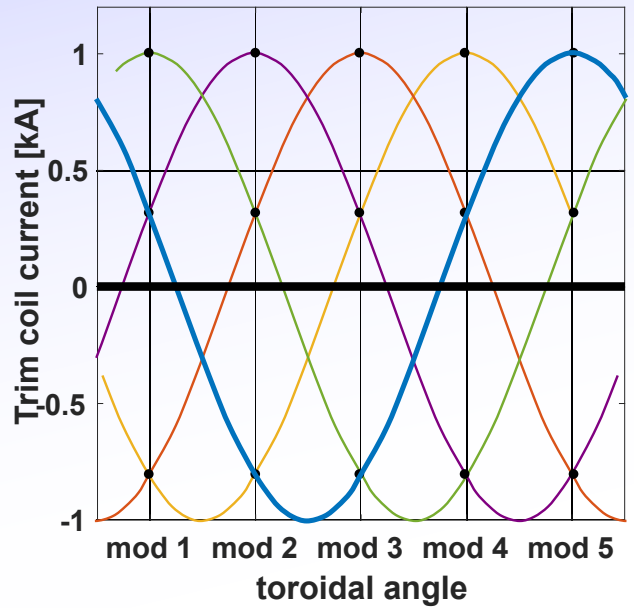


Best symmetrised at 1kA, but outgassing much higher. Lowest total outgassing at **60% amplitude**.

(A)symmetrisation

[M.Jakubowski, G.Wurden,
S.Lazerson, G. Kocsis,
Manipulator Group
DIAS Group]

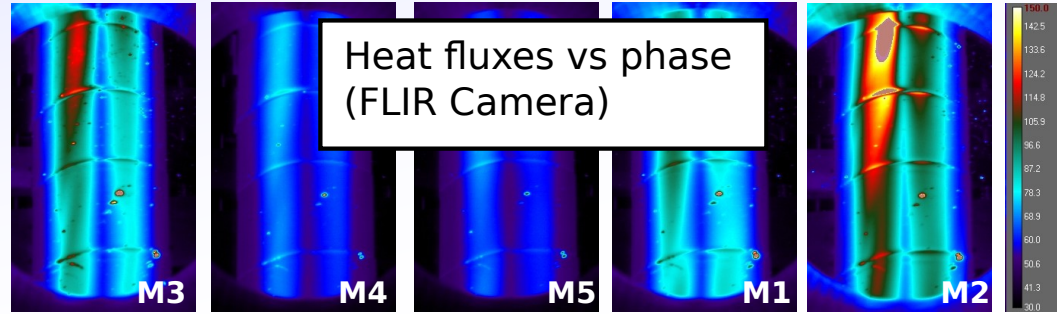
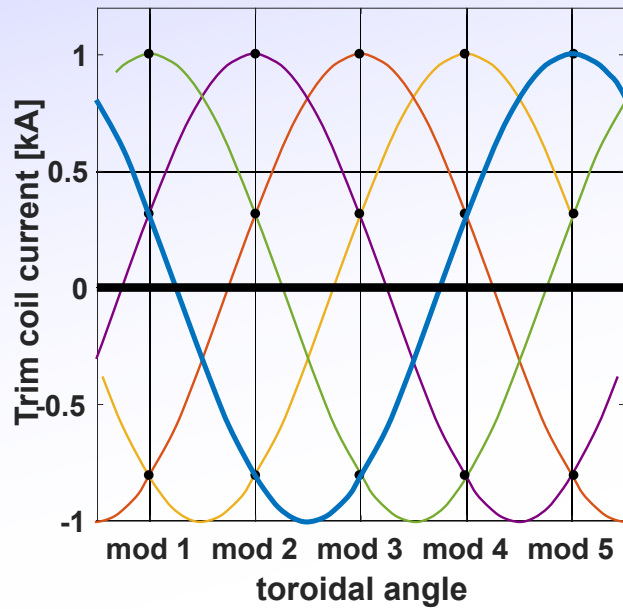
Other edge experiments using trim coils for assymetrisation:



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[M.Jakubowski, G.Wurden,
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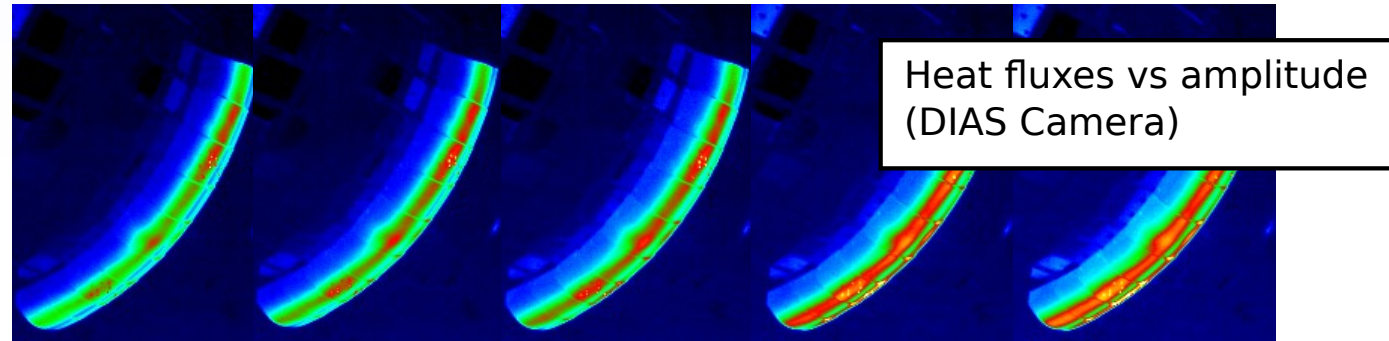
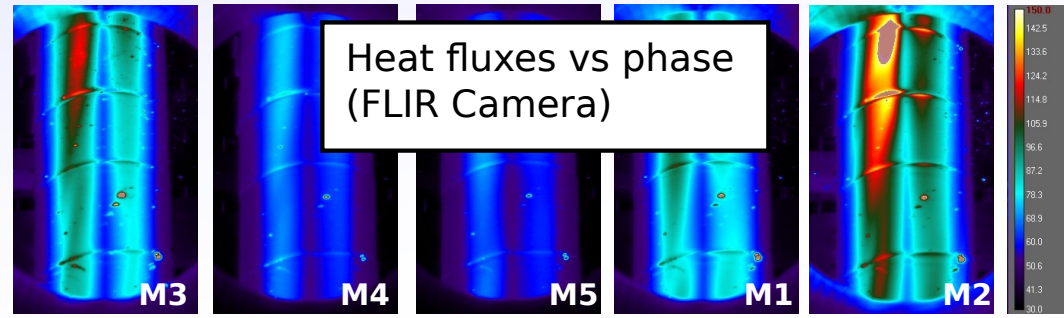
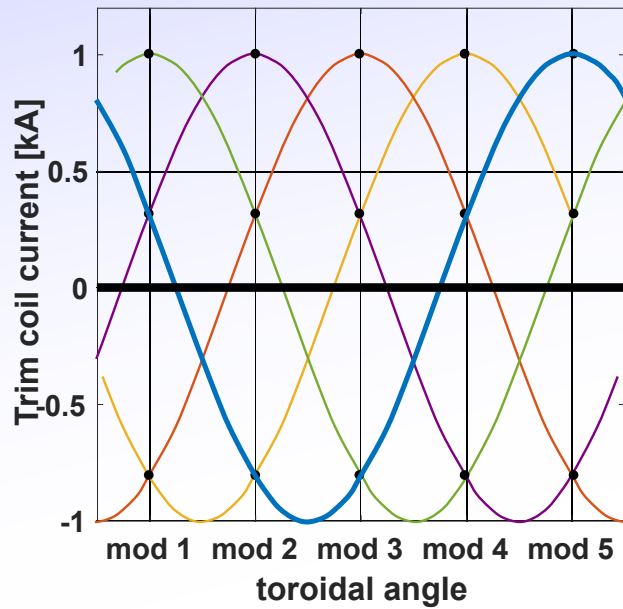
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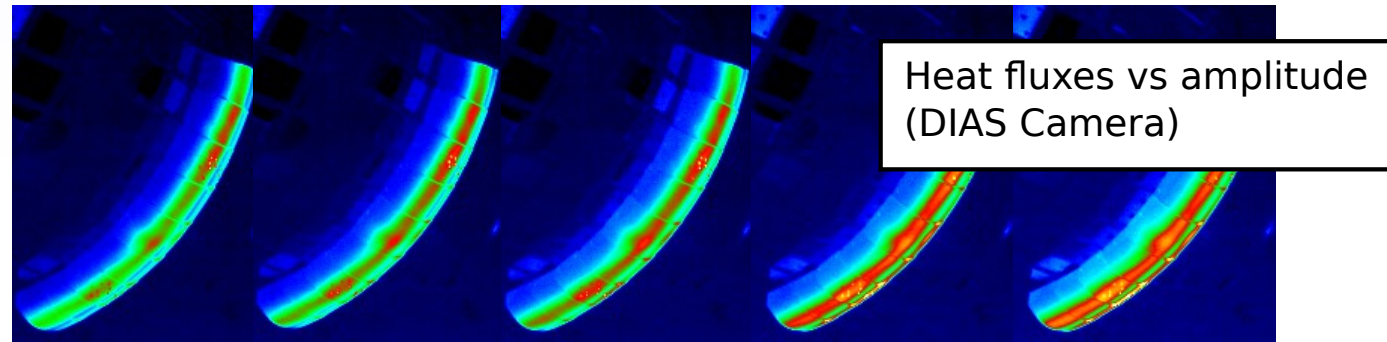
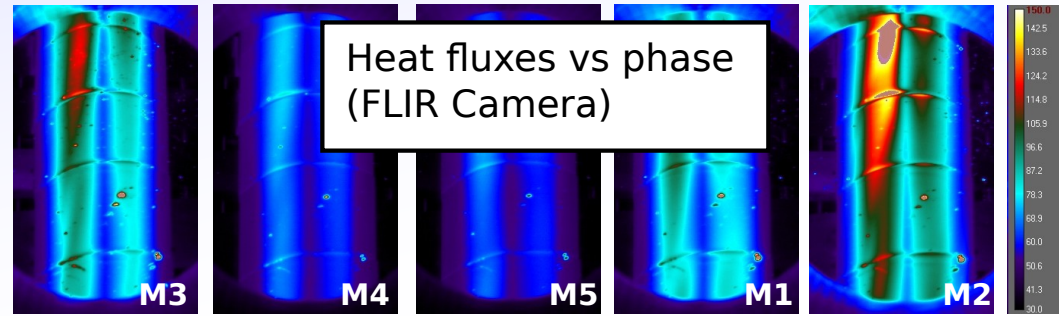
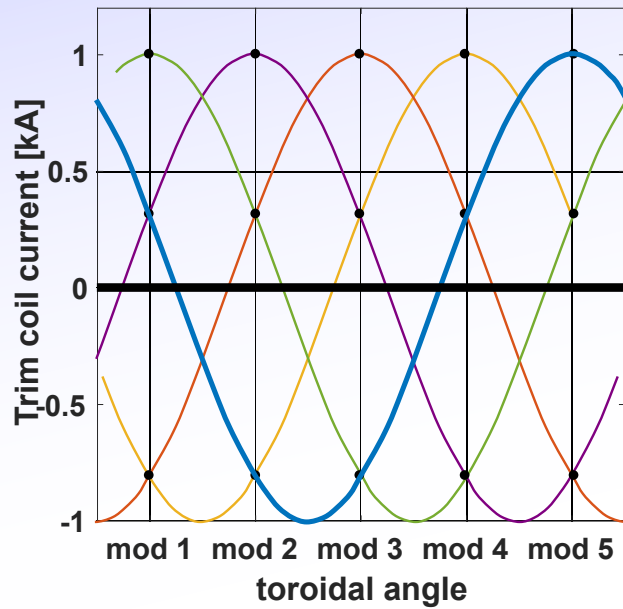
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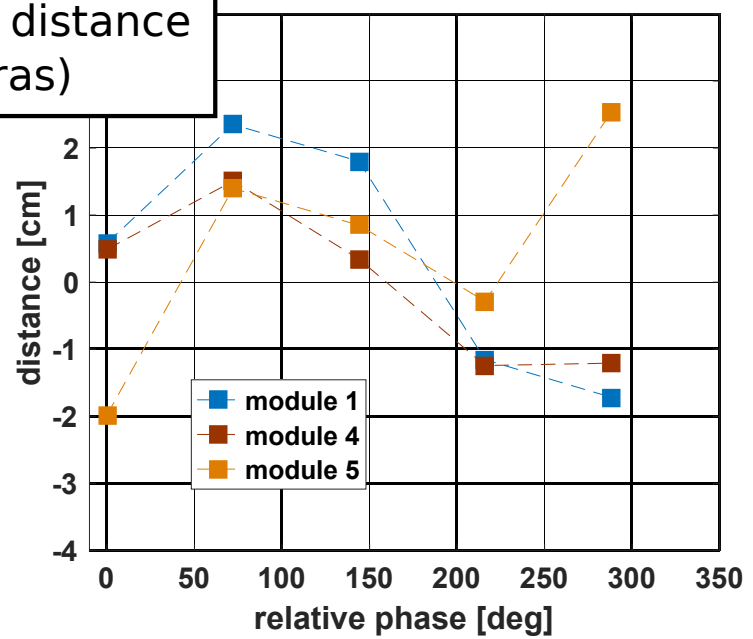
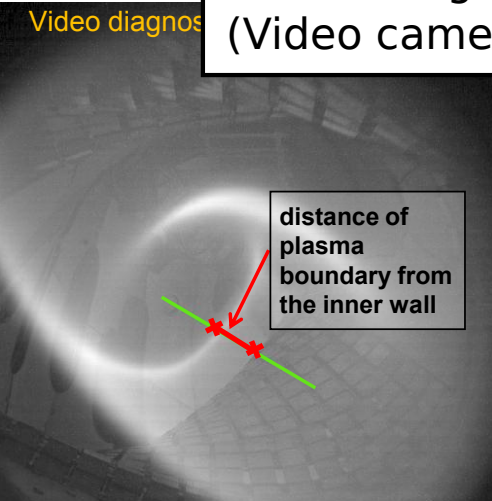
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[M.Jakubowski, G.Wurden, S.Lazerson, G. Kocsis, Manipulator Group DIAS Group]

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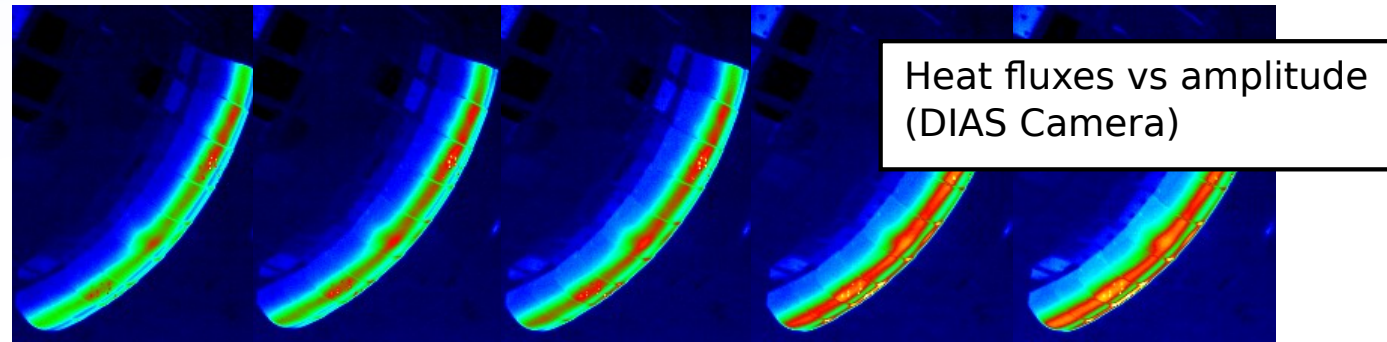
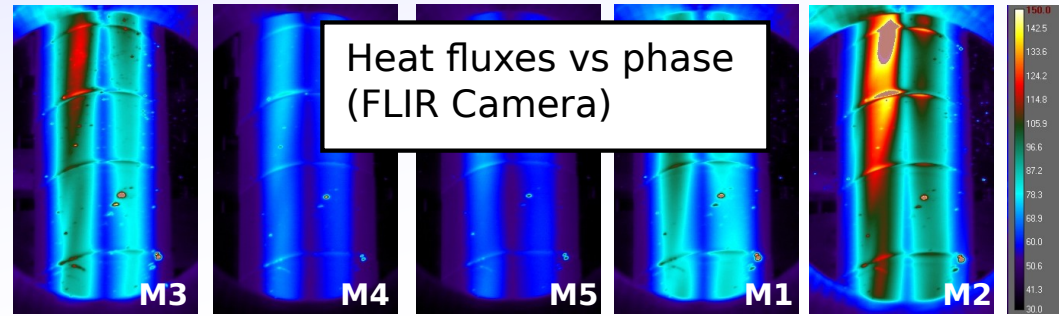
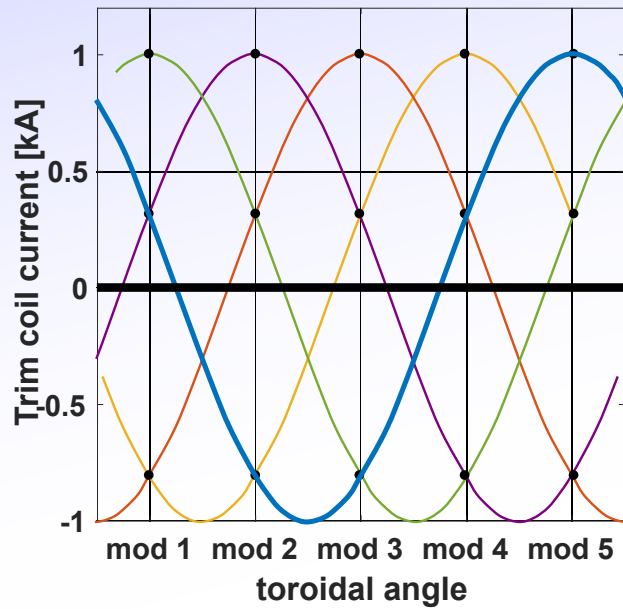
Plasma edge distance (Video cameras)



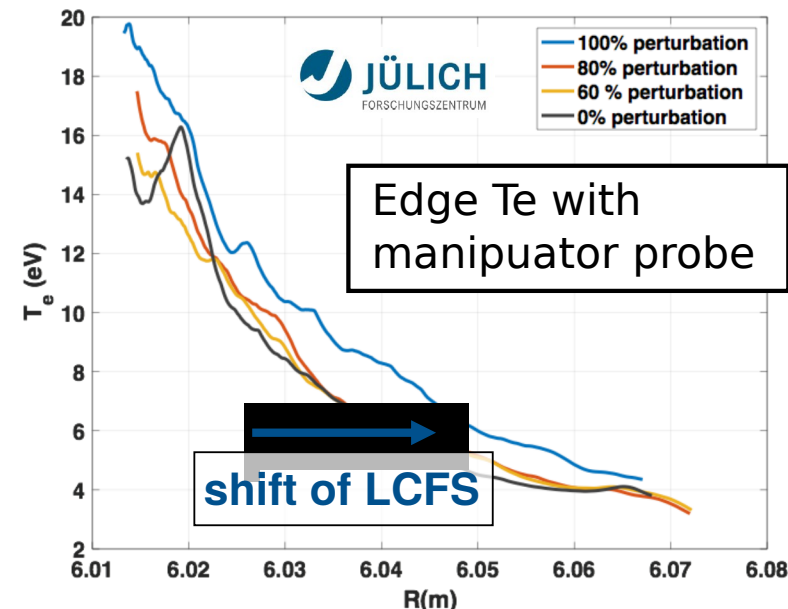
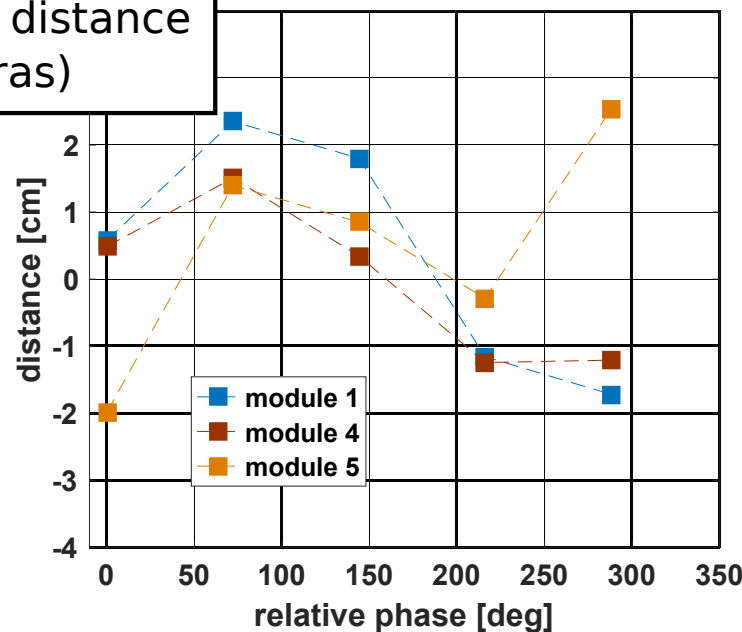
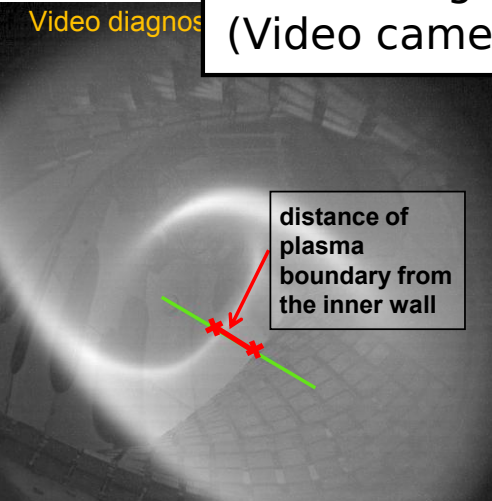
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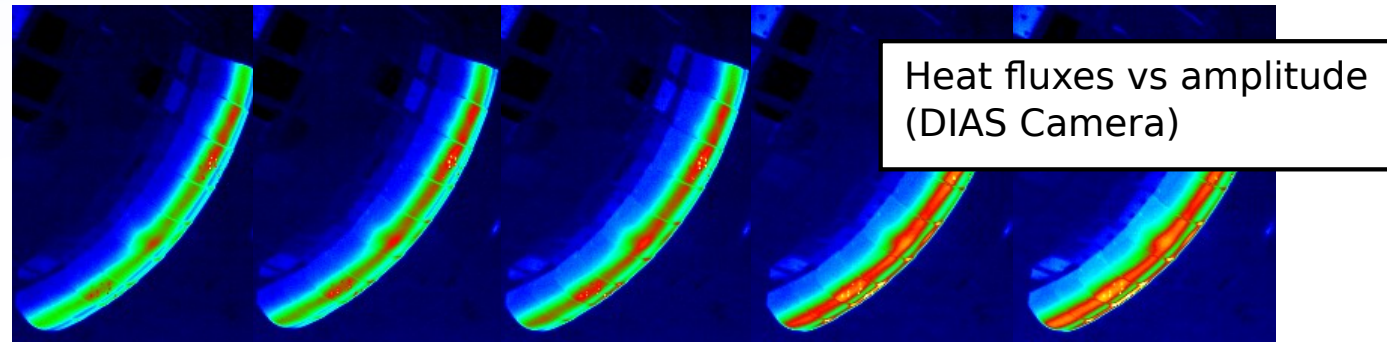
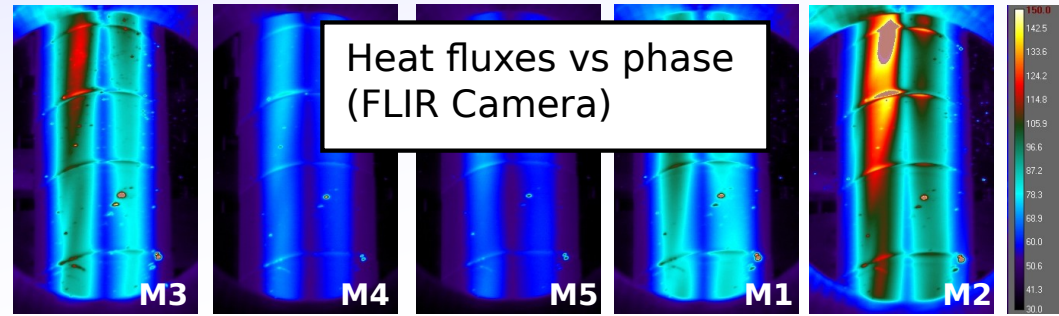
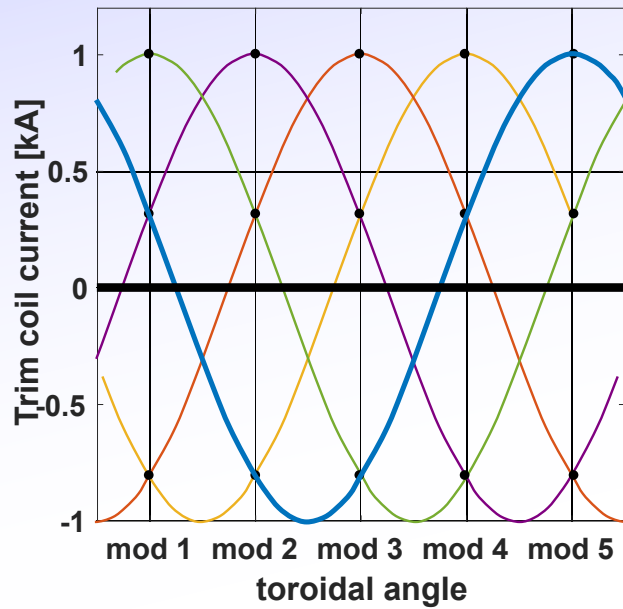
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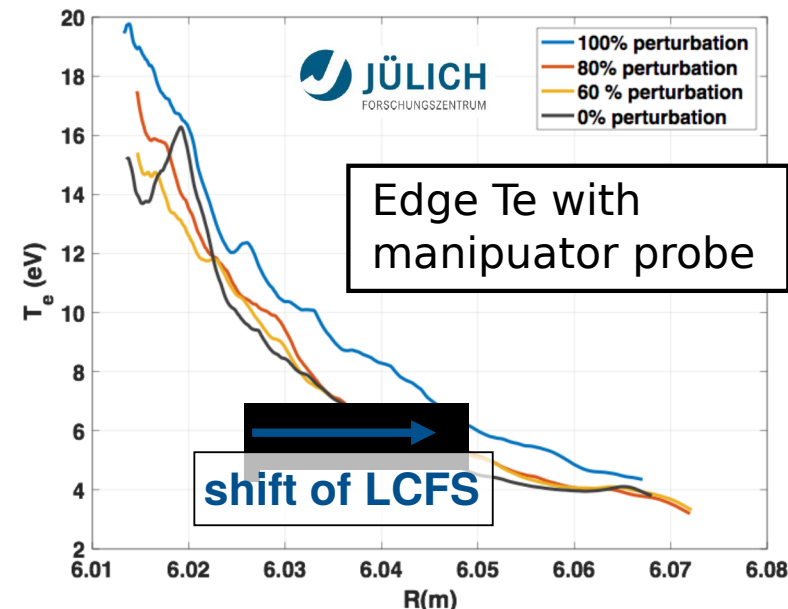
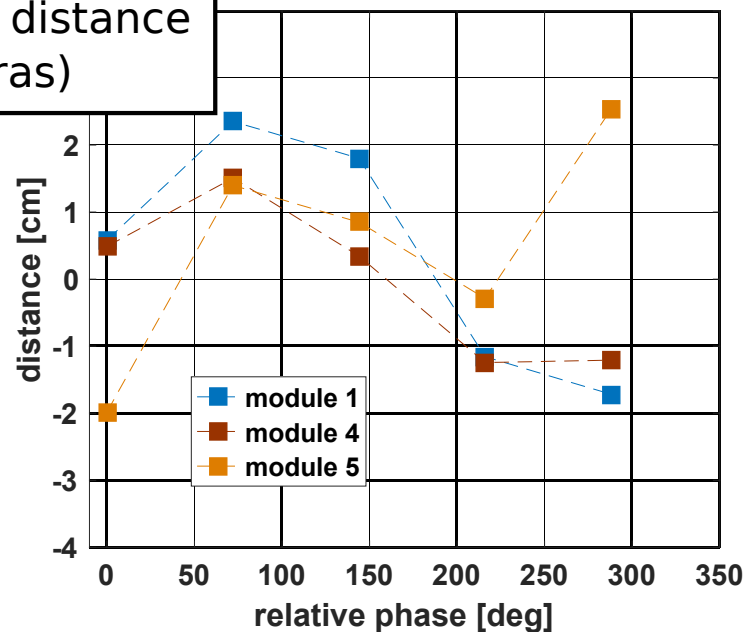
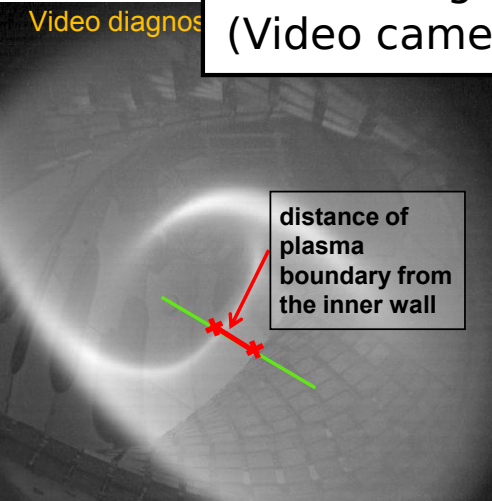
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[M.Jakubowski, G.Wurden, S.Lazerson, G. Kocsis, Manipulator Group DIAS Group]

