Stellarators and pair plasmas: An introduction

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- The entire W7-X Team (this includes external collaboration partners)

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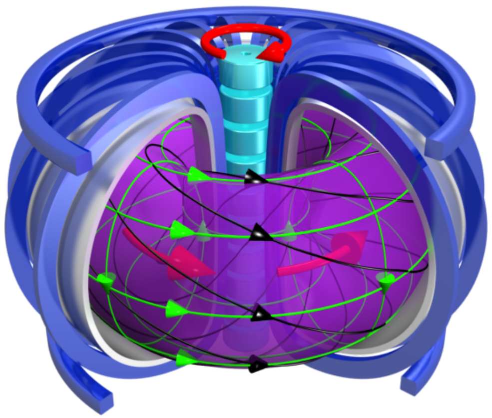
Outline

- Stellarators and the need for optimization
- Wendelstein 7-X
- Results from operation phase 1.1
  - Confirmation of the magnetic topology
  - Typical discharge evolution (early vs late in OP1.1)
  - Confinement and E-fields
- Stellarators as charged particle traps – also for pair plasmas
- Some unique properties of pair plasmas
- A short progress report from my group
- Summary

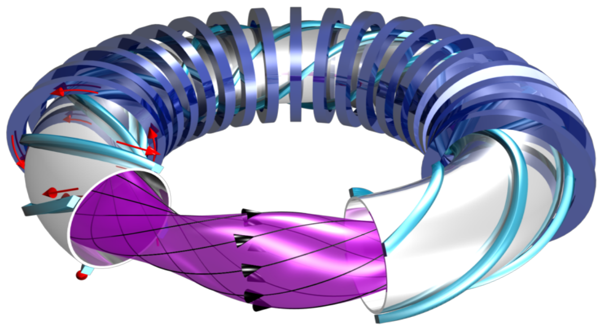
Tokamak and stellarator

- twisted magnetic field
- strong toroidal current in plasma



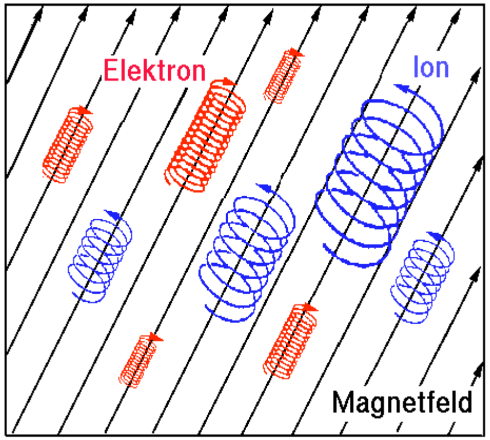
- excellent plasma confinement
- plasma instabilities require control
- steady-state operation requires strong current drive

- twisted magnetic field
- weak, self-generated toroidal current



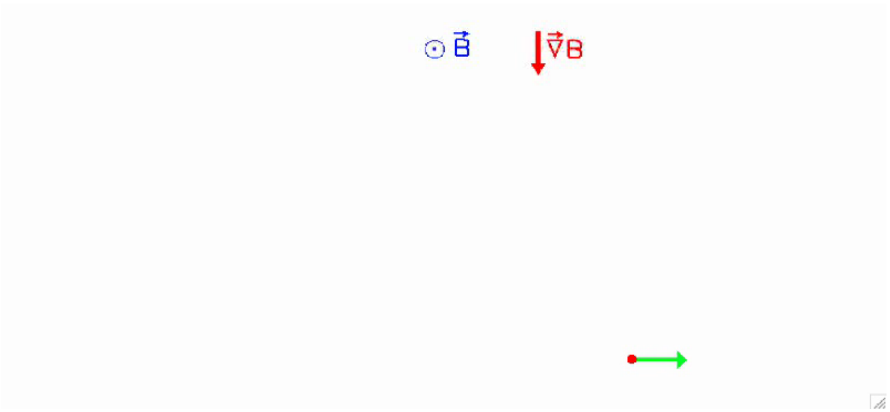
- excellent plasma confinement to be proven
- Free of major disruptions
- steady-state
- No Greenwald density limit

Guiding center drifts



In a straight, uniform magnetic field, charged particles gyrate around the magnetic field lines, but free-stream along the magnetic field and the guiding center is "stuck" to a field line – perpendicular confinement

In a toroidal magnetic field, there are no parallel losses, **but the guiding centers drift perpendicular to B and grad B**

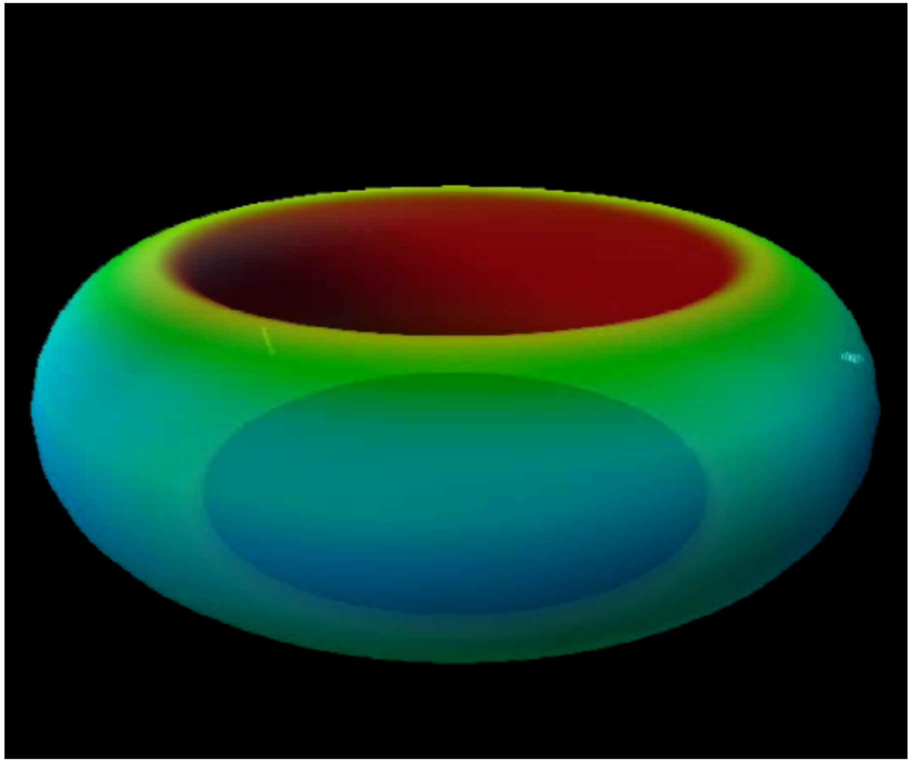


$$\vec{F} = -\mu \nabla B = -\frac{m v_\perp^2}{2B} \nabla B$$

$$\vec{v}_{\nabla B} = \frac{m v_\perp^2}{2B} \frac{\vec{B} \times \nabla B}{q B^2}$$

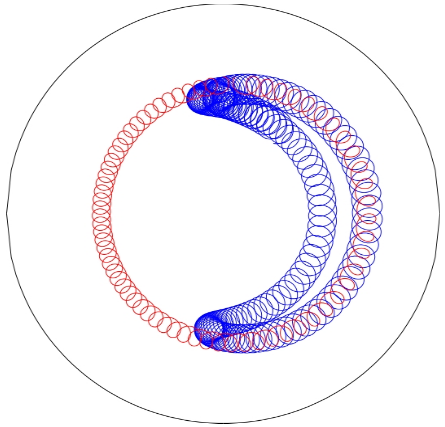
Net force away from high-field regions, and a perpendicular drift along the |B|=const contours

Why are the tokamak orbits closed?



$$\vec{v}_{\nabla B} = \frac{m v_\perp^2}{2B} \frac{\vec{B} \times \nabla B}{q B^2}$$

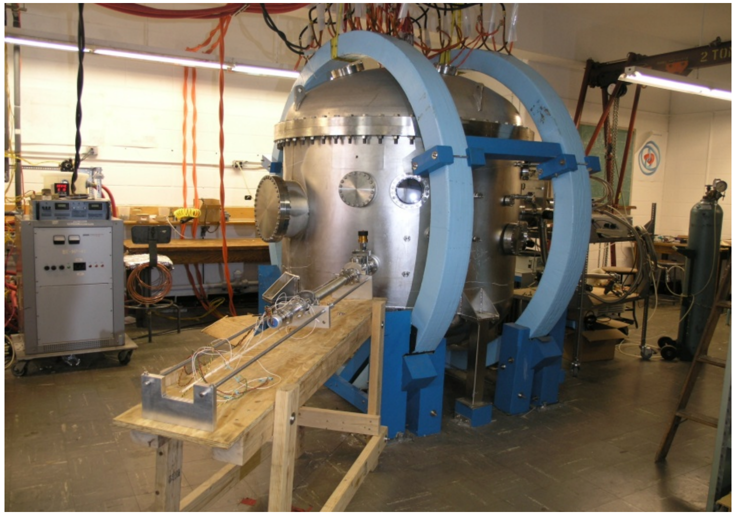
This drift is mostly vertical in a tokamak but it averages out due to symmetry

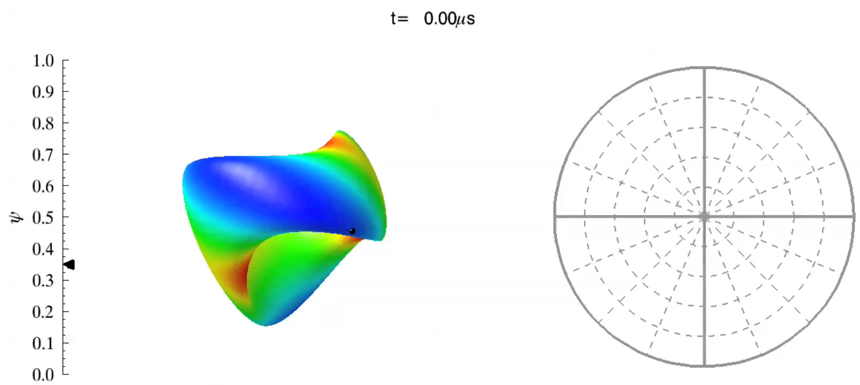


Poloidal projection: “banana orbit”

Stellarators need optimization

- There are stellarators that are simpler to build than tokamaks
- There are stellarator configurations that are remarkably error-field resilient
- **However**, so far, all of them suffer from poor particle confinement.
- Generically, magnetically passing particles are well confined, but magnetically trapped particles are not:





