PRINCETON
PLASMA PHYSICS
LABORATORY

PRINCETON
UNIVERSITY

Options and strategies towards fusion net electricity

Dr. Jonathan Menard
Princeton Plasma Physics Laboratory, USA

NAS Committee for a Strategic Plan
for U.S. Burning Plasma Research
Princeton Plasma Physics Laboratory
April 11, 2018

Thank you for the invitation to speak about:

- The state and potential of magnetic confinement-based fusion research in the United States and the options and strategies that may shorten the path to fusion energy…
- …for example, through design and construction of fusion energy facility to demonstrate electrical self-sufficiency

Outline

- Overview
- Tokamak Pilot Plants
- Stellarator Pilot Plants
- Summary

Electricity gain Q_{eng} determined primarily by engineering efficiencies and fusion gain Q ($=Q_{DT}$)

$$Q_{eng} \equiv \frac{\text{Electricity produced}}{\text{Electricity consumed}} = \frac{\eta_{th}(M_n P_n + P_\alpha + P_{aux} + P_{pump})}{\dfrac{P_{aux}}{\eta_{aux}} + P_{pump} + P_{sub} + P_{coils} + P_{control}}$$

$$Q_{eng} = \boxed{\eta_{th}\,\eta_{aux}\,Q} \times \frac{(4M_n + 1 + 5/Q + 5P_{pump}/P_{fus})}{5(1 + \eta_{aux} Q P_{extra}/P_{fus})}$$

η_{th} ≡ thermal power conversion efficiency

η_{aux} ≡ injected power wall plug efficiency

Q ≡ P_{fus} / P_{aux} = fusion power / auxiliary power

Parameter Assumptions:

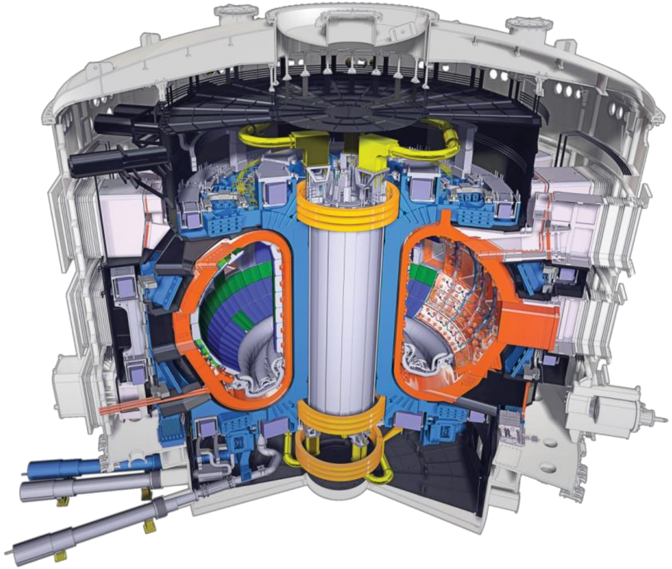
- $M_n = 1.1$, $P_{pump} = 0.03 \times P_{th}$
- $P_{sub} + P_{control} = 0.04 \times P_{th}$
- $\eta_{aux} = 0.3$
- $\eta_{CD} = I_{CD} R_0 n_e / P_{CD} \approx 0.3 \times 10^{20} \text{A/W/m}^2$

For more details see J. Menard, et al., Nucl. Fusion 51 (2011) 103014

Burning plasma demonstration remains essential

ITER: $Q = 10$

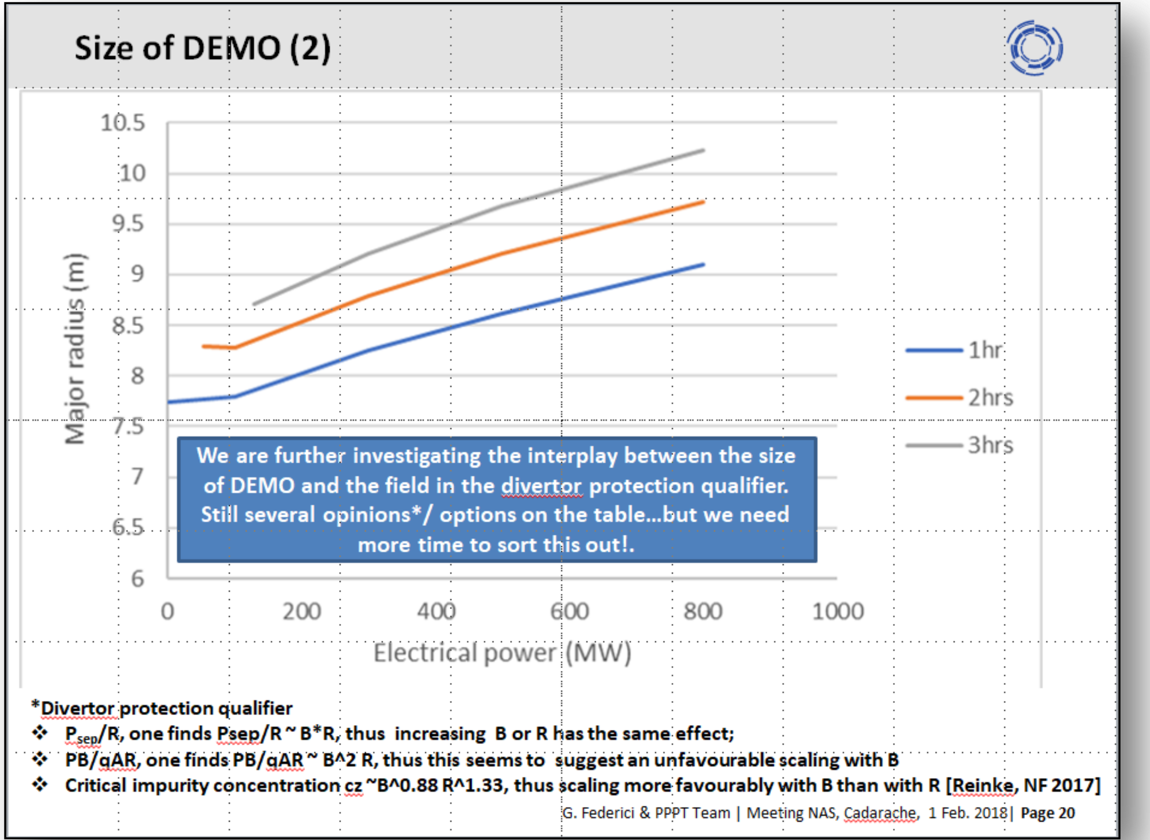
P_{fusion} = 400-500MW
t_{pulse} = 300-500s
R = 6.2 m, a = 2.0 m
B_T = 5.3 T, I_P = 15 MA



Critical knowledge to be gained:

- Non-linear dynamics from turbulence, majority self-heating by α-particles
- Confinement, stability at low ρ^*, ν^*
- High power exhaust handling, both steady-state and transient (ELMs)
- Disruption prediction, avoidance, and mitigation at reactor scale
- Nuclear facility: licensing, operation, diagnostics, plasma control, remote handling, T processing

ITER basis extrapolates to large, pulsed DEMO



Size of DEMO (2)

We are further investigating the interplay between the size of DEMO and the field in the divertor protection qualifier. Still several opinions*/ options on the table…but we need more time to sort this out!.

*Divertor protection qualifier

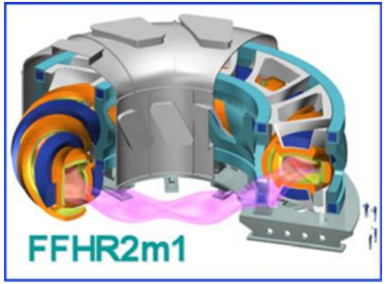
- P_{sep}/R, one finds Psep/R ~ B*R, thus increasing B or R has the same effect;
- PB/qAR, one finds PB/qAR ~ B^2 R, thus this seems to suggest an unfavourable scaling with B
- Critical impurity concentration cz ~B^0.88 R^1.33, thus scaling more favourably with B than with R [Reinke, NF 2017]

G. Federici & PPPT Team | Meeting NAS, Cadarache, 1 Feb. 2018| **Page 20**

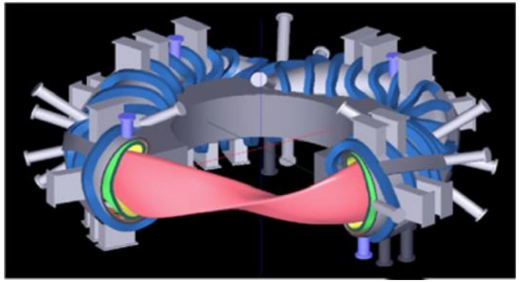
- R = 8-10m
- t_{burn} =1-3 hrs
- Advantage:
  - Use nearly/existing physics, technology
- Challenges:
  - Thermal, EM stress
  - Energy storage
  - Cost and schedule for construction

