Compact Stellarator Reactors: Status and Plans

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NCSX Project Meeting

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TOPICS

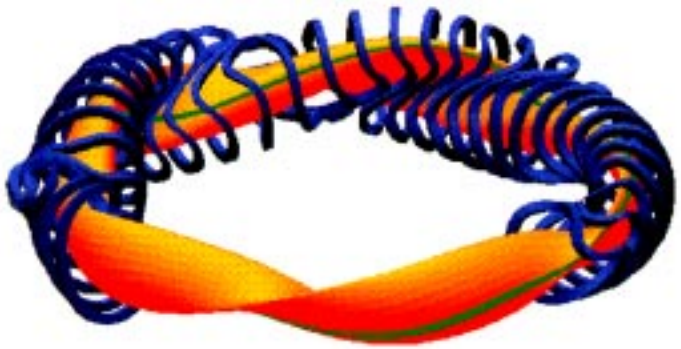
- Background
- Reactor Size Determination
- Results with Fixed Profiles
- Next Steps

Compact Stellarator Reactor Study

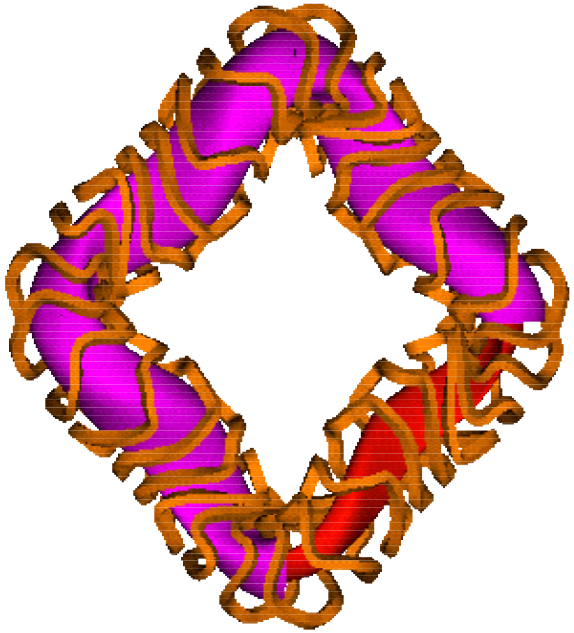
- Purpose -- assess QA concept as reactors
- Why do it?
  - Needed for PVR to explain “compact stellarator” reactor vision to DOE, FESAC, and the community
  - Understand sensitivity to assumptions
  - Potential influence on research program and design
- Tools -- reactor systems optimization code (integrated 1-D transport + plasma/coil geometry + ARIES cost algorithms and blanket/shield/coil assumptions)

Earlier Stellarator Reactor Studies

- **HSR based on W7-X and conservative physics, NbTi technology**
  - R_0 = 22 m, B_0 = 5 T, B_{max} = 10 T, $\langle\beta\rangle$ = 5%



- **SPPS based on W7-X like configuration (MHH4)**
  - R_0 = 13.9 m, B_0 = 4.9 T, B_{max} = 16 T, $\langle\beta\rangle$ = 5%
  - smaller size; more aggressive physics and technology assumptions



Most Important Measure of Reactor Attractiveness is COE

Reactor	Type	$R_0/\langle a \rangle$	R_0 (m) a(m)	p_{wall} MW/m^2	COE mills/kWh	Q_{eng}	B_{max}/B_0	B_0(T)
W7-X based HSR	high-A stellarator	12.2	22 1.8	0.5	>110		2.11	4.8
W7-X like SPPS	modular stellarator	8.6	13.9 1.6	1.3	75	19.3	2.94	4.9
ARIES-IV	2nd stability tokamak	2.8	6.0 2.1	2.7	68	5.2	2.09	7.6
ARIES-RS	reverse shear tokamak	3.1	5.5 1.8	4.0	76	5.9	1.98	8.0
ARIES-ST	spherical tokamak	0.87	3.2 3.7	4.1	>76	3.1	3.55	2.1

- R_0, p_{wall} not the most important measures!
- Higher value of Q_{eng} compensates for R_0, p_{wall}

May 1999 Look at QA Reactors

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Configuration	R_0/Δ $R_0/\langle a\rangle$	R_0 (m) a(m)	1.15 x B_{max}/B_0	B_0(T)	P_{elect} GW	p_{wall} MW/m^2
QA C82	5.8 3.4	8.9 2.6	2.54	6.3	2.0	4.7
QA A4.1	5.8 4.1	9.0 2.2	2.20	7.3	2.6	7.0
QA C93	5.8 3.4	9.0 2.7	2.14	7.5	4.2	9.5
ARIES-RS tokamak	3.4 3.1	5.5 1.8	1.98	8.0	1.0	4.1
SPPS stellarator	7.0 8.6	13.9 1.6	2.94	4.9	1.0	1.3

- **Closer to ARIES-RS than SPPS**
- **B_{max} = 16 T and $\langle\beta\rangle$ = 5% leads to large P_{elect}**

May 1999 Conclusions

- **QA Compact Stellarators lead to more attractive reactors, but not smaller reactors**
- **Ultimate figure of merit for a toroidal reactor is the cost of electricity, *not* major radius or wall power density, when comparing different concepts**
- **However, major radius and wall power density are important when optimizing a particular concept**
- **R_0/<a> = 3.4 and 4.1 QA configurations lead to smaller reactors closer to ARIES-RS in mass power density than the earlier *cost-competitive* SPPS**
- **QA configurations so far have not been optimized for a reactor; need to reduce A_Δ further**
- **ARIES study will be needed for better optimization**