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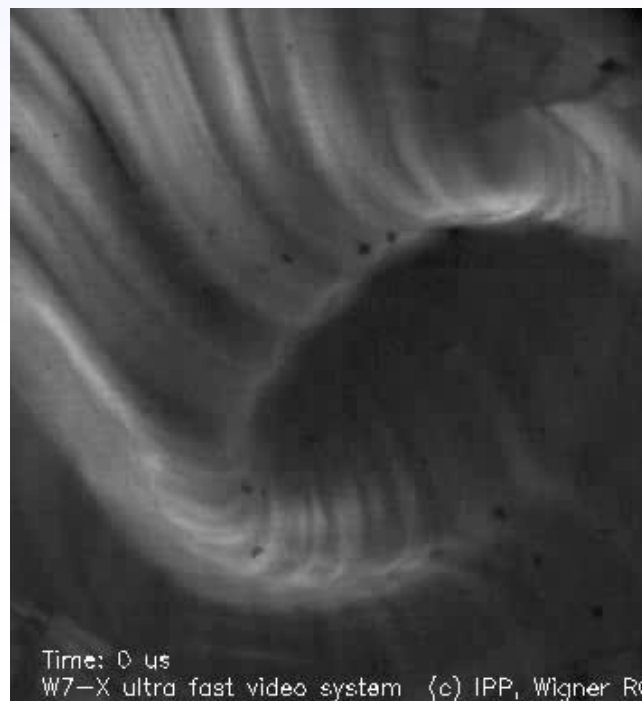




Edge Filaments

Filament structures observed on fast visible camera.

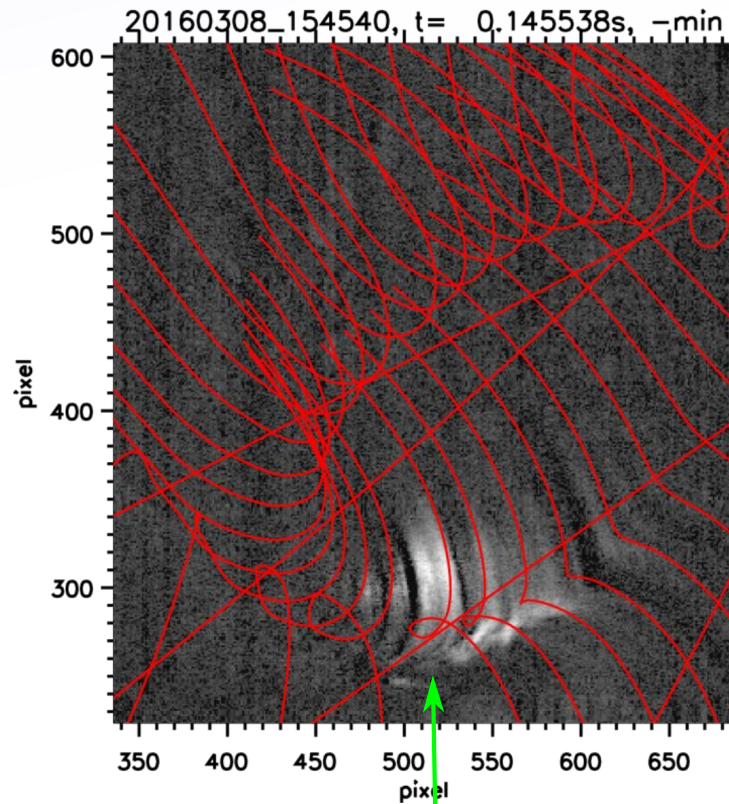
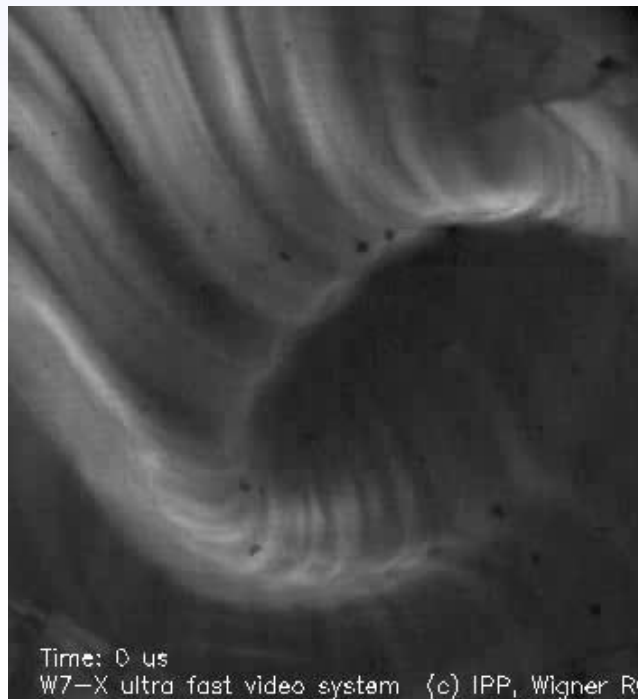
- Observed during strong gas puffing or wall outgassing.



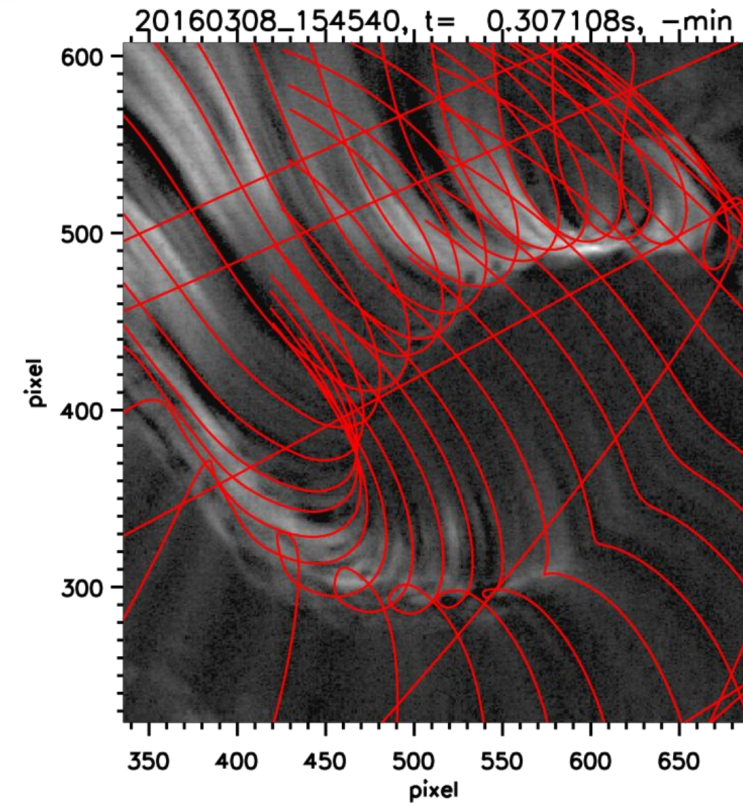
Edge Filaments

Filament structures observed on fast visible camera.

- Observed during strong gas puffing or wall outgassing.
- Filaments appear to be aligned with field lines.
- In certain conditions, the structure rotates.
- Otherwise not yet understood.... analysis ongoing.



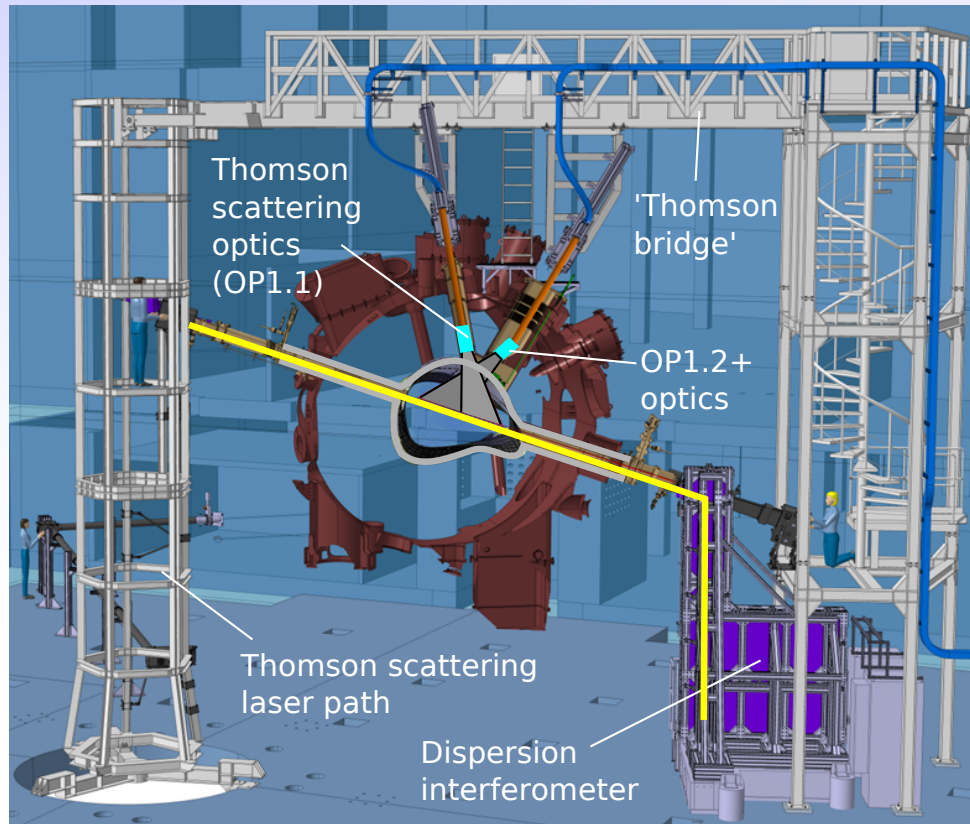
Strong gas puffing



Strong wall outgassing

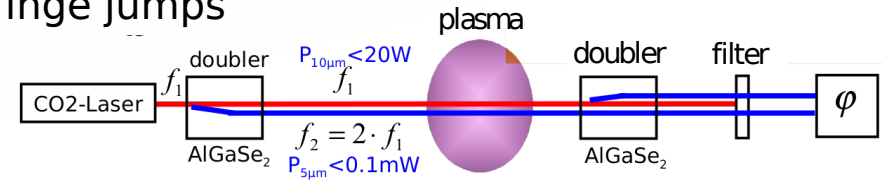
Electron Kinetic Diagnostics: n_e

[G. Fuchert, S. Bozhenkov, E. Pasch, P. Kornejew, J. Knauer, H. Trimino Mora]



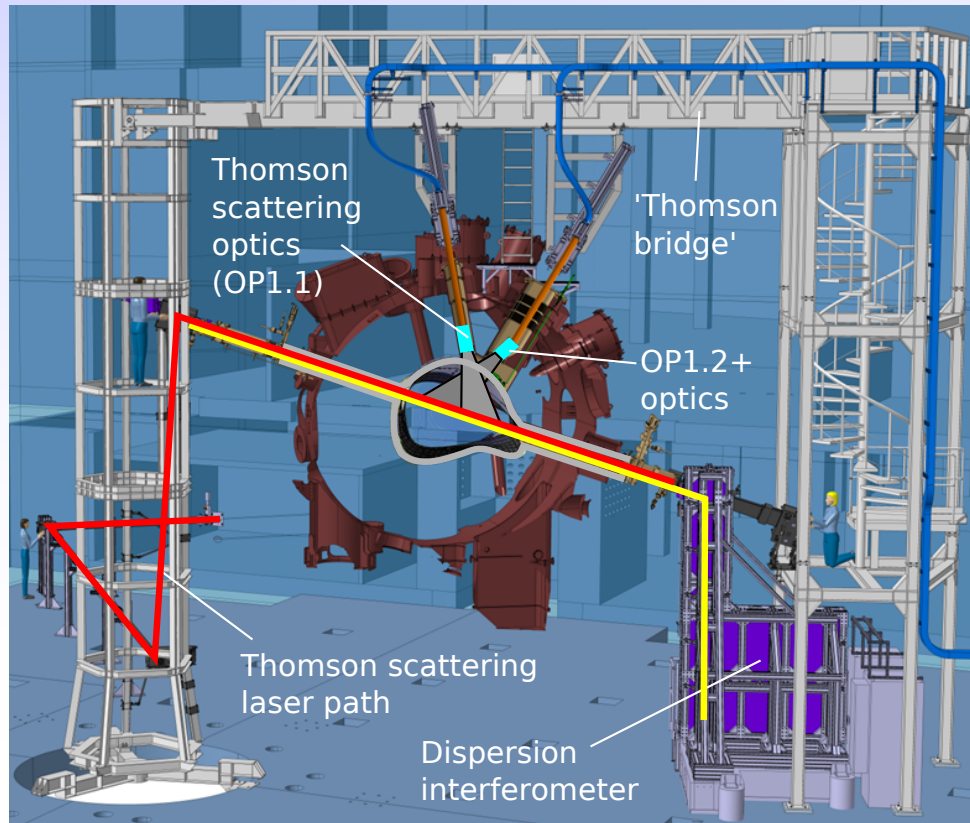
Single channel interferometer:

- CO² CW Laser
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 - Physical path changes cancel (to first order)
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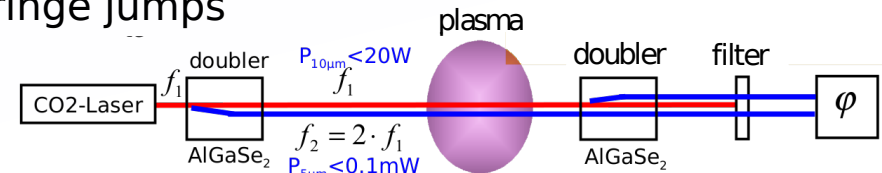
[G. Fuchert, S. Bozhenkov,
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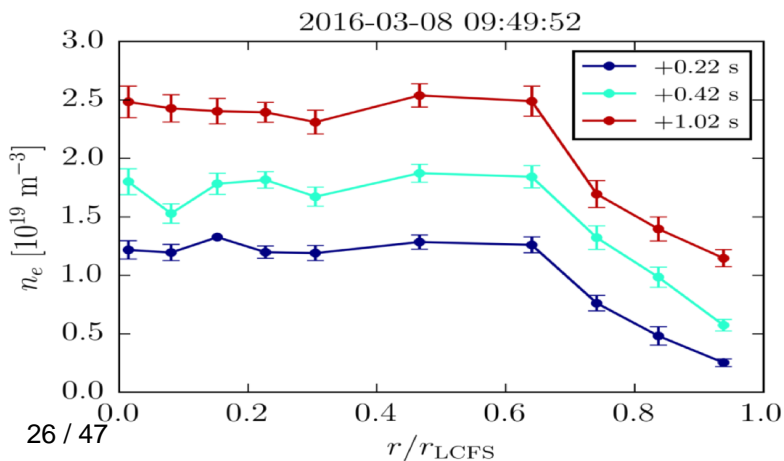
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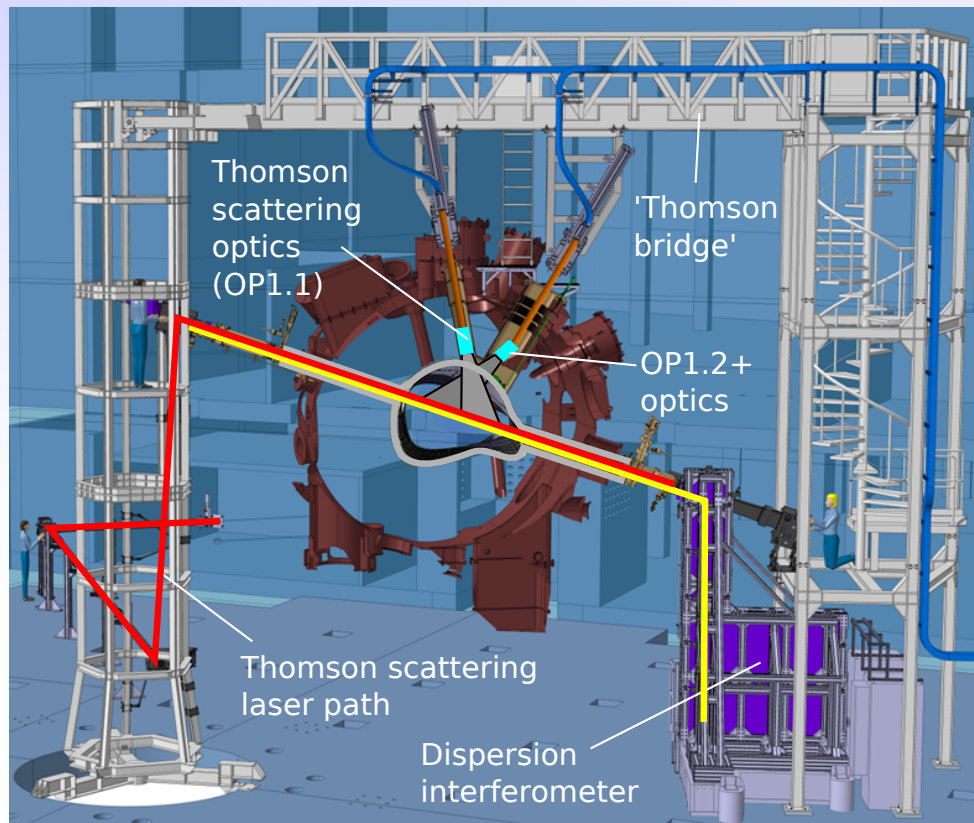
Thomson Scattering (OP1.1):

- 2J Nd:YAG laser: 1064nm, 100ms rep rate
- 5 spectral channels.
- 10 spatial points, 3-4cm resolution.
- Design range $n_e = 10^{19} - 10^{20}$, $10\text{eV} < T_e < 10\text{keV}$
- Bayesian inference of $P(T_e, n_e)$ [Minerva]



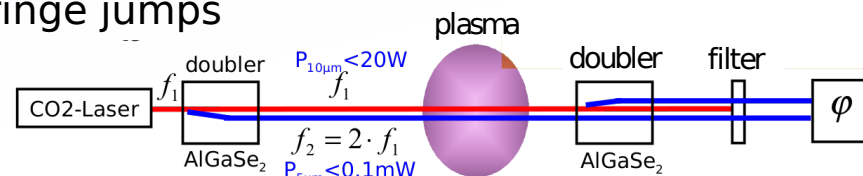
[G. Fuchert, S. Bozhenkov,
E. Pasch, P. Kornejew,
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Electron Kinetic Diagnostics: n_e



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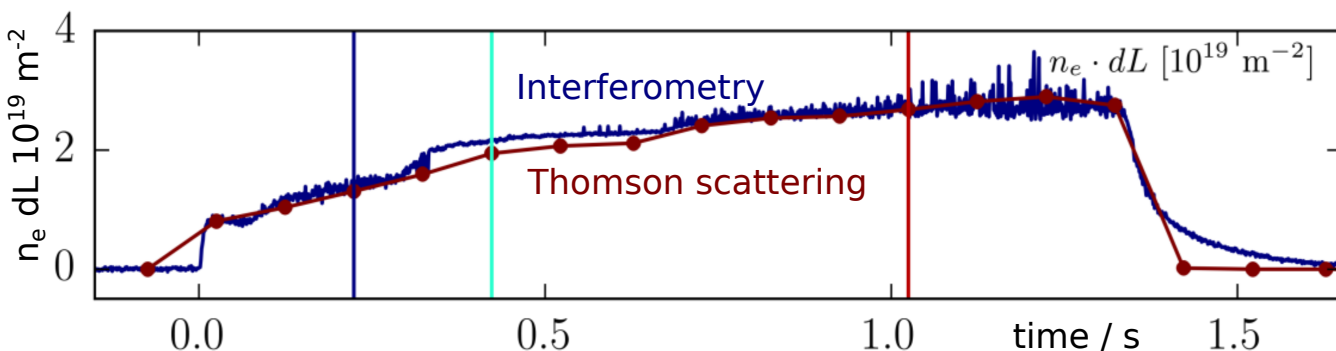
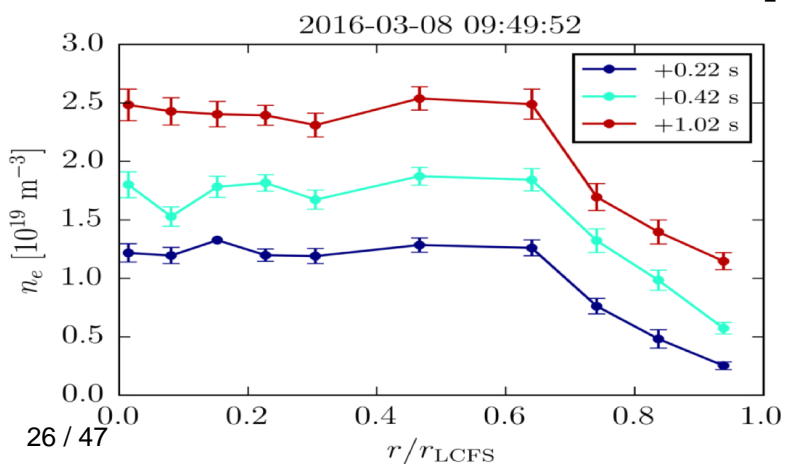
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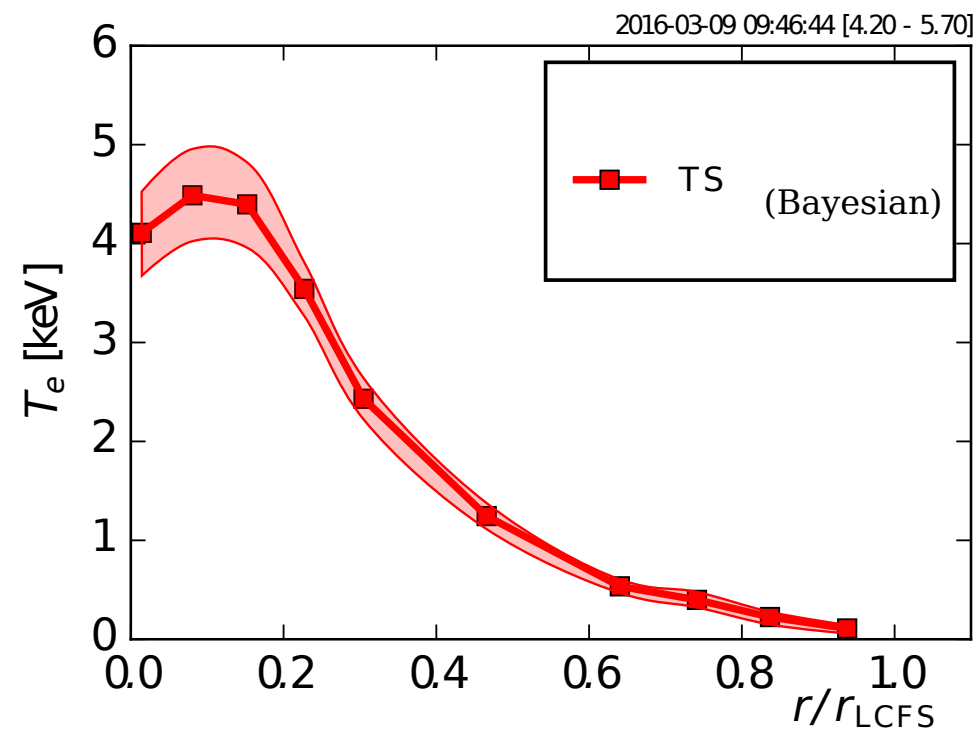
- TS absolute n_e from independent Raman Scattering calibration.
- Generally superb agreement with interferometry, occasional large deviations (up to 40%, cause as-yet unknown).