Some stellarator reactor designs also large R

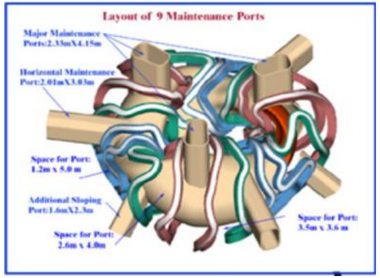
- FFHR-2ml (Japan), LHD-like
  - $R=14m$, $a=1.73m$, $B=6.2T$, $P_{fusion}=1.9GW$



- HSR (Germany), W7X-like
  - $R=20m$, $a=1.6m$, $B=5T$, $P_{fusion}\sim3GW$

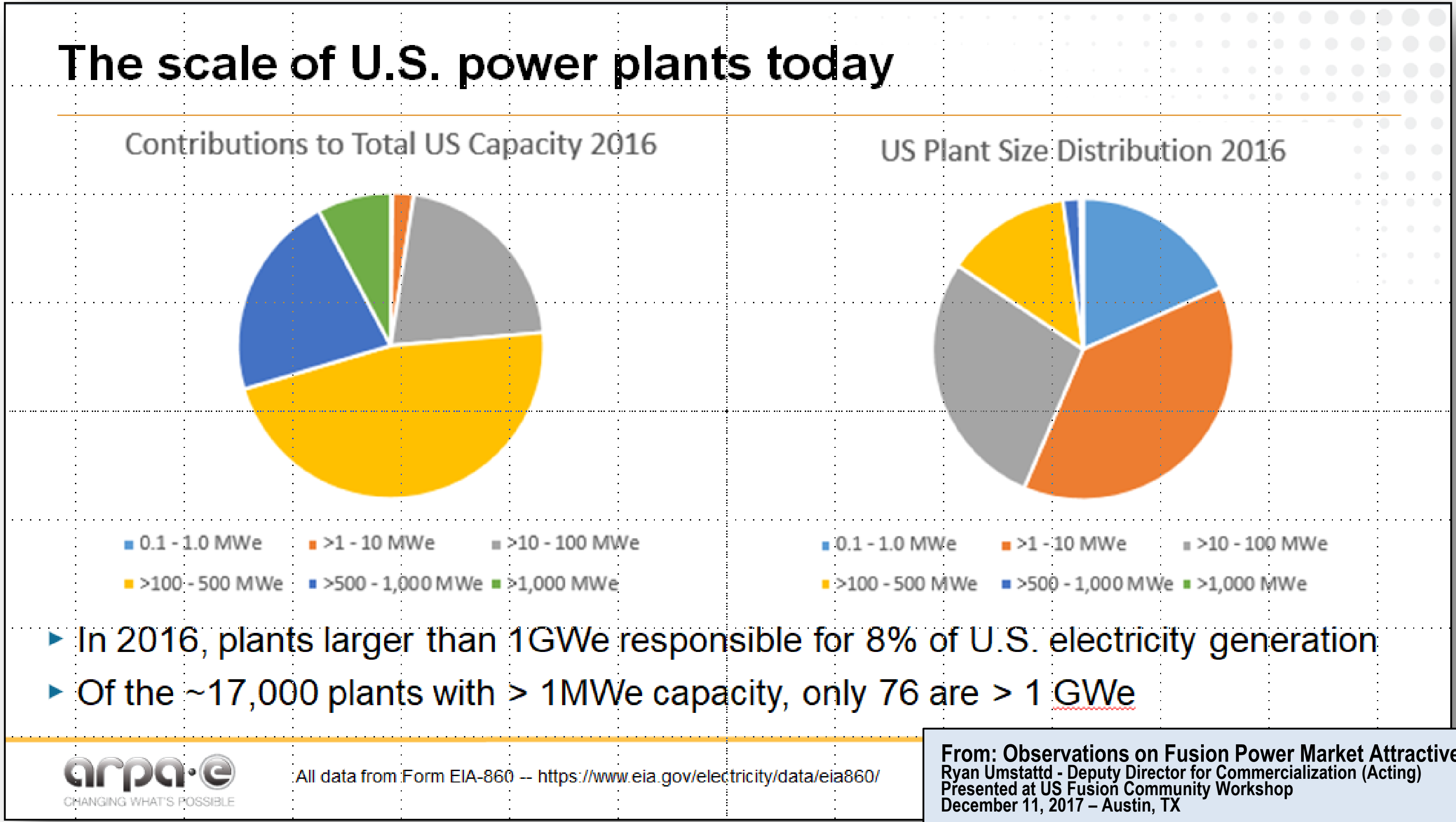


- ARIES-CS (US), NCSX-like
  - $R=7.75m$, $a=1.7m$, $B=5.7T$, $P_{fusion}=2.44$



Note: These are P_{elec}~1GWe → higher than largest-R tokamaks on previous slide

~70% of U.S. electricity from ≤ 500MWe sources



The scale of U.S. power plants today

- In 2016, plants larger than 1GWe responsible for 8% of U.S. electricity generation
- Of the ~17,000 plants with > 1MWe capacity, only 76 are > 1 GWe

All data from Form EIA-860 -- https://www.eia.gov/electricity/data/eia860/

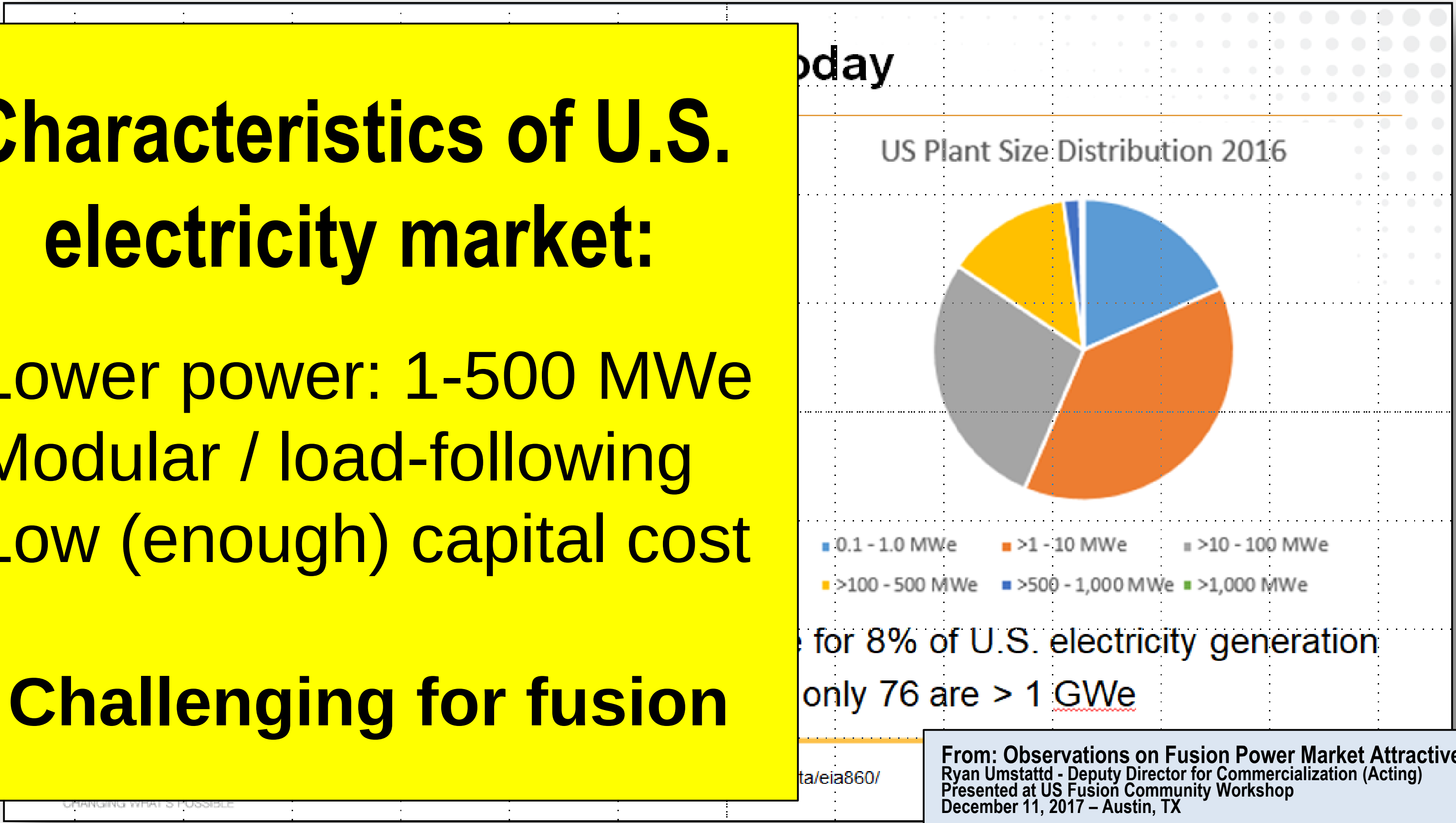
From: Observations on Fusion Power Market Attractiveness
Ryan Umstattd - Deputy Director for Commercialization (Acting)
Presented at US Fusion Community Workshop
December 11, 2017 – Austin, TX

