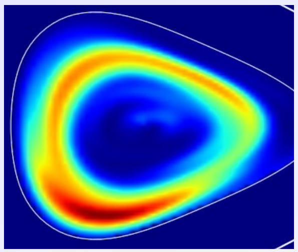
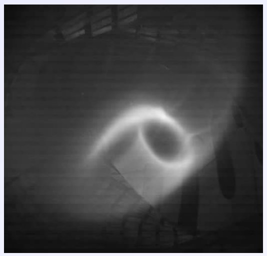
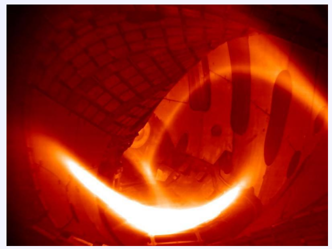
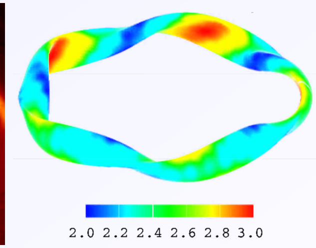
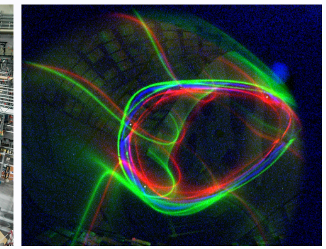
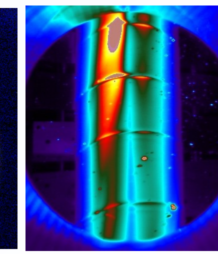
Wendelstein 7-X: Status and overview of diagnostics,

(with some emphasis on ITER relevance)

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

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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

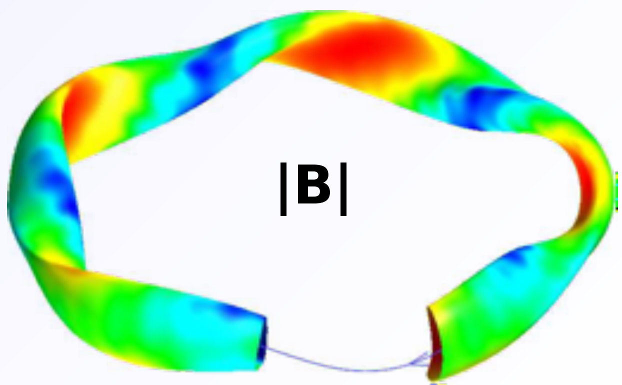
Planned:
Neutral Partical Analyzer
Laser Induced Flouresence
Divertory Bolometry
Multichannel Interferometer
Heavy ion veam probe

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



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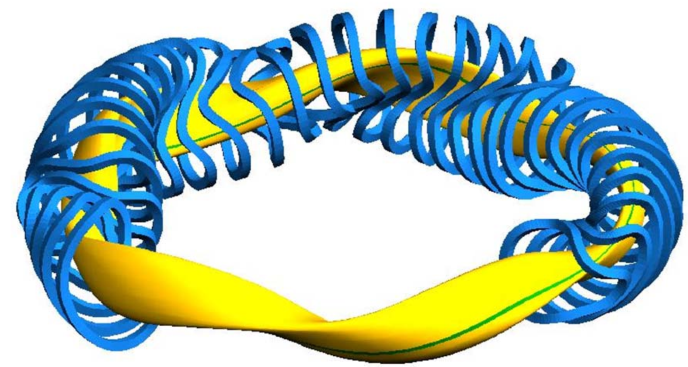
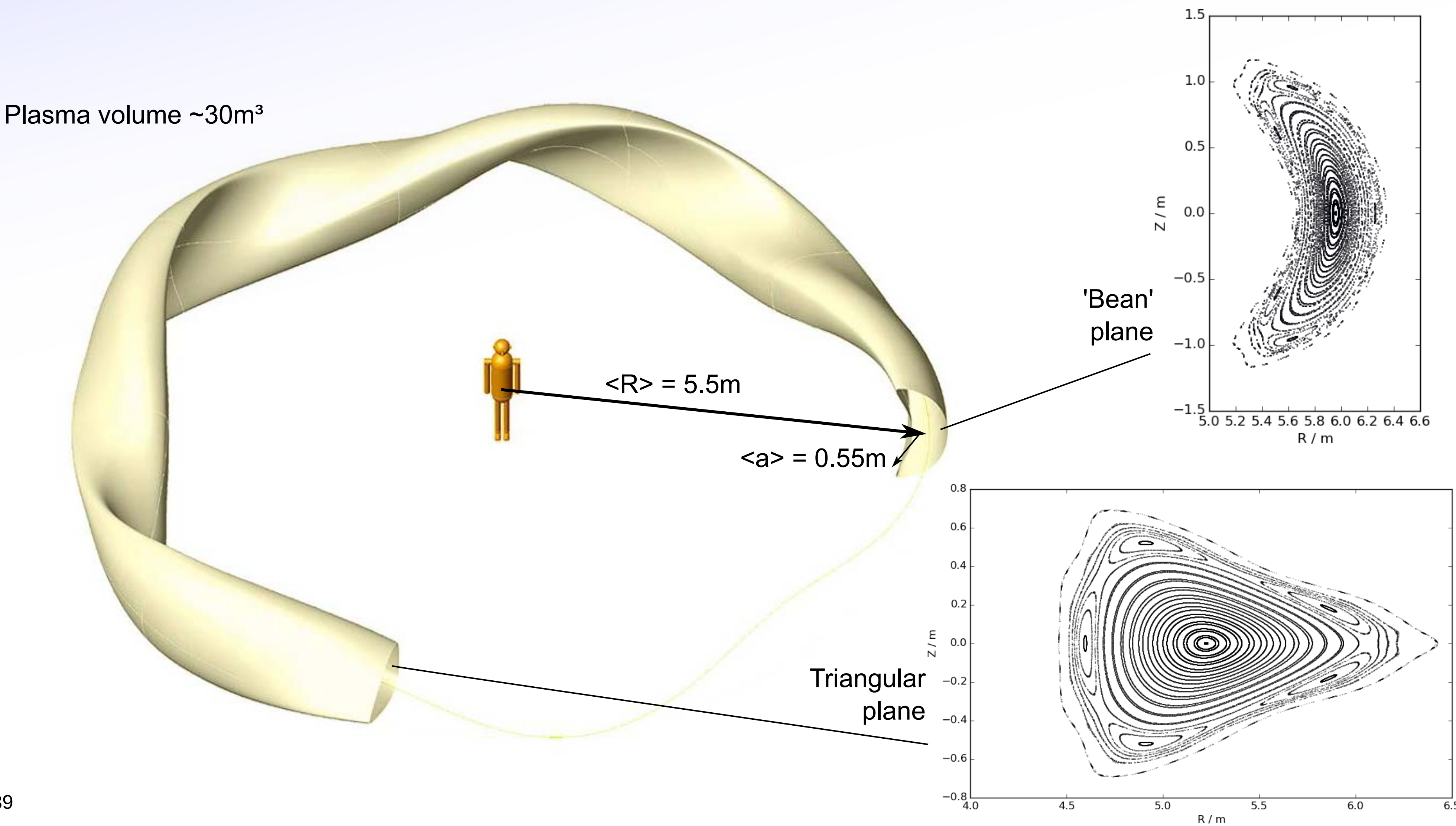
Steady-state operation
with superconducting coils



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

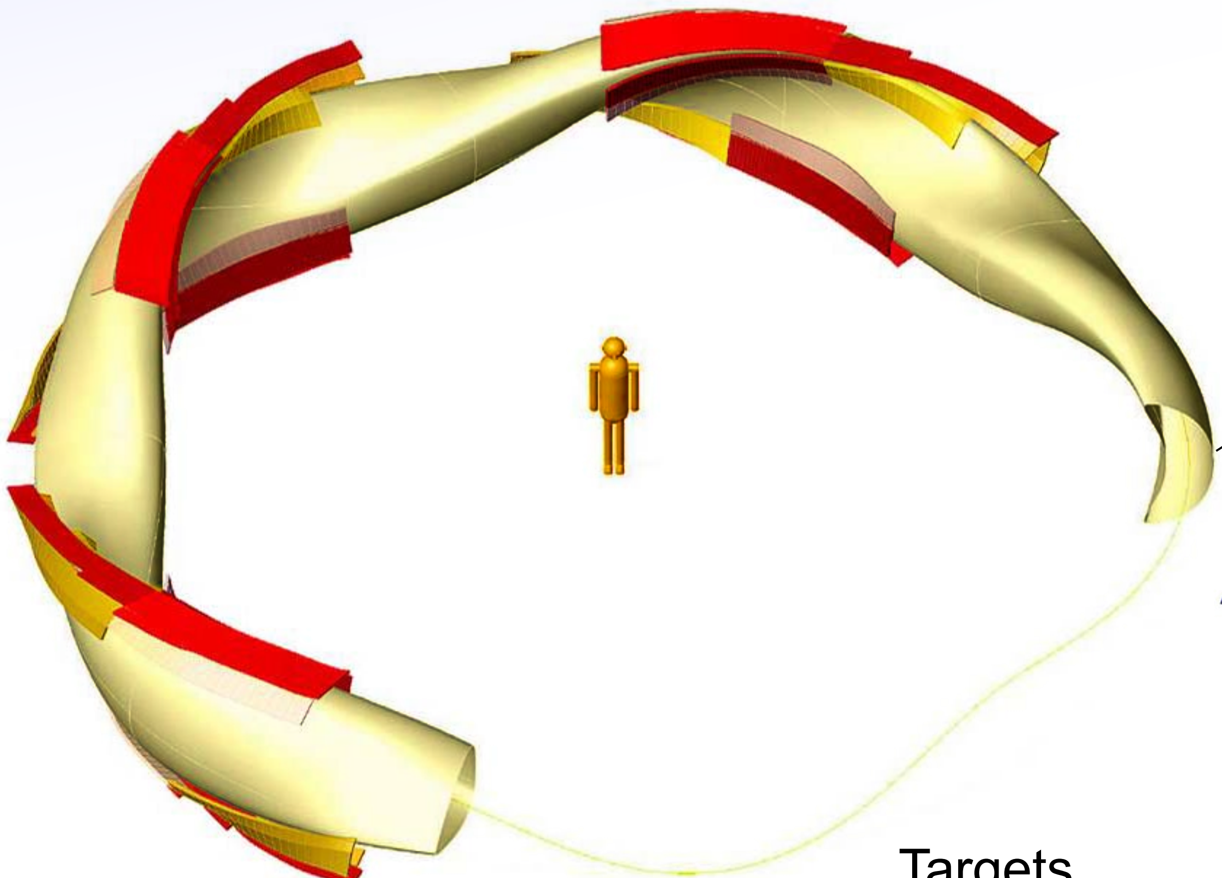
Steady-state operation requires steady-state coils --> Super-conducting --> Even more complexity!
After a lot of R&D, the final design of W7-X was complete:

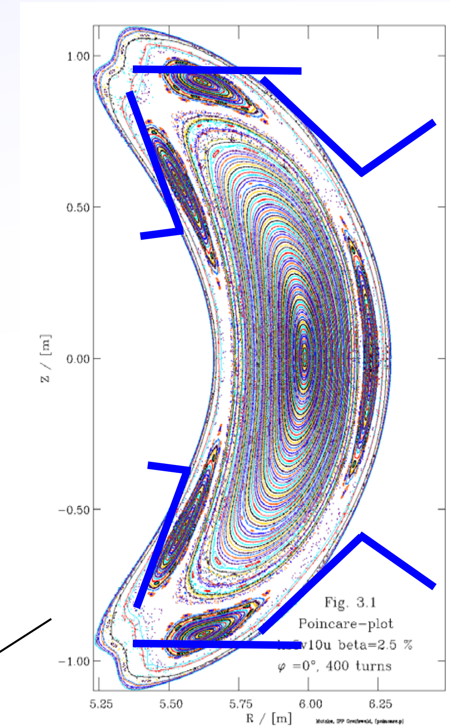


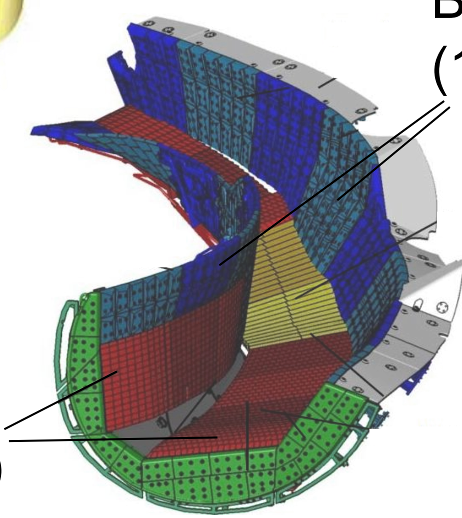
W7-X Construction

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).

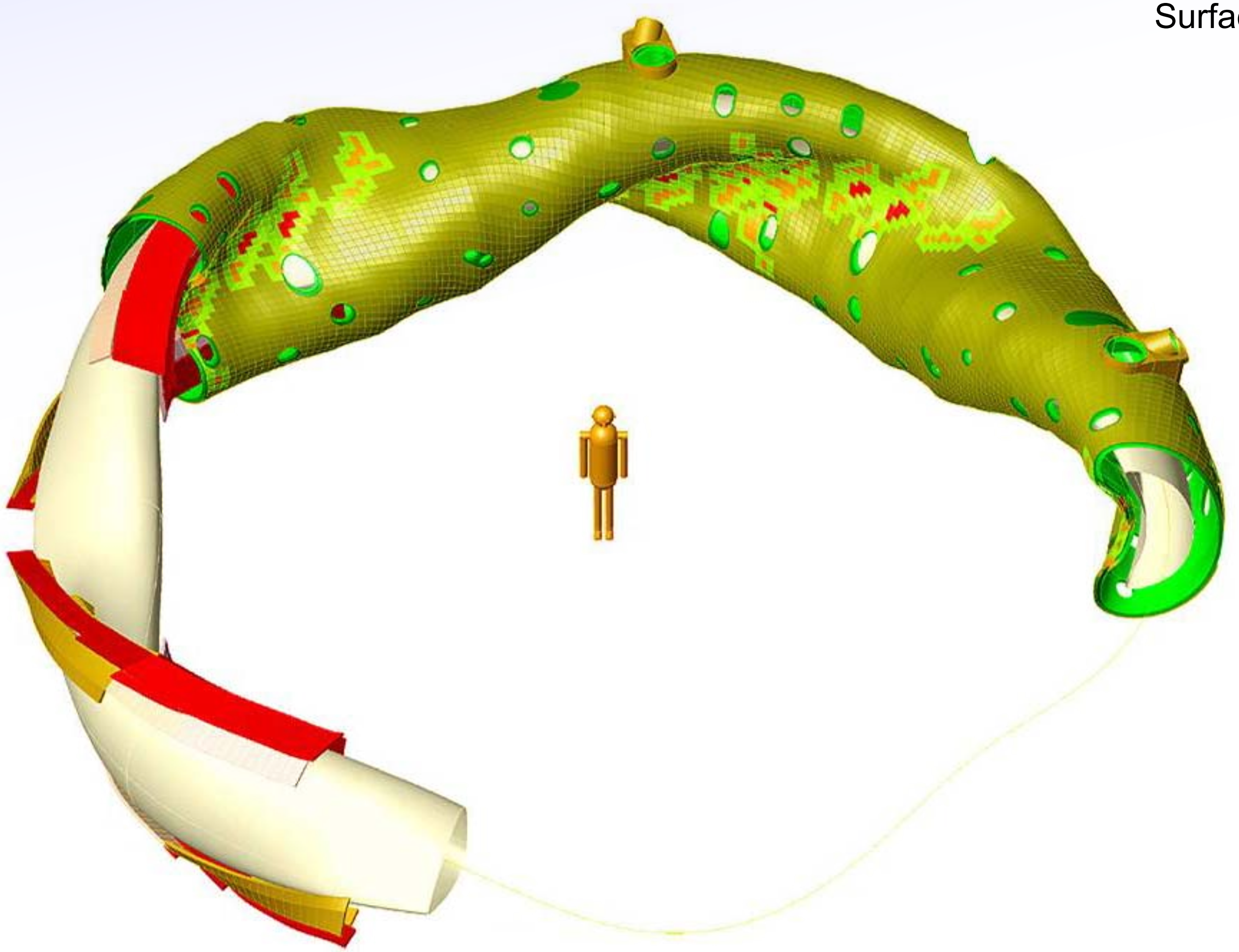






W7-X Construction

Vacuum Vessel



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

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.