First physics results from W7-X

50 keV ion in a previous-generation stellarator

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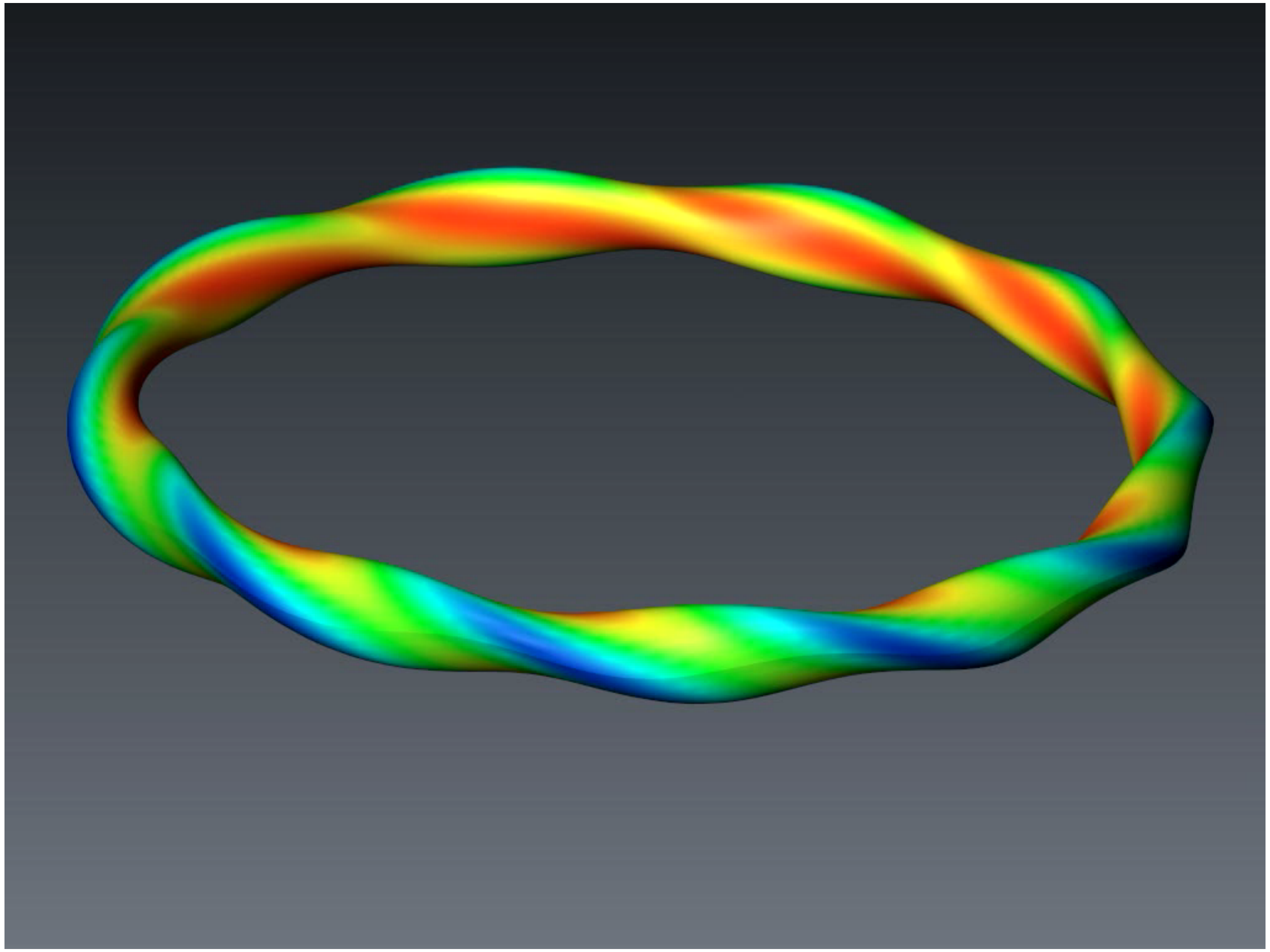

Progress in stellarator optimization

- Boozer (1983): Orbits will be confined and tokamak-like if |B| possesses a symmetry, when viewed in appropriately defined magnetic (Boozer) coordinates
  - This is known as quasi-symmetry
- Other related strategies for single-particle confinement include:
  - aligning constant J surfaces with the magnetic surfaces
  - making poloidally closed contours of |B| in low-field regions on a flux surface
- Optimization of other quantities also advantageous: MHD-stability, turbulent transport, bootstrap current,…
- This must be done on a computer and is CPU-intensive

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From surfaces to coils

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- Out of the optimization comes a desired 3D magnetic field that defines the stellarator magnetic surfaces
- Now starts the coil design – inverting the Biot-Savart law: Given B in the confinement volume, find an external current distribution that yields B

$$\nabla \times \vec{B} = \mu_0 \vec{j}$$

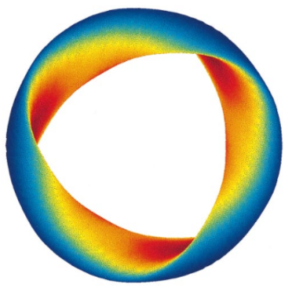
  - It is a problem that is ill-posed in a good way: There exists an infinity of solutions – the same stellarator can be created from different coil sets.
  - However, it is also a problem that has its challenges: The further away you place the current (the coils) the larger the current and the curvier the coils.
  - It becomes a trade-off between the different constraints:
    - Physics optimization, coil curvature, coil tolerances, distance between coils and plasma, stresses in the coils, etc.

A stellar(ator) comeback?

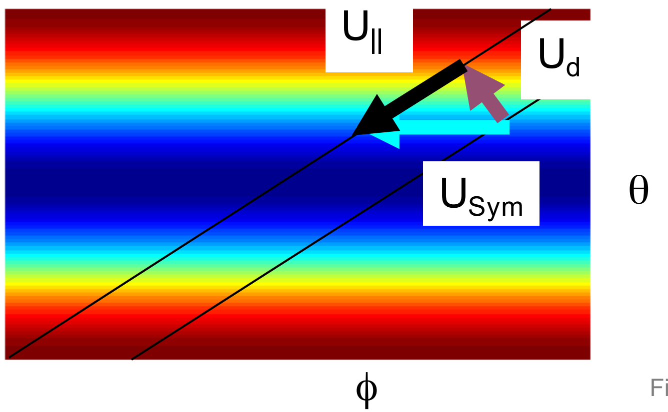
- These computations are now feasible because of advances in supercomputing power, and algorithmic development
- Our physics understanding has matured considerably
- 3D engineering design and manufacturing is becoming standard in industry
- High-precision metrology equipment is now common-place
- We can measure the as-built magnetic topology to the required accuracy using flux surface mapping

Quasi-symmetric stellarators

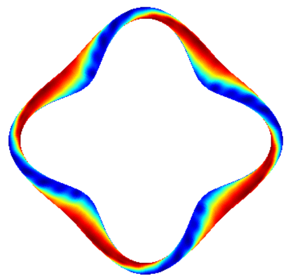
Quasi-axisymmetric
Nührenberg, Lotz, Gori(1994)
Garabedian (1996)



$B=B_o[1-\varepsilon_t\cos(m\theta)]$
No dependence on ϕ
Proposed experiments:
QUASAR, ESTELL

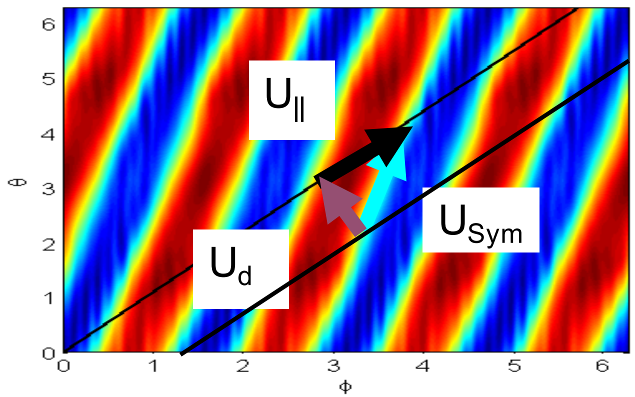


Quasi-helically symmetric
Nührenberg and Zille (1988)



$B=B_o[1-\varepsilon_h\cos(n\phi-m\theta)]$

Running experiment:
HSX: Next slides



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The Helically Symmetric Experiment (HSX)

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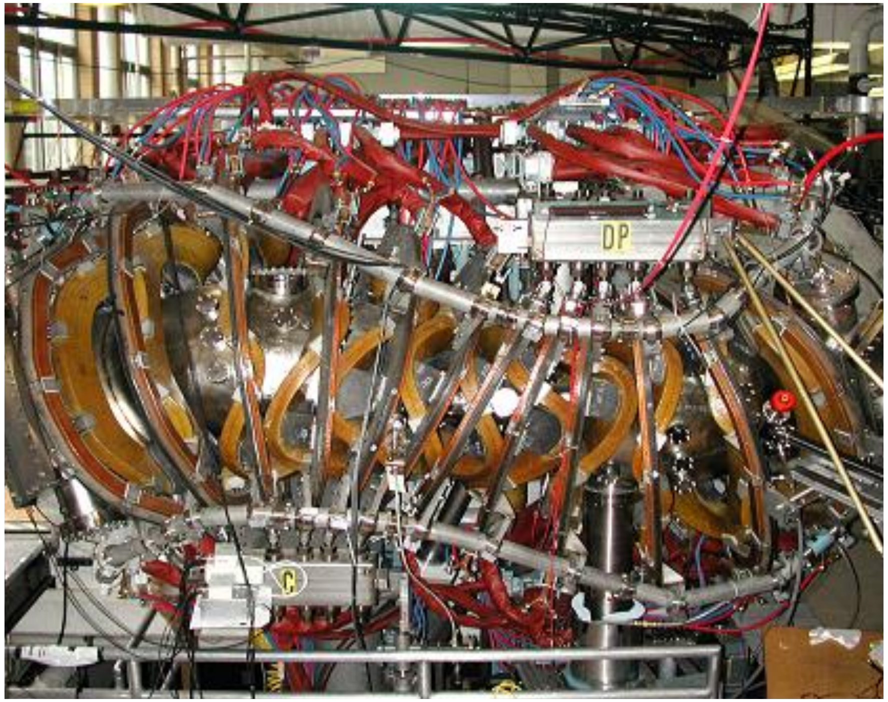