~70% of U.S. electricity from ≤ 500MWe sources

Characteristics of U.S. electricity market:

- Lower power: 1-500 MWe
- Modular / load-following
- Low (enough) capital cost

→ **Challenging for fusion**



oday

US Plant Size Distribution 2016

for 8% of U.S. electricity generation

only 76 are > 1 GWe

ta/eia860/

CHANGING WHAT'S POSSIBLE

From: Observations on Fusion Power Market Attractiveness
Ryan Umstattd - Deputy Director for Commercialization (Acting)
Presented at US Fusion Community Workshop
December 11, 2017 – Austin, TX

Possible high-level fusion development strategy

- ➢ Focus research and resources on key science and technology drivers that could lead to more compact and/or efficient fusion systems

1. If above R&D successful, develop small net electric demonstration (or equivalent) facility (Pilot Plant)
2. AND need substantial fusion nuclear materials and component R&D (Fusion Nuclear Science Facility)

- May be possible to combine 1. and 2. into FNSF/Pilot

Performance parameters for strategy

1. Integrate high-performance, steady-state, exhaust
    - Q_{DT} = 1-20, 100% non-inductive (tokamaks), $P_{heat}/S \sim 0.5\text{-}1 MW/m^2$
2. Fusion-relevant neutron wall loading
    - $\Gamma_n \sim 1\text{-}3 MW/m^2$, fluence: $\geq 6 MW\text{-}yr/m^2$
3. Tritium self-sufficiency
    - Tritium breeding ratio TBR ≥ 1
4. Electrical self-sufficiency
    - $Q_{eng} = P_{electric} / P_{consumed} \geq 1$

FNSF emphasis

Pilot emphasis

Possible to achieve in single device with phased program?

What are key drivers for compact fusion?

Consider tokamaks first….

Fusion gain $Q_{DT} \propto H^{2\rightarrow 5}$ from low → high gain

$$\text{Fusion power density} \equiv \Gamma_{DT} = n_D n_T \langle \sigma v \rangle_{DT} E_{DT} \propto p^2$$

$$P_{fusion} \propto (P\,\tau_E)^2 / V$$

$$\boxed{\tau_E \propto H} I_P^{\alpha_I} B_T^{\alpha_B} n_e^{\alpha_n} P^{-\alpha_P} R^{\alpha_R} \kappa^{\alpha_\kappa} \epsilon^{\alpha_\epsilon}$$

$$P = P_{aux}(1 + \lambda_{DT} Q_{DT}) \qquad Q_{DT} \equiv P_{fusion}/P_{aux} \quad \lambda_{DT} = 0.2$$

$$\boxed{Q^*_{DT} \equiv Q_{DT}/(1 + \lambda_{DT} Q_{DT})^{2(1-\alpha_P)}}$$

$$\boxed{\propto H^2} I_P^{2\alpha_I} B_T^{2\alpha_B} n_e^{2\alpha_n} P_{aux}^{1-2\alpha_P} R^{2\alpha_R - 3} \kappa^{2\alpha_\kappa - 1} \epsilon^{2\alpha_\epsilon - 2}$$

Fix current, field, density, geometry, auxiliary power, $\alpha_P = 0.7$:

$Q_{DT} \leq 1 \rightarrow Q_{DT} \approx Q^*_{DT} \propto H^2$ $\qquad$ $Q_{DT} \gg 1 \rightarrow Q_{DT} \propto {Q^*_{DT}}^{2.5} \propto H^5$

Gain vs. physics and engineering constraints

- In steady-state, current-driven kink limit weaker constraint than high f_{BS} → no *q** dependence → relevant variables are β_N / f_{BS} and f_{gw}:

Exponent	98y2	Petty-08
C_β	2.68	2.14
C_B	2.98	2.74
C_{gw}	0.82	0.64
C_P	-0.38	0.06
C_R	1.98	2.04
C_κ	5.92	5.04
C_ε	1.54	1.61

C. Petty, et al., Phys. Plasmas ***15*** *(2008) 080501*

$$Q^*_{DT} \propto H^2 (\beta_N / f_{BS})^{c_\beta} B_T^{c_B} f_{gw}^{c_{gw}} P_{aux}^{c_P} R^{c_R} \kappa^{c_\kappa} \epsilon^{c_\epsilon}$$

Choose electrostatic gyro-Bohm Petty-08 with no β degradation (JET, DIII-D, NSTX)

$$Q^*_{DT} \propto \overbrace{R^2 H^2 (1 - f_{CD})^{-2} f_{gw}^{0.7} B_T^3 \kappa^{3-5} \beta_N^2 \epsilon^{1.6}}^{\textbf{Gain depends on (at least) 8 global parameters}}$$

Key parameters for achieving high gain

$$Q^*_{DT} \propto R^2 \overbrace{H^2(1 - f_{CD})^{-2} f_{gw}^{0.7}}^{\text{Optimize: confinement, current drive vs density}} \overbrace{B_T^3 \kappa^{3-5} \beta_N^2 \epsilon^{1.6}}^{\text{aspect ratio}}$$

Normalized Gain

Major radius

Normalized Confinement

External Current Drive Fraction

Normalized Density

Toroidal field in plasma

Elongation

Normalized beta

Inverse aspect ratio

Potential Innovations for Compact Pilot

Tokamak

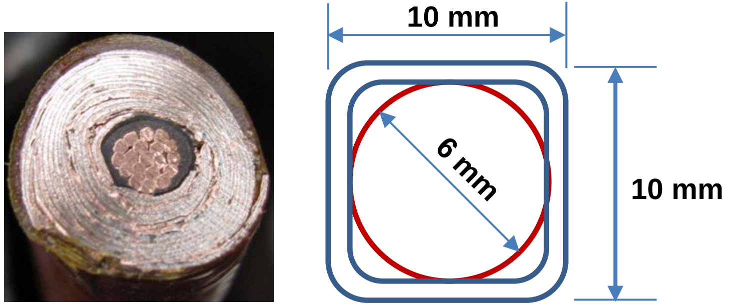
- Magnets – HTS for higher B_T and $J_{winding\text{-}pack}$
- Confinement – Optimize edge transport barrier
- Stability – Disruption avoidance, β_N > no-wall limit
- Aspect Ratio – Reduced A → higher β_N and κ
- Heating & Current Drive – New RF, Negative NBI
- Divertors – Advanced / long-leg, liquid metals
- Blankets – Liquid metal, high efficiency

High-current-density rare earth barium copper oxide (REBCO) superconductors motivate consideration of lower-A pilot plants

Conductor on Round Core Cables (CORC): High winding pack current density at high magnetic field

