From Wendelstein 7-X to a Stellarator Reactor

R C Wolf for the Wendelstein 7-X Team

Max-Planck-Institut für Plasmaphysik, Teilinstitut Greifswald,
Wendelsteinstr. 1, D-17491 Greifswald

robert.wolf@ipp.mpg.de

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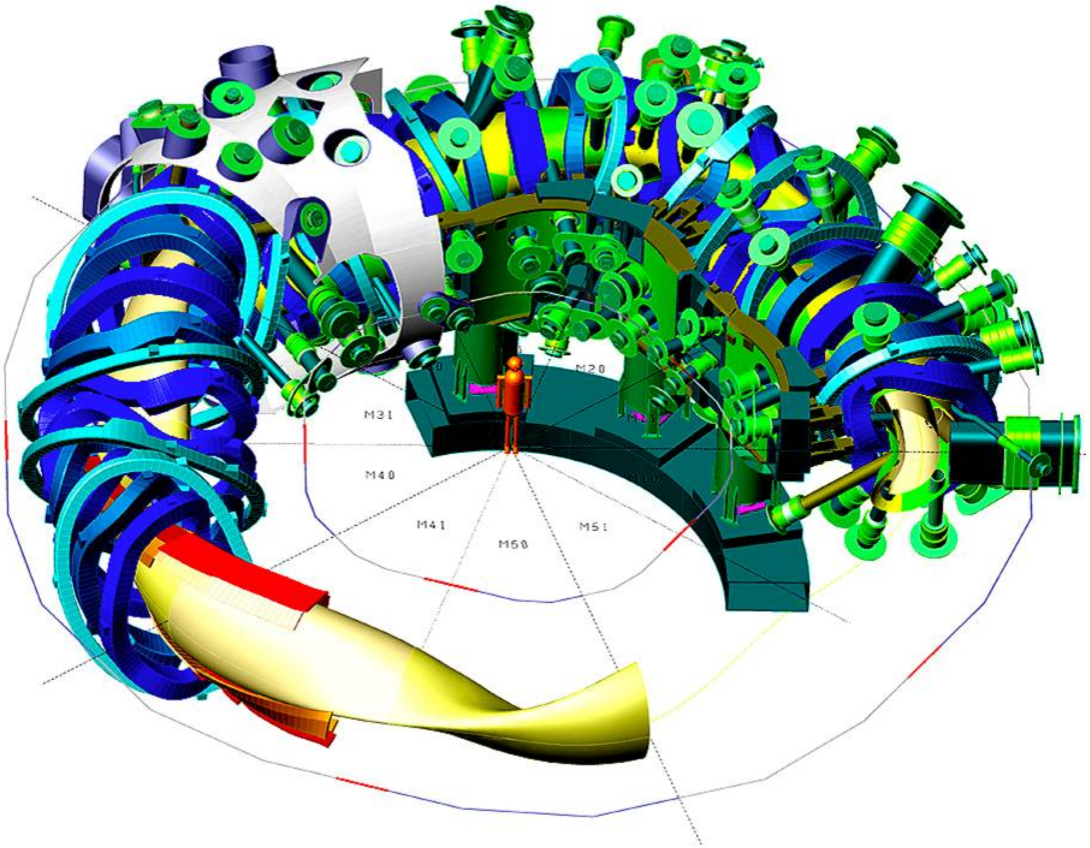
- A brief introduction to Wendelstein 7-X

- R&D missions of the EU fusion programme with references to
    - Wendelstein 7-X and
    - HELIAS studies

The Wendelstein 7-X device

Parameters

Major radius:	5.5 m
Minor radius:	0.53 m
Plasma volume	30 m^3
Rot. transform:	5/6 - 5/4
Magn. field (on axis):	≤ 3T
Magn. field energy:	600 MJ
Heating power	10 - 30 MW
Pulse length:	30 min



