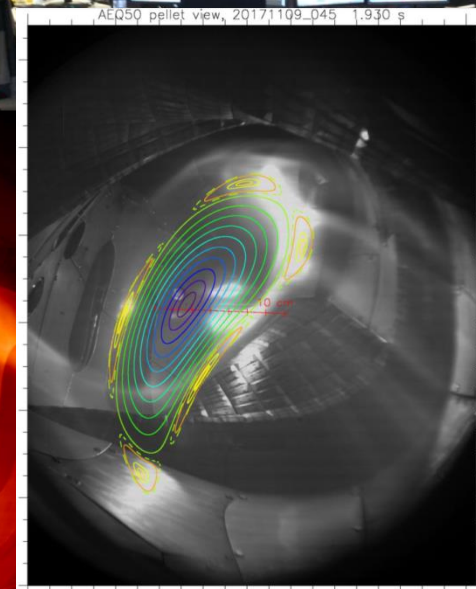
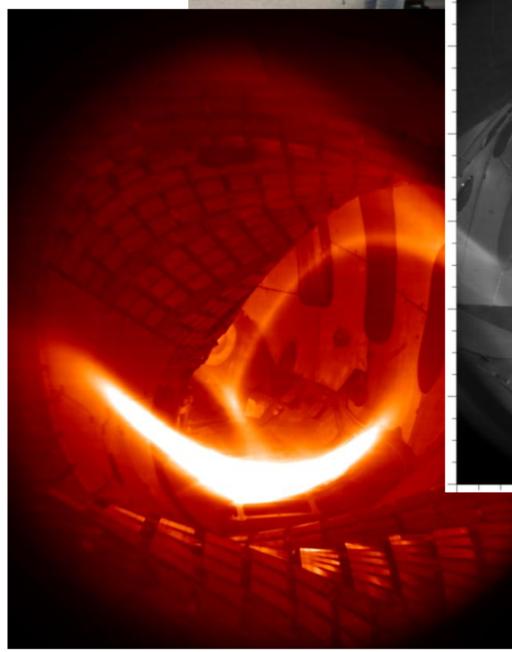
http://www.ipp.mpg.de/

Concept and Status of the Wendelstein 7-X Project

PLADyS Summer School

06.08.2021





first W7-X H-Plasma 3.2.2016

Matthias Hirsch
for the W7-X Team

Max-Planck-Institut für Plasmaphysik,
Greifswald, EURATOM-Association

matthias.hirsch@ipp.mpg.de

EUROfusion

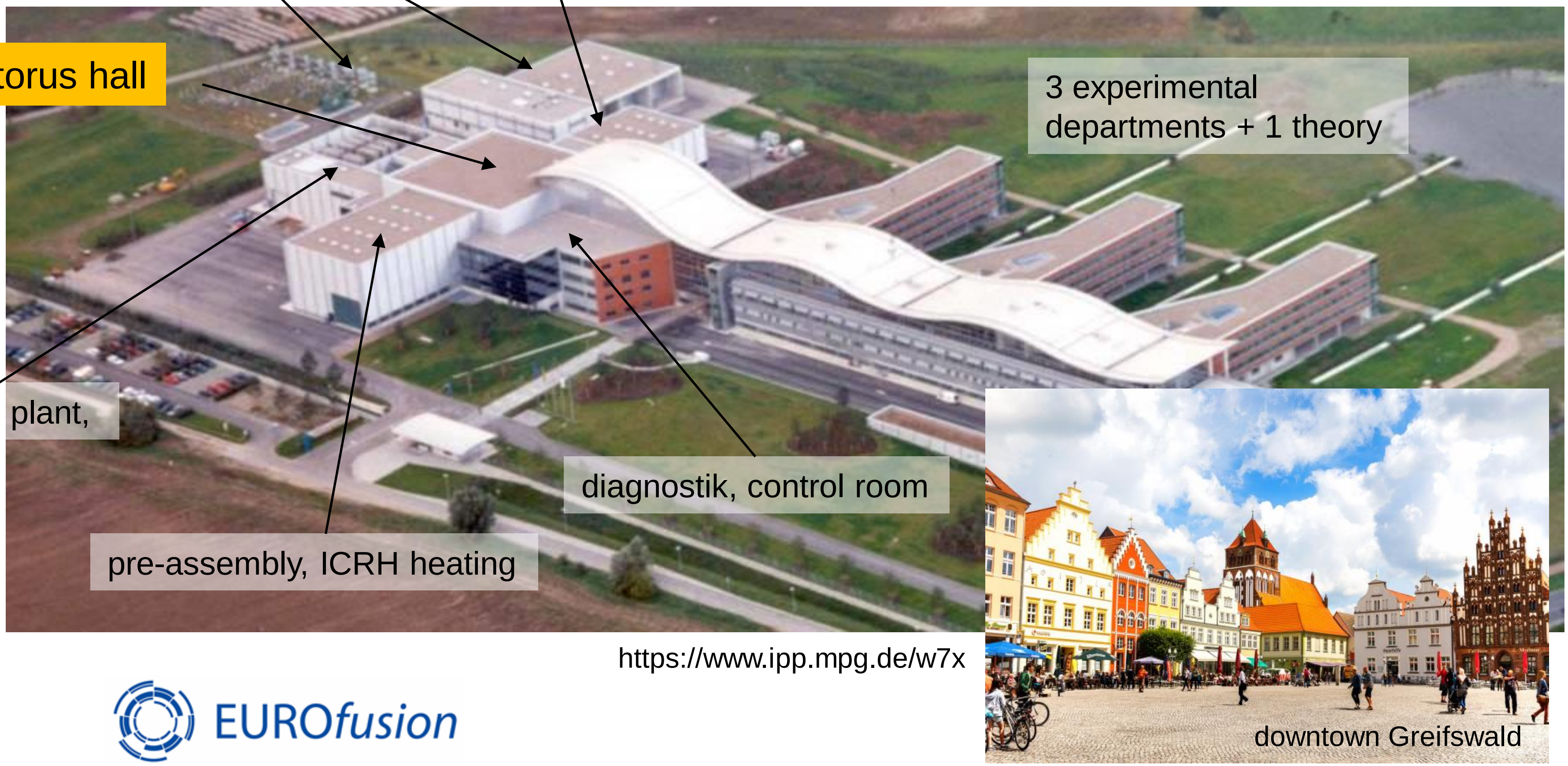
Max-Planck Institut für Plasmaphysik / Greifswald branch

IPP in Garching and Greifswald

Max-Planck Society :
86 Inst. ca 24000 People, ~2.5 Mrd. EUR/y
-> basic research besides the Universities

Greifswald branch dedicated to Projekt Wendelstein 7-X
~450 permanent staff: (typ.: 120 scientists
+ about 60 PostDocs, PhD , MSc students)

EUROfusion project + many oversees cooperations



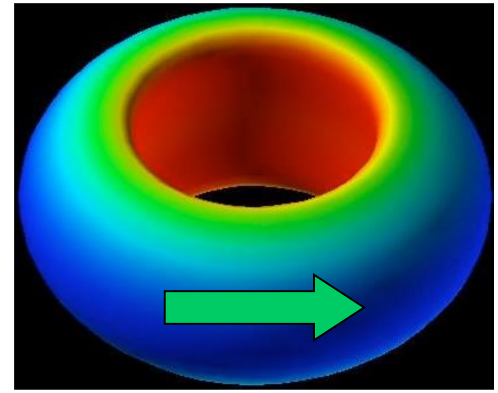
https://www.ipp.mpg.de/w7x

EUROfusion

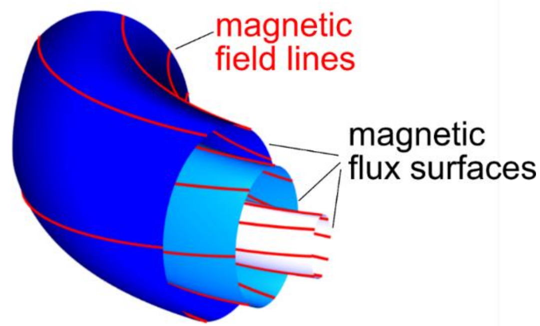
how to make the magnetic confinement

Lyman Spitzer Jr. 1951:
„there are three options to build nested flux surfaces densely covered by magnetic field lines“

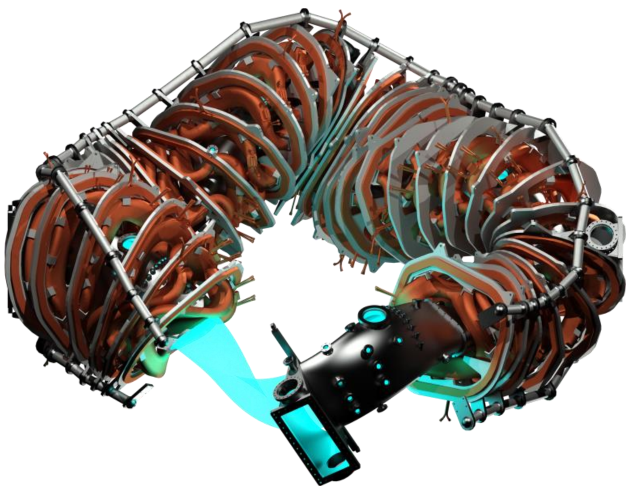
1. circular axis + internal current



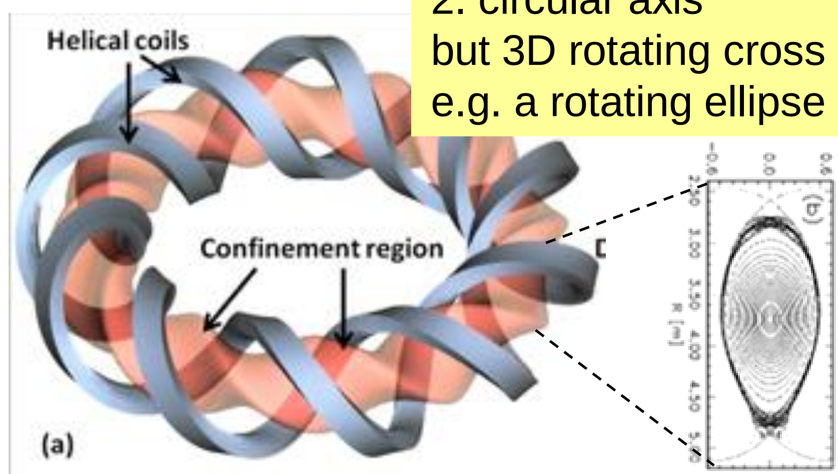
<u>Tokamak</u>
toroidally symmetry
+ but dynamic of internal current



3. twisted axis



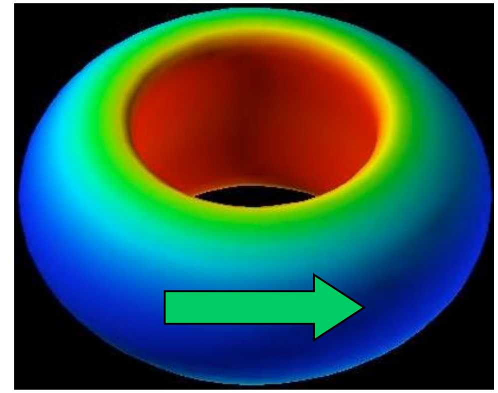
2. circular axis
but 3D rotating cross section,
e.g. a rotating ellipse



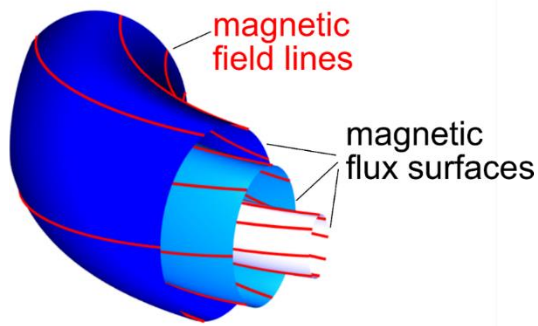
how to make it

Lyman Spitzer Jr. 1951:
„there are three options to build nested flux surfaces densely covered by magnetic field lines“

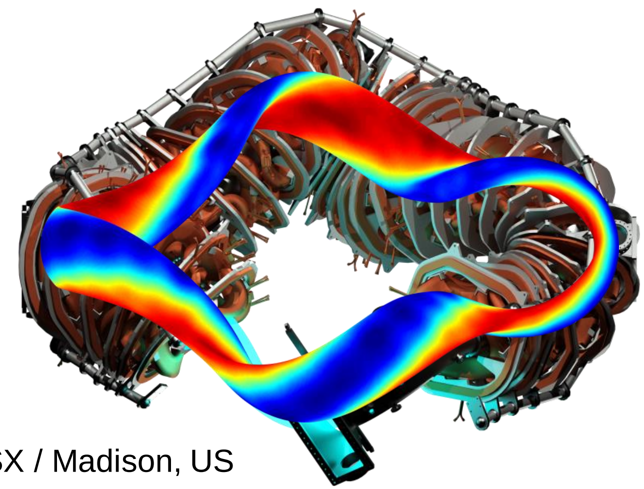
1. circular axis + internal current



<u>Tokamak</u>
toroidally symmetry
+ but dynamic of internal current



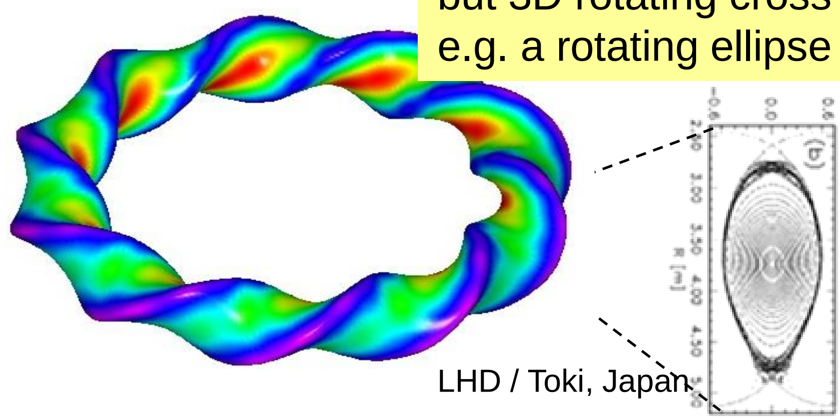
3. twisted axis



HSX / Madison, US

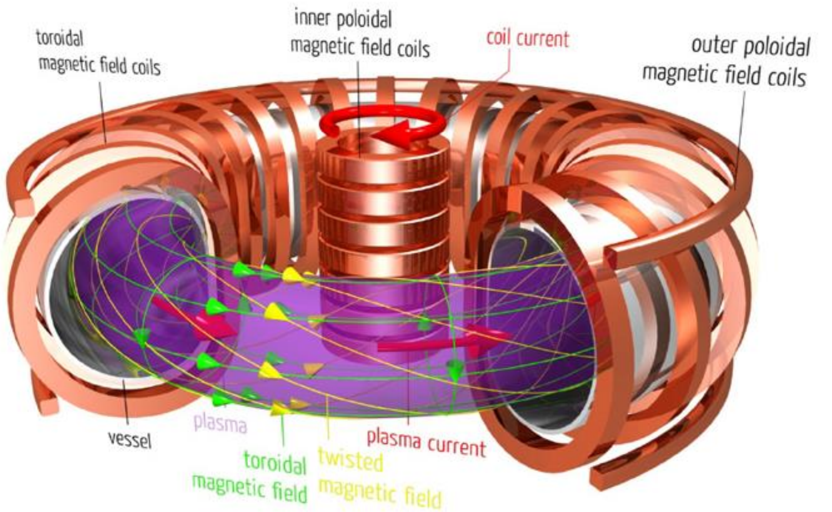
<u>Helical Devices / Stellarators</u> have a 3D topology and field strength

