REVIEW OF MODERN STELLARATOR REACTOR STUDIES

J. F. Lyon, ORNL

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TOPICS

- **Special Features of Stellarators as Reactors**
- **Modern Stellarator Reactor Studies**
- **Results from Garching Reactor Studies**
- **Compact Stellarator Reactors**

Stellarators Have Pros and Cons as Reactors

- **Advantage -- ignited, inherently steady state**
  - no recirculating power to plasma
    - * no need for current drive
  - no pulsed loads, higher availability
  - not subject to disruptions, current-driven modes
  - flux surfaces nearly independent of plasma current
  - stable against external kinks and vertical instability without a close conducting wall or active feedback

- **Disadvantage -- non-axisymmetric plasma**
  - requires complex, nonplanar coils relatively close to the plasma $\Rightarrow$ usually very large major radius
  - vacuum vessel, divertor and maintenance geometry more complex

Compact Stellarator Approach

- **Stellarators have distinct advantages as reactors**
  - **no disruptions, even at the highest β ⇒ less margin needed**
  - **maximum density determined by power, not disruptions**
  - **no current drive ⇒ low recirculating power, more flexibility and control in the operating point**
- **However, normal stellarators lead to large reactors**
- **Compact stellarators (stellarator + tokamak features)**
  - **optimized neoclassical transport, reduced below anomalous**
  - **bootstrap current incorporated in the optimization**
  - **aspect ratios ranging from 2 to 4 ⇒ smaller, lower cost than present designs in the non-US program**
  - **$\langle\beta\rangle > 5\%$ ⇒ similar to latest tokamak reactor (ARIES-RS)**
- **NSCX and QPS experiments are designed to test these characteristics**

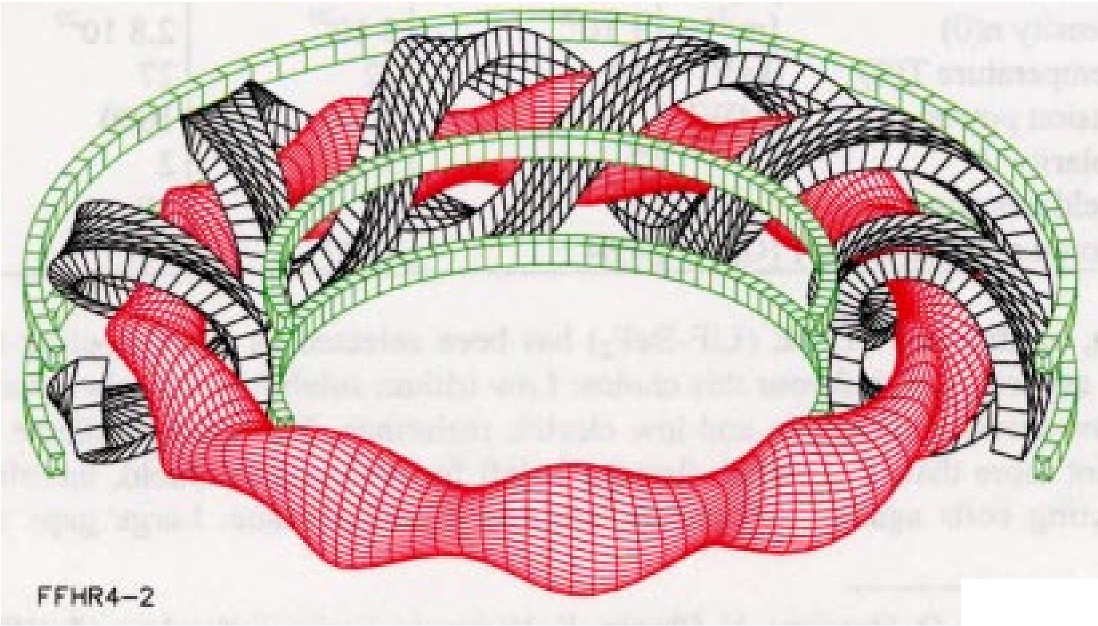
Stellarators are DIFFERENT from Tokamaks, STs and R FPs as Reactors

- **Non-axisymmetry requires complex, nonplanar coils relatively close to the plasma**
  - cannot move TF coils back from the plasma to make room for blankets and shielding as in other concepts
- **Complex 3-D magnetic fields means**
  - no simple scaling laws for β limits, confinement
  - divertor and maintenance geometry more complex
  - systems code must incorporate complex coil geometry and stellarator physics -- no geometry scaling studies

Modern Stellarator Reactor Studies

- **NIFS MHR studies**
  - based on LHD-like geometry with helical coils
- **Garching ASRA6C study**
  - based on W 7-AS/X-like geometry with modular coils
- **ARIES SPPS study**
  - based on MHH geometry with modular coils
  - used ARIES costing and reactor component algorithms
  - aggressive physics and technology
- **Garching HSR studies**
  - based on W 7-X geometry with modular coils
  - conservative physics and existing technology (NbTi coils)
- **NCSX & QPS reactors**