5 field periods

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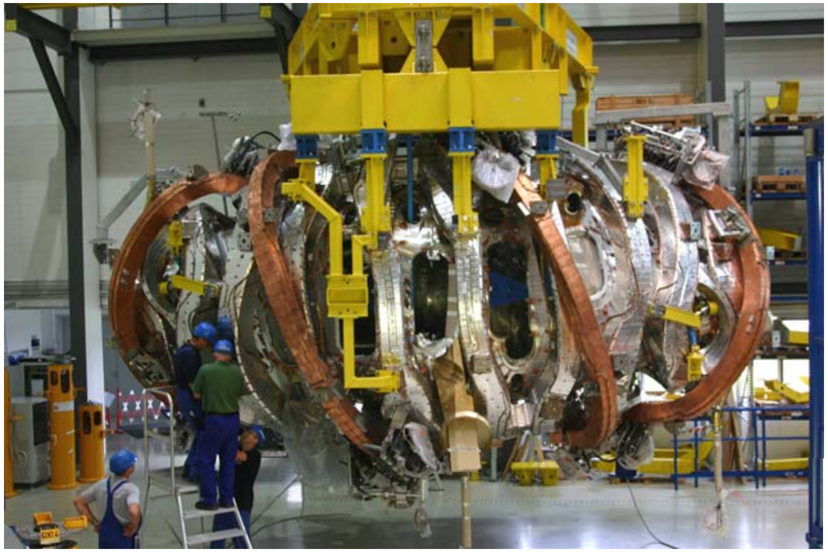
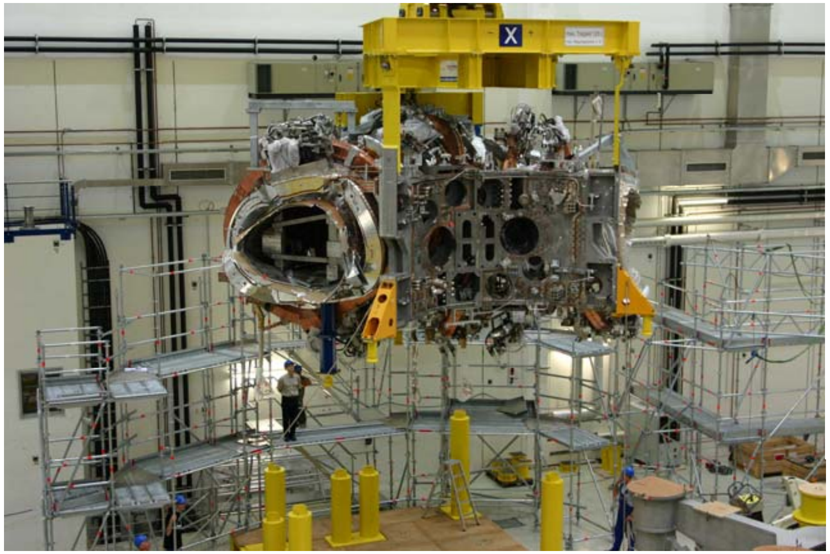
→ *see H.-S. Bosch*





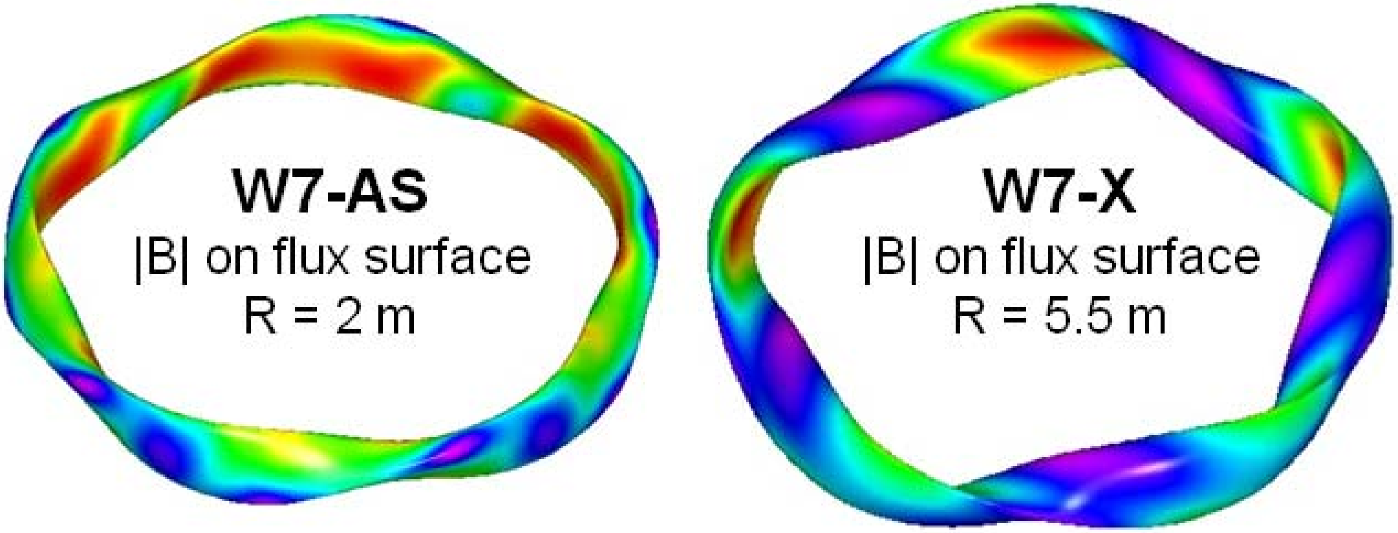
Optimization criteria of Wendelstein 7-X

Drift-optimized low magnetic shear stellarator with

- Stiff equilibrium configuration: small Pfrisch-Schlüter and bootstrap currents resulting in small Shafranov shift and high equilibrium beta limit
- MHD stability up to $<\beta> = 5\%$
- Small neoclassical transport $D \sim \varepsilon_h^{3/2}\, T^{7/2}$, good fast particle confinement

Additional objectives

Steady state operation including particle and energy exhaust with island divertor concept (superconducting coils with actively cooled divertor and first wall components)



