Max-Planck-Institut für Plasmaphysik

First physics results from Wendelstein 7-X

Thomas Sunn Pedersen
for the W7-X Team

Professor of Physics and
Director of Stellarator Edge and Divertor Physics
Max-Planck-Institut für Plasmaphysik, Greifswald

Acknowledgements/coauthors

- The entire W7-X Team
- In particular those contributing directly to the work highlighted in this presentation:
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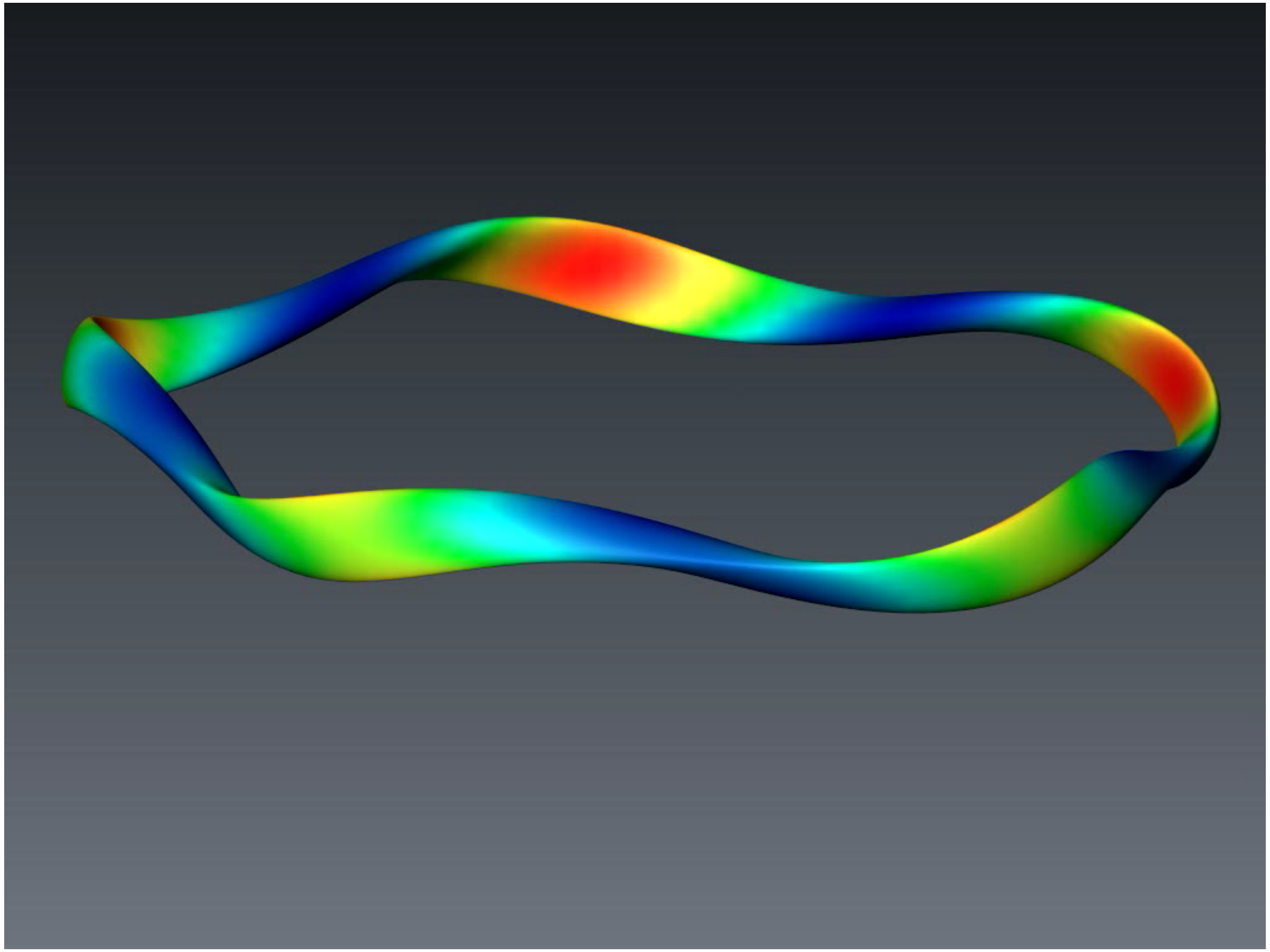
  - S. Lazerson, N. Pablant, PPPL
  - L. Stephey, T .Barbui, F. Effenberg, O. Schmitz, U Wisc. Madison
  - P. Traverso, U. Auburn

Outline

- Introducing the Wendelstein 7-X stellarator
- Time line and goals for operation phases 1.1, 1.2, and 2
- Some details about OP1.1
- OP1.1 results:
    - Flux surface measurements
    - First plasmas: Discharge development and collapse
    - Top performance discharges in He and H
    - Scrape-off layer physics
- Summary and conclusions

Magnetic field optimization

Advances in our understanding as well as in supercomputer power has allowed a comeback for the stellarator concept.



Design of magnetic field coils

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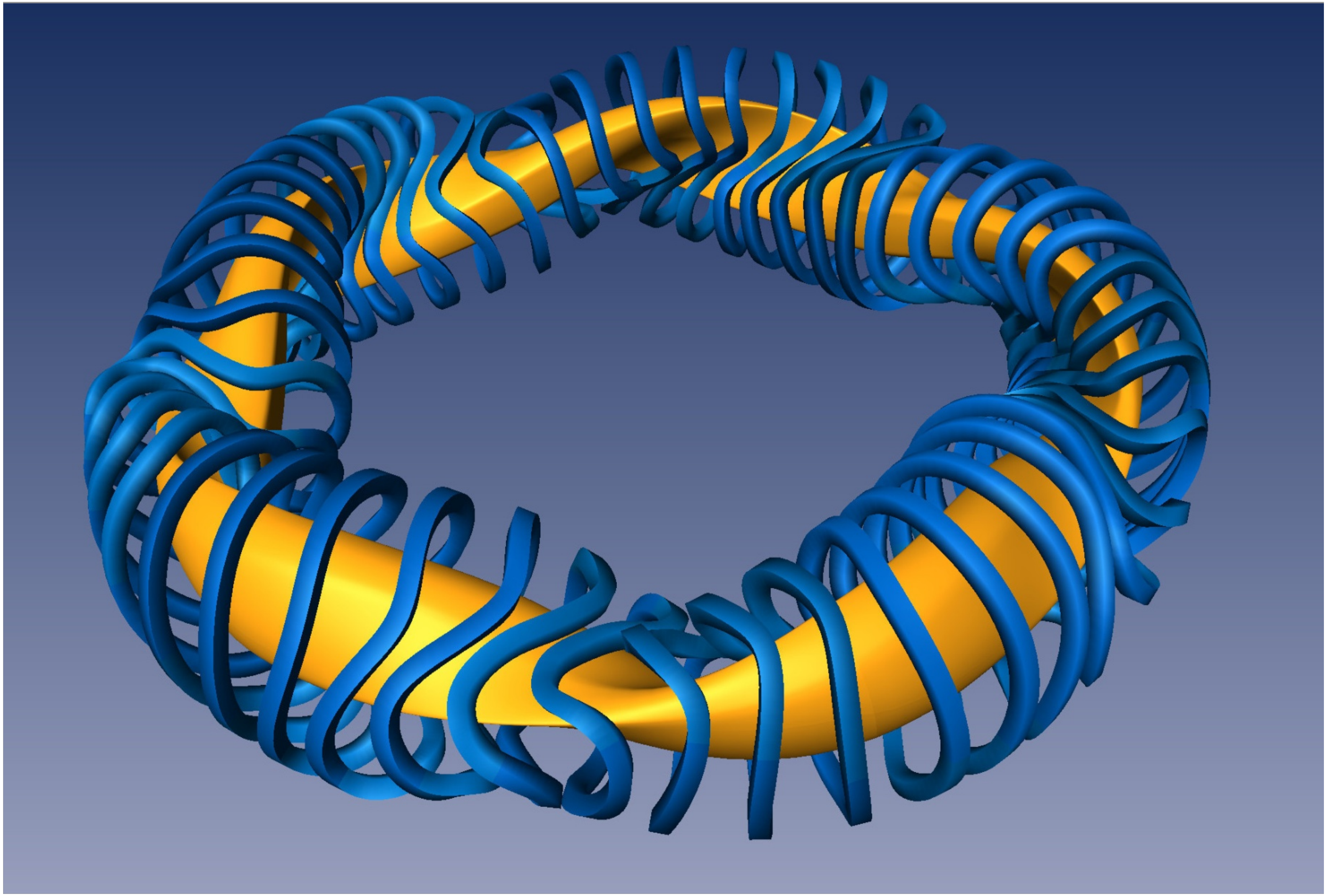
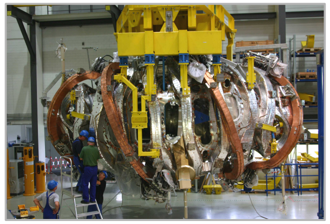
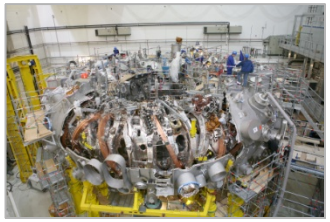
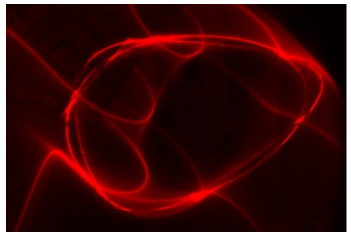
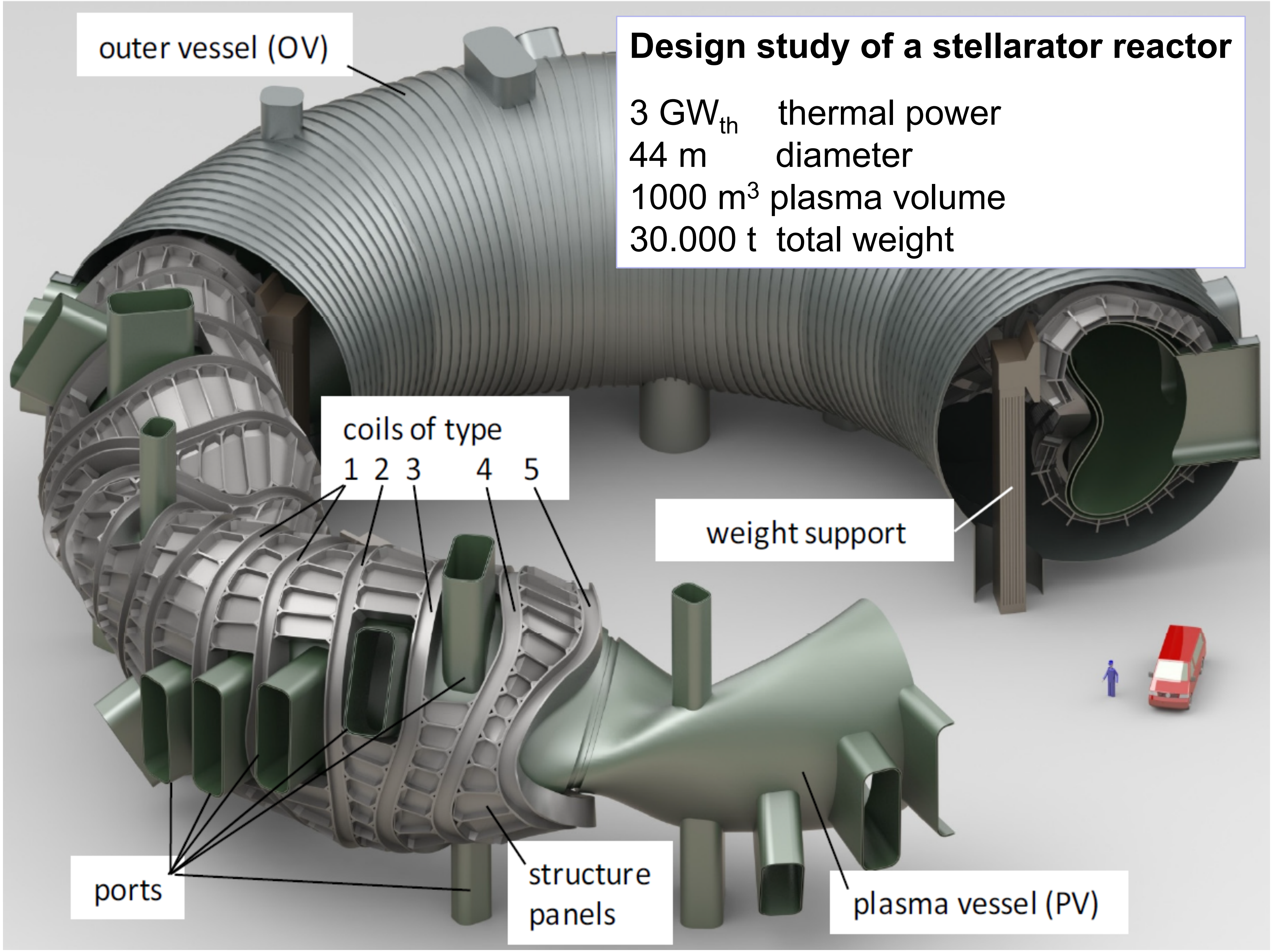


