# New HTS superconductors + integrated high-B physics enable an innovative strategic vision for US leadership in accelerated fusion energy development

Gaps

*G-8 High-B magnets*

*G-2 Integrated steady-state & boundary in burning plasma*

*G-4 Control at high $Q_p$*

*G-5 Predict & avoid damaging off-normal events*

*G-7 RF launchers & coupling*

*G-9 Tame PMI & heat exhaust*

*G-10-15 Integrated fusion materials & components*

**Next 10 years**

**HTS magnet R&D**

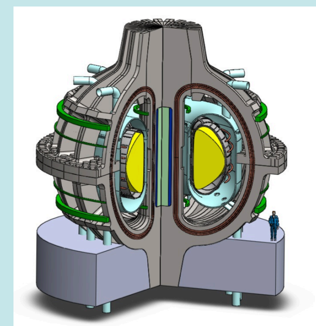
**High-B physics:**

- High gain at small size
- Margin to operational limits & disruptions
- Effective RF CD & innovative launchers for steady-state
- High pressure boundary & PMI control

**HTS joints & Blanket R&D**

HTS high $B_{peak}$> 20 T Superconductor coils

Demountable HTS coils & Modular replacement



**Steady-state Compact FNSF/Pilot**

# A strategic plan should accelerate fusion development by considering critical knowledge gained in past decade

## Key Observations

1. **Large size → risks in cost and schedule**
   **ITER successful fusion gain > 20 years away**
   *"At some point delay is equivalent to failure"*
   *FESAC 2007 Gaps report[5]*

2. **Superconductors evolved (G-8)**
   **HTS[1] tapes allow ~ double B field**
   **→ Steady-state, high gain small devices**

3. **Boundary physics evolved (G-9)**
   a) **ELMs disallowed in ITER →**
      **Transients disallowed in FNSF/Pilot/DEMO**
   b) **Power exhaust could threaten fusion viability**
      **& does not favor large size.**
   c) **Quiescent high-field SOL → locate RF launchers**

Strategic Input →

## Evolved Strategy

**Small +**
**High-B +**
**Superconductor**
**=**
**Margin to disruptions +**
**Steady-state +**
**Reduced cost & schedule**

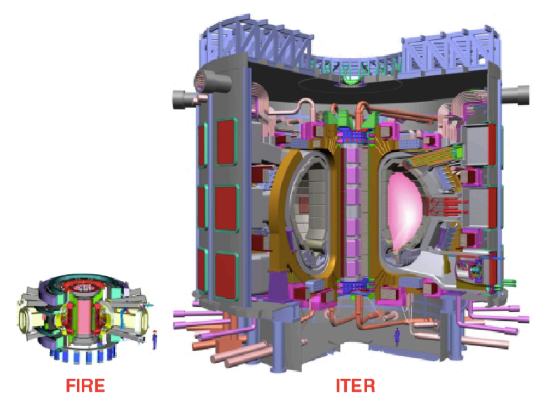
*Cost & schedule G-8 G10-15*

# Size has risk: *Lesson from fission & ITER*

# Minimize volume of first nuclear devices to assure timely development of physics and technology

| *Design parameter* | **Shippingport[2] "Pilot" Fission Plant ca. 1954** | **ITER[3] "Pilot" Fusion Plant ca. 2006** | **Scale factor ITER/Shippingport** |
|---|---|---|---|
| *$P_{thermal}$ (MW)* | 236 | 500 | **x 2.5** |
| *Core volume ($m^3$)* | 60 | ~1600 (shield + TF) | **x 27** |
| *Cost (2012 US B$)* | 0.6 | ~ 30 | **x 50** |
| ***Cost / Core volume ($M\$/m^3$)*** | **10** | **~ 18** | **~ 2** |
| ***Construction time to "burn" (years)*** | **3.3** | **~ 28** | **x 8** |

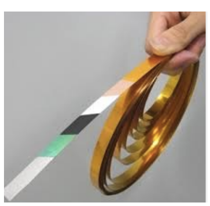
- **JET ~ 100 $m^3$ took < 5 years to construct**
- **FIRE B~10T burned at right size, but pulsed due to copper coils**

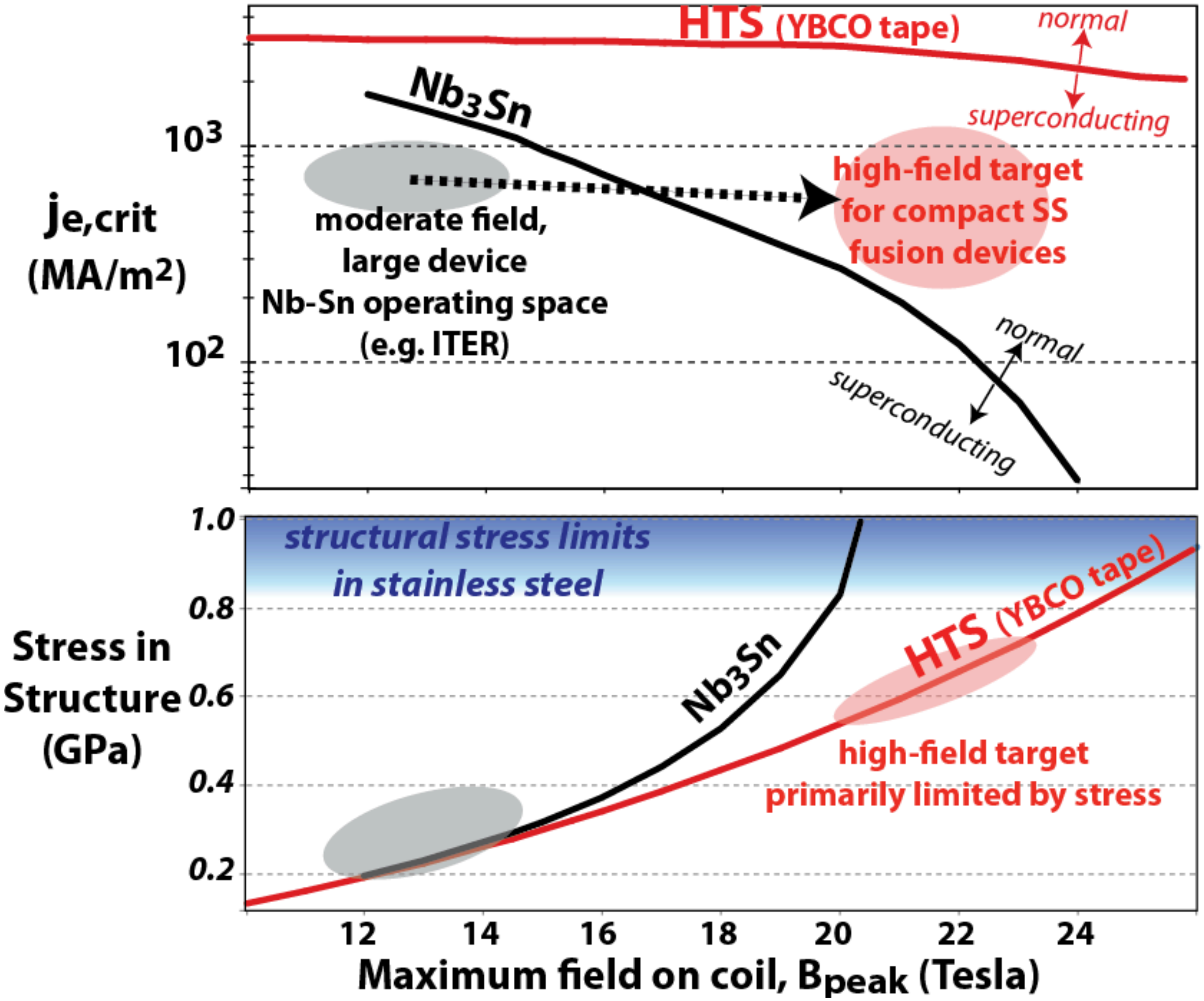



$$\frac{V_{FIRE}}{V_{ITER}} \sim \frac{1}{30}$$

# Superconductors evolved Astonishing critical current of new high-temperature superconductors (HTS) at $B_{peak}$>20 T provides possibility to ~double loss-free B field

- Sub-cooled tapes at ~20 K provides operational margin to superconductor[1].
- Limitation becomes the structural stress rather than superconductor.
- Tapes allow joints.