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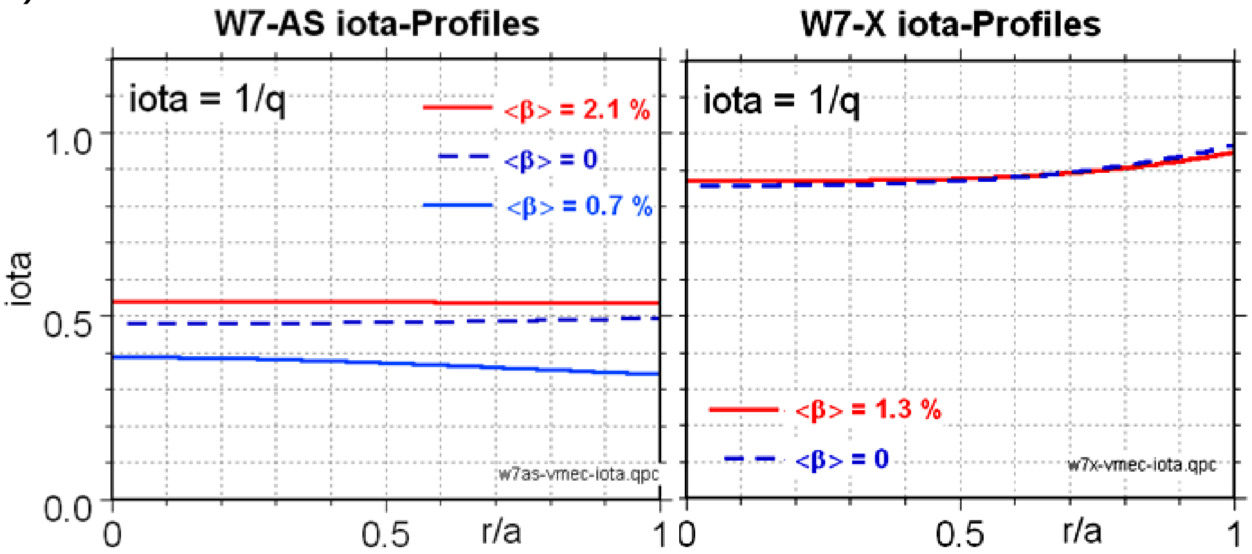
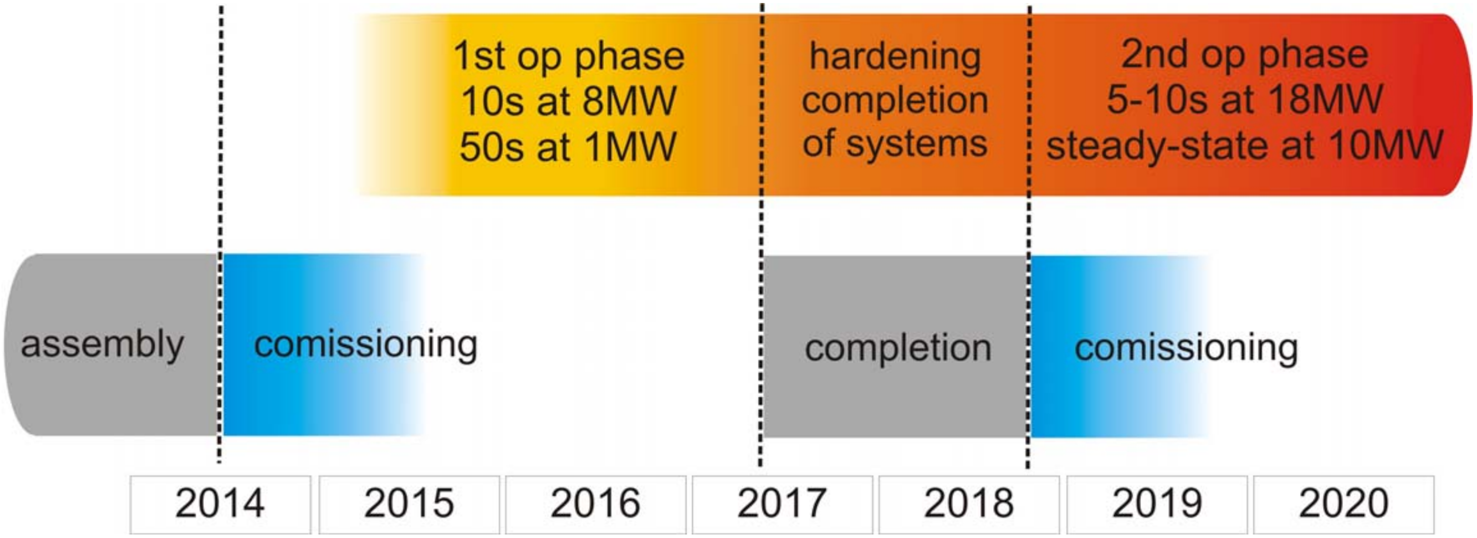


Time line



- **1st operation phase with 10s @ 8MW and 50s @ 1MW (ECRH, NBI, ICRH)**
- **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 (ECRH)**
- **Prepared upgrades: from 10 to 20MW NBI and from 2 to 10MW ICRH**

The HELIAS reactor concept

Requirements

- Sufficiently good confinement to provide ignition
- Average magnetic field on axis 5T (max. field at coils 10 T)
  → NbTi with super-fluid He at 1,8 K (or Nb_3Al at higher temperatures)
- Sufficient space for blanket (~1.3 m)