NIFS Reactor Studies

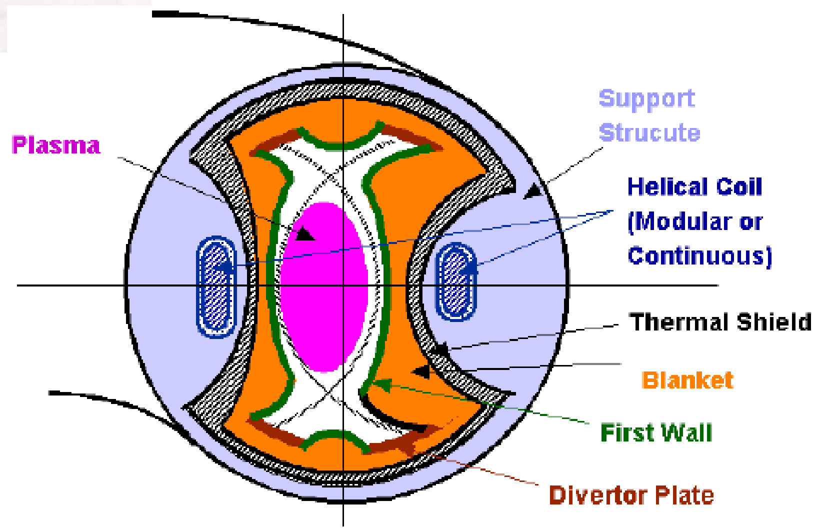


Helical coils, based on LHD

Large aspect ratio

Helical divertor structure

Thin blanket and shielding on small-R side

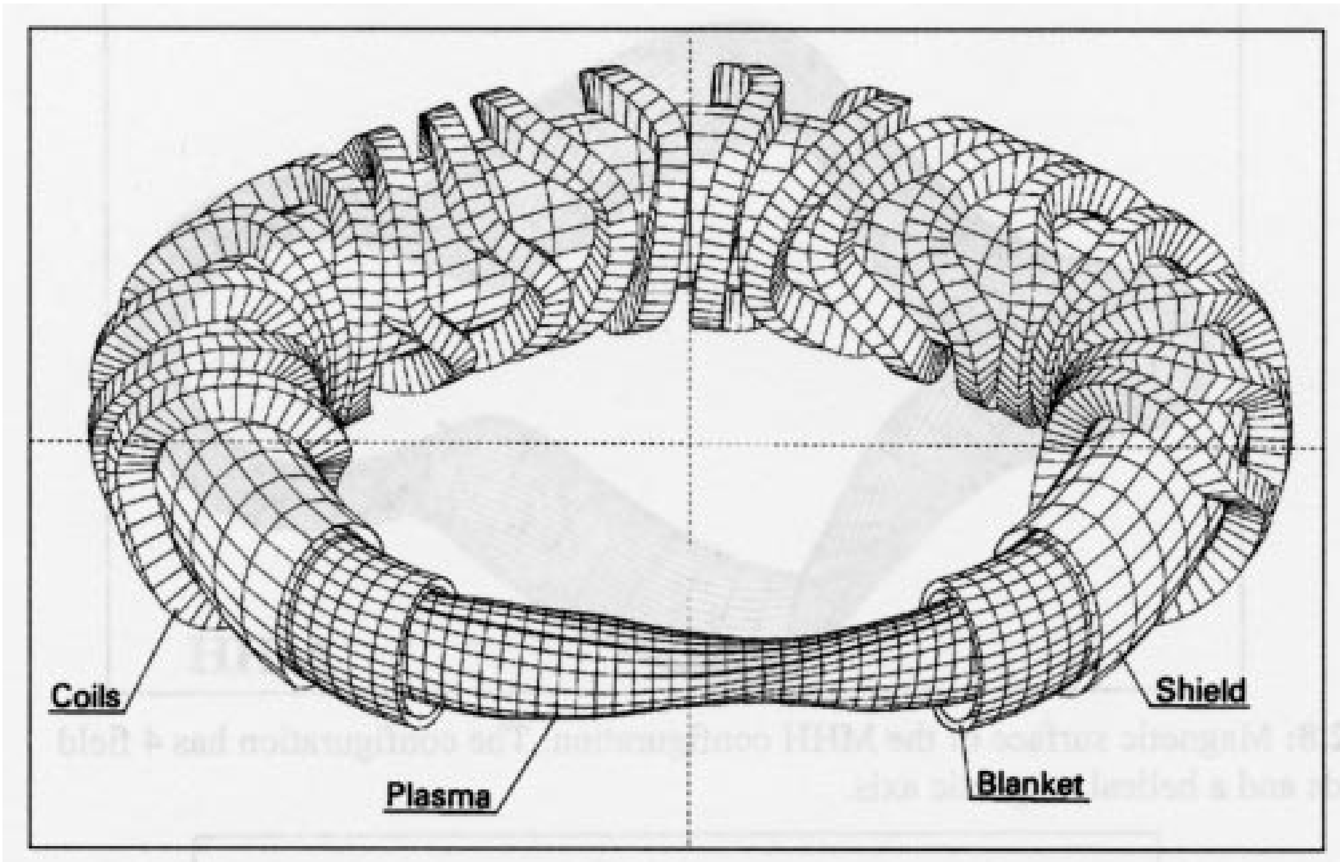


NIFS Reactor Studies

- **LHD-based MHR and Force-Free FFHR**

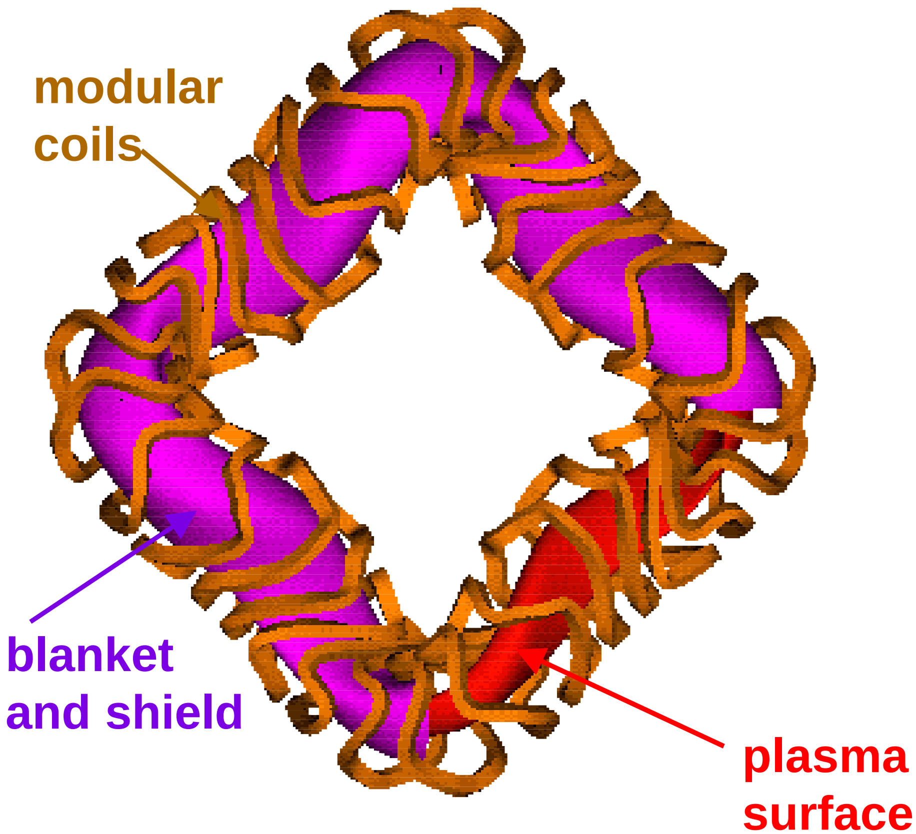
Name of Reactor Design	LHR/MHR-S	LHR/MHR-C	FFHR-1	FFHR-2
Major Radius R (m)	16.5	10.5	20	10
Average Plasm Radius a (m)	2.4	1.5	2	1.7
Toroidal Field B (T)	5	6.5	12	10
Maximum Coil Field B_{max} (T)	14.9	14.7	16	13
Average Plasma Density <n> ($10^{20}/m^3$)	2	3.4	1	1.4
Average Plasma Temperature <T> (keV	7.8	7.8	11	13.5
Volume Average Beta β (%)	5	5	0.7	0.59
Enhancement Factor Designed	2 (LHD)	2 (LHD)	1.5 (LHD)	2.5 (LHD)
Thermal Power P_{FT} (GW)	3.8	2.8	3	1
Effective Heating Power (MW)	600	400	200	400
Energy Confinement Time τ_E (s)	2.67	1.5	3.7	1.8
LHD scaling (s)	1.24	0.79	2.46	0.76
GRB scaling (s)	1.30	0.69	2.42	0.75
LG scaling (s)	1.66	0.89	3.58	0.90
ISS95 scaling (s)	1.20	0.66	2.52	0.76
New LHD-1 (heliotron-type) (s)	2.70	1.30	6.13	1.71
New LHD-2 (all helical) (s)	1.62	0.87	4.64	1.04