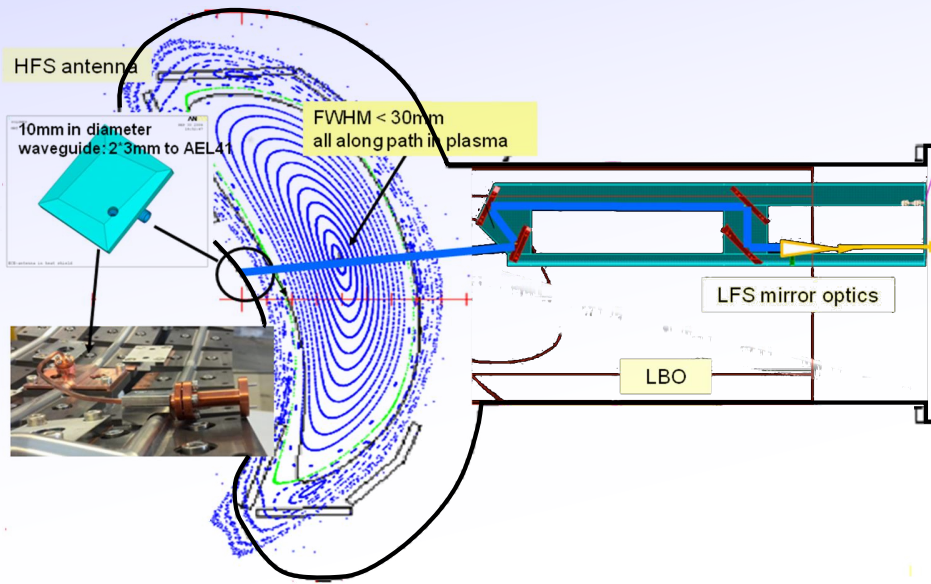
Electron Kinetic Diagnostics: T_e

[M. Hirsch, N. Pablant,
A. Langenberg, G. Fuchert,
S. Bozhenkov, E. Pasch]

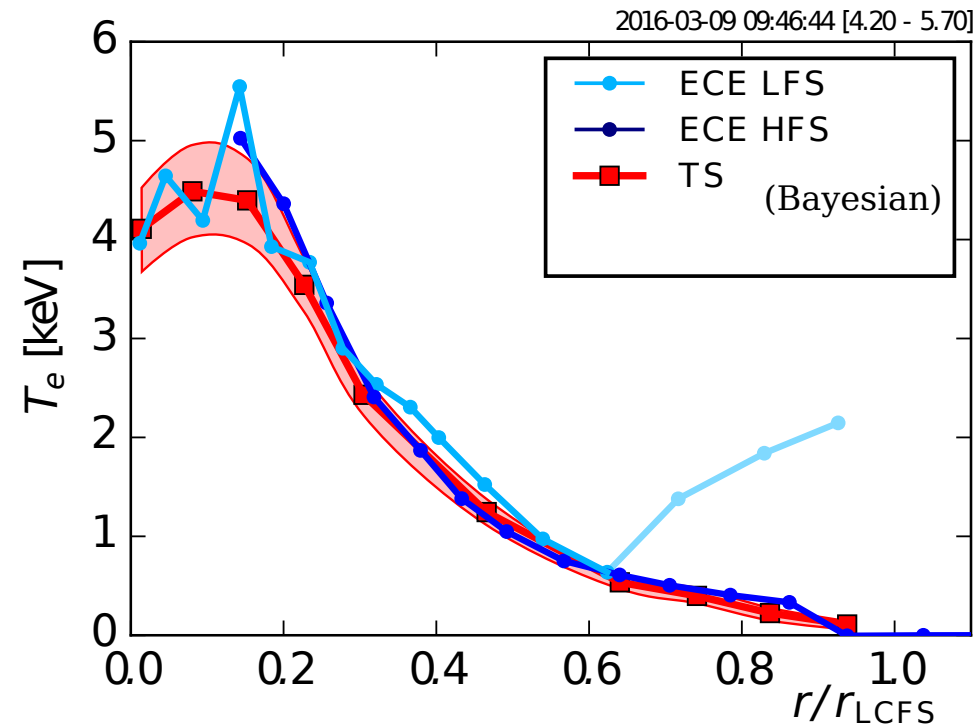


Electron Kinetic Diagnostics: T_e

Electron Cyclotron Emission:



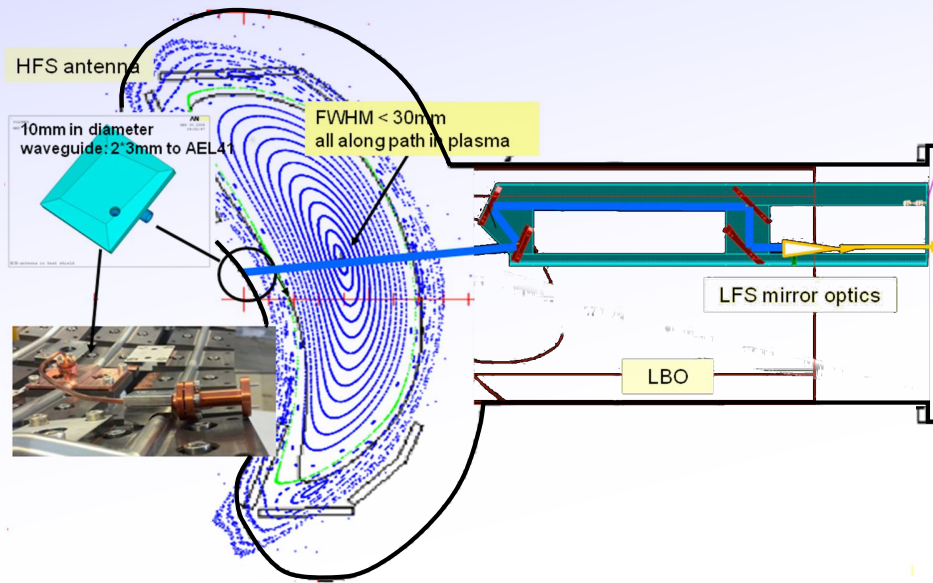
- Low and high field side antennae.
- 32 primary channels + 16 for high resolution 'zoom'
- 126-161 GHz
- Temporal resolution down to $0.5\mu\text{s}$
- Spatial resolution $\sim 1\text{cm}$
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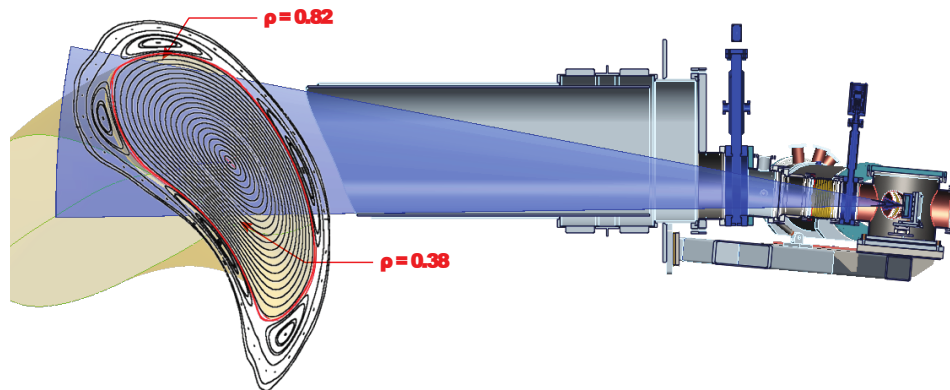
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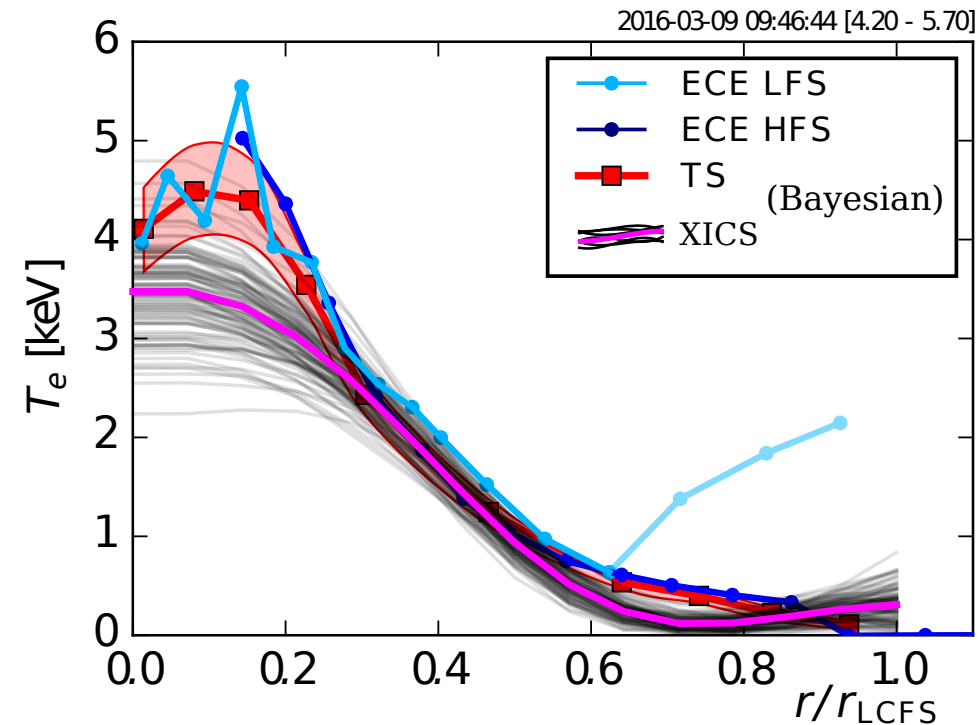
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End of OP1.1: Good broad agreement between TS, ECE and XICS for T_e profiles after much work by all diagnosticians. (Some inconsistencies remain)

X-Ray Crystal Imaging Spectrometer (XICS);

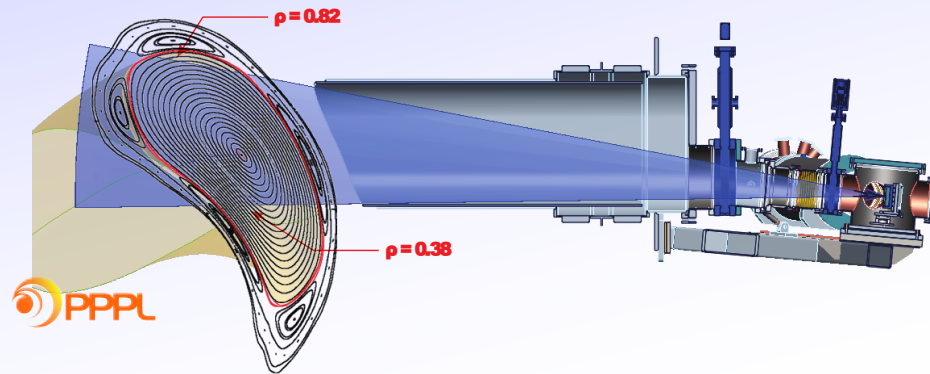


Line integrals of T_i , T_e , v_θ and n_{Ar} from observation of Argon emission lines.



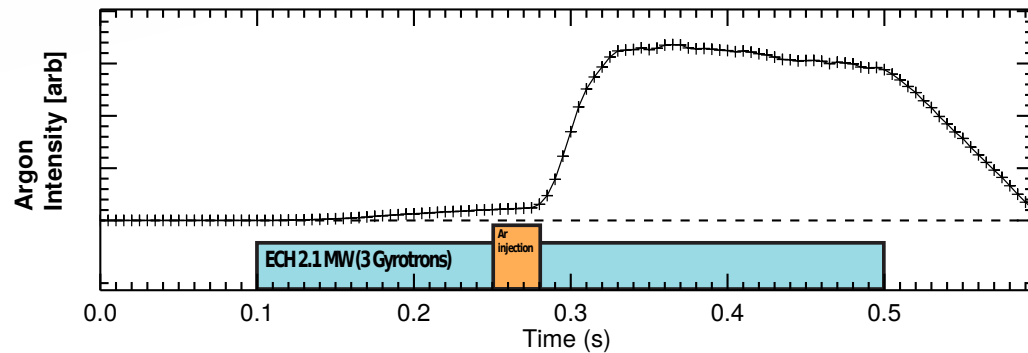
XICS: Argon Transport

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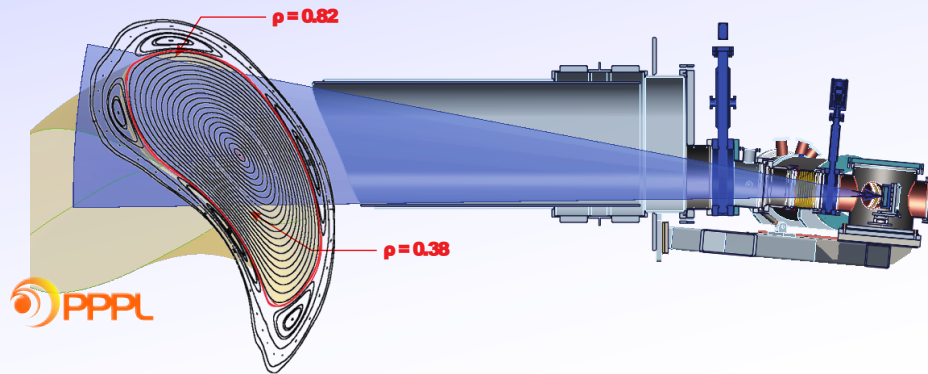
XICS | Shot 160128004



Argon gas puff from 'He-Beam' fast injection system.

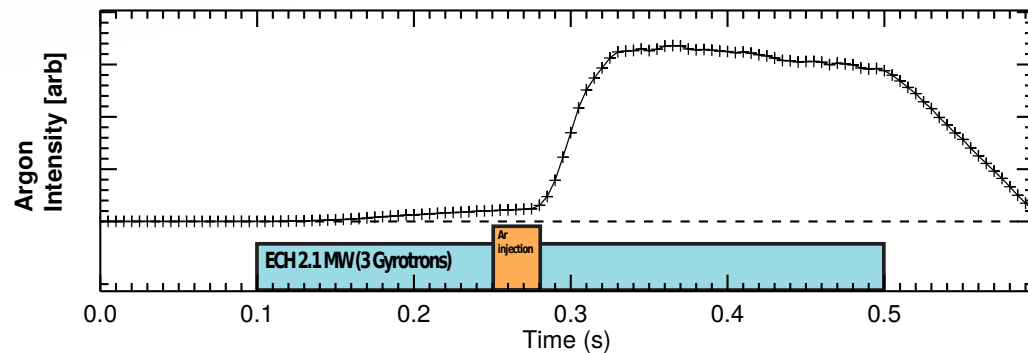
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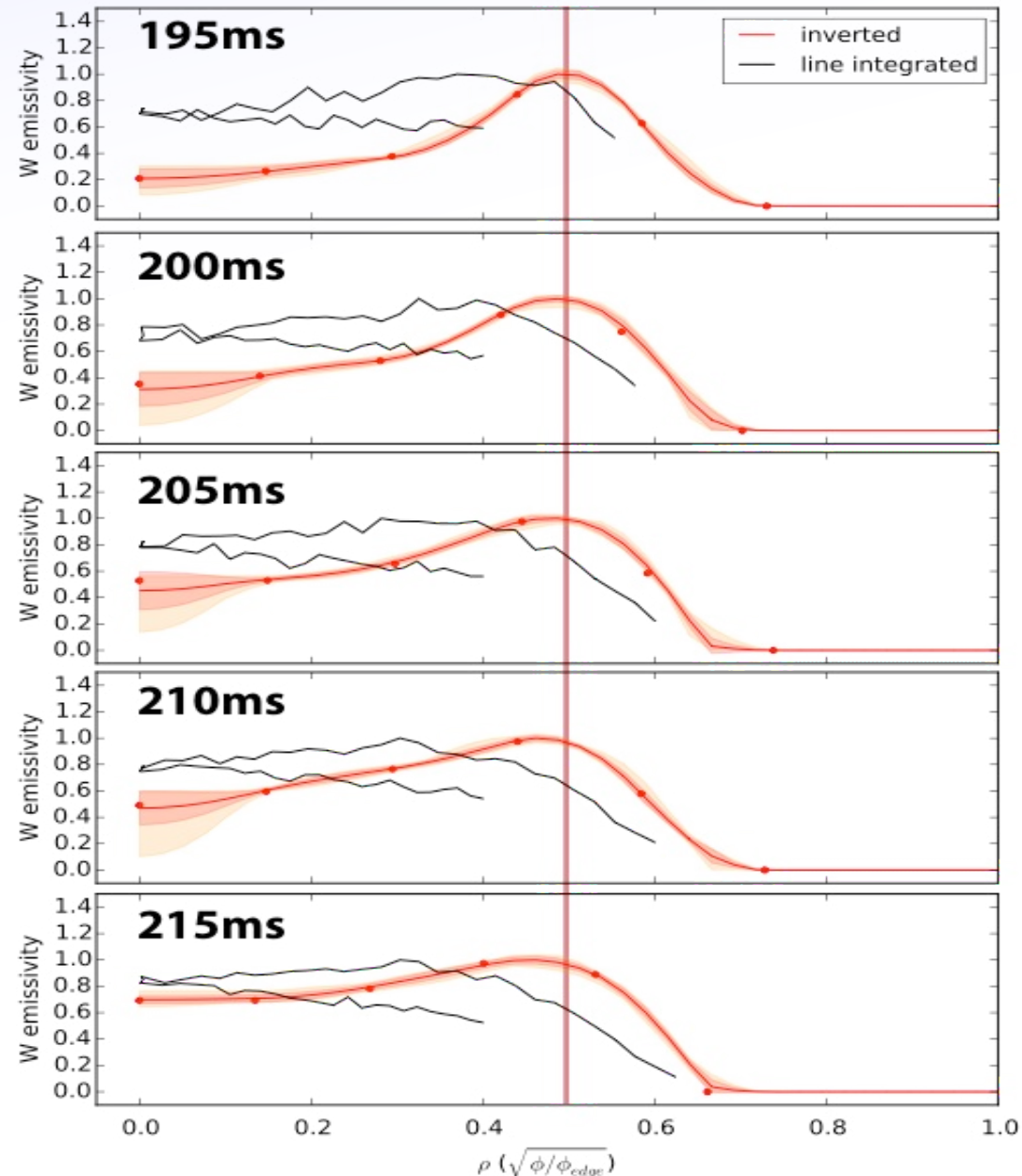
Argon gas puff from 'He-Beam' fast injection system.

XICS sees evolution of Argon 16+ profile and transport of Argon into the core.

Consistent with HEXOS Argon decay times.

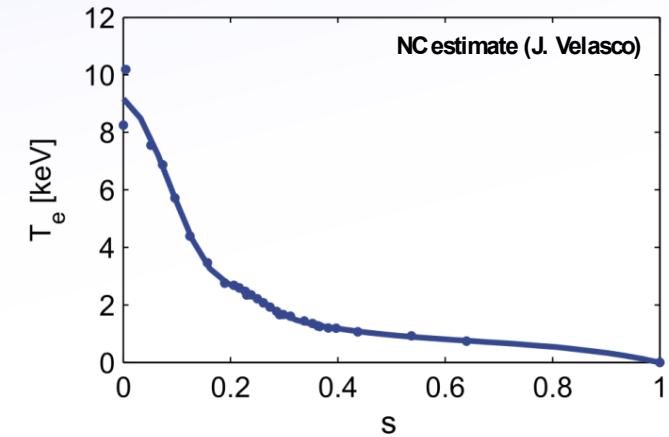
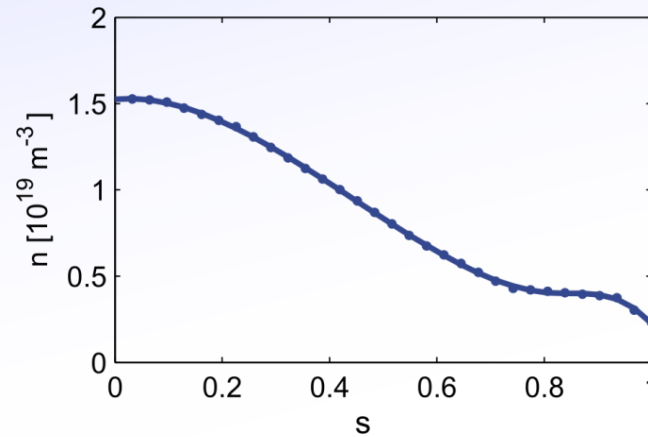
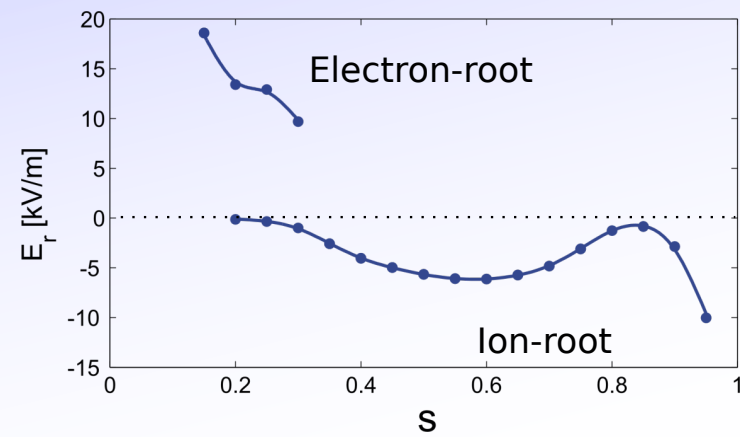
W7-X 20160128.04

AR16+ emissivity evolution



Core Electron Root Confinement (CERC)

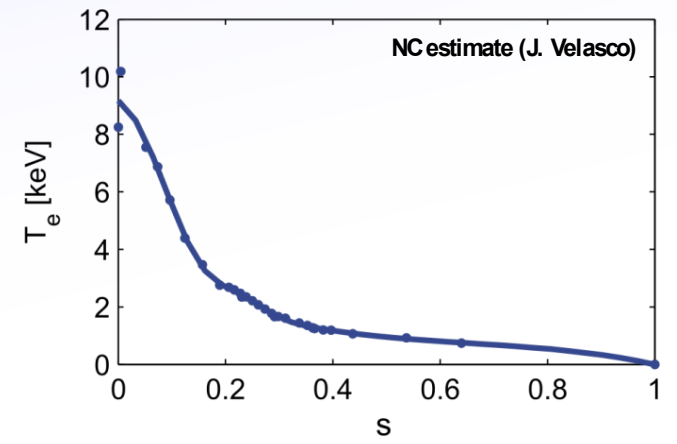
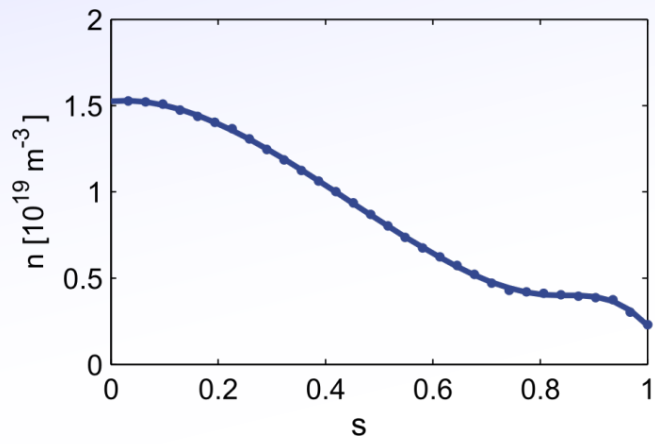
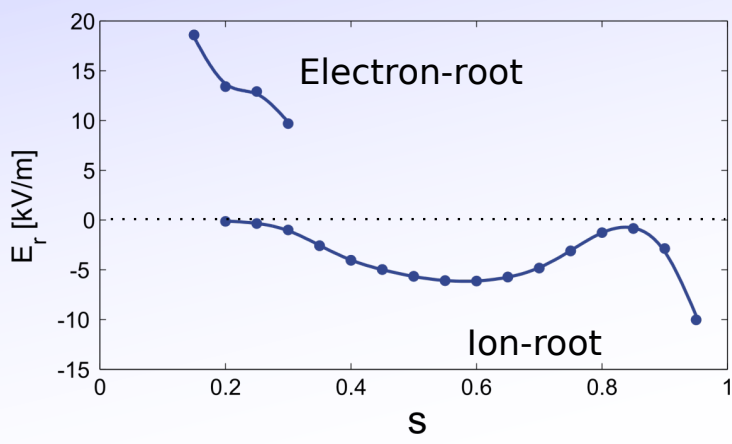
- Confinement regime with +ve E_r in core, associated with highly peaked T_e profile.