A short history

Major milestones of the project Wendelstein 7-X

Ministerial decision	1993
Offical start of the project	1996
Start of construction	1997
Move into new building	2000
Termination of predecessor W7-AS	2002
Arrival of first magnet	2004
Start of magnet assembly	2005
New timeline agreed	2007
Arrival of the last magnet	2010
Magnet system complete	2013
Last weld seam on the vessels done	2013
Start commissioning	2014
Technically ready for plasma operation	07.2015
Start plasma operation	12.2015


Design study of a stellarator reactor
3 GW$_{th}$ thermal power
44 m diameter
1000 m^3 plasma volume
30.000 t total weight
outer vessel (OV)
coils of type
1 2 3 4 5
weight support
ports
structure panels
plasma vessel (PV)

Time-lapse movie of construction

Planning (status mid-2015)

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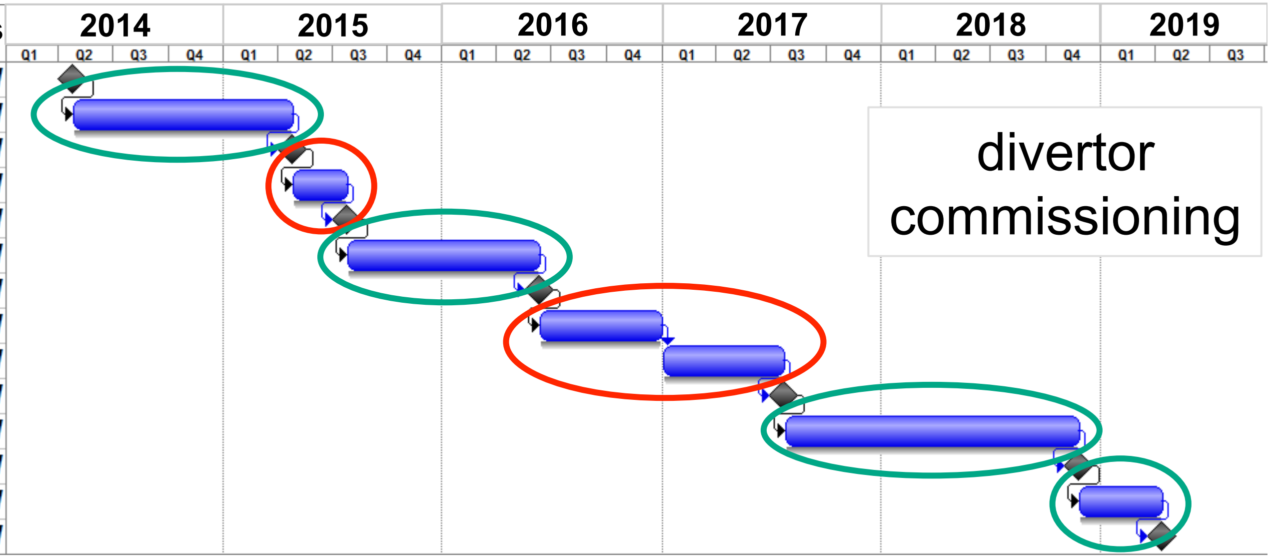
device commissioning | test divertor assembly | HHF divertor assembly

Nr.	task	weeks
1	Milestone Closure of Cryostat	0 W
2	Device Commissioning	52 W
3	Milestone 1st Plasma	0 W
4	OP1.1 (<1s 2MW)	13 W
5	Milestone OP1.1 Completed	0 W
6	KiP2 Assembly	46 W
7	Milestone KiP2 Complete	0 W
8	OP1.2 (5-10s 8 MW)	29 W
9	OP1.2 (5-10s 8 MW)	29 W
10	Milestone OP1.2 Completed	0 W
11	KiP3 Assembly	70 W
12	Milestone KiP3 Complete	0 W
13	Device Commissioning	20 W
14	Milestone Start OP2	0 W



plasma commissioning
diagnostics/control
first investigations

1st plasma w/o divertor

1st divertor plasmas

science

steady-state plasmas

MAX-PLANCK-GESELLSCHAFT

Updated planning

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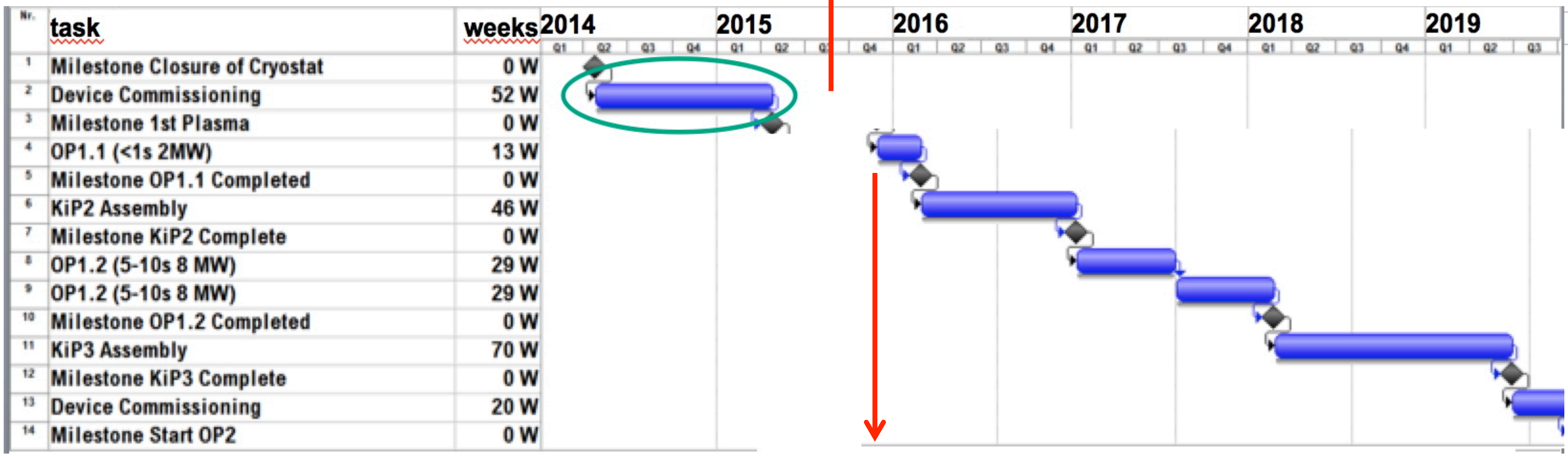
Technically ready for 1st plasmas in July 2015

device commissioning

test divertor assembly

HHF divertor assembly



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Dec. 10, 2015

1st plasma w/o divertor

1st divertor plasmas

steady-state plasmas 2020

plasma commissioning
diagnostics/control
first investigations

science

First physics results from W7-X

First Operation Phases (OP) in Figures

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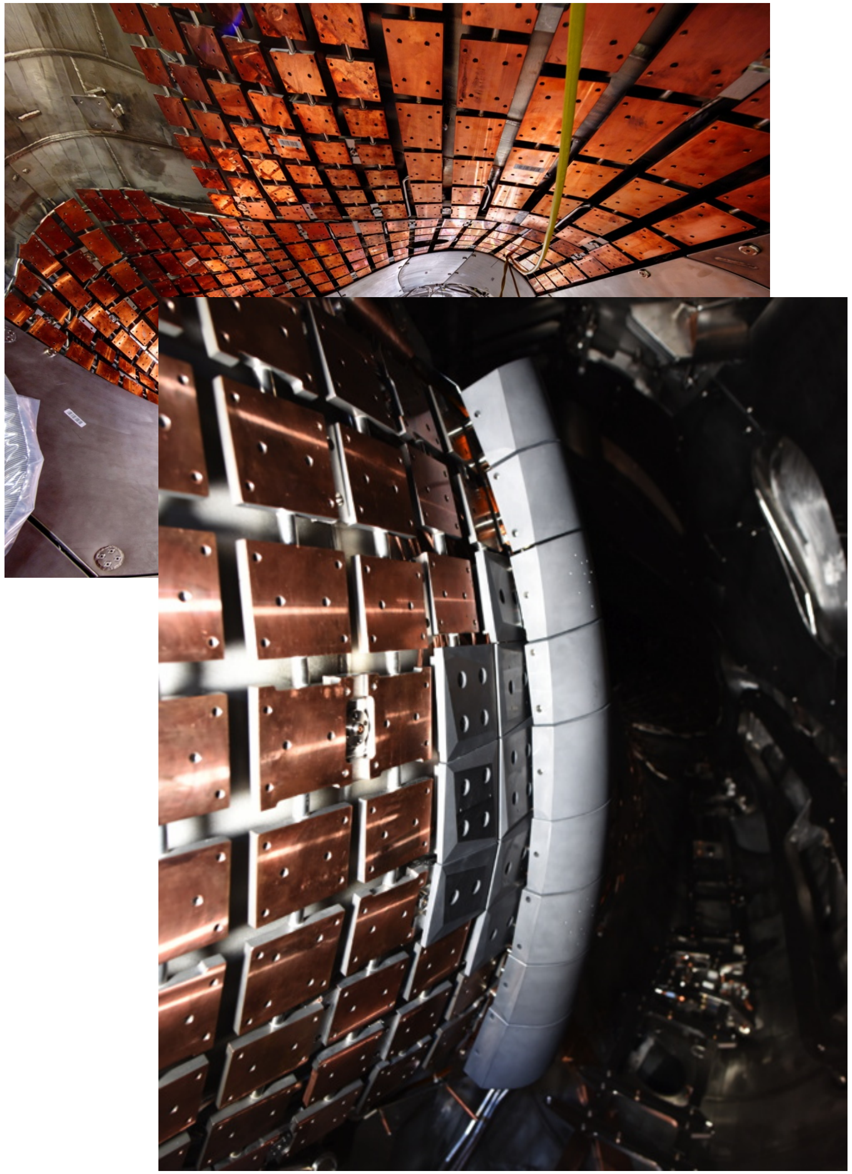
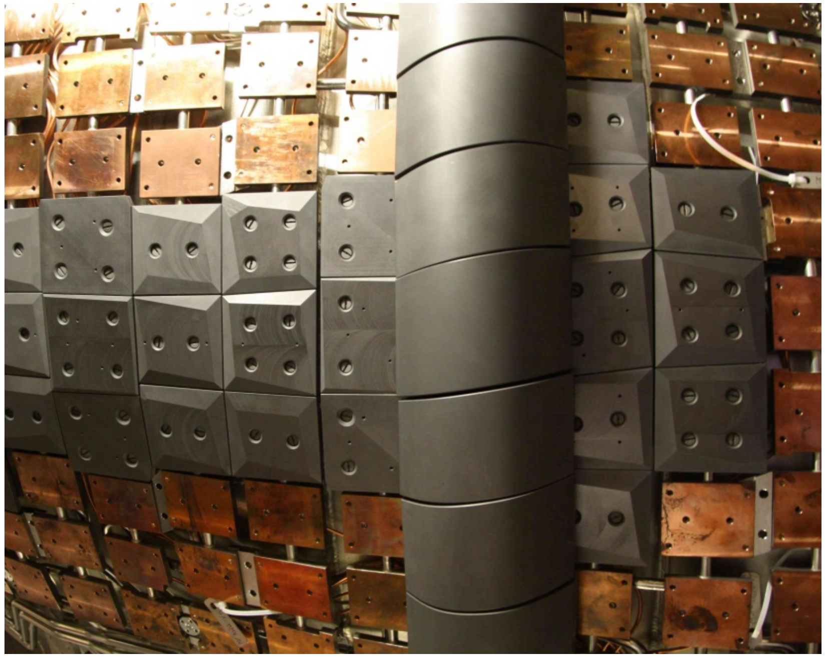
für Plasmaphysik

OP 1.1 **2015-16** **3 months**	Pulse energy: E_{max} ~ 2MJ Graphite limiters, uncooled	P_{ECRH} ~ 5 MW 6 gyrotrons	T_e^{NC} ~4 keV T_i^{NC} ~1 keV $n \sim 2 \cdot 10^{19}\ m^{-3}$ $\langle b_{NC} \rangle$ ~ 1%
OP 1.2 **2017** **2*5 months**	Pulse energy: E_{max} ~ 80 MJ Graphite divertor, uncooled	P_{ECRH} ~ 8 MW P_{NBI}^{H} ~ 7 MW P_{ICRH} ~ 1.6 MW	T_e^{NC} ~5 keV T_i^{NC} ~4 keV $n \sim 1.6 \times 10^{20}\ m^{-3}$ $\langle b_{NC} \rangle$ ~ 3%
OP 2 **2020**	Pulse energy up to ~ 18 GJ =10MW for 30 min 20 MW for 10 s at a time CFC water-cooled divertor	P_{ECRH} ~ 10 MW P_{NBI}^{D} ~ 10 MW P_{ICRH} ~ 4 MW **P_{tot} < 20 MW**	T_e^{NC} ~ 5 keV T_i^{NC} ~ 5 keV $n \sim 2.4 \times 10^{20}\ m^{-3}$ $\langle b_{NC} \rangle$ ~ 5 %