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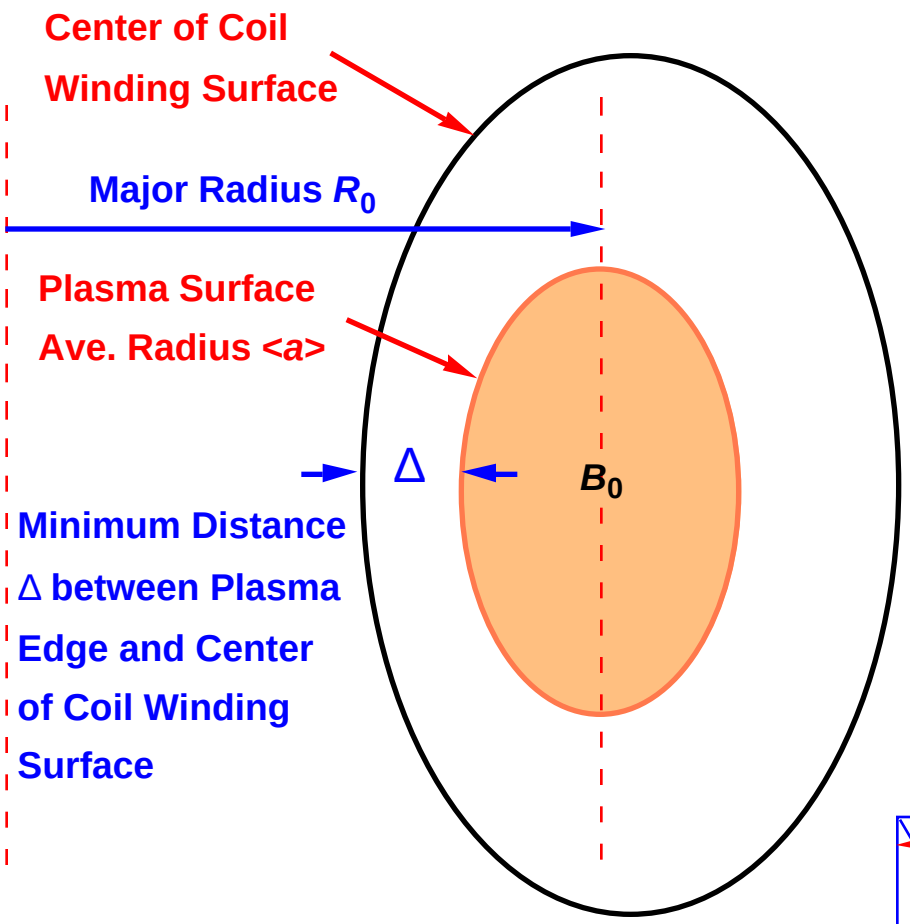
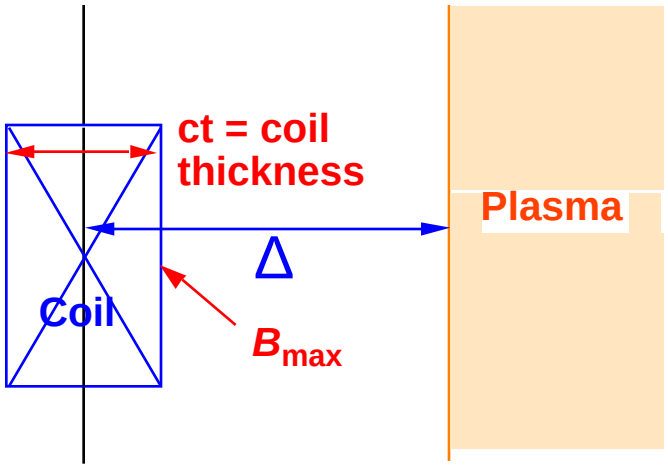
Minimum Reactor Size Is Determined by Δ



