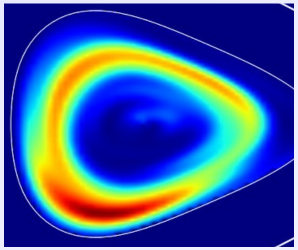
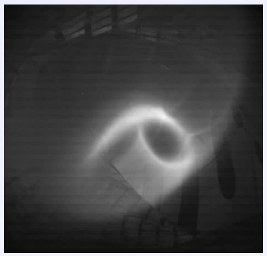
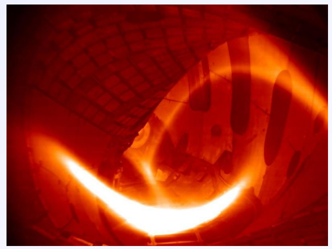
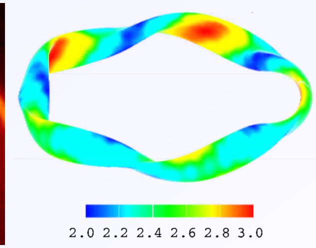
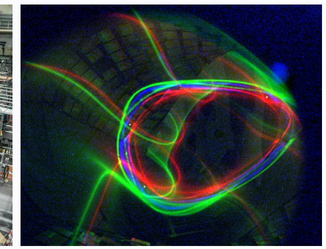
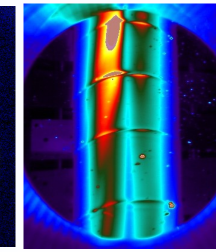
Wendelstein 7-X: Status and overview of diagnostics,

(with some emphasis on ITER relevance)

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. Endler1, V. Erckmann1, T. Estrada6, O. Ford1, T. Fornal5, G. Fuchert1, J. Geiger1, O. Grulke1, J. H. Harris13, H. J. Hartfuß1, D. Hartmann1, D. Hathiramani1, 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. Ryc2, 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

1Max Planck Institute for Plasma Physics, 17491 Greifswald, Germany,
2Institute of Energy- and Climate Research, Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany
3Instituto de Plasmas e Fusao Nuclear Instituto Superior Tecnico, Lisbon, Portugal
4 Wigner Research Centre for Physics, Konkoly Thege 29-33, H-1121 Budapest, Hungary
5IFPiLM, Hery Street 23, 01-497 Warsaw, Poland
6Laboratorio Nacional de Fusi´on, CIEMAT, Avenida Complutense, Madrid, Spain
7Univ. of Wisconsin, Dept. of Engineering Physics, 1500 Engineering Drive, Madison, WI 53706, USA
8CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France
9Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands
10Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543, USA
11Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
12Los Alamos National Laboratory, Los Alamos, NM 87544, USA
13Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA
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

W7-X Diagnostics

Already too many to cover in one talk. Almost all already installed and operated in OP1.2:

Langmuir probes
Divertor thermography
Divertor calorimetry
Divertor gas Injection
Neutron counters
Single channel dispersion interferometer
ECRH stray radiation diagnostics
ECRH infrared diagnostics
Video cameras
NBI heat-shield thermography
NBI neutraliser spectroscopy
Neutral gas pressure
Thomson Scattering
Laser blow-off
ECE radiometer
ECE Michelson interferometer
TESPEL impurity pellet injection
XMCTS soft X-ray camera
Visible divertor spectroscopy
Charge exchange recombination spectroscopy
Gas-puff imaging
Collective thomson scattering
Doppler reflectometry
Flux surface measurements
Penning gauges
Magnetic equilibrium diagnostics

Bolometry
Alkali-beam
X-Ray imaging crystal spectrometer
High resolution X-Ray spectrometer
Pulse height analysis X-Ray spectrometer
Carbon/oxygen monitor
Z_{eff}/Bremsstrahlung
Multipurpose manipulator (Mutiple heads)
Correlation reflectometry
Profile reflectometry
Coherence imaging spectroscopy
H-alpha video
H-alpha filterscopes
Phase contrast imaging
Mirnov Coils
HEXOS overview spectrometer
Fast ion loss detector
Beam Emission Spectroscopy
Fast Ion D-Alpha
Passive CX / visible spectroscopy

Neutral Partical Analyzer
Laser Induced Flouresence
Divertory Bolometry
Multichannel Interferometer
Heavy ion veam probe

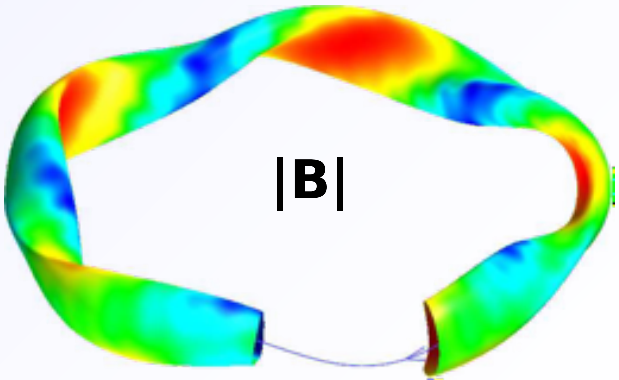
Planned

[J. Nührenberg PPCF 52 124003 2010]

W7-X: An optimised Stellarator

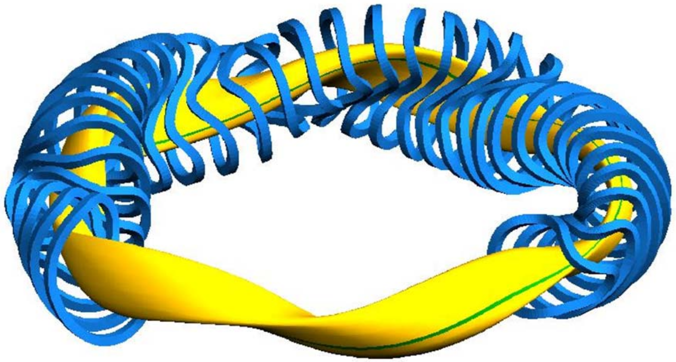
Wendelstein 7-X: 'Quasi-isodynamic' Stellerator configuration
- Trapped particles drift along constant |B|
- Magnetic configuration chosen to best confine trapped orbits.

Magnetic field optimisation



→

Steady-state operation
with superconducting coils

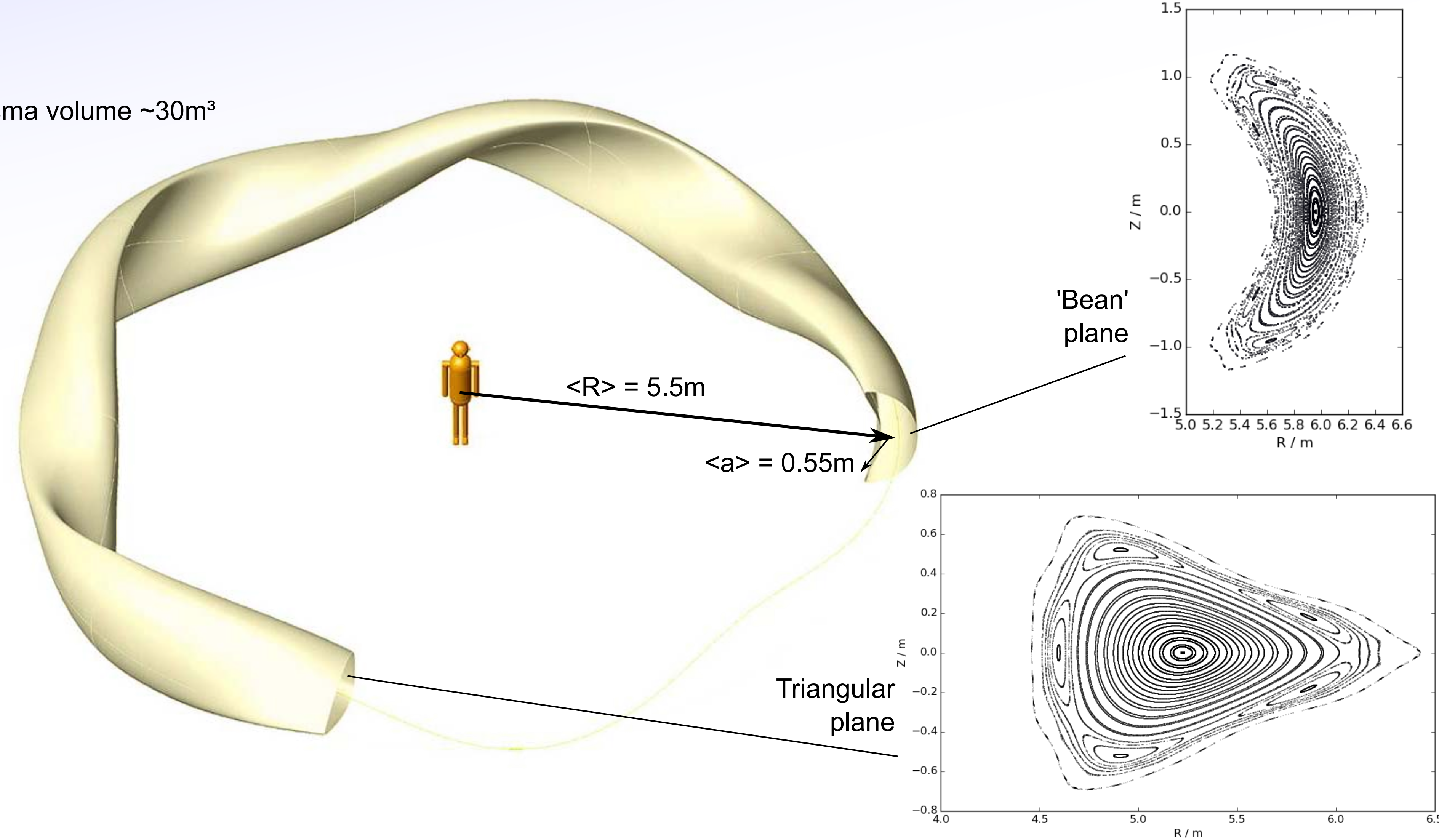


Missions:
- Build Wendelstein 7-X to the required precision.
- Verify construction by showing good vacuum flux surfaces.
- Demonstrate operation of 'Island-divertor'
- Confirm optimisation of neoclassical confinement - is it at Tokamak level?
- Show sufficient confinement of fast-ions.
- **Demonstrate steady-state operation at a relevant plasma β.** ⟵ ITER relevance for diagnostics

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

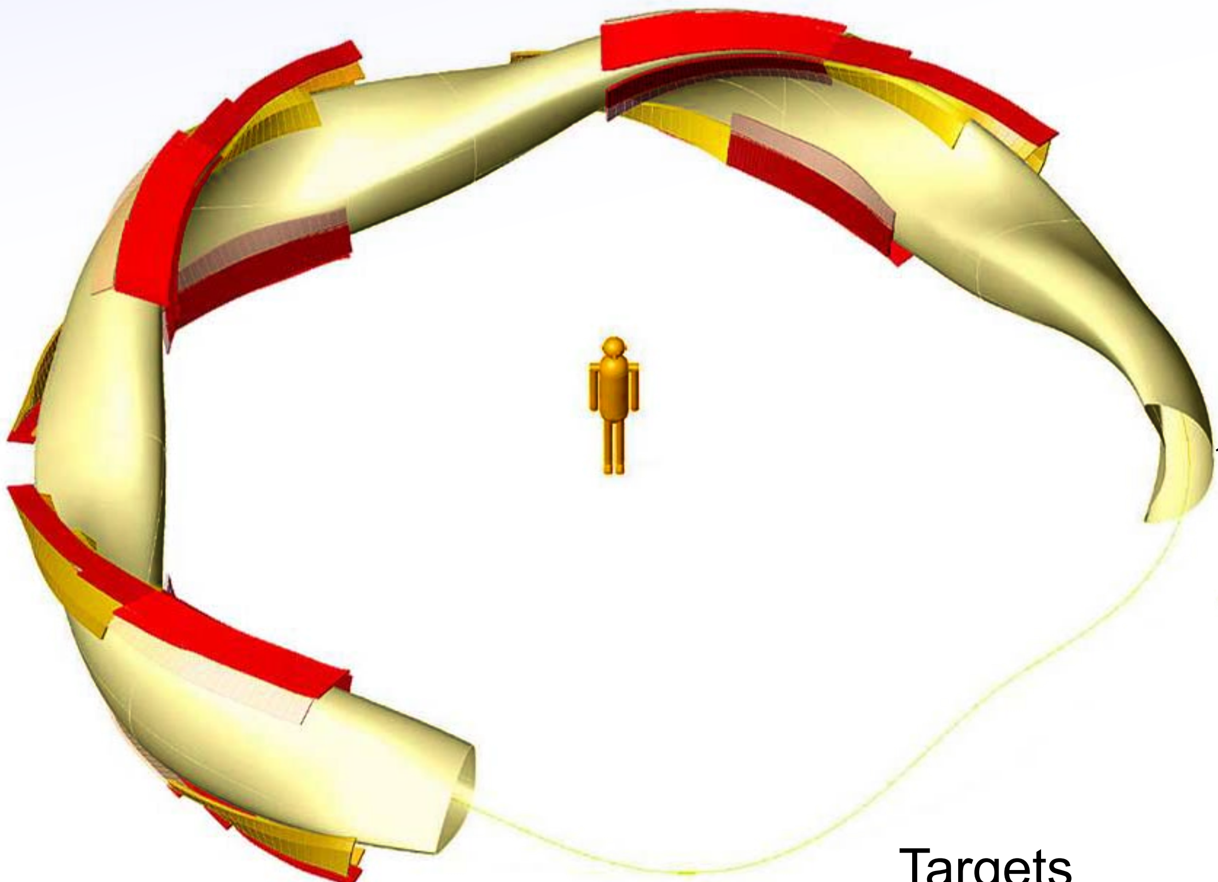


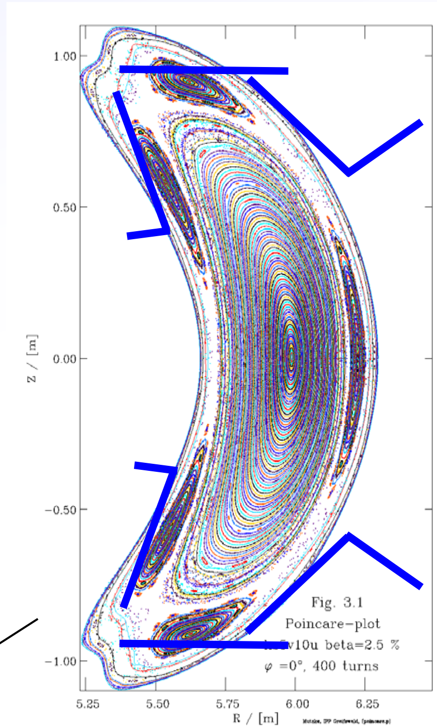
W7-X Construction

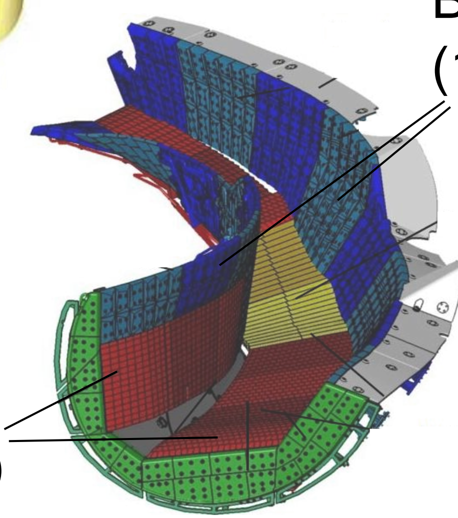
Island Divertor:

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

ITER-level heat loads in steady-state.
... (but graphite for forseeable future).



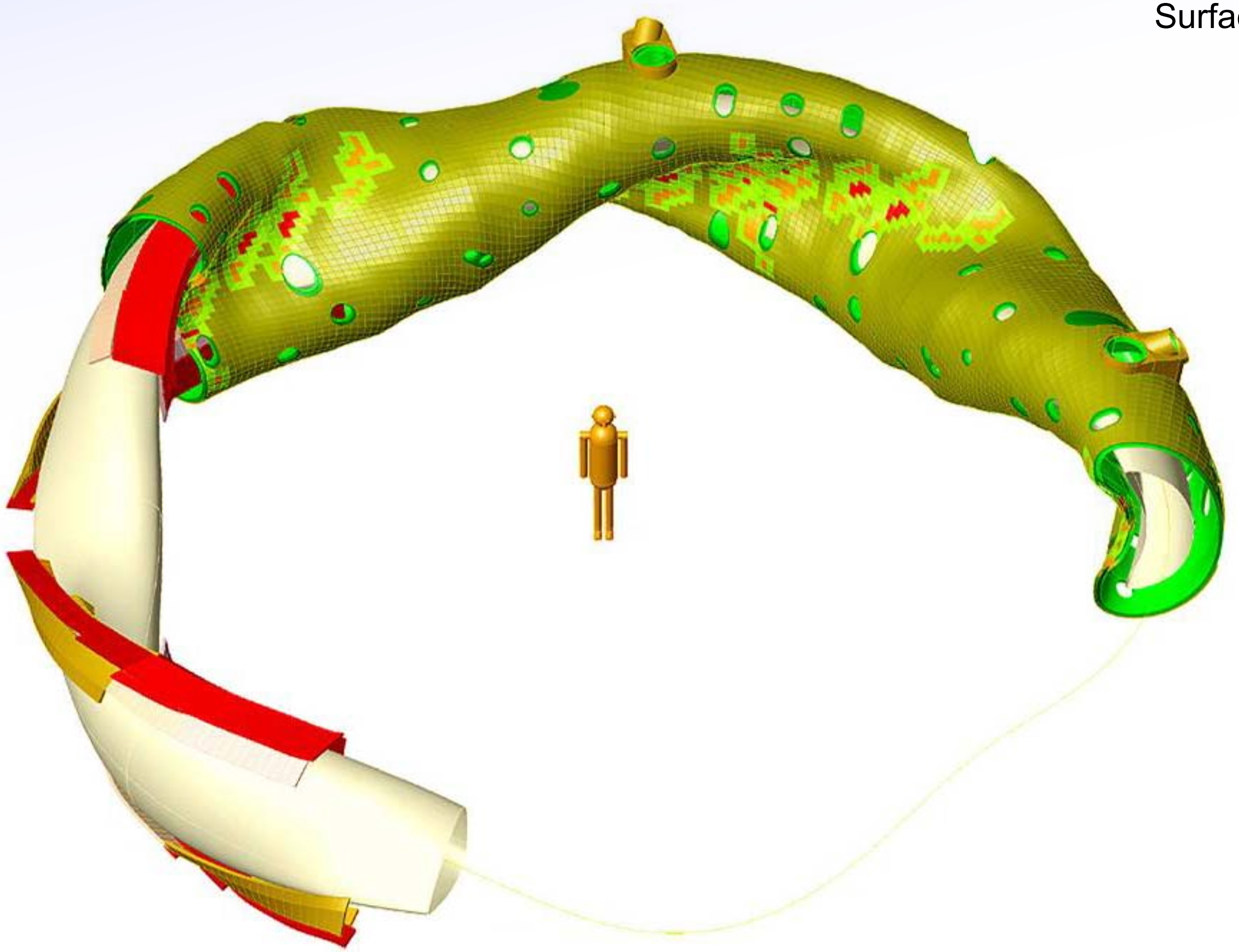




W7-X Construction

Vacuum Vessel

Vacuum Vessel:
Volume: 84m³
Surface area: ~200m²



W7-X Construction

Magnetic Coils
- Three campaigns of expeince with Superconducting coils in a large fusion experiment.
- Some issues with insulation and Paschen tests before last campaign but otherwise operating well.

