The Permanent Magnet Stellarator

Simpler Stellarators for Fusion Energy

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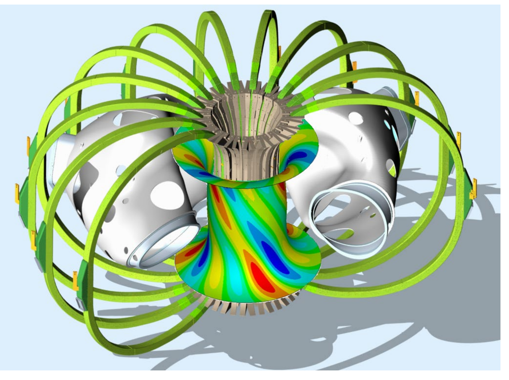
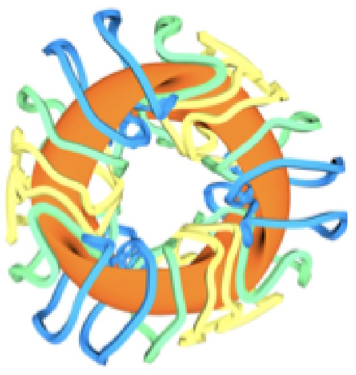
Largest Technical Gap for Stellarators: Coil Simplification

- Identified as gap and main barrier in many reports (ARIES, FESAC, ReNeW)
- 3D magnetic fields require 3D coils – more complicated than tokamaks
- Greatly complicates access and maintenance of core components (e.g. blankets)

Approach: Extreme Simplification using Planar Coils & Permanent Magnets

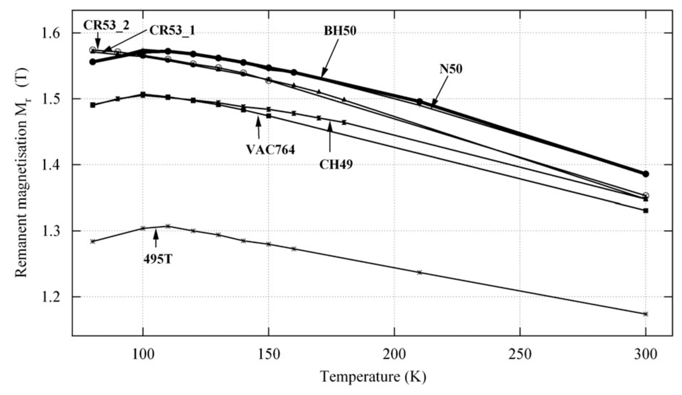
- Resolve main engineering risk and barrier for stellarators (ARIES, FESAC, ReNeW)
- Crucial for maintenance and availability; cost reduction
- Optimized quasi-symmetry for good confinement
- Vary configuration by redistributing magnets
- Made possible by modern, neodymium/RE magnets





