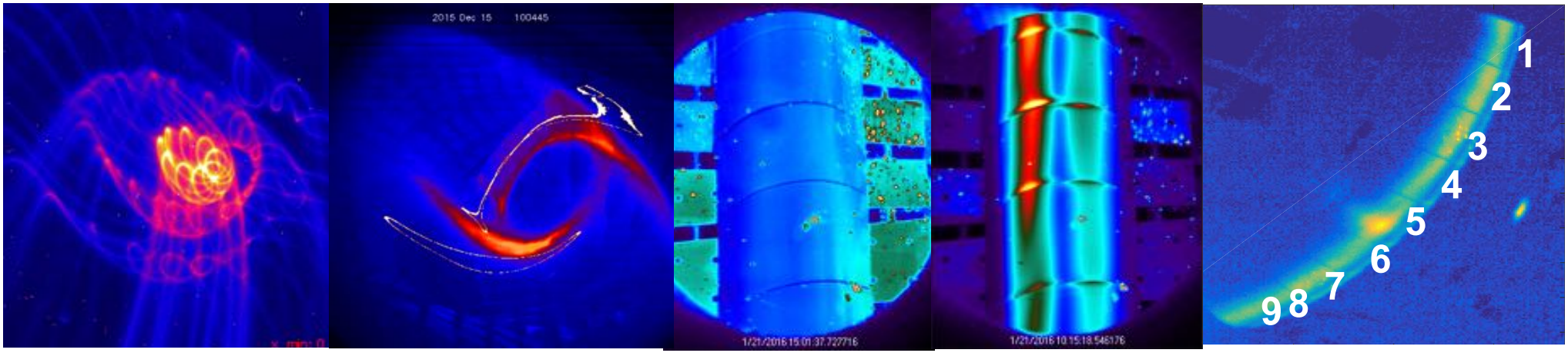
Recent results and near-term plans for Wendelstein 7-X

Thomas Sunn Pedersen
on behalf of the W7-X team

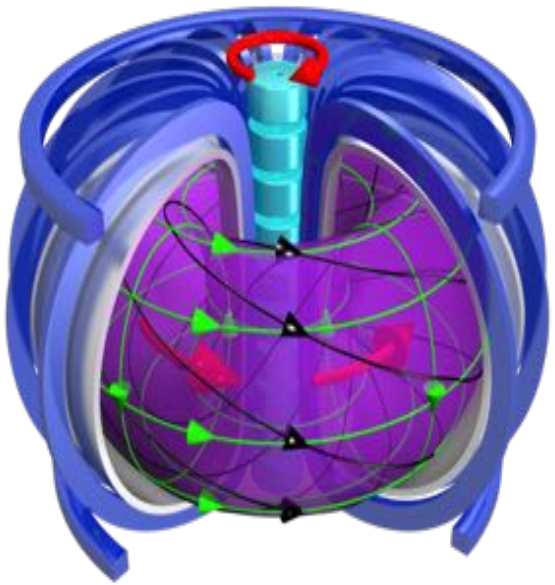


Overview

- The optimized stellarator W7-X
- Planned operation phases
- Plasma-facing components and magnetic topology in OP1.1
- Examples of physics results in OP1.1 and international participation
- Plans for OP1.2
- Summary

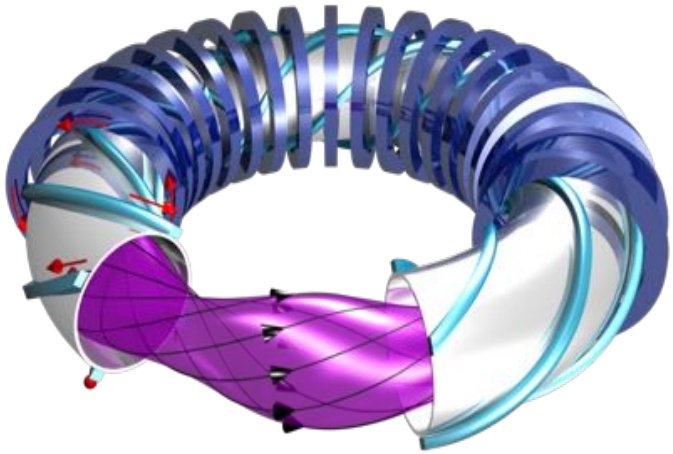
Tokamak and stellarator

- twisted magnetic field
- strong toroidal current in plasma



- excellent plasma confinement
- plasma instabilities require control
- steady-state operation requires strong current drive

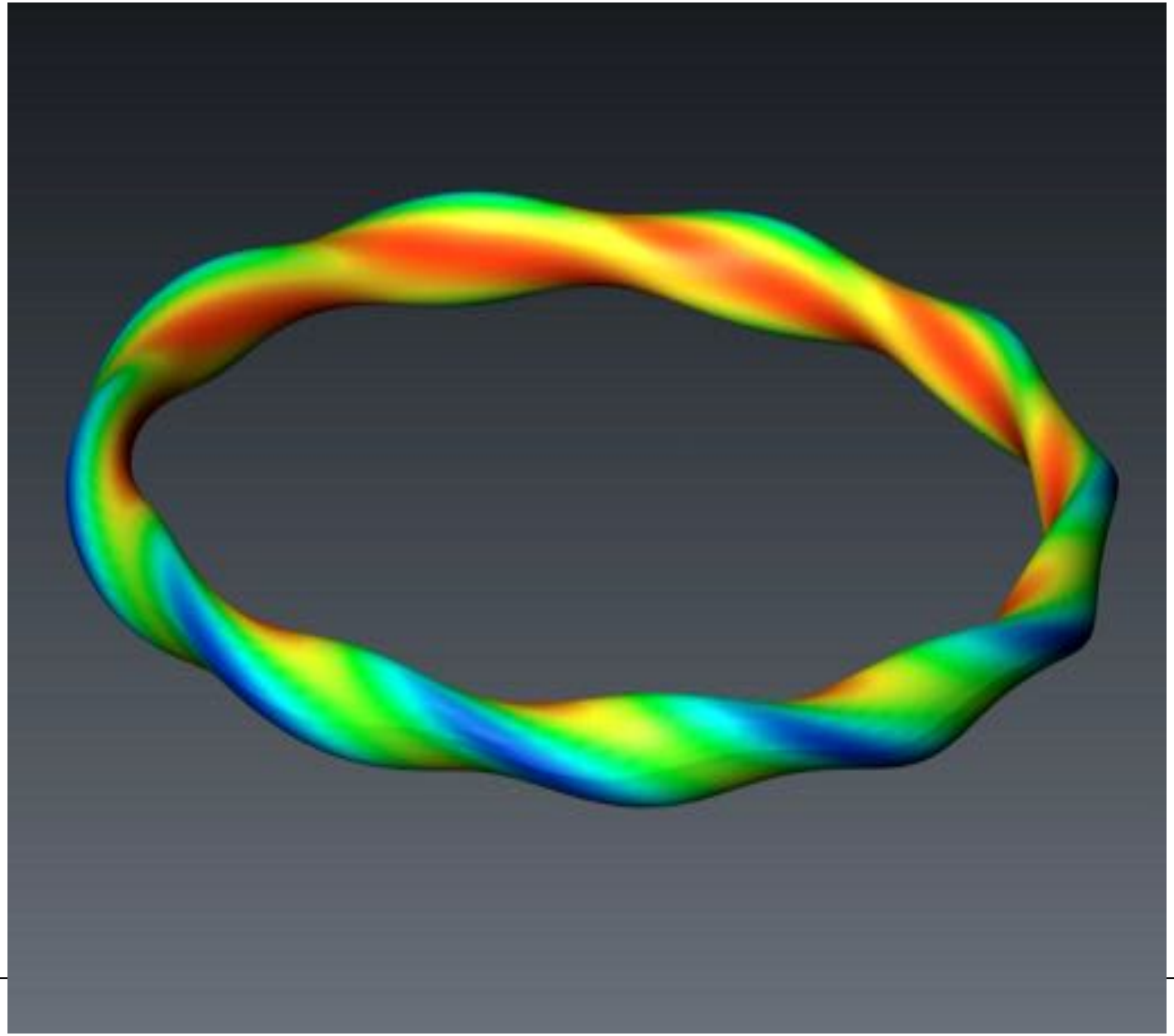
- twisted magnetic field
- weak, self-generated toroidal current



- excellent plasma confinement to be proven: computer optimization needed
- Free of major disruptions
- steady-state

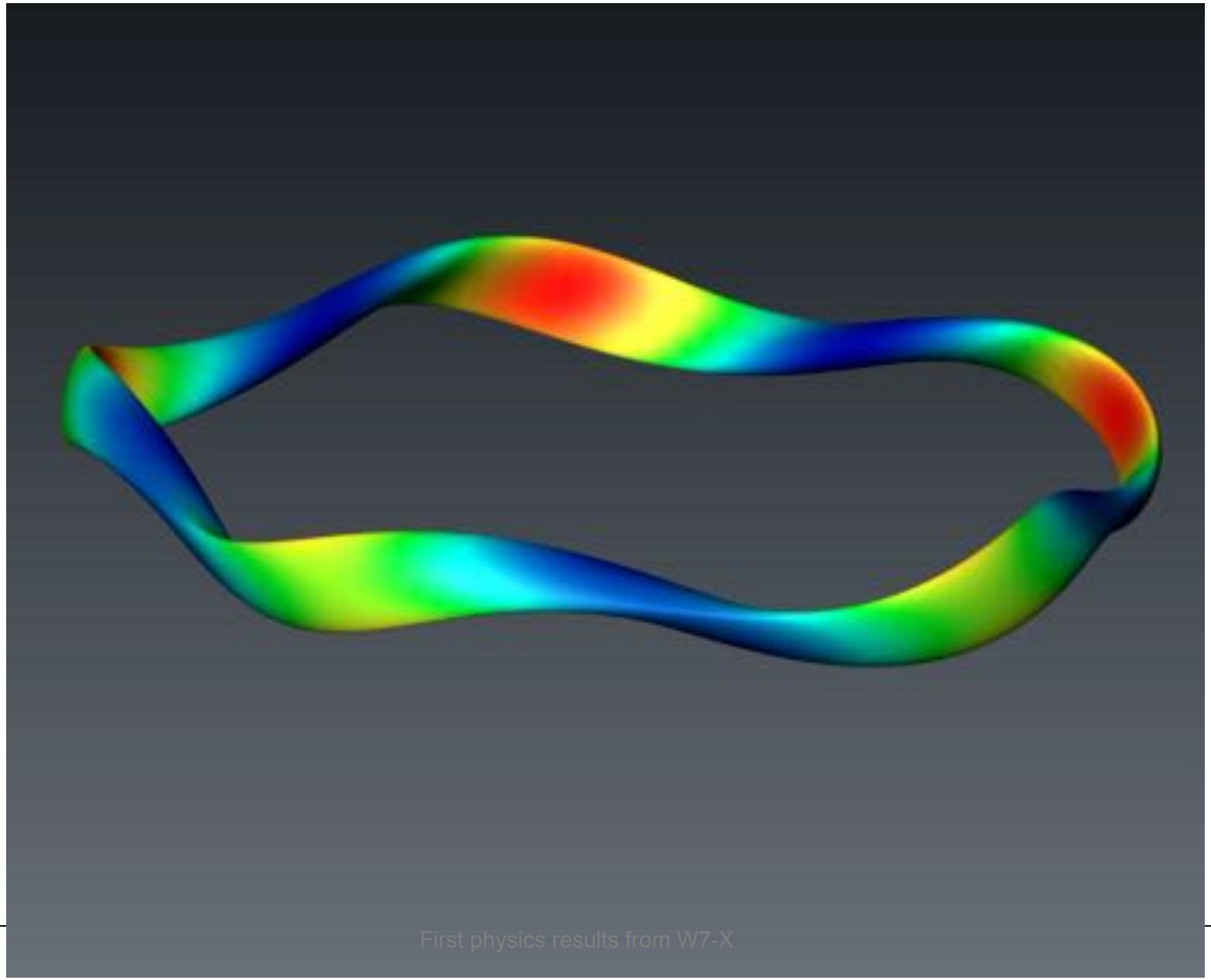
50 keV ion in a classical stellarator

50 keV D-ion in a B=2.5 T R=5 m classical stellarator – scales to α-particle in reactor



W7-X magnetic field optimization

50 keV D-ion in W7-X – scales to α-particle in HELIAS reactor



The optimized stellarator Wendelstein 7-X

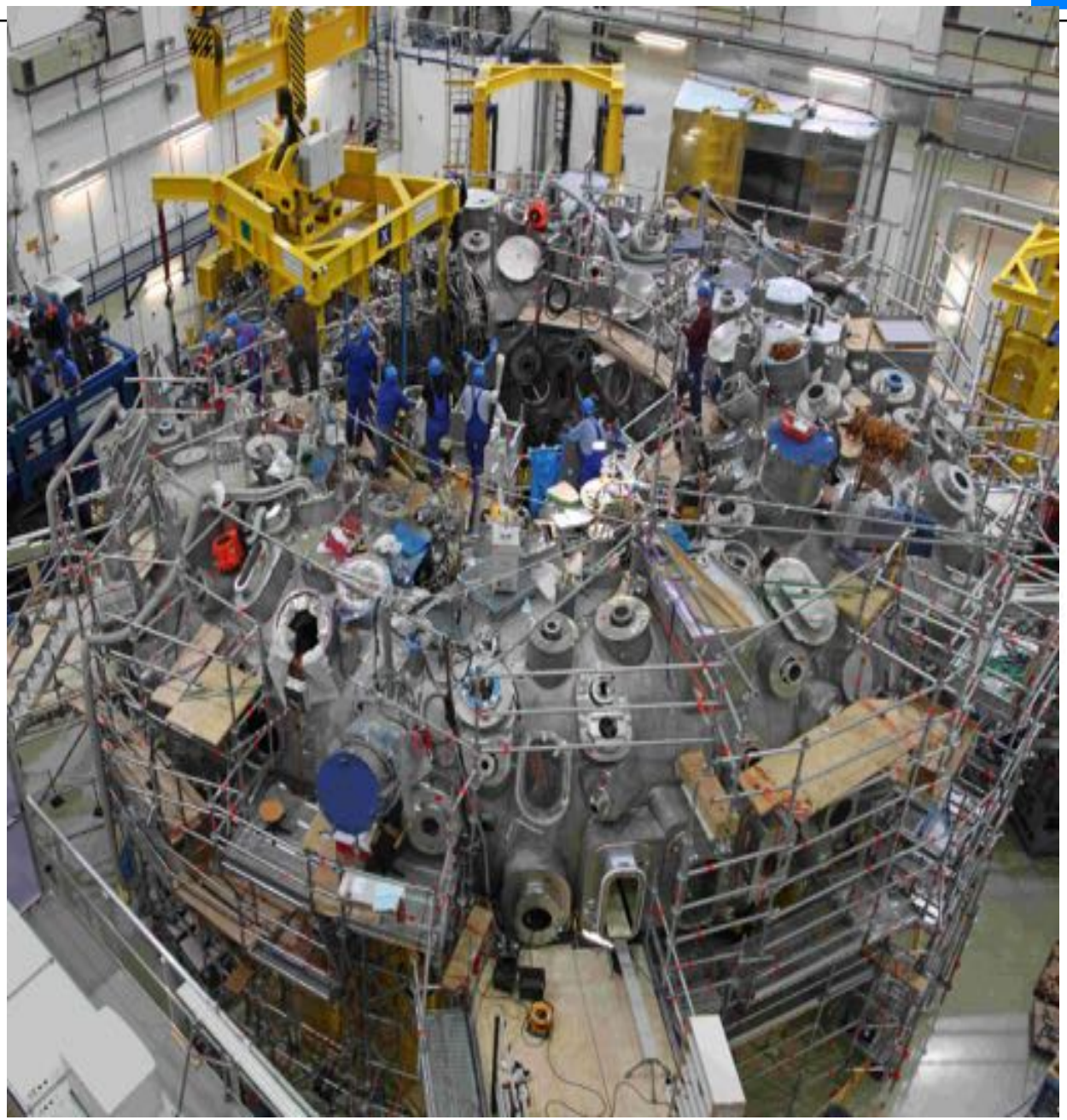
Plasma volume **30 m^3**
Magnetic field **2.5 T (up to 3 T)**