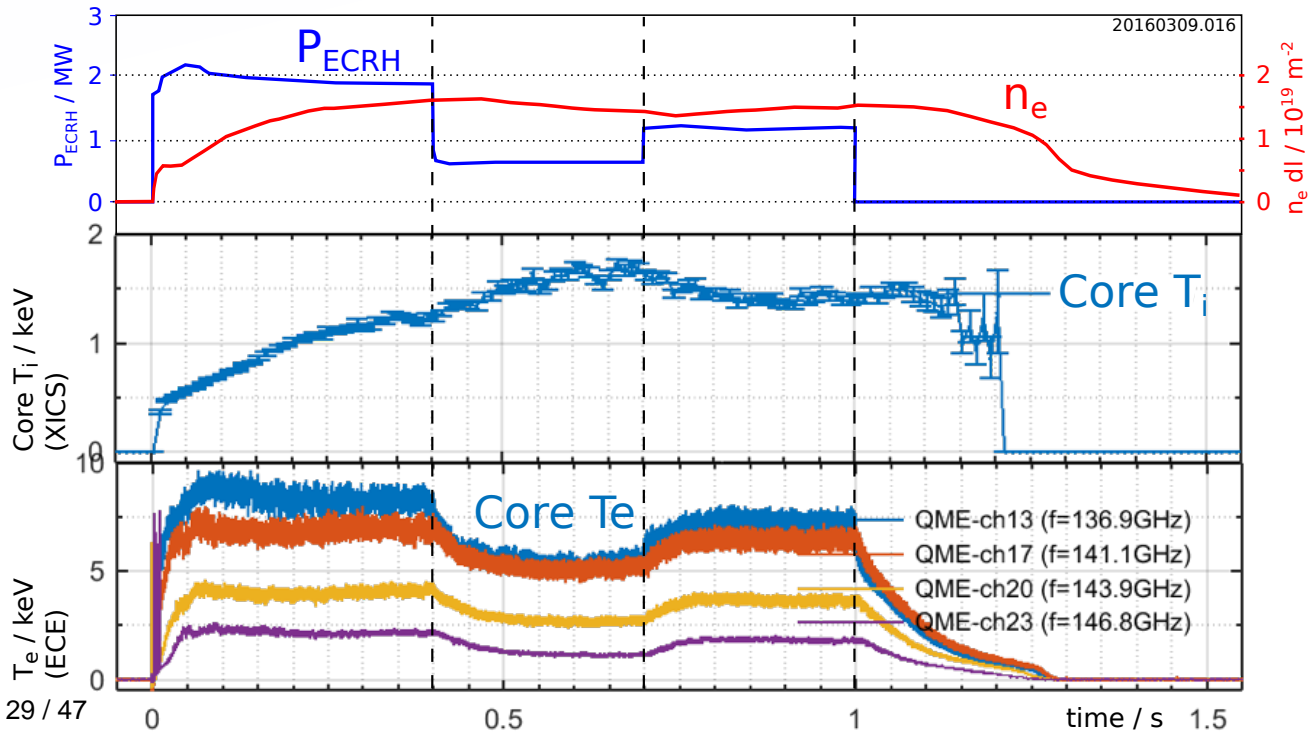


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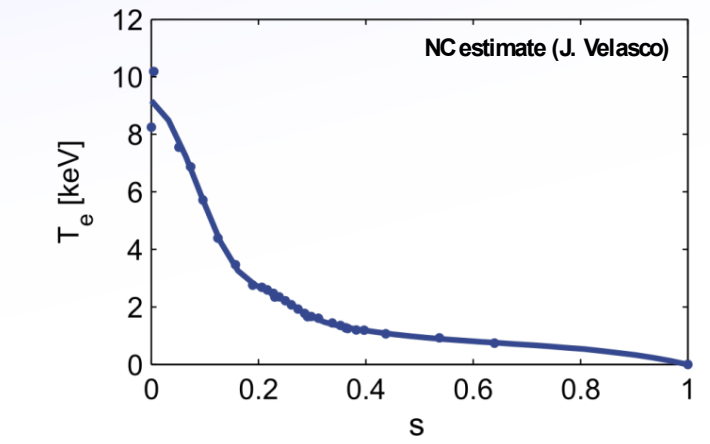
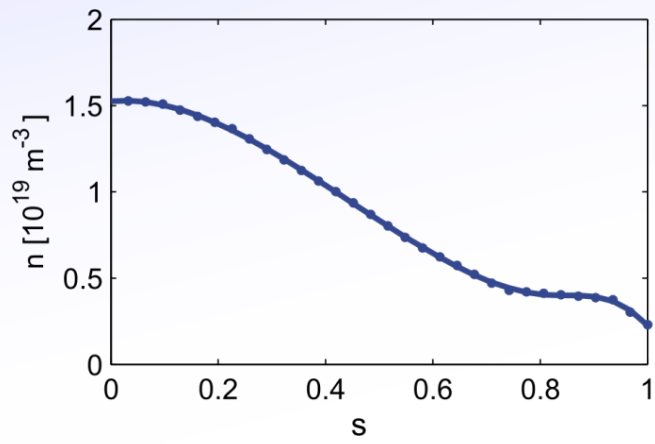
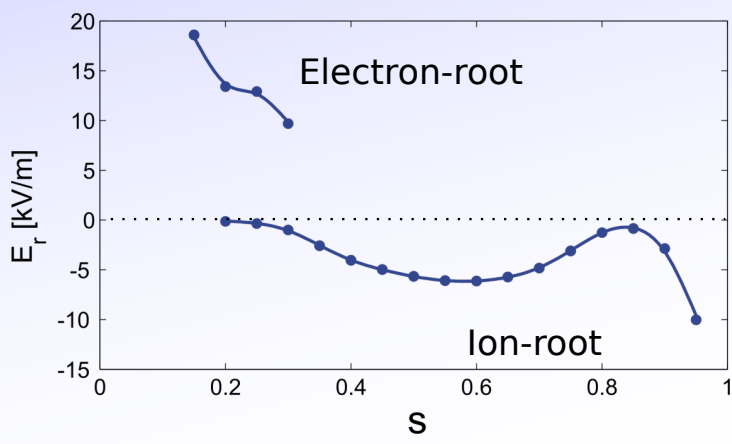
- All OP1.1 plasmas investigated have this CERC.
- Experiments to explore power and density ranges to see extent.



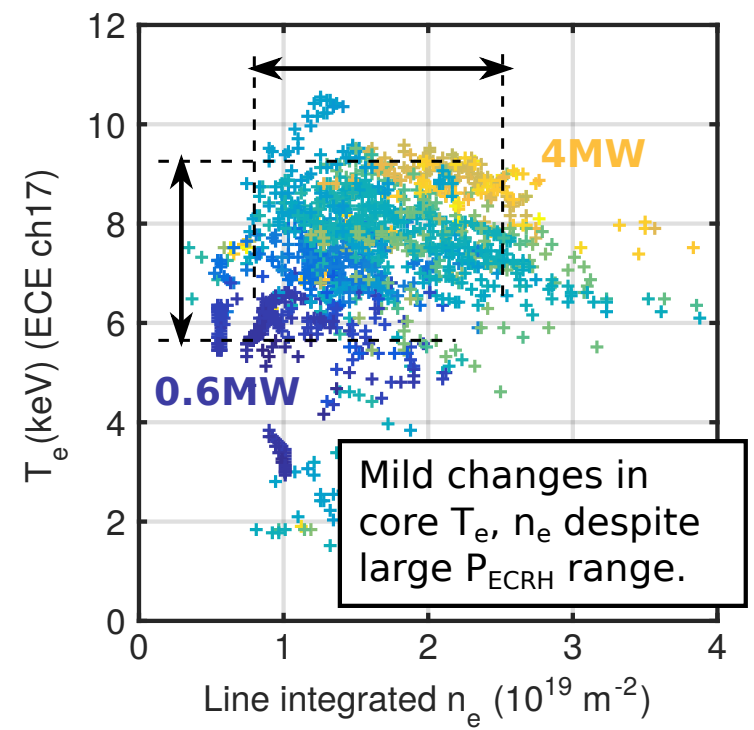
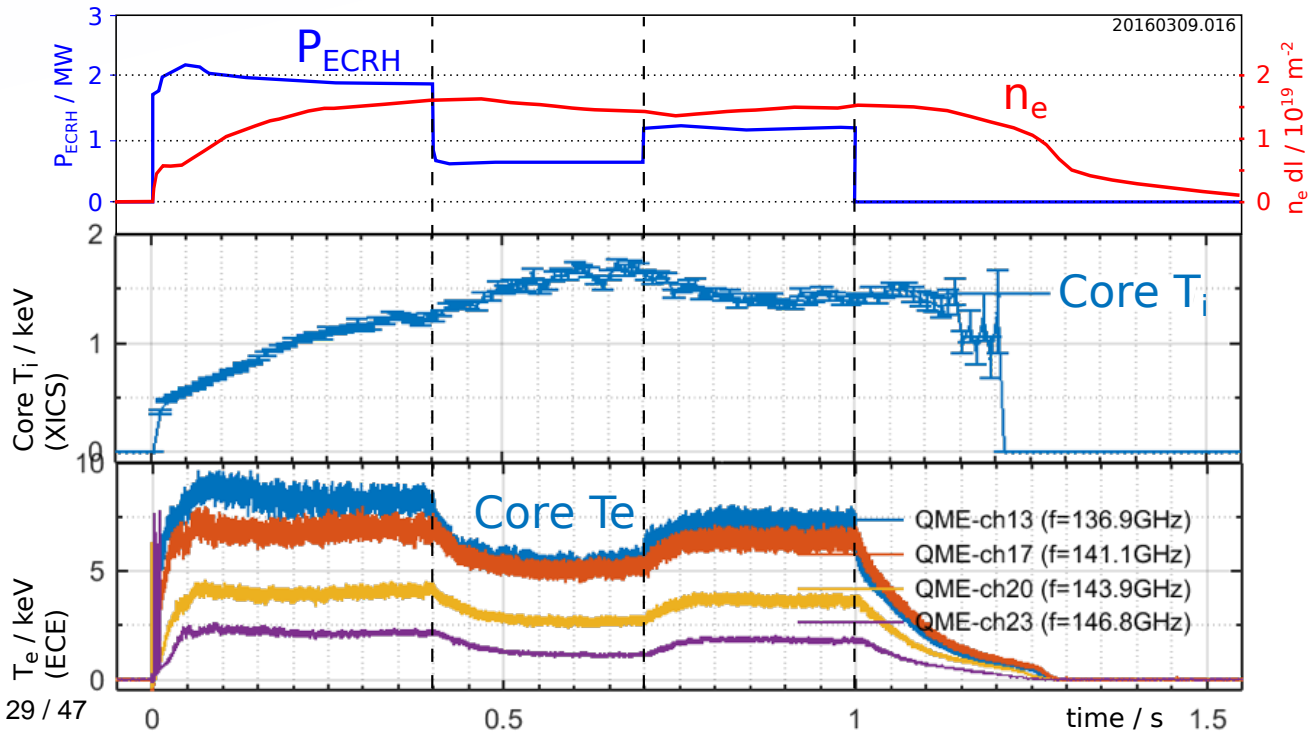


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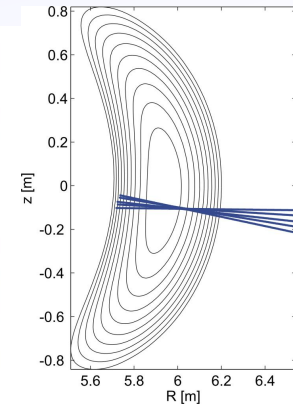
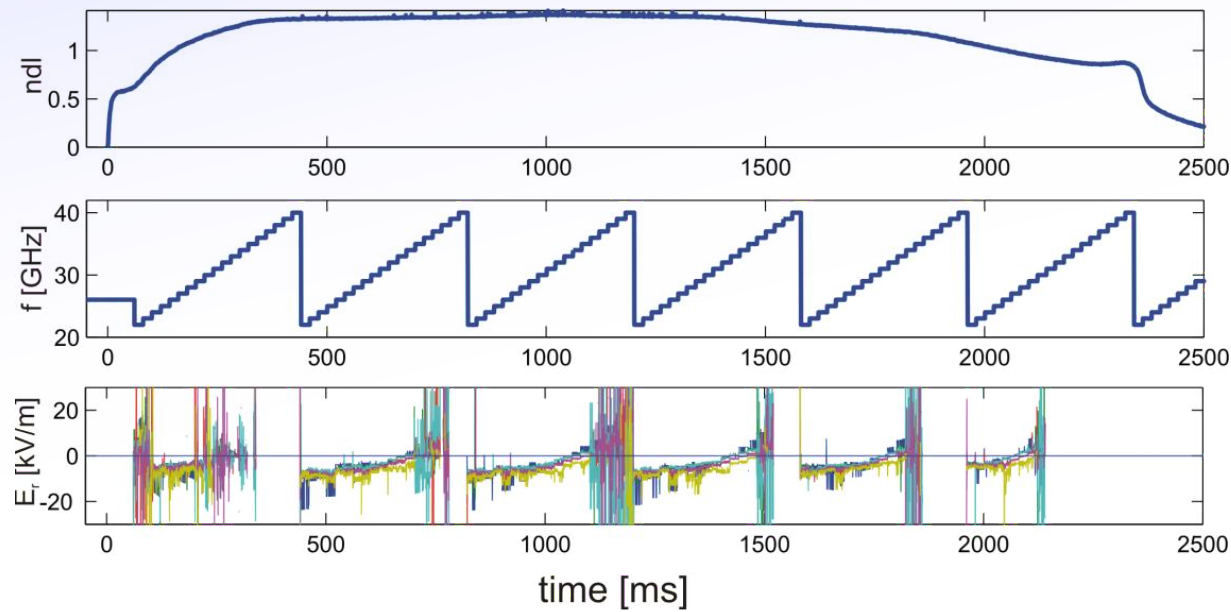


Reflectometry: E_r measurements

[T. Windisch, A. Krämer-Flecken,
J. L. Velasco]

Poloidal correlation reflectometer:

- Five poloidally separated microwave antennae.
- Doppler velocity of density fluctuations at the cut-off.
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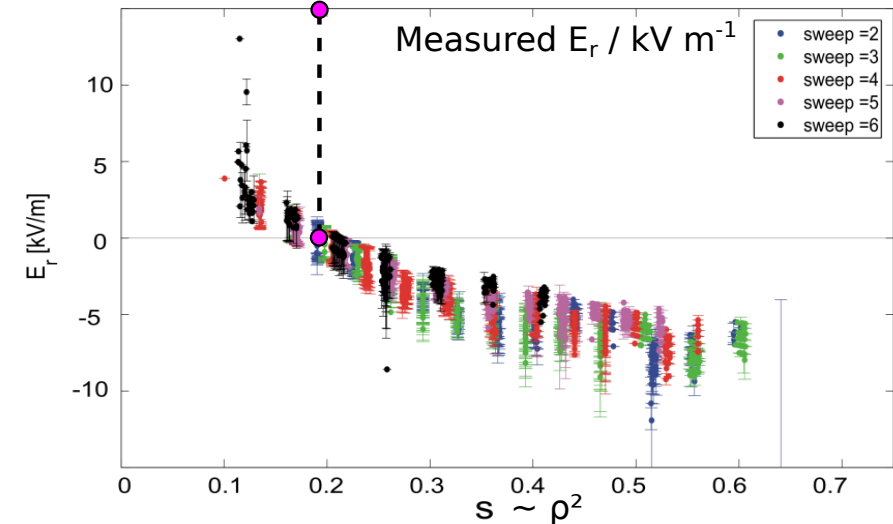
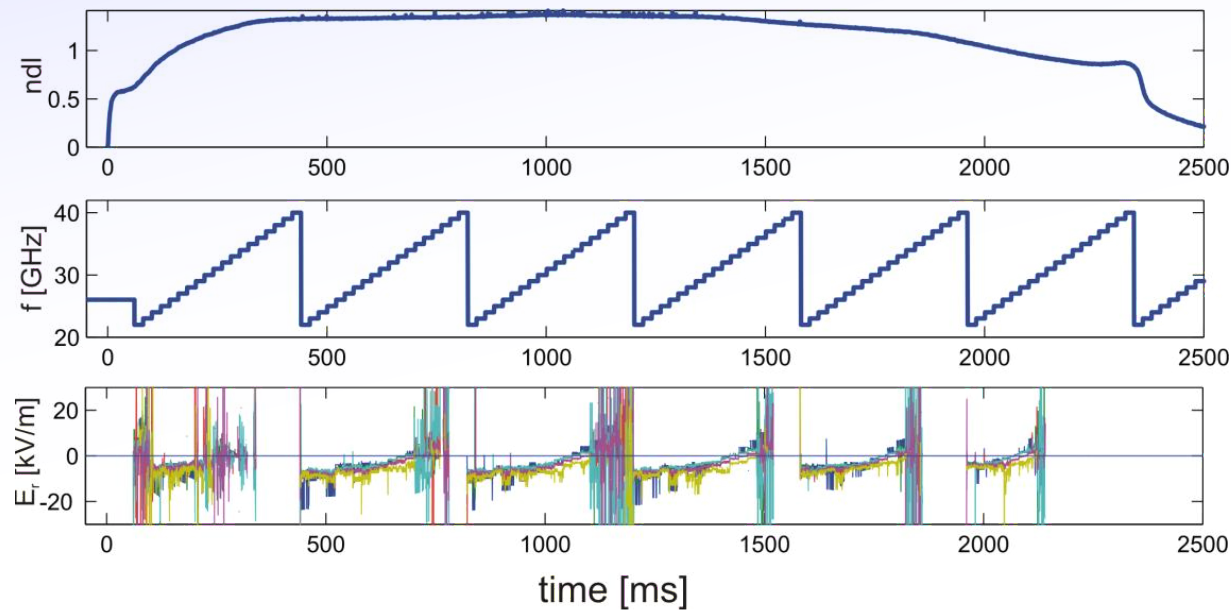
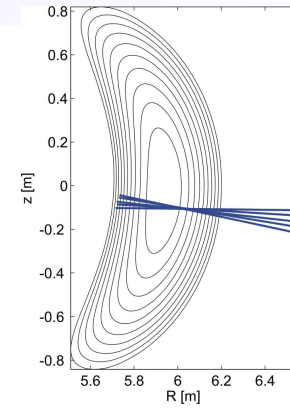


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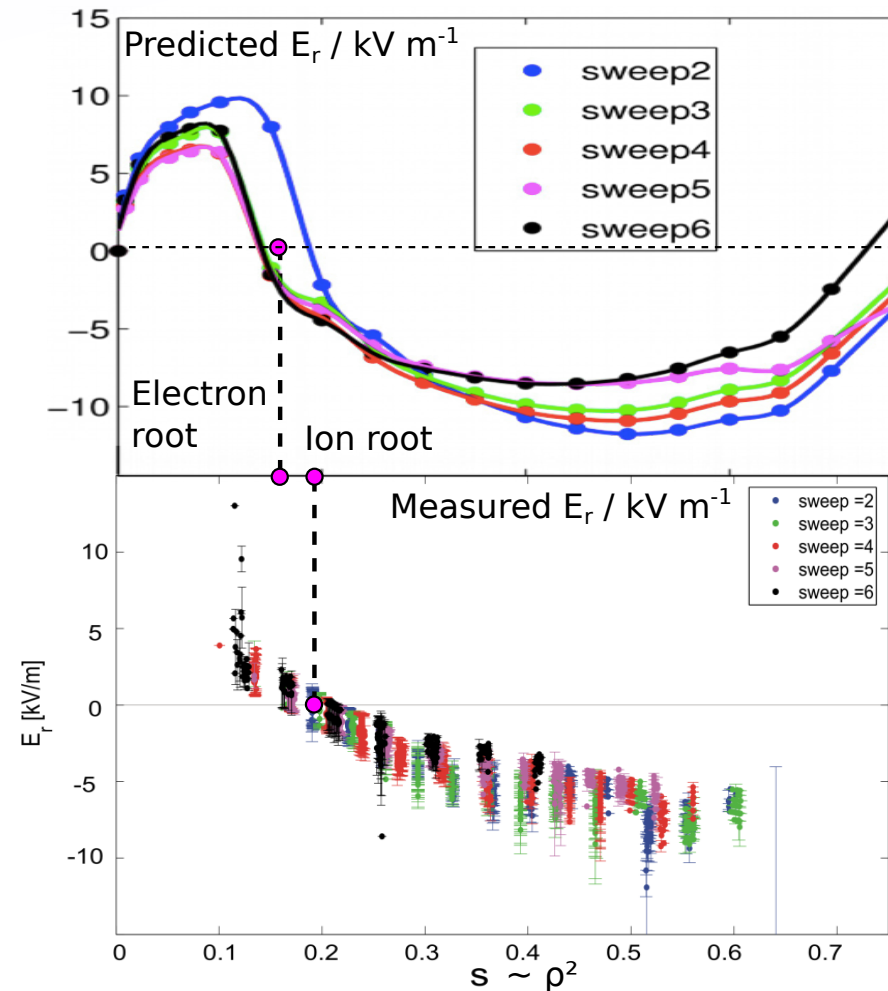
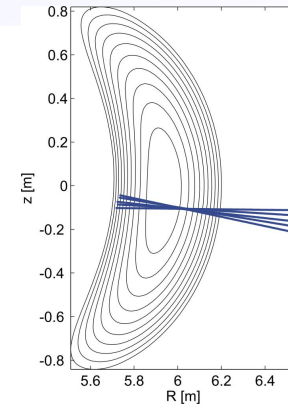
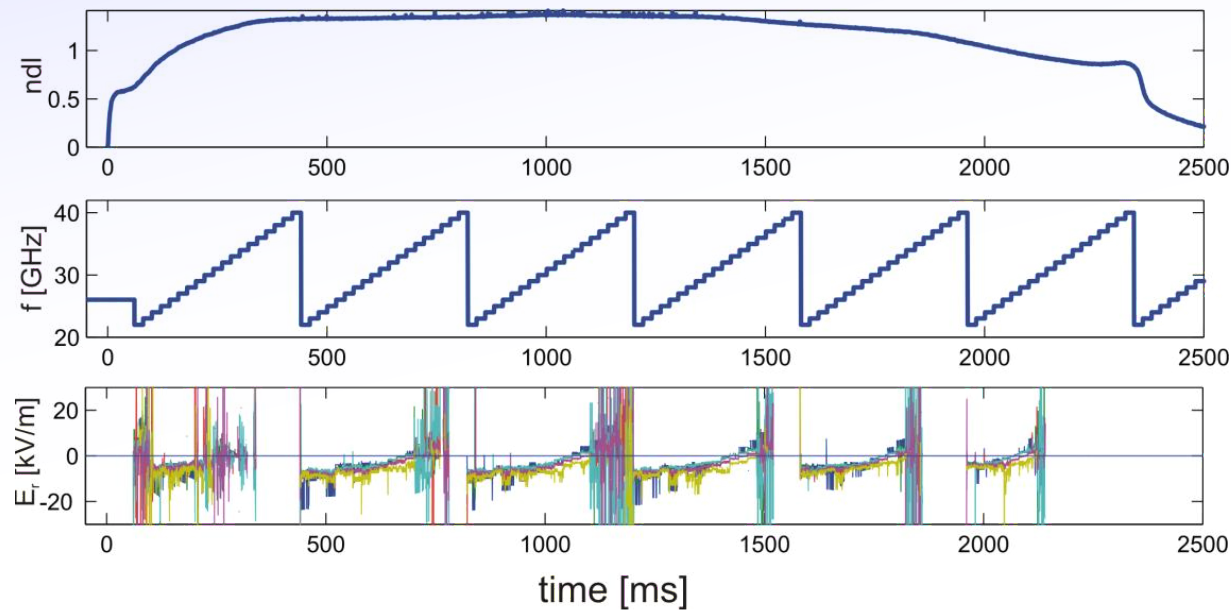


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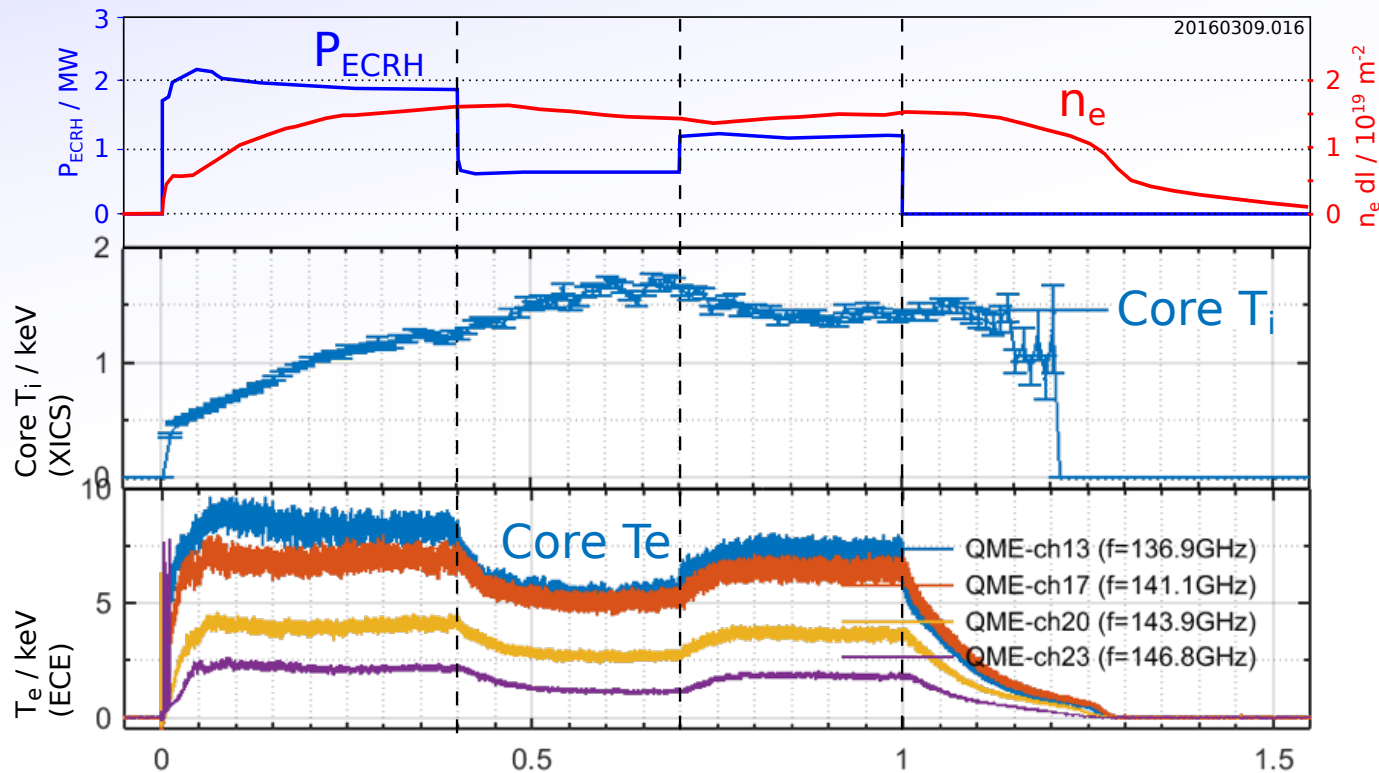


Measured E_r comparison with neoclassical predictions:

- Core electron root with transition to iron root at similar radial position.
- No change seen in $E_r(s=0.5)$ for CERC discharges.

