Wendelstein 7-X

IPP Max-Planck-Institut für Plasmaphysik

Overview of first high-performance operation of Wendelstein 7-X with island divertor

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on behalf of the Wendelstein 7-X Team*

* author list in R. C. Wolf et al. Nuclear Fusion **57** 102020 (2017)

HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

EUROfusion

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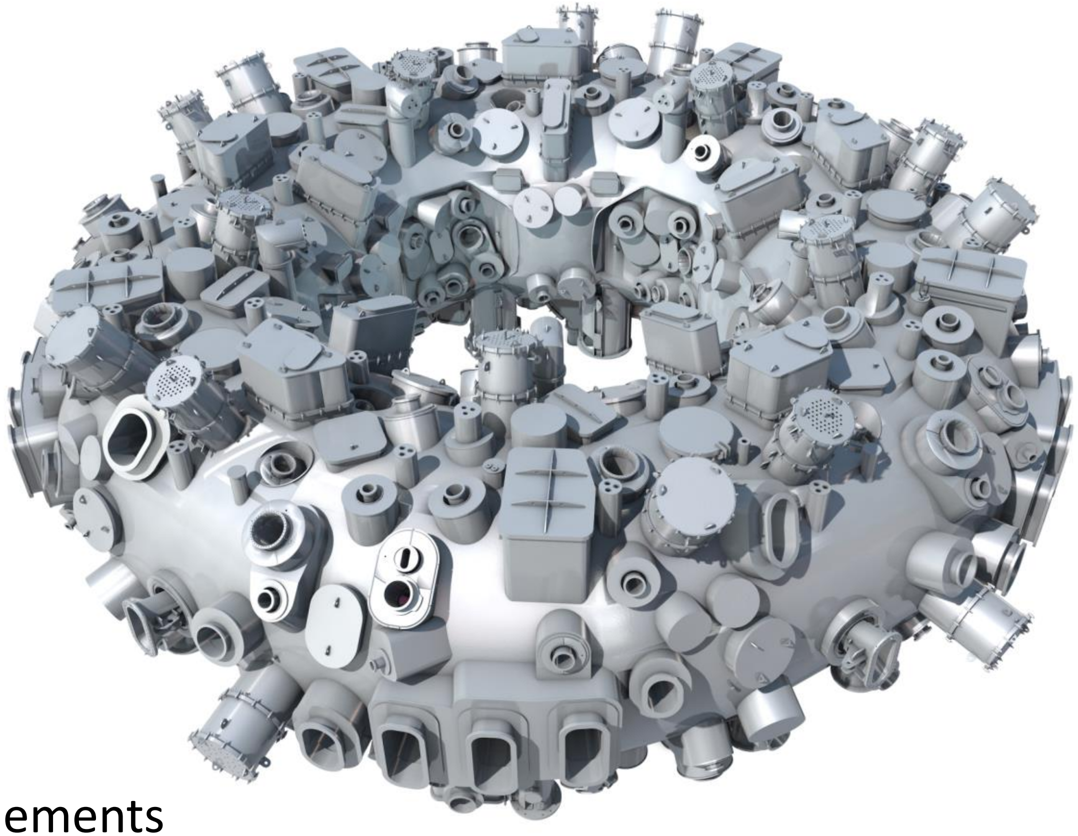
Major elements of Wendelstein 7-X

50 non-planar NbTi coils
5 types DC <18 kA

plasma 30 m^3

20 planar NbTi coils
2 types DC <16 kA



plasma vessel 80 m^3
265 m^2 in-vessel components

254 ports 120 shapes

4.5 m machine height
16 m machine diameter
735 t device mass
435 t cold mass 3.4 K

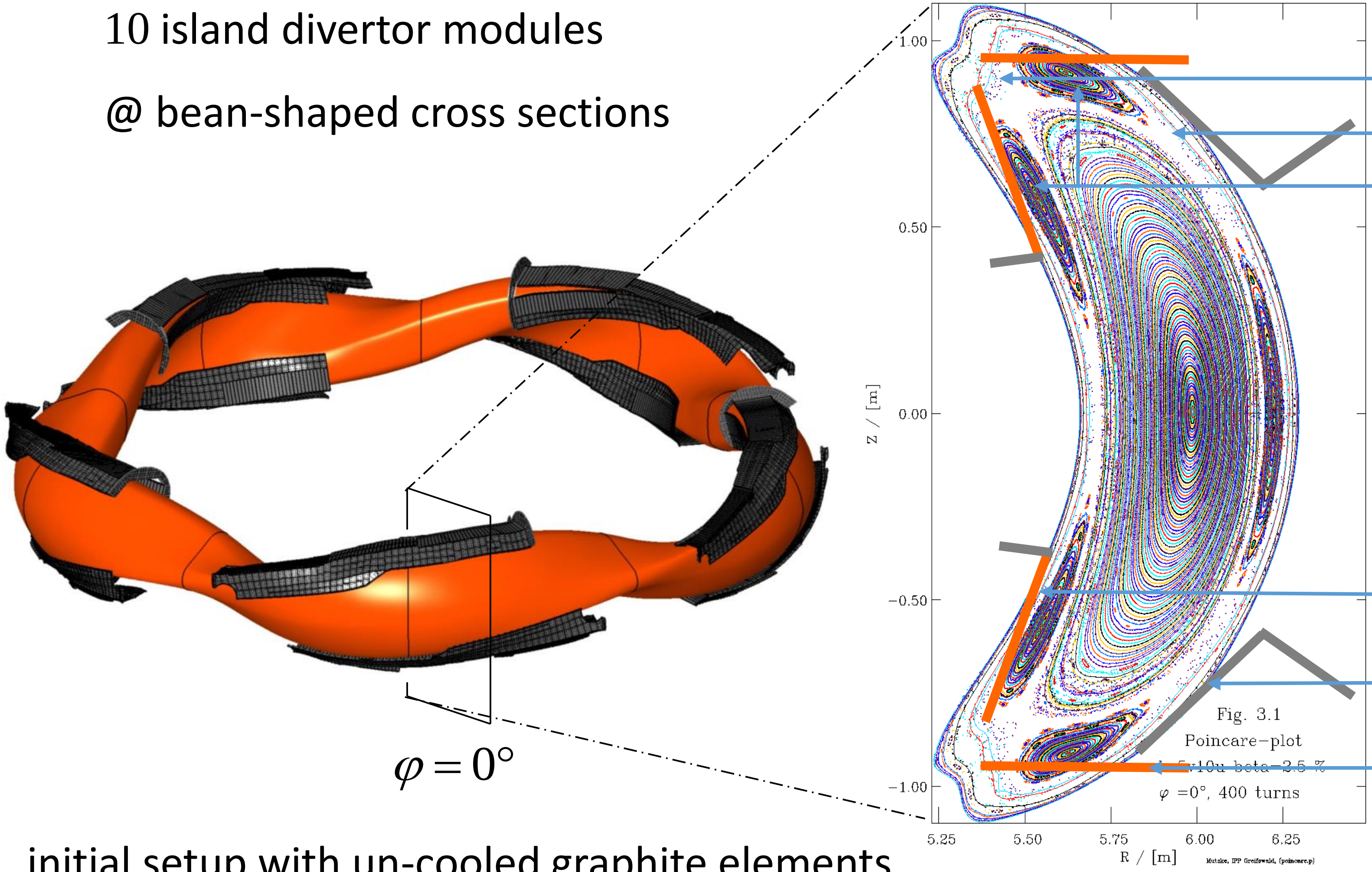
113 NbTi bus bars
14 HTSC current leads
about 1000 helium pipes
10 central support ring elements

cryostat vessel 420 m^3
thermal insulation

The island divertor concept

10 island divertor modules

@ bean-shaped cross sections



total target area 19 m^2

heat flux ≤ 10 MW/m^2

connection lengths ≤ 500 m

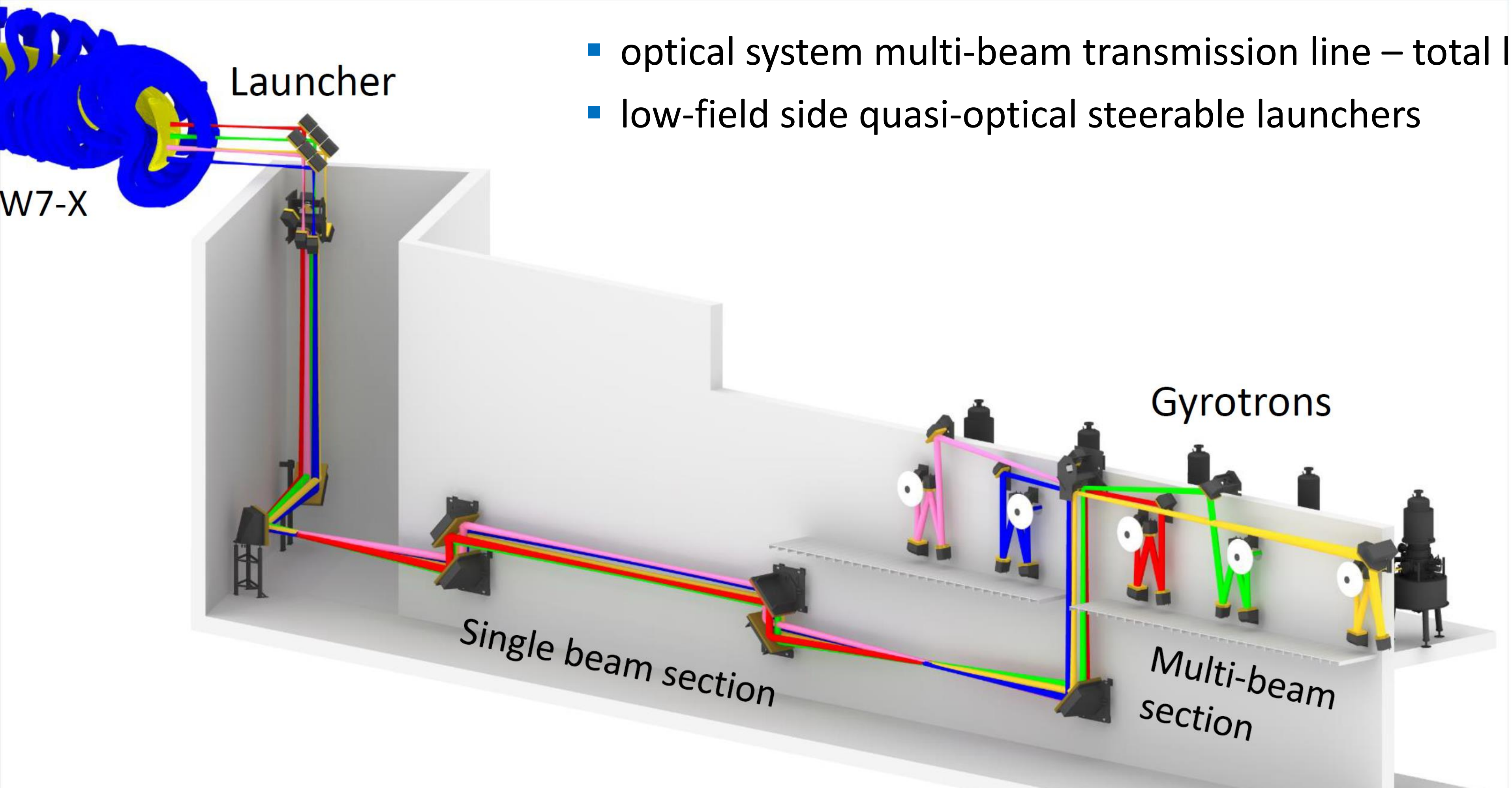
incidence angles 2-3°

initial setup with un-cooled graphite elements
future setup with water-cooled CFC elements

Electron cyclotron resonance heating

- 10 gyrotrons 140 GHz 2nd harmonic O and X polarization
- designed for 1800 s pulse length with output power 0.8 MW avg.

