MAX-PLANCK-GESELLSCHAFT

PPPL Colloquium

IPP Max-Planck-Institut für Plasmaphysik

Steady-State Operation of Fusion Plasmas
- the Stellarator Project Wendelstein 7-X

Thomas Klinger
Max-Planck Institute for Plasma Physics

on behalf of the

enterprise Wendelstein 7-X

Introductory comments

steady-state operation: this is likely to be a requirement in a future FPP

Tokamak steady-state operation is a subject of current research

- β_N~4 required - achieved only with advanced tokamak scenarios (ITB‘s)
- Control of pressure profiles, current profiles and instabilities required
- Several 100MW of CD required – efficiency only 20-40% must go up

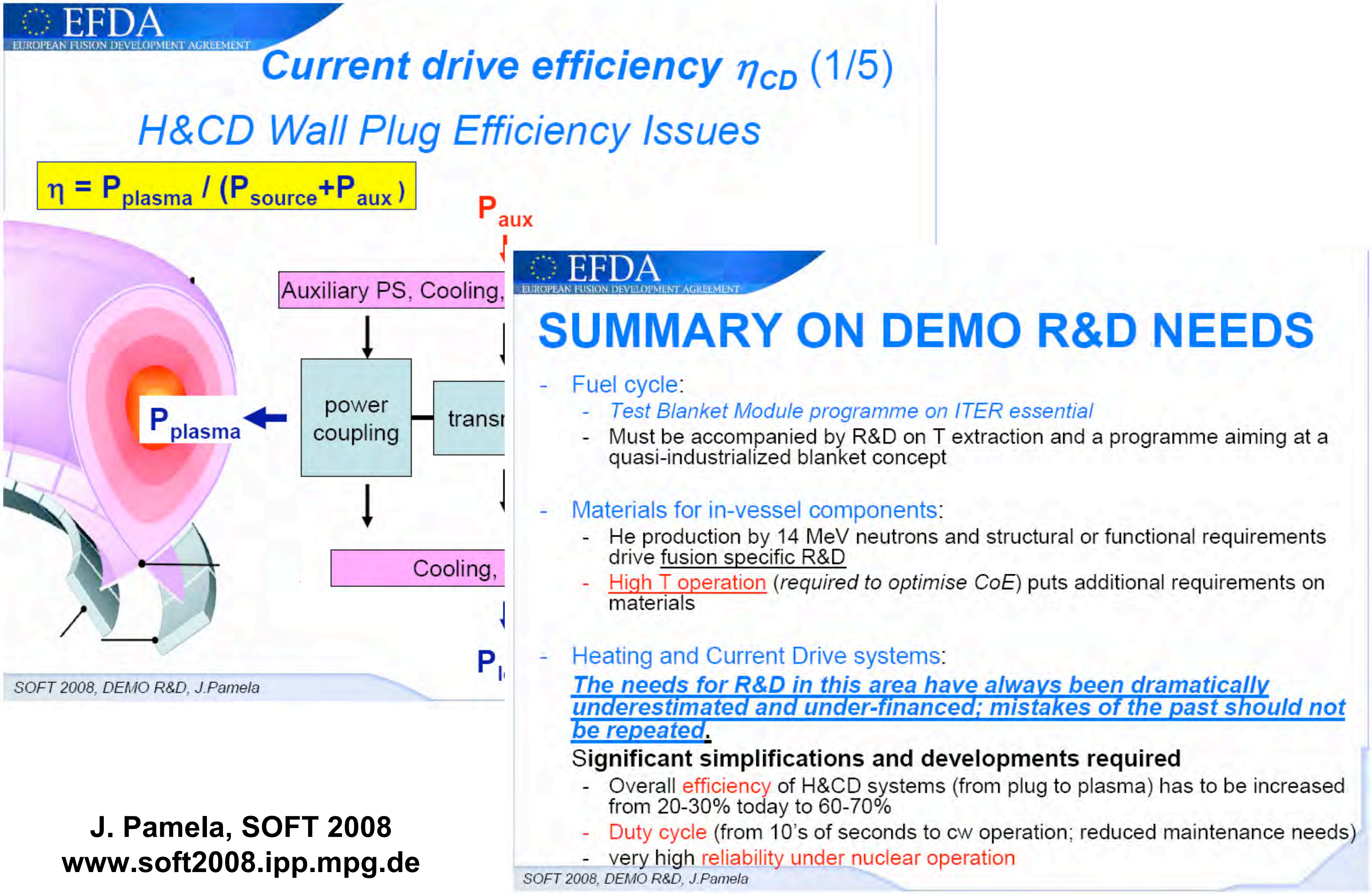
Stellarators are steady-state „by nature“

- The control issue is much less a problem – only weak CD needed
- Plasma performance not yet satisfactory (esp. τ_E and β)
- Divertor solution and control of impurities required

Several technologies must be developed in general

- Superconducting magnets (also HTSCs)
- Steady-state H&CD solutions
- Steady-state capable in-vessel components
- The right materials in general

Introductory comments



EFDA
EUROPEAN FUSION DEVELOPMENT AGREEMENT

Current drive efficiency η_{CD} (1/5)

H&CD Wall Plug Efficiency Issues

$\eta = P_{plasma} / (P_{source}+P_{aux})$

SOFT 2008, DEMO R&D, J.Pamela

EFDA
EUROPEAN FUSION DEVELOPMENT AGREEMENT

SUMMARY ON DEMO R&D NEEDS

- Fuel cycle:
  - *Test Blanket Module programme on ITER essential*
  - Must be accompanied by R&D on T extraction and a programme aiming at a quasi-industrialized blanket concept
- Materials for in-vessel components:
  - He production by 14 MeV neutrons and structural or functional requirements drive fusion specific R&D
  - High T operation (*required to optimise CoE*) puts additional requirements on materials
- Heating and Current Drive systems:

  ***The needs for R&D in this area have always been dramatically underestimated and under-financed; mistakes of the past should not be repeated*.**

  Significant simplifications and developments required
  - Overall efficiency of H&CD systems (from plug to plasma) has to be increased from 20-30% today to 60-70%
  - Duty cycle (from 10's of seconds to cw operation; reduced maintenance needs)
  - very high reliability under nuclear operation

SOFT 2008, DEMO R&D, J.Pamela

J. Pamela, SOFT 2008
www.soft2008.ipp.mpg.de

Outline of the talk

I. Principles

II. Island divertor

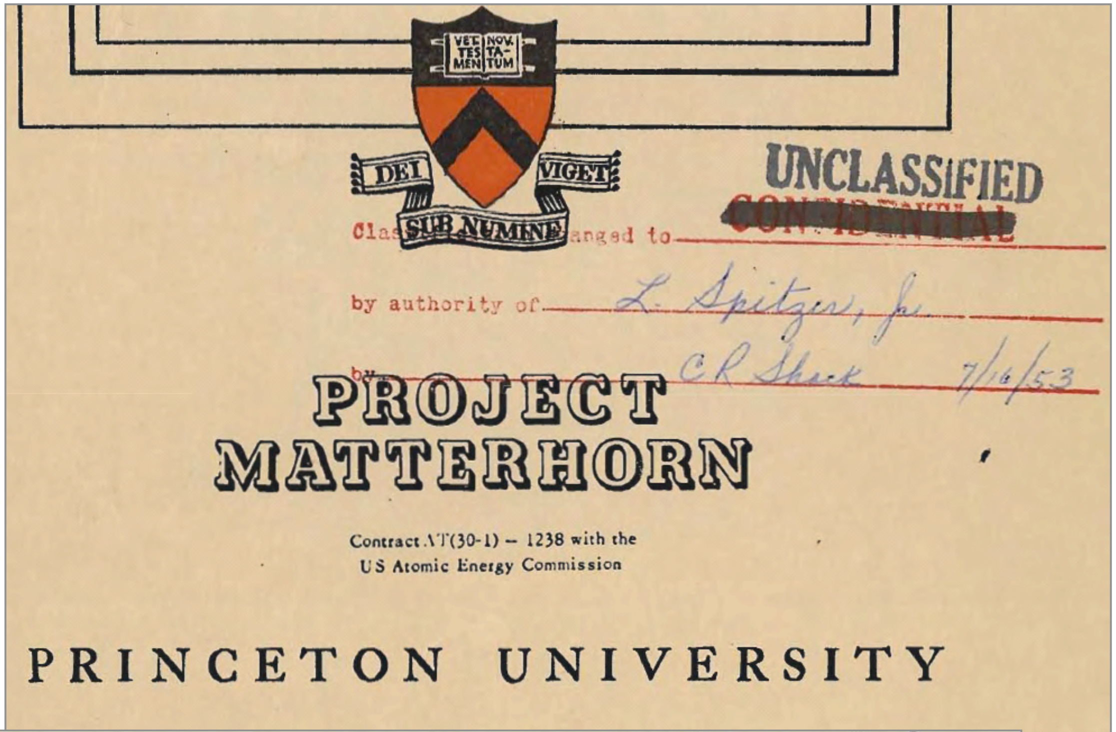
III. Plasma currents

IV. Performance

V. Construction status

Steady-state – a stellarator feature

In stellarators steady state operation is taken for granted.



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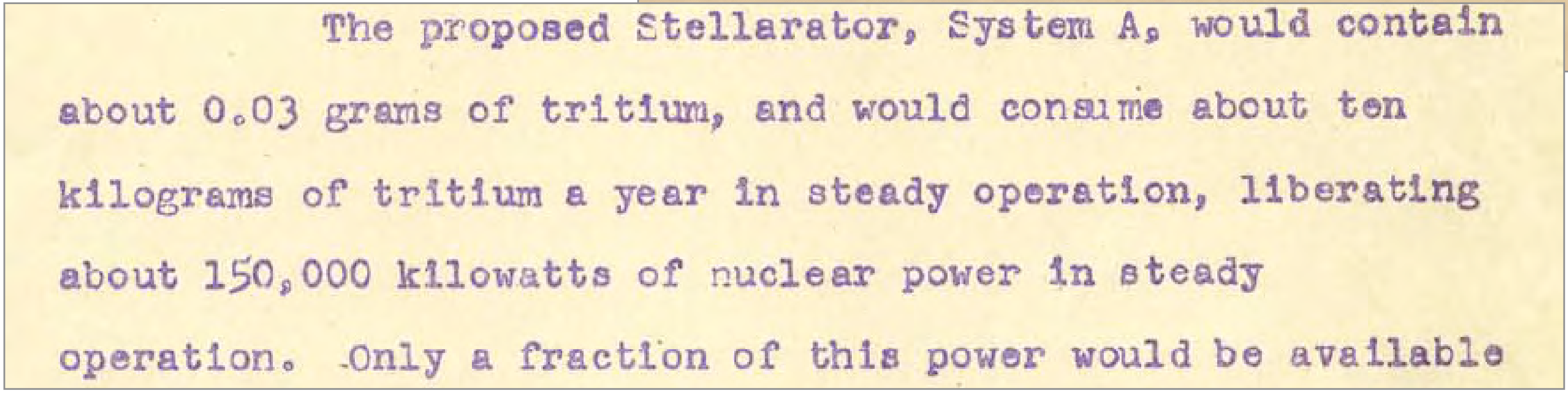
by authority of L. Spitzer, Jr.

by C R Sheck 7/16/53

PROJECT MATTERHORN

Contract AT(30-1) – 1238 with the
US Atomic Energy Commission

PRINCETON UNIVERSITY

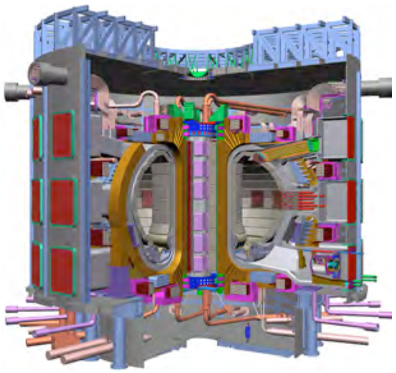


The proposed Stellarator, System A, would contain about 0.03 grams of tritium, and would consume about ten kilograms of tritium a year in steady operation, liberating about 150,000 kilowatts of nuclear power in steady operation. Only a fraction of this power would be available

Tokamak and Stellarator

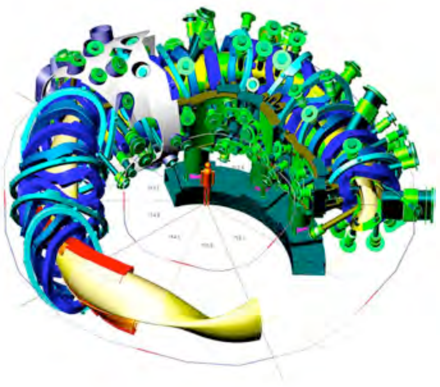
A very schematic comparison …

- current in coils and plasma
- current-carrying plasma
- self-organized equilibrium



- ✣ good neoclassical confinement
- ✣ toroidal symmetry
- ✧ advanced scenarios and current drive
- ✧ active control of plasma instabilities

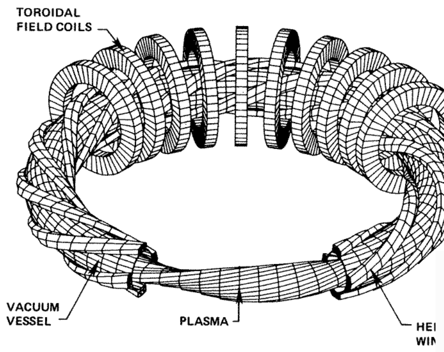
- current in the coils only
- very small plasma current
- field-defined equilibrium

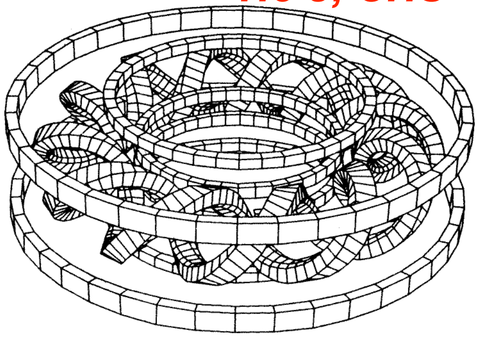


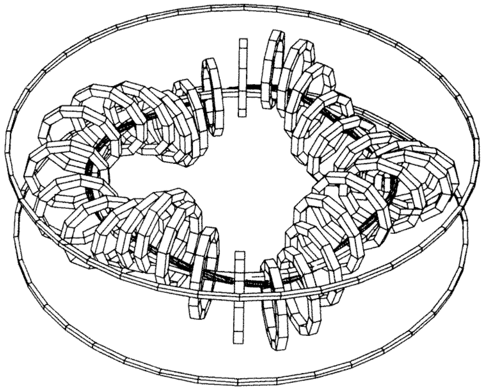
- ✣ good neoclassical confinement
- ✧ quasisymmetry
- ✣ steady state operation
- ✣ no current driven instabilities

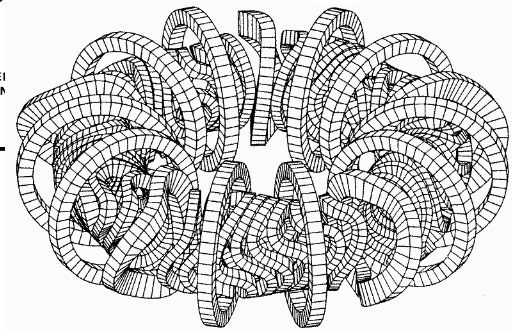
The stellarator family

- **Stellarators**
  - classical
    - *C,Cleo,W7-A, L2, WEGA*
  - modular
    - advanced
      - *W7-AS*
    - quasi-symmetric
      - q-helical
        - *HS*
        - *X*
      - q-axial
        - *NCSX*
        - *CHS-qa*
      - q-poloid.
        - *W7-X*
        - *QPS*
- **Torsatrons**
  - *ATF, CAT, URAGAN*
- **Heliotrons**
  - *He-E, LHD, He-J, CHS*
- **Heliacs**
  - *H1, TJ-II*