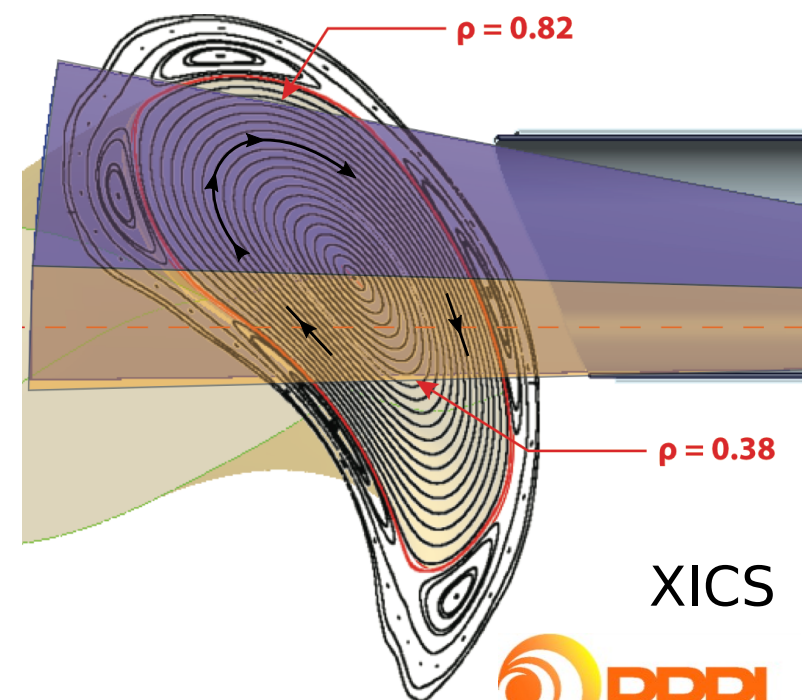
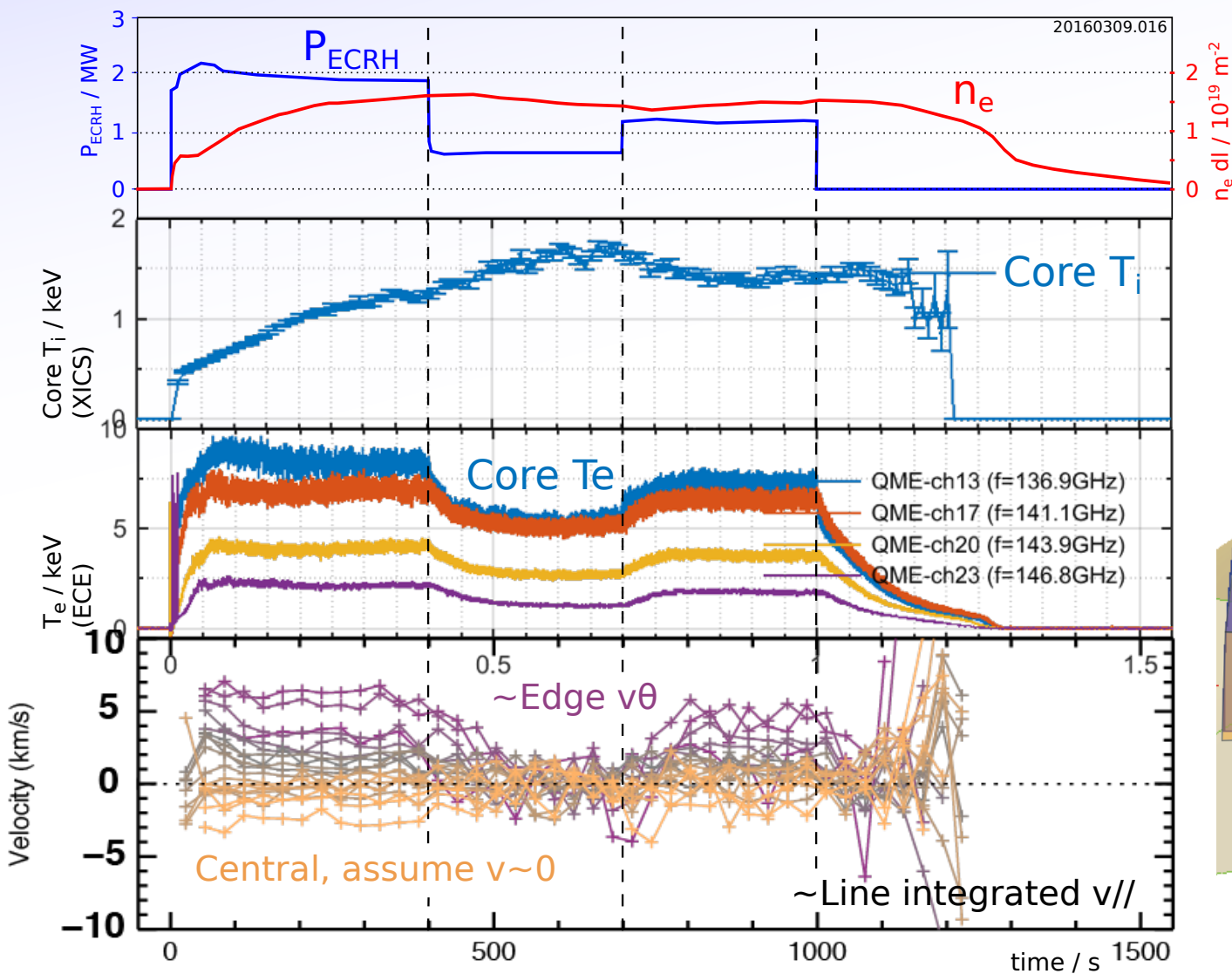
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- Preliminary analysis of XICS data does show dependence of $v\theta$ (E_r) on input power.
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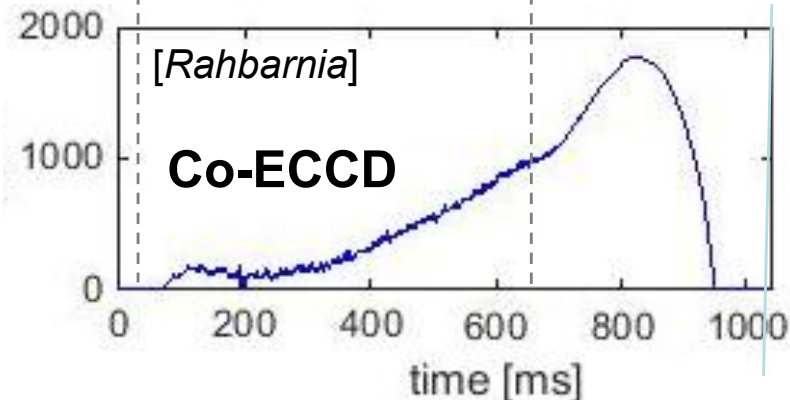
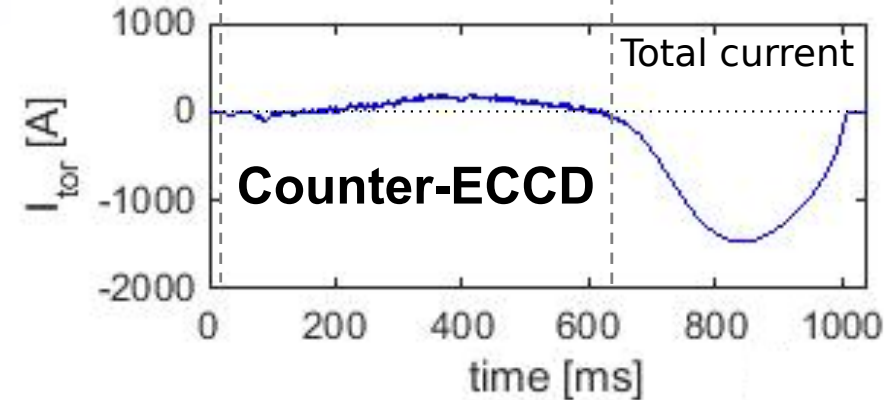
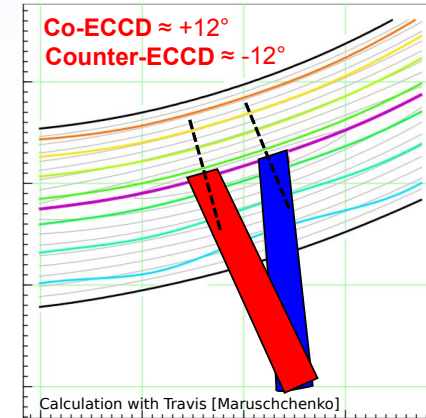
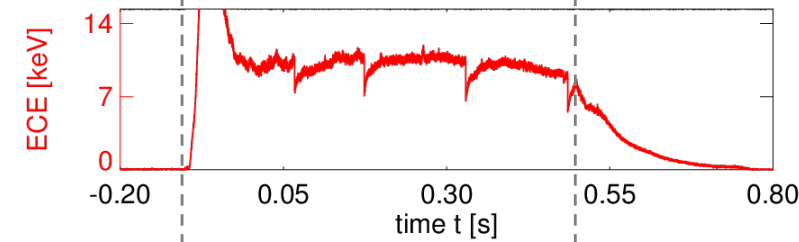
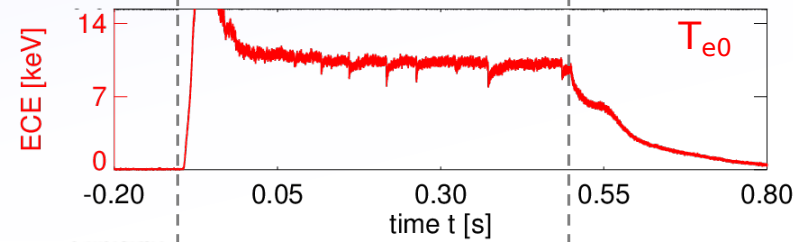
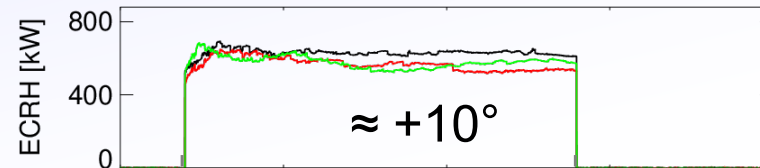
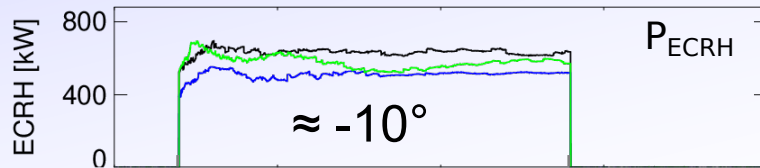
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W7X ECRH Current Drive

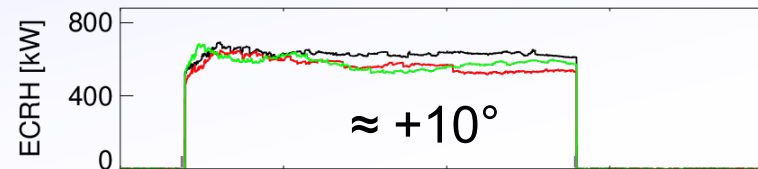
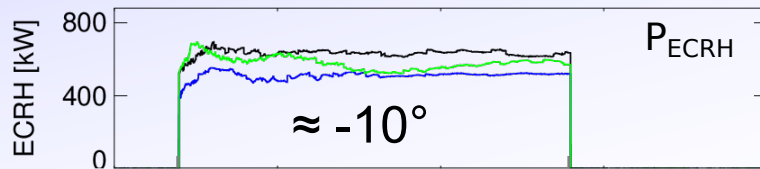
- W7X optimised for low bootstrap current, but it will still build over 30min plasmas (OP2)
- ECCD may be used compensate total current, to maintain edge iota (for island divertor).
- In OP1.1 ECCD could already be tested.



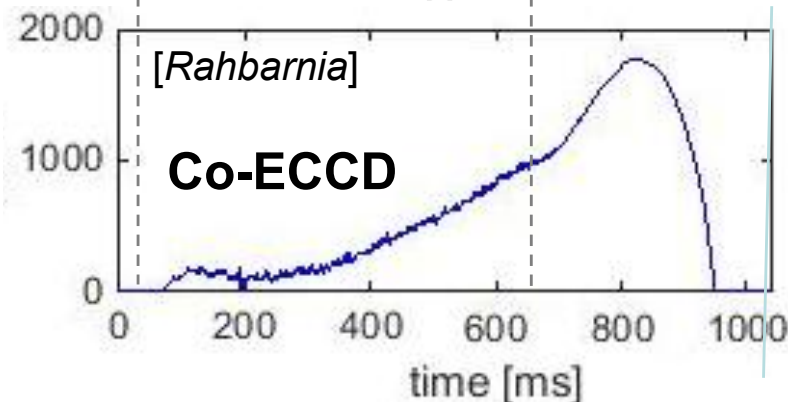
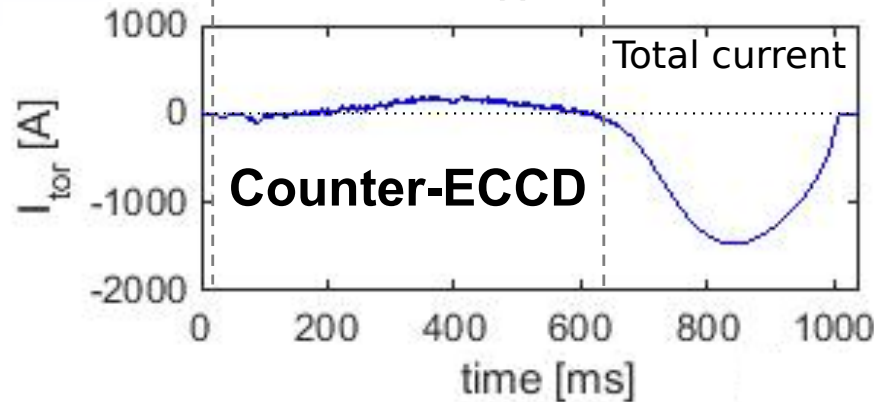
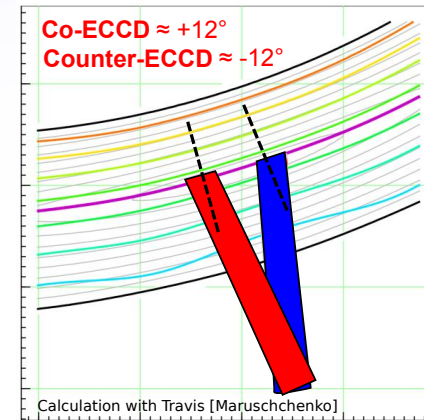
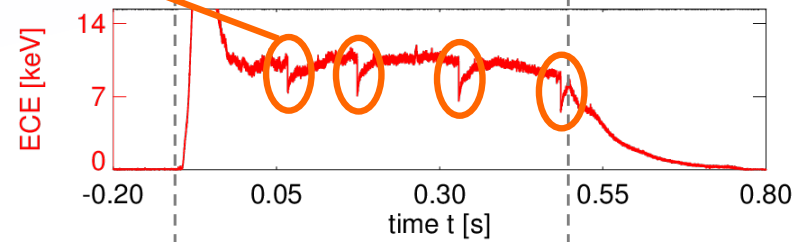
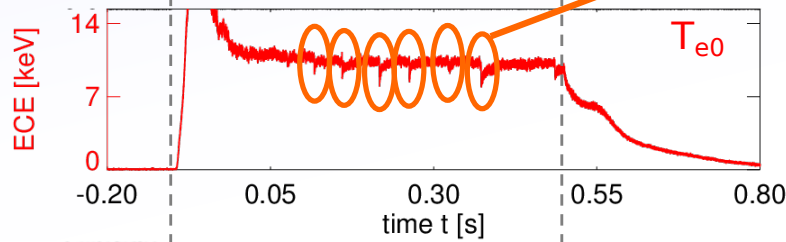
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central collapses
by iota change

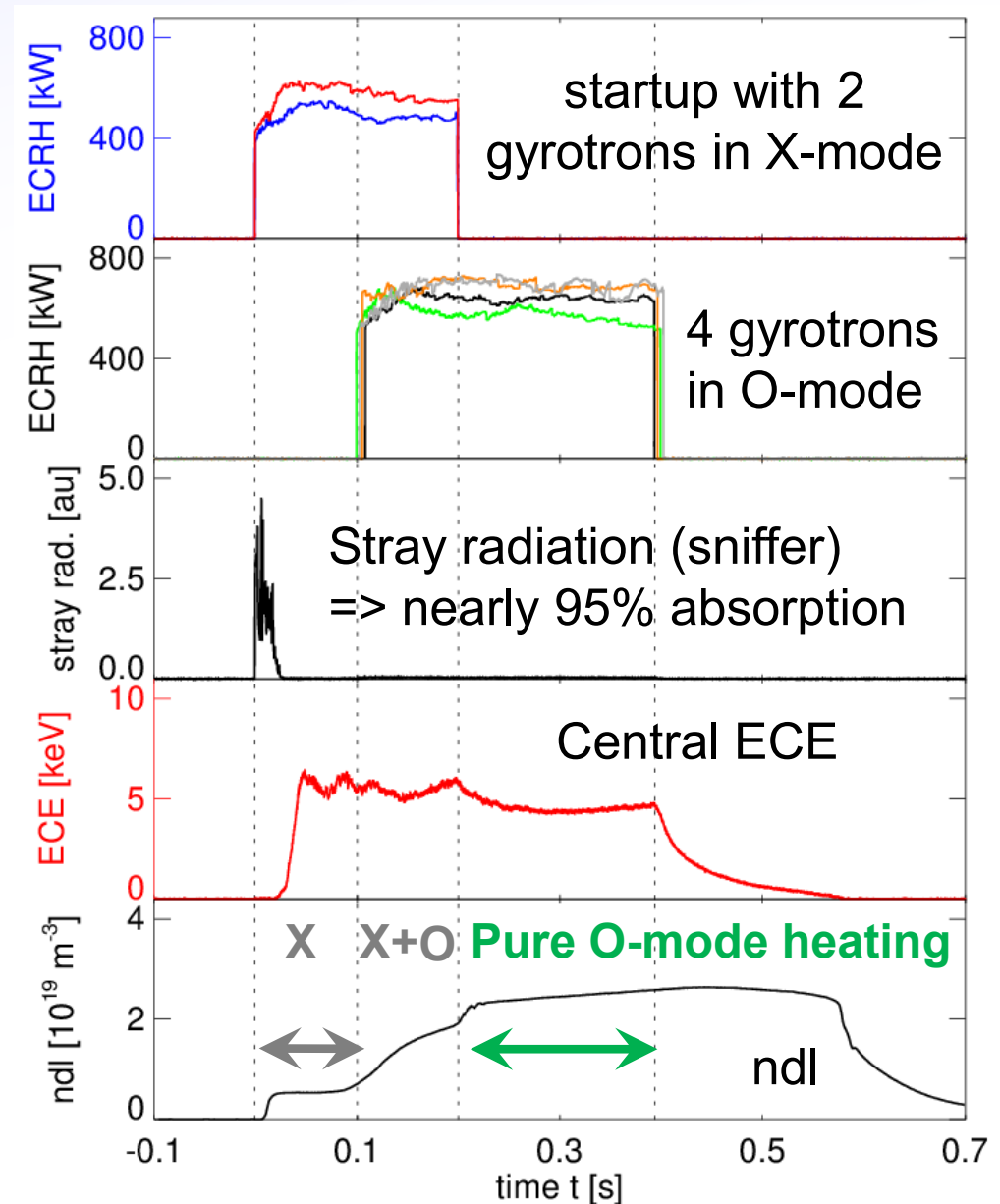
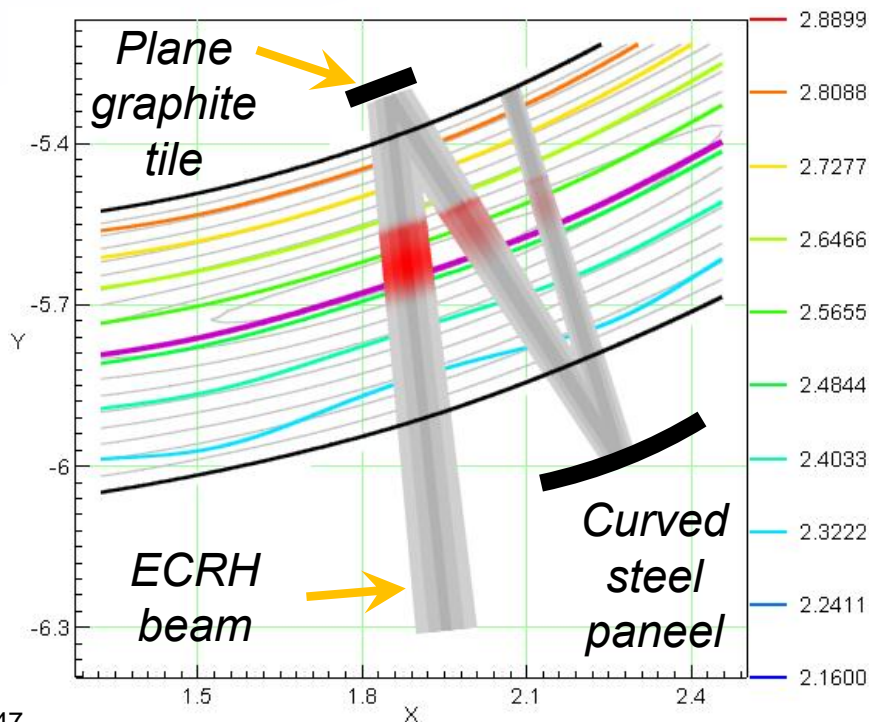


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W7X ECRH O2 heating

- O2-mode advanced heating for expected high density ($n_e > 1.2 \times 10^{20}$) operation (OP1.2+)
- Originally not intended for OP1.1, but tried anyway.

- Multi-pass scenario for 4 of 6 gyrotrons.
- 3 pass allows up to 95% absorption.
- Measurements in good agreement with predictions of Travis code.
- Very successful, should be able to go up to at least $n_e \sim 2.4 \times 10^{20}$ in OP1.2.



Energy Content

- Thermal energy content calculated from:

Flux surfaces: Vacuum magnetics.