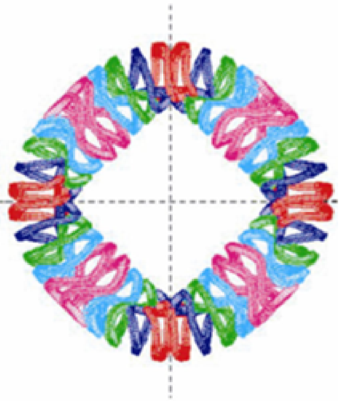
Consequences, additional aspects

- <β> = 4 – 5 % (W7-X value!)
- Similar volumes, fusion power ~ 3GW
- Advantage of large aspect ratio
  → reduced neutron flux to the wall (average 1 MW/m^2, peak 1.6 MW/m^2)

HSR5/22

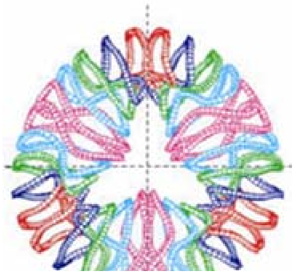
R = 22 m
A = 12

HSR4/18



R = 18 m
A = 9

HSR3/15



α-confinement ?

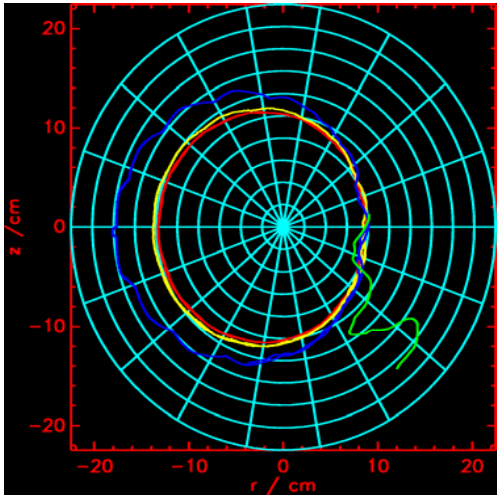
R = 15 m
A = 6

R&D missions of the EU fusion programme

- **Burning plasma**
- **Reliable operation**
- **Operation compatible with first wall**
- **Technology and physics for steady state operation**
- **Predicting fusion performance**
- ***Operation in nuclear environment***
- ***DEMO integrated design***

Burning plasma

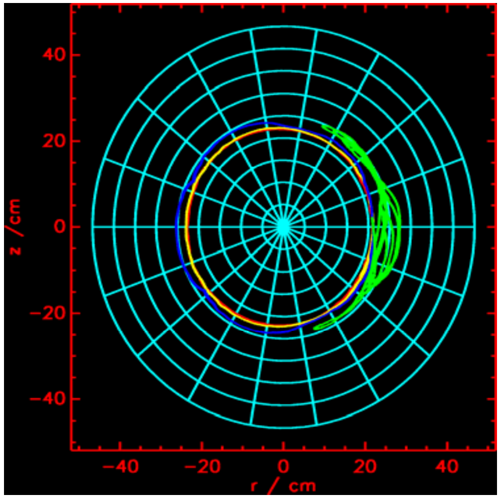
W7-X
- optimization for good fast particle confinement (drift optimization) at finite β
- no DT operation



W7-AS

partially
drift optimized

A. Werner



W7-X

drift optimized

50 keV protons

pitch angle
0°, 50°, 70° 80°

2^{nd} phase
- demonstration of fast particle confinement at high beta
- requires plasma duration longer than *L/R* time (> 30 sec) and high heating power

HELIAS
- alpha loss energy fraction ≈ 2.5% (HSR4/18)

Reliable operation (approaching operational boundaries)

No current or current driven instabilities / no disruptions

W7-X

- stability limit at $<\beta> = 5\%$
- high equilibrium beta limit
- equipped for high density operation (ECRH prepared for 2nd harmonic O-mode with multi-pass absorption)

1st phase

- high density operation (at $n_e = 1.8\times10^{20}\mathrm{m}^{-3}$ for 10 MW ECRH predicted $T_e = 6.2$ keV, $T_i = 4.2$ keV, $P_{abs} = 9.75$ MW, $<\beta> = 4.1\%$)
- high beta at low magnetic field (limited power, depending on actual confinement)