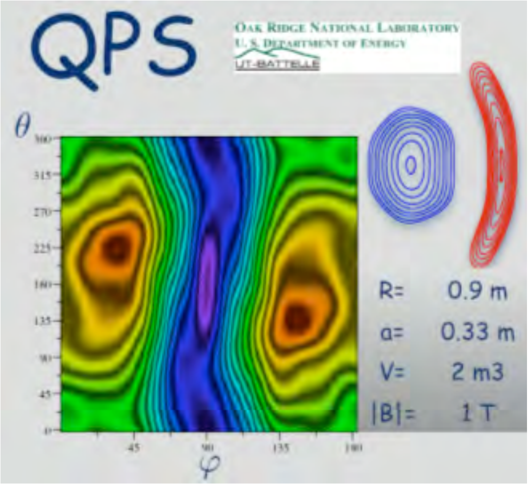


shut down
operating
under construction
planned

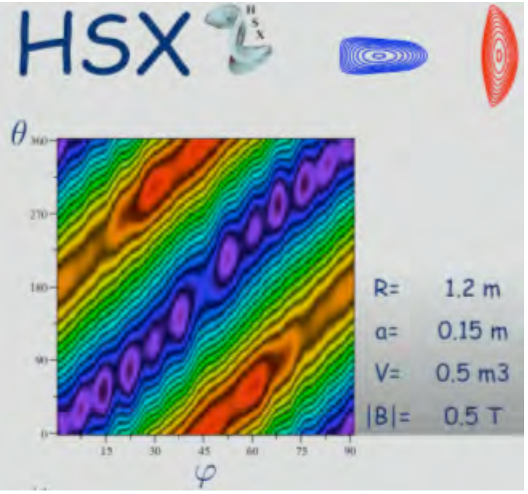
Stellarator symmetries

$|B|$

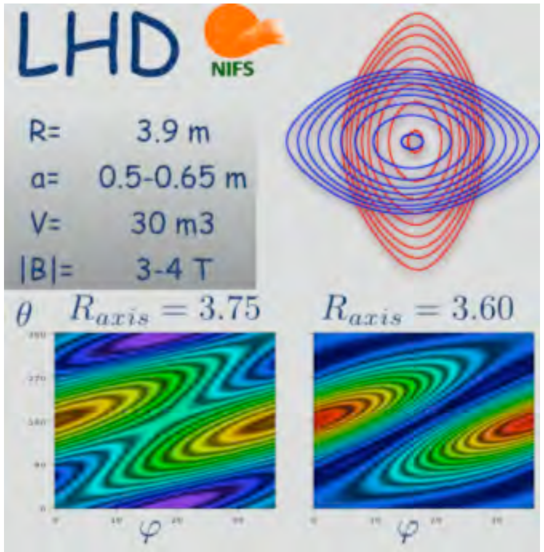
quasi-poloidal



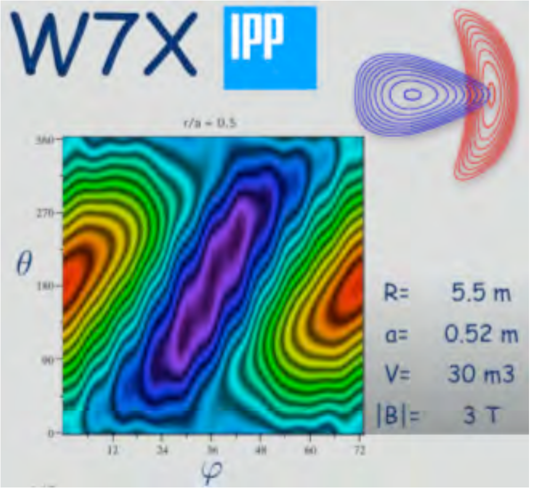
quasi-helical



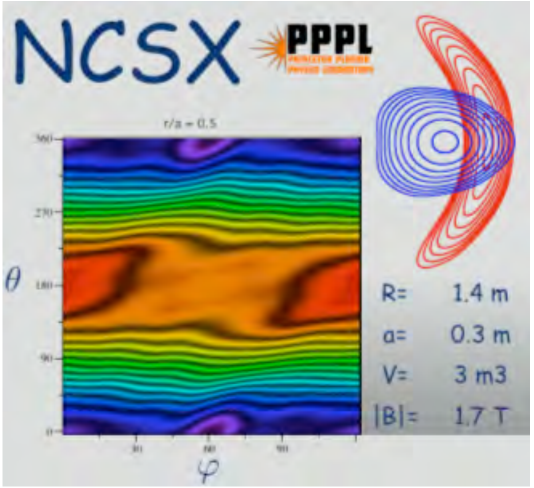
classical



quasi-isodynamic

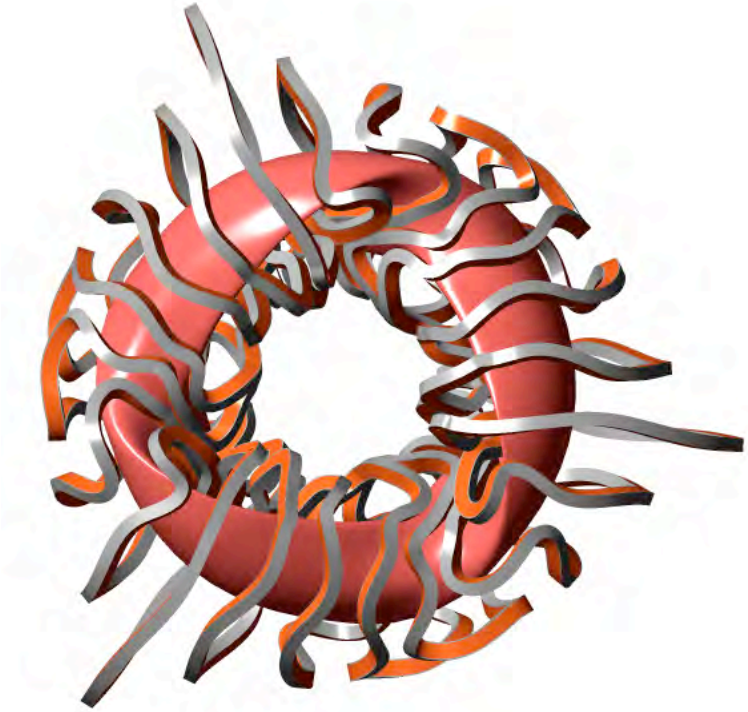


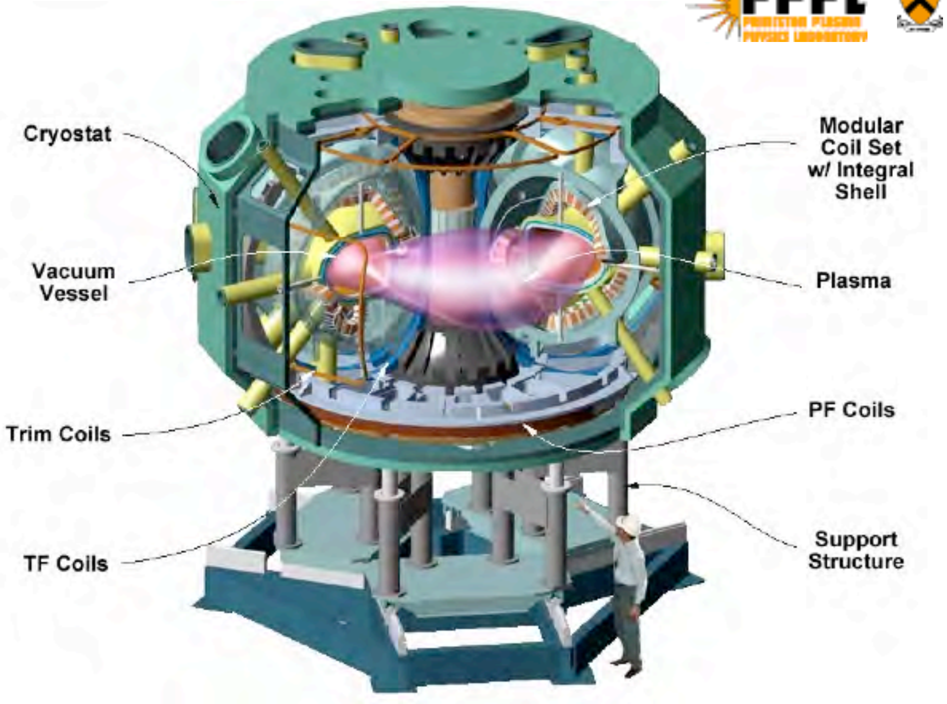
quasi-toroidal



by courtesy of J. Sanchez

A missing link

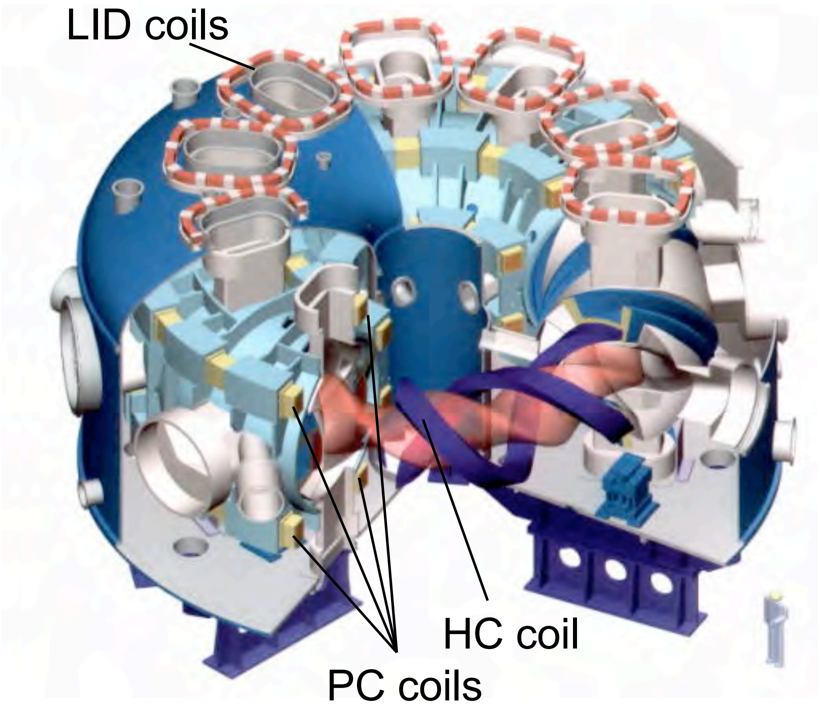


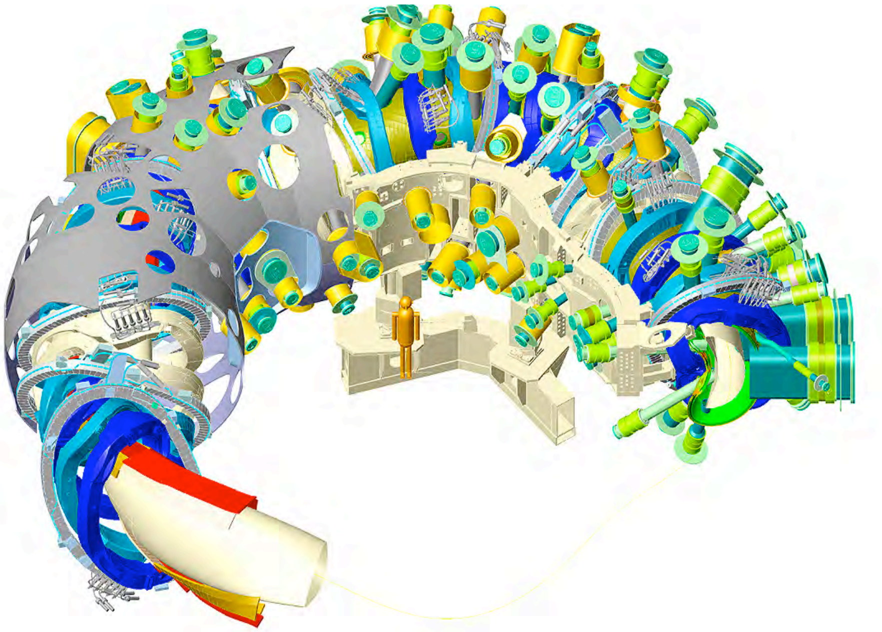


- **complete the physics understanding of quasi-symmetry**
- **development of compact stellarators**
- **a physics link to advanced tokamak operation**

- **let‘s advertise a revision of previous decisions**

LHD and W7-X





LHD

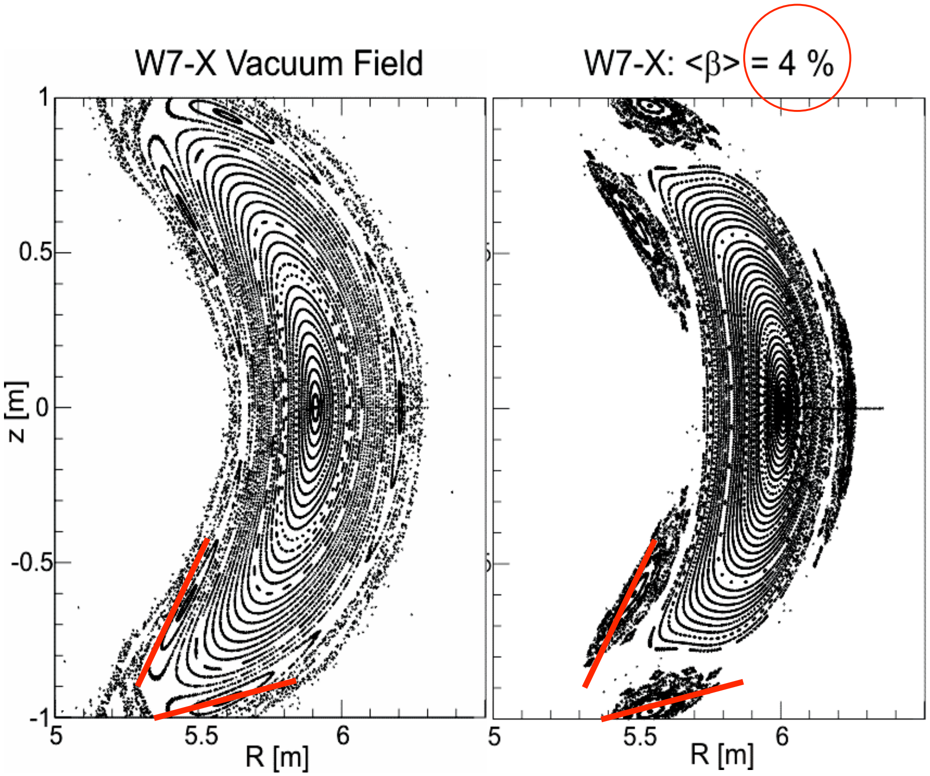
$R_{ax} = 3.4 – 4.1$ m, $a \leq 0.65$ m
$V_{pl} = 30m^3$
$B \leq 2.9$ T, $\iota(0) \geq 0.35$, $\iota(a) \leq 1.5$
high shear, 10 field periods, l = 2

W7-X

$R_{ax} = 5.5$ m, $a \leq 0.53$ m
$V_{pl} = 30m^3$
$B \leq 3.0$ T, $\iota(0) \geq 0.88$, $\iota(a) \leq 0.97$
low shear, 5 field periods

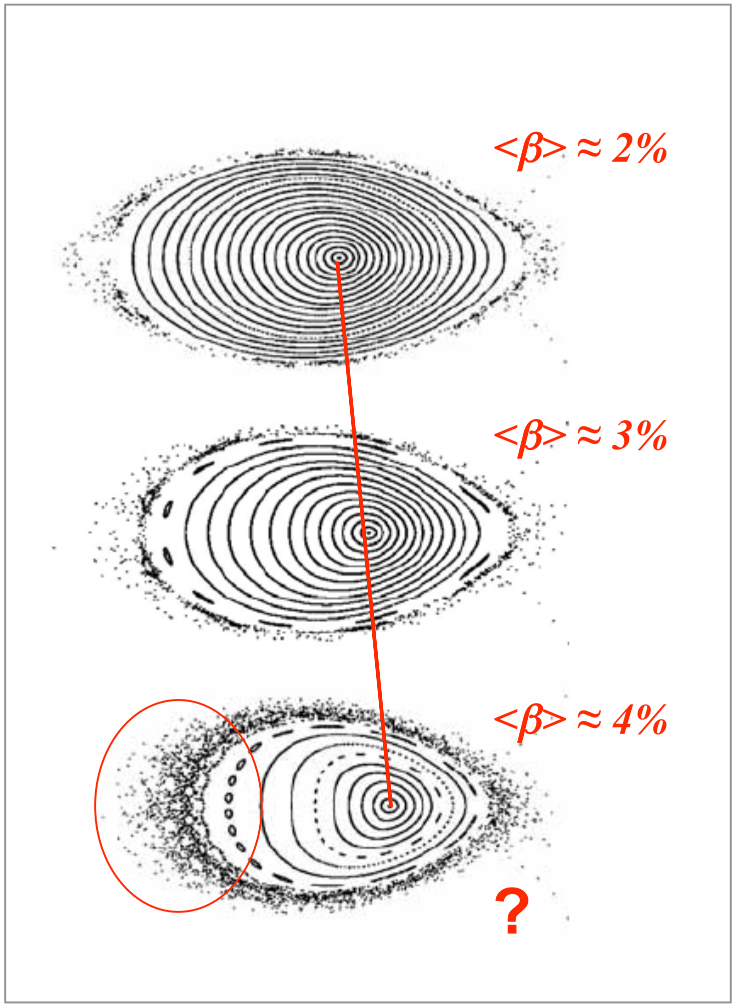
MHD equilibrium - comparison

W7-X (PIES-Code)

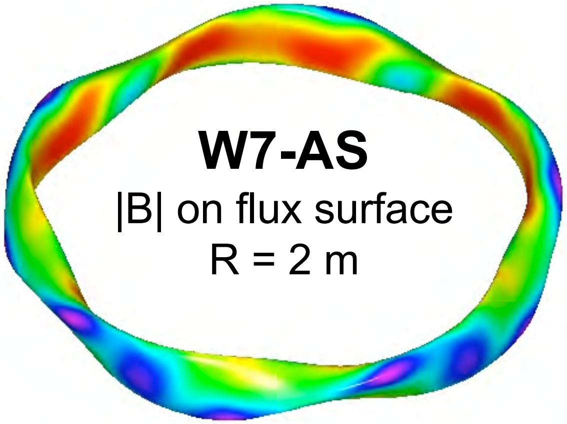


- **stable high-pressure equilibrium**
- **minimized stochastic layer formation**
- **required for reasonable divertor solution**

LHD (HINT-Code)