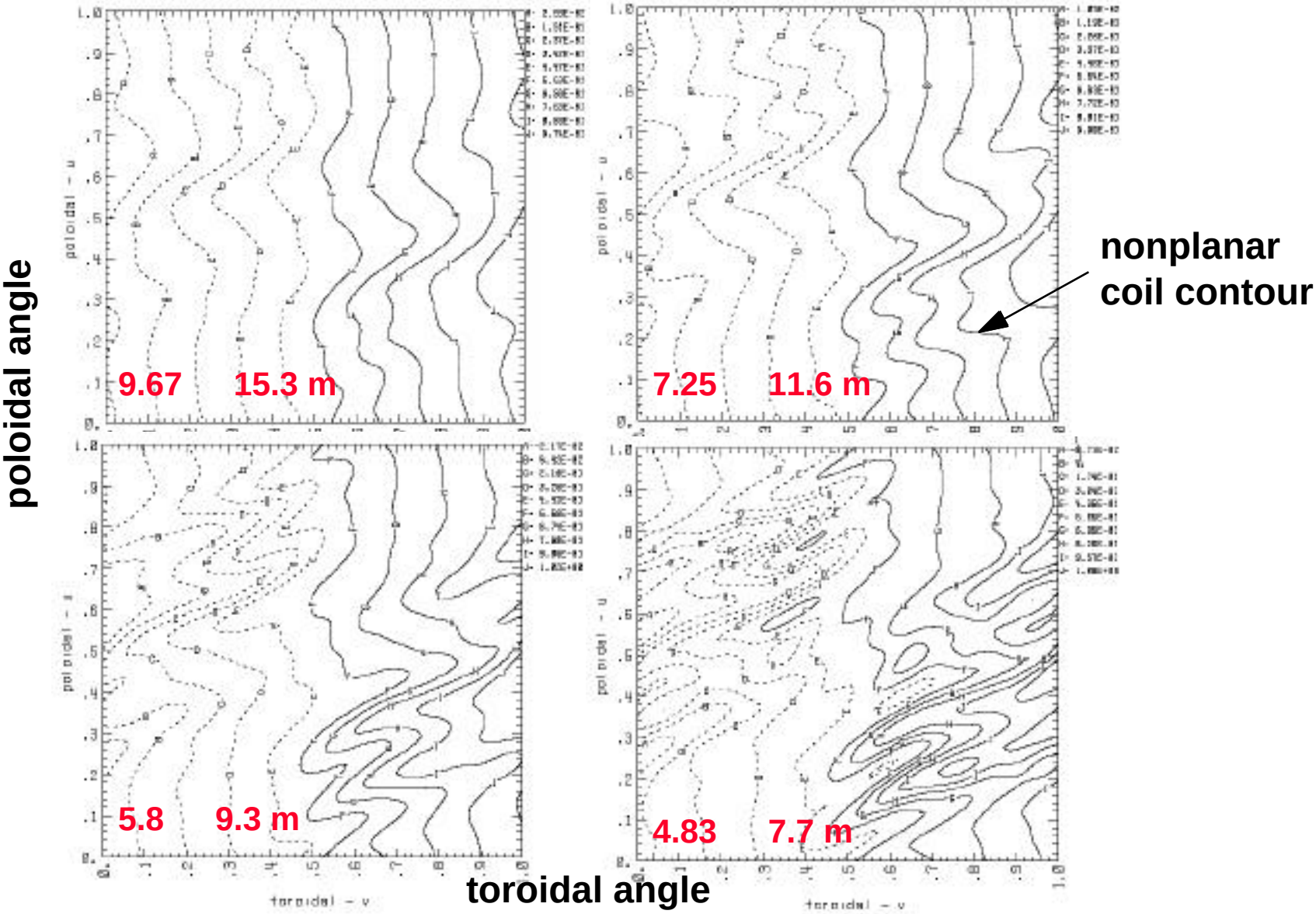
- A configuration is chacterized by the ratios $A_\Delta = R_0/\Delta$, $A_p = R_0/\langle a\rangle$, and B_{max}/B_0
- The minimum reactor size is set by $R_0 = A_\Delta(D + ct/2)$ where D is the space needed for scrapeoff, first wall, blanket, shield, coil case, and assembly gaps
- Cost surface area A_Δ^2/A_p



Simplest Extrapolation of a Compact Stellarator to a Reactor

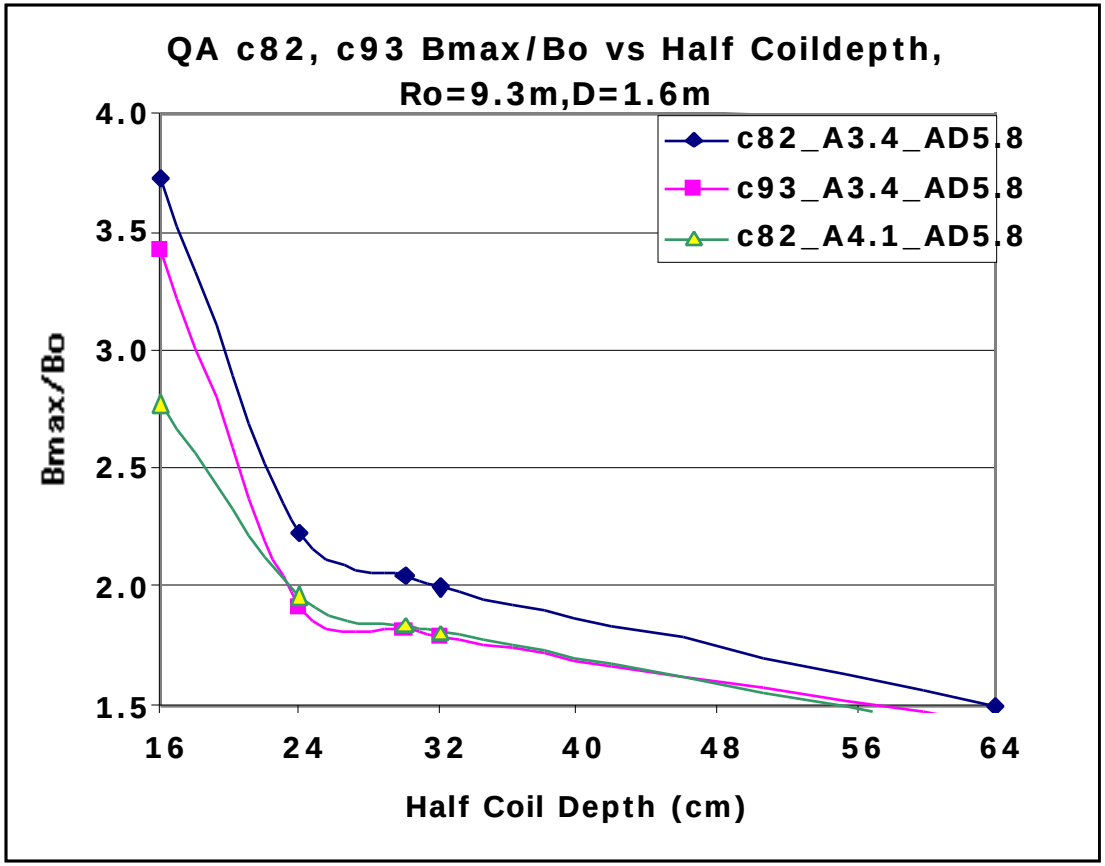
- **Vary distance Δ for compact stellarator configurations**
  - **calculate sheet-current solution at distance Δ from plasma that recreates desired plasma boundary**
  - **calculate B_{max}/B_0 at distance ct/2 radially in from current sheet**
  - **B_{max}/B_0 is larger for actual modular coils, so use $1.15B_{max}/B_0$**
- **Choose maximum credible distance Δ $\quad R_0 = A_\Delta(D + ct/2)$**
  - **Coil complexity (kinks) *increases* with increasing Δ**
- **Choose minimum ct/2 that satisfies constraints**
  - **Ampere's law: $B_0 = 2\mu_0 N j ct^2/(2\pi R_0)$; coil aspect ratio = 2 assumed**
  - **$B_0 = B_{coil}(j_{coil})/(B_{max}/B_0)$; B_{max}/B_0 increases as ct decreases**
- **$R_0^3 \quad P_{fusion}/B_0^4$, so want high B_0 for smaller reactor**
  - ***but* B_0 *decreases* with increasing Δ (B_{max}/B_0 increases)**
- **Need to redo for real modular coils**