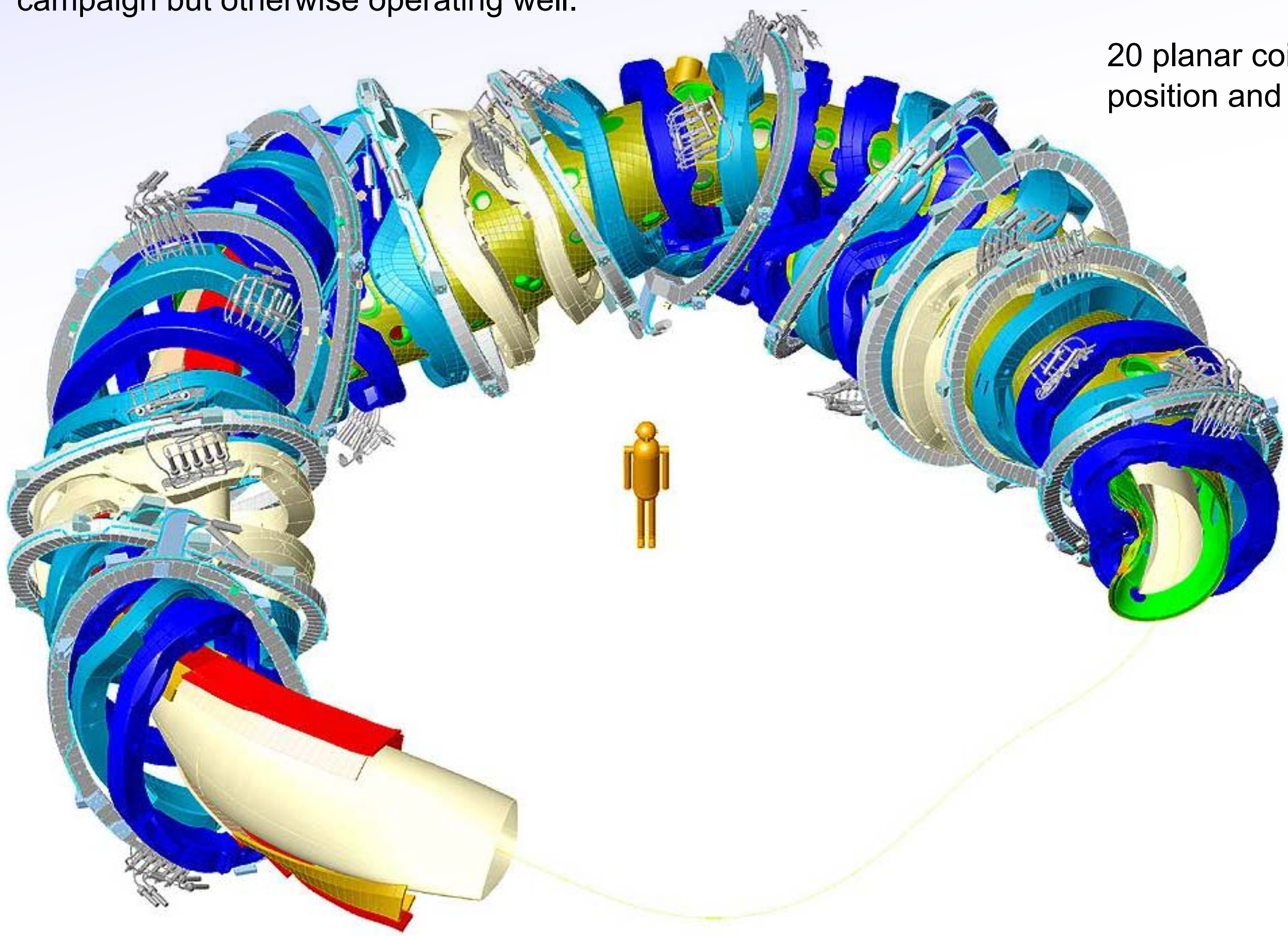
Super-conducting coils:

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

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

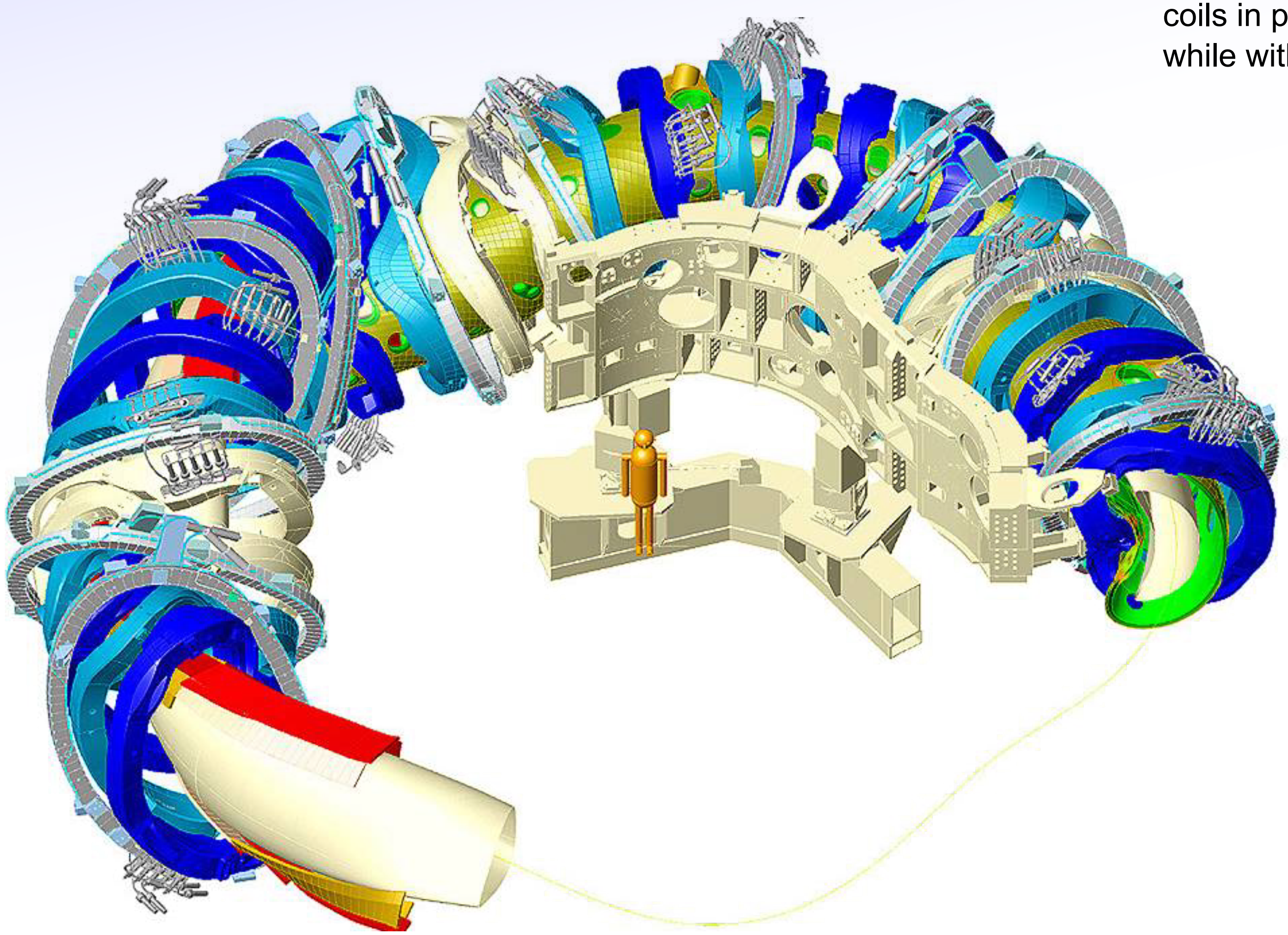
Non-superconducting coils:

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



W7-X Construction

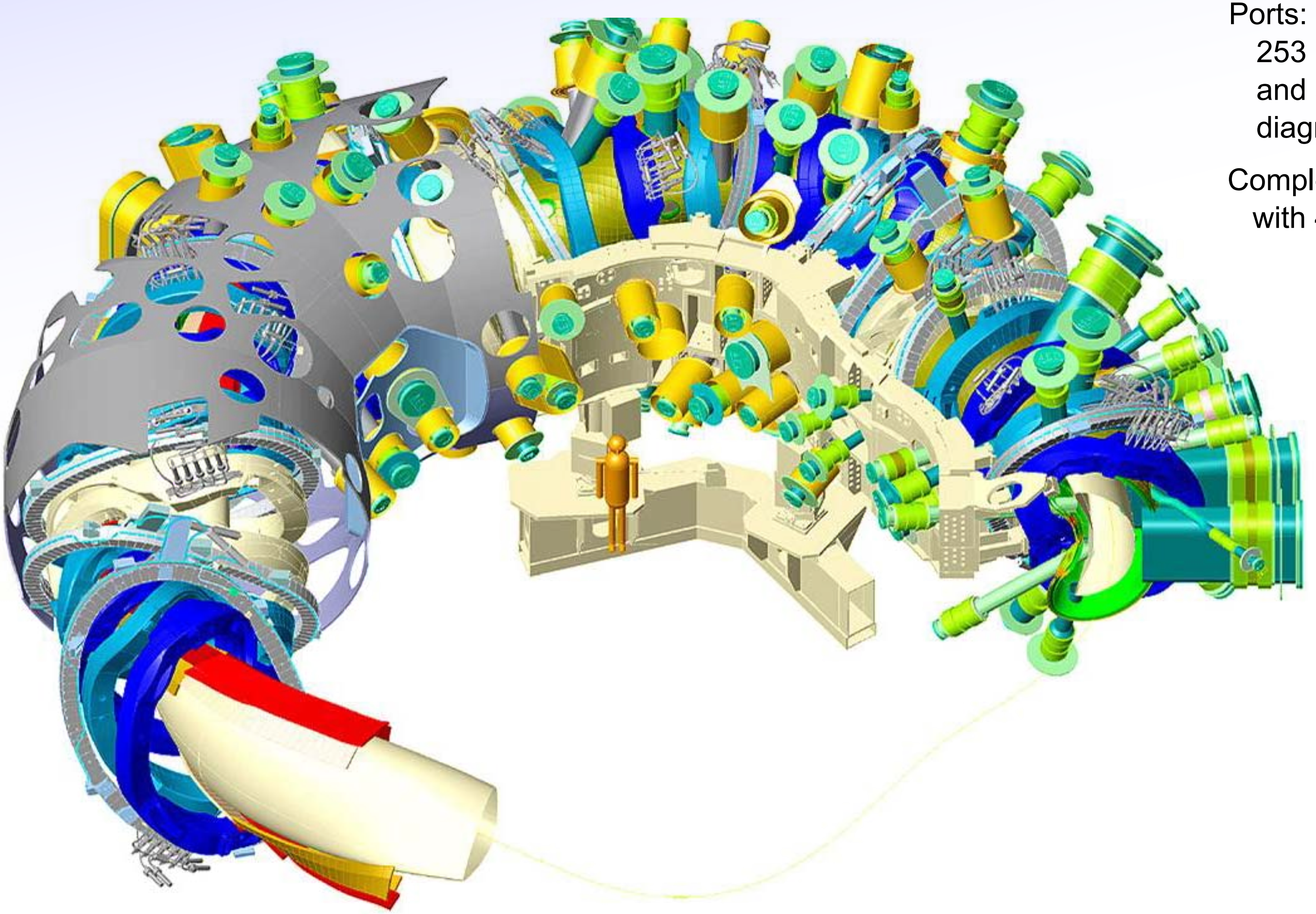
Support structure:



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.

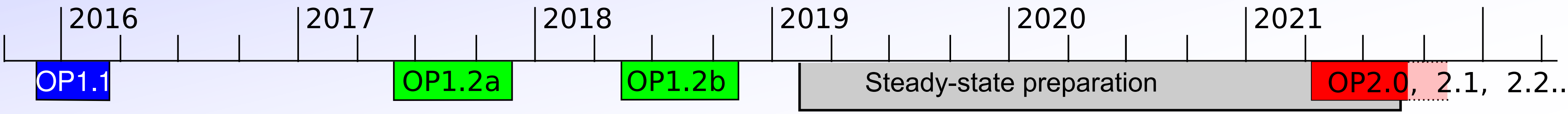
Complete construction 735t with 435t cold mass.

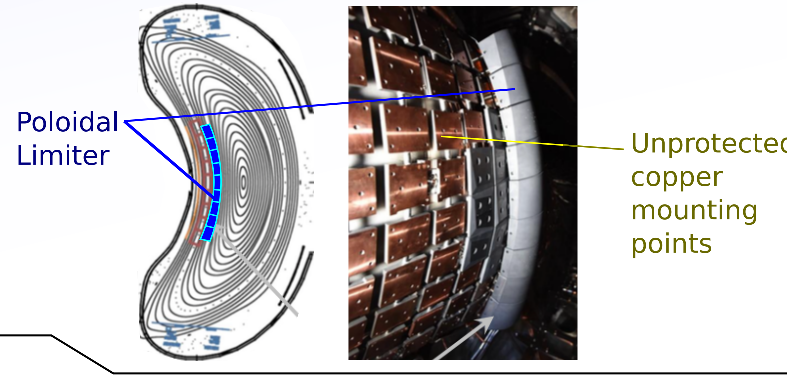
[R. Wolf, R. König]

W7-X Operational Phases

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

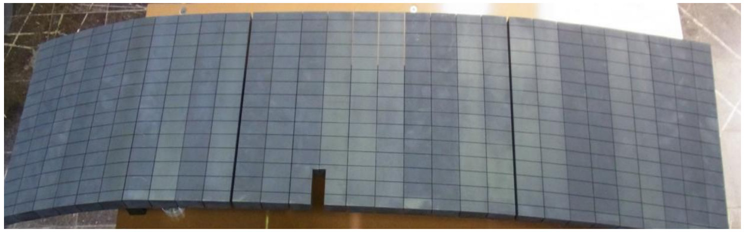
(Plan as in Jan 2019)





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.

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.

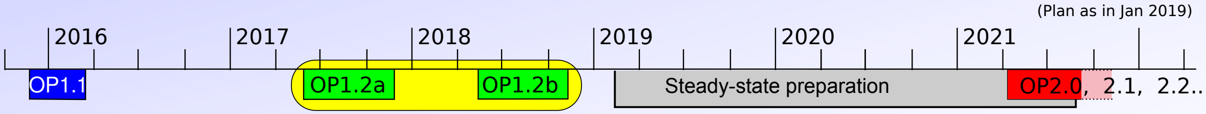

OP1.2: Test Divertor Unit

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.**

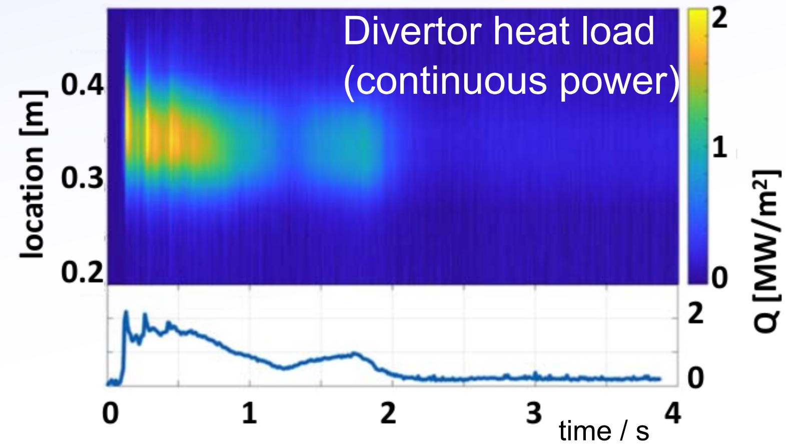
OP?: Future phases
- Tungsten wall??


OP2: High Heat Flux divertor

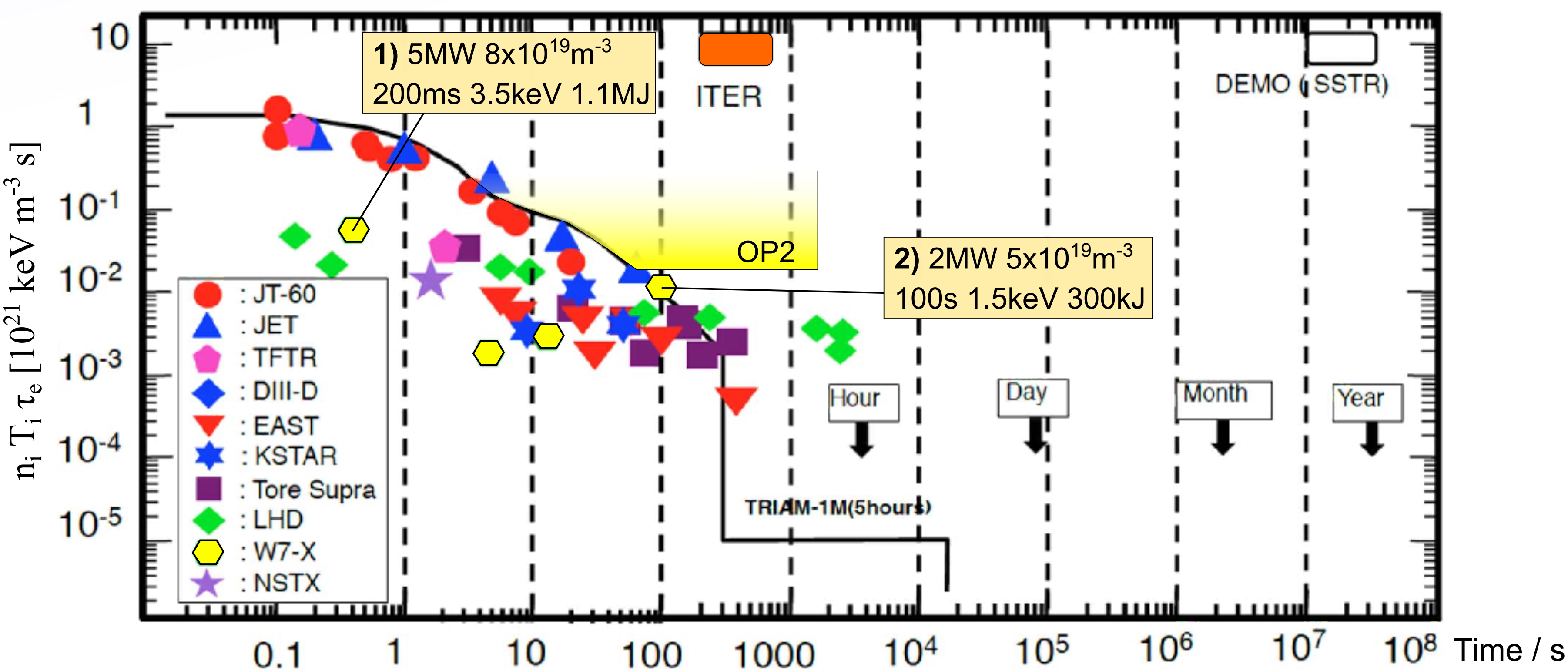
W7-X OP1.2 (2017/8) Complete



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



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



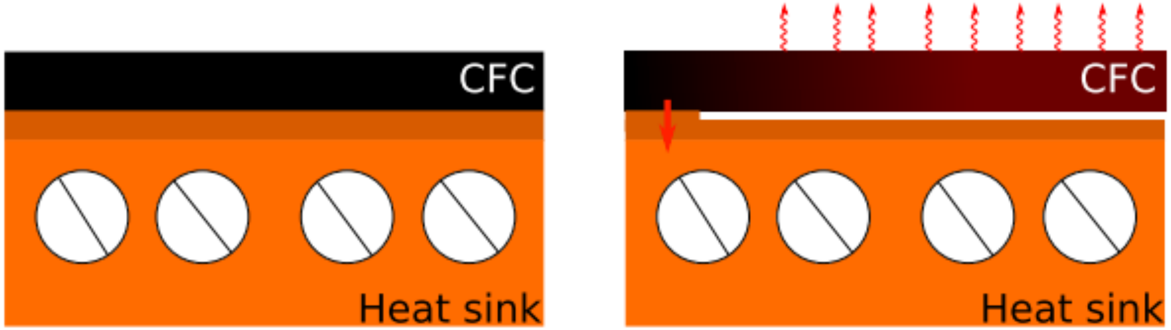
W7-X OP2 (2021+) Plans

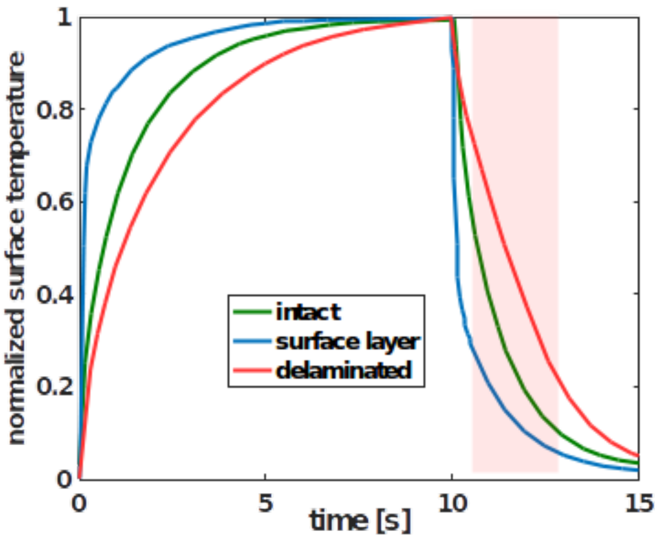
Primary objective of OP2:
- Demonstrate long-pulse operation at high beta (~5%).
  10MW ECRH Power, 30min discharges.