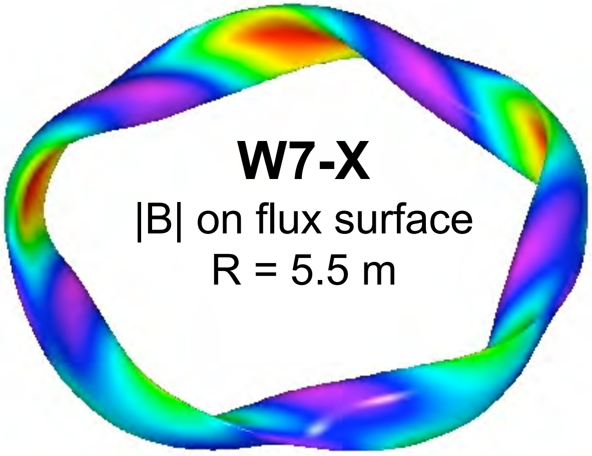
W7 & LHD magnetic configuration



W7-AS

|B| on flux surface

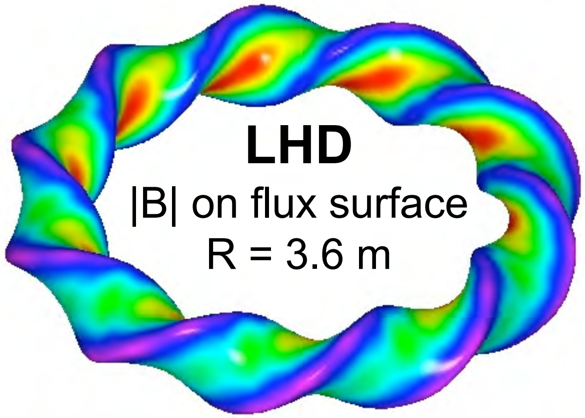
R = 2 m



W7-X

|B| on flux surface

R = 5.5 m

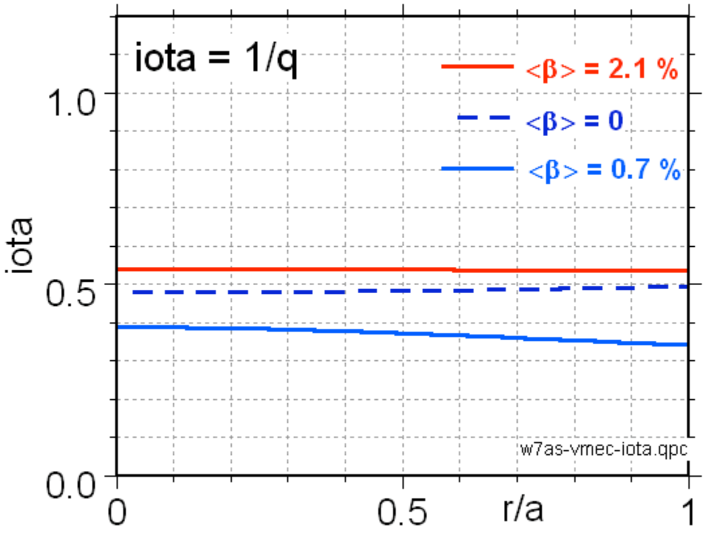


LHD

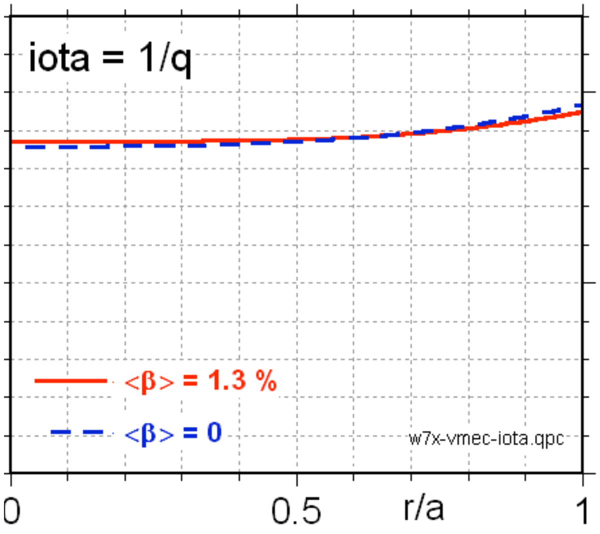
|B| on flux surface

R = 3.6 m

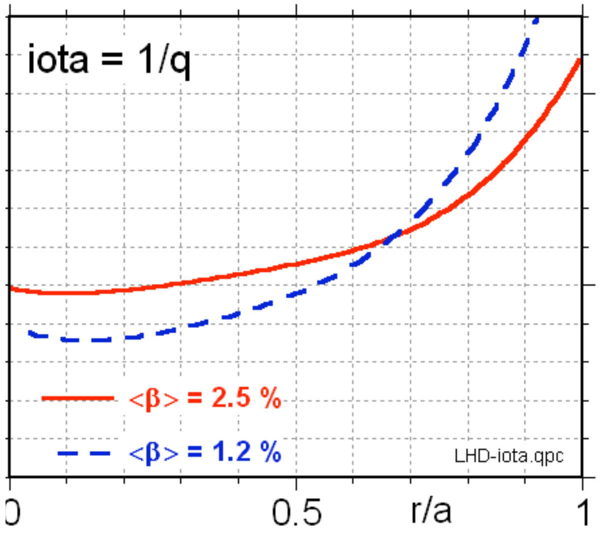
W7-AS iota-Profiles



W7-X iota-Profiles



LHD iota-Profiles



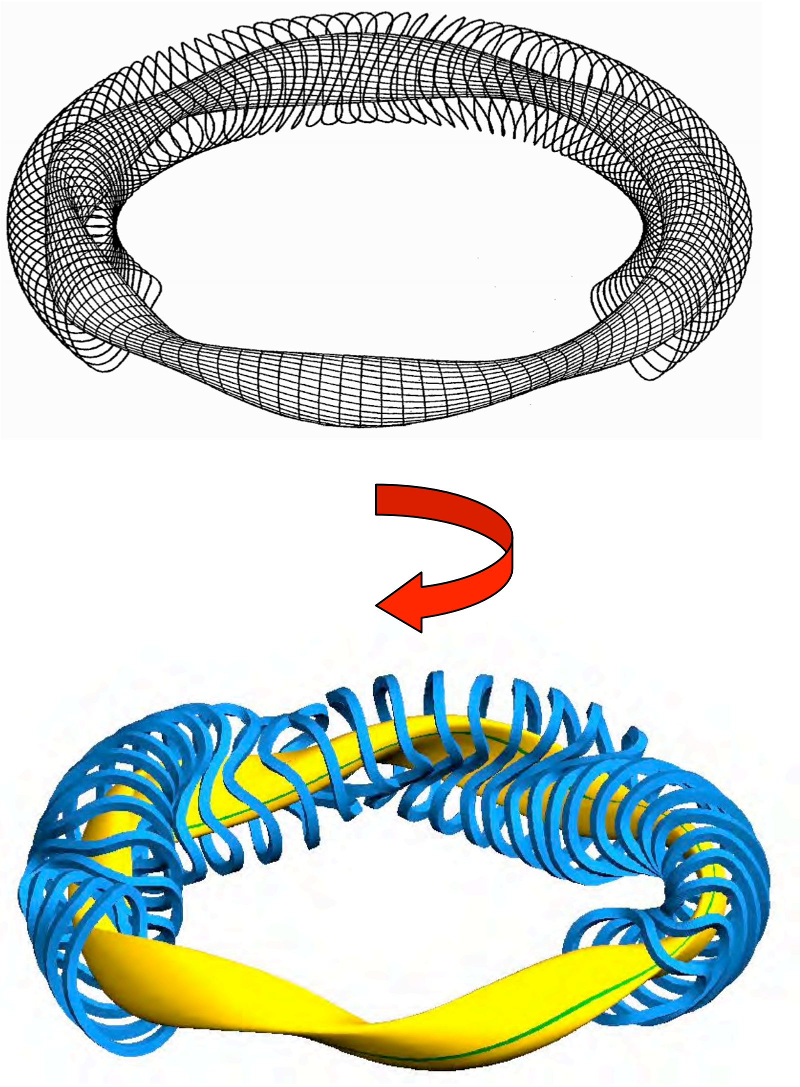
W7-line: avoid islands by low shear

LHD-heliotron: high shear, small islands

The optimized stellarator W7-X

7 optimization criteria

1. feasible modular coils
2. good, nested magnetic surfaces
3. good finite-β equilibria
4. good MHD stability
5. small neoclassical transport
6. small bootstrap current
7. good confinement of fast particles



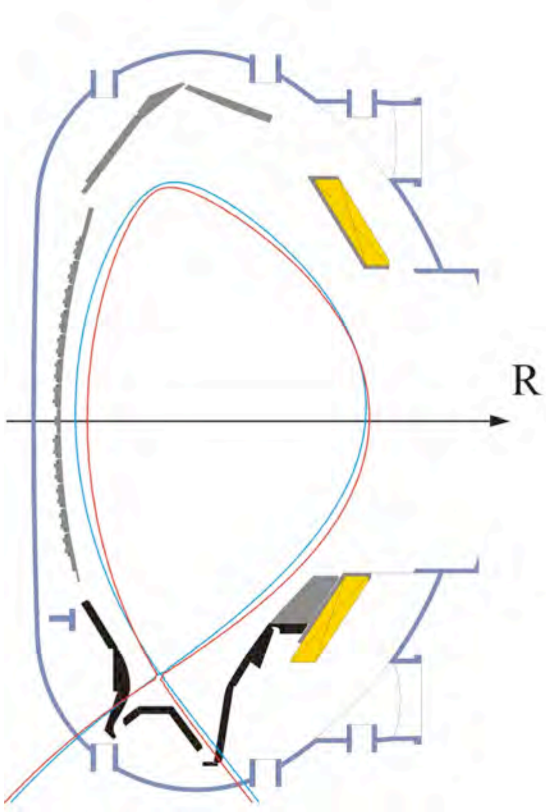
development tasks

1. optimum $nT\tau_E$ and high β discharges
2. steady state operation
3. plasma-wall interaction
4. island divertor operation
5. turbulent transport