J_{WP} ~ 70MA/m^2 at 19T

Higher current densities, B likely possible…

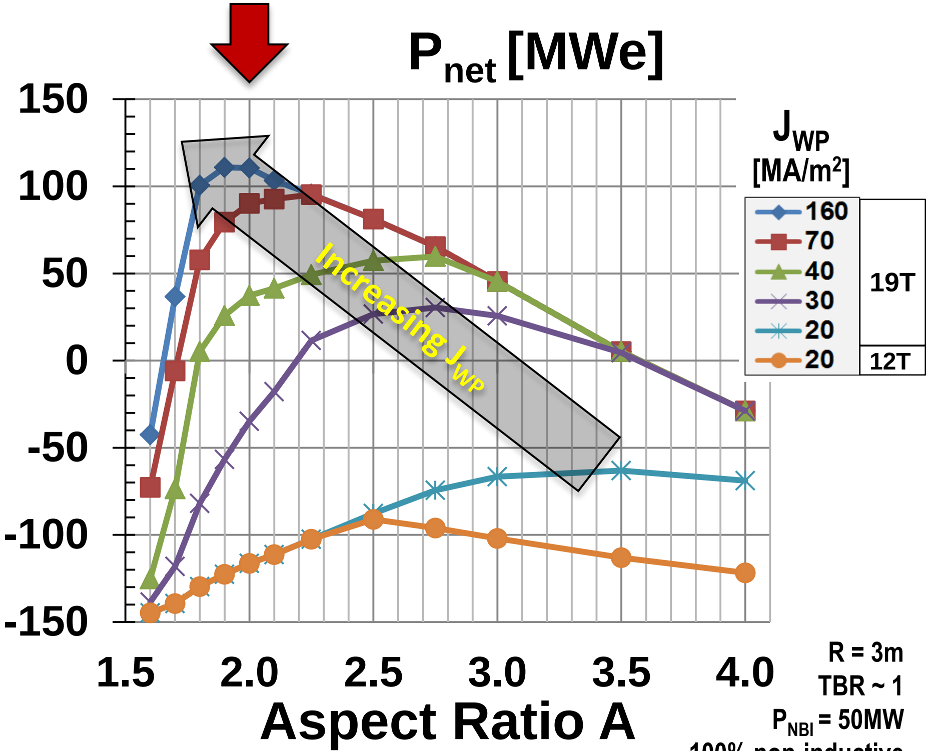


7 kA CORC (4.2K, 19 T) cable

Base cable: 50 tapes YBCO Tapes with 38 μm substrate

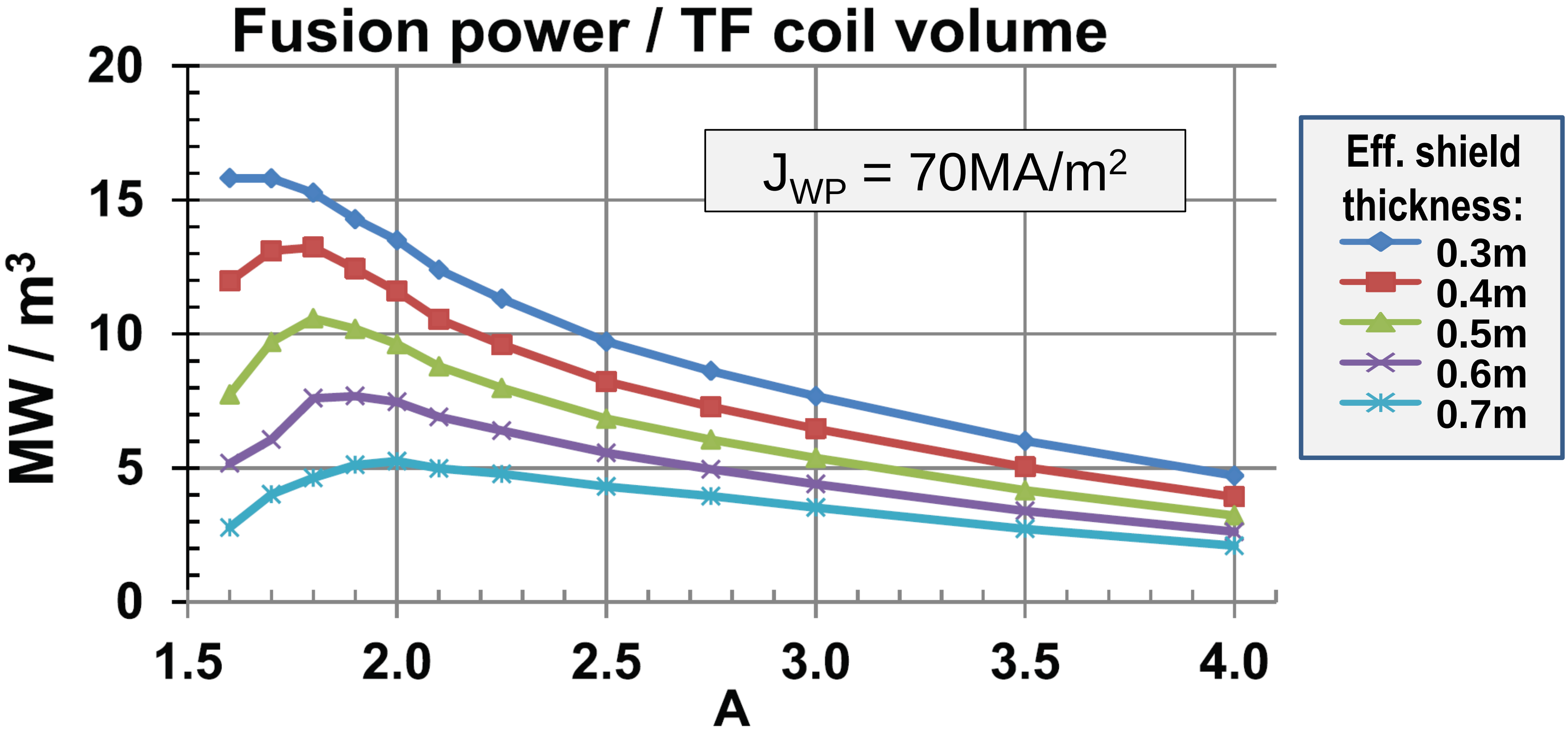
(Van Der Laan, HTS4Fusion, 2015)