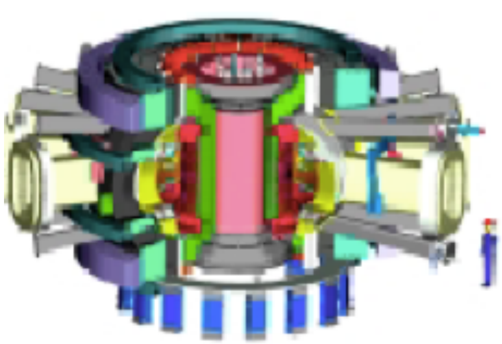


*Cost & schedule G-2 G-4*

# Known physics scaling + Superconductor $B_{peak}$ > 20 T → High-gain burning plasma compact size & Steady state!

**Gain** $nT\,\tau_E \sim \frac{\beta_N H}{q_*^2} R^{1.3} B^3$ — $\$ \propto R^3$ — $\frac{P_{fusion}}{S_{wall}} \sim \frac{\beta_N{}^2 \epsilon^2}{q_*^2} R B^4$ **Power density**

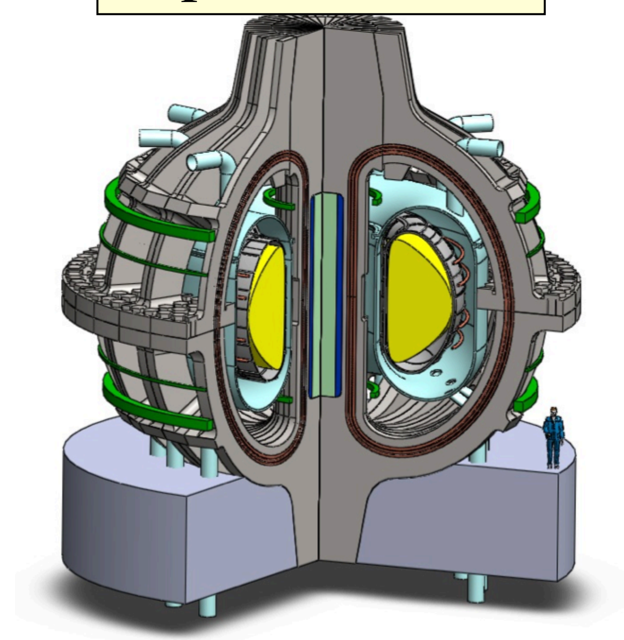
FIRE /w copper coils



*To scale*

| | FIRE[12] | ARC[10,14] |
|---|---|---|
| R (m) | 2.14 | 3.2 |
| $B_o$ (T) | 10 | 9.2 |
| $Q_p$ | >10 | >10 |
| Steady-state | No | Yes |
| Tritium breeding | No | Yes |
| $Q_{electric}$ | 0 | ~ 4 |

ARC /w HTS superconductor



*Cost & Schedule G-2 G-4 G-5 G-8*

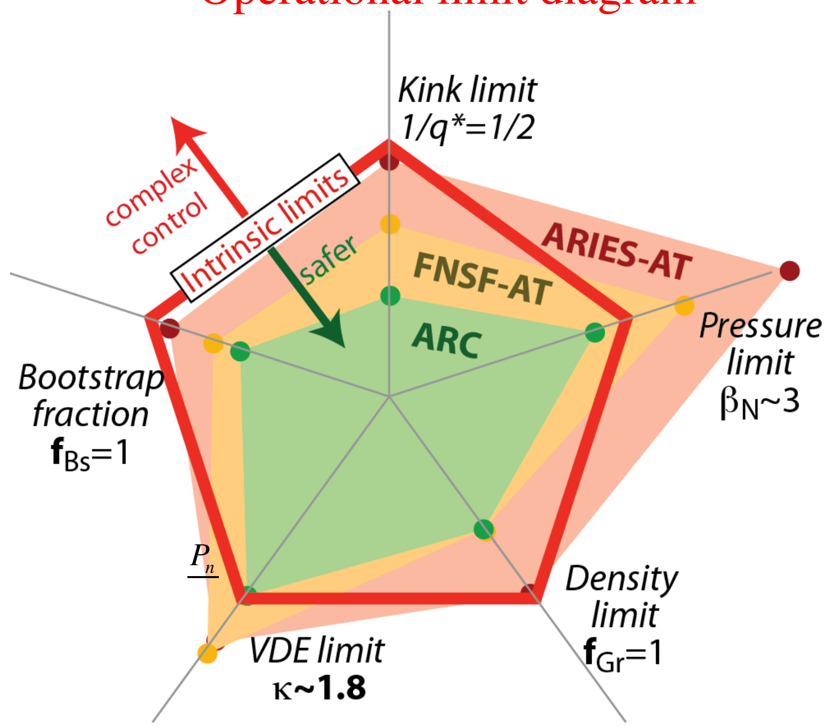
# $B_0$~10 T, compact SC HTS tokamak enables more realistic high-$Q_p$ steady-state option by providing margin to intrinsic disruption, control & operation limits

Capital & Operating Costs / Economics — Nuclear mission — Disruption damage relative to ITER

| Steady-state tokamak | $B_0$ (T) | R (m) | $P_{elec}$ (MW) | $Q_p$ | $\frac{Pn}{S}$ $\frac{MW}{m^2}$ | $\frac{W_{th}/S}{(W_{th}/S)_{ITER}}$ |
|---|---|---|---|---|---|---|
| ARIES-AT[6] *SC-NbSn* | 5.8 | 5.2 | +1000 | 44 | 3.3 | 2.5 |
| ARC[14] *SC-HTS* | 9.2 | 3.3 | + 230 | 14 | 2.2 | 1.2 |
| FNSF-AT[4,7] *Copper* | 5.5 | 2.7 | - 600 | 2.6 | 1.6 | 1 |

**Electrical cost[13] ~ 250-500 M$/FPY**

Operational limit diagram



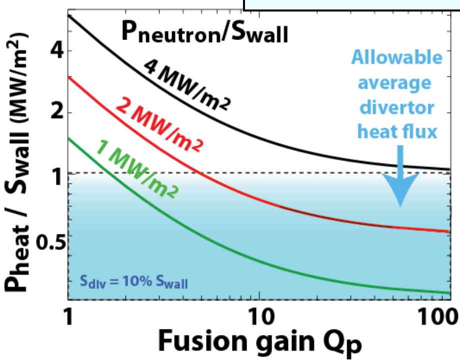

$$nT\ \tau_E \sim \frac{\beta_N H}{q_*^2} R^{1.3} B^3$$

# Heat exhaust critical to the viability of all FNSF/Pilot designs

## New edge physics favors small size + high gain → high B

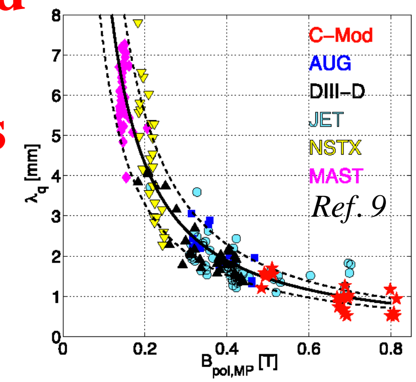
**Neutron mission**

$$P_{heat} \sim P_{neutron} \frac{\left(1+5/Q_p\right)}{4} \sim R^2$$




**Evolved edge physics**

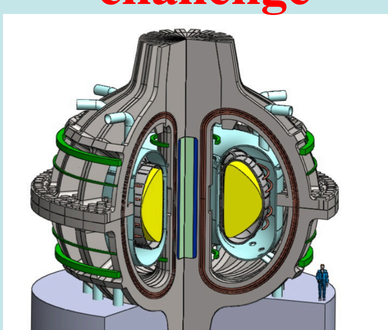
$$\lambda_q \sim \frac{1}{B_p}$$




$$q_{//} \sim \frac{P_{heat} B}{R}$$

$$q_{//} \sim R\,B\left(1+5/Q_p\right)$$

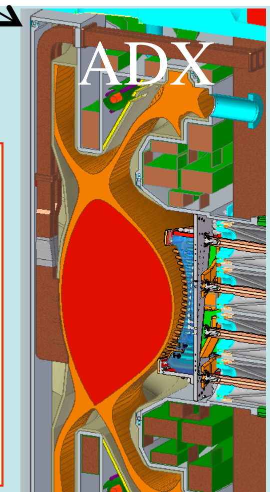
**FNSF design challenge**



$$nT\,\tau_E \sim \frac{\beta_N H}{q_{95}^2} R^{1.3} B^3$$

**Near-term Edge physics**

Innovative solutions at reactor-matched B, q//




*LaBombard*

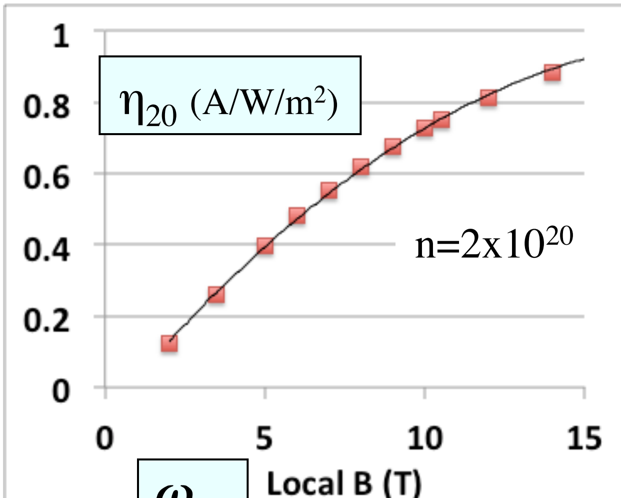
**US Leadership opportunity**

# Efficient RF current drive is synergistic with high-B & critical to developing robust steady-state in tokamaks

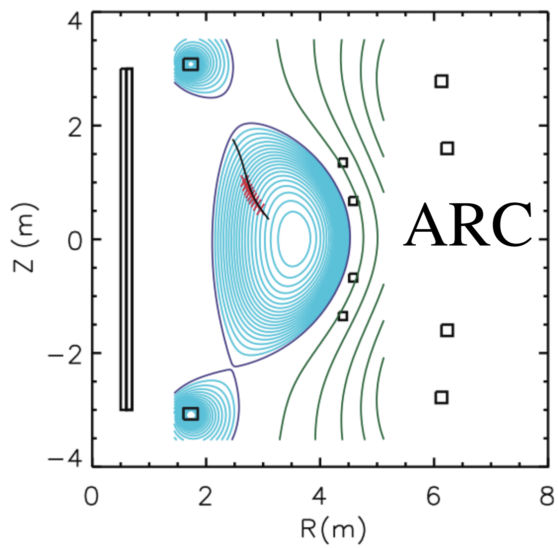
Higher LHCD efficiency at high field

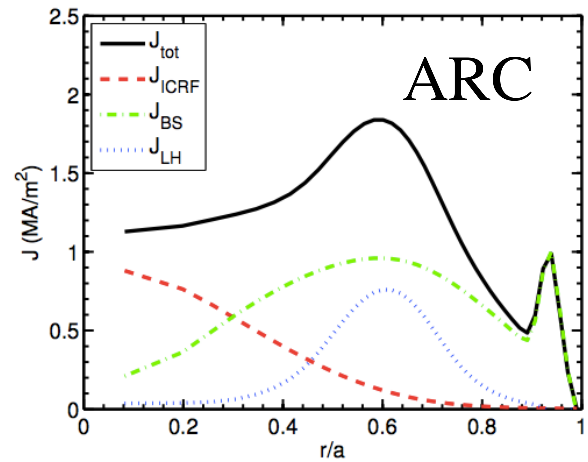
Quiescent PMI high-field-side RF launchers