R=1.20 m

a=0.12 m

B=1.0 T

T_e up to 2.5 keV

n_e up to 10^{19} m^{-3}

τ_E= 3 ms

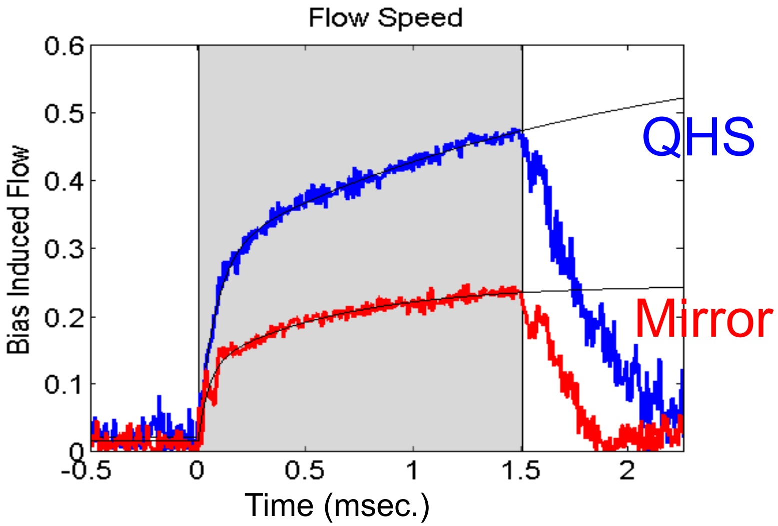
WISCONSIN UNIVERSITY OF WISCONSIN–MADISON

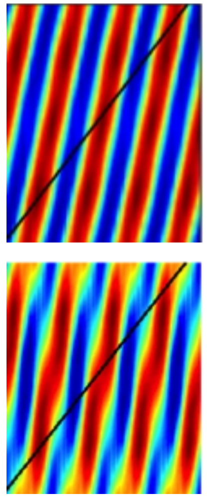
University of Wisconsin-Madison
First plasma September 1999

HSX

HSX: Larger plasma flow with QHS

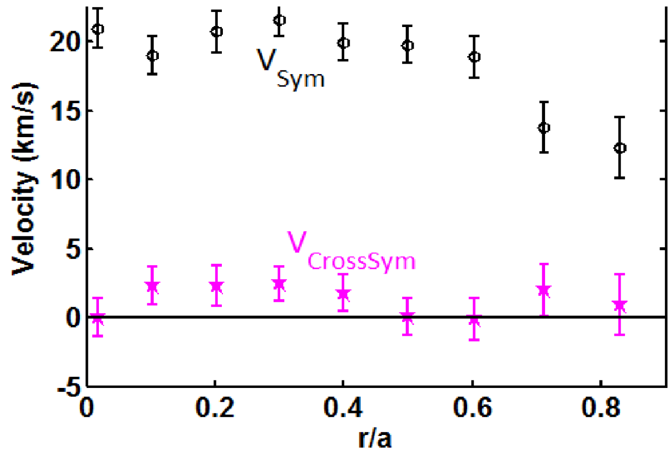
Driven flow stronger in QHS





Plasma Edge: Electrode Induced Flow, measured with probes, is larger with quasisymmetry

Intrinsic flow is in direction of symmetry



Charge Exchange Recombination Spectroscopy

The optimized stellarator Wendelstein 7-X

Plasma volume **30 m³**
Magnetic field **2.5 T (up to 3 T)**

Superconducting coils **70**

Magnetic field energy **600 MJ**

Cold mass **435 t**

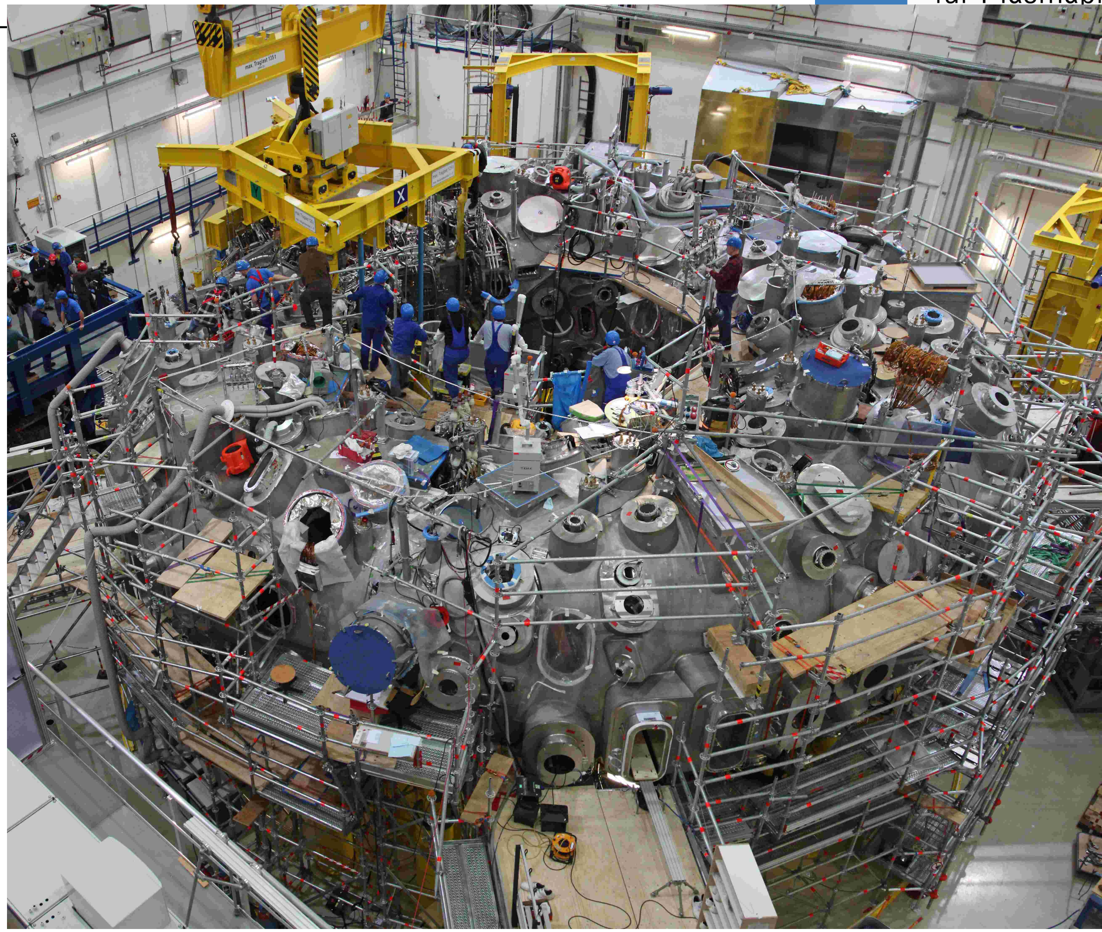
Total mass **735 t**

Plasma duration **30 minutes**

Heating power **10 MW**

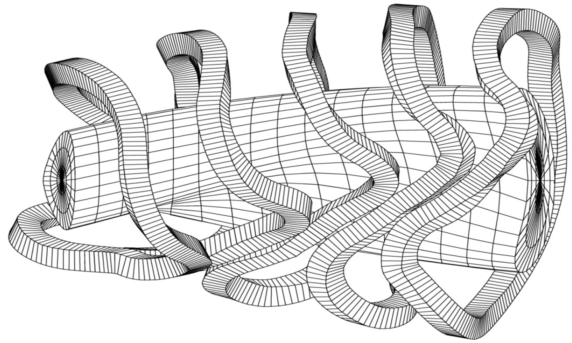
(Pulsed 10 sec: **20 MW)**

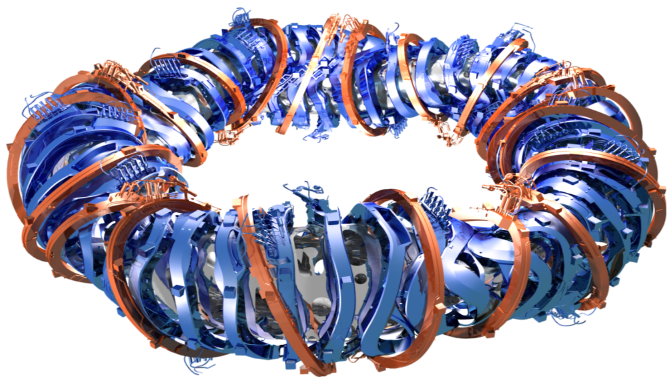
Maximum heat flux **10 MW/m²**



W7-X optimization

- High quality of vacuum magnetic surfaces
- Good MHD equilibrium and stability properties @ $<\beta> = 5\%$
- Reduced neoclassical transport
- Small bootstrap current (for divertor operation)
- Good fast particle confinement
- Good modular coil feasibility