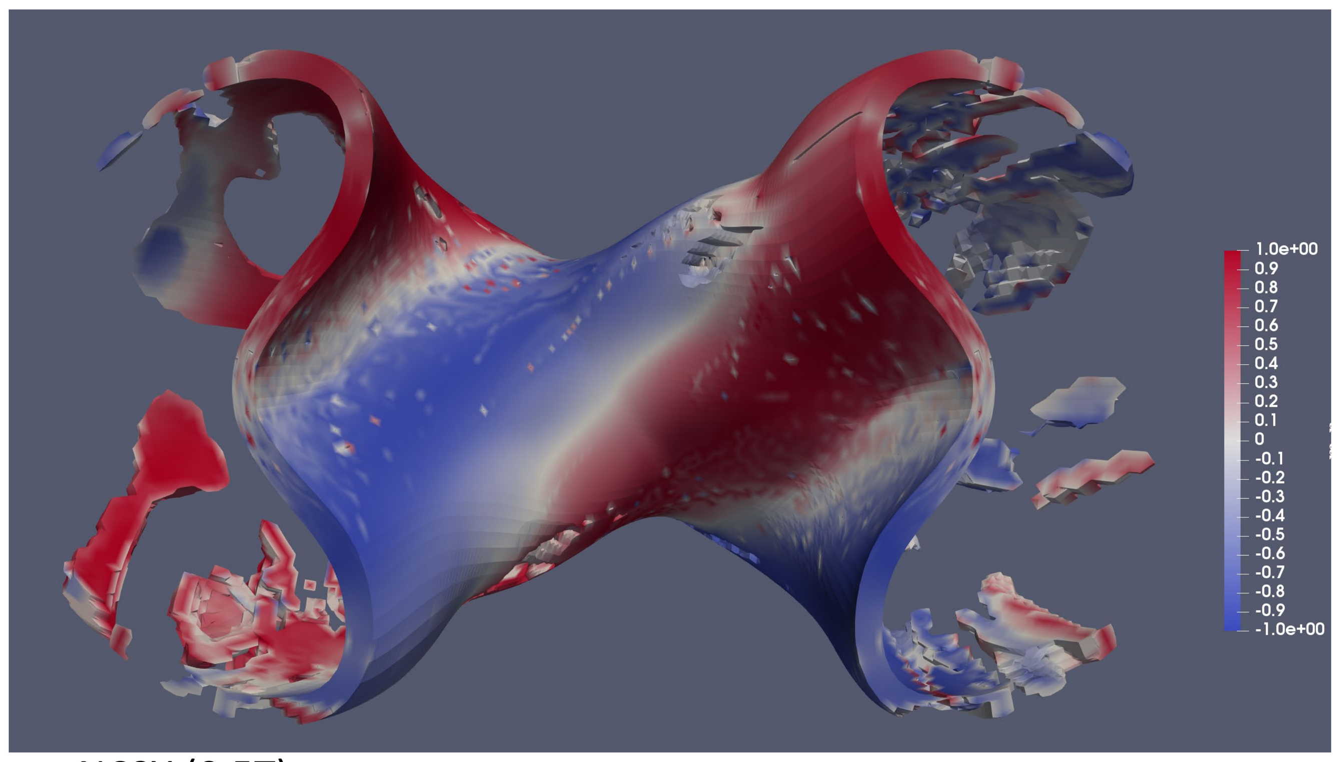
- Assess key properties:
  - Confinement
  - Explore β limit
  - Low-Z vs. high-Z metal first wall, use of liquid-metals, build on LTX-β and LM initiative

Rare Earth Magnets Almost Ideal



- High remnant magnetic field and coercivity
- Properties improve as temperature drops
  - 293K: B_r=1.49T, coercivity ~2.8 T
  - 77K: B_r= 1.59T, coercivity > 7.7 T

- μ_r = 1.01 – 1.05. Highly anisotropic.
- Commercially available in quantity
- Fe-N may (someday) offer B_r > 2.5T
- Diamagnets (bulk superconductors) can give similar shaping control to > 17T (but require cryogenic cooling)



NCSX (0.5T):			
Perp. only	20cm thick	2.9 m^3	
Perp. & tangential	10cm thick	1.9 m^3	Halbach array

Initial perm. magnet solutions

Almost all magnets on inner region in major radius.

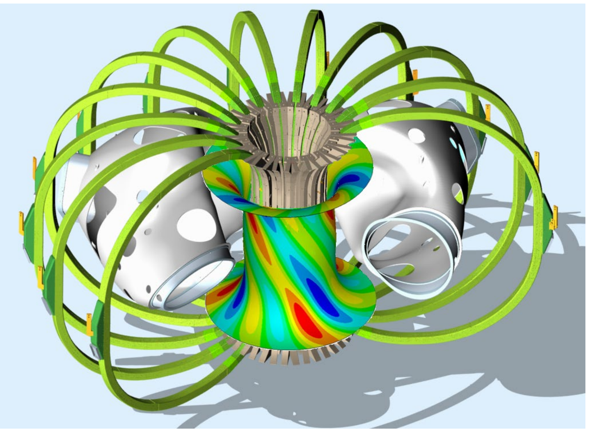
Perm. magnet distribution not unique to make specified plasma shape.

Can exclude port regions.

