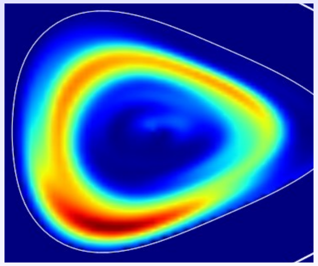
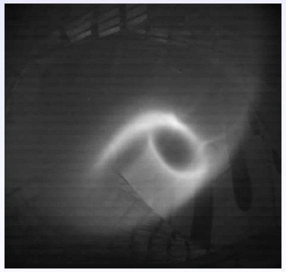
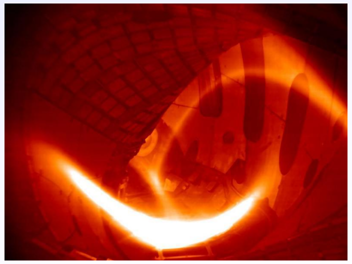
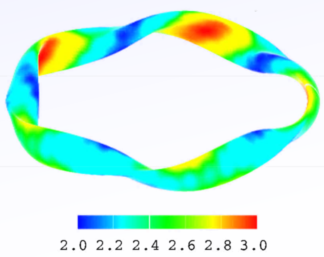
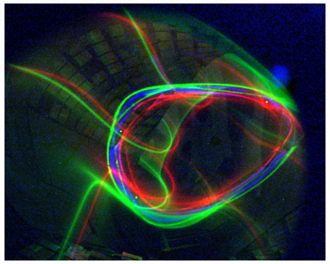
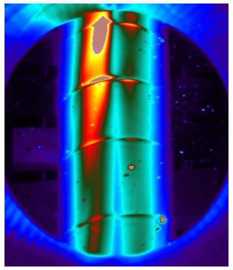
Max-Planck Institut für Plasmaphysik

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:

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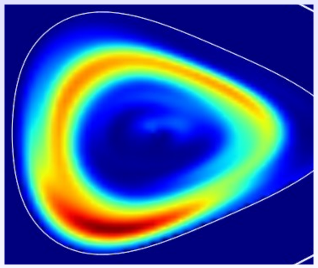
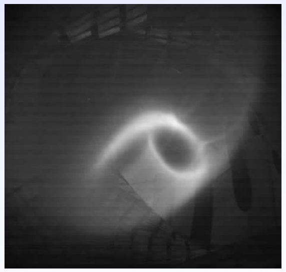
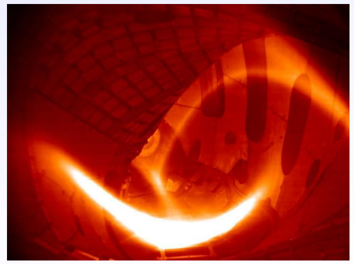
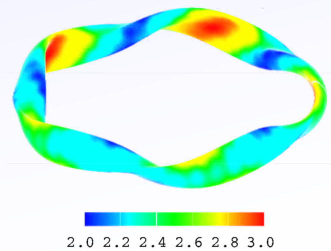
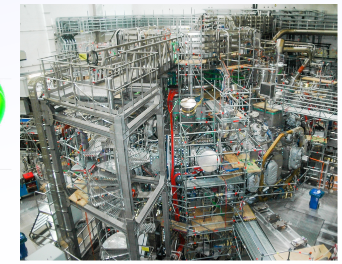
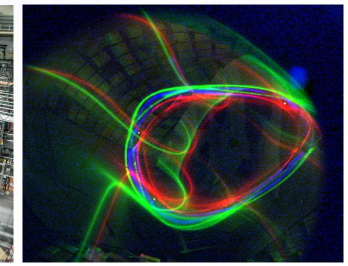
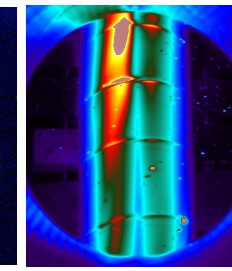
US Contributors

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

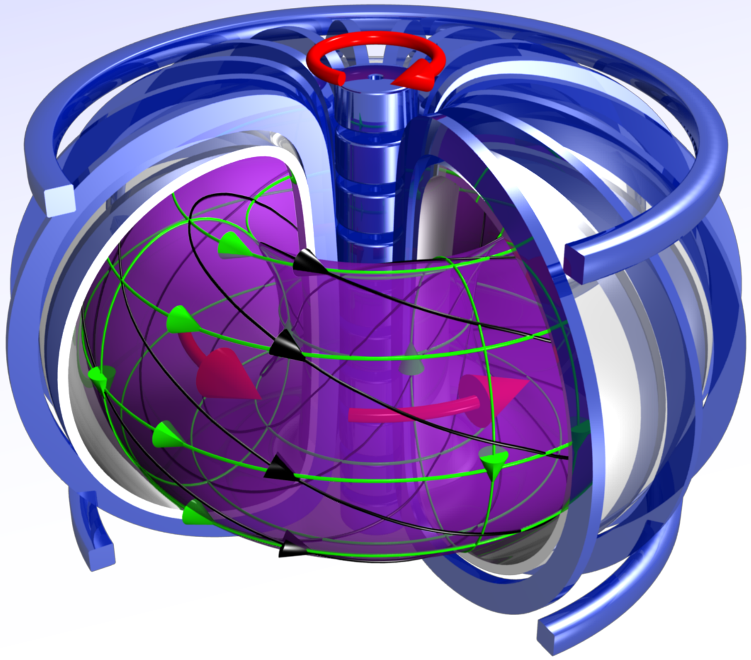
Disclaimer....

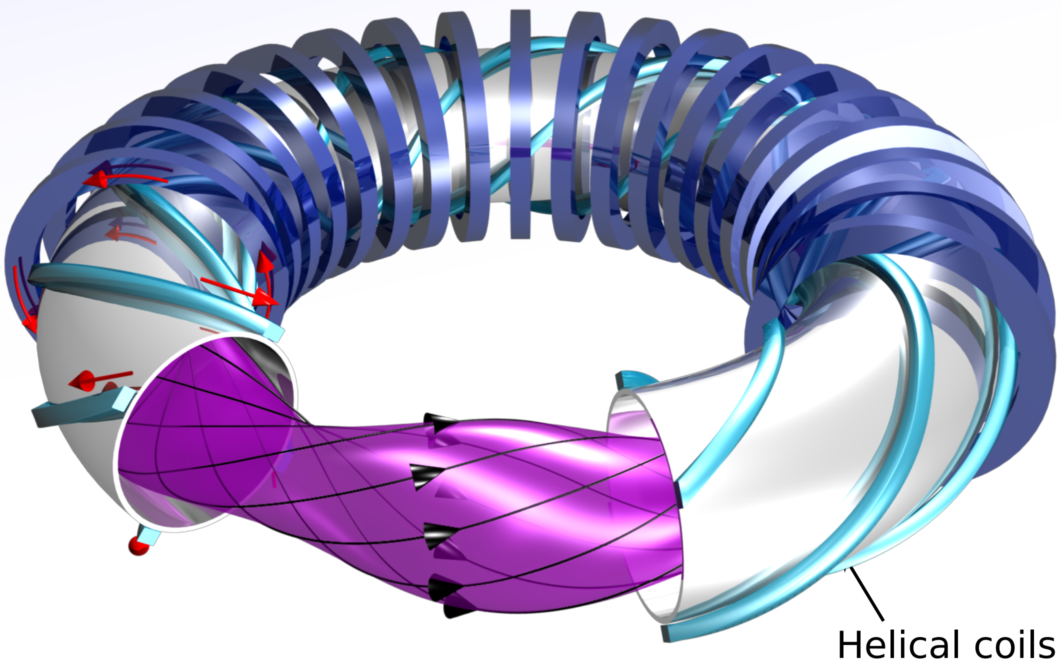
The results presented here are the preliminary work of the W7X team and collaboration partners analysed very shortly after the end of the first operational phase. Despite very little time, best efforts have been made to understand and qualify them. However, they should be taken as indicative only, and 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.

[R. Wolf, T. Klinger]

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)

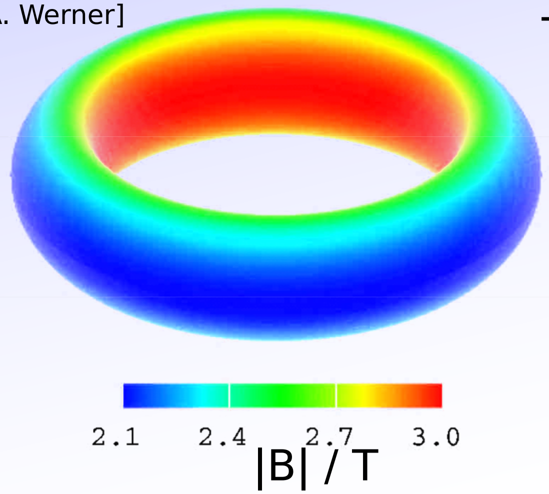
- Helical field created externally by coils.

- Classically poor confinement.
- Complex construction - 3D.
+ Inherently steady state.
+ No current instabilities or disruptions.
+ Higher densities.

[R. Wolf, A.Werner, J.H.E. Proll]

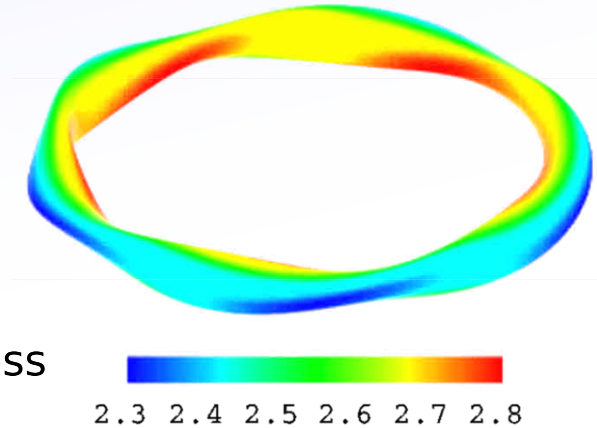
Stellarator Optimisation

[A. Werner]



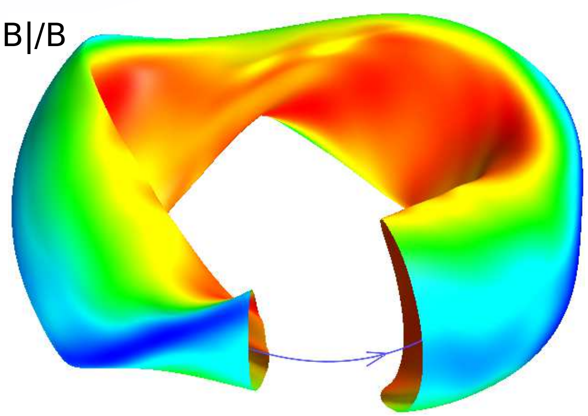
Tokamak:
Trapped particles precess toroidally because |B| is axi-symmetric.

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

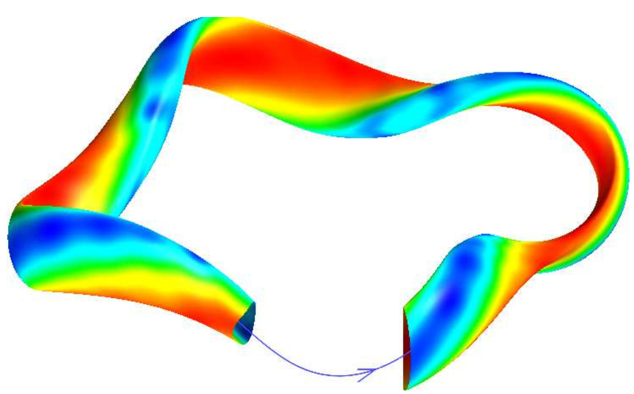


Optimised Stellarator: Create a field with a quasi-symmetry of |B| in some direction:

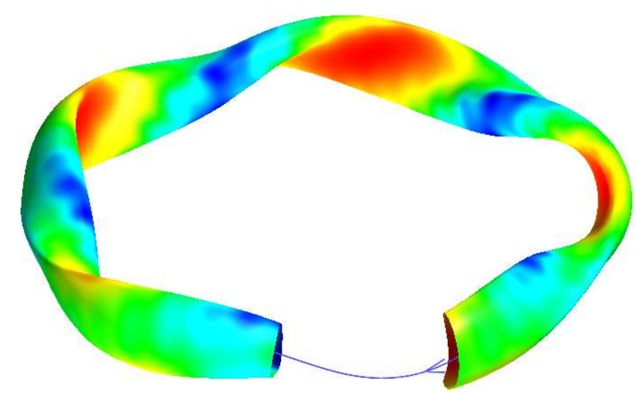
|B|/B



Quasi-axisymmetric
(NCSX: National Compact Stellarator Experiment)



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

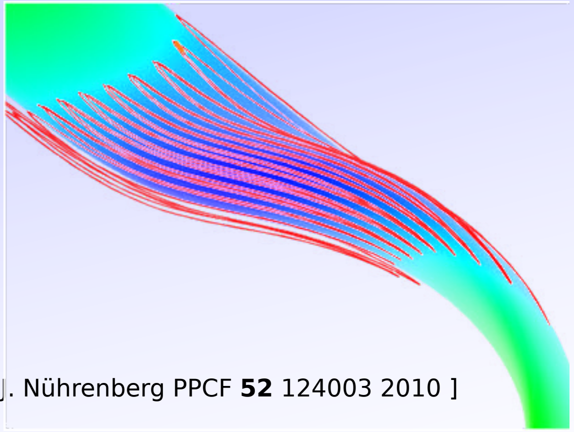


Quasi-isodynamic:
Mixed symmetry chosen to minimise bootstrap current.
(Wendelstein 7-X)

[J.H.E. Proll PPCF **58** 1 2016]

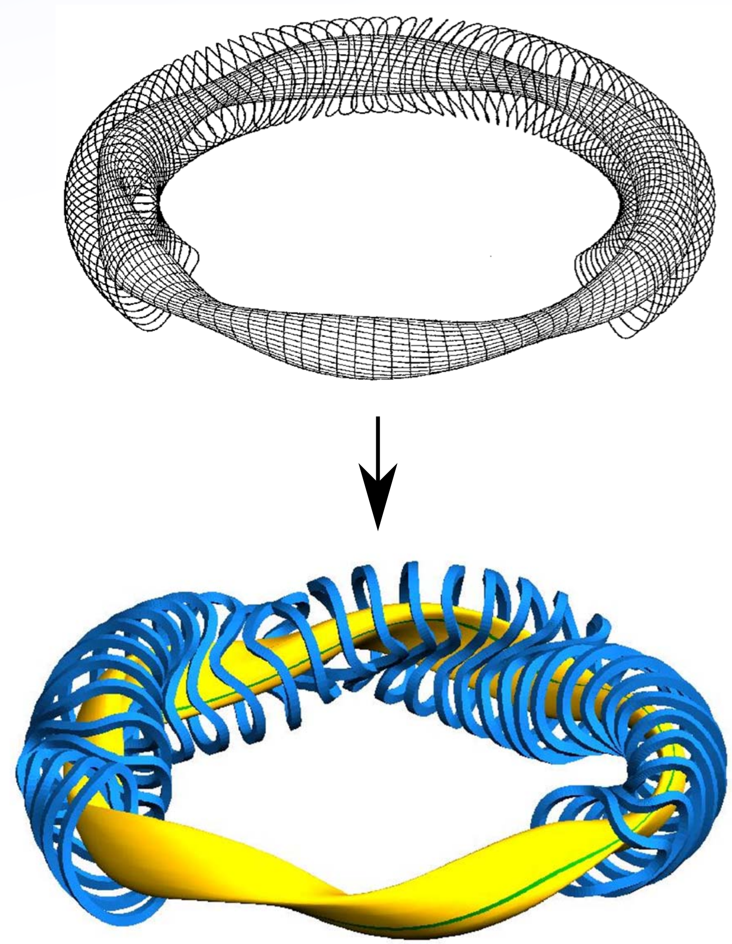
[J. Nührenberg, T. Klinger]

Stellarator Optimisation



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

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



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

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

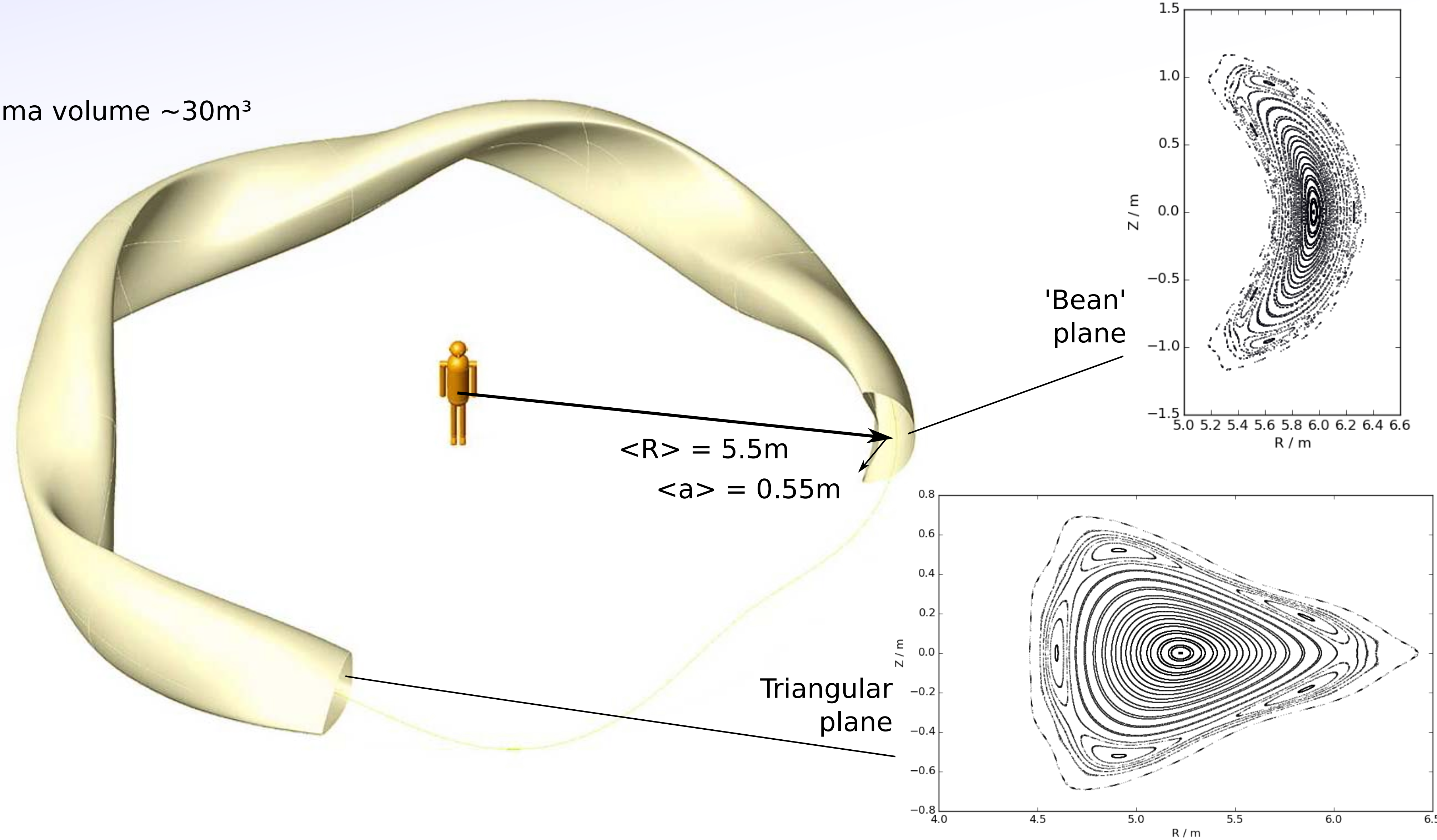
Missions:

- 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

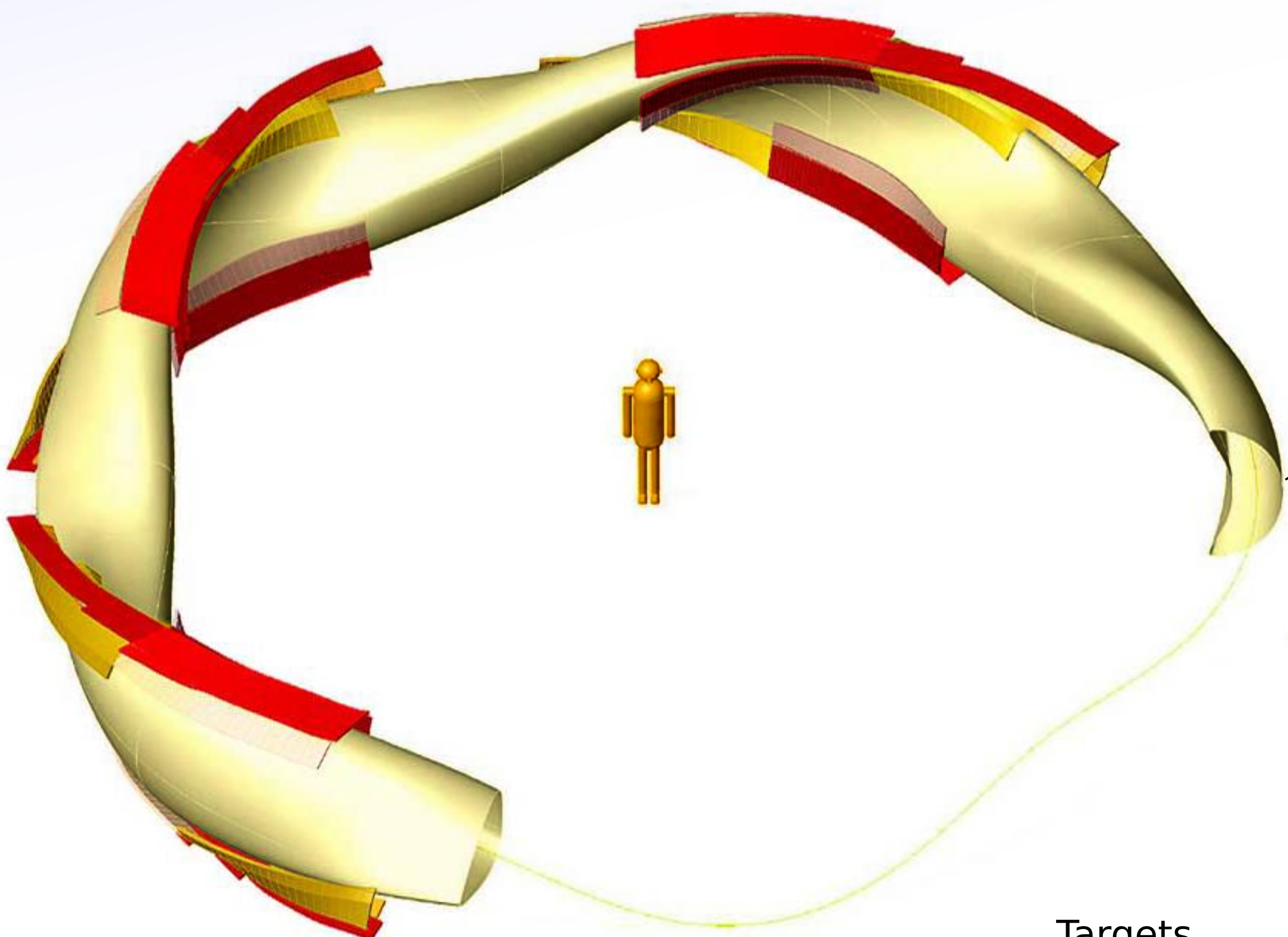
Steady-state operation requires steady-state coils --> Super-conducting --> Even more complexity!
After a lot of R&D, the final design of W7-X was complete:

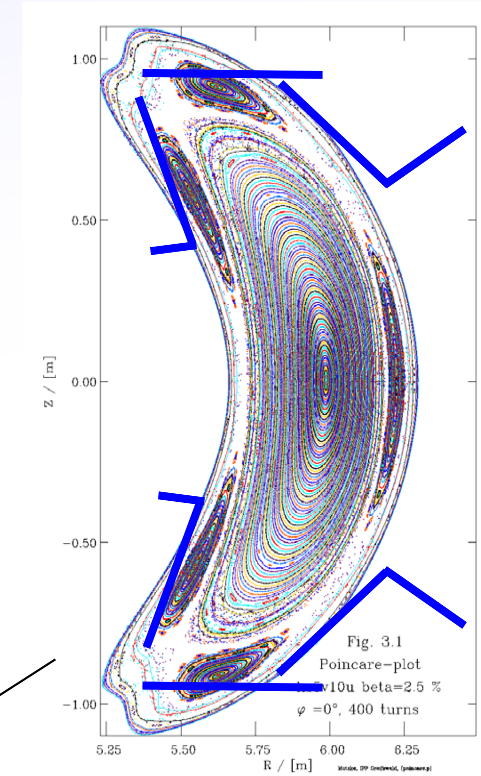
Plasma volume ~30m³

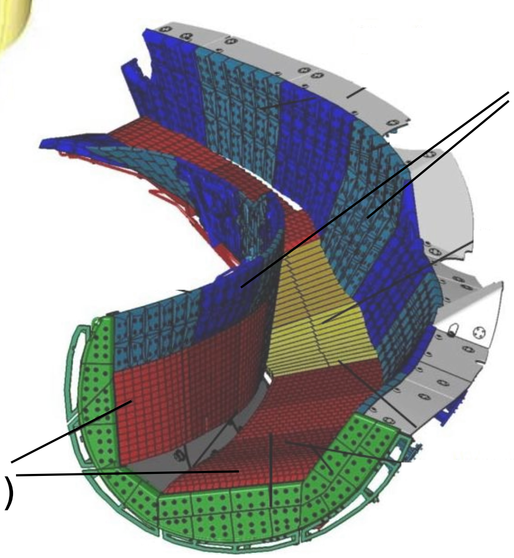


W7-X Construction

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.