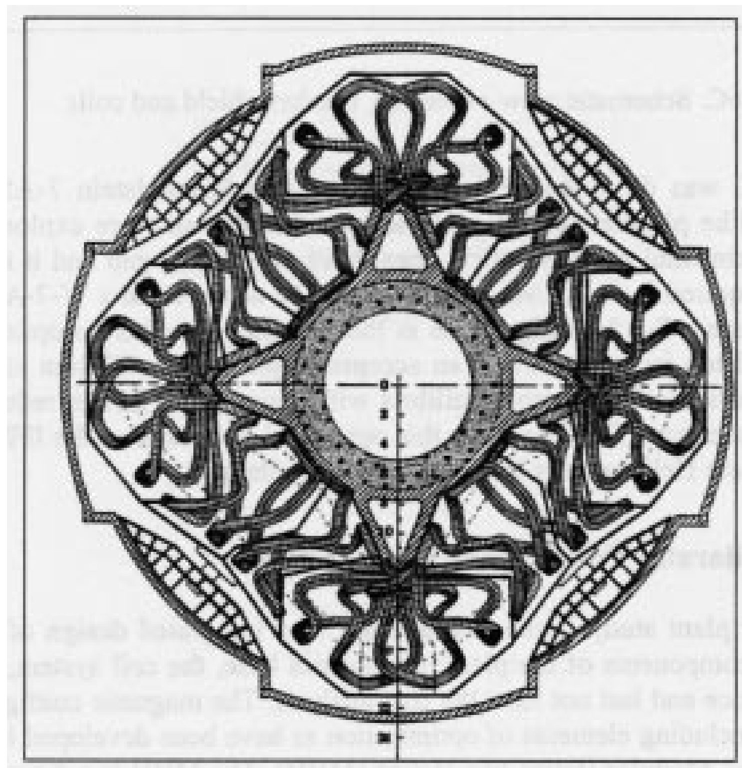
Garching ASRA6C Study



Based on large *R*/*a* W 7-AS/X geometry

ARIES SPPS Study





SPPS based on W7-X like configuration, but aimed at smaller size

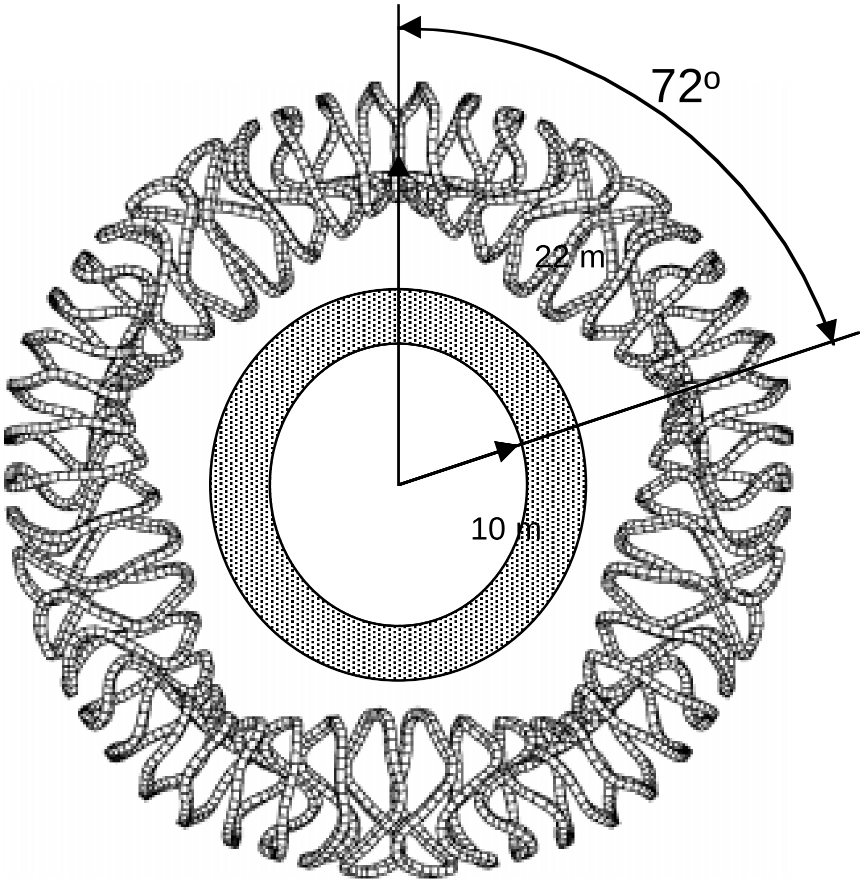
- R_0 = 13.9 m, $\langle\beta\rangle$ = 5%
- B_0 = 4.9 T, B_{max} = 16 T
- $P_{electric}$ = 1 GW

ARIES SPPS (MHH) Study

		ASRA6C	MHH
Major radius	[m]	20	14
Av. radius of coils	[m]	4.57	4
Coil current	[MA]	18	13.8
Number of modular coils		30	32
Av. plasma radius	[m]	1.6	1.63
Number of field periods		5	4
Field on axis	[T]	5.3	5
Max. field on coils	[T]	10.4	14.5
Magnetic energy	[GJ]	117	80
Av. beta [%]		5	5
Thermal output	[MW]	4000	2290

Fusion power, PF (GW_{th})	1.73
Thermal conversion efficiency, η_{TH}	0.46
Thermal power, PTH (GW_{th})	2.29
Gross electrical power, PET (GW_e)	1.05
Net electrical power, PE (GW_e)	1.0
Recirculating power fraction, ε	0.052
Plant capacity factor, p_f	0.76
Total direct cost (B$)([a])	2249
Total capital cost (B$)([b])	4340
Cost of electricity, COE (mill/kWeh)([c])	74.6

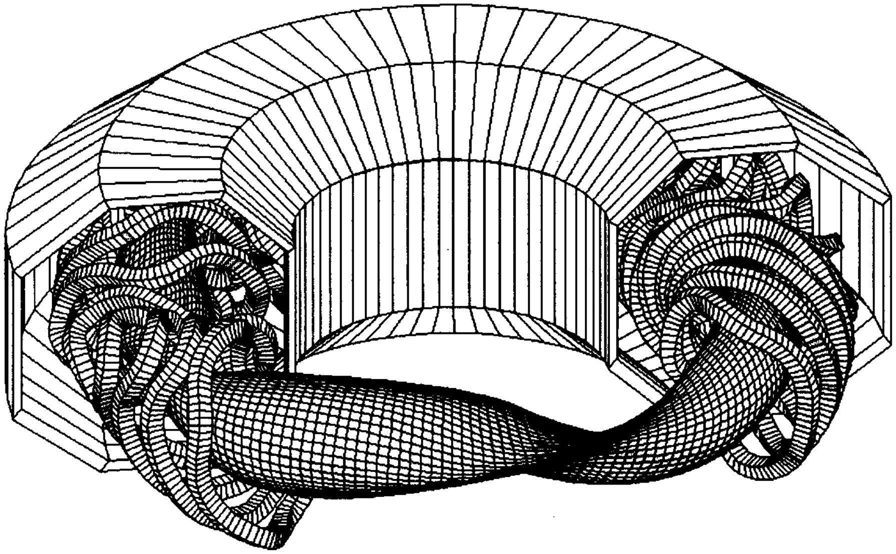
HSR Reactor Based on Wendelstein 7-X

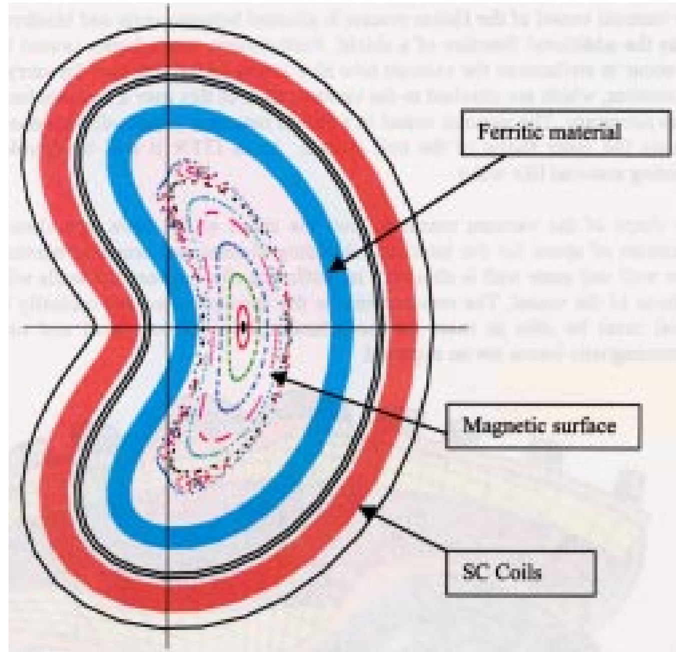


Based on conservative physics, technology

- **Major Radius** **22 m**
- **Ave. Plasma Radius** **1.85 m**
- **Plasma Volume** **1400 m^3**
- **Rotational Transform** **0.87 - 0.98**
- **Magnetic Field** **5 T**
- **Max. Magnetic Field** **10 T**
- **Number of Coils** **50**
- **Magnetic Energy** **100 GJ**
- **$\langle\beta\rangle$ = 5%;** **NbTi SC coils**