Minimum Credible A_Δ Value for C82 is 5.8 Minimum $R_0 \approx 9.3$ m



B_{max}/B_o Scan for Reactor-Scale QA's

B_{max}/B_o calculated at coil inner edge
(on a surface shifted inward by half coil depth)
from Nescoil surface current solution at coil center



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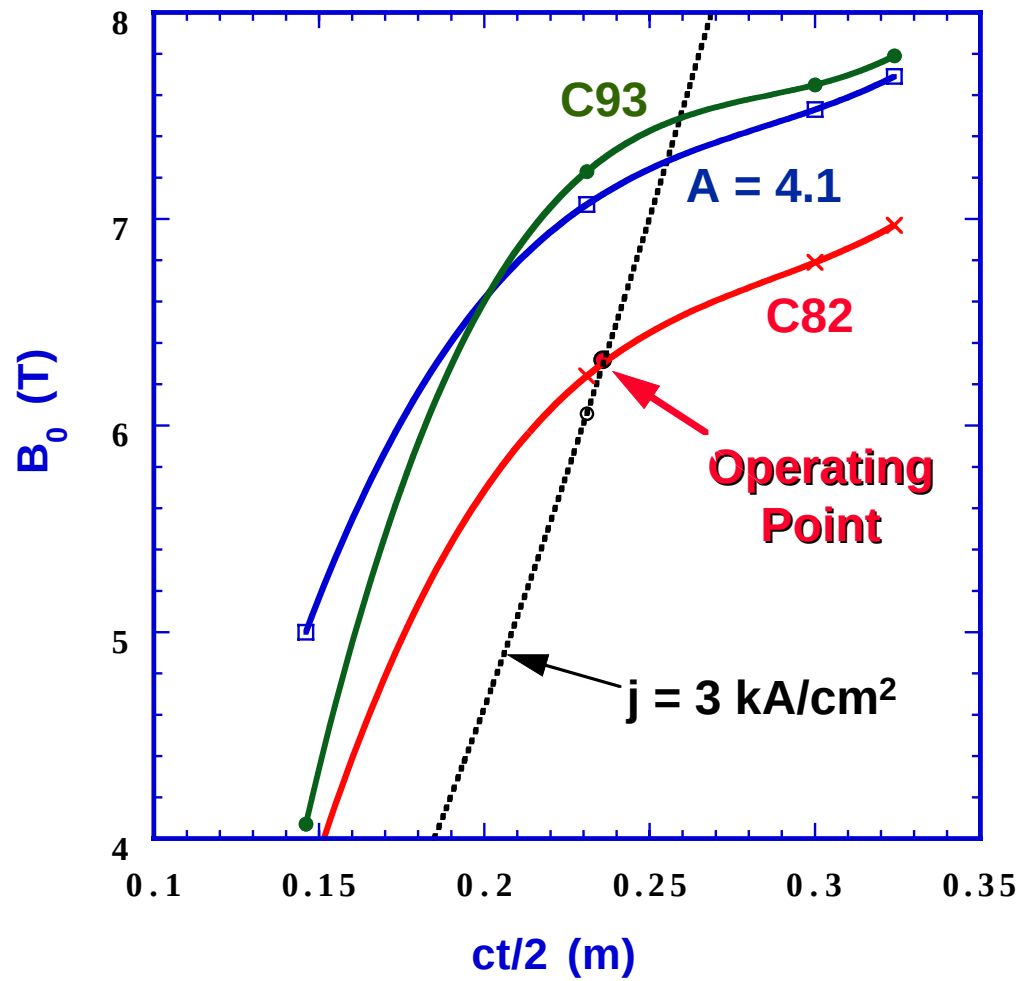
Coil Half-Depth Is Chosen to Minimize R_0



based on $1.15B_{max}/B_0$

- R_0/Δ = 5.8 case, 21 coils, 2:1 coil aspect ratio; B_{max} = 16 T
- Based on surface current distribution, not modular coils