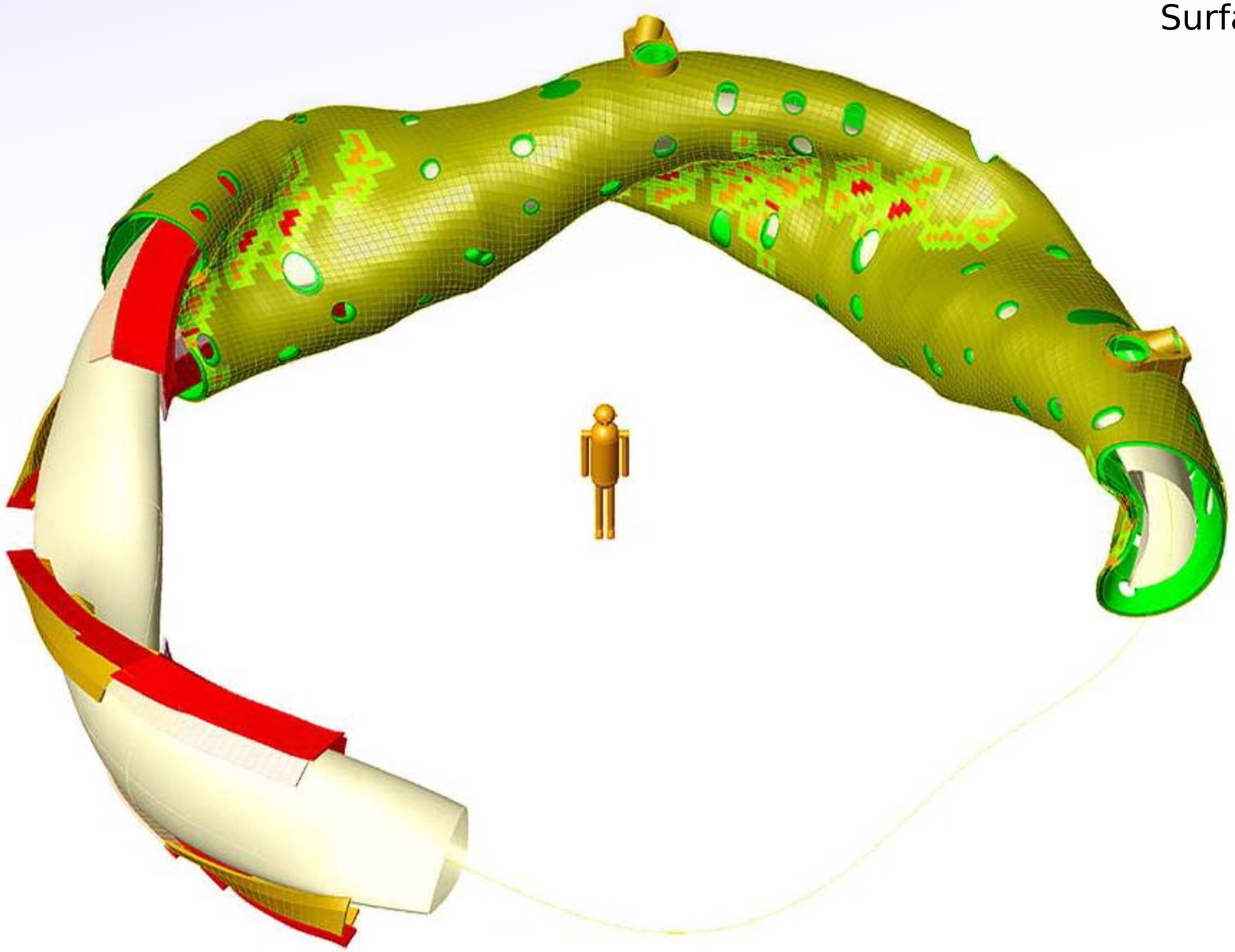






W7-X Construction

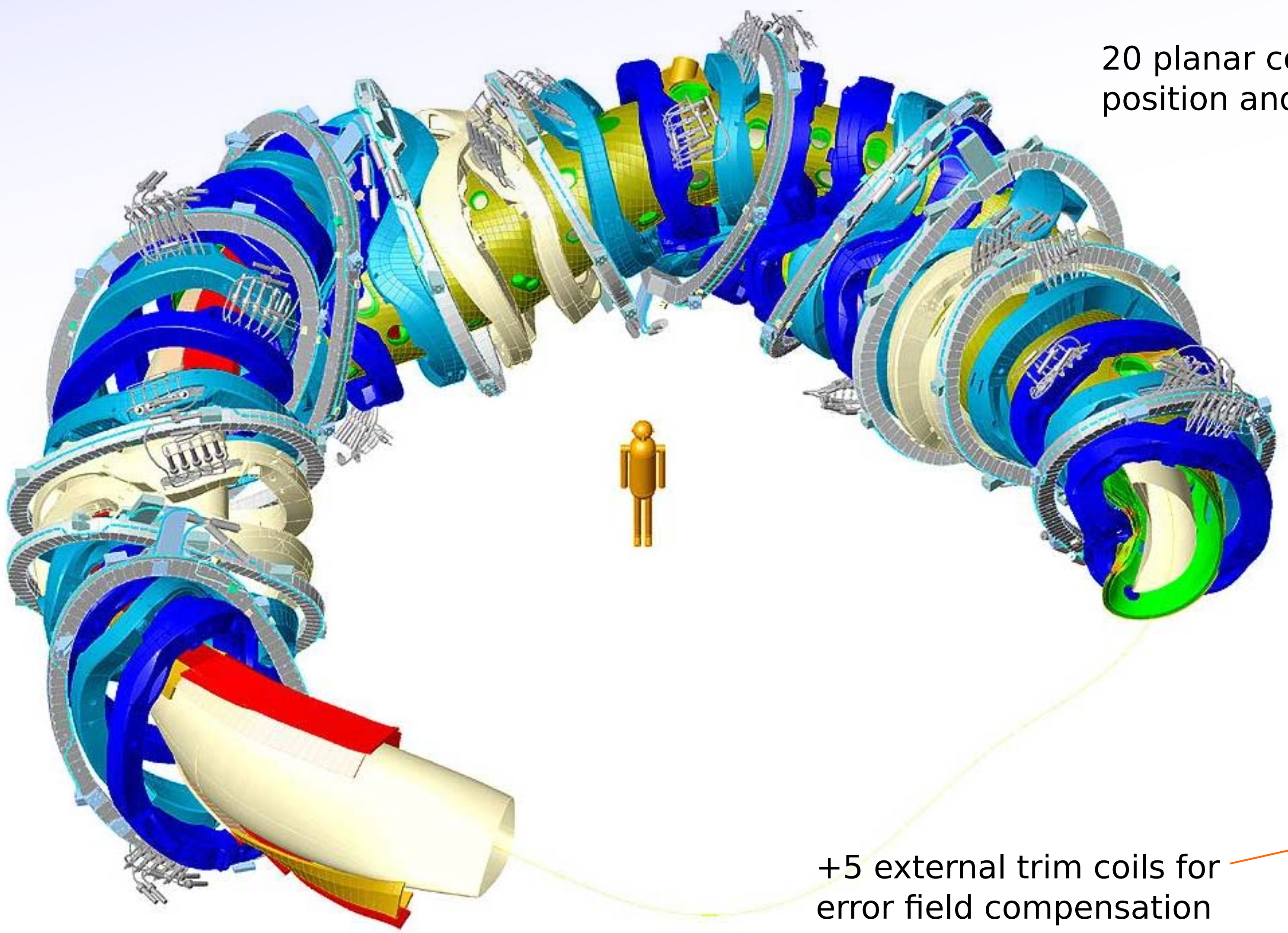
Vacuum Vessel



Vacuum Vessel:
Volume: $84m^3$
Surface area: ~$200m^2$

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.

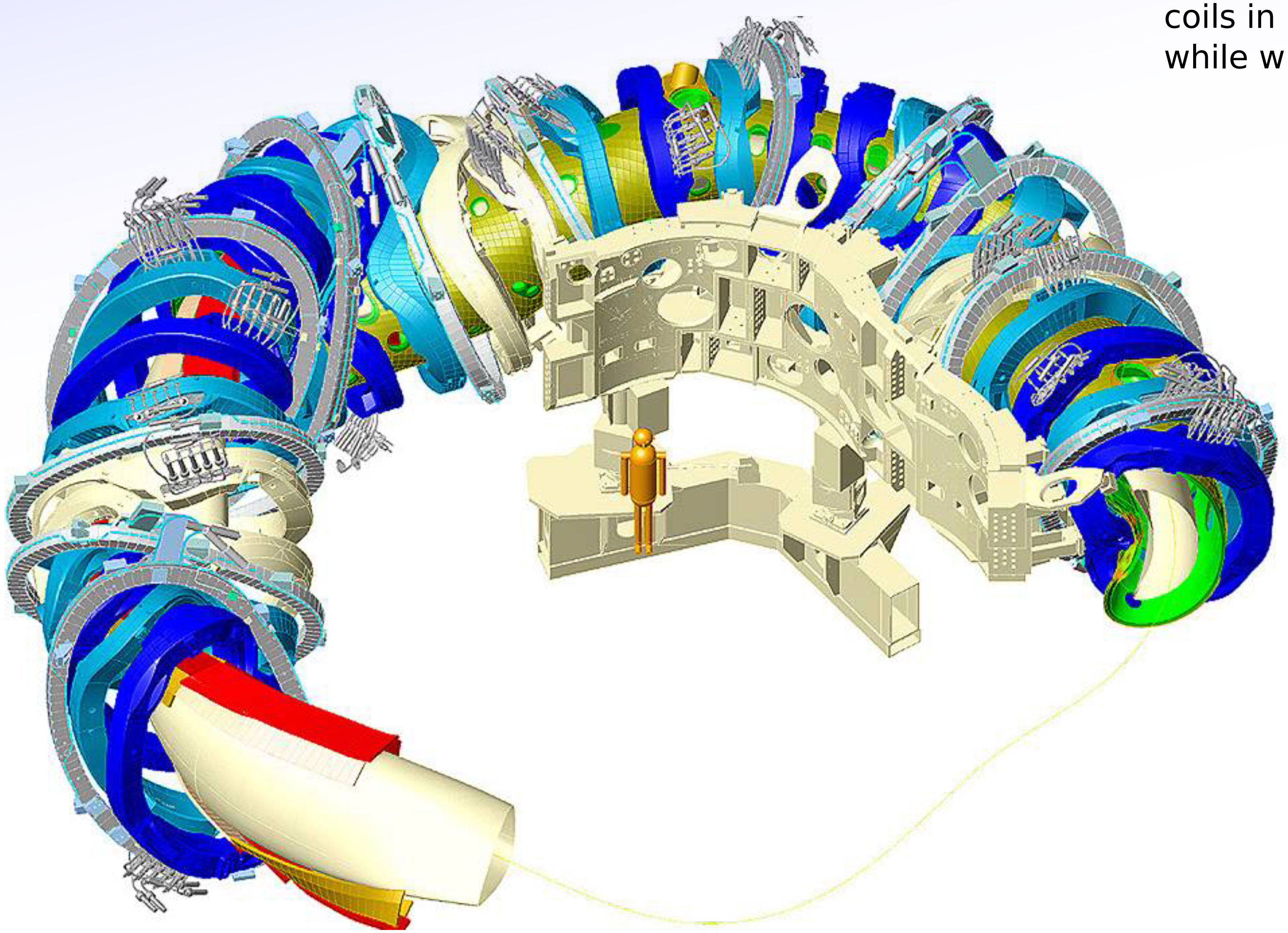
Non-superconducting coils:

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

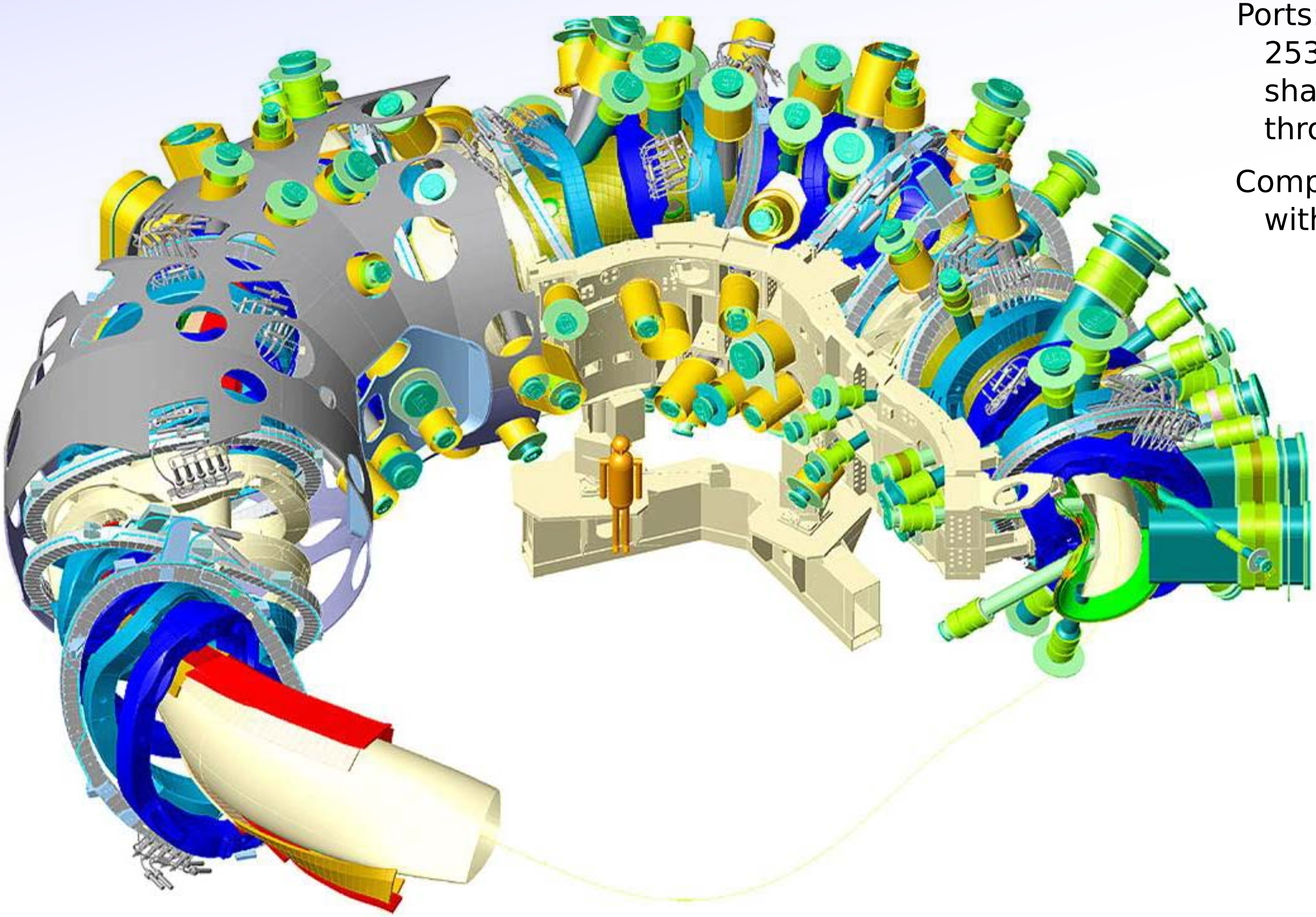
Support structure:



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

W7-X Construction

Ports and Cryostat



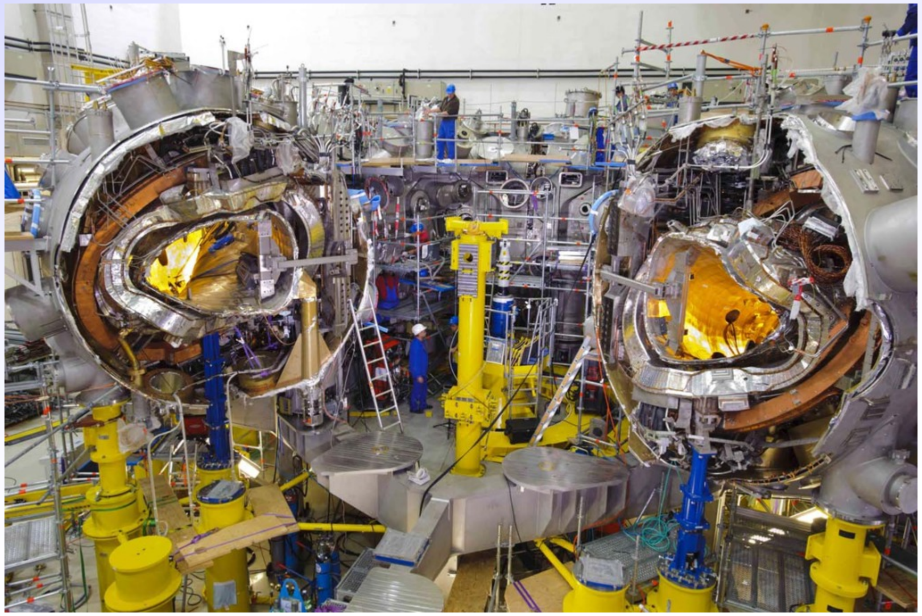
Cryostat:
Liquid helium cooling for all superconducting coils.

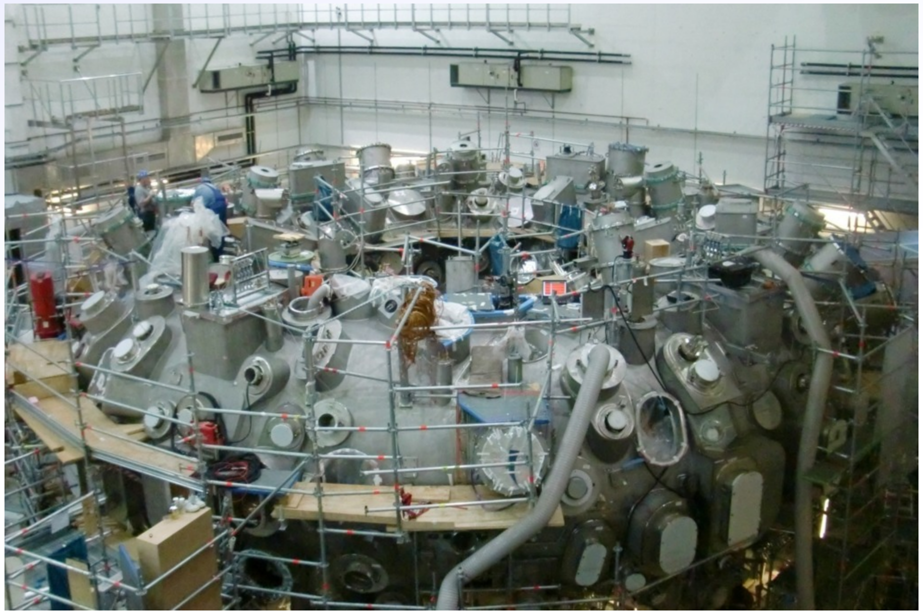
Ports:
253 ports of wide range of shapes and sizes for feed-throughs and diagnostics.

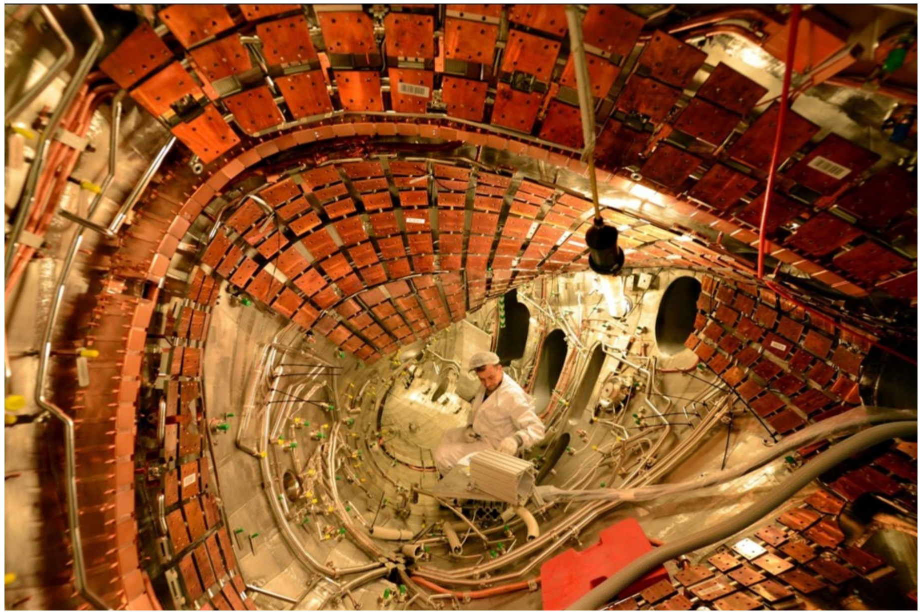
Complete construction 735t with 435t cold mass.

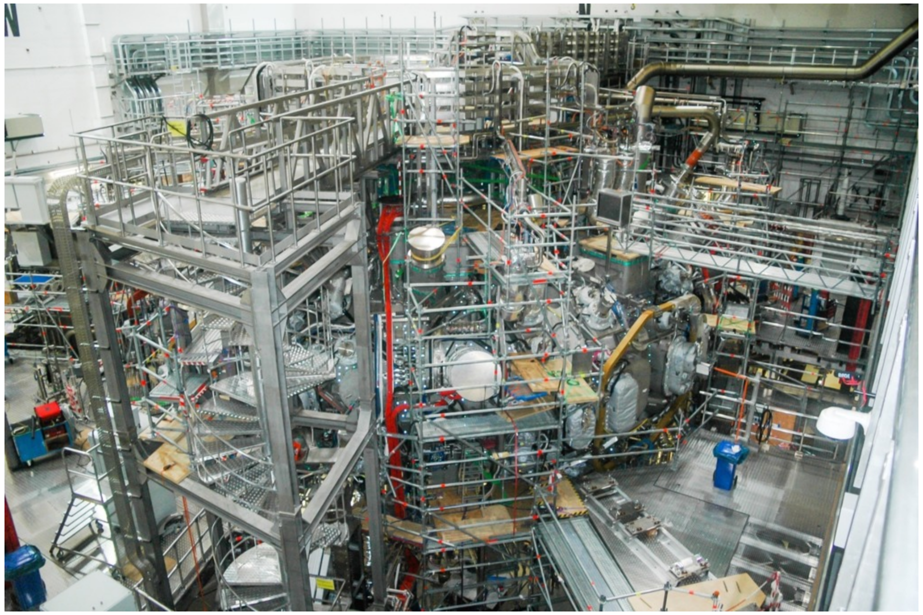
W7-X Construction

Construction was completed by 2013.







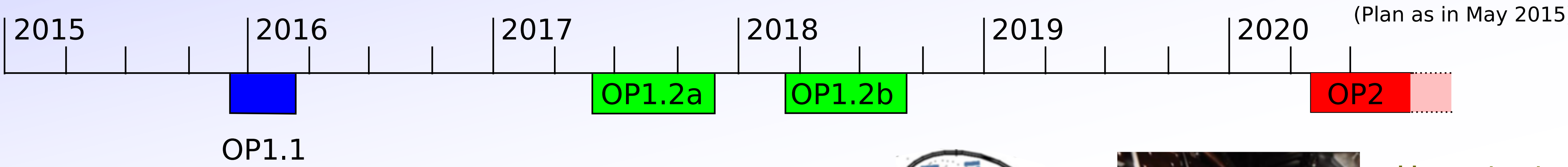


✓ Build Wendelstein 7-X to the required precision.

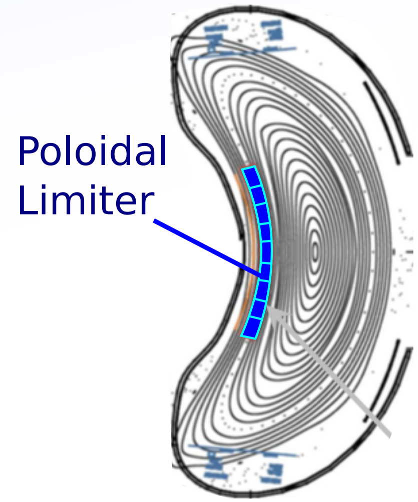
[R. Wolf, R. König]

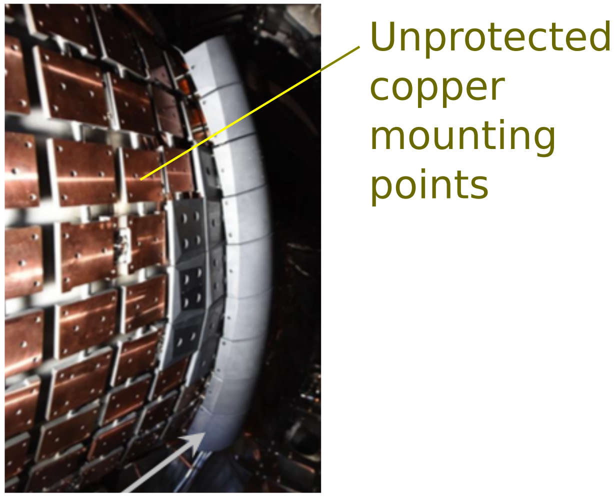
W7-X Operational Phases

- 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

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.

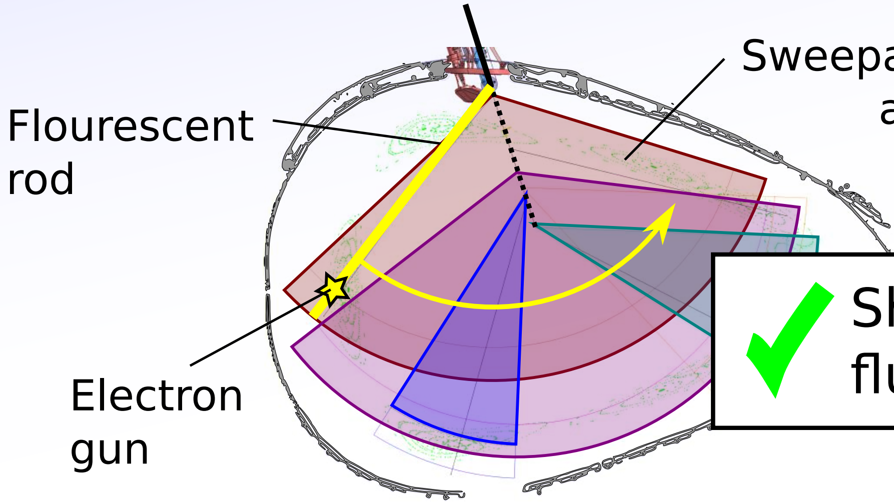
OP2: High Heat Flux divertor

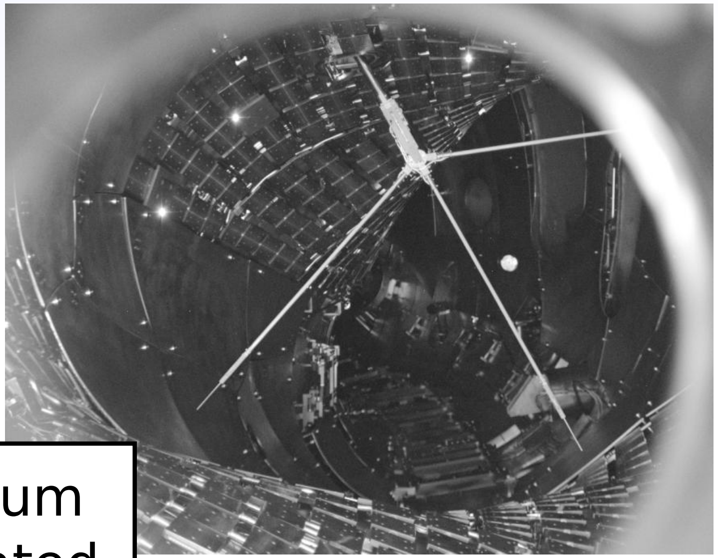

???: Future phases
- Tungsten wall??

[M. Otte]

Flux surfaces

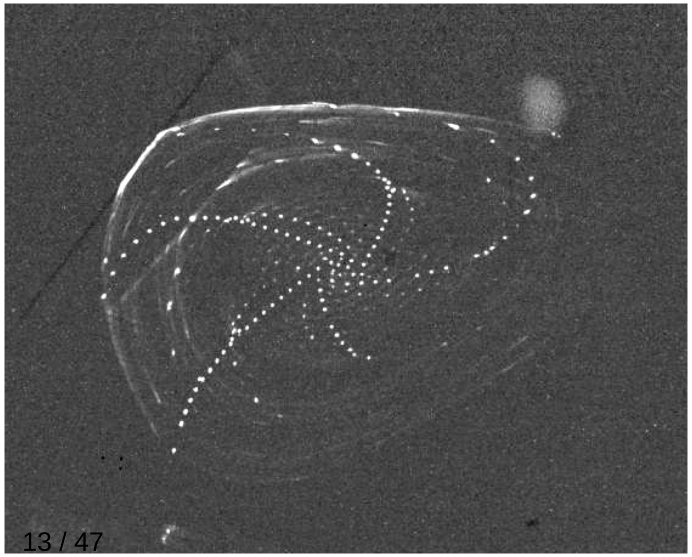
- 2x 90cm retractable flourescent rods, with an electron gun near the tip.
- Rods extend into the vessel and sweep the poloidal plane.
- Electrons follow field lines until they interact with the rod or background gas.
- Electron interaction viewed by video cameras.