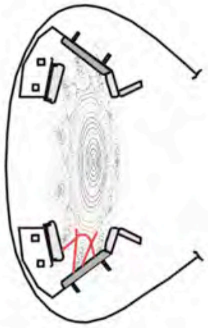
Island divertor – the idea

poloidal divertor

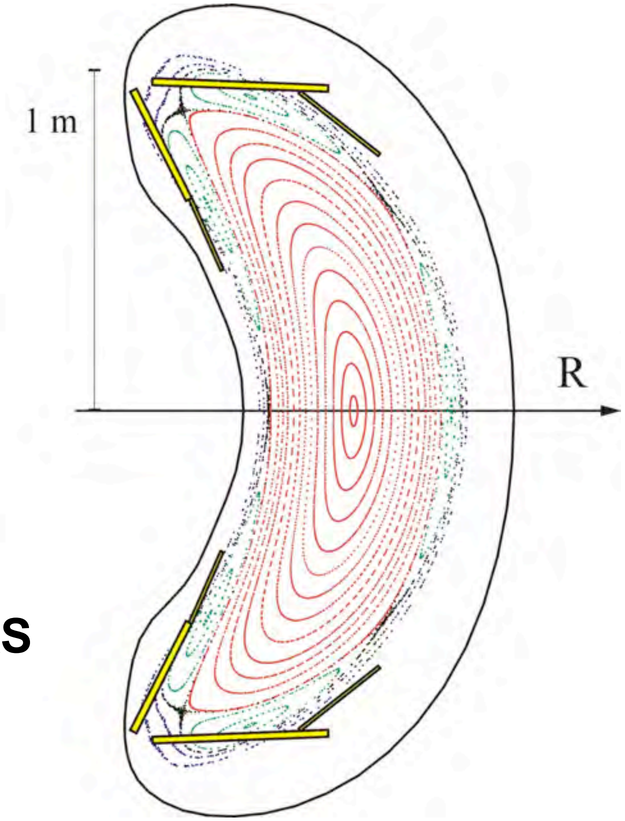
island divertor



ASDEX upgrade

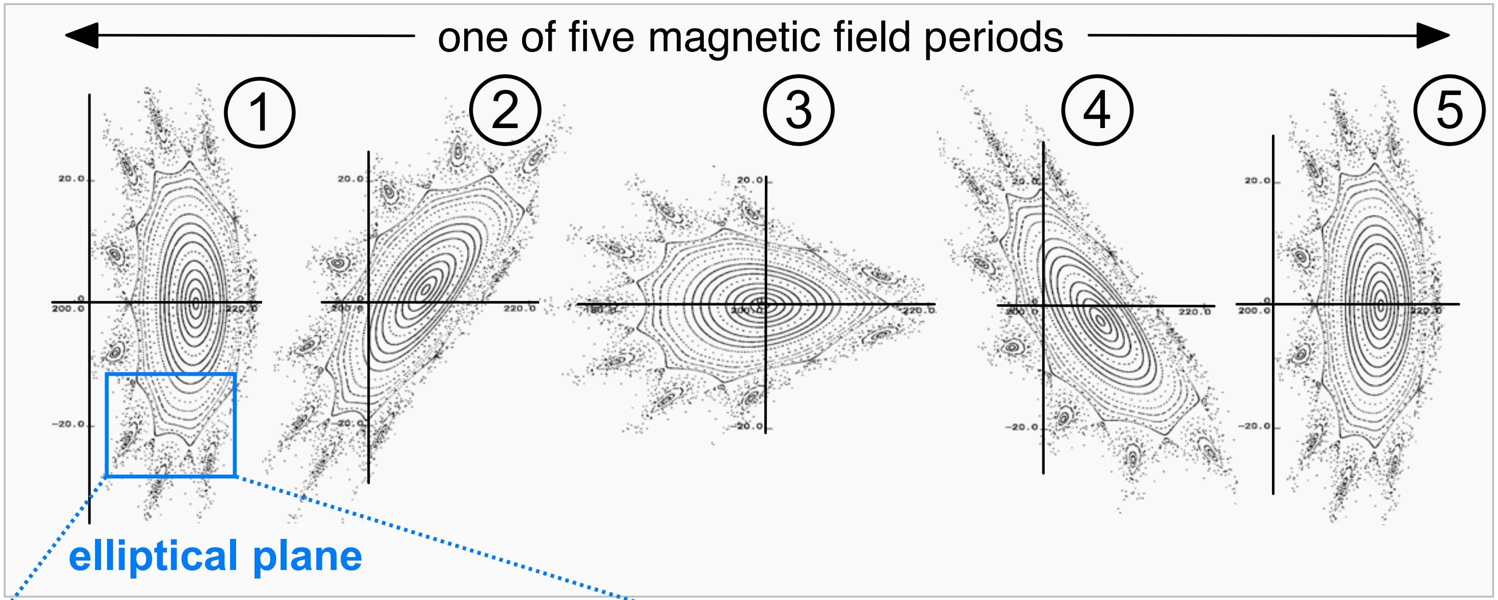


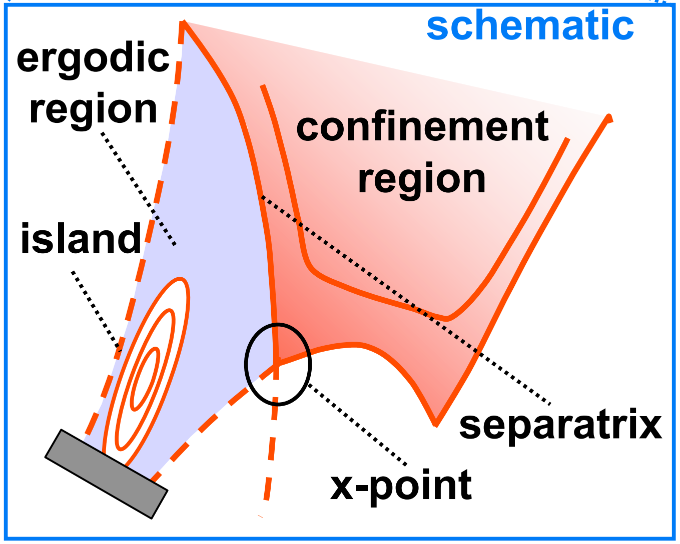
Wendelstein 7-AS



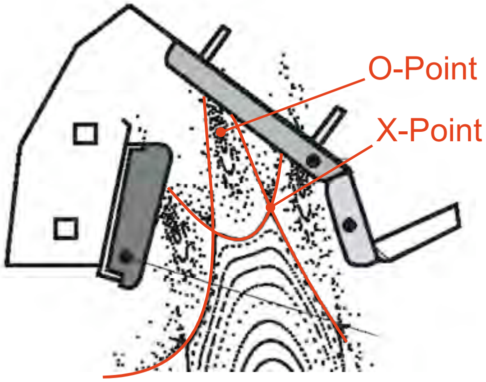
Wendelstein 7-X

The W7-AS island divertor



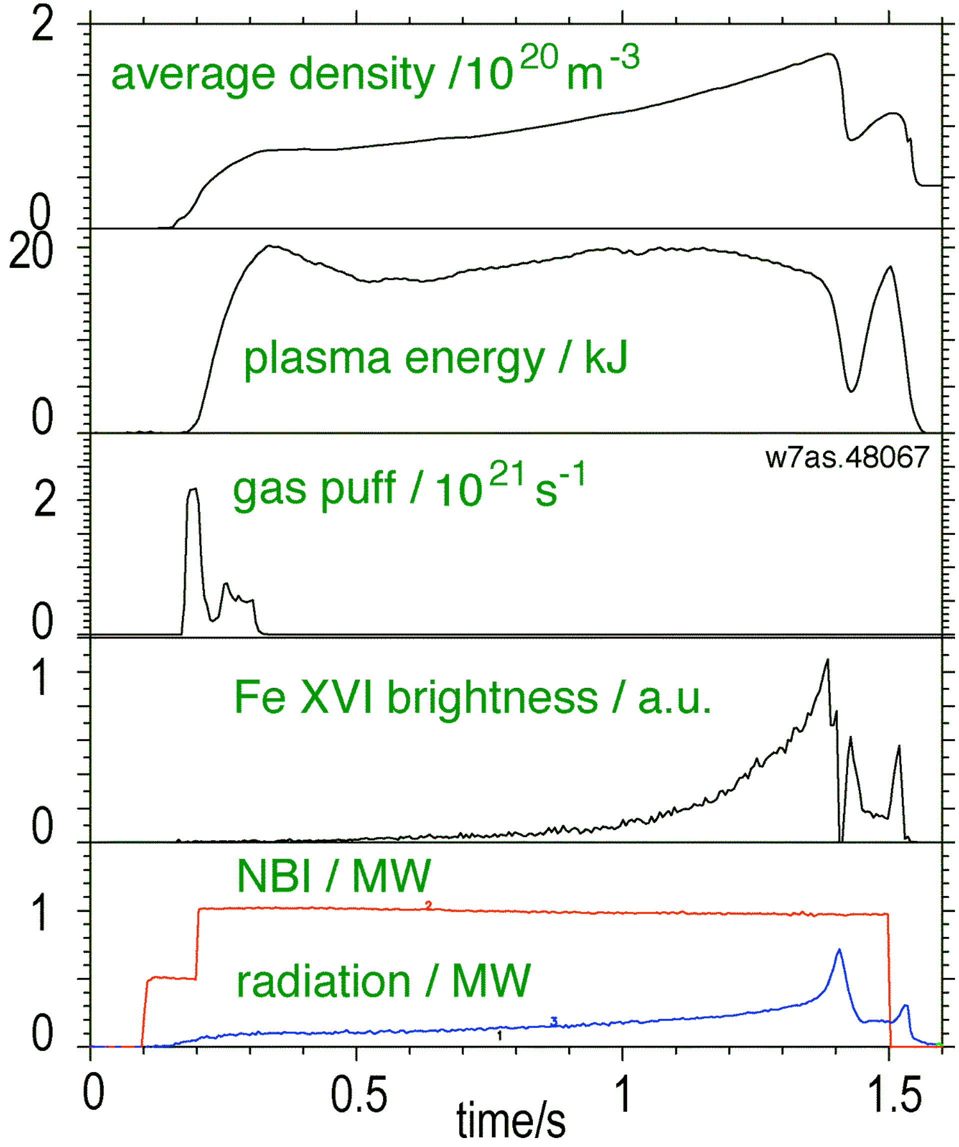


the idea:



natural islands are intersected with target

Operation without divertor ✤



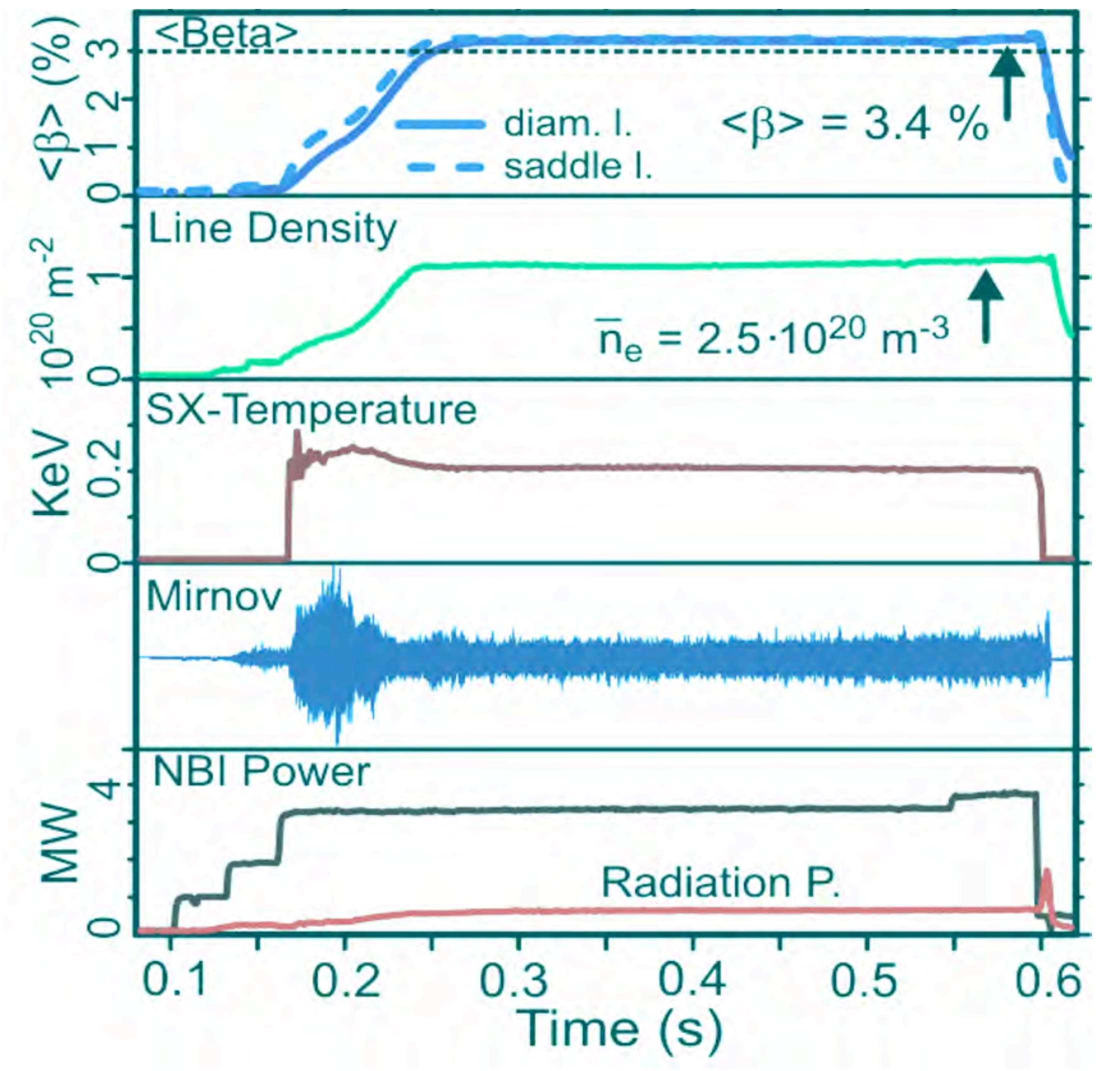
no density control

radiation collaps

impurity accumulation

radiation losses

Operation with divertor – HDH



high pressure $\beta = 3.4\%$
$\beta_N \sim 9.3$

high density $n_e = 2.5\cdot10^{20}\ \mathrm{m}^{-3}$
$n_e/n_{eGW} = 2.5$

confinement $H_{ISS95} = 1.4$

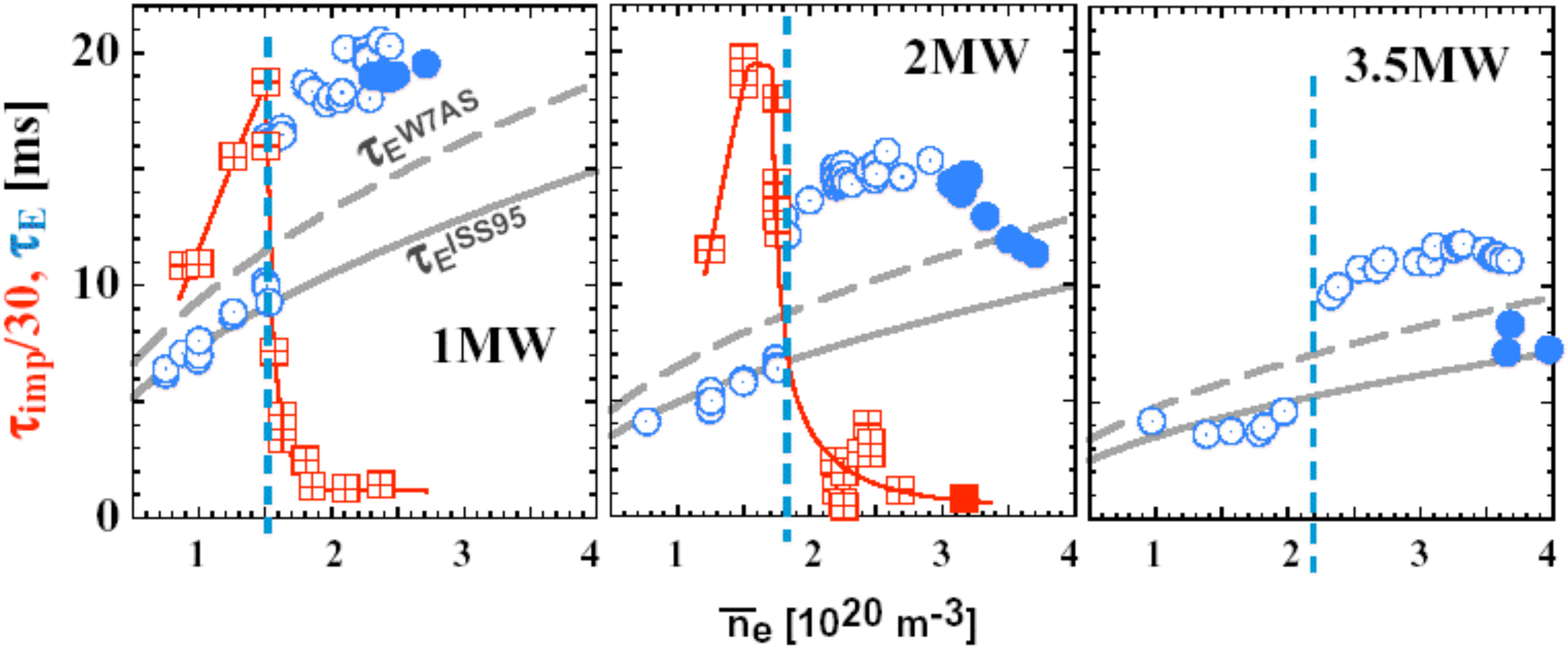
MHD stability

absorption $P_{abs} = 2.5$ MW

stationarity $T_{flattop} \sim 100\ \tau_E$

HDH - an advanced operation regime

the high-density high-confinement (HDH) mode was discovered in 2002 on W7-AS

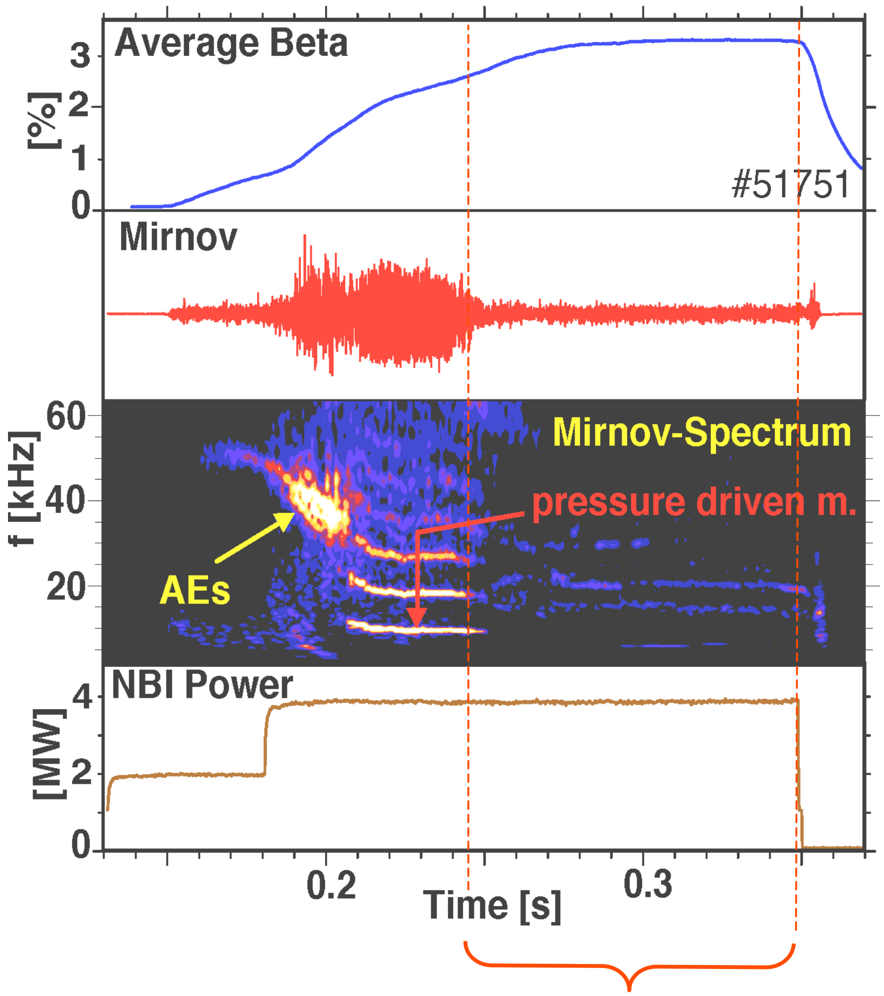


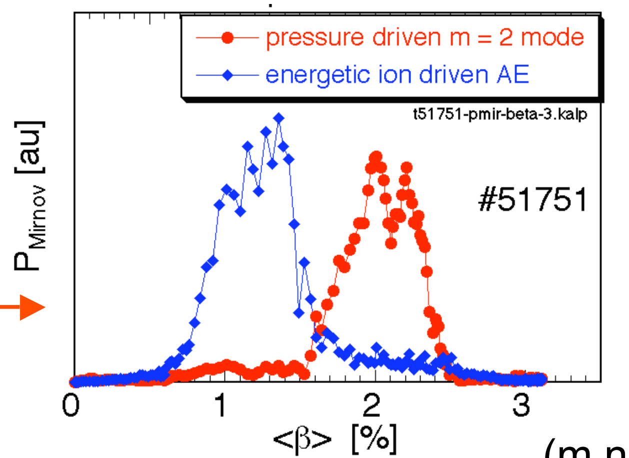
HDH-regime - a true bifurcation with hysteresis, profile differences, ...

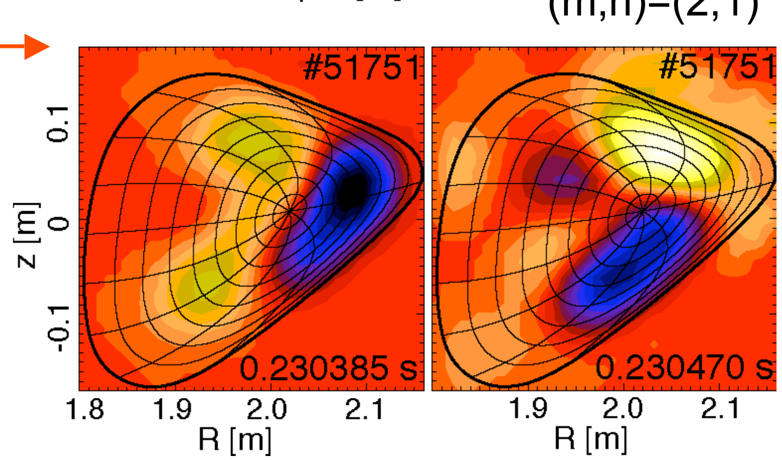
- **confinement of energy increases**
- **confinement of impurities deteriorates**

[McCormick PRL 2002 No 015001]

High-beta experiments in HDH







MHD modes dissappear at high β

- **inwards shift of ι=1/2 surface**
- **formation of magnetic well**

} β → 3%

[Weller 2003]
[Werner 2003]

W7-AS Performance /w island divertor

- Based on resonant magentic islands @ edge
- A viable divertor solution for stellarators
- Controlled heat and particle deposition
- Density control even at high plasma densities ~ $2 \cdot 10^{20} m^{-3}$

- Establishment of High-density H-mode (HDH)
  - Establishes at n~1.5 … 2.5 $\cdot 10^{20}$ m^{-3}
  - Quiescent and MHD stable ← magnetic well formation
  - Different from ELM-free H-mode
  - Improved energy confinement
  - Impurity screening ← high edge densities