Superconducting coils **70**

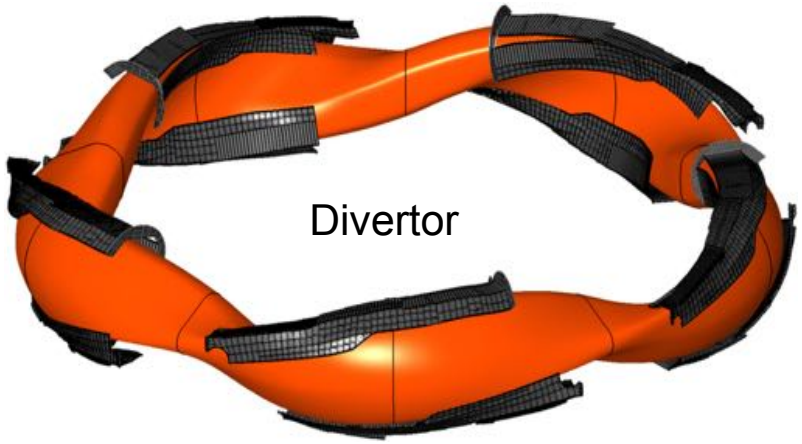
Magnetic field energy **600 MJ**

Cold mass **435 t**

Total mass **735 t**



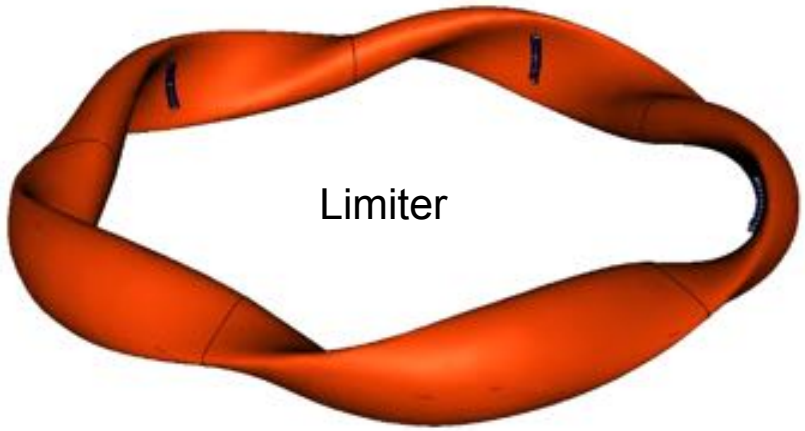
Wendelstein 7-X operational phases



OP 2: 2020 …
Steady-state operation
Actively cooled divertor configuration
P_{cw} ~ 10 MW
P_{pulse} ~ 20 MW (10 s)
Technical limit **30 minutes** @ 10 MW

OP 1.2: 2017 / 2018
Uncooled divertor configuration
P ~ 10 MW
$\int P\,dt \leq 80$ MJ
τ_{pulse} ~ 10 s at 8 MW
(... 60 s @ reduced power)

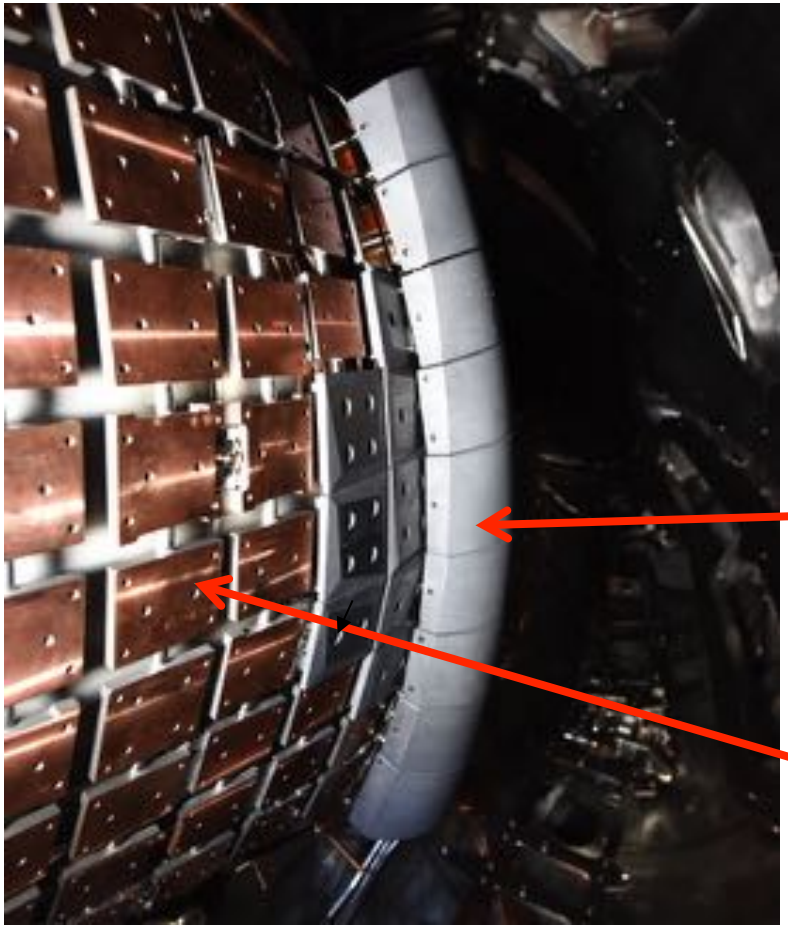
OP 1.1: 2015 / 2016
Limiter configuration
P < 5 MW -> 4.3 MW
$\int P\,dt \leq 2$ MJ -> 4MJ
τ_{pulse} ~ 1 s -> 6 s



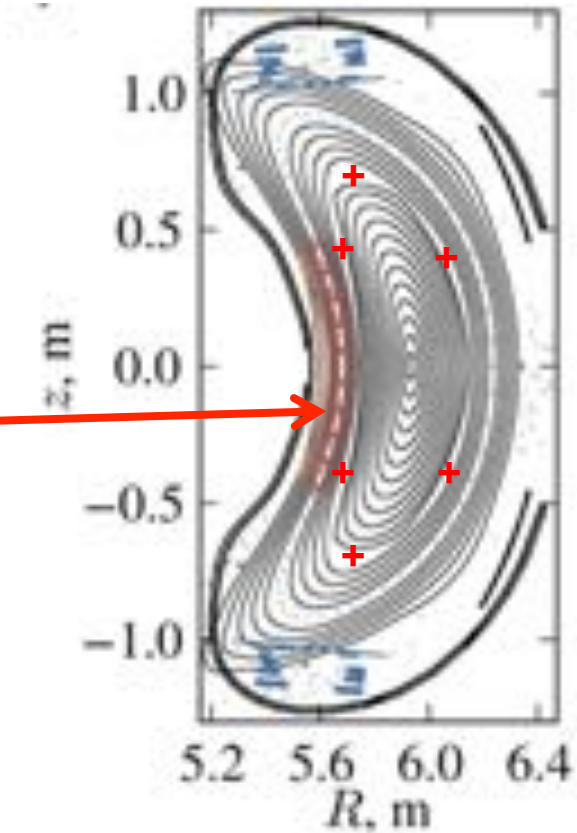
PFCs and topology for OP1.1

- 5 shaped graphite limiters
- Designed to intersect >99% of the convective plasma heat loads
- The rest of the PFCs shielded from direct convective plasma loads

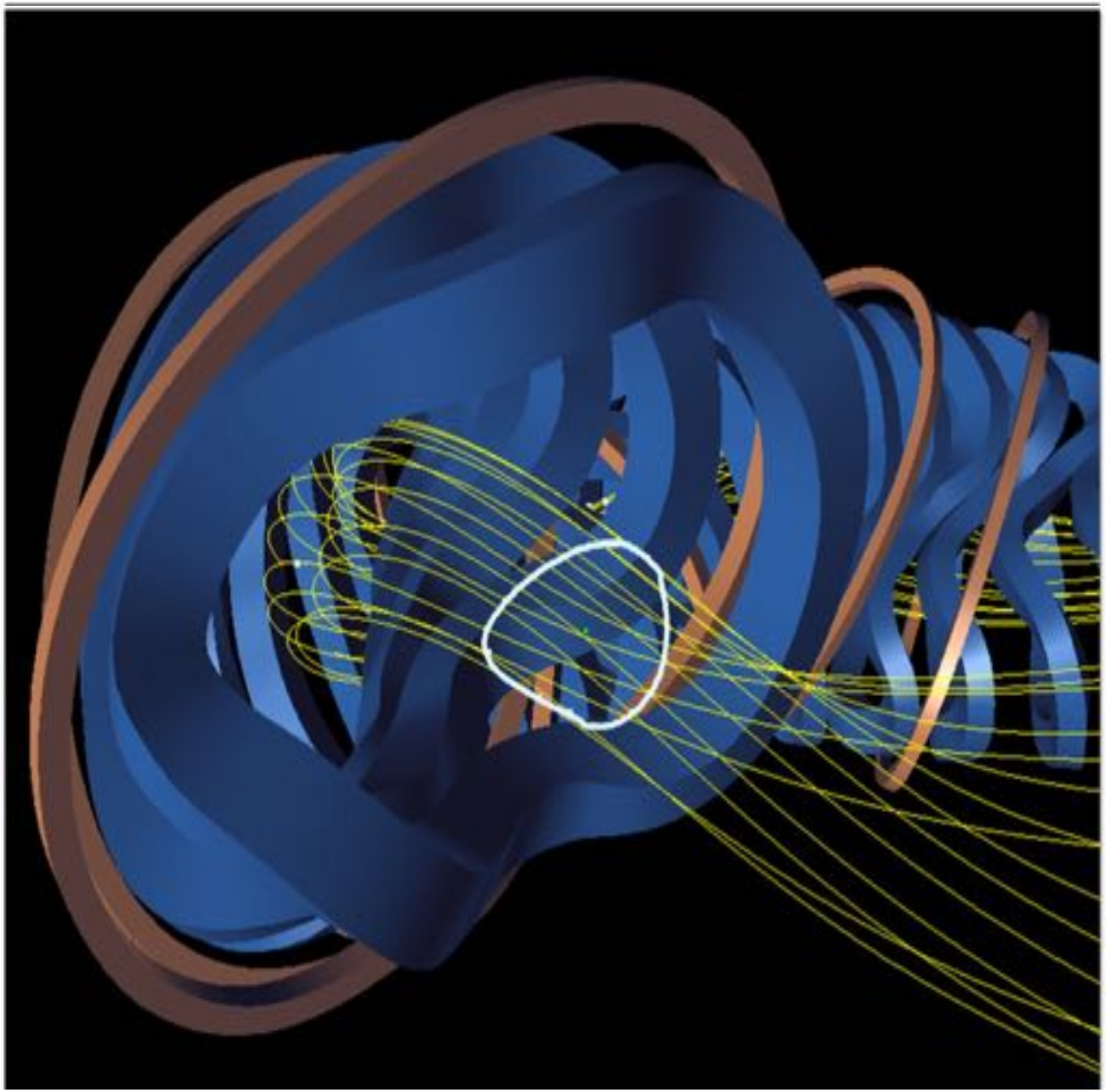
- Magnetic configuration without edge islands ensures “sharp edge”
- Internal 5/6 island chain (+) serves as marker for the topology, indirectly confirming the absence of near-shadow island chains



Bare CuCrZr heat sinks
(all being covered with graphite for OP1.2)

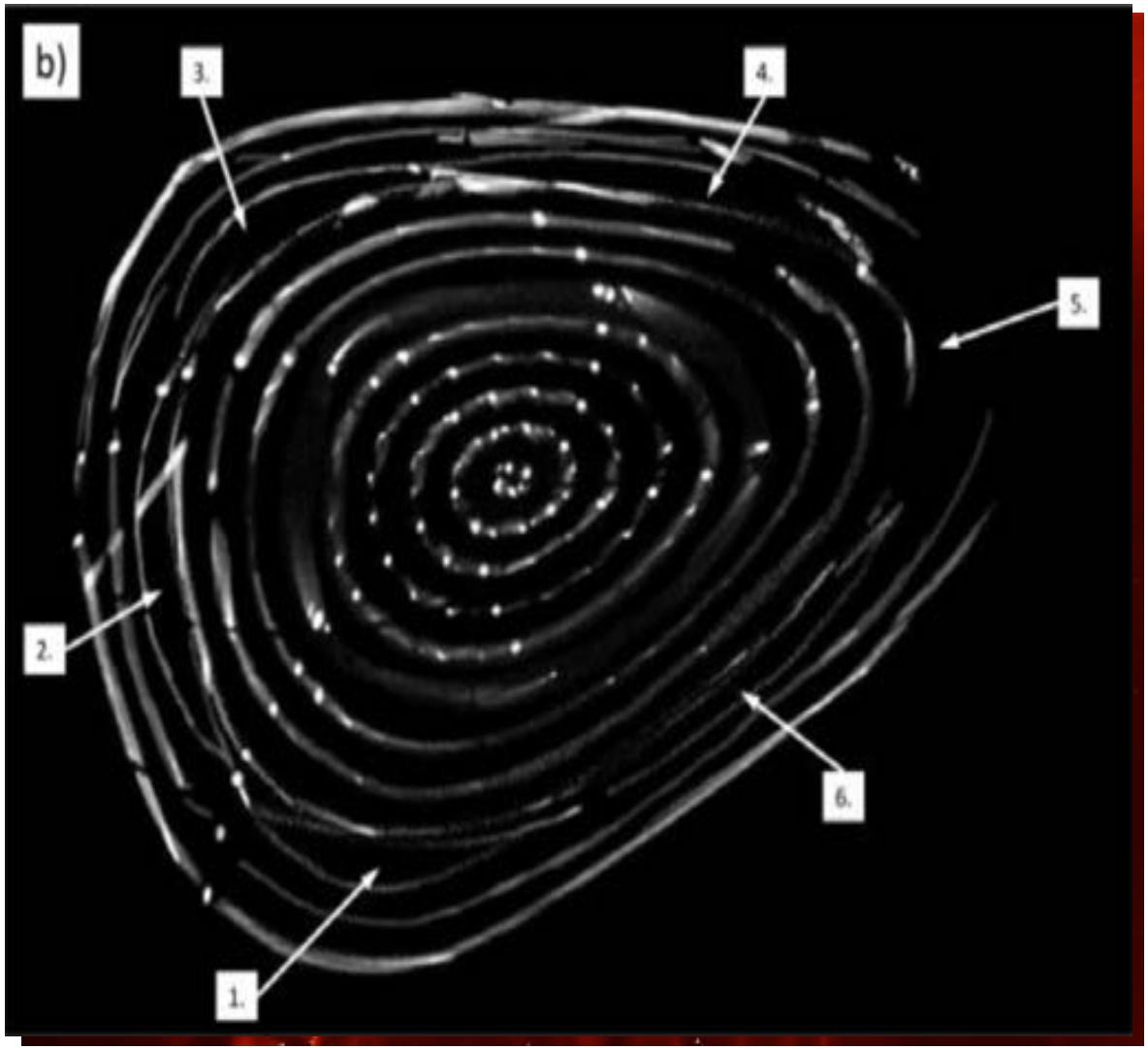


Confirming the topology



Measurements confirmed nested flux surfaces

- As reported earlier[a,b], the expected nested flux surface topology has been verified in great detail, including the intrinsic 5/6 island chain
- There were some deviations but all small
- The configuration chosen for OP1.1 plasma operation was particularly robust against field errors.
- With a different configuration[c,d] we confirmed the topology to an accuracy of better than 1:100000



[a]APS-DPP meeting San Jose, CA (2016)
[b]M. Otte et al., PPCF 58, 064003 (2016)

[c]S. Lazerson et al., Nucl, Fusion (2016)
[d]T. Sunn Pedersen et al., Nature Comm. (2016)