- optical system multi-beam transmission line – total loss ≤ 6%
- low-field side quasi-optical steerable launchers



Erckmann et al.
Fusion Science and Technol.
52 (2007) 291-312

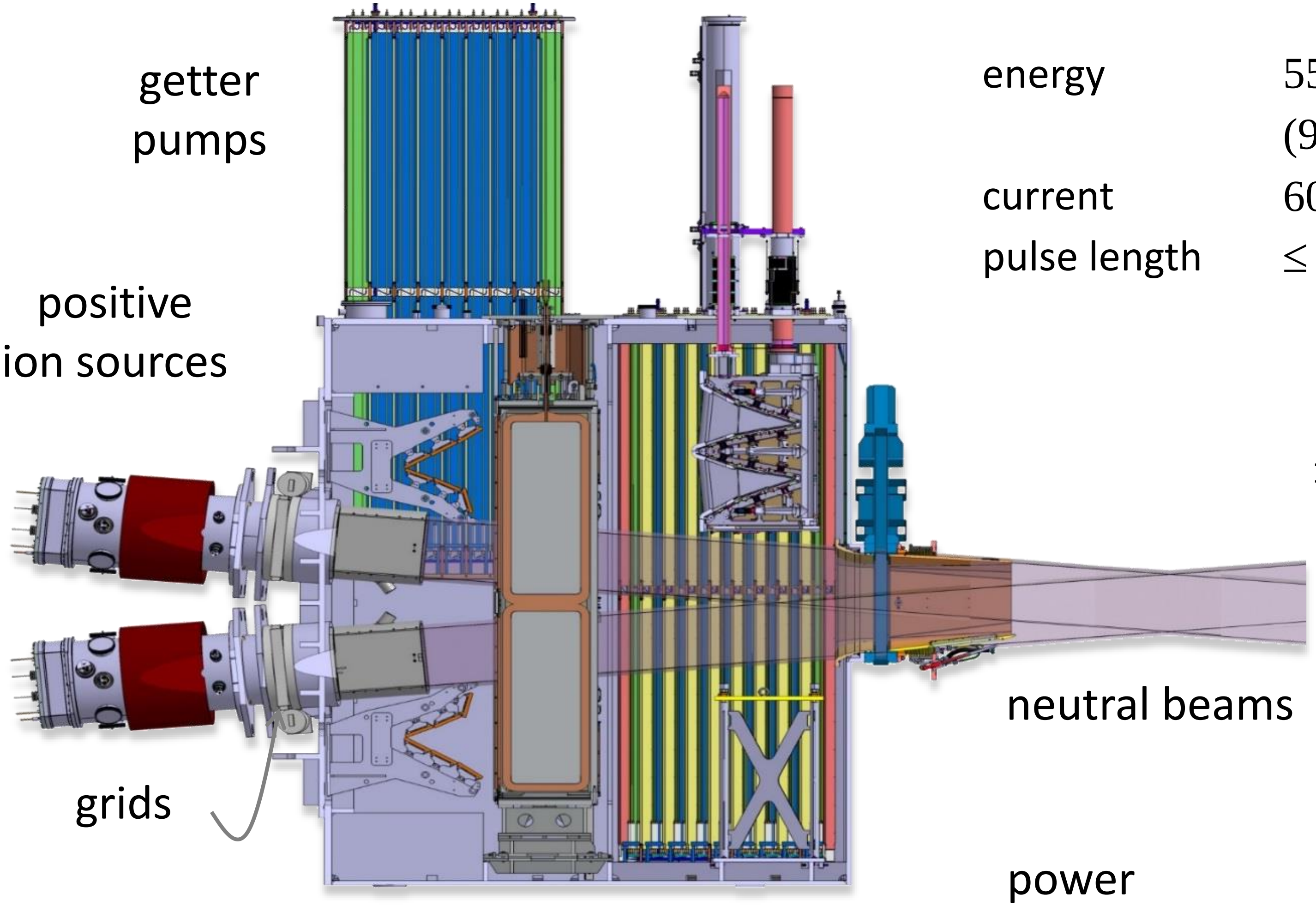
one of the two transmission lines

Neutral beam injection heating

getter pumps

positive ion sources

grids

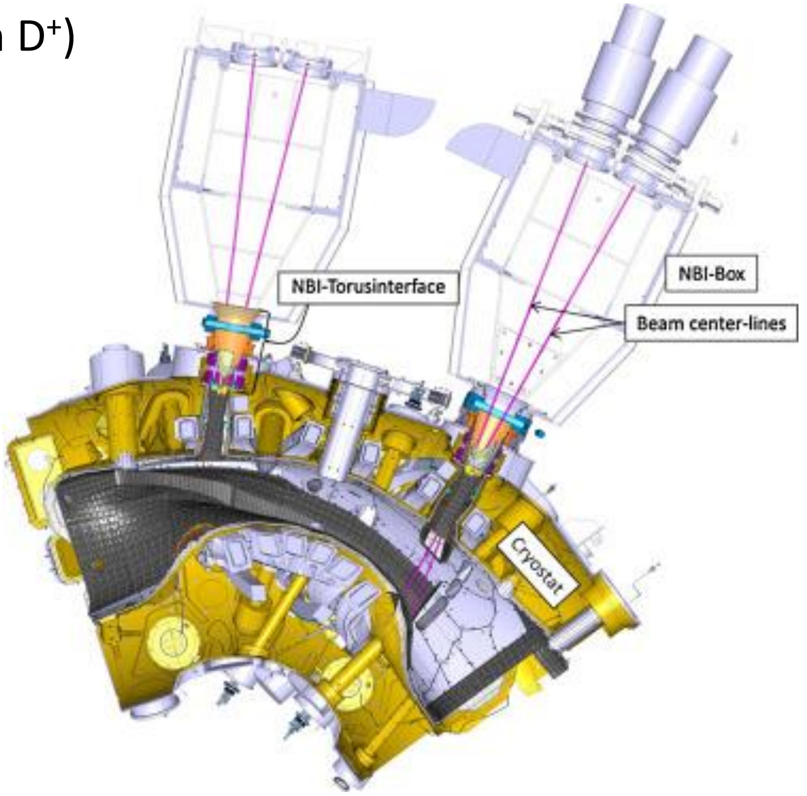


neutralization chamber

neutral beams

∓

energy	55 keV in H^+ (93 keV in D^+)
current	60-80 A
pulse length	≤ 10 s

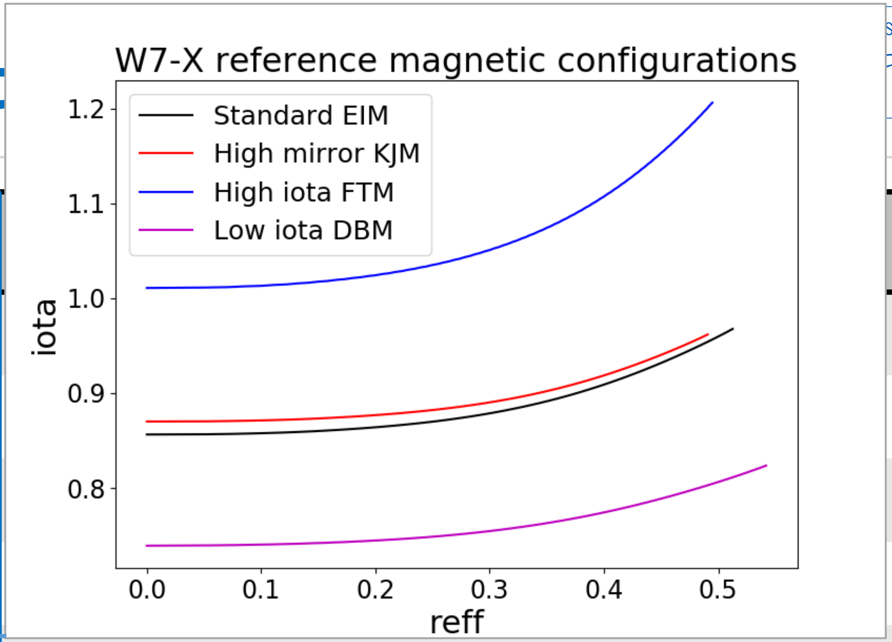


power 3.5 MW in H^+

one injector box with two sources

Nocentini et al.
Fusion Engineering and Design
100 (2015) 453-460

Wendelstein 7-X device and operat



quantity	unit	stage 1	stage 2			
plasma volume	m^3	30				
major radius	m	5.5				
minor radius	m	0.5				
magnetic induction	T	2.5				
rotational transform	2π	5/6 … 5/4				$1/q$
ECRH power	MW	4.3	8.5	10	10 (15)	1 (1.5) MW gyrotrons
NBI power	MW		3.5	7/10	14/20	H/D 60 keV $\leq$ 10 s
ICRH power	MW			1.5	3.5	25-38 MHz $\leq$ 10 s
heating energy	MJ	4	200	1000	18000	max heat loads
typical pulse length	s	1-2	10-100	100-200	100-1800	typ-max
		operation phase 1.1	operation phase 1.2	operation phase 2.1	operation phase 2.x/3	

Stellarator (physics) optimisation

reduced neoclassical transport
@ low-collisionality 1/ν -regime

improved fast particle confinement
drift orbits of helically trapped particles

classical stellarator issues

1. poor confinement at high temperatures
2. loss of fast (non-thermal) particles
3. strong Shafranov shift of the magnetic axis
4. pressure driven stability limits
5. lack of divertor concept

good finite equilibrium properties
reduced PS current & Shafranov shift

good MHD stability properties
ballooning and Mercier stable

reduced bootstrap current
stable and robust equilibrium

good modular coil feasibility
acceptable curvature and shear stress

nested vacuum magnetic surfaces
low-order natural islands @ edge

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   equilibrium, stability, global confinement, impurity transport, turbulence
3. **Island divertor operation**
   power deposition, power exhaust, pumping, radiation, detachment

a. **Overall performance assessment**

b. **Conclusions and way forward**

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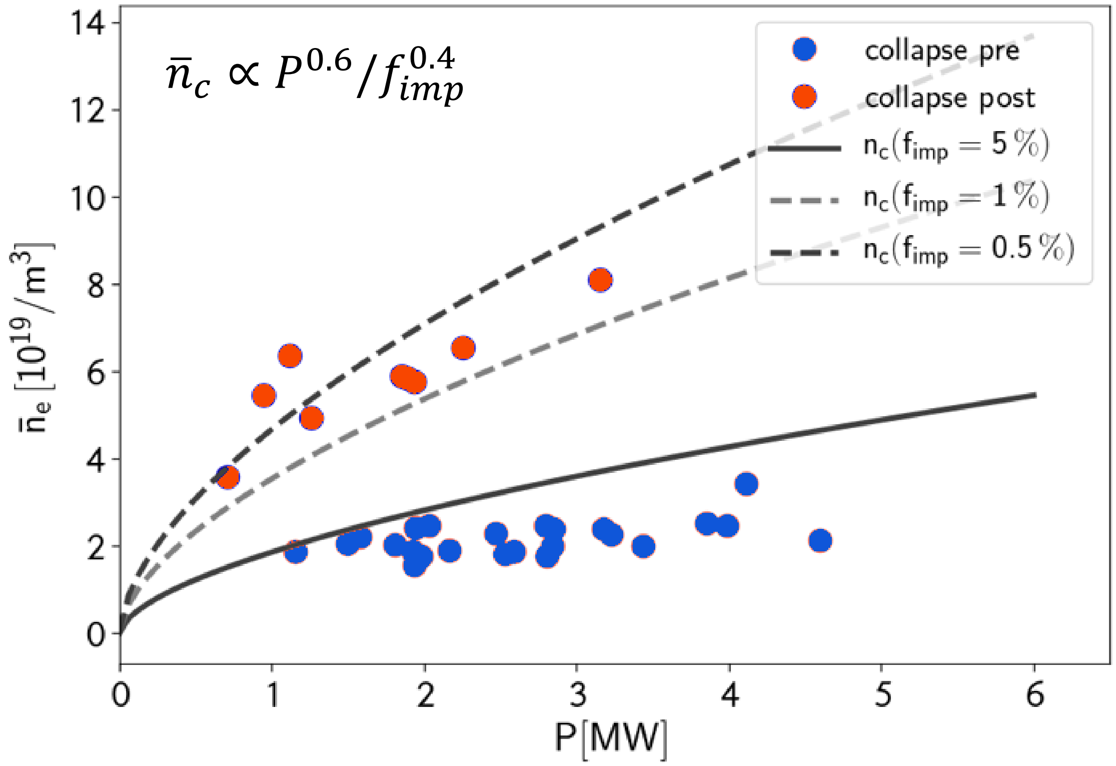
Radiative density limit – role of wall conditioning