A ~ 2 attractive at high J_{WP}

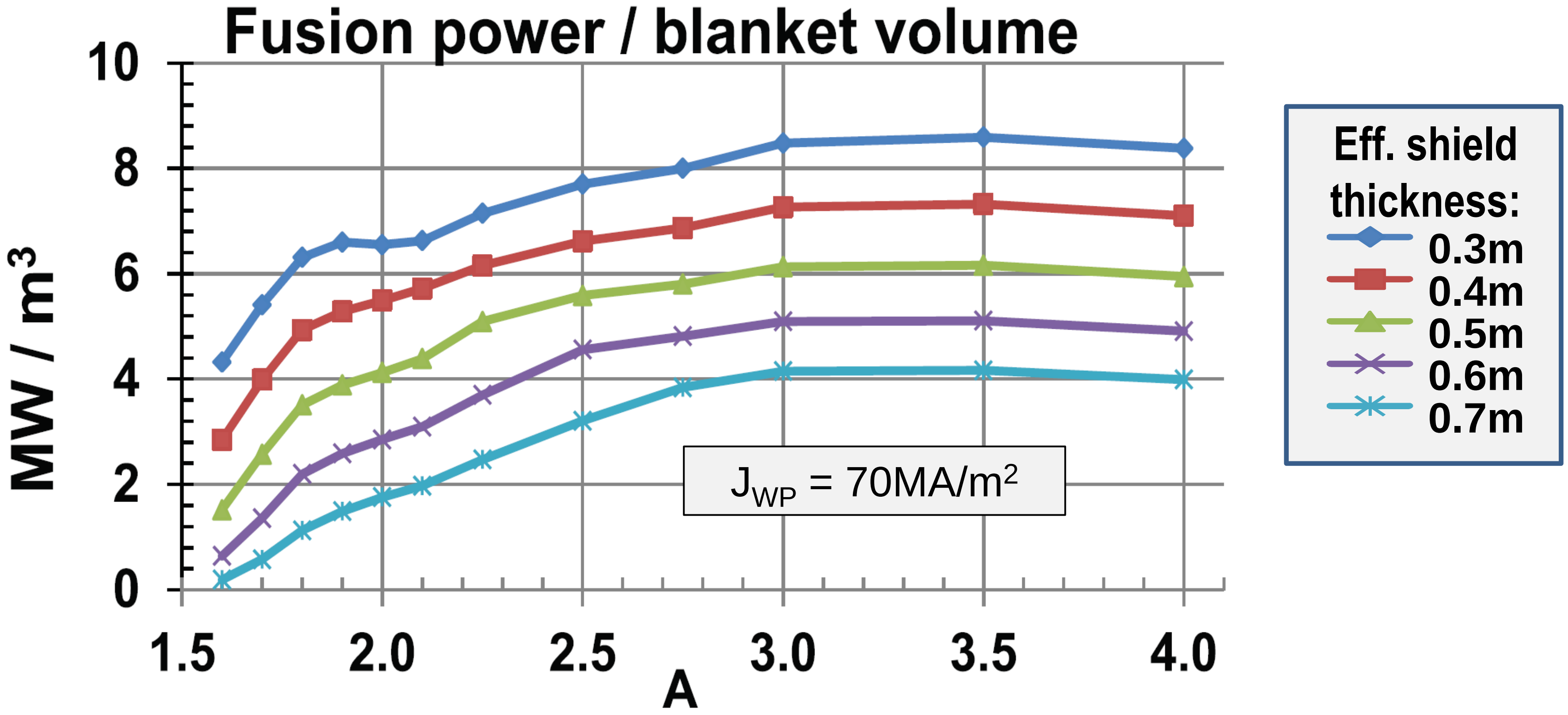


R = 3m
TBR ~ 1
P_{NBI} = 50MW
100% non-inductive
β_N (A) at no-wall limit

A ≤ 2 maximizes TF magnet utilization



A ≥ 3 maximizes blanket utilization

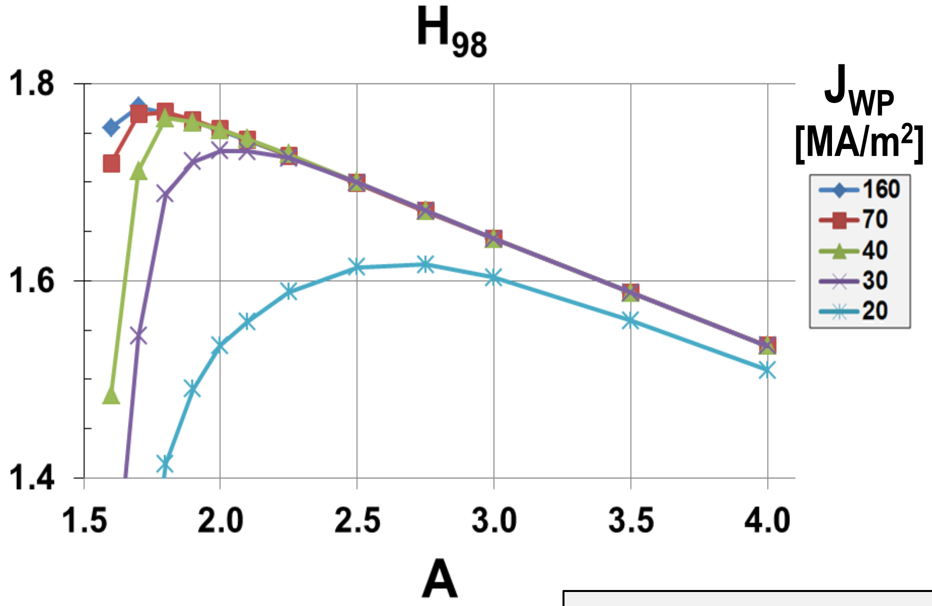


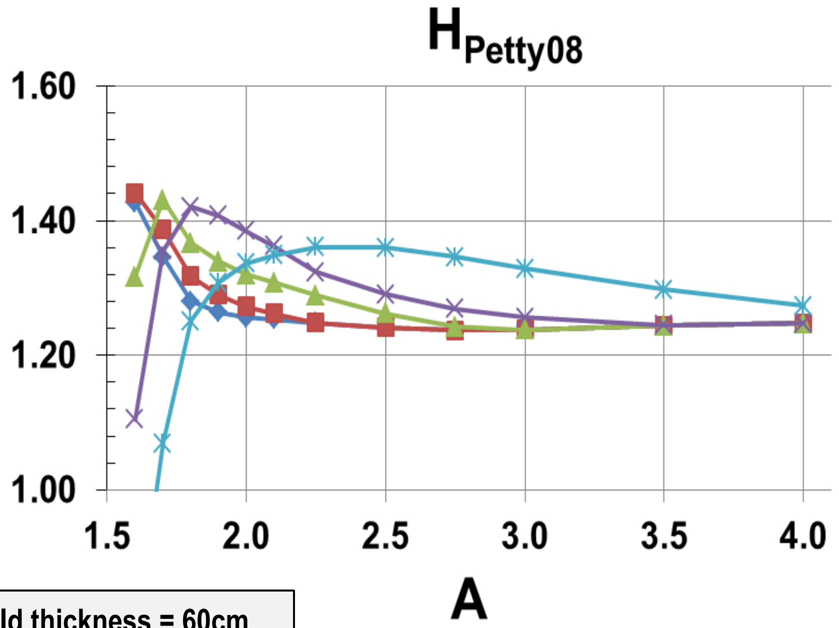
All R=3m pilots require enhanced confinement

i.e. H > 1 vs. conventional aspect ratio confinement scalings

H_{98y2} = 1.5-1.8

$H_{Petty-08}$ = 1.25-1.4

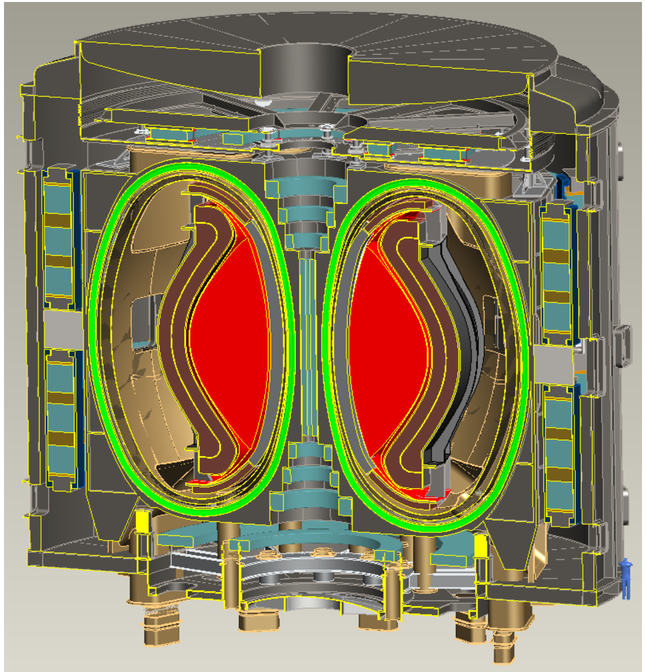




Effective inboard WC n-shield thickness = 60cm

Example: A=2, R_0 = 3m HTS-TF FNSF/Pilot Plant

*J. Menard, et al., Nucl. Fusion **56** (2016) 106023*



Cryostat volume ~ 1/3 of ITER

B_T = 4T, I_P = 12.5MA

κ = 2.5, δ = 0.55

β_N=4.2, β_T=9%, f_{gw}=0.8

H_{98} = 1.75, $H_{Petty-08}$ = 1.3

H_{ST} = 0.7-0.9

f_{NI} = 100%, f_{BS} = 0.76

Startup I_P (OH)~2MA

J_{WP} = 70MA/m^2

$B_{T\text{-}max}$ = 17.5T

No joints in TF

Vertical maintenance

P_{fusion} = 520 MW

P_{NBI} = 50 MW

E_{NBI}=0.5MeV

Q_{DT} = 10.4

Q_{eng} = 1.35

P_{net} = 73 MW

$\langle W_n \rangle$ = 1.3 MW/m^2

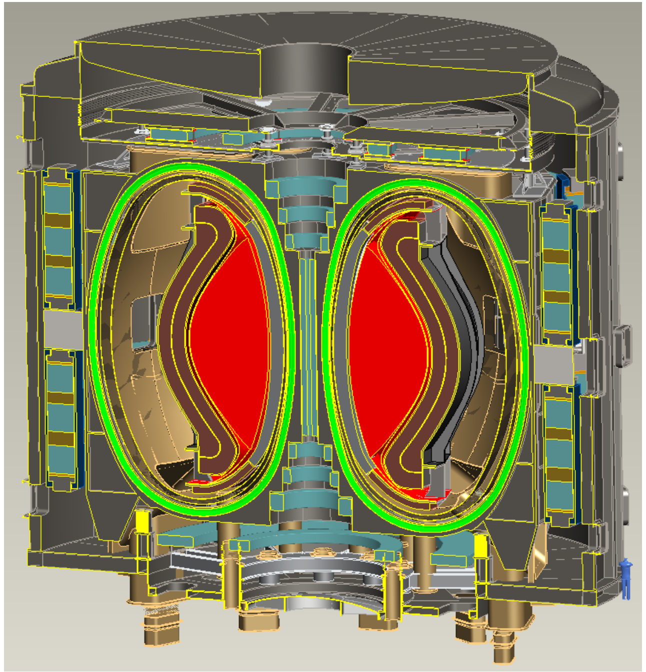
Peak n-flux = 2.4 MW/m^2

Peak n-fluence: 7MWy/m^2

TBR $\geq$ 1

Example: A=2, R_0 = 3m HTS-TF FNSF/Pilot Plant

*J. Menard, et al., Nucl. Fusion **56** (2016) 106023*



Cryostat volume ~ 1/3 of ITER

B_T = 4T, I_P = 12.5MA

κ = 2.5, δ = 0.55

β_N=4.2, β_T=9%, f_{gw}=0.8

H_{98} = 1.75, $H_{Petty\text{-}08}$ = 1.3

H_{ST} = 0.7-0.9

f_{NI} = 100%, f_{BS} = 0.76

Startup I_P (OH)~2MA

J_{WP} = 70MA/m^2

$B_{T\text{-}max}$ = 17.5T

No joints in TF

Vertical maintenance

P_{fusion} = 520 MW

ST confinement scaling uncertain, but potentially favorable

ST non-inductive sustainment at high performance remains to be demonstrated

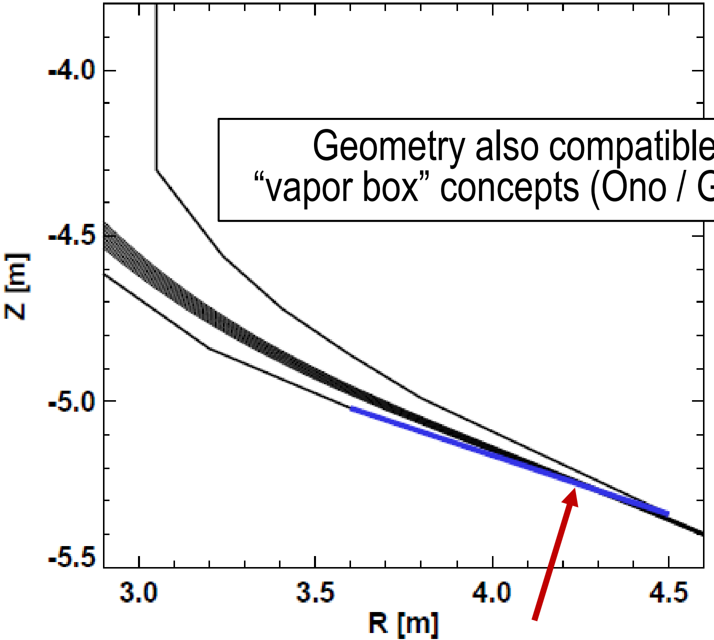
Peak n-fluence: 7MWy/m^2

TBR $\geq$ 1

Understanding ST confinement, sustainment = drivers for NSTX-U – *See Gerhardt talk*