Garching HSR Studies





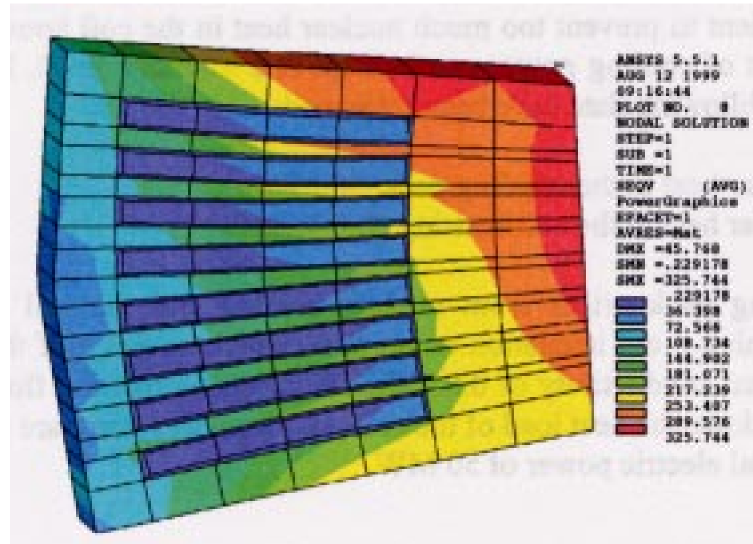
	HSR 4/18/i	HSR4/18	HSR 5/22	
Major radius	18	18	22	[m]
Av. minor radius	2.1	2.1	1.8	[m]
Plasma volume	1524	1524	1407	[m^3]
Iota(0)	0.86	0.83	0.84	
Iota(a)	0.97	0.96	1.00	
Av. field on axis	4.4	5	4.75	[T]
Max. field on coils	8.5	10.3	10.0	[T]
Number of coils	40	40	50	
Magnetic energy	76	98	100	[GJ]
Fusion power	1500	3000	3000	[MW]

HSR Coil Calculations

- **Design of NbTi conductor**
  - Al jacket, cable, conductor, insulation
- **Winding pack design, fabrication**
- **Coil support system, stress analysis**
- **Coil cooling, fault protection**
- **Other component calculations**
  - effect of ferritic steel on magnetic configuration
  - effect of finite-β on magnetic islands
  - thermal loading on divertor plates
  - spatial distribution of neutron power and radiation on first wall