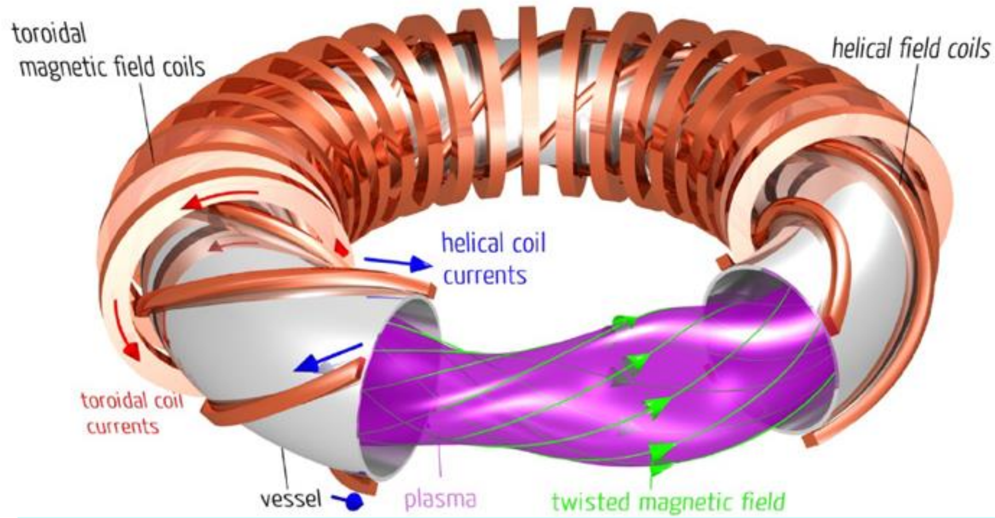
2. circular axis
but 3D rotating cross section,
e.g. a rotating ellipse



LHD / Toki, Japan

Tokamaks and Stellarators





conceptual advantage:

-> inherent ohmic heating

-> symmetry - engineering advantage

drawbacks:

-> current drive required

-> current disruptions endanger device

-> density limit

-> current driven instabilities limit pressure gradient

conceptual advantage:

-> no need for current drive: steady state capability

-> (no) current disruptions or current driven instabilities, "less dynamic plasma control"

drawbacks:

-> flux surfaces not guaranteed

-> EM forces between coil systems

-> no axissymmetry, plasma is 3D

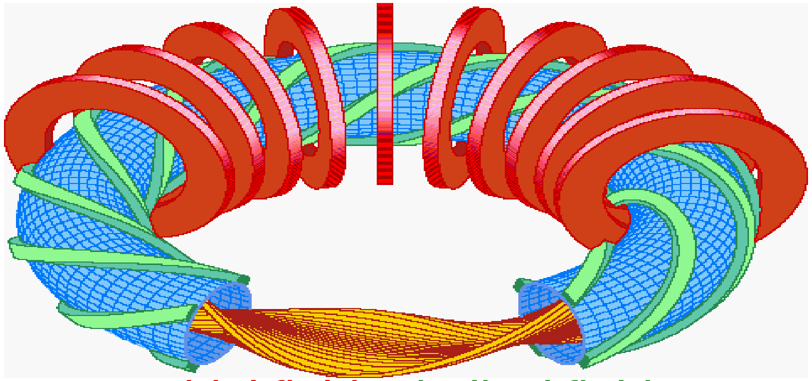
-> additional loss channels for collisionless particles
-> engineering and assembly complexity
-> danger of assymmetric wall load

however ...

... the 3rd dimension provides an additional degree of freedom
-> the design of magnetic confinement

the concept of modular coils – the second generation

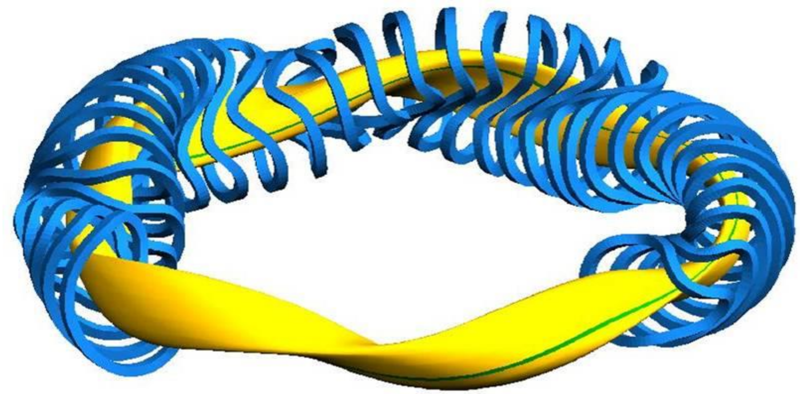
first modular concept by Rehker and Wobig in 1972



W7-A

toroidal field coils

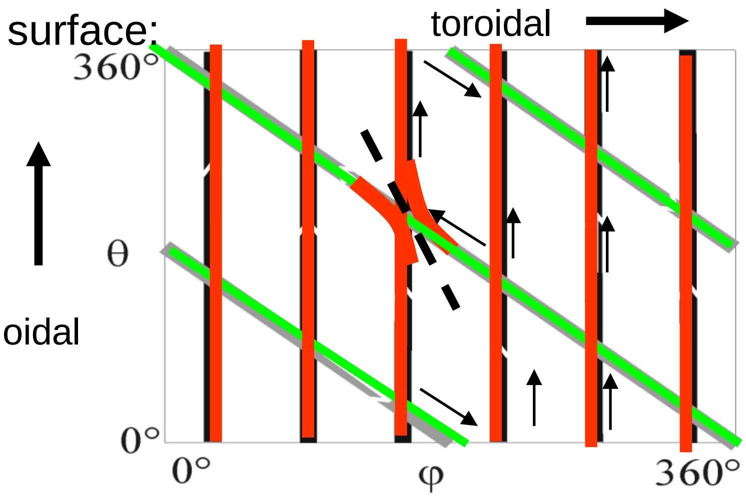
helical field coils

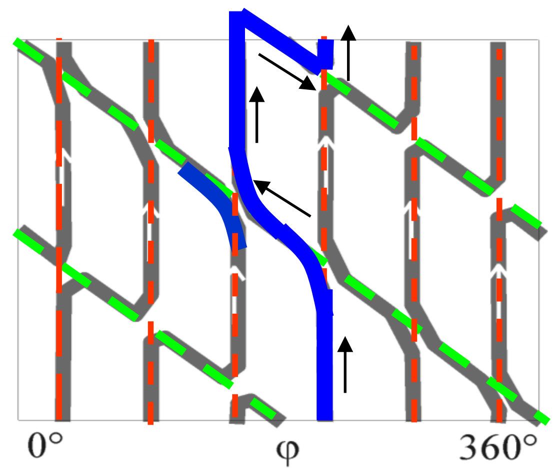


W7-X

modular coils

“unrolled” torus surface:





-> no huge helical coils + mechanical forces remain in coil structure

-> design magnetic field geometry (cross section and magnetic axis) *and* field strength

-> vary Fourier spectrum of current distribution

the design of magnetic confinement

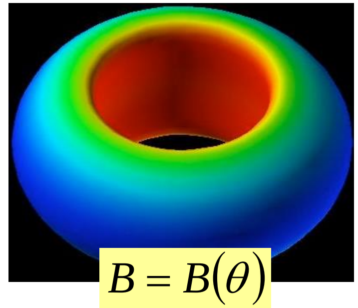
Boozer, Nührenberg, Garbedian

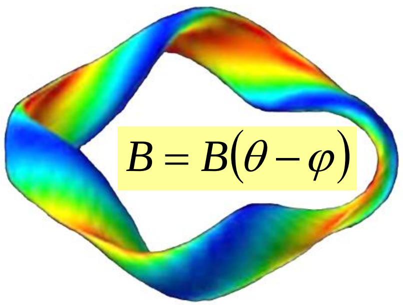
drawings show Bmod on a flux surface :
red high, blue small

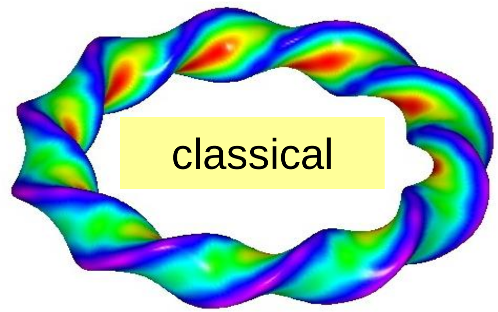
"quasi symmetries": with respect to mod(B) on flux surfaces; cannot be exact but sufficient if B=const in grove where the trapped particles drift.

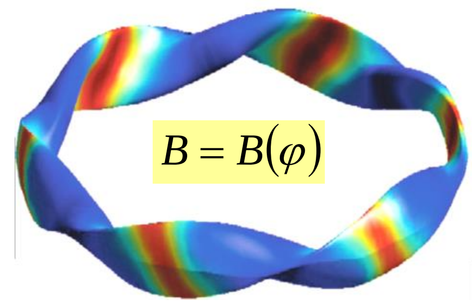
toroidal symmetry (Tokamak):

Lagrange formalism of guiding partice motion a new invariant of motion is derived if B depends on two of the coordinates (psi, phi, theta) only. The canonical momentum of this invariant is then conserved.





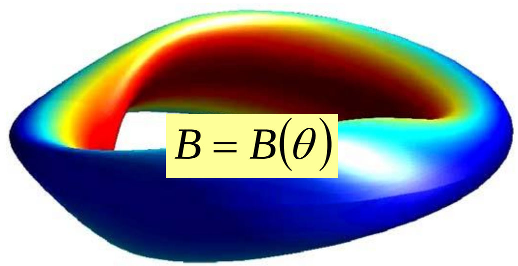




quasi-helical "linear Stellarator like"

-> virtually no toroidal curvature -> (high equilibrium beta!)
-> but j_{BS} reduces shear

(HSX, Madison/Wisconsin)



quasi-toroidal : "Tokamak-like"

(NCSX), China, Stellatok
+ several smaller approaches,

quasi-isodynamic:
" linked mirror"

-> cannot be relized in toroidal geomety but approximations ...

(W7-X is close to this class, Helioptron-J has aspects of it**)**

outline

1. the design of magnetic confinement

2. the WENDELSTEIN project – the optimized superconducting Stellarator

3. a review on Operational Phase 1 ...

4. and an outline towards OP2 (and beyond ...)

an integrated optimzation concept - the HELIAS

(HELIcal axis Advanced Stellarator)

modular coils allow to combine helical axis and plasma shaping such that necessary optimization criteria are fulfilled simultaneously:

-> drift optimization for thermal and fast ions

-> *and* reduced Shafranov shift (small PS currents

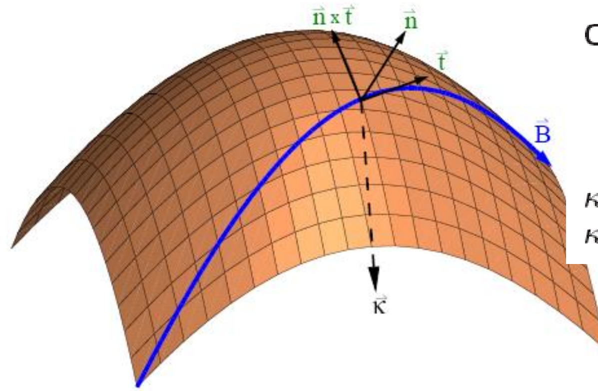
can be realized *simultaneously* by the concept of isodynamicity

(minimization of geodesic curvature of fieldlines = minimize field inhomogenities perpendicular to fielc lines = "minimizing the *poloidal* variation of modB = "a *weak quasi-poloidal symmetry*")

+ "helical and toroidal components of j_{BS} cancel" !