Advanced / long-leg divertors, and/or fast-flow liquid metal likely required to enable compact Pilots

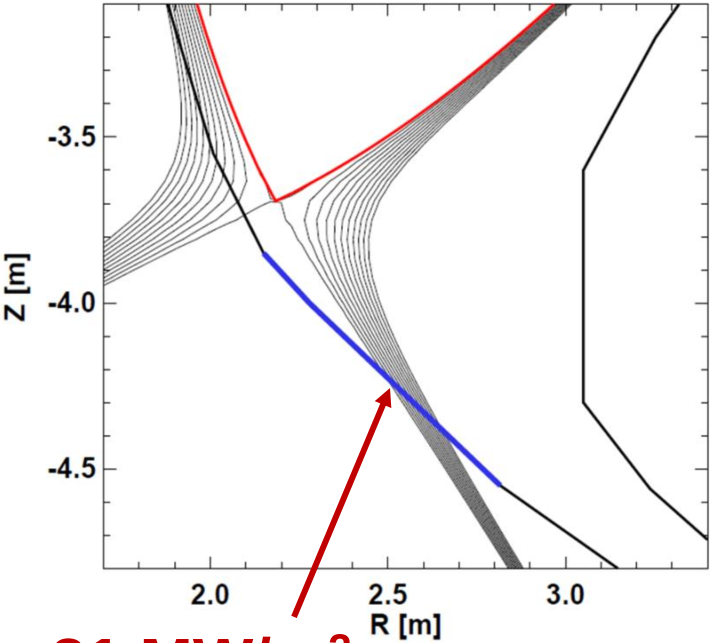
Long-leg / Super-X divertor



Geometry also compatible with “vapor box” concepts (Ono / Goldston)

9 MW/m²

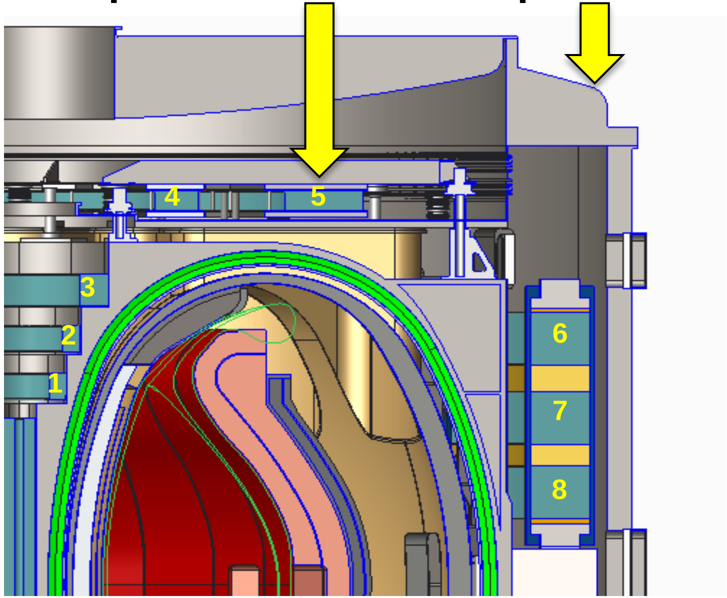
Shorter leg LM divertor

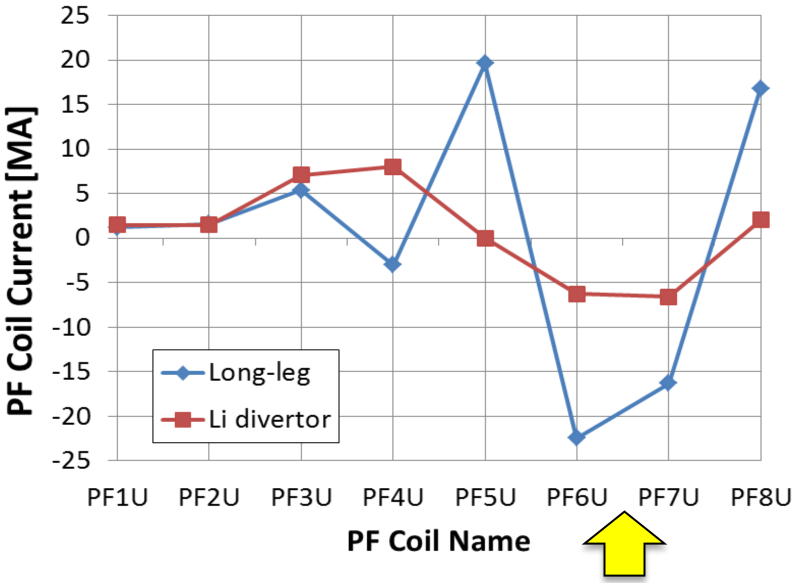


21 MW/m²

Benefits of shorter-leg liquid metal divertor:

- No top PF coil or separate cryo-stat → simplified maintenance



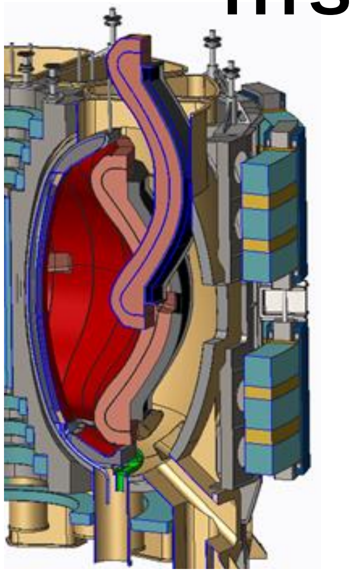


- Significantly reduce outboard PF coil current, force, structure
- If liquid lithium, wall pumping could help increase H-factor

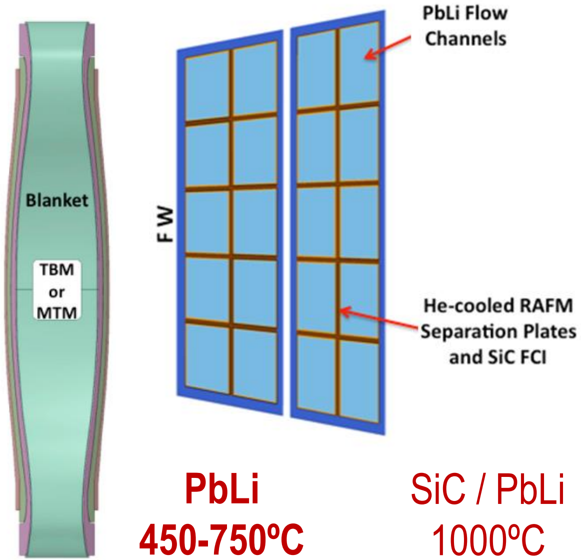
Power handling, mass control/removal, pumping drivers for LM – *See Jaworski talk*

Liquid metal / molten salt blankets offer potential for high thermal efficiency, modular design

HTS ST-FNSF/Pilot



L. El-Guebaly, et al., Energies, ***9*** *(2016) 632*

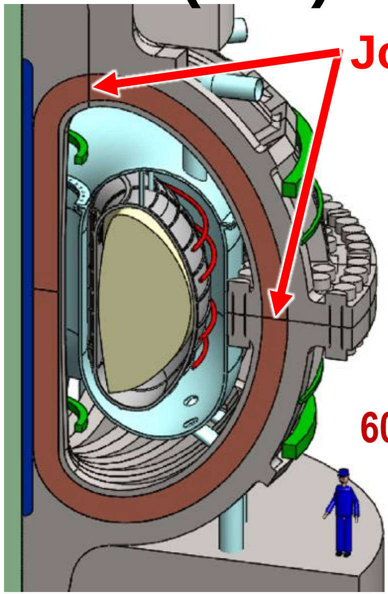


PbLi
450-750ºC

SiC / PbLi
1000ºC

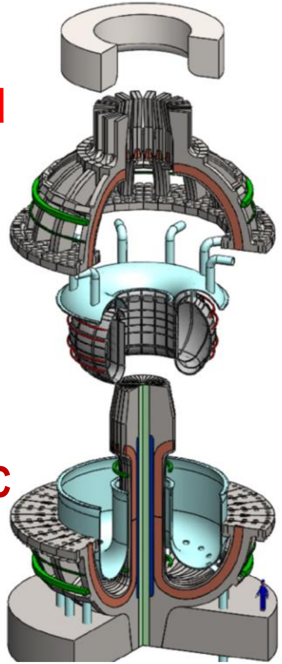
Dual-coolant Lead-Lithium (DCLL) blankets, 20 vertical sectors: η_{th} **= 30-45%** (55% SiC/SiC)