boronization broadens the operation window

critical density for radiation collaps increased by ×3

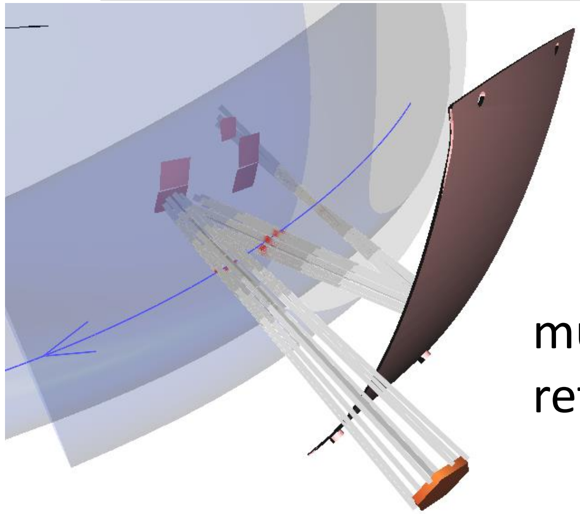
O radiation reduced by ×10
C radiation reduced by ×5

very close to the critical density the energy confinement τ_E deterioates

R. Brakel EX/P8-17

G. Fuchert EX/3-5

Electron cyclotron resonance heating above X2 cut-off



only 70% single beam O2 absorption (at 10^{20} m^{-3} and 3 keV)

multi-pass absorption/w reflection at tiles & panel

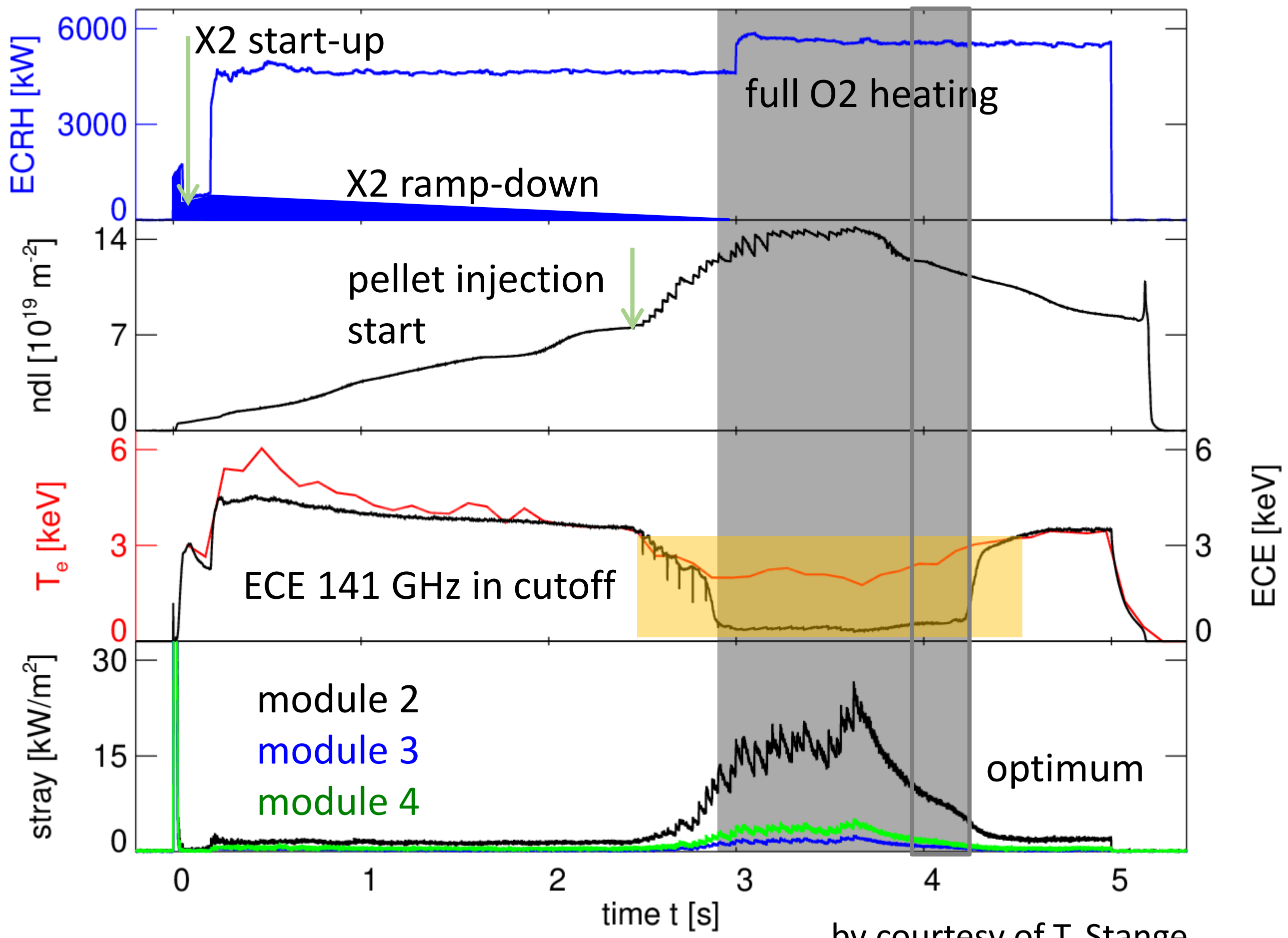
cut-off limits

ECR X2 heating $n_e < 1.2 \cdot 10^{20}$ m^{-3}

ECR O2 heating $n_e < 2.4 \cdot 10^{20}$ m^{-3}

ECE and TS

stray radiation < 20 kW/m^2



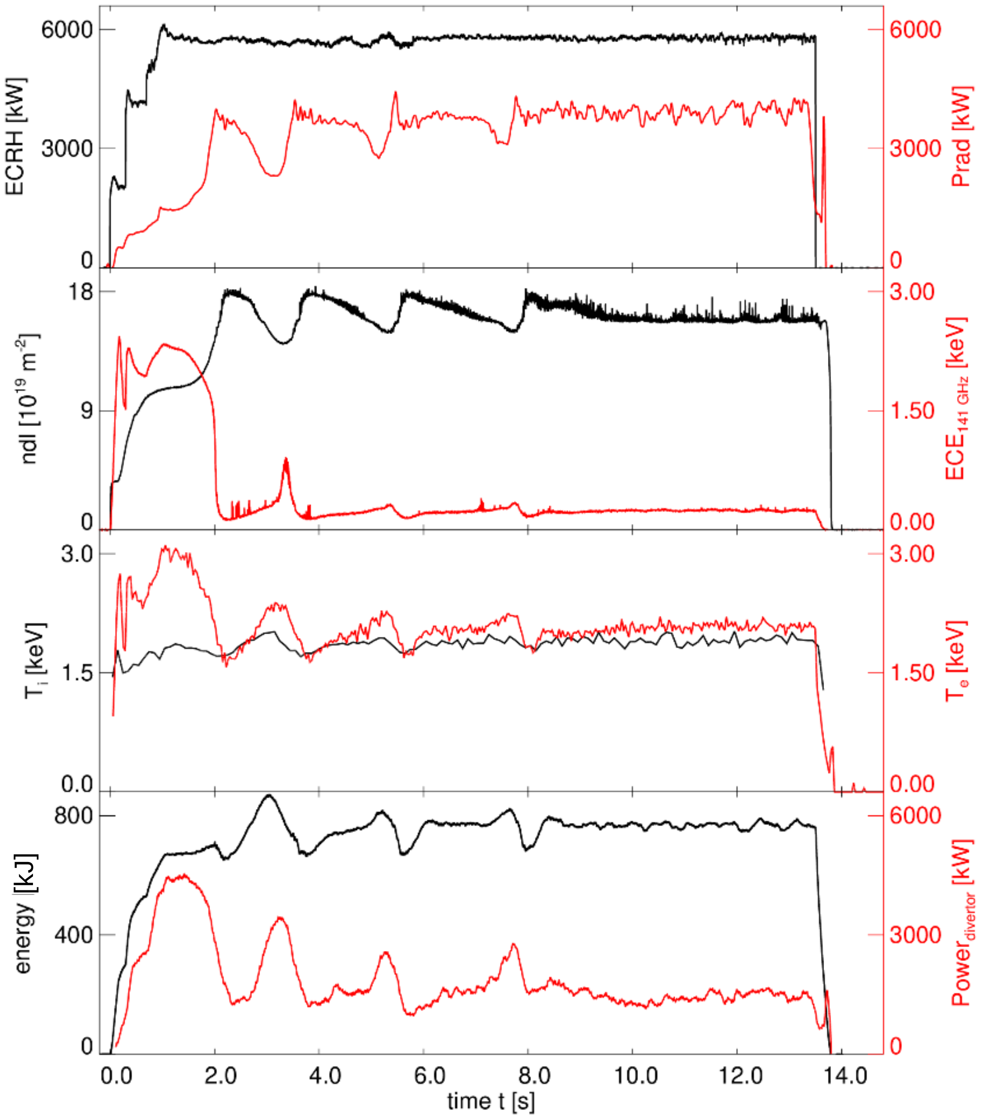
by courtesy of T. Stange

OXB mode conversion schemes under development

Aleynikov TH/P4-6

H. Laqua EX/P8-28

Long pulse high density plasmas



O2 ECR heating with 6 MW power
with nine gyrotrons operating
radiative power fraction ~60 %

$1.6 \cdot 10^{20}$ m^{-2} line-integrated density
10 s flat-top full density control

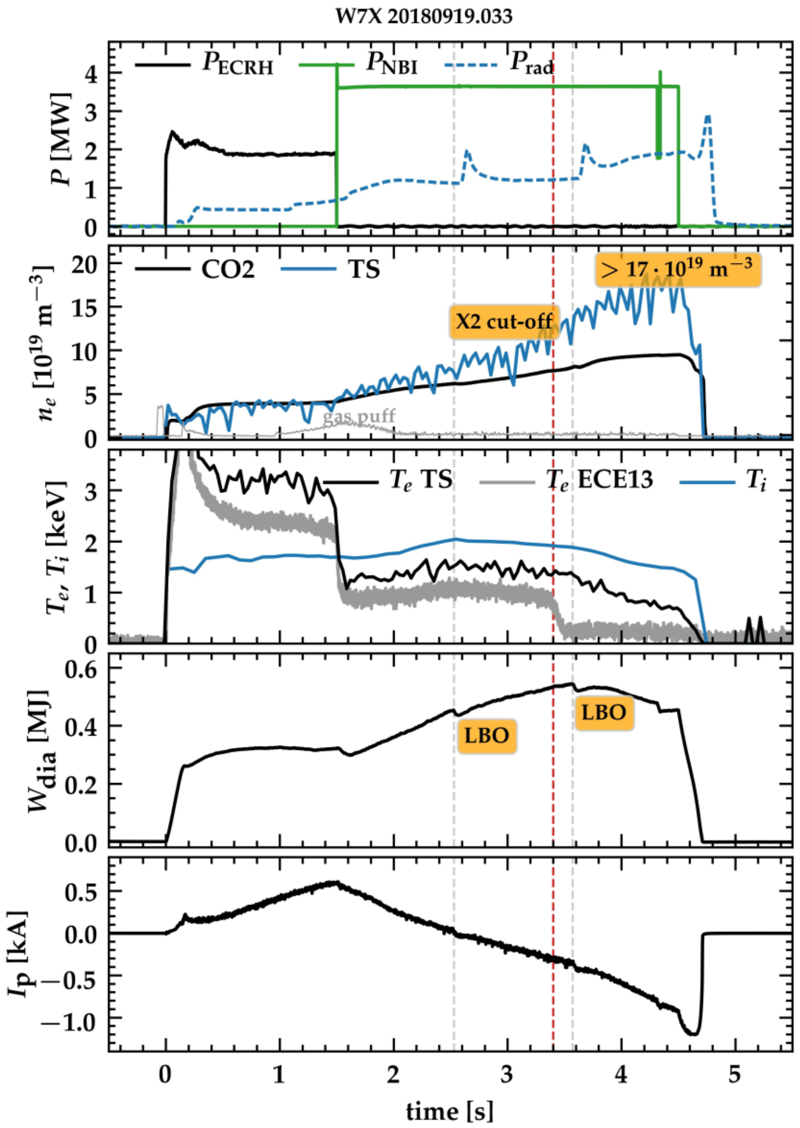
1.8 keV central electron temperature
1.8 keV central ion temperature