Control current profile at small R, T~12 keV for optimized AT[13,14]




$\frac{\omega_{ce}}{\omega_{pe}}$ →




$I_{CD}/I \sim 37\%$ & $Q_p \sim 15$

- **Compels near-term research in high-field & inside launch RF.**

*R. Parker*

**US Leadership opportunity**

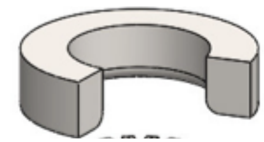
*G-8*
*G-10*
*G-13*
*G-15*

# FNSF mission favors demountable coils for modular replacement

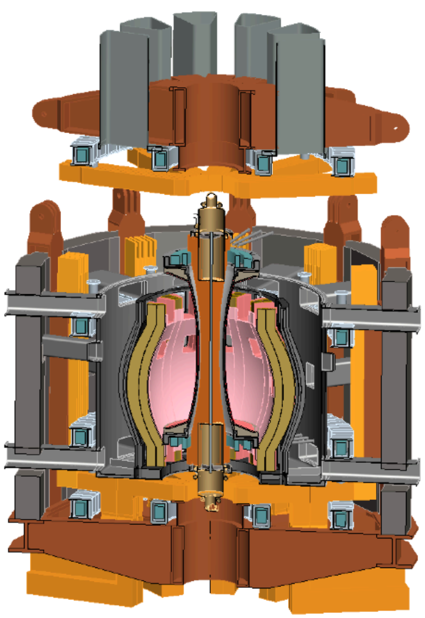
## Finite resistance HTS joints → minimal $P_{coil}$ → Pilot option

## US Leadership opportunity in configuration & maintainability

Conceptual FNSF designs

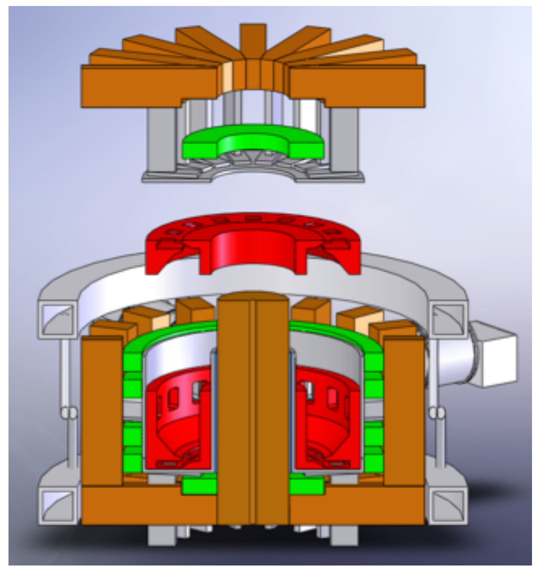


**R/a=1.7**



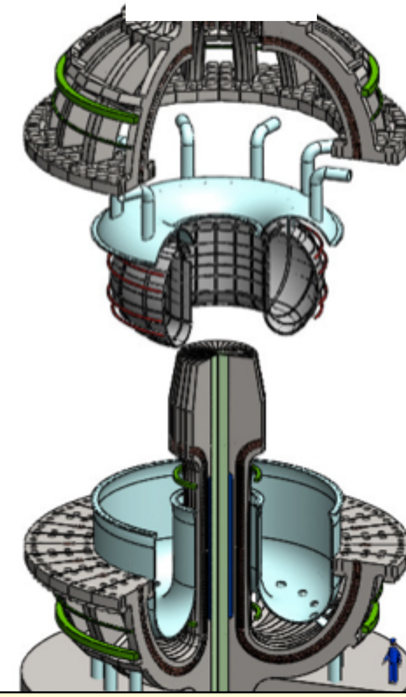
**Copper FNSF-ST**[8]
$P_{coil}$~400 MW

**R/a=3.5**



**Copper FNSF-AT**[7]
Coil $P_{coil}$~600 MW

**R/a=3**



**ARC**: Resistive joints /w HTS superconductors[11]
Coil $P_{coil}$~ 1 MW

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*G-9 Tame PMI & heat exhaust*

**Next 10 years**

**HTS magnet R&D**

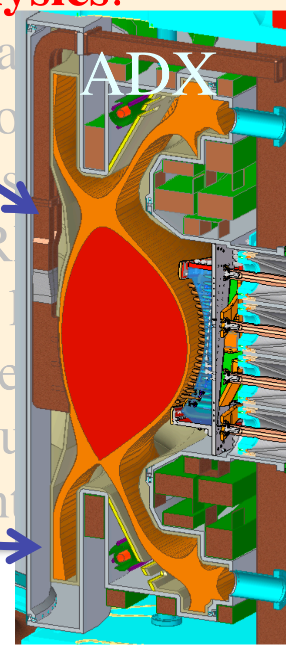
*Minervini*: HTS magnets

**High-B physics:**

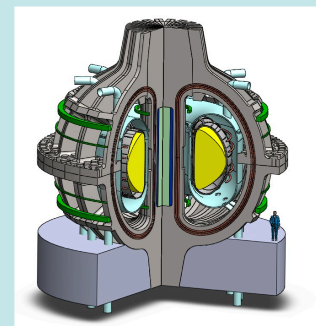
- High gain a
- to o
- & dis
- Effective R
  innovative
  steady-state
- High pressu
  cont

*Parker*
RF current drive

*LaBombard*
PMI & heat exhaust




HTS high $B_{peak}$> 20 T Superconductor coils



**Steady-state Compact FNSF/Pilot**

*G-10-15 Integrated fusion materials & components*

**HTS joints & Blanket R&D**

Demountable HTS coils & Modular replacement

# Backup materials

# References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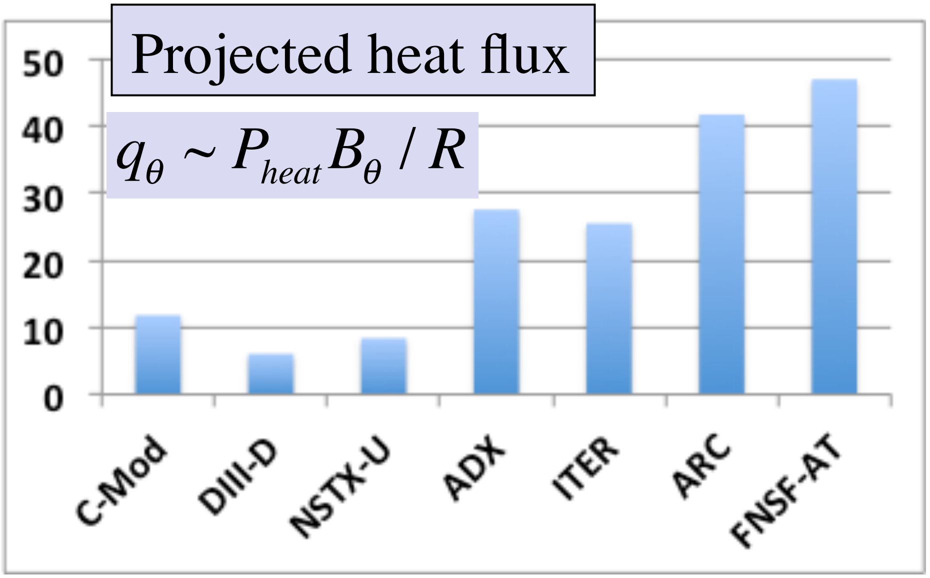
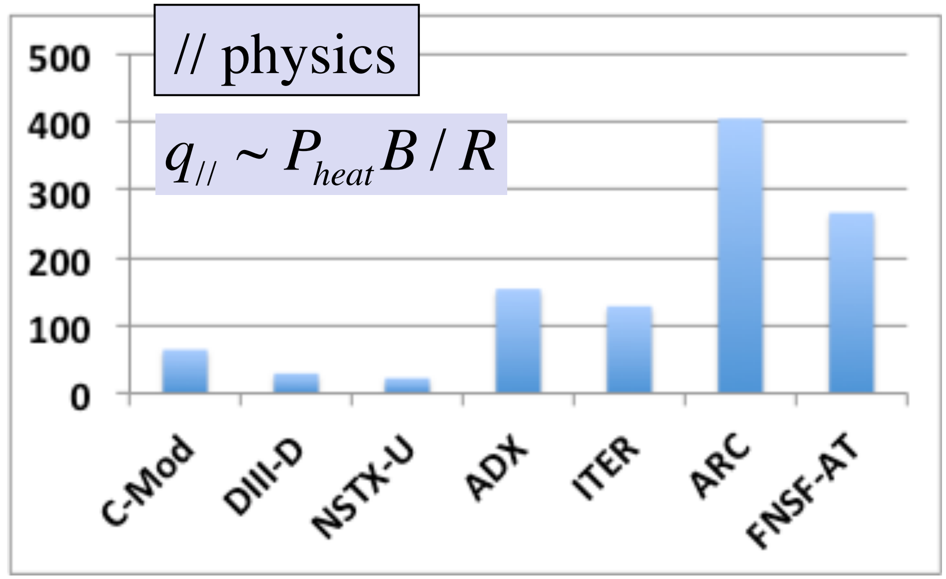
# National ADX and HTS magnet and ADX initiatives are aligned and timely to the OFES Burning Plasma Science mission