ARC (MIT)



Jointed TF

FLiBe:
600-900ºC



FLiBe liquid immersion blanket, single component/removable: η_{th} **= 40-50%**

Outline

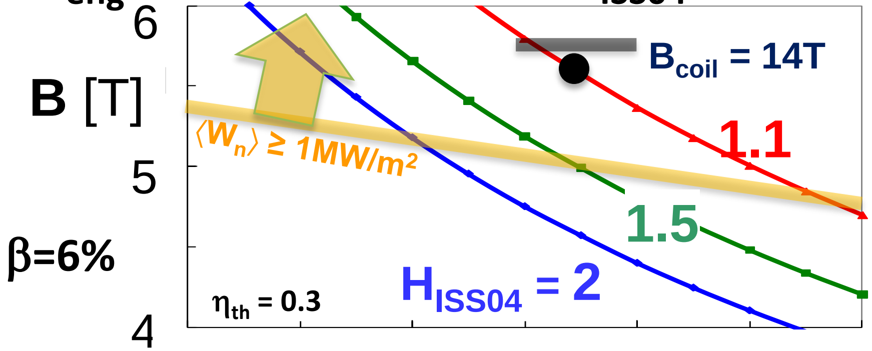
- Overview
- Tokamak Pilot Plants
- Stellarator Pilot Plants
- Summary

Stellarator strengths, challenges for FNSF/Pilot

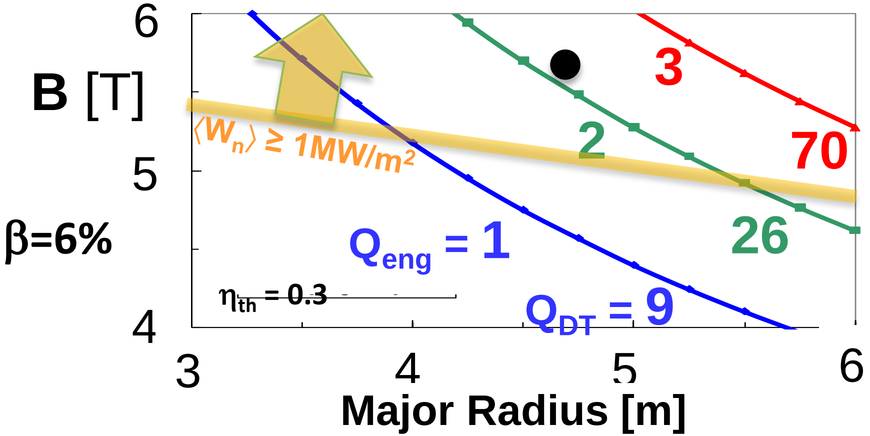
- No current drive required / intrinsically steady-state
  - Lower recirculating power, smaller wall penetrations
- MHD-stable without active feedback control
  - Reduced diagnostic and actuator needs
  - No coils inside blanket/shield, internal stabilizing shells, disruption mitigation systems, or runaway electron risk
  - Thinner first wall, improved T breeding
- Challenges:
  - Thermal / fast particle confinement, complex coils / blanket / maintenance, 3D power / particle exhaust, compactness

2010-11: Size of compact stellarator (CS) pilot driven by magnet technology and neutron wall loading, but not Q_{eng}

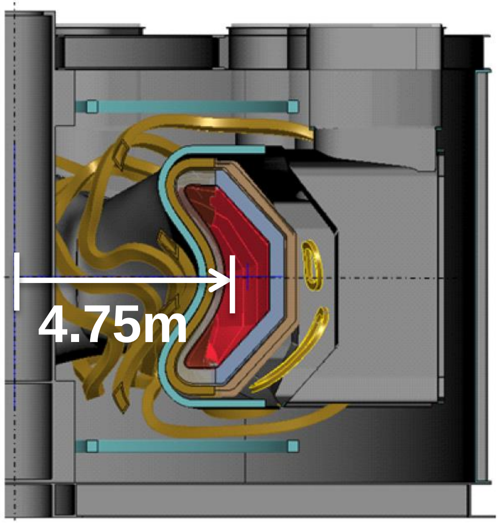
Q_{eng}=1.1 accessible at H_{ISS04} ≥ 1.1 (~L-mode)



H_{ISS04}=2 → Q_{eng}=2-3, high Q_{DT} (~H-mode)



● = Pilot design point



- A = 4.5 = 4.75m / 1.05m
- B_T = 5.6T, I_P = 1.7MA (BS)
- Avg. W_n = 1.2-2 MW/m^2
- Peak W_n = 2.4-4 MW/m^2

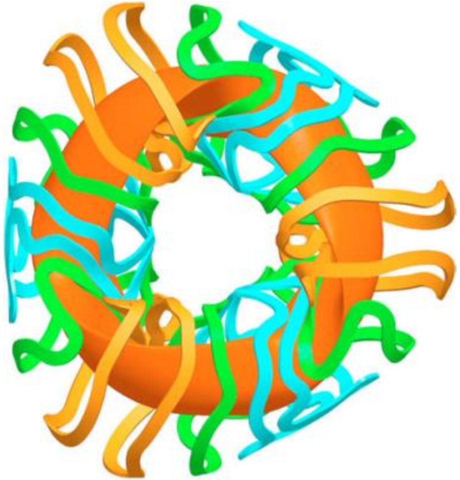
New stellarator optimization initiated at PPPL

- Study intended to map out the configuration and physics program for a future stellarator project

- Current topics include (a subset):
  - Generate a database of starting point equilibria by varying aspect ratio, elongation, bootstrap fraction and beta.
  - Include coil force constraints (COILOPT++ code modified)
  - Neoclassical transport, bootstrap (SFINCS), REGCOIL coupled to STELLOPT
  - Extend turbulent transport optimization from Quasi-Axisymmetric (QA) to Quasi-Helically (QH) symmetric configurations
  - Develop metrics that will be used in an eventual divertor optimization algorithm

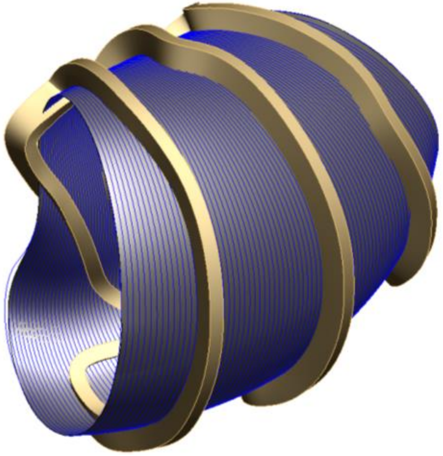
Recent design efforts: Reactor (not Pilot Plant) designs modified to improve physics/engineering self-consistency

- Increase A = 4.5 → 6, R=7.75m to 9.4m, straighten outer legs for vertical maintenance