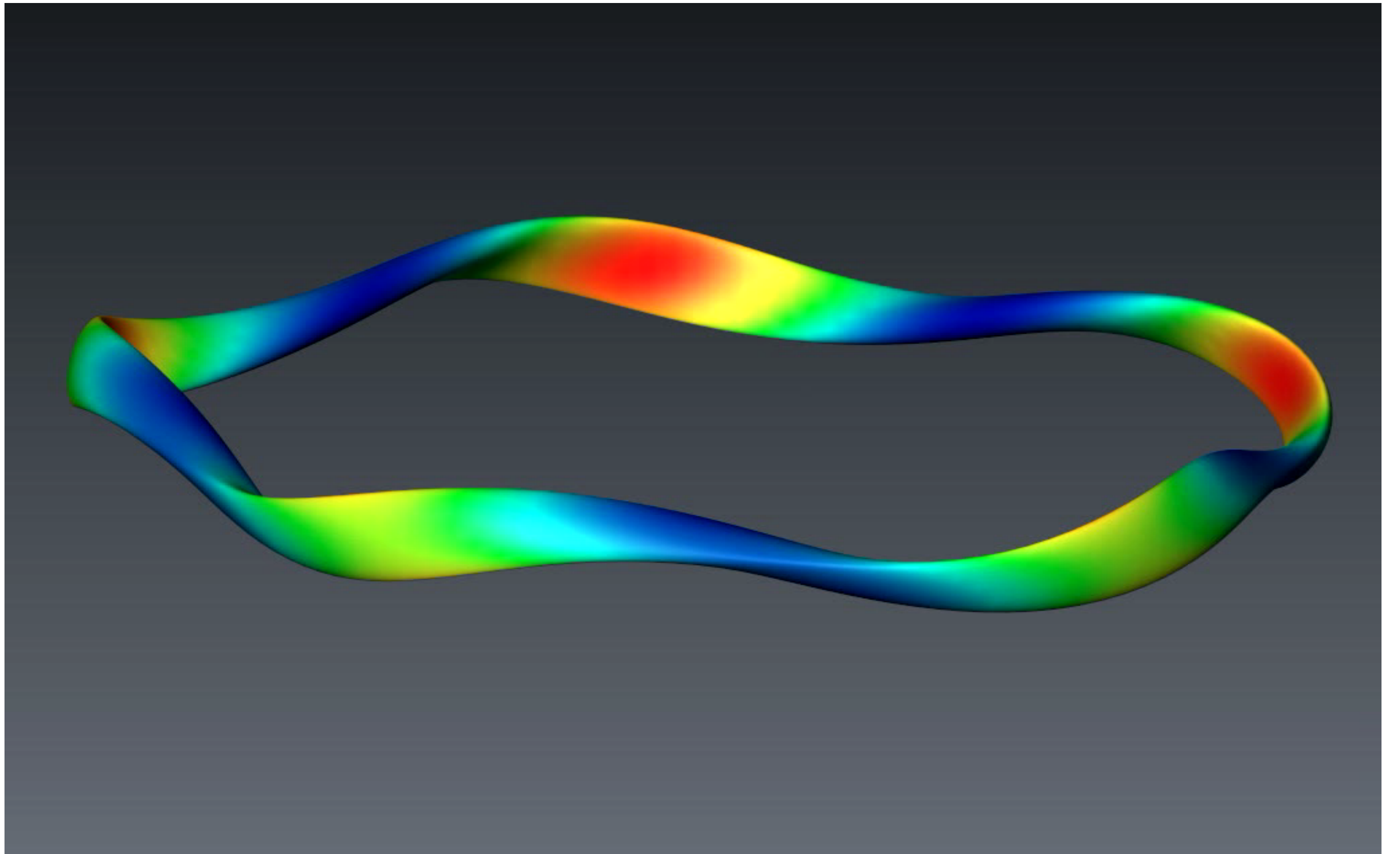




- Non-planar coils (blue)
  - Standard configuration
- Planar coils (red)
  - Iota changes
  - (De)optimization

W7-X magnetic field optimization

Illustrated for a 50 keV ion launched on an inner flux surface – scales to α-particle in reactor



First Operation Phases (OP) in Figures

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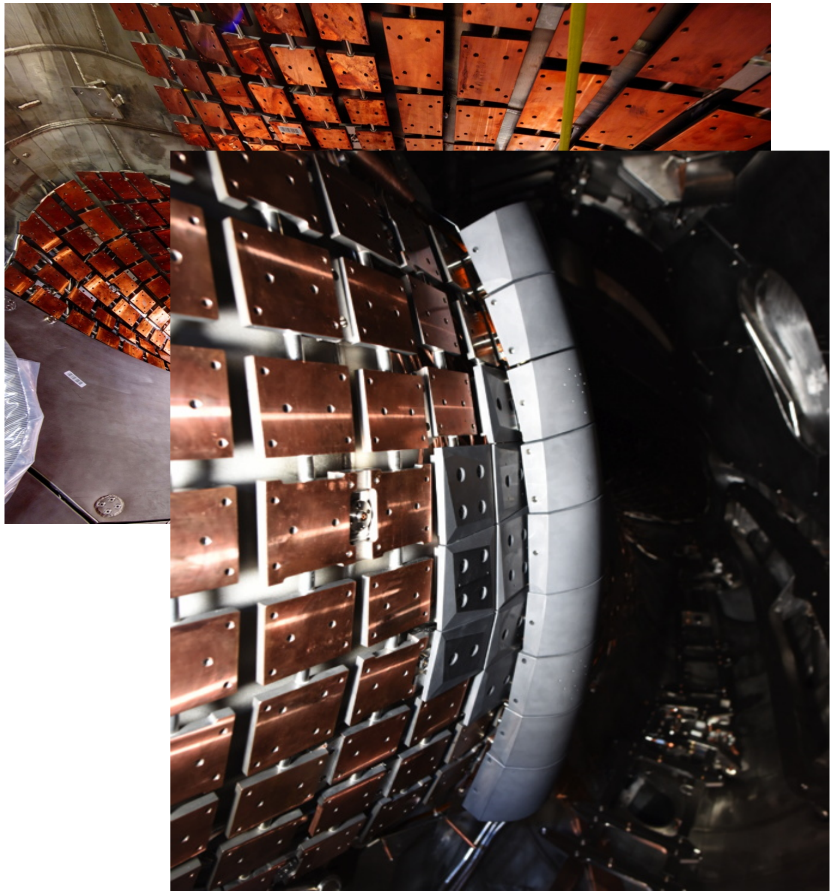
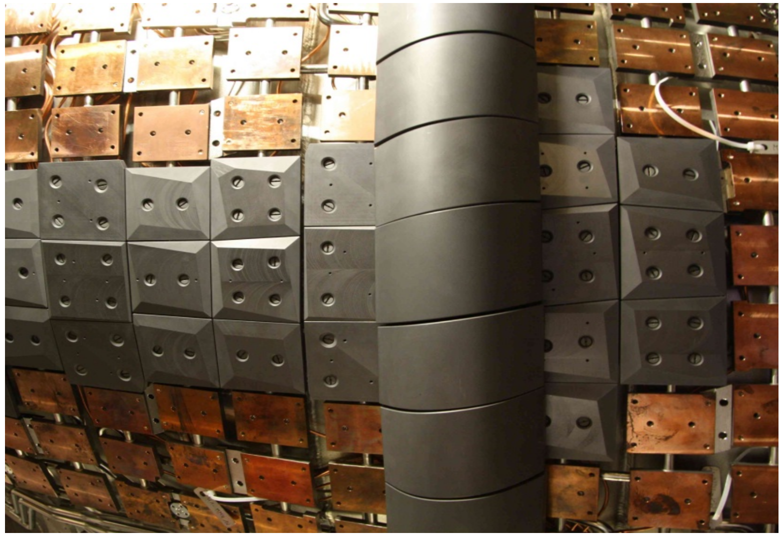
OP 1.1 **2015-16** **3 months**	Pulse limit: E_{max} ~ 2MJ Graphite limiters, uncooled	P_{ECRH} ~ 5 MW 6 gyrotrons	T_e^{NC} ~4 keV T_i^{NC} ~1 keV $n \sim 2 \cdot 10^{19}\ m^{-3}$
OP 1.2 **2017-18** **2*4.5** **months**	Pulse limit: E_{max} ~ 80 MJ Graphite divertor, uncooled	P_{ECRH} ~ 8 MW P_{NBI}^{H} ~ 7 MW P_{ICRH} ~ 1.6 MW	T_e^{NC} ~5 keV T_i^{NC} ~4 keV $n \sim 1.6 \times 10^{20}\ m^{-3}$
OP 2 **2020+**	Pulse limit: E_{max} ~ 18 GJ =10MW for 30 minutes 20 MW for 10 seconds 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 $n \sim 2 \times 10^{20}\ m^{-3}$ $\langle \beta_{NC} \rangle$ ~ 5 %

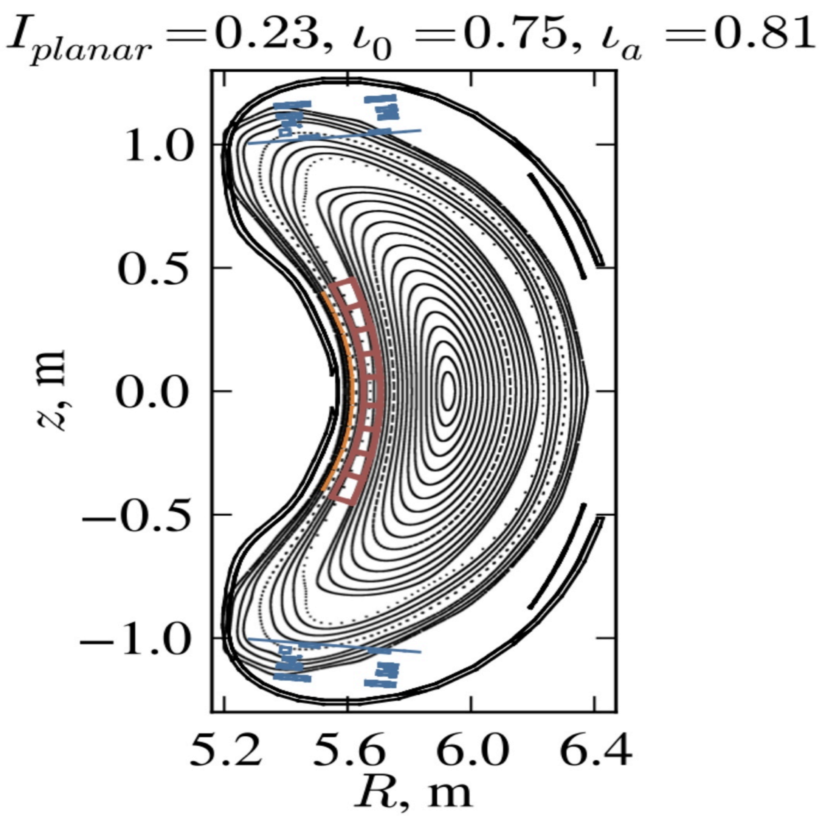
PFCs for first plasma operation (OP1.1)



- Wall protection (SS)
- Heat shields (CuCrZn heat sinks)
- No divertor in OP1.1
  - 5 graphite limiters at the inner wall
- Must intersect convective plasma heat loads
- Designed for 5*0.4 MJ=2MJ per pulse