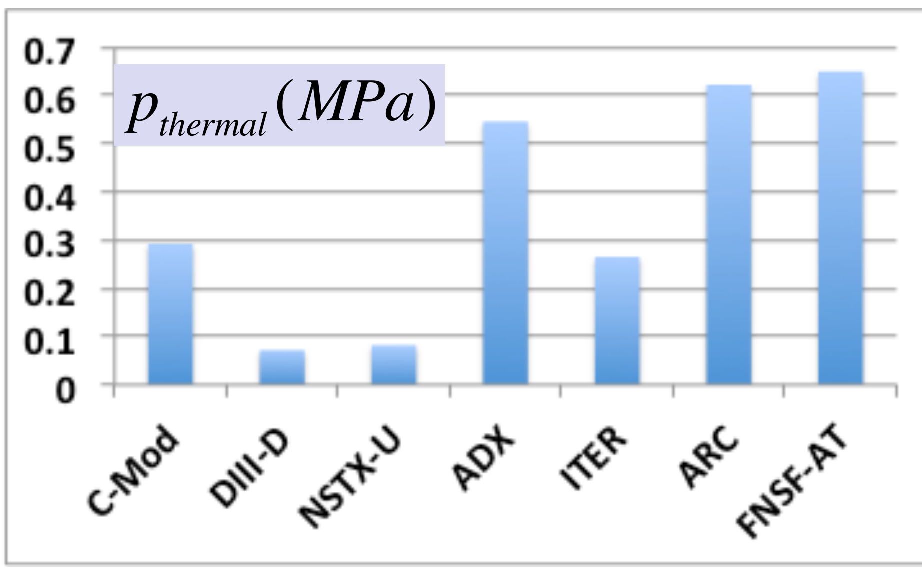
| **Foundations** | **Year 1-3** | **Year 4-7** | **Year 8-10** | **FNSF options** |
|---|---|---|---|---|
| Transport | | $H_{98}$ OK, no X-point MARFE | | Disruptivity vs. performance assessment |
| Stability | | | ELM-free stationary ped. | |
| Wave-particle | Design HFS launch: LHCD & ICRF | Install, assess PMI & coupling | High $\eta_{CD}$, j profile control | Valid RF model & launchers |
| PMI | Design divertors PMI diagnostics | Install divertors, q// vs. B physics | Integrated q// PMI solution @ high pressure | Heat exhaust/ PMI solutions Solid vs liquid |
| **Long Pulse** | | | | |
| Plasma sustainment | | CD efficiency f(B) on HFS | Disruption rates away from limits | Current control toolkit |
| B-field sustainment | Prototype HTS conductor & joints | Wound coils /w joints, HEP | B>20 T jointed coil demo | Cu vs. HTS Pilot? |
| Materials | Erosion resistance high-Z PFC | Study: modular replacement | High-T, high-Z, low $E_{ion}$ divertor | Modular replacement |

**~17 M$/y** | **~4 M$/y + demo coil**

# ADX provides a critically needed near-term, small-scale step into the ITER/FNSF heat exhaust & PMI parameter range



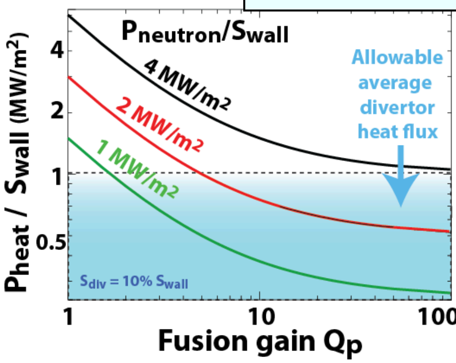

Atomic & PMI physics

# Heat exhaust critical to the viability of all FNSF/Pilot designs

## New edge physics favors small size + high gain → high field

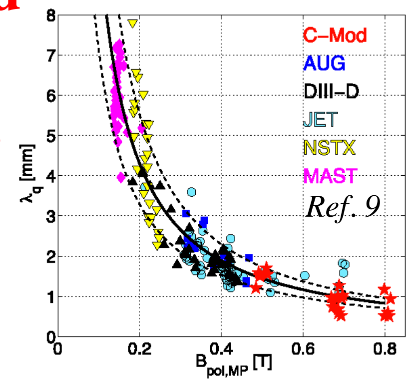
**Neutron mission**

$$P_{heat} \sim P_{neutron} \frac{\left(1+5/Q_p\right)}{4} \sim R^2$$




**Evolved edge physics**

$$\lambda_q \sim \frac{1}{B_p}$$



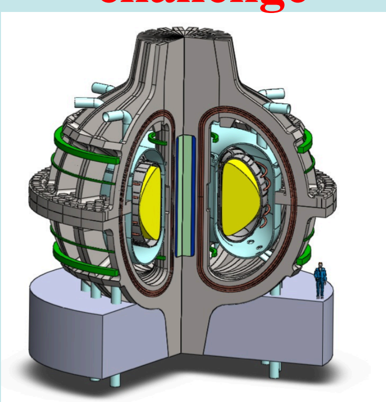

$$q_{//} \sim \frac{P_{heat} B}{R}$$

$$q_{//} \sim R\,B\left(1+5/Q_p\right)$$

$$nT\,\tau_E \sim \frac{\beta_N H}{q_{95}^2} R^{1.3} B^3$$

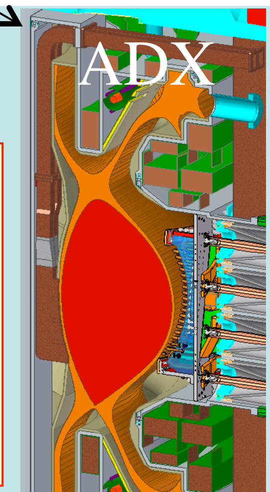
$$q_{//} \sim \frac{\left(1+5/Q_p\right)}{B^{1.3}}$$

**FNSF design challenge**



**Near-term Edge physics**

Innovative solutions at reactor-matched B, q//

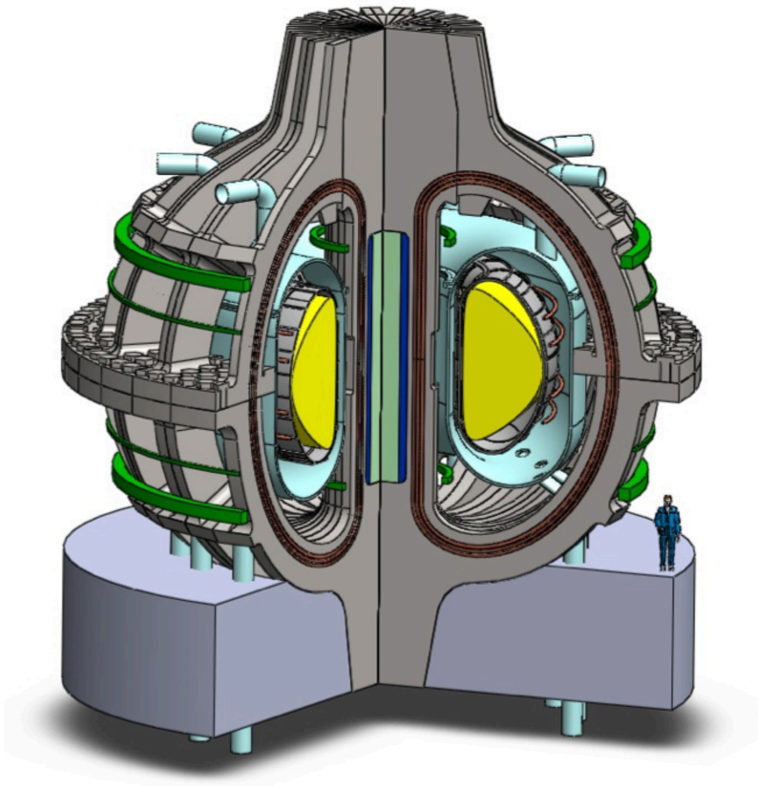



*LaBombard*

**US Leadership opportunity**

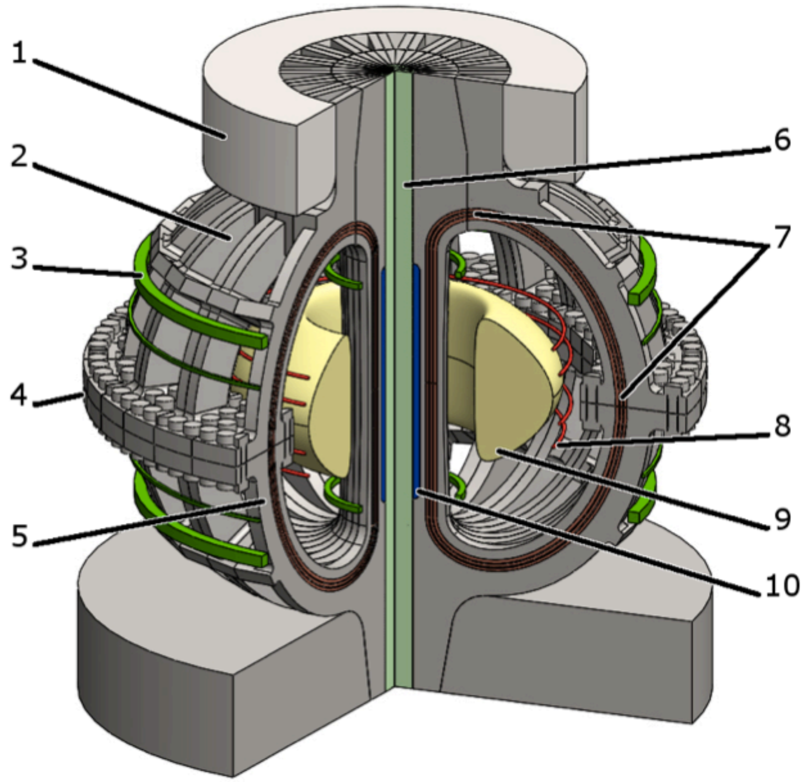
# ARC: 9 Tesla "JET", 250 MW net electricity
## Steady-state tokamak far from disruptive limits