800 kJ diamagnetic energy
only 1.5 MW total divertor load
in full detachment

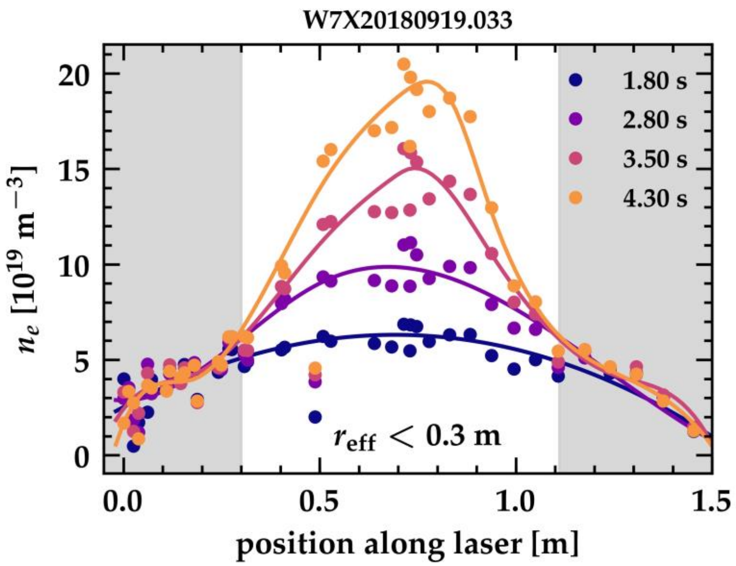
reference scenario

H. Laqua EX/P8-28

NBI heated discharges with high density



- pure NBI heating can sustain plasma
- stabilization of ion heating w/o ECRH



- centrally peaked high density plasma core
- density peaking can be controlled by additional ECRH
- pure NBI heating with $n_{peak}(0)=2\cdot10^{20}\,\mathrm{m}^{-3}$ demonstrated

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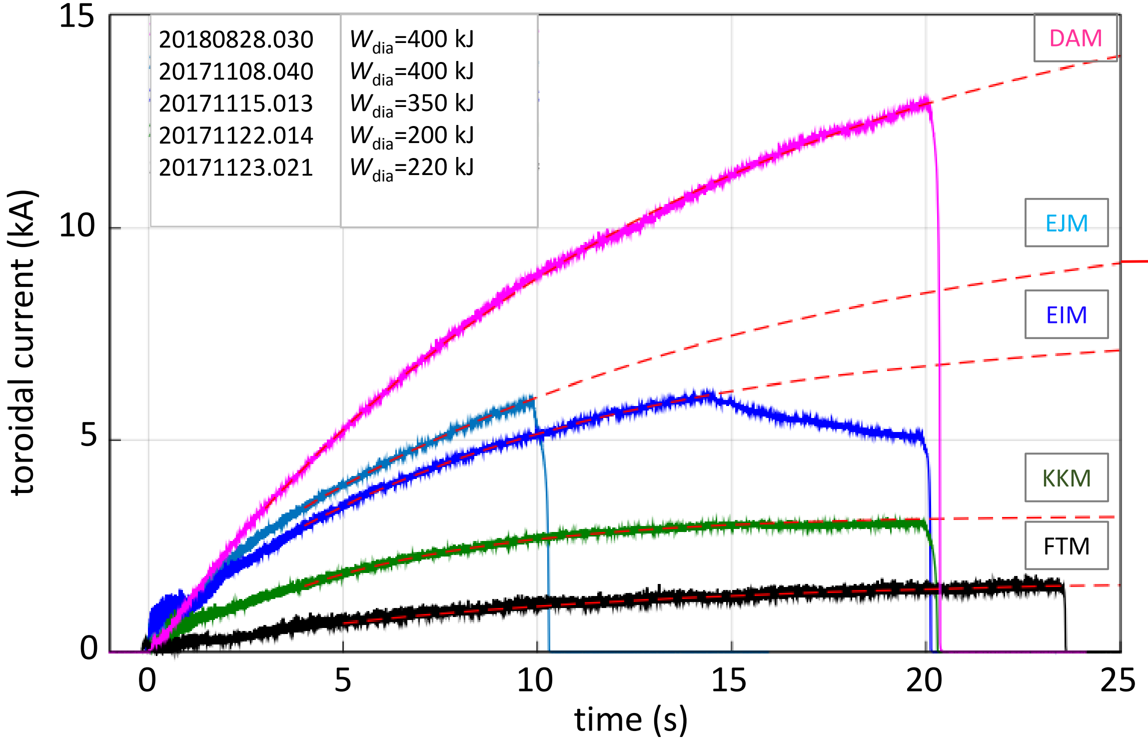
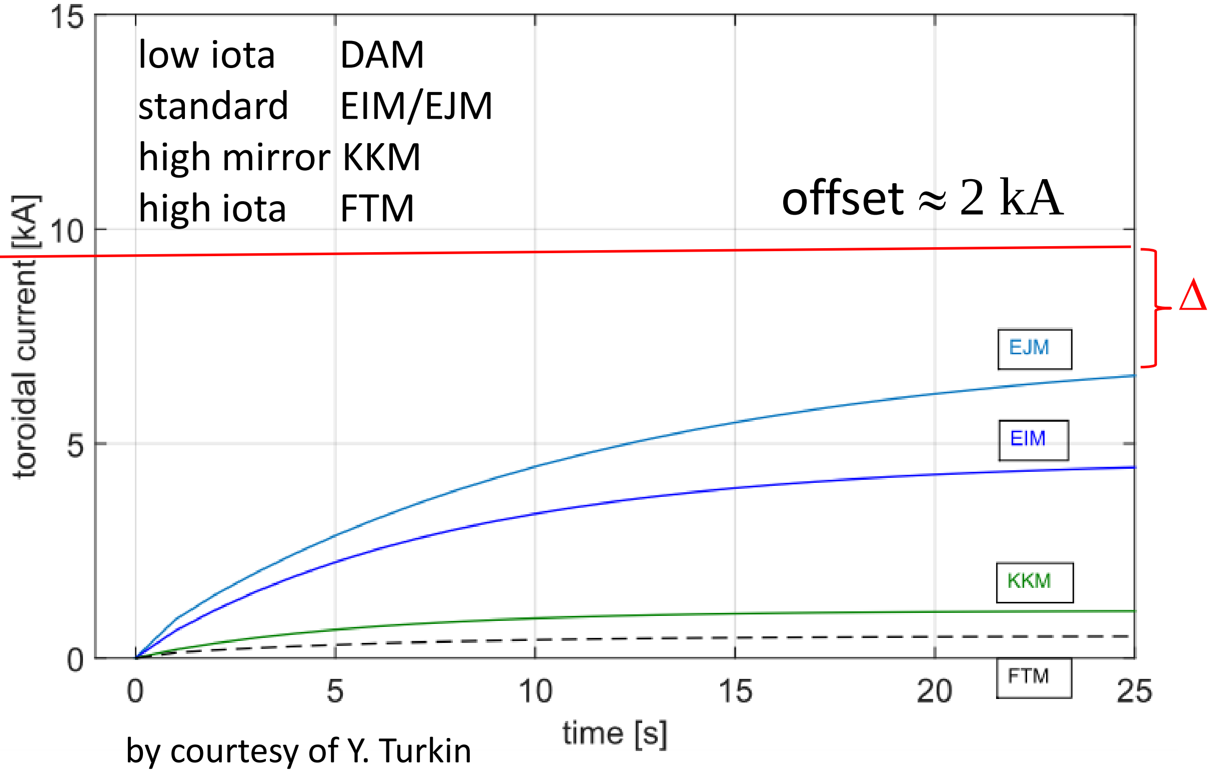
Toroidal plasma current

Rogowski coil measurement



by courtesy of K. Rahbarnia

1d transport modelling



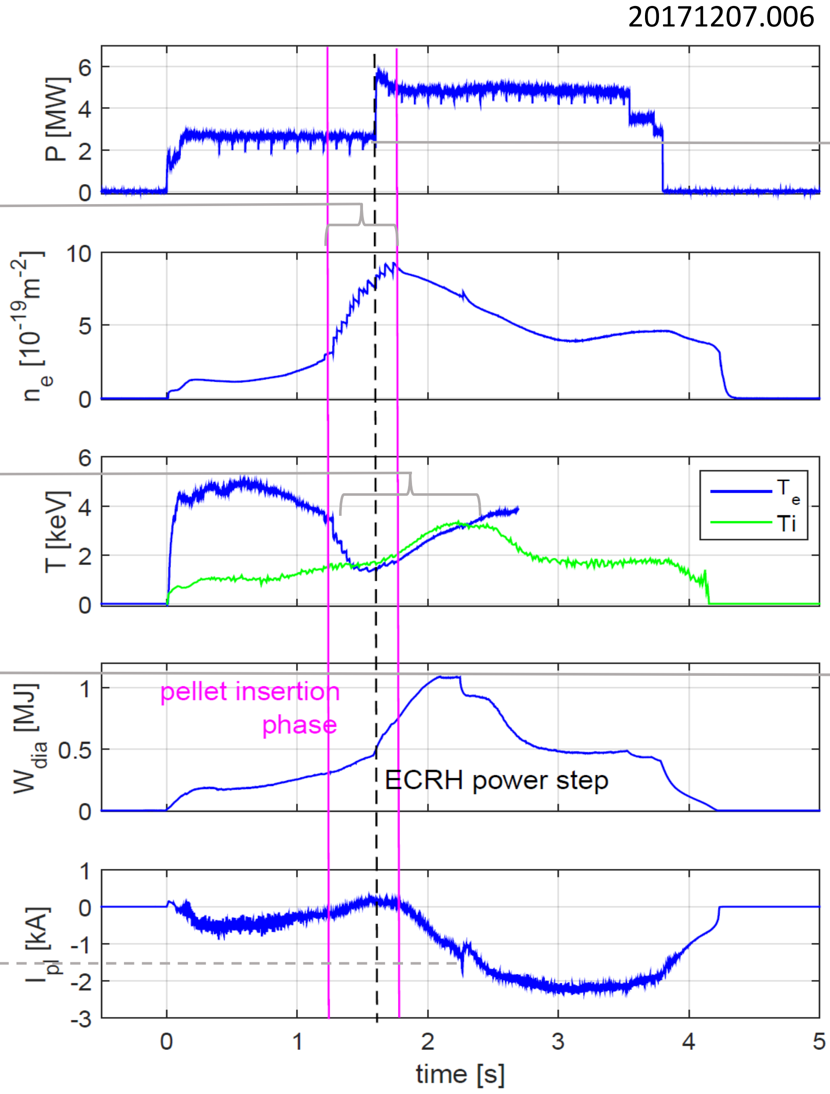
by courtesy of Y. Turkin

$$I(t) = I_{BS}(1 - e^{-(t-t_0)/\tau})$$

bootstrap current shielding current

good agreement with transport simulation
but current offset due to ECCD contribution?