-> minimization of the bootstrap current = "stiff configuration"

+ low magnetic shear -> island divertor



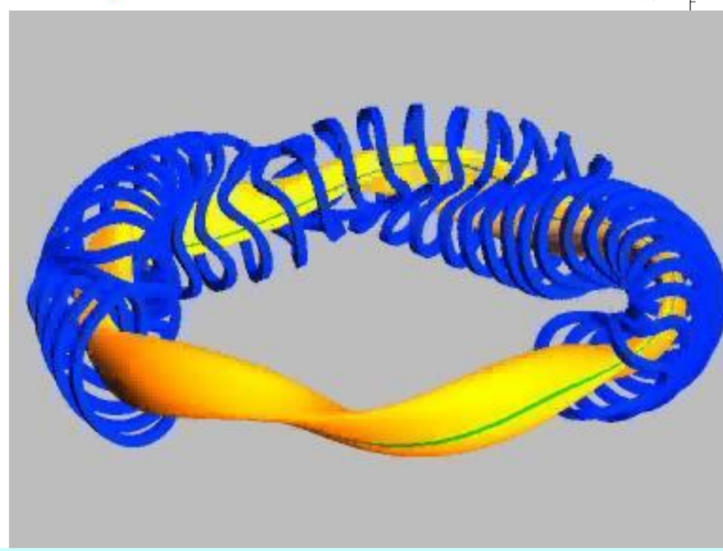
Curvature:

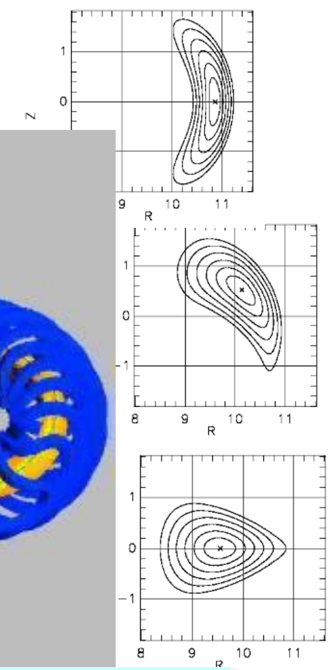
$$\vec{\kappa} := \left(\vec{b}\cdot\nabla\right)\vec{b}$$

$$\vec{\kappa} = \kappa_n \vec{n} + \kappa_g \vec{n} \times \vec{t}$$

κ_n: normal curvature

κ_g: geodesic curvature

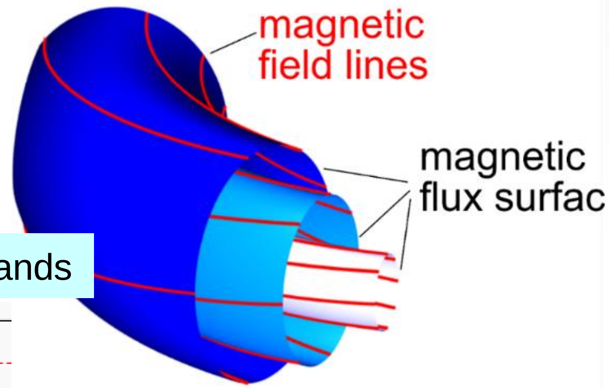




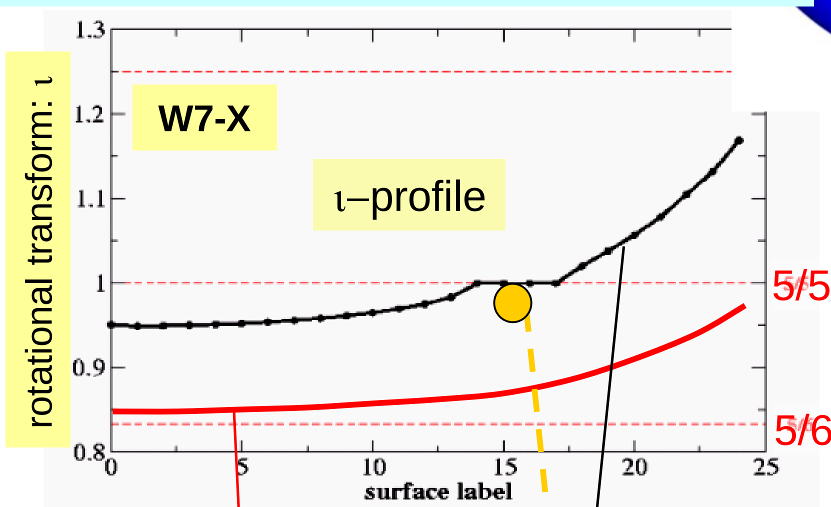
=> Plasma and magnetic field decoupled as far as possible: "The pure Stellarator ...."

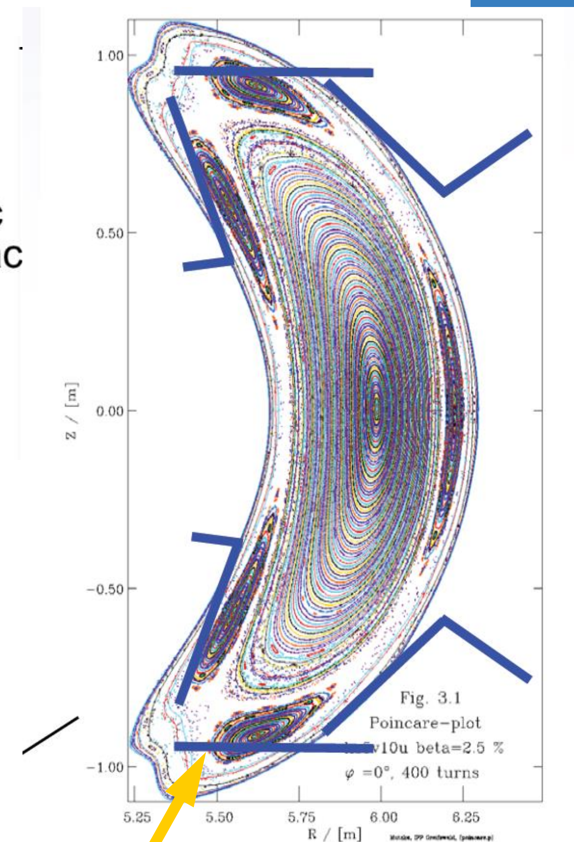
using perturbed rational surfaces (“islands”) for plasma exhaust

rotational transform: ι

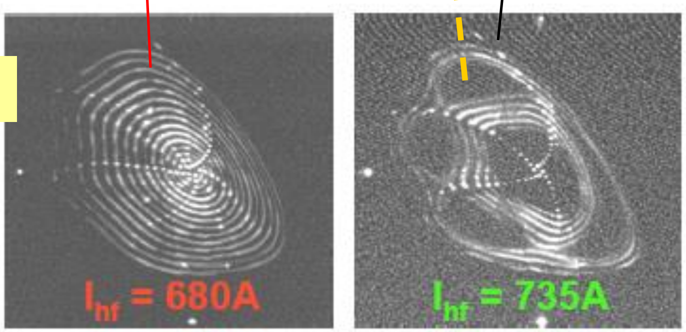


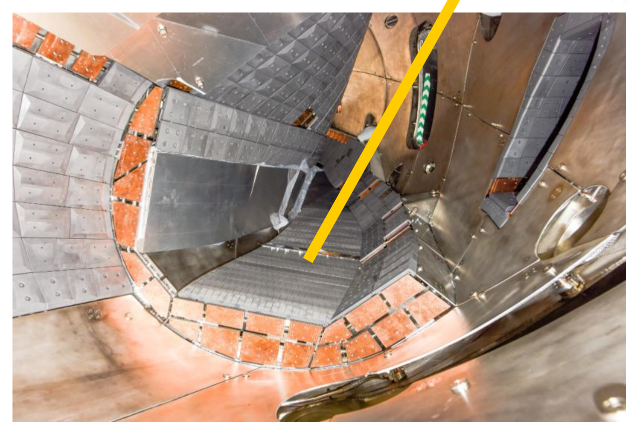
rational surfaces may result in magnetic islands





WEGA





The WENDELSTEIN Project - the optimized superconducting Stellarator

1) verify stellarator optimization

-> optimum mag. configuration, ι-profile, divertor

-> reduced neoclassical transport in lmfp-regime

-> good fast particle confinement

-> minimized Shafranov shift improved MHD stability limits

-> minimized bootstrap current

-> *turbulent transport ?*

2) superconducting coils to develop an integrated high-density scenario with

-> configuration control

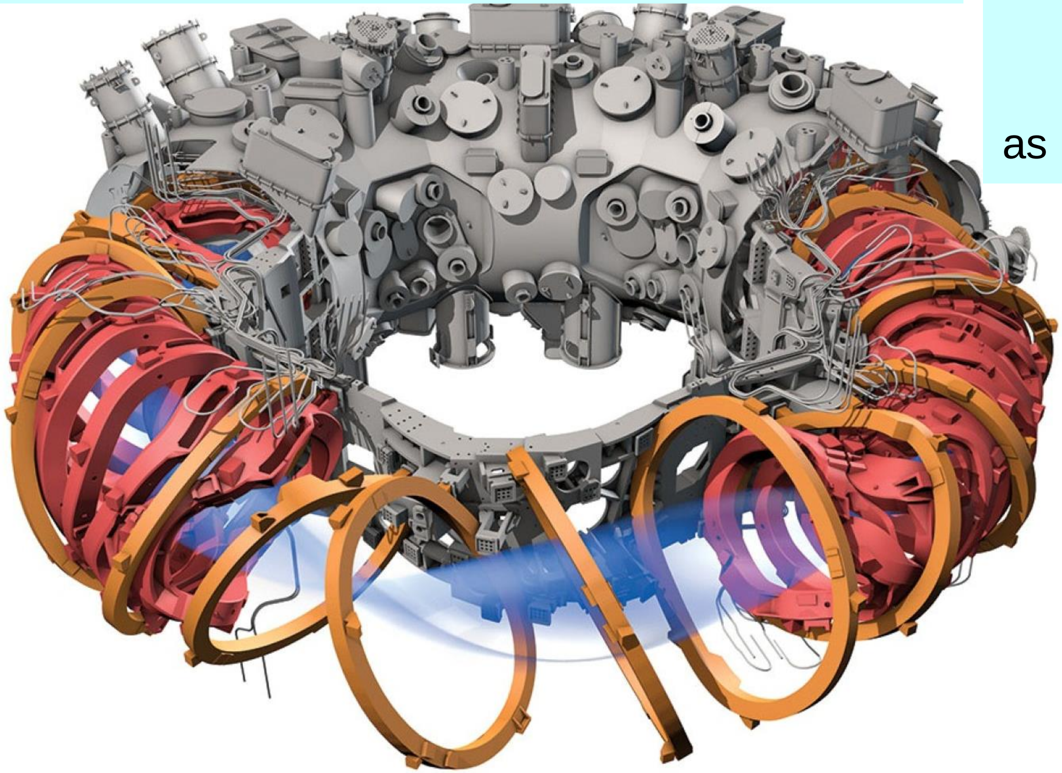
-> density control (fuelling, pumping)

-> steady state ECRH in O2-polarization allowing for high densities <2.4 10^{20} m^{-3}

-> acceptable low impurity confinement a these densities

-> edge conditions compatible with divertor load (symmetry, detachment, pumping)

as basis for high-power steady-state operation



R= 5.5m, a= 0.52 m, B=2.5T

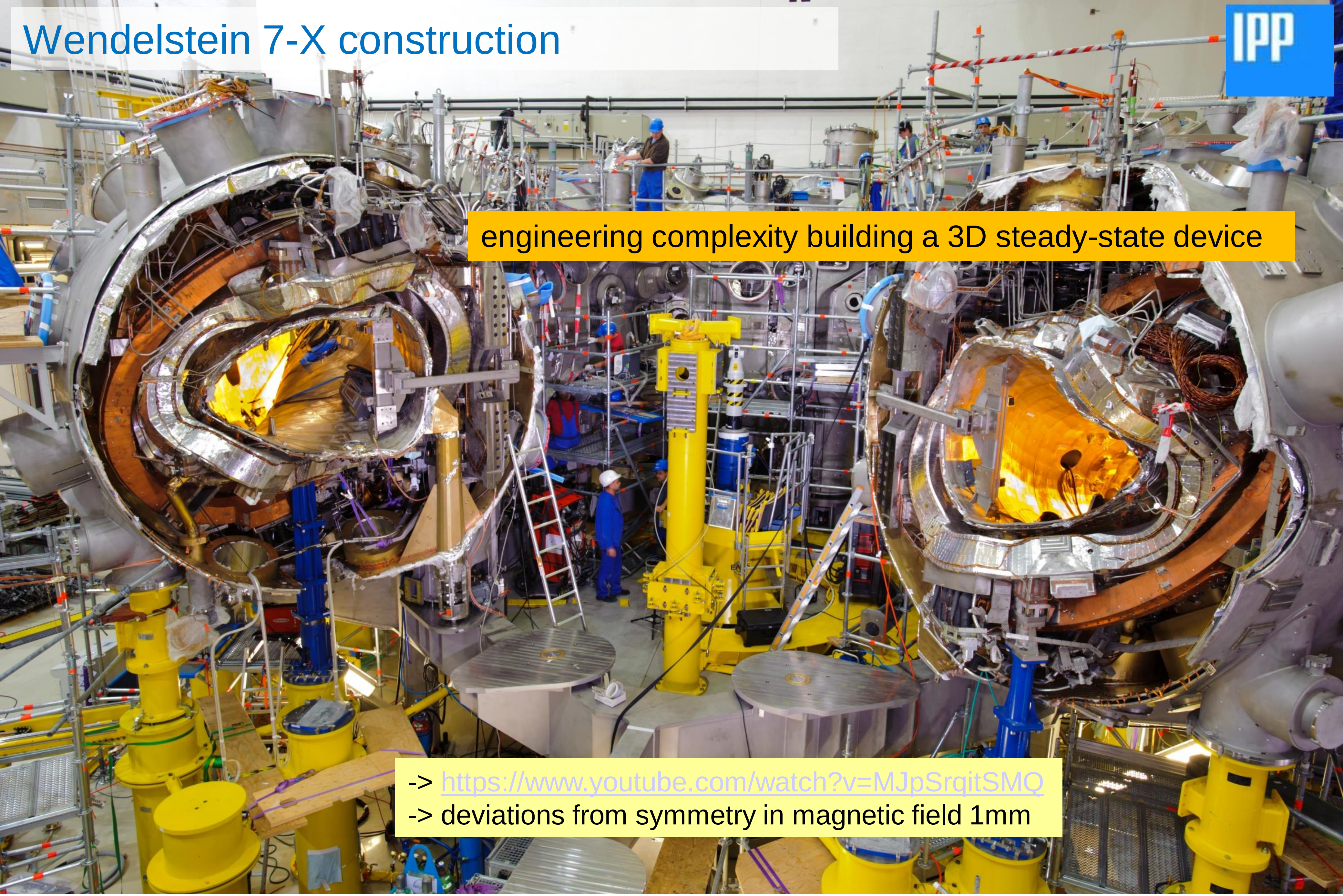
50 non-planar coils + 20 planar + 5 trim coils + in vessel divertor contro coils