| Nuclear | |
|---|---|
| Fusion Power | 525 MW |
| Blanket & Depth | Liquid FLiBe > 0.8 m |
| $\eta_{thermal}$ / $T_{blanket}$ | ~ 0.5 / ~ 900 K |
| Tritium breeding ratio | 1.11 |
| **Plasma core** | |
| R / a / $\kappa$ | 3.3 m / 1.1 m / 1.8 |
| $B_0$ | 9.2 T |
| $q_{95}$ / $q_{min}$ | 7.2 / ~ 3 |
| $\beta_N$ / $H_{89}$ | 2.59 / 2.7 |
| $G_{89}$ : $\beta_N$ $H_{98}$ / $q_{95}^2$ | ~ 0.15 |
| Greenwald fraction | ~0.6 |
| **RF current sustainment** | |
| CD Efficiency | > 0.4 $10^{20}$ A/W/m$^2$ |
| Bootstrap fraction | 63% |



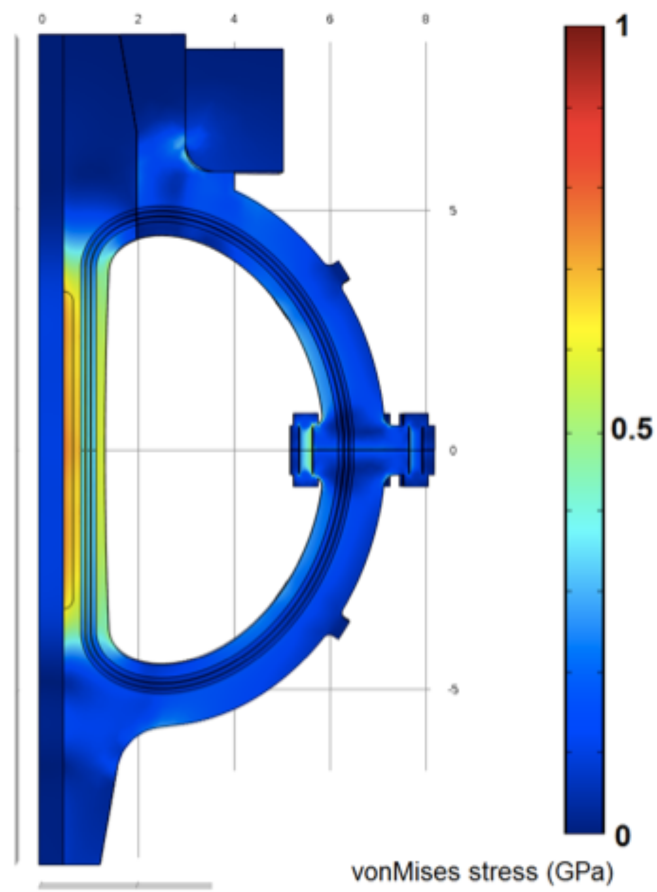
Margin to limits!
Scenario already achieved
In present tokamaks

# ARC exploits two features of new SC: $B_{coil,max}$~23 T + Tapes used for joints

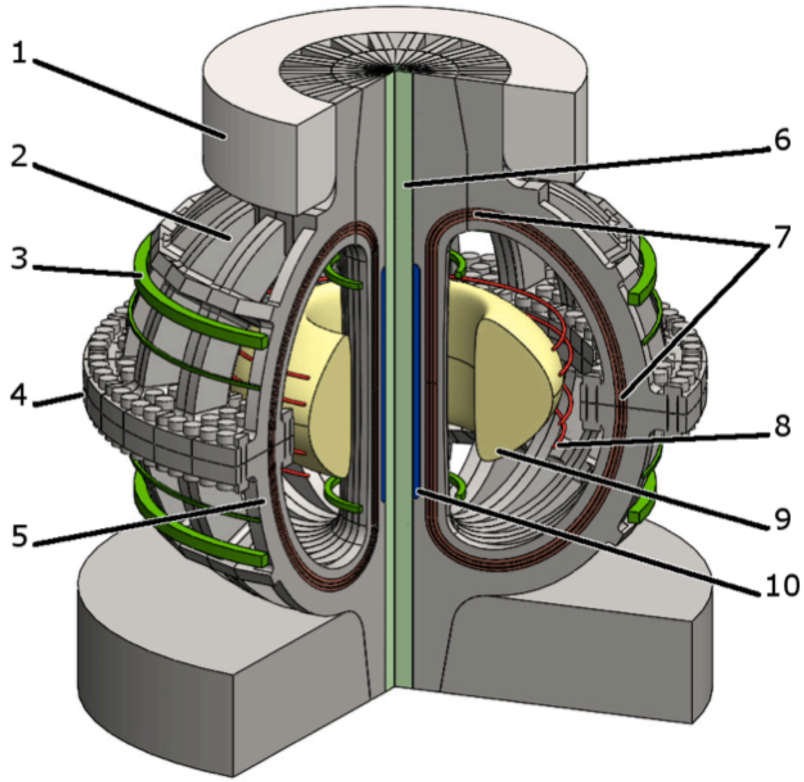



1. Support ring, 2. Top TF leg
4. Mechanical joint 6. Epoxy
enforcement 7. Electrical joint

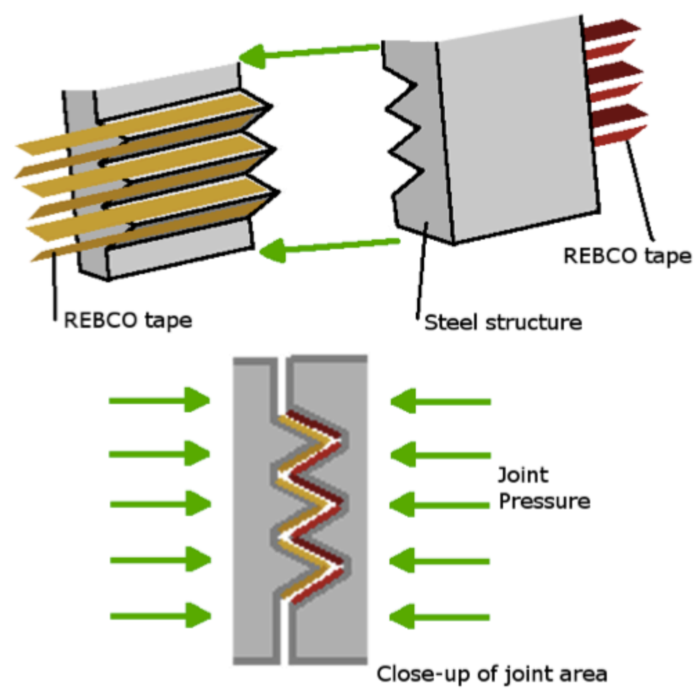
Peak stress ~ 0.75 GPa
~30% margin for 316SS LN