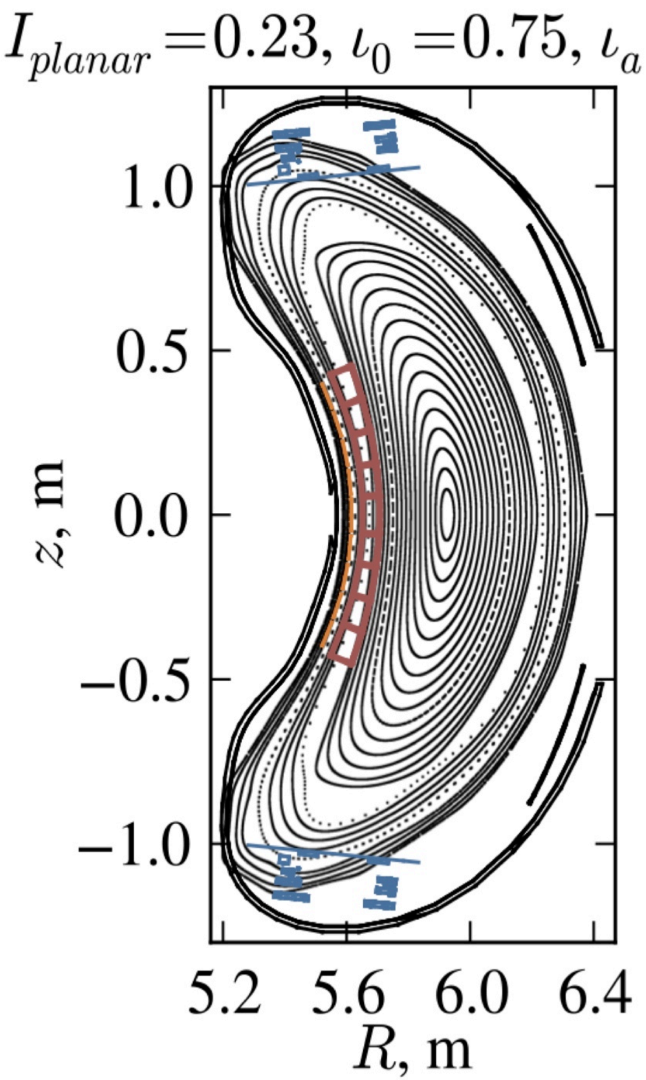
PFCs for first plasma operation (OP1.1)



- Wall protection (SS)
- Heat shields (CuCrZn heat sinks)
- Water-cooled (starting OP 1.2)
- No divertor in the first phase
- 5 graphite limiters at the inner wall
- Must intersect convective plasma heat loads
- Designed for >5*0.4 MJ=2MJ per pulse



Magnetic configuration for limiter operation

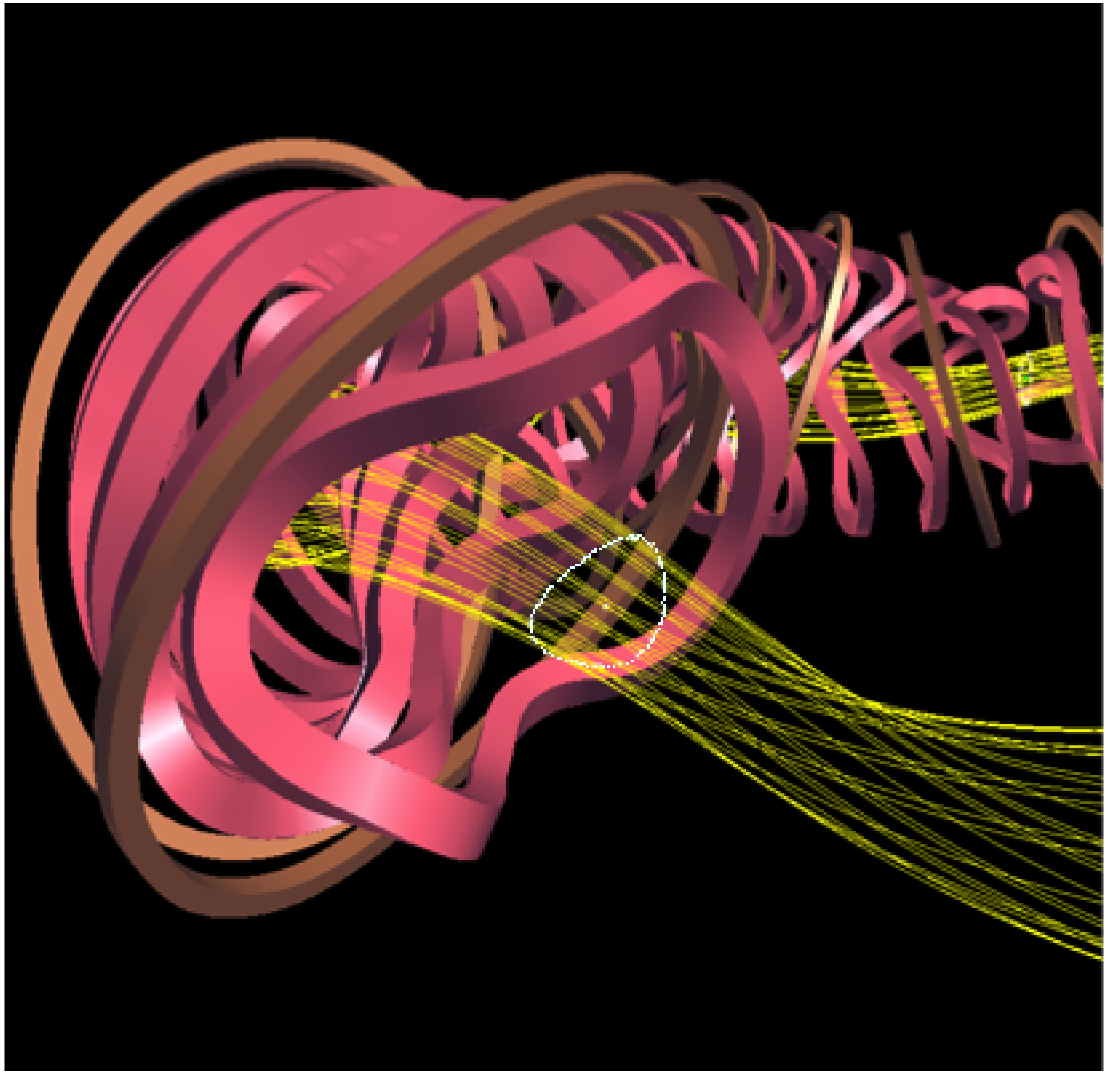


- Make sure limiter intersects >99% of the heat load: Vary iota using planar coils:
  - Avoid large islands at the edge
  - Avoid stochastic regions at the edge
  - Limit several cm of good flux surfaces
  - Robust against field errors (in particular 1/1)

✓ I_{planar}=0.13 chosen

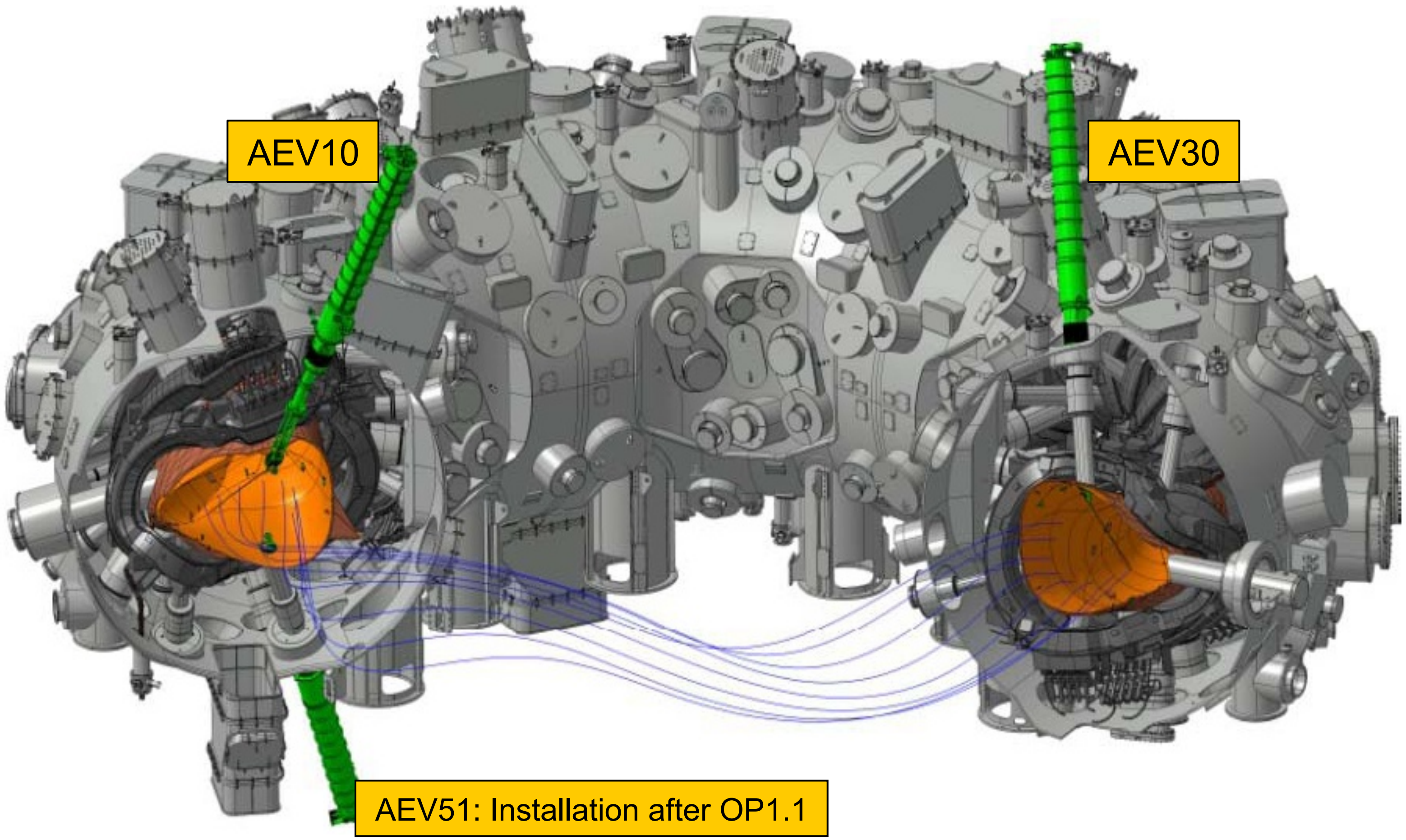
FSM: Basic Concept

- Electron beam emitted parallel/antiparallel to magnetic field line
- Intersected in one cross-section by rod covered with a fluorescent powder
- Poincaré cross-section appears on time-integrated photograph