Plasma currents - overview

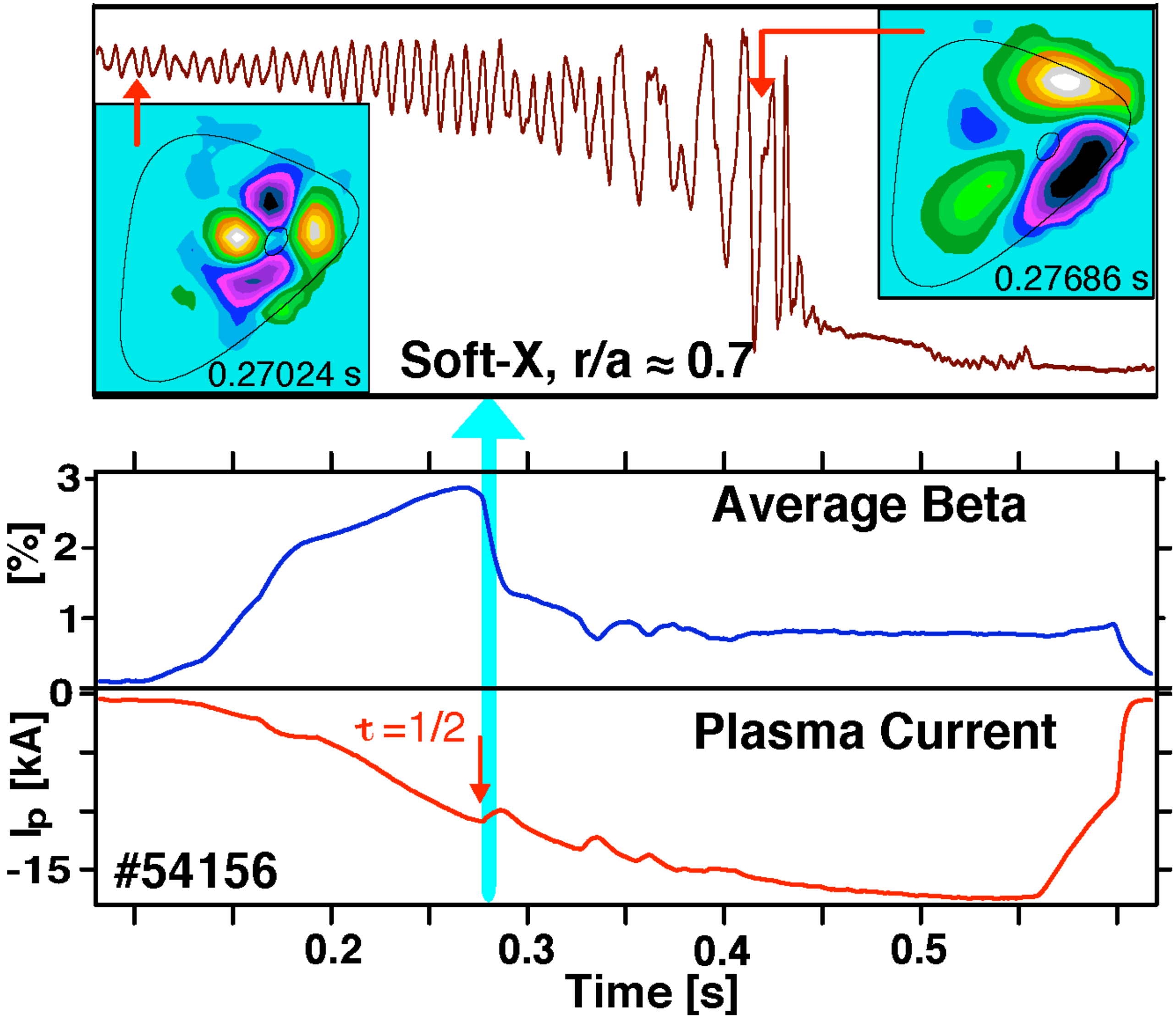
	RFP	Tokamak	W7-X	LHD	NCSX
diamagnetic current	O (1)	O (1)	**O (1)**	O (1)	O (1)
Pfirsch-Schlüter current	0	O (1)	**→ 0**	O (1)	O(1)
bootstrap current	0	→ O (1)	**→ 0**	O (-1)…O (1)	O (1)
induced current	→ O (1)	O (1) → 0	**0**	0	0
plasma dynamo	O (1) → 0	0	**0**	0	0
current drive	0 → O (1)	0 → O (1)	**0**	0	0

all currents are normalized to their respective frame

By courtesy of F. Wagner

It is possible to reduce systematically the currents in the plasma.

W7-AS with induced current



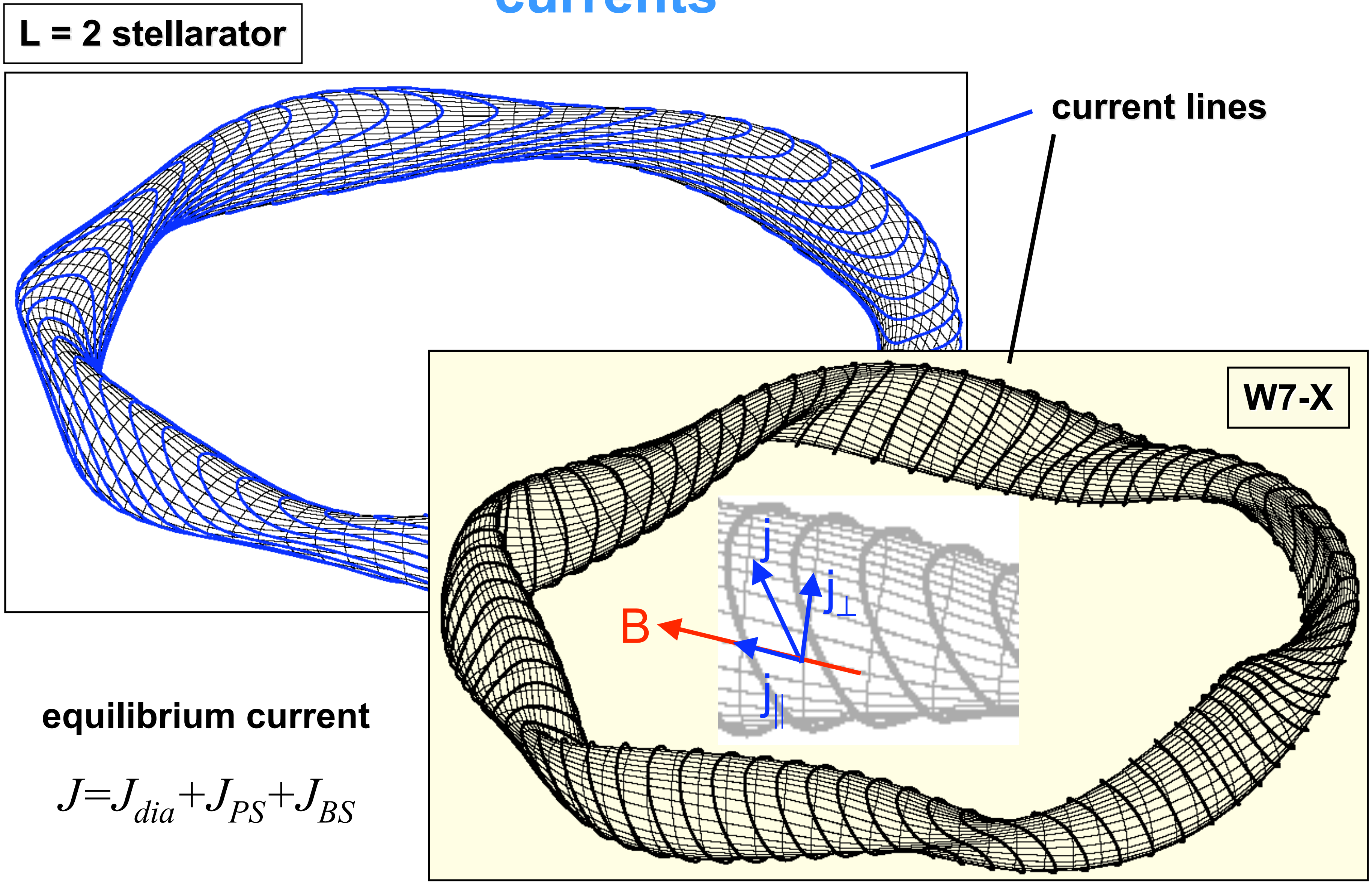
[Zarnstorff 2003]

magnetic
fluctuations
and
soft-X radiation

current driven
instability

tearing-mode type
onset at iota=1/2

Non-inductive equilibrium currents

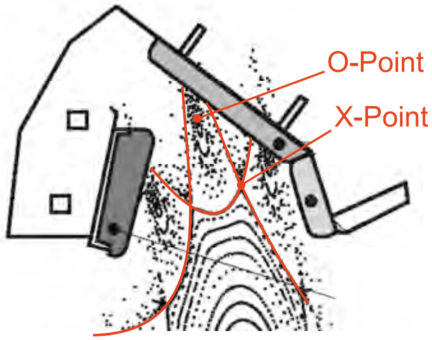


equilibrium current

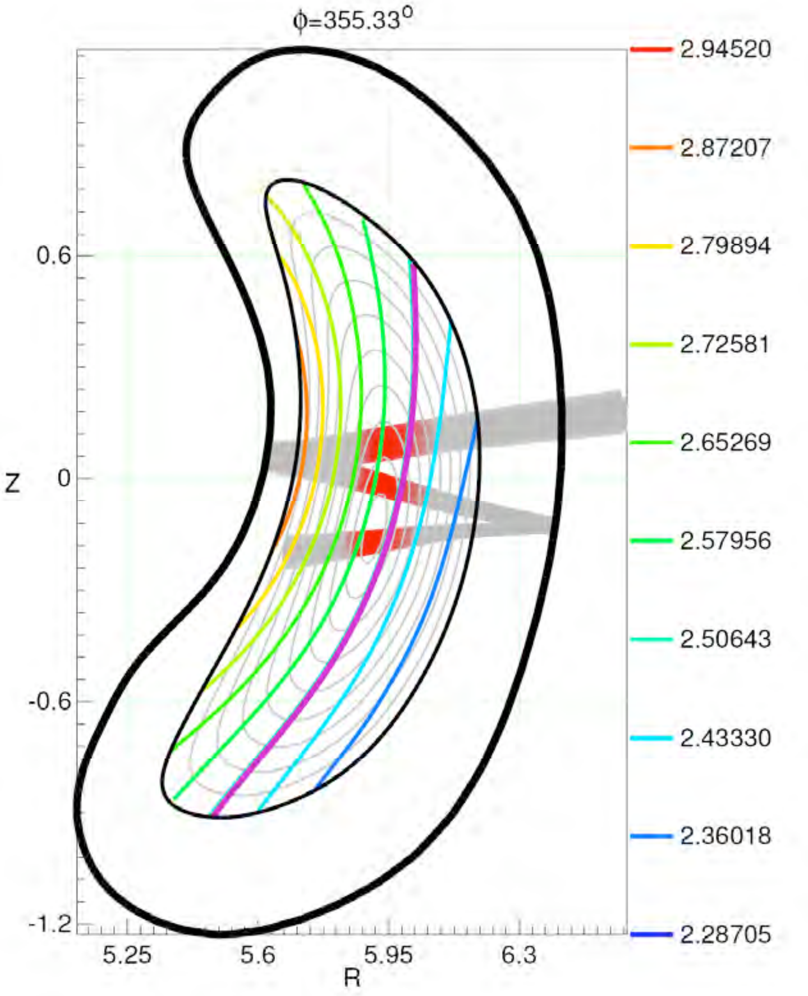
$$J=J_{dia}+J_{PS}+J_{BS}$$

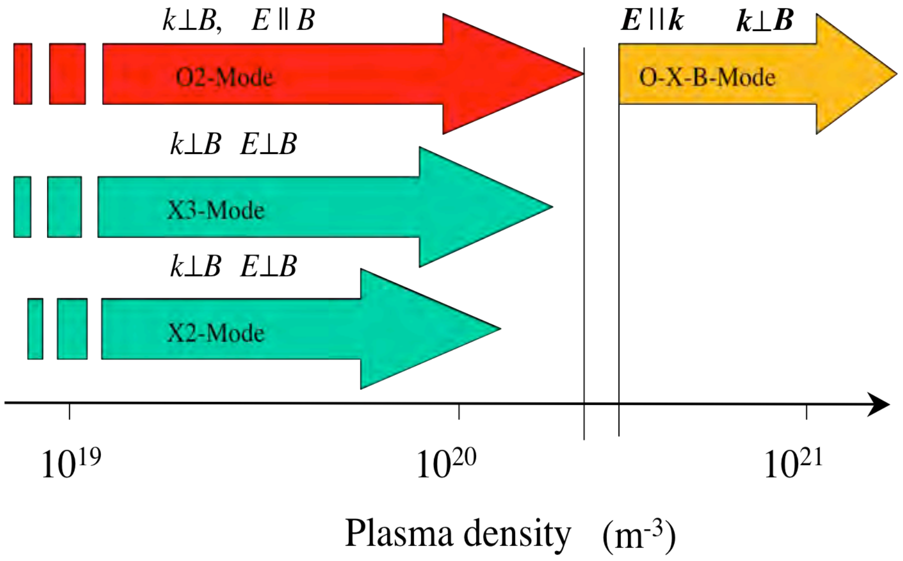
Electron-cyclotron current drive – Ex:

- **1d transport modelling coupled with ray-tracing code**
- **Off-axis X2-heating in standard configuration**
- **Current drive required for control of edge iota**
- **Current drive efficiency P=10MW $<\beta>=2.7\%$ I_{CD}=-88kA**



ECR heating of dense plasmas

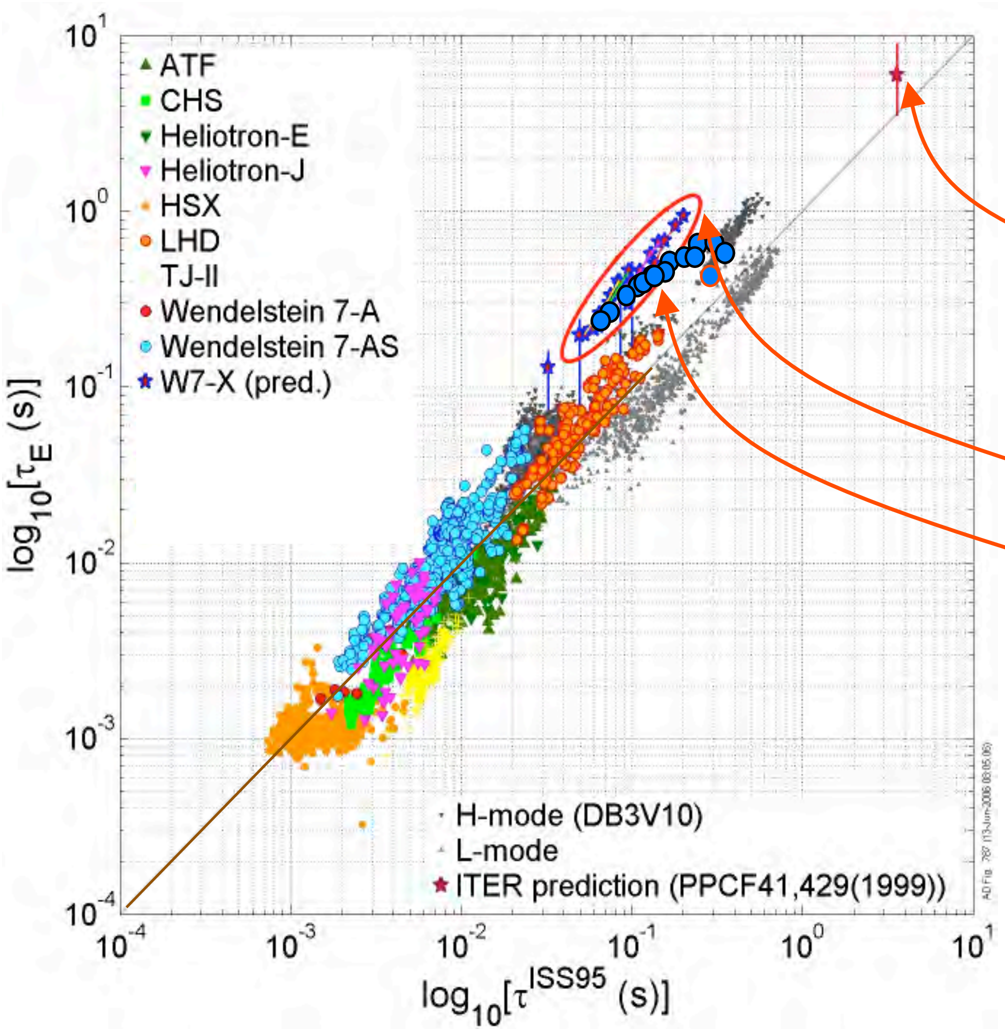




- **O2-launch angle 12°**
- **Heating up to $2.1 \cdot 10^{20} m^{-3}$**
- **Single pass absorption drops to 50%**
- **Double pass with retro-reflectors**

Current drive in X2 and O2

Global energy confinement



ITER

10 MW ECRH

10 MW NBI (H^+)

Numerical simulations:

much improved confinement

$$\tau^{ISS95} = 0.256 a^{2.21} R^{0.65} P^{-0.59} n_{20}^{0.51} B^{0.83} \iota_{2/3}^{0.4}$$