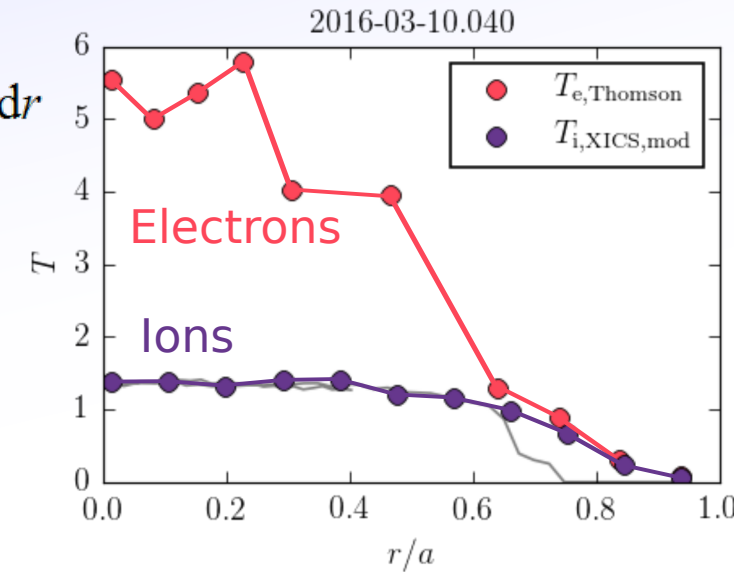
n_e, T_e : Thomson scattering

T_i : XICS if available or $W_i \sim 1/3 W_e$ (observed during flat-top)

$Z_{\text{eff}} = 1$ for now as Z_{eff} measurements yet to be analysed.

but ions carry only $1/4$ of energy content anyway.

$$W_{\text{therm}} = \frac{3}{2} \int \frac{dV}{dr} p(r) dr$$



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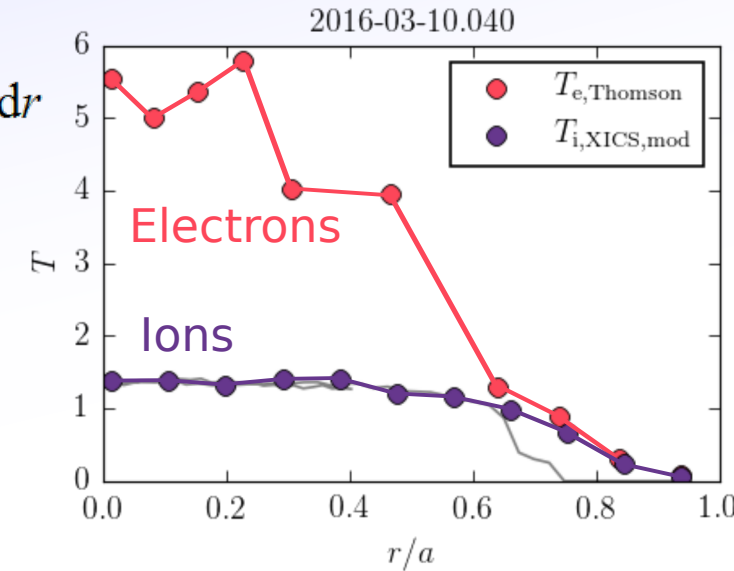
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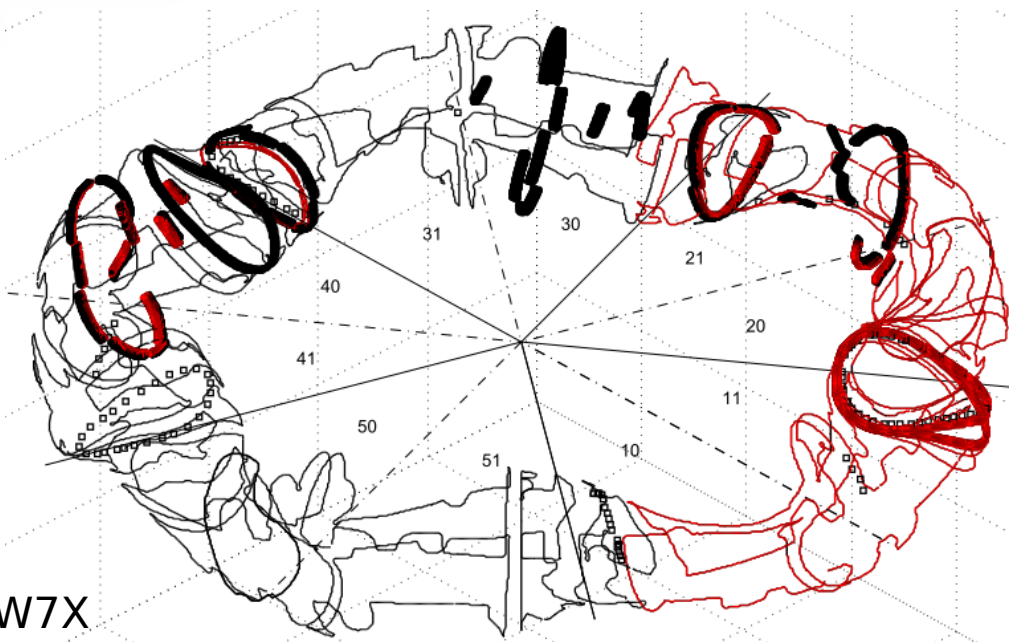
Checked against...

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Magnetic diagnostics:

- Plasma current (Continuous Rogowski coils)
- Plasma current distribution (Segmented Rogowski coils)
- MHD mode activity (Mirnov coils)
- Plasma energy (Diamagnetic Loop + Compensation coils)



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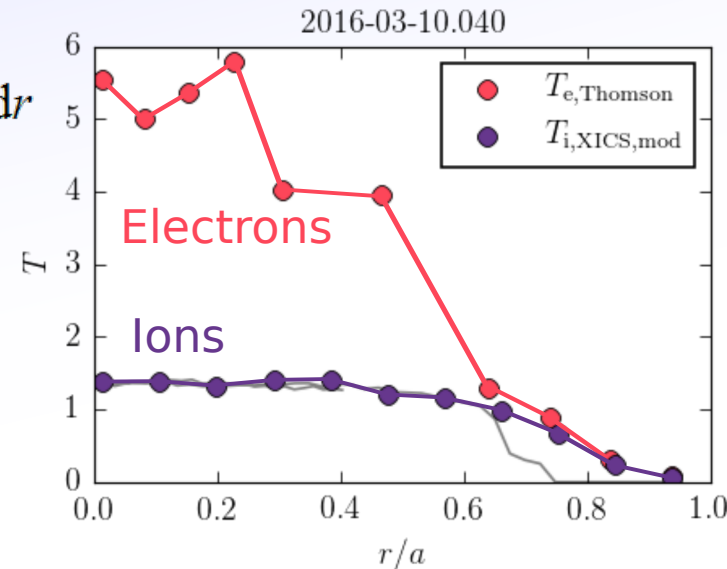
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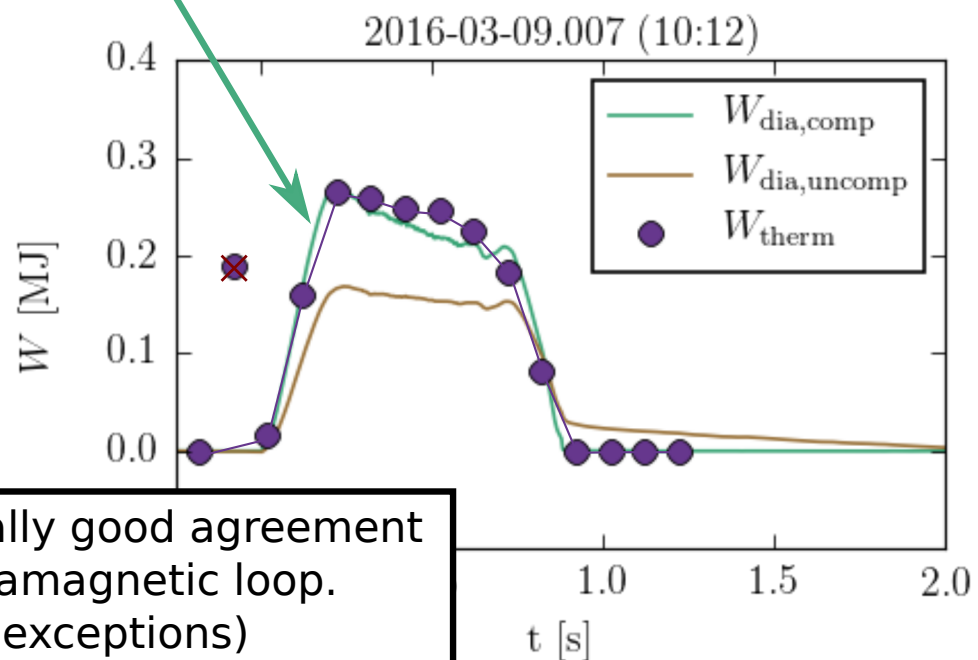
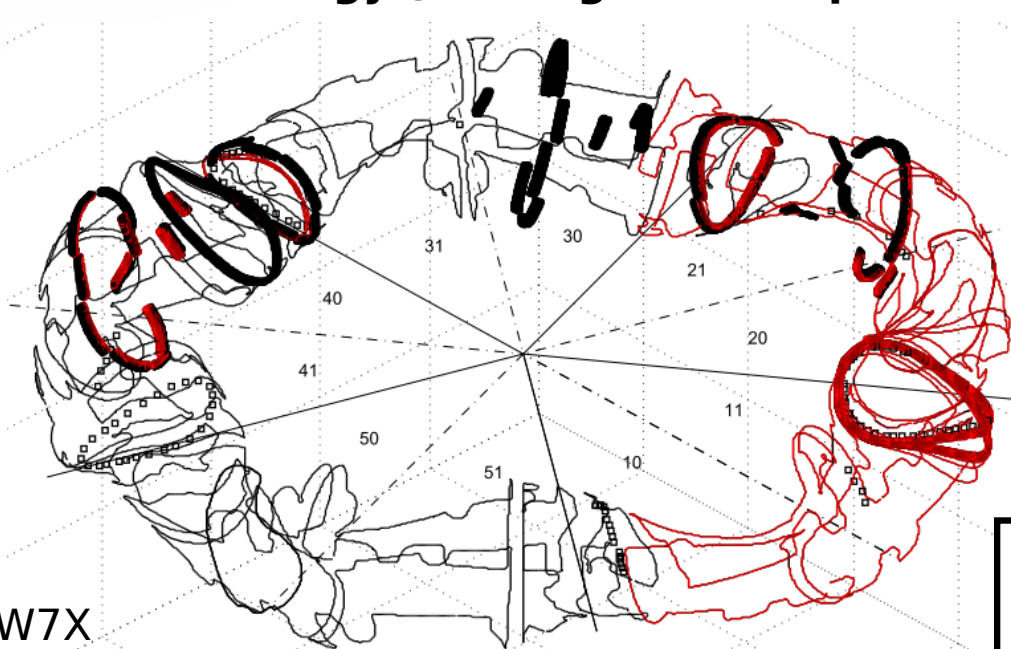
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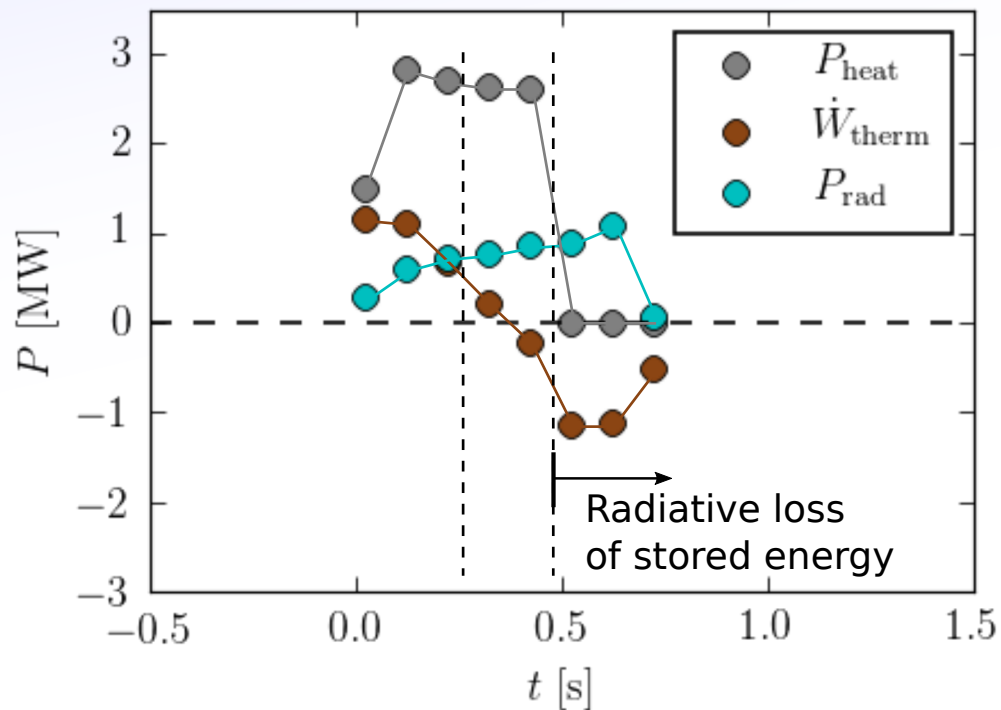
Generally good agreement with diamagnetic loop.
(Some exceptions)

Power Balance

- Comparing change in stored energy with radiated and input power.
- (Limiter heat fluxes not yet included)

High power ($\sim 3\text{MW}$)

2016-03-10.040



First conclusions:

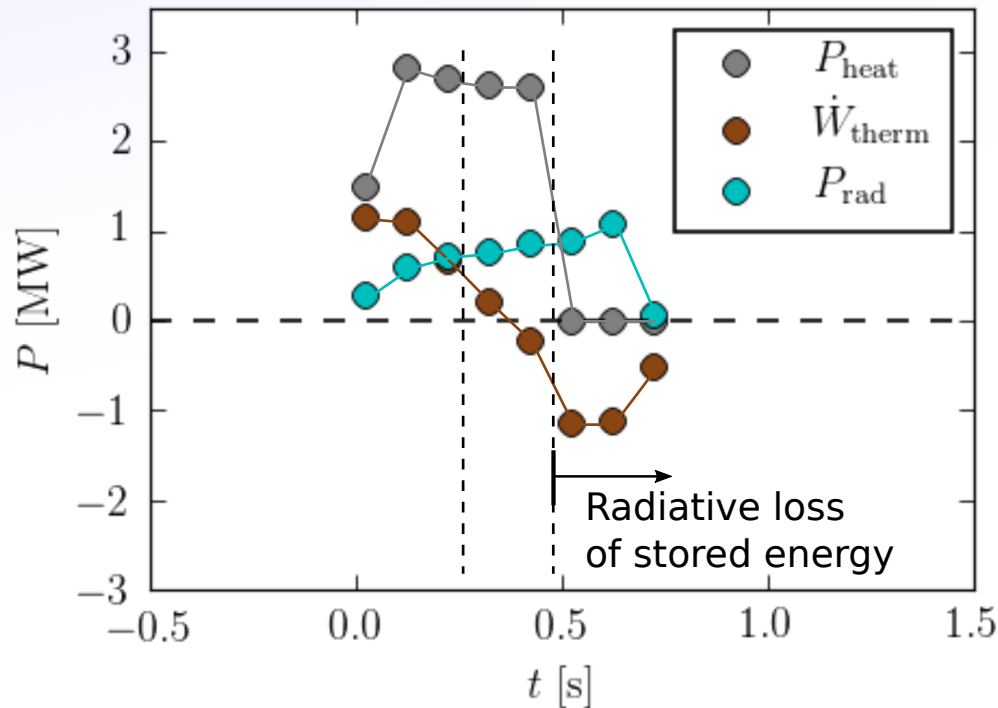
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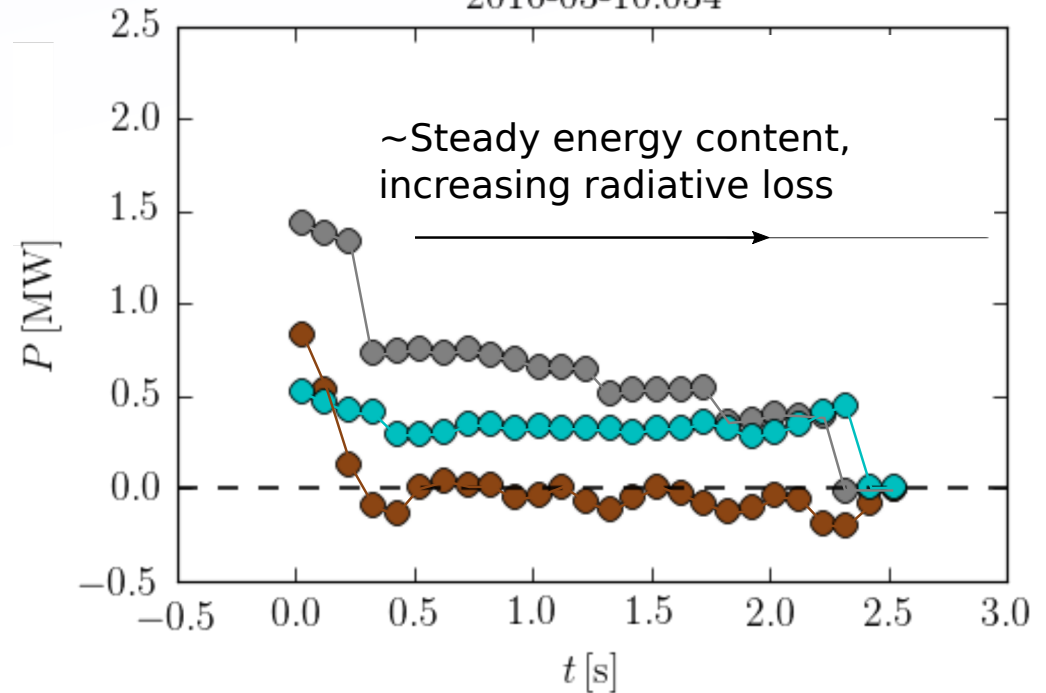
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High power ($\sim 3\text{MW}$)

2016-03-10.040

Low power ($< 1\text{MW}$)

2016-03-10.034



First conclusions:

- Radiation typically 30-50% of the power loss.
- Higher fraction of radiation loss at low power.



Confinement Times

- Preliminary estimate of energy confinement time from P_{ECRH} , W_{therm} , and dW/dt :
- Typically $\sim 150\text{ms}$, matching ISS04 for best plasma conditions.

$$\tau_E = 0.134 a^{2.28} R^{0.64} P^{-0.61} n^{-0.54} B^{0.84} \iota^{0.41}$$

$$\tau_E = \frac{W}{P_{\text{heat}} - \dot{W}}$$

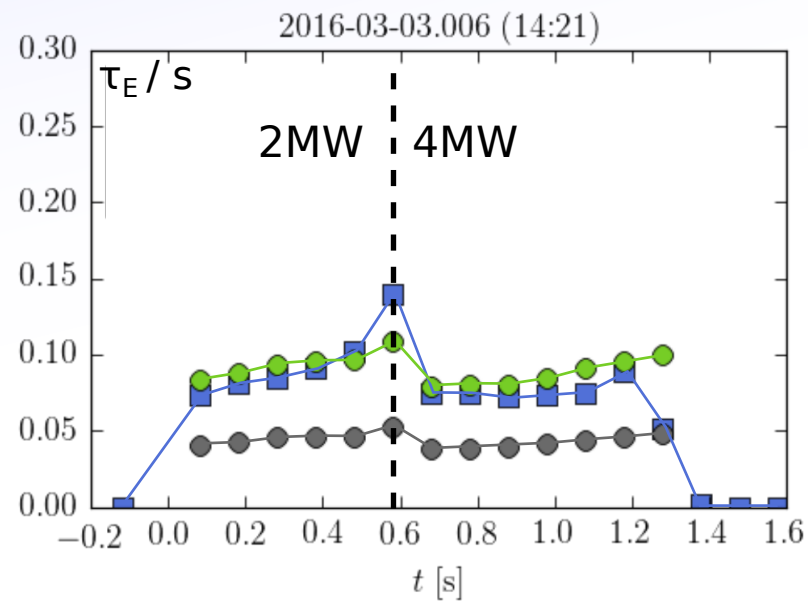
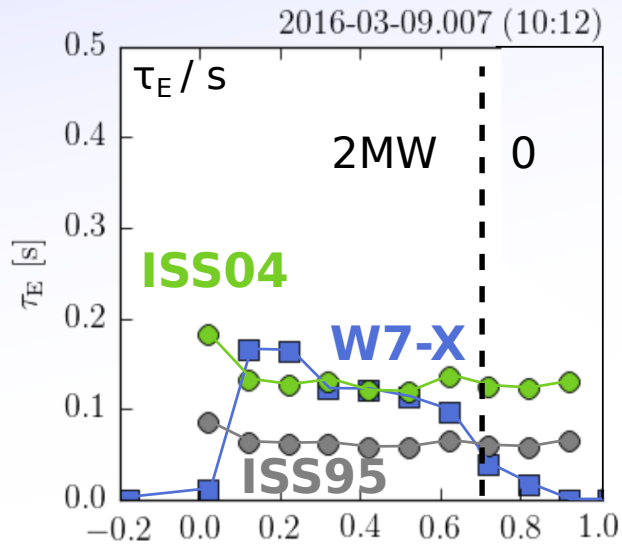
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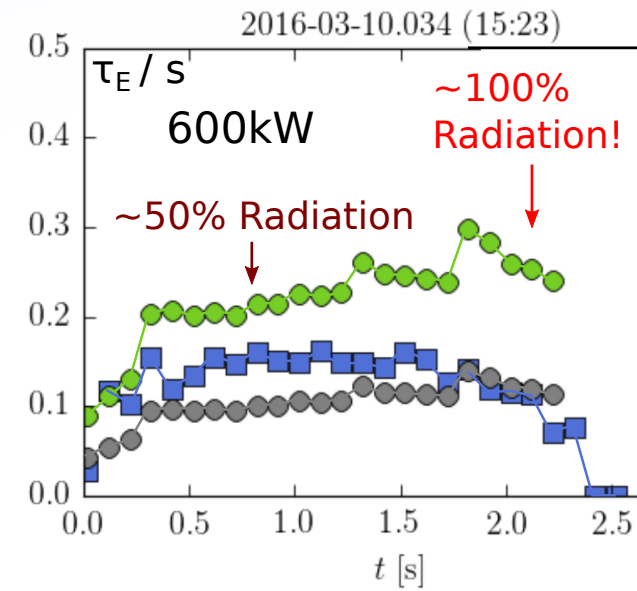
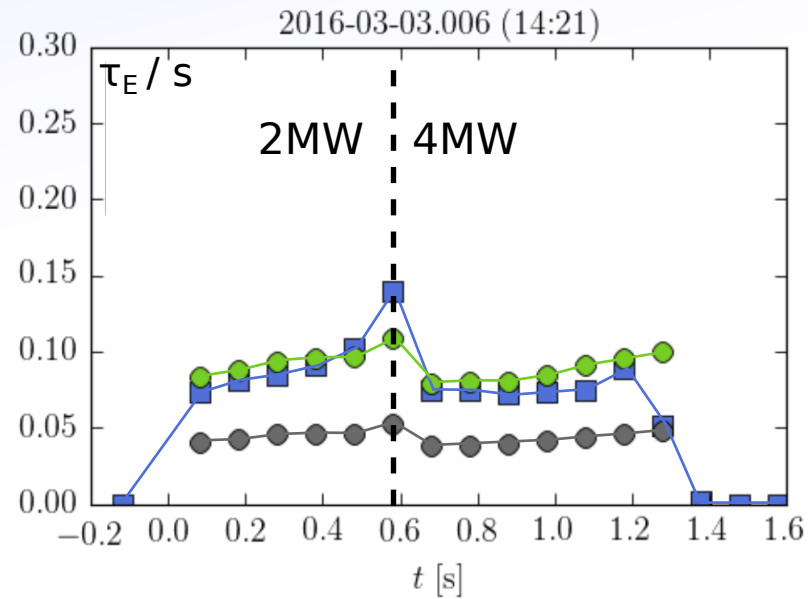
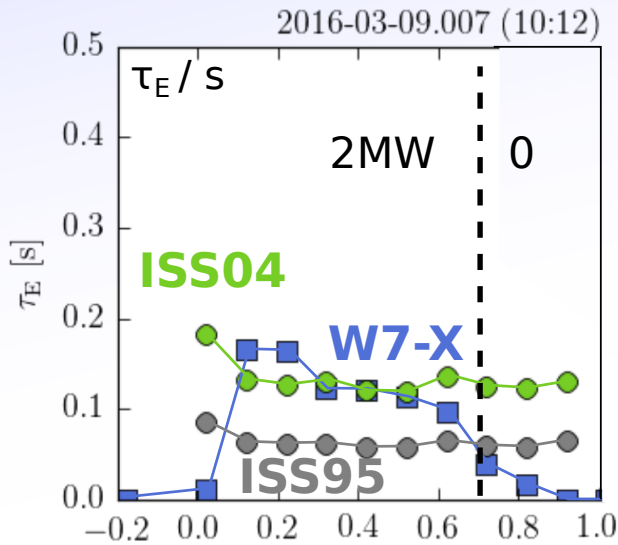
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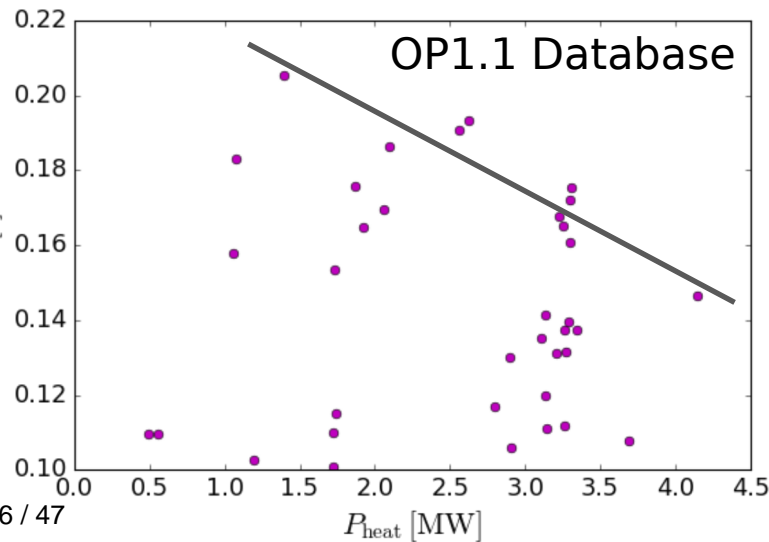
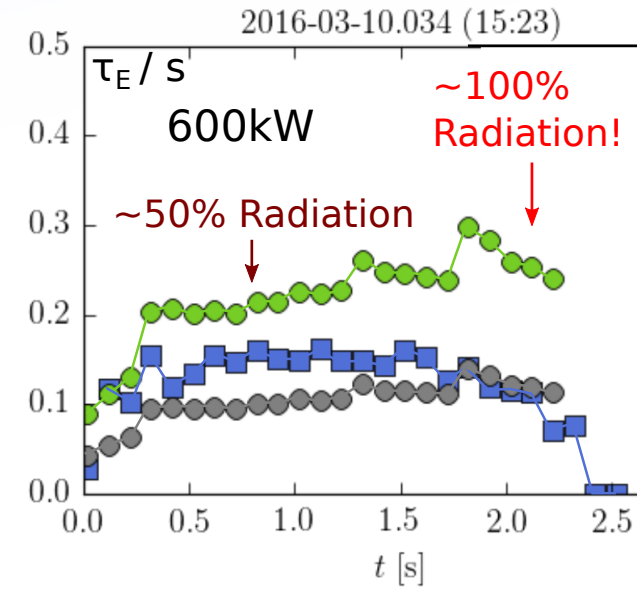
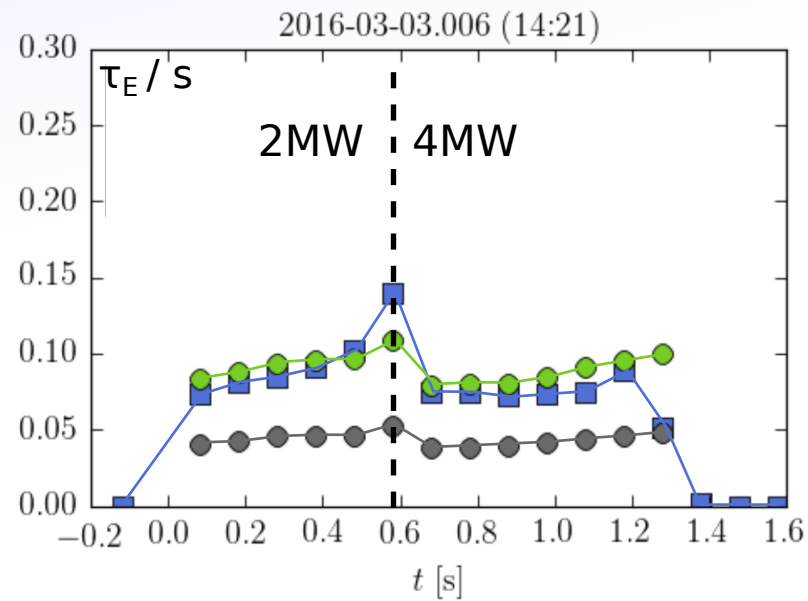
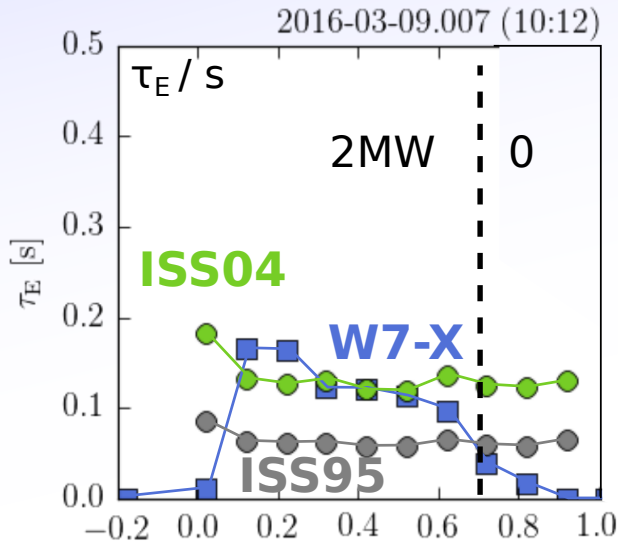
Confinement Times