# ARC exploits two features of new SC: $B_{coil,max}$~23 T + Tapes used for joints

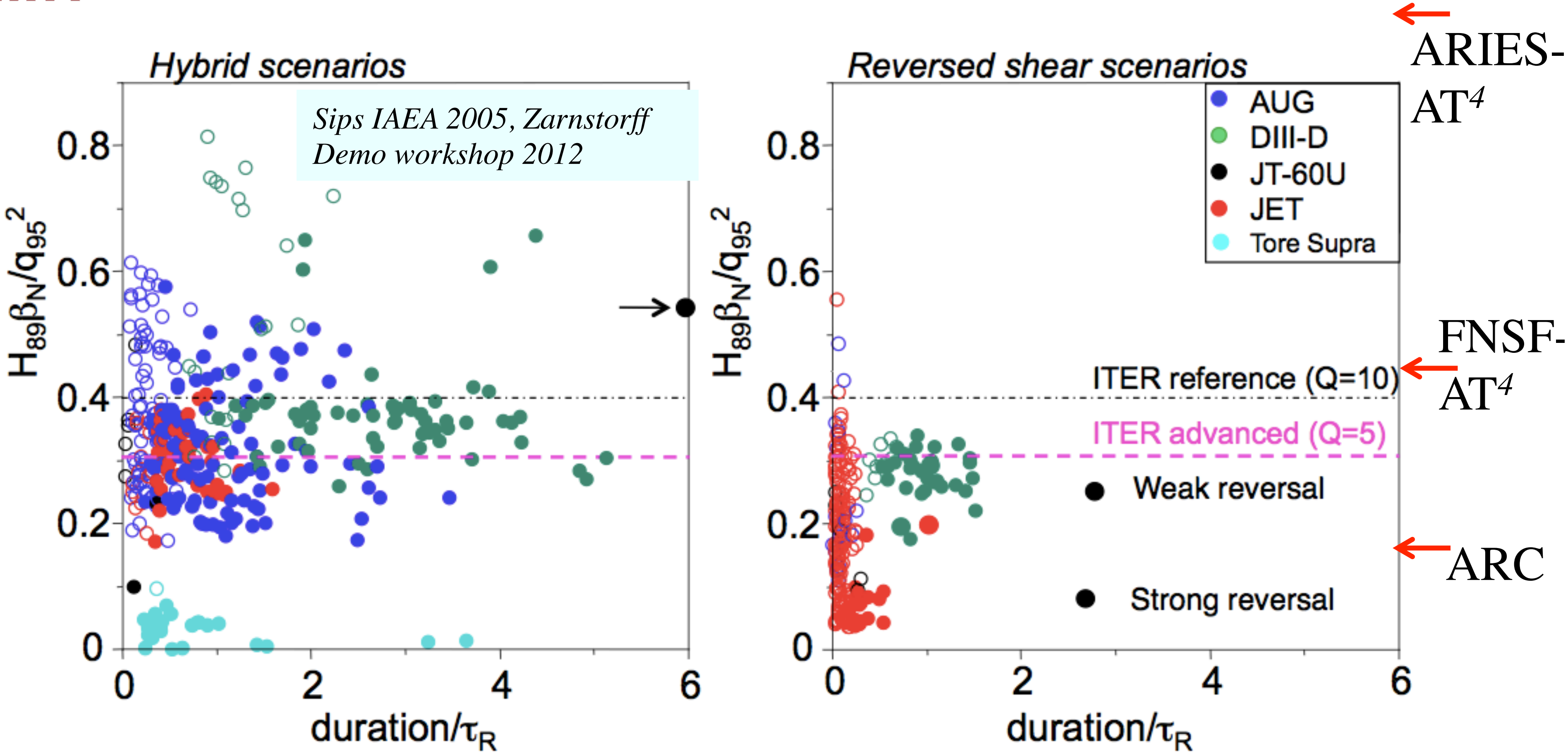



"Comb-style" TF resistive joints are expected to lead to ~ 1 $MW_{electric}$ dissipation




1. Support ring, 2. Top TF leg 4. Mechanical joint 6. Epoxy enforcement 7. Electrical joint

# HTS high-field allows FNSF/Pilot fusion & nuclear requirements with a modest integrated physics gain $G_{89}$ already achieved in AT plasmas




$$nT\,\tau_E \sim \frac{\beta_N H}{q_{95}^2} R^{1.3} B^3$$

*Cost & Schedule G-2 G-4 G-5 G-8*

# B~10 T, SC compact tokamak provides realistic high-gain steady-state option far from intrinsic operating and disruptive limits

Capital & Operating Costs — Nuclear & Electricity — Power exhaust — Steady-state & Disruptions

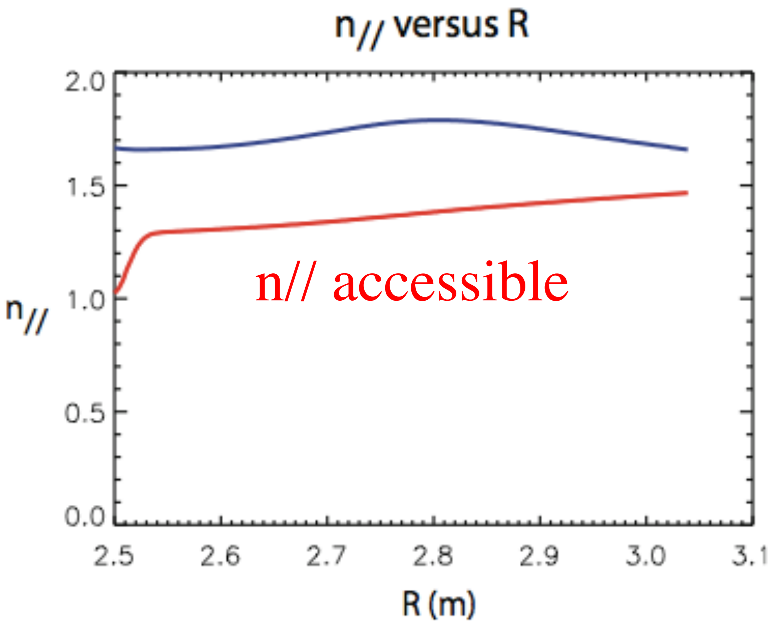
| Steady-state tokamak | B (T) | R (m) | $P_{elec}$ (MW) | $P_f$ (MW) | $P_n$ / S ($MWm^{-2}$) | $Q_p$ | $P_{heat}$ / $4P_n$ | $f_{BS}$ | $\kappa$ | $\beta_N$ | $q_*$ | $f_{Gr}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ARC *SC-HTS* | 9.2 | 3.3 | 230 | 525 | 2.2 | 14 | 1.3 | 0.63 | 1.8 | 2.6 | 4.8 | 0.65 |
| ARIES -AT *SC-NbSn* | 5.8 | 5.2 | 1000 | 1760 | 3.3 | 44 | 1.1 | 0.92 | 2.2 | 5.4 | 2.1 | 0.95 |
| FNSF-AT *Copper* | 5.5 | 2.7 | -600 | 230 | 1.6 | 2.6 | 2.9 | 0.74 | 2.3 | 3.7 | 2.8 | 0.63 |

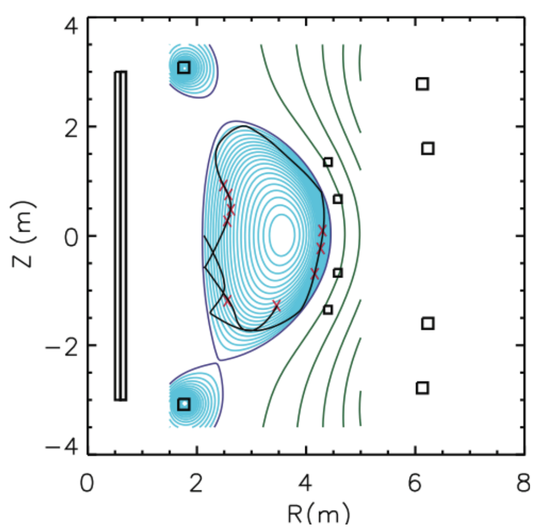
Electrical cost ~ 500 M$/FPY

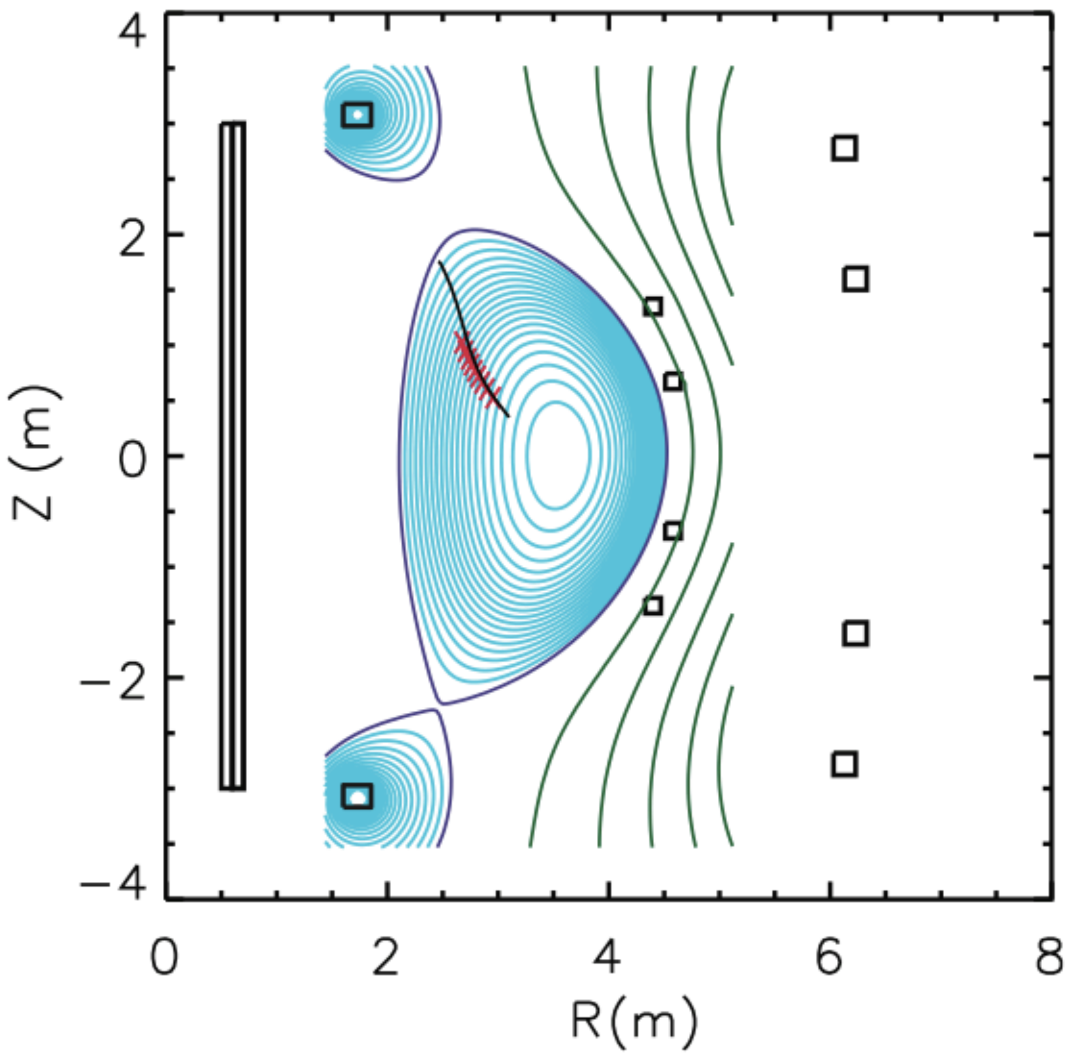
$Q_p < 5$ → excess relative heat loading per neutron