HSR Coil Calculations

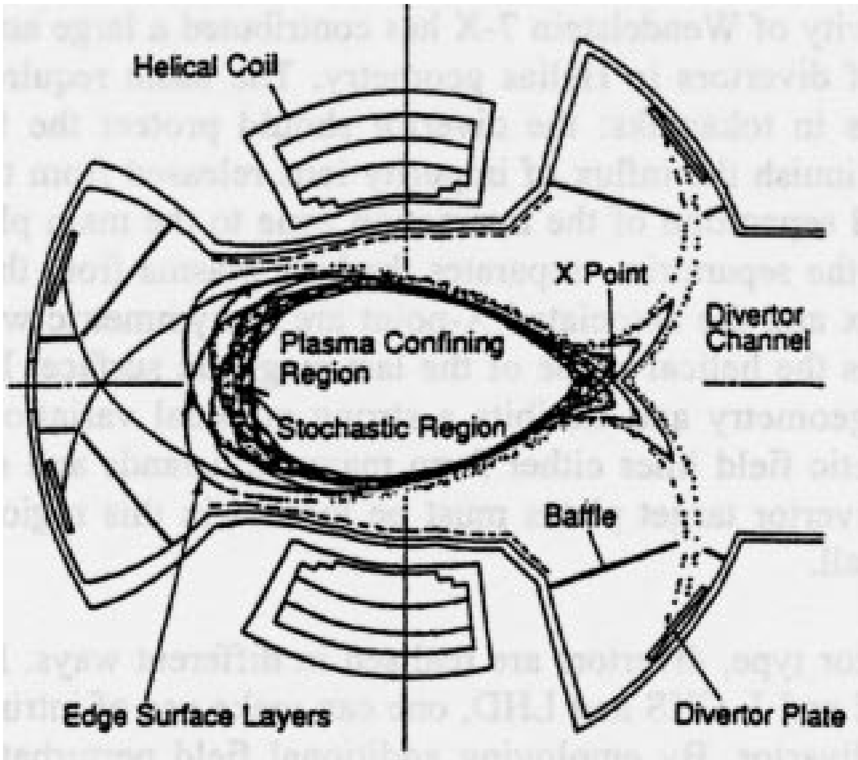
Van Mises Stresses

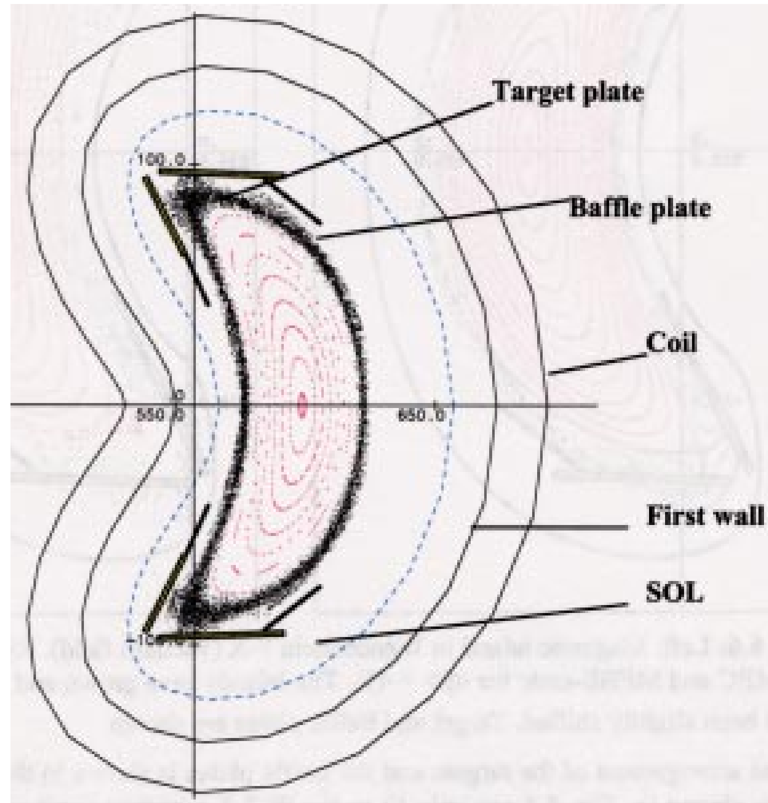


Coil housing ≤ 750 MPa **Coil ≤ 70 MPa**

1.8K superfluid He, 10 T max on coils

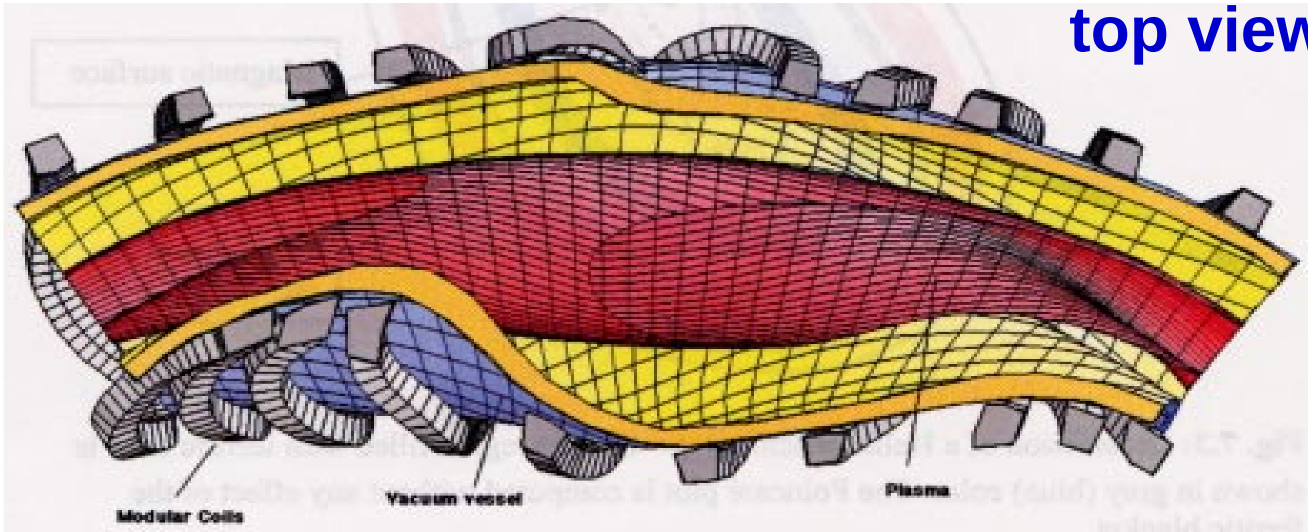
Divertor Concepts



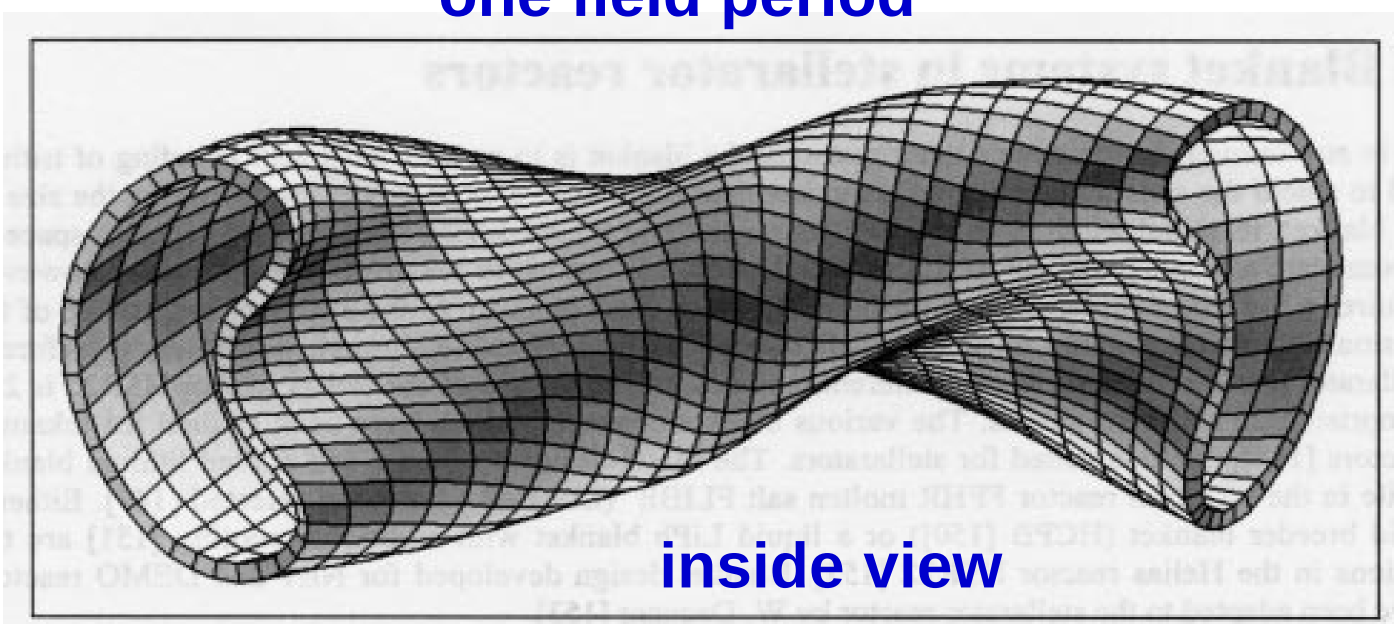


LHD helical divertor **W 7-X divertor**

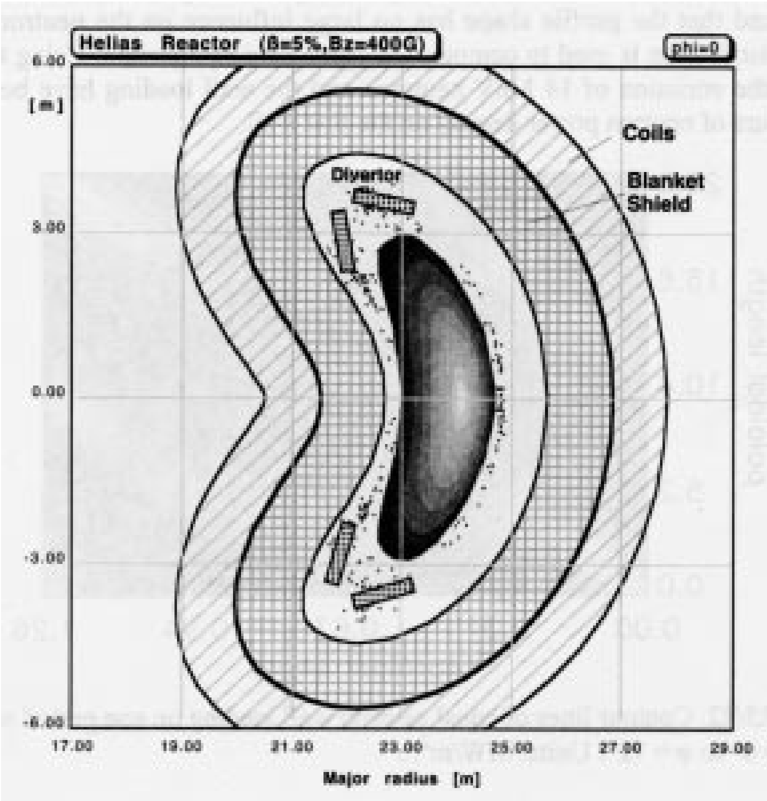
HSR Vacuum Vessel Geometry

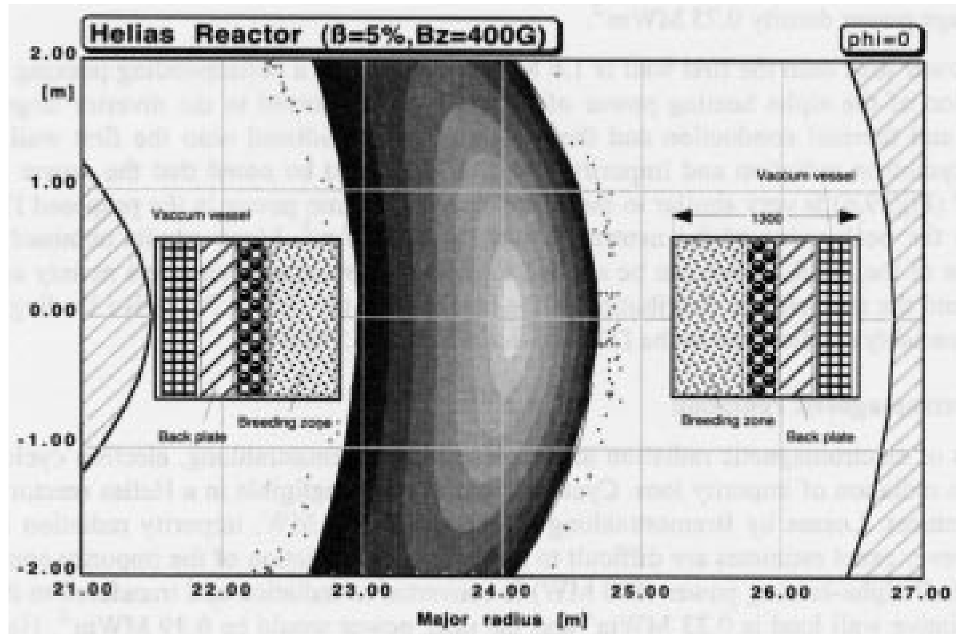