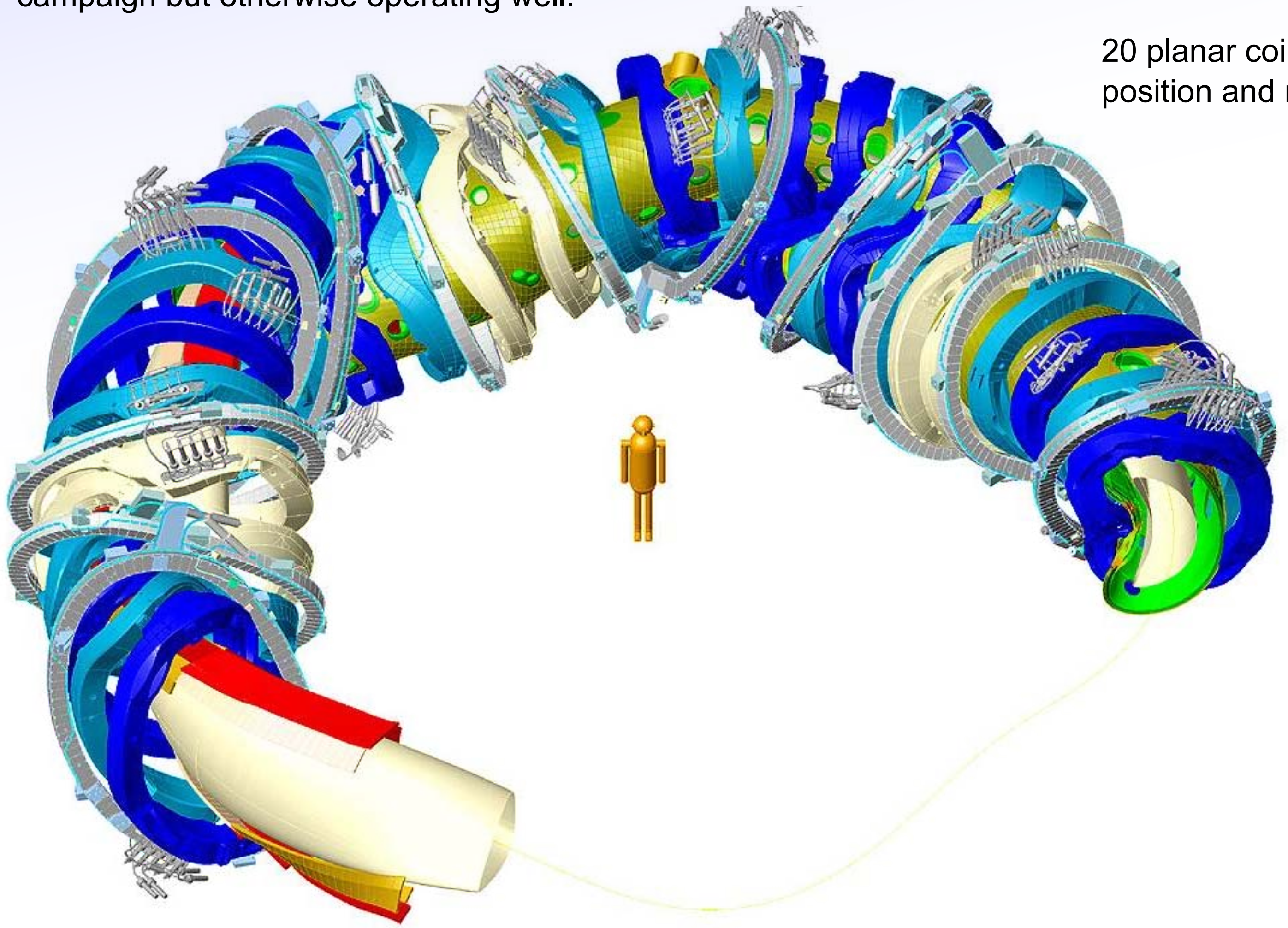
Super-conducting coils:

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:

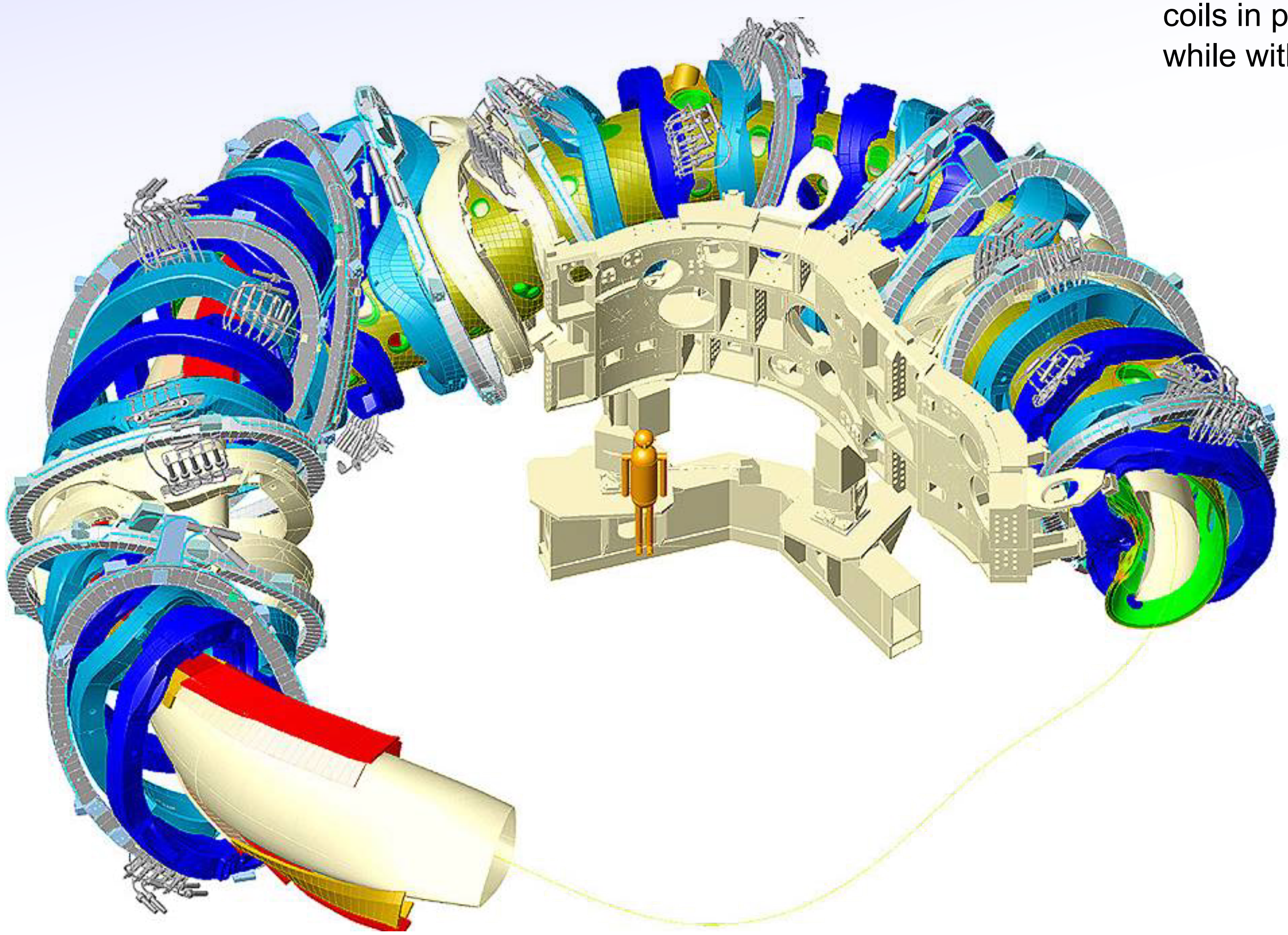
10 control/sweep coils for modifying the edge and moving the divertor strike points.



W7-X Construction

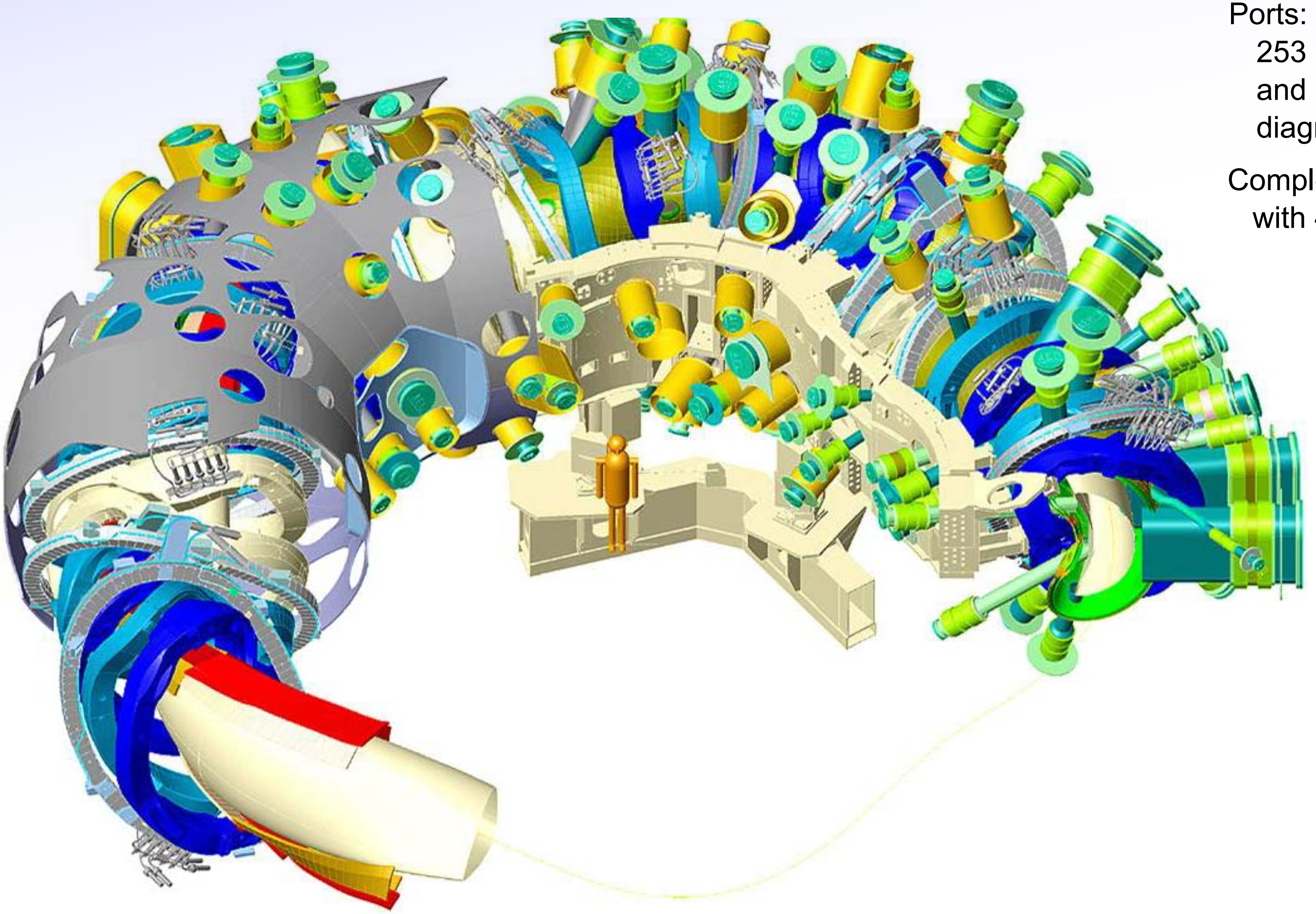
Support structure:

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.

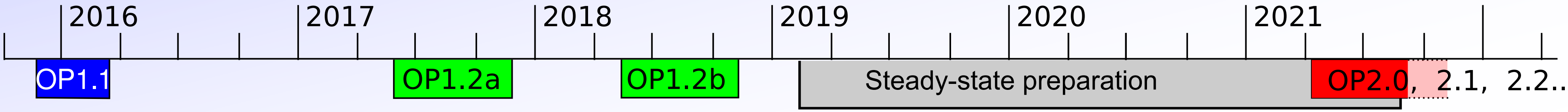
Complete construction 735t with 435t cold mass.

[R. Wolf, R. König]

W7-X Operational Phases

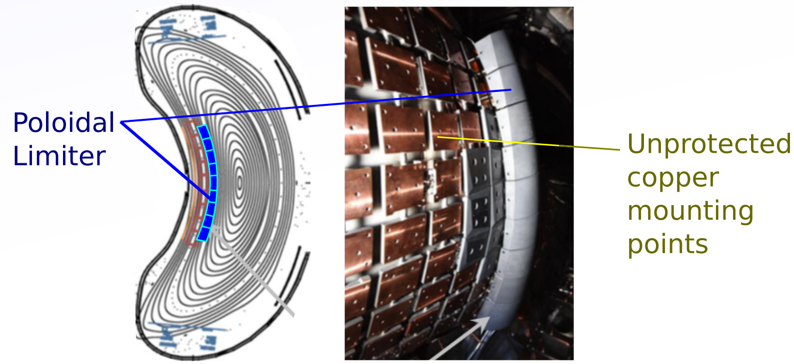
- Steady-state operation is a long term goal. 10MW/m² 'high heat flux' divertor took longer to construct.

(Plan as in Jan 2019)



OP1.1: **Limiter phase** - 4MJ

- 5 Graphite inboard limiters.
- No tiles protecting the inner wall.
- Generally high Te, low Ti plasmas of ~few seconds.
- Limited diagnostic and heating systems.



[R. Wolf, R. König]

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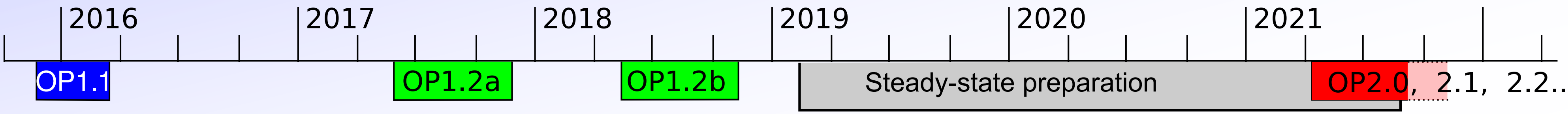

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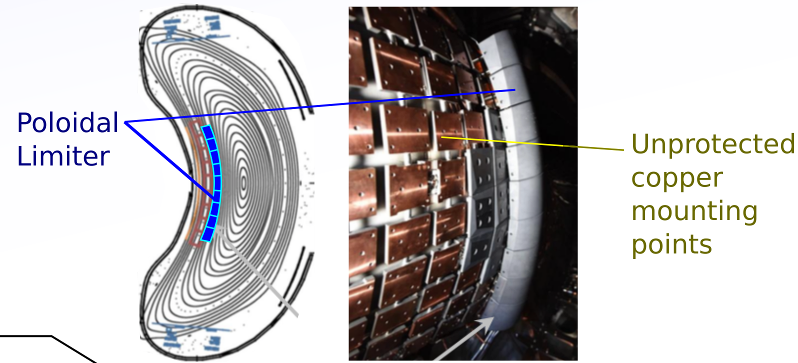

OP1.2: **Test divertor phase** - 200MJ

- Inertially cooled 'test' divertor unit (TDU)
- Water cooled heat shield tiles and panels.
- Pulse energy up to 200MJ, 100 seconds. Max power ~6MW.
- Many more diagnostic systems
- NBI heating.

OP1.2: Test Divertor Unit

[R. Wolf, R. König]

W7-X Operational Phases

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

(Plan as in Jan 2019)

2016 | 2017 | 2018 | 2019 | 2020 | 2021

OP1.1 | OP1.2a | OP1.2b | Steady-state preparation | OP2.0, 2.1, 2.2...

OP1.1: **Limiter phase** - 4MJ

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- No tiles protecting the inner wall.
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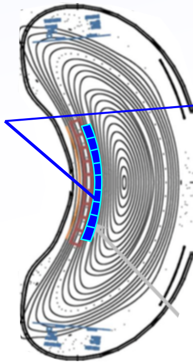

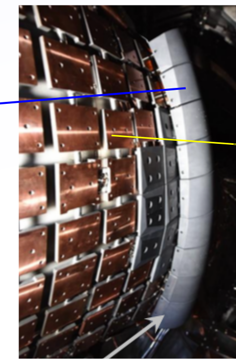

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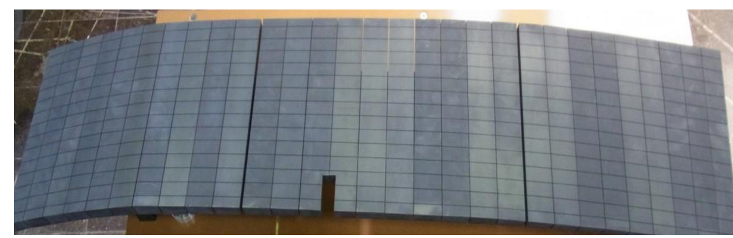


OP1.2: Test Divertor Unit

OP2: **Steady-state phase**. (1GJ, ... 18GJ)

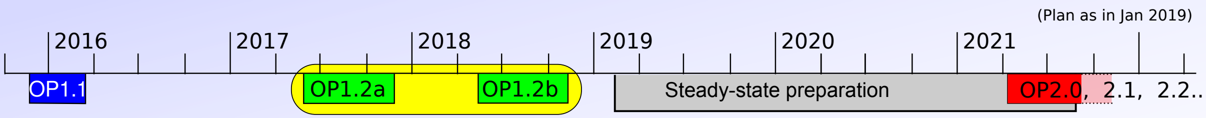
- Actively cooled high heat flux (HHF) divertor.
- All wall components water cooled.
- 10MW for up to 30 minutes, 20MW pulsed.
- **Full steady-state capable diagnostics suite.**

OP2: High Heat
Flux divertor

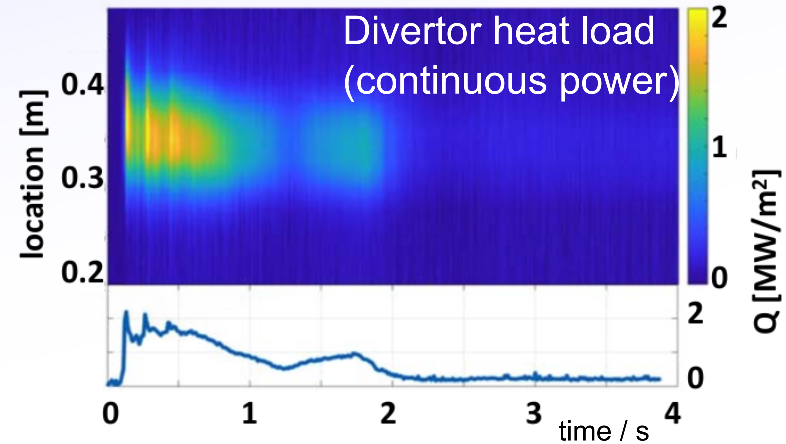
OP?: Future phases

- Tungsten wall??

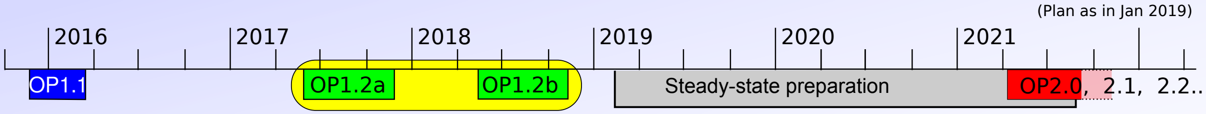
W7-X OP1.2 (2017/8) Complete



- Boronisation --> Higher density limit (problem in OP1.2a)
- 3MW NBI --> densities up to $n_e \sim 2 \times 10^{20}\ m^{-3}$.
- Fully deteached divertor operation



W7-X OP1.2 (2017/8) Complete



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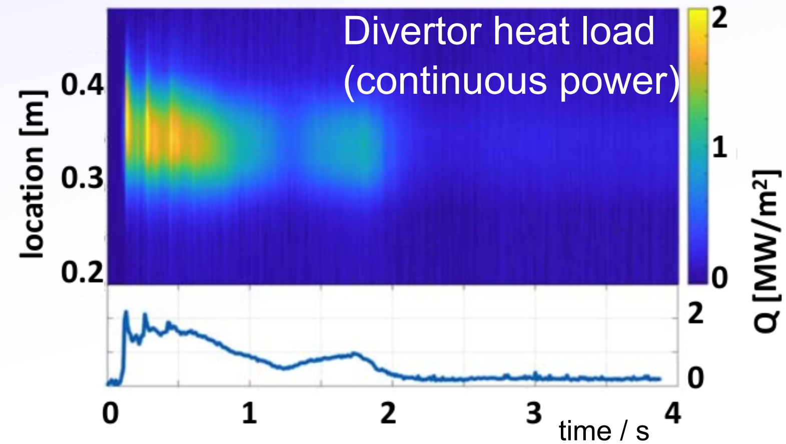
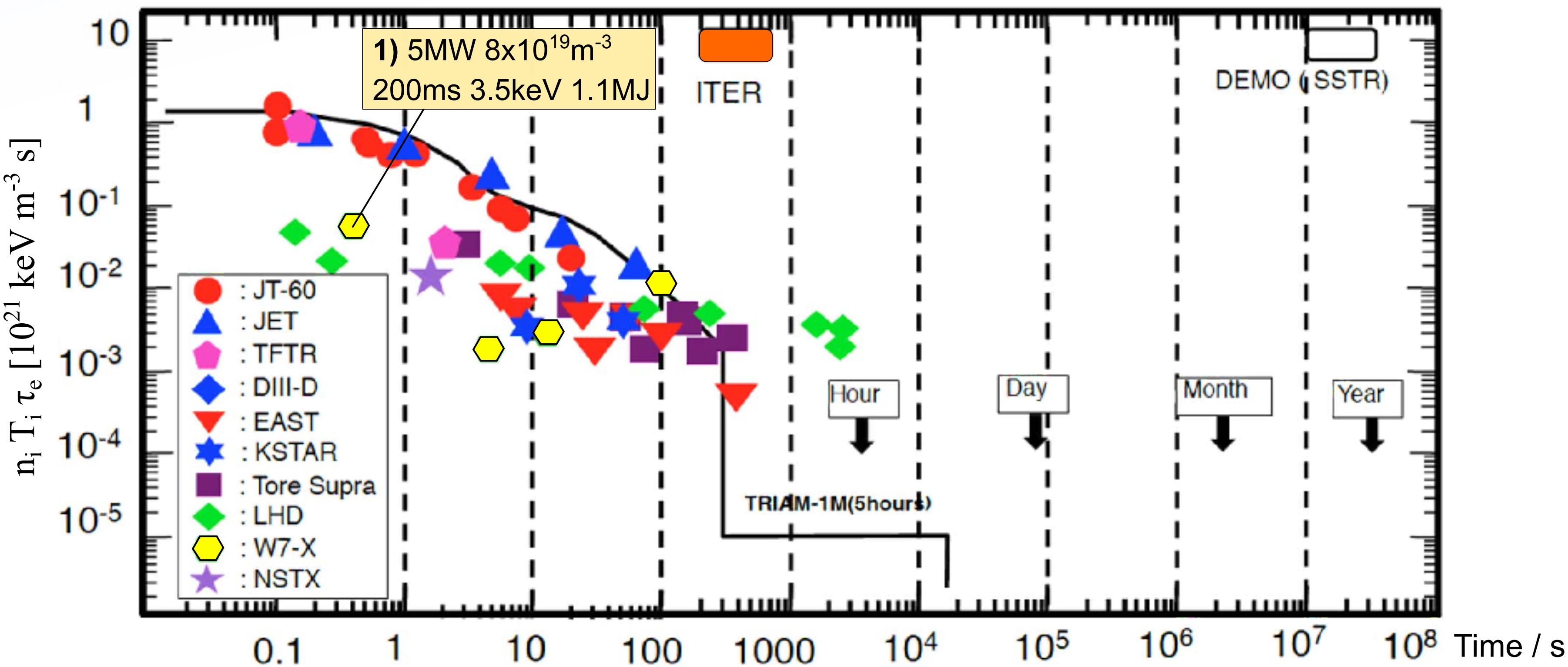
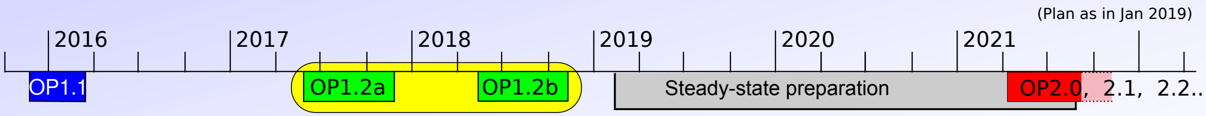


1) Pellets + 5MW: Record stellarator confined energy 1.2MJ, (transiently).