All goals of OP 1.1 were attained …

OP 1.1 priorities: Integral commissioning and first plasma operation

1. Integral commissioning of all systems needed for successful plasma operation ✓
2. Existence of closed flux surfaces all the way to the limiter (at B=2.5 T) ✓
3. Measurement and adequate reduction of B_{11} field errors (✓)
4. Reliable ECRH plasma startup scenario in He ✓
5. Basic ECRH interlocks and safe operation scenarios: $\int P\,dt \leq 2$ MJ ✓
6. Basic impurity content monitoring ✓
7. Central $T_e > 1$ keV at $n_e > 5 \cdot 10^{18}$ m^{-3} in at least 10 discharges in He ✓

$P_{ECRH} \leq$ 4.3 MW

4 MJ / 6 s

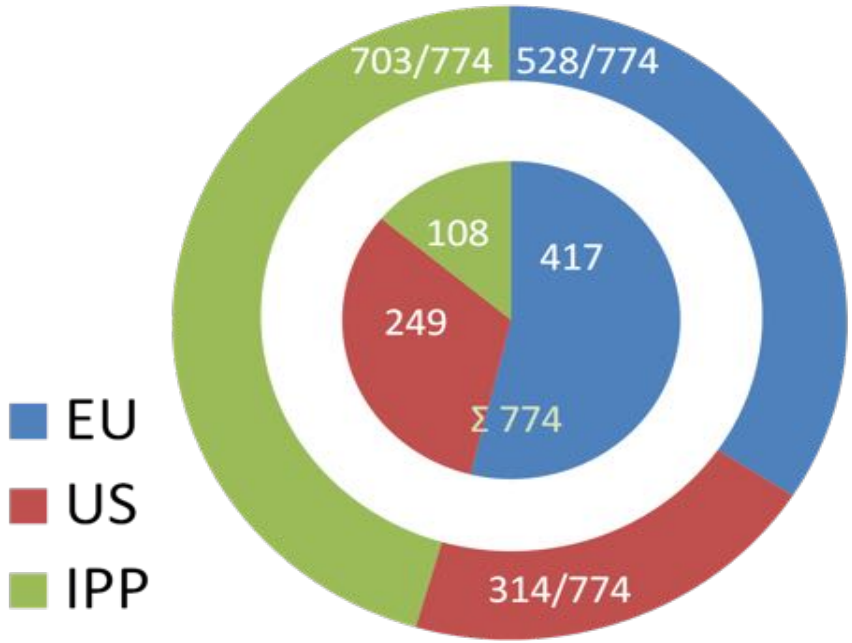
$T_e \sim 10$keV
$T_i \leq 2$ keV

He $\leq 8 \cdot 10^{19}$m^{-3}
H $\leq 2...3 \cdot 10^{19}$m^{-3}

Confirmation of optimization goals of W7-X will be done in later operation phases

Success of OP 1.1: A collaborative effort

Contributors to conducted proposals



inner circle: 'first proponent'
outer circle: contributor

- 402 out of 843 plasma experiments (discharges) with physics proposals
- 774 proposals conducted in the 402 physics programs

US Construction Contributions

US contributions to the device

- development of a lifting device for current leads (ORNL)
- support in structural engineering and metrology (PPPL and ORNL)
- design, engineering and manufacturing of trim coils (PPPL)
- design, engineering and manufacturing of power supplies (PPPL)
- development and design of scraper element (PPPL and ORNL)
- design and manufacturing of TDU scraper element (PPPL)

successful engineering collaboration „across the pond“ with the help of common tools, video links, frequent visits

Success story for international fusion research collaborations

US science contributions

diagnostics instruments for OP 1.1 and OP 1.2

- X-ray imaging crystal spectrometer XICS (PPPL)
- high-resolution infrared and visible camera system (LANL)
- Penning gauge with optical observation (U Wisconsin)
- filterscope array (ORNL)
- phase contrast imaging (MIT)
- exhaust spectroscopy (U Wisconsin)

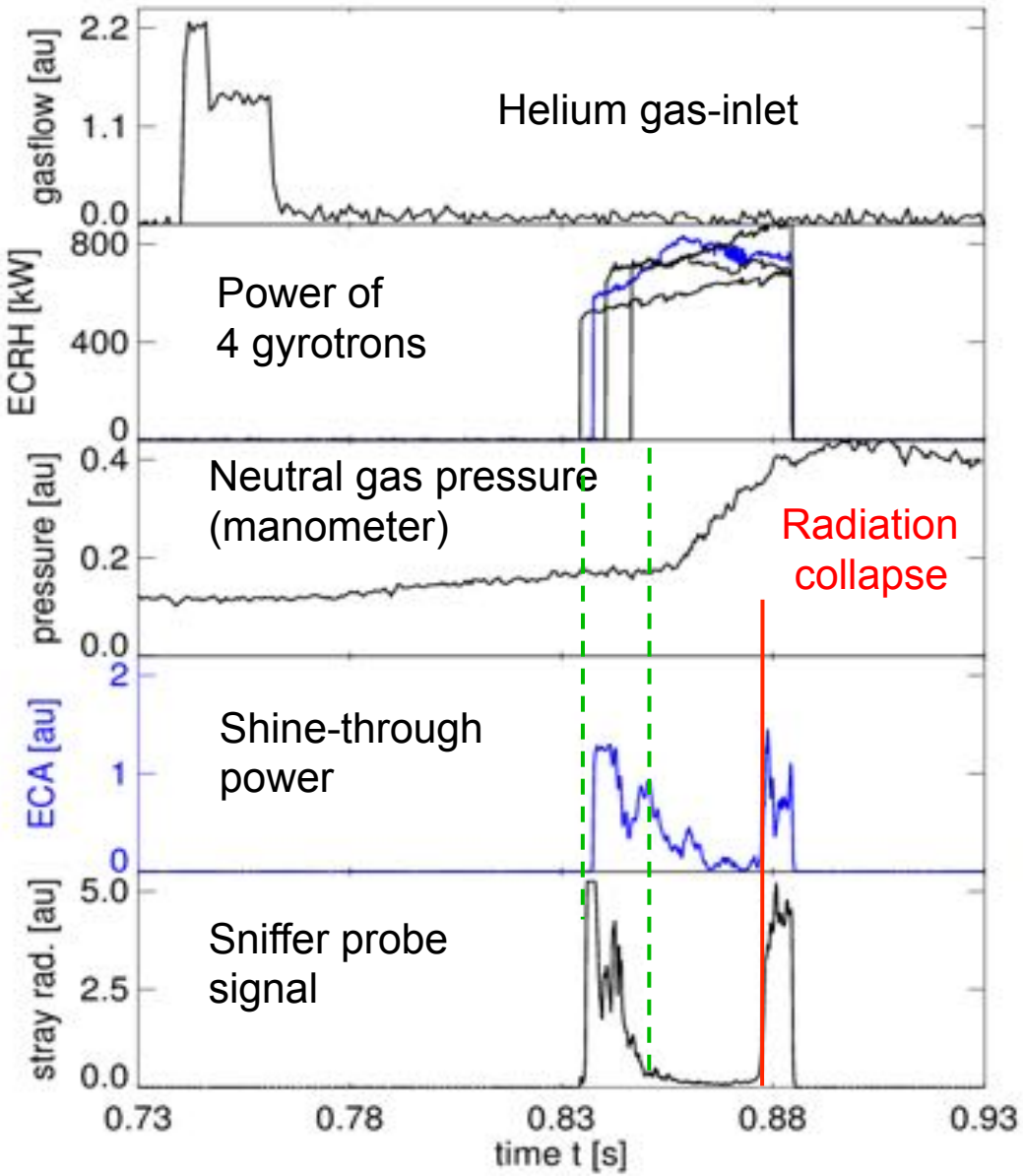
concept studies and developments

- pellet injection - mass detectors, guide tubes (ORNL)
- gas puff imaging (MIT)
- heavy ion beam probe (Xanthos)

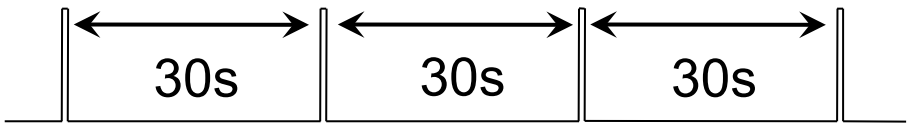
program participation

- program planning and device commissioning (Neilson, PPPL)
- magnetic field and equilibrium (Lazerson, PPPL, Maurer, Auburn U)
- various researchers on site for OP 1.1 and OP 1.2

Plasma generation (early phase)



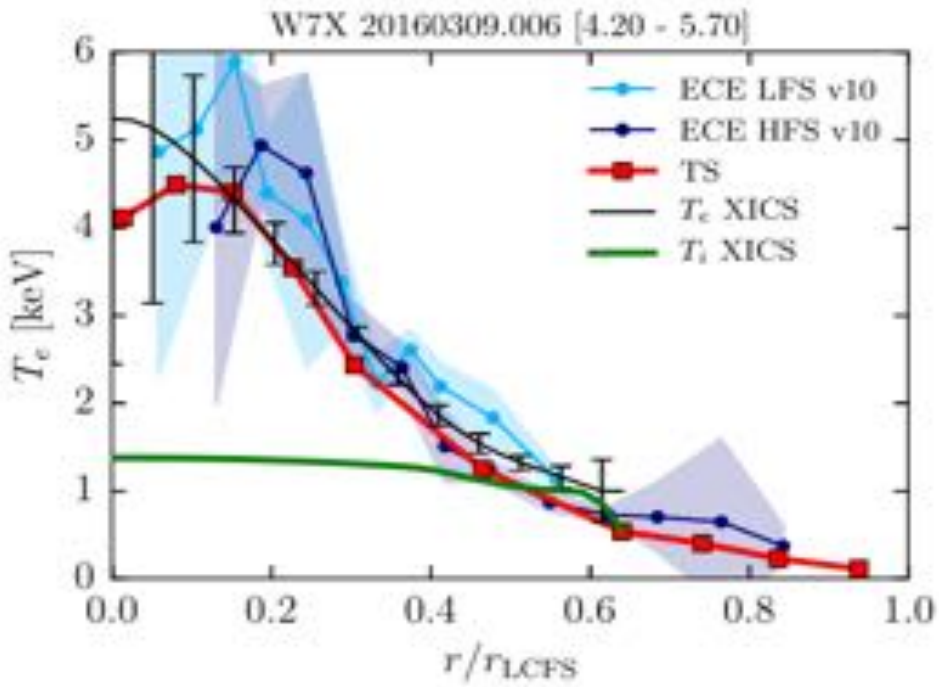
- Plasma break-down within 10ms
- Sniffer interlock (radiation collapse) terminates plasma after ~20 ms
- Hundreds of short ECRH cleaning discharges (3 days corresponding to about 4 sec plasma operation)

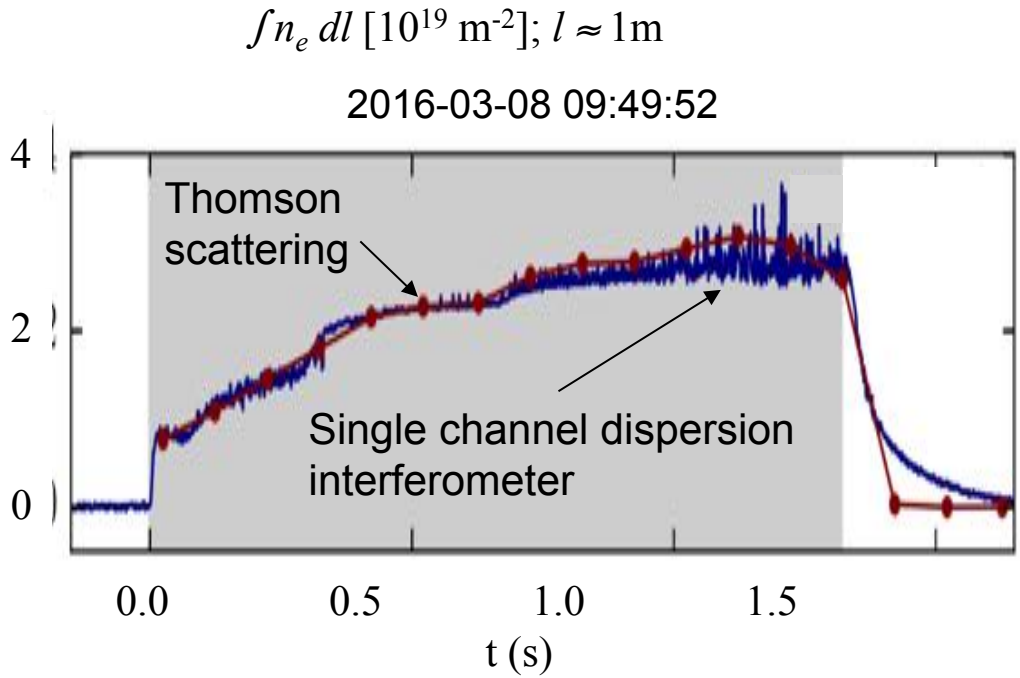


⇒ discharge length extended to ~50ms

⇒ With more pulses and glow discharge cleaning, eventually 6 seconds

Measurement of basic plasma parameters



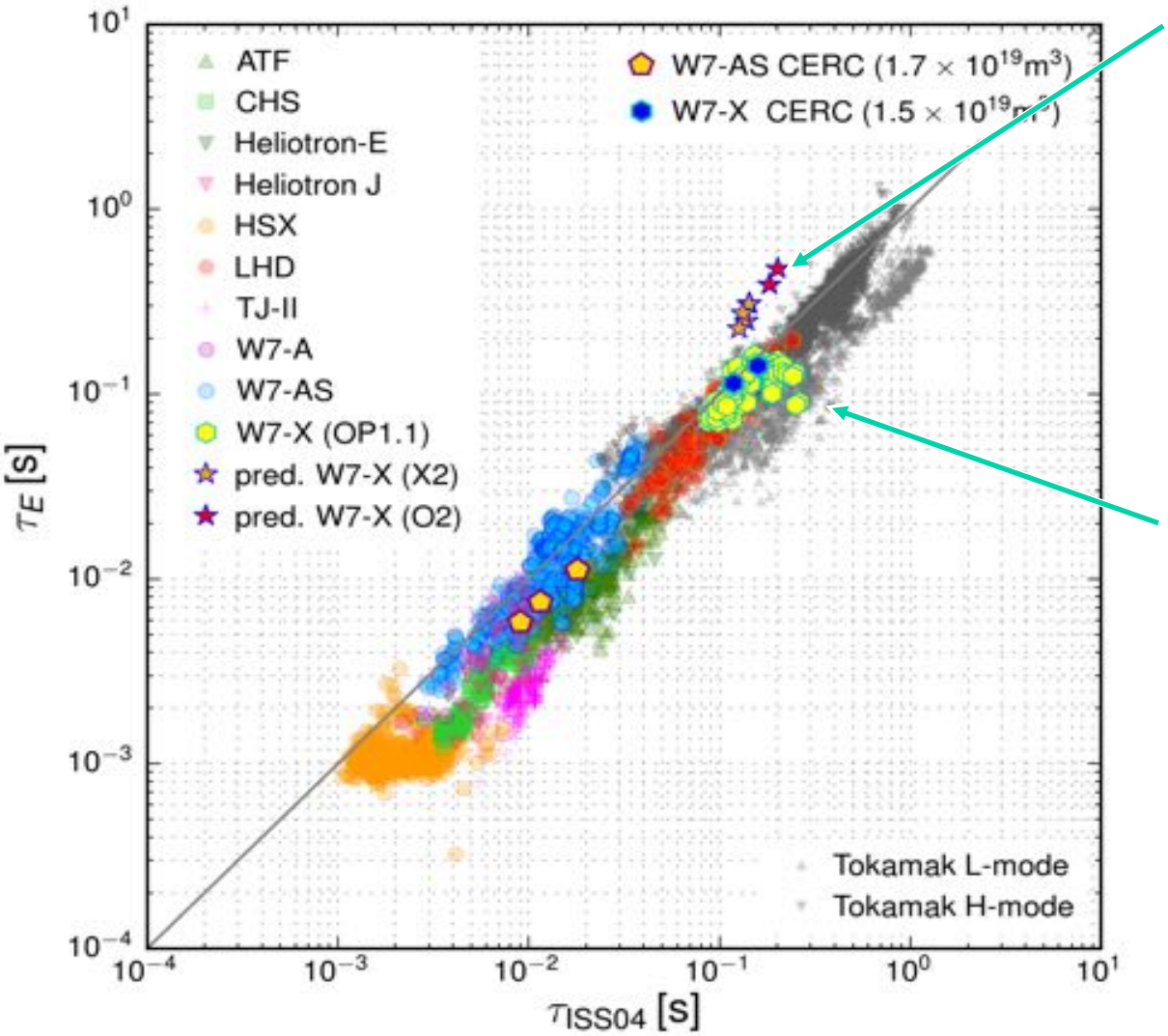


Hydrogen plasma
P_{ECRH} = 0.6 MW, 6 sec

Hydrogen plasma
P_{ECRH} = 4 MW

- Low densities and electron heating by ECRH resulted in $T_e >> T_i$
- Results in outward pointing electric field in the core giving so-called Core Electron Root Confinement (CERC) – more on that later