254 peripheral ports

V_{plasma}= 30 m^3 (-> AUG: 14 m^3)

max. 1/30 g fuel in the plasma

Wendelstein 7-X construction

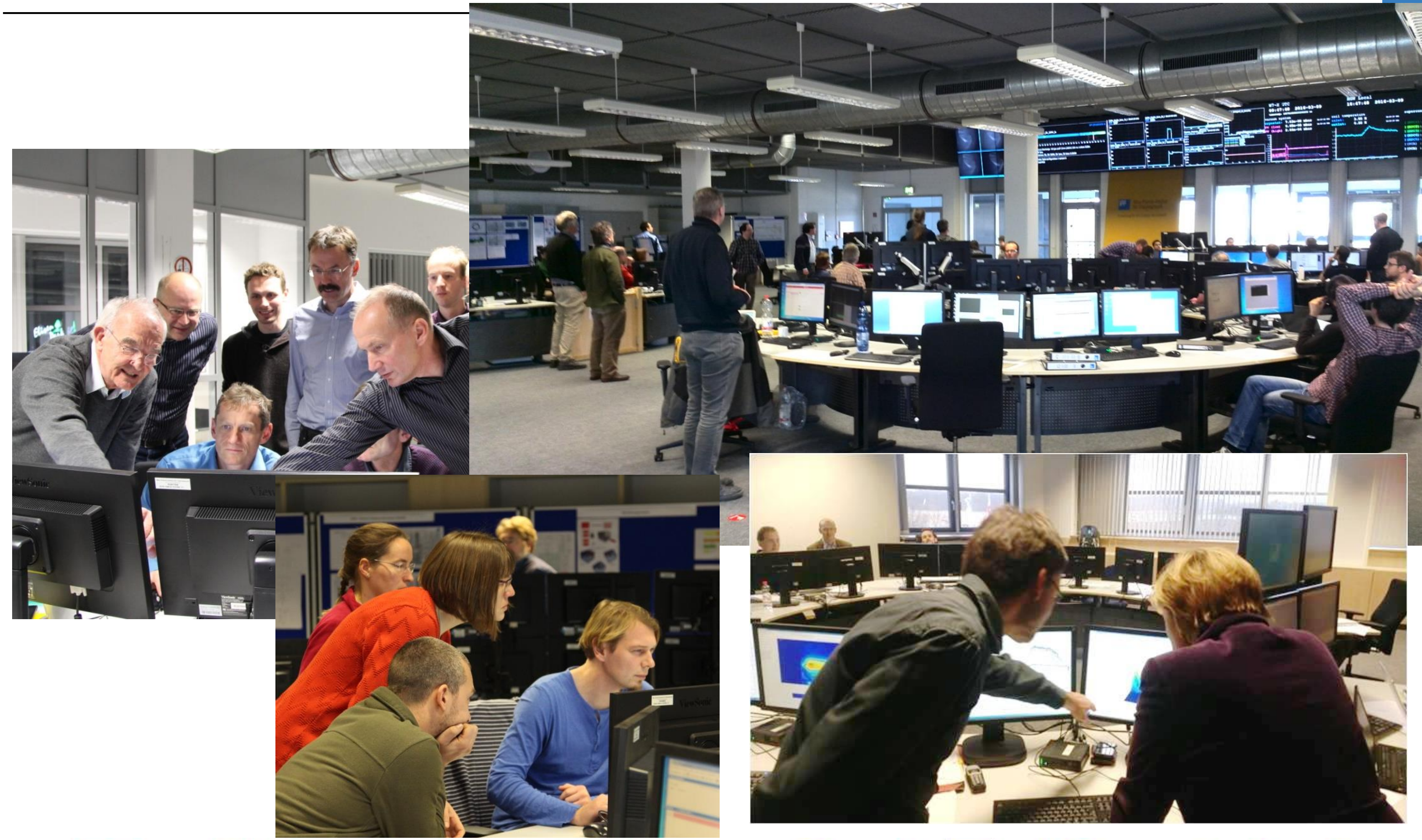


engineering complexity building a 3D steady-state device

-> https://www.youtube.com/watch?v=MJpSrqitSMQ

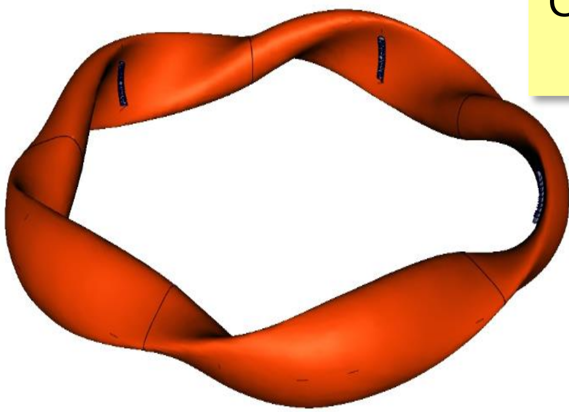
-> deviations from symmetry in magnetic field 1mm

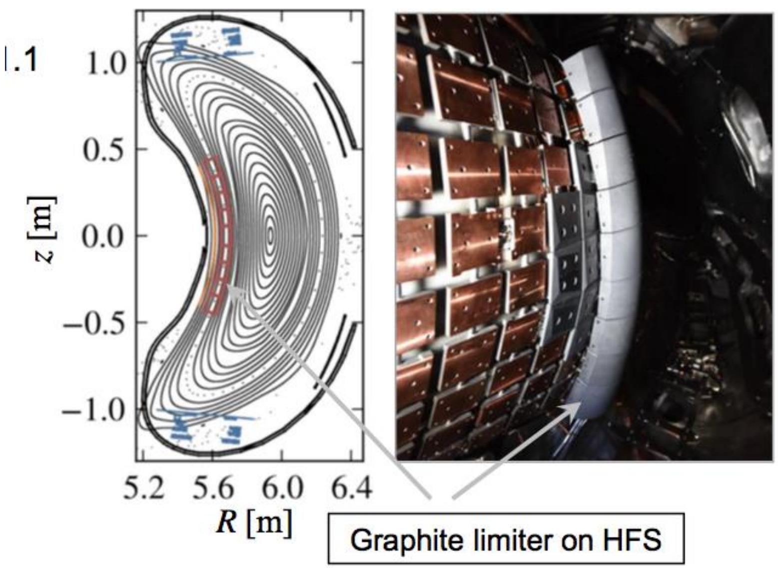
W7-X – Operational Phase 1 (2015-2018)

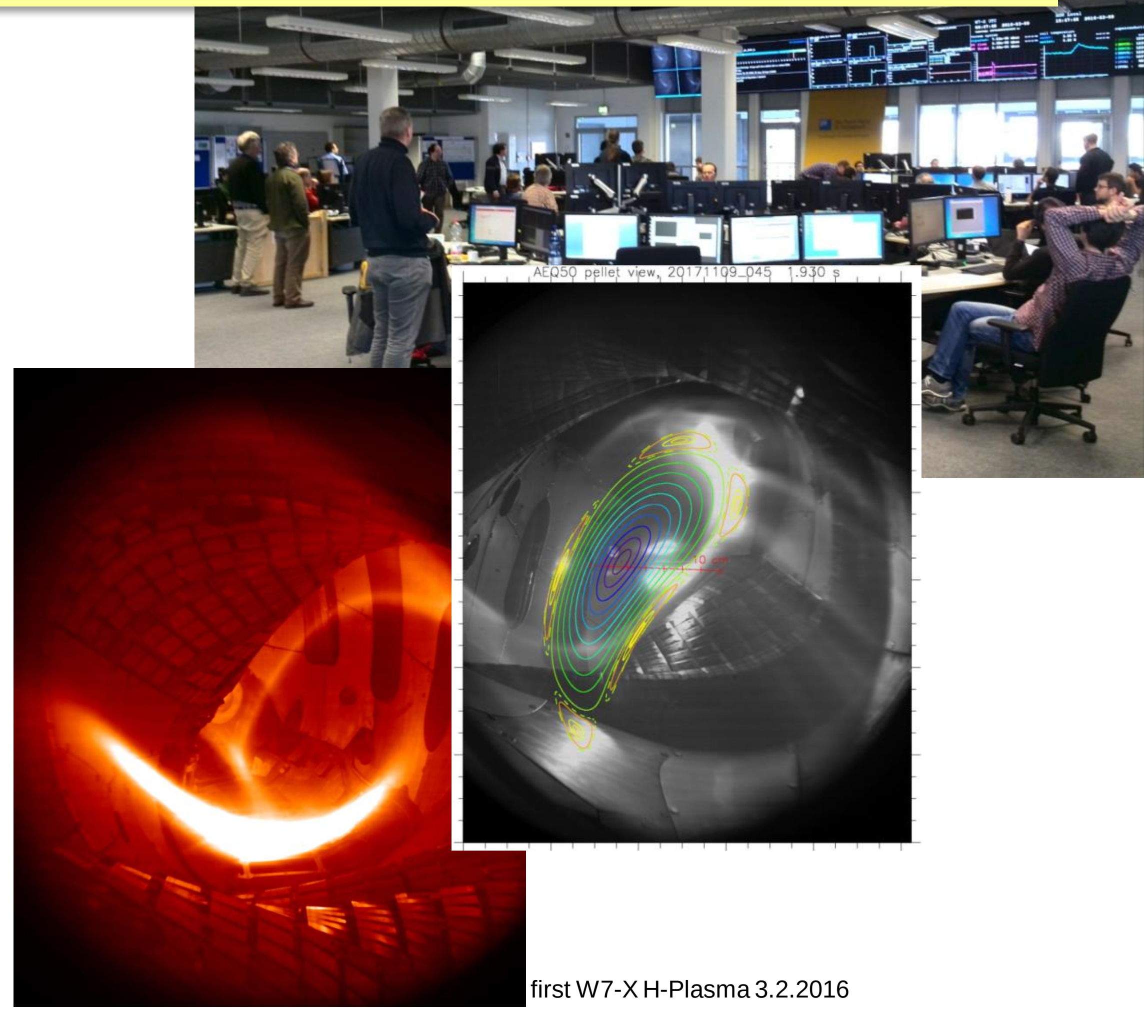


W7-X – Operational Phase 1.1 (2015/16)

OP1.1 (2015/16): 5 inboard limiters, yet uncoverd first wall
-> short pulses (~few s), 6MW ECRH