W7-X OP1.2 (2017/8) Complete



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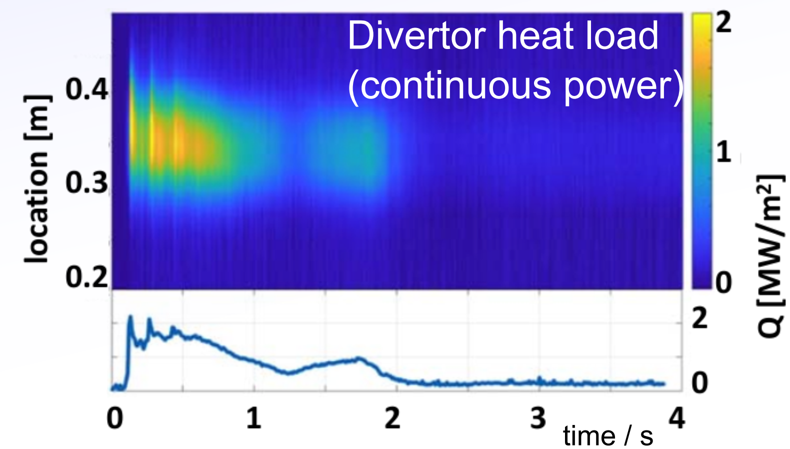
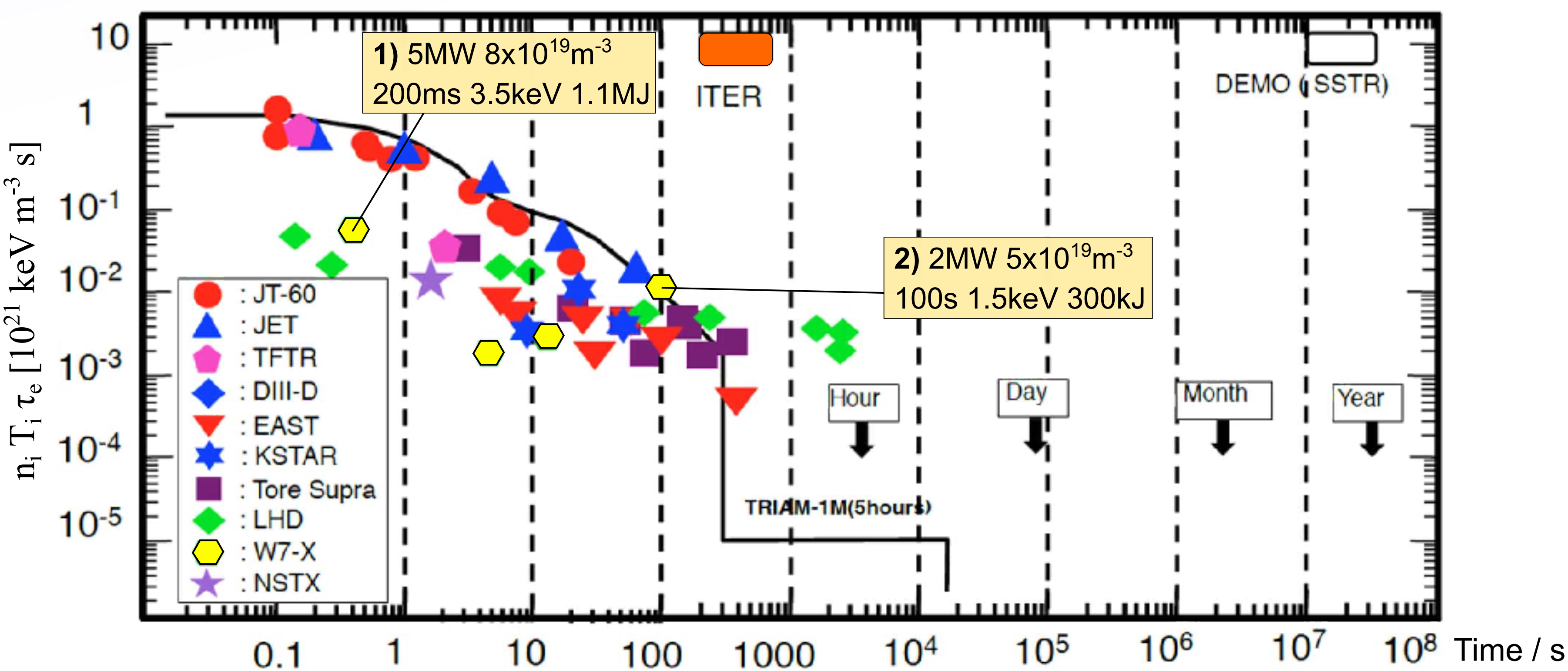


1) Pellets + 5MW: Record stellarator confined energy 1.2MJ, (transiently).
2) Long duration 2MW 100s



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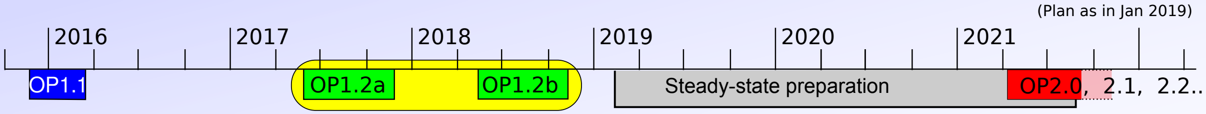
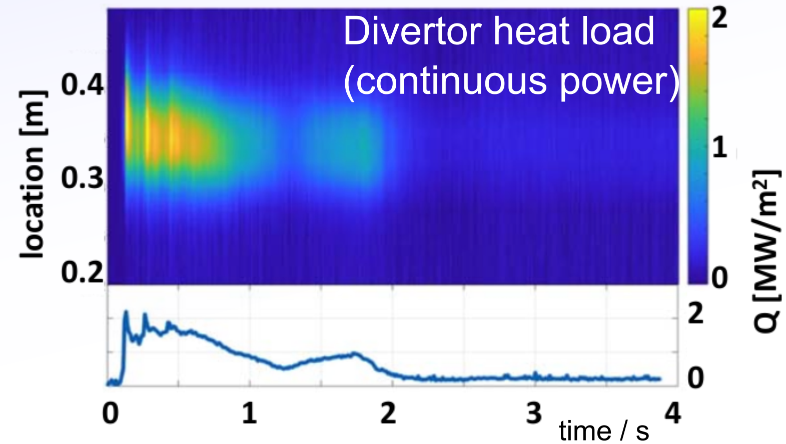


- Boronisation --> Higher density limit (problem in OP1.2a)
- 3MW NBI --> densities up to n_e ~ 2 $x10^{20}$ m^{-3}.
- Fully deteached divertor operation



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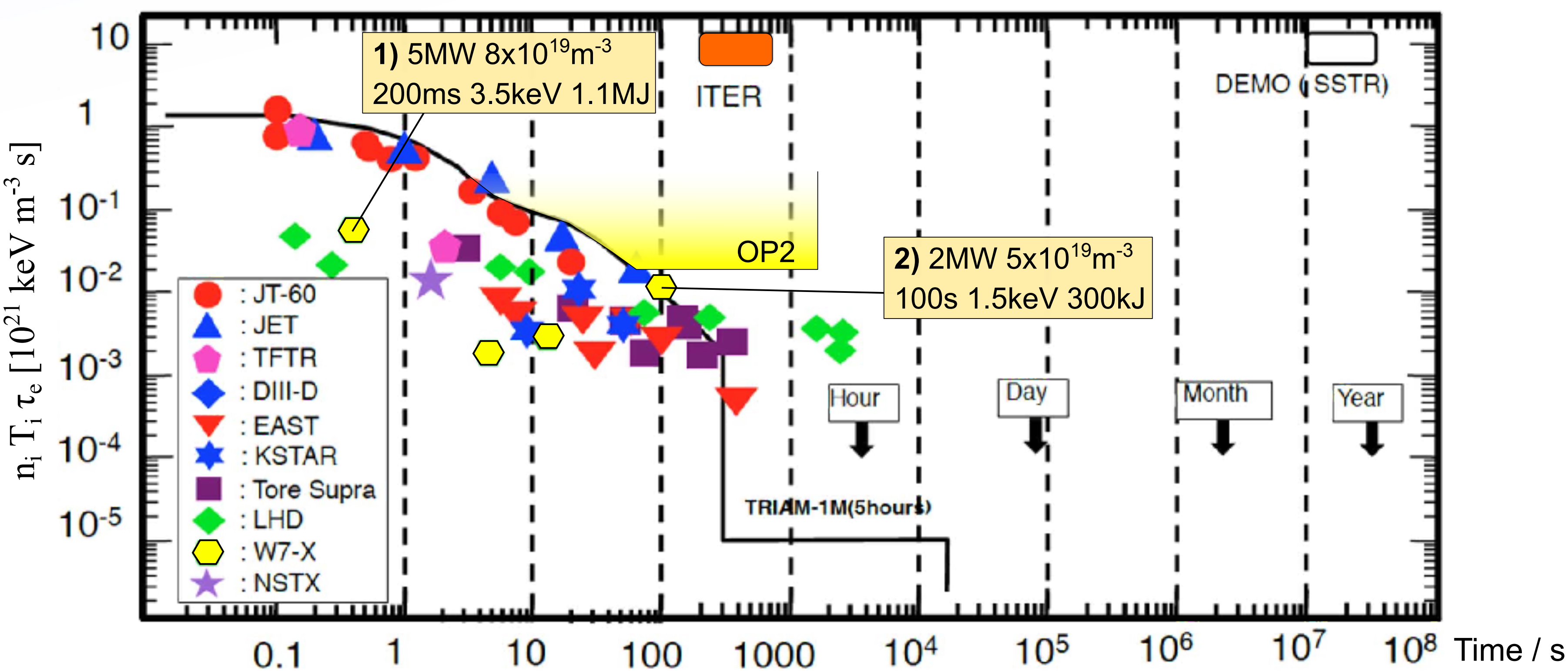


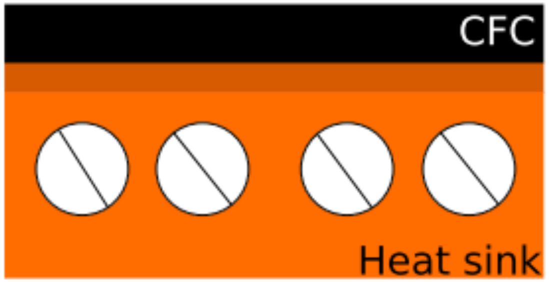
W7-X OP2 (2021+) Plans

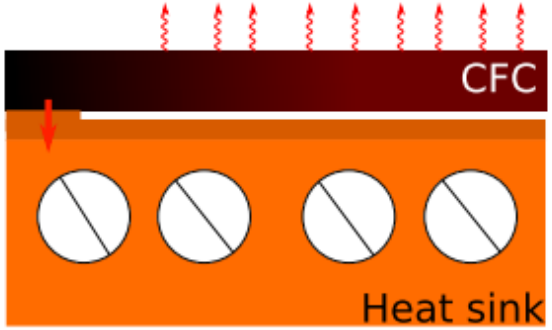
OP2: High Heat Flux divertor

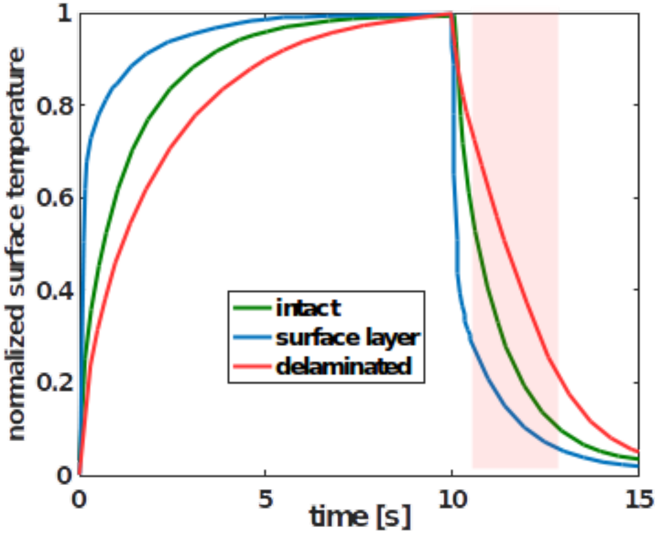
Primary objective of OP2:
- Demonstrate long-pulse operation at high beta (~5%).
  10MW ECRH Power, 30min discharges.

--> Up to **10MW m^{-2}** continuous heat load to divertor (without detachment)

- Steady-state high-heat flux **graphite** to Copper-Chrome-Zirconium bonded water cooled divertor targets.
- Requires online monitor for safety against overheating and delamination of tiles.



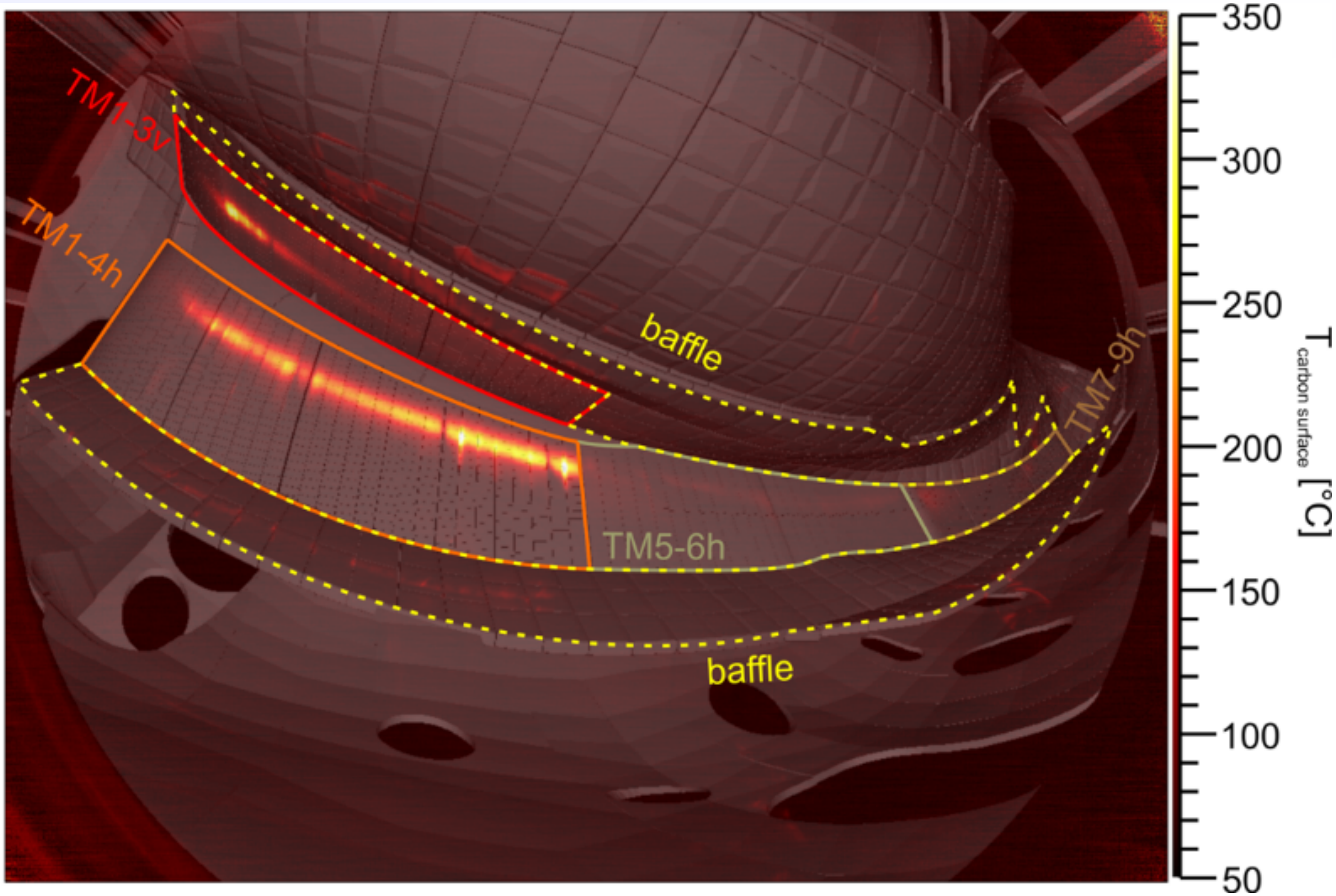




Visible/Infrared video + Real-time protection

Temporary immersion tubes with infrared μ-Bolometer cameras used for OP1.2
Good resolution achieved.
Immersion tube is not long-pulse capable (cooling!)

Infrared data overlaid on to CAD: (1 of 10 divertors)



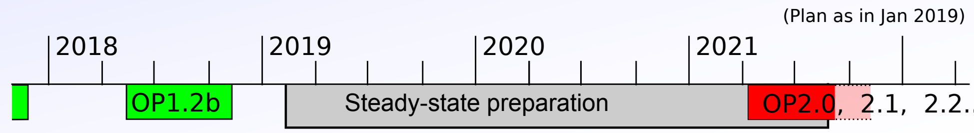
10 x high resolution video x 30min --> huge data

200TB already for OP1.2

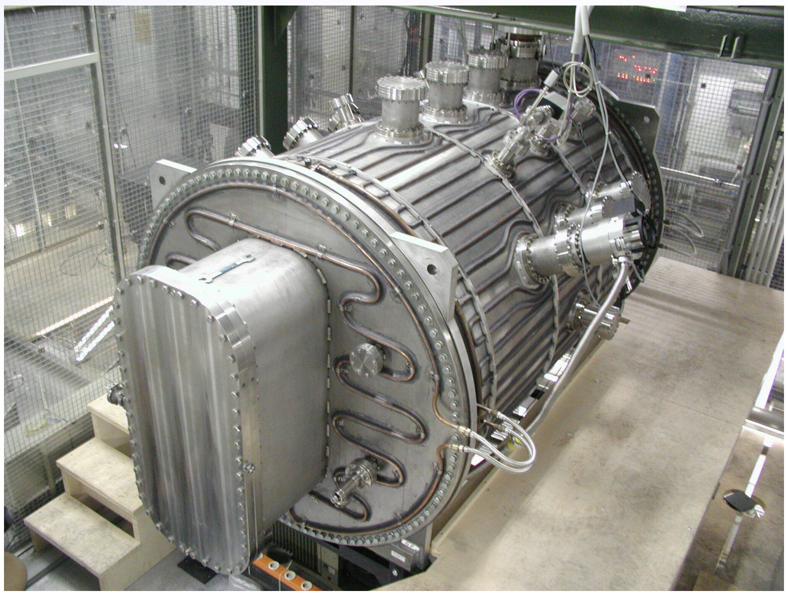
Will need to process in near real time. Investigating advanced algorithms, deep-learning, neutral networks etc.

W7-X OP2 Cooling - Diagnostics

Primary objective of OP2:
- Demonstrate long-pulse operation at high beta (~5%).
  10MW ECRH Power, 30min discharges.

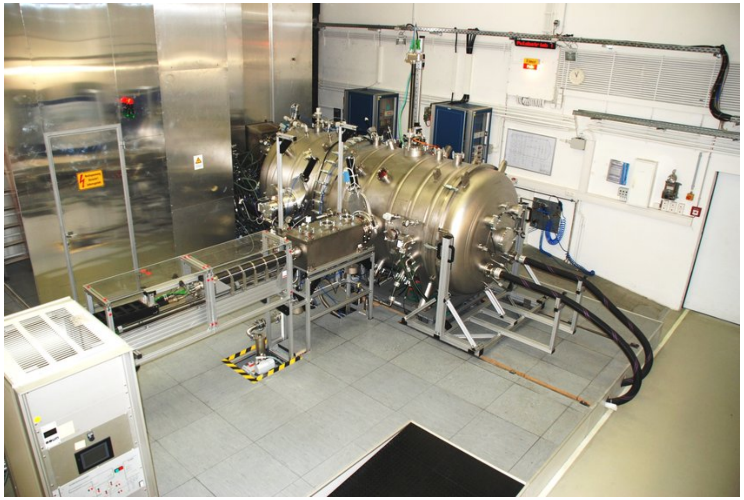


--> Up to **100KW m^{-2}** continuous radiative heat load + ECRH stray radiation on all wall components, including diagnostics.
- All diagnostics required to survive continuous heat loads and ECRH stray radiation since conception.
- Many new developments / technologies were required as well as thorough testing. Experience available for ITER.



MISTRAL:
Greifswald ECRH stray radiation test facility will be operated again during current shutdown for testing new components/concepts.

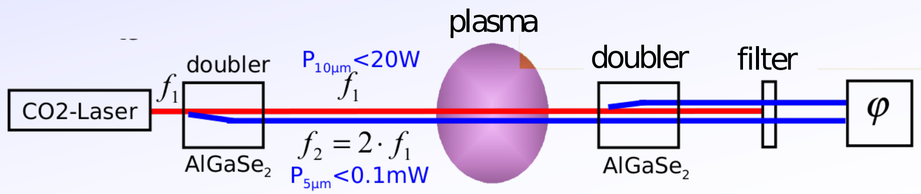
GLADIS Test facility in Garching available.
- 2x 1MW ion sources.
- Heat fluxes up to 45 MW m^{-2}
- Pulses up to 45s.