one field period



HSR Blanket Approach





1.2-m blanket thickness

Plasma-first wall distance = 0.3 m; 3200 m^2 wall area

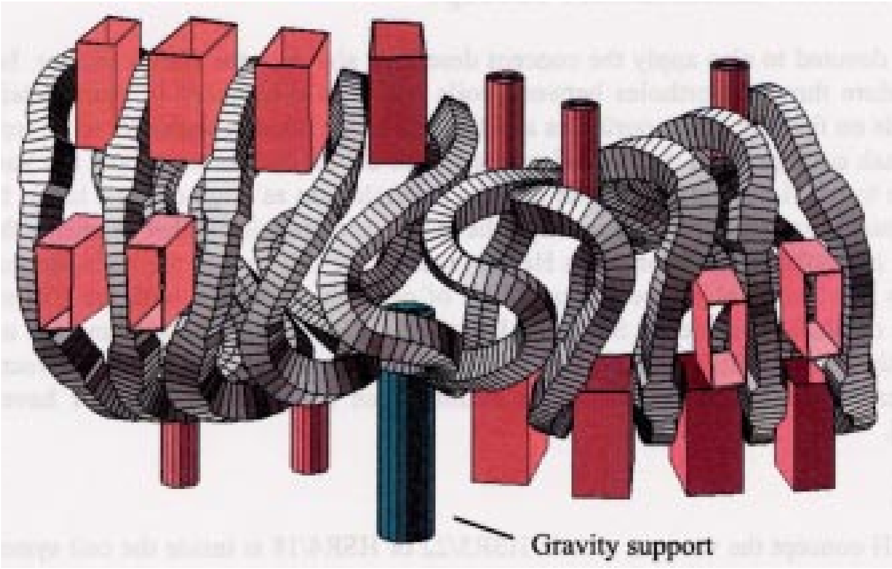
Plasma-coil distance ≥ 1.5 m

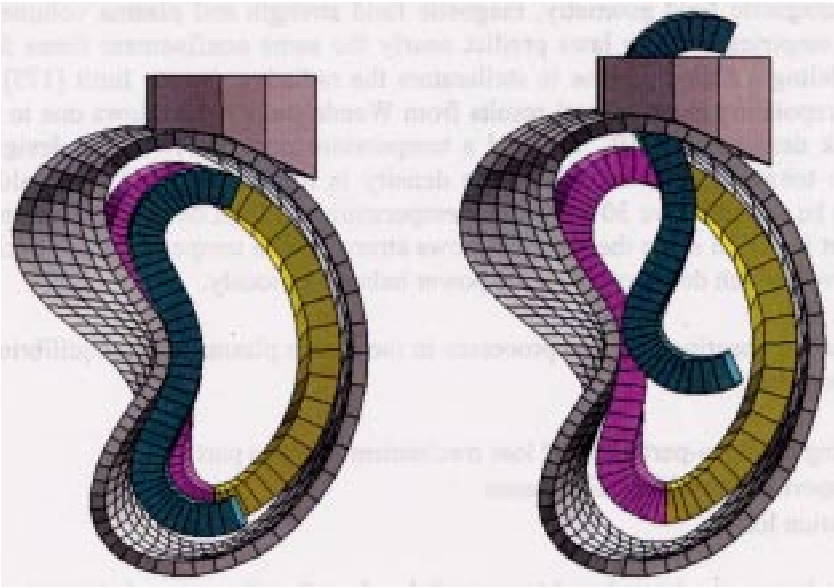
Blanket + vacuum vessel = 1.3 m

water-cooled Pb-^{17}Li blanket

HSR Maintenance Concept

- **HSR5/22: small modules thru ports**





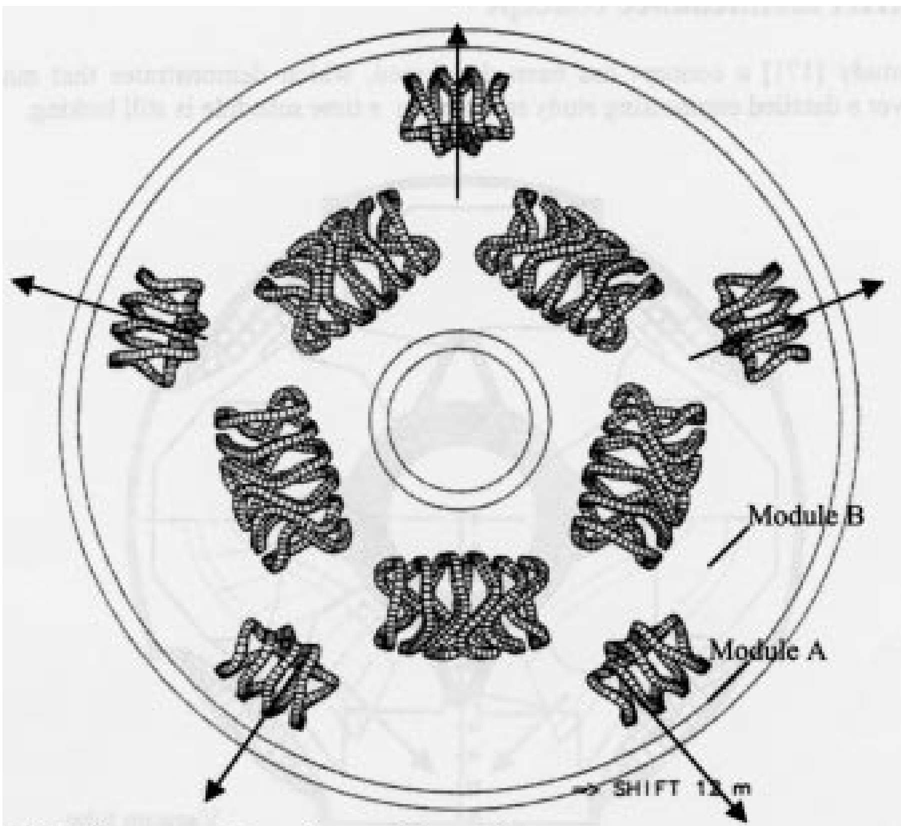
One field period of the coil system with ports