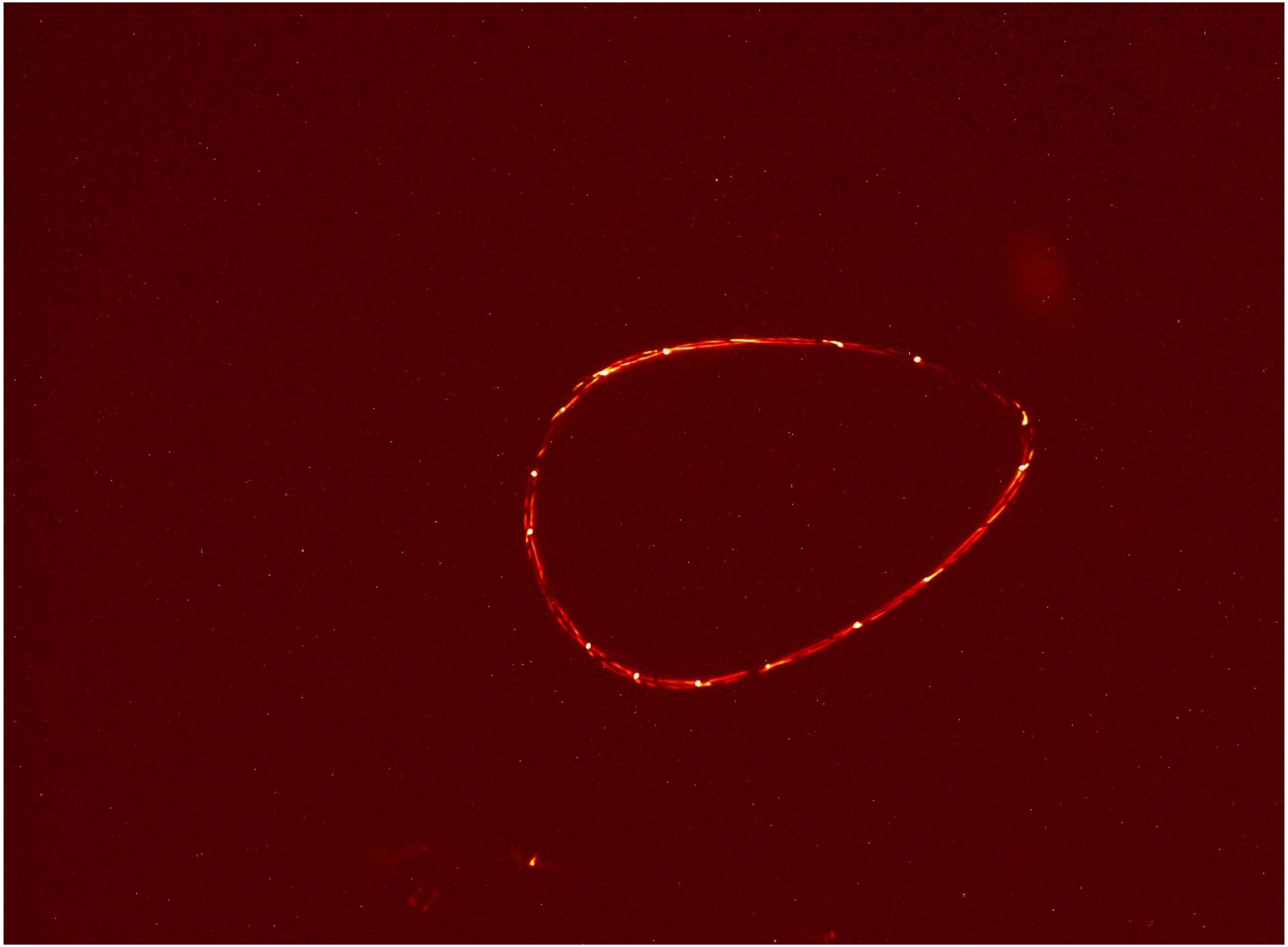


Flux surface measurement manipulators

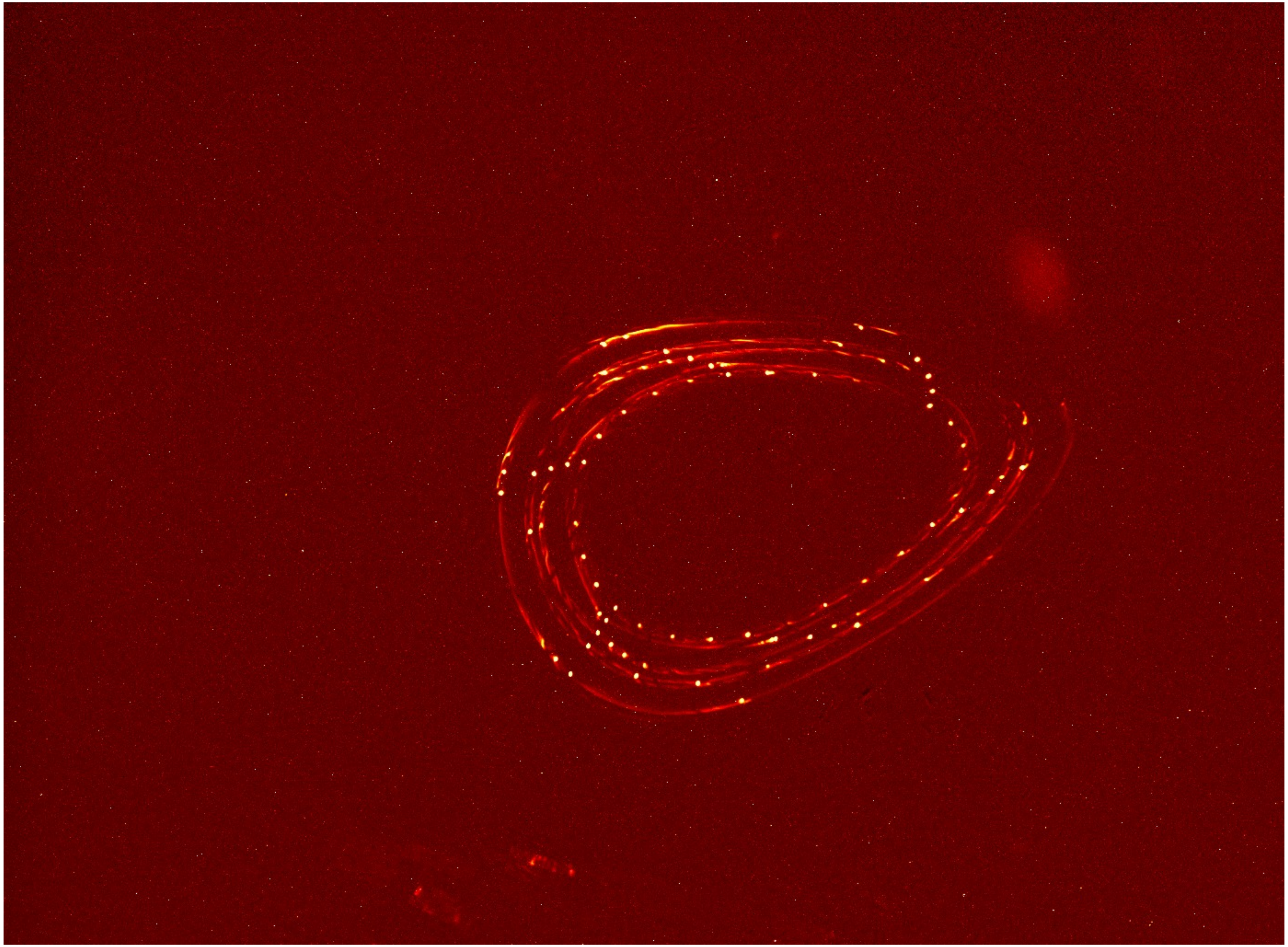
- Three manipulators designed, manufactured and tested
- Two manipulators installed (AEV10 & 30) for measurements in two different modules



A cut through a magnetic flux surface

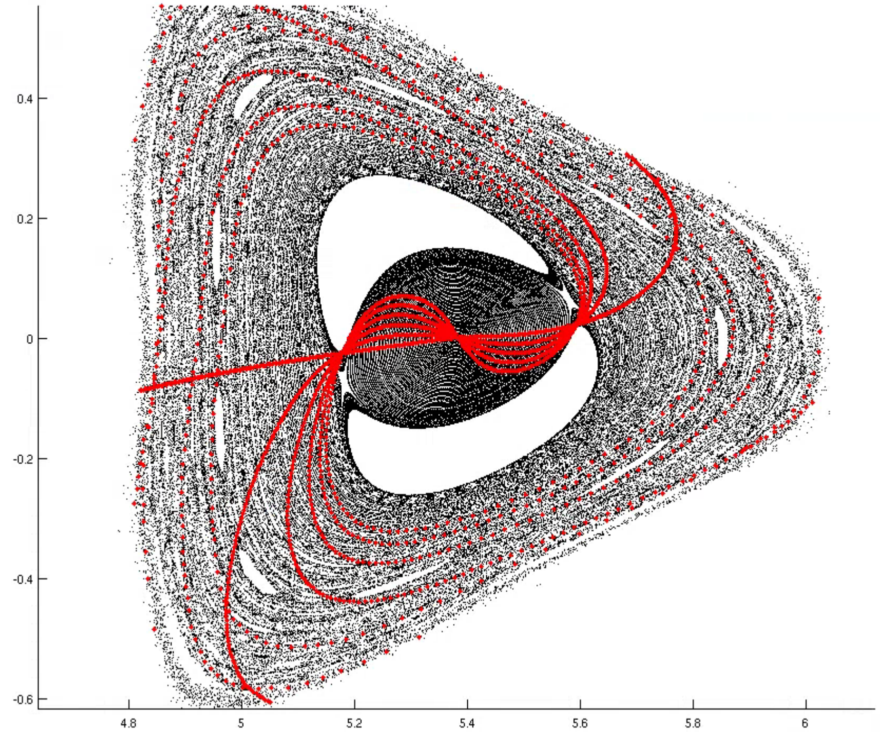


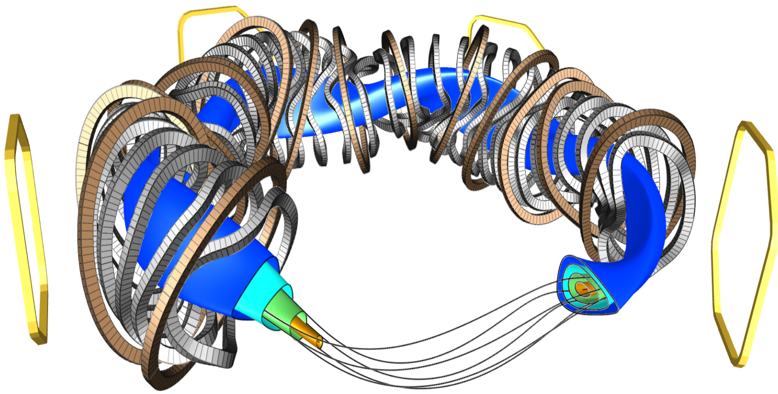
Nested magnetic flux surface



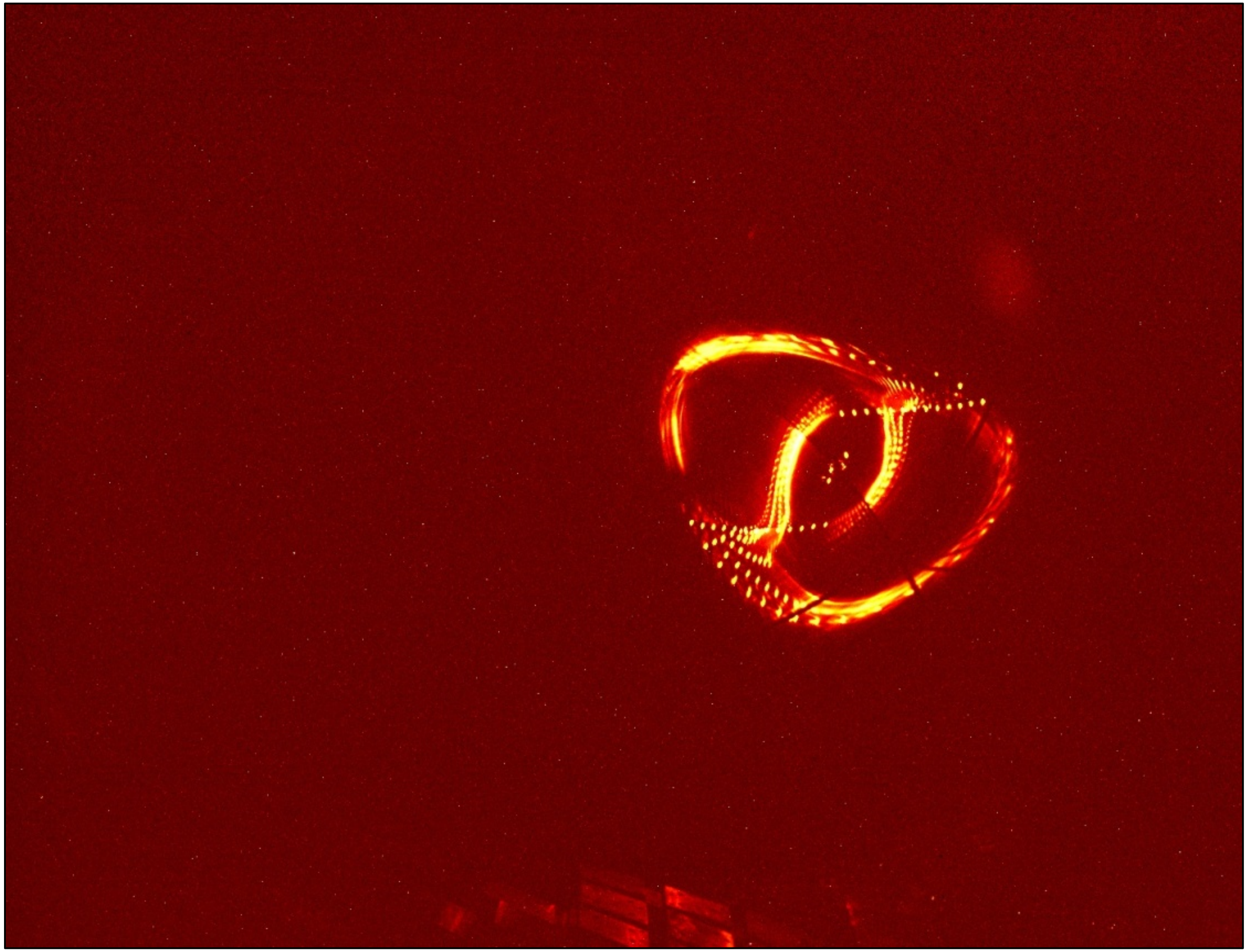
iota~1/2 for pre-OP1.1 error field studies

- In OP1.1 we have a slightly lower iota than the future "standard configuration"
  - The planer coils are hooked up to lower iota
- We could not easily access a high iota configuration before OP1.1
- Iota=0.5 is also resonant with n=1 field errors (iota=n/m=1/2), and can be accessed with the polarity used in OP1.1
- Thus, an m=2 island should be measurable with FSM
- Trim coils can be used to create well-defined n=1 error fields, since the intrinsic error is too small to be measured
  - Shadowing prevents us from measuring small islands
  - (First ten e-beam transits shown)