A record high performance plasma



X2 ECRH power doubled

hydrogen pellet injection into helium target plasma

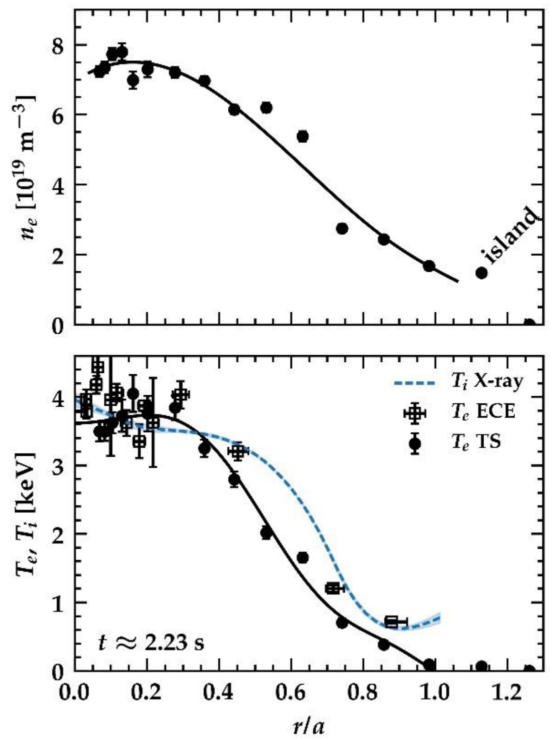
record triple product $\geq 0.6 \cdot 10^{20}$ keVs/m^3

thermalization $T_e = T_i$

diamagnetic energy $\geq$ 1 MJ

MHD event

by courtesy of S. Bozhenkov

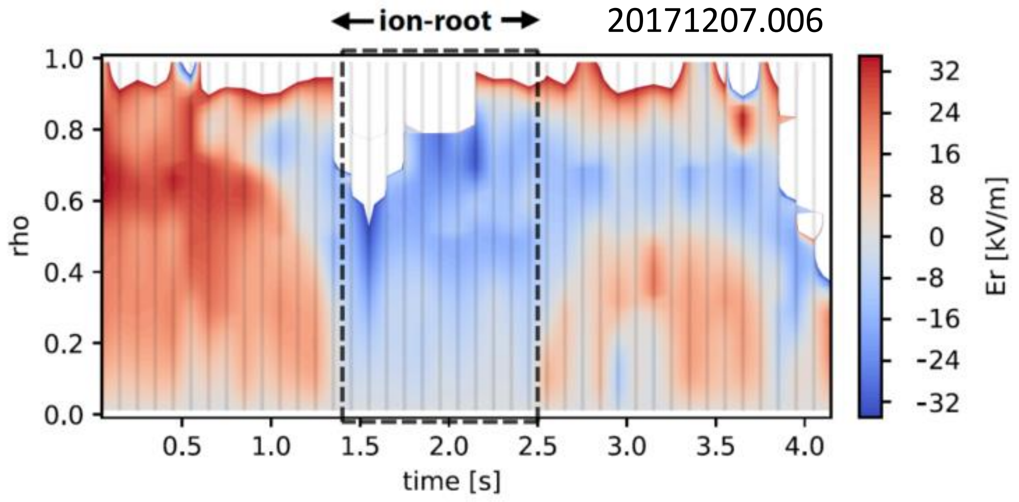


S. Bozhenkov EX/P8-8
O. Grulke EX/P8-9

Neoclassical transport and plasma equilibrium

the ambipolarity condition in a stellarator yields multiple roots (electron-, ion-root)

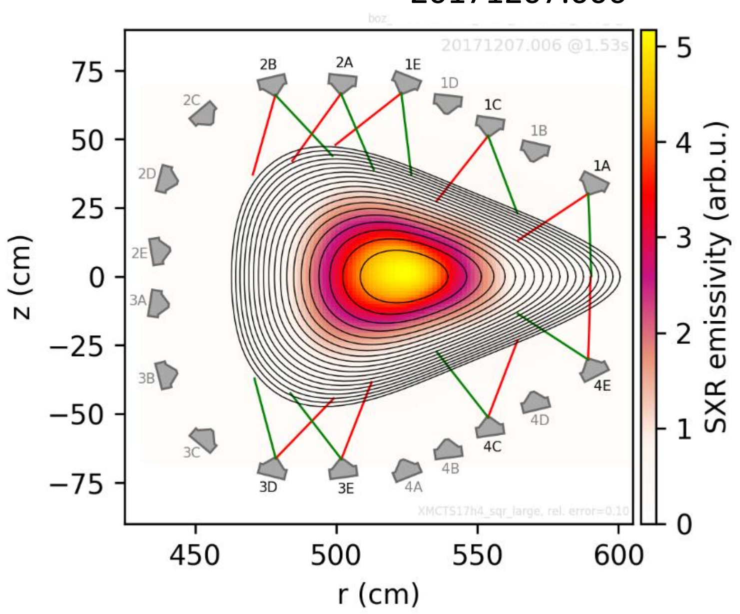
radial electric field measured with XICS



by courtesy of N. Pablant

at T_e=T_i the ion root with $E_r < 0$ is established

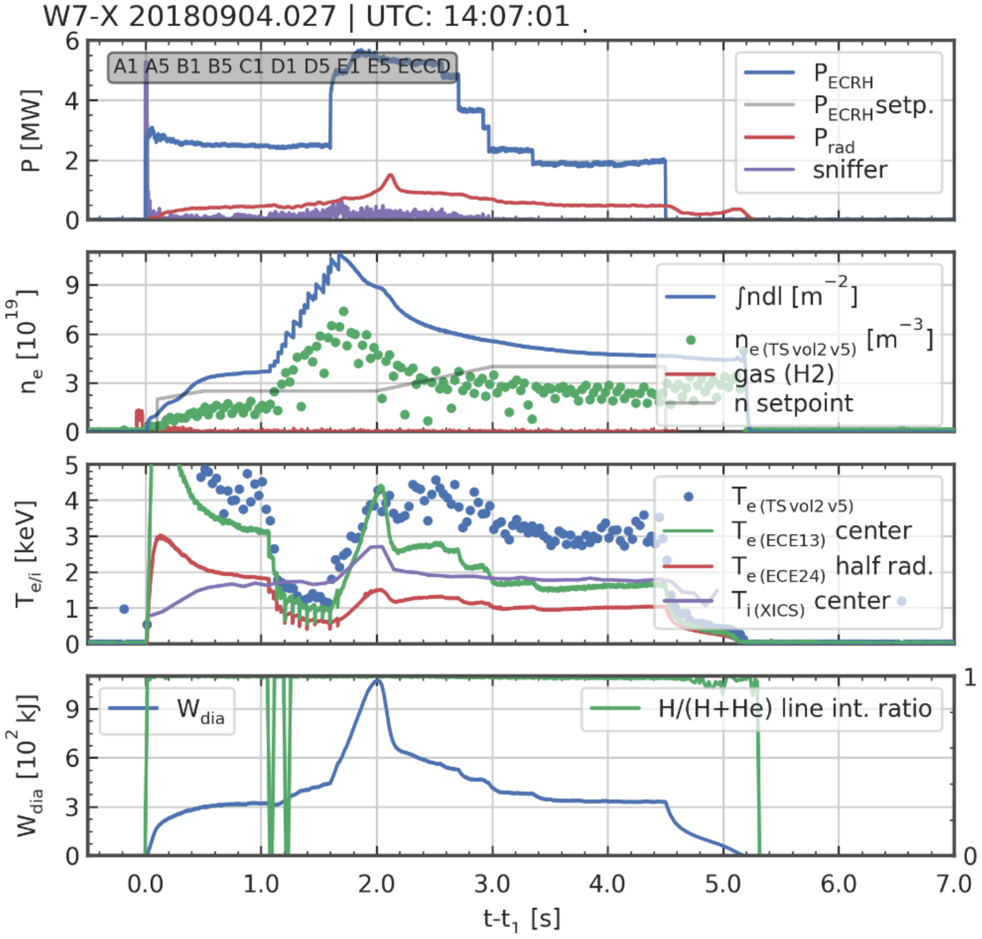
plasma equilibrium obtained with the X-ray tomographic multi camera system



by courtesy of C. Brandt

- good agreement with VMEC calculations
- Shafranov shift of only 1-2 cm at $\langle\beta\rangle$=1%

Phase contrast imaging of core turbulence



$< t < t_2$ and $t > t_4$

uctuation amplitude $\propto$

ıe integrated density

$< t < t_3$

ter pellet injection

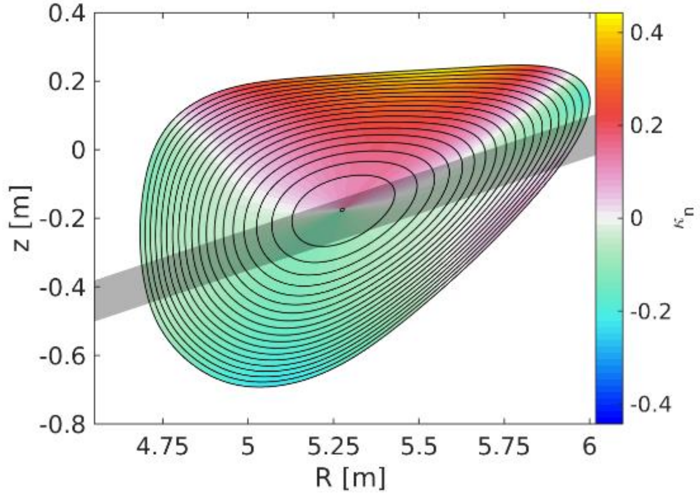
ırbulence suppression

$< t < t_4$

ɔectrogram shows

equency chirping

phase contrast imaging yields density fluctuations



IR laser beam along unfavourable magnetic curvature $\rightarrow$ ITG, TEM

pellet injection moves density gradient inward and $L_n \approx L_{Ti}$

density profile in the core flattens $t > t_3$ chirping mode transient

O. Grulke EX/P8-9
R. Kleiber TH/P2-4
E. Sanchez EX/P1-11

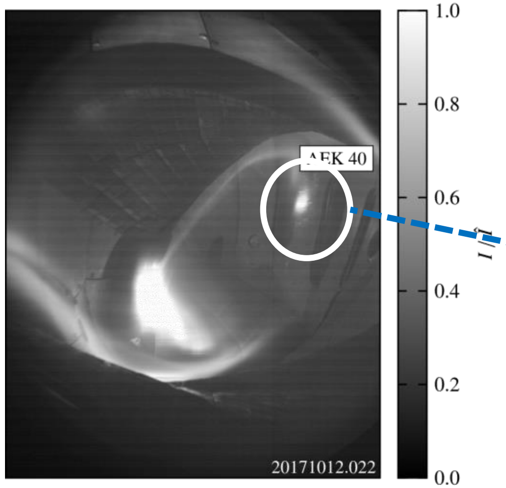
by courtesy of A. von Stechow

Impurity transport studies with laser blow-off

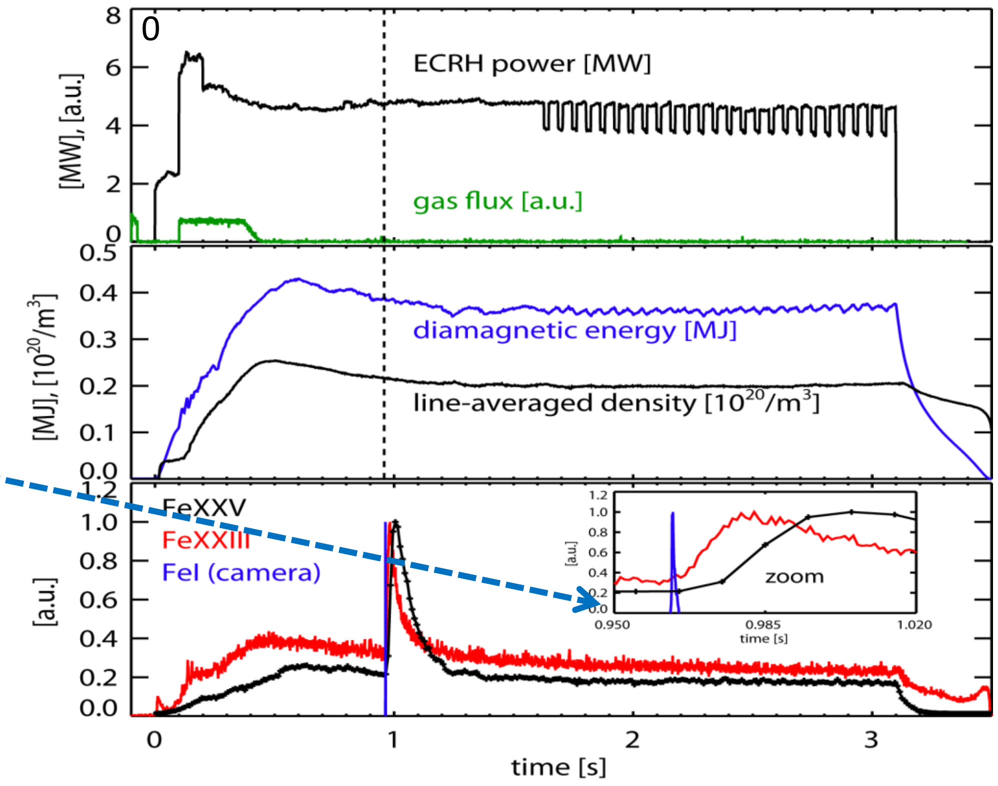
laser blow-off (LBO)