Maintenance scheme for blanket segments

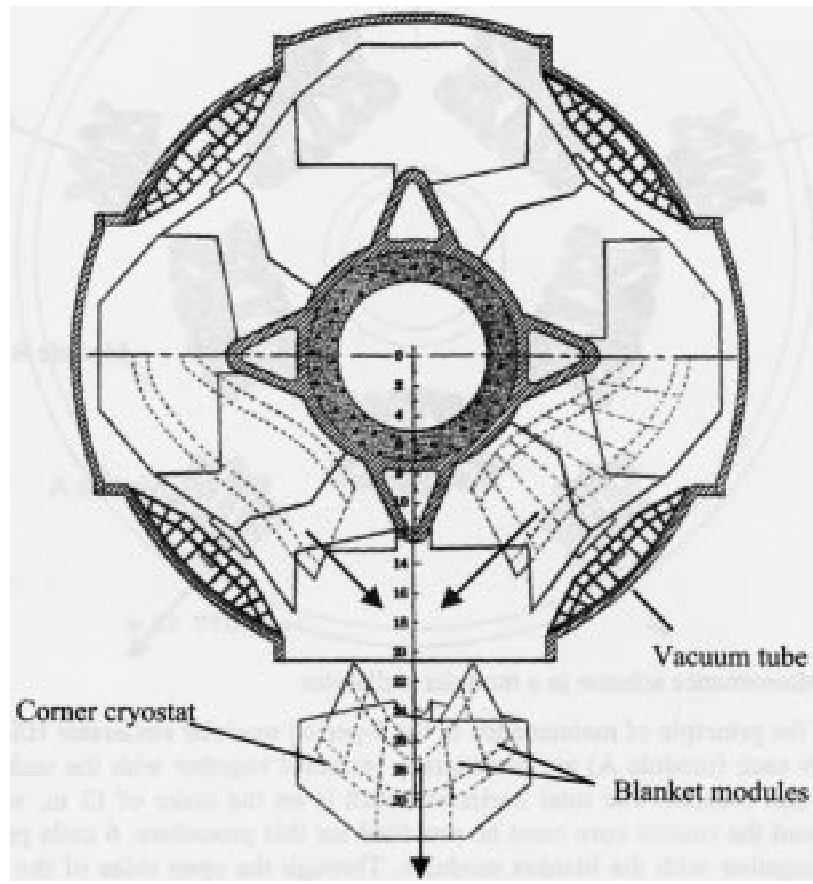
Alternate Maintenance Concept

- **Radial/toroidal movement of large modules**

ASRA6C



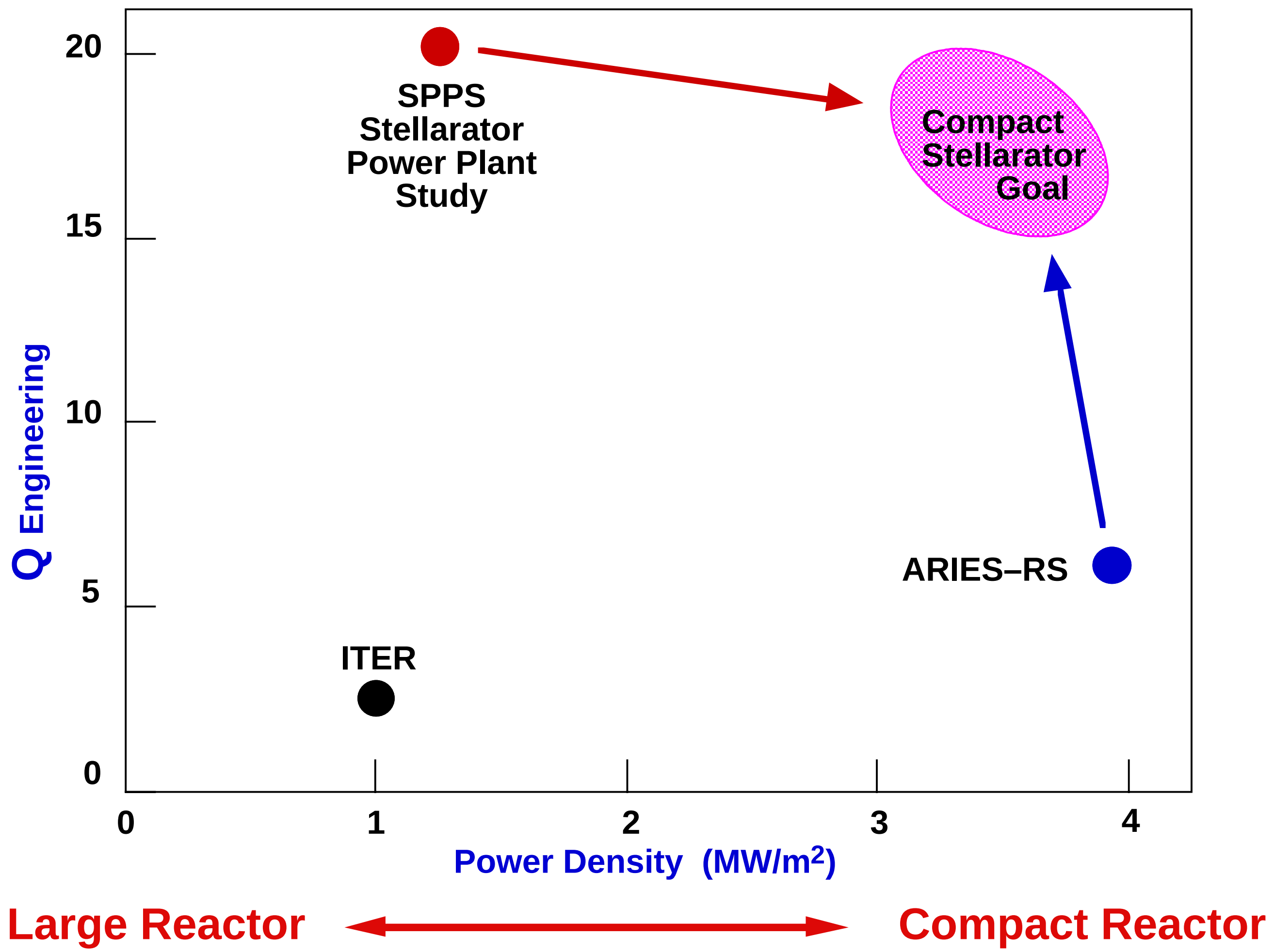
SPPS



Power Plant Issues

- **Thermal cycle, recycling power**
- **Safety issues**
  - **magnet and plasma energy reservoirs**
- **Plasma control**
  - **position and density control**
  - **startup to ignition, power level, shutdown**
- **Tritium inventory, decay heat**
- **Cost vs. size tradeoffs**

A Compact Stellarator Could Combine the Best Features of Tokamaks and Stellarators!