--> 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.

OP2: High Heat Flux divertor

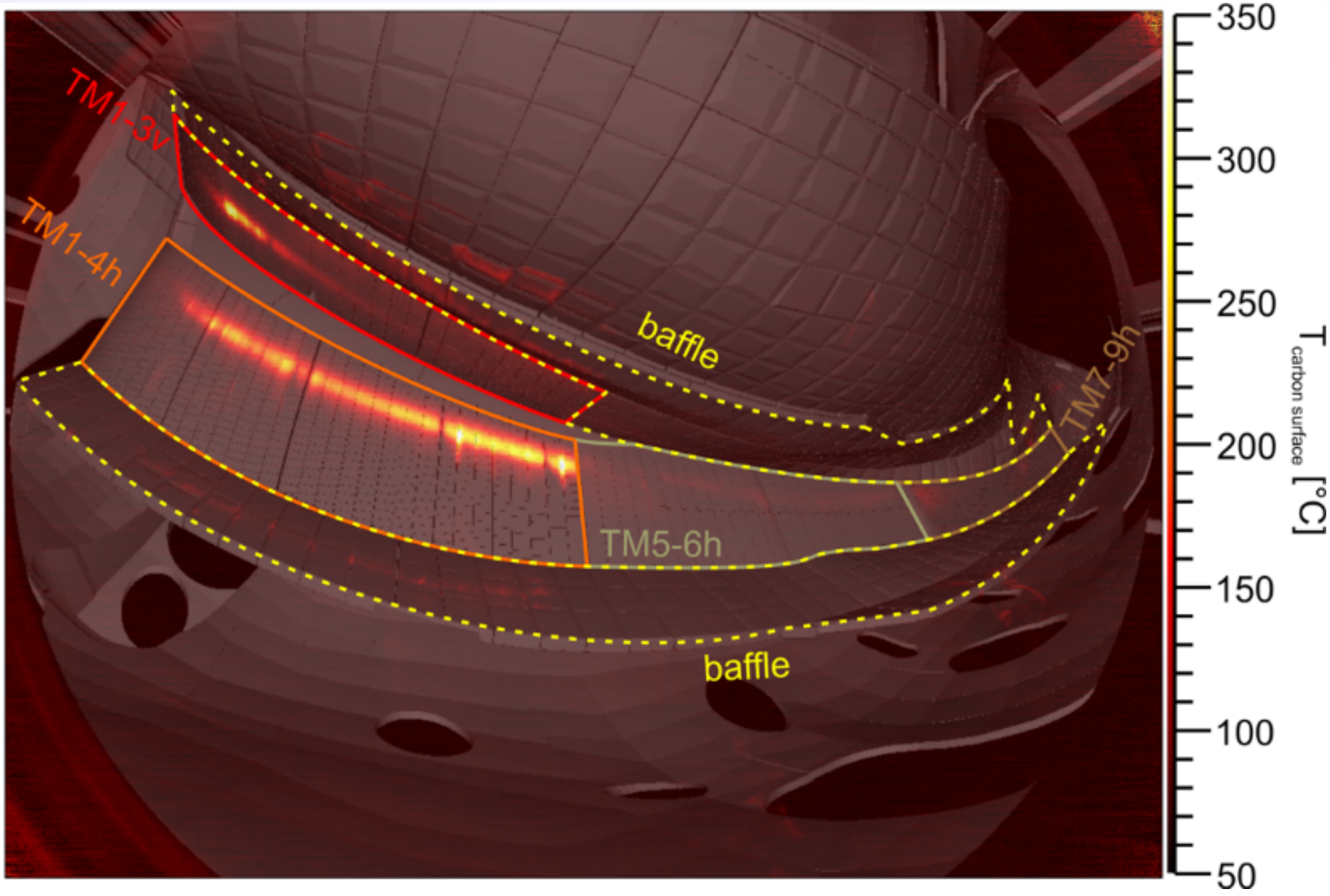




Visible/Infrared video + Real-time protection

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)



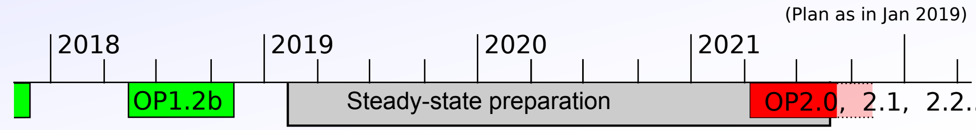
10 x high resolution video
x 30min --> huge data

200TB already for OP1.2

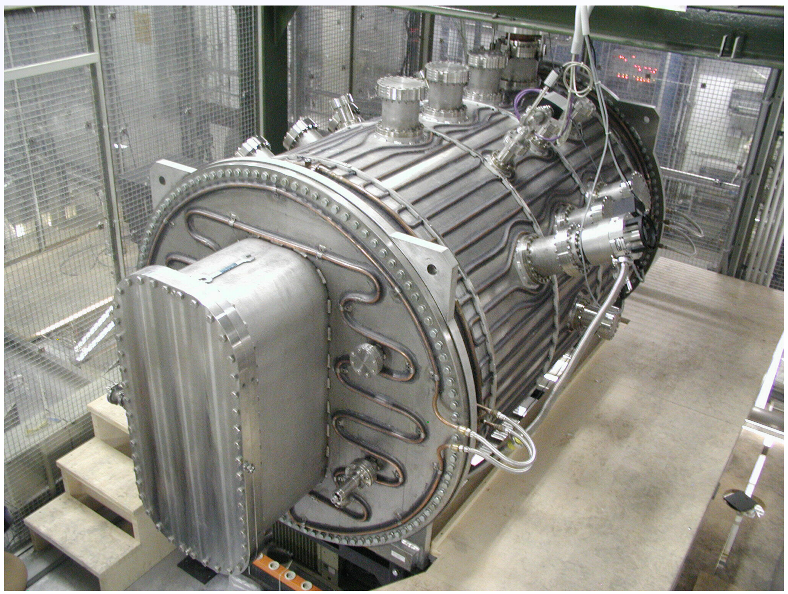
Will need to process in near real time. Investigating advanced algorithms, deep-learning, neutral networks etc.

W7-X OP2 Cooling - Diagnostics

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

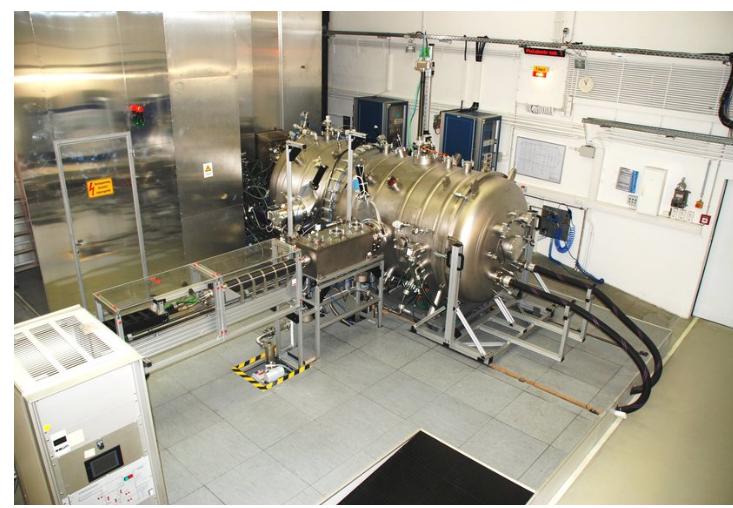


--> Up to **100KW m^{-2}** continuous radiative heat load + ECRH stray radiation on all wall components, including diagnostics.
- All diagnostics required to survive continuous heat loads and ECRH stray radiation since conception.
- Many new developments / technologies were required as well as thorough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



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

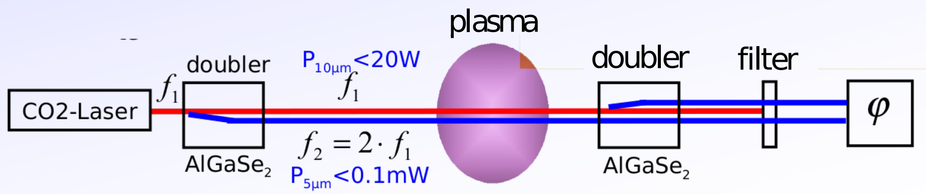
GLADIS Test facility in Garching available.
- 2x 1MW ion sources.
- Heat fluxes up to 45 MW m^{-2}
- Pulses up to 45s.



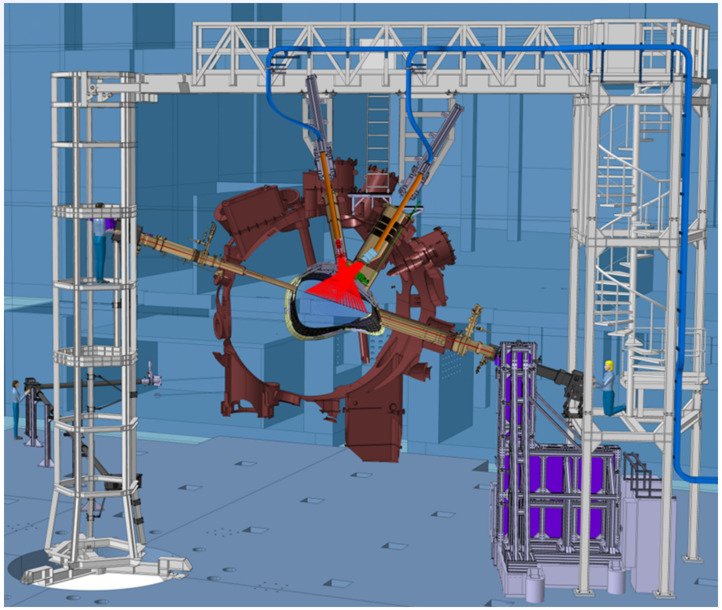
Dispersion Interferometer

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

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



- Inherent viabration insensitivity



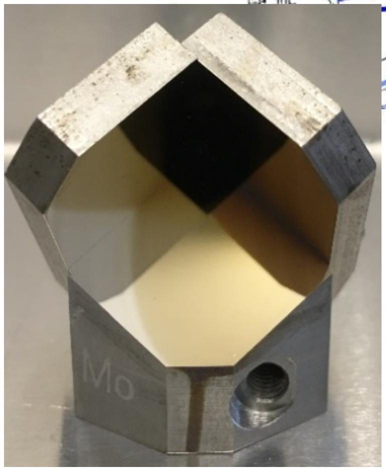
- Generally running very well.
- Real time FPGA analysis --> Density feedback controller.
- Some issues with unexplained non-ideal behaviour ('non-circularity') also with long term environmental drifts --> Long pulse relevance

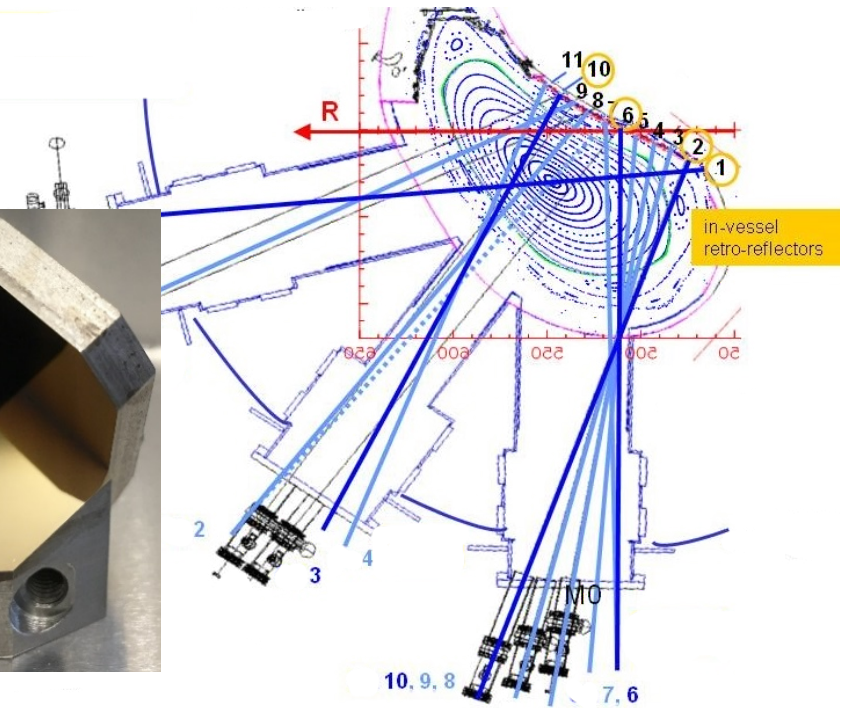
Multichannel Interferometer

- 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.



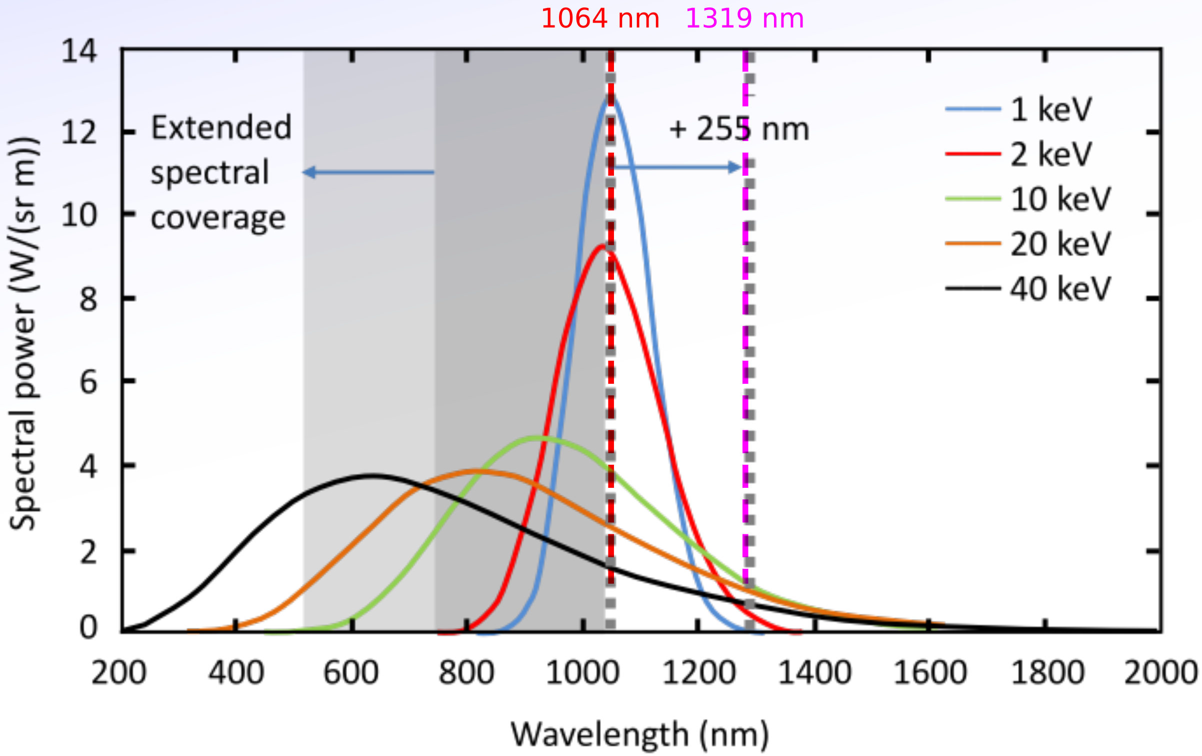


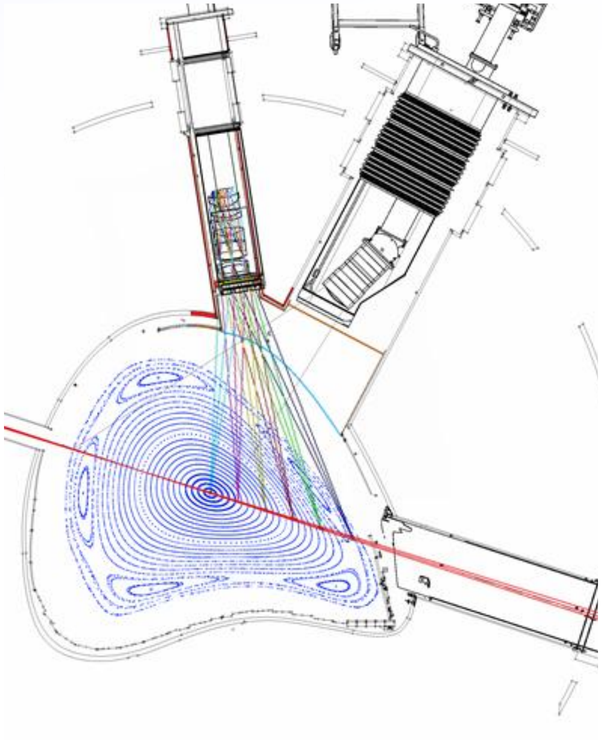
Thomson Scattering

- 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)





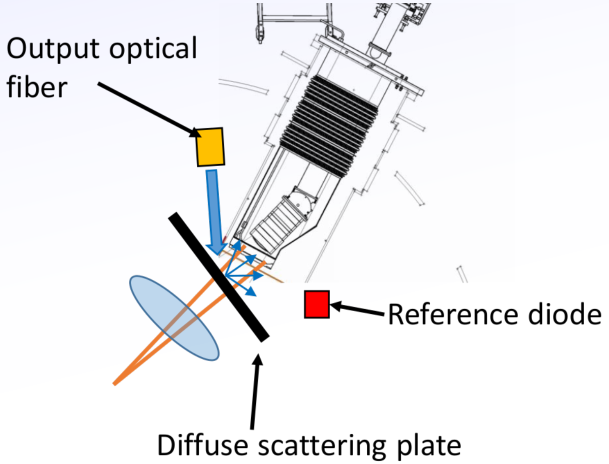
Development work on-going with modelling support from Italy but low-priority project for W7-X due to target high-n_e, lower-T_e plasmas.