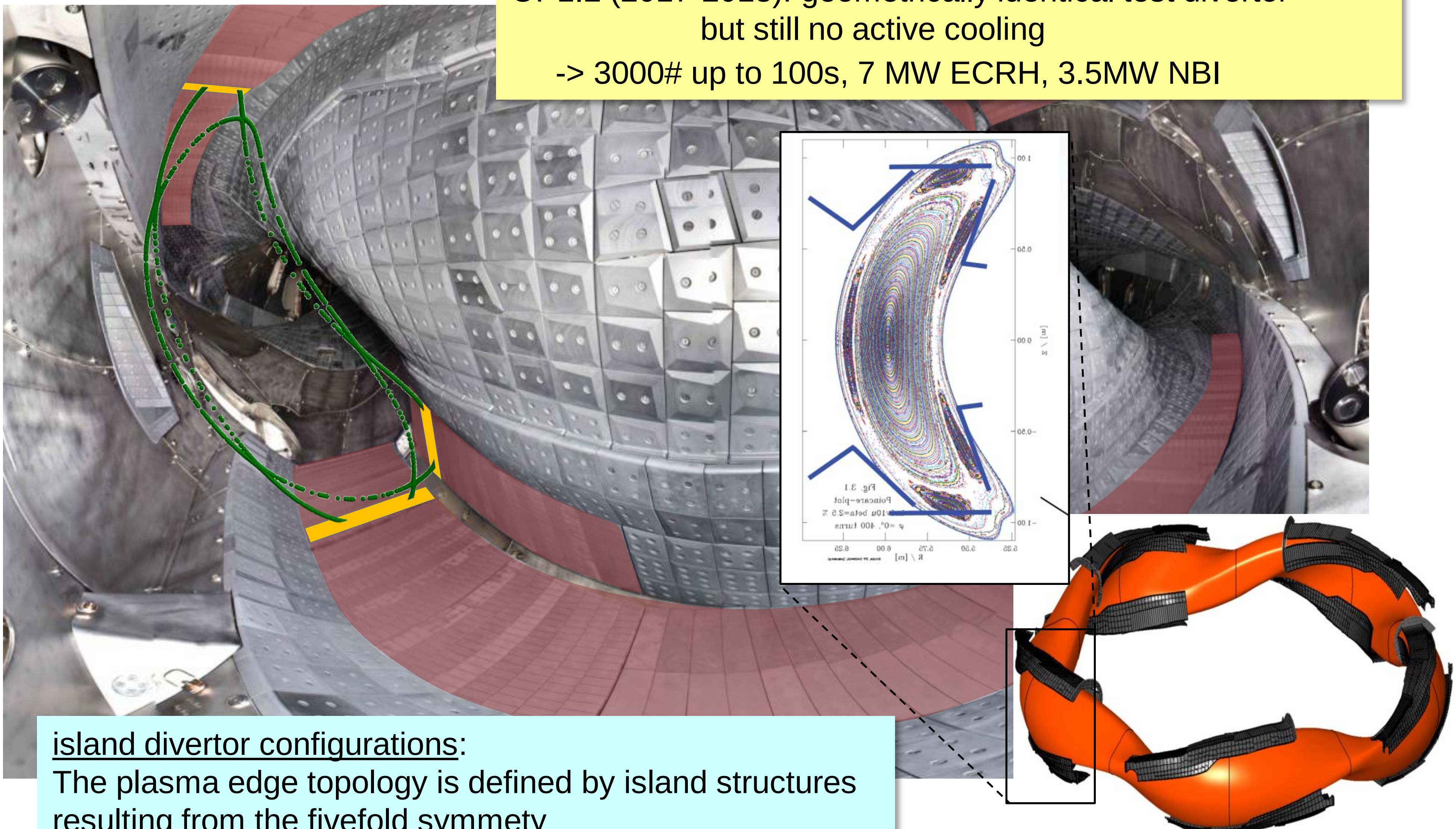






first W7-X H-Plasma 3.2.2016

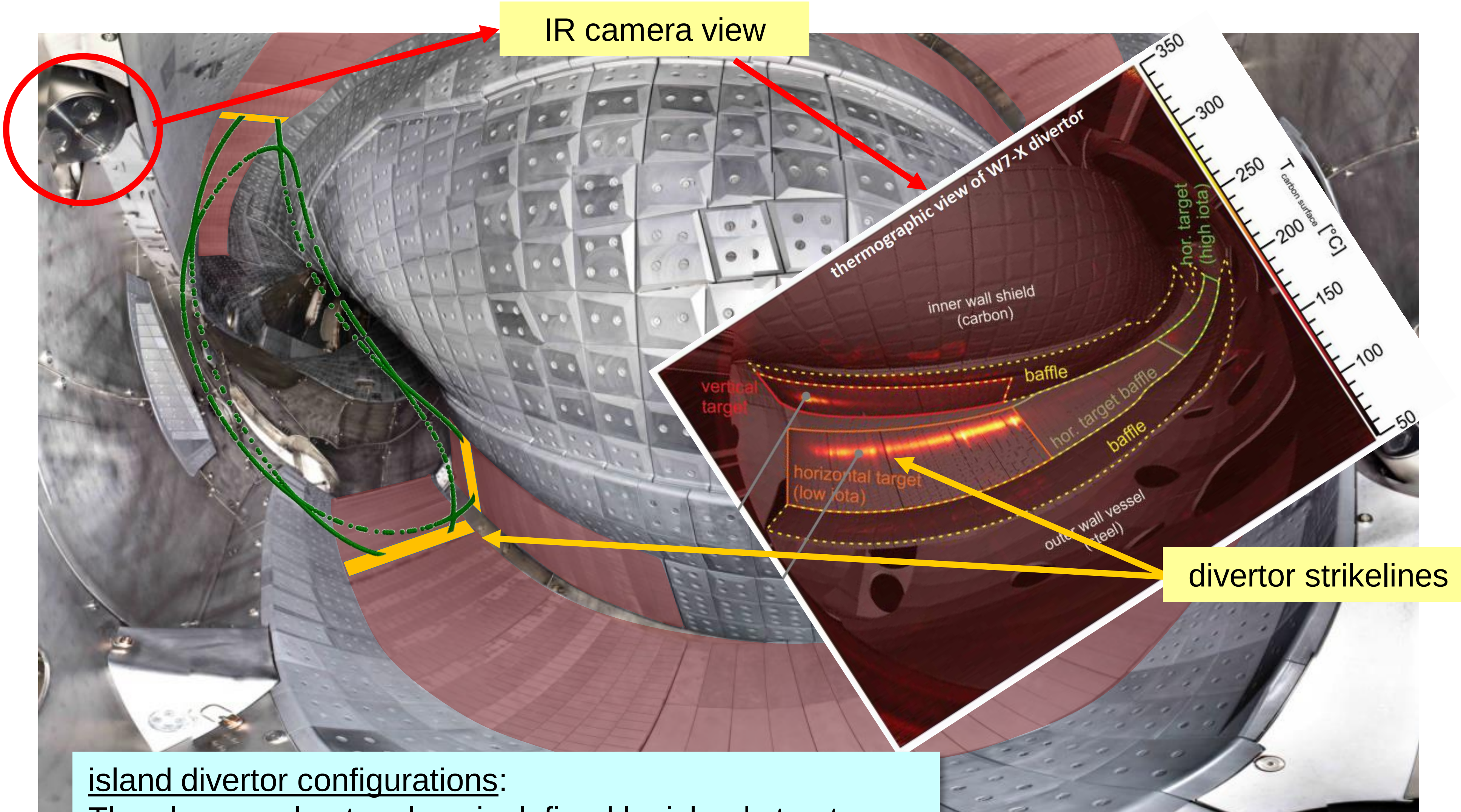
W7-X – Operational Phase 1.2 (2017-2018)



OP1.2 (2017-2018): geometrically identical test divertor
but still no active cooling
-> 3000# up to 100s, 7 MW ECRH, 3.5MW NBI

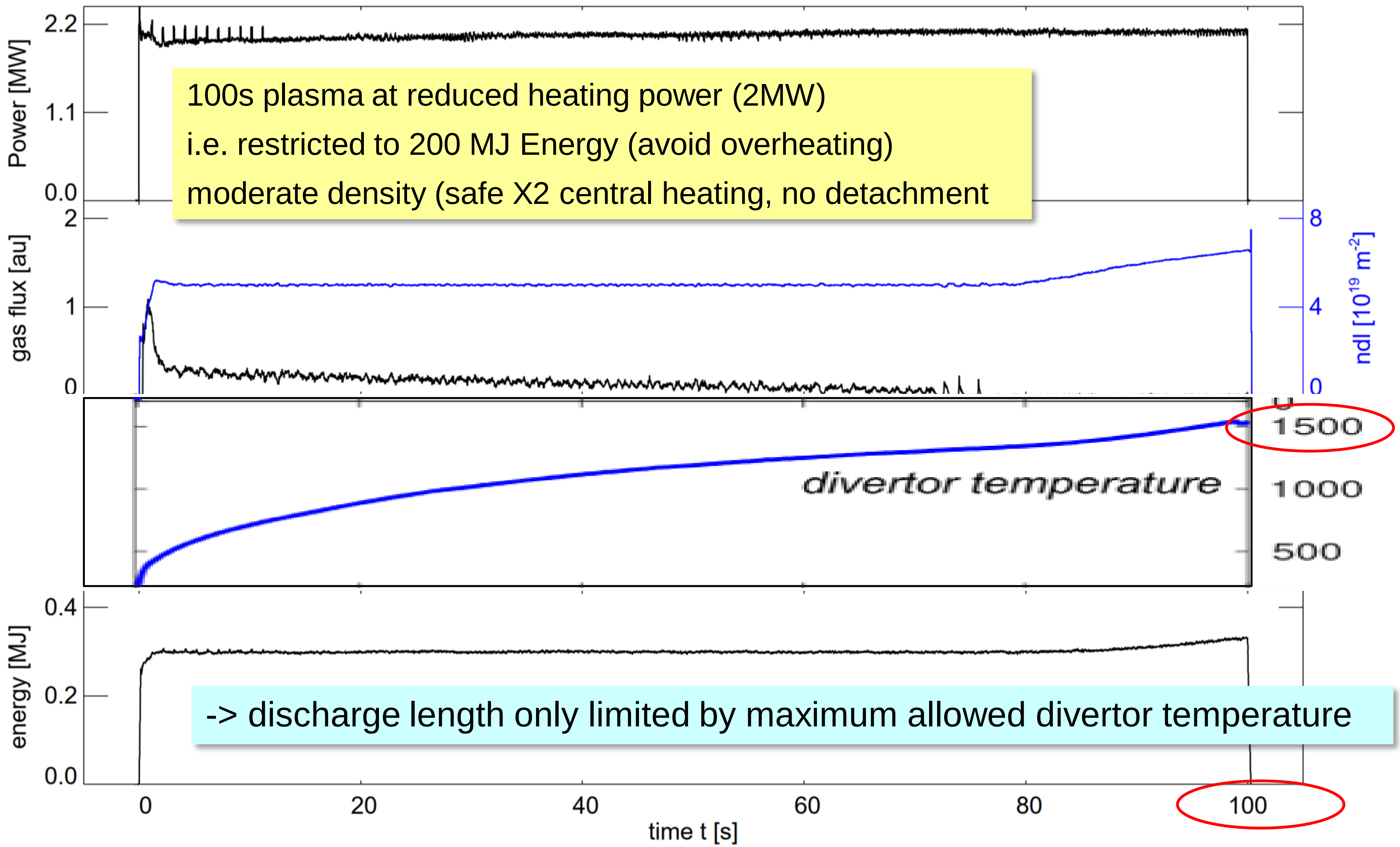
<u>island divertor configurations</u>:
The plasma edge topology is defined by island structures resulting from the fivefold symmety

plasma boundary – the island divertor



<u>island divertor configurations</u>:
The plasma edge topology is defined by island structures resulting from the fivefold symmety

a long-pulse probing the energy limit (status OP1.2b)



high-density operation – the stellarator way to fusion

the magnetic field can confine a certain pressure ~ n ·T

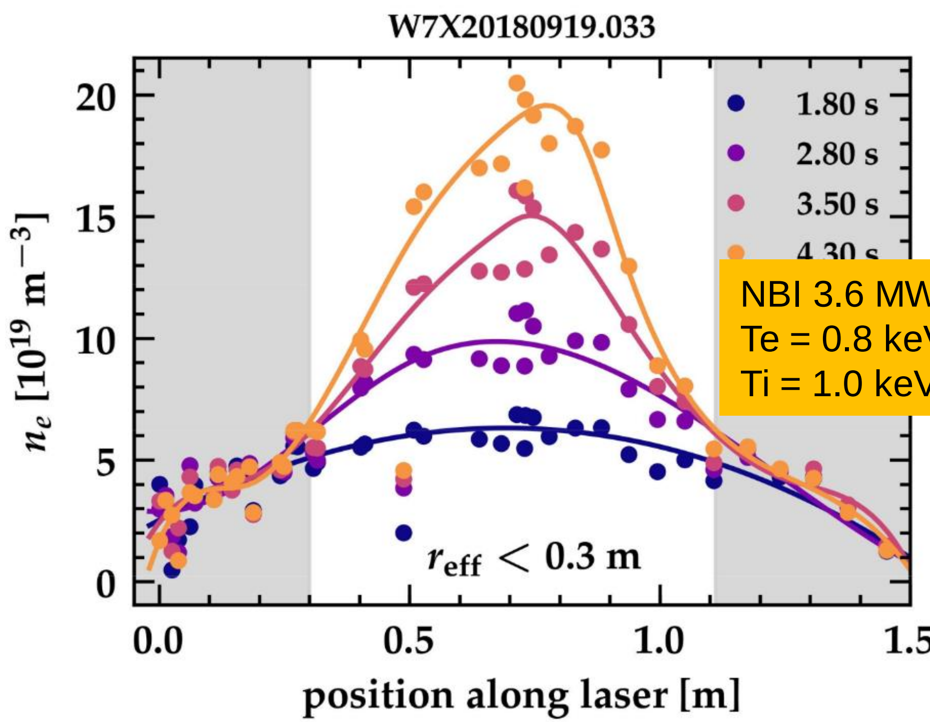
high-density operation is preferable:

- ignition n · Ti · τ
- confinement (τ) improves with density
- improved e-i coupling ~ n^2
- fusion yield : ~ n^2
- reduce fast ion losses to wall (α- particles !)
- lower Tedge -> eases load to targets
- Bremsstrahlen and ECE losses increase with Te

Stellarators have no disruptive density limit.
(in Tokamaks: Greenwald limit) and
a generally benign behaviour at operational limits

but high-density operation requires
-> heating to the core
-> density and impurity control
to avoid radiatin collapse
(good wall conditions)

W7-X < 2 10^{20} m^{-3} reached with deep fuelling (NBI)
or with XXX m^{-3} with pellets and O2 ECRH



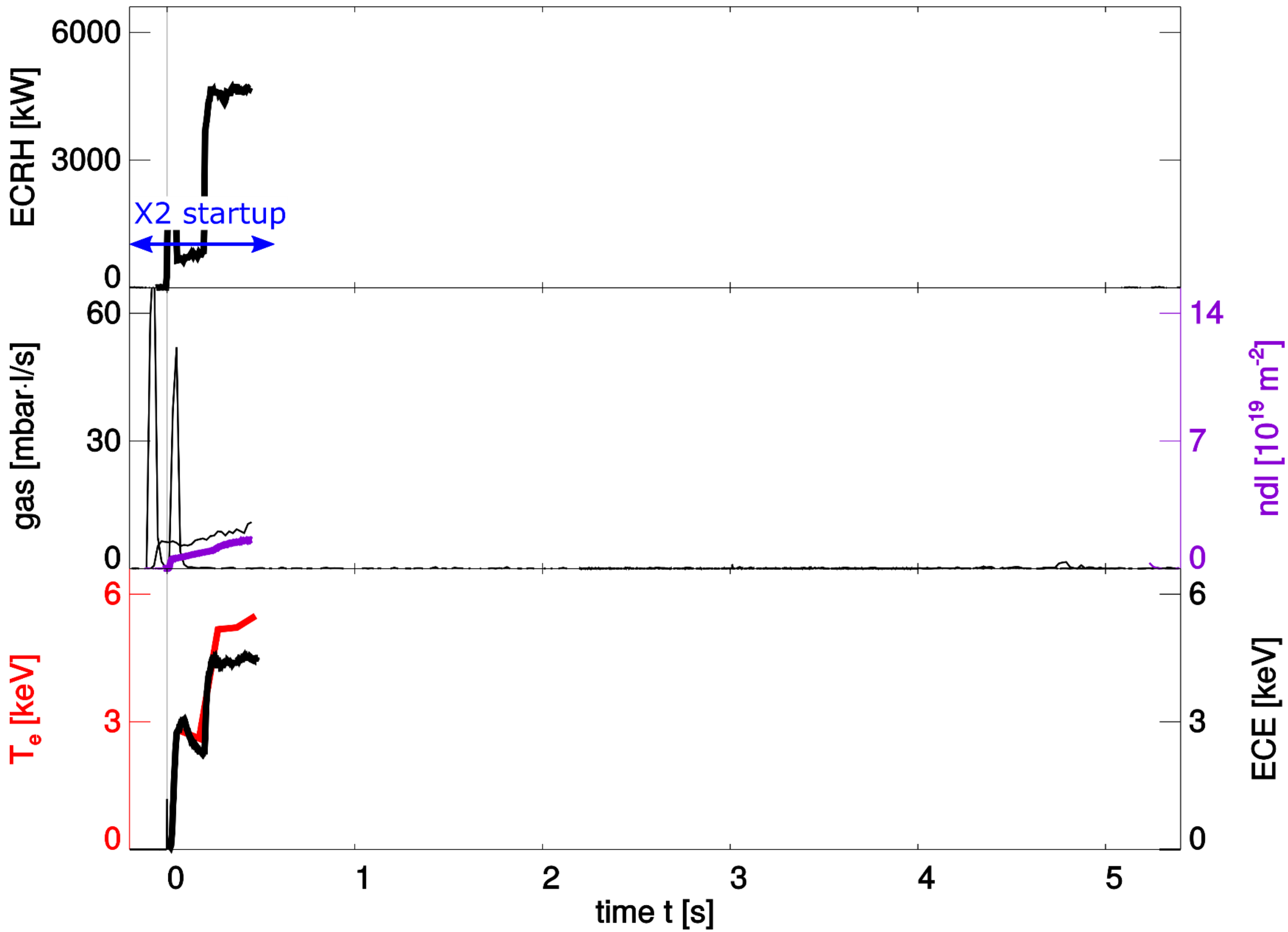
NBI 3.6 MW
Te = 0.8 keV
Ti = 1.0 keV

- **LHD** "superdense core plasmas“
- **W7-AS** High Density H-mode

O2 core ECR Heating

could be extended to steady state

- X2 plasma startup
- dynamic change of polarization from X2 to O2
- O2 power increase