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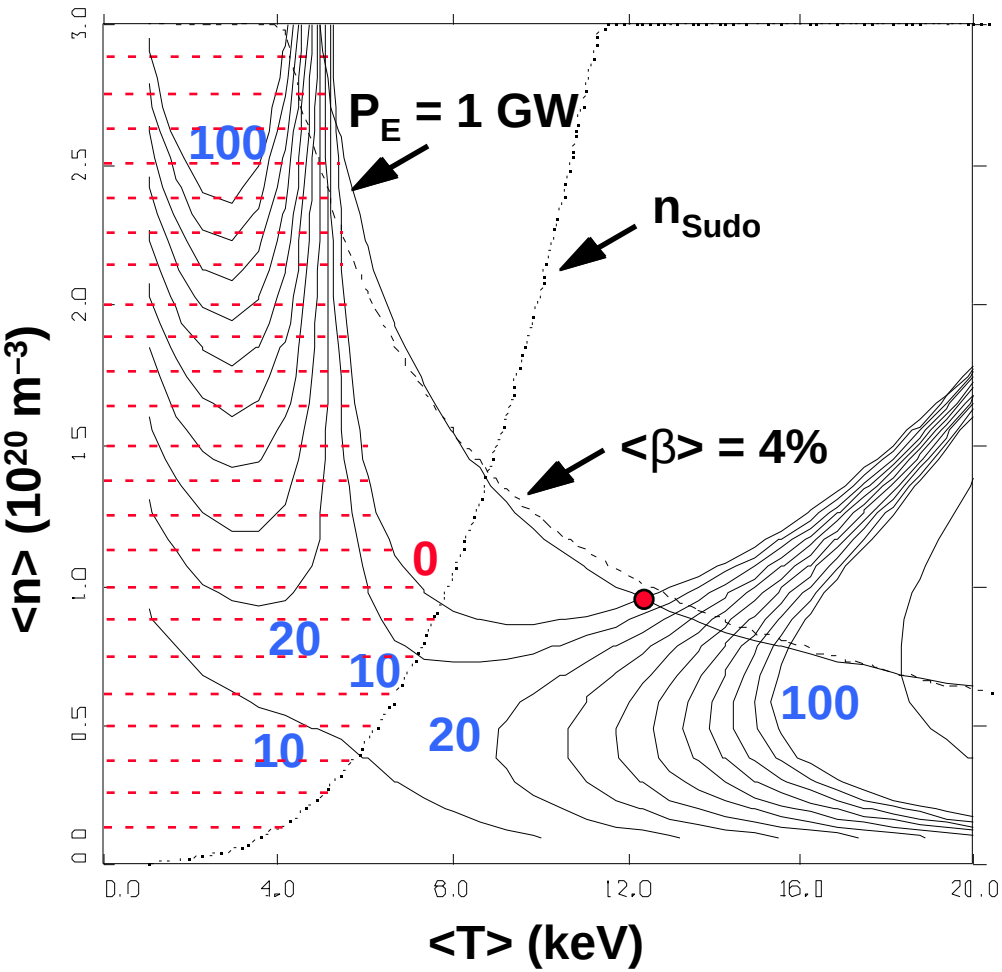
Systems Code Integrates Physics, Materials, Cost Models

- **Stellarator transport options (ISS95 + Shaing-Houlberg)**
  - **(a) 1-D evalutions with fixed profiles**
  - **(b) solve for T_e(r) and T_i(r) with fixed n_e(r) and E_r(r)**
  - **(c) solve for T_e(r), T_i(r), n_e(r) and E_r(r) with fixed particle source**
- **ARIES magnet and reactor material assumptions**
  - **multi-region blanket and shield (except for divertor regions)**
  - **B_{max} vs j in coil from ARIES studies**
  - **allowable stresses, reactor safety penalties, etc. from ARIES**
- **ARIES costing algorithms based on cost per kg**
  - **ARIES-RS values, to be updated soon by Miller for ARIES-AT**
- **Minimize cost (<R>) with constraints from above models**
- **First step is with fixed profile shapes**

A Typical C82 Reactor Case



Operating Point

- $\langle n \rangle = 1.0\ 10^{20}\ m^{-3}$
- $\langle T \rangle = 11.8$ keV
- $\langle \beta \rangle = 3.8$ %
- $P_{fus} = 1.73$ GW

Saddle Point

- $\langle n \rangle = 5.8\ 10^{19}\ m^{-3}$
- $\langle T \rangle = 6.1$ keV
- $\langle \beta \rangle = 1.1$ %
- $P_{aux} = 14$ MW