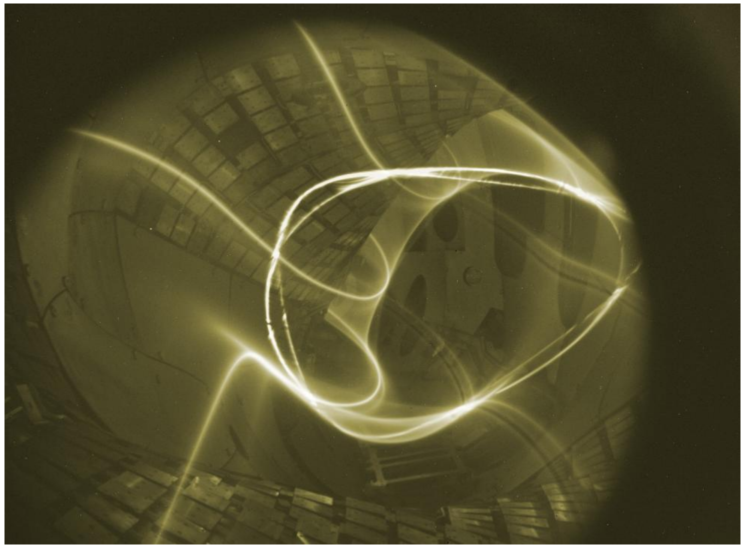
Video system viewing the manipulator.

Show that good vacuum flux surfaces are created.



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

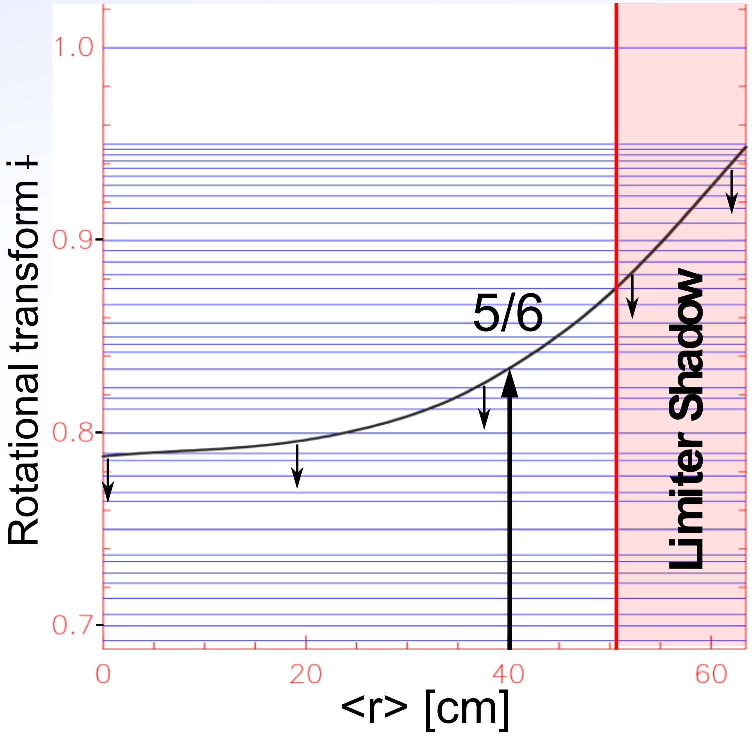
5/6 Island chain with flourescent rod and background gas. Islands have expected position, orientation and symmetry.

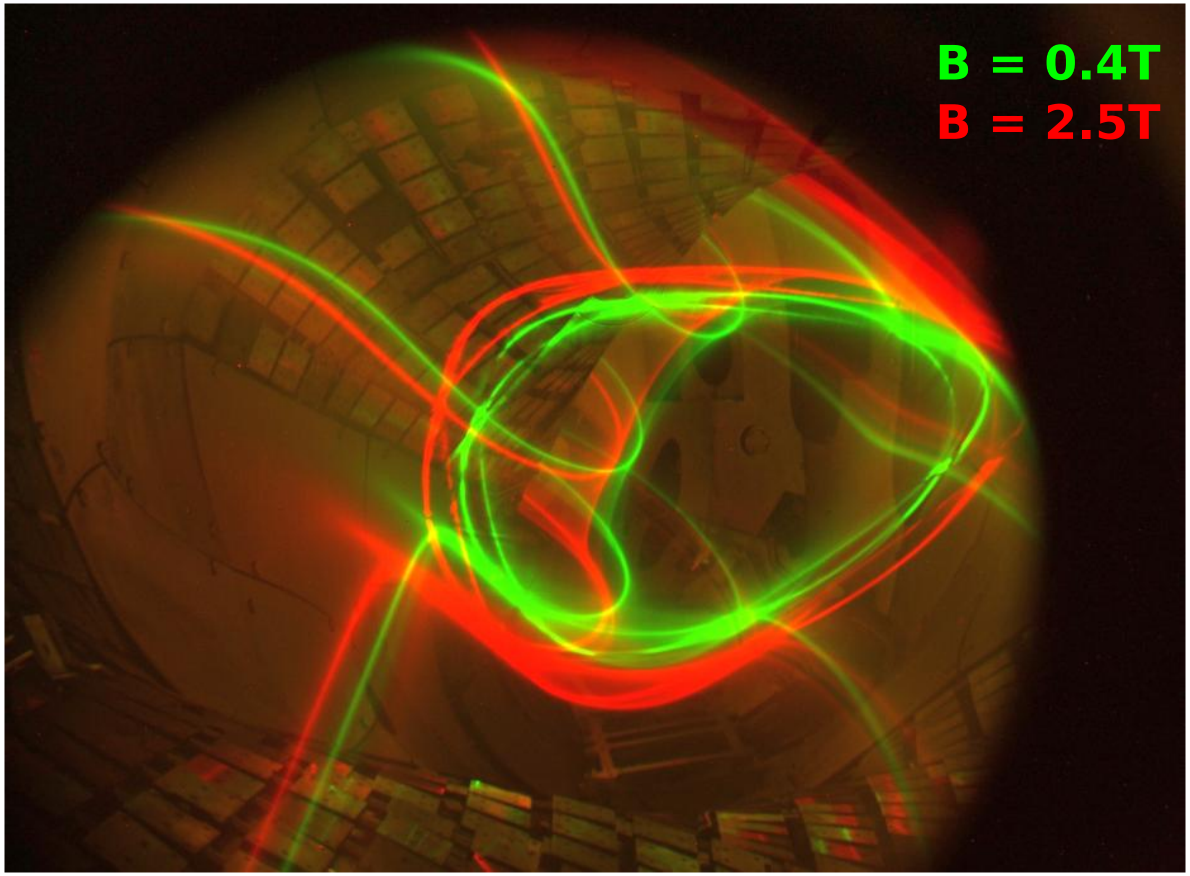


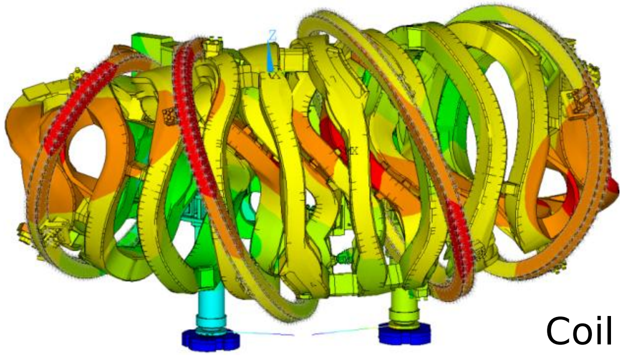
[M. Otte, V. Bykov]

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 and movement of the 5/6 islands.
- Seen clearly with the flux surface measurements.
- Coil currents are adapted to correct for this.







Coil stress/deformation [V. Bykov]

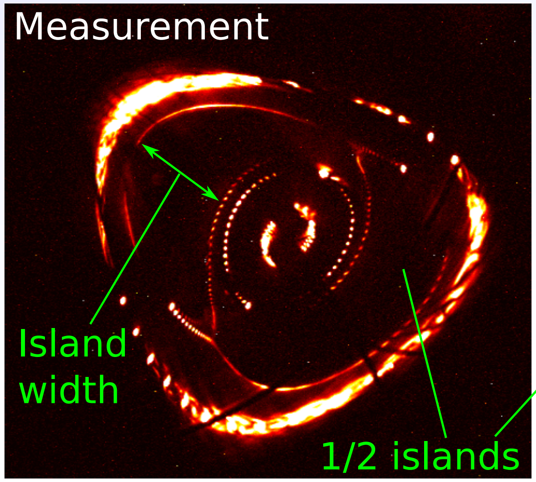
[S.Lazerson, M.Otte]

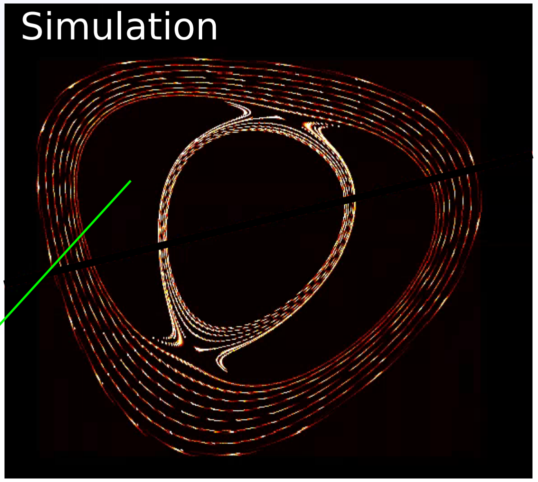
Flux surfaces: Error Fields

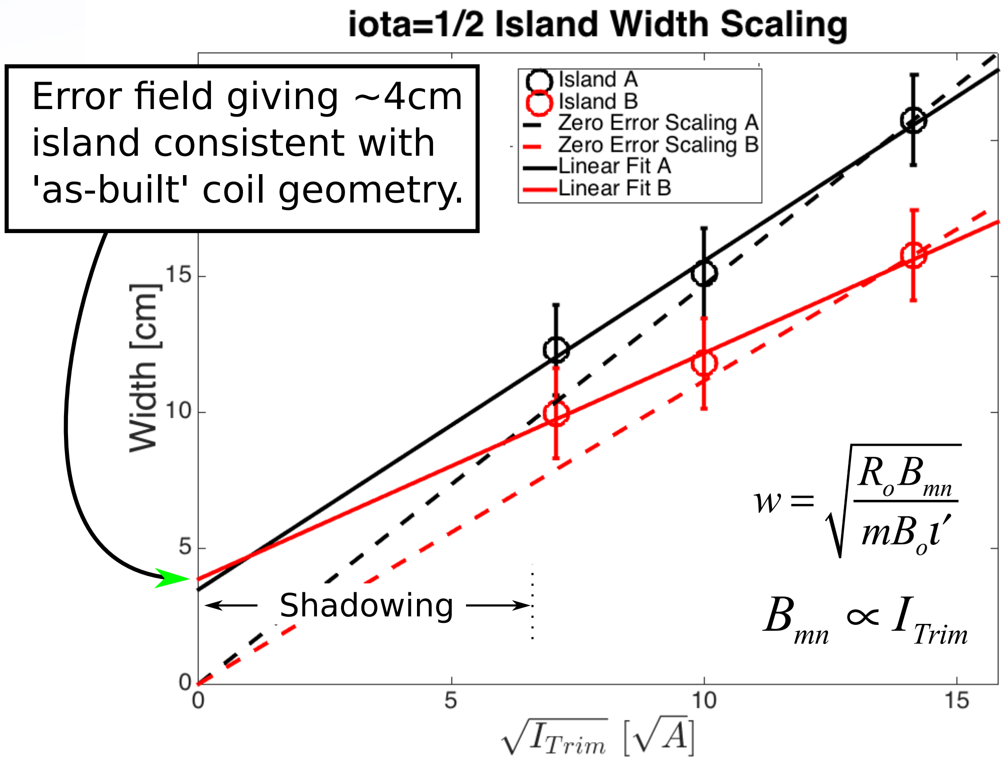
- Developed magnetic field configuration with iota=$^1/_2$ at ~mid radius.

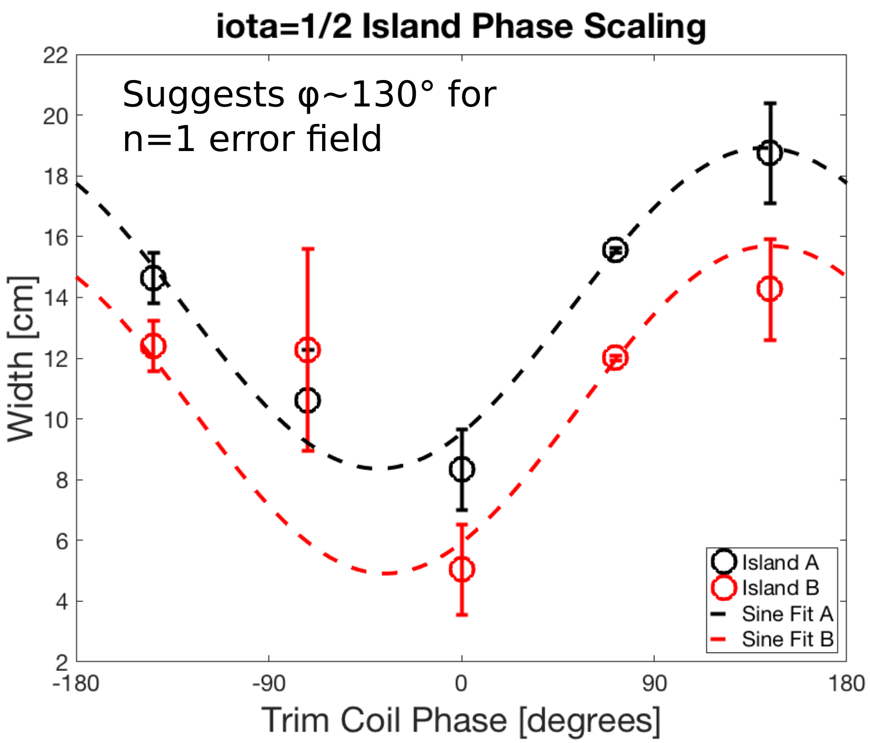
- Apply n=1 perturbation using PPPL trim coils.

- Scan phase and amplitude of perturbing field and examine width of 1/2 island from flux surface measurement.









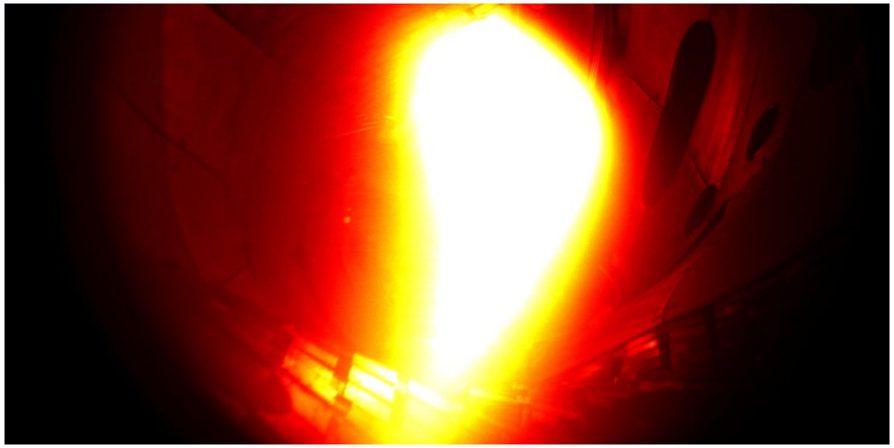
Start-up: Timeline

2015

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

Dec

10th Dec 2015: First Helium plasma



2016

Feb

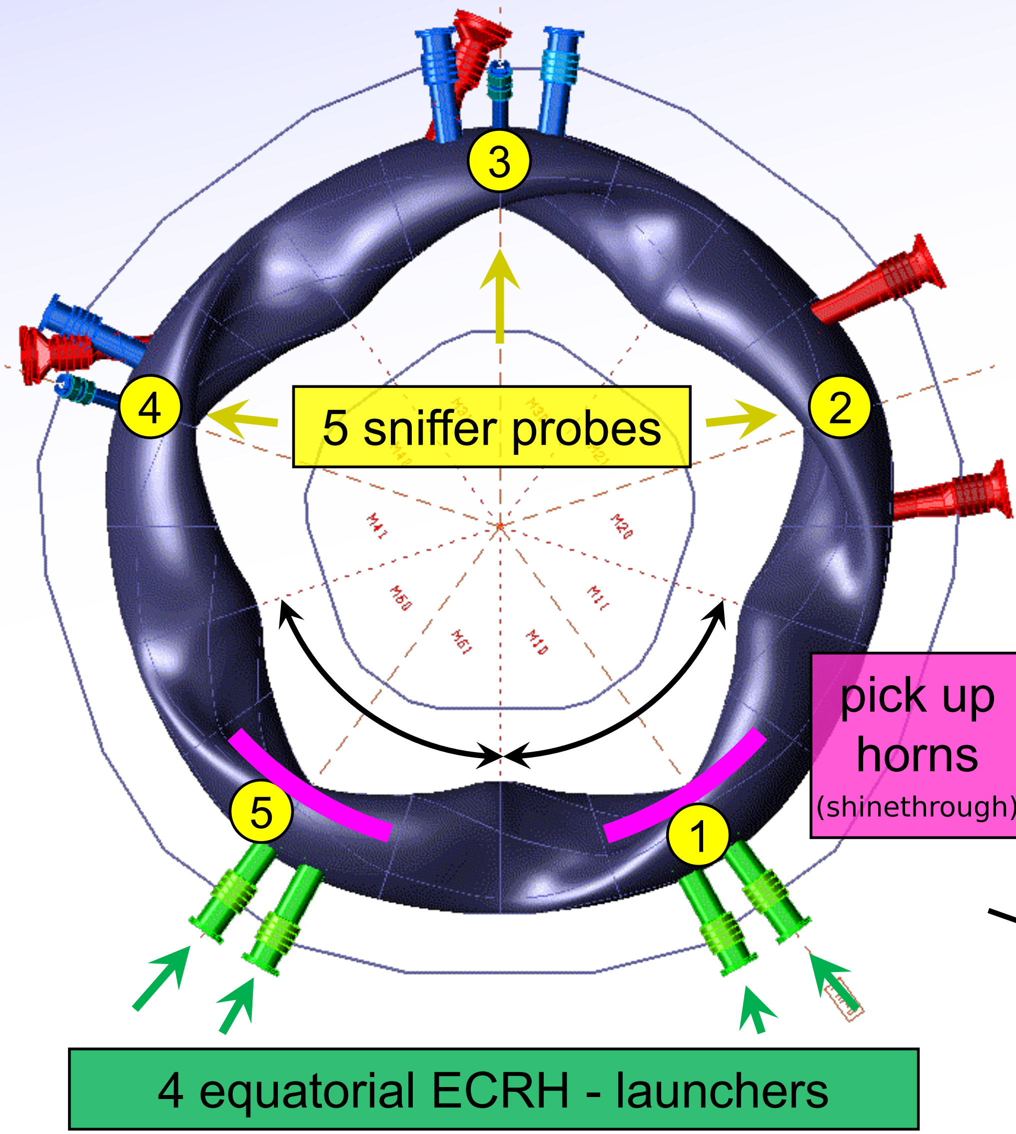
Mar

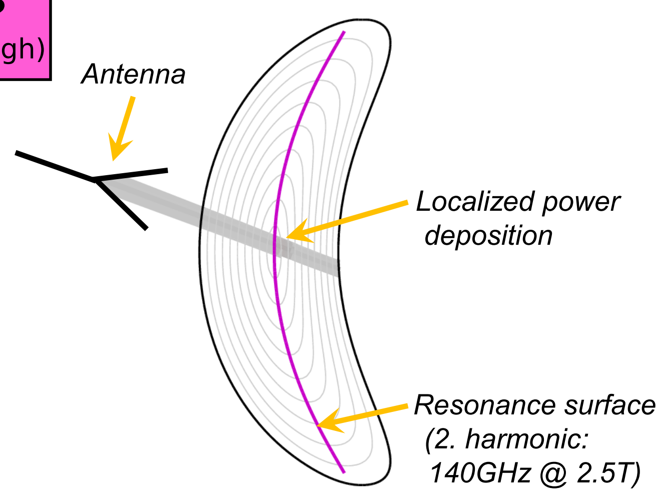
[T. Stange, H. Laqua, ECRH Team]

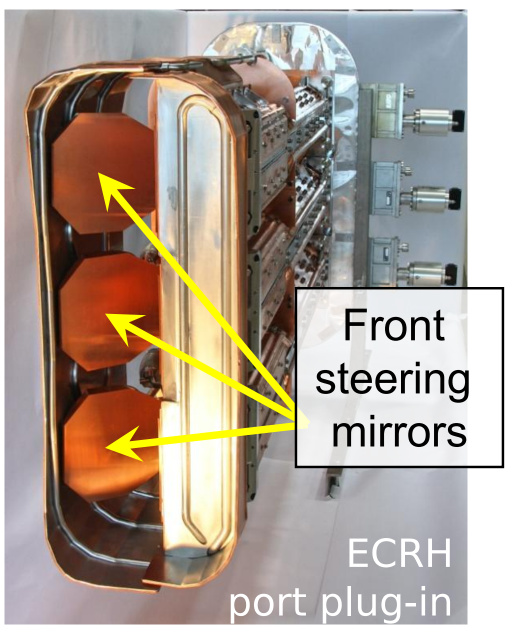
W7X ECRH Heating

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

Capabilities:
- 6 Gyrotrons giving 5MW in OP1.1.
- Modulation up to at least 1kHz.
- Polarisation fully variable.
- Steady-state operation up to 30mins.
- Steerable mirrors:
  - Poloidally: ±30° (off-axis heating)
  - Toroidally: -15 - +30° (current drive)
- X2 mode heating ($n_e < 1.2\times10^{20}$ m^{-3})
- O2 mode heating up to 2.4 x 10^{20}m $^{-3}$ (was not planned for OP1.1)







[C. Biedermann, G. Kocsis]

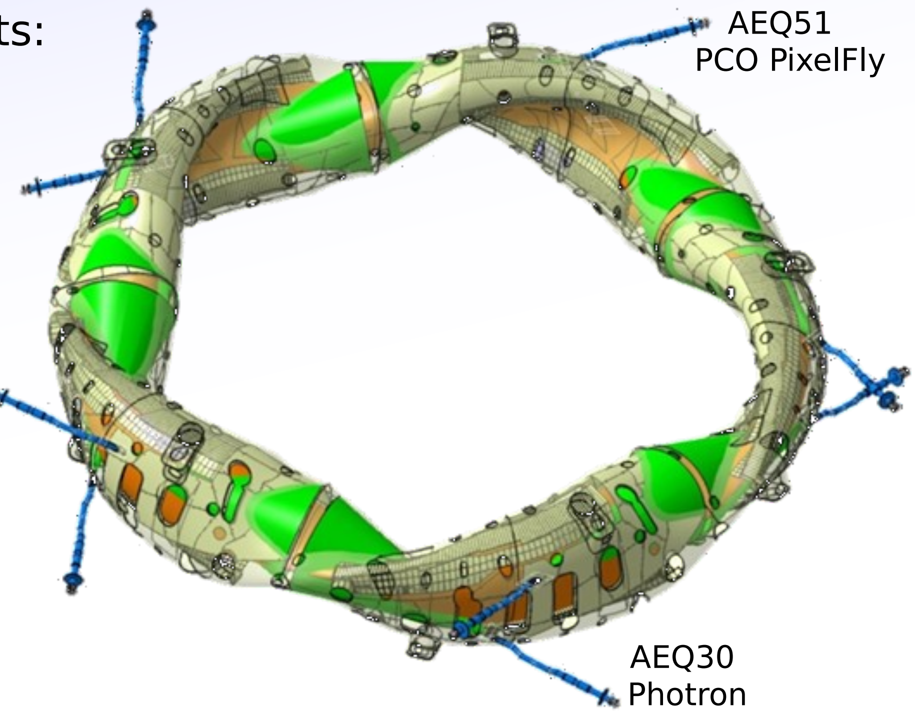
W7X Video Diagnostics

Tangential view of the whole plasma vessel from 10 ports:

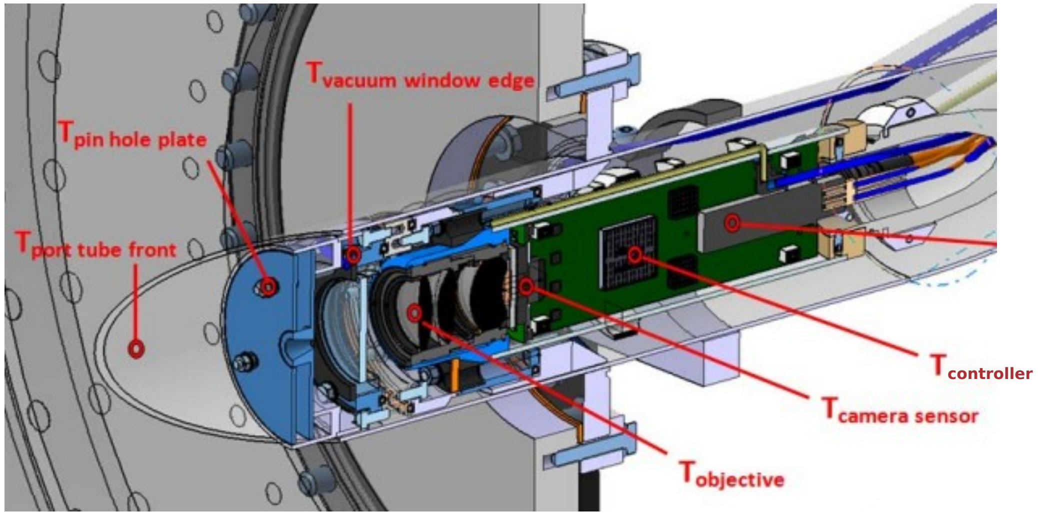
7x EDICAM (CMOS, up to 50kHz)
- Standard plasma observation