Main 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 islands in near SOL

✓ I_{planar}=0.13 chosen

Confirming the stellarator topology

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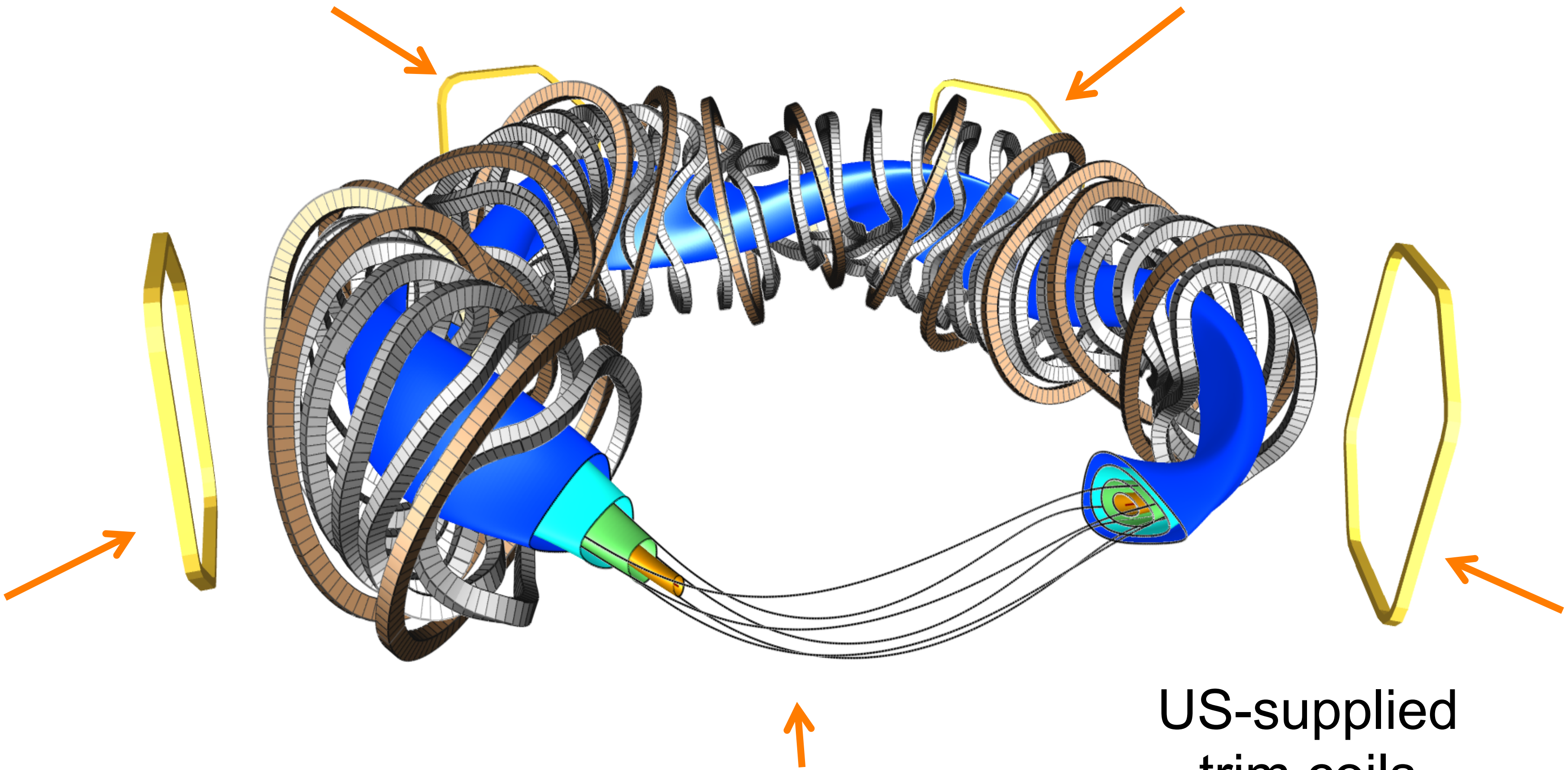
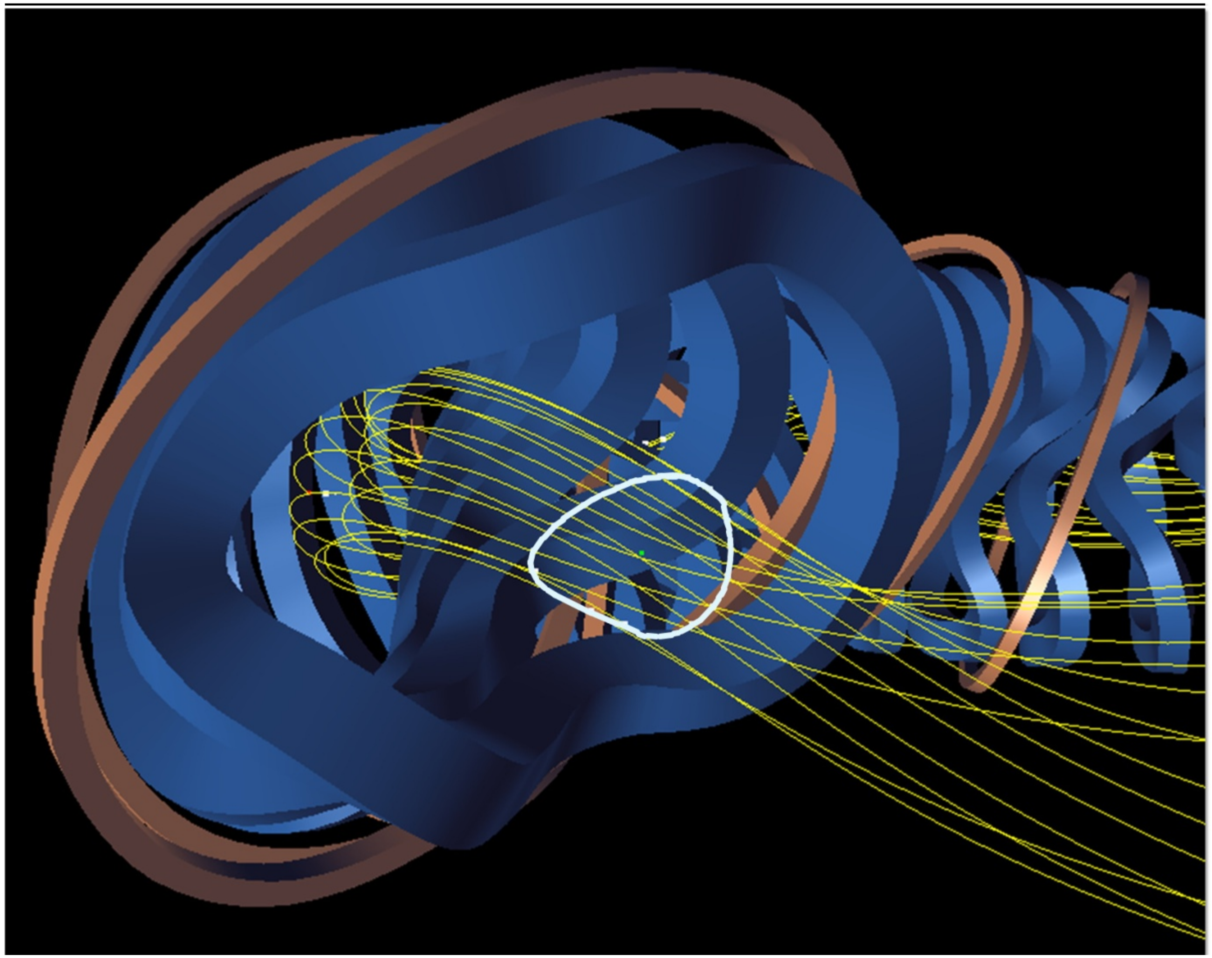


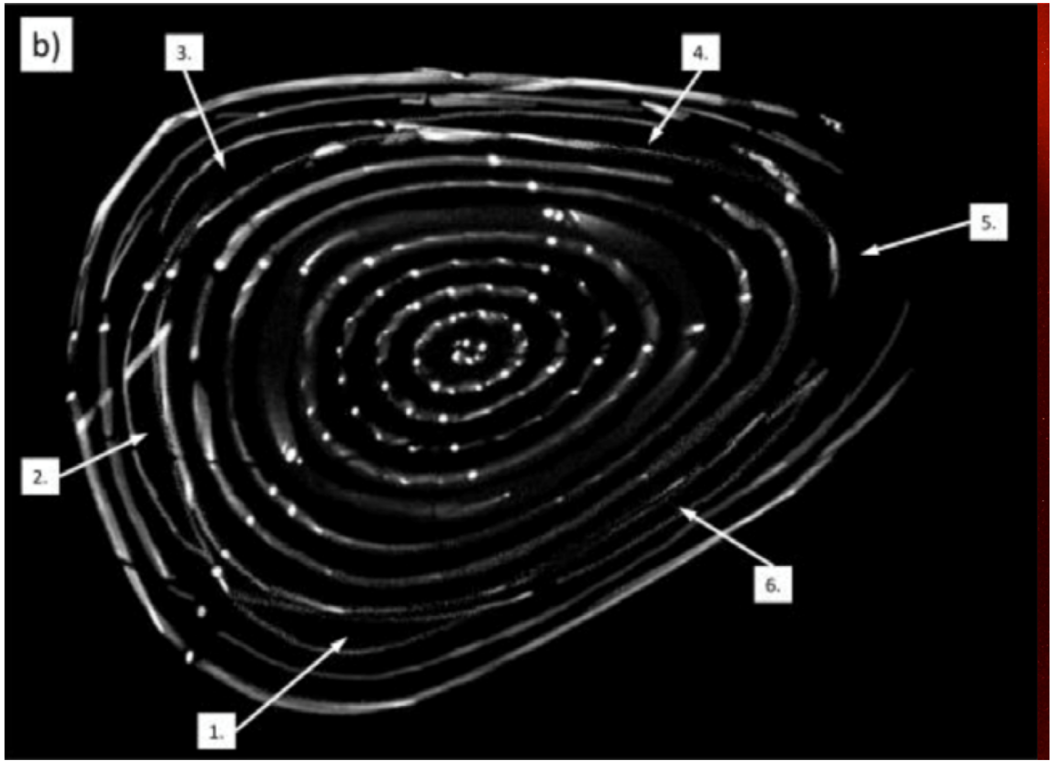
US-supplied
trim coils

Flux surface measurement principle



Measurements confirmed expected nested flux surfaces

- The expected nested flux surface topology has been verified in great detail*
- There were some deviations but all small – better than 1:100,000
- Deviations agree with coil models based on metrology #
- The configuration chosen for OP1.1 plasma operation was particularly robust against field errors.



* T. S. Pedersen et al., S. Lazerson et al., APS-DPP 2015
* M. Otte et al., PPCF 58, 064003 (2016)
* S. Lazerson et al., Nucl, Fusion (2016)
# T. S. Pedersen et al., Nature Comm. (2016)

First (helium) plasmas

First plasmas end in a radiation collapse

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- Video diagnostic: visible light
- Central ignition
- Expansion from inner to outer magnetic surfaces is slow due to good confinement
- Radiation/ionization layer defines the expanding edge
- UV photons and charge exchange neutrals from plasma hit the walls, impurities come off the walls
- Impurity radiation kills the plasma from the outside
- No heat to the limiters (yet)!