- Mirrors capable of reflecting high energy at both wavelengths.

Thomson Scattering

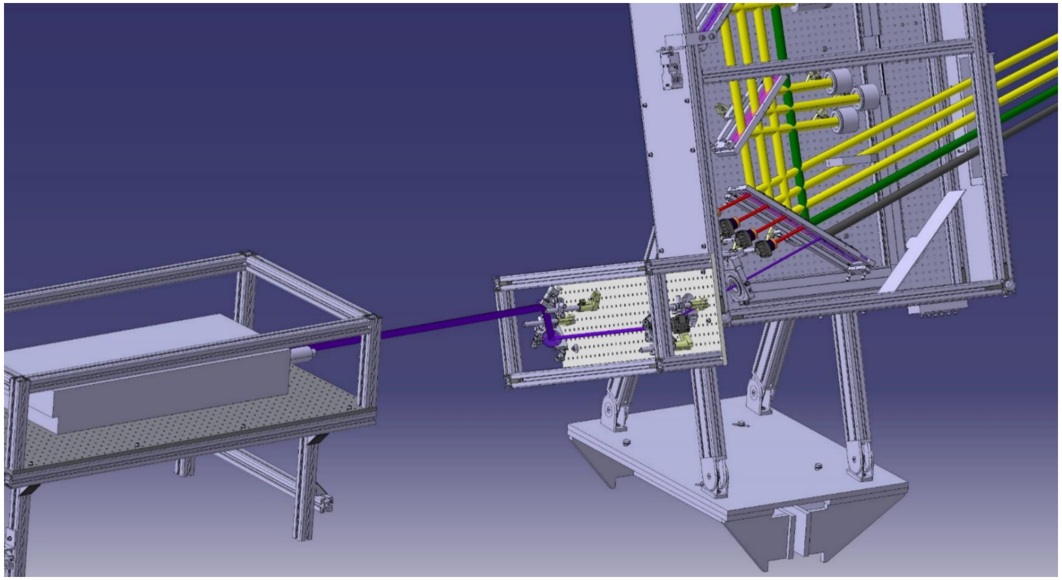
2) OPO-Tunable wavelength laser, in-situ calibration Rayleigh calibration technique.

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).

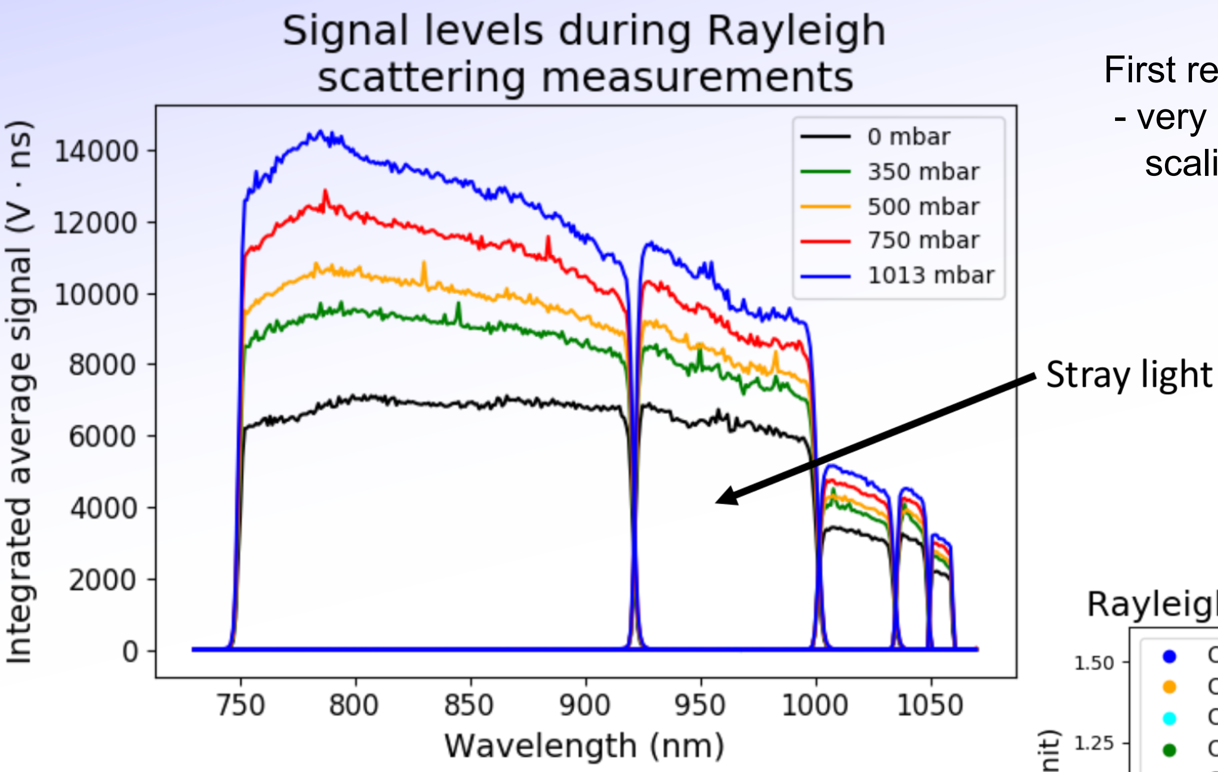


New method:
- Fill vessel with gas
- Fire high energy tunable OPO laser along normal laser path
- Measure Rayleigh scattering with all same optics as normal system.

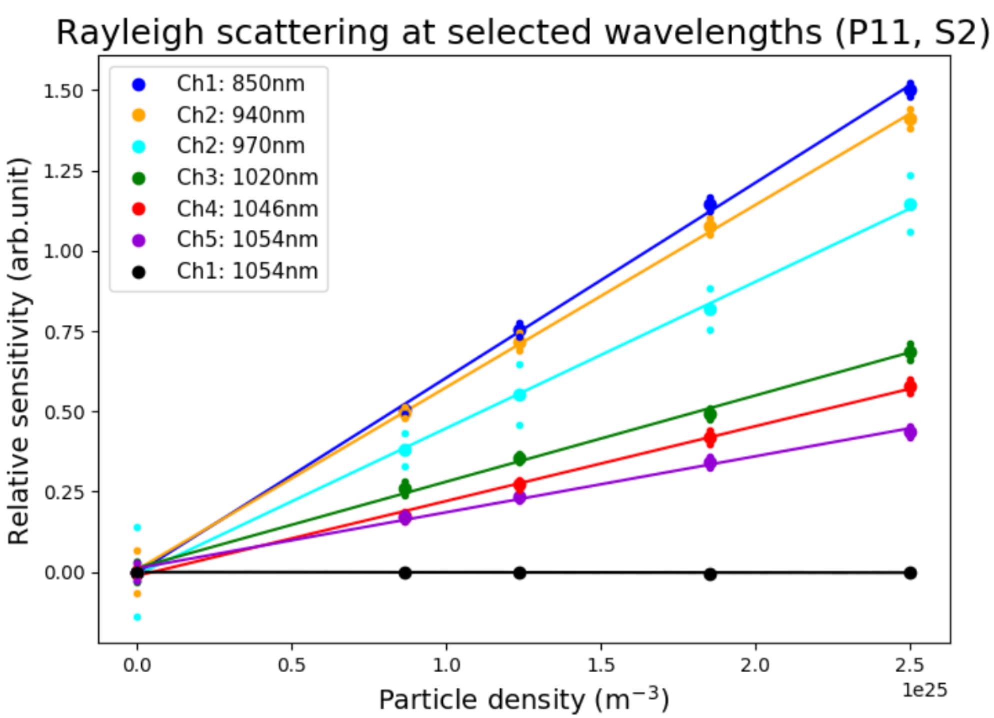
- First real in-situ tests made at W7-X after OP1.2.
- OPO Installed temporarily in torus hall:



Thomson Scattering

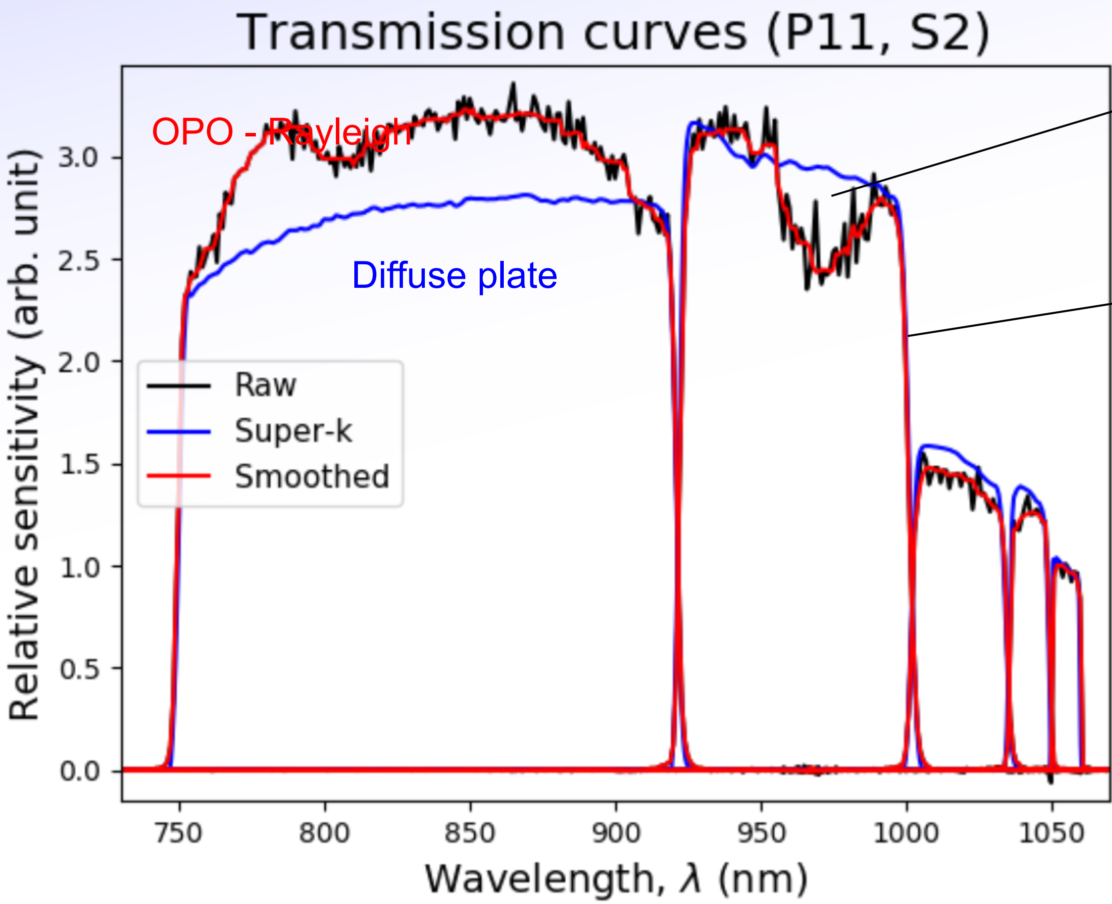


First results:
- very strong stray light but good linear scaling with pressure:



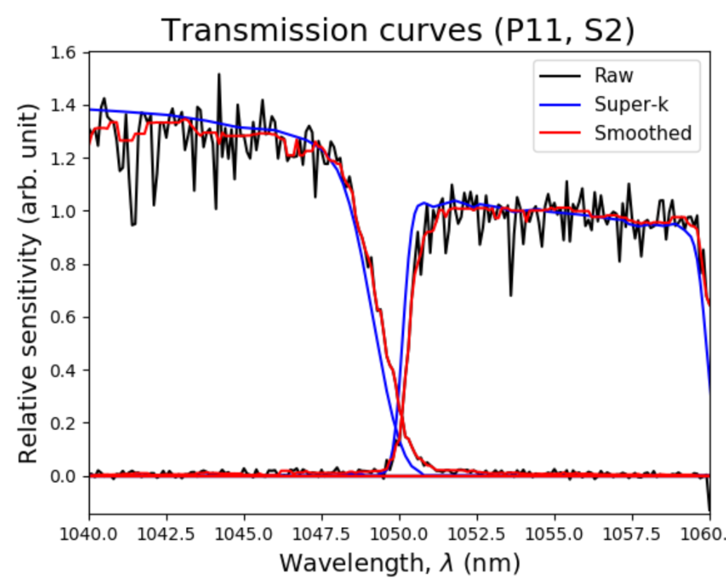
Thomson Scattering

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:

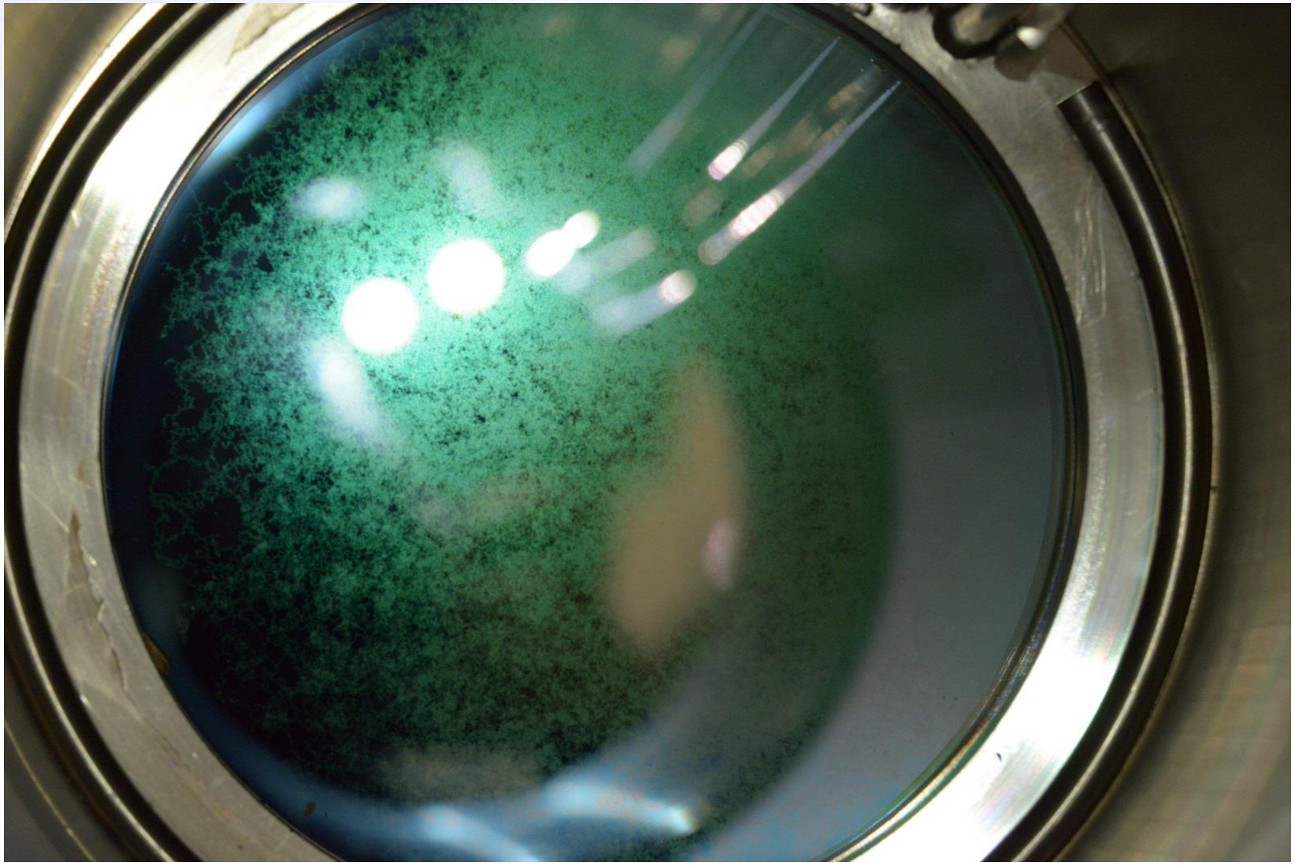


- For now using diffuse plate curves scaled to match Rayleight scattering intensity.
- Will be installed for OP2 and further developed / tested.

Thomson Scattering

Possible difference...

- Arcing damage to Thomson Scattering window:



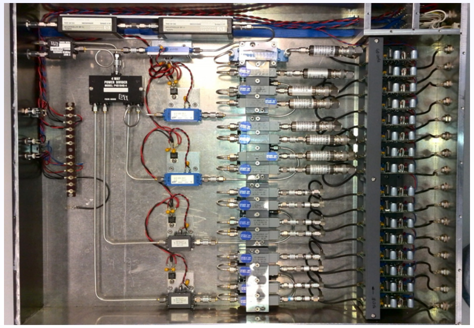
- Arcing from shutter to window surface?
- Possible that ITO coating for stray radiation was installed on vacuum side?

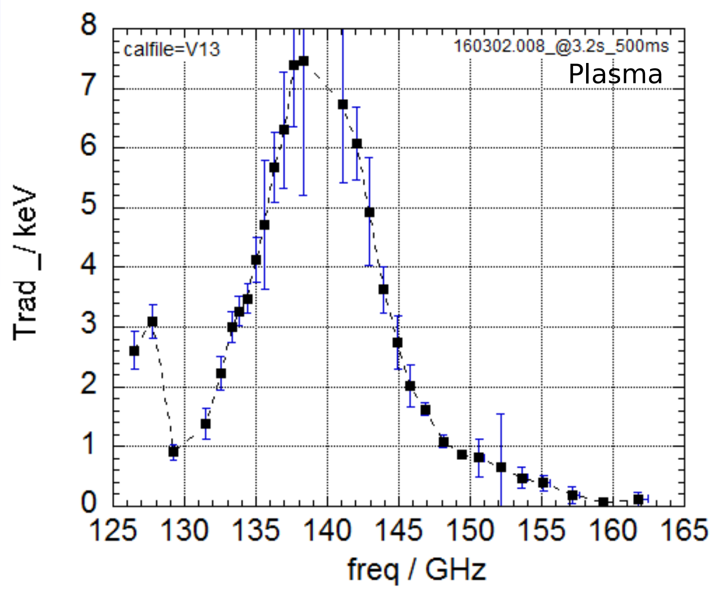
--> ECRH stray radiation can be a real problem!