2x PixelFly (CCD, long exposures)
- Flux surface measurements

1x Photron (CMOS, up to 1MHz) + image guide
- Turbulence, fast events



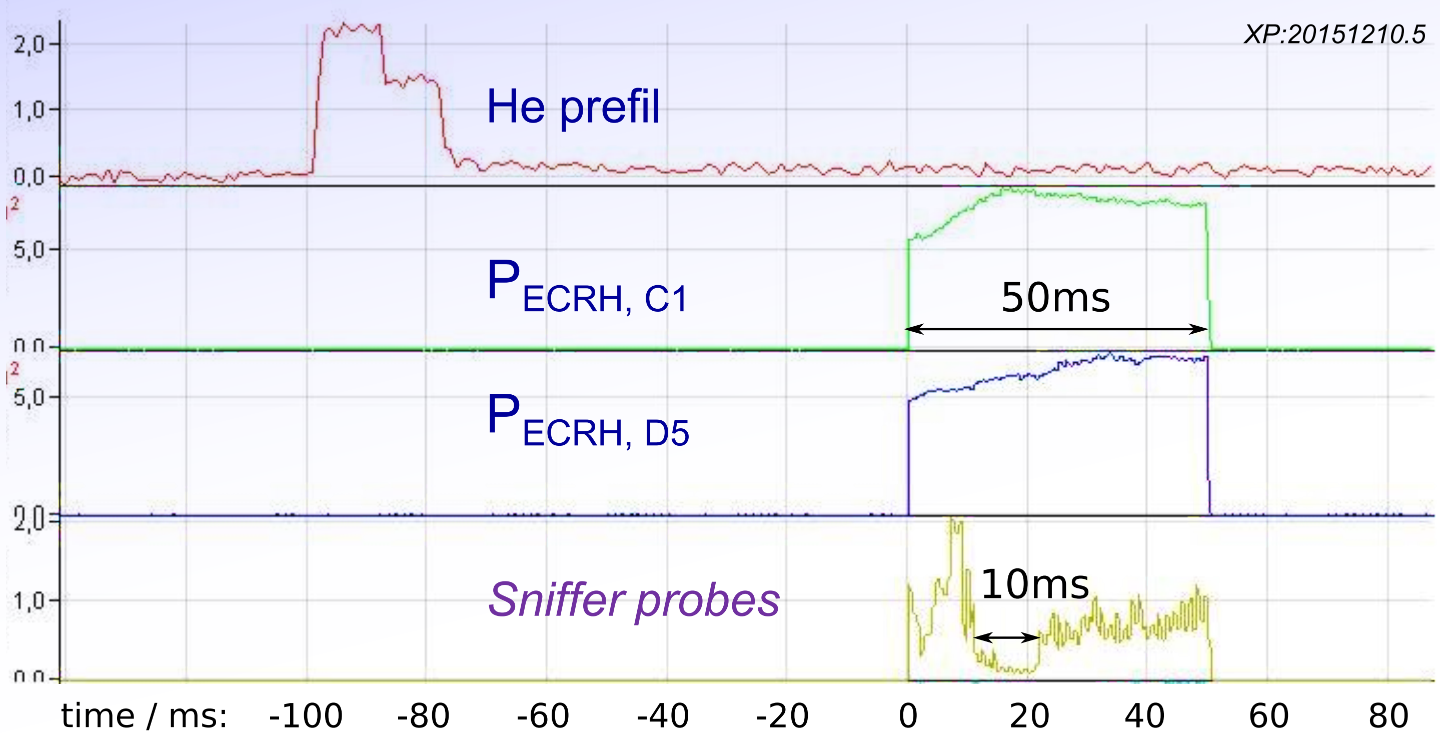
Good spatial resolution: 2mm @ 7m
Variable exposure 10µs to 10s



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

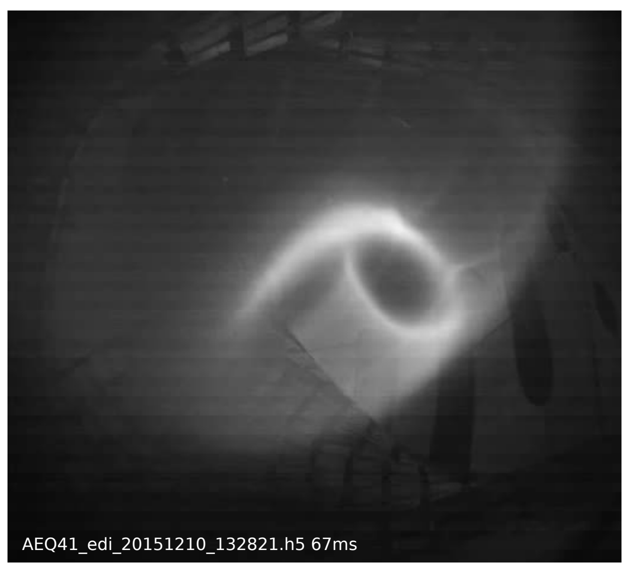
[R.Brakel, M.Krychowiak]

W7X First Plasma



First helium plasma very short:

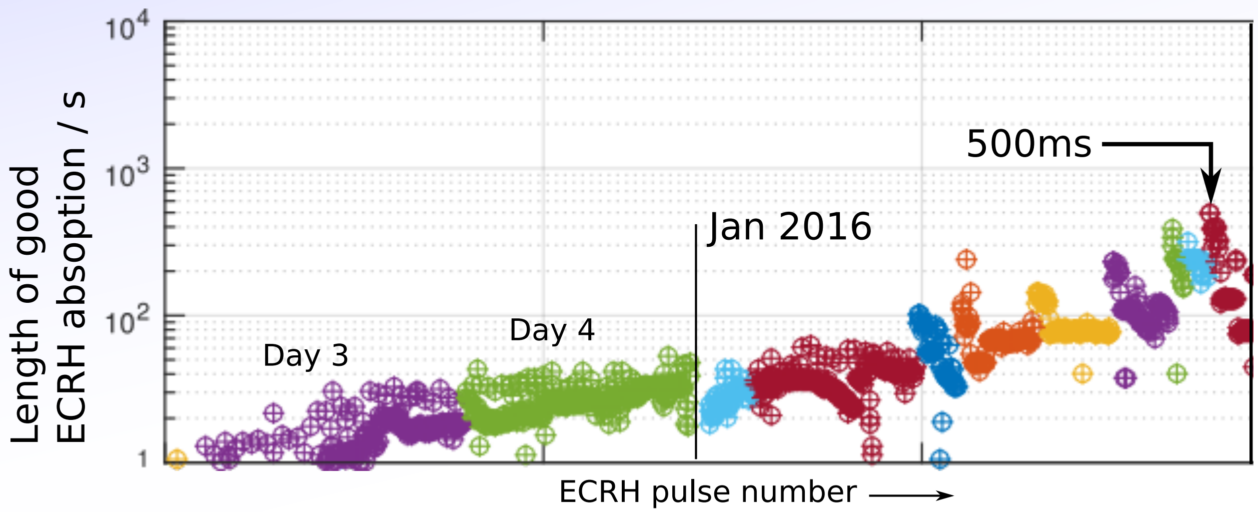
- No preceeding wall conditioning except baking.
- 50ms ECRH heating, but only 10ms absorption.
- Small plasma in vessel centre.
- Pulse length limited by outgassing and radiation.



[T. Wauters]

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.

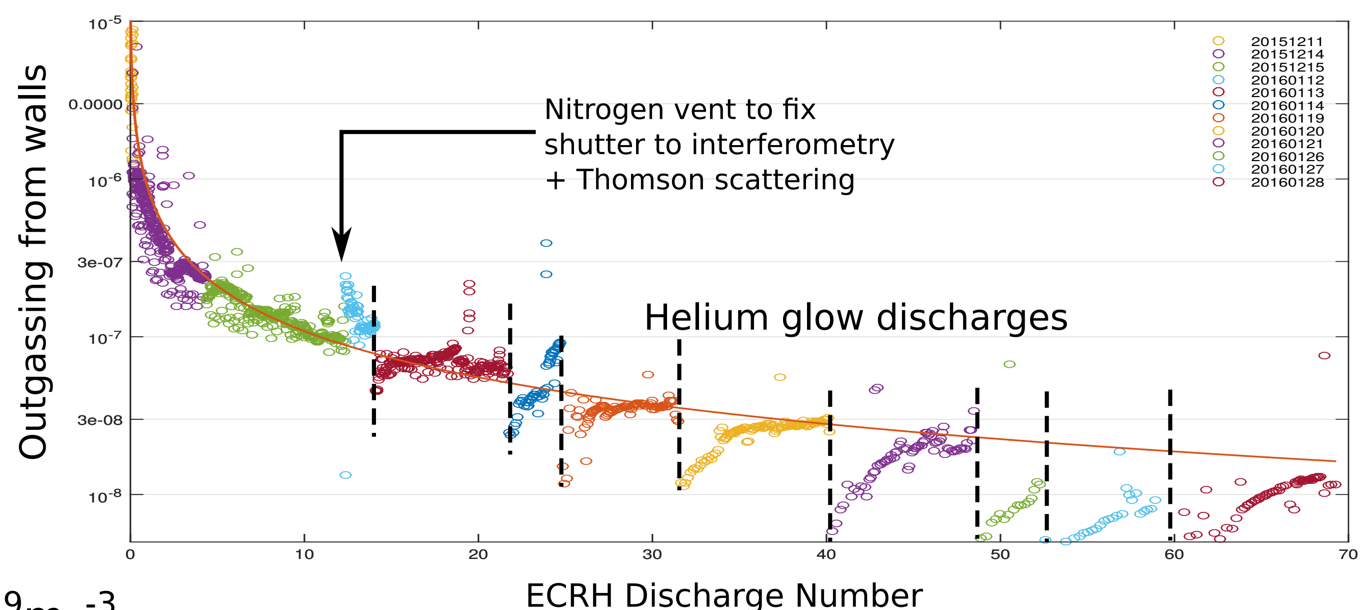


After the Christmas break...

- 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 ~8 keV, T_i ~ 1.5keV, n_e ~ $3x10^{19}m^{-3}$



Start-up: Timeline

2015

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

Dec

☆ 10th Dec 2015: First Helium plasma

ECRH Wall Conditioning

2016

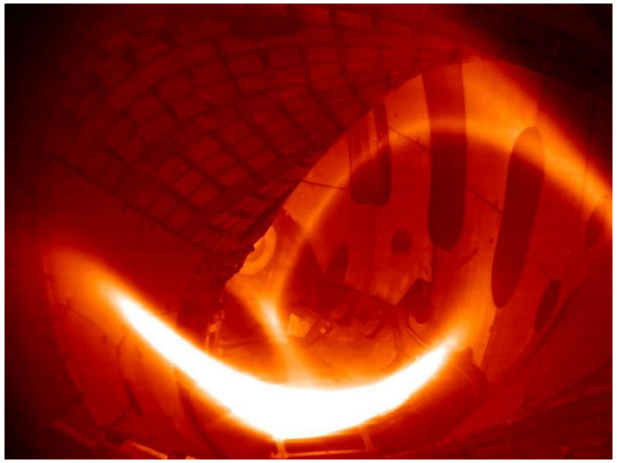
12th Jan: Helium glow discharges available.

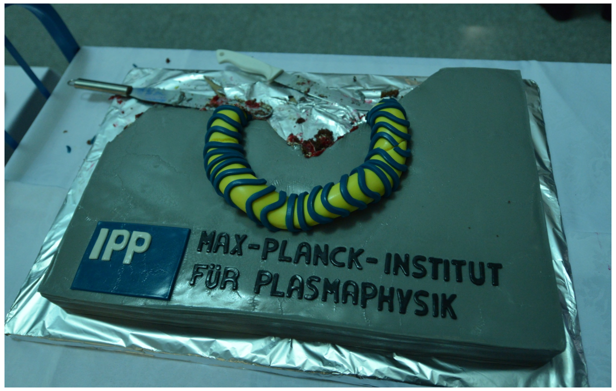
Improved conditioning

Feb

3rd Feb: First H plasma - Visit of Chancellor Merkel, big party, cake!

Mar

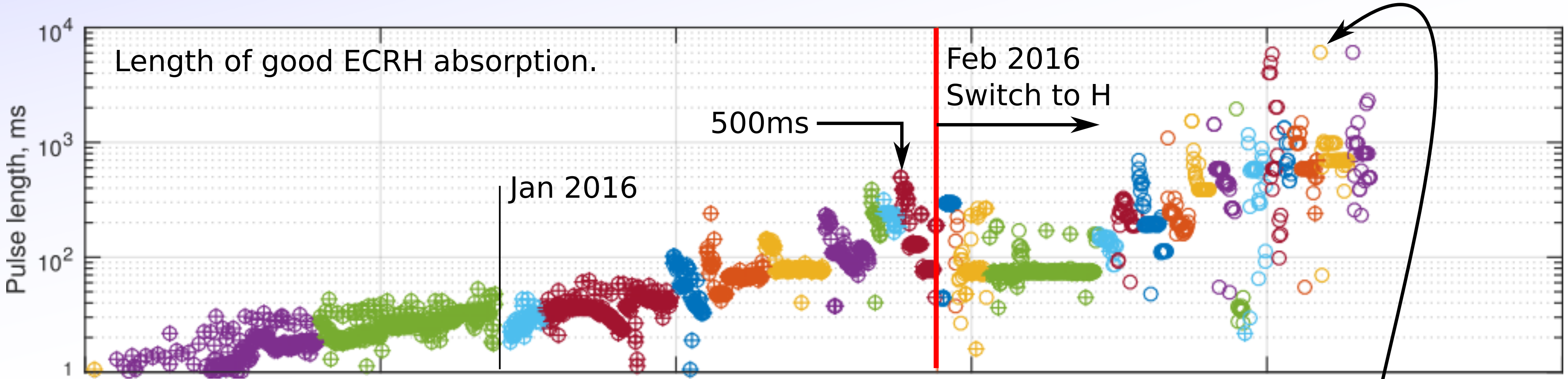


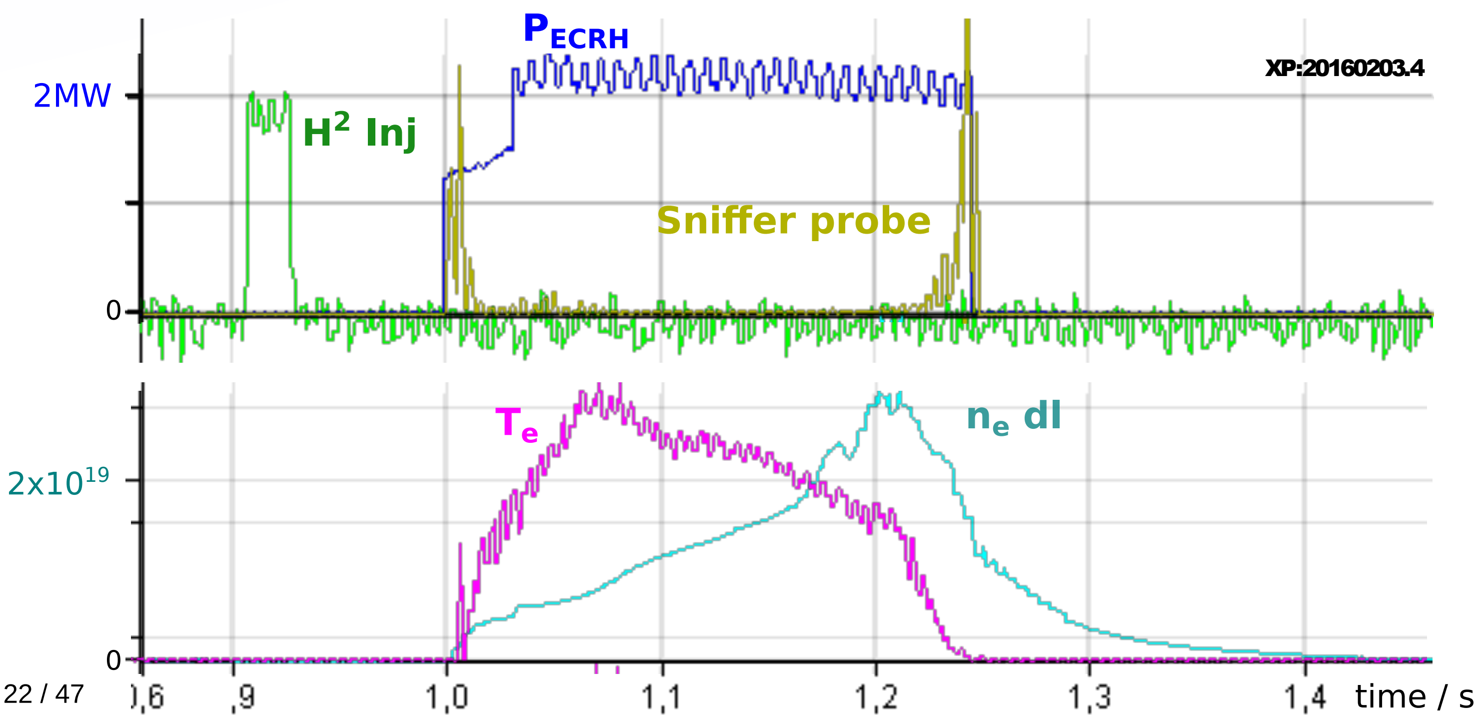


[T. Wauters, R. Brakel]

Start-up: Conditioning: Hydrogen

- Switched to hydrogen as primary fill gas.
- Performance considerably better (after glow discharge) but also deteriorated rapidly during day.
- Helium conditioning discharges could recover some performance.





6 seconds!

OP1.1 Expectation was < 1s

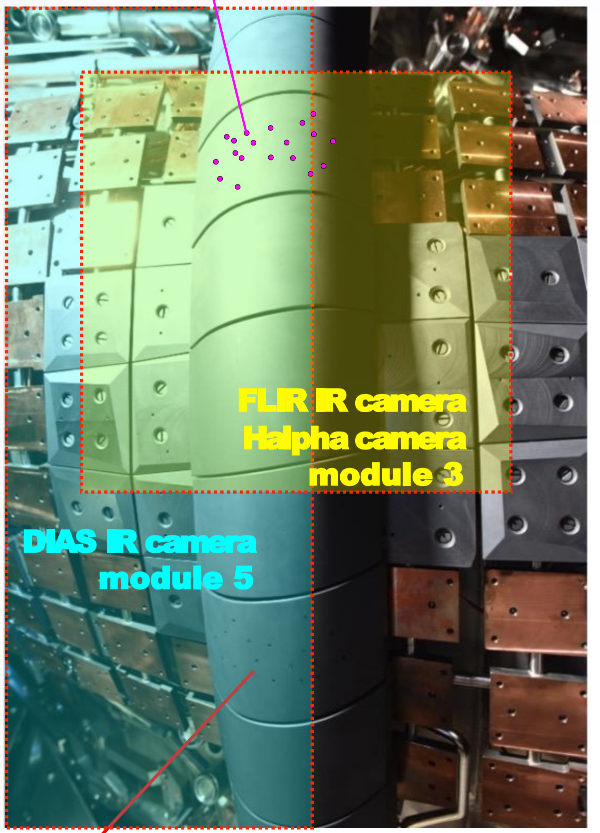
[M. Jakubowski]

Limiter Observation Diagnostics

- Total plasma energy initially limited to 2MJ to avoid damage to limiters.
- Several diagnostics to monitor the limiters:
    - DIAS IR Camera: FIR 8 - 14μm (Module 5)
    - FLIR IR Camera: MIR 3 - 5μm (Module 3)
    - Two Langmuir probe arrays (n_e, T_e, φ)
    + Hα and NIR cameras in all modules
      (For OP1.2 divertor monitor, but can see limiters)

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

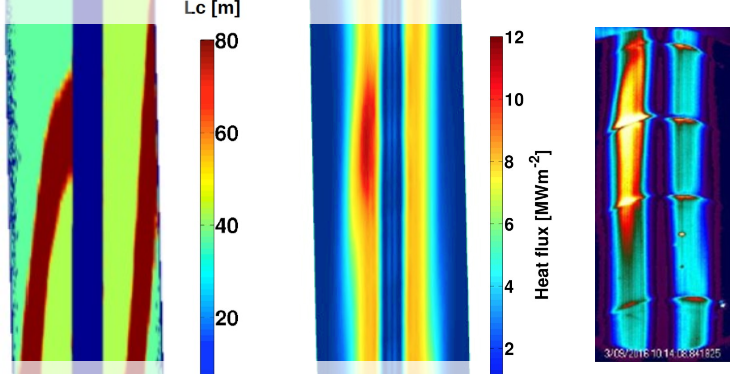
Langmuir probes
module 5



Langmuir probes
module 5

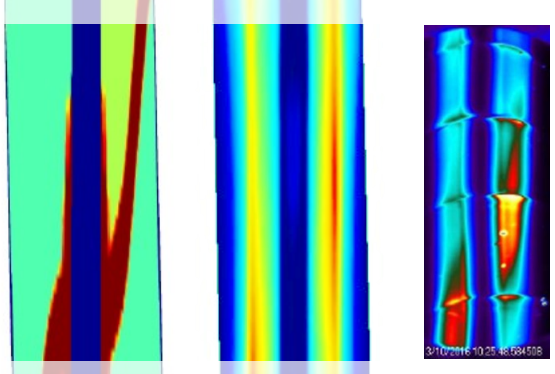
(Later in OP1.1): Power flux patterns to limiters matched qualitatively that predicted from EMC3-EIRENE, including with changes to magnetic configuration:

OP1.1 standard configuration.



Connection length **Predicted heat load** **Measured Temperature (FLIR)**

OP1.1 increased iota.



Connection length **Predicted heat load** **Measured Temperature (FLIR)**

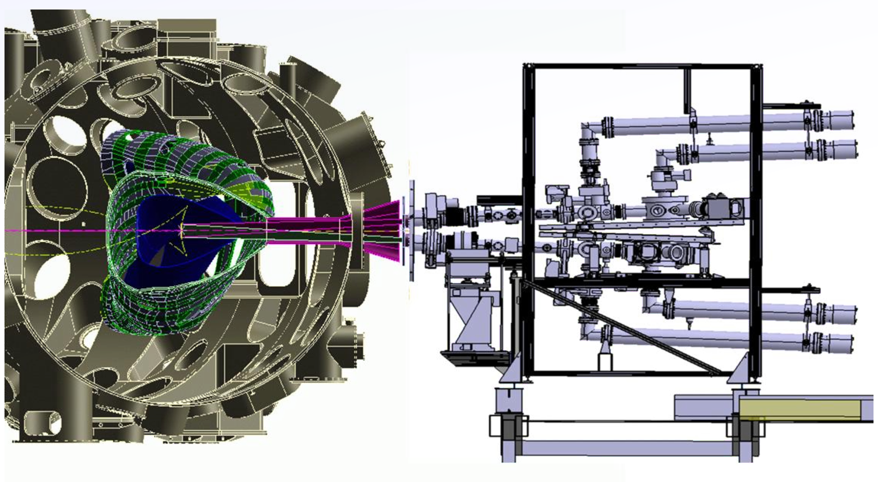
Impurity Content

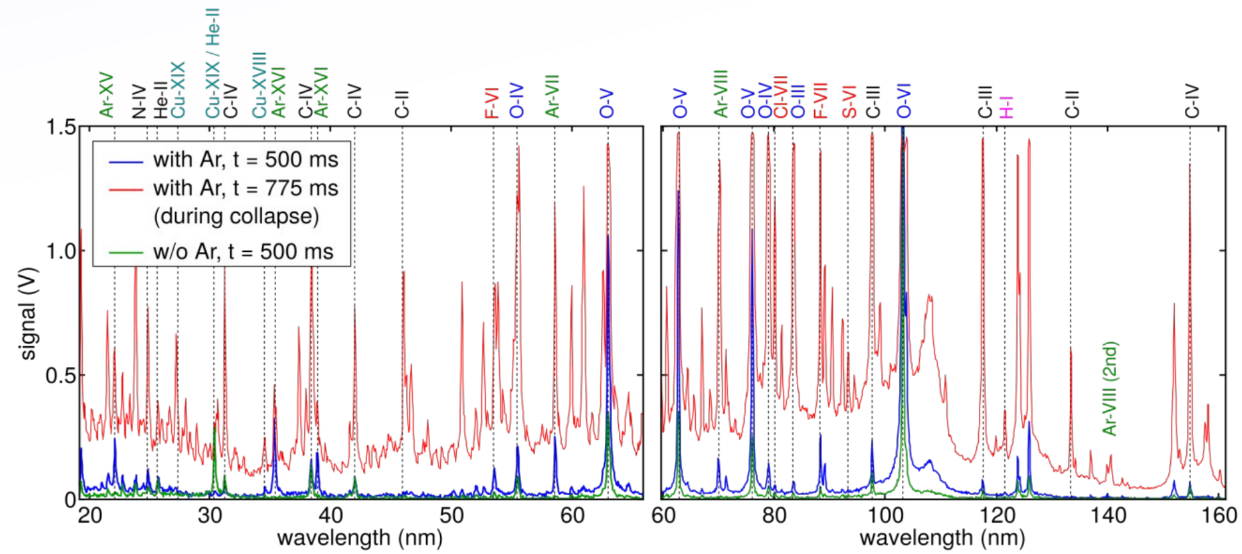
[B. Buttenschön, HEXOS Team, PHA Team]

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

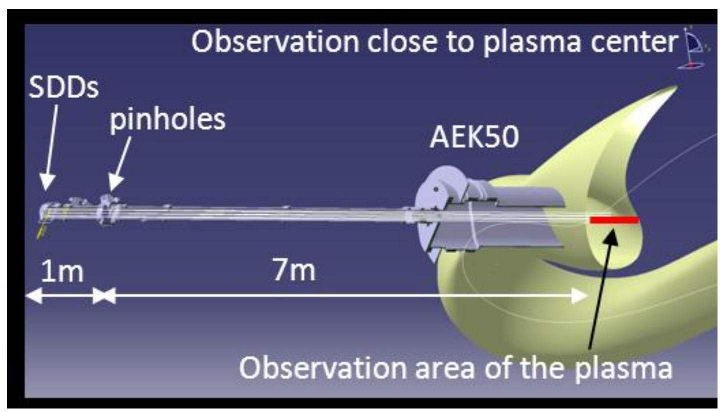
HEXOS VUV-Spectrometer (High Efficiency eXtreme ultraviolet Overview Spectrometer):

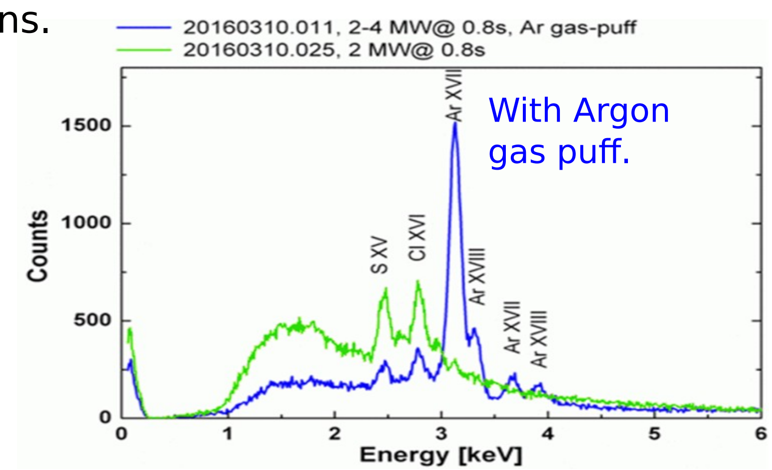
- 2.5 - 160nm (20-160nm available in OP1.1)
- High spectral and temperal resolution.
- Observes the expected Oxygen, Carbon and puffed Nitrogen, Neon, Argon etc
- Also sees Chlorine and Sulfur, but no significant Copper (from unprotected heat shield mounts)





- X-Ray Pulse Height Analysis (PHA): Core medium to high-Z impurity ions.
  - Single line of sight
  - Sulfur and Chlorine detected.