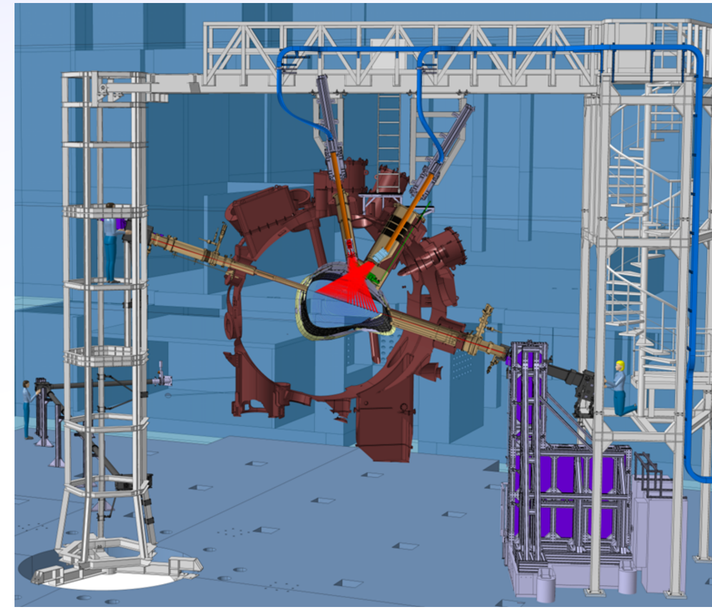
Dispersion Interferometer

- Single channel core interferometer provides average density in real-time

- Dispersion-interferometer type, (as 'DIP' on ITER)



- Inherent viabration insensitivity



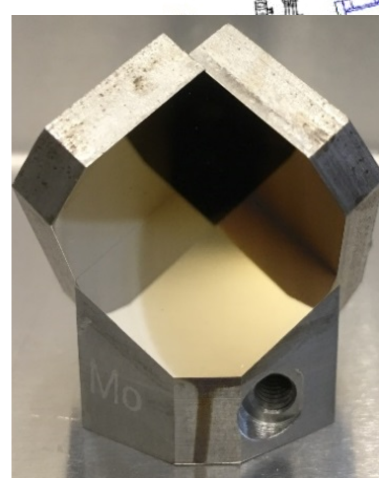
- Generally running very well.
- Real time FPGA analysis --> Density feedback controller.
- Some issues with unexplained non-ideal behaviour ('non-circularity') also with long term environmental drifts --> Long pulse relevance

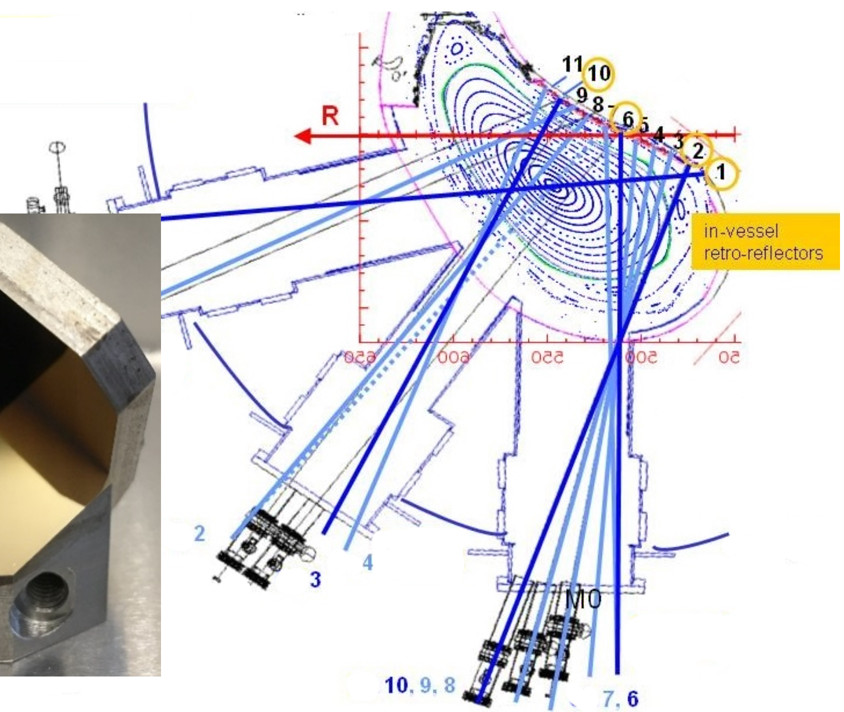
Multichannel Interferometer

- Planned but currently on-hold due to funding.

- In-vessel Molybdenum corner-cube retroreflectors installed before OP1.2.
  - Problems with manufacturing/polishing
  - Inspection and testing after OP1.2 shows surface deposition leads to significant reduction in visible reflectivity, but ok at required 5µm.

  - Will continue to monitor in long-pulse operation.



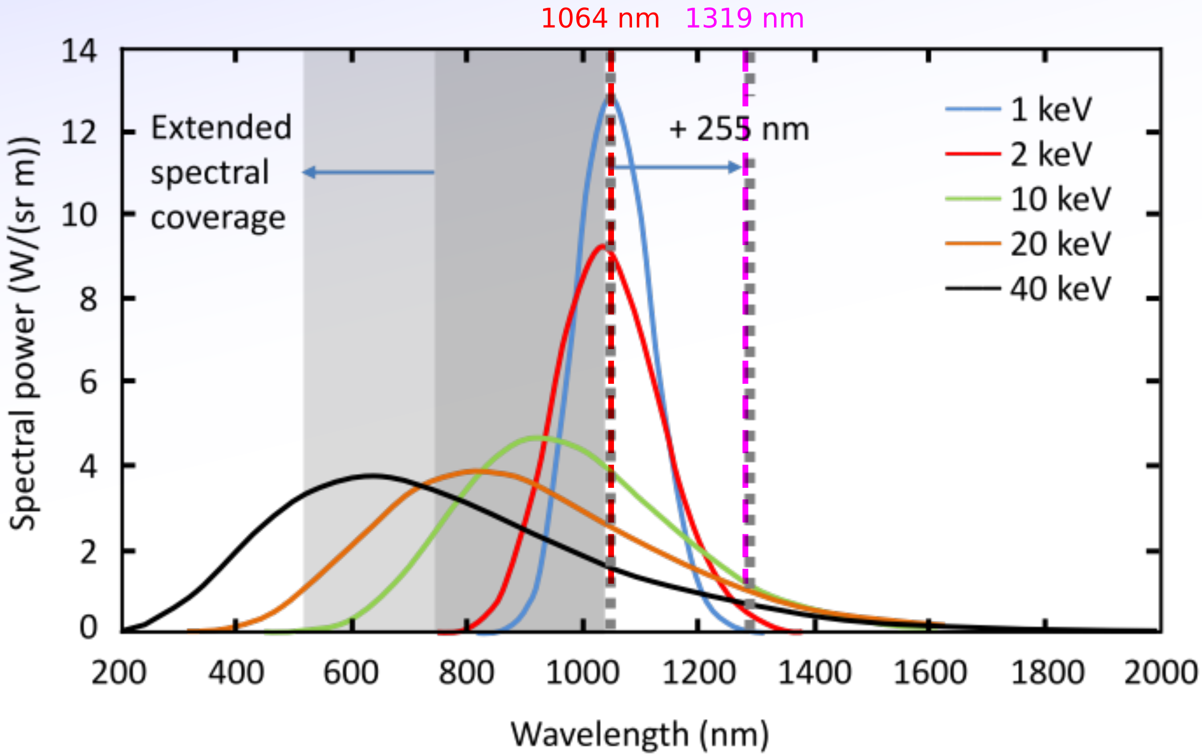


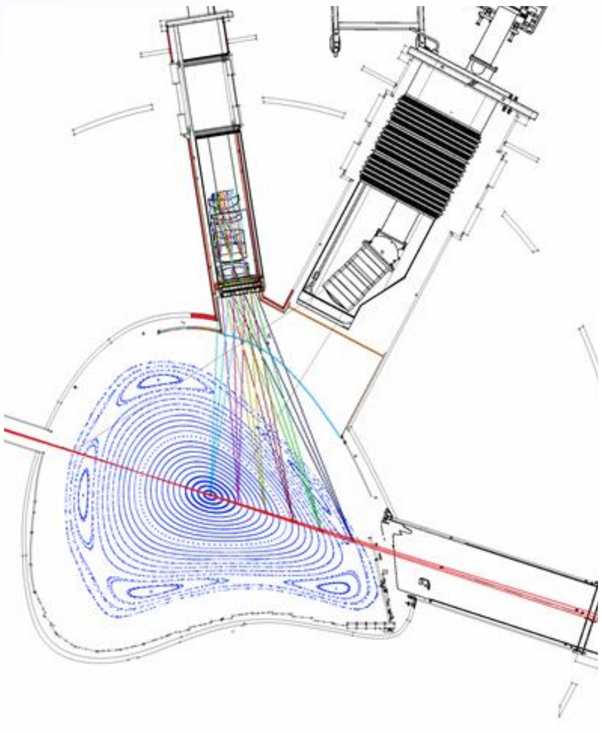
Thomson Scattering

- Typical high-resolution Nd:YAG 1064nm system 3/4 Lasers.

Two ITER-relevant developments:

1) Dual-wavelength system to extend T_e range and allow some calibration check (reported Nov 2018)





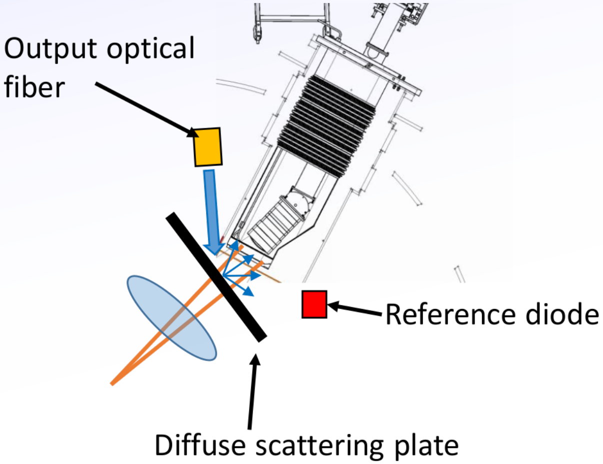
Development work on-going with modelling support from Italy but low-priority project for W7-X due to target high-n_e, lower-T_e plasmas.

- Mirrors capable of reflecting high energy at both wavelengths.

Thomson Scattering

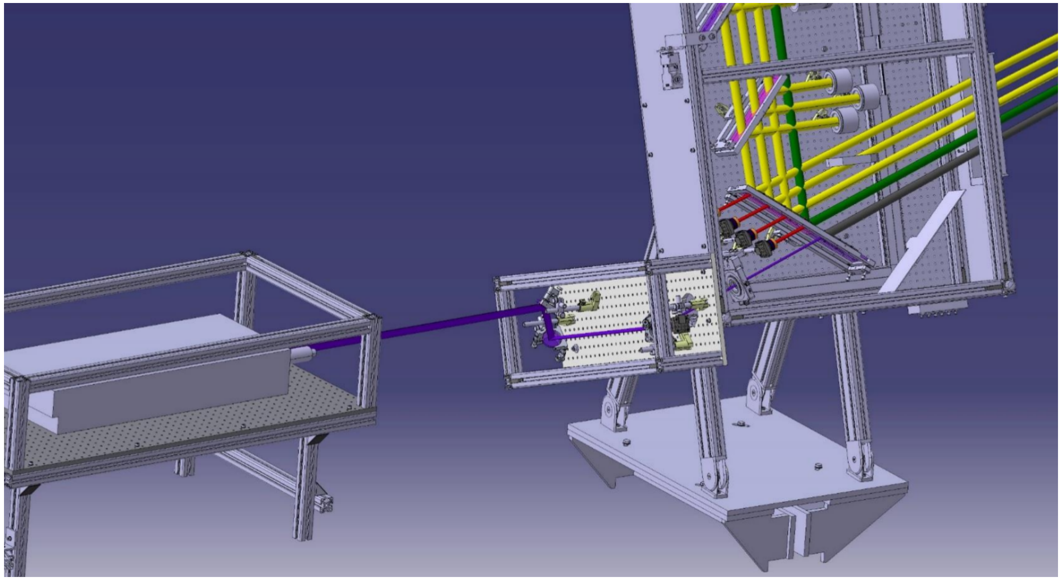
2) OPO-Tunable wavelength laser, in-situ calibration Rayleigh calibration technique.

Usual calibration: Super-K variable wavelength laser fired at diffuse scattering surface placed in front of optics. Does not include vacuum window. (Would anyway not be possible for ITER).

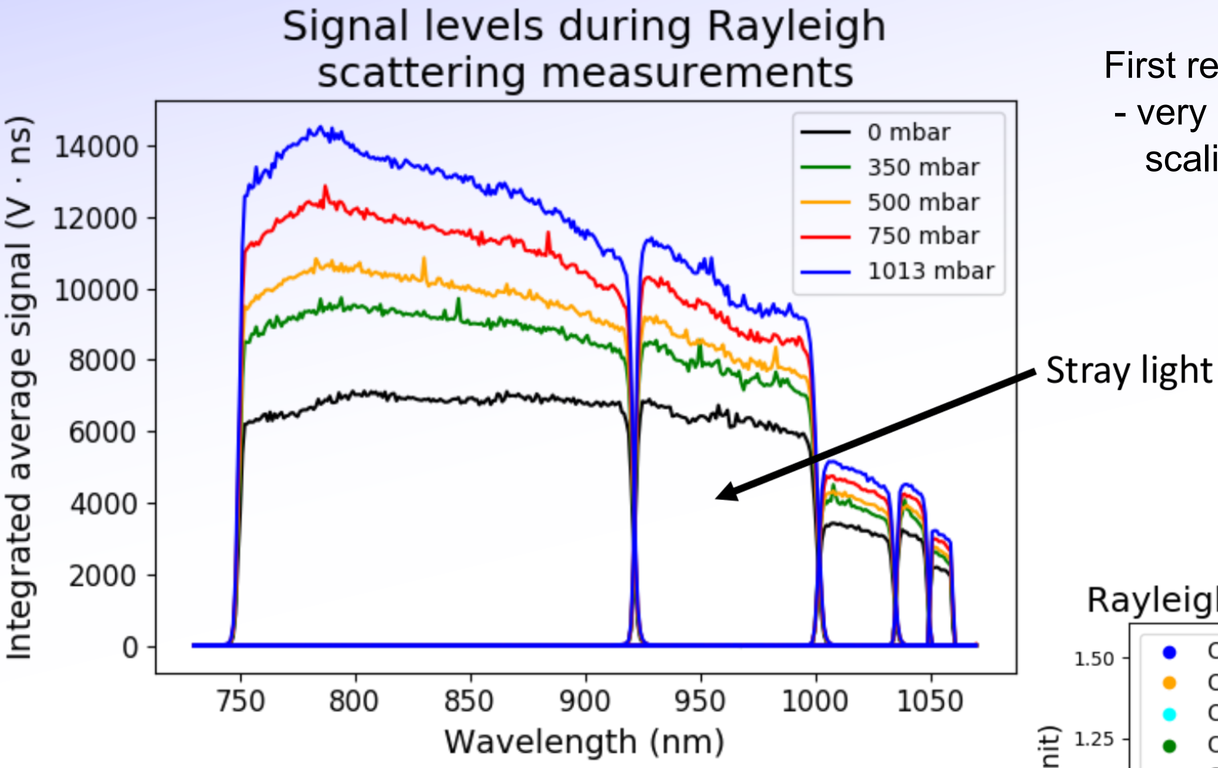


New method:
- Fill vessel with gas
- Fire high energy tunable OPO laser along normal laser path
- Measure Rayleigh scattering with all same optics as normal system.

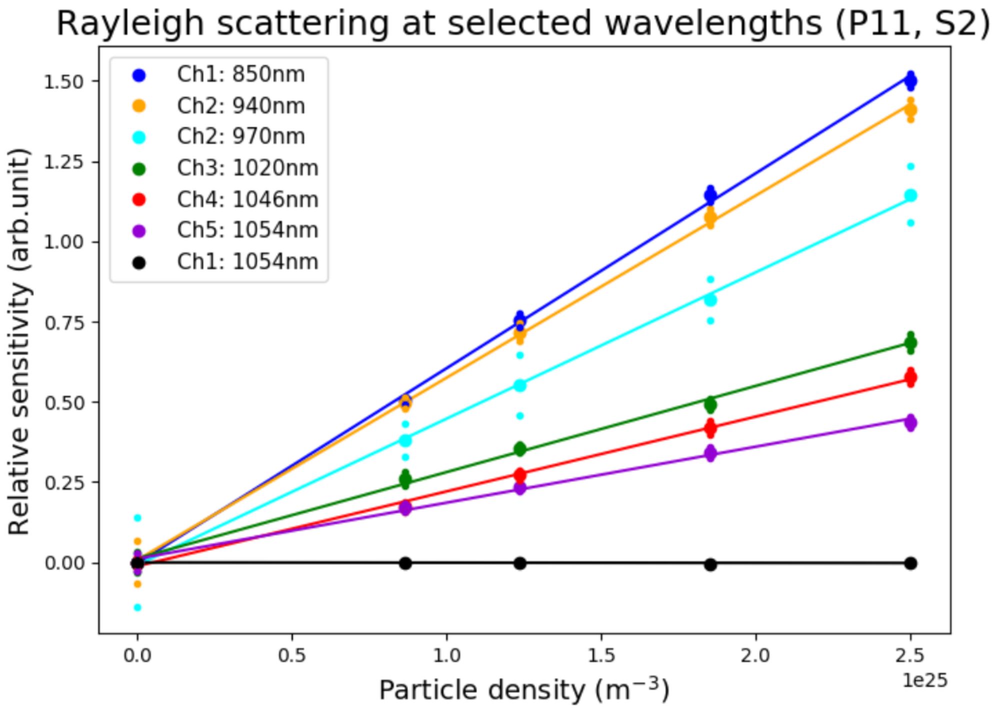
- First real in-situ tests made at W7-X after OP1.2.
- OPO Installed temporarily in torus hall:



Thomson Scattering

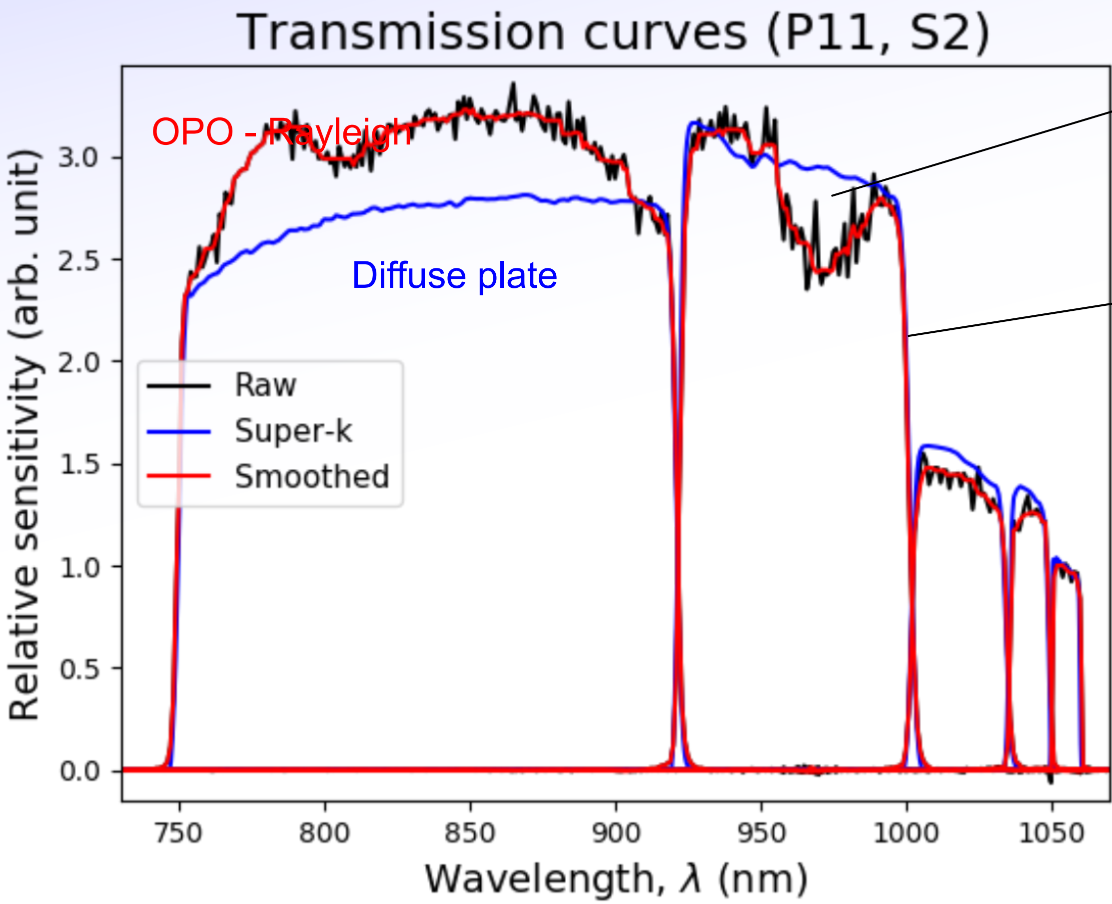


First results:
- very strong stray light but good linear scaling with pressure:



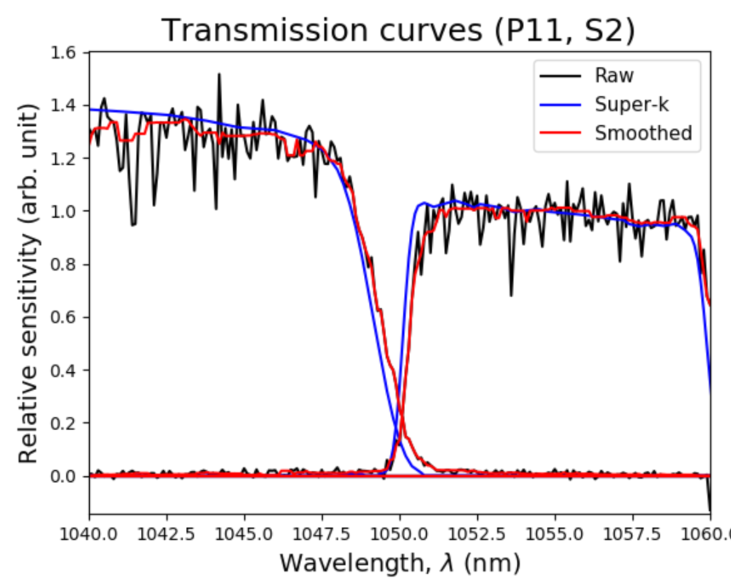
Thomson Scattering

Good first results - mostly same curves as diffuse plate calirbation:



Suspected H^2O vibrational mode ~970nm or interference from mirrors?