Characterization of energy confinement



$$\tau_E^{\mathrm{ISS04}} = 0.134 a^{2.28} R^{0.64} P^{-0.61} \bar{n}_e^{0.54} B^{0.84} \iota_{2/3}^{0.41}$$

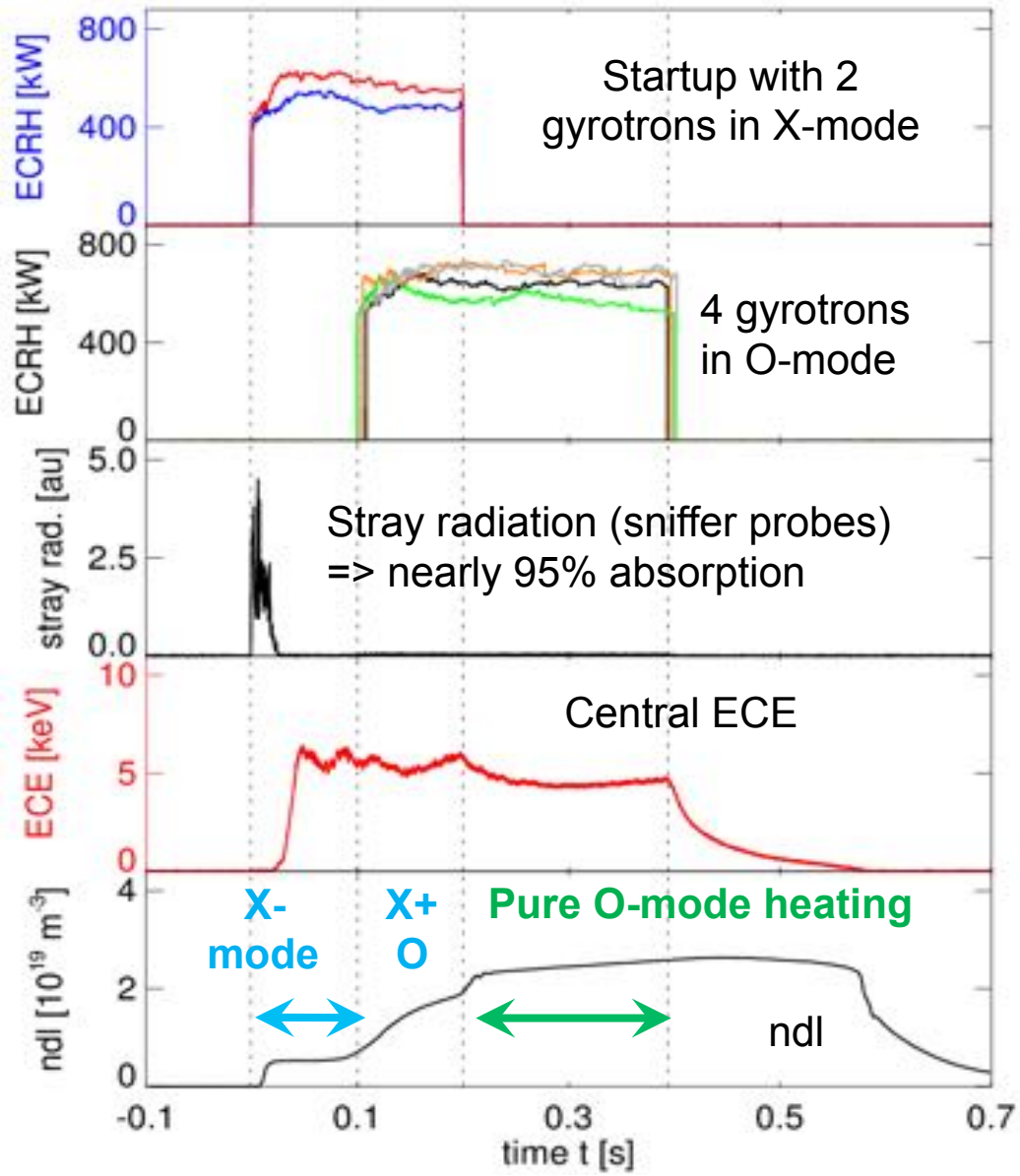
Optimized confinement time as predicted for W7-X ion-regime ($\chi_{e,1/\nu} \sim \varepsilon_{eff}^{3/2}$)

Confinement times during 1st W7-X campaign

- Best plasmas lie on ISS04-scaling
- Only 16 days of hydrogen operation
- Conditioning of wall was still ongoing; impurity issues

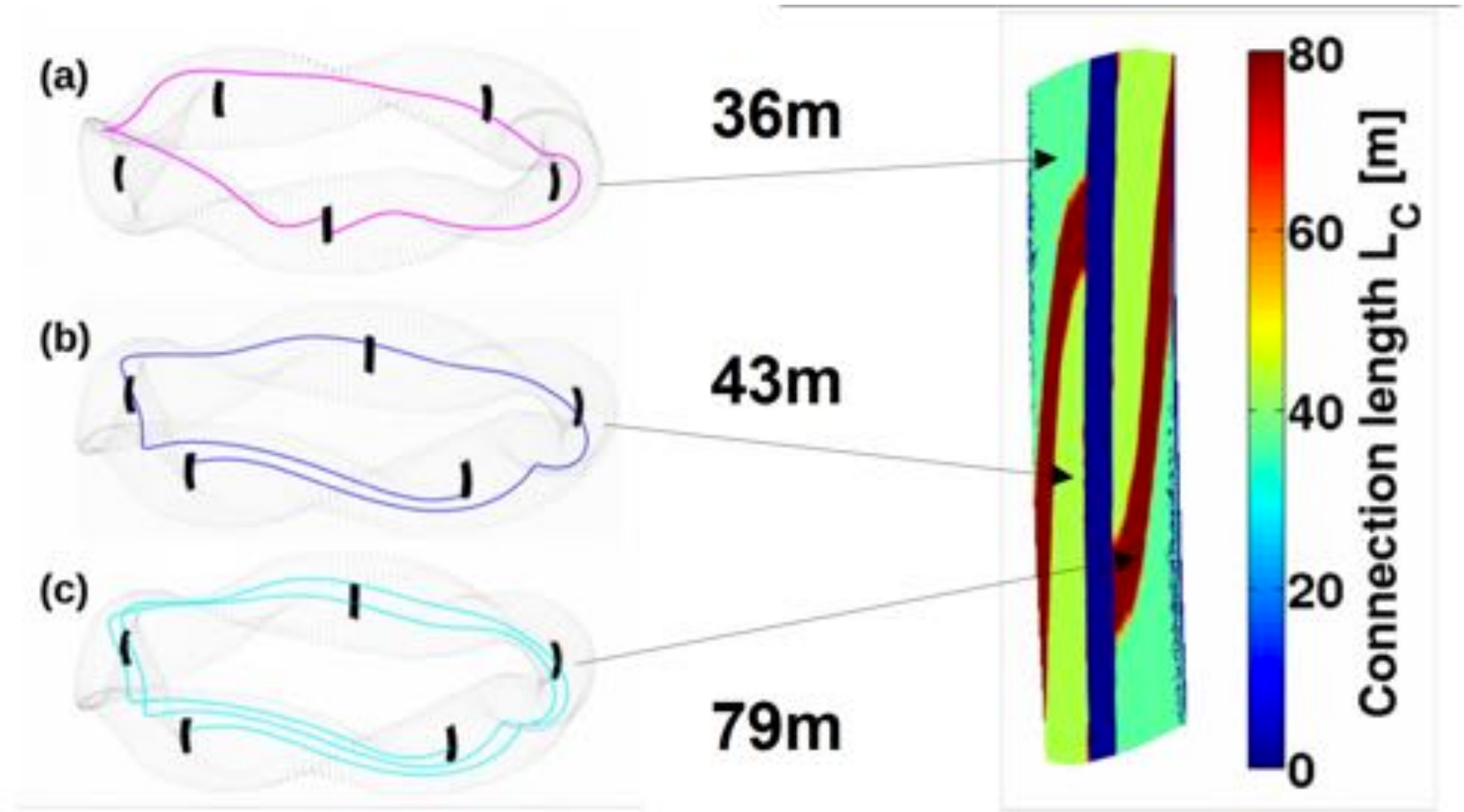
Demonstration of O2-ECRH

- Proof-of-principle for high-density operation with ECRH in future operation phases
- Plasma start-up in X2-mode
  - X2-cutoff at n_e=1.2*10^{20} m^{-3}
- For $T_e \geq$ 5 keV simultaneous X2- and O2-heating
- Finally, sustainment of plasma with only O2-heating
  - O2-cutoff is at 2.4*10^{20} m^{-3}



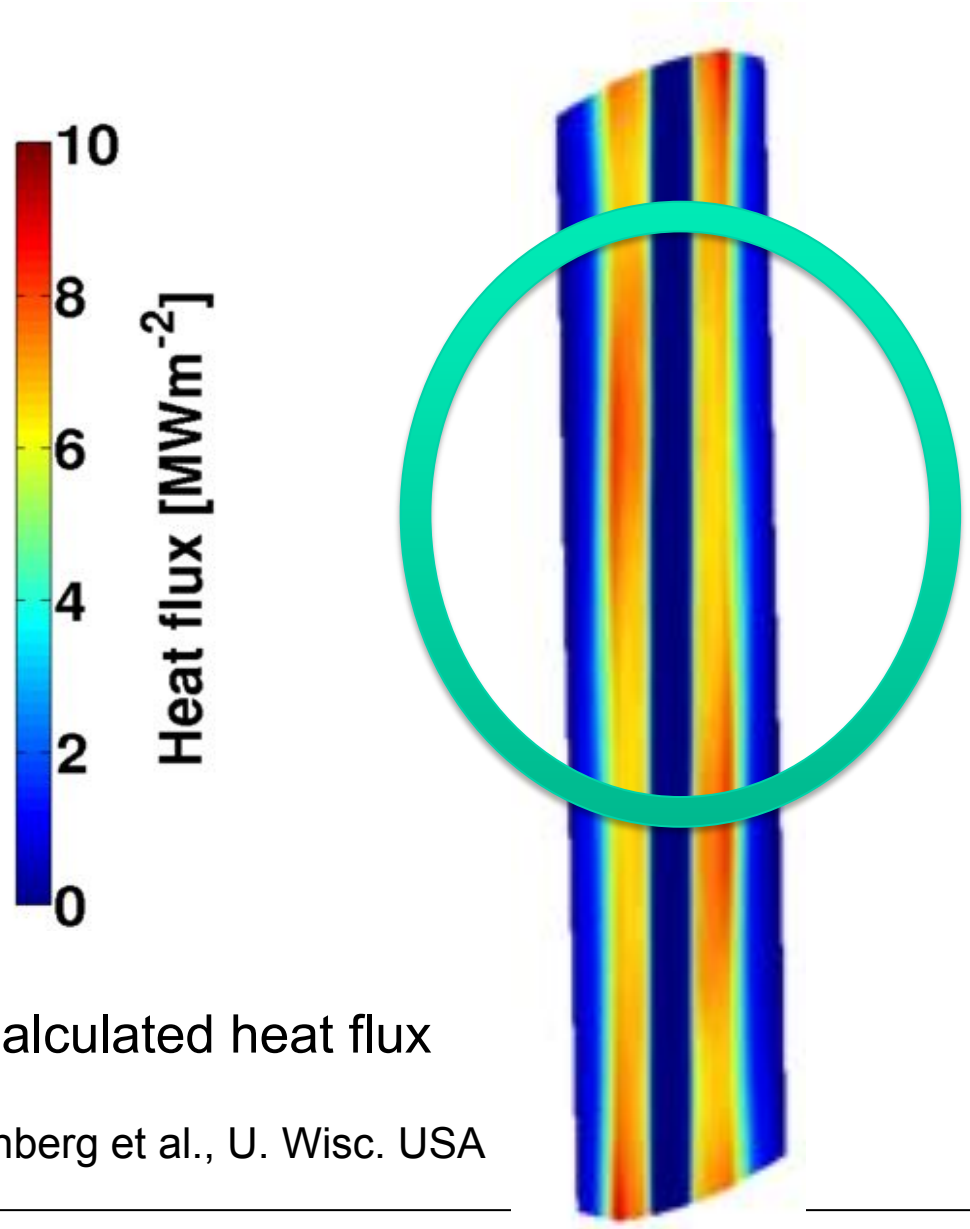
Limiter heat load patterns and a slightly altered configuration

Pattern of connection lengths on limiters



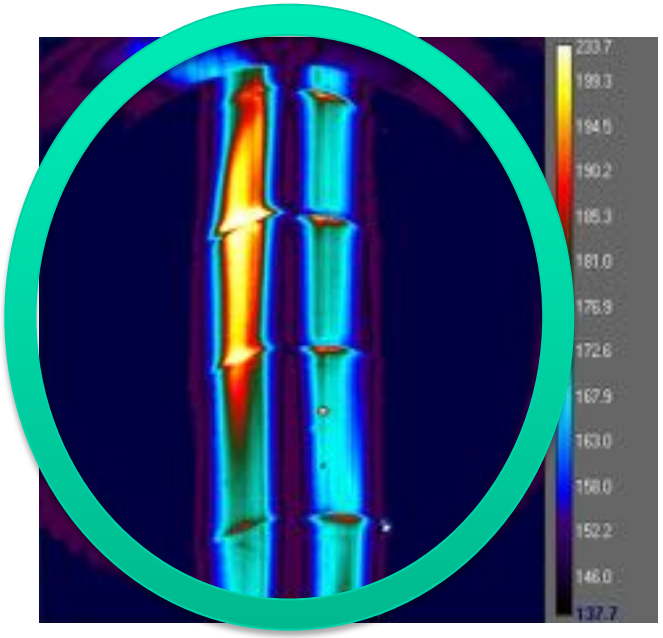
F. Effenberg, O. Schmitz, University of Wisconsin-Madison