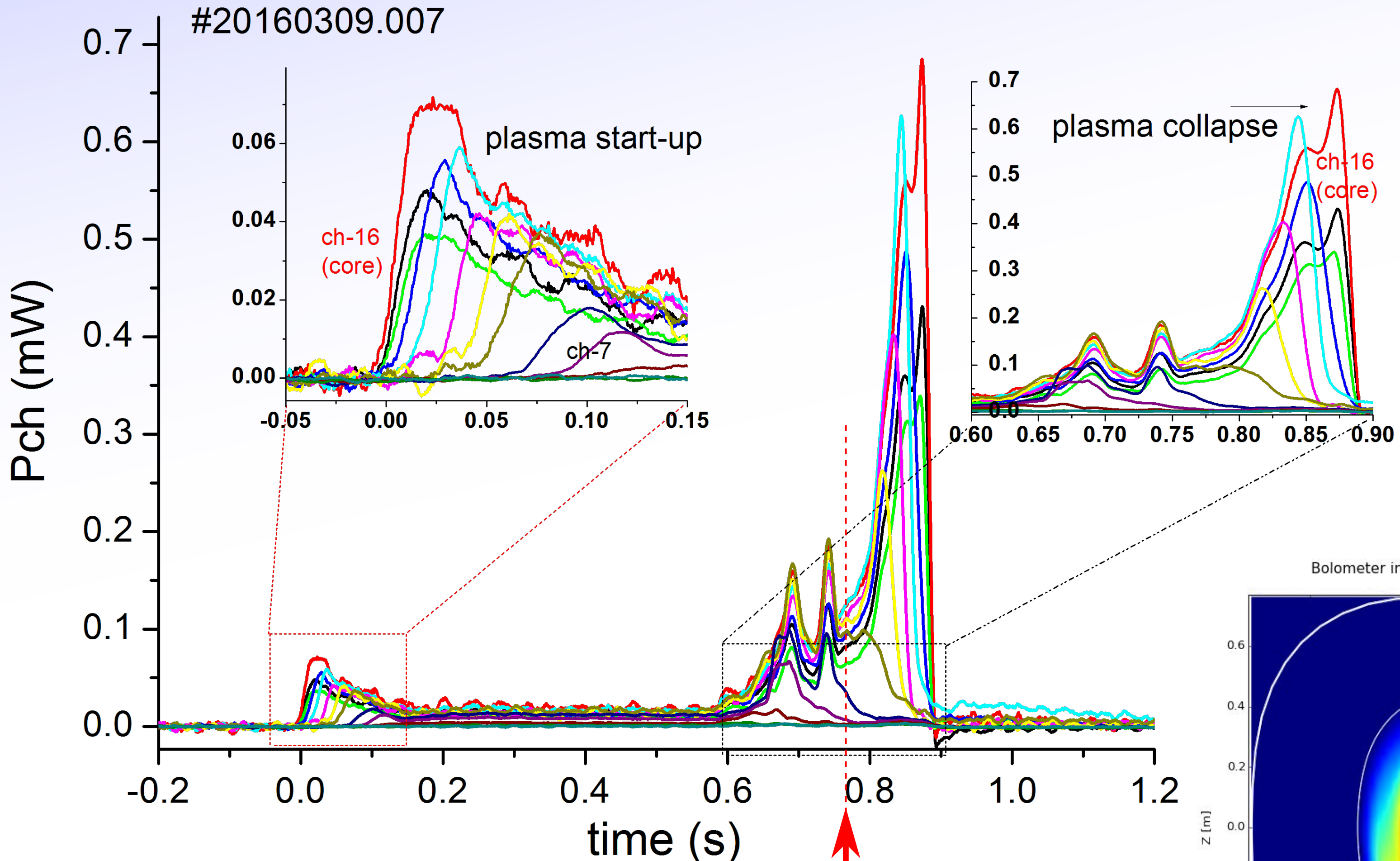




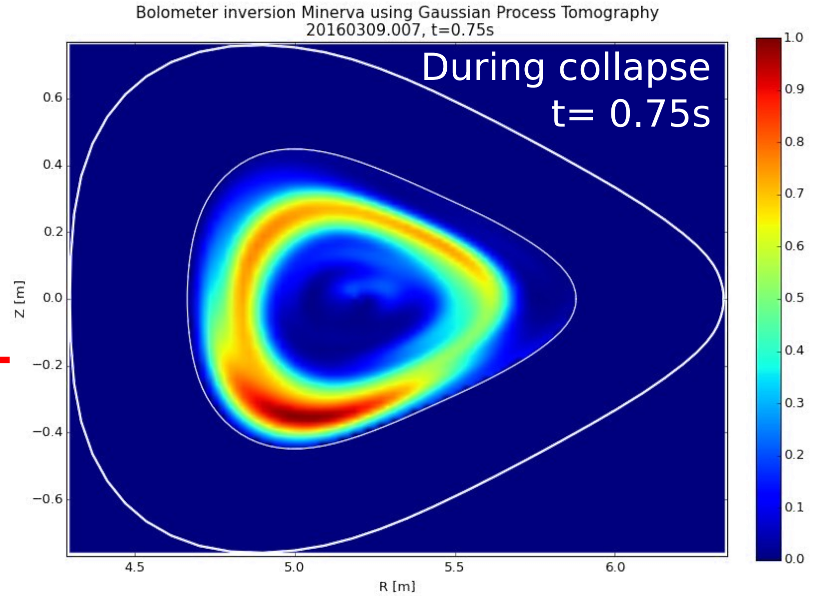
Impurity Content

[B. Buttenschön, D. Zhang
J. Svensson]

- 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.

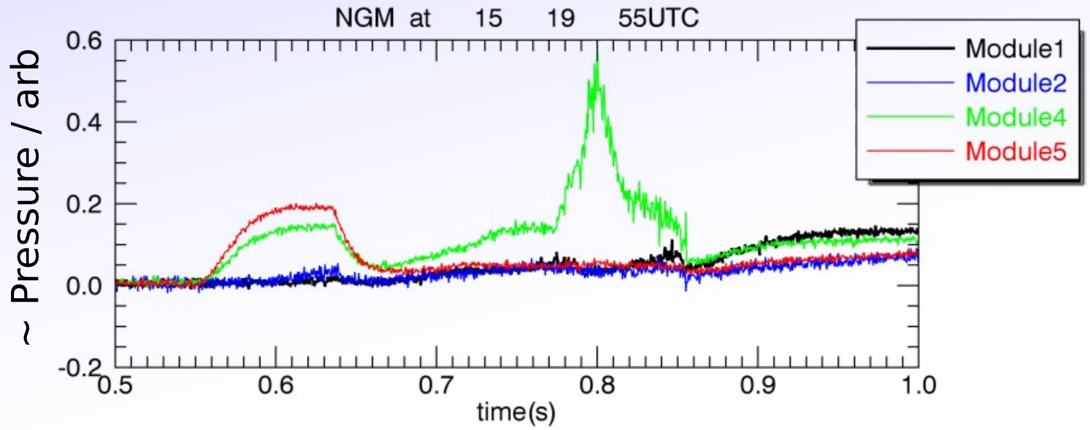


Bayesian Gaussian Process Tomography
[Minerva]

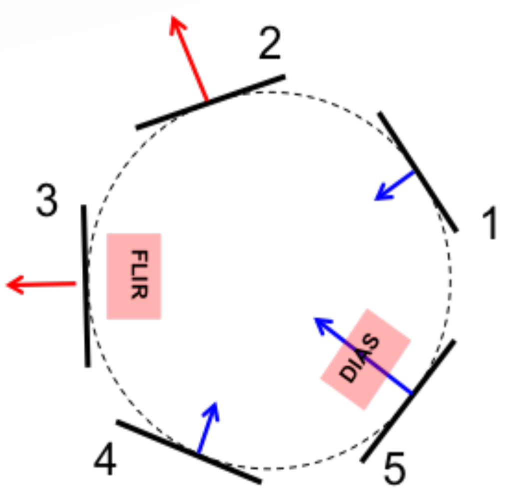
(A)symmetrisation: outgassing

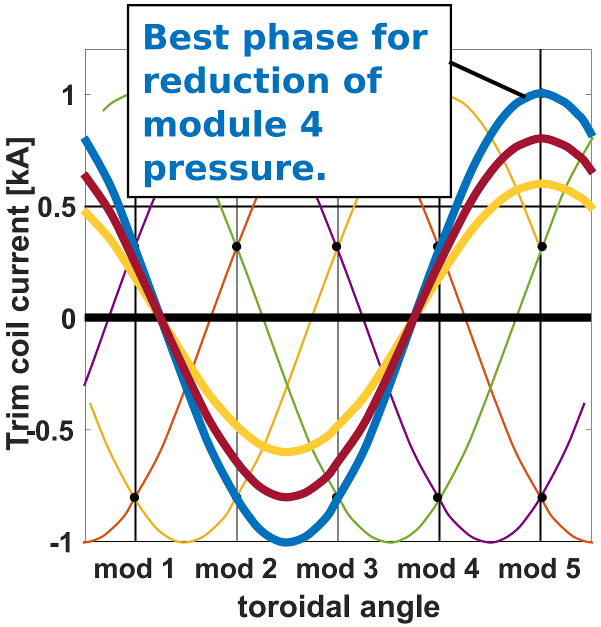
[U. Wenzel, M.Jakubowski, G.Wurden, S.Lazerson]

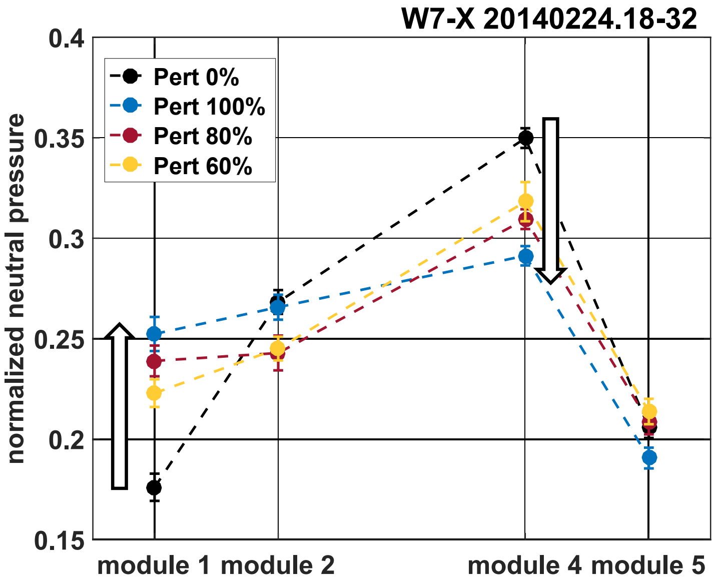
- Neutral gas manometers installed in each module: 1kHz continuous data acquisition.
- High pressure event seen in module 4, often limiting discharge length.



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





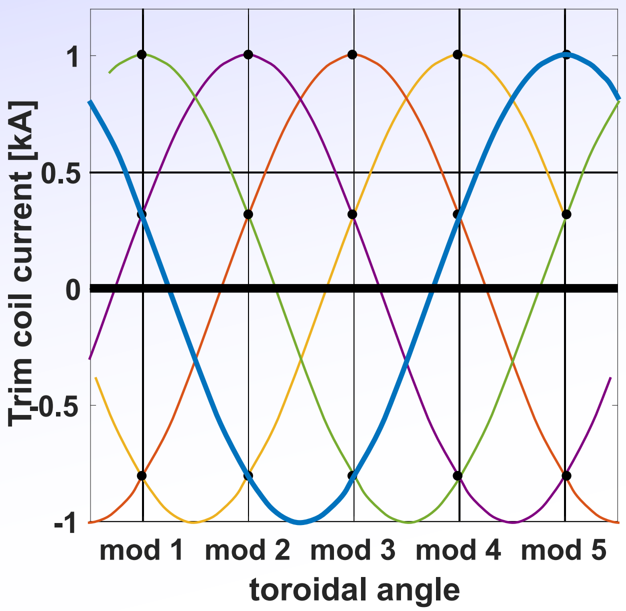


Best symmetrised at 1kA, but outgassing much higher. Lowest total outgassing at 60% amplitude.

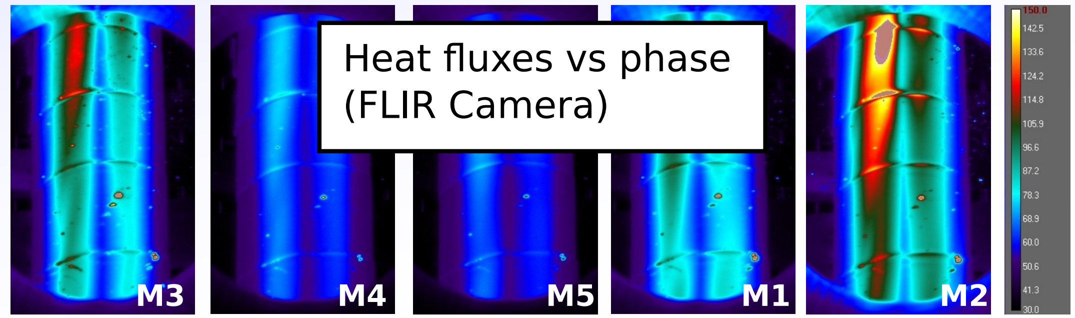
(A)symmetrisation

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

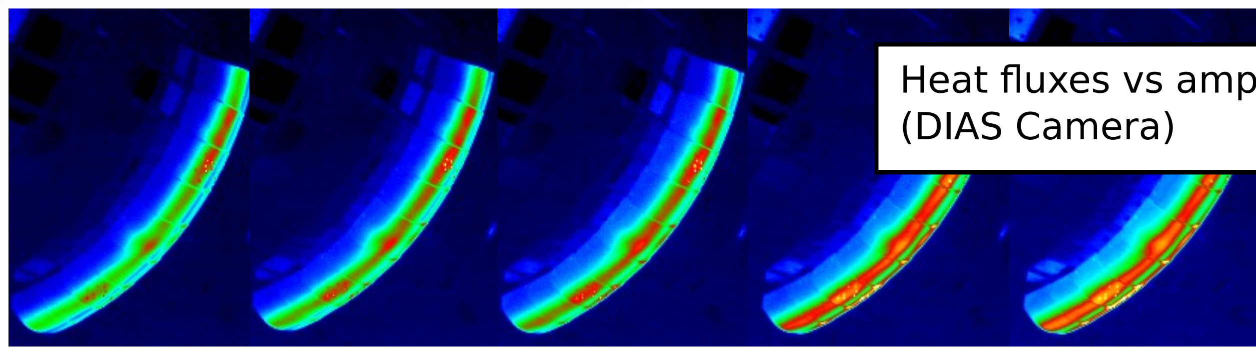
Other edge experiments using trim coils for assymetrisation:



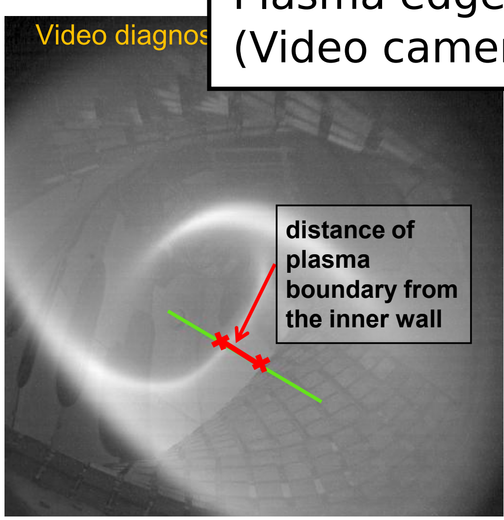
Heat fluxes vs phase (FLIR Camera)

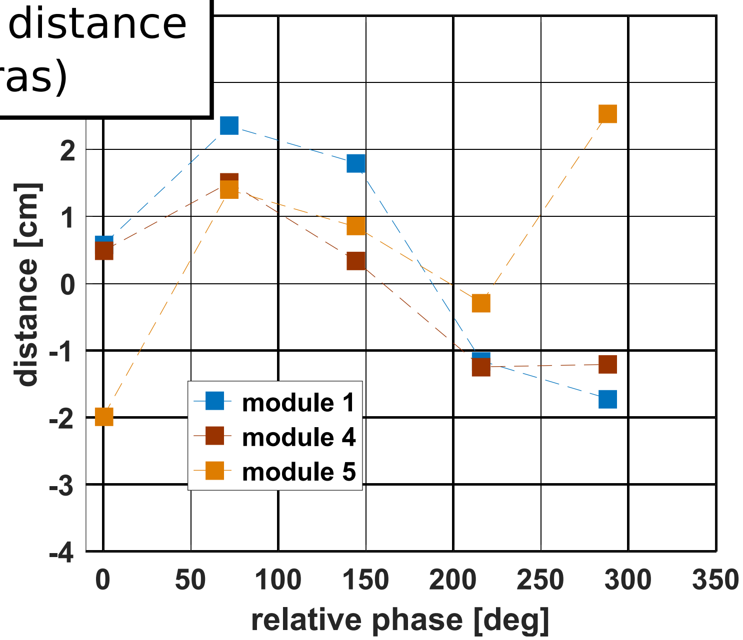


Heat fluxes vs amplitude (DIAS Camera)

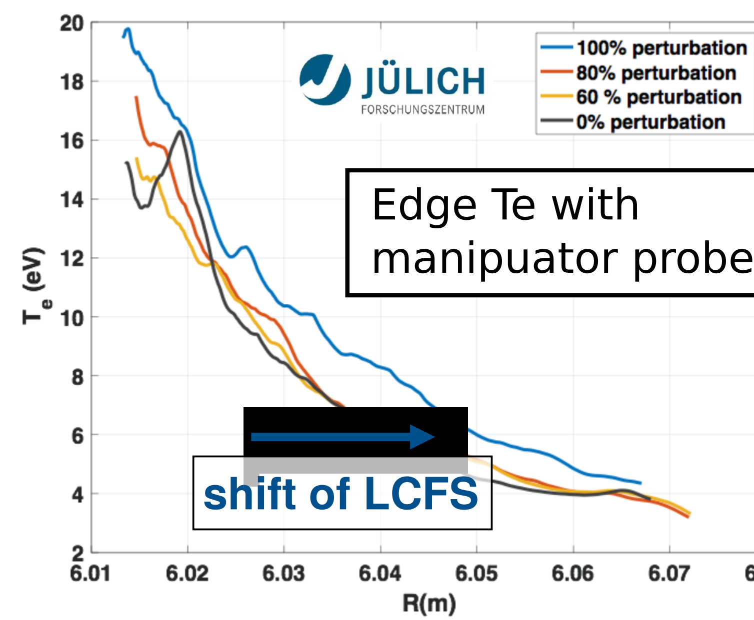


Plasma edge distance (Video cameras)





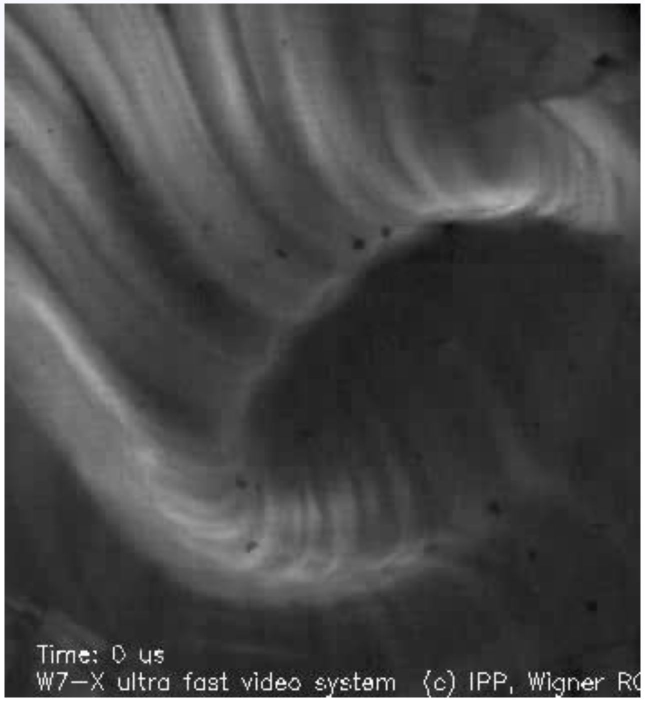
Edge Te with manipuator probe

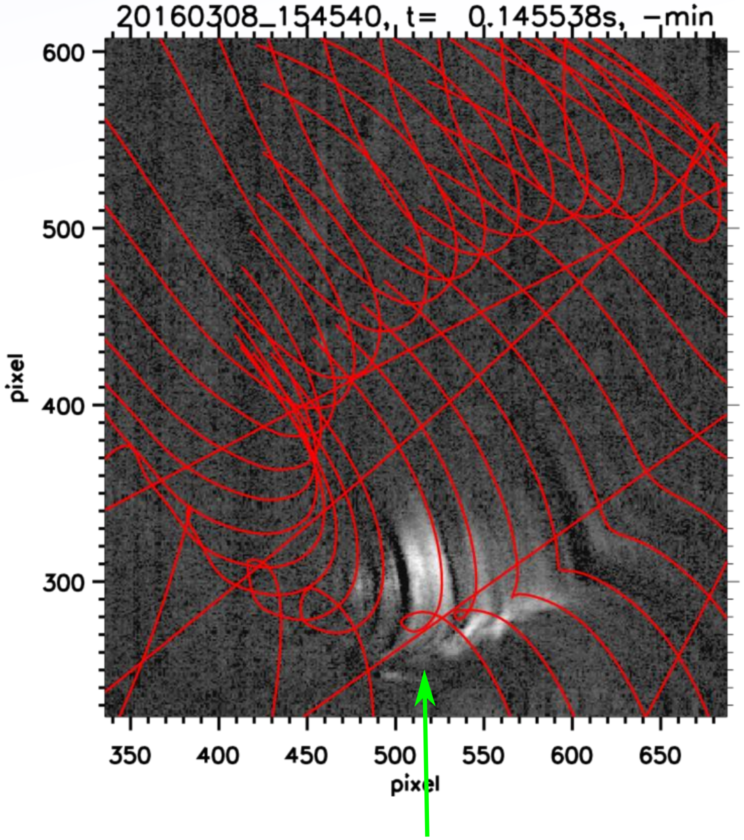


[G. Kocsis, C.Biedermann]

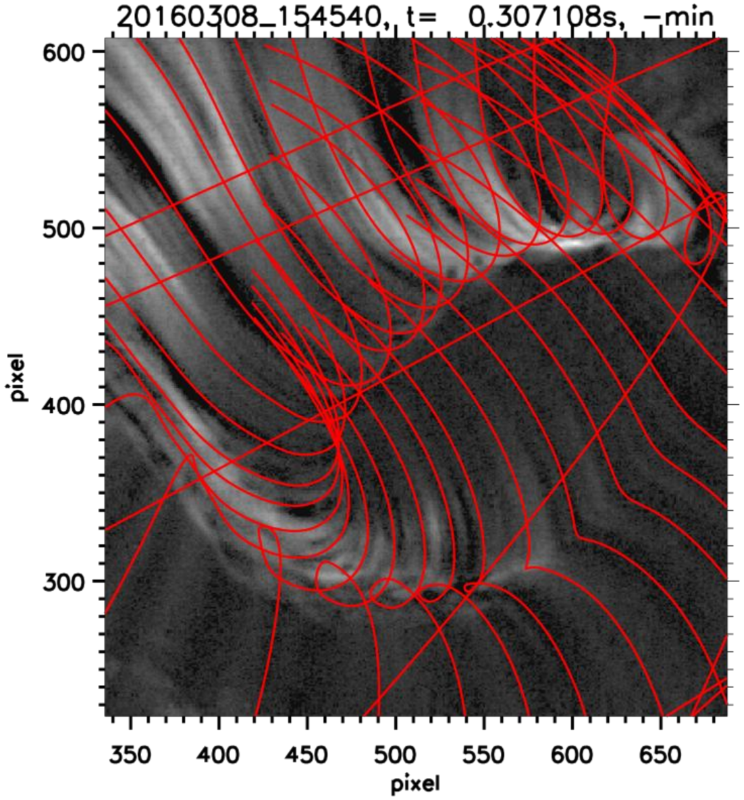
Edge Filaments

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.