Success! m/n=2/1 island measured

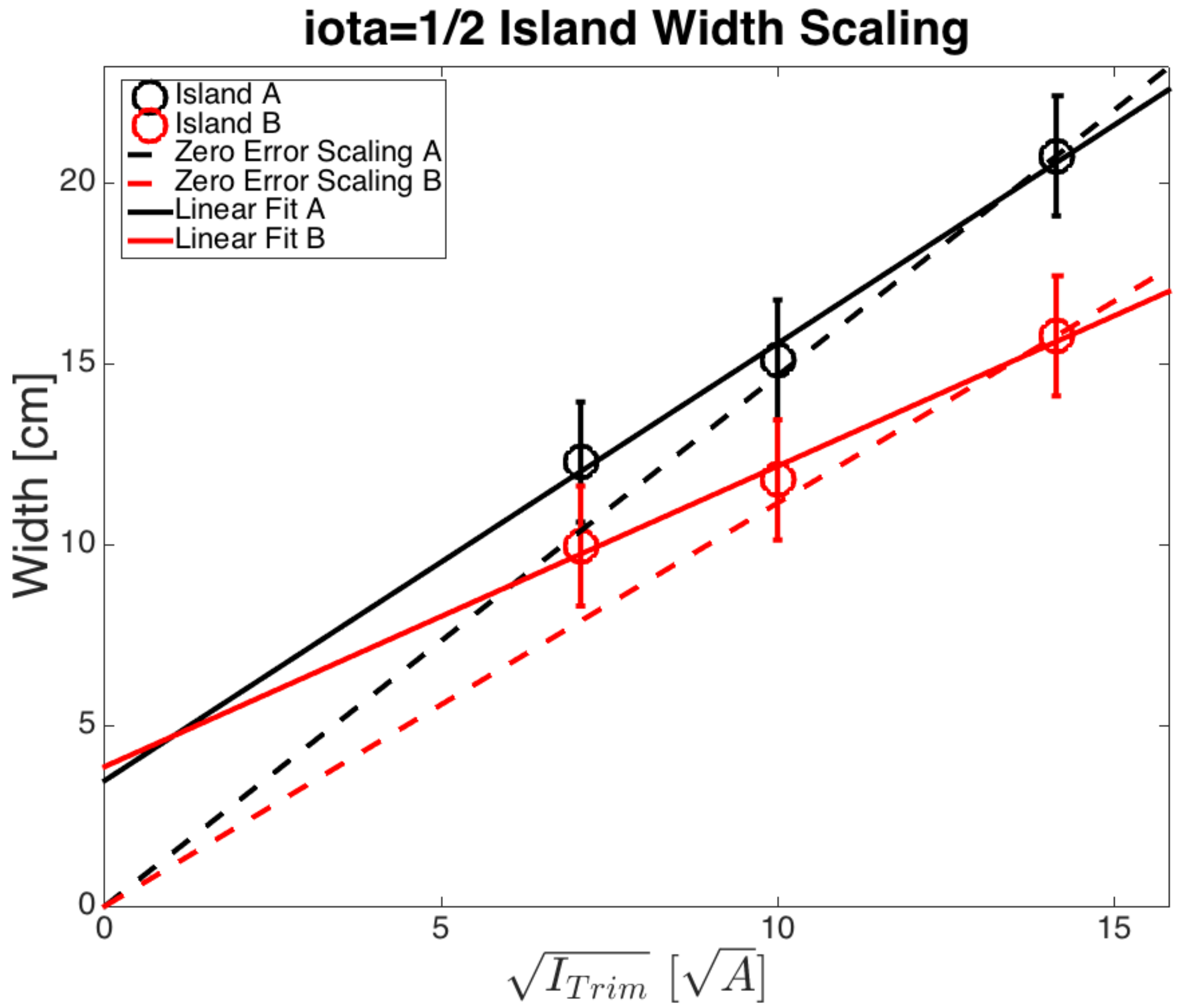


2/1 island chain induced by trim coils set to produce n=1 error field

Island width scaling with trim coil current

- Scaling suggests an intrinsic 2/1 island with a width of about 4 cm is present.
- This island size is consistent with the estimated n=1 error originating from construction inaccuracies*: $B_{11}/B_0 \sim 2\text{-}3 \cdot 10^{-5}$

$$w = \sqrt{\frac{R_o B_{mn}}{m B_o \iota'}} \qquad B_{mn} \propto I_{Trim}$$



Sam Lazerson, PPPL, USA

*T. Andreeva et al., EPS 2012

First Helium Plasmas
Observed with camera diagnostics

Early plasma 15.12.2016

First plasmas end in a radiation collapse

- Central ignition
- Expansion from inner to outer magnetic surfaces is slow due to good confinement
- Radiation/ionization layer defines the expanding edge
- Plasma acts as MW UV heater lamp
- UV photons hit the walls, impurities come off the walls
- Impurity radiation kills the plasma from the outside

T. Szepesi, G. Koczis

First plasmas “100% edge cooling”

- For these plasmas, the limiters received essentially no convective heat flux
  - 0-2 degree temperature rise
  - Very low limiter Langmuir probe signals
- All the plasma energy was radiated away at the edge – no convective loading
- (Impurity radiation is too intense)

T. Szepesi, G. Koczis

Best performance in He

- Right before switching from He to H plasmas, we achieved plasmas with lifetimes of 0.4-0.5 seconds (28.01.2016)
- The plasma had prolonged contact with the limiters
- Limiter temperature rose to over 300 C
- Movie:
  - 100 Hz (10 ms) frame rate
  - Total movie 0.46 s real time

$T_e \sim 8$ keV
$T_i \sim 1.5$ keV
$n_e \sim 3\ 10^{19}\ m^{-3}$

Hydrogen Plasmas

High performance in H

- 2 MJ milestone reached on Thursday Feb 18, 2016!
- 1 second 2 MW reference discharge
- Look closely 1.52 (5.34 msec), 2.21 (744 msec) and 2.90 (944 msec)

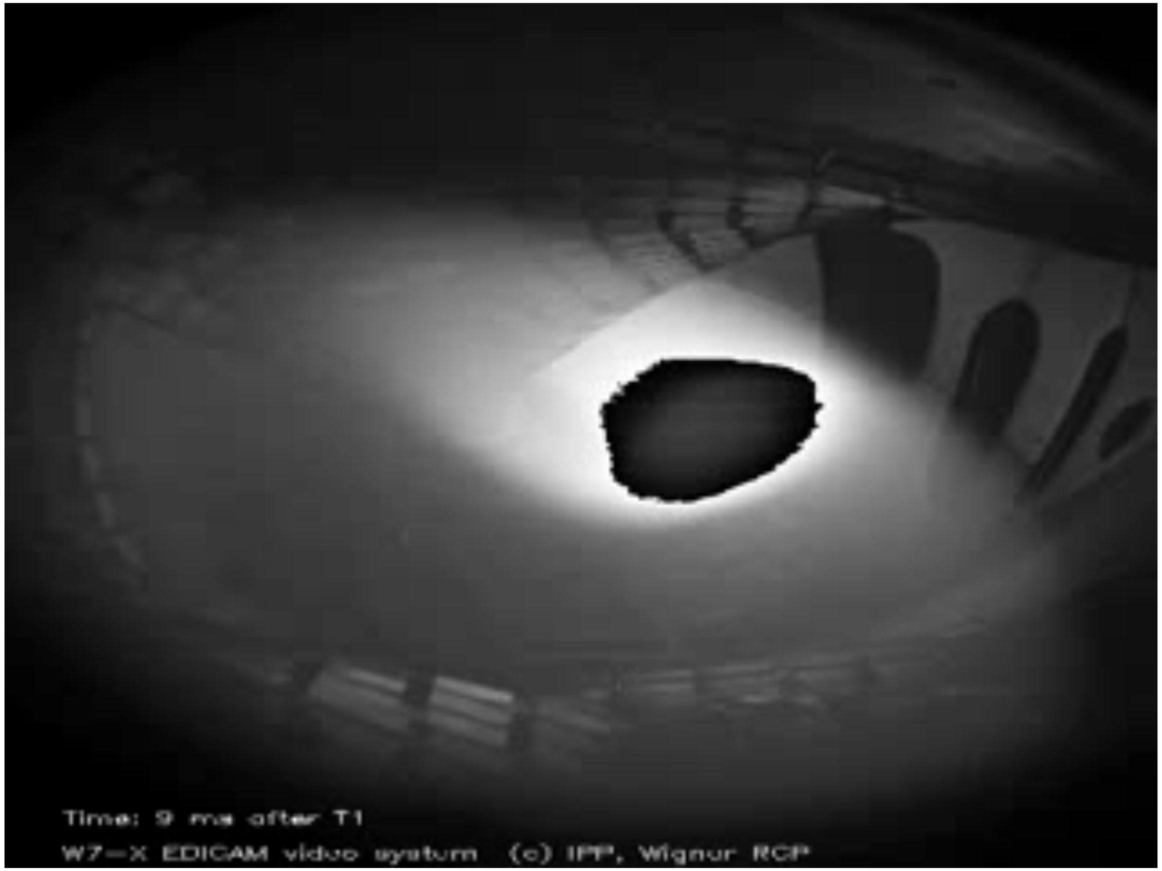
- 100 Hz/ 10 msec frame rate
- Total movie 1.2 seconds real time

T. Szepesi, G. Koczis

High performance in H

- Since the limiters were not overheated even in 2 MJ discharges, 4 MJ per discharge was allowed during the last weeks of operation
- 6 second discharge shown (1 s 1MW, then 5 s 0.6 MW):

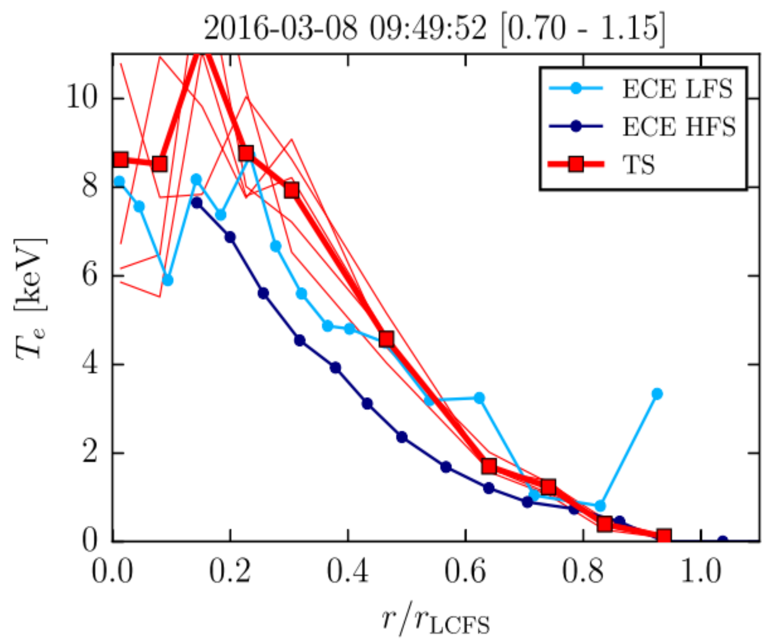
- Discharge terminates peacefully, as pre-programmed



Core parameters and estimates of confinement times: Preliminary data!!!

Core profiles of n_e and T_e: Consistency check

Thomson scattering and ECE

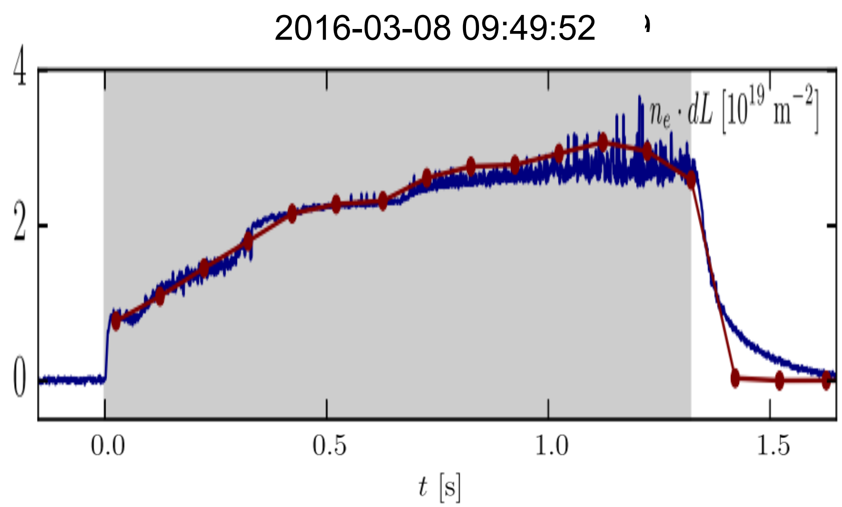


$\beta_e \approx 2.1\%$

ECE comparison

- For β ≤ 0.5% there is a good agreement
- For higher β the difference between LFS ECE and HFS ECE becomes larger
- More careful mapping should be used

Thomson scattering and interferometry



Interferometer comparison

- In many cases TS and interferometer agree within 10%
- Sometimes there is a discrepancy
- No clear dependence on plasma parameters

Core transport: on- and off-axis heating

Two comparable, low power (0.6 MW) , long-lived plasmas:

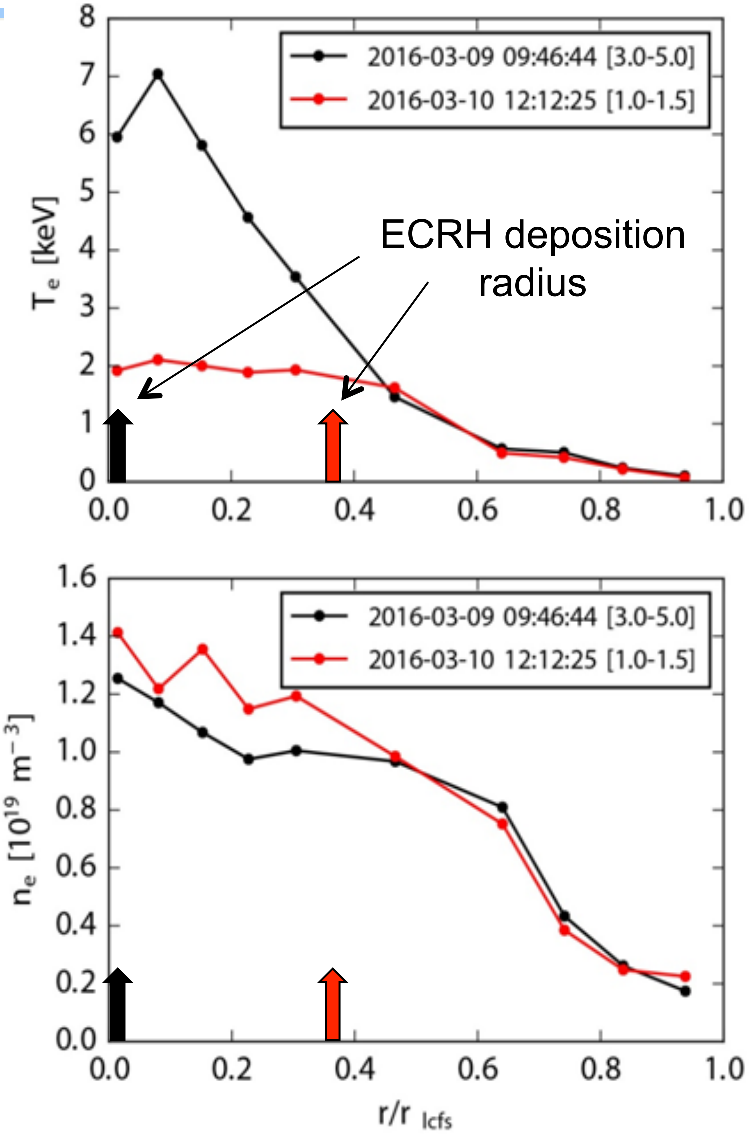
- On-axis ECRH
- Off-axis ECRH

Clear and expected response in Te profiles

Density does not hollow out (concern from neoclassical estimates)

Peaked profiles:

- Inward pinch?
- Core fueling (n_e low)

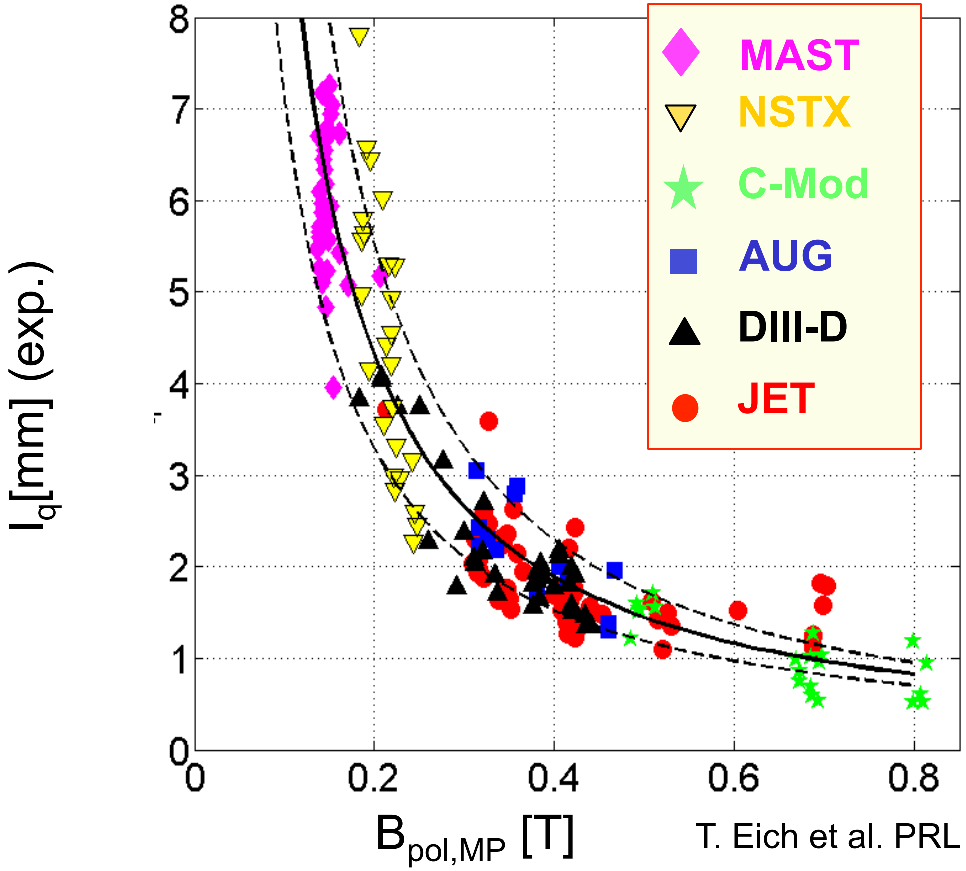


Limiter SOL physics

- As the walls progressively cleaned, and the pulses got longer, the plasmas started to touch the limiters
- Several hundred degrees of temperature rise during the longest plasma pulses
- Large I_{sat} values on Langmuir probes ($n \sim 2*10^{19}$ m^{-3})
- A real scrape-off layer has formed
- Is there anything interesting to be learned from a limiter SOL?

Why SOL and λ_q studies are important

•The width of the heat deposition region, λ_q, scales with $1/B_p$ in tokamaks , and NOT with machine size, leading to a prediction of $\lambda_q \leq 1$ mm for ITER and DEMO (problematic).

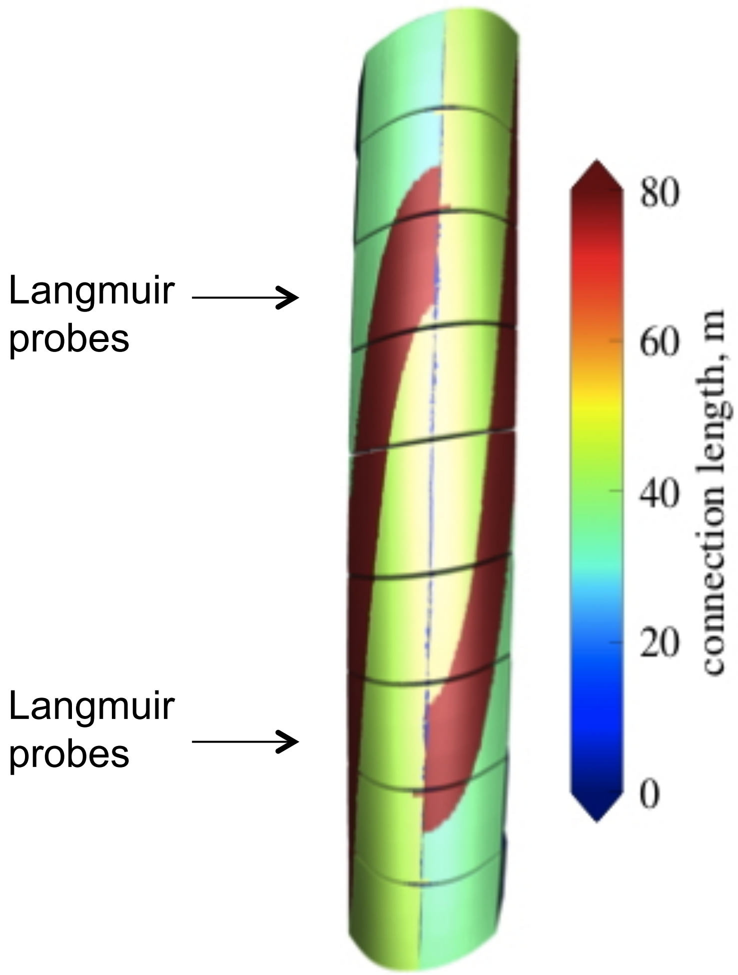


T. Eich et al. PRL 107 2011

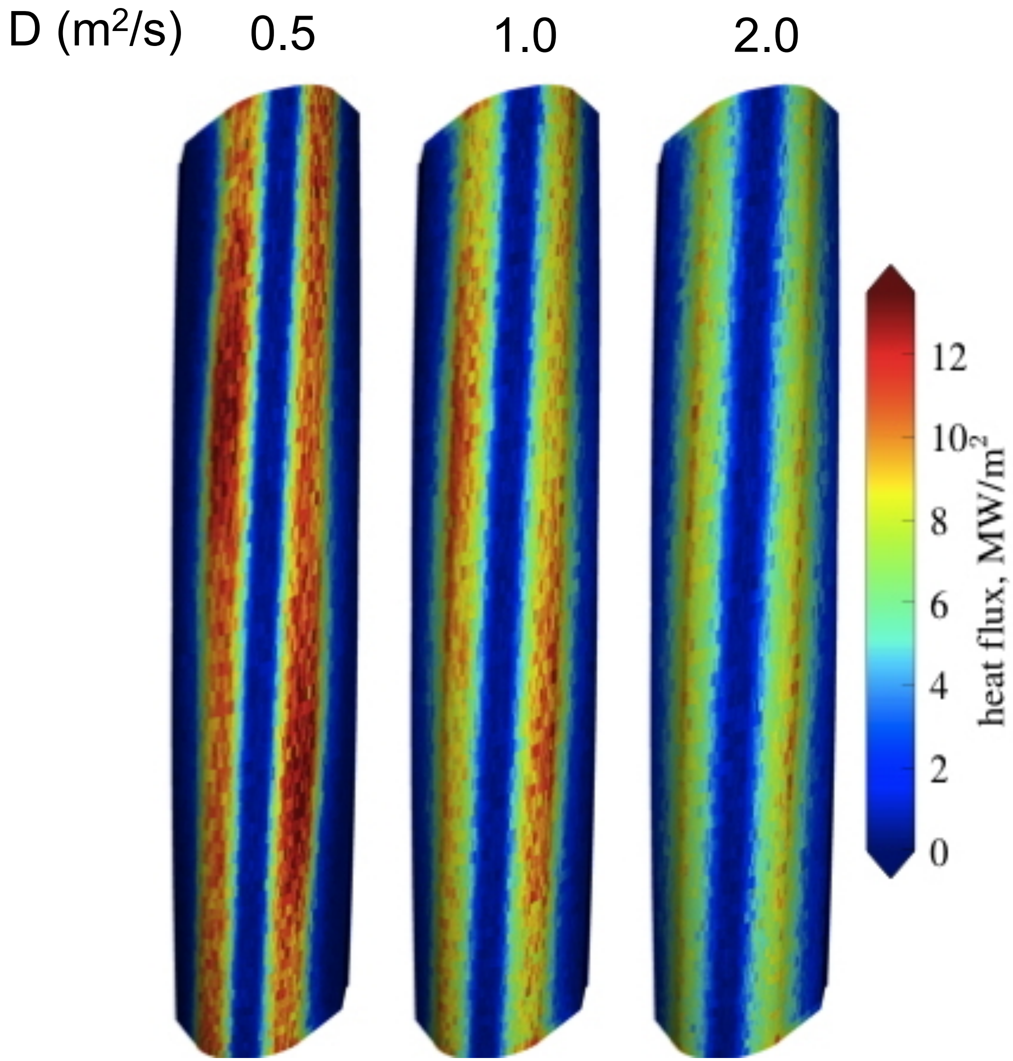
- Heuristic model:
  Goldston, Nuclear Fusion 52 013009 (2012)
  - $\lambda_q \sim L_c * v_D$
  - In tokamaks, L is proportional to $1/B_p$ leading to B_p scaling
  - In a stellarator, L_c is not related to B_p but to the inclination of the divertor relative to the field lines
  - Limiter operation gives data points at L_c ~30-80 m
  - Divertor operation will give data at L_c ~100-500 m

Scrape-off layer physics with a limiter

Connection length is short compared to divertor phase two distinct regions on limiter



Cross field diffusion rate visibly affects heat load patterns



Edge Filaments

Fast movie “gas puff imaging”

- Superfast movie shows filamentary structures rotating
- 20 kHz<->50 μs per frame
- The counter-clockwise rotation is consistent with inward-pointing radial electric field
- “Ion root”
- As expected for low T_e plasma
- Reminiscent of tokamak “blob” visualizations using gas puff imaging.