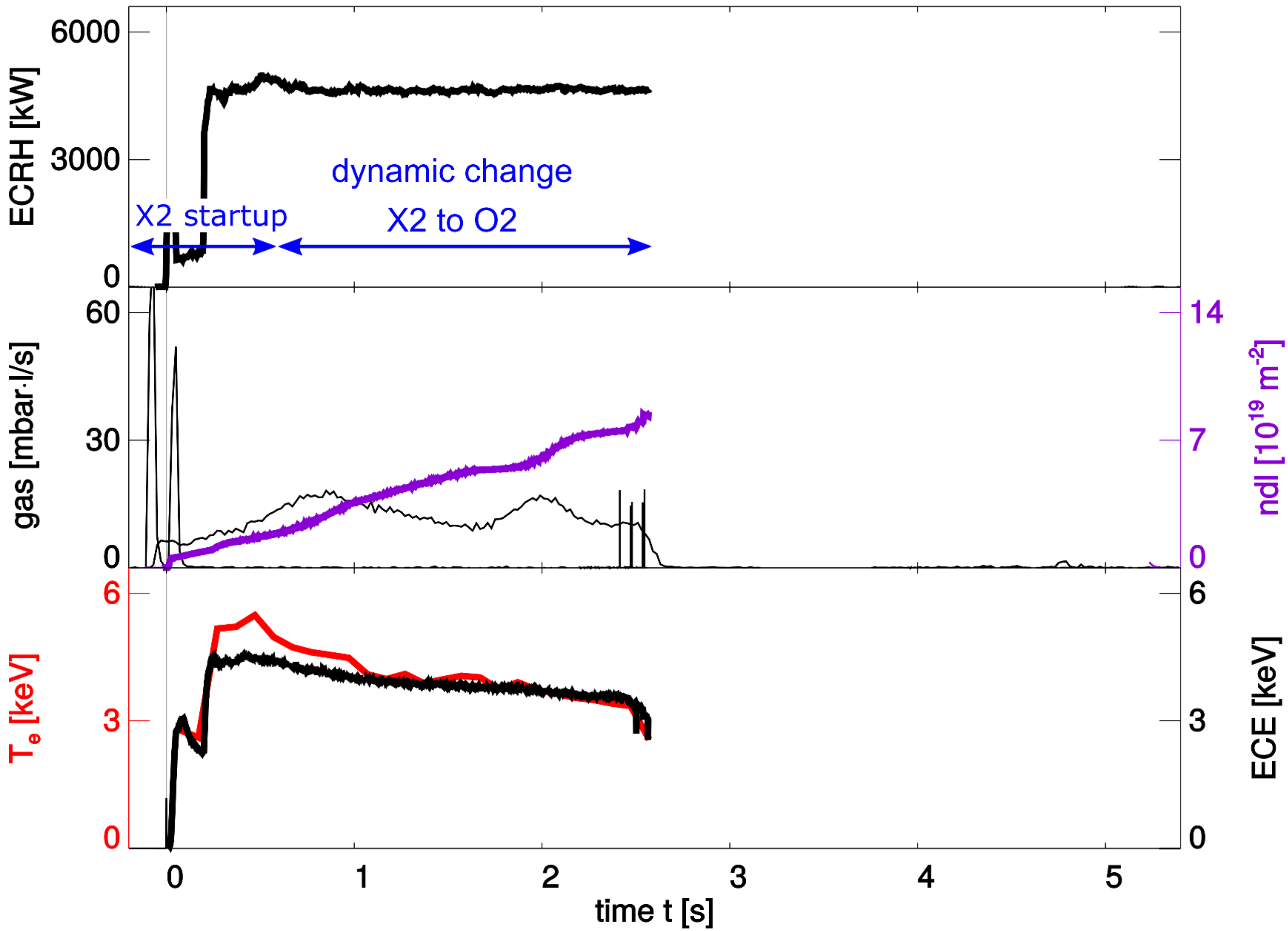


O2 core ECR Heating

could be extended to steady state

- X2 plasma startup
- dynamic change of polarization from X2 to O2
- O2 power increase

⇨ discharge maintained by O2 heating only



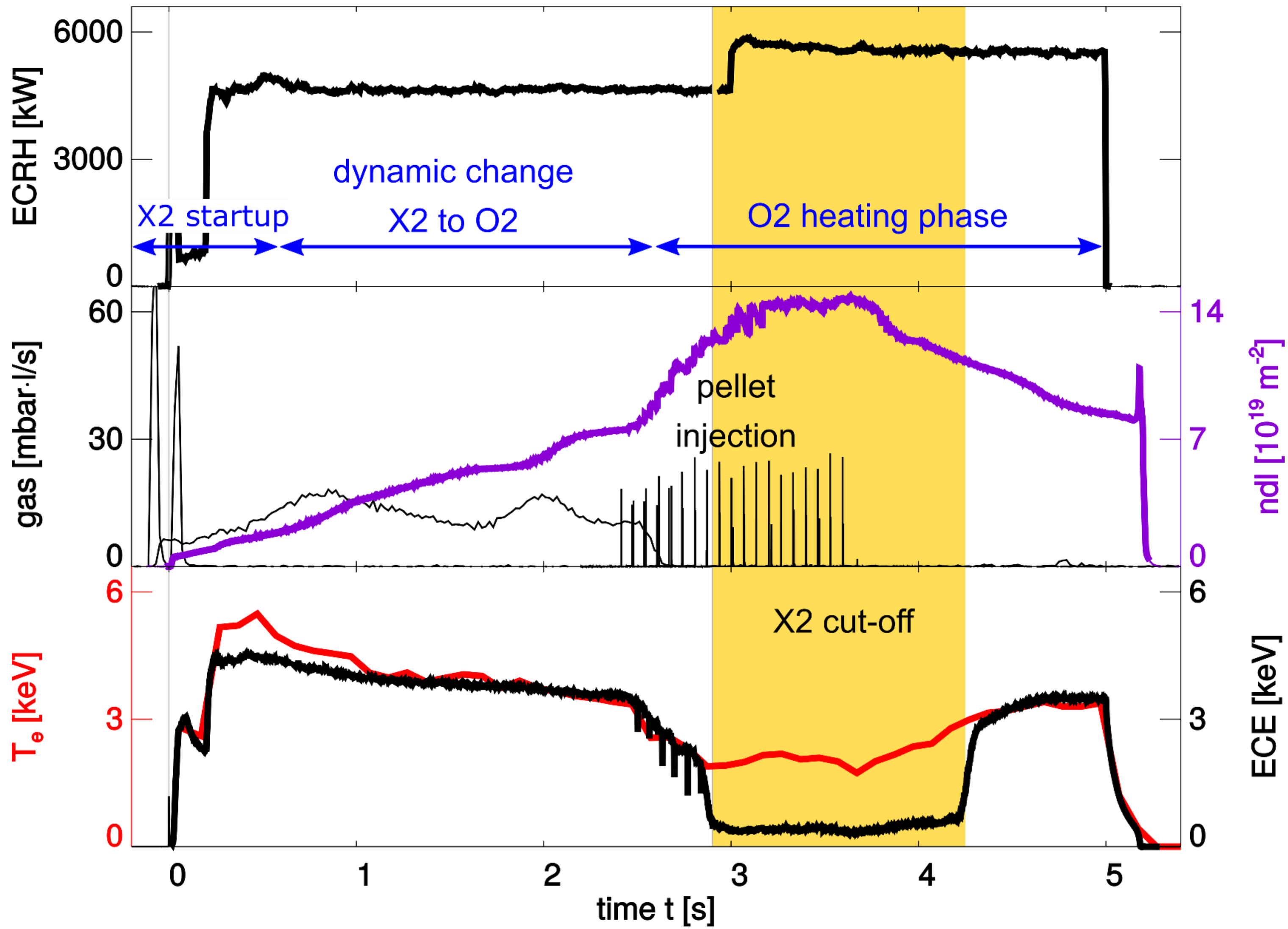
O2 core ECR Heating (and peaked ne profiles)

could be extended to steady state ??

- X2 plasma startup
- dynamic change of polarization from X2 to O2
- O2 power increase

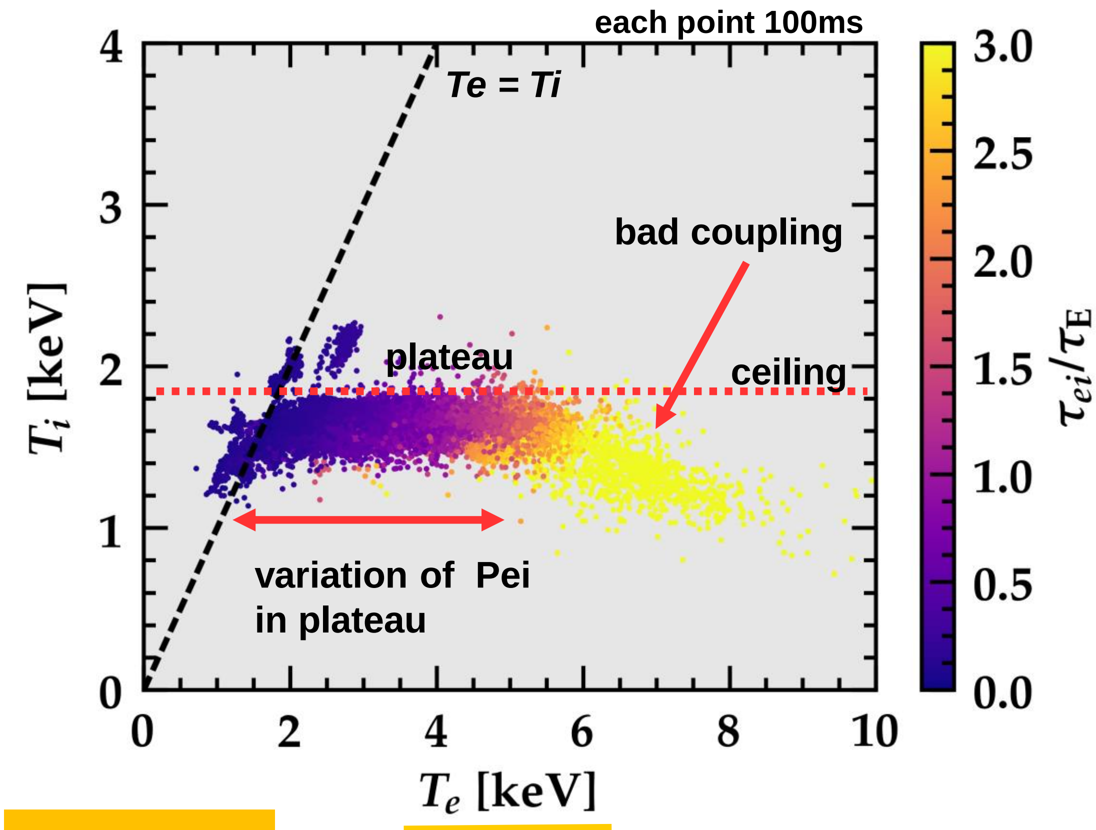
⇨ discharge maintained by O2 heating only