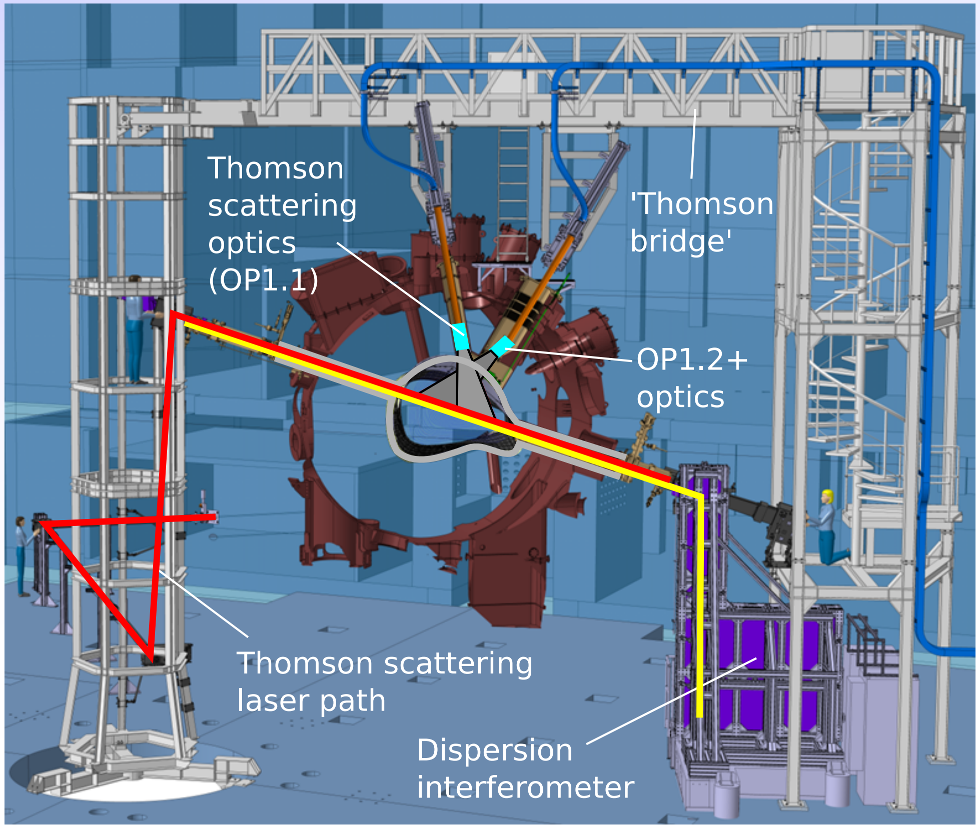
Strong gas puffing



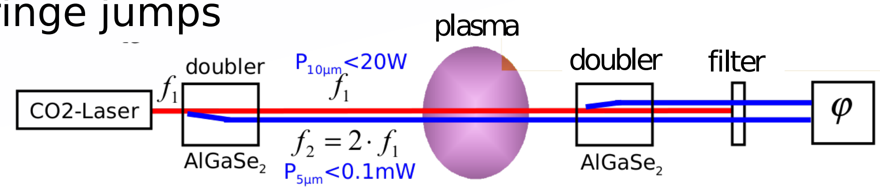
Strong wall outgassing

Electron Kinetic Diagnostics: n_e

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

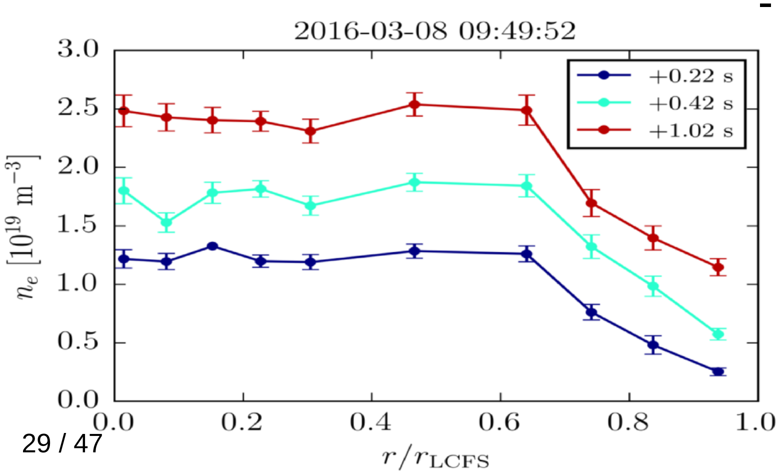


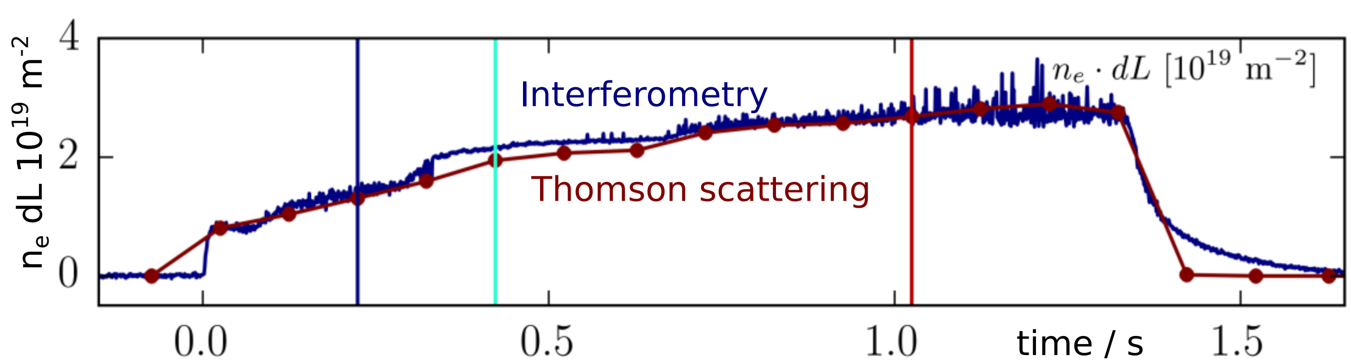
Single channel interferometer:
- CO^2 CW Laser
- Steady state density control (30min)
- Dispersion interferometer:
  - Two frequencies on same path
  - Physical path changes cancel (to first order)
  - No fringe jumps



Thomson Scattering (OP1.1):
- 2J Nd:YAG laser: 1064nm, 100ms rep rate
- 5 spectral channels.
- 10 spatial points, 3-4cm resolution.
- Design range $n_e = 10^{19} - 10^{20}$, 10eV < T_e < 10keV
- Bayesian inference of $P(T_e, n_e)$ [Minerva]

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

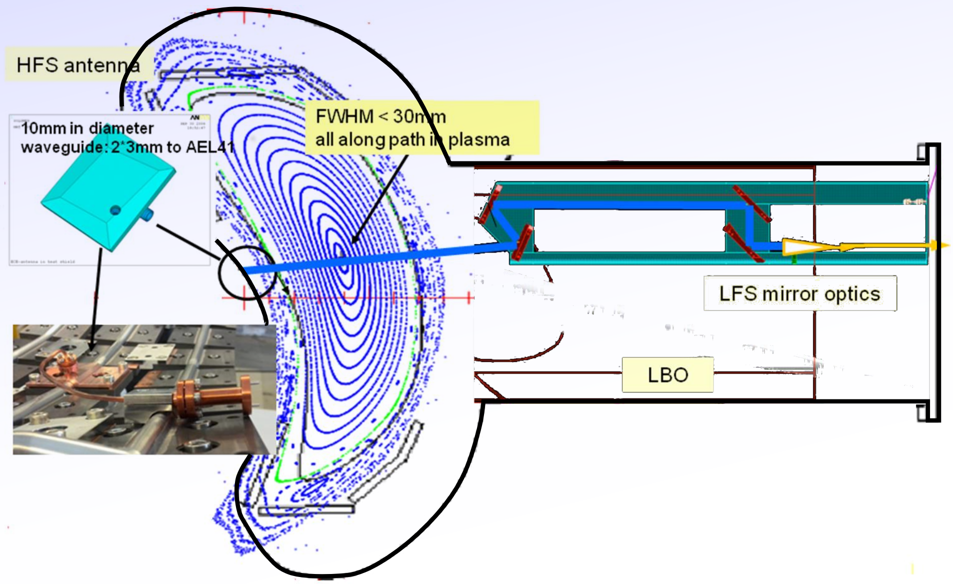




Electron Kinetic Diagnostics: T_e

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

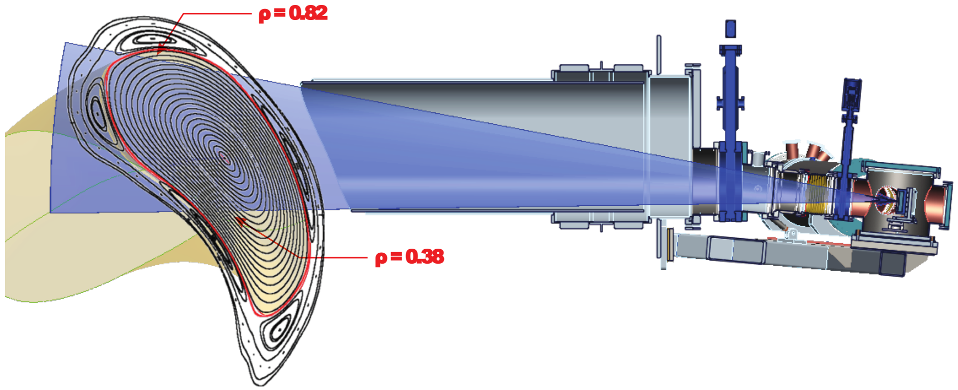
Electron Cyclotron Emission:



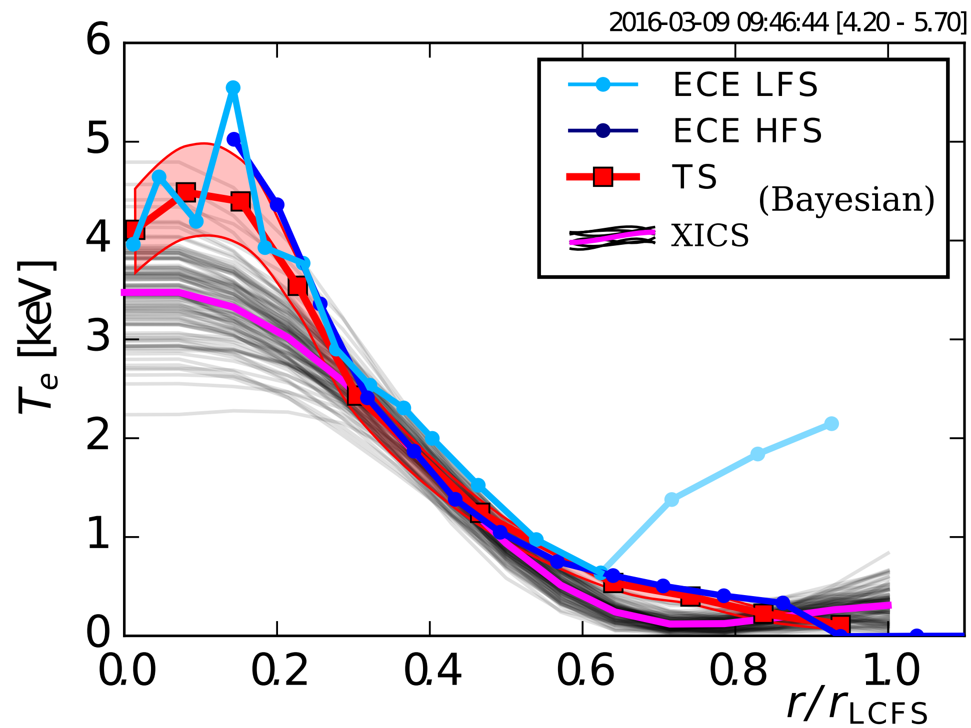
- Low and high field side antennae.
- 32 primary channels + 16 for high resolution 'zoom'
- 126-161 GHz
- Temporal resolution down to 0.5μs
- Spatial resolution ~ 1cm
- Absolute T_e calibration.

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);



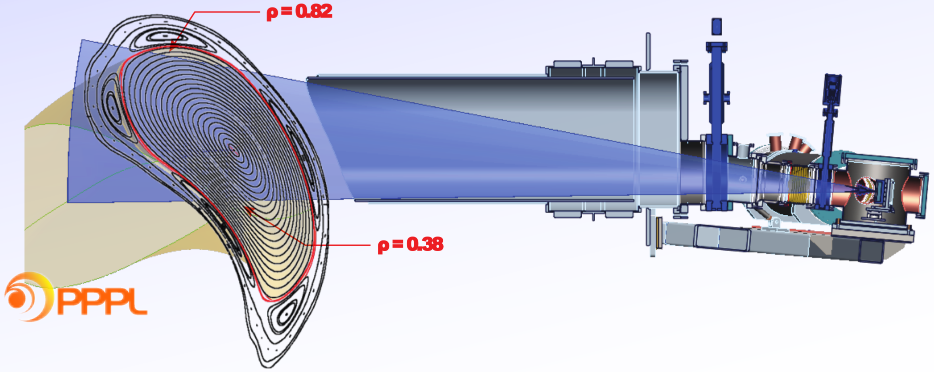
Line integrals of T_i, T_e, v_θ and n_{Ar} from observation of Argon emission lines.



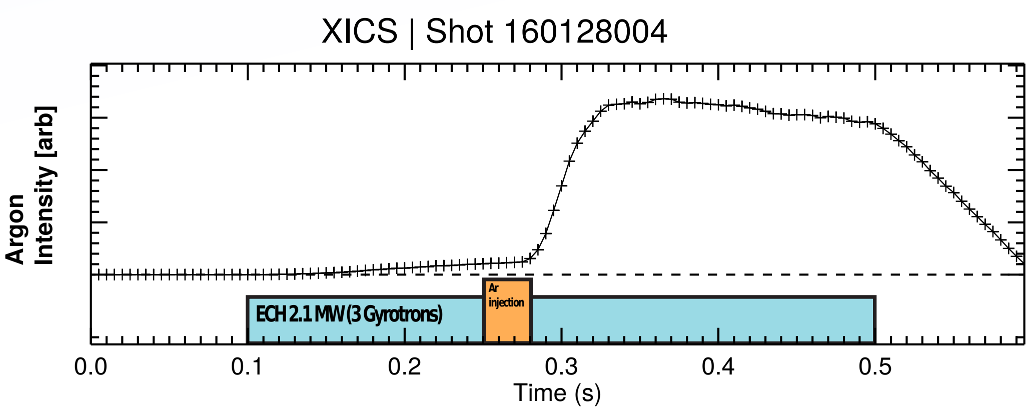
XICS: Argon Transport

[N.Pablant, A.Langenberg, P Valson, P. Traverso]

X-Ray Crystal Imaging Spectrometer (XICS);

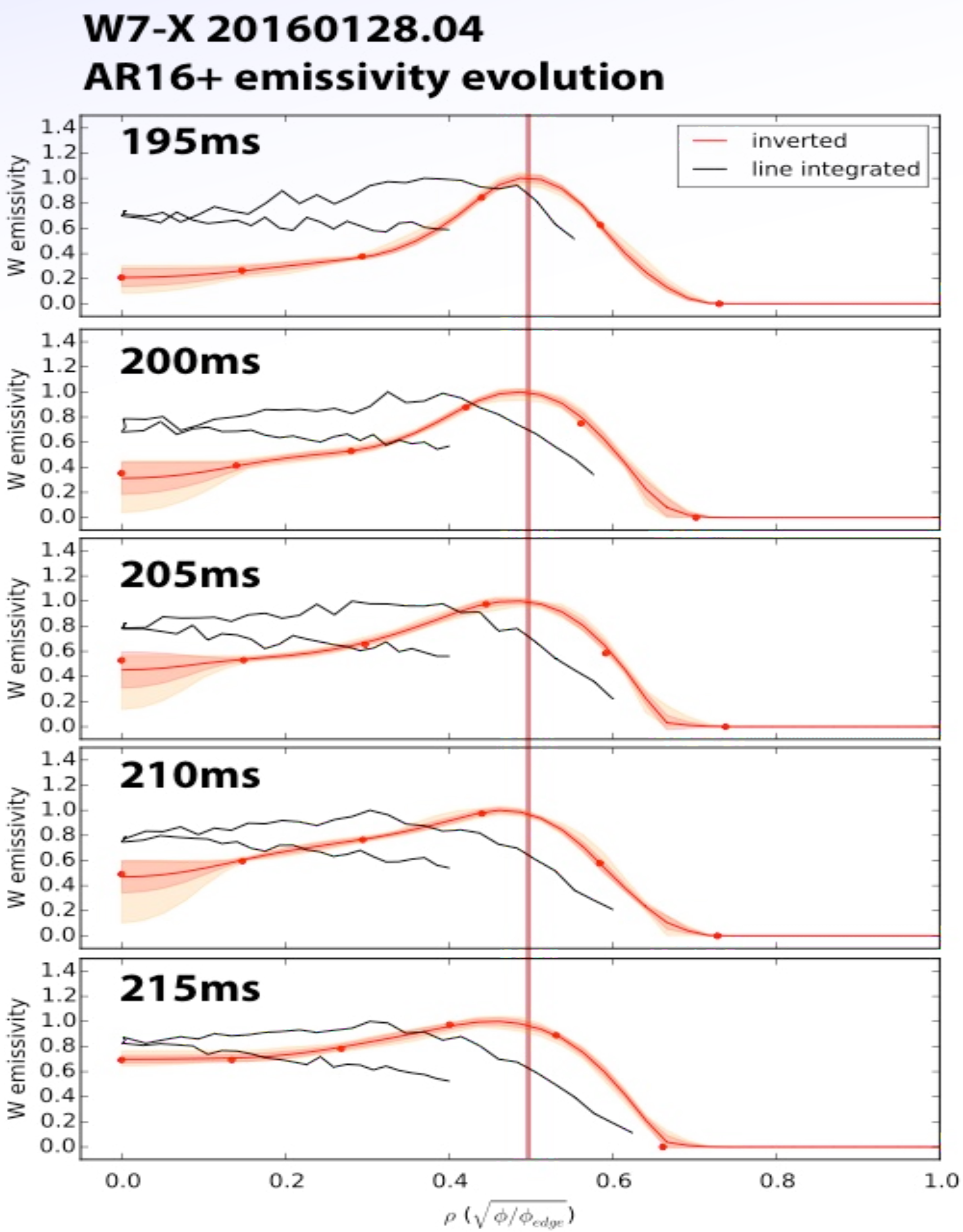


Line integrals of T_i, T_e, v_θ and n_{Ar} from observation of Argon emission lines.



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

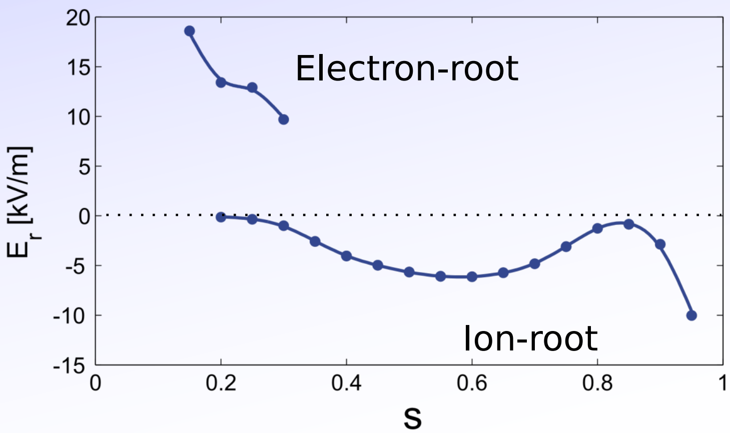
XICS sees evolution of Argon 16+ profile and transport of Argon into the core.
- Consistent with HEXOS Argon decay times.

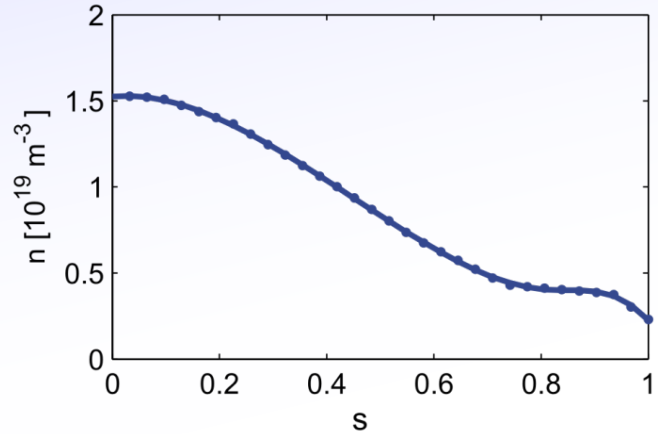


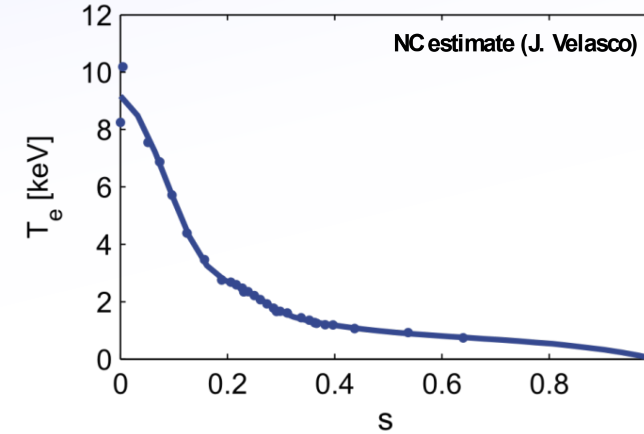
[A. Dinklage, A. Alonso]

Core Electron Root Confinement (CERC)

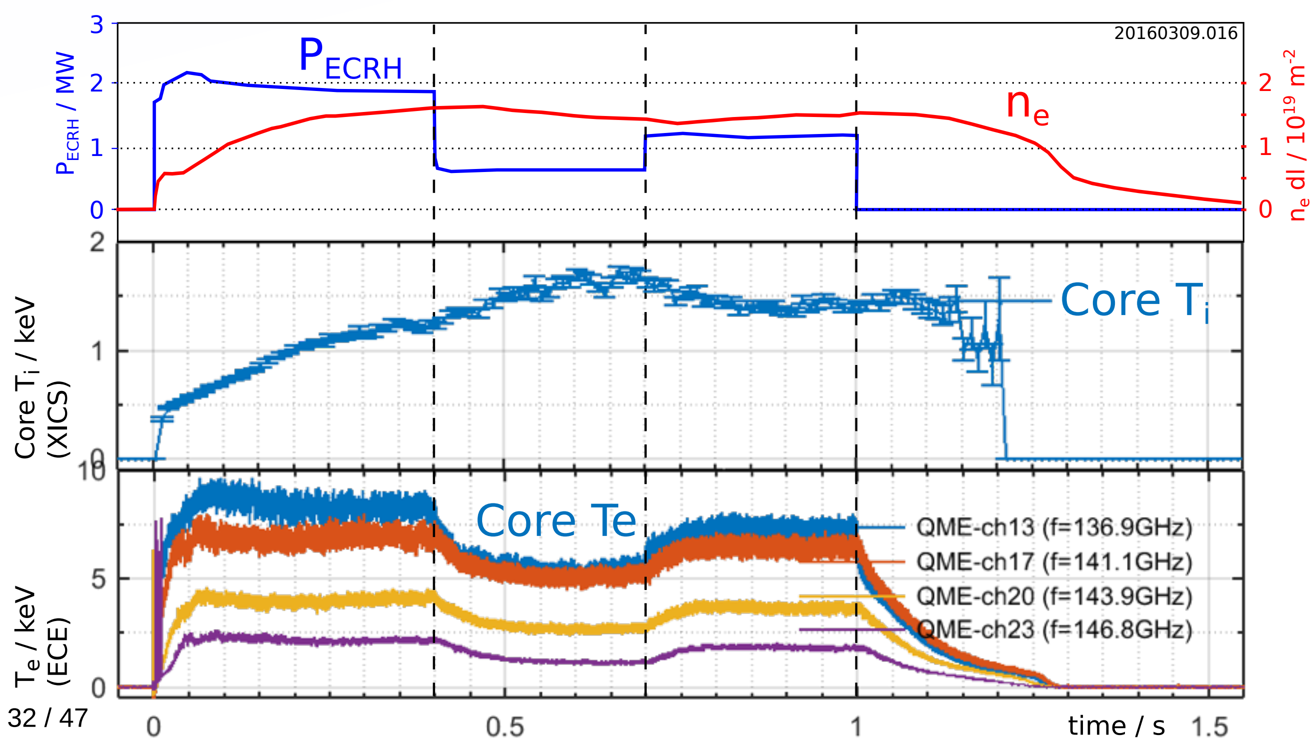
- Confinement regime with +ve Er in core, associated with highly peaked Te profile.

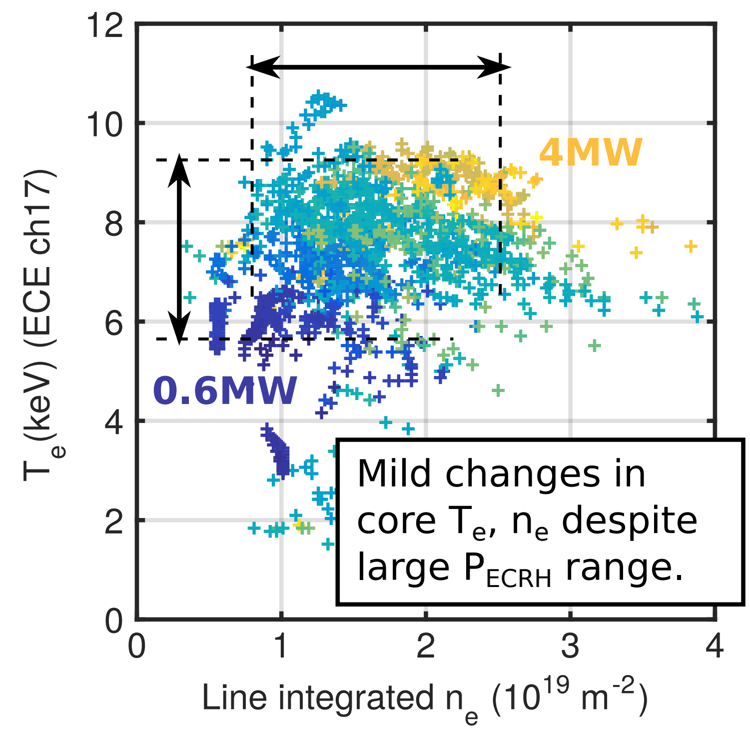






- All OP1.1 plasmas investigated have this CERC.
- Experiments to explore power and density ranges to see extent.

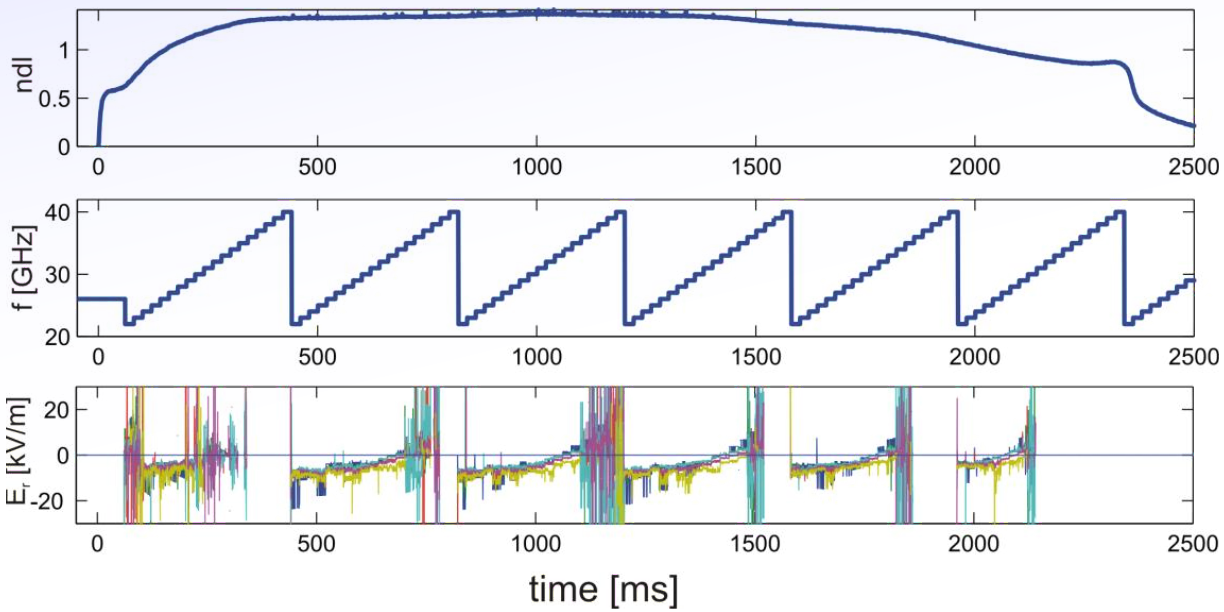


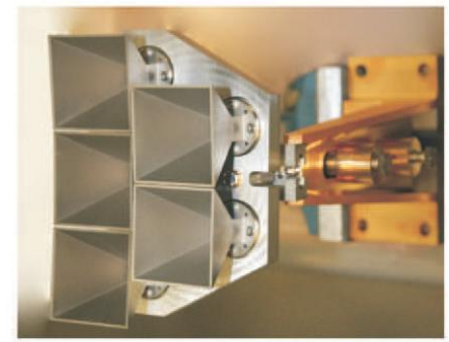


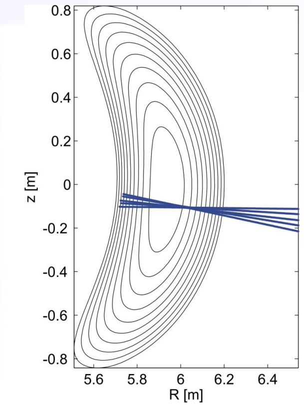
Reflectometry: E_r measurements

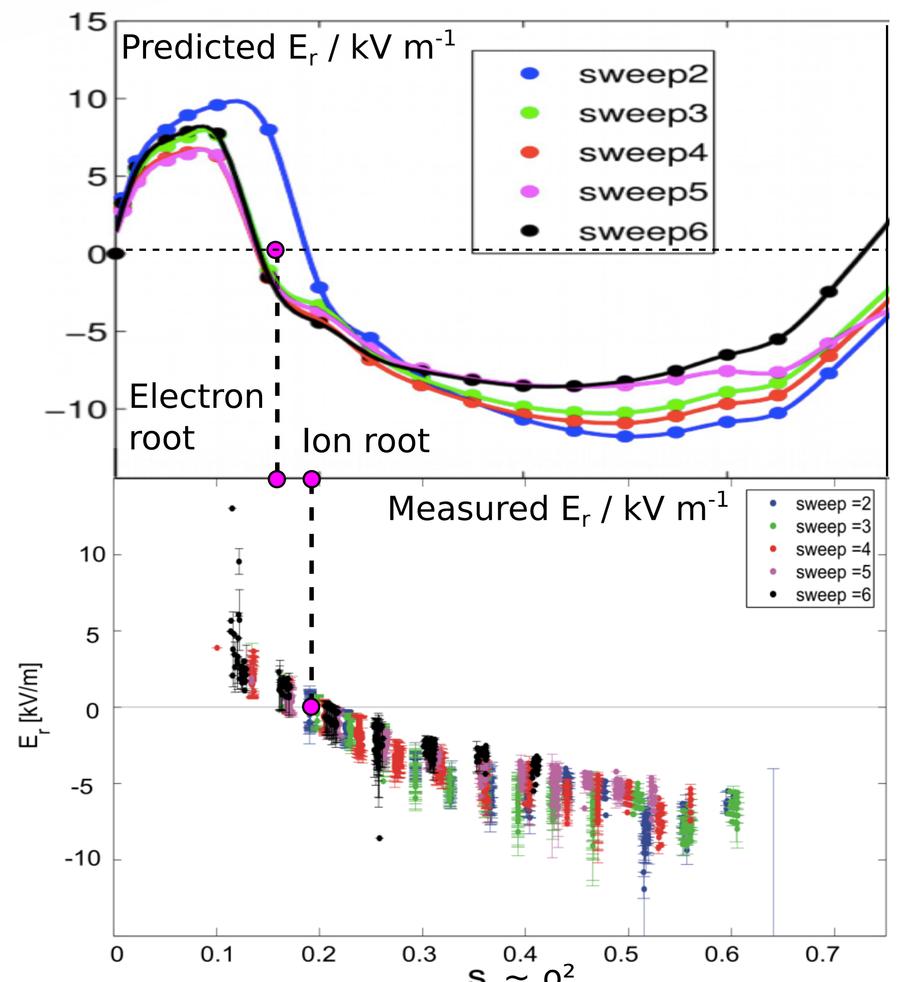
[T. Windisch, A. Krämer-Flecken, J. L. Velasco]

Poloidal correlation reflectometer:
- Five poloidally separated microwave antennae.
- Doppler velocity of density fluctuations at the cut-off.
- Frequency hopping for frequency/position scan.