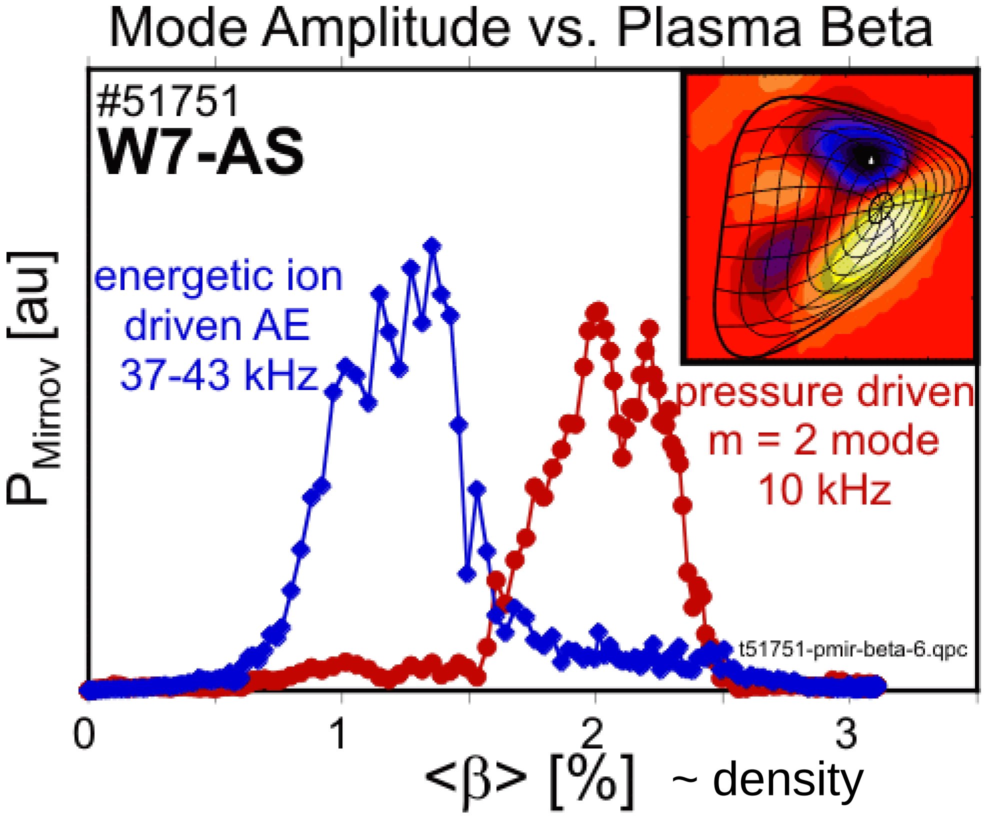
2nd phase

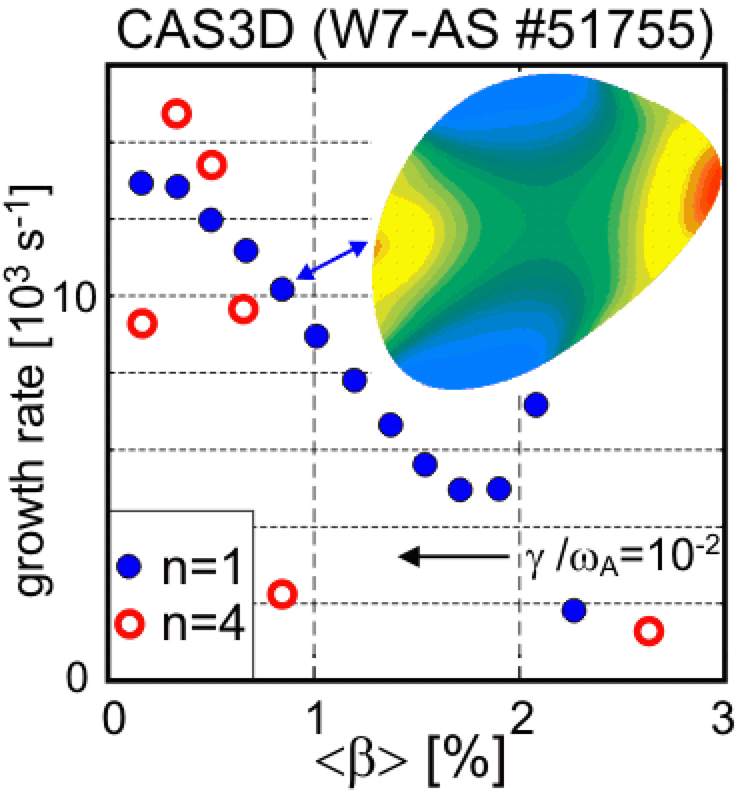
- operation at beta limit

HELIAS

- $<\beta> = 4 – 5\%$
- density and temperature at ignition $n = 2\text{-}3\times10^{20}\ \mathrm{m}^{-3}$, $T = 11\text{-}15$ keV