Heat load patterns in OP1.1 agree with predictions



Calculated heat flux

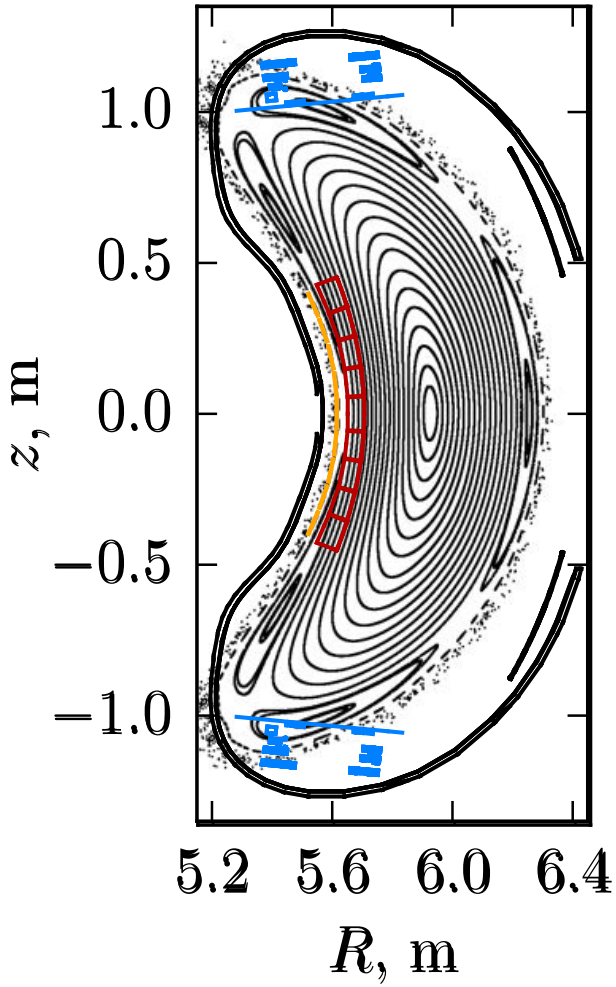
F. Effenberg et al., U. Wisc. USA



IR camera temperature

G. Wurden, LANL, USA

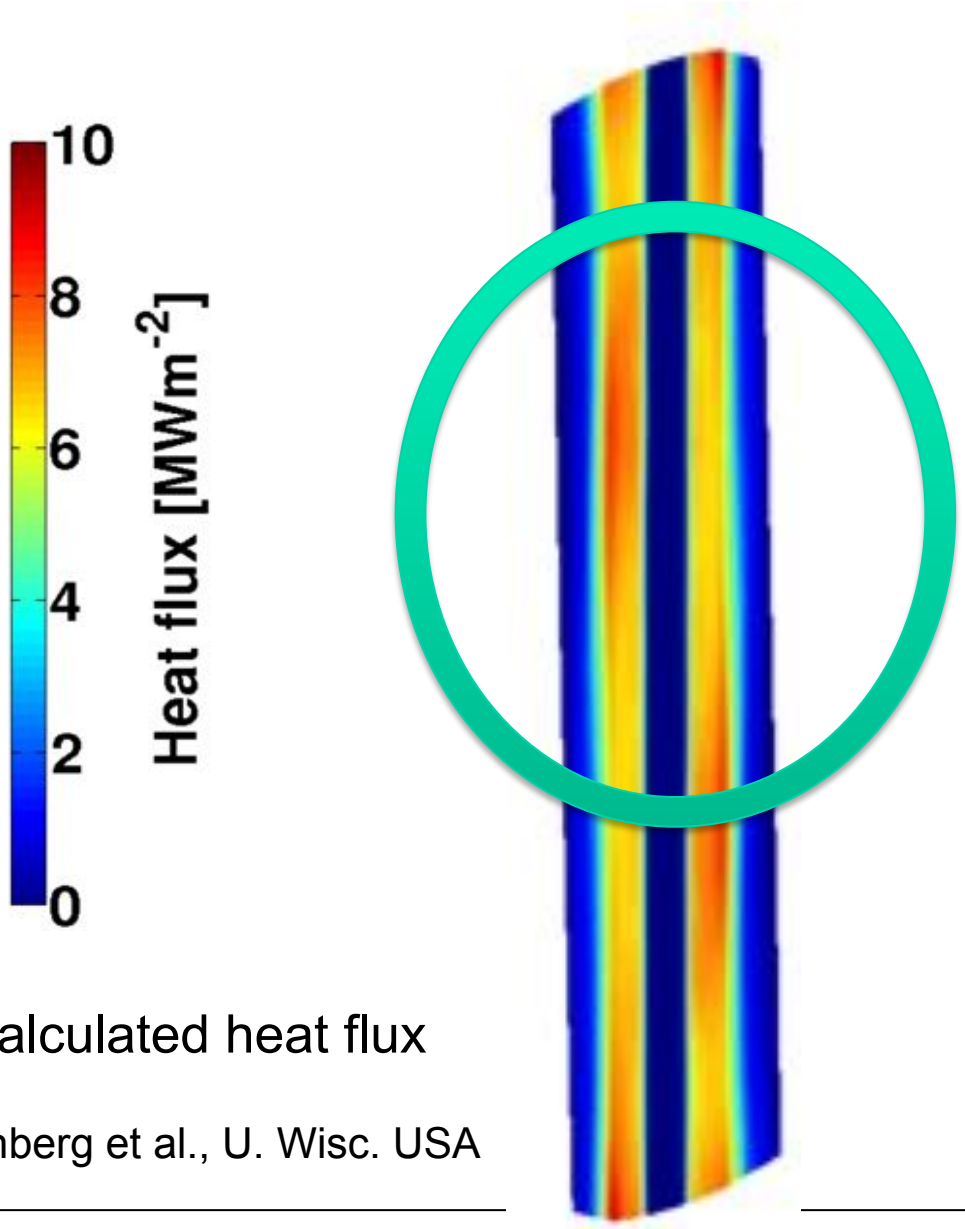
“De-optimized” configuration for OP1.1



This configuration offered:

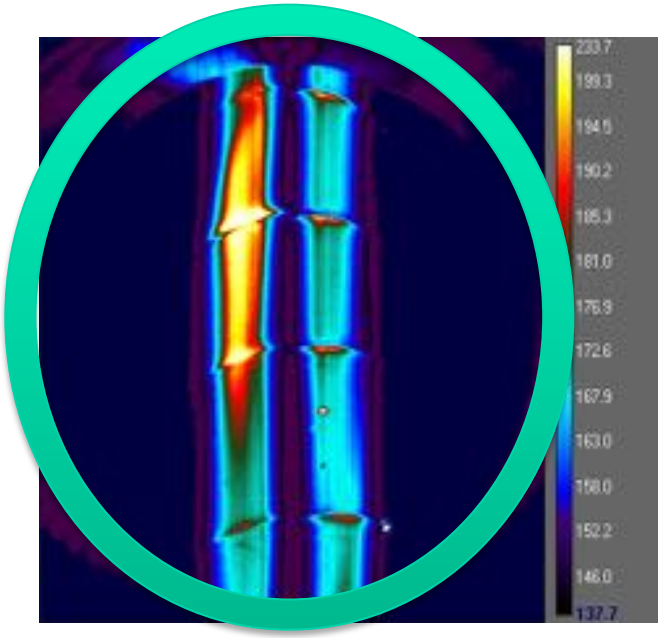
- Shift of 5/6 island chain inward, away from neutral source region:
  - (It is so small now that it’s not visible on the Poincare plot)
  - Expected particle confinement time increase confirmed [collab, U. Wisconsin]
- Slightly higher iota
  - Shift of heat loads on the limiters
- Neoclassics de-optimized: ε_{eff} factor of 2 higher by increasing mirror term
  - $\varepsilon_{eff}^{3/2}$ is a measure of losses due to bad orbits – almost a factor of 3 naively expected
- More “risky” scrape-off layer topology: 5/5 island chain comes closer [was not a problem]

Heat load patterns in OP1.1 agree with predictions



Calculated heat flux

F. Effenberg et al., U. Wisc. USA



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G. Wurden, LANL, USA

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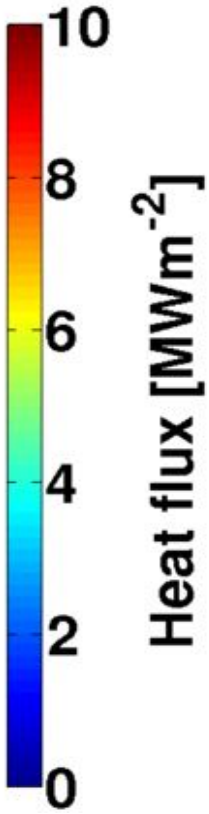

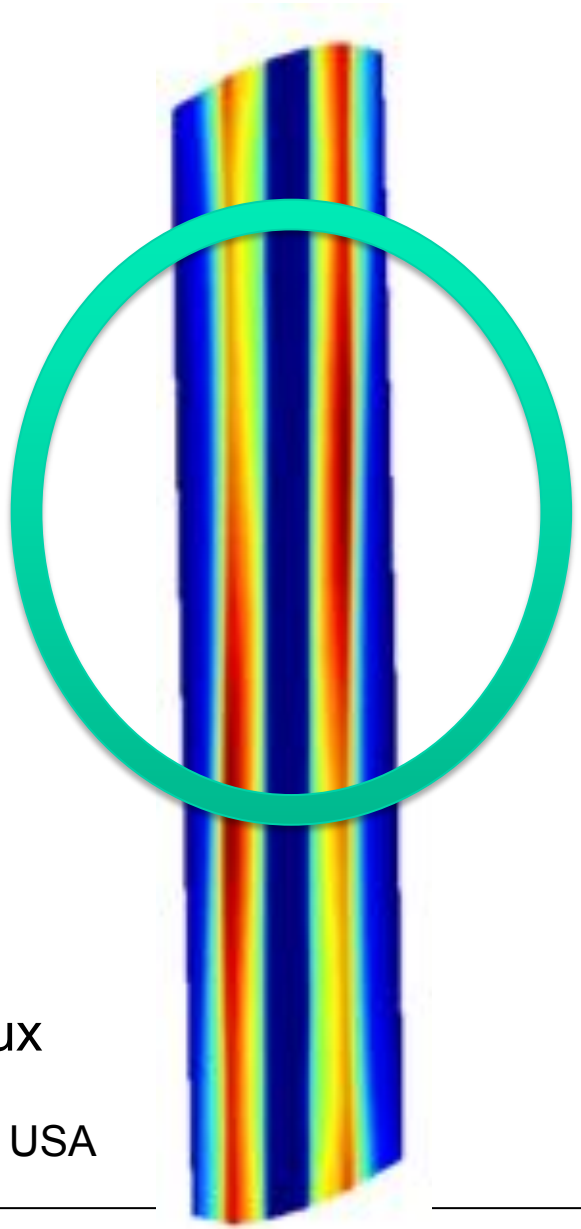

Calculated heat flux

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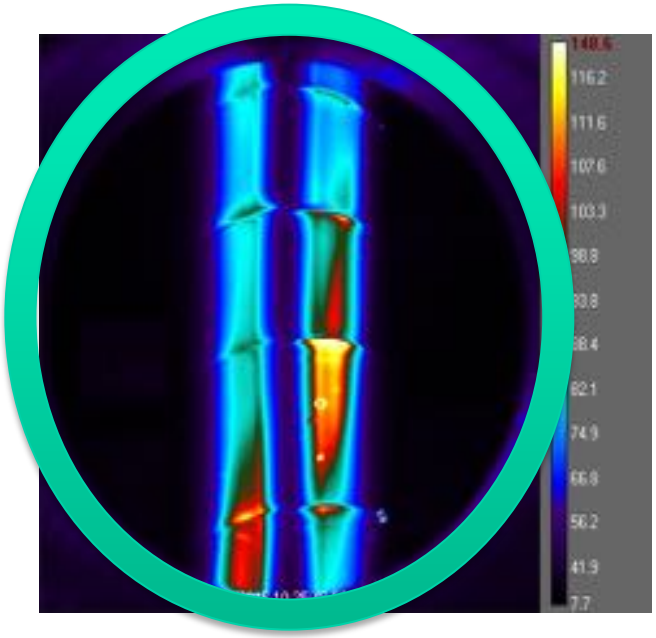
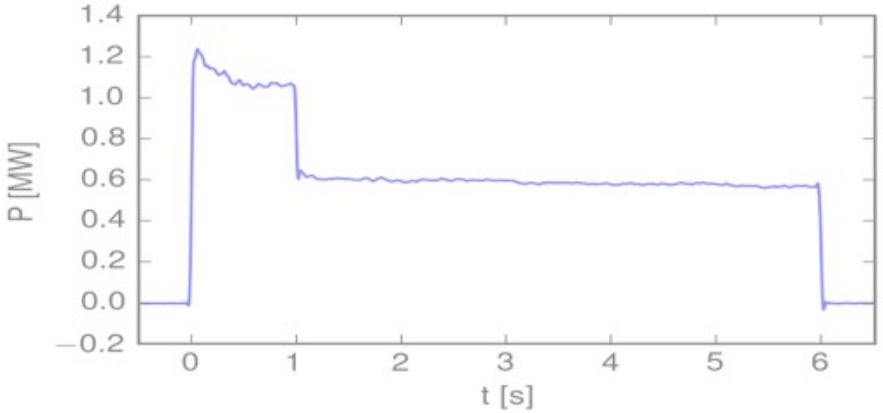