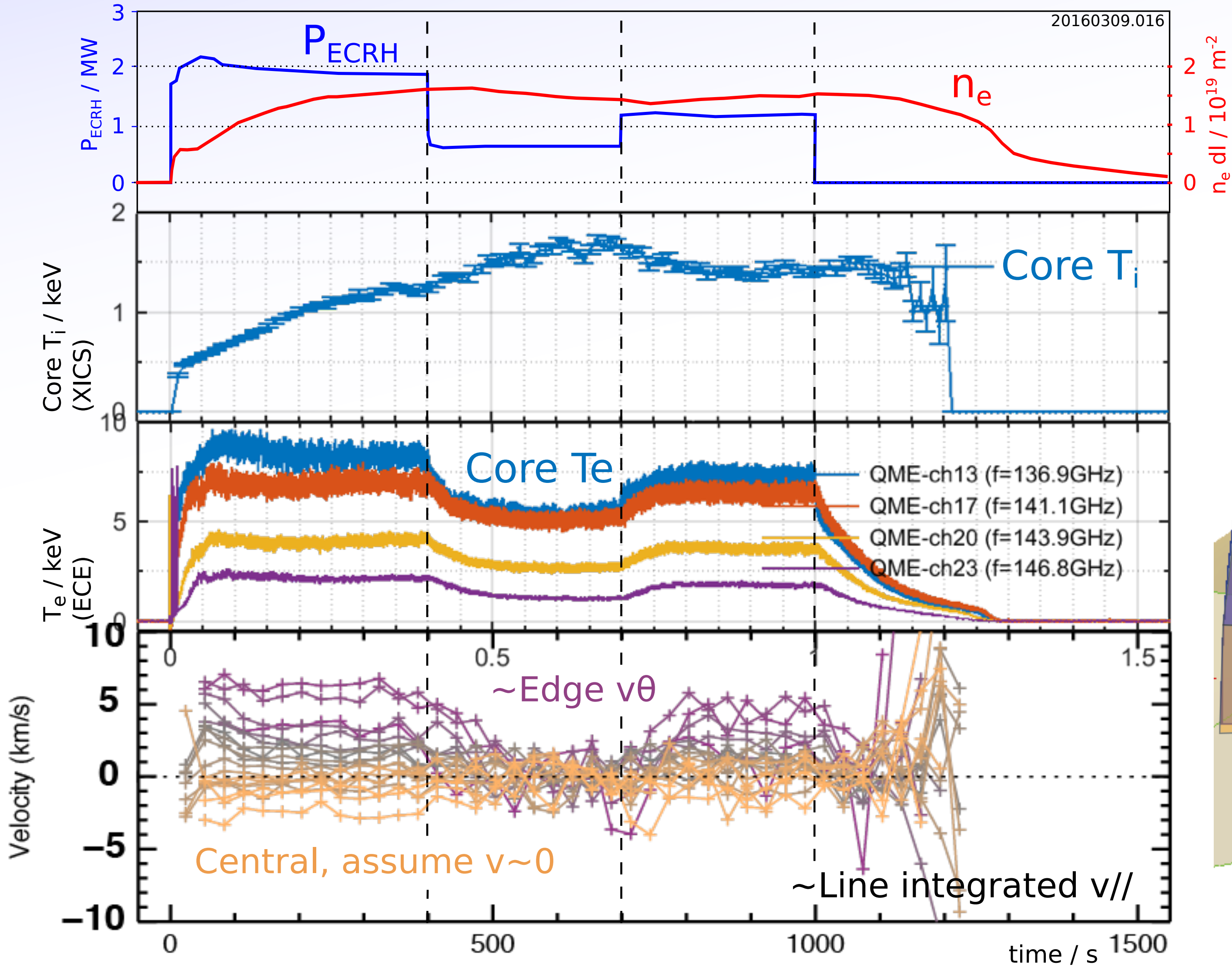


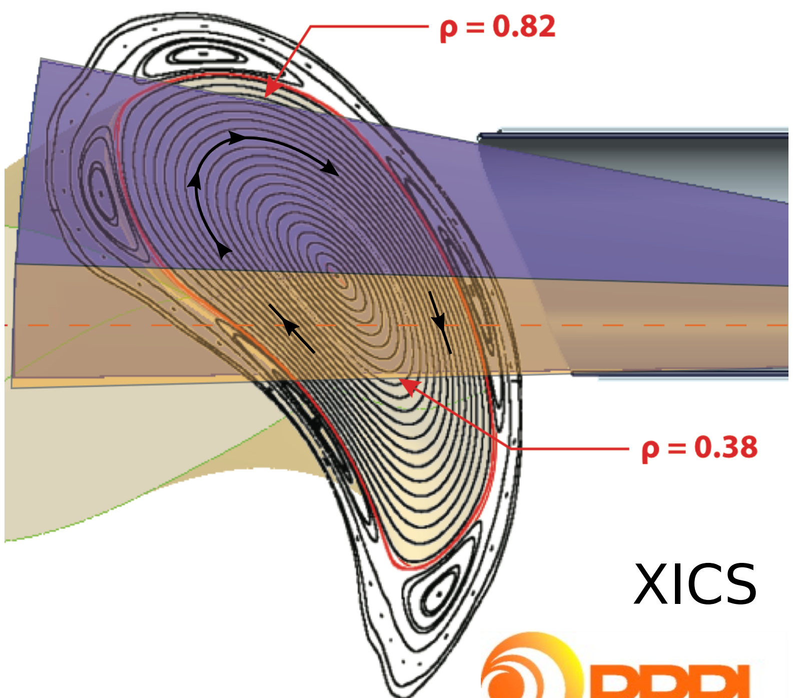
Measured Er comparison with neoclassical predictions:
- Core electron root with transition to iron root at similar radial position.
- No change seen in $E_r(s=0.5)$ for CERC discharges.

Core Electron Root Confinement (CERC)

[N. Pablant, A. Langenberg, A. Dinklage, A. Alonso]

- Preliminary analysis of XICS data does show dependence of vθ (Er) on input power.
- Analysis on-going.

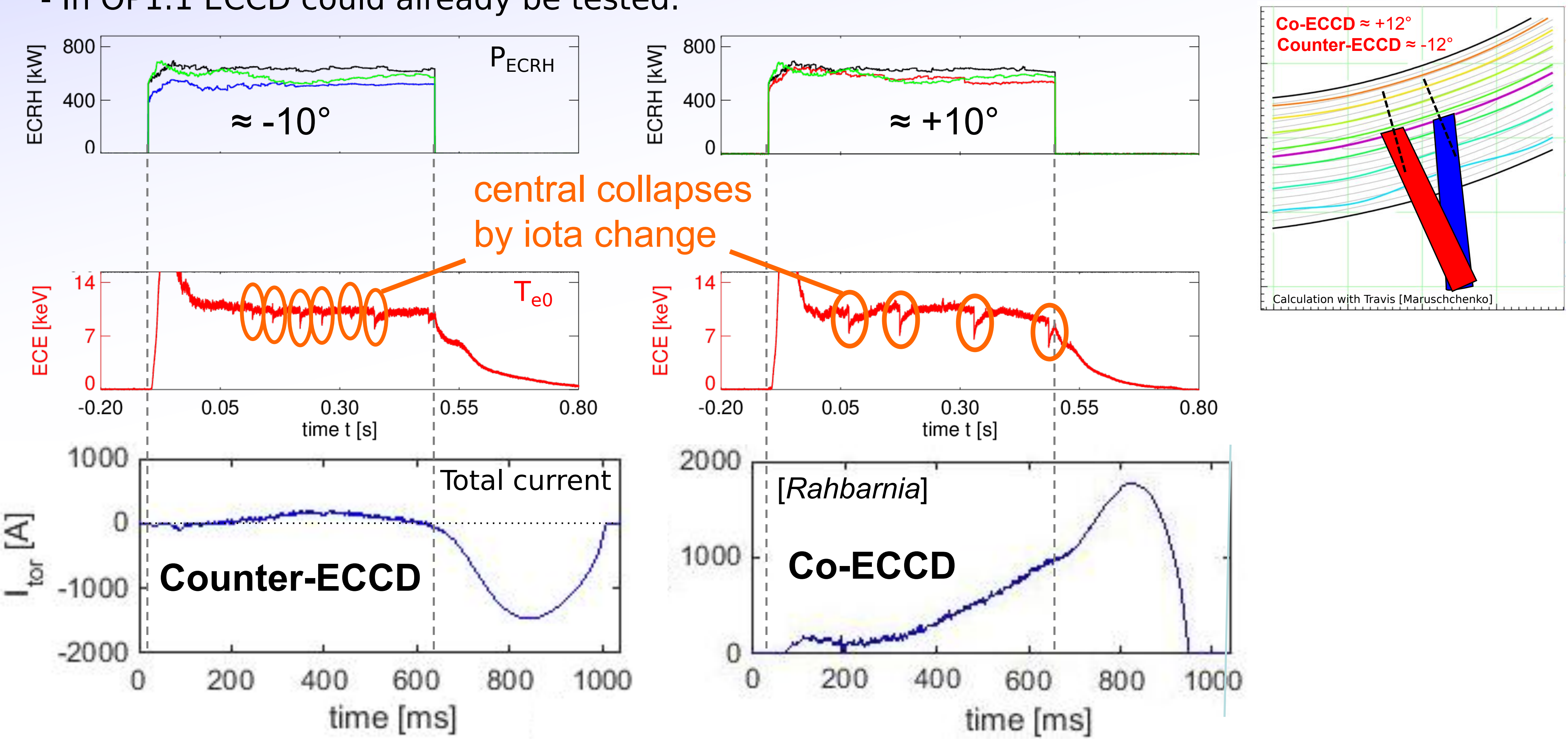




[T. Stange]

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.



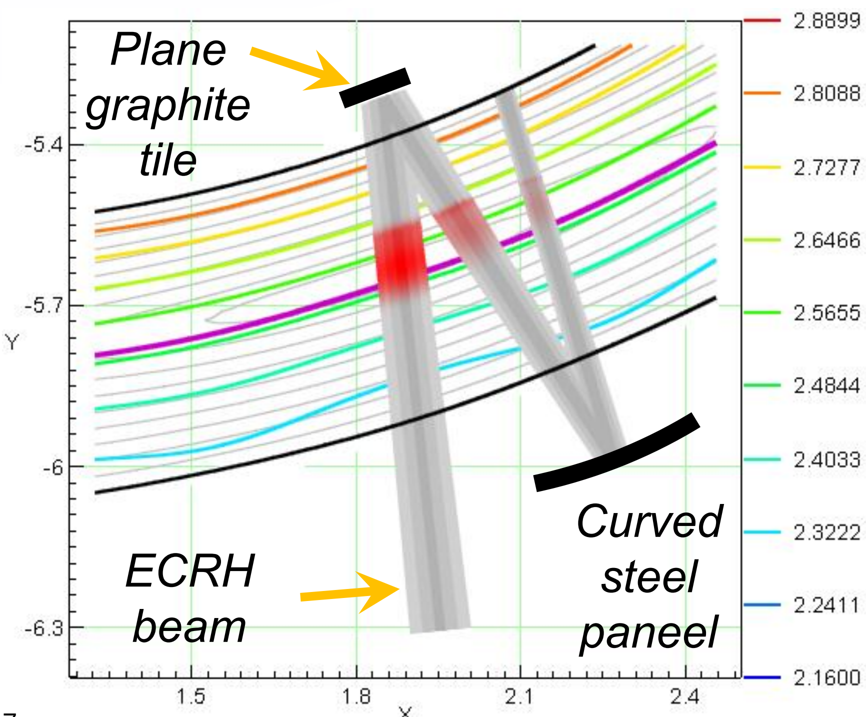
- ECCD succesful at ±10°, compensating or exaggerating bootstrap current
- Agreement with predicted currents.
- Large iota change leads to crashes of central T_e observed *similar* to sawteeth in a Tokamak (still under analysis)

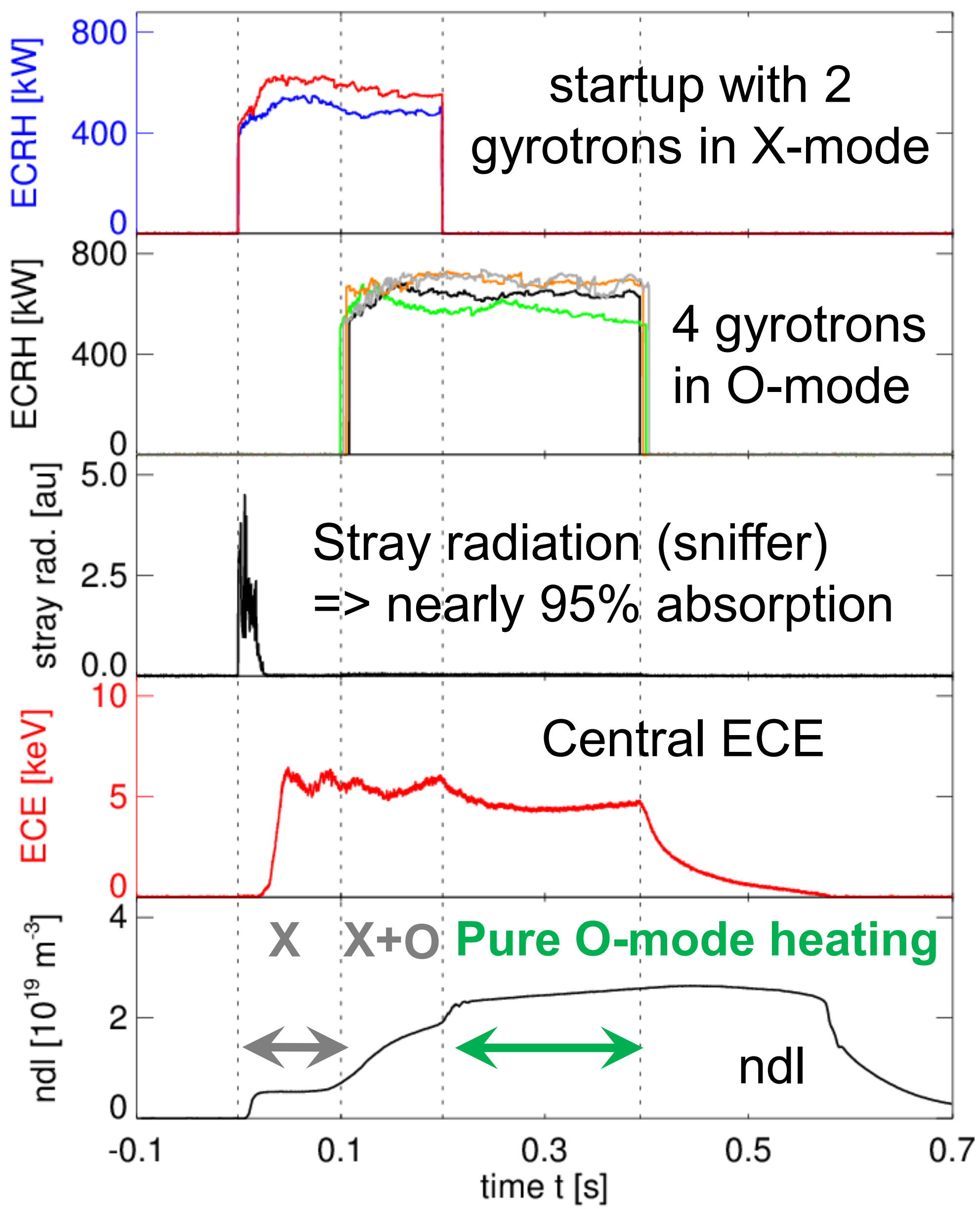
[T. Stange, H. Laqua]

W7X ECRH O2 heating

- O2-mode advanced heating for expected high density (n_e > 1.2x1020) 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 ne ~ 2.4 x 10^{20} in OP1.2.



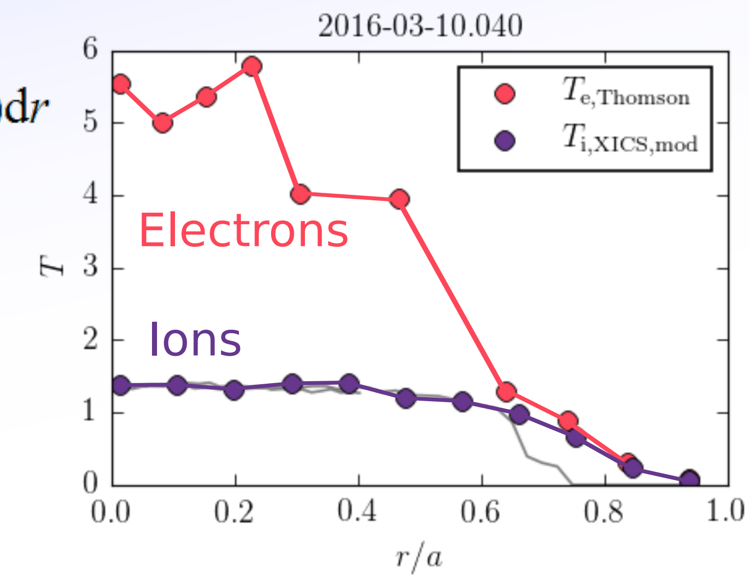


[G. Fuchert, K. Rahbarnia]

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_{eff} = 1 for now as Z_{eff} measurements yet to be analysed.
    but ions carry only ¼ of energy content anyway.

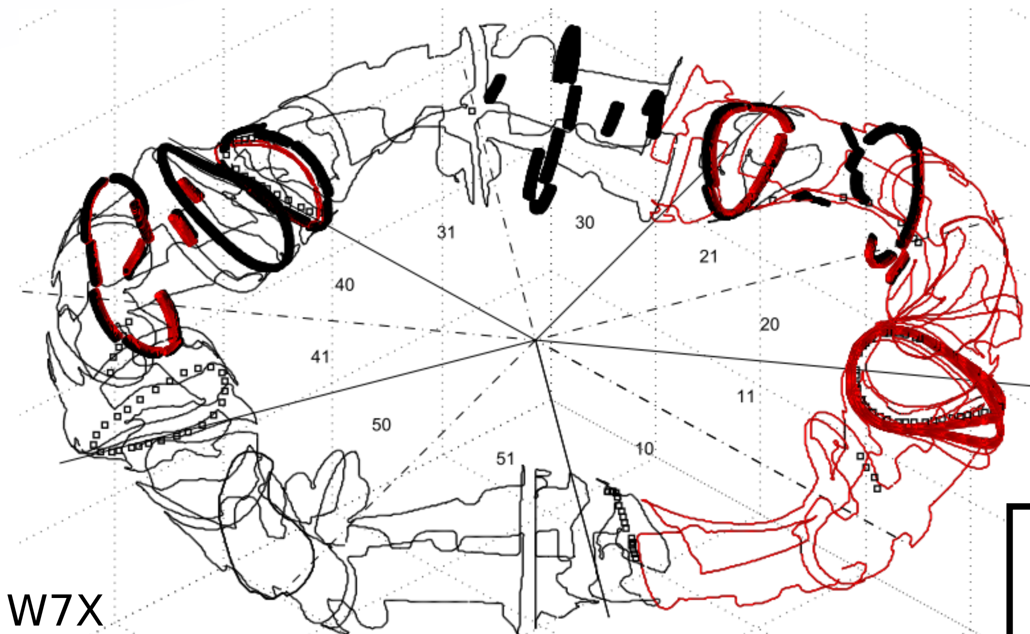
$$W_{\mathrm{therm}} = \frac{3}{2}\int \frac{\mathrm{d}V}{\mathrm{d}r}\, p(r)\,\mathrm{d}r$$



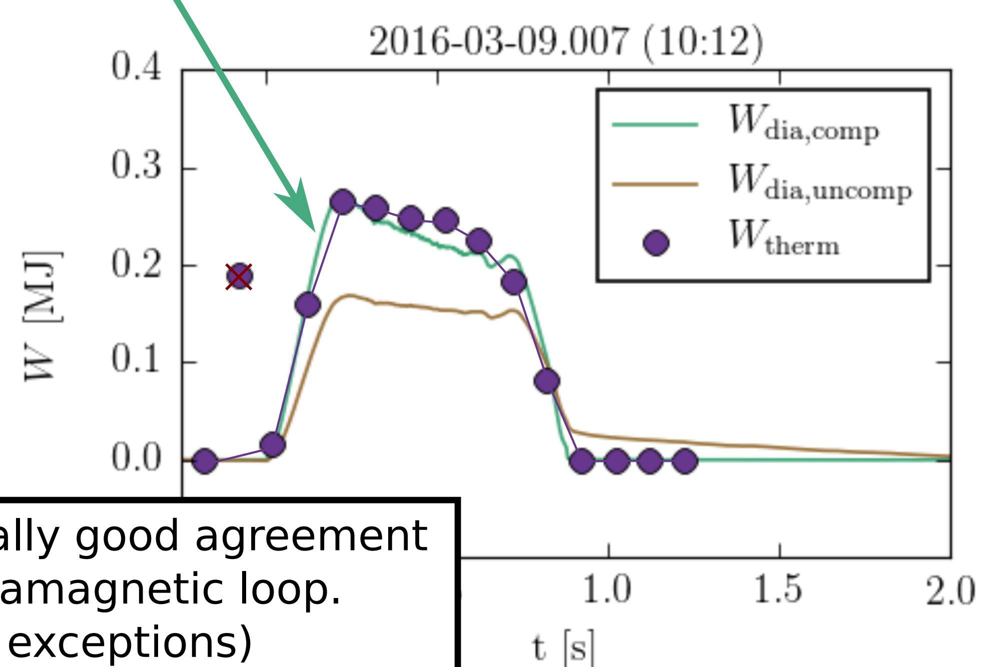
Checked against...

Magnetic diagnostics:

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



W7X
Magnetic diagnostics



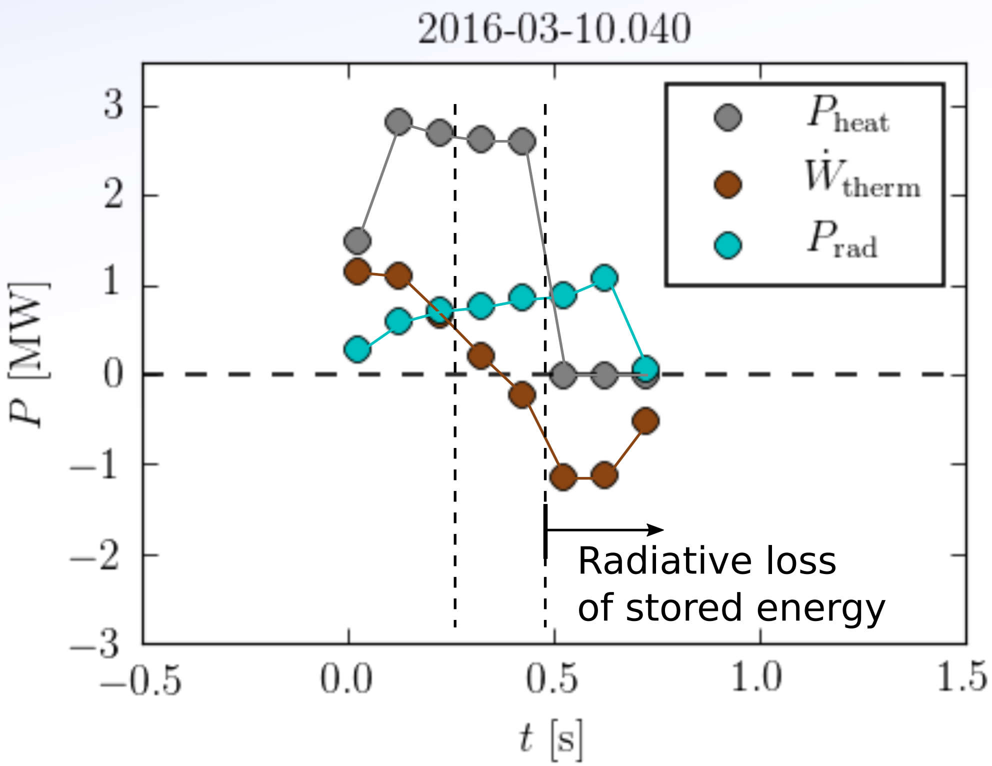
Generally good agreement
with diamagnetic loop.
(Some exceptions)

[G. Fuchert,]

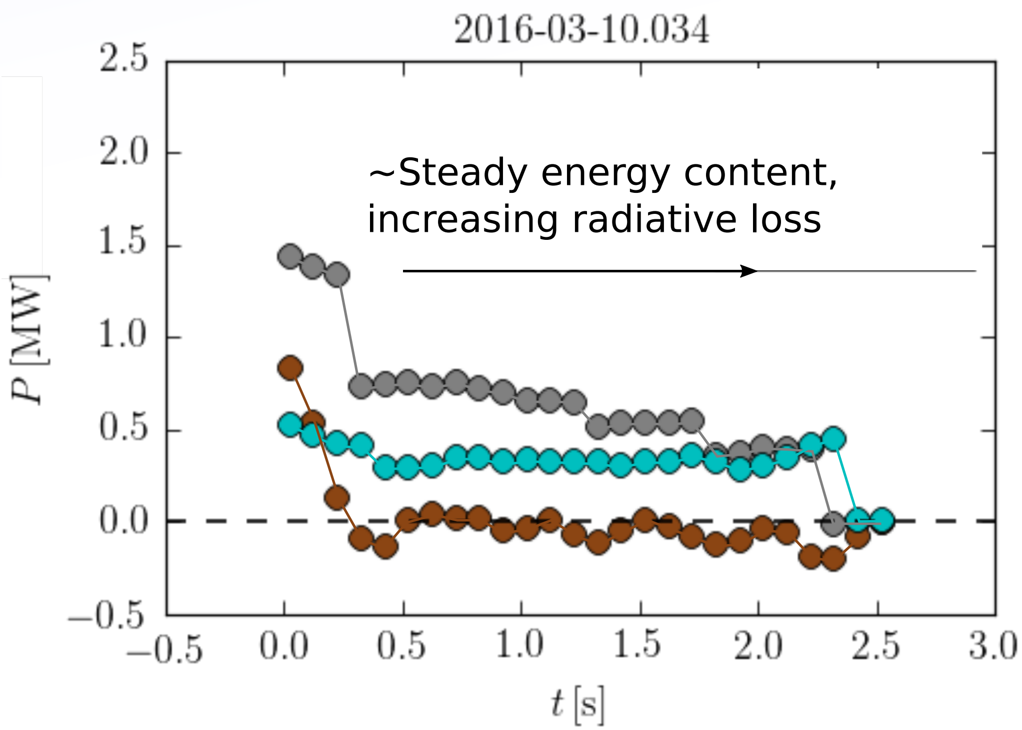
Power Balance

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

High power (~3MW)



Low power (< 1MW)



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

Confinement Times

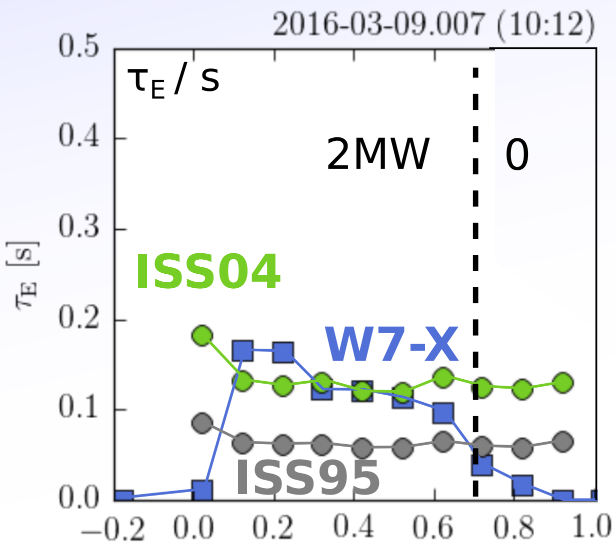
[G. Fuchert]
[ISS04: Yamada et al, NF **45** 1685 (2005)]

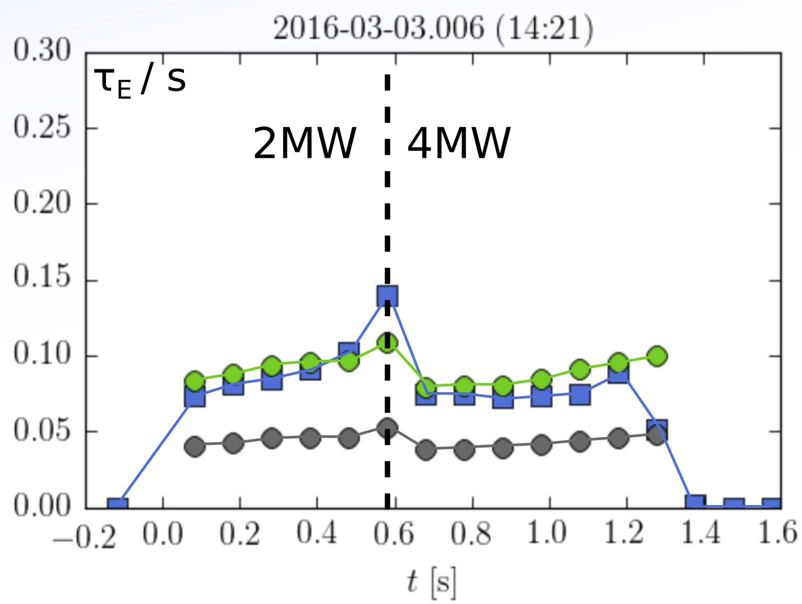
- Preliminary estimate of energy confinement time from P_{ECRH}, W_{therm}, and dW/dt:
- Typically ~ 150ms, matching ISS04 for best plasma conditions.