Electron Cyclotron Emission

ECE Radiometer:

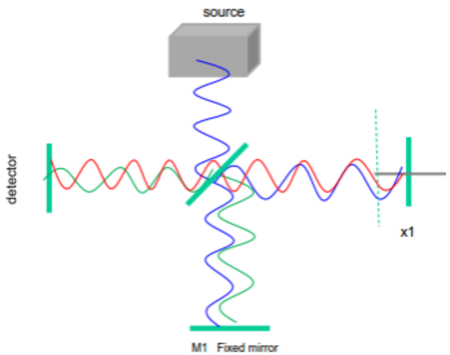
- 32 channel radiometer
  - Performs well up to cut-off density 1.2 x 10^{20} m^{-3}.



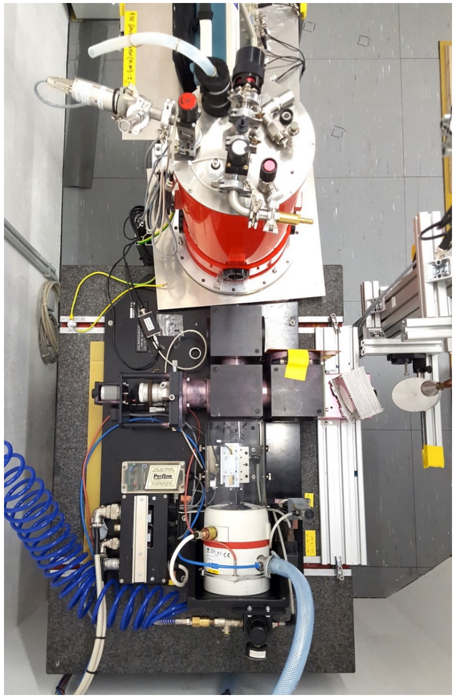


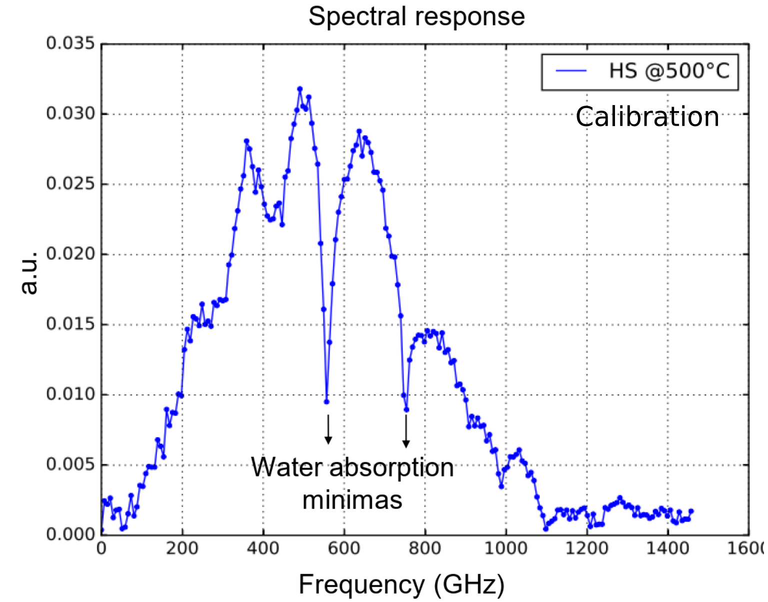
ECE Michelson-Interferometer:

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



(a)

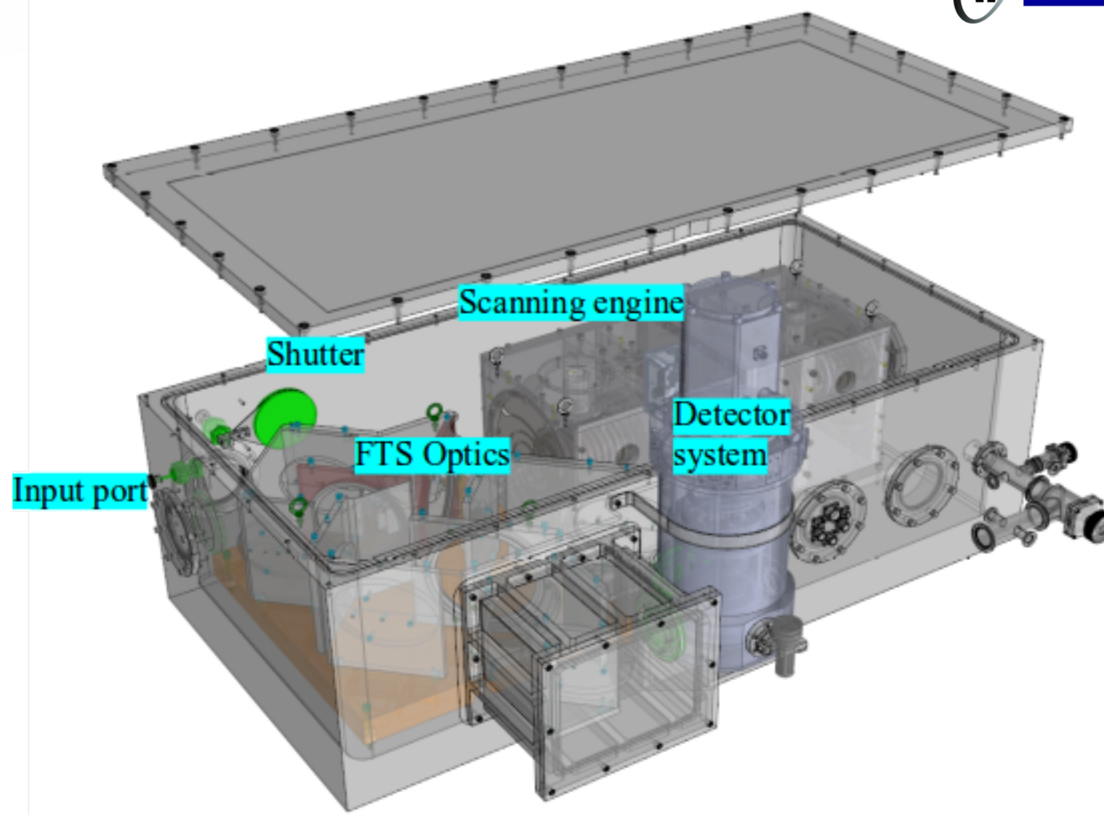




Electron Cyclotron Emission

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.

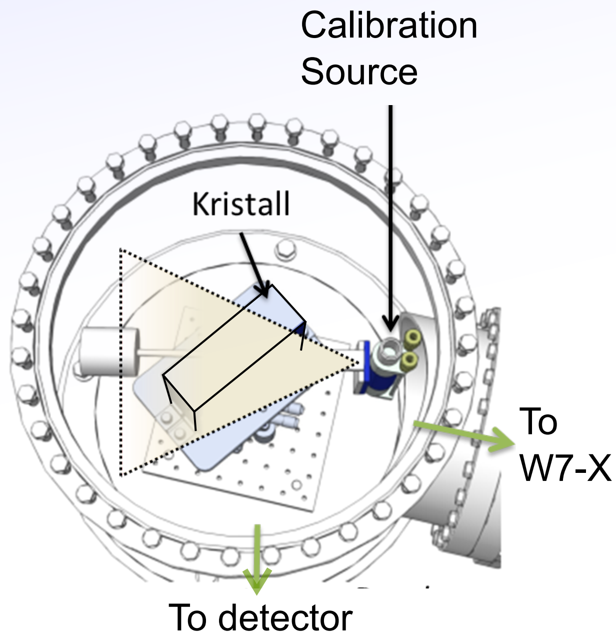
ITER-India

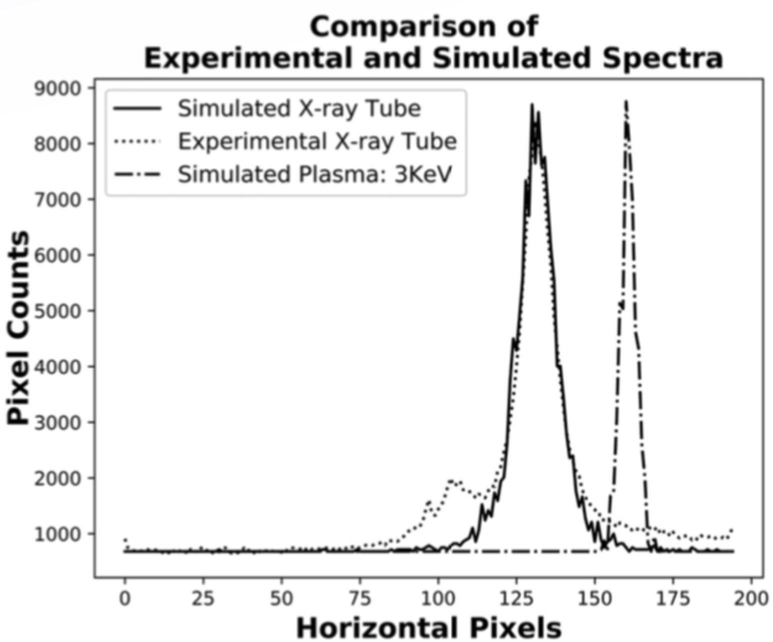


X-Ray Crystal Spectroscopy

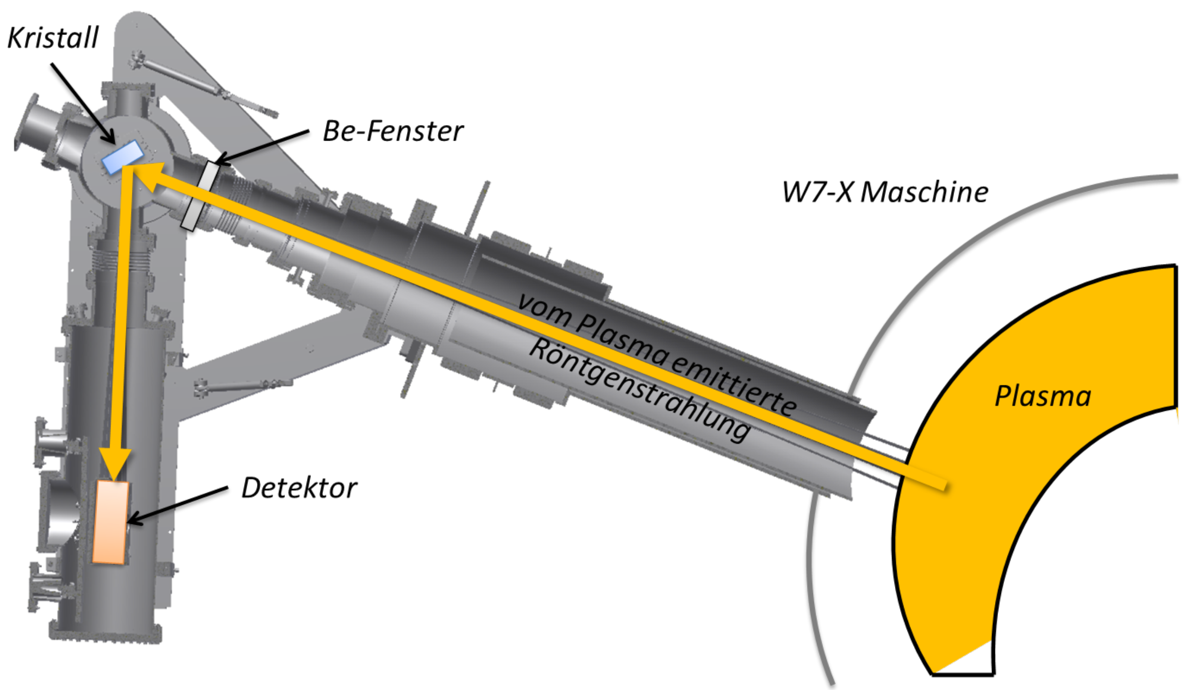
X-Ray Imaging Crystal Spectrometer
+ High-resolution X-ray Crystal Spectrometer

- 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



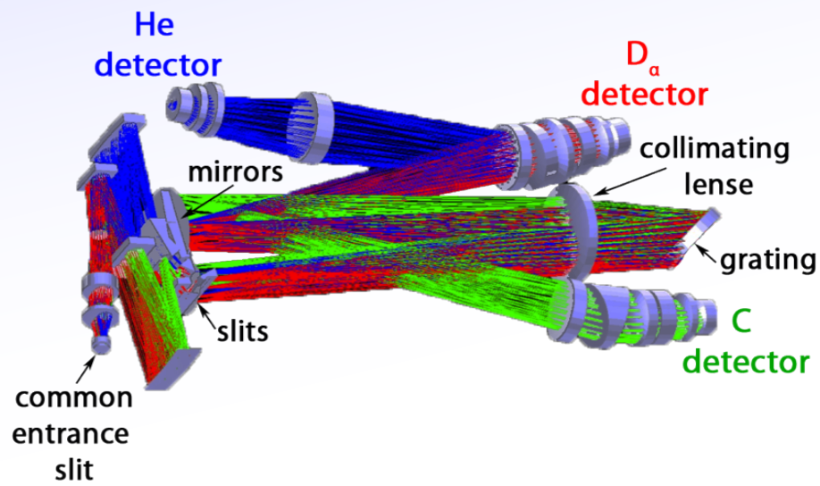


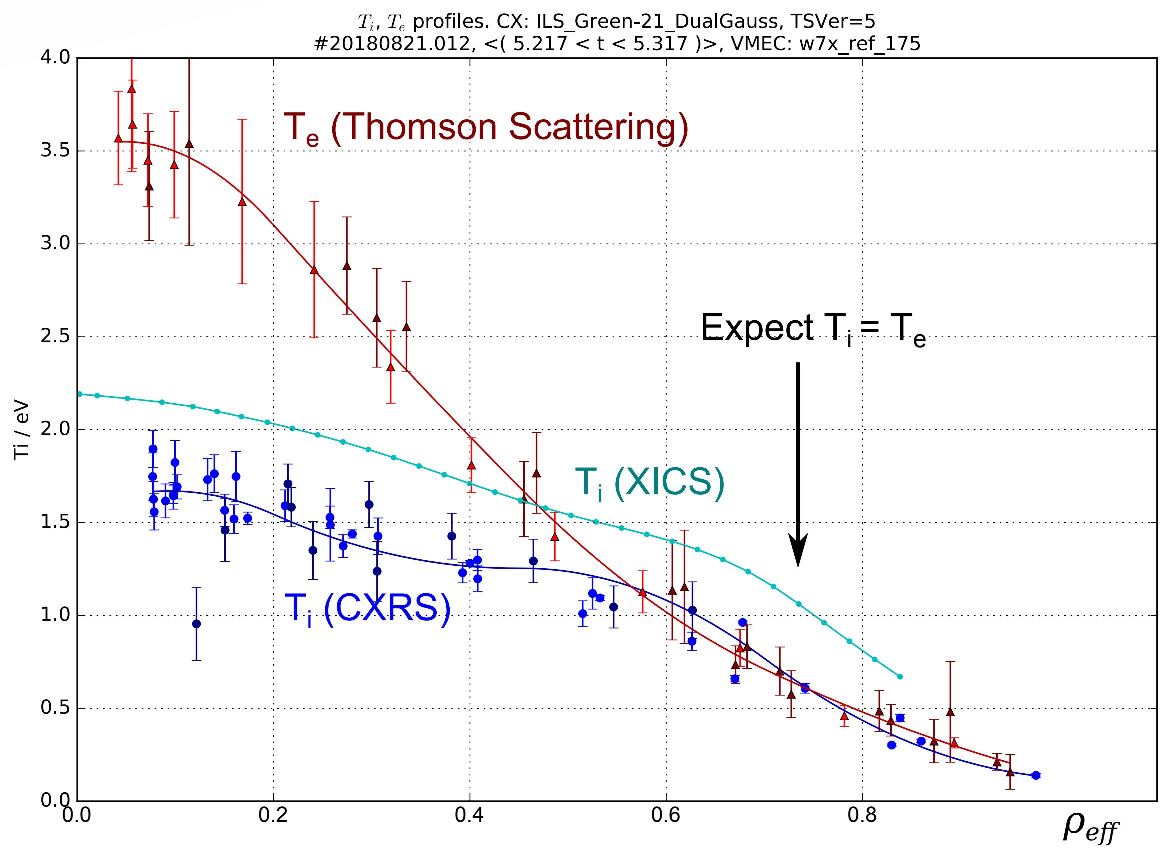
(c)



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!



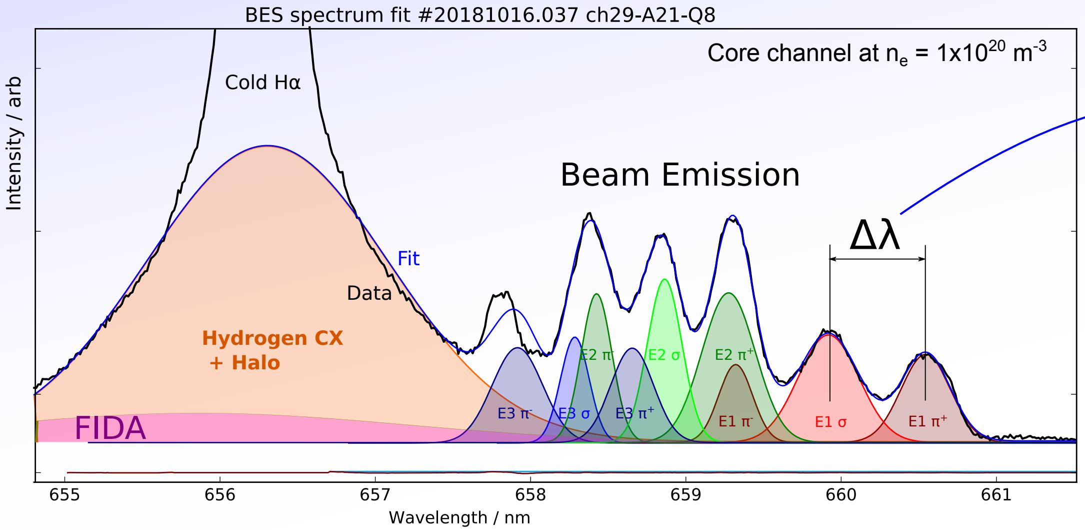


- ~200 - 400eV apparent over-estimation by both X-Ray spectrometers.