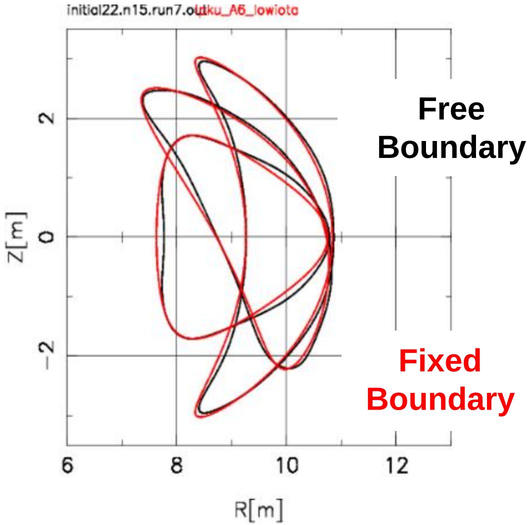


ARIES-CS 4.5 AR,
7.75-m R_{axis}

MC with straight back legs

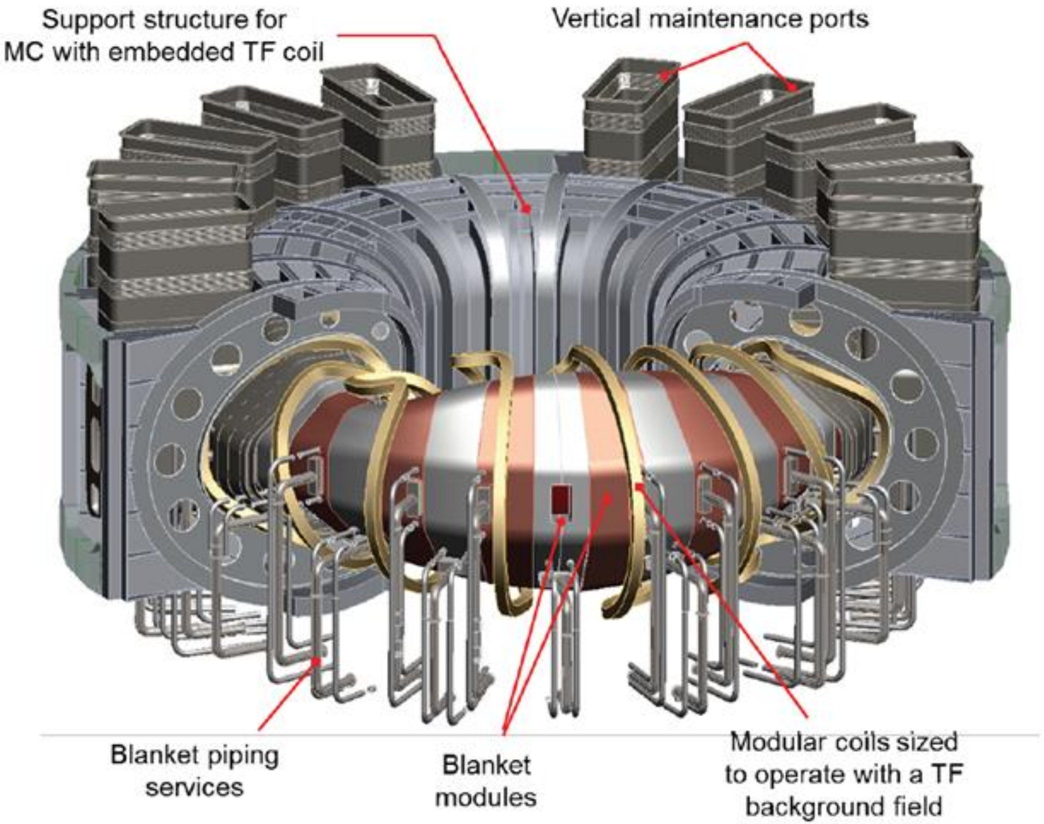


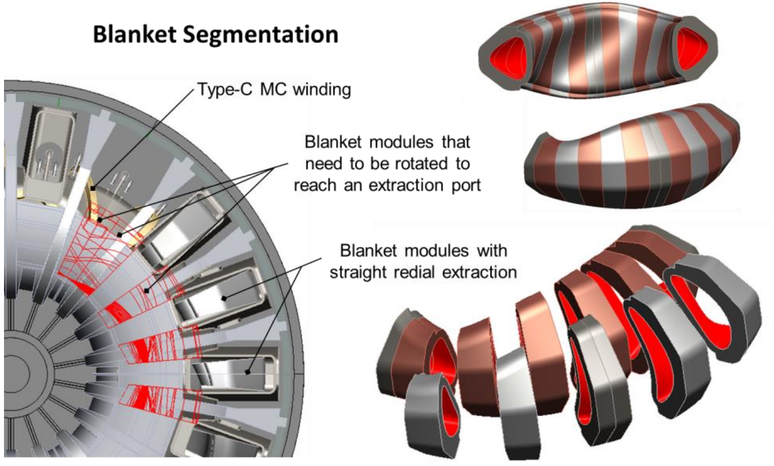
ARIES-CS 6.0 AR,
9.4-m R_{axis}



High AR device meets targeted ARIES-CS plasma boundary

Result: simplified tokamak like vertical maintenance





- Future: Need to revisit design and performance implications for CS FNSF / Pilot Plant

Potential Innovations for Compact Pilot

Stellarator

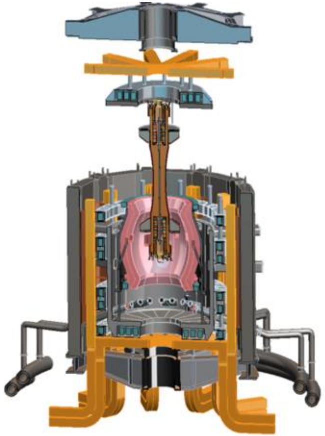
- Magnets – HTS for higher B_T, $J_{\text{winding-pack}}$ beneficial?
- Confinement – Optimize 3D core, edge, fast-ion
- Stability – intrinsically avoid runaways, EM loads
- Aspect Ratio – maintenance vs. mass-power density
- ~~Heating & Current Drive – New RF, Negative NBI~~
- Divertors – Further design needed, liquid metals
- Blankets – Liquid metal, high efficiency

Outline

- Overview
- Tokamak Pilot Plants
- Stellarator Pilot Plants
- Summary

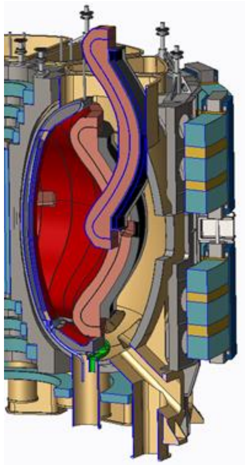
U.S. is leader in scoping studies for range of possible compact FNSF/Pilot Plants

ST



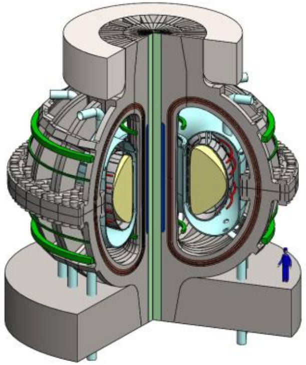
A = 1.7
R = 1-2.2m

Low-A

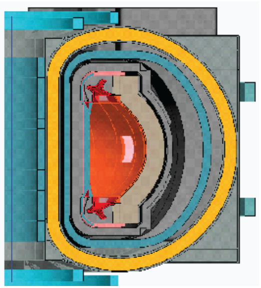


A ~ 2
R = 3m

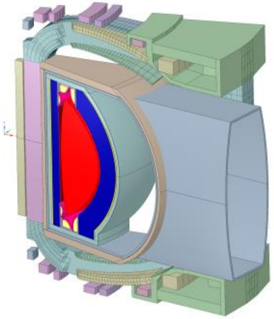
Standard-A Tokamak



A = 3
R = 3.3m

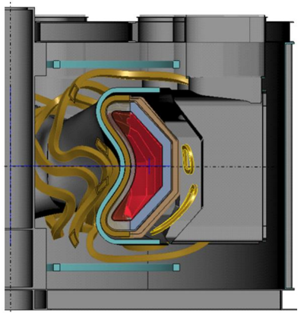


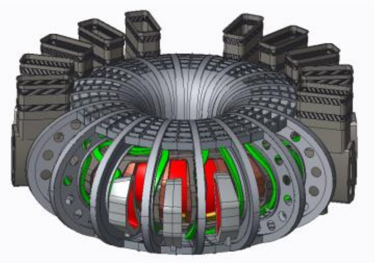
A=3-4, R=4m



A=4, R=4.8m
(FESS FNSF)

Quasi-symmetric (QS) Stellarator





A ≥ 4.5, R ≥ 3.5m

U.S. could / should lead in establishing physics & technology basis for compact FNSFs/Pilots

- **Integrated** experimental demonstrations plus validated predictive capability to confidently proceed to FNSF/Pilot:
  - Adequate / elevated confinement - thermal and fast particle
  - High efficiency CD for tokamaks, steady-state operation ($10^{4\rightarrow6}$s)
  - Divertor + first-wall solutions for high power (P/S~1MW/m^2), high T_{wall} (350-550C possibly higher), mass removal for erosion/dust
  - ELM & disruption avoidance/mitigation (leverage ITER R&D)
- HTS magnets for higher field, current density, temperature
- Radiation-resistant materials, high-efficiency blankets

Summary

- Extrapolations of present physics and technology basis appears to lead to large fusion devices which may not be well matched to U.S. electricity market

- For more attractive fusion end-products, innovations are needed, and several appear very promising

- U.S. research to advance compact AT/ST/stellarator combined FNSF + Pilot Plants could form complementary and highly impactful contribution to world fusion program

Backup

Comparison of low-A FNSF / Pilot Plants

TF coil type	R [m]	A	Q_{eng}	Q_{DT}	TBR	Surf-avg n-fluence [MWy/m^2]	P_h / S [MW/m^2]	H_{98}	H_{Petty}	H_{ST}	κ_X	β_N	β_T [%]	f_{BS}	I_P [MA]	B_T [T]	P_{fus} [MW]
Copper	1	1.7	0.1	1.0	≤ 0.9	6	1.6	1.25	1.25	0.70	2.75	5	20	0.82	7.3	3.0	60
	1.7	1.7	0.15	2.0	1.0	≥ 6	0.9	1.25	1.1	0.72	2.75	4	16	0.76	11	3.0	160
REBCO	1.8	2	1	7.3	0	0.04	0.5	2.3	2.1	0.64	2.30	4	7.1	0.84	7.4	5	160
	3	2	1.3	10	1.0	4 - 6	0.5	1.8	1.3	0.69	2.50	4	8.7	0.76	13	4.0	510