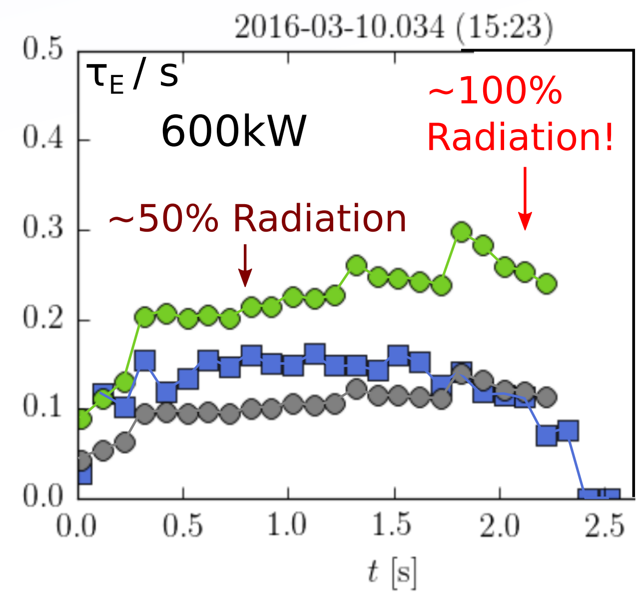
$$\tau_E = 0.134\, a^{2.28}\, R^{0.64}\, P^{-0.61}\, n^{-0.54}\, B^{0.84}\, \iota^{0.41}$$

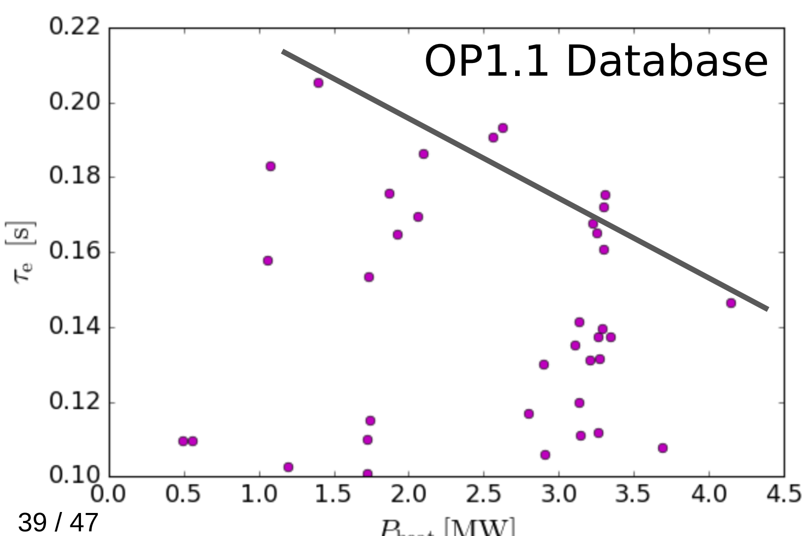
$$\tau_E = \frac{W}{P_{heat} - \dot{W}}$$

Some examples:









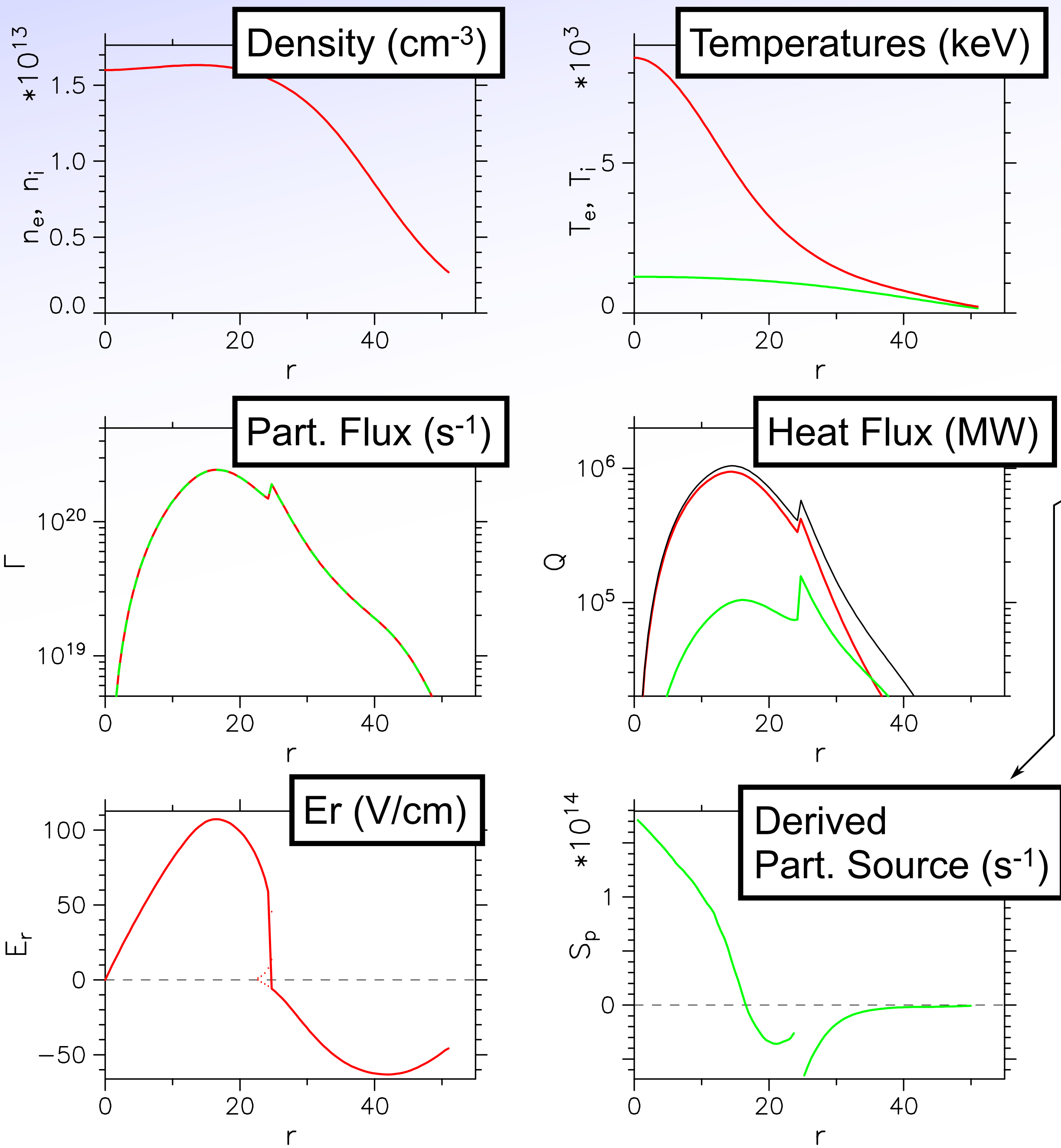
- Points with poor performance (High radiation)
- Degradation with higher power.
- Very poor performance for low power (P < 1MW) (due to radiation loss)

(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!

[H. Maaßberg, A. Dinklage]

Transport Modelling



Initial transport modelling for typical high core T_e:

- Electron root core of varying extent.

- Predicted core particle depletion not observed.

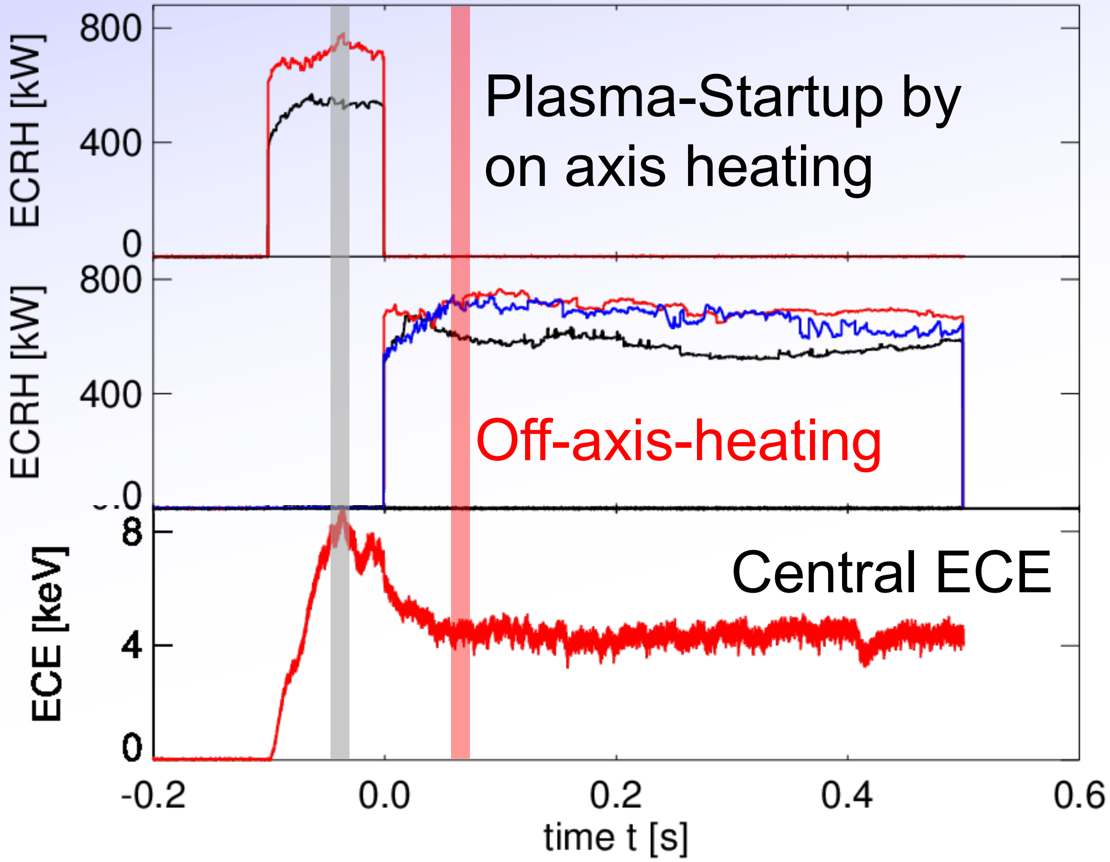
- Modeling requires unrealistic core particle source or anomalous pinch.

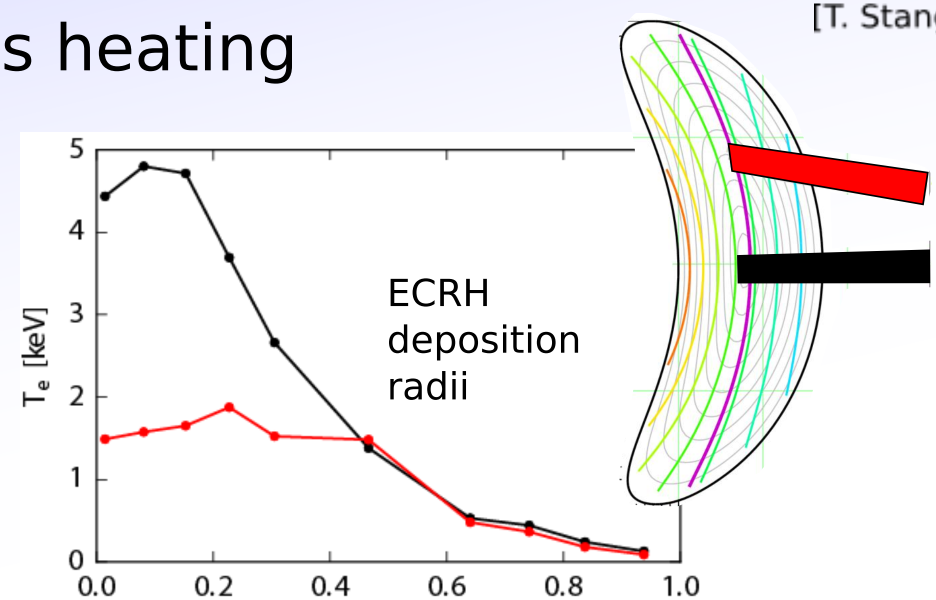
- Peak neoclassical integrated heat flux (1.1MW) falls short of the input power (2MW).

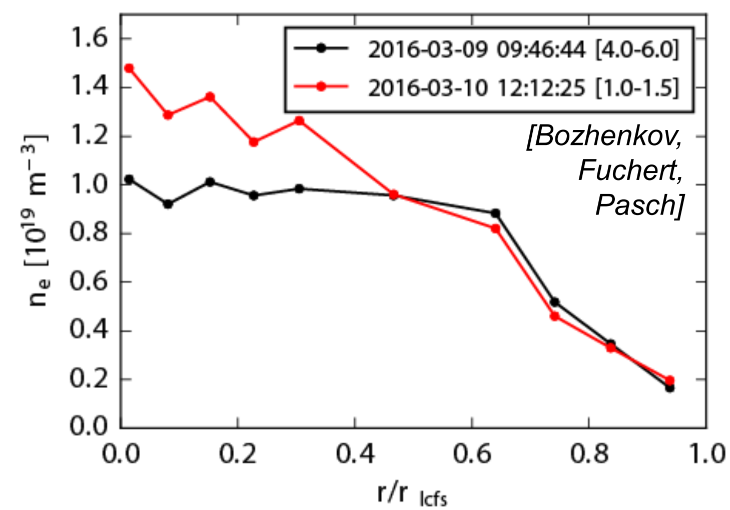
- Modeling on-going...

[T. Stange]

W7X ECRH Off-axis heating





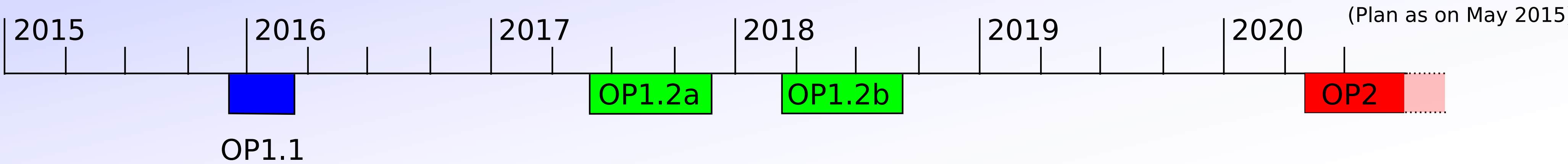


- Successful demonstration of off-axis heating!
- Apparent peaking of central n_e for flat T_e - Inward pinch or central neutrals??

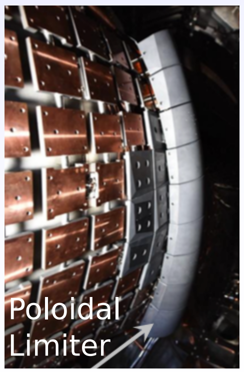
Off-axis ECRH useful for:
- Control of profile / gradients.
- Influence on impurity accumulation.

O. P. Ford

W7-X Operational Phases



OP1.1: Limiter Phase



	Anticipated	Achieved
	13 Weeks	
	P <= 4MW, W_{limit} = 2MJ	P <= 4MW, W_{limit} = 4MJ
	Te < 3 keV, Ti < 1 keV	Te < 10 keV, Ti < 2 keV
	ne < 0.2 x 10^{20} m^{-3}	ne < 0.8 x 10^{20} m^{-3}
	τ_{pulse} < 1s	τ_{pulse} < 6s

OP1.2: Test divertor phase.

26 + 26 Weeks
P <= 10MW, W_{limit} = 80MJ
Te < 3 keV, Ti < 3 keV
ne < 1.6 x 10^{20} m^{-3}, β < 3%
τ_{pulse} < 10s

?

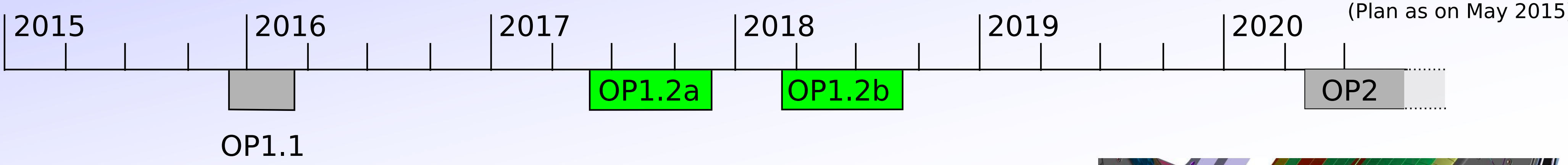
OP2: Steady-state phase.

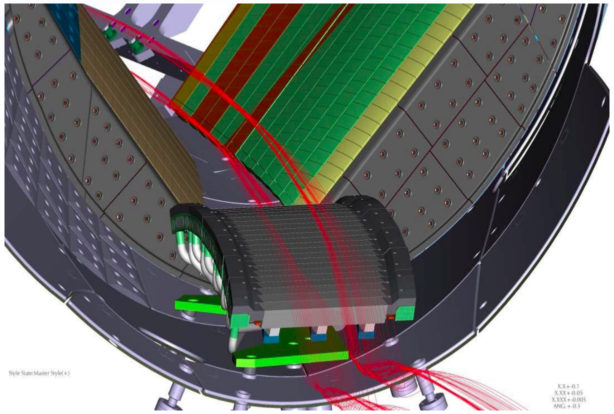
P <= 20MW, P/A < 10MWm^{-2}
Te < 5 keV, Ti < 5 keV
ne < 2.4 x 10^{20} m^{-3}, β < 5%
τ_{pulse} < 30 mins (~2/day, cooling capacity)

?

[R.Wolf, R.Konig]

W7-X OP1.2 Upgrades





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

Primary components:
- Inertially cooled 'test' divertor unit (TDU)
- 'Scraper Element' in OP1.2b to protect HHF divertor near pumping gap.

--> Pulse energy limited to 80MJ.

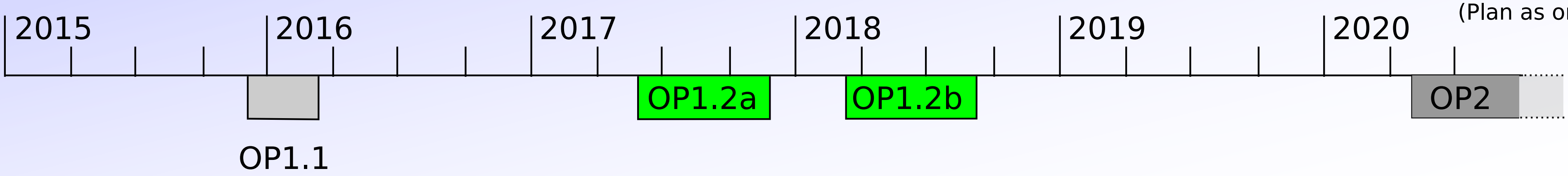
--> Full range of magnetic configurations (high/low iota, shear, ...)

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 Fluorescense, 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

[R. Konig]

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 ß on 3D topology, divertor performance and plasma wall interaction

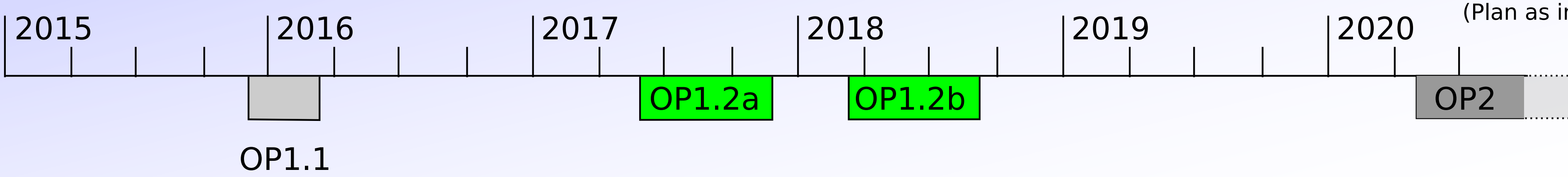
- Investigate plasma sweeping.

- Use planar/control coils to mimic effect of β and bootstrap current in OP2 scenarios.

W7-X OP1.2 Core Physics

[R. Wolf, M. Beurskens, H. Laqua]

(Plan as in May 2015)



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

- Explore extent of neoclassical confinement optimisation.

- Core electron vs ion root confinement.

- Core fuelling / hollow density profiles?

- Impurity accumulation.

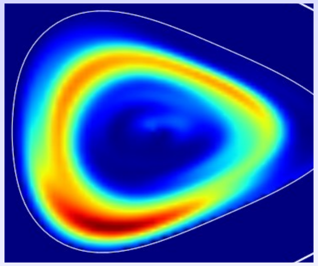
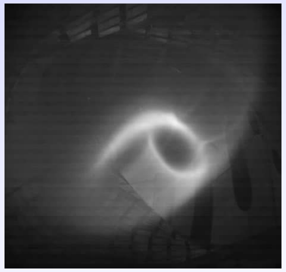
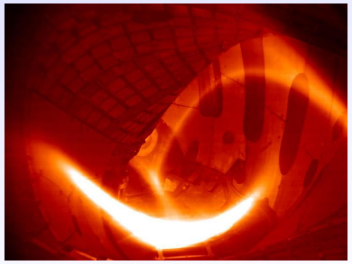
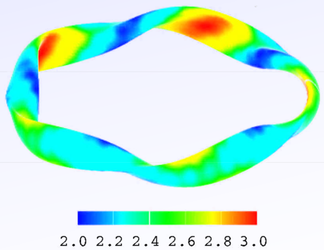
- Explore confinement modes: Quiescent H-Mode, high density H-Mode?

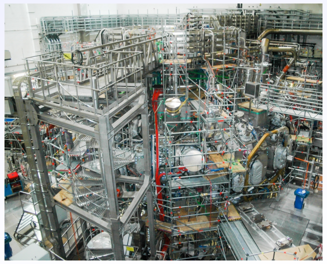
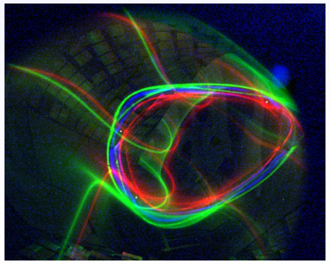
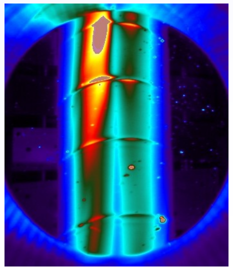
- ECRH O2 Heating experiments (started OP1.1)

- Fast ion generation (ICRH/NBI)

[Wendelstein 7-X team and all collaboration partners]

Summary

✓ Wendelstein 7-X optimised stellartor has been constructed succesfully.

✓ Good flux surfaces demonstrated. Expected behaviour of magnets.

✓ First operational phase succesfully commissioned device and many diagnostics.

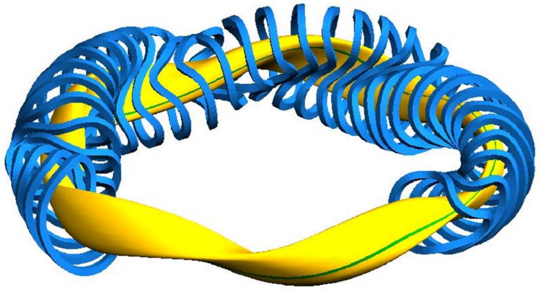
✓ Short but rich physics program was also possible.

✓ Much hotter, denser and longer plasmas than expected.

... Major device limit was wall outgassing, should be improved in OP1.2 with divertor.

✓ Confinement times as ISS04, may be better with less impurity radiation.

... Lots of interesting things seen that are not yet explained or explored:
- Filaments? - 7kHz modes? - Peaked density profiles? - Sawteeth?



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

Many thanks for PPPL contributions!