Three different numerical approaches developed
-- C. Zhu (PPPL)
-- M. Landreman (U.Md)

Initiative Plan

- Establish initial experiment at minimum cost by re-using components
  - Some parts from NCSX (TF coils, vacuum vessel), but room-temperature
  - NB (1.5MW, 20kV), some diagnostics, wall-coatings (Li) from LTX-β
  - Improved configuration designs- beyond NCSX (e.g. fast ion conf.).
  - Initial operation at B=0.5 T (set by exiting TF coils)
  - Cost: $10 - 20 M.
  - World's first simple optimized stellarator!
  - β: 4-9% accessible, depending on confinement enhancement achieved.



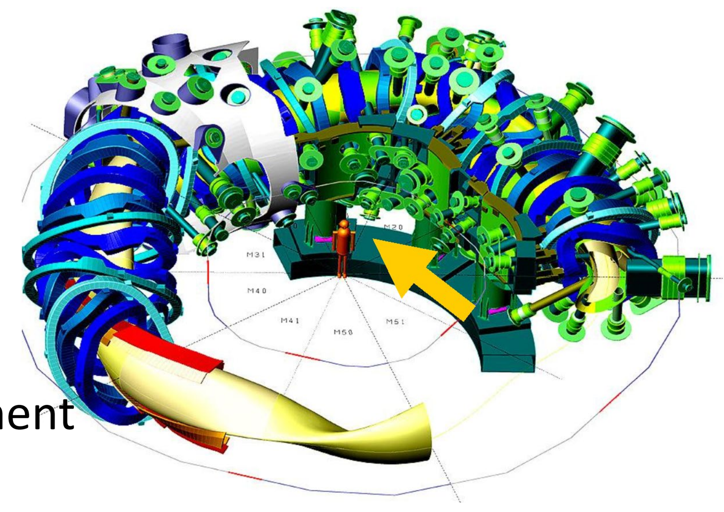
- Re-configure magnets to test and improve shaping configuration
- Upgrade to B=1 T after ~2 years of research, to reduce collisionality
- Consider second upgrade to B=2 T after ~2 more years.

Stellarators simplify fusion systems

Reduce challenges

- Magnetic field from magnets ➔ no current driv
  v. low recirculating power, high Q
  steady state easy
- Disruption free ➔ no runaways & EM loads
- Soft density and pressure limits
- Density limit much higher than tokamaks, easing divertor design
- Long divertor connection lengths, easing controlled detachment
- Sustained high β in LHD (4.8%) and W7-AS (3.2%).
- Ability to design for good confinement: W7X, HSX, LHD.