⇨ plasma density increase by pellet injection above X2 cut-off



ion temperatures are clamped

Beurskens et al NF_2019
Bozhenkov et al NF 2019

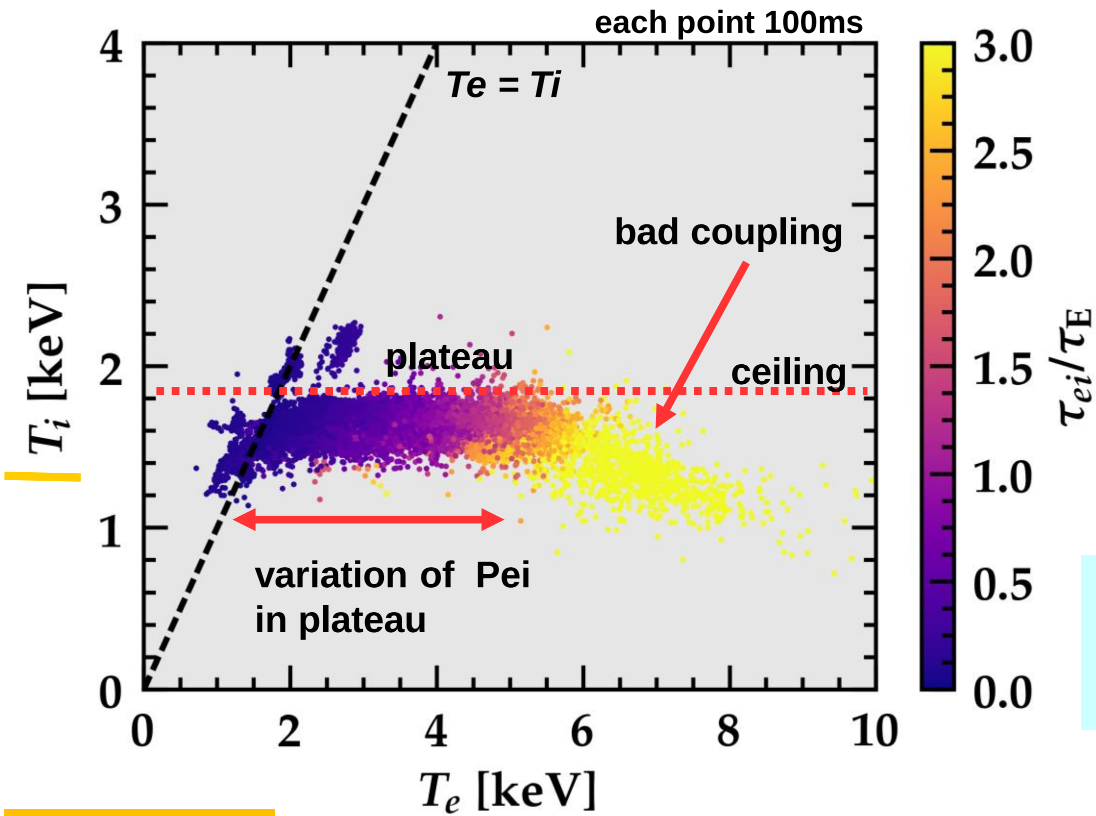


electrons

-> direct electron heating by (up tp 7.3MW ECRH) provides up to Te=10keV

steady state achievements: ion temperature clamping

Beurskens et al NF_2019
Bozhenkov et al NF 2019



τ_{e-i} = 0.06 x $T_e^{3/2}/n_e$

P_{e-i} = 3/2 x n_e x (T_e-T_i) / τ_{e-i}
= 0.1 x n_e^2 x (T_e-T_i) /$T_e^{3/2}$

ions

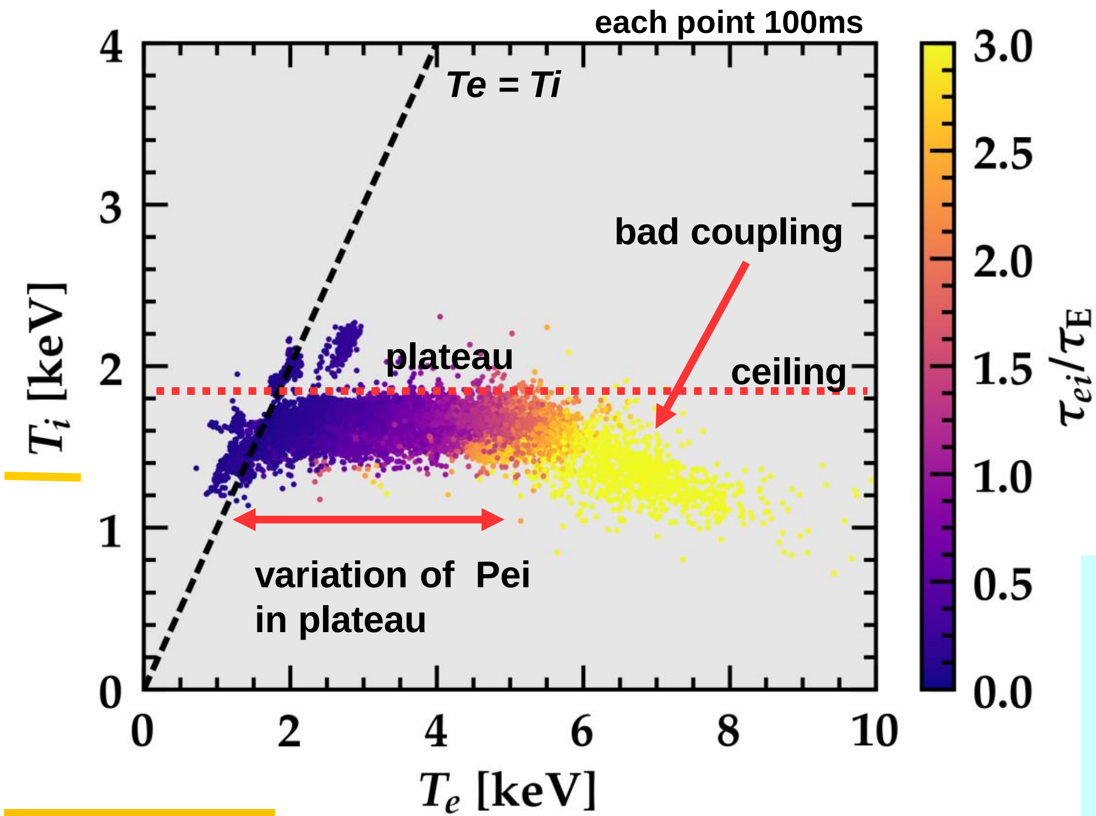
-> anomalous transport (ITG turbulence?) clamps Ti and inhibits to reach neoclassical levels

electrons

-> direct electron heating by (up tp 7.3MW ECRH) provides up to Te=10keV

ion temperature clamping

Beurskens et al NF_2019
Bozhenkov et al NF 2019



weak influence of the configuration <-> neoclassics

$\tau_{e\text{-}i} = 0.06 \times T_e^{3/2}/n_e$

$P_{e\text{-}i} = 3/2 \times n_e \times (T_e\text{-}T_i) / \tau_{e\text{-}i}$

$= 0.1 \times n_e^2 \times (T_e\text{-}T_i) / T_e^{3/2}$

electrons

-> direct electron heating by (up tp 7.3MW ECRH) provides up to Te=10keV

ions

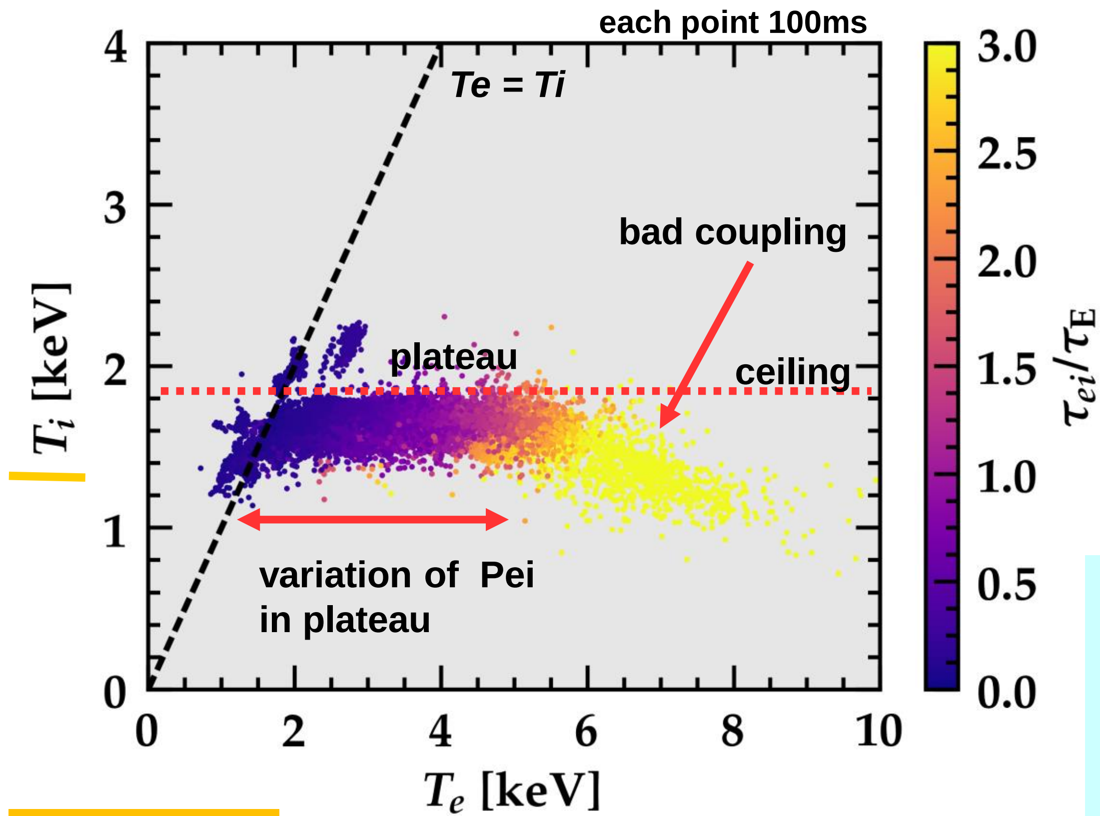
-> anomalous transport (ITG turbulence?) clamps Ti and inhibits to reach neoclassical levels

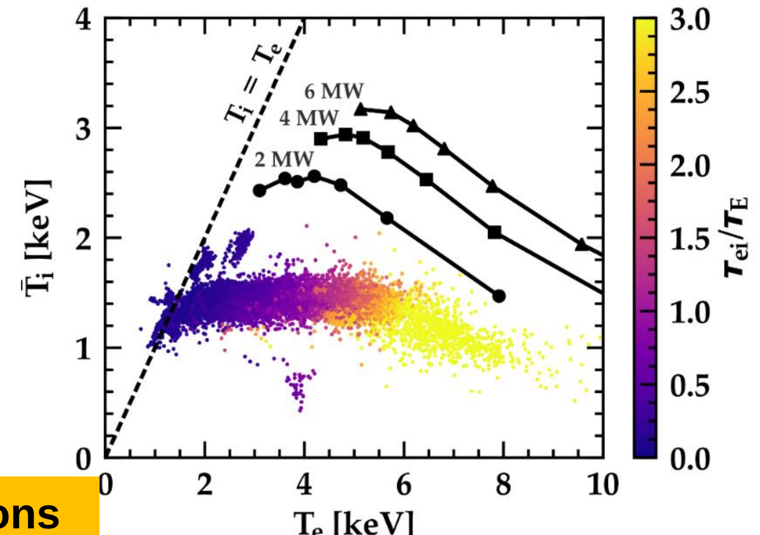
-> calculated neo-classical enery fluxes are well below the observed ones (30% stationary, 60% transient)

-> in classical stellarators similar parameters require much more heating power (e.g. W7-AS ~ factor 2) (optimization ?)

ion temperature clamping

Beurskens et al NF_2019
Bozhenkov et al NF 2019





electrons

-> direct electron heating by (up tp 7.3MW ECRH) provides up to Te=10keV

ions

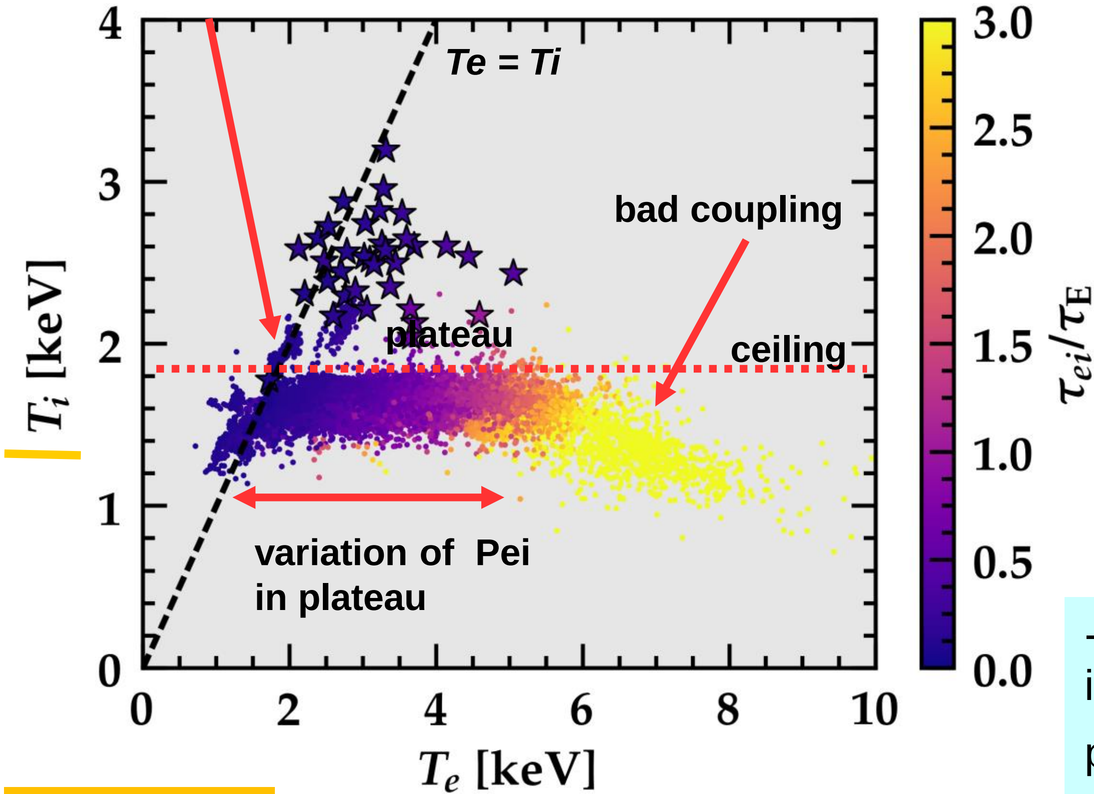
-> anomalous transport (ITG turbulence?) clamps Ti and inhibits to reach neoclassical levels

-> calculated neo-classical enery fluxes are well below the observed ones (30% stationary, 60% transient)

-> in classical stellarators similar parameters require much more heating power (e.g. W7-AS ~ factor 2) (optimization ?)