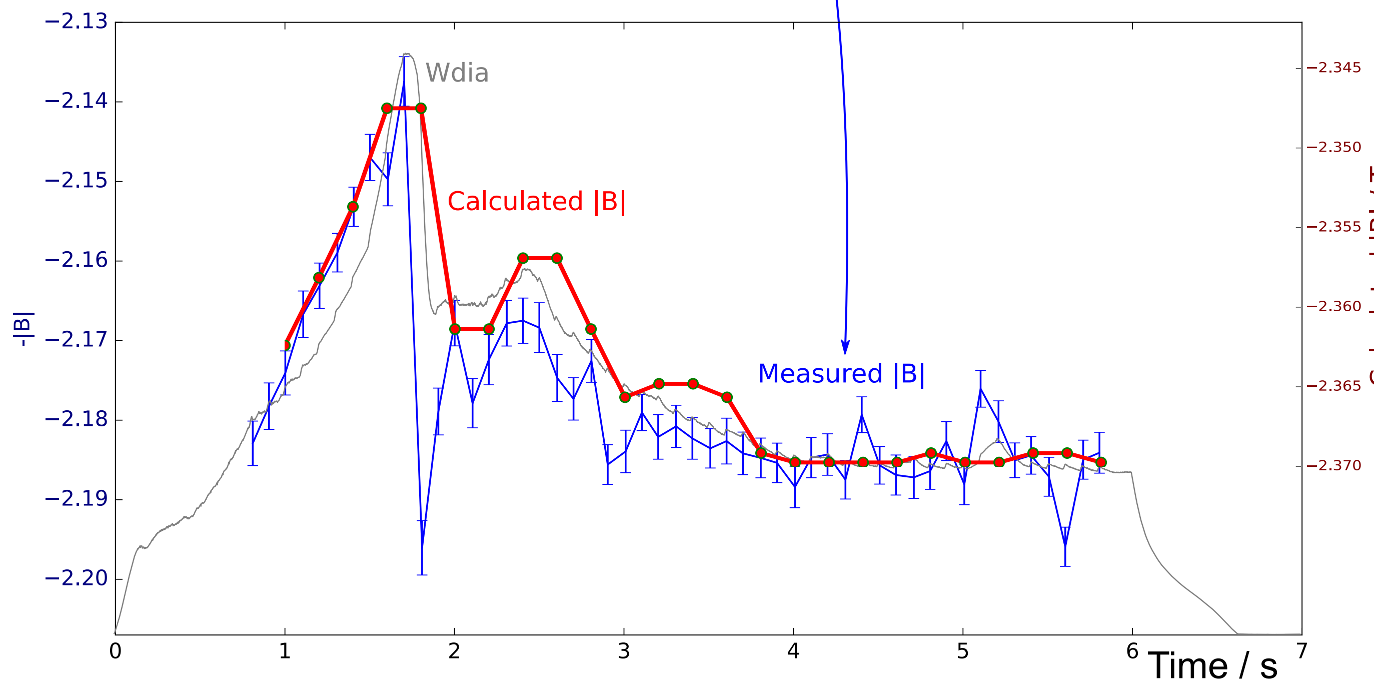
- Still under investigation but so far no obvious explanation.

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!



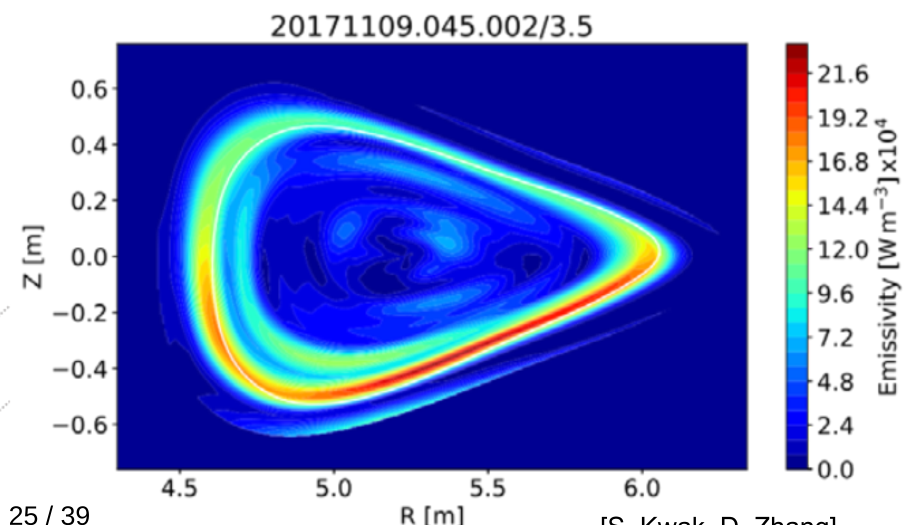
[D. Zhang]

Bolometer

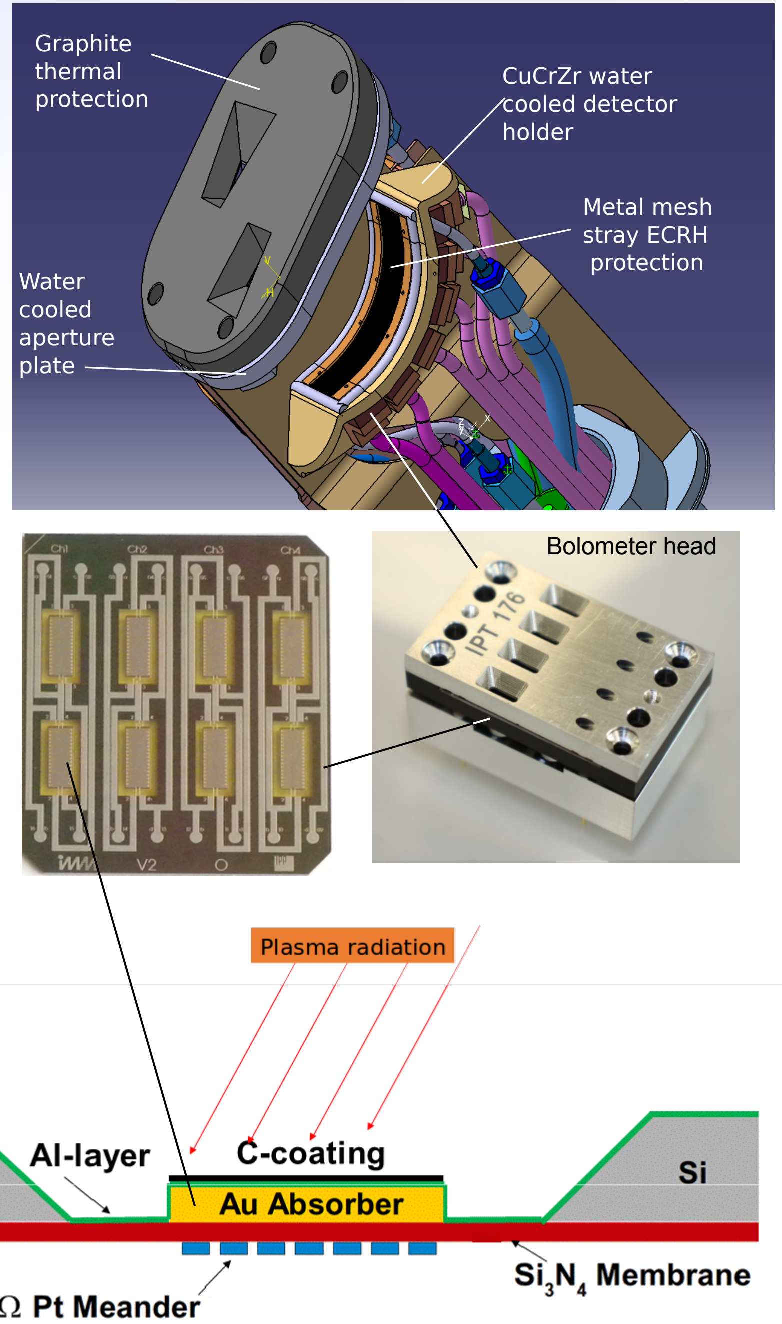
Measurements of radiated power were critical for last campaign OP1.2a due to radiative density limit:

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]



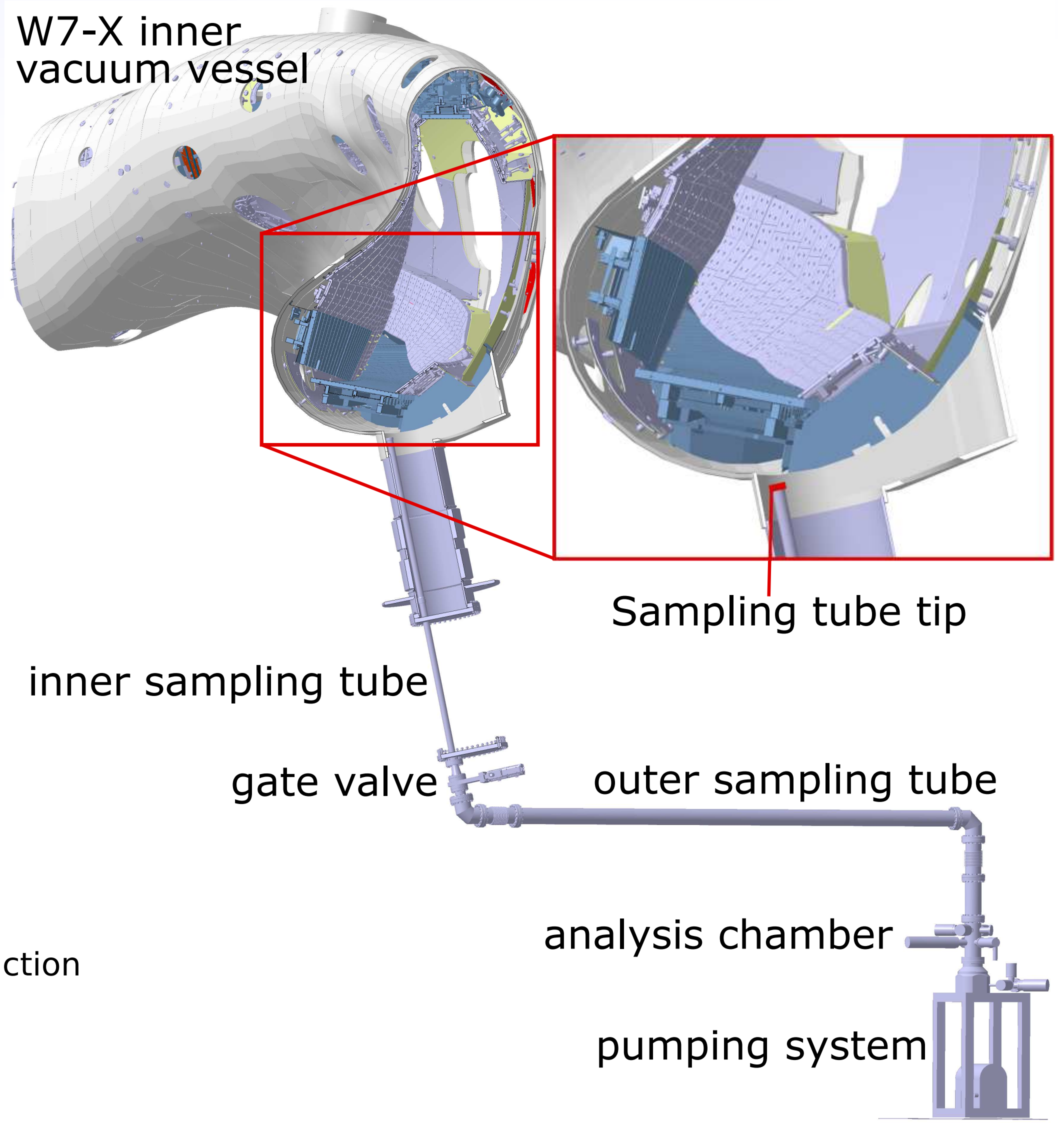
G. Schlisio, *Rev. Sci. Instrum.* Submitted March 2018

Diagnostic Residual Gas Analyzer

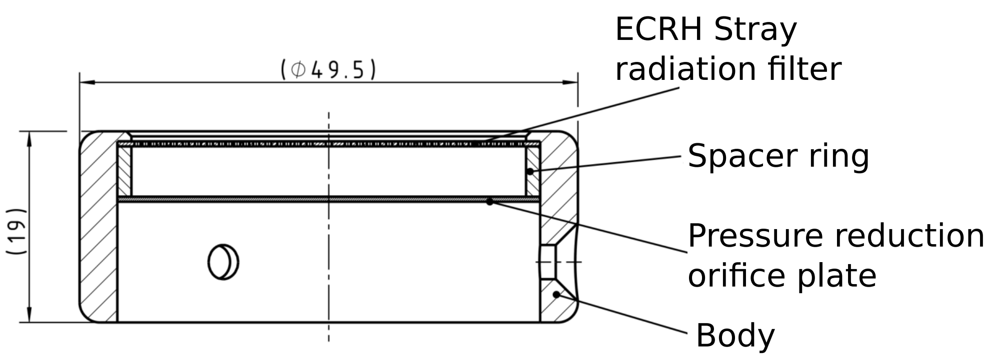
- DRGA Prototype analysis chamber developed by US-ITER at ORNL (for divertor pumping DRGA)
- Tested on test setup and linear machine in US.
- Operated on W7-X in last campaign (OP1.2b):

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.



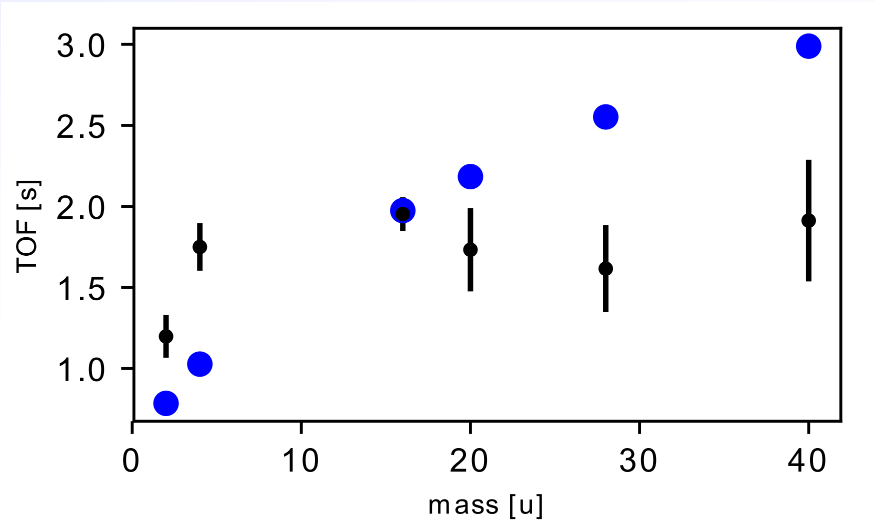
- Cap:

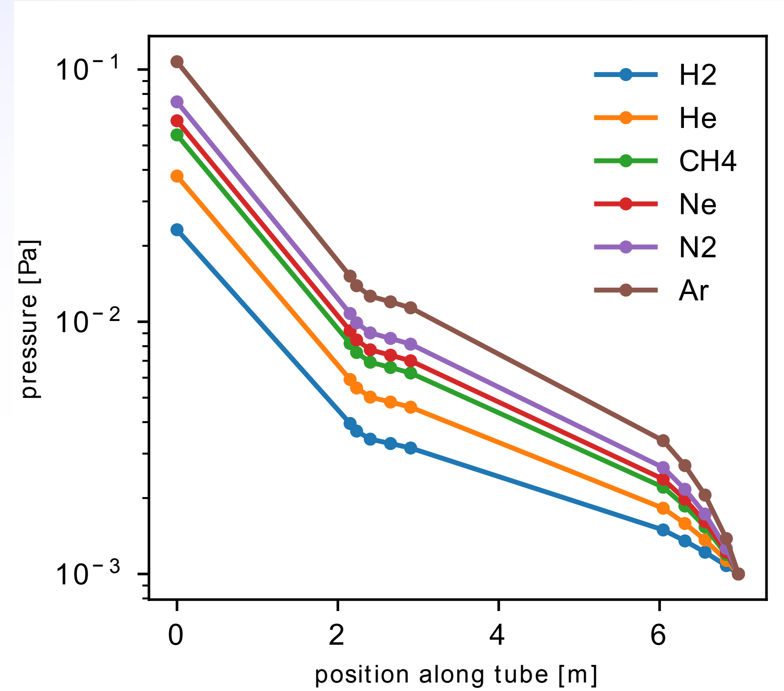


G. Schlisio, *Rev. Sci. Instrum.*
Submitted March 2018

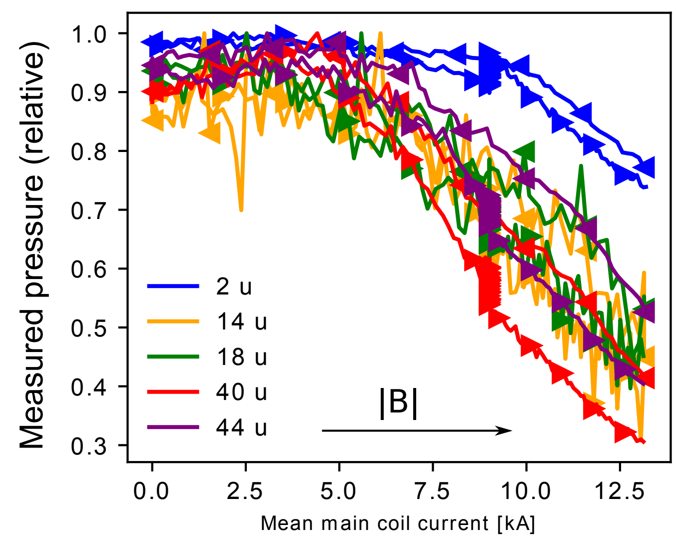
Diagnostic Residual Gas Analyzer

- 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)