Violation or within 10% of intrinsic limits:
$f_{bs}$=1, $\kappa$ < 5.4/A, no-wall $\beta_N$, kink $q_*$~2, density limit $f_{Gr}$ =1

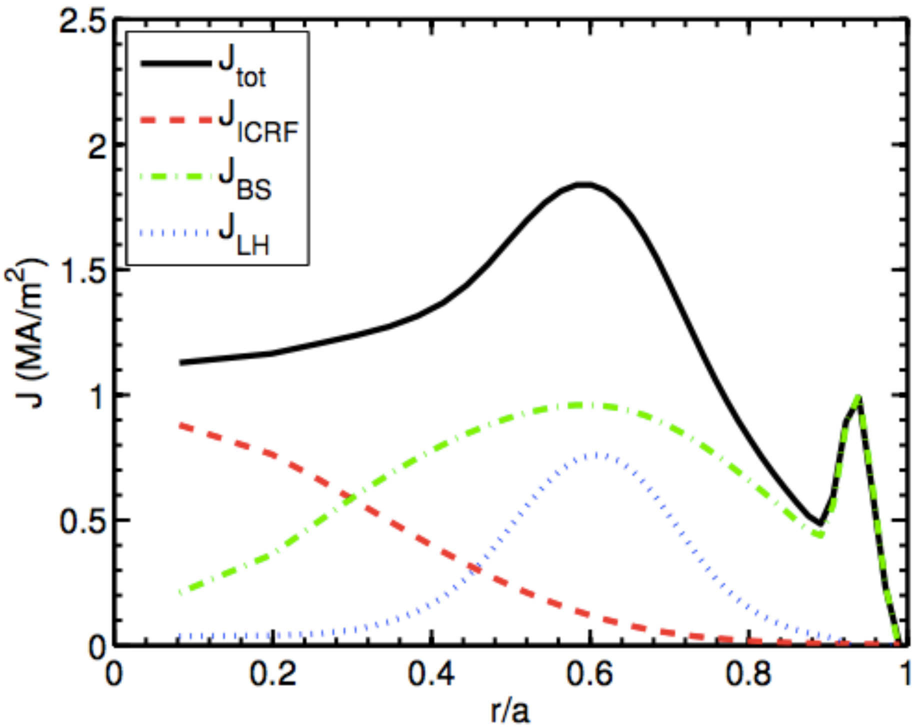
# ACCOME has optimized large advantages of HFS-LHCD + poloidal launch location near X-point

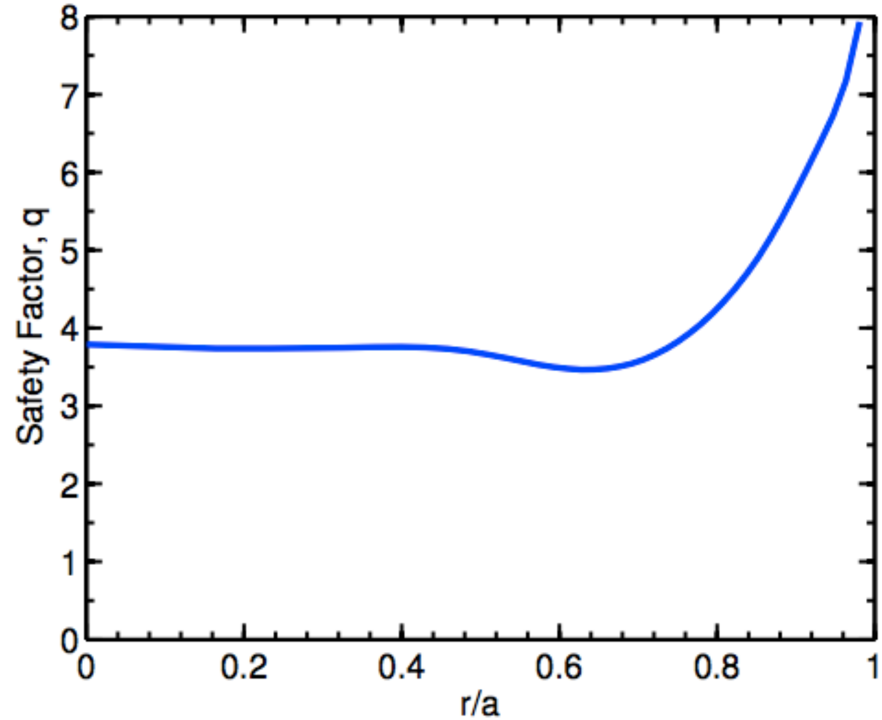


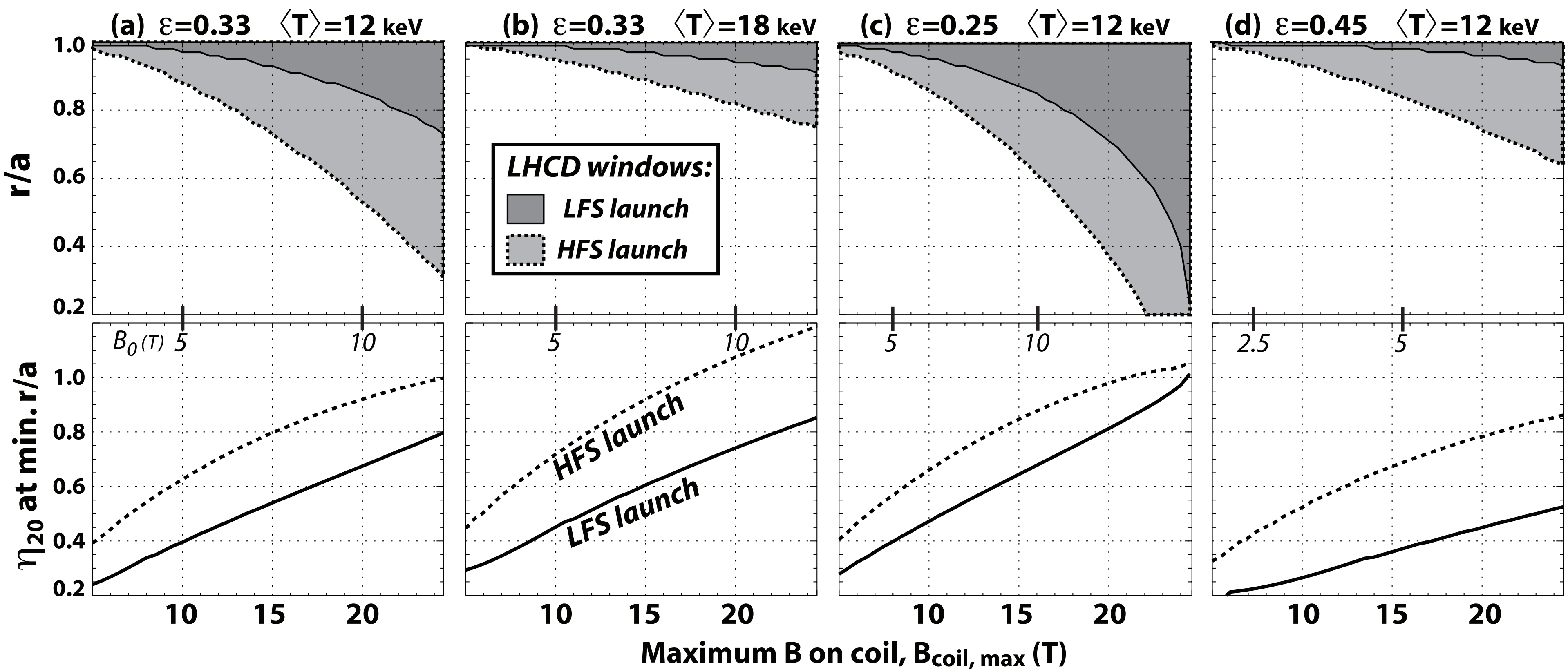



# Optimized CD efficiency leads to substantial control of AT current profile below no-wall $\beta_N$ limit



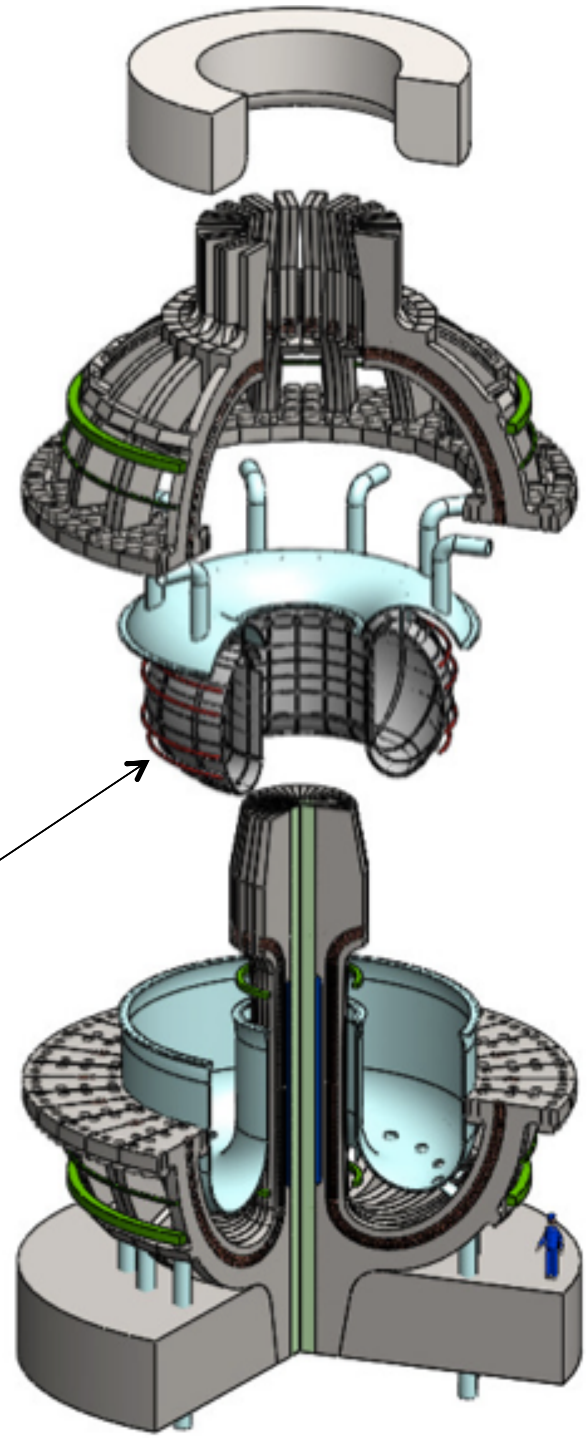
# HFS-LHCD+ high B: Excellent penetration at Lawson criterion minimum <T>~12 keV, ~ doubled CD efficiency to standard scenarios