Minor issues:
- Bandwidth limit
- Noise
- Wavelength uncertainty
  --> issues near filter edges:

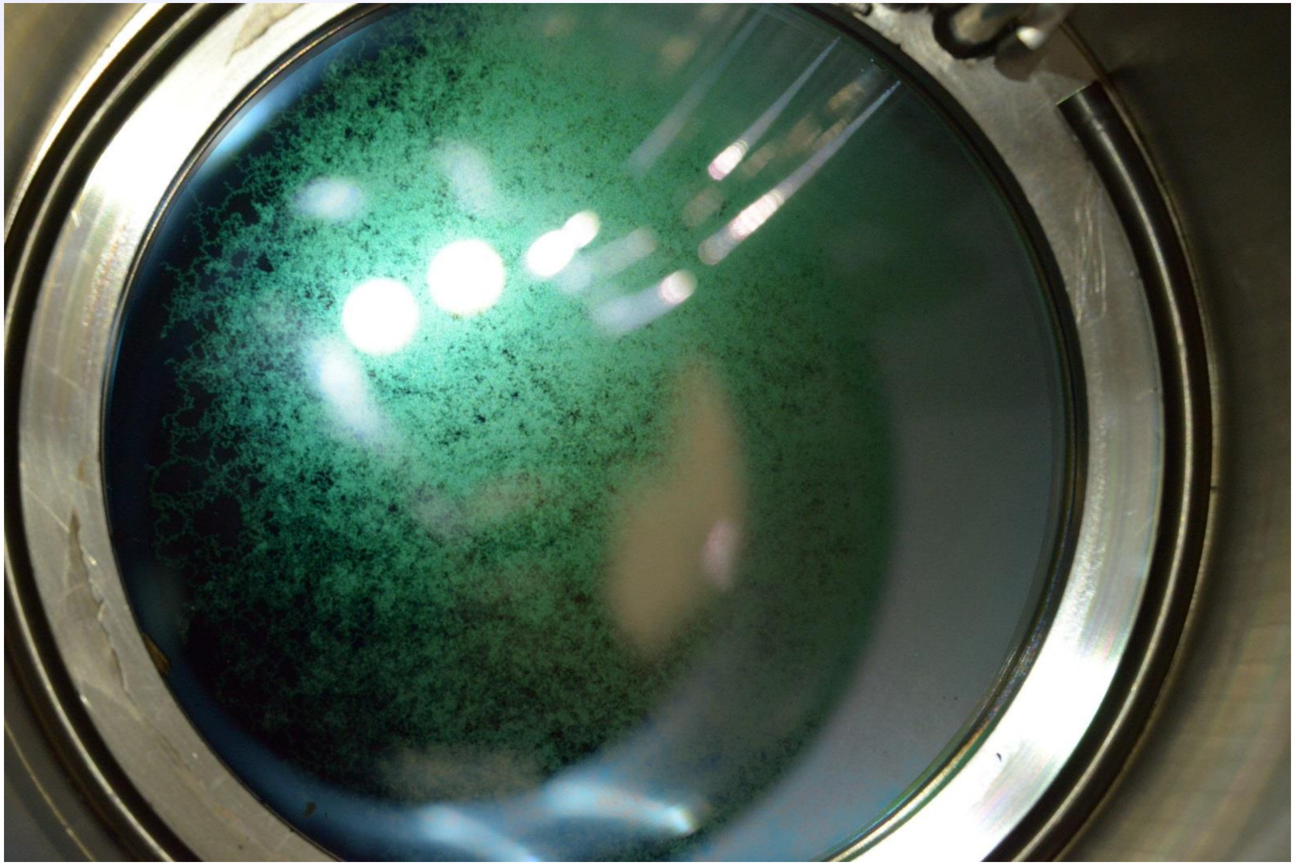


- For now using diffuse plate curves scaled to match Rayleight scattering intensity.
- Will be installed for OP2 and further developed / tested.

Thomson Scattering

Possible difference...

- Arcing damage to Thomson Scattering window:



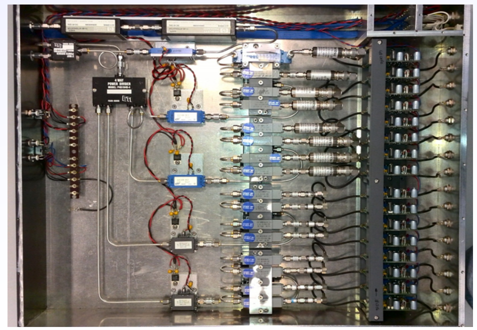
- Arcing from shutter to window surface?
- Possible that ITO coating for stray radiation was installed on vacuum side?

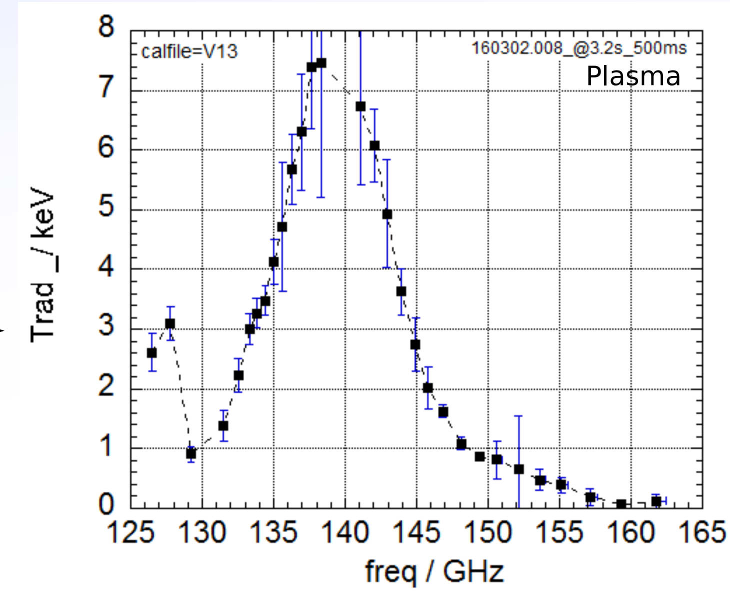
--> ECRH stray radiation can be a real problem!

Electron Cyclotron Emission

ECE Radiometer:

- 32 channel radiometer
  - Performs well up to cut-off density 1.2×10^{20} m^{-3}.





Electron Cyclotron Emission

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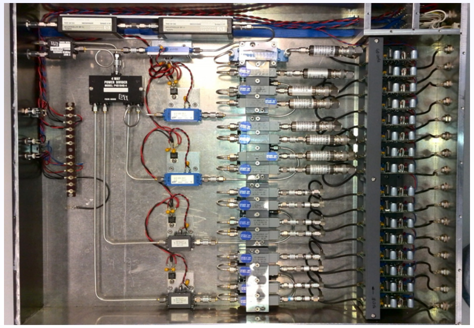
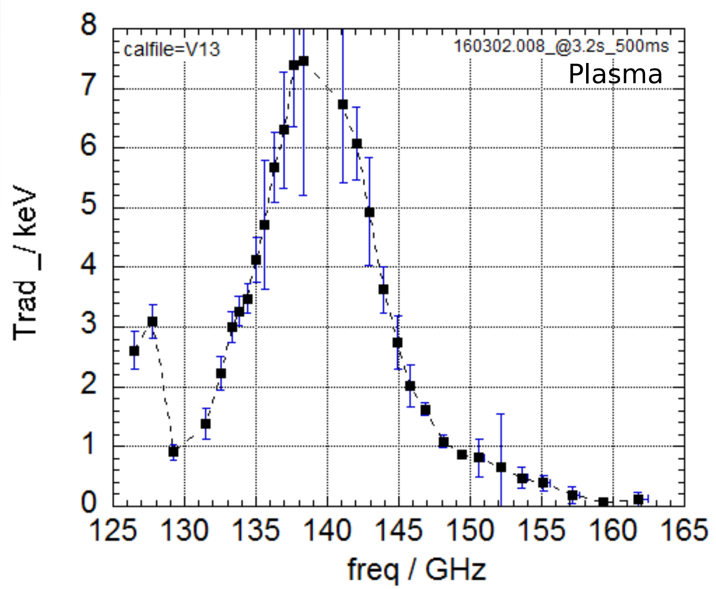
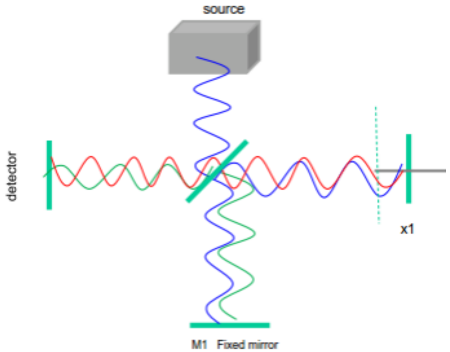


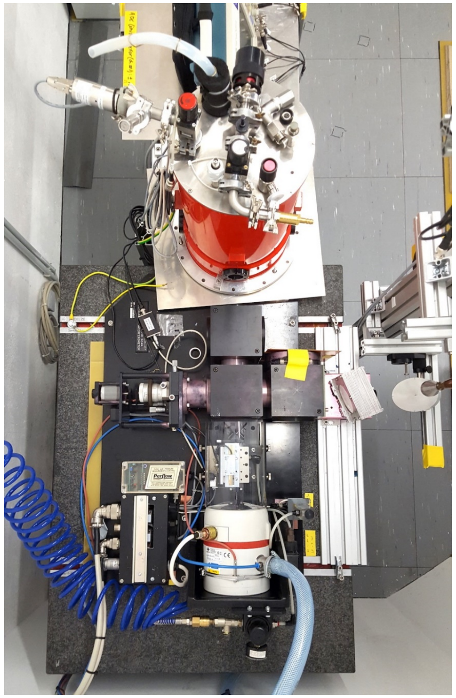


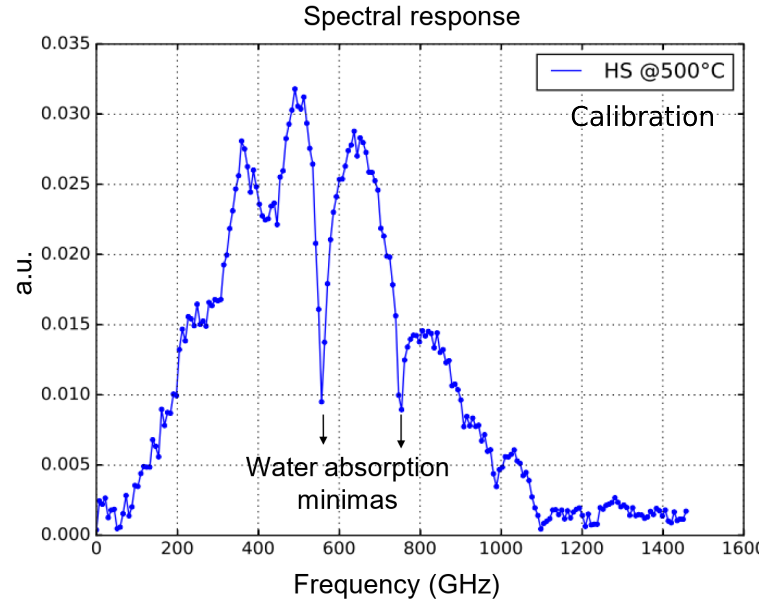
ECE Michelson-Interferometer:

- Development of notch filter for ECRH stray-radiation, difficult for broadband system
- 45ms time resolution (mirror scan).
- 5GHz resolution --> Poor radial resolution



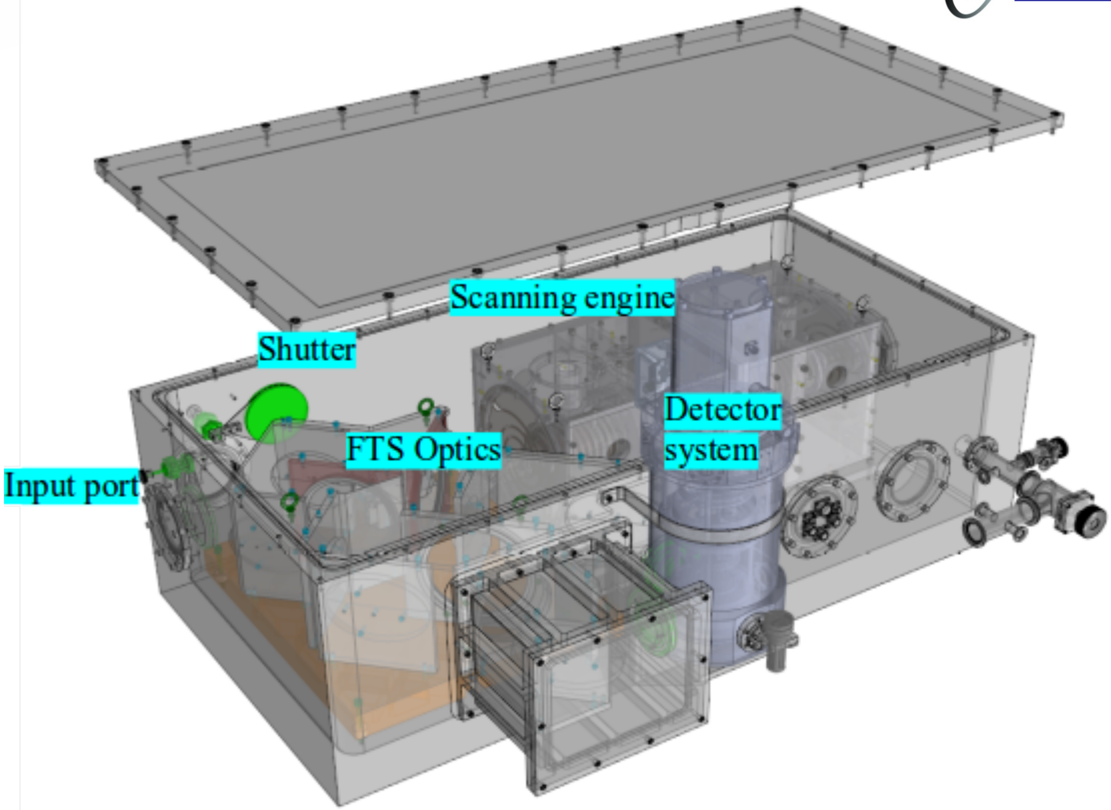
(a)





Electron Cyclotron Emission

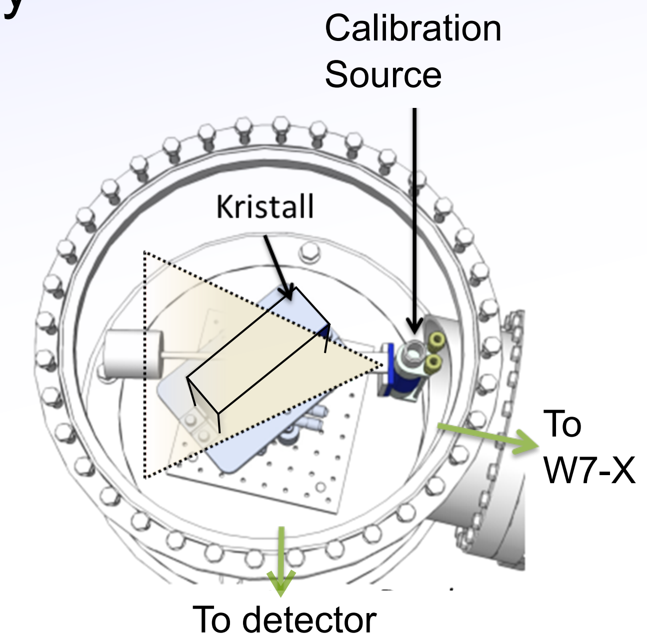
Possibility to test ITER Compact ECE Michelson Interferometer.
- Presently at ITER-India until delivery to ITER.
- W7-X could be used for full test/demonstrate under realistic conditions of ECRH dominant
  (e.g. to develop a suitable notch fitler)
- Collaboration with ITER-India - positive from both sides.
- Still investigating funding possibilities for transport/installation at W7-X.

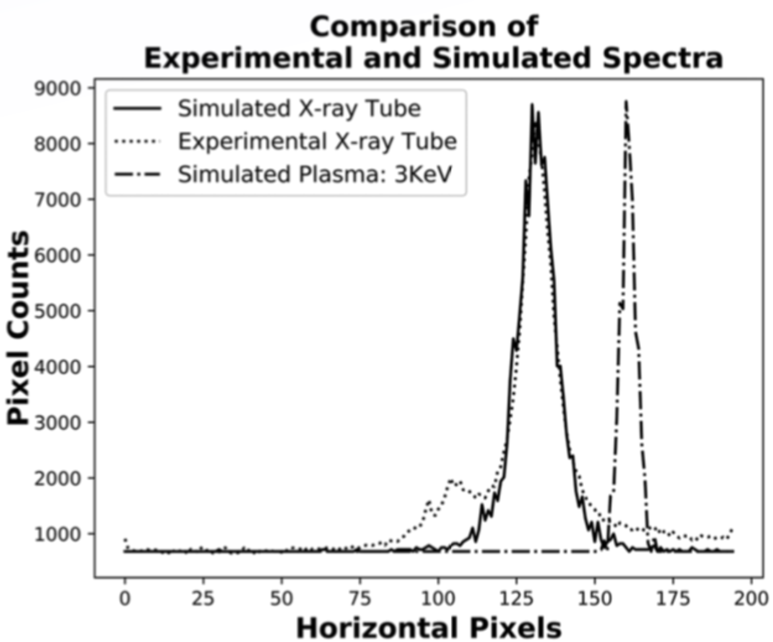


X-Ray Crystal Spectroscopy

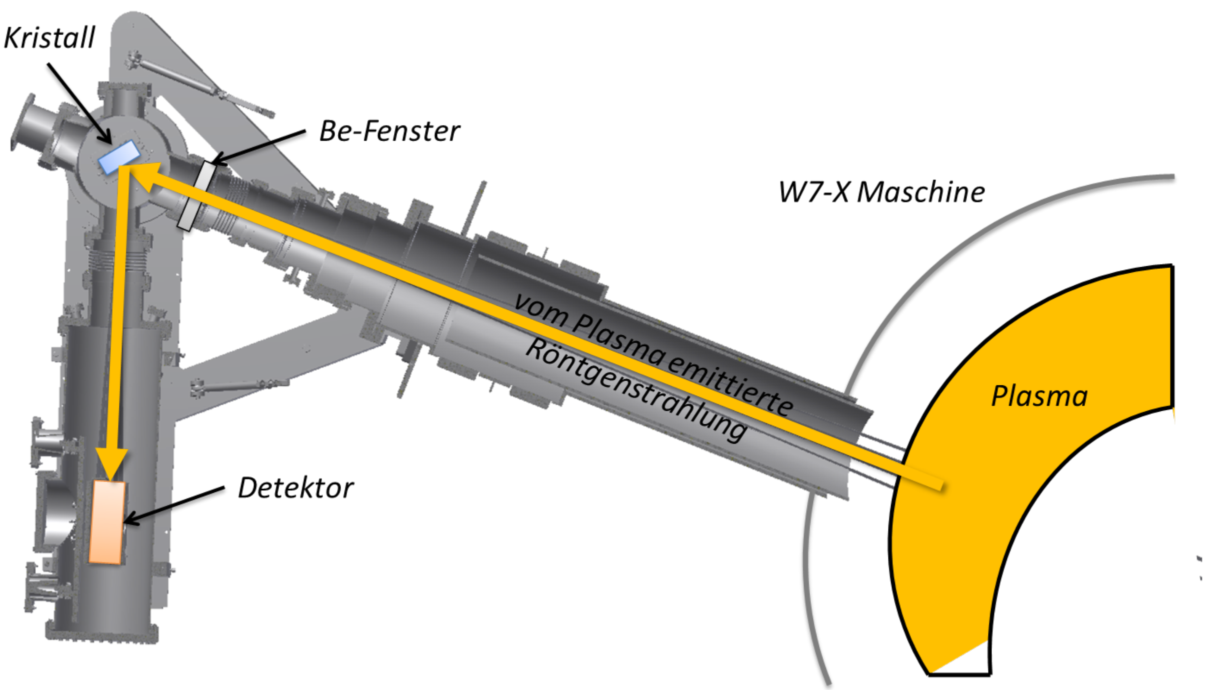
X-Ray Imaging Crystal Spectrometer
+ High-resolution X-ray Crystal Spectrometer

- Operating since OP1.1 very reliably delievering good Ti measurements.
- Core flow measurements reasonable quality but ...
  - No absolute calibration
  - Calibation variation with environment (~ few °C)
- In-situ calibration system planned for OP2.
- Lab comparisons to simulation conducted.
- Expected accuracy ~ 1km/s



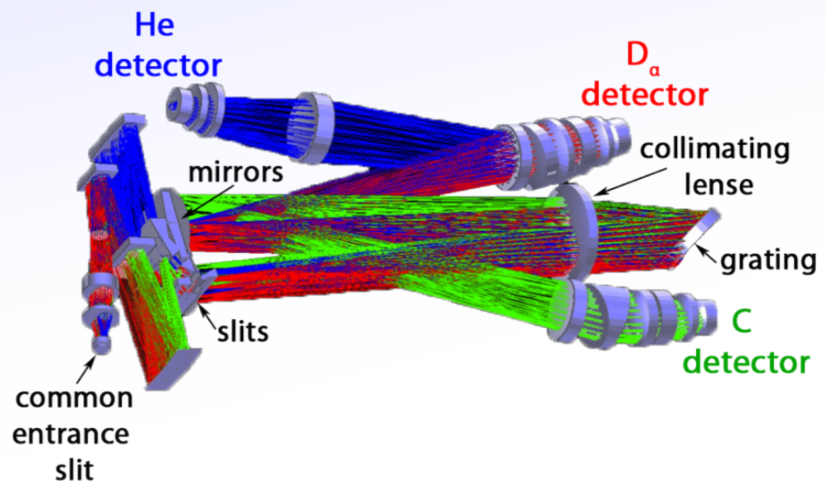


(c)



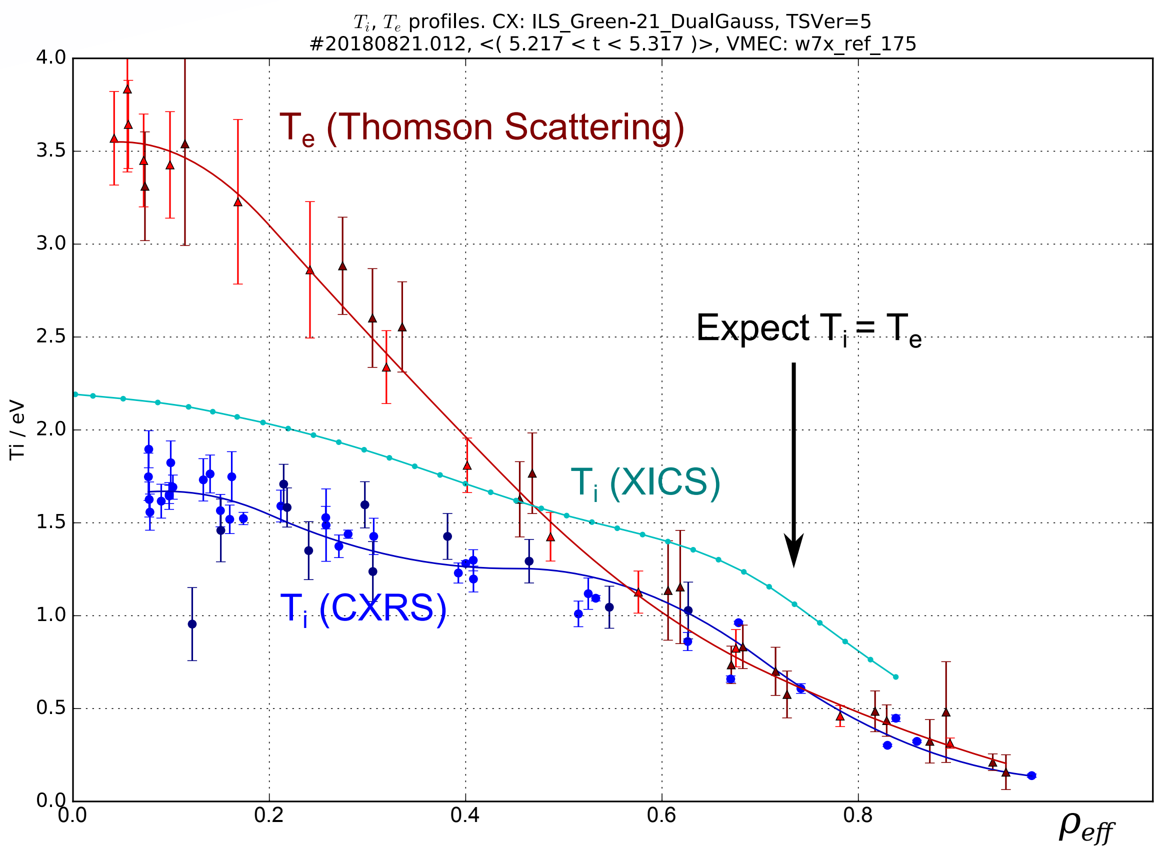
T_i: Crystal X-ray vs Charge Exchange

OP1.2b also included first NBI operation --> CXRS
- Not directly relevant as observation of carbon is easy in Carbon wall machine!
- Using TU/e, FZJ Jülich, TNO prototype high-étendue ITER core spectrometer
  - Not now forseen for ITER, but very good for us!