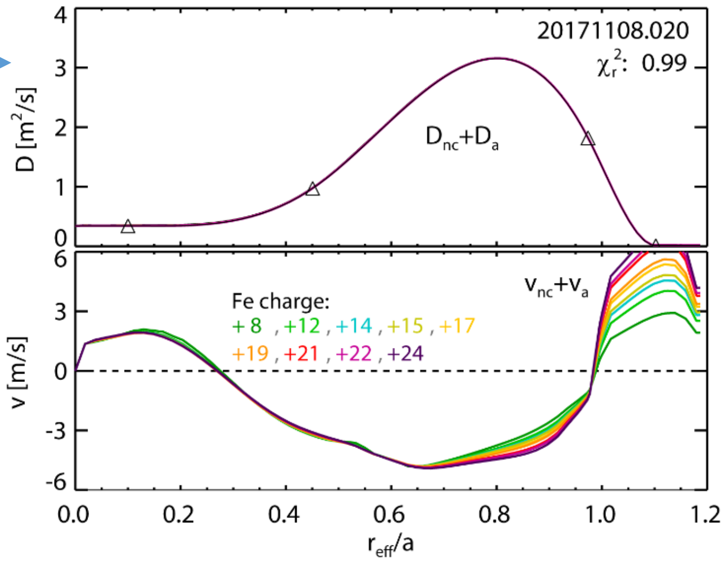
Nd:YAG laser 20 Hz
1064 nm 1J @ 6 ns

Al, C, Fe, Mo, Si, Ti, W
approx. 10^{16} particles



forward modelling (fit)
based on the STRAHL code





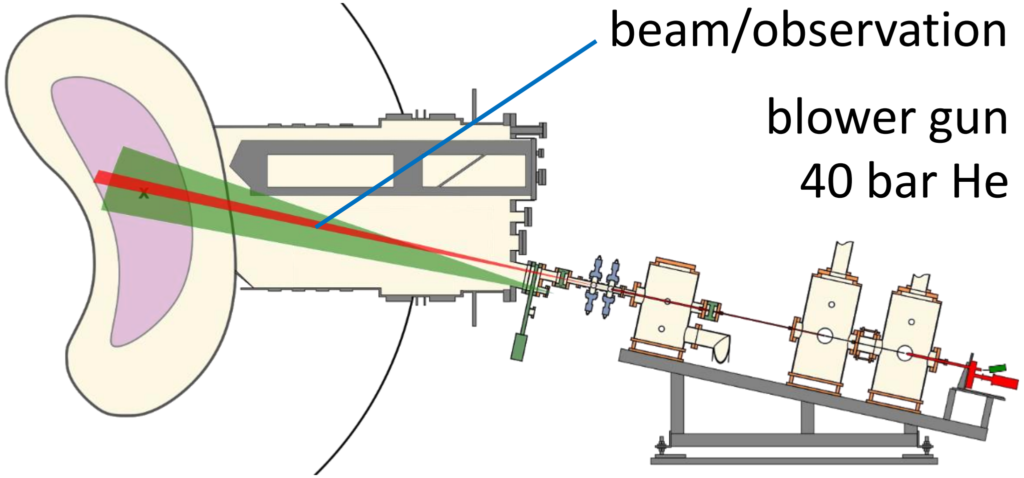
strong anomalous diffusion
> 100 × neo-classical value

time evolution of
successive ionization levels

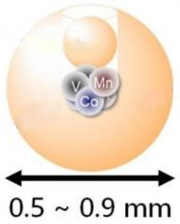
Impurity transport in the core and in the edge plasma

TESPEL = tracer-encapsulated solid pellet

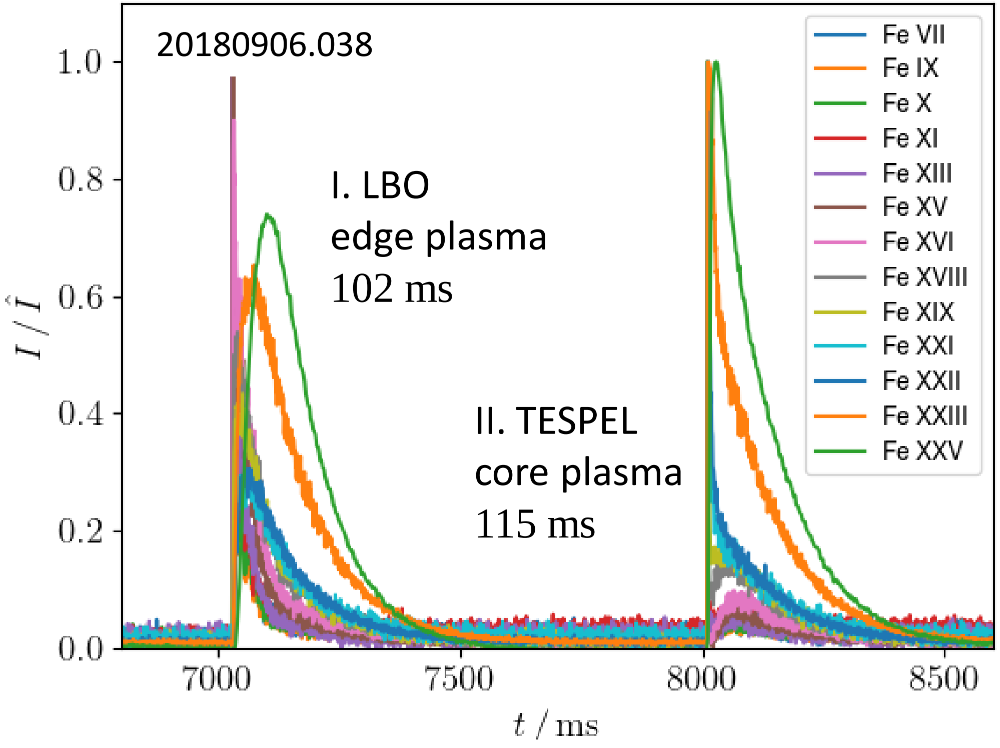
R. Bussiahn, N. Tamura et al. Rev. Sci. Instrum. **89**, 10K112 (2018)



polysterene shell 0.5 – 0.9 mm
metal core Al, V, Fe, Mn, W, …
200 – 500 m/s with 3 min repetition rate



by courtesy of B. Buttenschön and R. Bussiahn



subsequent LBO and TESPEL injection
similar impurity transport times ~100 ms

TESPEL and LBO provide complimentary information on impurity transport

O. Grulke EX/P8-9
A. Dinklage EX/P8-30

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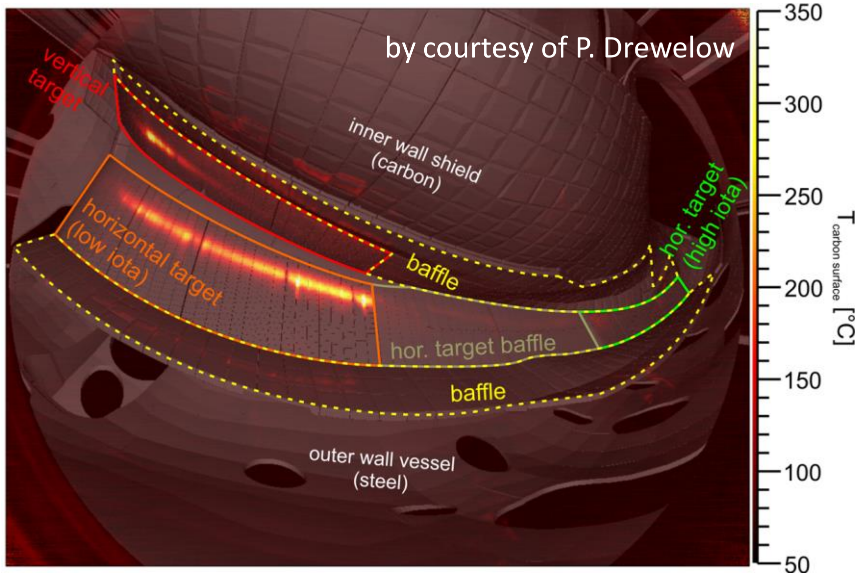
Divertor heat flux

10 high resolution IR cameras



asymmetry toroidal ≤ 40 / 25% (trim coils)
up/down ~ 10-20%

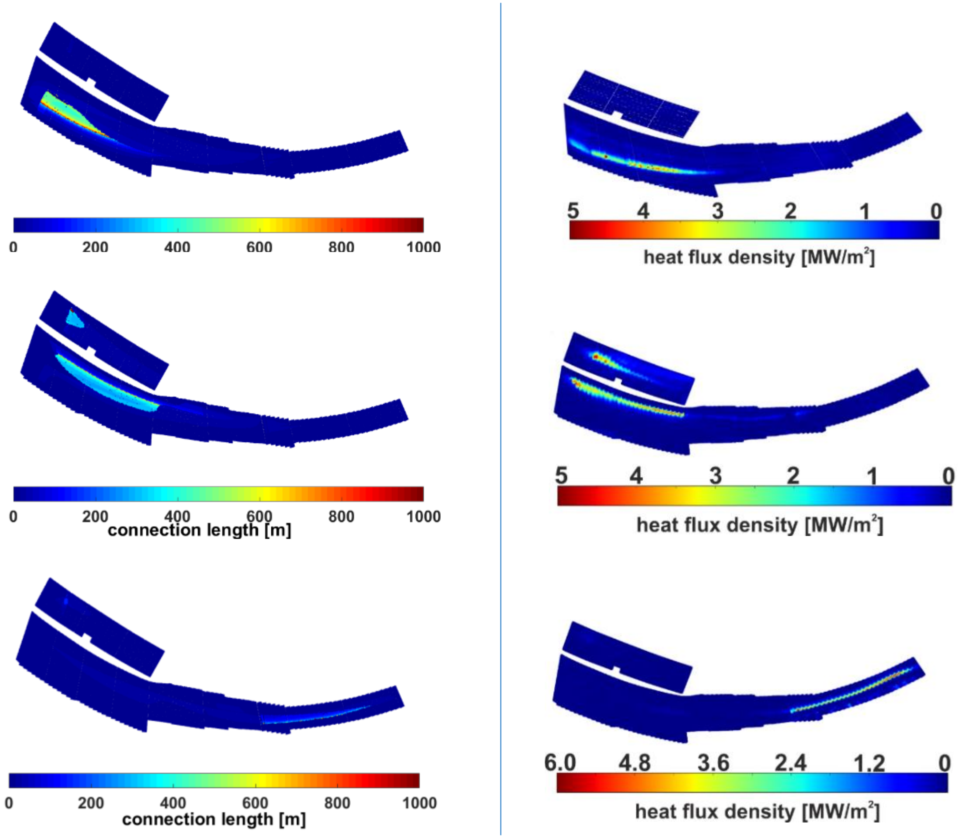
power fall-off length $\lambda_q = 15 \ldots 30$ mm
power wetted area $A_{wet} \sim 1.2$ m^2