ion temperature clamping

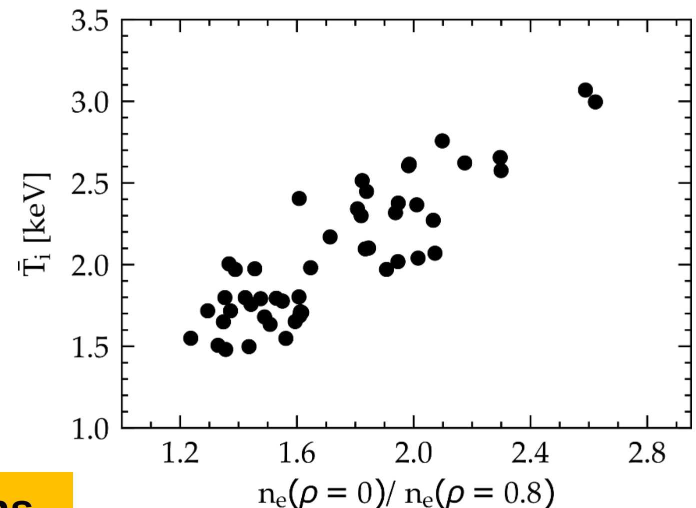
peaked density profiles
(only at low ECRH power)



electrons

-> direct electron heating by (up tp 7.3MW ECRH) provides up to Te=10keV

Beurskens et al NF_2019
Bozhenkov et al NF 2019



ions

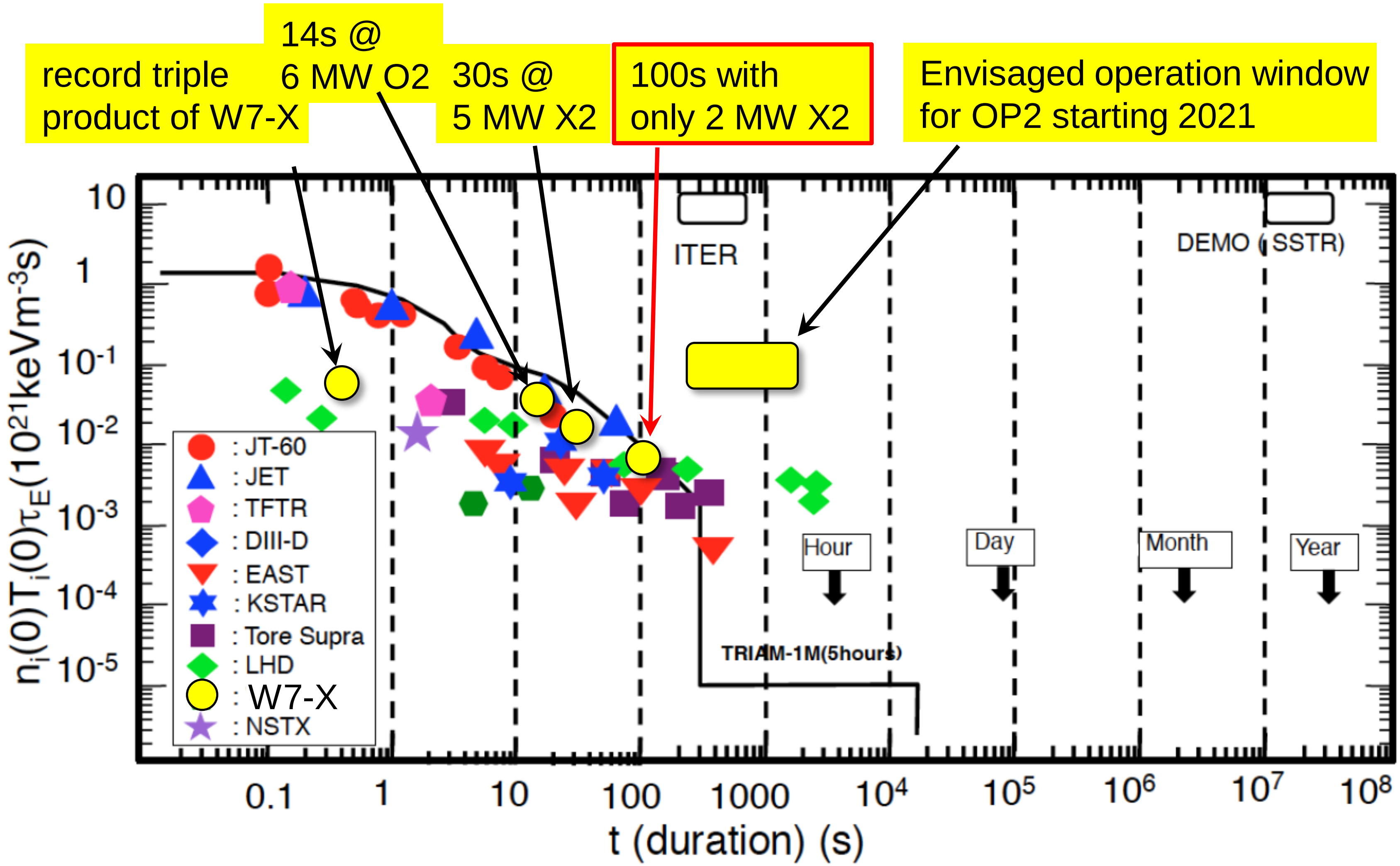
-> peaked density profiles provide transiently improved ion confinement

peaking of the density profile achived by deep fuelling and low edge densities

- -> pellets
- -> sufficient NBI heating
- -> or off-axis ECRH (?)

towards long-pulse operation (status OP1.2b)

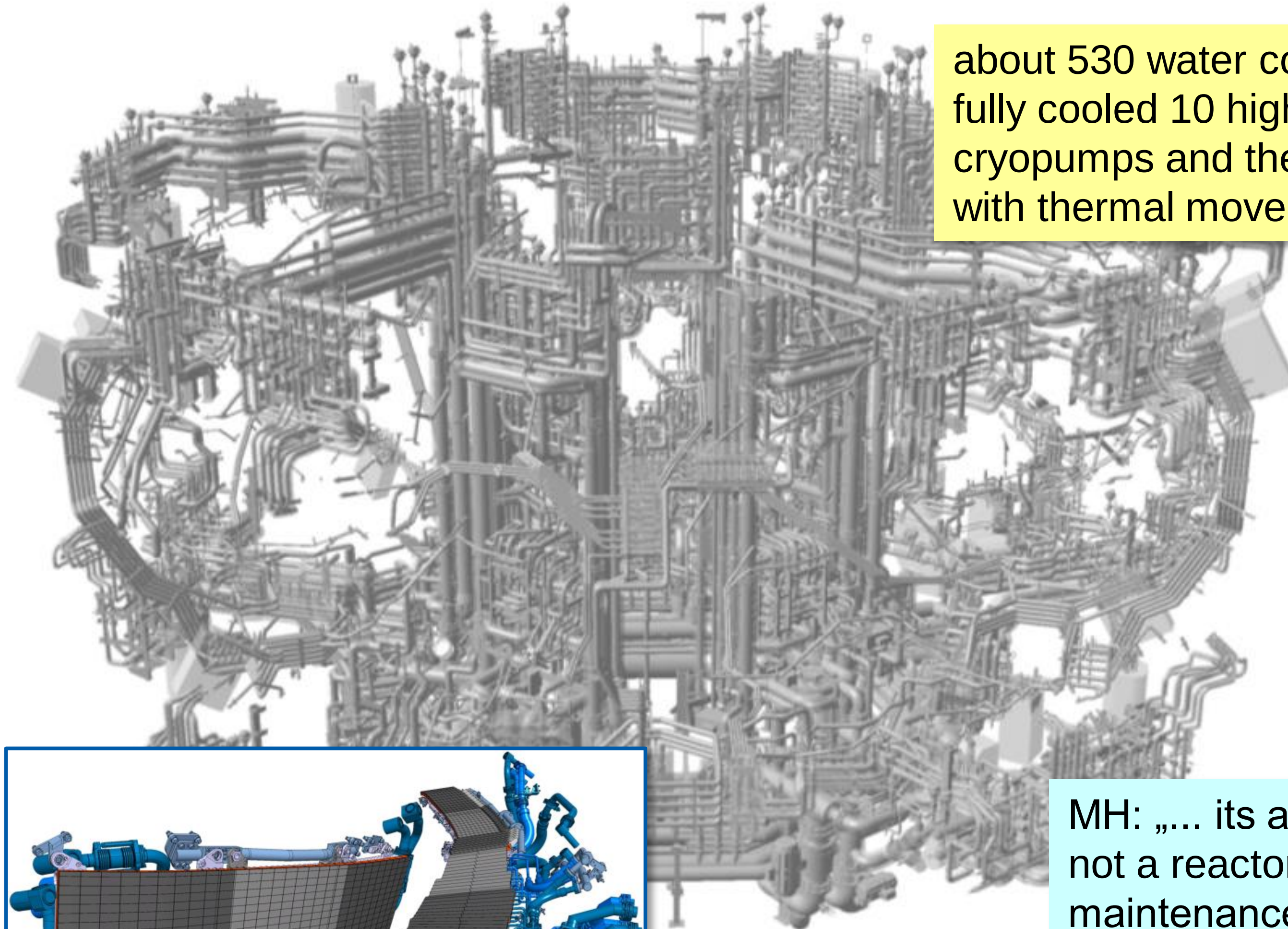
W7-X already broke all stellarator records



Courtesy of M. Kikuchi

T. Sunn Pedersen et al, Phys. Plasmas 24 (2017) 055503

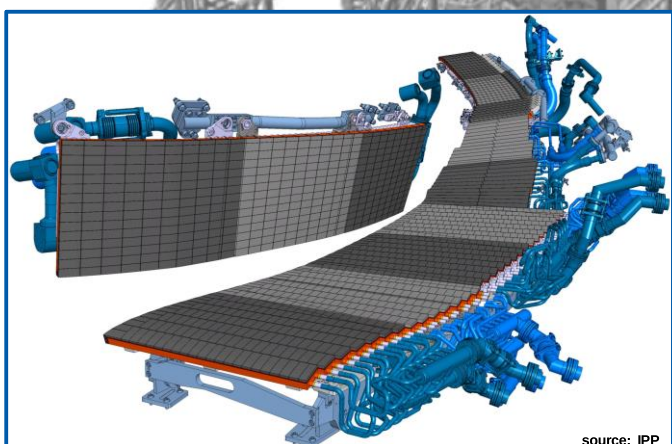
engineering complexity – Completion Phase 2 (at present)



about 530 water cooling circuits for the fully cooled 10 high-heatflux divertors, 10 cryopumps and the first wall. -> issues with thermal movements, vacuum ..

MH: „... its an experiment with high flexibility not a reactor for reliable operation and easy maintenance .... „

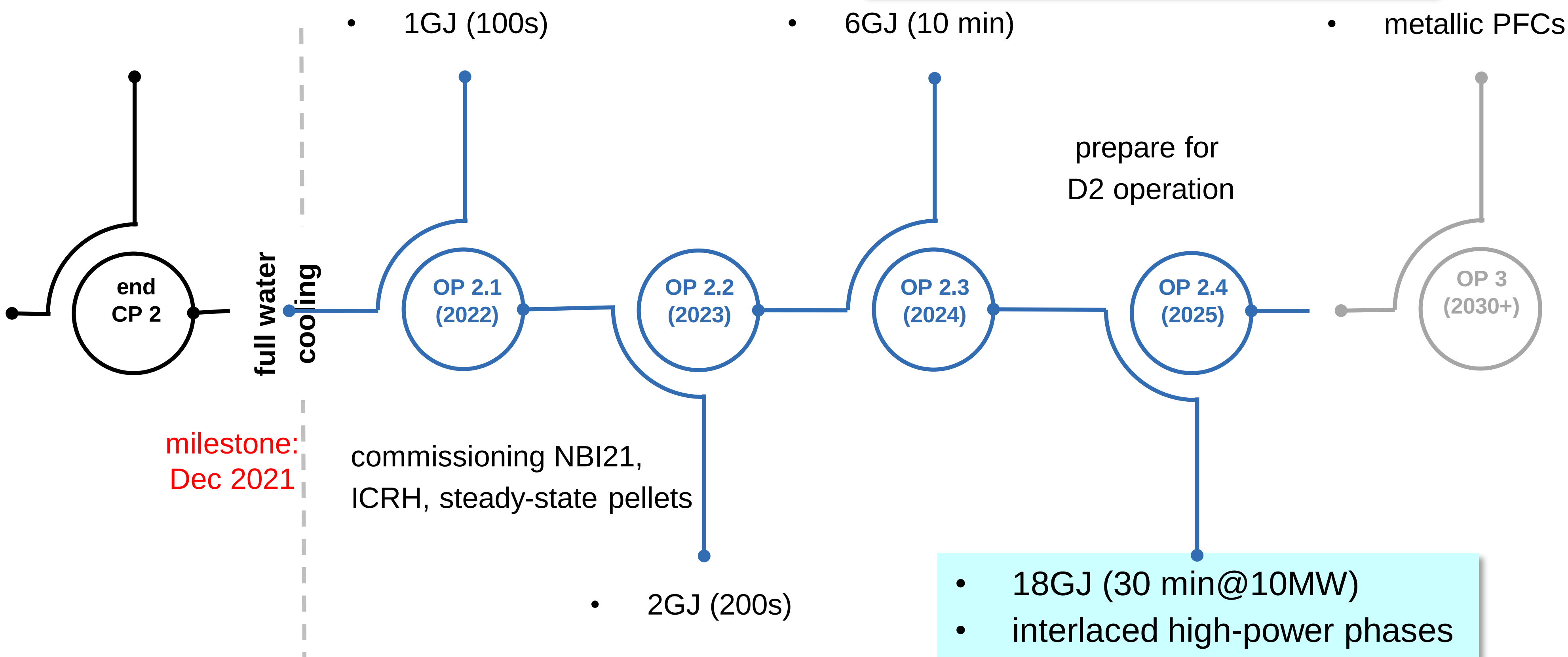
Note : The optimization was with respect to the magnetic field – nor for operability !



Operational Phase 2

finalization of long-pulse capability

development of full metal machine
...



Heating extension: development 2MW gyrotrons -> PECRH ~14 MW cw
-> NBI ~ 9MW (in H_2) for ~10s
-> ICRH for start-up + fast particles

finally : thank you for yor interest .... and offering a Hybrid

S. A. Henneberg et al Nucl. Fusion 58 026014