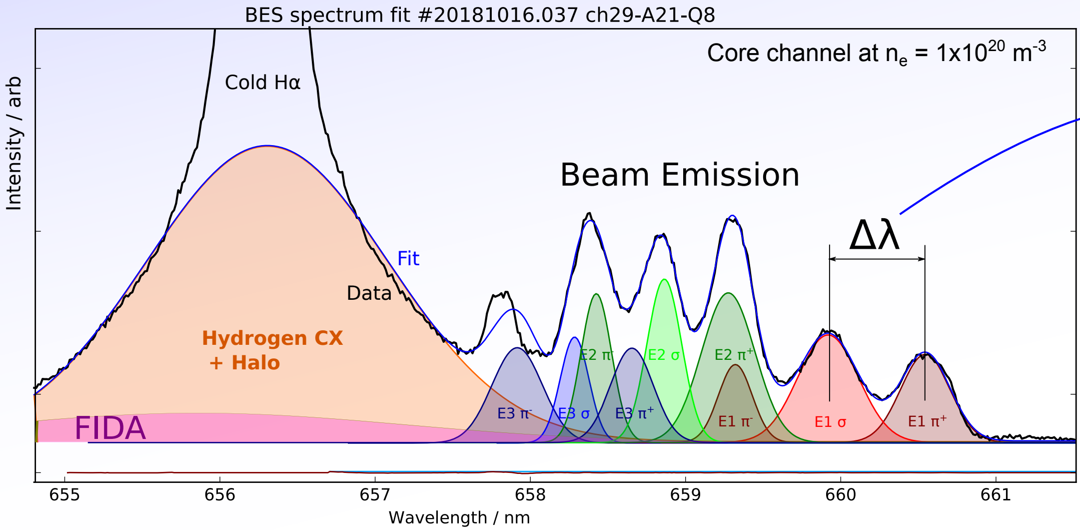
- ~200 - 400eV apparent over-estimation by both X-Ray spectrometers.

- Still under investigation but so far no obvious explanation.

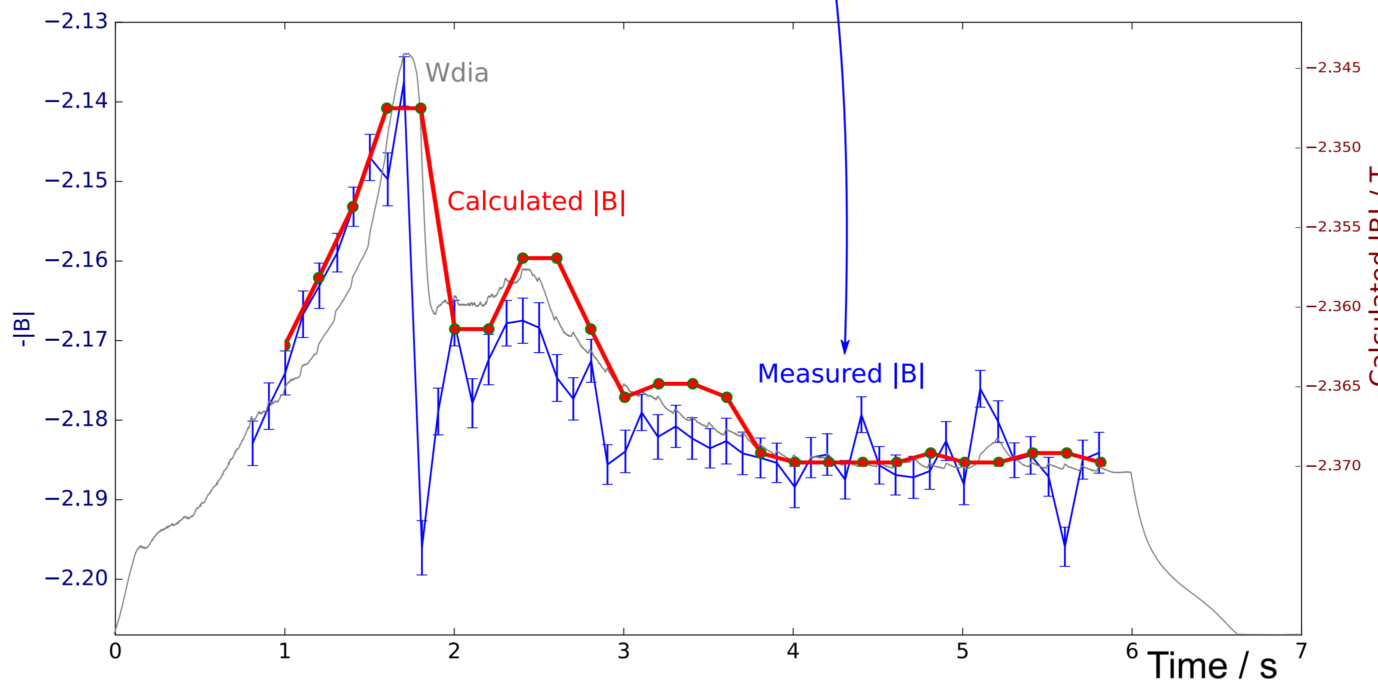


Beam Emission Spectroscopy (+MSE)

CXRS 'ITER' Spectrometer Hα channel provides Beam Emission Spectrum:



Stark-splitting derived |B| from BES matches well with expected.
--> Unexpected diagnostic!



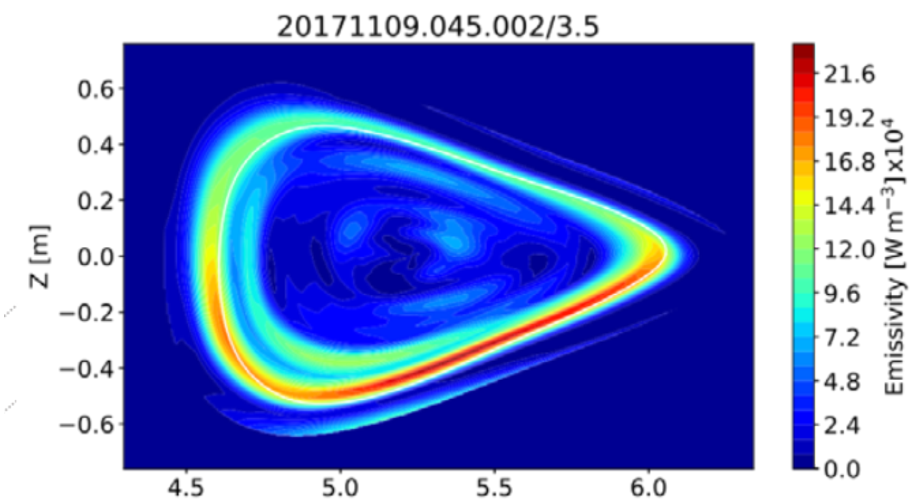
[D. Zhang]

Bolometer

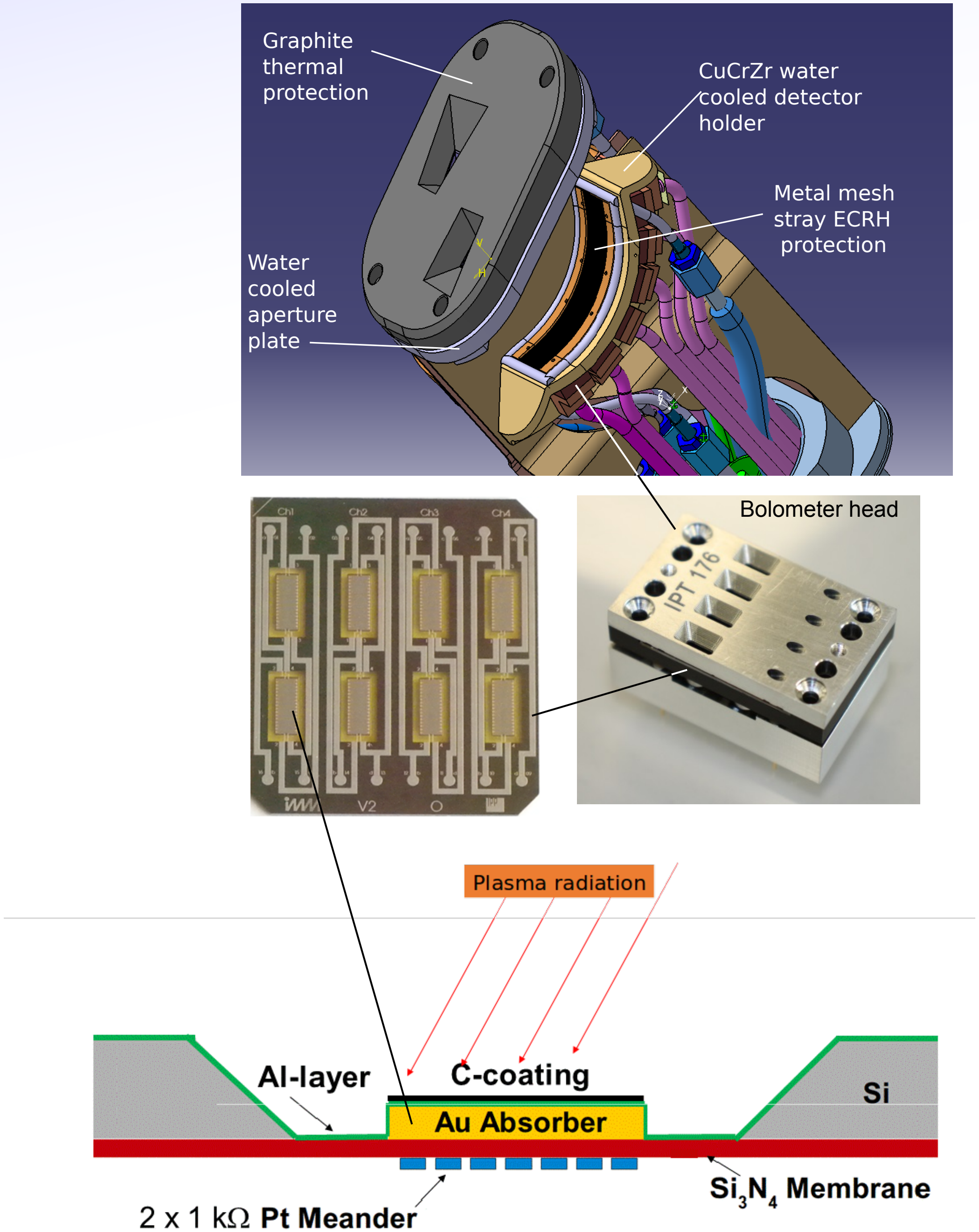
Measurements of radiated power were critical for last campaign OP1.2a due to radiative density limit:

Bolometer design:
- Metal resistive thin-film type.
- Water cooled and encased in graphite to withstand long pulse operation.
- Metal mesh and TiO/Al2O3 coating to supress expected 20kW m^{-2} ECRH stray-radiation.
- Collaboration with ITER-bolometer team & IMM (Fraunhofer-Institut for Microtechnology and Microsystems)
- W7-X as a test-bed of ITER bolometers.

Tomographic reconstruction during detached plasma: (Radiation at seperatrix)



[S. Kwak, D. Zhang]



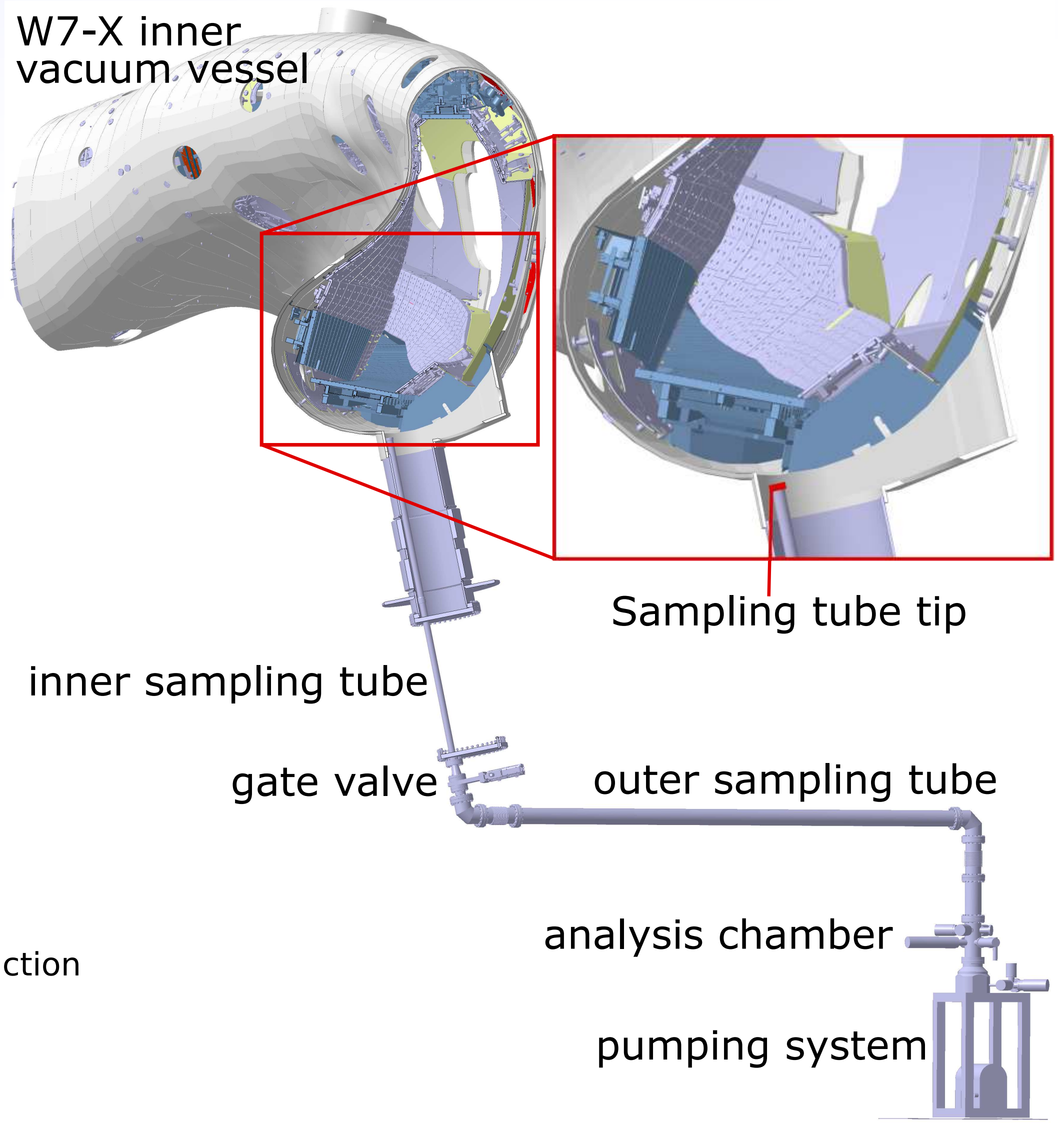
Diagnostic Residual Gas Analyzer

G. Schlisio, *Rev. Sci. Instrum.* Submitted March 2018

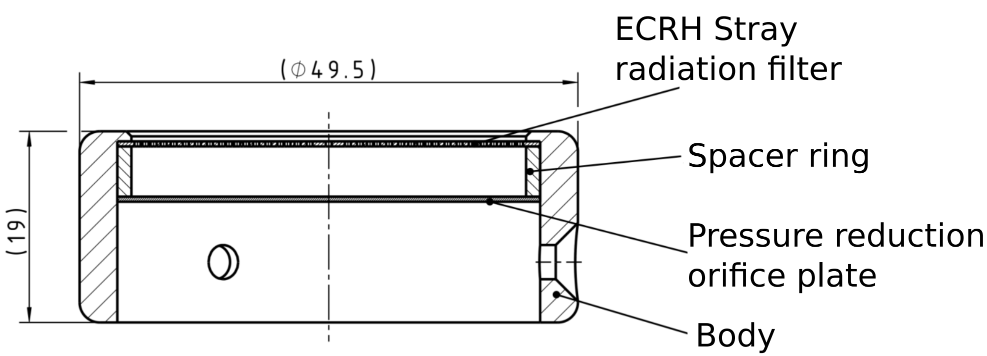
- DRGA Prototype analysis chamber developed by US-ITER at ORNL (for divertor pumping DRGA)
- Tested on test setup and linear machine in US.
- Operated on W7-X in last campaign (OP1.2b):

Sampling tube build to connect to W7-X divertor:
  - Simplified but similar to ITER concept.
  - 7m length (ITER = 10m)
  - Multiple turns.
  - No tritium handling complications

- First demonstration of pressure-reduced long sampling tube.



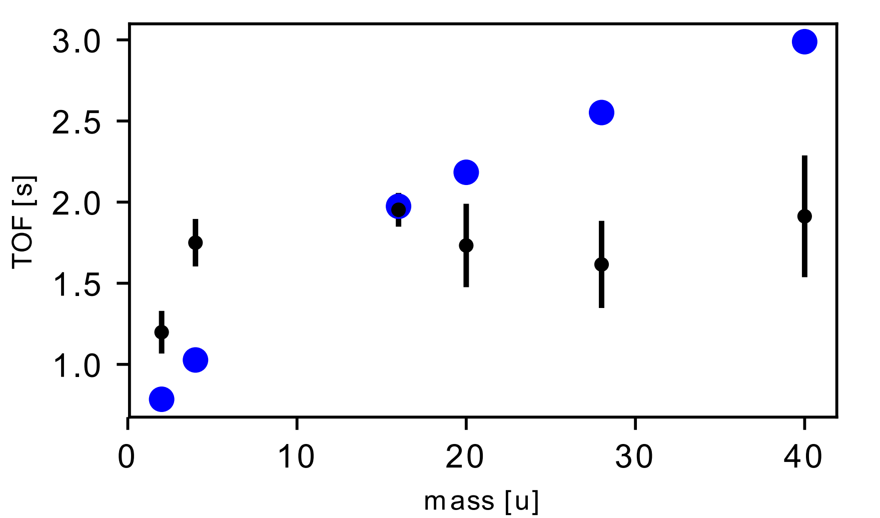
- Cap:

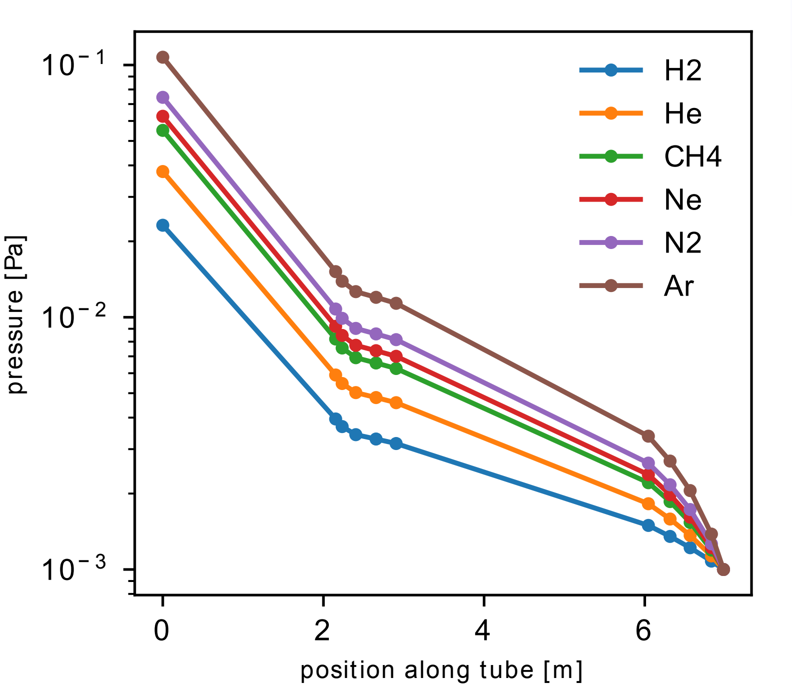


G. Schlisio, *Rev. Sci. Instrum.* Submitted March 2018

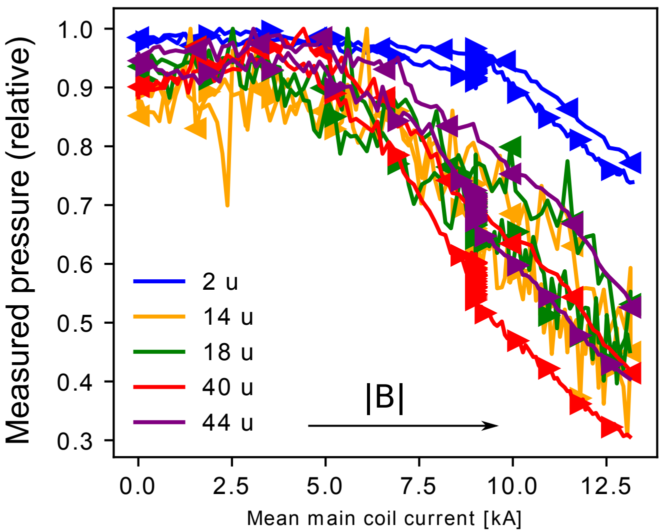
Diagnostic Residual Gas Analyzer

- Linear analytical model for pressure along tube dependent on gas:
- Prediction of time-of-flight ~1-2sec roughly agrees with measurements and with ITER design requirement.
- Different TOFs needs to be deconvolved to interpret relative time evolution of gases.