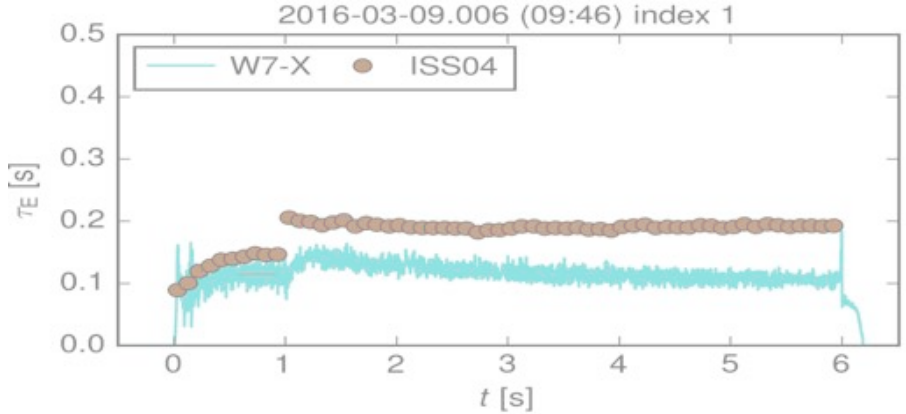
IR camera temperature

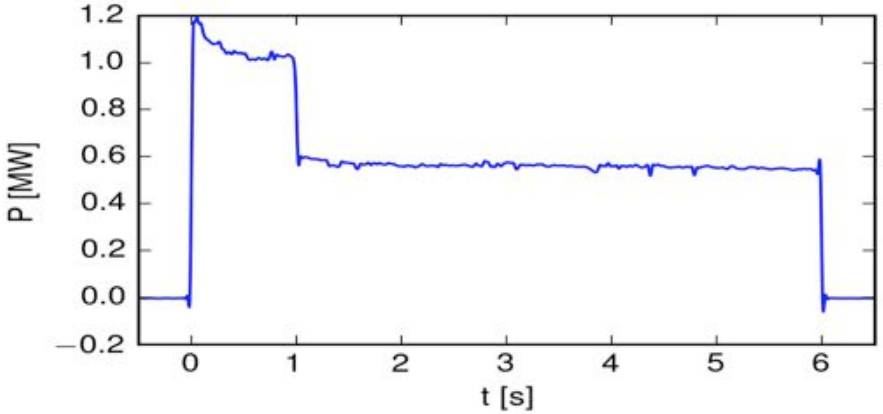
G. Wurden, LANL, USA

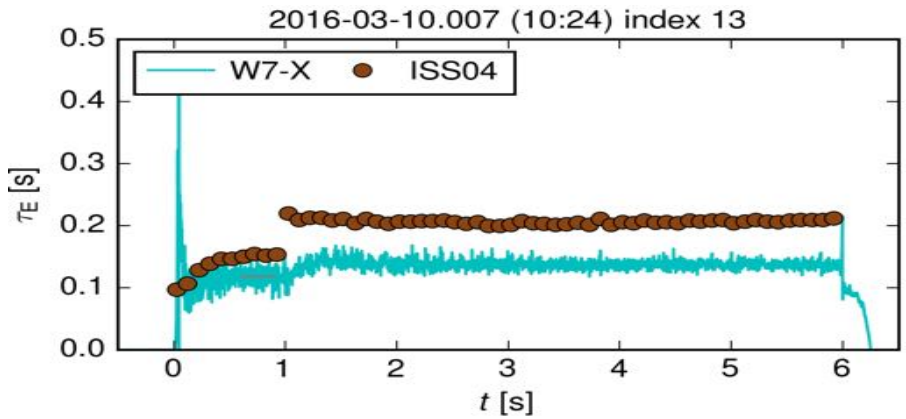
“De-optimized” configuration

Confinement time with “de-optimized” configuration







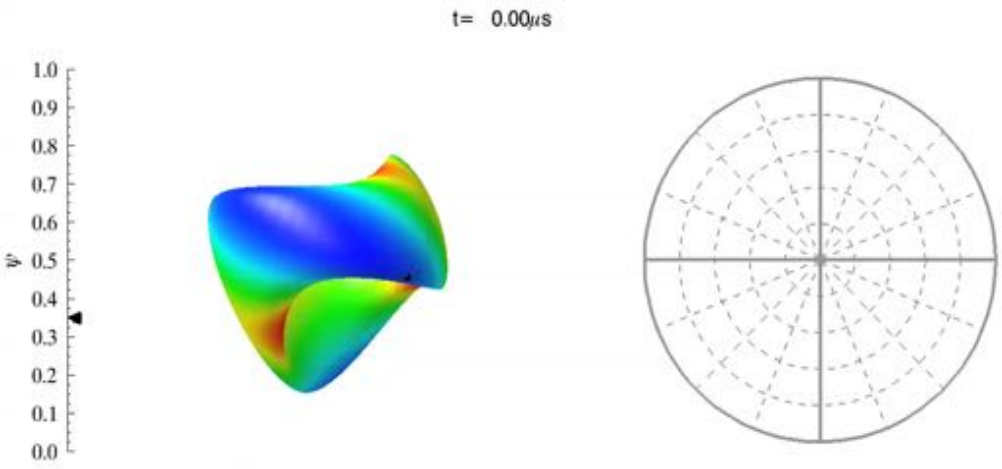


Essentially no change in confinement, as expected

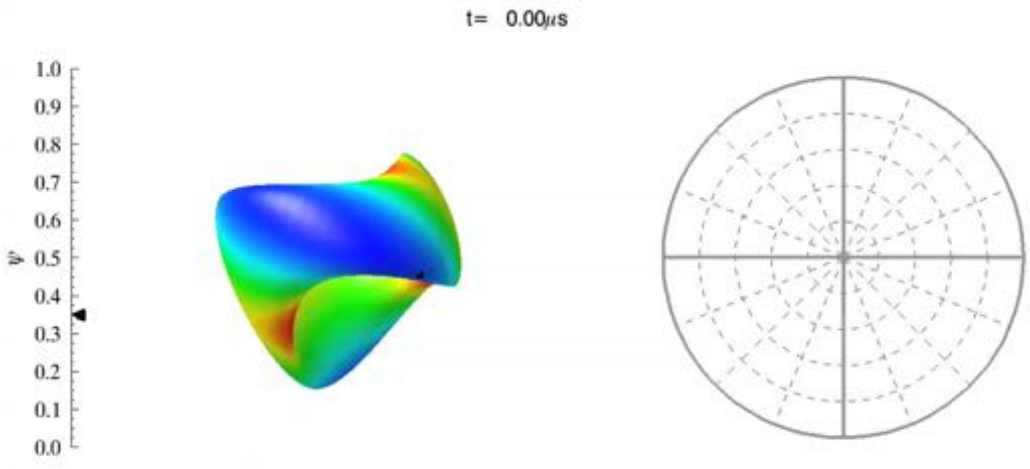
Why expected? Because of electric field effects….

Strong electric fields in stellarators: CNT

This brings me back to the good old CNT days…



Particle drifts out – CNT is not an optimized stellarator



Add a strong radial electric field: Particle stays in

Experimental findings in CNT: 20 ms initially[a], then up to 320 ms[b]

Conclusion: Radial electric fields can significantly heal bad stellarator orbits and therefore effectively mask any ε_{eff} dependences that there would have been otherwise

[a] J. P. Kremer et al. , PRL **97**, p. 095003 (2006),
[b] P. W. Brenner et al., CPP **50** p.678 (2010)

Electric fields in stellarators

How large of a role does the bulk ExB drift play relative to the magnetic drifts?

$$\left|\frac{v_{ExB}}{v_{\nabla B}}\right| \approx \left|\frac{\nabla\phi / B}{(W_k \nabla B / qB^2)}\right| \approx \left|\frac{q\phi}{W_k}\right|$$

Pure-electron plasma: Dominant (factor of 10-1000, CNT: 50)

Thermal particles in a quasineutral plasma: Depends.. (0.2-5)

Set by ambipolarity

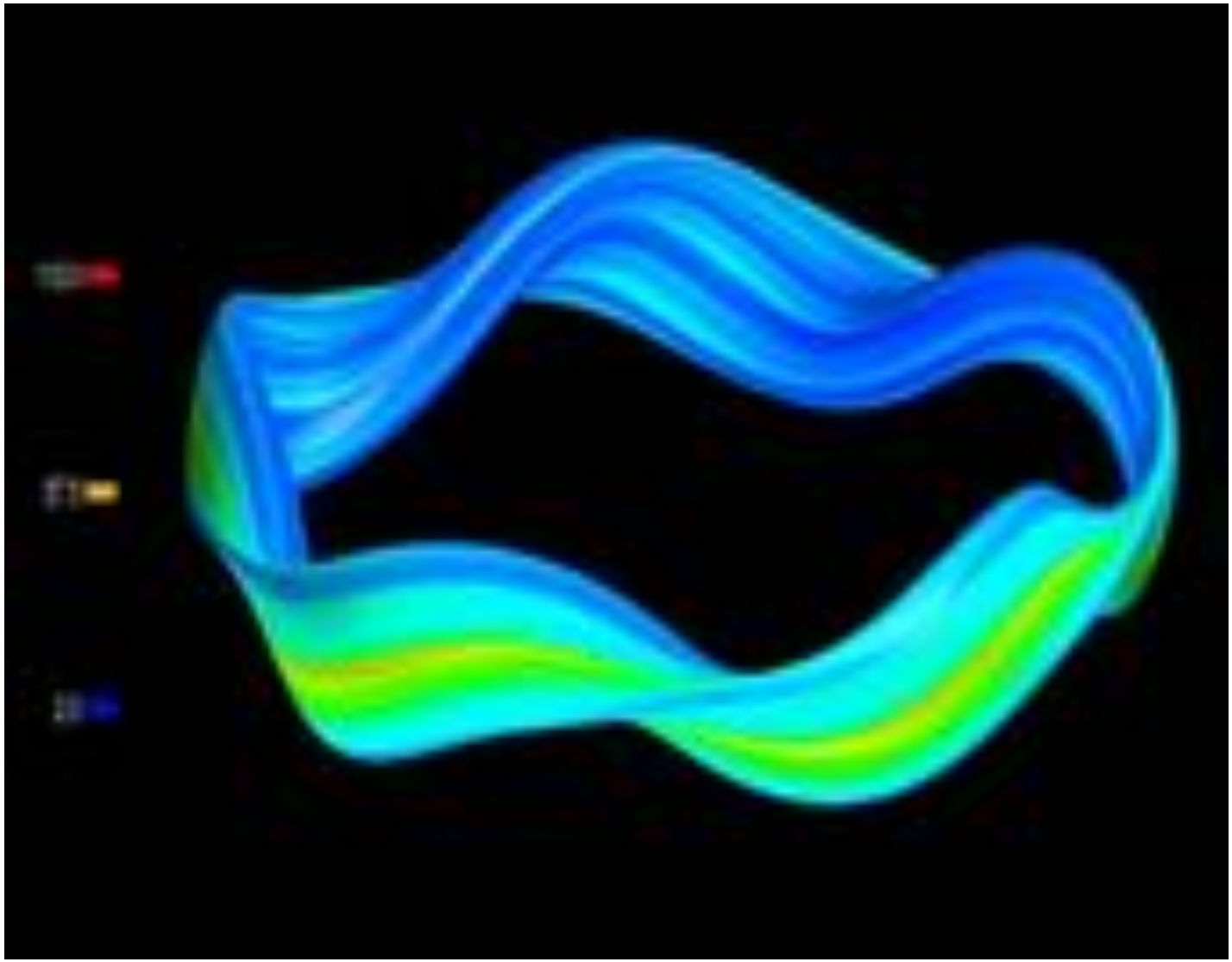
OP1.1 $T_e >> T_i$ leads to relatively strong role in core - CERC

Fusion α's: Negligible (~35 keV/3.5 MeV~0.01)

So, the orbit-healing effects of E_r is going to be smaller in later operation phases, and cannot "fix" α-confinement in a future reactor

Turbulence Filaments

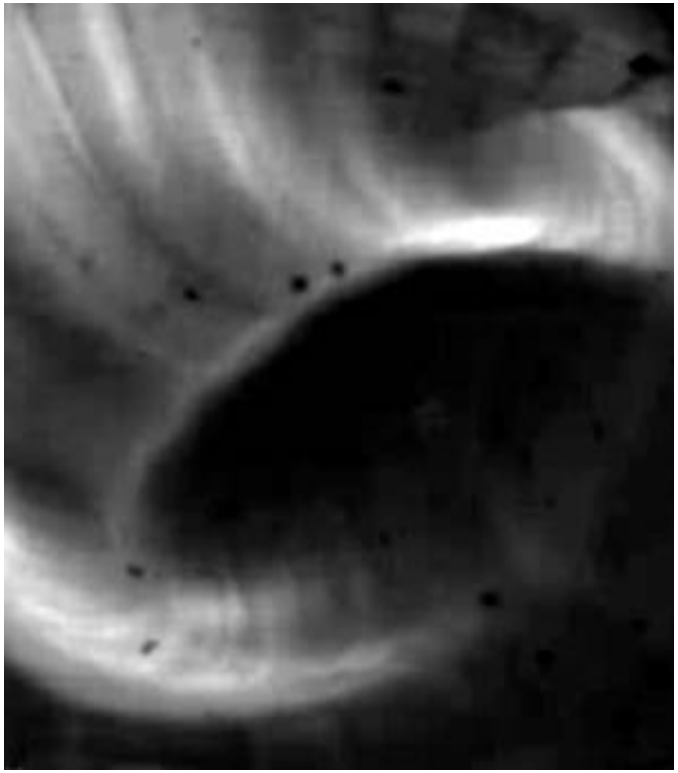
3D turbulence in W7-X

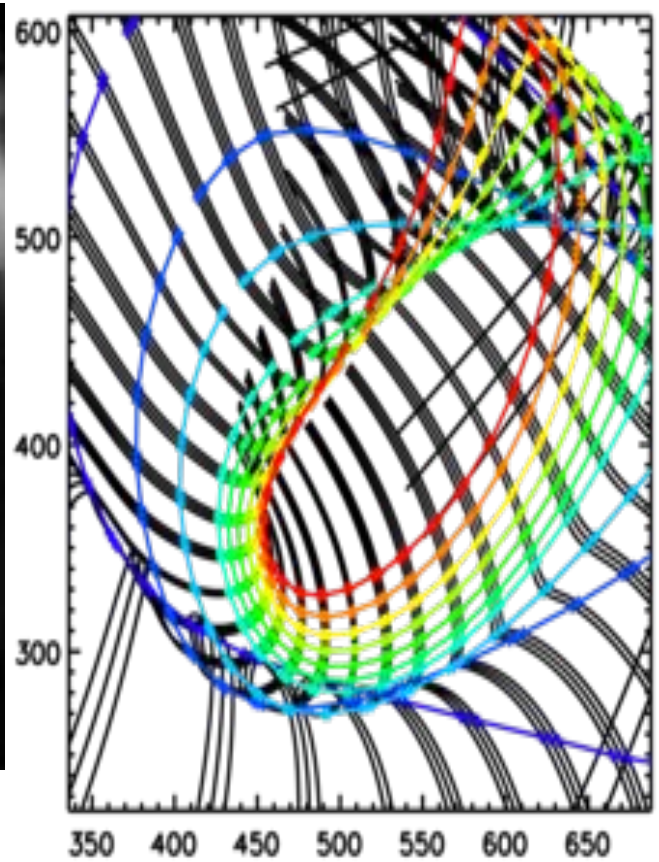


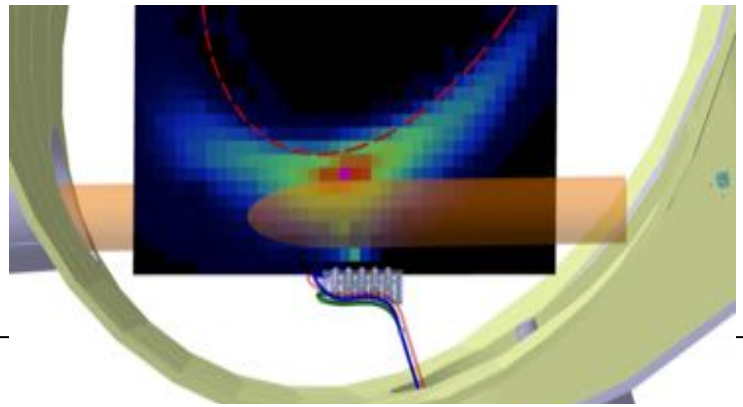
- Structures are highly field-aligned-filamentary
- Rotate and pulsate

Courtesy of Pavlos Xanthopoulos, ST

Filaments are visible when plasma is “cold”



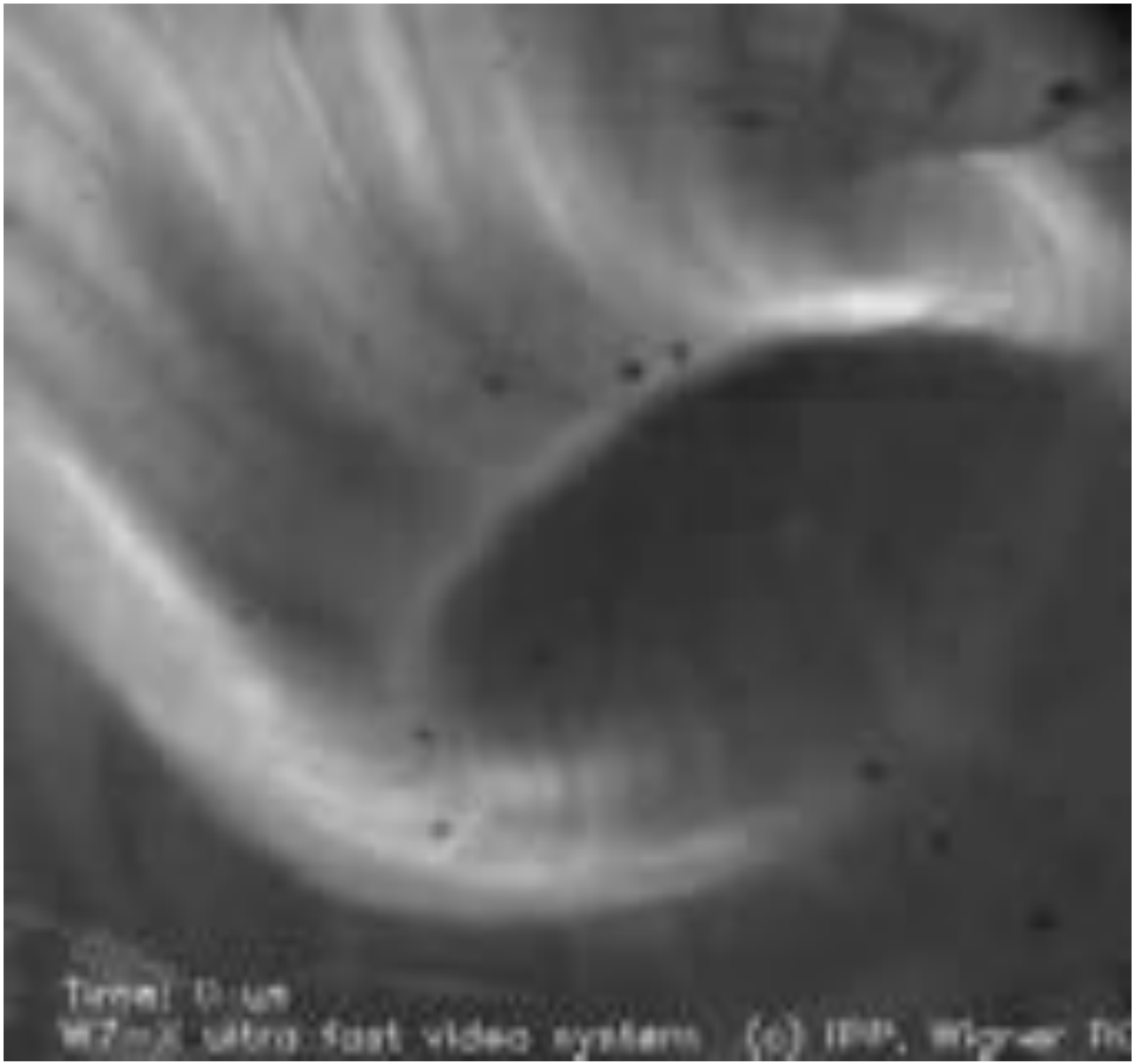




- We have a diagnostic for that:
- Photron SA5 camera
  - 46.5kframe/s @ 384x352 pixels
- Field lines in the camera view shown here
- Visualizations can be induced with nitrogen injections from He-beam diagnostic