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

Hydrogen Plasmas

High performance in H

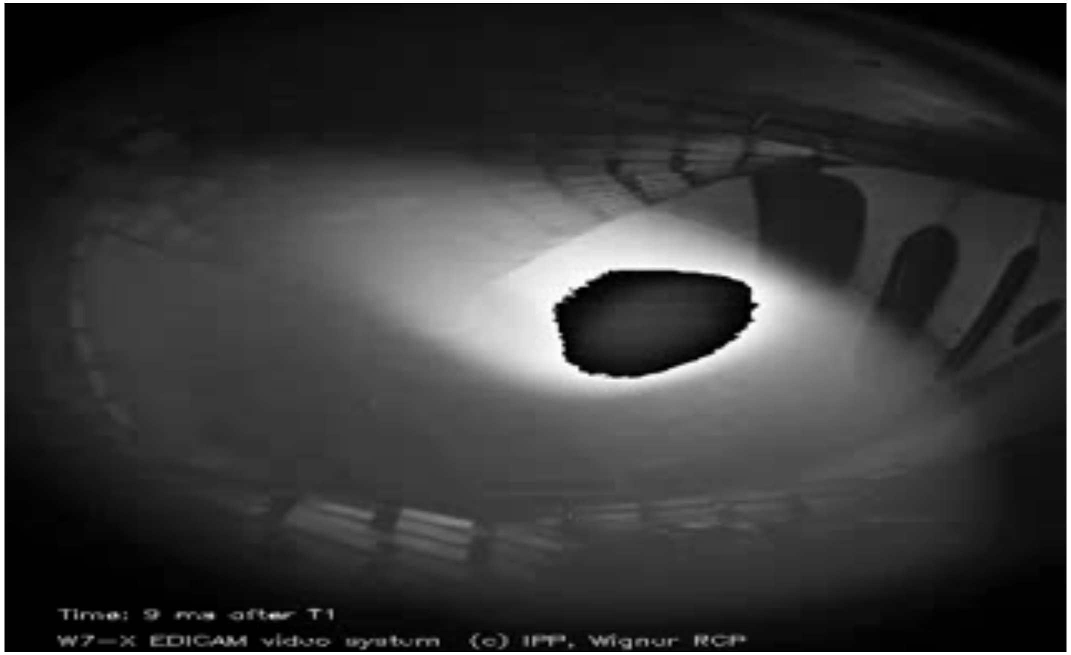
- 2 MJ milestone reached on Thursday Feb 18, 2016!
- 1 second 2 MW reference discharge
- Look closely 1.52 (5.34 msec), 2.21 (744 msec) and 2.90 (944 msec)

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

T. Szepesi, G. Koczis

High performance in H

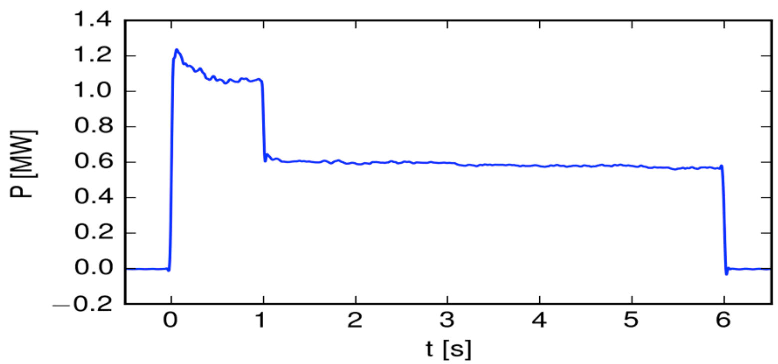
- Since the limiters were not overheated even in 2 MJ discharges, 4 MJ per discharge was allowed during the last weeks of operation
- 6 second discharge shown (1 s 1MW, then 5 s 0.6 MW):

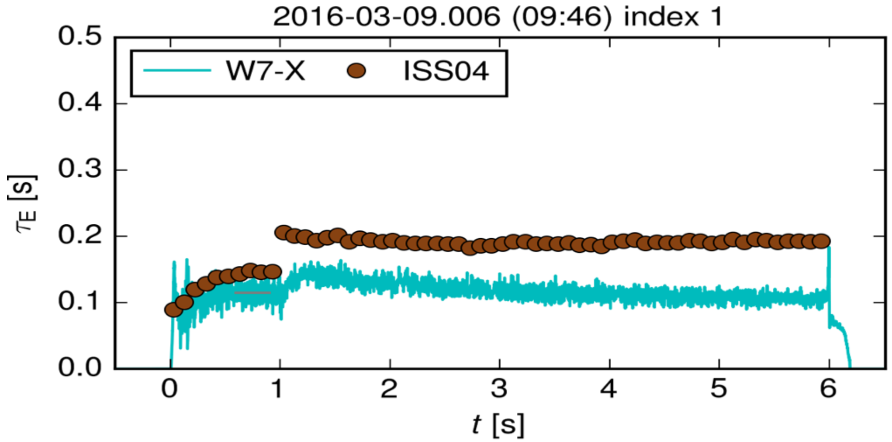


- Discharge terminates peacefully, as pre-programmed
- See next slides for analysis of such 6 second shots

T. Szepesi, G. Koczis

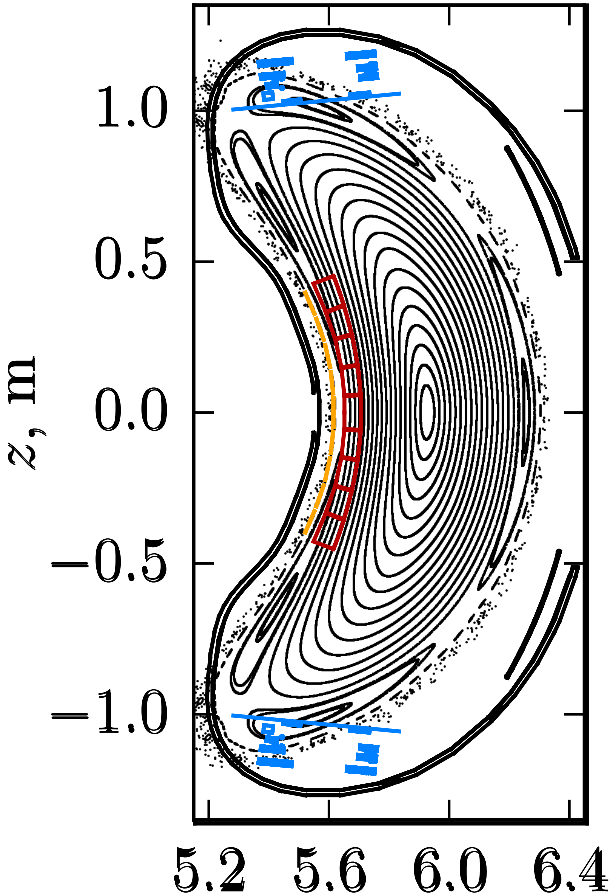
Confinement times of order 100-150 msec





- Remarkably stable discharges over 6 seconds despite having no divertor
- 4 MJ=1MW*1s+0.6MW*5s
- Confinement time decays slightly over time
  - Possibly due to increased radiation

"De-optimized" configuration for OP1.1



This configuration offered a test of the optimization:

- By removing current from one coil set, we created an extra bump in the magnetic field
- This should lead to significantly more loss orbits
- The resulting confinement degradation would be almost a factor of 3 – clearly measurable
- However, there was reason to believe that this effect would not be seen at all
- These are predictions worth testing!

Confinement time with “de-optimized” configuration

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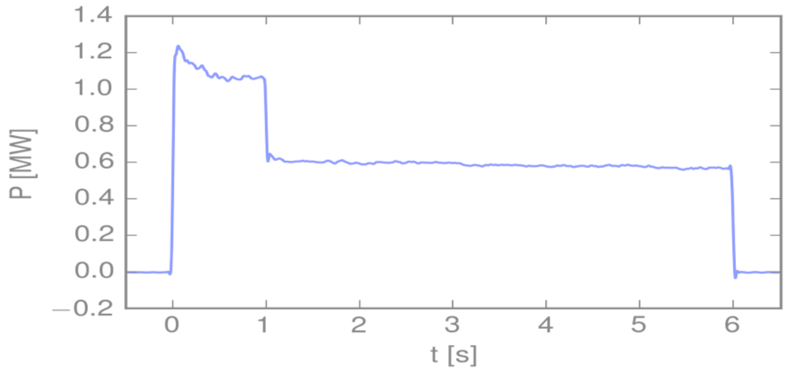
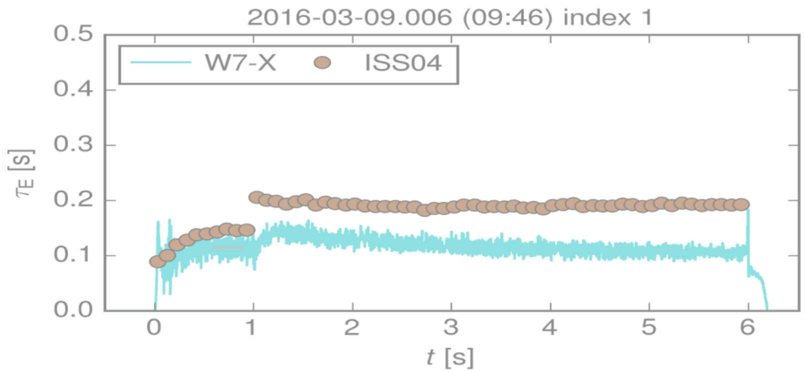
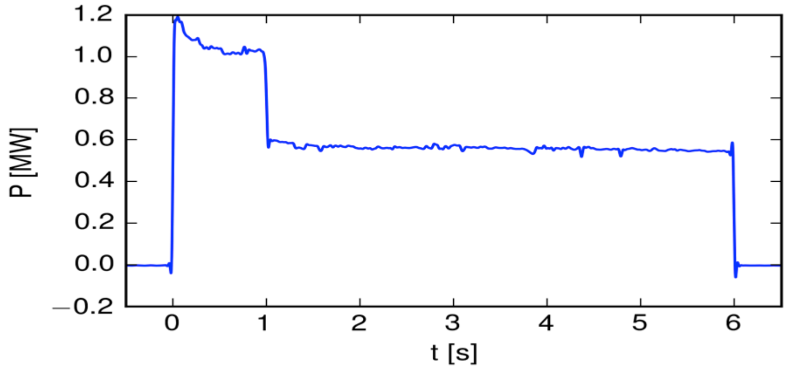
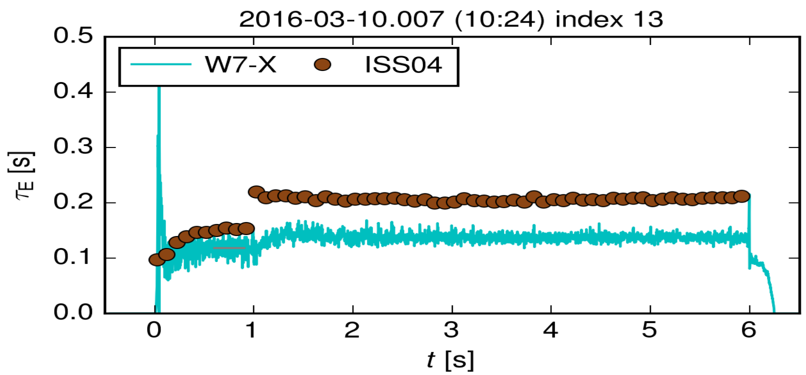








Essentially no change in confinement, as expected

Why no change despite de-optimization?