Ignition minimum

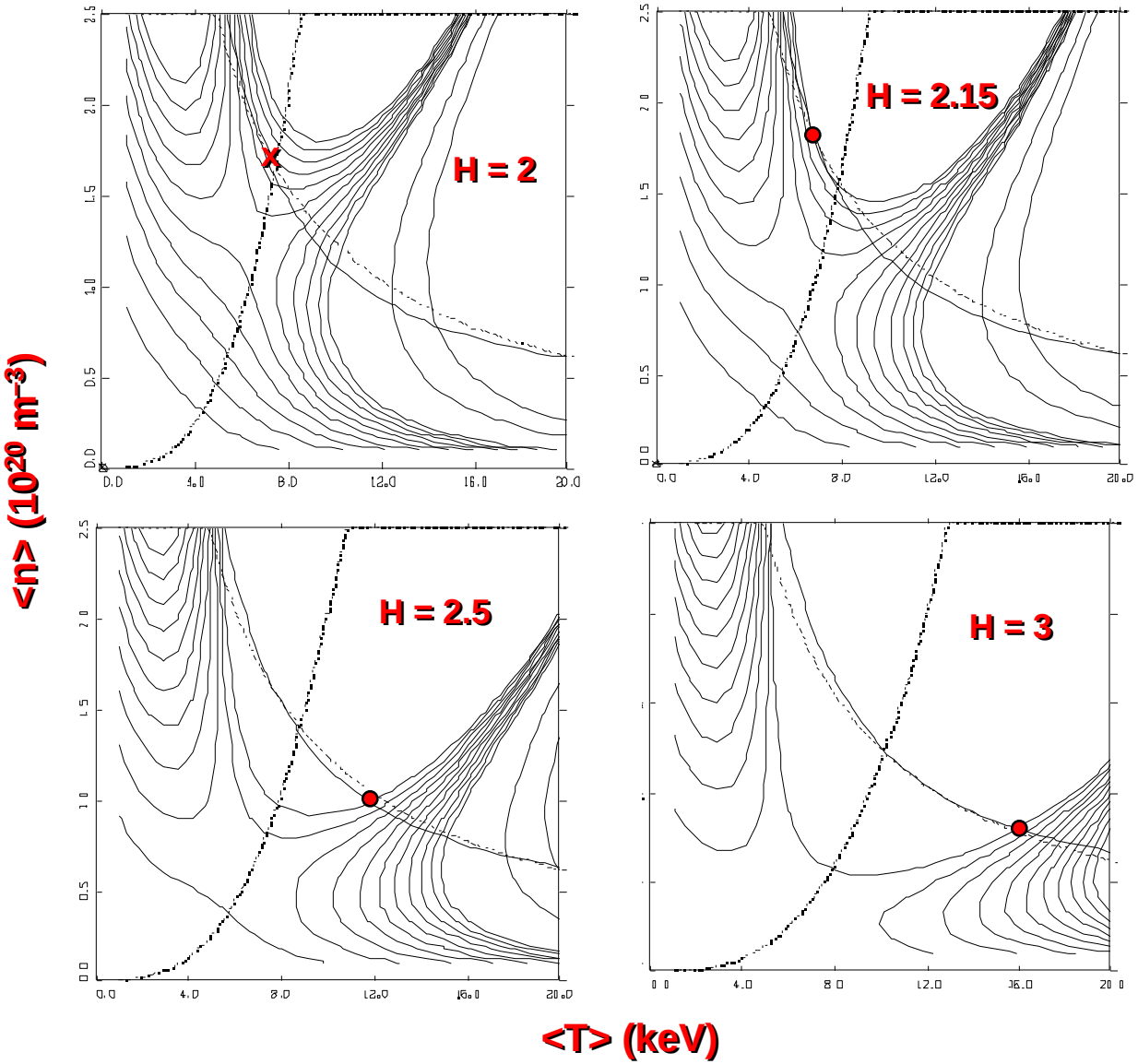
- $\langle \beta \rangle = 2.5$ %
- $P_{fus} = 0.7$ GW

- **R = 9 m, B_0 = 5 T (B_{coil} = 12.7 T), 2.5 x ISS-95, 5% α loss**

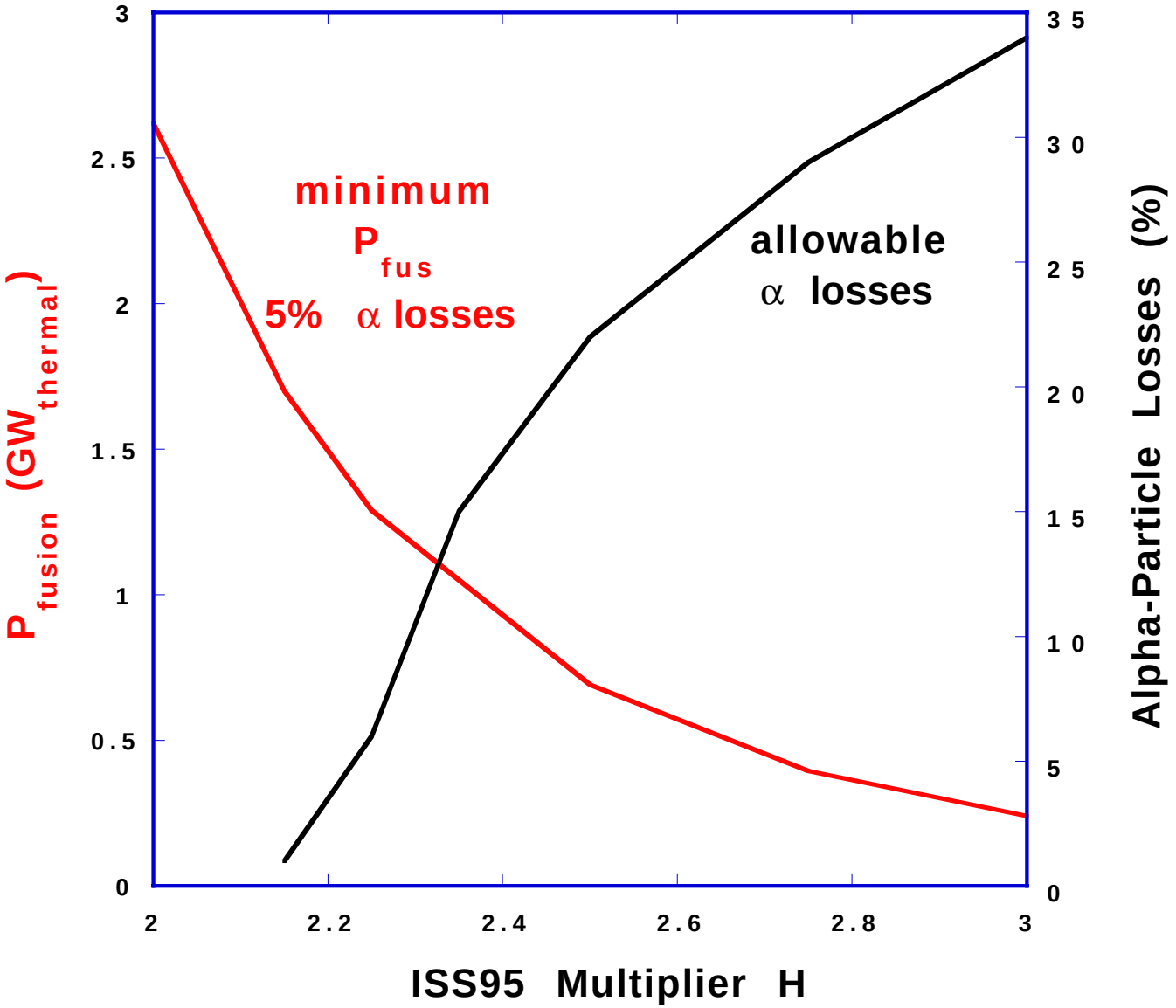
  $\tau_{He}/\tau_E = 6$ 5.3% He, $n_{DT}/n_e = 0.83$, $Z_{eff} = 1.5$