- Preliminary estimate of energy confinement time from P_{ECRH} , W_{therm} , and dW/dt :
- Typically $\sim 150\text{ms}$, matching ISS04 for best plasma conditions.

$$\tau_E = 0.134 a^{2.28} R^{0.64} P^{-0.61} n^{-0.54} B^{0.84} \iota^{0.41}$$

$$\tau_E = \frac{W}{P_{\text{heat}} - \dot{W}}$$

Some examples:



- Points with poor performance (High radiation)
- Degredation with higher power.
- Very poor performance for low power ($P < 1\text{MW}$) (due to radiation loss)

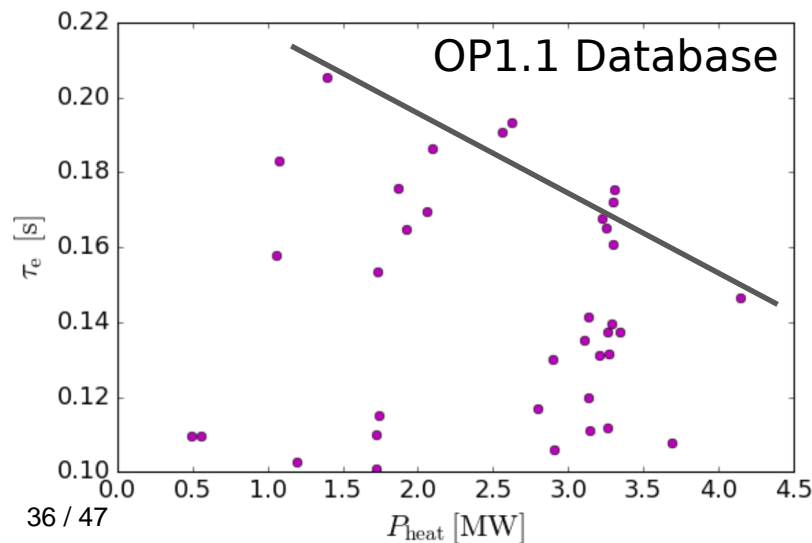
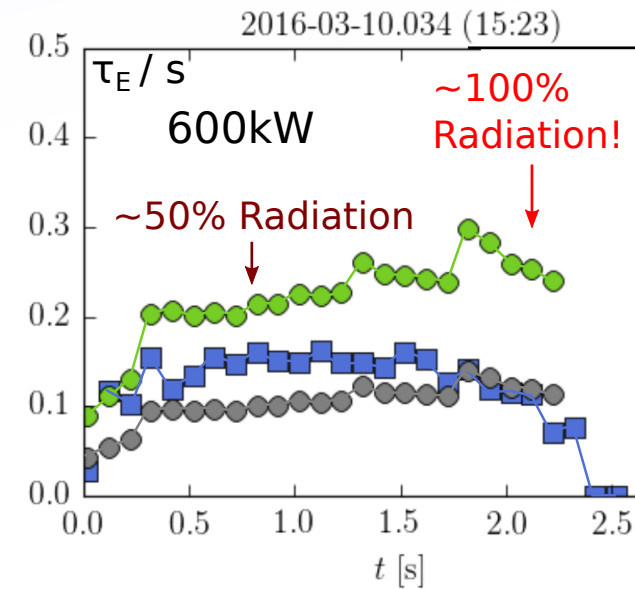
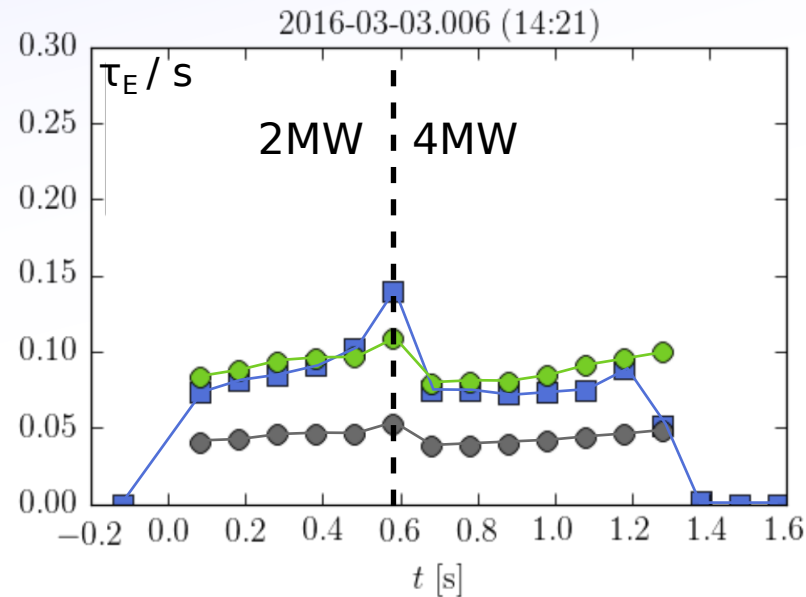
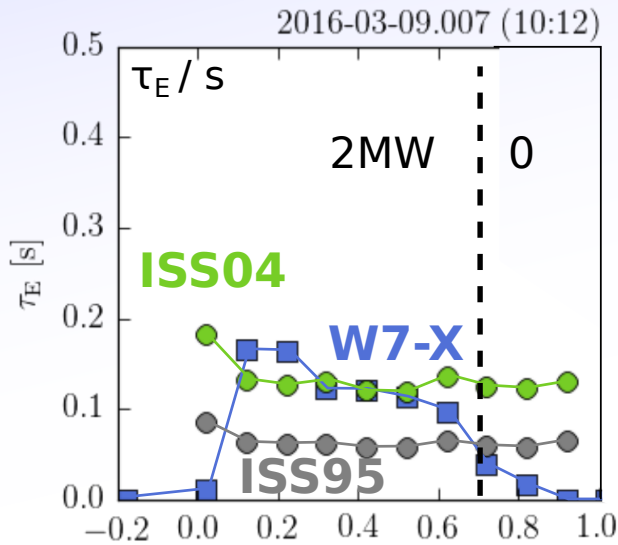
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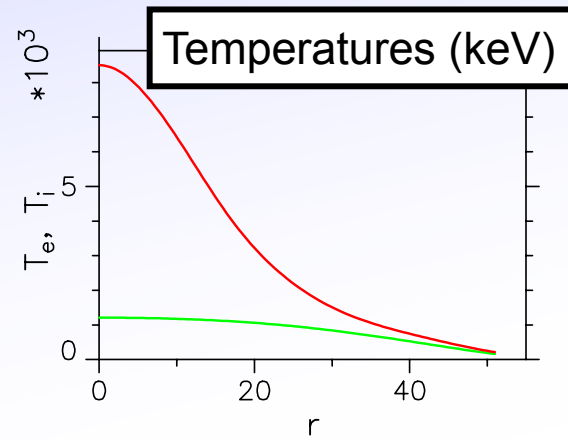
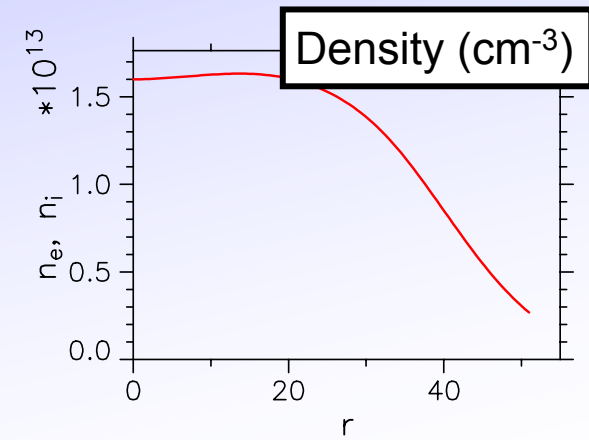


- Points with poor performance (High radiation)
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- (Later analysis: some up to 20% above ISS04)

Things to remember....

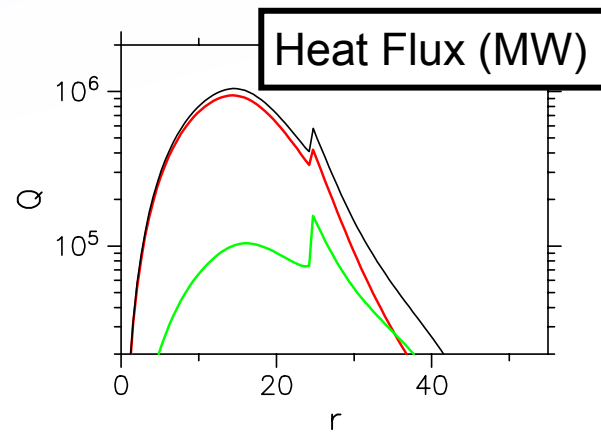
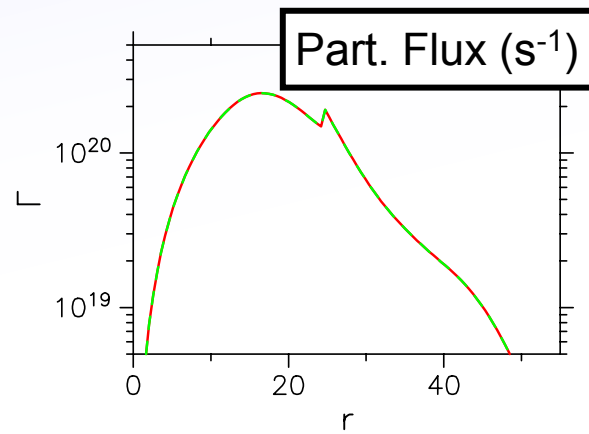
- Plasmas had significant radiation loss fraction.
- OP1.2 will have divertor unit, full glow discharge system and boronisation - this should improve!

Transport Modelling

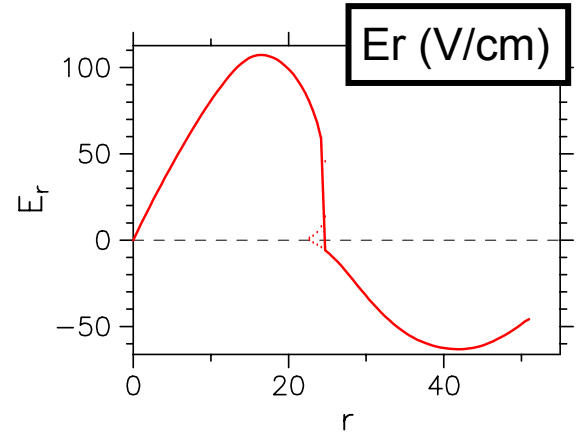


Initial transport modelling for typical high core T_e :

- Electron root core of varying extent.
- Predicted core particle depletion not observed.

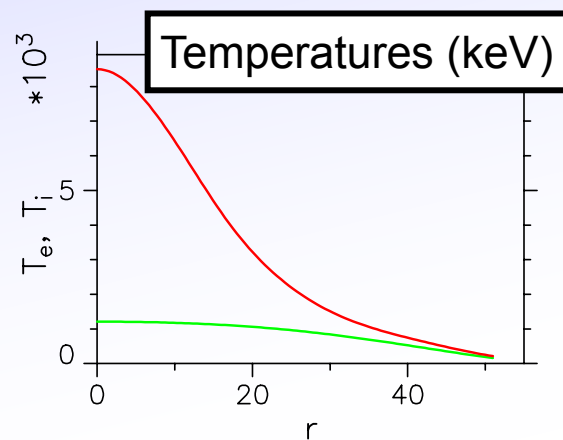
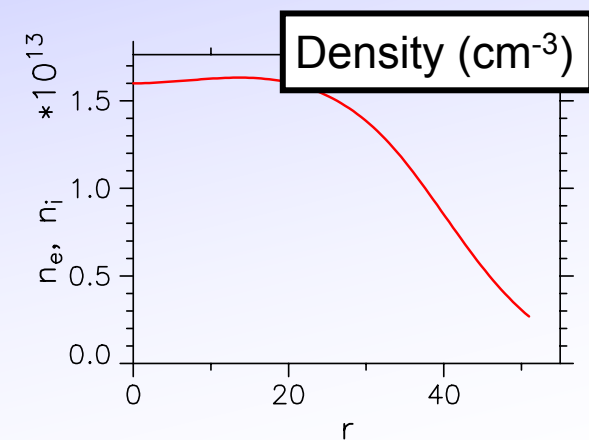


- Peak neoclassical integrated heat flux (1.1MW) falls short of the input power (2MW).



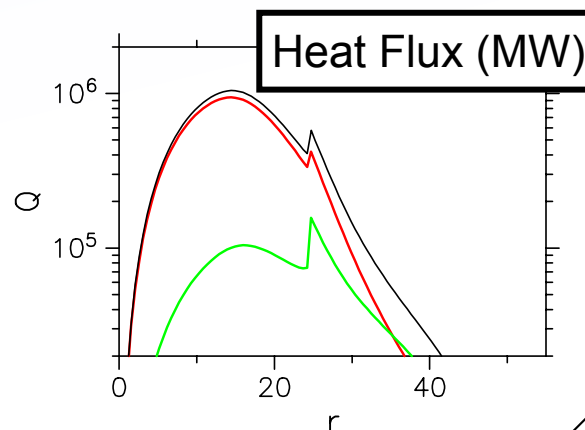
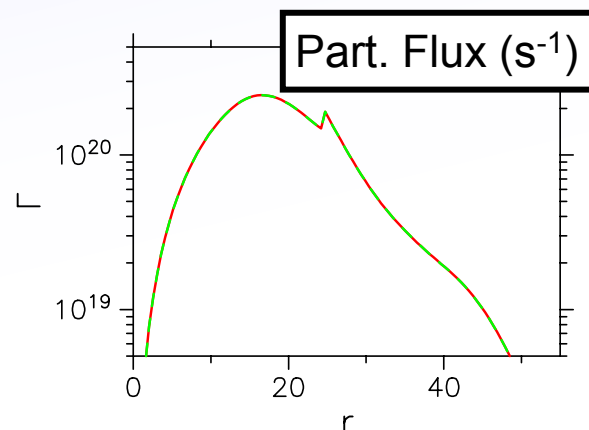
- Modeling on-going...

Transport Modelling



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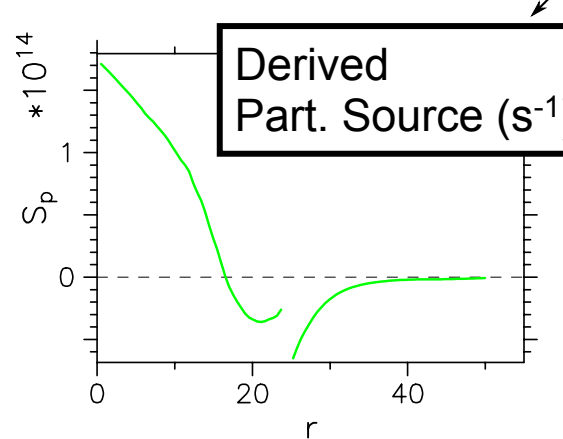
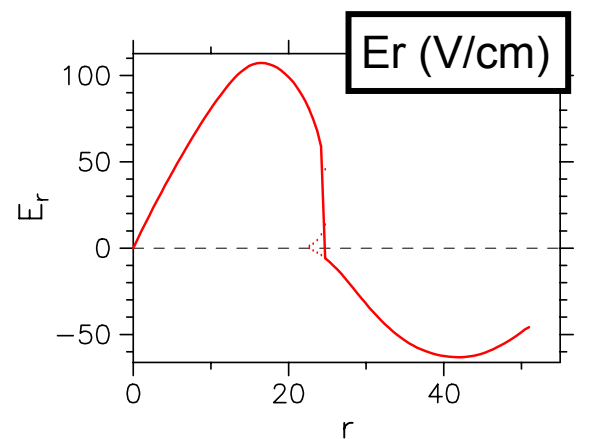
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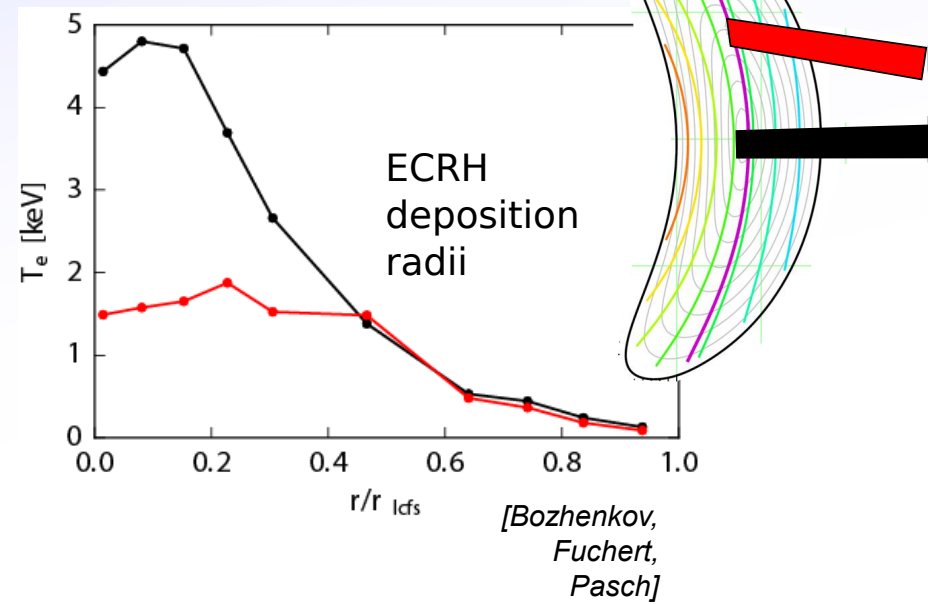
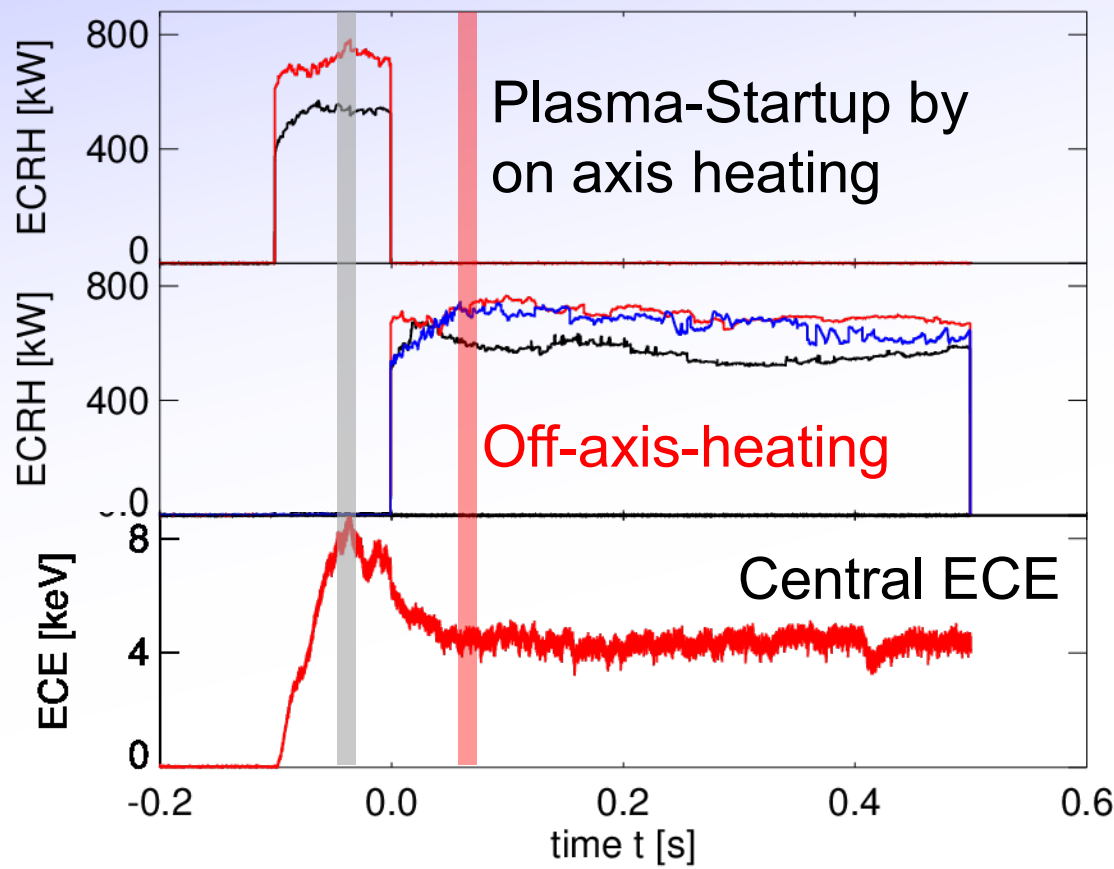
- Modeling requires unrealistic core particle source or anomalous pinch.

- Peak neoclassical integrated heat flux (1.1MW) falls short of the input power (2MW).

- Modeling on-going...