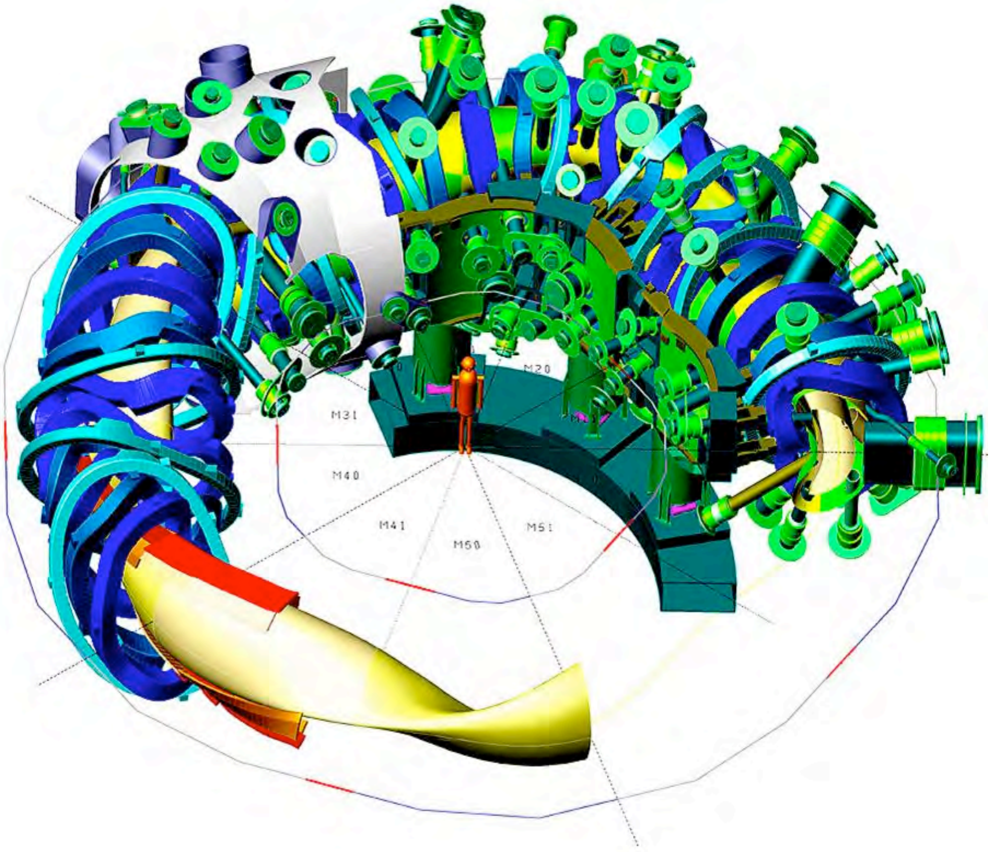
Wendelstein 7-X key parameters

Max-Planck-Institut
für Plasmaphysik

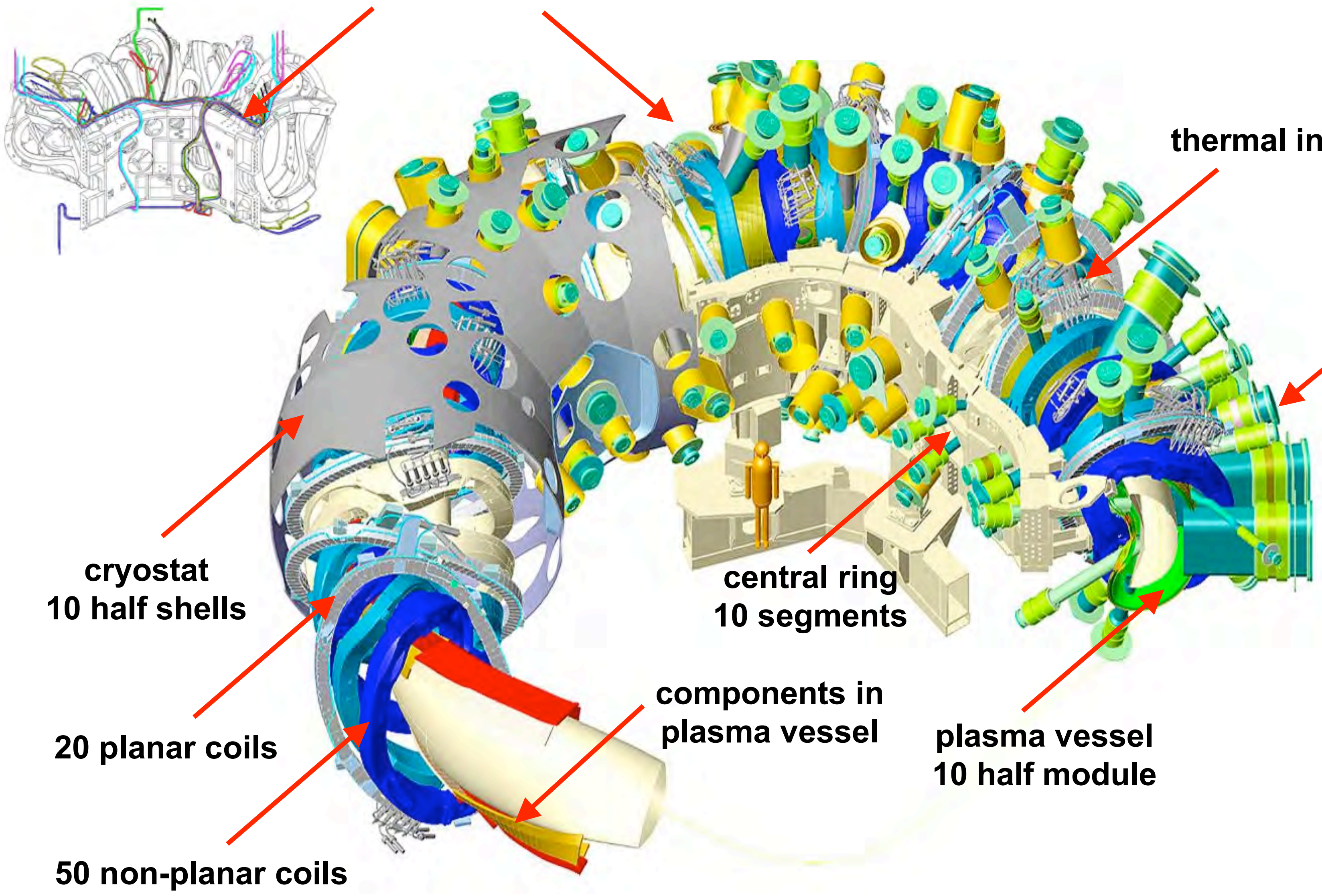
key parameters

major radius:	5.5 m
minor radius:	0.53 m
plasma volume	30 m^3
non-planar coils:	50
planar coils:	20
number of ports:	253
rot. transform:	5/6 - 5/4
induction on axis:	< 3T
stored energy:	600 MJ
heating power	15 - 30 MW
pulse length:	30 min
energy turn ar.:	18 GJ

machine height:	4.5 m
machine diameter:	16 m
machine mass:	725 t
cold mass:	425 t



Wendelstein 7-X main components



bus bar system

thermal insulation

ports

cryostat
10 half shells

central ring
10 segments

20 planar coils

components in
plasma vessel

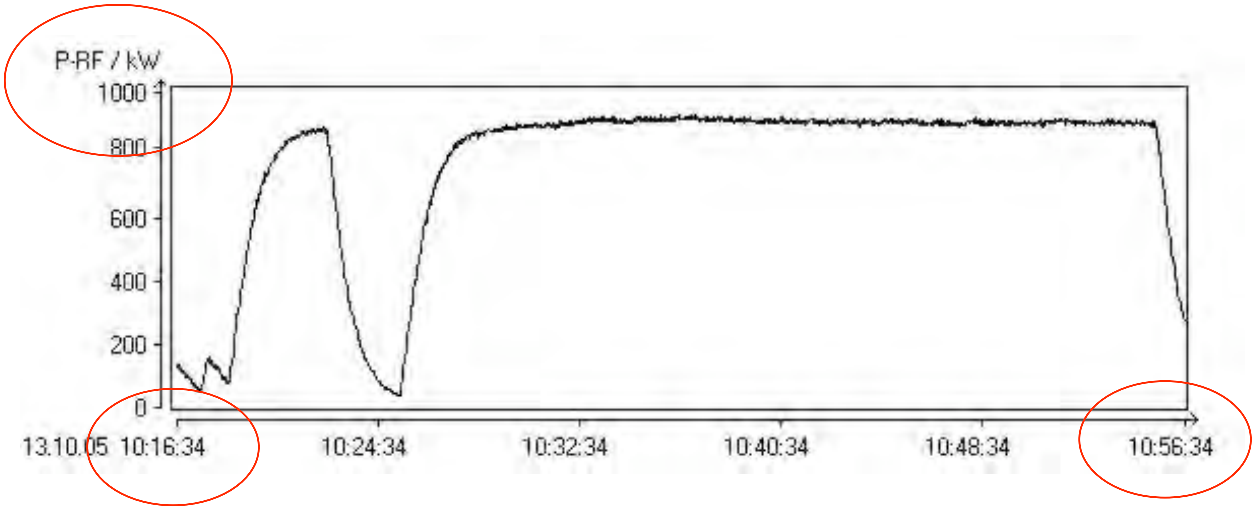
plasma vessel
10 half module

50 non-planar coils

the volume in the cryostat is very constrained

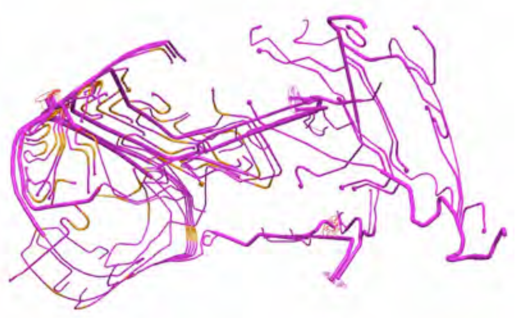
Steady-state ECRH heating

- power gyrotrons
- 10 × 1MW 140GHz
- pulse length 1800s
- quasi-optical duct

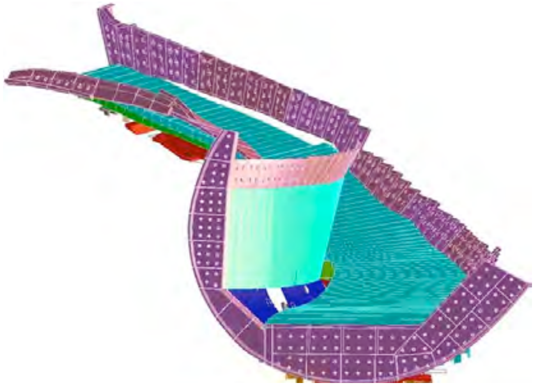


- world record shot
- integrated cw design
- series production?

Design of In-vessel components

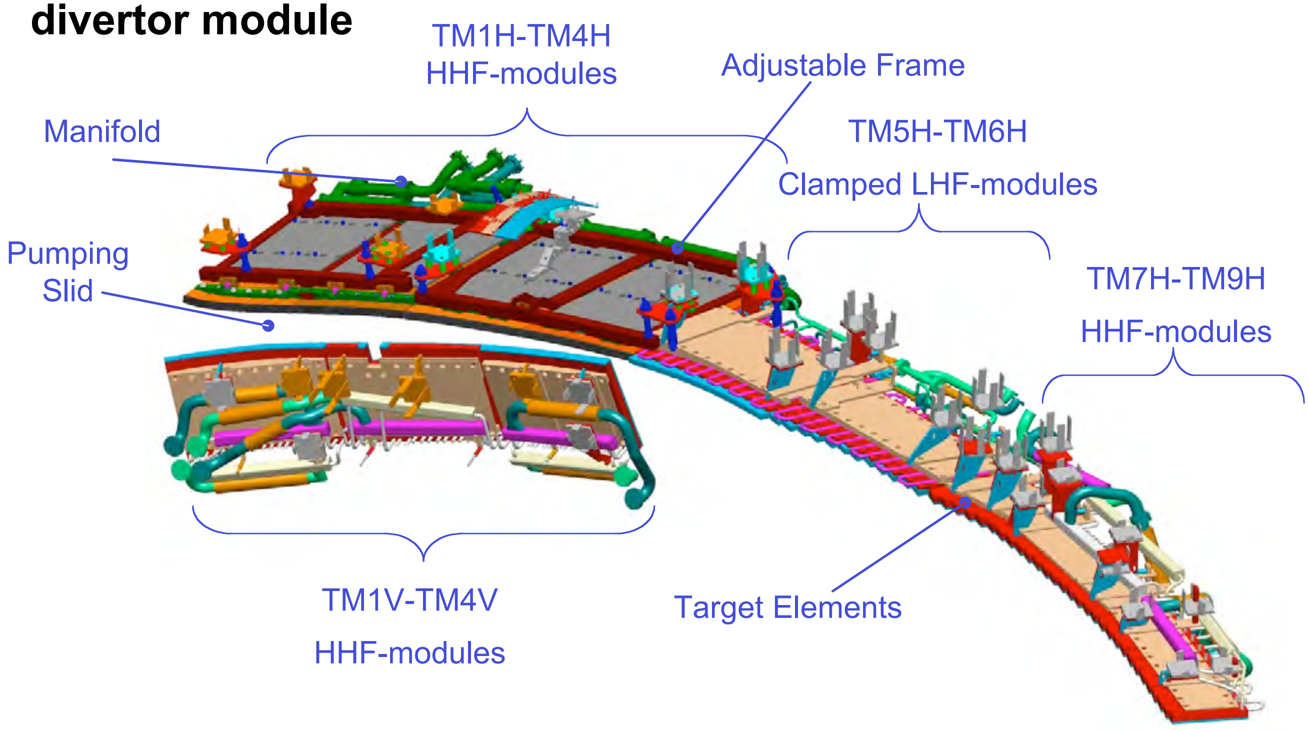


wall panel cooling



test divertor

divertor module

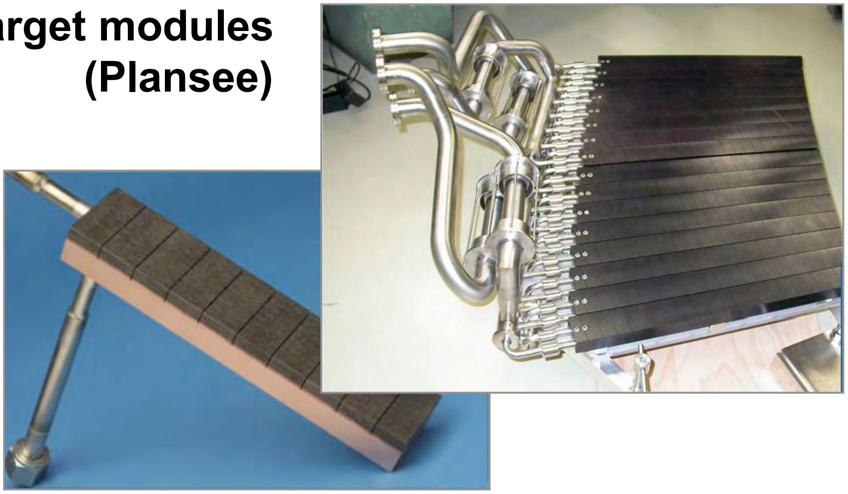


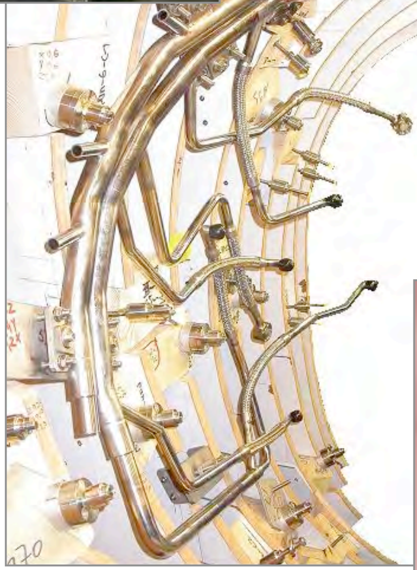
- **target elements CFC sealed on cooled CuCrZr**
- **baffle elements graphite clamped on CuCrZr**
- **cryopumps and sweep coils**
- **about 250.000 parts w 130.000 being non-standard**
- **about 4km in-vessel water pipe lines**
- **start of operation with inertially cooled test divertor**

Manufacturing in-vessel comp‘s

Heat shield (IPP)

Target modules (Plansee)

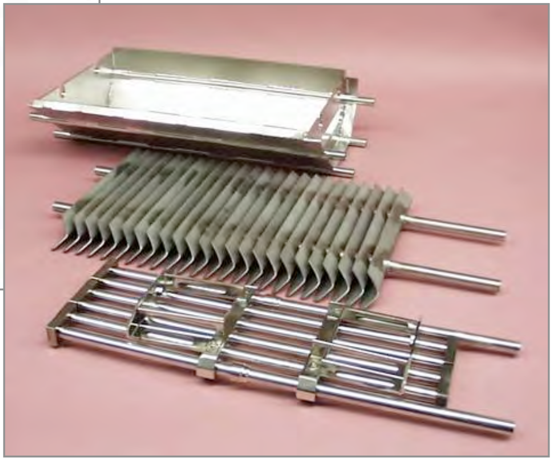




Cooling pipes (IPP and n.n.)