connection length | thermography

low-iota

standard

high-iota

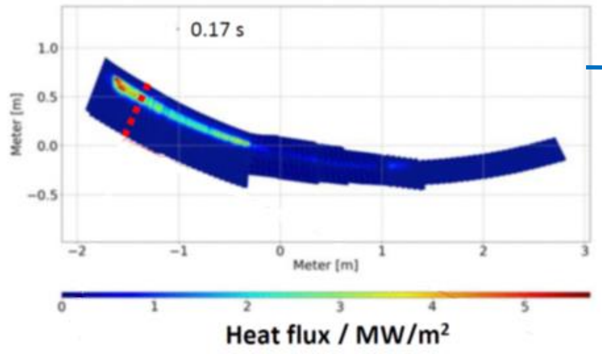


strike line position controllable with coils and ECCD

T. S. Pedersen EX/9-1
C. Killer EX/P8-18
F. Schluck TH/P1-5

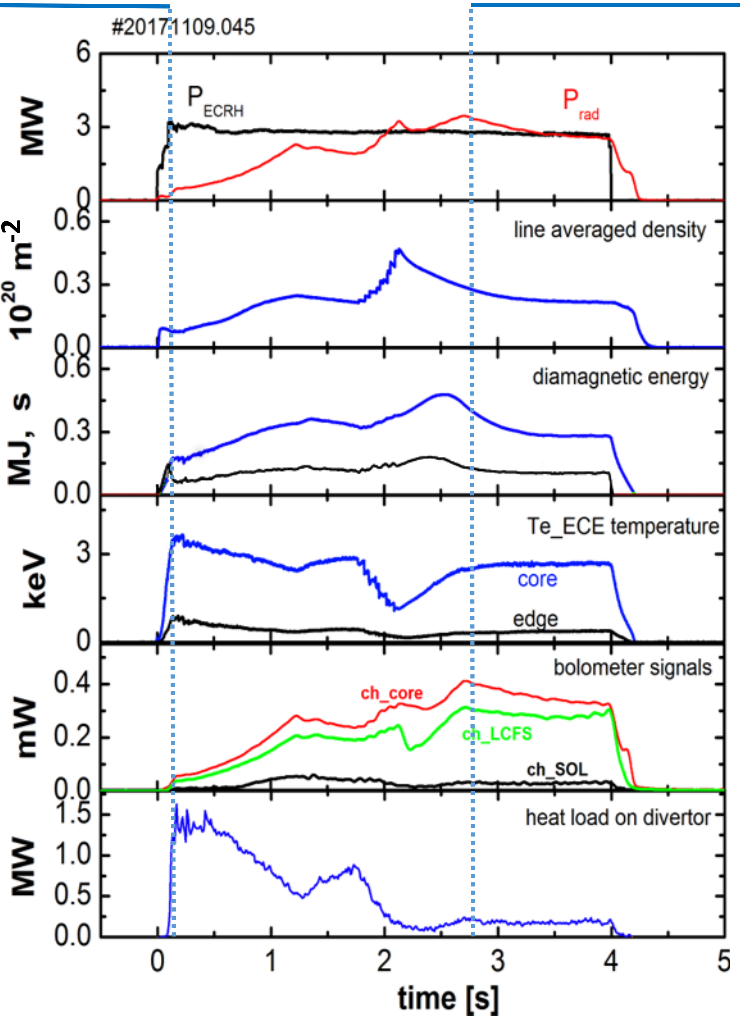
M. Jakubowski EX/P8-16
H. Laqua EX/P8-28

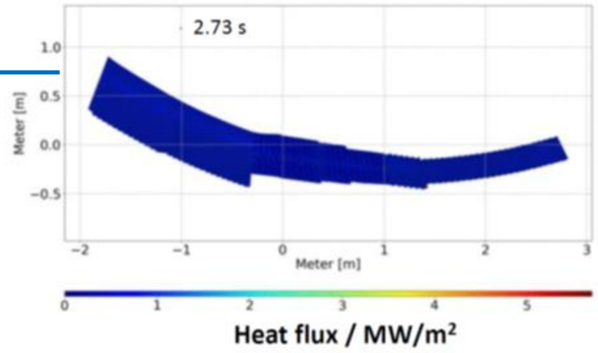
Power detachment



before detachment

detachment by pellet injection

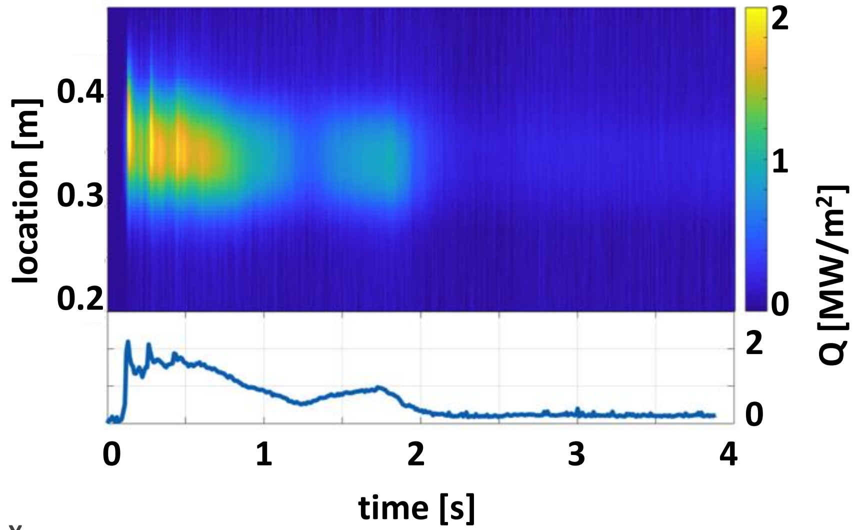




after detachment

H pellet injection into He
density ramp-up
to 4-5·10^{19}m^{-2}

time evolution of heat flux

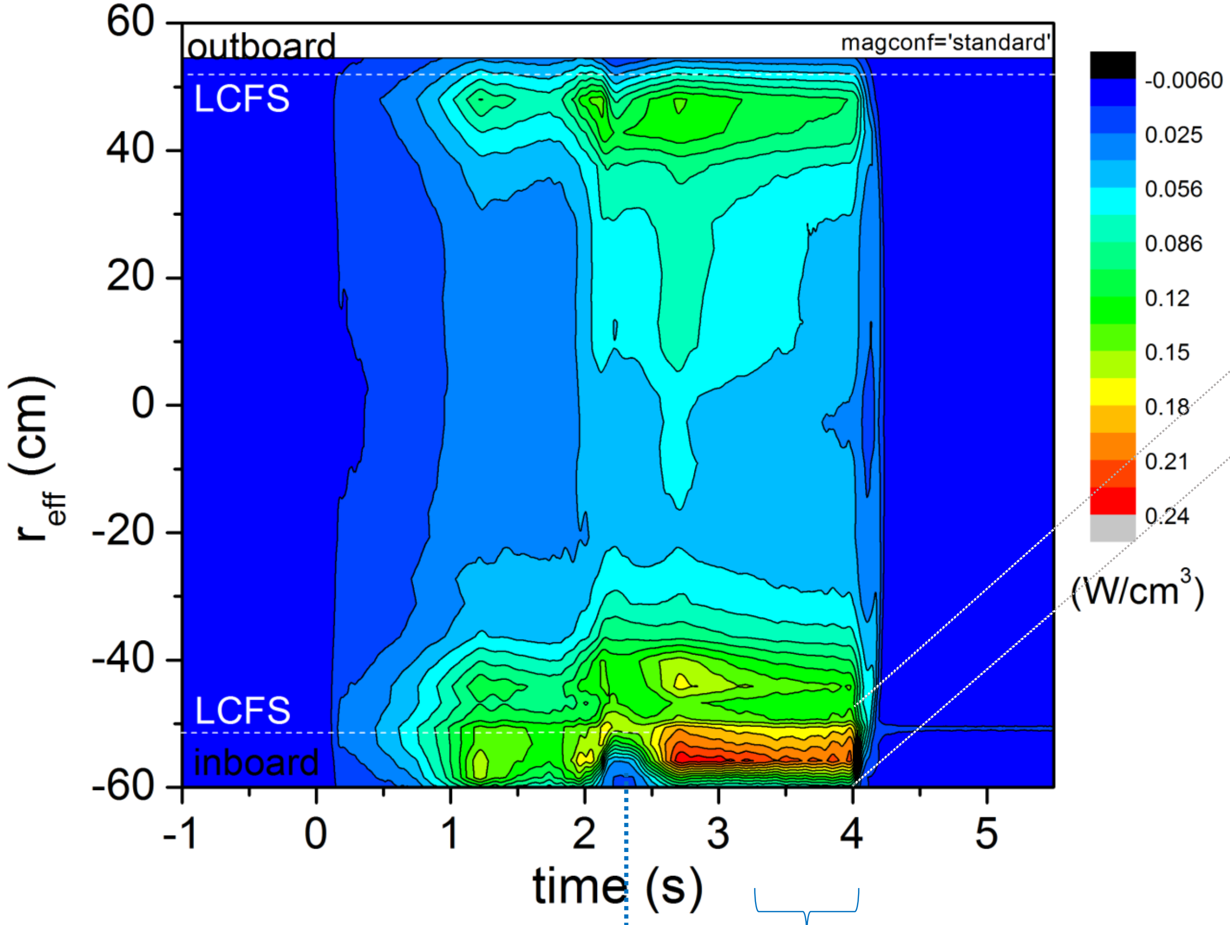


power load drops to ~ zero

T. S. Pedersen EX/9-1
M. Jakubowski EX/P8-16

Radiation during detachment

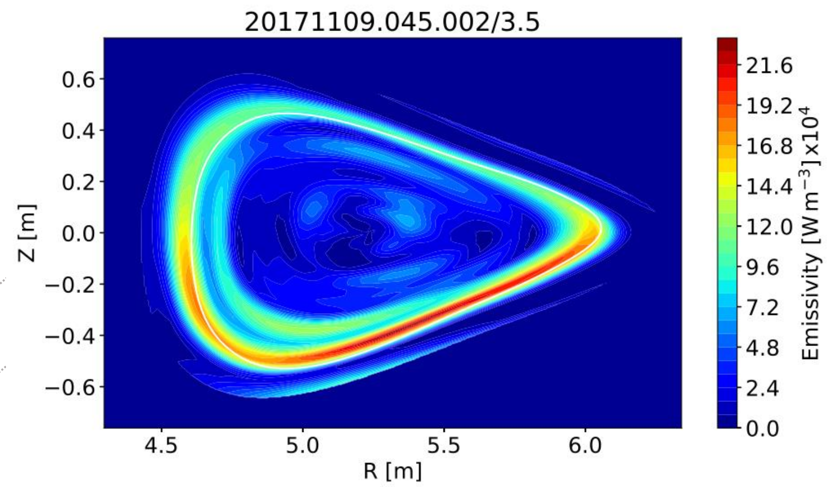
20171109.045 by courtesy of D. Zhang



pellet injection

$6\times\tau_E$

tomographic reconstruction



by courtesy of S. Kwak

radiation at the separatrix

constant plasma conditions (n, T_{ei}, W_{dia}, P_{rad})

$P_{rad}/P_{ECRH} \approx 95\%$

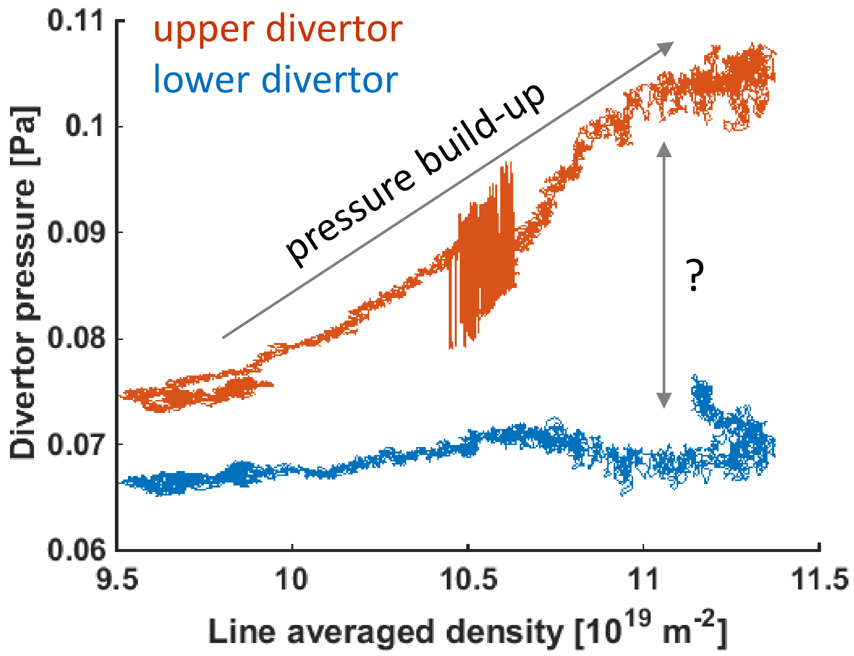
$\tau_E \approx 0.1$ s not degraded w.r.t. ISS04