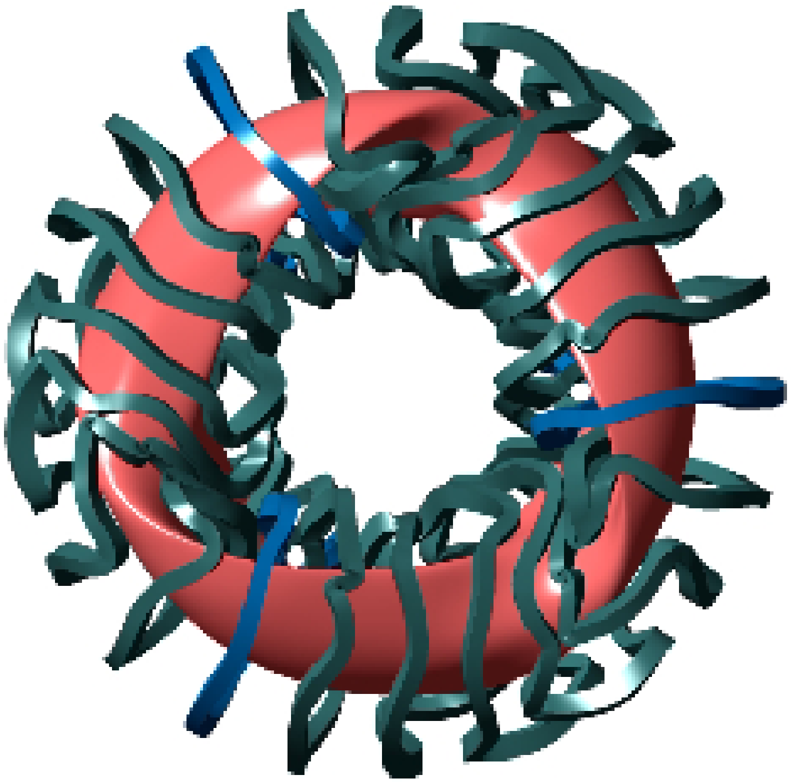


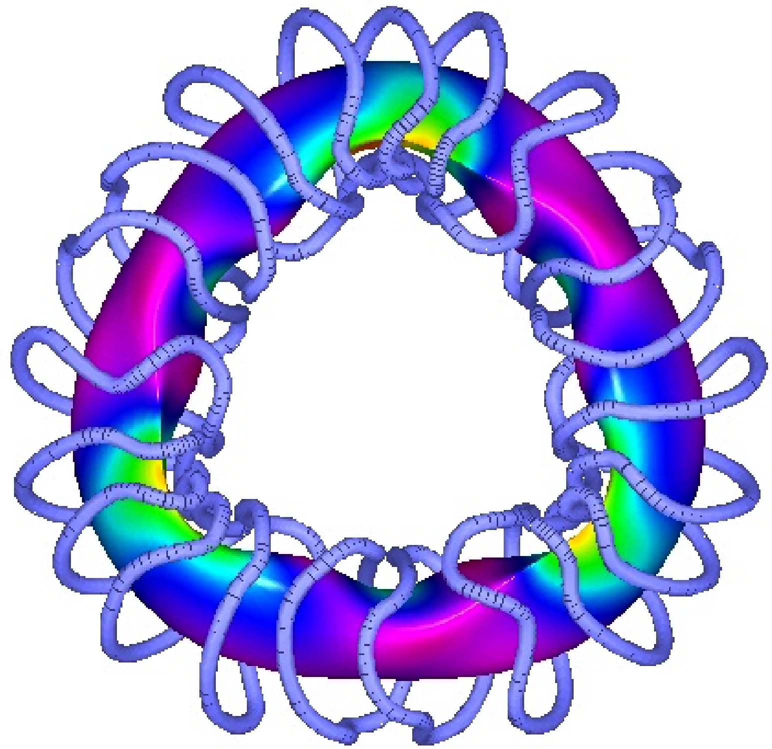
- Compact, power density similar to tokamaks
- Without disruptions, feedback, or external current drive

Compact Stellarators Could Lead to a Better Reactor

- **14-m SPPS (with lower wall power density) was cost competitive with 6-m ARIES-IV and 5.5-m ARIES-RS because of its low recycled power (high Q_{eng})**
- **CS's can retain low recycled power of SPPS, but has smaller size (lower cost) and higher wall power density, so could have lower cost of electricity**
- **However, the power produced is more than the 1 GW_e assumed in the ARIES studies (β margin)**
- **The details of plasma shapre, coil geometry, size, field, and wall power density need to be studied further to optimize a reactor**

Reactors Based on NCSX & QPS





NCSX variant
Quasi-Axisymmetric

QPS variant
Quasi-Poloidal

Scaled 1-GW Compact Stellarator Reactors with B_{max} = 12 T, $\langle\beta\rangle \le \beta_{limit}$, H-95 ≤ 5

	QA#1	QA#2	QP#1	QP#2
Plasma aspect ratio R/a_p	2.96	4.4	2.70	3.70
Volume average β limit $\langle\beta\rangle_{limit}$ (%)	4	4.1	10	15
Average major radius R (m)	**8.22**	**9.93**	**7.34**	**7.84**
Average plasma radius a_p (m)	2.78	2.26	2.72	2.12
Plasma volume V_{plasma} (m^3)	1250	1000	1040	690
On-axis field B_0 (T)	**5.41**	**5.65**	**5.23**	**5.03**
τ_E/τ_E^{ISS95} multiplier H-95	**2.65**	**2.62**	**3.61**	**4.42**
Volume average beta $\langle\beta\rangle$ (%)	**4**	**4.1**	**4.6**	**6.2**
Energy confinement time τ_E (s)	2.69	2.41	2.49	2.01
Vol.-ave. density $\langle n\rangle$ (10^{20} m^{-3})	1.31	1.50	1.40	1.70
Density-average $\langle T\rangle$ (keV)	11.1	10.8	11.3	11.5
Neutron wall load Γ_n (MW m^{-2})	**1.34**	**1.37**	**1.54**	**1.85**

Scaled 2-GW Compact Stellarator Reactors

with B_{max} = 12 T, $\langle\beta\rangle \leq \beta_{limit}$, H-95 ≤ 4

	QA#1	QA#2	QP#1	QP#2
Average major radius *R* (m)	**10.35**	**12.51**	**7.34**	**7.85**
Average plasma radius a_p (m)	3.50	2.84	2.72	2.12
Plasma volume V_{plasma} (m^3)	2500	2000	1070	700
τ_E/τ_E^{ISS95} multiplier H-95	**2.07**	**2.04**	**3.56**	**3.94**
Volume average beta $\langle\beta\rangle$ (%)	**4**	**4.1**	**6.5**	**8.75**
Energy confinement time τ_E (s)	2.69	2.41	1.76	1.42
Vol.-ave. density $\langle n\rangle$ (10^{20} m^{-3})	1.31	1.50	1.62	2.40
Neutron wall load Γ_n (MW m^{-2})	**1.69**	**1.72**	**3.07**	**3.68**

Lessons Learned

- **Non-axisymmetry requires complex, nonplanar coils relatively close to the plasma**
- **3-D magnetic fields means more complex vacuum vessel, divertor and maintenance geometry, no geometry scaling studies with a systems code**
- **Plasma-coil spacing and coil bend radii are more important than the plasma configuration or aspect ratio**
- **Can’t just enlarge an experiment to reactor size; reactor considerations are different**