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

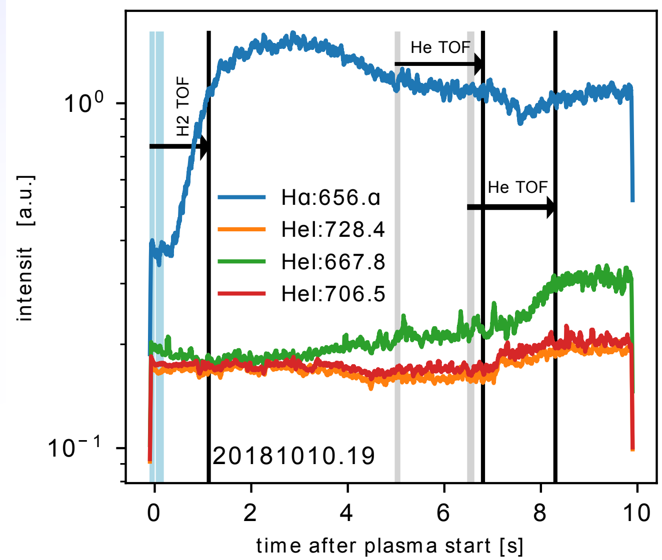
Diagnostic Residual Gas Analyzer

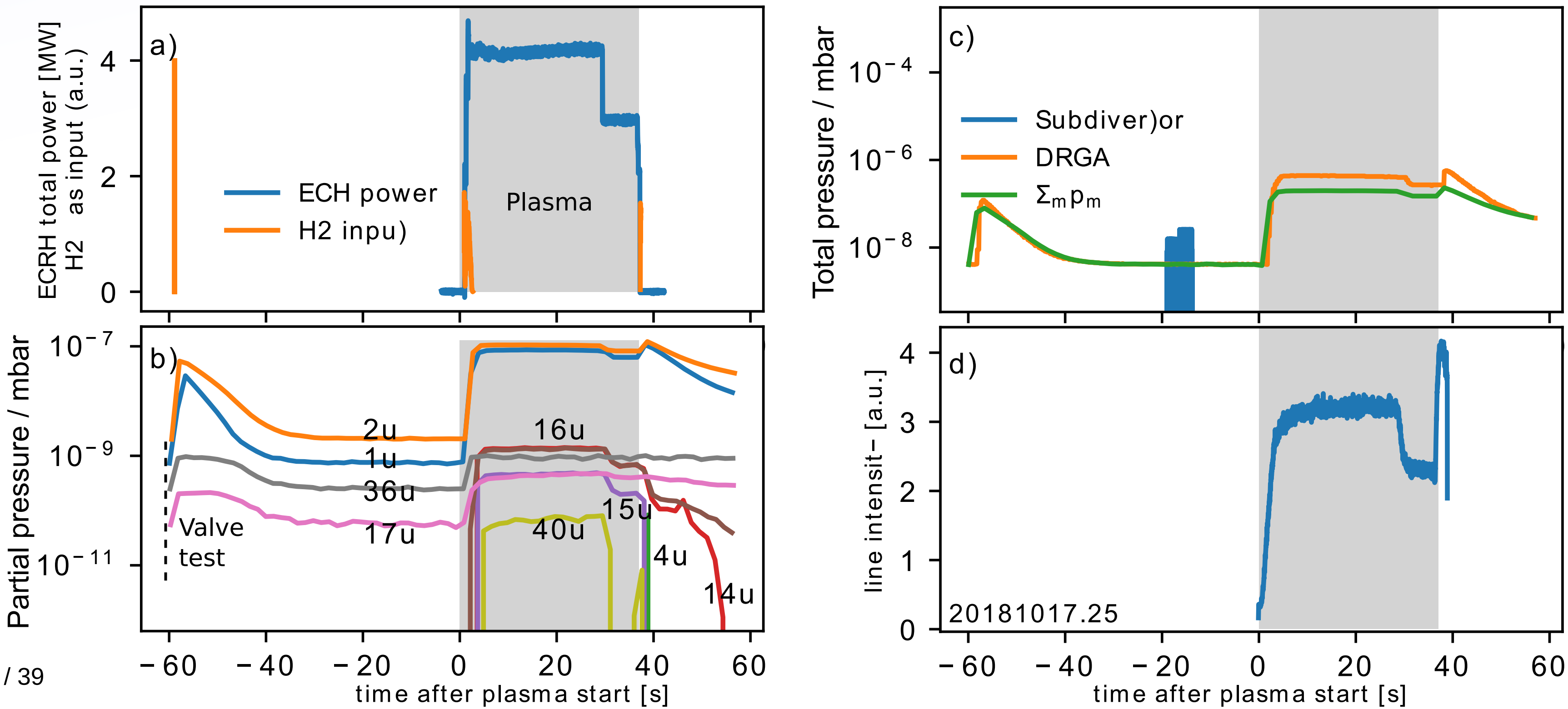
- Useful plasma results obtained:
e.g. during divertor detachment program:

- 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)



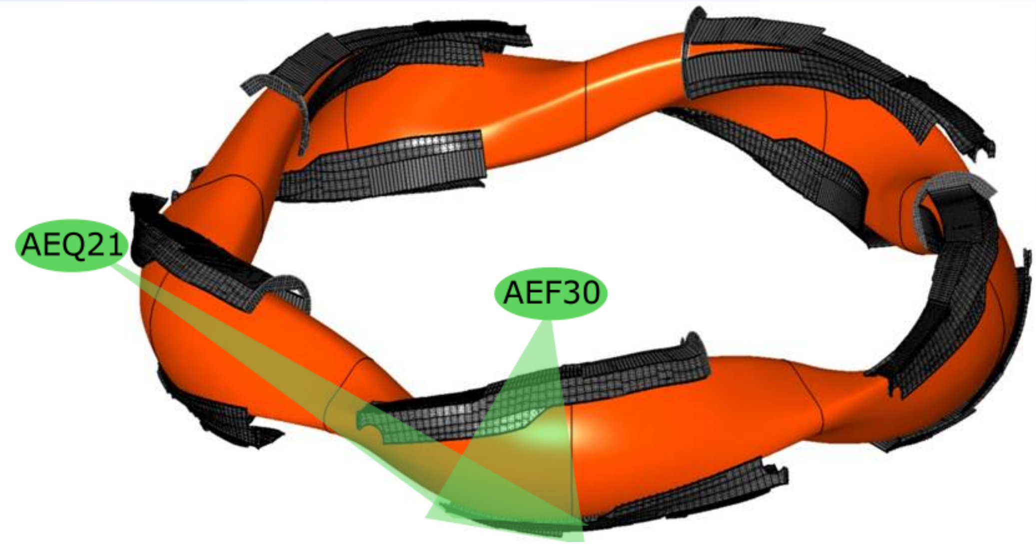


Coherence Imaging Spectropscopy

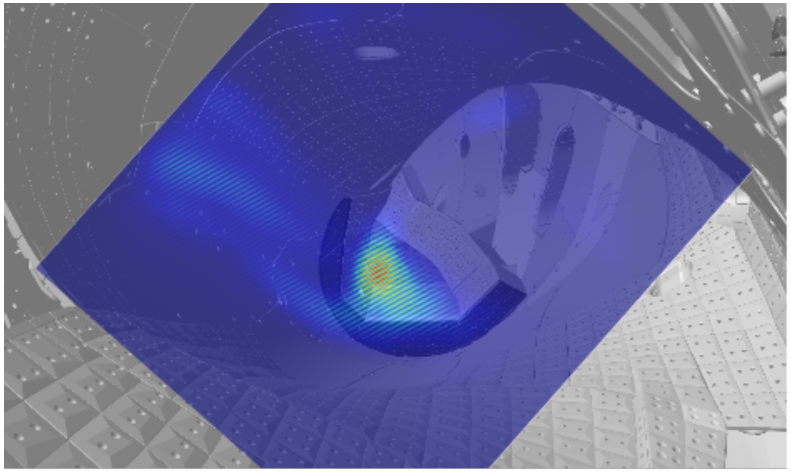
(a.k.a 'Flow Monitor')

- 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)

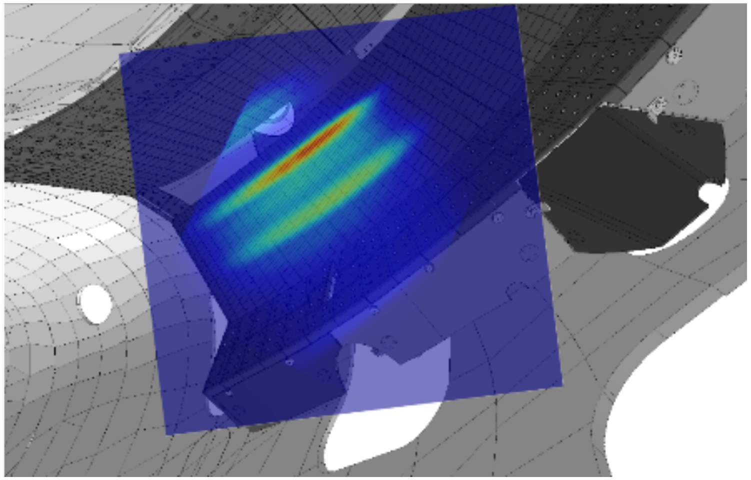
- Measurements made in Carbon, Helium, Hydrogen



Toroidal view:



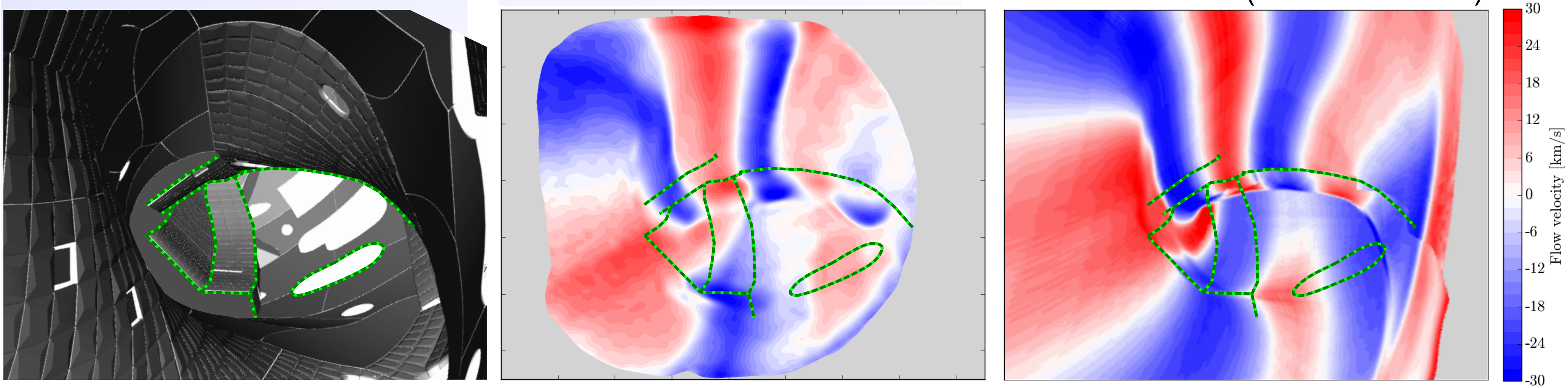
Vertical view:



Coherence Imaging Spectropscopy

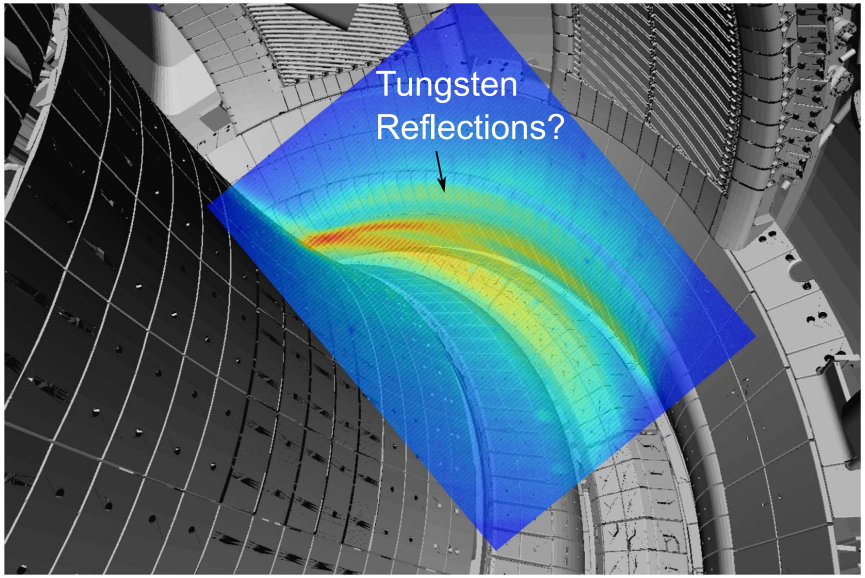
- Calibrated flow images reveal counter-propargating flows expected due to island/divertor geometry.
- High frictional coupling of measured C flows to main ion SOL flows.

CAD | Measurement | Prediction (EMC3-EIRENE)

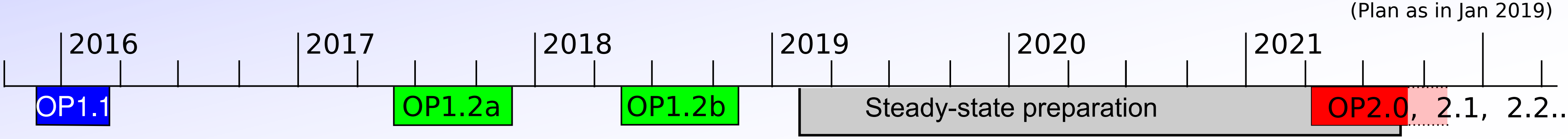


ASDEX Upgrade CIS:

- 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

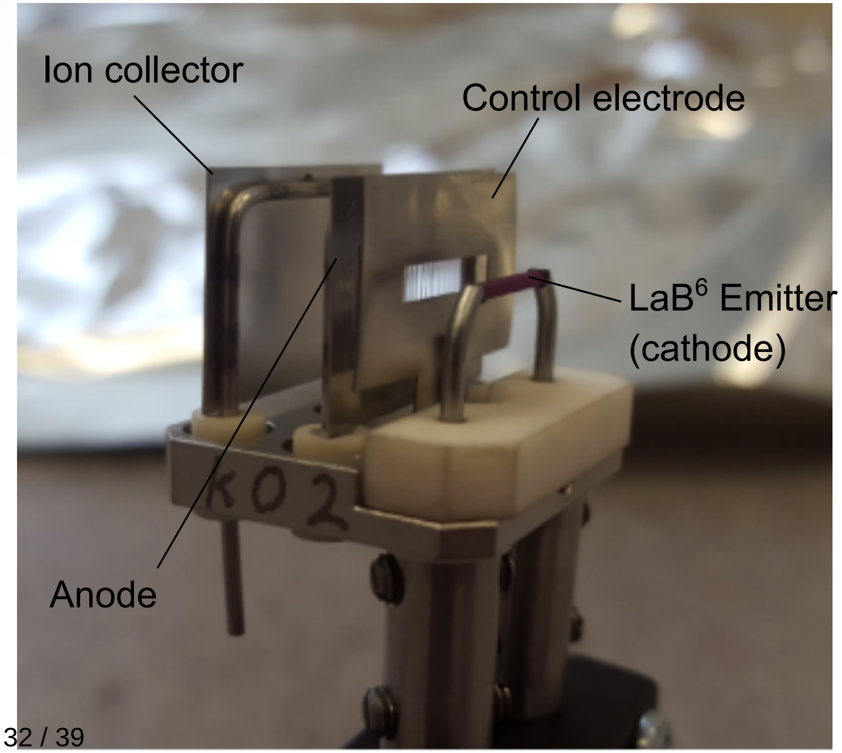
[Wenzel et al., RSI 89, 033503 (2018)]

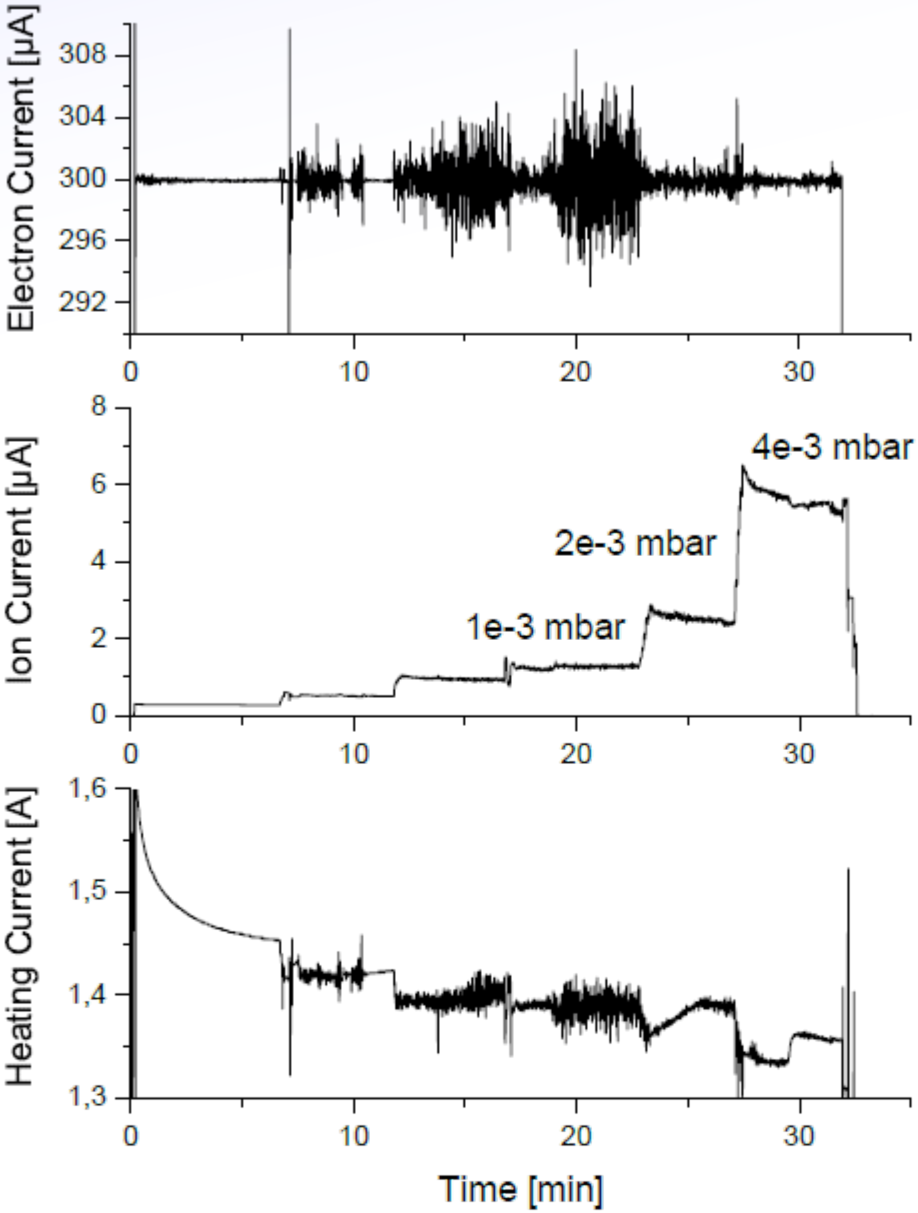
The ASDEX-Upgrade type neutral gas manometers were are also under test in the first campaign but showed failure after several hours cumulative operation.