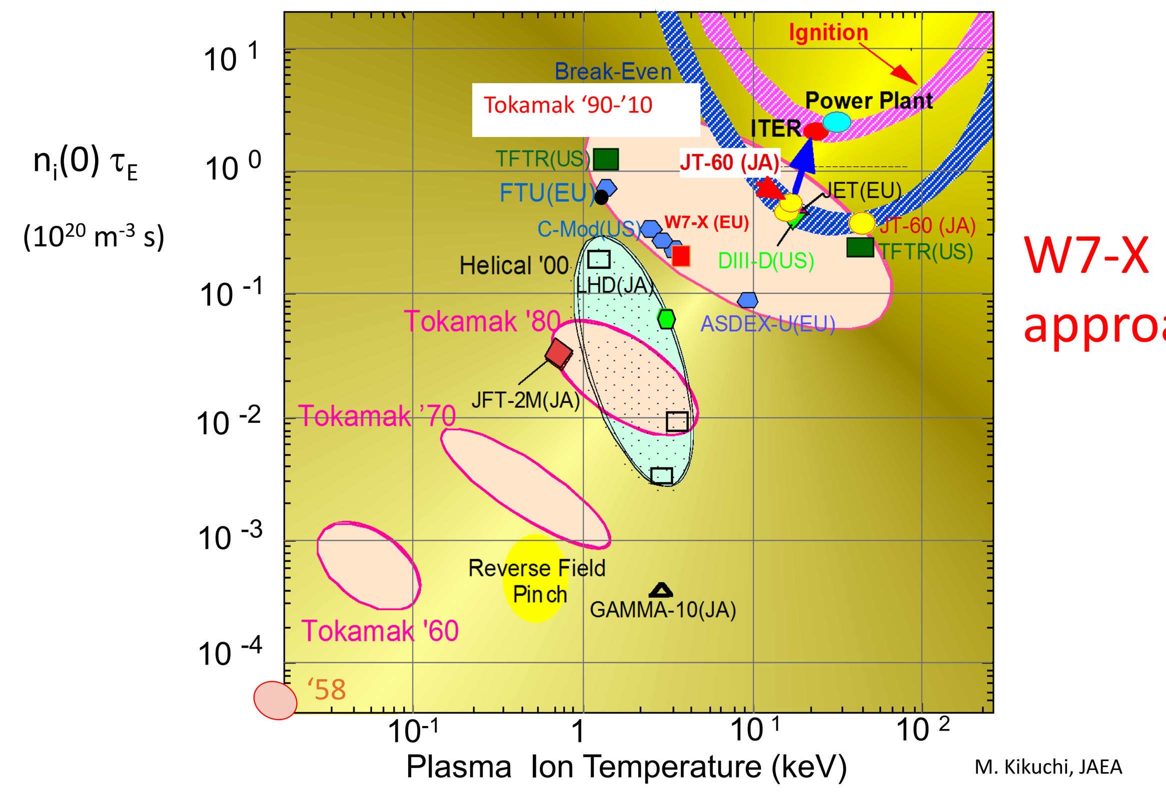
W7-X has Rapidly Exceeded Expectations



- $T_e(0)$ ~ 10 keV; τ_E up to ~0.24 sec
- Initial validation of optimization strategies
- Turbulence dominated confinement,
- No impurity accumulation
- Well functioning 3D divertor, controlled detachment

Building on results from W7-AS, HSX, LHD

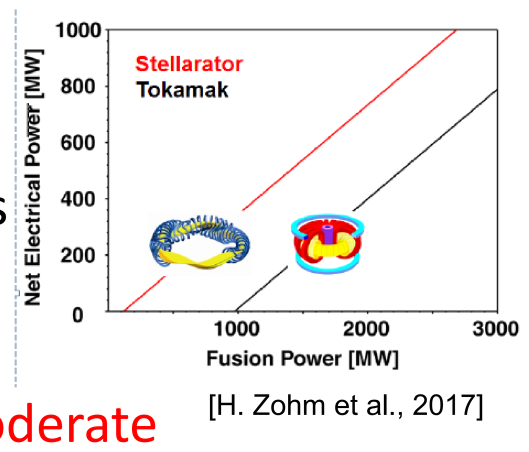
Conclusion: Stellarator optimization works!



W7-X $nT_i\,\tau_E$ early op. approaching tokamaks

Stellartors Project to Simpler Pilot Plants

- Eliminate CD systems
  - Increase energy efficiency, Q
  - Retire η_{CD} risk, disruption risks
  - Simplify and increase TBR



[H. Zohm et al., 2017]

- Could Produce net power at moderate scale and plasma power flux.
  Aim for
  - 50 - 100 MWe
  - JET/W7-X scale

- *Need integrated high-β, high confinement & boundary solutions*

	AT Pilot	ST Pilot	CS Pilot
A = R_0 / a	4.0	1.7	4.5
R_0 [m]	4.0	2.2	4.75
B_T [T]	6.0	2.4	5.6
I_P [MA]	7.7	20	2.1
q_{95}	3.8	7.3	1.5
f_{BS} or iota from BS	0.69	0.90	0.23
n_e / $n_{Greenwald}$	1	0.7	-
H_{98} or H_{ISS04}	1.22	1.35	1.75
β_T [%]	4.8	39	6.9
β_N	3.7	6.1	-
P_{fus} [MW]	674	1016	529
P_{aux} [MW]	79	50	12
Q_{DT}	8.5	20.3	44
Q_{eng}	1.0	1.0	2.5
Net Electric [MW]	0	0	110

[J.E. Menard et al., NF 2011)]

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