Formation of magnetic well in W7-AS





A. Weller et al.

Formation of magnetic well stabilizes pressure driven modes

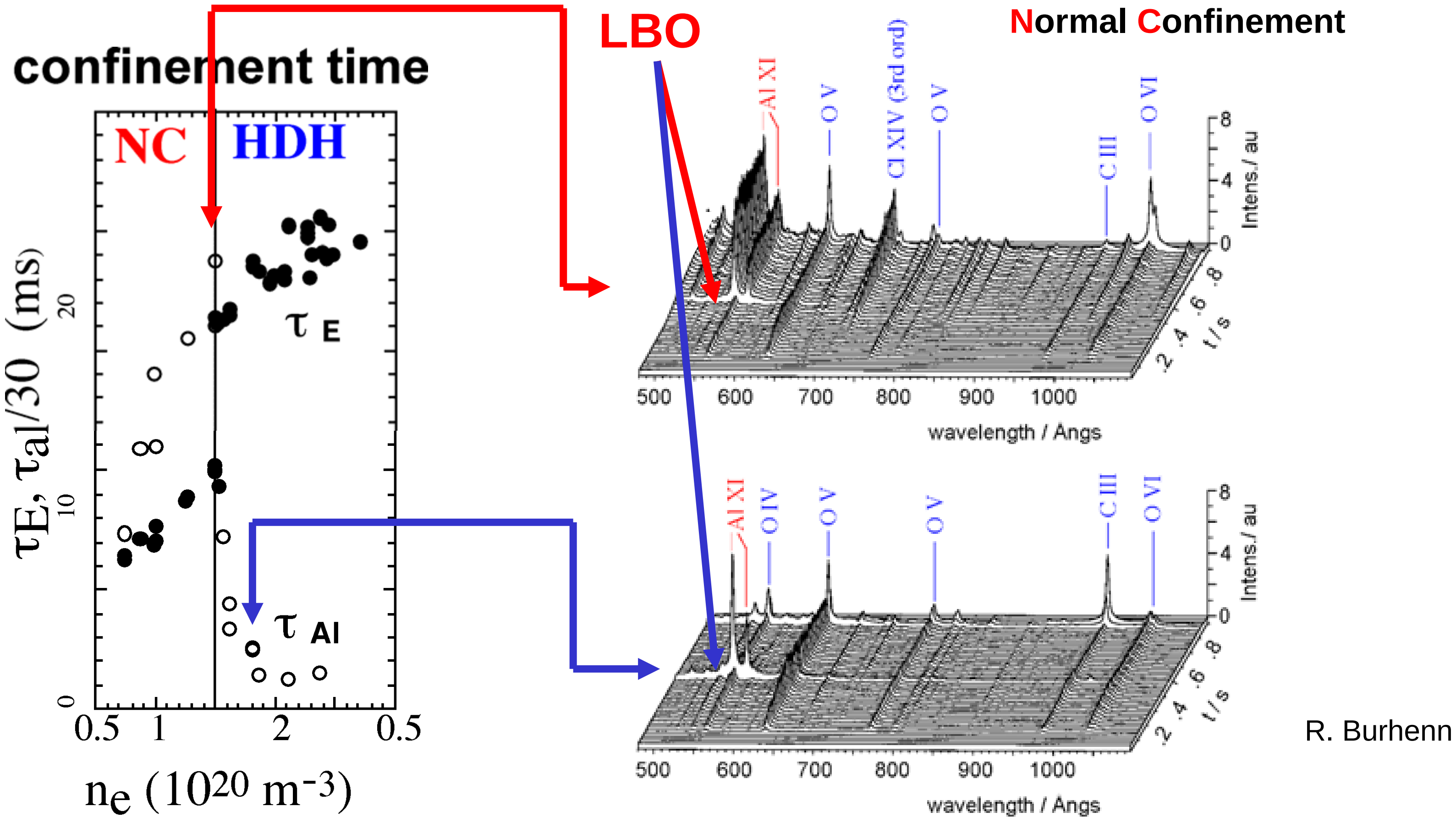
W7-X stable against pressure driven modes (e.g. interchange) up to <β> = 5% (applicable to standard & high mirror configuration according to optimization)

Operation compatible with first wall

The use of high-Z materials is an issue in stellarators

W7-X	- magnetic island divertor - high heat flux PFCs made of carbon
1st phase	- validation of island divertor
2nd phase	- demonstration of steady state power and particle exhaust - development of fully integrated scenario with reactor relevant first wall (tungsten)
HELIAS	- first wall material not yet addressed

HDH-mode: Candidate scenario with low impurity content



High Density H-mode

- Impurity screening by strong density gradients
- In addition increased outward impurity transport
- Question: how does the HDH mode scale to W7-X or a stellarator DEMO ?

Technology and physics for steady state

W7-X: **optimized stellarator with integrated design including**

- steady state magnetic field (up to 3 T, superconducting coils)
- actively cooled first wall (up to 10 MW/m^2, completion after 1st phase) → *see R. Stadler*
- steady state control & data acquisition, diagnostics and heating (ECRH) → *see M. Thumm*

1st phase

- confirmation of improved neoclassical confinement
- exploration & validation of island divertor concept
- investigation of impurity confinement