- Magnetic field effect also checked:
  - 6mT W7-X field at DRGA position.
  - 2-layer μ-metal shielding was insufficient (agrees with ORNL test findings)



Diagnostic Residual Gas Analyzer

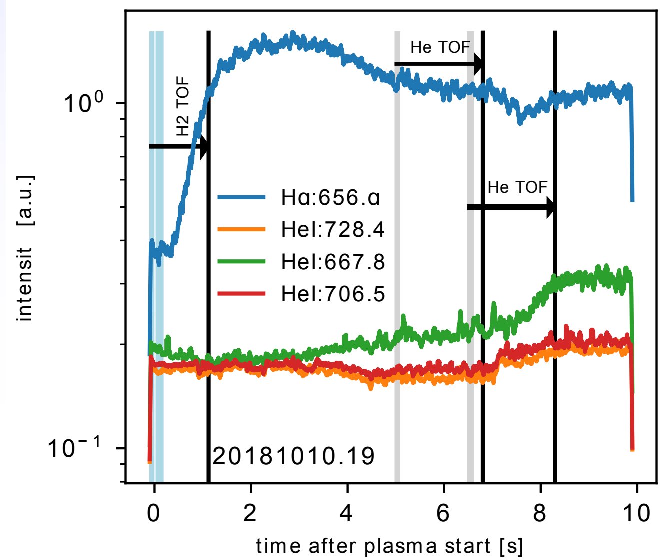
G. Schlisio, *Rev. Sci. Instrum.* Submitted March 2018

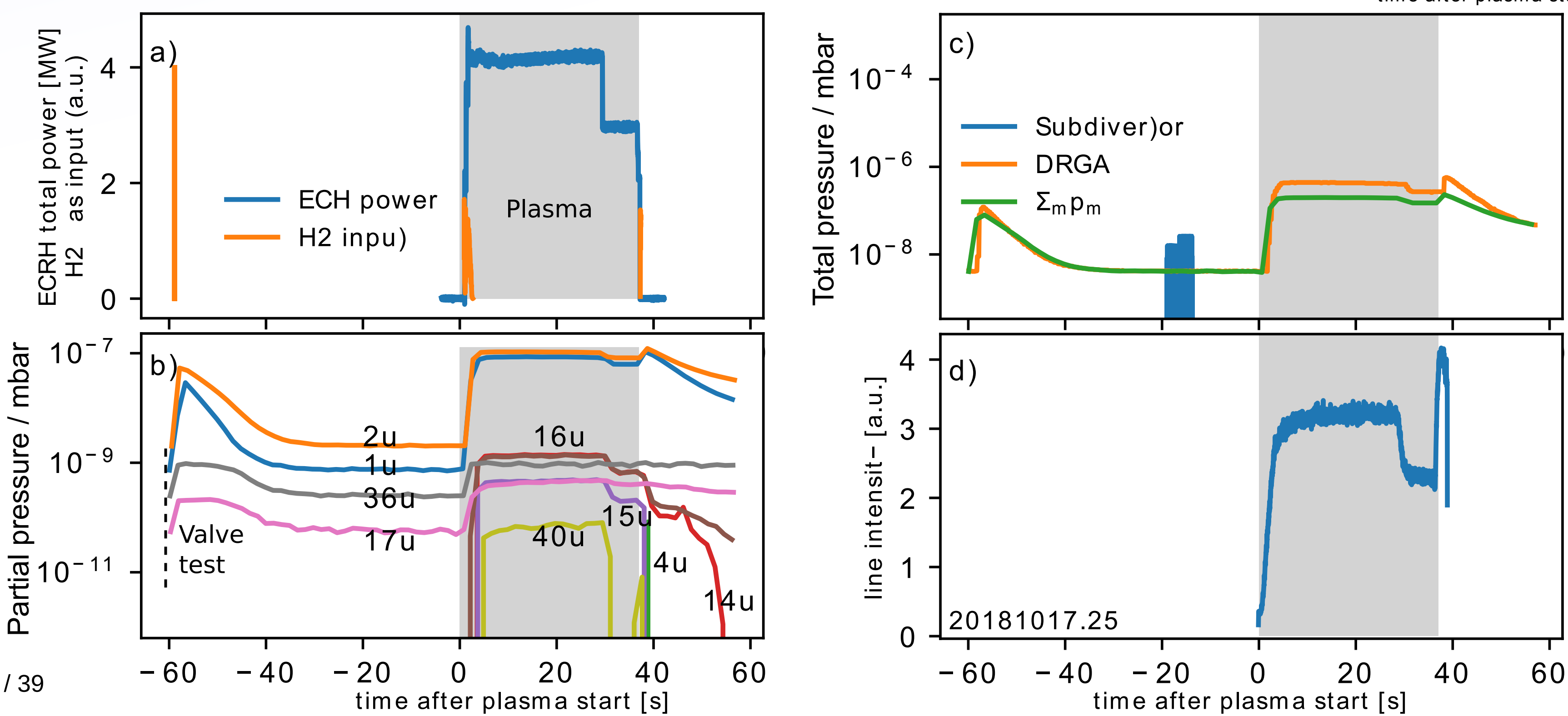
- Useful plasma results obtained:
e.g. during divertor detachment program:

- Not corrected for significant |B| effect.
- Time behaviour as expected from TOF calculations.

- Wide range of trace gases can be detected.

- Will now be installed also for OP2.1 (next campaign)



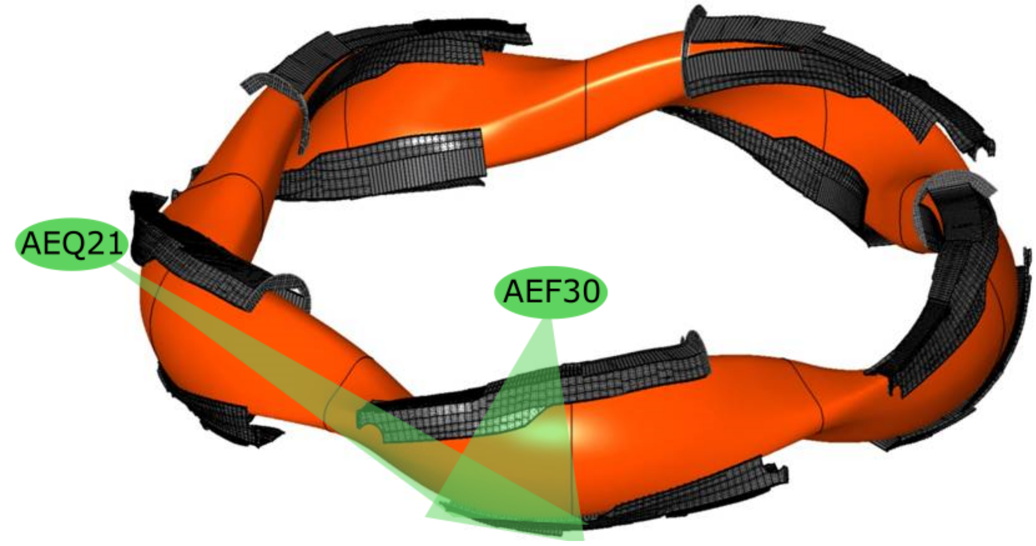


Coherence Imaging Spectropscopy

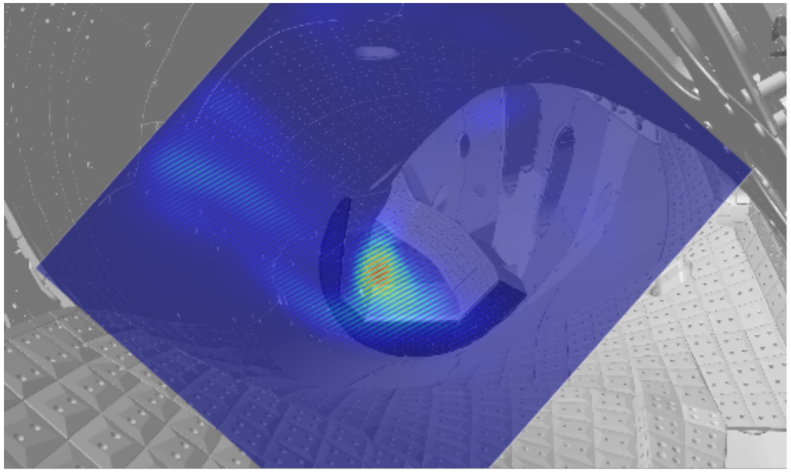
(a.k.a 'Flow Monitor')

- 2 CIS Systems operated at W7-X over OP1.2a+b
- Calibration with OPO tunable laser
  - Good experience with calibration when laser works. (Pushing stability development at supplier)

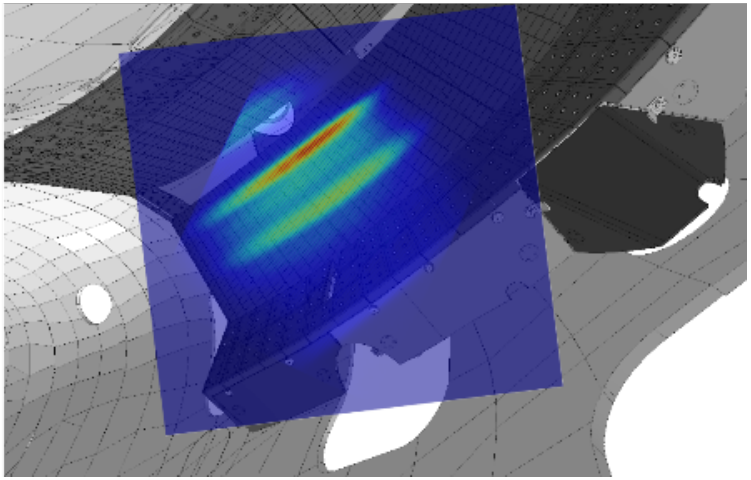
- Measurements made in Carbon, Helium, Hydrogen



Toroidal view:



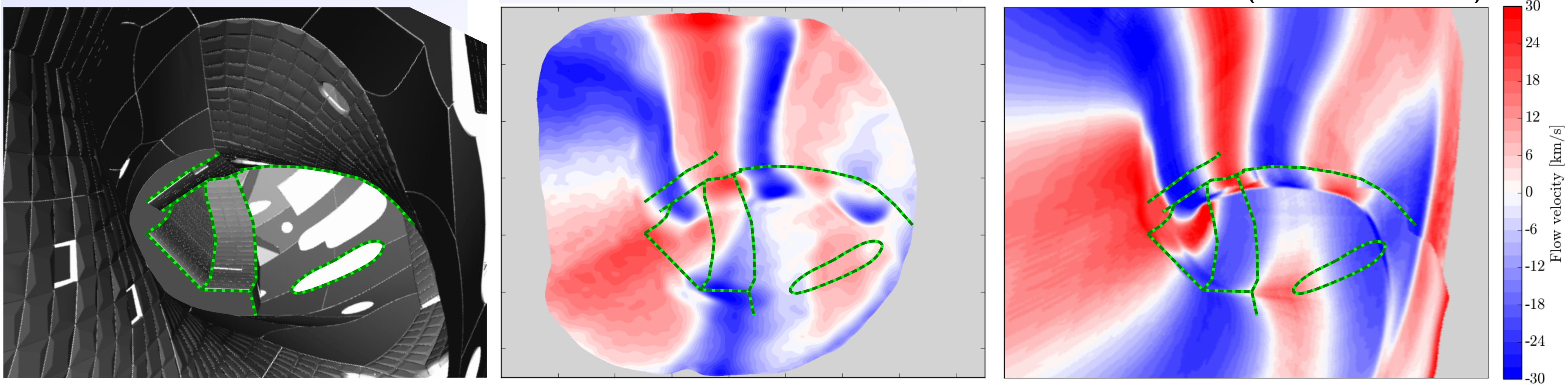
Vertical view:



Coherence Imaging Spectropscopy

- Calibrated flow images reveal counter-propargating flows expected due to island/divertor geometry.
- High frictional coupling of measured C flows to main ion SOL flows.

CAD | Measurement | Prediction (EMC3-EIRENE)



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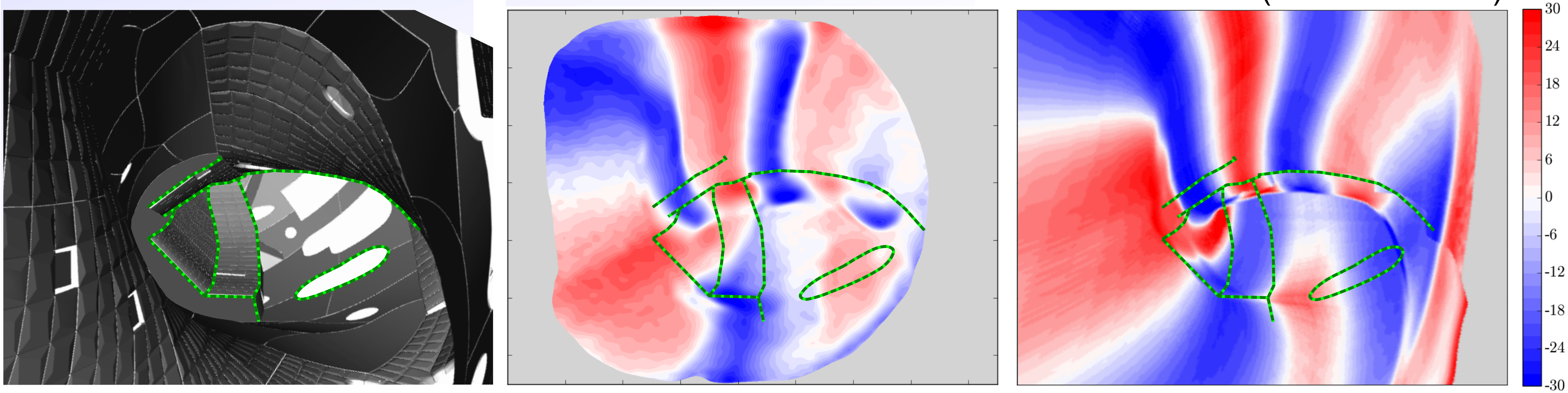
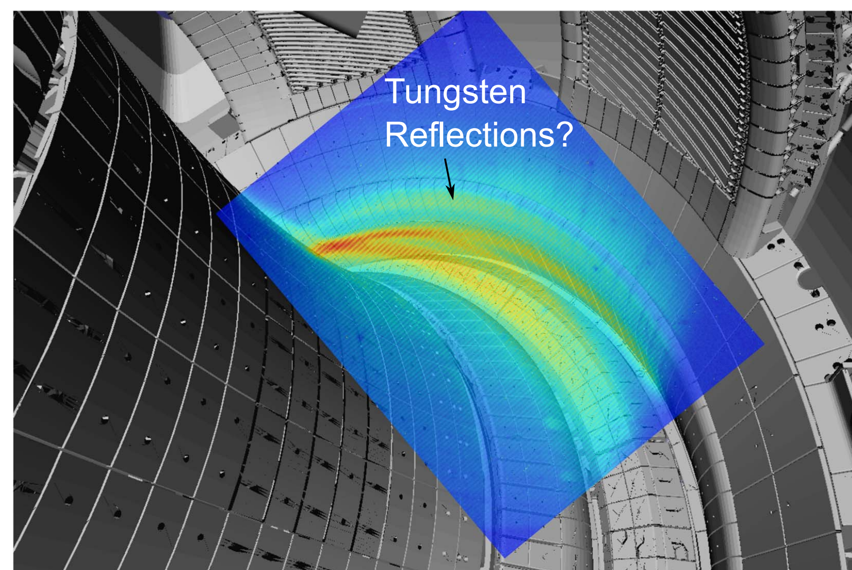
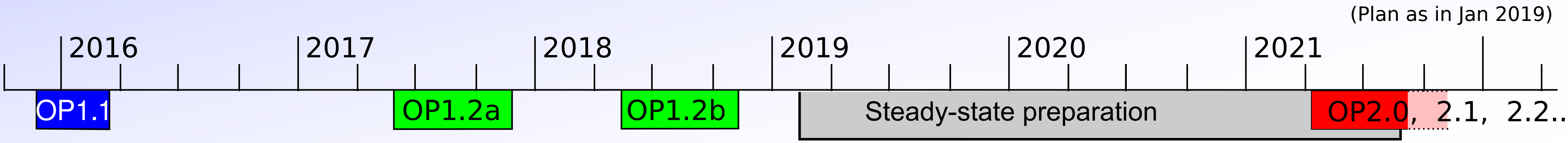


ASDEX Upgrade CIS:

- IPP Greifswald also operating CIS at ASDEX Upgrade
  - Similar view as ITER Flow Monitor.
  - Metal walls and possible reflection problems as ITER.
  - Neutral Hydrogen flow measurements show promise
    as proxy to bulk ion flow.
  - W7-X CIS Instrument (higher performance) used in next
    weeks for new measurements at AUG, including
    calibration laser.
    --> Assist ITER detailed design.



Summary



W7-X 'Test Divertor' campaign OP1.2 now complete.

- Very many diagnostics have been operated sucessfully, several with particular ITER relevance, some as direct ITER prototypes.

- W7-X now preparing for OP2 - full actively cooled long pulse operation from 2021 onwards...

- We are open to ideas and proposals how we can best support ITER diagnostics work.

Thanks for listening!