So why did we expect no change when we de-optimized?

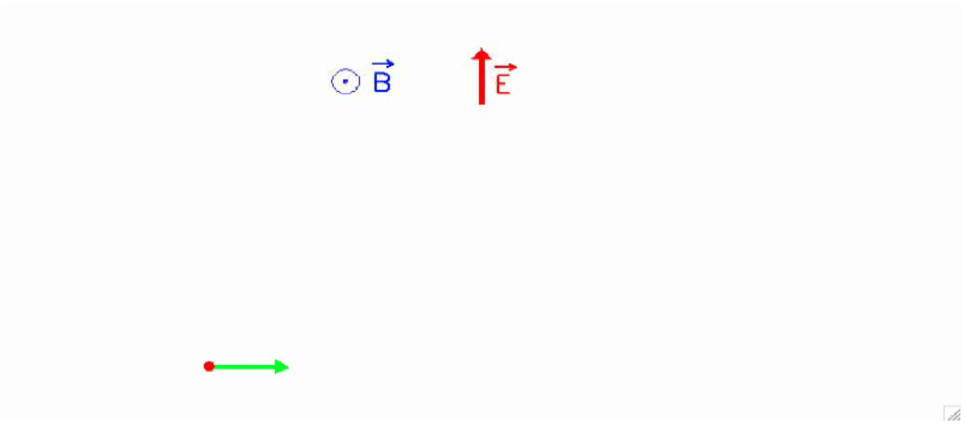
1. Is it because turbulent transport already dominates and we need to further de-optimize to see an effect?
2. Is it because the orbits are “magically” well-confined even for de-optimized configurations?

Answer is 2: The magic is in the electric field

Electric fields in magnetized plasmas

The electric field is near-zero in the direction along B, otherwise the plasma would create a large current – electrostatic potential is (almost) constant on a magnetic surface
From magnetic surface to magnetic surface the potential can vary strongly –thus, the electric field is predominantly radial.

Electron

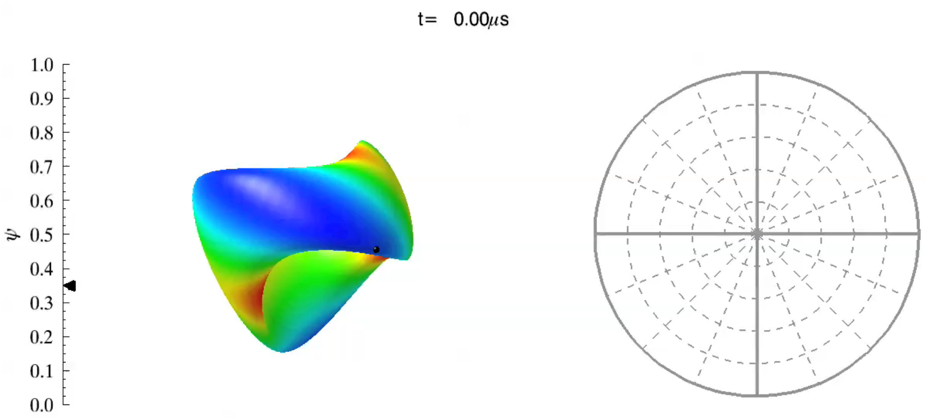


$$\vec{v}_E = \frac{\vec{E} \times \vec{B}}{B^2} = -\frac{\nabla\phi \times \vec{B}}{B^2}$$

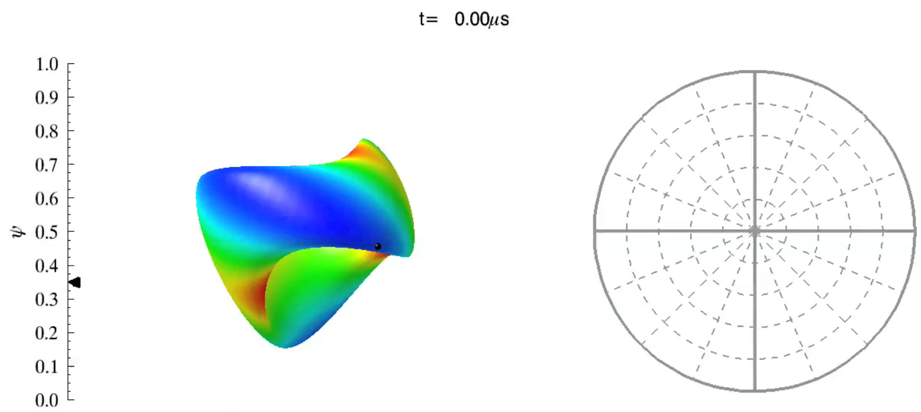
Drift is along constant potential contours (ie. lies almost exactly within magnetic surface) and is poloidal

Strong electric fields in stellarators: CNT

This brings me back (again) to the good old CNT days…



Trapped particle drifts out



Trapped particle stays confined

Predicted excellent confinement time (many seconds)[a]
Experimental findings: 20 ms initially[b], then up to 320 ms[c]
The whole story is more complicated than that

[a] T. Sunn Pedersen and A. H. Boozer, PRL **88**, 205002 (2002)
[b] J. P. Kremer et al. , PRL **97**, p. 095003 (2006), [c] P. W. Brenner et al., CPP **50** p.678 (2010)

Electric fields in stellarators

How large of a role does the bulk ExB drift play relative to the magnetic drifts?

$$\left|\frac{v_{ExB}}{v_{\nabla B}}\right| \approx \left|\frac{\nabla\phi / B}{(W_k \nabla B / eB^2)}\right| \approx \left|\frac{e\phi}{W_k}\right|$$

Pure-electron plasma: Dominant (factor of 10-1000, CNT: 50)

Thermal particles in a quasineutral plasma: Depends.. (0.2-5)

Set by ambipolarity

OP1.1 T_e>>T_i leads to relatively strong role

Fusion α's: Negligible (~35 keV/3.5 MeV~0.01)

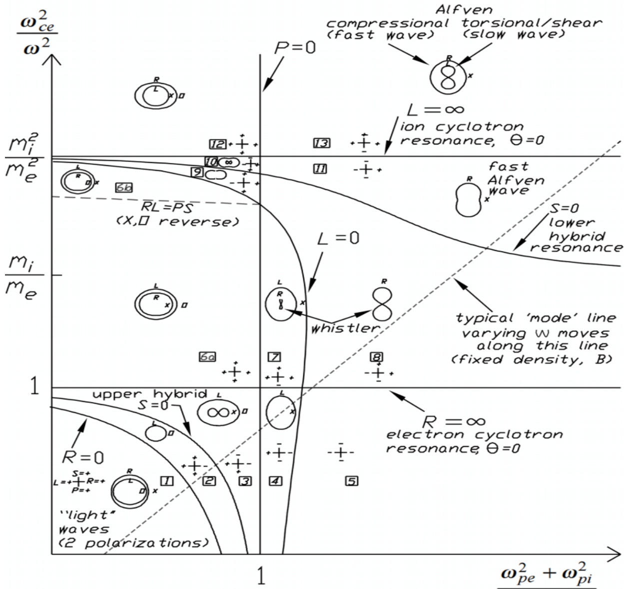
So, the orbit-healing effects of E_r is going to be smaller in later operation phases, and cannot "fix" α-confinement in a future reactor

The stellarator as flexible plasma trap

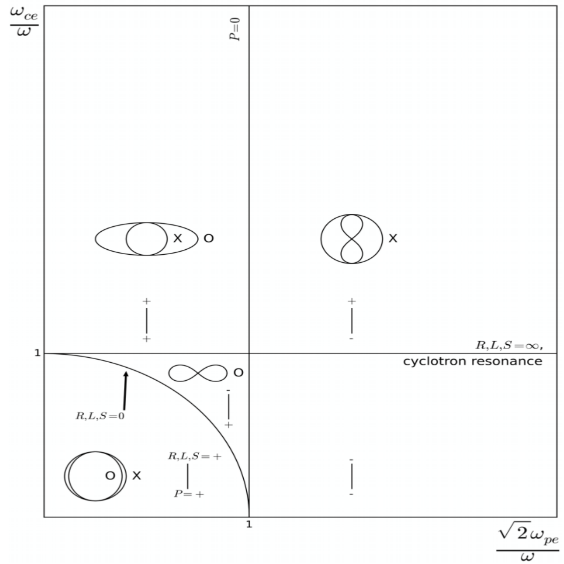
- Stellarators can do more than confine hot, dense plasmas for fusion research
- The stellarator provides a confining "cage" for charged particles of both signs of charge – regardless of how low the plasma density might be
  - In many fusion confinement concepts, including tokamaks, a strong plasma current is needed, effectively precluding confinement of plasmas at very low densities and temperatures
- Pure electron plasmas (CNT)
- Plasmas of any degree of neutralization (CNT)
- Electron-positron (pair) plasmas
  - My initial plan was to create long-lived electron plasmas in a stellarator, and then use these as "attractive target" for the positrons

Pair plasmas: Why

- The mass symmetry between the positive and negative species:
  - Presumably relevant for the early Universe (?)
  - Simplifies theoretical and numerical treatments significantly
    - About 1000 papers written on pair plasmas
  - Should simplify the behavior of the plasma: For example waves:



From Bellan



E. V. Stenson et al, JPP, 2017

“Textbook example”: L, R, and X waves coalesce in pair plasma

- L-wave propagates along B and is circularly polarized in the ion gyration sense
- R-wave propagates along B and is circularly polarized in the electron gyration sense
  - Because of the mass difference, they have different cutoffs and resonances and generally do not propagate at the same phase velocity
  - This leads to Faraday rotation
- X-wave propagates perpendicular to B and is elliptically polarized
- All three get the exact same dispersion relation in an electron-positron plasma!

$$n^2 = L \qquad n^2 = L$$

$$n^2 = R \qquad n^2 = R = L$$

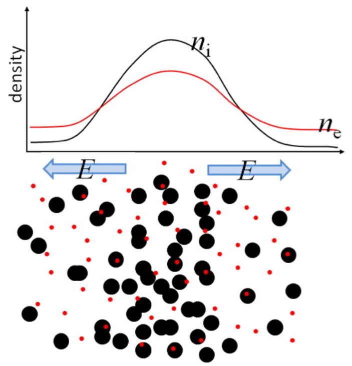
$$n^2 = \frac{2RL}{R+L} = \frac{2LL}{L+L} = L$$

$$R = 1 - \frac{\omega_p^2}{\omega(\omega-\omega_c)} - \frac{\Omega_p^2}{\omega(\omega+\Omega_c)} = 1 - \frac{\omega_p^2}{\omega(\omega-\omega_c)} - \frac{\omega_p^2}{\omega(\omega+\omega_c)}$$

$$L = 1 - \frac{\omega_p^2}{\omega(\omega+\omega_c)} - \frac{\Omega_p^2}{\omega(\omega-\Omega_c)} = 1 - \frac{\omega_p^2}{\omega(\omega+\omega_c)} - \frac{\omega_p^2}{\omega(\omega-\omega_c)}$$