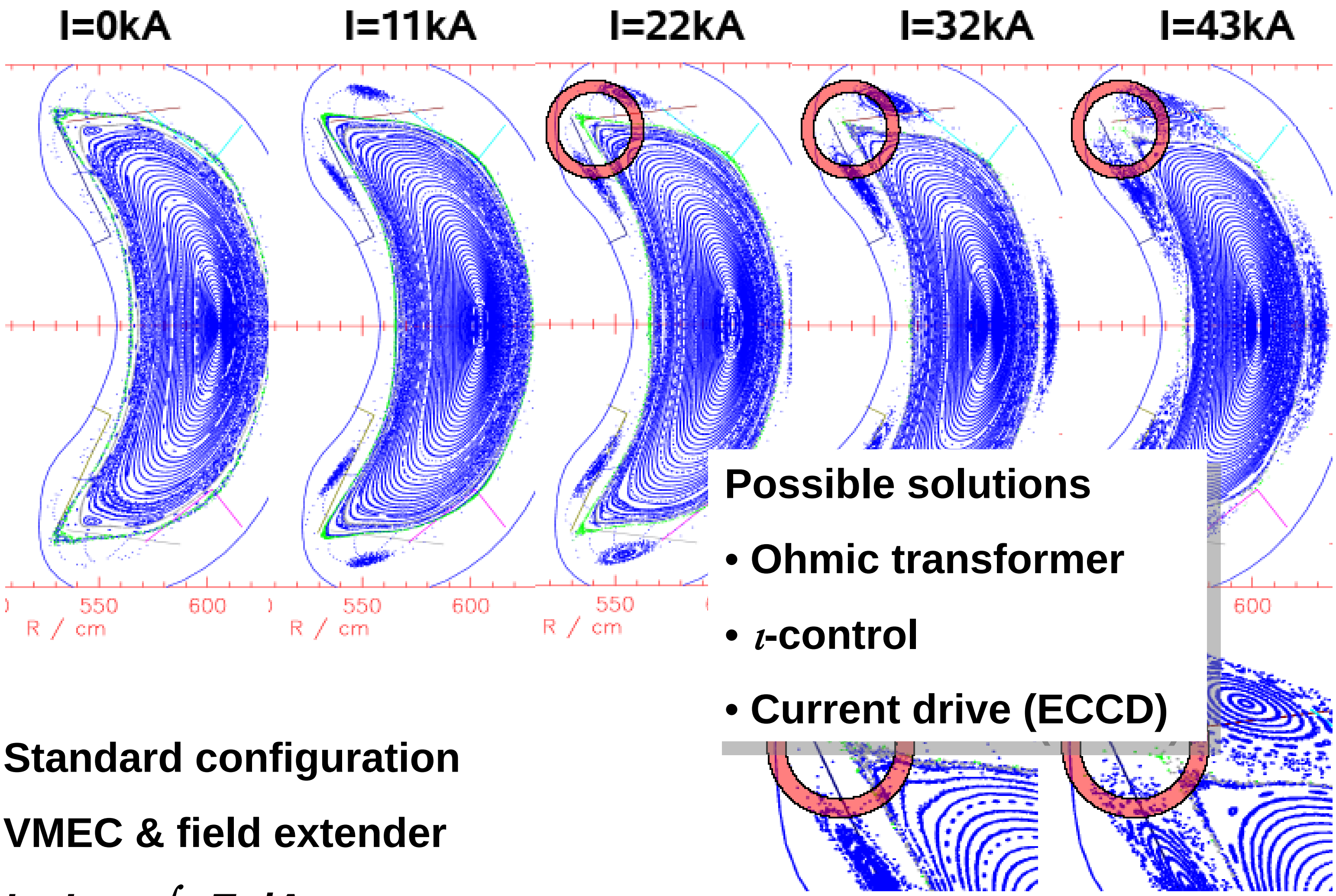
2nd phase

- development of fully integrated high power steady state scenario (HDH-mode type scenario)

HELIAS

- provide basis for validation / improvement of HELIAS design
- DEMO relevant (including tokamak) high density operation