Neutral Gas Manometers

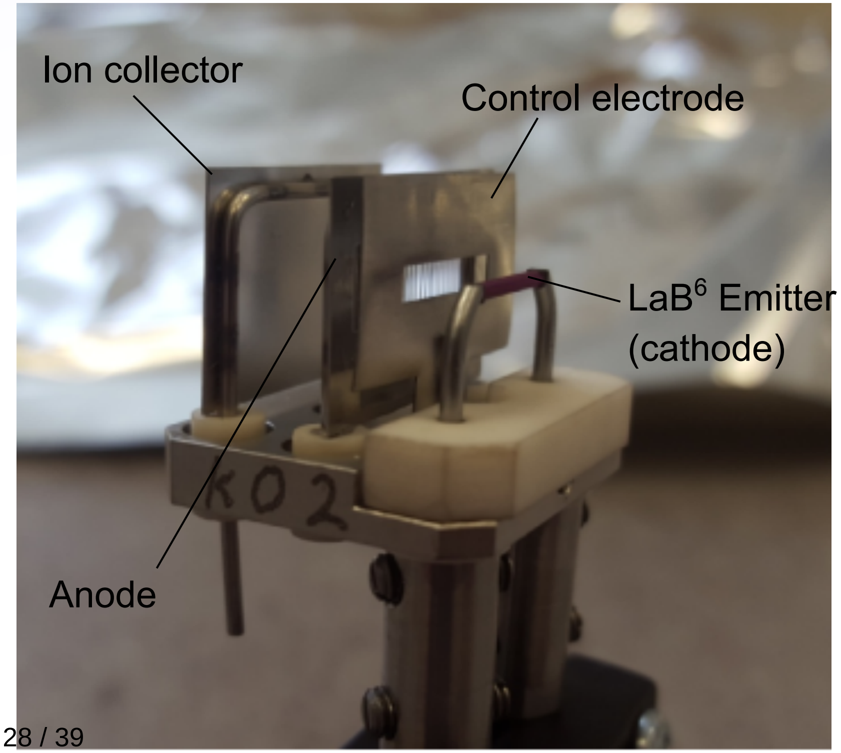
[Wenzel et al., RSI 89, 033503 (2018)]

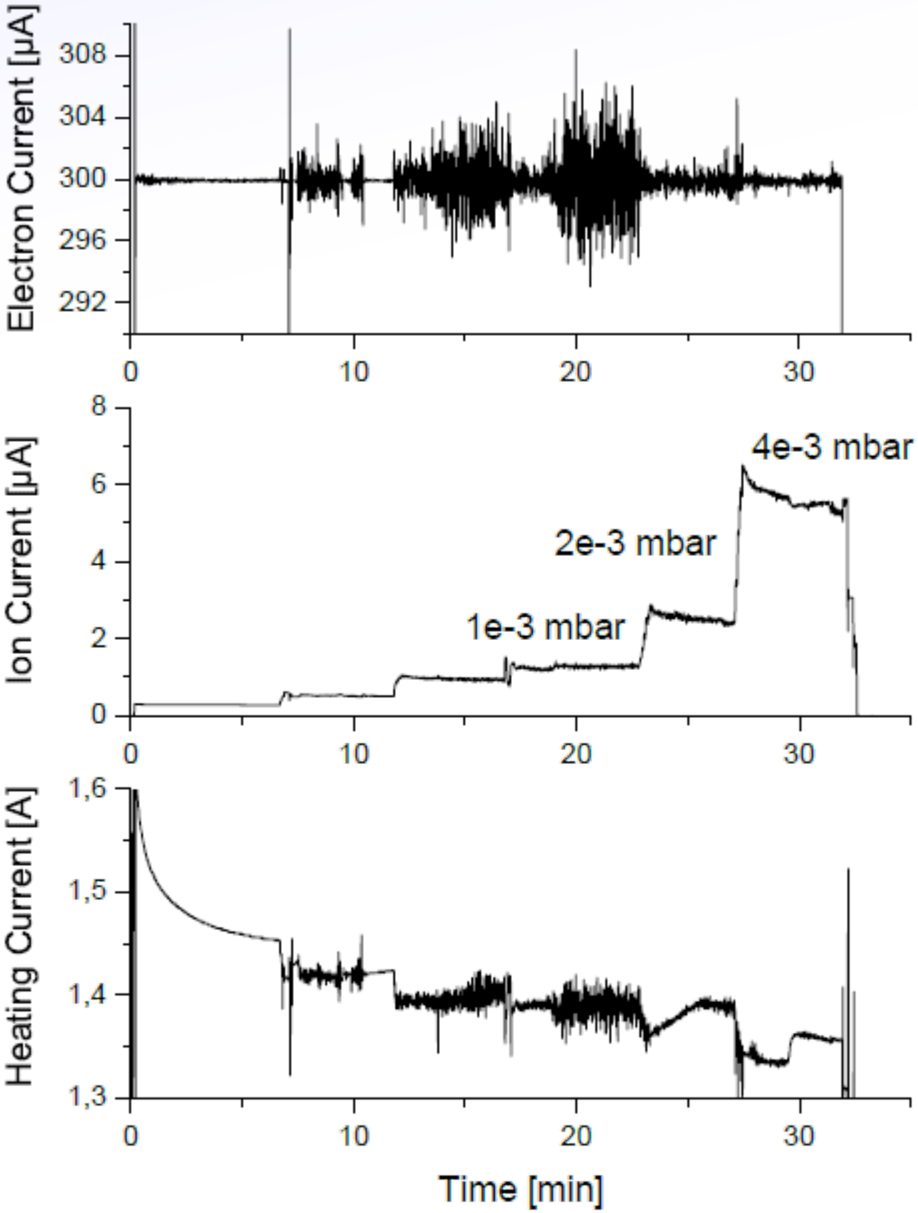
The ASDEX-Upgrade type neutral gas manometers were are also under test in the first campaign but showed failure after several hours cumulative operation.

- OP1.1: Tungsten filaments at 15-20A
  Operated 4, two degraded and one failed completely
  at ~5h total operational time.

- Prototype with LaB[6] crystal instead of filament.

Tested in 3T magnet ahead of installation for OP2.
Only 1 - 2A required for 300μA electron current at 3T.
Goal is to show robust operation over long-pulses.

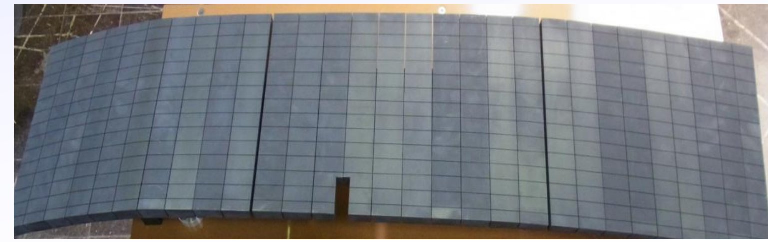




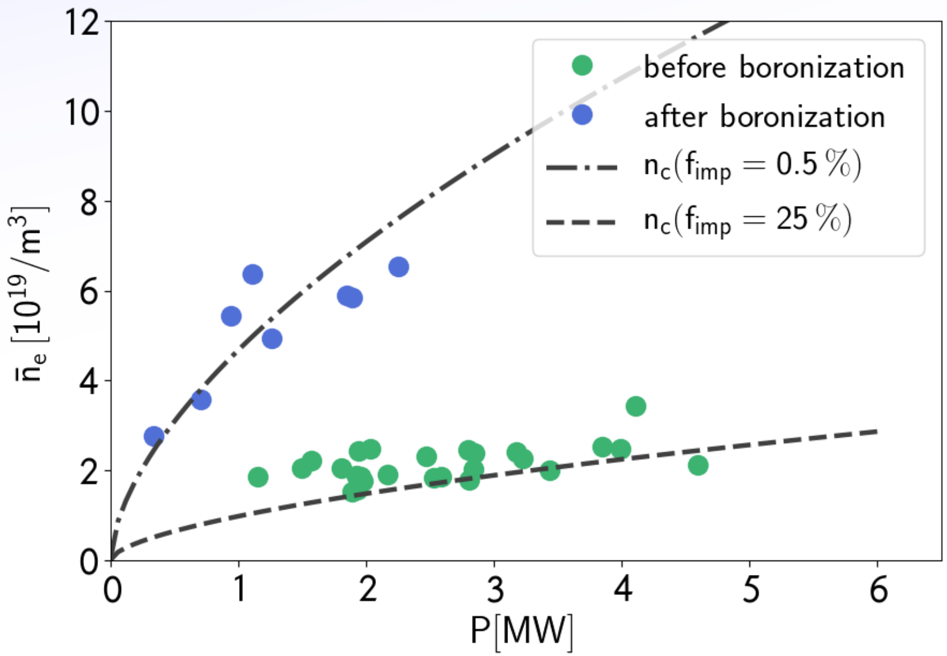
W7-X OP1.2 (2018) Complete

Highlights of OP2.1

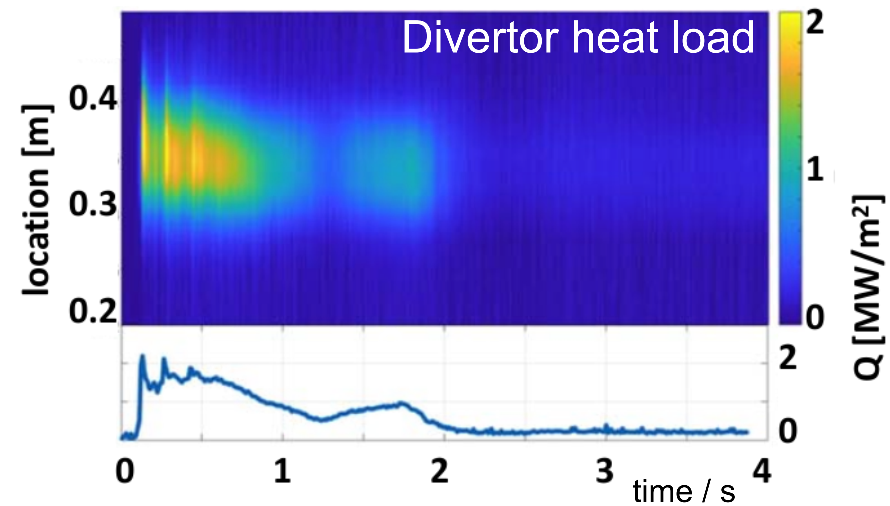
- OP1.2a: Limited densities due to radiative density limit.
- OP1.2b: Boronisation allowed operation to high densities ($n_e \sim 1.8 \times 10^{20}\ m^{-3}$) with up to 6MW ECRH heating.



OP1.2: Test Divertor Unit



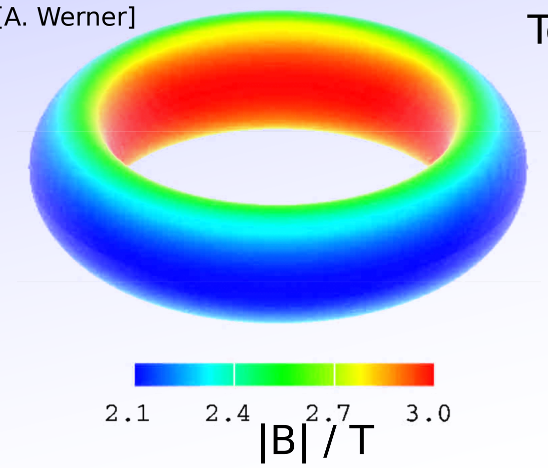
- Full detached divertor operation:



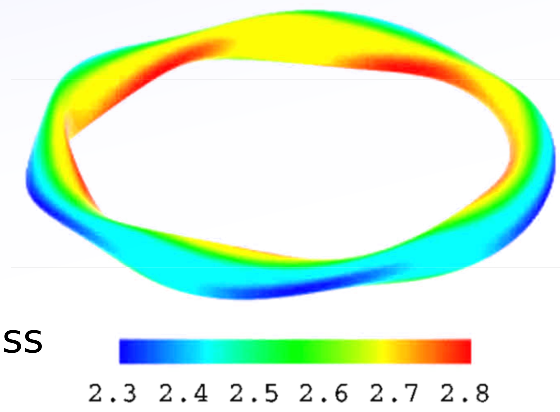
[R. Wolf, A.Werner, J.H.E. Proll]

Stellarator Optimisation

[A. Werner]



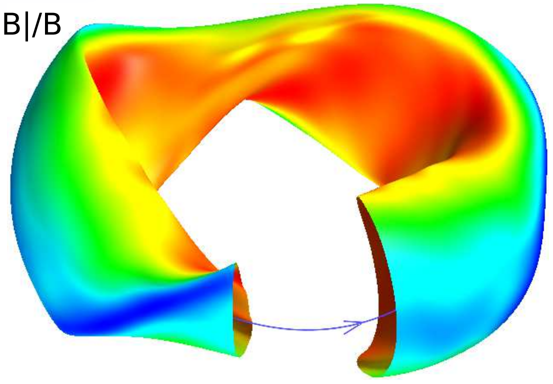
Tokamak:
  Trapped particles precess toroidally because |B| is axi-symmetric.



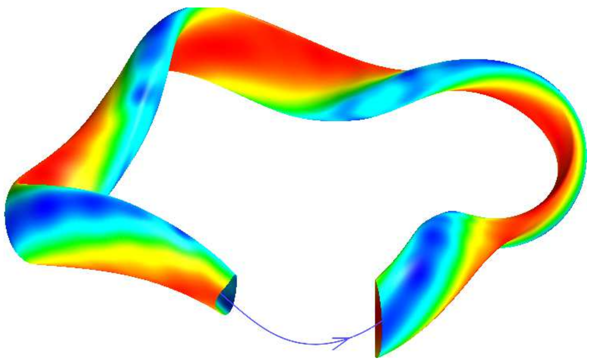
Classical Stellarator:
  Poor neoclassical confinement due to loss of trapped particles.

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

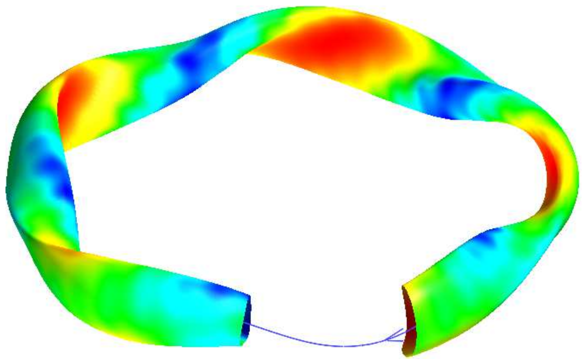
|B|/B



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)

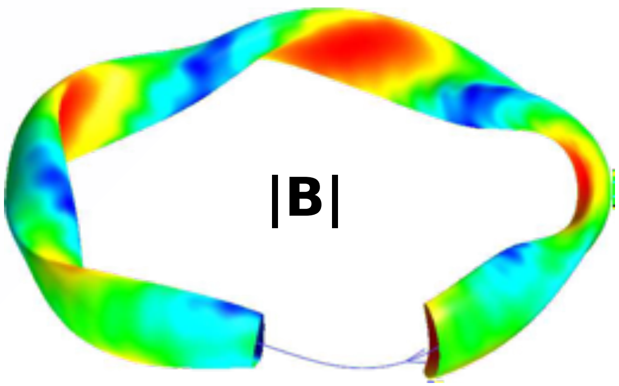
[J.H.E. Proll PPCF **58** 1 2016]

W7-X: An optimised Stellarator

[J. Nührenberg PPCF 52 124003 2010]

Wendelstein 7-X: 'Quasi-isodynamic' Stellerator configuration
- Trapped particles drift along constant |B|
- Magnetic configuration chosen to best confine trapped orbits.

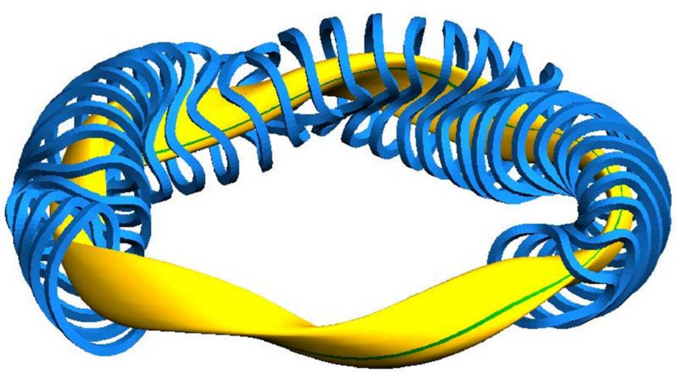
Magnetic field optimisation



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

Steady-state operation
with superconducting coils

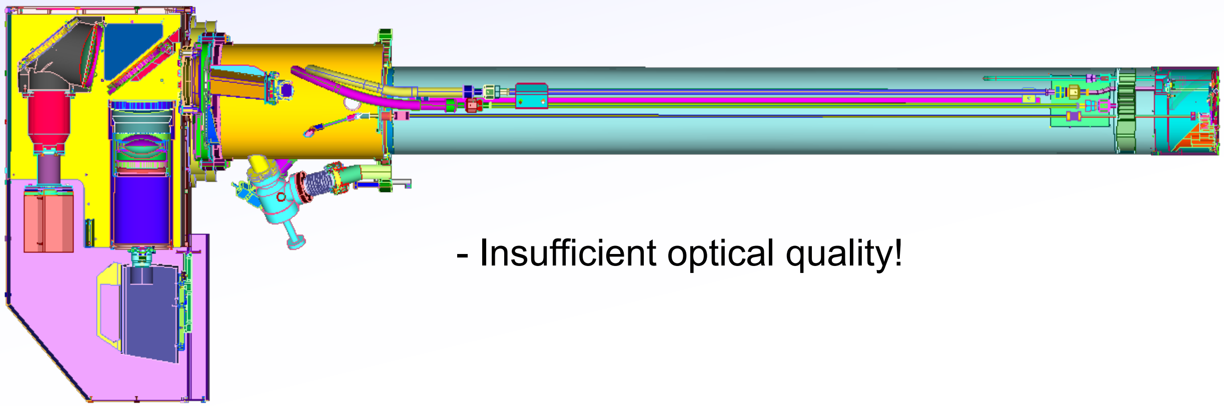


Missions:
- Build Wendelstein 7-X to the required precision.
- Verify construction by showing good vacuum flux surfaces.
- Confirm optimisation of neoclassical confinement - is it at Tokamak level?
- Show sufficient confinement of fast-ions.
- **Demonstrate steady-state operation at a relevant plasma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

Visible/Infrared video + Real-time protection

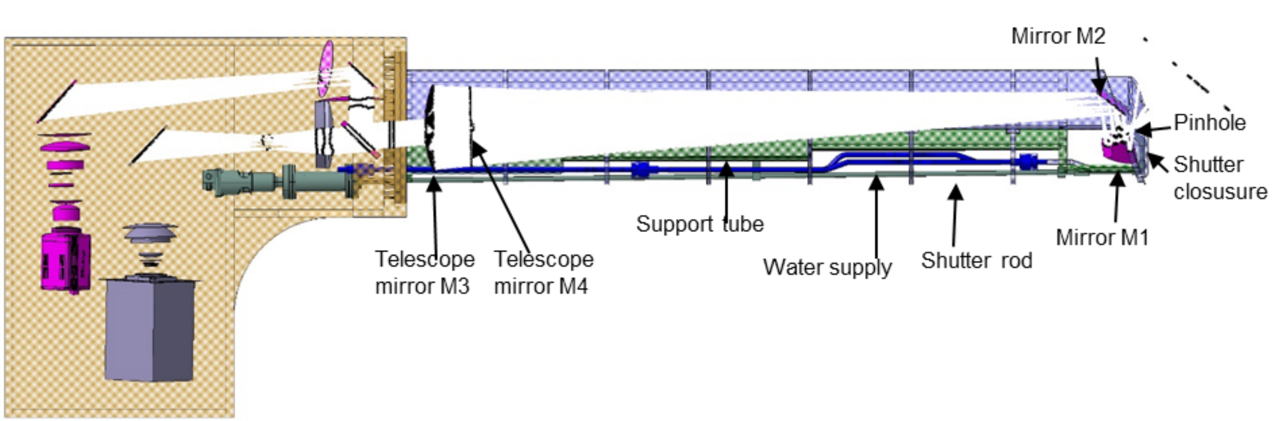
VIS/IR Endoscopes:

- Prototype OP1.2:



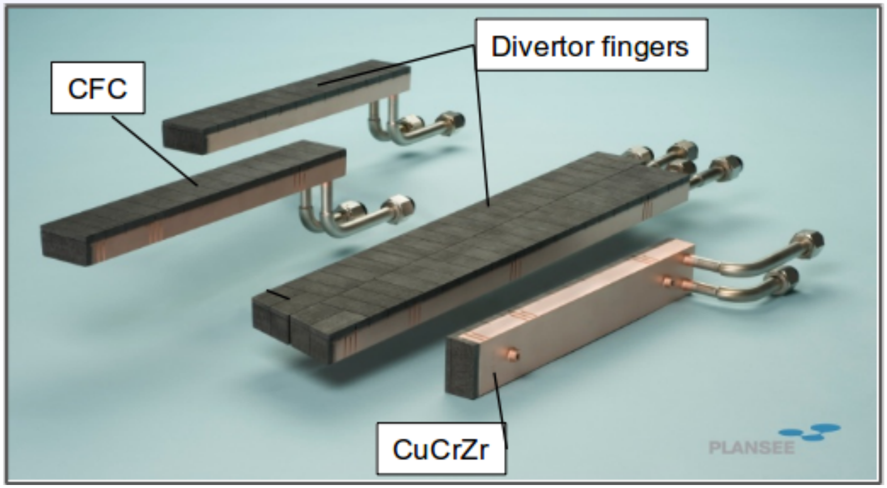
- Insufficient optical quality!

- Redesigning optical system (in-house) to develop new endoscopes for OP2:



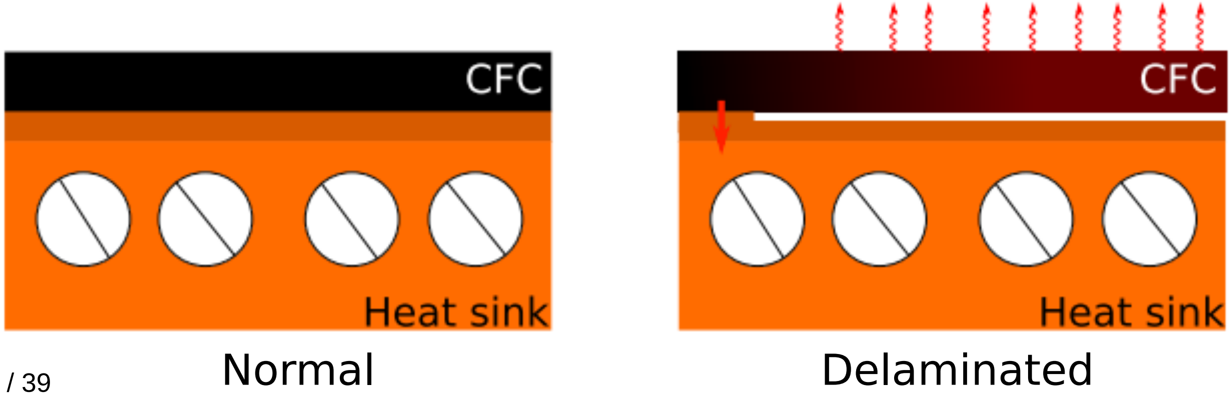
Visible/Infrared video + Real-time protection

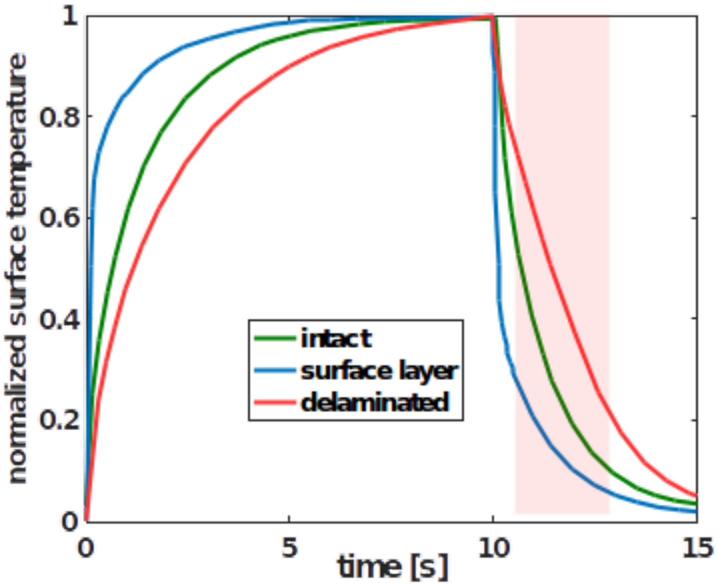
- Stady-state 10MW with sensitive high heat flux divertor.
  --> Require video monitoring and intelligent protection system.



- Hot spot detection
- False positives from surface layers.
- Avoid but detect delamination of tiles

Delamination and surface layer detection from time-dependant response to heat:





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