G. Kocsis et al., Wigner RCP, Hungary

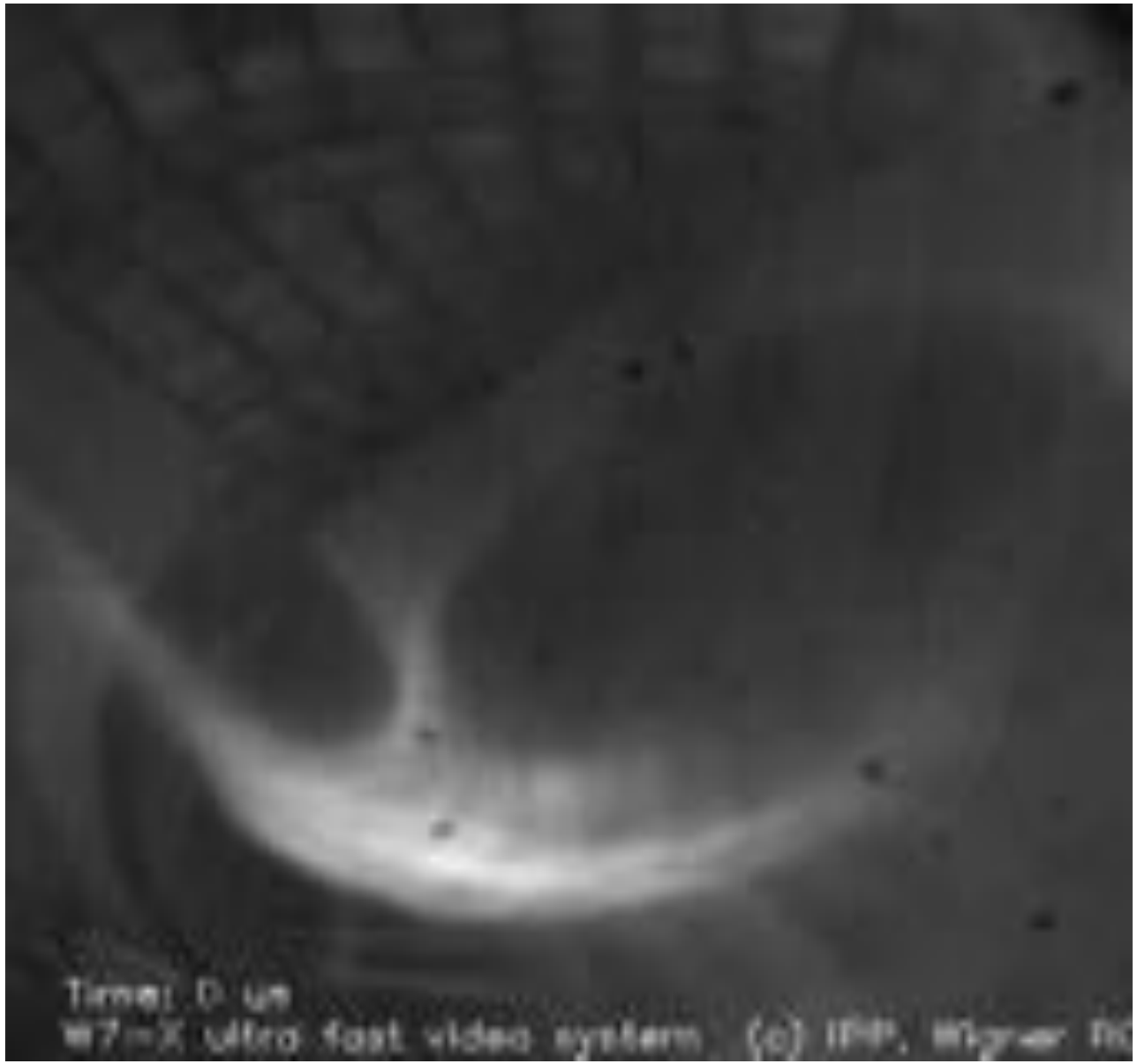
2.5 ms of dynamics just inside the LCFS



- This is radiation on closed flux surfaces
- Filaments are clearly seen
- They rotate clockwise in this view
- Assuming ExB drift
  - Inward pointing (negative) E-field
  - Expected at $T_e \sim T_i$ at the edge of the plasma

G. Kocsis et al., Wigner RCP, Hungary

2.5 ms of dynamics just outside the LCFS

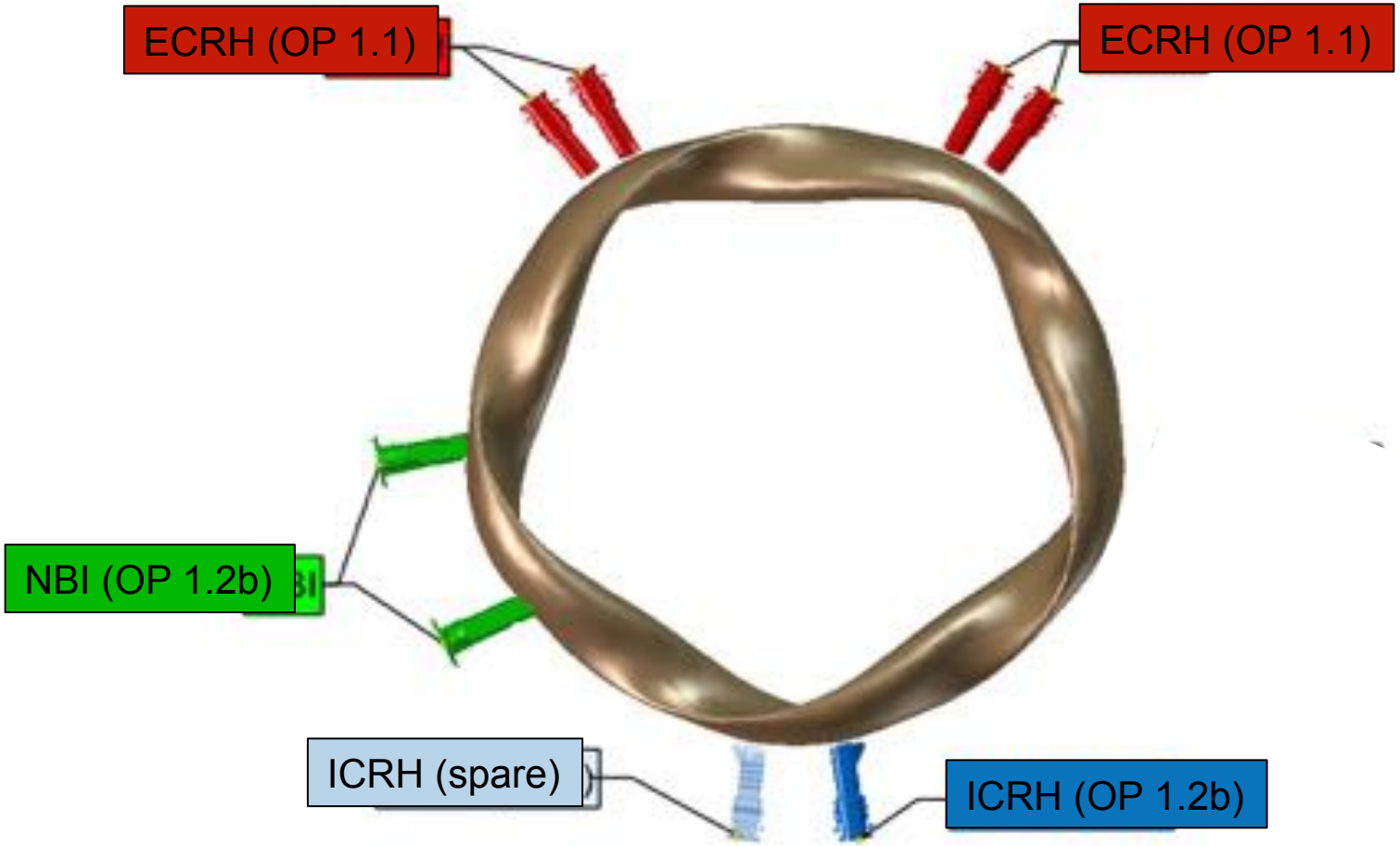


- This is radiation in the SOL induced by a nitrogen puff
- Counter-clockwise rotation initially at least!
- Assuming ExB drift:
  - Outward pointing (positive) E-field
  - Not surprising on open field lines

G. Kocsis et al., Wigner RCP, Hungary

Looking forward to OP1.2

Wendelstein 7-X heating systems



Development of heating systems

Method	OP 1.1	OP 1.2	OP 2
ECRH steady state 140 GHz 2.5 T	**5 MW** X2 LFS launch (front steering)	**9 MW** X2 / O2 LFS & HFS launch (front & remote steering)	**9 MW** X2 / O2 / OXB LFS & HFS launch (front & remote steering)
NBI pulsed 55 keV (H) 60 keV (D)		**7 MW (H)**	**10 MW (D)** **7 MW(H)**
ICRH pulsed 25 – 38 MHz		**2 MW** ^{3}He, H minority	**4 MW** ^{3}He, H minority
		Upgrade of power supplies	**...**

Major topics for OP1.2

Optimization of confinement of W7-X ion-regime ($\chi_{e,1/\nu} \sim \varepsilon_{eff}^{3/2}$)

- Requires high heating power and high density
- Strong coupling of ions and electrons
- Involved issues: Fuelling (pellet injection), density limit

Investigation of confinement and core transport

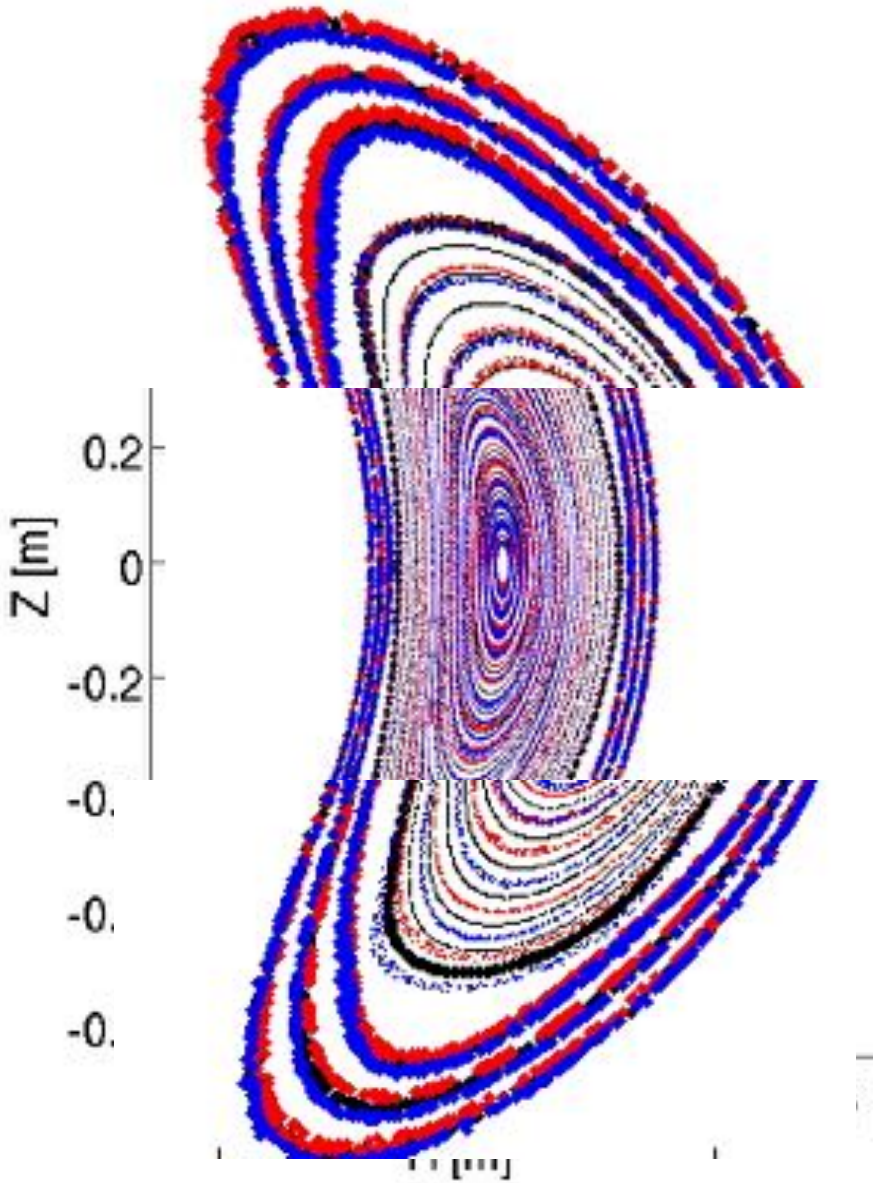
- Anomalous versus neoclassical transport
- Role of neoclassical effects (e.g. thermo-diffusion)
- Role of radial electric field
- Role of heating method and deposition profile
- Tailoring of plasma temperature, density and ι-profiles

Heating scenarios, current drive and fast ion production and confinement

- High density heating and current drive with ECRH (O2-heating beyond X2 cut-
- Ion heating with NBI
- Fast ion production with NBI and ICRH
- Validation of W7-X drift optimization, fast ion driven instabilities (long-term)

Up-down asymmetry in divertor heat loads

- Up-down asymmetries of up to a factor of two in the divertor heat and particle fluxes have been observed in tokamaks and stellarators
- Effect reverses sign when the magnetic field changes sign
  - Guiding-center drift effect (ExB or magnetic drift)
- We will reverse the magnetic field towards the end of OP1.2b
- We have particularly well-diagnosed divertors in HM 30 and 51 (one up, one down)
- By applying an n=0 (ie radial) magnetic field with the trim coils, we can move the flux surfaces (and therefore the plasma) about 1 cm vertically – roughly the SOL width