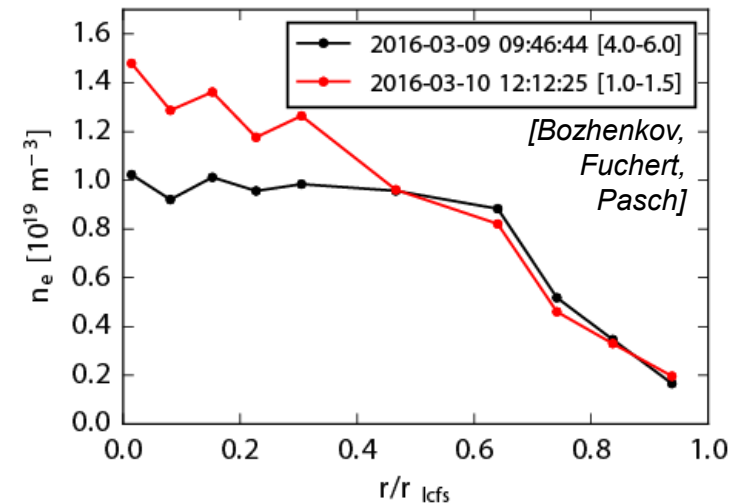
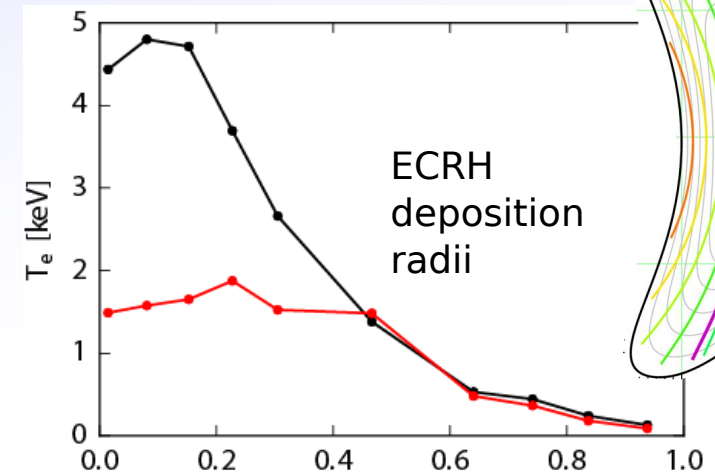
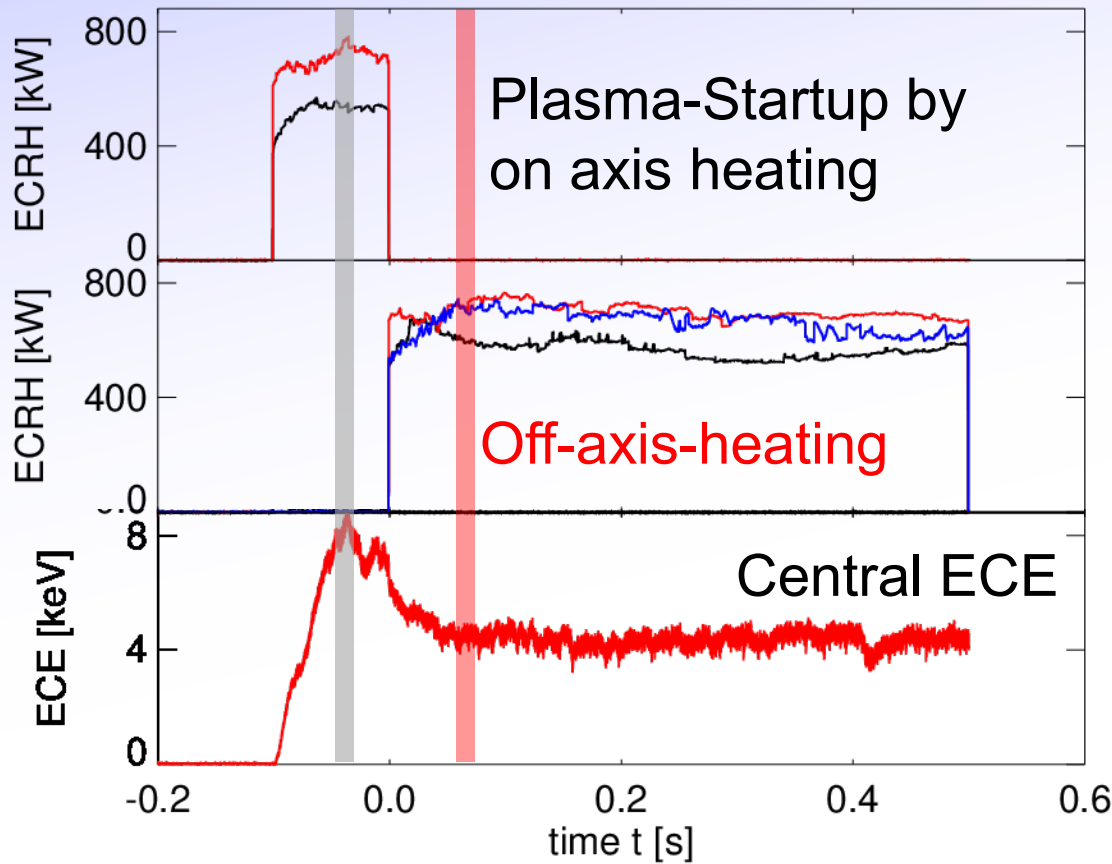


W7X ECRH Off-axis heating



- Successful demonstration of off-axis heating!

W7X ECRH Off-axis heating

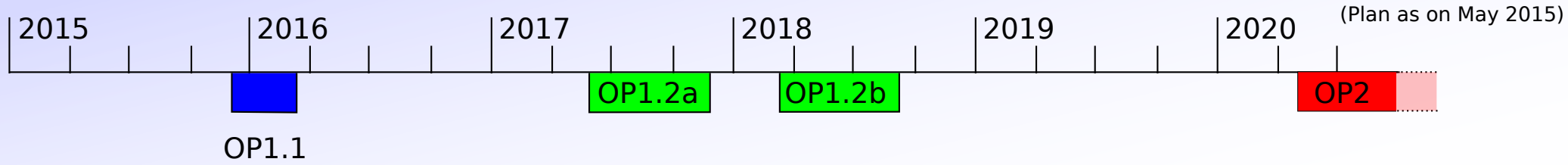


- Successful demonstration of off-axis heating!
- Apparent peaking of central n_e for flat T_e - Inward pinch or central neutrals??

Off-axis ECRH useful for:

- Control of profile / gradients.
- Influence on impurity accumulation.

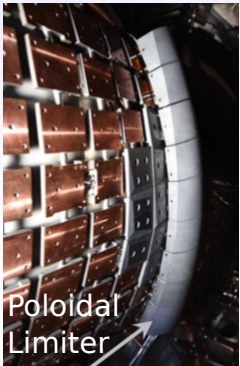
W7-X Operational Phases



OP1.1: Limiter Phase

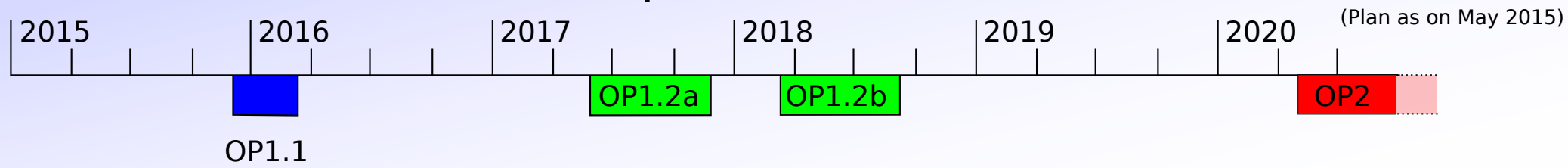
Anticipated

Achieved



13 Weeks
 $P \leq 4\text{MW}$, $W_{\text{limit}} = 2\text{MJ}$
 $T_e < 3\text{ keV}$, $T_i < 1\text{ keV}$
 $n_e < 0.2 \times 10^{20}\text{ m}^{-3}$
 $\tau_{\text{pulse}} < 1\text{s}$

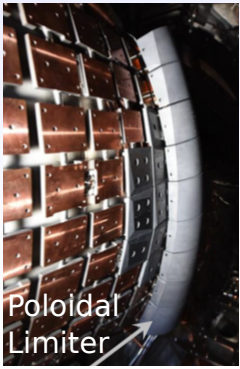
W7-X Operational Phases



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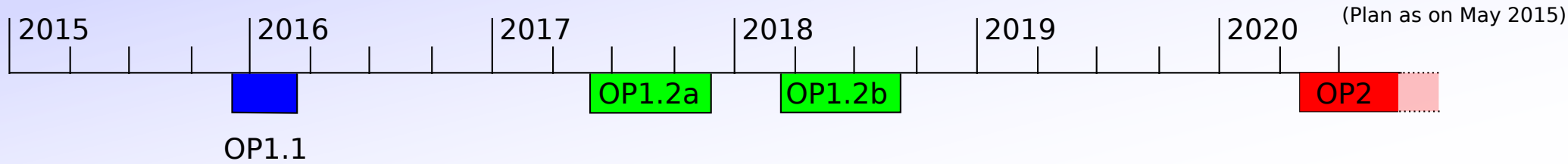
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 $T_e < 10\text{ keV}$, $T_i < 2\text{ keV}$
 $n_e < 0.8 \times 10^{20}\text{ m}^{-3}$
 $\tau_{\text{pulse}} < 6\text{s}$

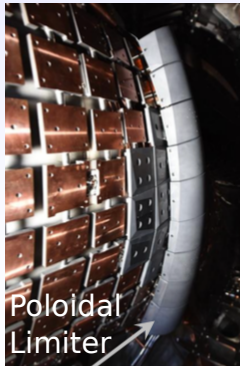
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$\tau_{\text{pulse}} < 6\text{s}$

OP1.2: Test divertor phase.



26 + 26 Weeks

$P \leq 10\text{MW}$, $W_{\text{limit}} = 80\text{MJ}$

$T_e < 3\text{ keV}$, $T_i < 3\text{ keV}$

$n_e < 1.6 \times 10^{20}\text{ m}^{-3}$, $\beta < 3\%$

$\tau_{\text{pulse}} < 10\text{s}$

?

OP2: Steady-state phase.



$P \leq 20\text{MW}$, $P/A < 10\text{MWm}^{-2}$

$T_e < 5\text{ keV}$, $T_i < 5\text{ keV}$

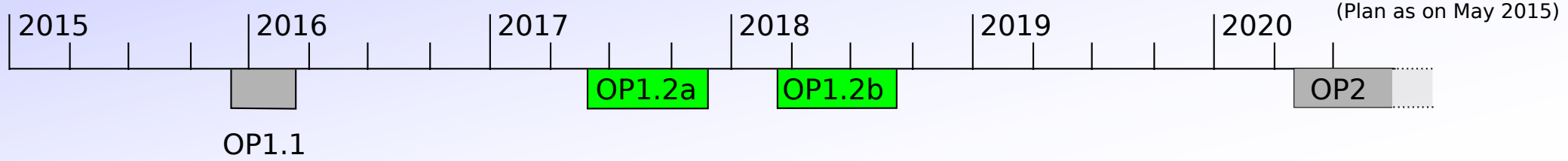
$n_e < 2.4 \times 10^{20}\text{ m}^{-3}$, $\beta < 5\%$

$\tau_{\text{pulse}} < 30\text{ mins}$ (~2/day, cooling capacity)

?



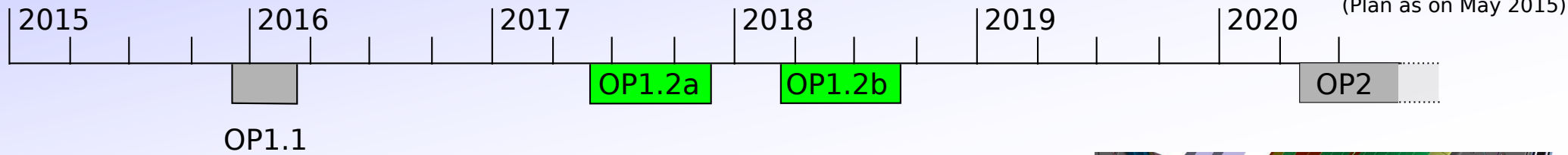
W7-X OP1.2 Upgrades



Primary components:

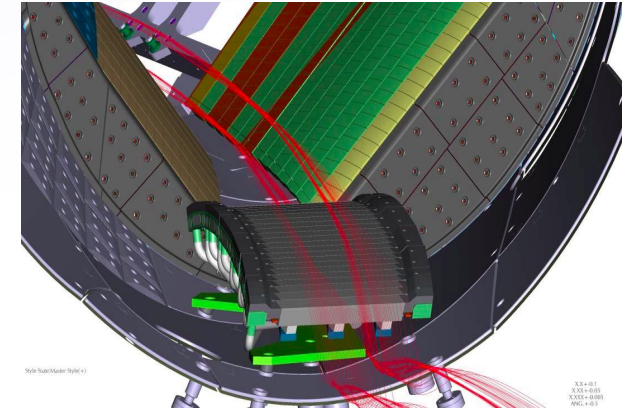
- Inertially cooled 'test' divertor unit (TDU)

W7-X OP1.2 Upgrades



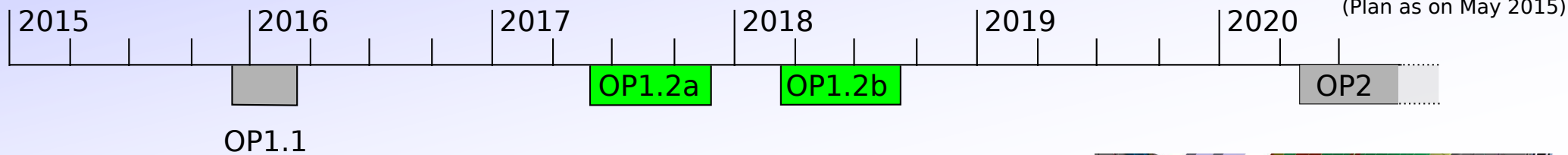
Primary components:

- Inertially cooled 'test' divertor unit (TDU)
- 'Scrapper Element' in OP1.2b to protect HHF divertor near pumping gap.
- > Pulse energy limited to 80MJ.
- > Full range of magnetic configurations (high/low iota, shear, ...)



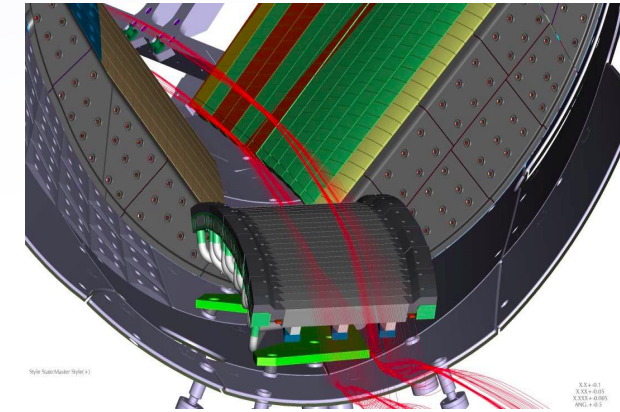
OP1.2b: Scapper Element
(ORNL, PPPL)

W7-X OP1.2 Upgrades



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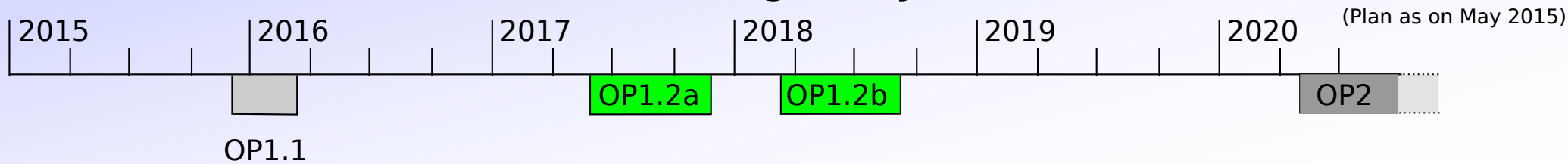


OP1.2b: Scaper Element
(ORNL, PPPL)

Sub-system upgrades:

- ECRH Gyrotrons: up to 8.8MW
- NBI heating: up to 7MW H (10MW D)
- ICRH Antenna: 1.6MW (1st of 2)
- HFS+LFS Pellet launcher.
- 20 new diagnostics, including:
 - Collective Thomson Scattering, Coherence Imaging Spectroscopy, Soft X-Ray Tomography, Charge Exchange Spectroscopy, Profile Reflectometer, TDU Langmuir Probes, Laser Blow Off, Laser Induced Fluorescence, Alkali Metal Beam, Phase Contrast Imaging, ...
- Upgrades to existing diagnostics:
 - Flux surface measurements, NIR Cameras, Video diagnostics, Thomson Scattering, Manometers, Helum Beam, Z_{eff} , Fast Manipulator, Reflectometer, Pulse Height Analysis Neutron Counters, ECE, XICS, HEXOS, Magnetics

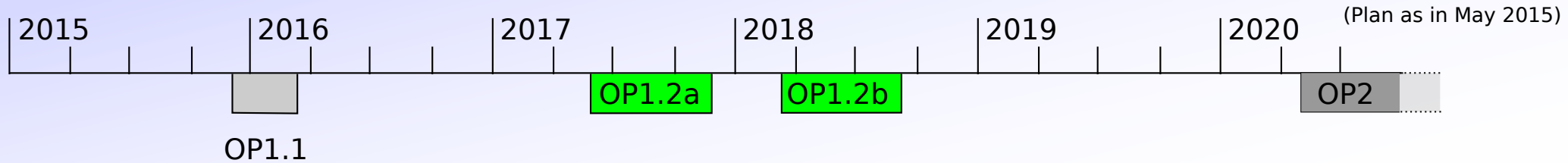
W7-X OP1.2 Edge Physics



- OP1.2:**
- Prepare for safe high power steady state operation in OP2.
 - Prove and assess stellarator optimisation.

- Prove safe operation, monitoring and control of test divertor.
- Study particle exhaust, divertor closure and pumping capability.
- Investigate routes to detachment.
- Effect of divertor on screening the core from impurity contamination.
- Experimentally investigate EMC3/EIRENE model predictions.
- Study effect of increasing β on 3D topology, divertor performance and plasma wall interaction
- Investigate plasma sweeping.
- Use planar/control coils to mimic effect of β and bootstrap current in OP2 scenarios.

W7-X OP1.2 Core Physics

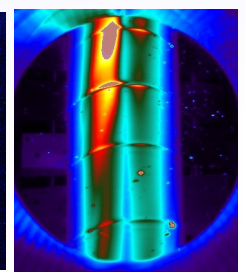
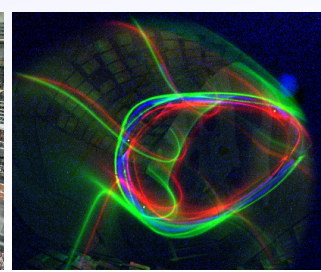
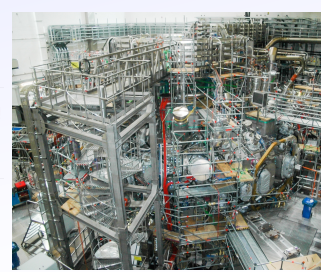
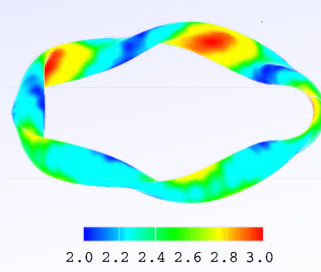
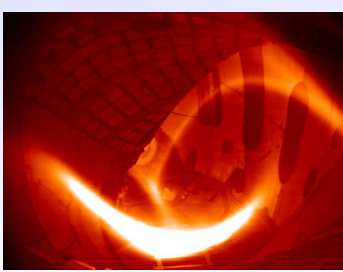
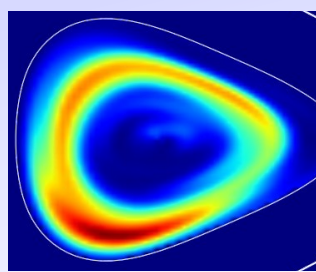


OP1.2: - Prepare for safe high power steady state operation in OP2.
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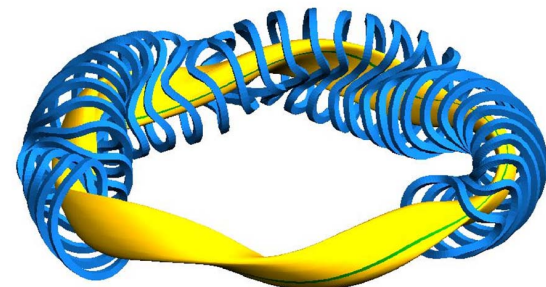
- Explore extent of neoclassical confinement optimisation.
- Core electron vs ion root confinement.
- Core fuelling / hollow density profiles?
- Impurity accumulation.
- Explore confinement modes: Quiescent H-Mode, high density H-Mode?
- ECRH O2 Heating experiments (started OP1.1)
- Fast ion generation (ICRH/NBI)

Summary

[Wendelstein 7-X team and all collaboration partners]

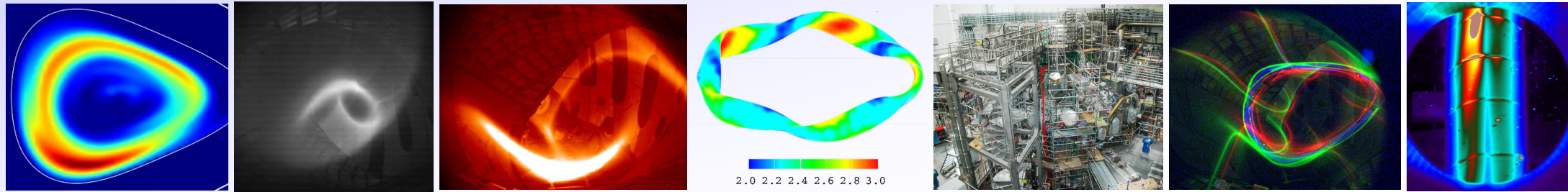


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- ✓ Good flux surfaces demonstrated. Expected behaviour of magnets.
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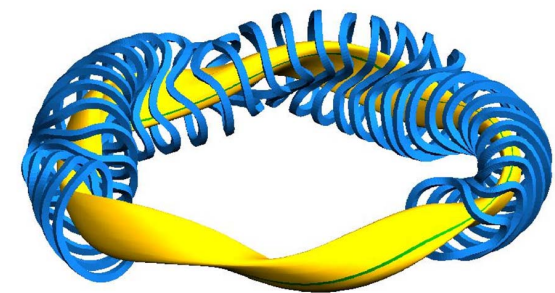


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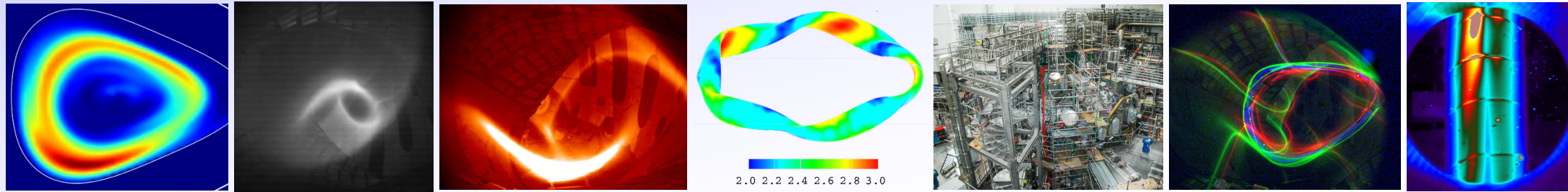


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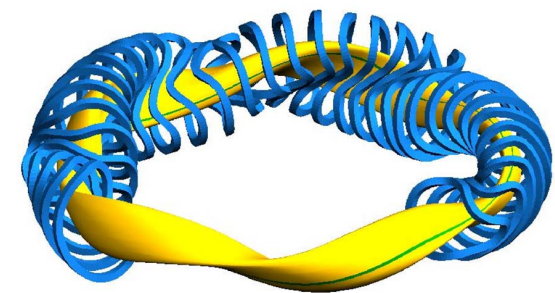


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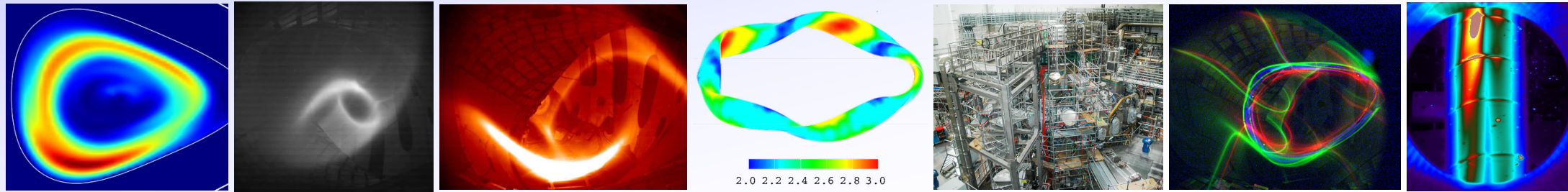


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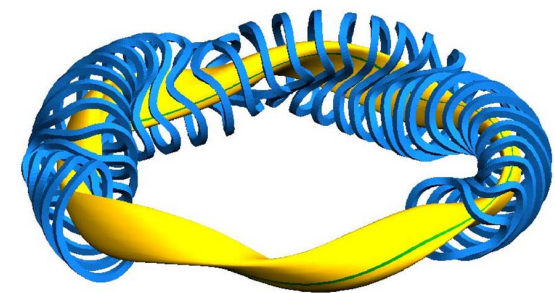


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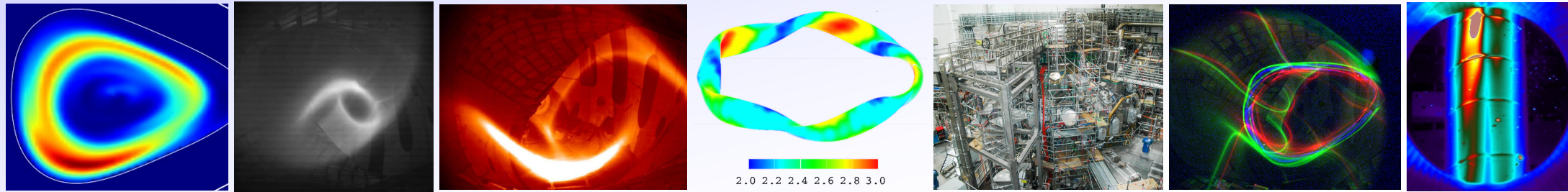


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 - 7kHz modes?
 - Peaked density profiles?
 - Sawteeth?



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Details and much more from the OP1.1 data is coming. See conferences:
IAEA, EPS, APS

Many thanks for PPPL contributions!