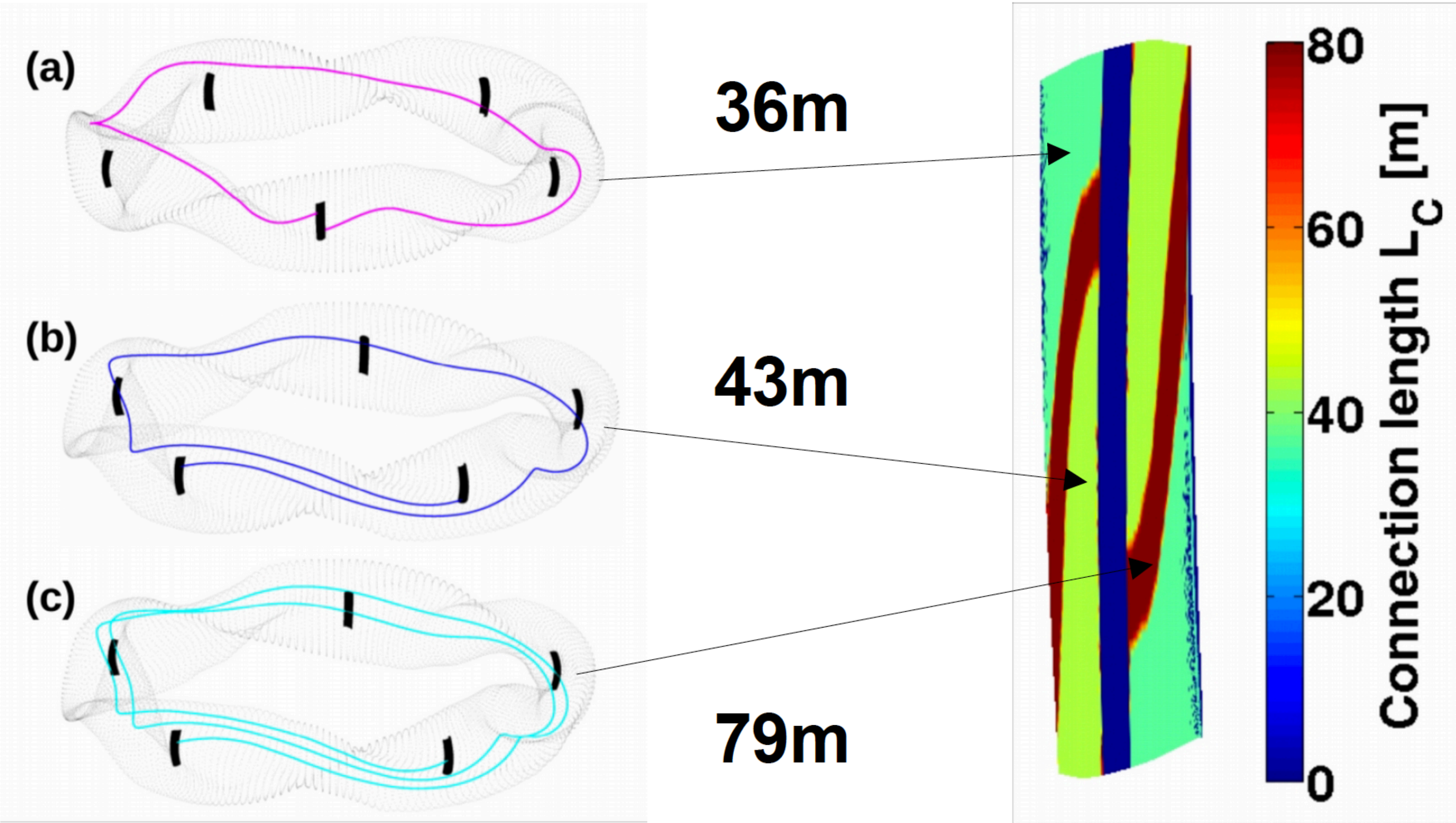
T. Szepesi, G. Koczis, Wigner RCP, Hungary

EUROfusion

Scrape-off Layer Physics with a Limiter

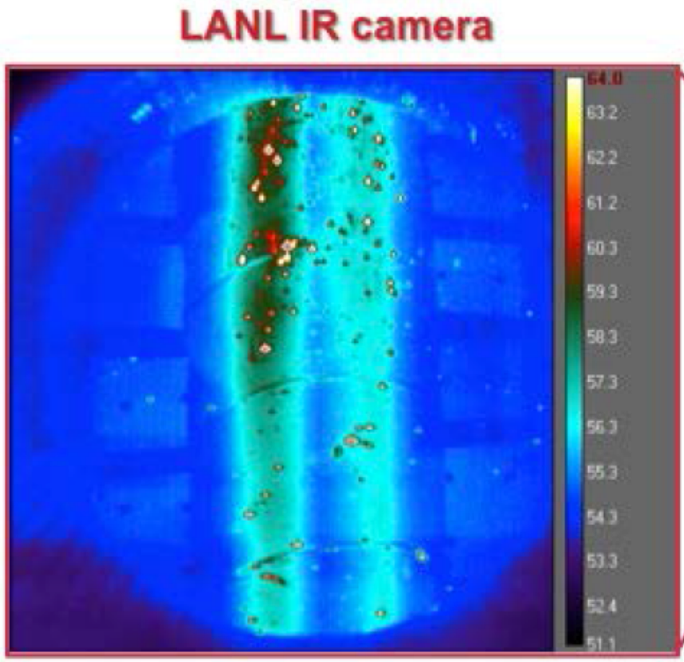
Standard limiter configuration

L_c variation on the limiter explained

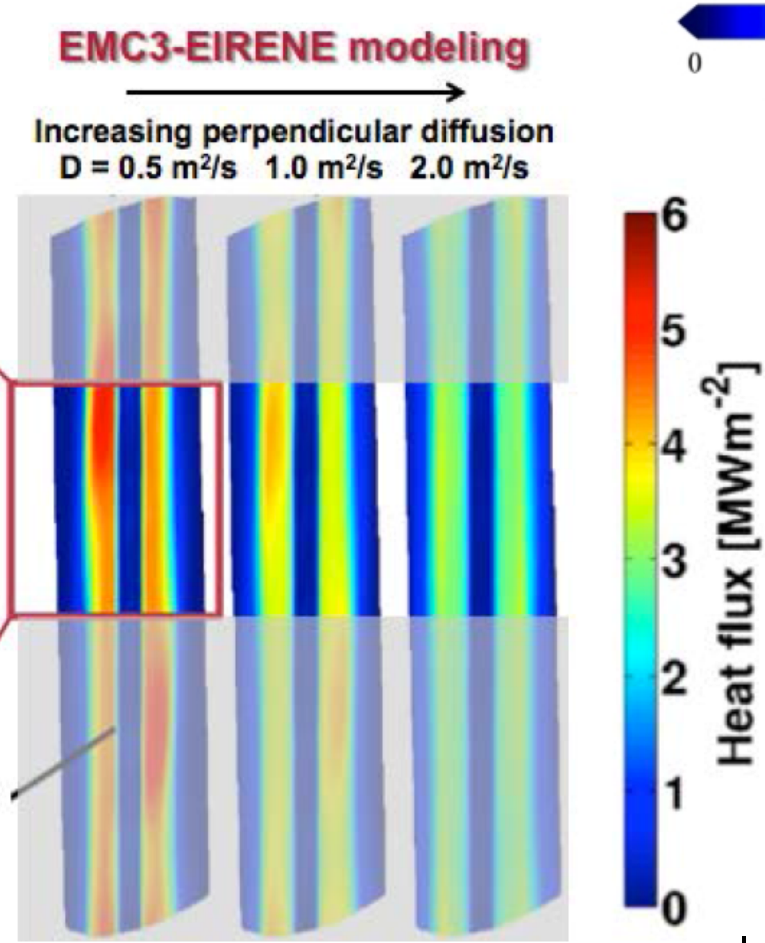


Scrape-off layer physics with a limiter

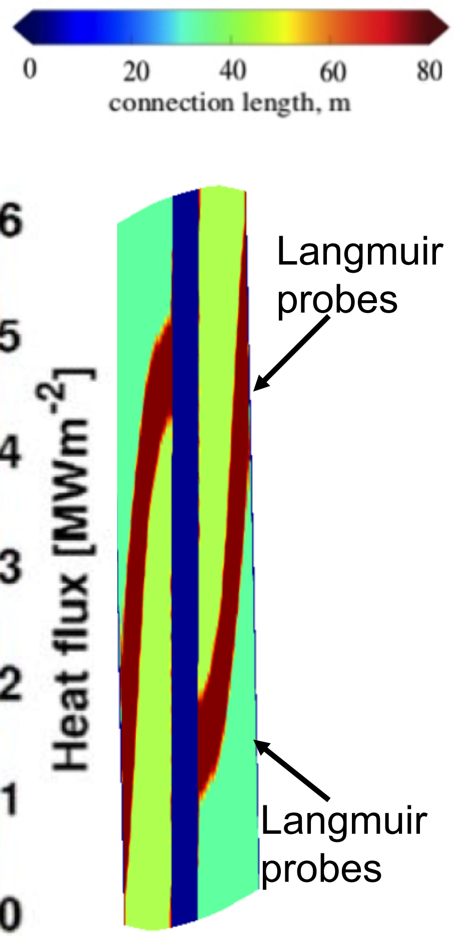
High-res. IR camera view directly onto limiter in module 3



G. Wurden, LANL



Cross field diffusion rate visibly affects heat load patterns

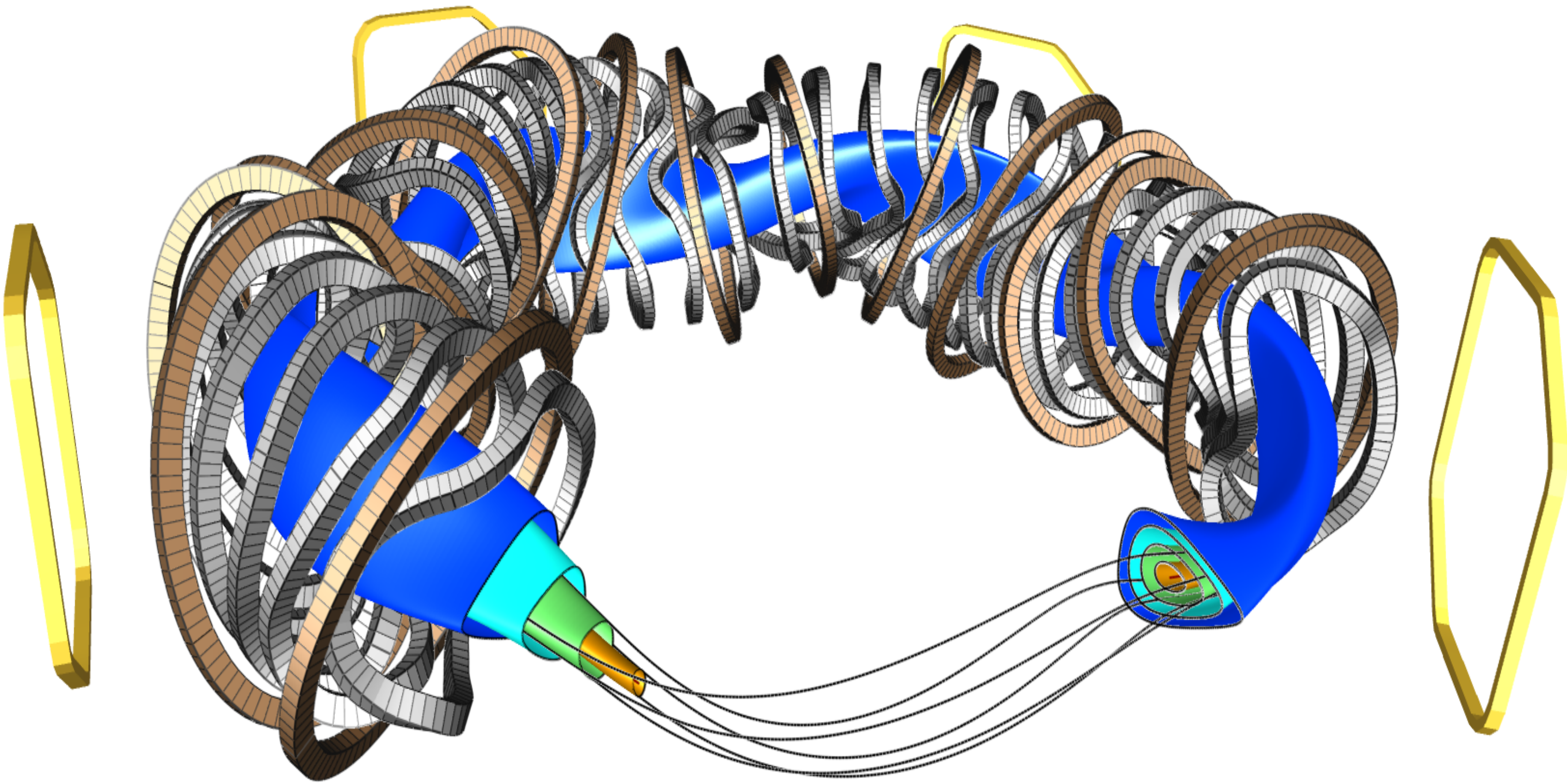


L_c short compared to divertor phase
Three distinct regions on limiter

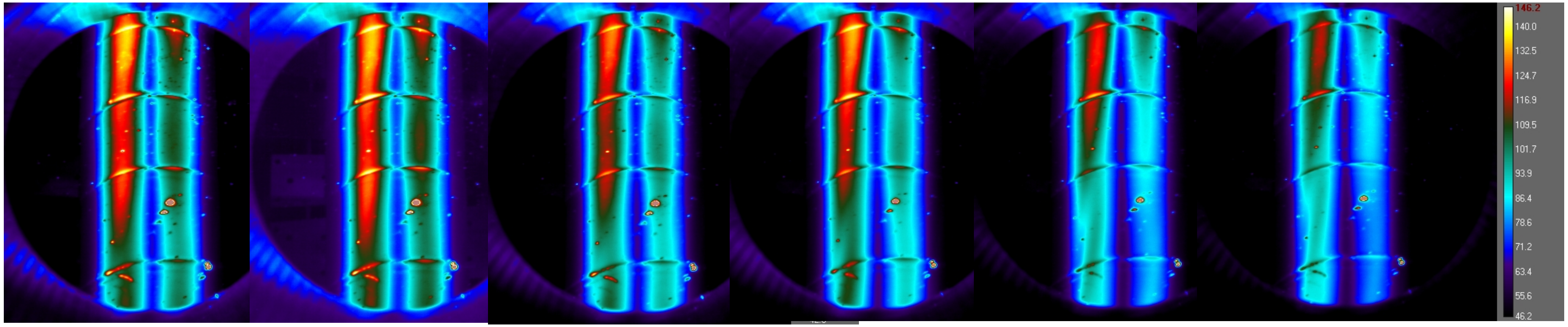
F. Effenberg, O. Schmitz

Scrape-off layer physics experiments using the trim coils

Trim coils

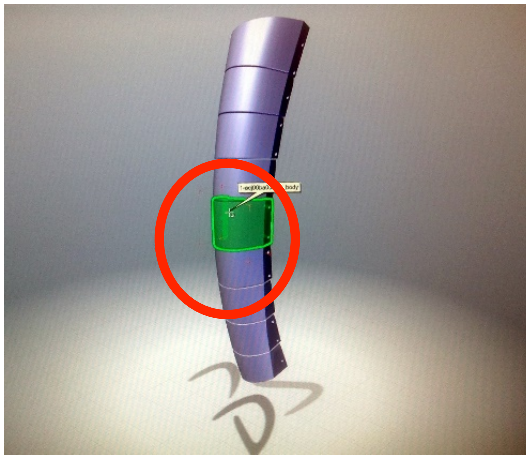


Trim coils exp.: max. power load module 3 - current scan



0 +100 +200 +400 +800 +1000 A

Heat load shifts upwards as the n= 1 perturbation trim coil currents with a maximum in Module 3, are increased (while holding the phasing fixed).