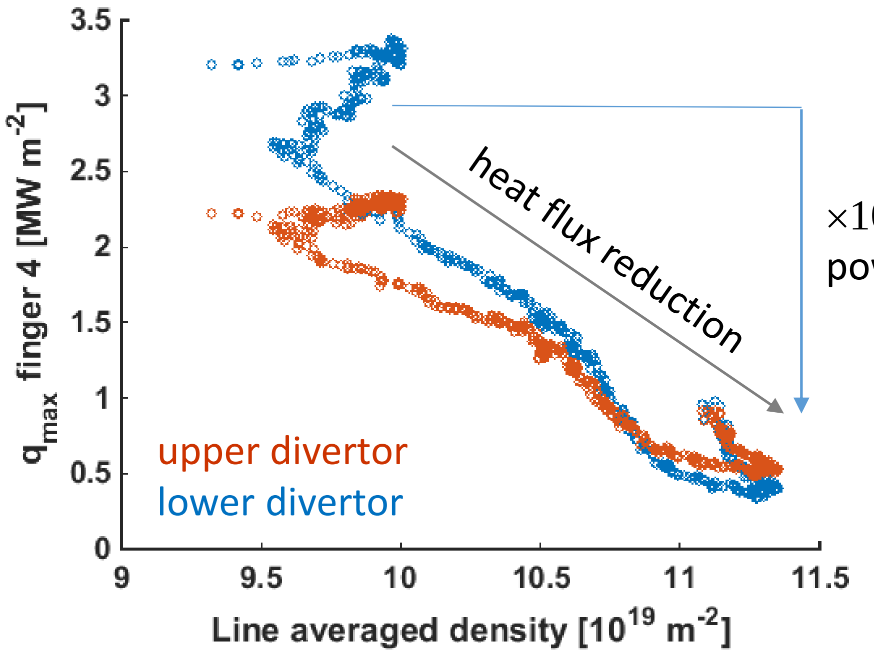
T. S. Pedersen EX/9-1
F. Effenberg EX/9-2

Significant particle exhaust with simultaneous detachment

- prior to boronization: neutral gas compression × 6-8 only with $p_{div} < 0.005$ Pa
- after boronization: neutral gas compression × 30 with $p_{div} = 0.1$ Pa ⟶ high density
  high power
  reduced power starvation?

20180814.024





×10
power drop

detachment szenario

high recycling?

by courtesy of O. Schmitz
U. Wenzel and G. Schlisio

O2 mode ECRH plasma P_{ECRH}=6.8MW with a density ramp $n = 7 \ldots 12 \cdot 10^{19}$ m^{-2}

F. Effenberg EX/9-2

T. S. Pedersen EX/9-1

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a. **Overall performance assessment**

b. **Conclusions and way forward**

Related papers on this conference: P. Aleynikov TH/P4-6, S. A, Bozhenkov EX/P8-8, R. Brakel EX/P8-17, A. Dinklage EX/P8-30, F. Effenberg EX/9-2, G. Fuchert EX/3-5, O. Grulke EX/P8-9, M. W. Jakubovski EX/P8-16, C. Killer EX/P8-18, R. Kleiber TH/P2-4, H. P. Laqua EX/P8-28, S. C. Liu EX/P8-15, J. D. Lore EX/P8-19, J. Ongena EX/P8-27, N. Pablant EX/P8-10, T. S. Pedersen EX/9-1, E. Sanchez EX/P1-11, F. Schluck TH/P1-5

Ingredients for integrated performance plasma scenarios

wall conditioning

glow discharge cleaning
ECRH pulse trains
wall boronization

plasma profile control

overdense O2 ECR heating
peaked density/temperature
central fueling with pellets

control of plasma radiation

reduction of core radiation
no impurity accumulation

high density plasmas

ion root confinement
τ_E in ISS04 scaling with $n^{0.6}$
⇨ triple product scaling with $n^{1.6}$

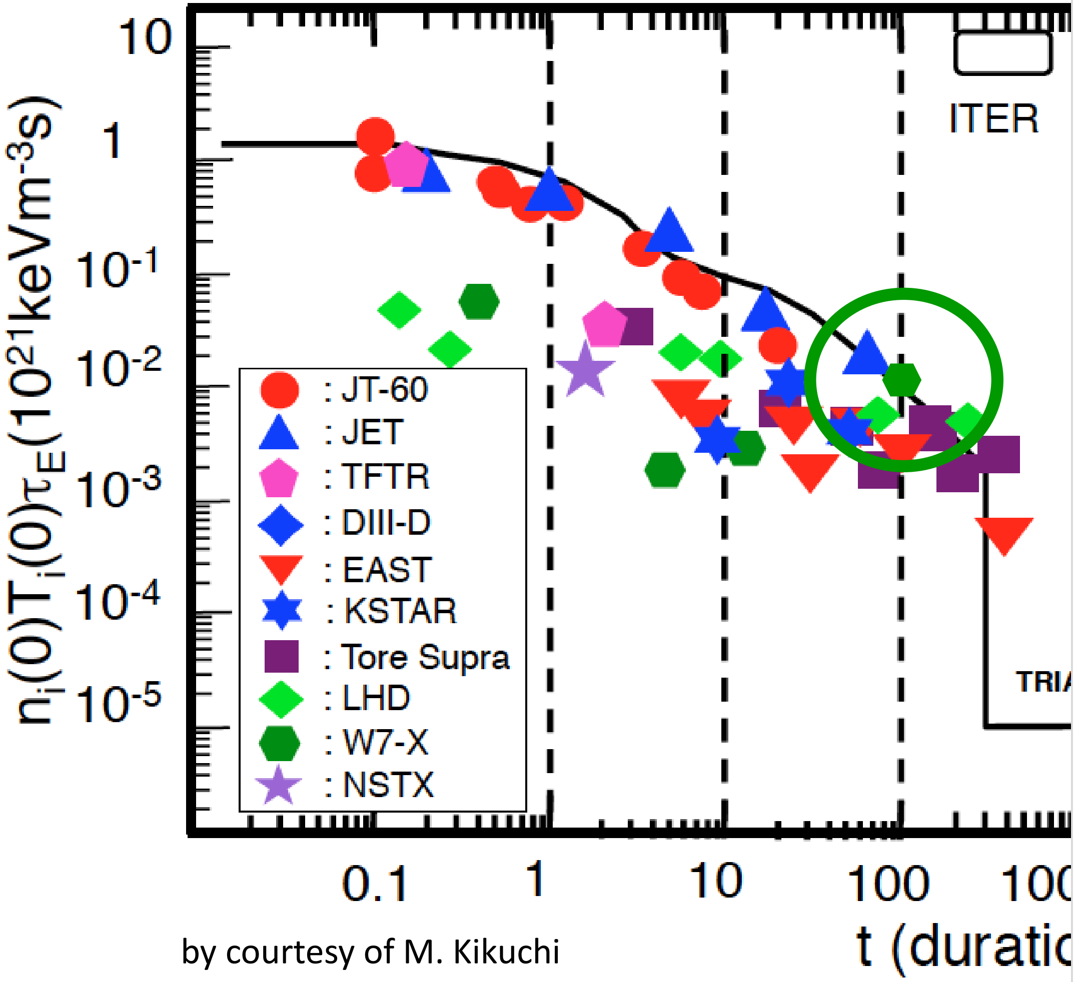
transport reduction

ion root confinement regime
suppression of turbulence

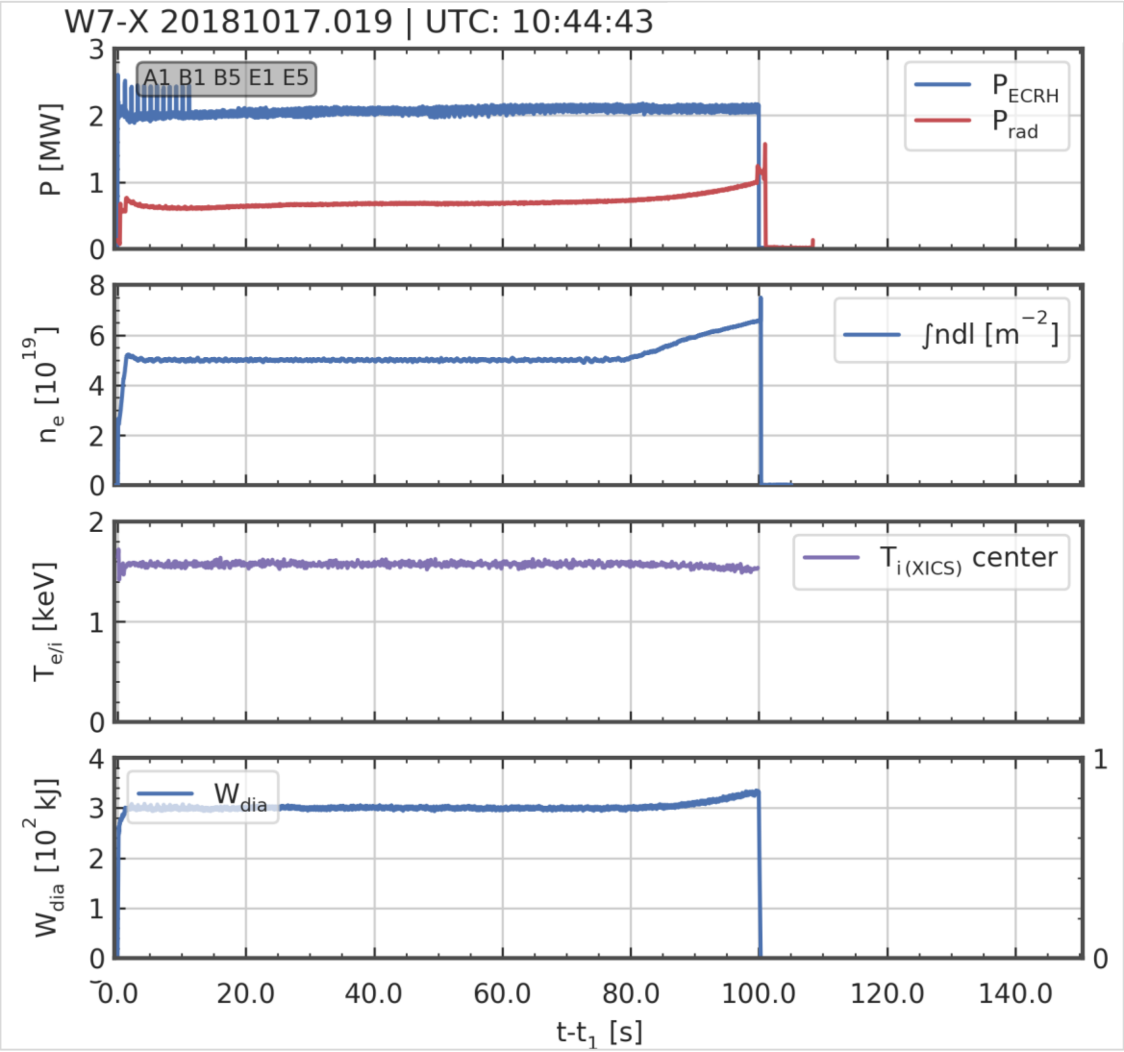
control of heat and particle exhaust

control of power loads by strike line control
detachment with sufficient neutral compression
high recycling (?)

Fusion triple product and pulse length



by courtesy of M. Kikuchi
T.S. Pedersen submitted to PPCF



Summary and conclusions

1. **Wall conditioning, in particular boronization gave access to an operation window with stationary high-power high-density discharges. ECRH has proven to be a most flexible heating and current drive scheme.**

2. **Transport seems to be dominated by turbulence and no impurity accumulation at high densities is observed – confinement times are within ISS04 and normalized plasma pressure is $\leq$ 1.5%.**

3. **The island divertor shows power detachment and discharges with controlled plasma radiation and high neutral compression rates. The power load distribution is favourable with acceptable asymmetry.**

More heating power and active cooling of in-vessel components are needed.


Well done, Wendelstein 7-X team!
Daily Experiment Plan
Thursday, October 18th, 2018
Diamagnetic Energy
Line Integrated Density
Total Gasflow
ECRH Total Power
W7-X CoDaC
IT Services 1868
Segment Control 1567
DAQ / Monitoring 1492