Evolution of magnetic field configuration in the presence of bootstrap current



Possible solutions

- **Ohmic transformer**
- **ι-control**
- **Current drive (ECCD)**

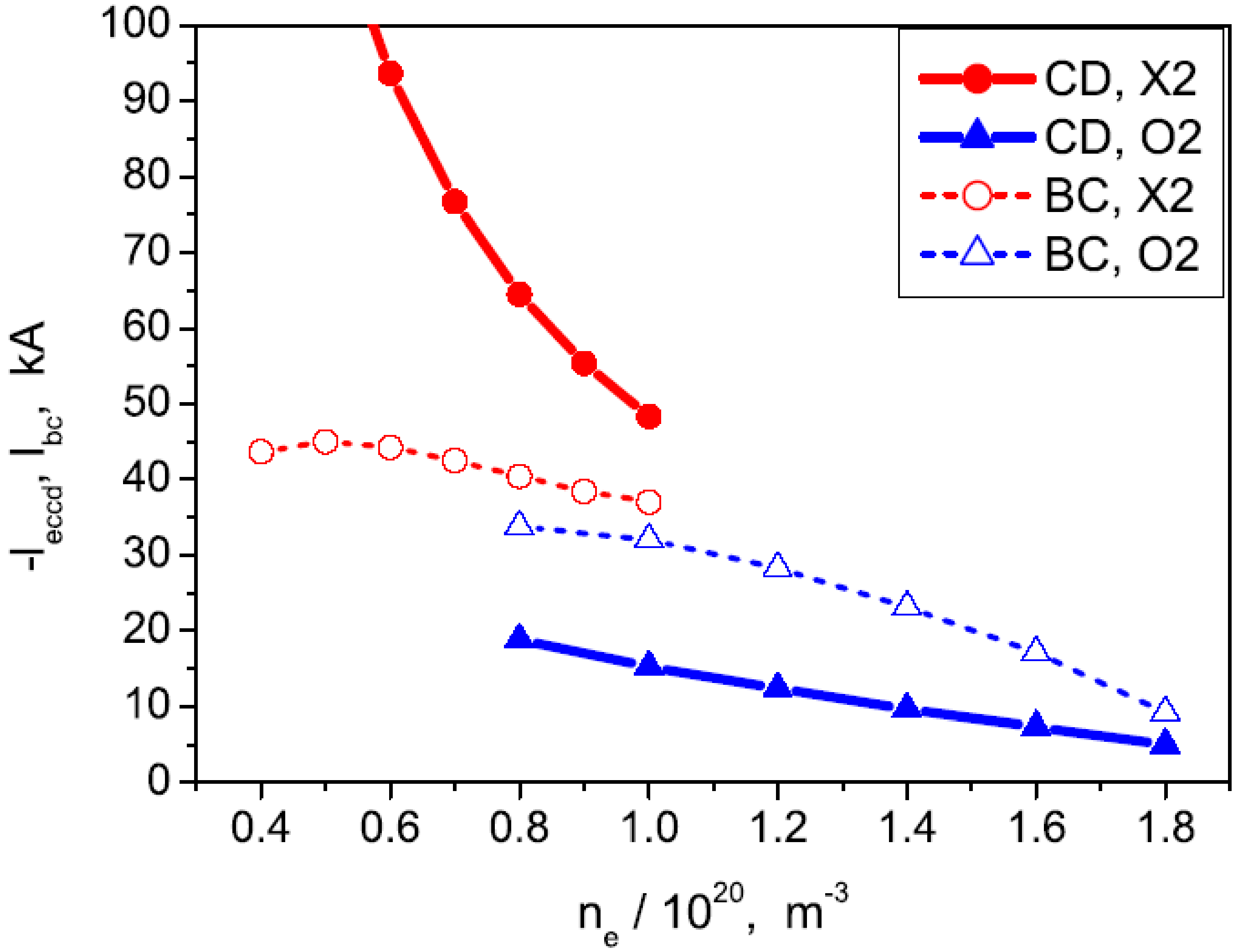
Standard configuration

VMEC & field extender

$$I = I_{BS} + \int \sigma E \, dA$$

J. Geiger

ECCD and bootstrap current for O2 Launch geometry, 5 MW (standard configuration)



C. Beidler et al.

Predicting fusion performance

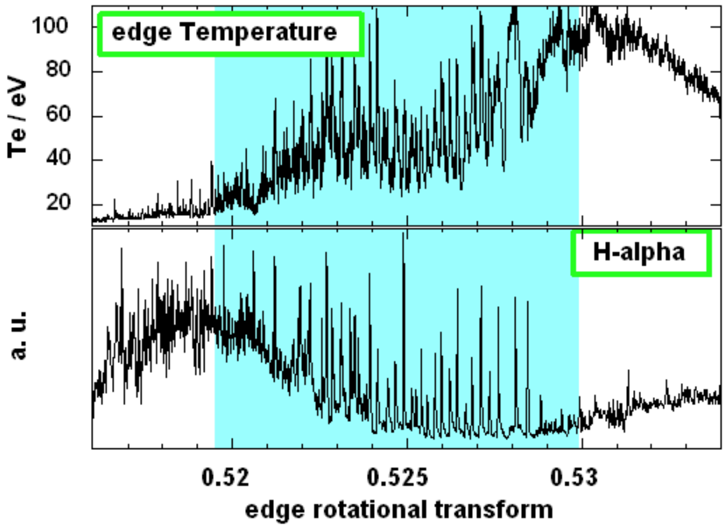
W7-X

- first large optimized stellarator with integrated design for steady state operation
- contributions to 3D physics:

  ambipolar electric fields and their effect on momentum transport

  ELMs without current driven instabilities

  ELM control by ergodization (now part of ITER design)



ELMs in W7-AS (M. Hirsch)

Together with results from ITER (burning plasma) and other stellarators, W7-X will form the basis for next step stellarator

Relies on advancement of first principle (3D) physics models and the possibility to combine results from different devices

Fits well into EU HPC (& Broader Approach IFERC computer) and ITER schedules

Summary & conclusions

Starting with plasma operation in 2015, high power Wendelstein 7-X steady state operation is approached in two steps

The increment to a next step stellarator depends on

- Results from W7-X and other stellarators
- Comparison of stellarator concepts
- Transfer of ITER results to stellarator (in particular α-physics) on the basis of first principle theory

Resuming stellarator reactor studies as part of a European DEMO study group (proposal of the European Facilities Review)

- aiming at further improvement / simplification of concept
- aiming at simplification of engineering (to that effect a first-of-a-kind device such as W7-X is not optimized)

Summary & conclusions (cont’d)

Physics issues for a stellarator DEMO

- Fast particle confinement, fast particle driven instabilities (confirm reduced drive for fast particles due to high density)
- Neoclassical versus turbulent transport (configuration dependence of confinement, only weak isotope effect) → *see F. Jenko*
- Impurity confinement (avoidance of impurity accumulation my need turbulent drive)
- 3D divertor configuration

Technology issues for a stellarator DEMO

- Coil configuration, coil support structure, superconductor
- Divertor (e.g. alignment requirements)
- Blanket design
- Accessibility
- Maintainability