Operating Point Moves to Higher <T> as ISS95 Multiplier H Increases

- R = 9 m, B = 5 T, 5% α losses, t_{He}/t_E = 6

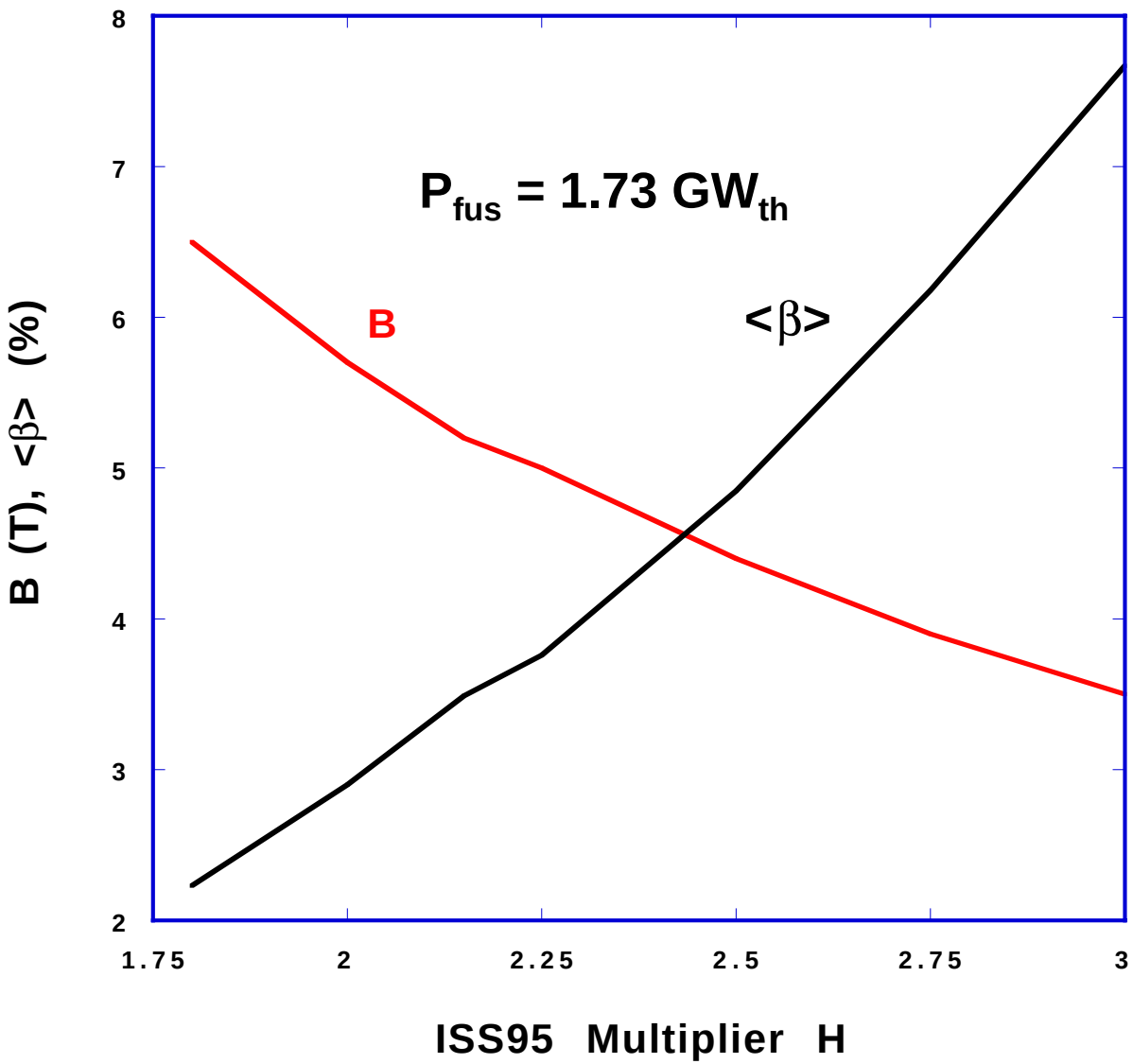


Operating Point Characteristics



- R = 9 m, B = 5 T, $\tau_{He}/\tau_E = 6$

Higher B Required at Lower H

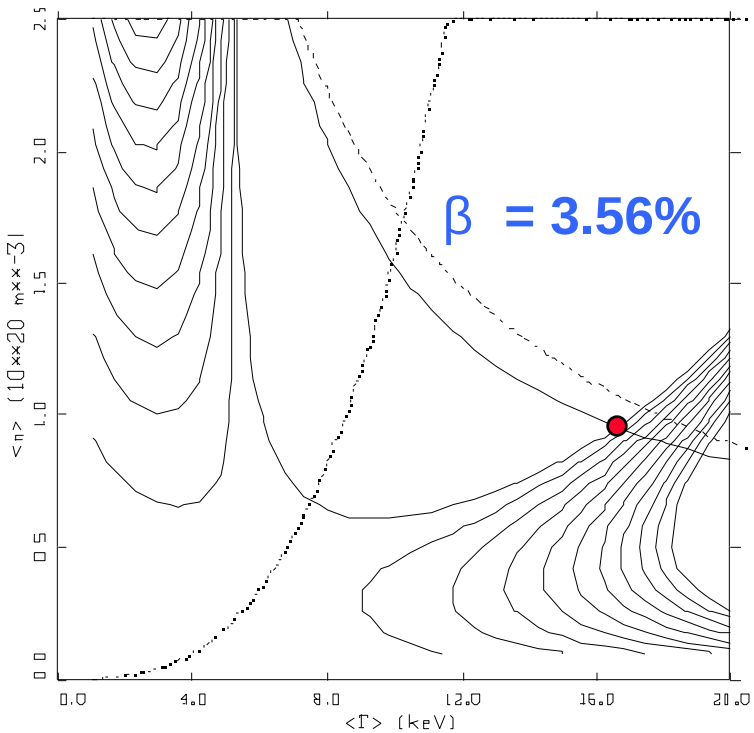


- R = 9 m, 5% α losses, $\tau_{He}/\tau_E = 6$

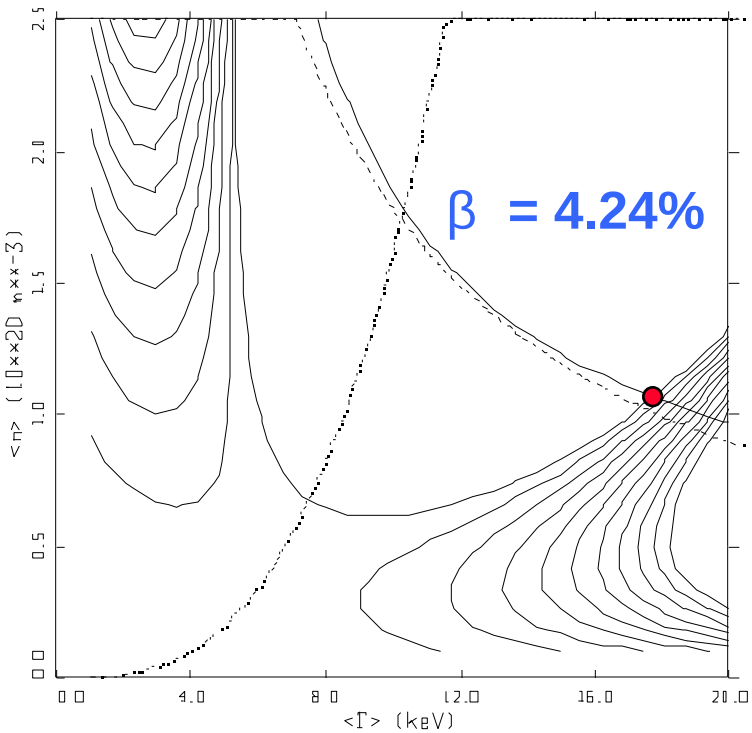
B = 6 T Allows Higher $P_{Electric}$

- R = 9 m, B = 6 T, 5% α losses, t_{He}/t_E = 6

P_E = 1.5 GW



P_E = 2 GW



C82-Based Reactors Are Sensitive to Plasma-Coil Spacing

Plasma-coil spacing (m)	p_{wall} MW/m^2	P_{elect} GW	R_0 (m) a(m)	B_0(T)	1.15 x B_{max}/B_0
1.3 (ARIES-RS inboard bl+sh)	4.7	2.0	8.9 2.6	6.3	2.54
1.5	4.5	2.5	10.1 3.0	6.0	2.65
1.7 (ARIES -IV, SPPS bl+sh)	4.0	2.8	11.3 3.3	5.7	2.81

- **ARIES study is needed to determine realistic plasma-coil spacing and estimated COE**

Next Steps in Reactor Studies

- Minimize CoE with 1-D transport models
  - examine sensitivities to assumptions
- Need better modular coil representation
- Improve QA plasma and transport model
- Incorporate ARIES-AT models, costing (Miller)
- Involve ARIES Group (Najmabadi)
  - May meeting to organize ARIES studies
  - thinner blanket and shield
  - advanced superconducting coils
- Look at high-β QO reactor case?
- IAEA paper in October, PVR documentation