$p_{th}$~ 0.8 MPa

# Small scale + demounting has surprising synergistic benefits: Reduced volume → reduce cool/heat time to ~2-3 days of structure → Modular maintenance

A single, module is only replaced unit (vacuum vessel + PFCs + Built-in test stations integrated off-site)



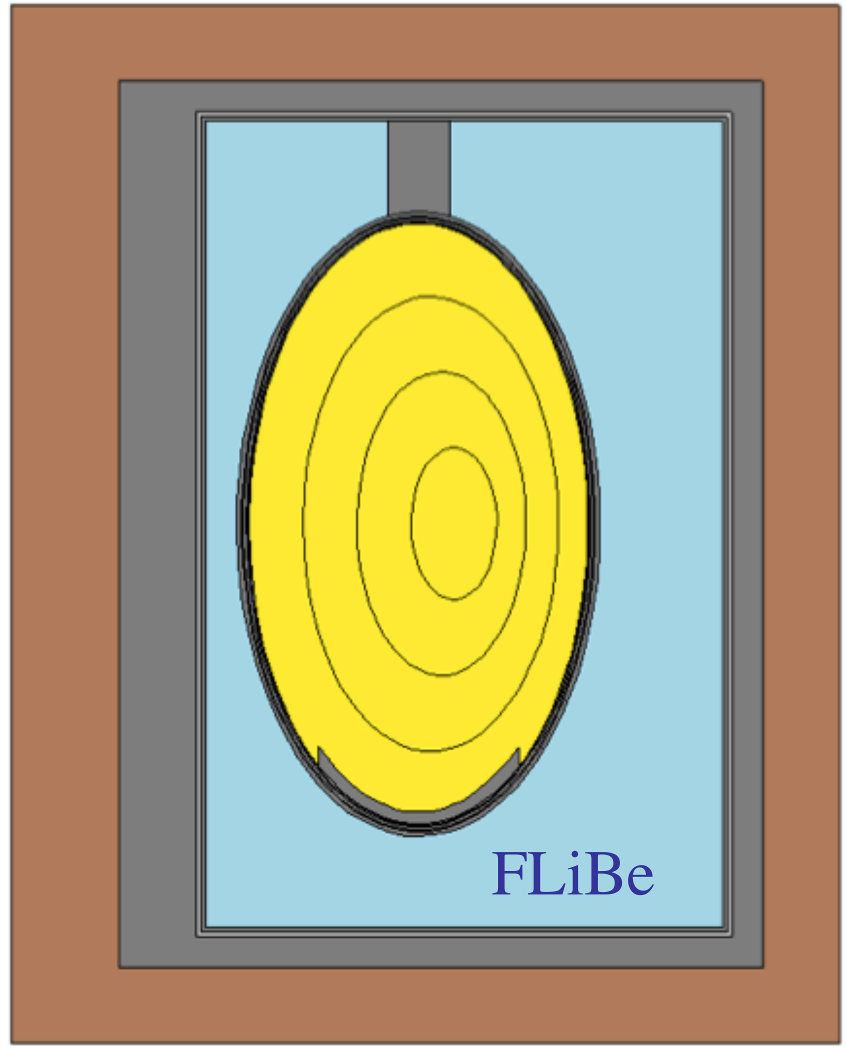
# Small scale → Modular VV → Low-risk immersion liquid blanket (FLiBe) for FNSF

| Property | FLiBe | Water |
|---|---|---|
| Melting Point (K) | 732 | 273 |
| Boiling Point (K) | 1703 | 373 |
| Density (kg/m$^3$) | 1940 | 1000 |
| Specific Heat (kJ/kg/K) | 2.4 | 4.2 |
| Thermal Conductivity (W/m/K) | 1 | 0.58 |
| Viscosity (mPa-s) | 6 | 1 |

Tritium Breeding Ratio: 1.14

Eliminate blanket solid waste

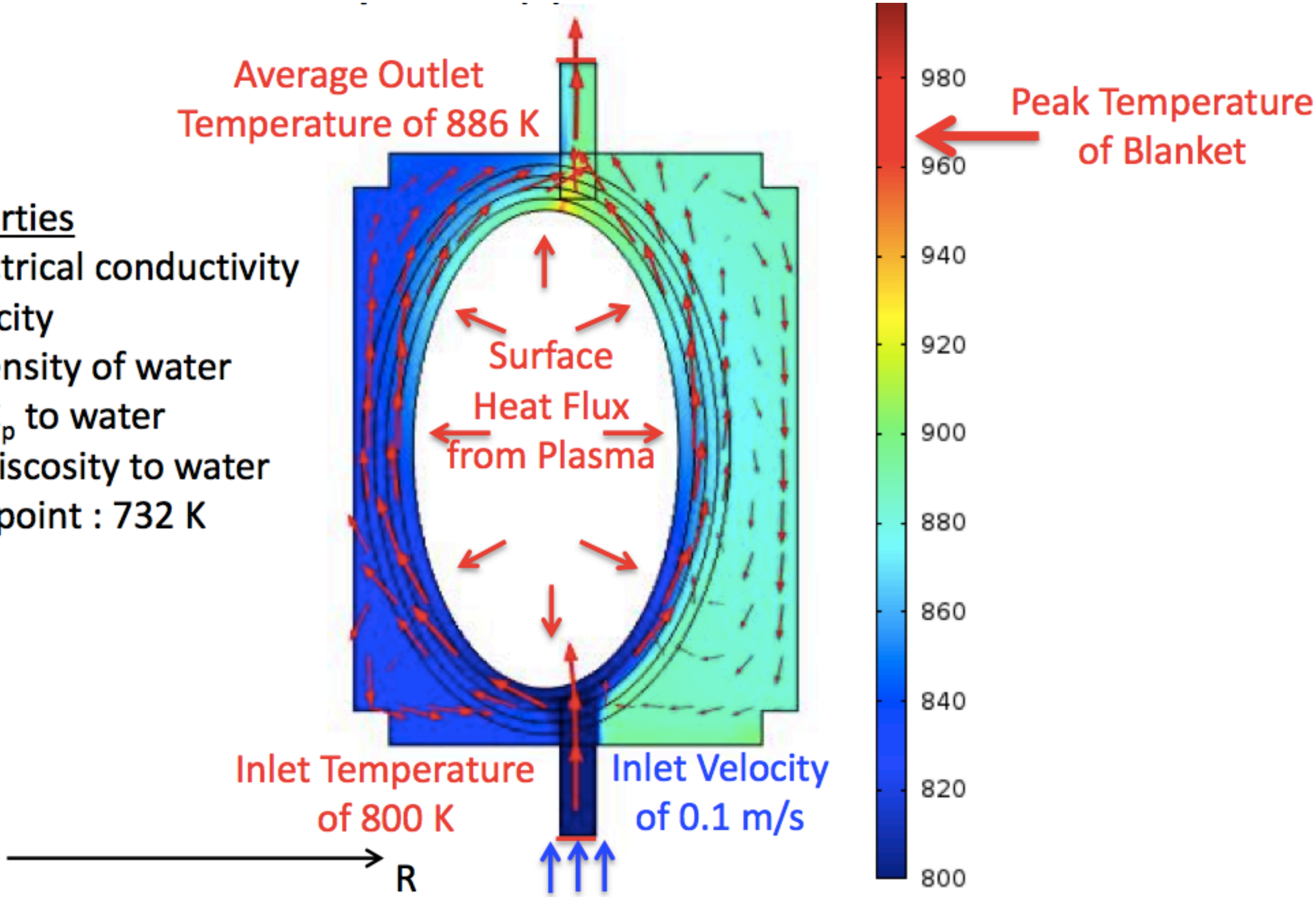
No “blanket” DPA limit



# FLiBe provides outstanding heat removal capabilities at high T → thermal efficiency

<u>FLiBe Properties</u>

- Low electrical conductivity
- Low toxicity
- Twice density of water
- Similar $C_p$ to water
- Similar viscosity to water
- Melting point : 732 K



# Lessons from ARC..

- **Is NOT that ARC is the ultimate, best fusion reactor design..**

- **Or that every detail of ARC is settled and easily done…**

- **ARC and it innovations was the result of ~dozen MIT students working for a semester+ , showing that it was feasible to produce high gain, SS reactor at JET size**

- **The real lesson of ARC is that when you change the most fundamental aspects of your MAGNETIC fusion device, i.e. scale, B strength and coil configuration, you also fundamentally change the design options and solutions open to you…**