Wall pannels (MAN DWE)

Cryo pumps (IPP)



Superconducting coils

CAD drawing non-planar coil

Status coil delivery

20 planar coils

50 non-planar coils

100M€ contract → consortium

100% manufactured

70% successfully cold tested

Components and assembly

plasma vessel modules

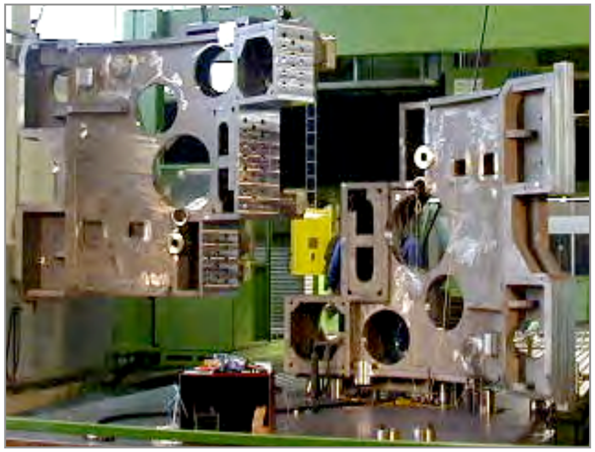
assembly progress

outer vessel with domes

thermal insulation

assembly

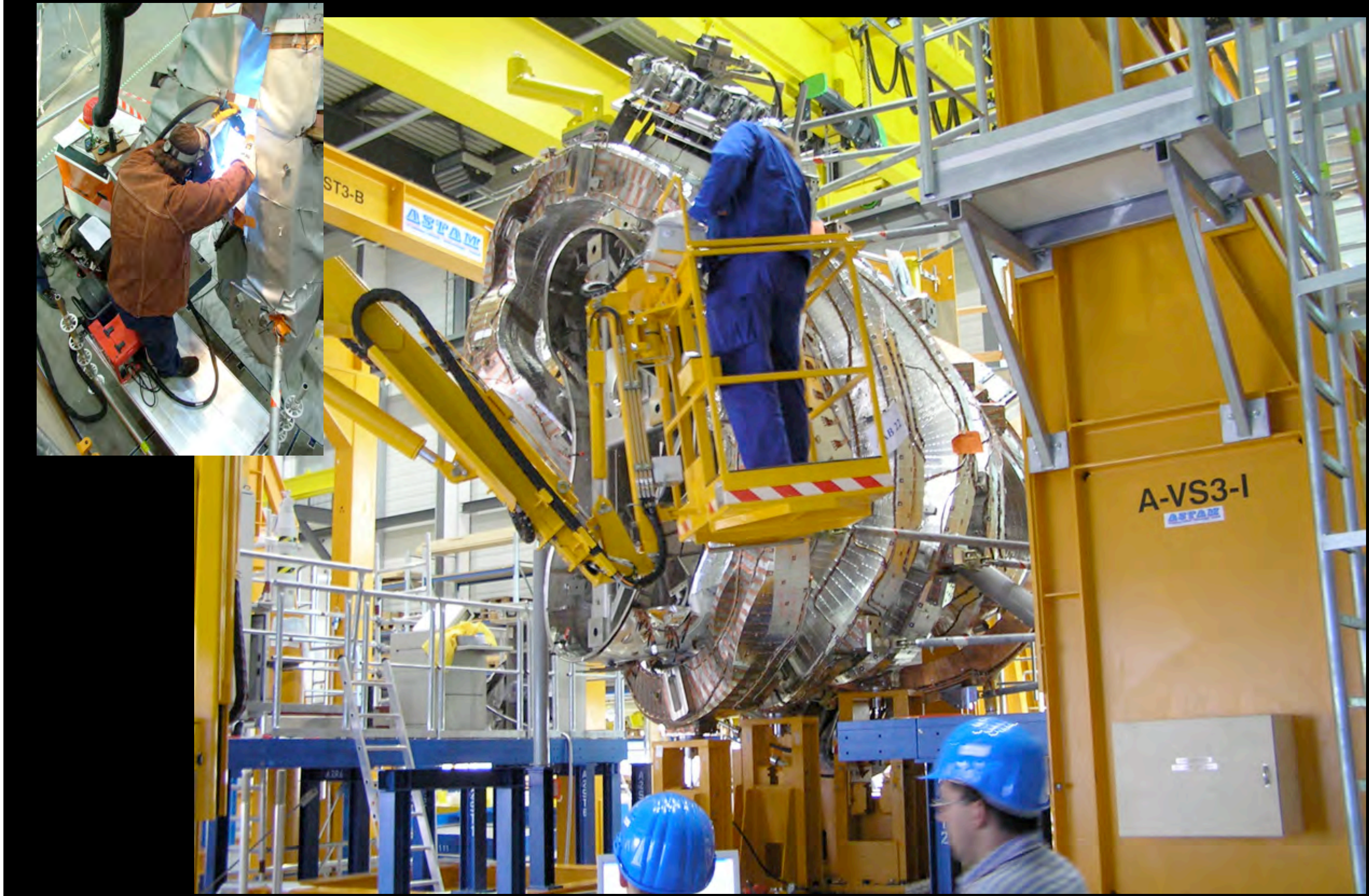
central ring modules



The outer vessel

More than 1000 openings ~ thermal insulation laborious

Coil assembly

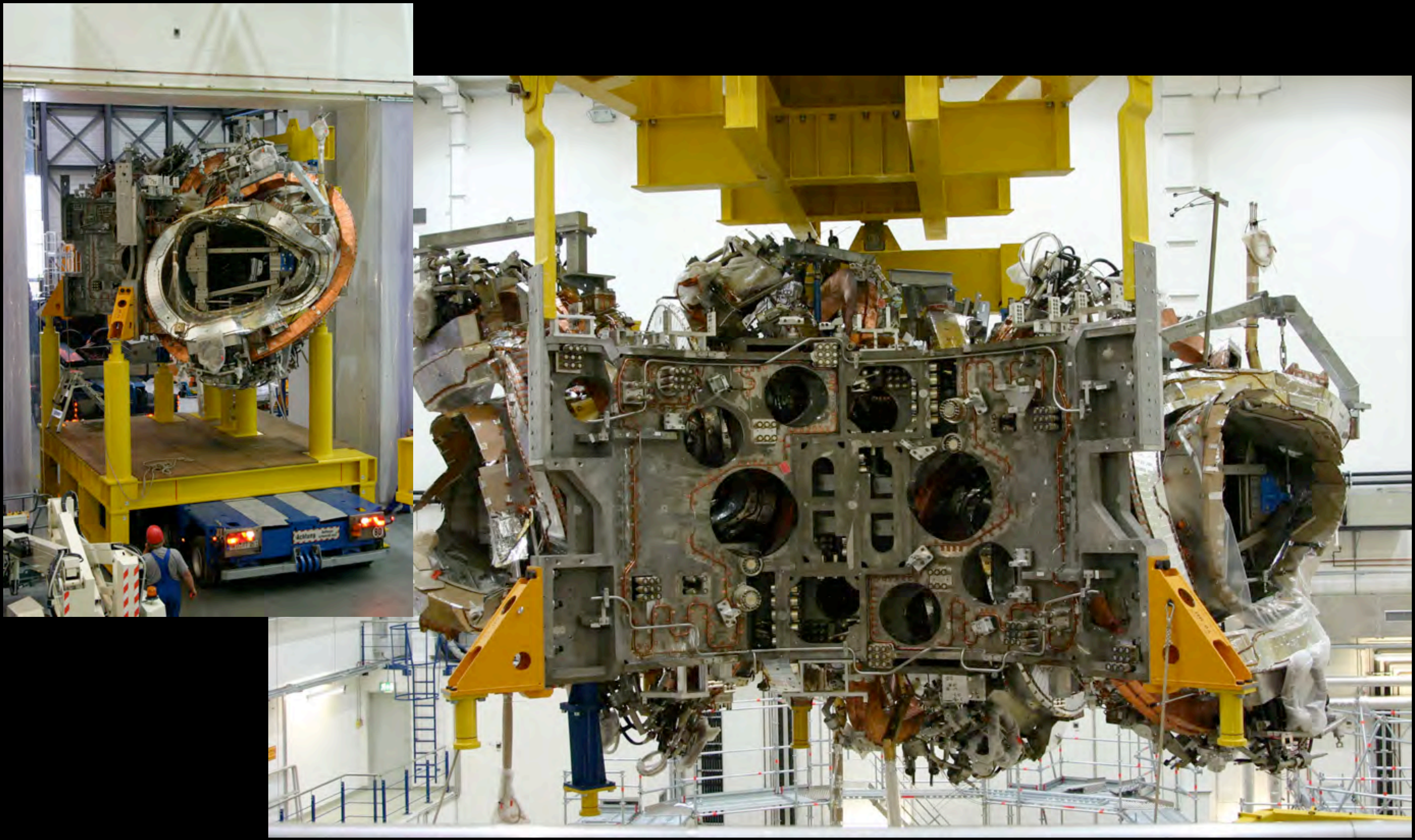


The 20 coils of first two modules assembled ▮ – supports are welded

Torus hall - machine base

The five assembly stands are ready and fill step-wise (now 3/5)

Magnet module

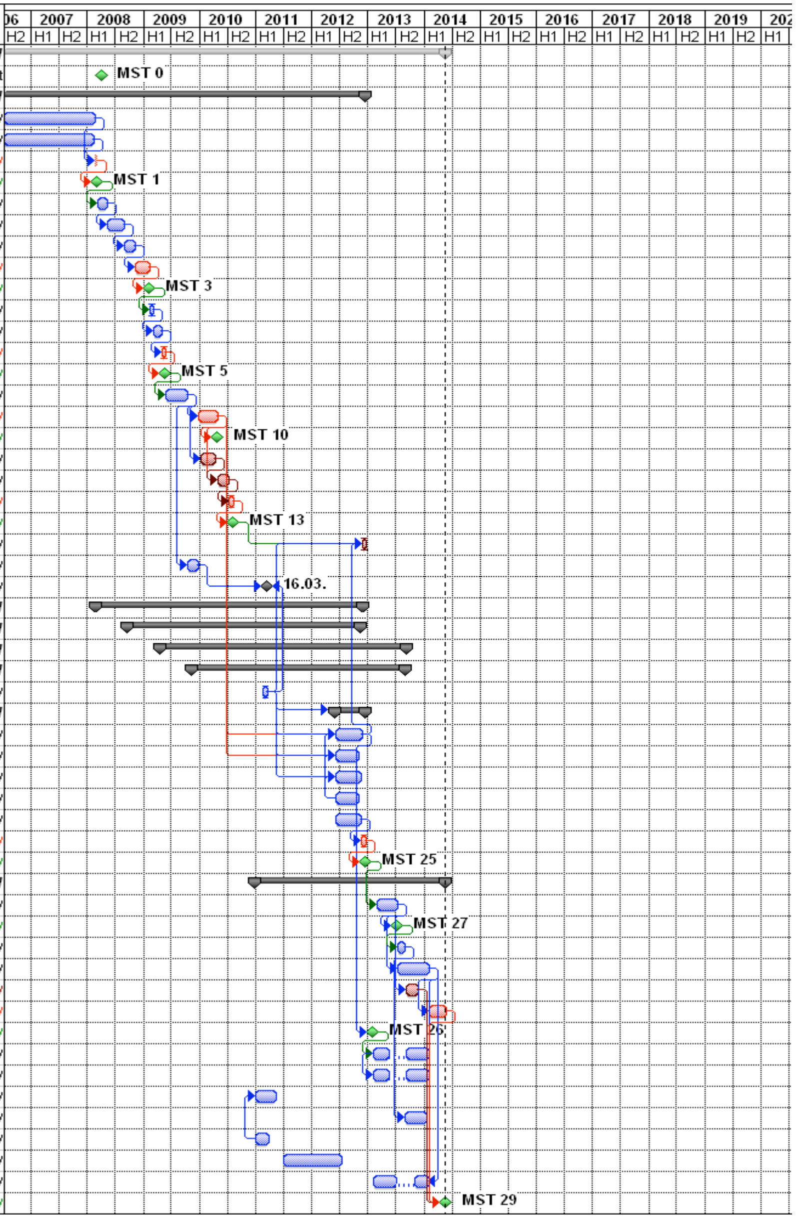


The completed first magnet module went into the next assembly stand

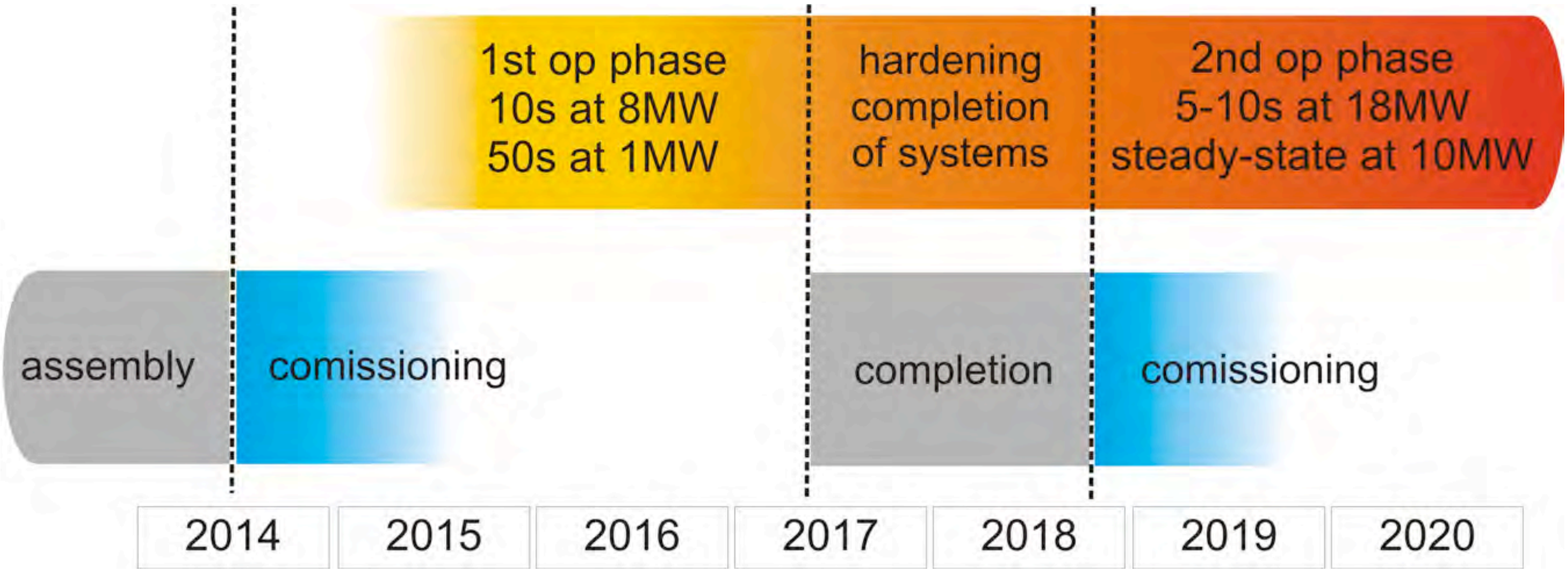
Schedule

- **completion date 2014**
- **68 weeks buffer time**
- **29 milestones**
- **tight schedule control**

Nr.	Vorgangsname	Anfang	Ende	Dauer
0	**Ablaufplan der Montage (Technologische Sequenz)**	**Mo 21.03.05**	**Mo 19.05.14**	**464,5 W**
1	**MST 0: TOSKA operational**	Di 01.04.08	Di 01.04.08	0 t
2	**1. Module (#5)**	**Mo 21.03.05**	**Fr 14.12.12**	**393,5 W**
		Mo 21.03.05	**Mi 13.02.08**	150 W
		Mo 09.05.05	**Mi 06.02.08**	142 W
		Mi 13.02.08	Mi 05.03.08	3 W
		Mi 05.03.08	Mi 05.03.08	0 W
		Mi 05.03.08	Mi 30.04.08	7,5 W
		Mi 30.04.08	Di 26.08.08	16,5 W
		Di 26.08.08	Mo 03.11.08	9,5 W
		Mo 03.11.08	Sa 07.02.09	13 W
		Sa 07.02.09	Sa 07.02.09	0 W
		Sa 07.02.09	Sa 28.02.09	3 W
		Sa 28.02.09	Sa 25.04.09	7,5 W
		Sa 25.04.09	Mo 18.05.09	3 W
		Mo 18.05.09	Mo 18.05.09	0 W
		Mo 18.05.09	Mo 05.10.09	19,5 W
		Mo 21.12.09	Mo 26.04.10	7,58 W
		Mo 26.04.10	Mo 26.04.10	0 W
		Mi 06.01.10	Fr 09.04.10	5,67 W
20	1. Module, part 2 of in-vessel components (inner module)	Mo 26.04.10	Do 01.07.10	4 W
21	Contingency KiP (design not yet finished)	Do 01.07.10	Do 05.08.10	5 W
22	**MST 13: KIP assembly in 1st module finished (parts 1 and 2)**	Do 05.08.10	Do 05.08.10	0 W
23	1. Module, part 3 of in-vessel components (module plane)	Do 22.11.12	Fr 14.12.12	1,42 W
24	Module piping, vacuum	Mo 05.10.09	Di 15.12.09	10 W
25	1. Module connection with supply systems	Mi 16.03.11	Mi 16.03.11	0 W
26	**2. Module (#1)**	**Mi 27.02.08**	**Mi 28.11.12**	**239,26 W**
53	**3. Module (#4)**	**Mi 17.09.08**	**Do 08.11.12**	**208,12 W**
80	**4. Module (#2)**	**Mi 15.04.09**	**Do 05.09.13**	**221,13 W**
107	**5. Module (#3)**	**Do 05.11.09**	**Fr 30.08.13**	**191,99 W**
134	**Final adjustment of modules**	Do 10.02.11	Do 10.03.11	4 W
135	**Module connections (parallel work)**	**Mi 30.05.12**	**Mi 12.12.12**	**27,7 W**
136	1-2 connection of modules #5-#1	Mi 30.05.12	Mi 21.11.12	24,8 W
137	1-3 connection of modules #5-#4	Mi 30.05.12	Di 23.10.12	20,7 W
138	4-2 connection of modules #1-#2	Mi 30.05.12	Sa 10.11.12	23,3 W
139	4-5 connection of modules #2-#3	Mi 30.05.12	Fr 26.10.12	21,3 W
140	5-3 connection of modules #4-#3	Mi 30.05.12	Mi 07.11.12	22,7 W
141	Contingency module connection 5 W (from risk analysis)	Mi 07.11.12	Mi 12.12.12	5 W
142	**MST 25: All modules connected**	Mi 12.12.12	Mi 12.12.12	0 W
143	**Completion of torus**	**Di 21.12.10**	**Mo 19.05.14**	**171,1 W**
144	Completion OV (ports and domes in support openings)	Mo 18.02.13	Mi 03.07.13	18,4 W
145	**MST 27: Completion of cryostat**	Mi 03.07.13	Mi 03.07.13	0 W
146	Installation current leads	Mi 03.07.13	Mo 19.08.13	6,7 W
147	Completion of Periphery (cables (25W), piping, vacuum...)	Mi 03.07.13	Mi 29.01.14	29 W
148	KiP 4. Part	Fr 30.08.13	Mi 20.11.13	11,41 W
149	Contingency 15 W (from risk analysis)	Mi 29.01.14	Mo 19.05.14	15 W
150	**MST 26: Start of assembly ECRH**	Mo 28.01.13	Mo 28.01.13	0 W
151	Module #5: Installation of ECRH	Mo 28.01.13	Sa 25.01.14	34 W
152	Module #1: Installation of ECRH	Mo 28.01.13	Fr 24.01.14	34 W
153	Installation ICRH in torus hall	Di 21.12.10	Di 10.05.11	19 W
154	Assembly ICRH	Mo 19.08.13	Mo 13.01.14	20 W
155	Completion of NBI boxes in assembly hall	Di 21.12.10	Fr 18.03.11	12 W
156	Assembly NBI 1. Part	Mo 27.06.11	Sa 07.07.12	52 W
157	Assembly NBI 2. Part	Mi 30.01.13	Mi 29.01.14	33,31 W
158	**MST 29: Start Commissioning**	Mo 19.05.14	Mo 19.05.14	0 W