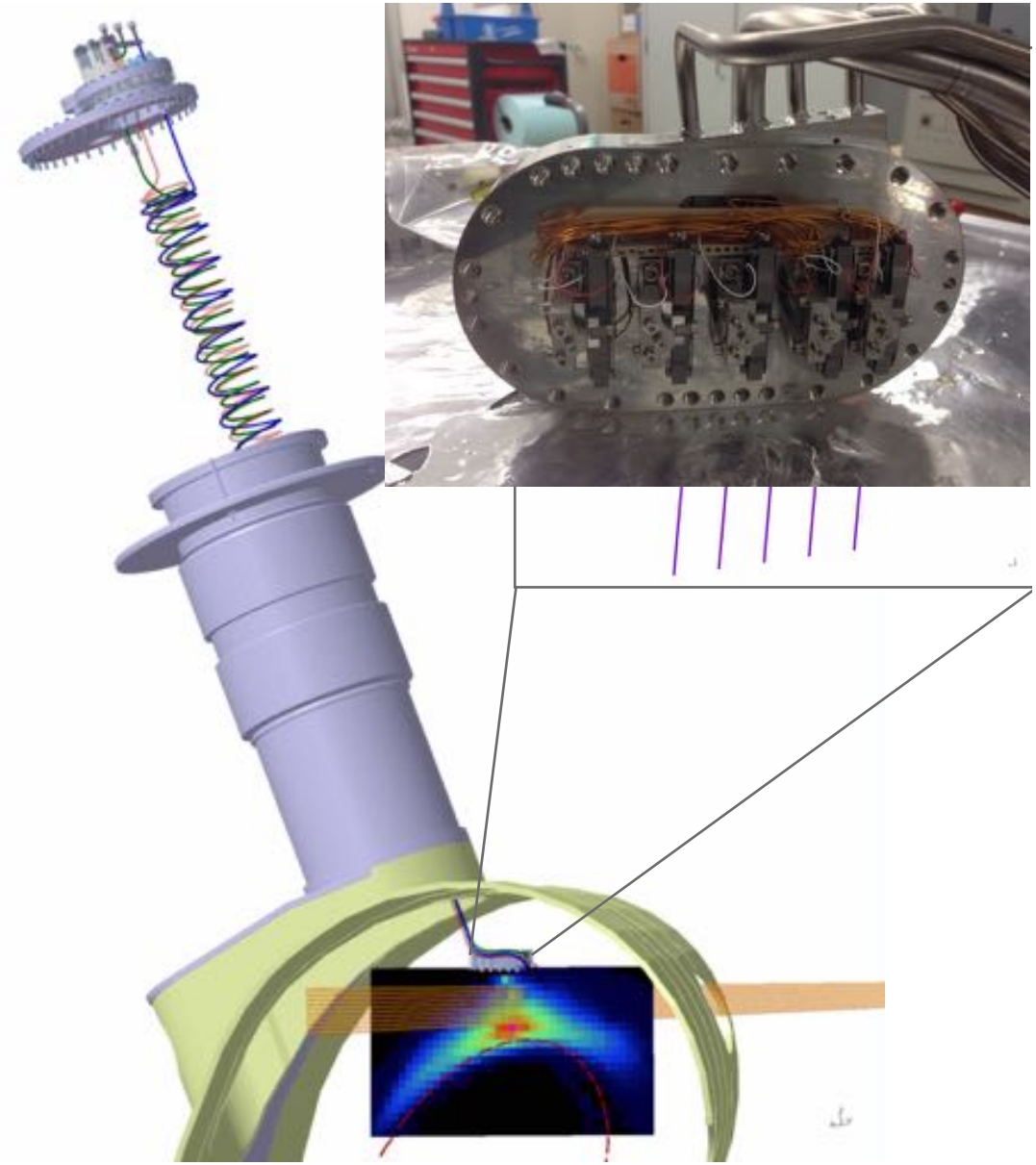


Collaboration with Sam Lazerson, PPPL (USA)

High-pressure fast divertor gas injection system

- Multiple functions
  - Fast fuelling (H_2) in divertor region (msec time scale)
  - He-beam injection as He-beam divertor diagnostic
    - First results in OP1.1 – improved design for OP1.2
  - Ar, Ne, CH_4, N_2 injection for edge radiative cooling in OP1.2

- Multiple locations
  - OP1.2: HM 30 and 51 (installation complete Dec 2016)
    - (Up-down symmetric)
  - OP2: All 10 divertor units

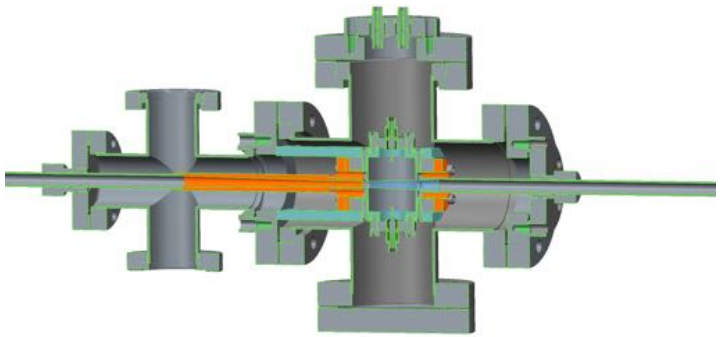


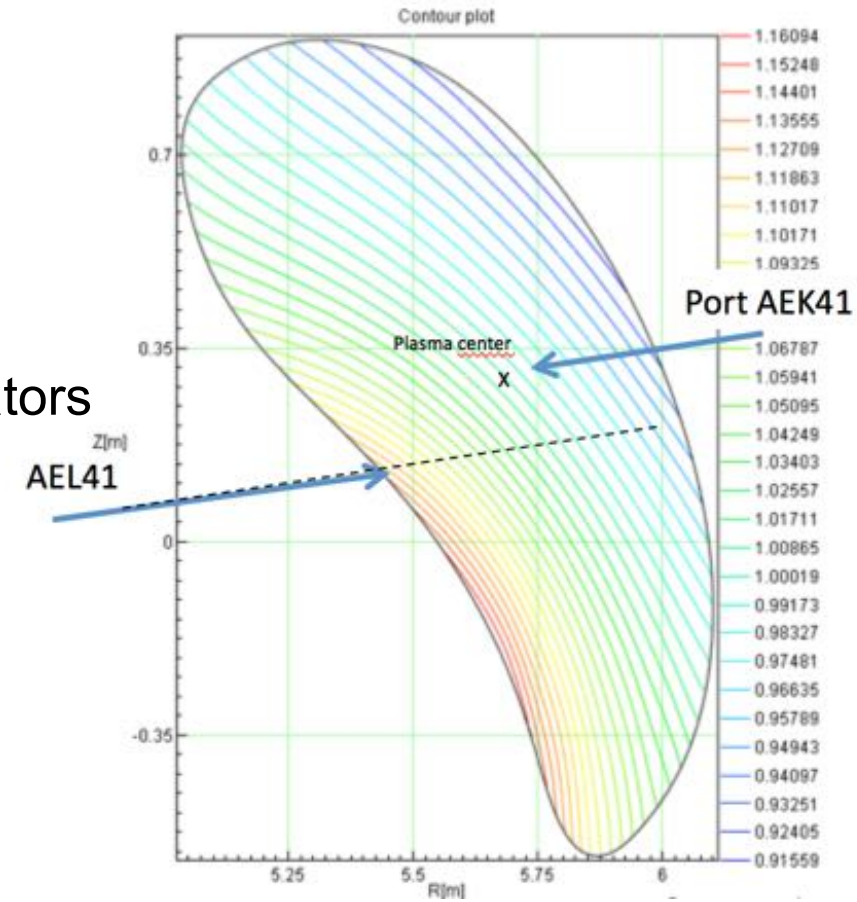
Pellet injection system(s)

Pellet injection system OP1.2

OP 1.2:

- Collaboration IPP Garching: former AUG pellet injection system: operational
- Collaboration ORNL, USA: Microwave cavity in-flight pellet mass detector: operational
- Pellet size: 2 mm
- Pellet speed: 250 m/s
- Repetition rate: 25 Hz
- Comparison LFS vs HFS injection
  - Unclear if HFS injection is better in stellarators





Pellet injection system OP2

OP 2:

- Collaboration NIFS, Japan and ORNL, USA
  - First hardware purchases now in Japan and Germany
  - Exact scope of ORNL part is not yet clear
- Pellet size: 3 mm x 3 mm
- Density increase per pellet ~$3*10^{19}$ m^{-3}
- Pellet speed: 600 m/s
- Repetition rate: 10 Hz for 30 minutes
- Low field side injection
  - Verification in OP1.2 that LFS injection works well
  - If not, a plan B for HFS injection will be challenging given pipe work for water cooling

Status January 2017: 46 new or upgraded diagnostics

4 Heating and fueling systems
(1 upgrade, 3 new) plus 2 associated safety diagnostics

12 Must-have diagnostics (A)
(2 new, 10 upgrades/exchanges)

23 Should-have diagnostics (B)
11 new, 12 upgrades/exchanges

11 Might-get diagnostics (C)
5 new, 6 upgrades/exchanges

Diagnostic name			In-vessel components					Vacuum barrier					Periphery						CoDaC				
KKS number: Name	OpPhase	Division	Design	Drawing	Procure	Manufa	Installed	Design	Drawing	Procure	Manufa	Installed	DIA: media specified (PS)	Racks specified	Design without collisio	Media ordered	Racks available	Media available	CoDaC specified (Lasten	Sensors / interlocks	PLC available	Network + data base	Operation tested
Heating and Fuelling																							
CBD: ECRH	1.2a	E3	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	90	100	100	100	100	100
CBD20BD: ECRH diagnostic	1.2a	E3	100	100	100	100	100	100	100	100	100	90	100	100	100	100	100	100	100	100	100	80	80
CDA: NBI	1.2a	E3	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	80	90	50	25	5
QY: NI Safety diagnostics	1.2a	E3	100	100	100	100	40	100	100	100	100	50	100	100	100	100	50	50	100	100	100	100	50
CHD: Pellet injector	1.2a	E4	100	100	100	100	100	100	100	100	100	100	100	100	100	100	50	90	100	100	95	50	50
CC: ICRH	1.2b	E3	95	80	90	70	0	100	100	100	0	0	60	100	100	60	0	0	100	80	10	10	0
Diagnostic Priority A+/ A																							
QNC: Neutron counter	1.2a	E3	100	95	100	100	100	100	95	100	100	100	100	95	100	100	100	100	80	80	80	80	80
QMJ: Single channel interferometer	1.2a	E3	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	90	60	80	90	80
QSV: Video diagnostic: Image guides / cameras at AEQ21 und AEQ30	1.2a	E4	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	60	0	100	0	100	80
QRI: Coherence imaging systems beam splitter & support structor with video	1.2a	E4	100	100	100	100	100	100	100	100	100	100	100	100	100	100	50	50	100	100	100	100	100
QME: ECE	1.2a	E3	100	100	80	60	0	100	100	100	100	0	100	100	95	80	50	50	100	100	95	80	50
QXD: Diamagnetic loop (interlock)	1.2a	E5	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	70	70	100	0
QSD: HEXOS	1.2a	E5	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
QTB: Thomson scattering (+ports)	1.2a	E3	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	90	100	50	50	50
QSR: QSR:Exchange of 8 IR cameras *(He-II immersion tube system)*	1.2a	E4	100	100	100	100	100	100	100	100	100	90	100	100	100	100	100	90	100	100	100	100	70
QRI: Coherence imaging systems image guide for CIS and fibre bundle for QSS	1.2a	E4	100	100	100	100	100	100	100	100	100	0	100	100	100	100	50	50	100	100	100	100	100
QRG: QRG: Neutral gas (TDU) *(Neutral gas pressure 6 bar. TS systems)*	1.2a	E4	100	100	100	100	100	100	100	100	80	0	100	100	100	100	80	80	100	100	20	60	30
QXG: Calibration system I magnetics	1.2a	E5	100	100	100	90	0	100	100	100	100	0	100	100	100	100	100	100	100	100	100	100	0
Diagnostic Priortiy B																							
QSB: Core Bolometer	1.2a	E5	100	100	100	100	0	100	100	100	100	0	100	100	100	100	100	100	100	100	100	100	0
QSW: XICS	1.2b	E3	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	0
ACB: ACB:Preparation TDU-SE diagnostics (PPPL)	1.2b	E4	100	100	100	100	50	100	100	100	100	0	100	100	70	100	100	100	80	100	0	80	0
QMI: Multi Channel Interf./ 3 test channels	1.2a	E3	100	100	60	50	0	100	100	50	50	0	0	0	0	0	10	10	0	0	0	0	10
QRT: QRT: 2 Endoscopes	1.2a	E4	100	100	100	100	100	100	100	100	90	0	100	60	100	80	60	80	90	60	60	100	0
QSR07: QSR07 SE-obs : IR and vis. (LANL/Wisconsin)	1.2b	E4	100	100	100	100	100	80	0	0	0	0	100	100	70	100	80	0	100	100	100	100	0
QXT: XMCTS	1.2a	E5	100	100	100	100	100	100	100	100	70	50	100	50	100	60	50	0	100	50	0	0	0
QXM: QXM: Completion of OP1.1 magnetics	1.2a	E5	100	100	100	100	100	100	100	100	100	100	100	100	100	100	70	100	100	100	100	90	0
QXG: QXG: Completion of OP1.1 magnetics	1.2a	E5	100	100	100	100	100	100	100	100	100	100	100	100	100	100	90	100	100	100	100	90	0
QSL: Laser Blow Off	1.2a	E5	100	100	100	100	100	100	100	100	100	33	100	100	100	100	100	50	100	100	100	0	0
QSP: impurity pellet injection	1.2b	E5	100	100	100	100	100	100	100	0	100	0	50	0	0	0	0	0	0	0	0	0	0
QSQ: QSQ: Helium beam	1.2a	E4	100	100	100	100	100	100	100	100	100	30	100	100	100	100	100	70	70	100	50	100	70
QSK: CXRS / BES at NBI	1.2a	E3	100	100	50	50	0	100	100	100	80	0	100	100	100	80	100	50	100	100	100	0	0
QRP: QRP: TDU Langmuir probes	1.2a	E4	100	100	100	100	100	100	100	100	100	80	70	30	80	100	30	100	70	100	0	50	0
QRH: QRH: PWI TDU targets	1.2a	E4	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
QSI: QSI: Alkali metal-beam diagnostic (EUROfusion enhancement project, Wigner, Hungary)	1.2a	E4	100	100	100	100	100	100	100	100	100	0	100	100	50	100	100	0	100	80	100	0	0
QSZ: QSZ: Zeff profile	1.2a	E4	100	100	100	100	100	100	100	100	100	100	100	30	100	100	30	100	70	100	100	30	0
QSR: QSR: single line of sight observations (filterscopes, Oak Ridge/Wisconsin) *(He-II immersion tube system)*	1.2a	E4	100	100	100	100	100	100	100	100	100	50	100	50	100	50	20	0	100	100	100	50	50
QSS: QSS: Visible divertor spectroscopy	1.2a	E4	100	100	100	100	100	100	100	100	70	0	100	30	70	70	30	70	70	70	0	70	0
QRH: QRH: PWI Si-wafer on panels	1.2a	E4	100	100	100	100	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
QSS: QSS: Visible divertor spectroscopy (3 simple oba. Systems)	1.2a	E4	100	100	100	100	100	100	100	100	100	70	100	30	70	100	30	100	70	100	100	30	0
QMR: QMR: Doppler Reflectom. (V+Extens. W)	1.2a	E5	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	0	100	100
QXE: QXE: 3rd Manipulator Flux Surfaces	1.2a	E4	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Diagnostic Priortiy C																							
CBS: CTS	1.2b	E3	100	100	100	80	50	100	100	100	100	50	90	50	100	100	100	100	100	50	100	0	0
QOC: Phase Contrast Imaging	1.2a	E5	100	100	100	100	100	100	100	80	90	50	100	20	100	100	20	0	100	100	100	10	0
QMB: QMB: Profile Reflectometer	1.2b	E3/E5	100	100	80	50	0	100	100	80	60	0	50	50	20	0	100	0	80	100	100	0	0
QSX: High-res X-ray	1.2a	E3	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	0
QSF20: QSF20: LIF (visible light)	1.2b	E4	100	100	100	100	100	100	100	100	100	100	70	0	90	50	20	50	80	10	0	0	0
QRI: Coherence imaging systems (ANU)	1.2a	E4	100	100	100	100	100	100	100	100	100	100	100	100	100	100	50	50	100	100	0	50	0
QXP: PHA (completion)	1.2a	E5	100	100	100	100	100	100	100	100	70	0	100	100	100	100	100	70	100	70	100	100	0
QMR: QMR: Doppler Reflecto (neu, AEK51)	1.2a	E5	100	100	100	100	100	100	100	80	80	0	100	100	100	100	100	0	100	100	100	10	0
QSO: CO Monitor	1.2b	E5	100	100	100	100	100	100	100	0	0	0	100	0	100	100	0	0	100	0	0	0	0
QRN: QRN: Competion of multi-purpose manipulator	1.2a	E5	100	100	100	100	100	100	100	100	100	90	100	100	100	100	100	90	100	100	100	100	100
QXU: MFS (IPPLM)	1.2b/2	E5	100	100	100	100	100	70	30	0	0	0	70	0	50	0	50	0	0	0	0	0	0

Summary

- Successful first campaign produced many interesting and encouraging results
- Limiter operation provided a comparison basis for future divertor operation
- In general, good agreement between expected and observed phenomena
  - Data are still being analyzed…
- OP1.2 will be very important for the preparation of OP2, in particular with respect to divertor operation
- New tools are/will be ready for exciting physics program in OP1.2, e.g.:
  - > 15 new diagnostics
  - TDU scraper elements (PPPL/ORNL coll.): now at IPP
  - Two OP1.2 IR endoscopes: now at IPP
  - Pellet injection
  - More power: NBI (7 MW), ICRH (2 MW) , ECRH (now up to 9 MW)