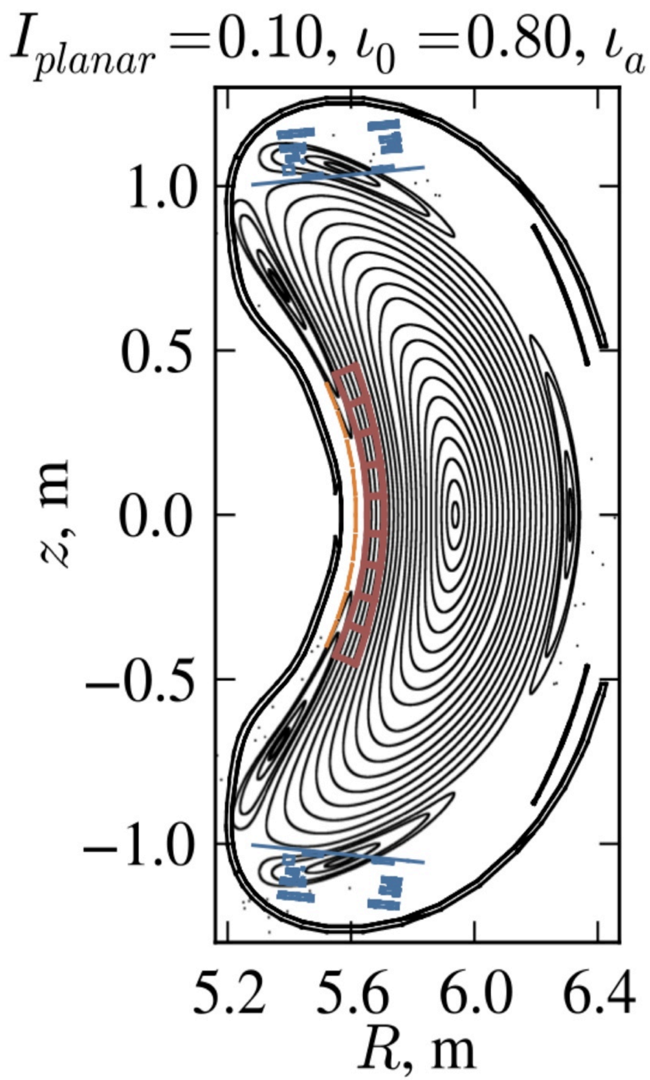
Green tile: center tile of the limiter

FLIR MIR camera

Scrape-off Layer Physics with a Limiter

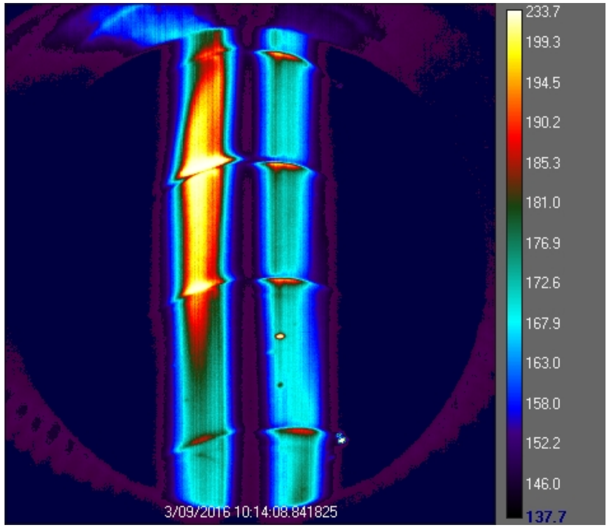
Increased iota limiter configuration

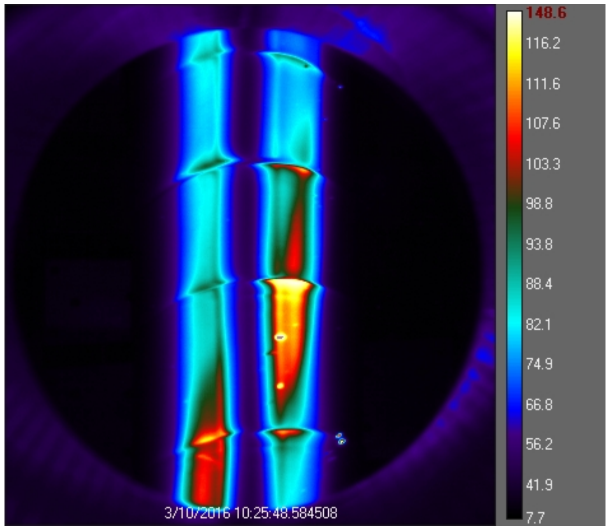
Slightly increased iota



- 5/5 island chain still in SOL but closer
- Given the large radiated power, this was deemed safe (for the last two days of operation)
  - Limiter shadowing is different – different load patterns
  - 5/6 island chain is deeper in core region
  - Mirror term is larger
    - De-optimized neoclassical transport

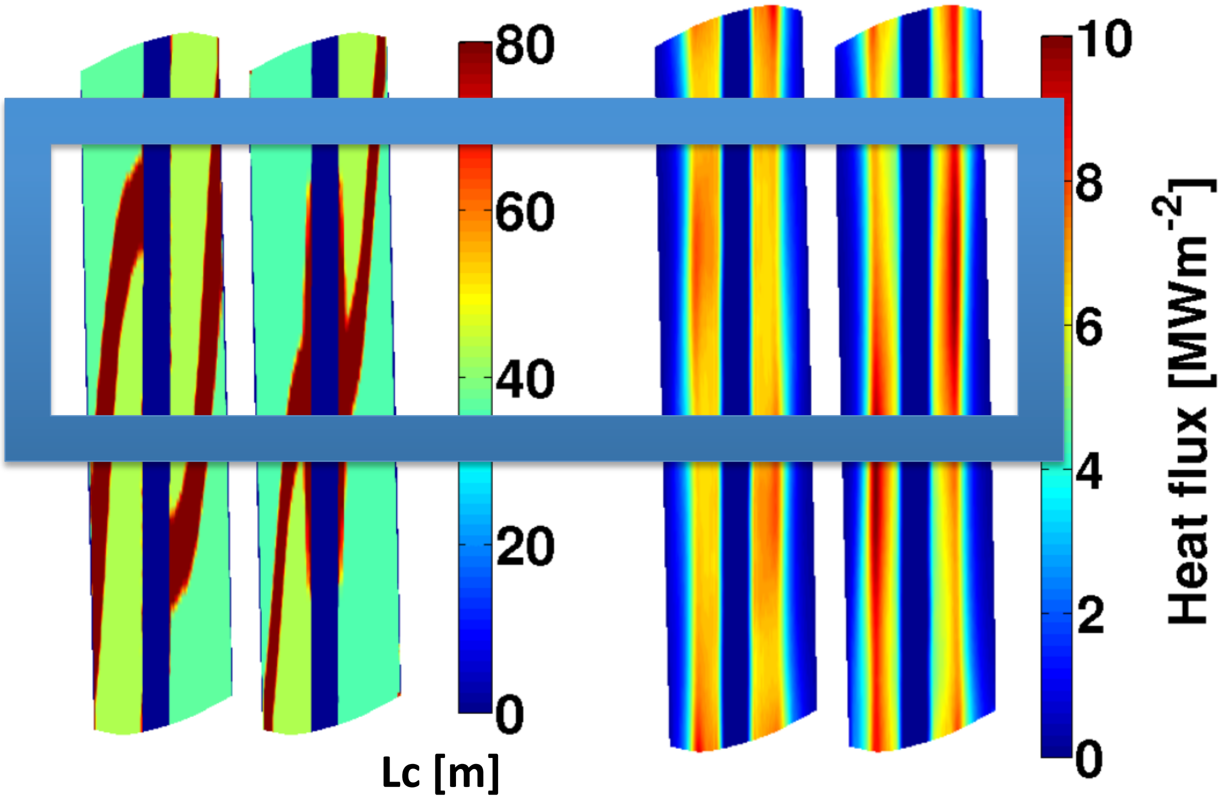
Changing the heat flux pattern between standard original OP1.1 and increased-iota (index 13) configuration





G. Wurden

EMC3-Eirene prediction: change in heat load pattern correlated to change in Lc footprint



IR observation s shows a clear shift in heat load pattern due to iota variation

Summarizing…

At the end of OP1.1, ~30 diagnostic systems were operational

QMC: Correlation reflectometry	QRT-h: High-resolution H-alpha	QSV-f: fast video camera
QMJ: Single channel interferometer	QSZ: Z_{eff} single line of sight	QRT: Near Infrared limiter observation
QTB: Thomson scattering	QSS-f: Filterscope line of sight	QSR: Limiter observation: Hα
QME: ECE	Vis. spectroscopy	QRT-h: high-resolution infrared obs.
QSX: FZJ crystal spectrometer	QSD: HEXOS (broadband x-ray spectr)	QNC: neutron counters
QSW: US crystal spectrometer	QSB: bolometry	QSQ: therm. He-beam obs. systems
QXD: diamagnetic loops	QXP: pulse height analysis	CBD-v: NIR-video
QXR, QXO: Rogowoski coils	QRP: limiter Langmuir probes	CBD-s: Sniffer probes
QXM: Mirnov coils	QRG: neutral gas pressure gauges	CBB: gyrotron power measurement
QXS: Saddle coils	QRG-p: Penning gauge	QSV: video diagnostic
QXE: flux surface measurements	QRN: multi-purpose manipulator	QSQ: thermal He, Ne, Ar, N, -beam gas boxes

Status end of OP1.1 (red bold font)

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OP 1.1 2015-16 3 months	Pulse energy: E_{max} ~ 2MJ **E reached: 4 MJ** **Pulse length: 6 sec** Graphite limiters, uncooled	P_{ECRH} ~ 5 MW 6 gyrotrons **6 gyrotrons in operation, 4.3 MW**	T_e^{NC} ~4 keV **8 keV** T_i^{NC} ~1 keV **>2 keV** n~2*10^{19} m^{-3} **5*10^{19} m^{-3}** $<\beta_{NC}>$ ~ 1% **$\beta_{central}$ >2.5 %** $<\beta>$ to be calculated
OP 1.2 2017 2*5 months	Pulse energy: E_{max} ~ 80 MJ Graphite divertor, uncooled	P_{ECRH} ~ 8 MW P_{NBI}^{H} ~ 7 MW P_{ICRH} ~ 1.6 MW	T_e^{NC} ~5 keV T_i^{NC} ~4 keV n ~ 1.6 x 10^{20} m^{-3} $<\beta_{NC}>$ ~ 3%
OP 2 2020	Pulse energy: E_{max} ~ 18 GJ =10MW for 30 minutes 20 MW for 10 seconds CFC water-cooled divertor	P_{ECRH} ~ 10 MW P_{NBI}^{D} ~ 10 MW P_{ICRH} ~ 4 MW **P_{tot} < 20 MW**	T_e^{NC} ~ 5 keV T_i^{NC} ~ 5 keV n ~ 2.4 x 10^{20} m^{-3} $<\beta_{NC}>$ ~ 5 %

Summary of other preliminary results

- Toroidal current measured (bootstrap and ECCD): up to 2 kA
- Confinement time of He in H plasmas ~ 5 seconds
- Confinement changes observed in power-step down experiments
- Electric field profiles measured
- SOL diffusion coefficients and λ_q studies started, D~0.5 m/s^2
- Successful ECRH wall-conditioning in He
- Efficient edge cooling also possible with targeted N injection
- Feed-forward density control successful
- On- and off-axis ECRH, heat pulse propagation studies performed

Conclusions

- Demonstrated good flux surfaces as expected, with error fields $\sim 10^{-5}$
- Managed to increase pulse lengths from initially 10 ms to 6 s
- As wall-conditioning improved, excellent plasma performance achieved:

  4 MJ: $T_e \sim 8$ keV, $T_i \sim 2.0$ keV, $n \sim 1$ to $5 * 10^{19}\ m^{-3}$, $\beta_c \sim 2.5\%$
- Successfully demonstrated functioning of the trim coils
- Confirmed predicted limiter heat load patterns in two limiter configurations
- Many well-diagnosed plasmas made; detailed analysis in progress.