Pair plasmas: More motivation

- There should be:
  - No Debye sheath around internal objects
  - No Faraday rotation of electromagnetic waves [1]
  - No acoustic waves[1] and – related to that – no drift waves [2]
  - No instabilities whatsoever in a large (and experimentally relevant) parameter range: “Remarkable stability properties” [3,4]

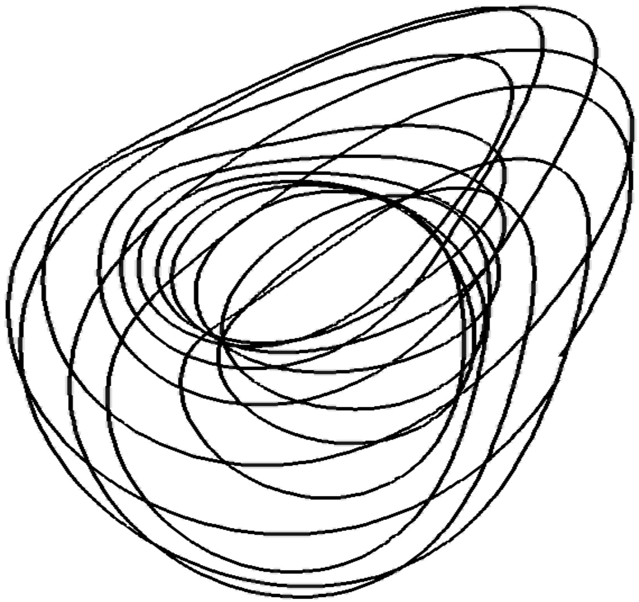


electron-ion plasma

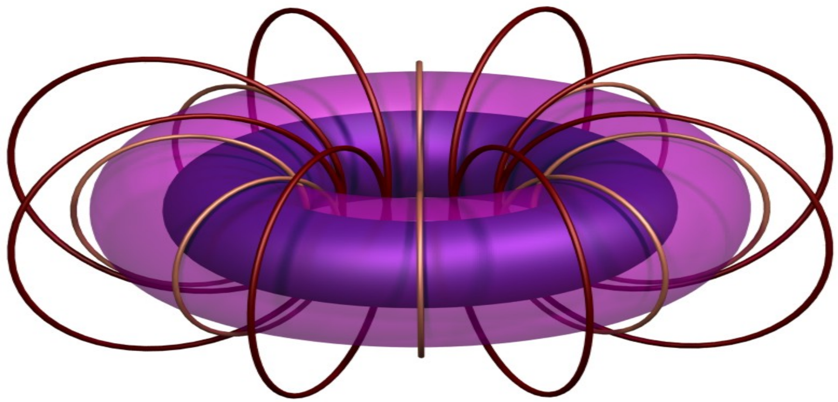
1. V. Tsytovic and C. B. Wharton, Comments Plasma Phys.Controlled Fusion **4**, p.91 (1978)
2. T. Sunn Pedersen et al, J. Phys. B: At. Mol. Opt. Phys. **36** 1029 (2003)
3. P. Helander, PRL (2016)
4. P. Helander and J. W. Connor, Journal of Plasma Physics (2016)

Magnetically confined pair plasmas: Two traps

Stellarator



Dipole



Two potential confinement schemes: Different physics

Stellarator

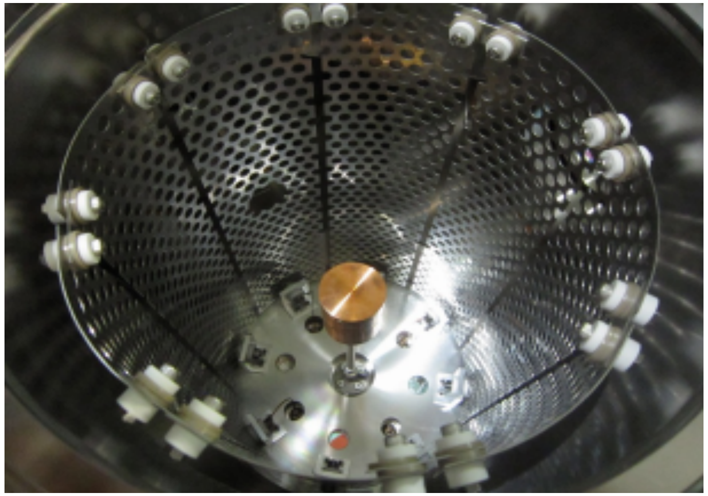
- Steady state, purely magnetic confinement, no driven currents
- Non-neutral plasmas: 0.3 sec confinement (CNT)
- Relevance to fusion
- Drift orbits confined if optimized
- Parallel force balance counteracts macroscopic instabilities

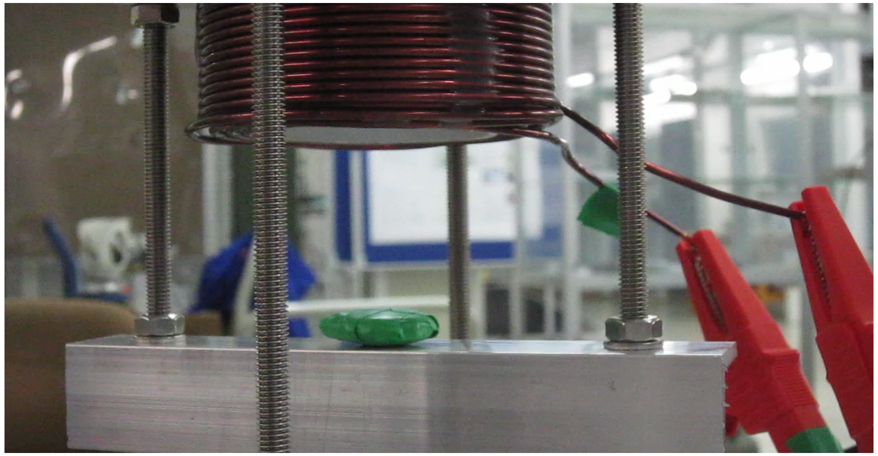
Levitated dipole

- Steady state, purely magnetic confinement, no driven currents
- Non-neutral plasmas: 300 sec confinement(RT-1)
- Relevance to astrophysics
- Drift orbits confined
- Flux expansion counteracts instabilities – leads to stable profiles with centrally peaked density

Pair plasmas: How

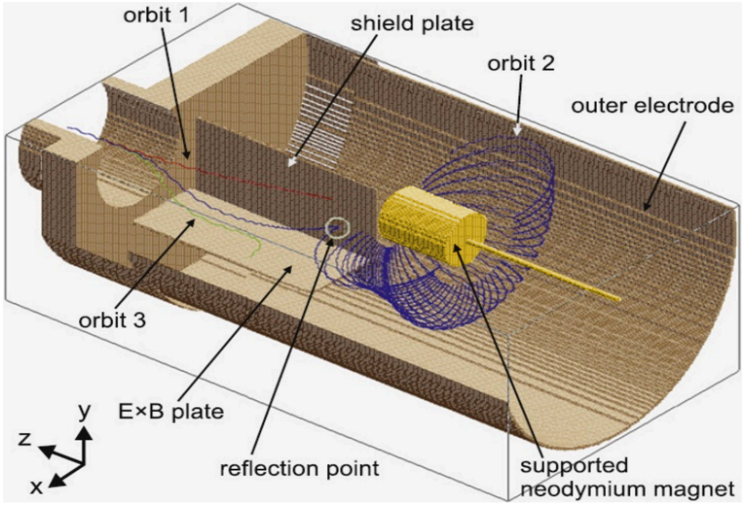
- Find a suitable trap: Levitated dipole current ring (eventually – now: permanent magnet)
  - Astrophysically relevant – magnetospheric topology
  - Confines both signs of charge
  - Advantageous confinement properties: inward transport creates density gradient
- Find a suitable source: Reactor-based positron beam NEPOMUC in Garching
- Find a suitable injection and accumulation method: Next slide

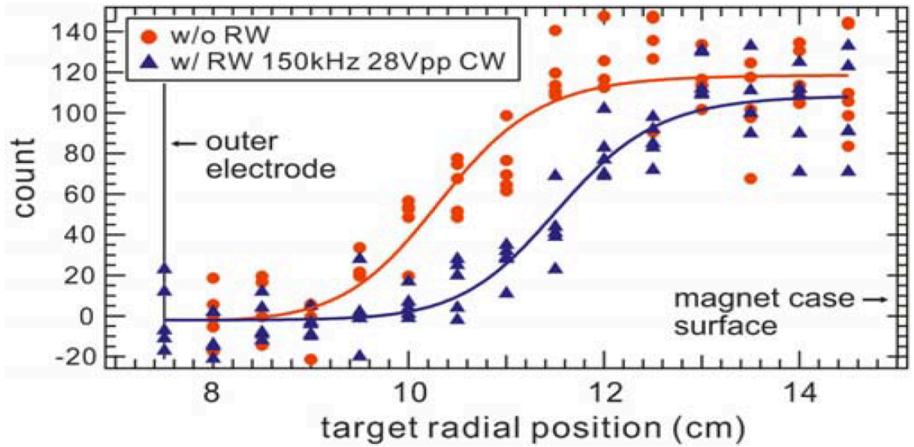




Pair plasmas: How far are we?

- Injection: Use ExB plates
  - 2015: 30% injection efficiency of positrons (Saitoh et al, NJP 2015)
  - 2016: ~100% injection efficiency of positrons
- Accumulation: Inward dipole-specific transport may be induced by external rotating fields: Potential evidence achieved in Dec 2016 beam time





Summary

- It is exciting times for stellarators – we may be seeing a stellar(ator) comeback!
- W7-X has successfully gone into operation with impressive parameters
  - T_e~8 keV, T_i~2.2 keV, n~4.5*10^{19} m^{-3}, β_c>2.5%, τ_E~100 ms
- Hydrogen plasmas lasted up to 6 seconds w/o feedback control
- Next phases will focus on performance extension, divertor operation, ion heating, β effects, density control, etc.
- Stellarators can also be used for basic plasma physics research
  - Including pair plasmas, which deserve to be studied!