- 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.

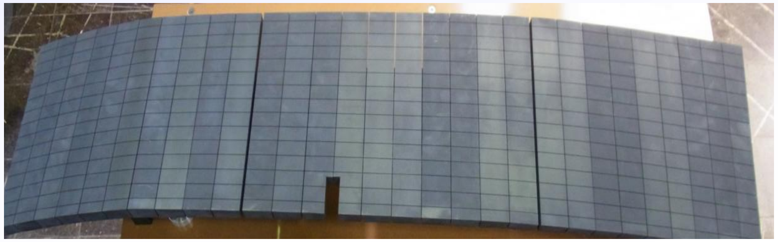




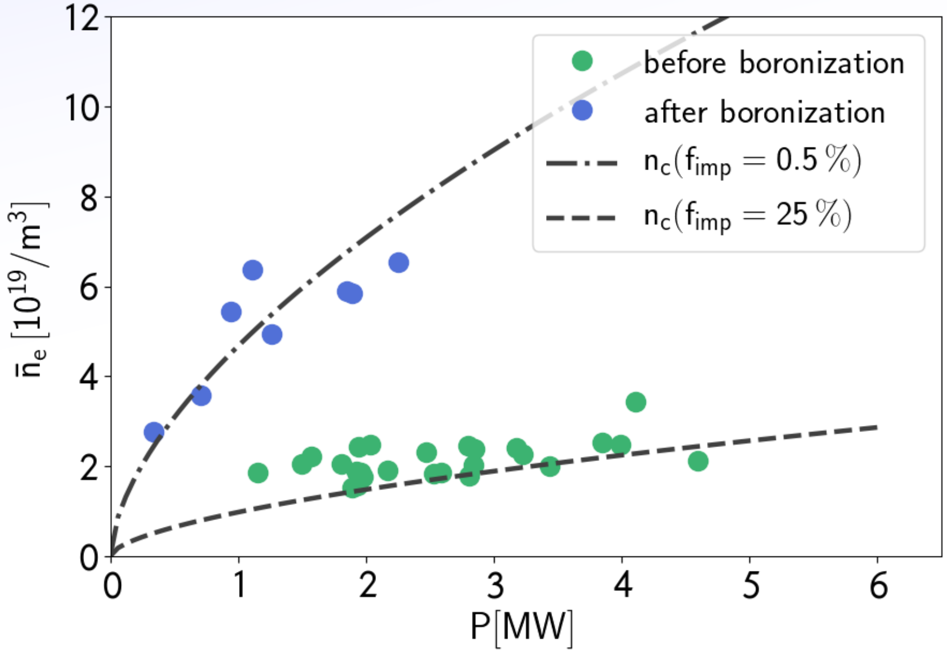
W7-X OP1.2 (2018) Complete

Highlights of OP2.1

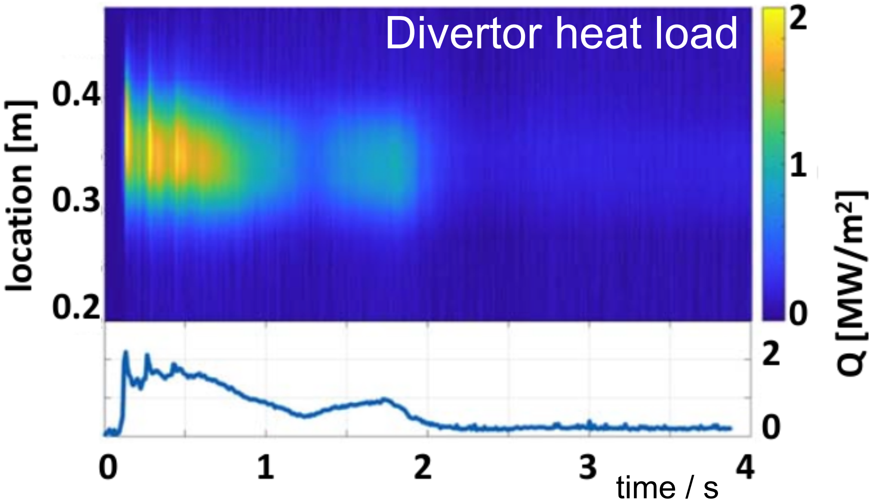
- OP1.2a: Limited densities due to radiative density limit.
- OP1.2b: Boronisation allowed operation to high densities (n_e ~ 1.8 x 10^{20} m^{-3}) with up to 6MW ECRH heating.



OP1.2: Test Divertor Unit



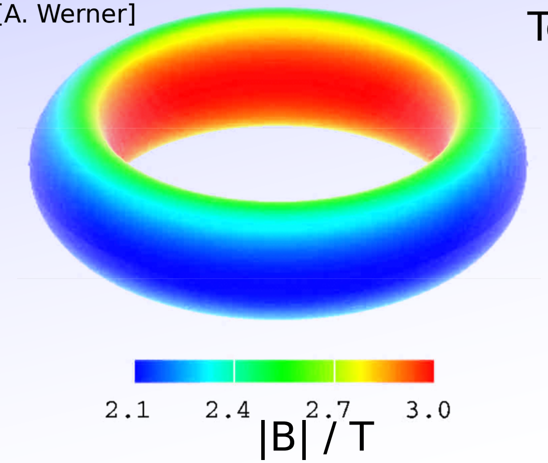
- Full detached divertor operation:



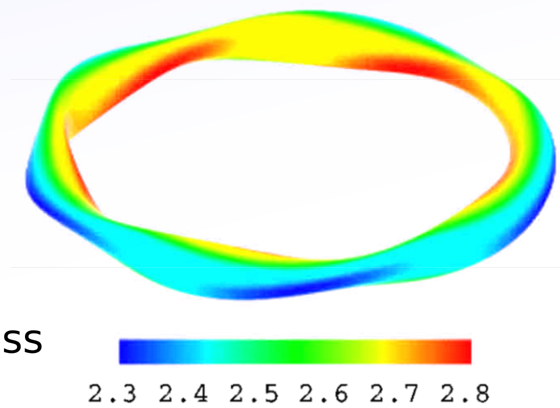
[R. Wolf, A.Werner, J.H.E. Proll]

Stellarator Optimisation

[A. Werner]



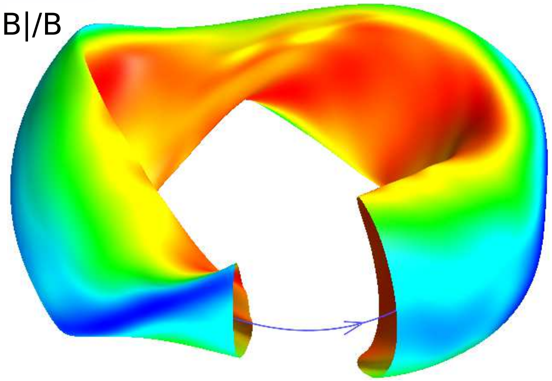
Tokamak:
Trapped particles precess toroidally because |B| is axi-symmetric.

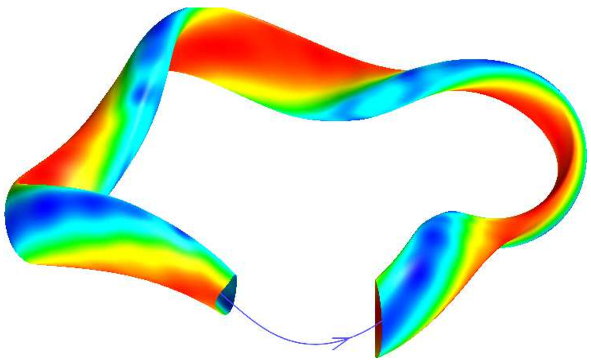


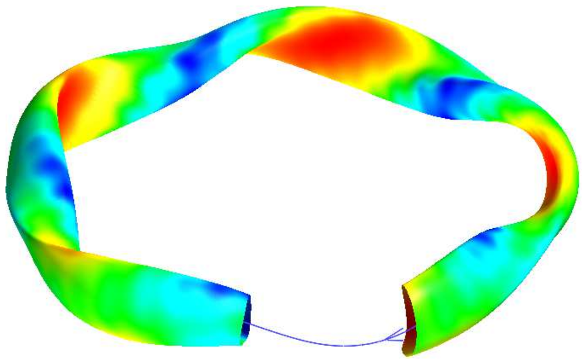
Classical Stellarator:
Poor neoclassical confinement due to loss of trapped particles.

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)

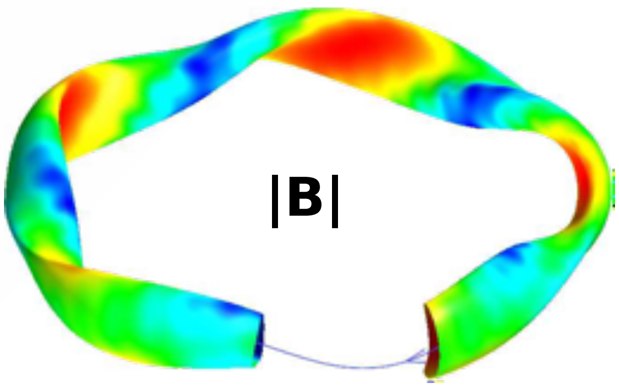
[J.H.E. Proll PPCF **58** 1 2016]

W7-X: An optimised Stellarator

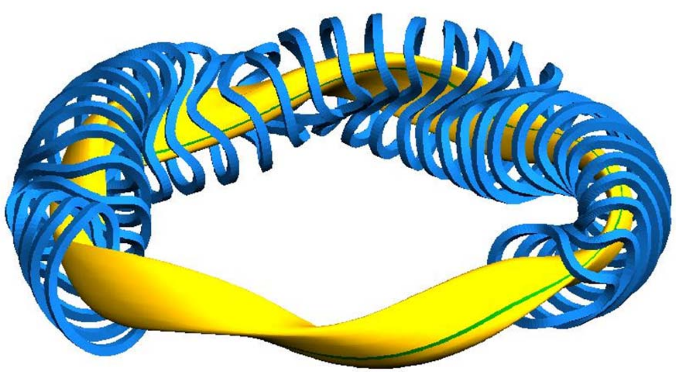
[J. Nührenberg PPCF 52 124003 2010]

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

Magnetic field optimisation



Steady-state operation with superconducting coils



Optimisation of W7-X:

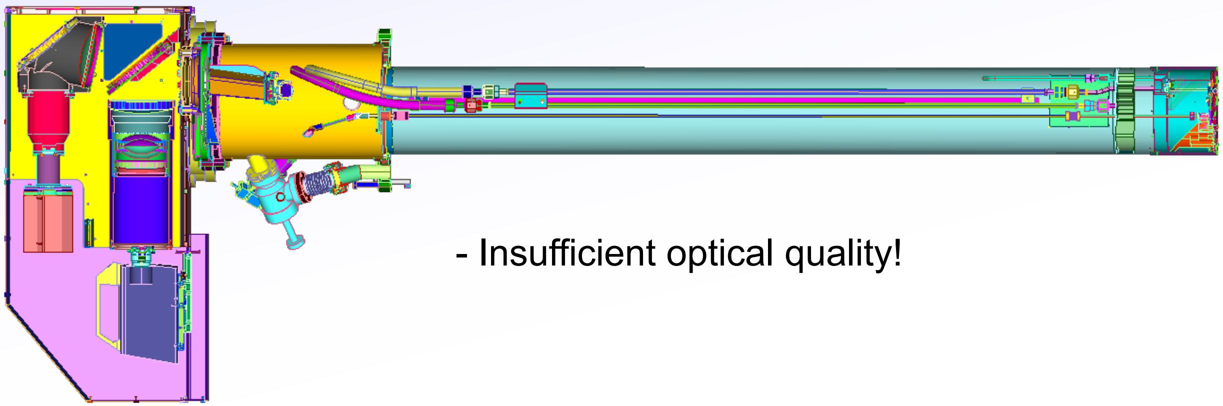
1. Feasible modular coils (no toroidal conductors)
2. Good, nested magnetic surfaces
3. Good finite-β equilibria
4. Good MHD stability
5. Small neoclassical transport
6. Small bootstrap current
7. Good confinement of fast particles

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

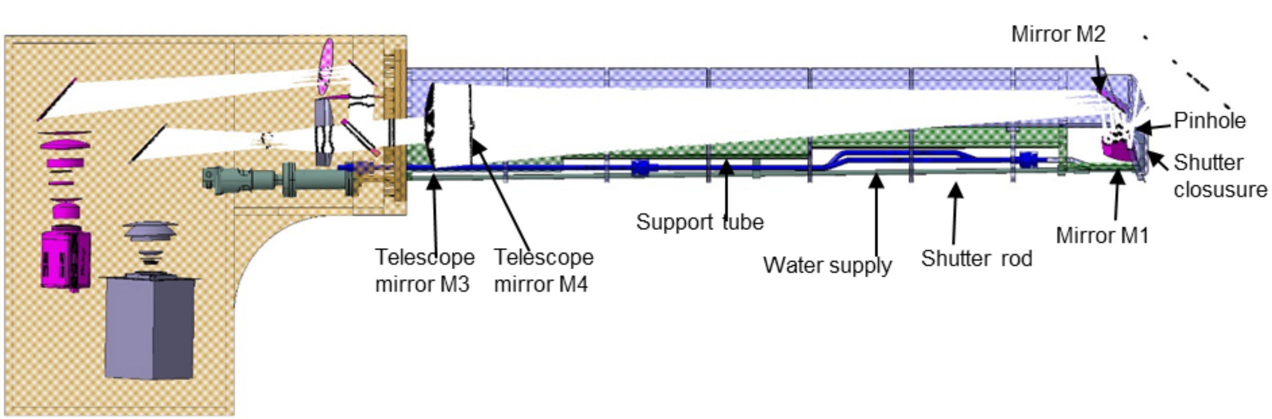
VIS/IR Endoscopes:

- Prototype OP1.2:



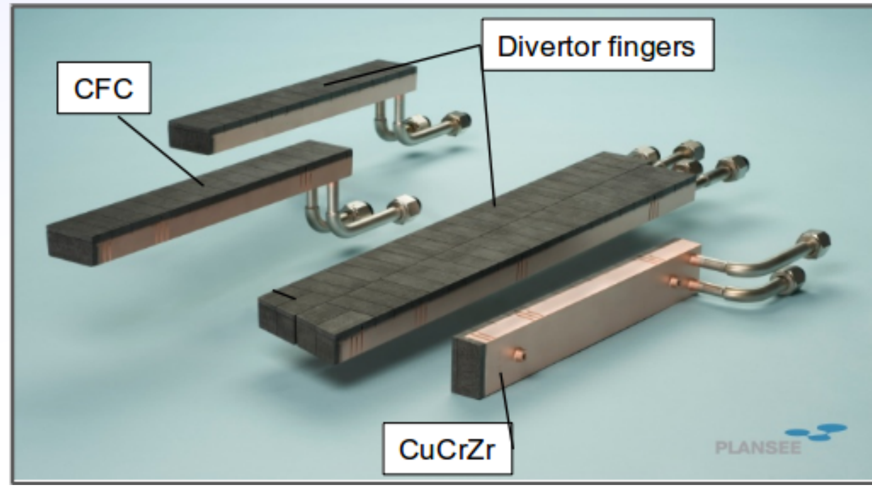
- Insufficient optical quality!

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



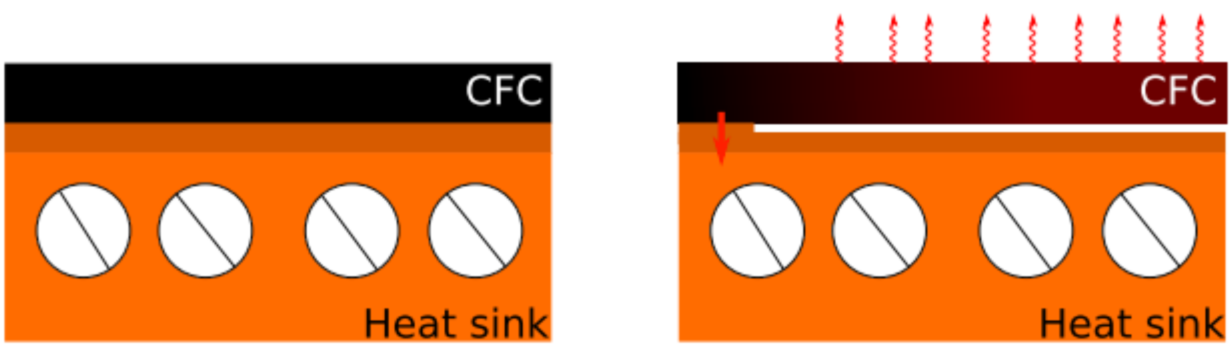
Visible/Infrared video + Real-time protection

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

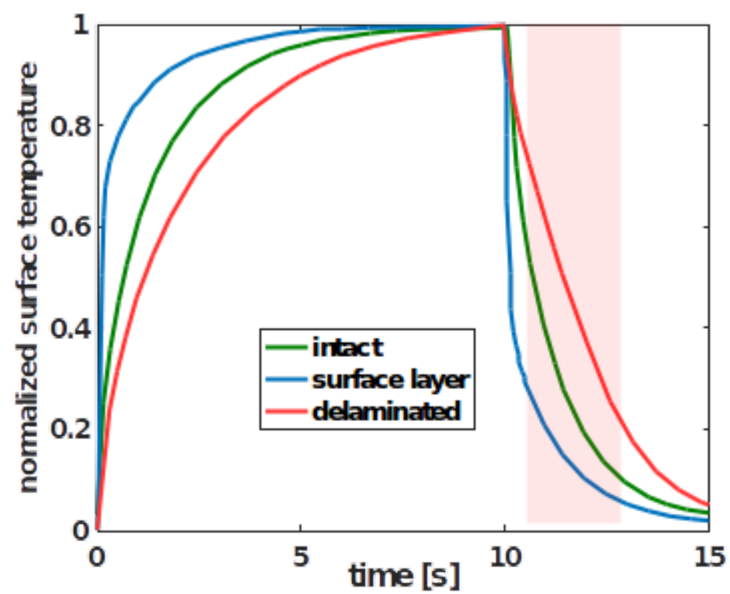


- Hot spot detection
- False positives from surface layers.
- Avoid but detect delamination of tiles

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



Normal   Delaminated



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