The start of exploitation



1st op phase
10s at 8MW
50s at 1MW

hardening
completion
of systems

2nd op phase
5-10s at 18MW
steady-state at 10MW

assembly

comissioning

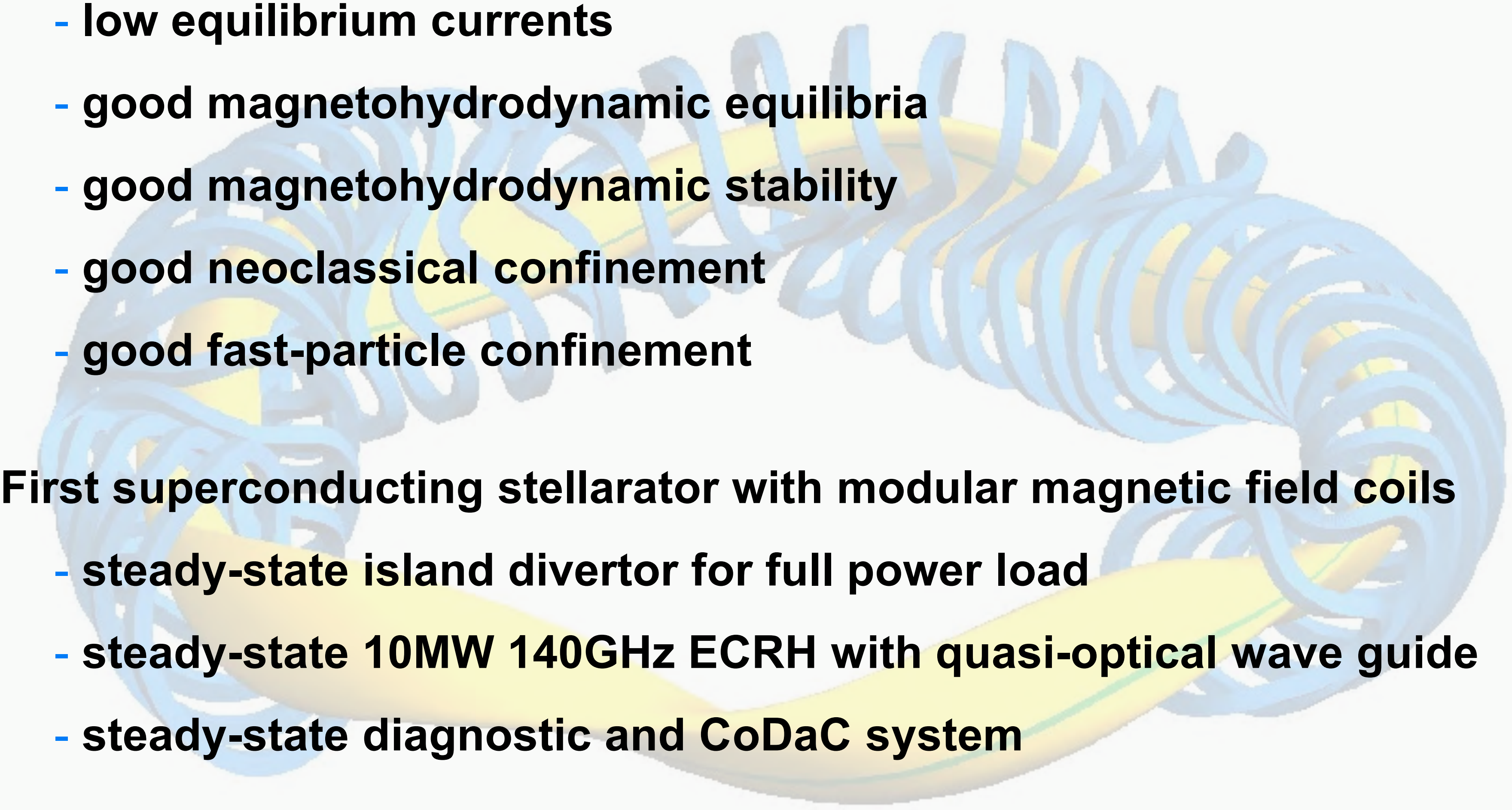
completion

comissioning

2014 2015 2016 2017 2018 2019 2020

- 1st operation phase with 10s @ 8MW and 50s @ 1MW
- inertially cooled divertor and only partial cooling of in-vessel comp‘s
- shut-down (15 months) for completion and hardening
- 2nd operation phase to approach 30min @ 10MW
- 3rd operation phase with 10MW ECRH, 20MW NBI and 10MW ICRH

The Wendelstein 7-X stellarator

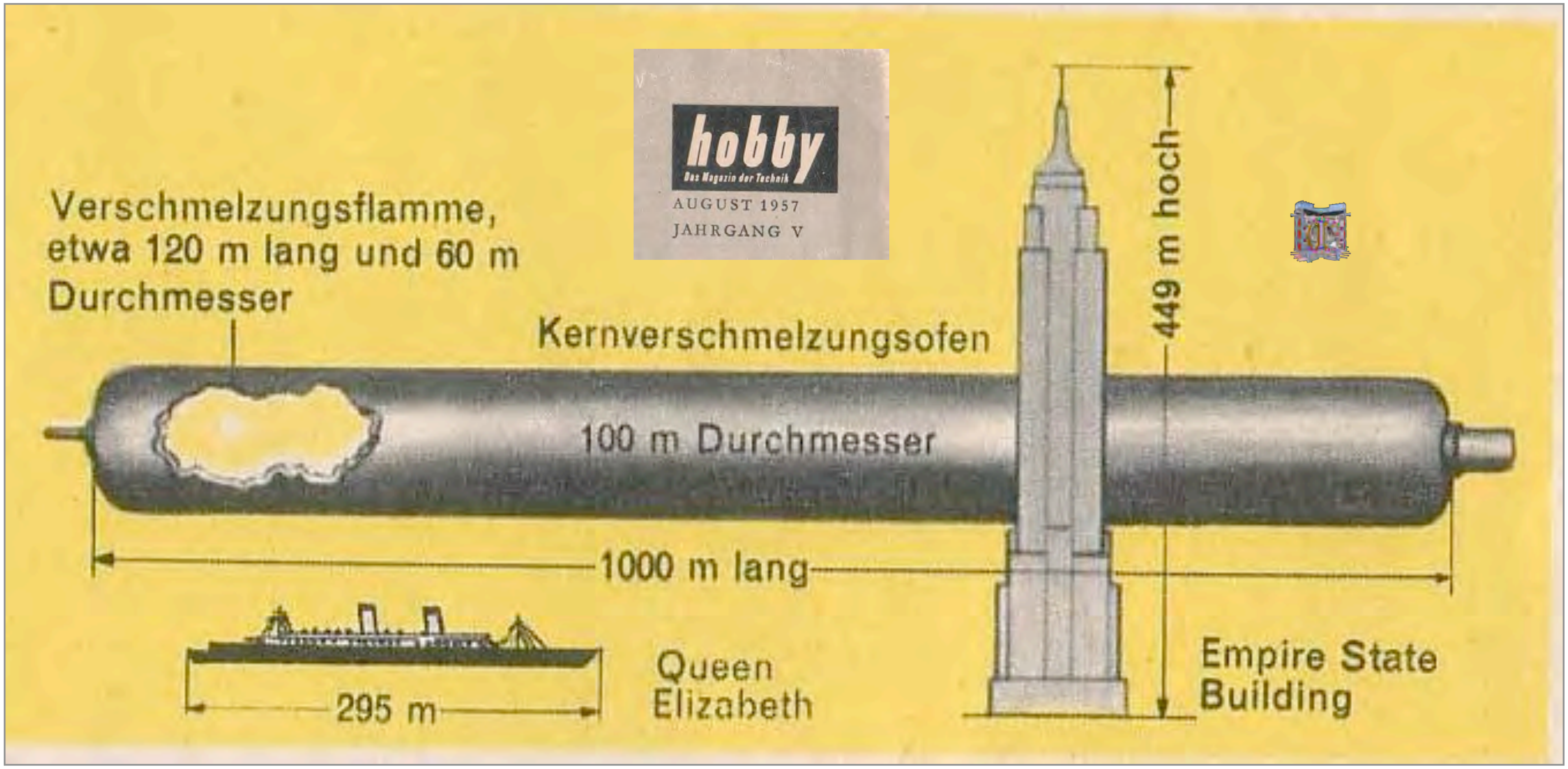


- „Fully“ optimized magnetic field configuration with simultaneously …
  - low equilibrium currents
  - good magnetohydrodynamic equilibria
  - good magnetohydrodynamic stability
  - good neoclassical confinement
  - good fast-particle confinement

- First superconducting stellarator with modular magnetic field coils
  - steady-state island divertor for full power load
  - steady-state 10MW 140GHz ECRH with quasi-optical wave guide
  - steady-state diagnostic and CoDaC system

A promising new high-temperature plasma device

Fusion power - „think big“

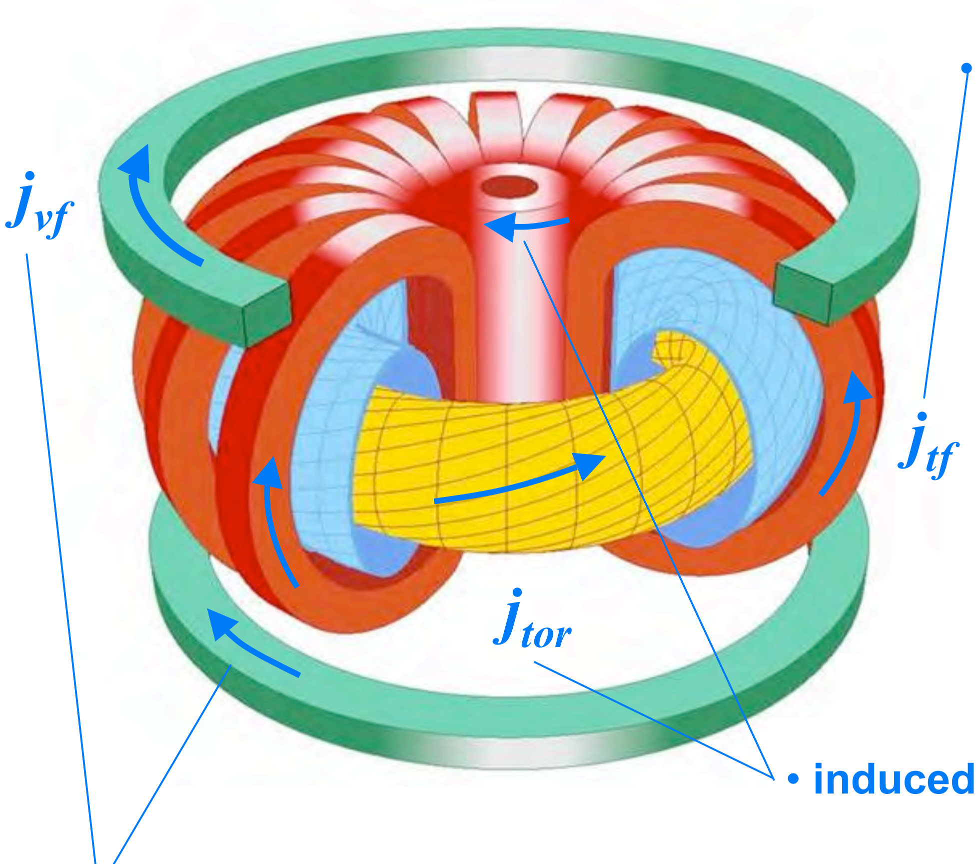


The tokamak principle

Tokamak (1951 Sacharov und Tamm)

тороидальная камера в магнитных катушках

„toroidal chamber in magnet coils“

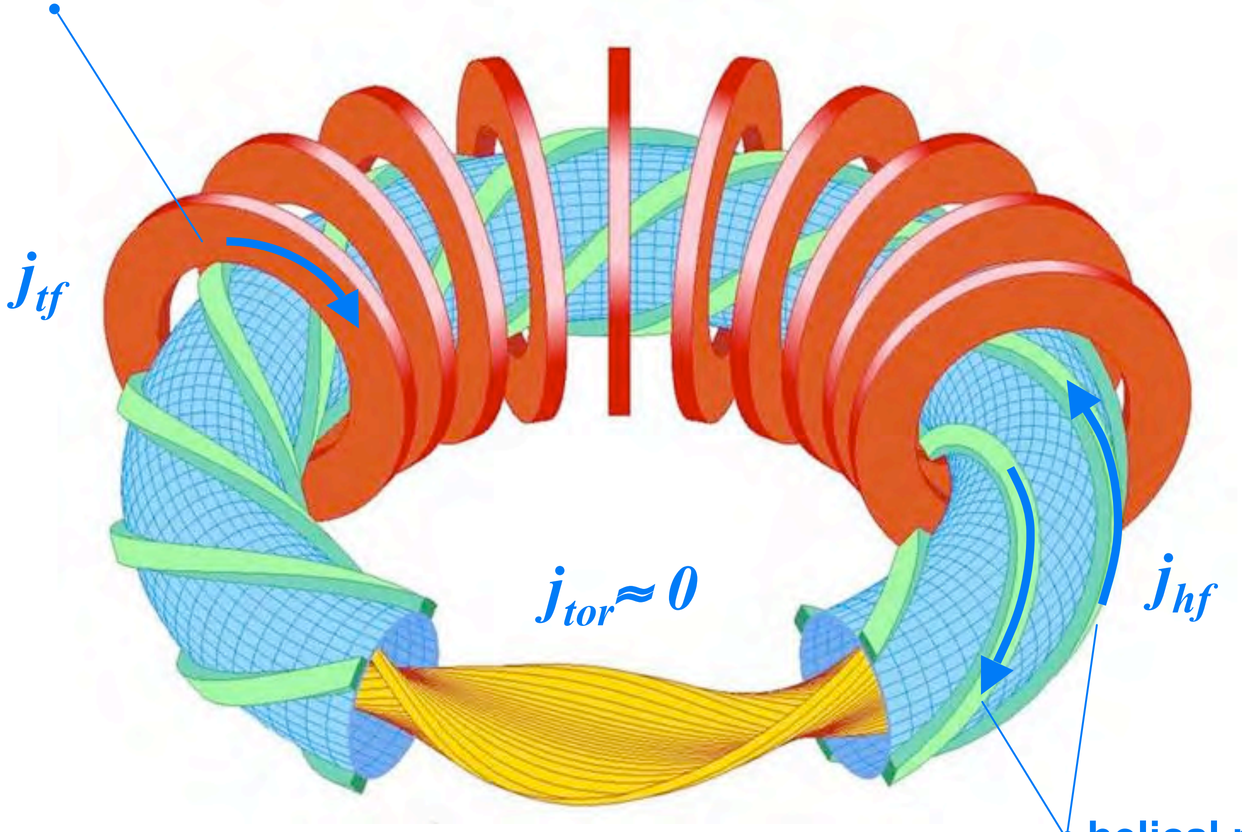


- toroidal magnetic field
- induced toroidal plasma current
  ~ MAmps
- radial shift of plasma axis

The stellarator principle

Stellarator **(1951 Spitzer)**
***Stella* = the star**

toroidal magnetic field



helical magnetic field