Prospects for a next-step ST

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October 24, 2009

Comprehensive assessment of ST issues, gaps, needs has been performed within U.S. during last two years

- FESAC Toroidal Alternates Panel (2008)
- OFES Research Needs Workshop (ReNeW) (2009)
- Ongoing: ST community, PPPL strategic planning

FESAC Toroidal Alternates Panel (TAP) recently prioritized issues and gaps for the Spherical Torus (ST) for the ITER era

ST ITER-era goal: ***"Establish the ST knowledge base to be ready to construct a low aspect-ratio fusion component testing facility …. to inform the design of a demonstration fusion power plant"***

"Tier 1" issues and key questions from TAP, and NSTX goals:

1. **Startup and Ramp-Up:** Is it possible to start-up and ramp-up the plasma current to multi-MA levels using non-inductive current drive w/ minimal or no central solenoid?
   – NSTX goal: demonstrate non-inductive ramp-up and sustainment

2. **First-Wall Heat Flux:** What strategies can be employed for handling normal and off normal heat flux consistent with core and scrape-off-layer operating conditions?
   – NSTX goal: assess high flux expansion, detached divertors, liquid metals

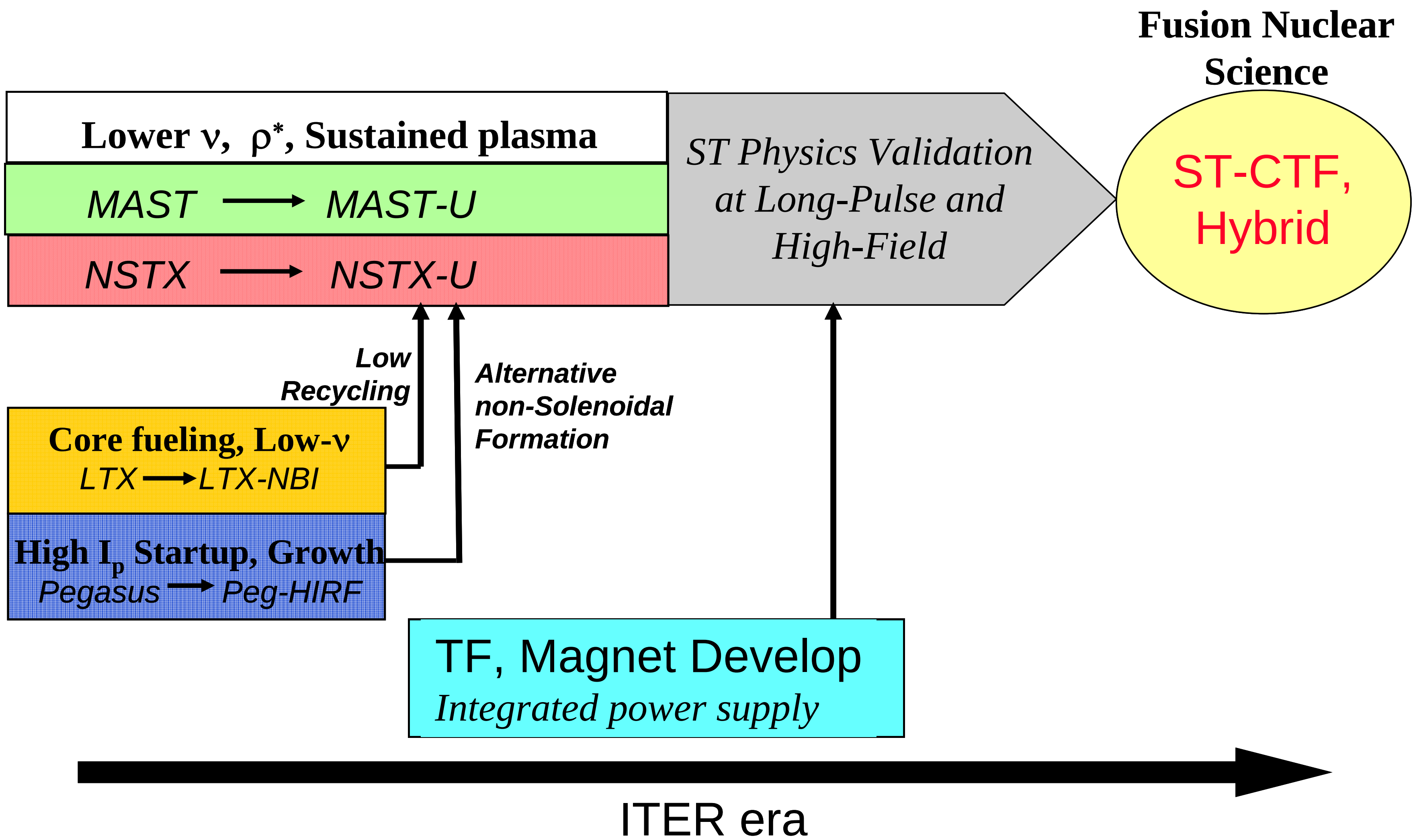
3. **Electron Transport:** What governs electron transport at low-A & low collisionality?
   – NSTX goal: determine modes responsible for electron turbulent transport and assess the importance of electromagnetic (high β) and collisional effects

4. **Magnets:** Can we develop reliable center-post magnets and current feeds to operate reliably under substantial fluence of fusion neutrons?
   – NSTX goal: develop and utilize higher performance toroidal field magnet

ReNeW ST Thrust 16 Identified 7 actions for ST research:

1. Develop MA-level plasma current formation and ramp-up
2. Advance innovative magnetic geometries, first wall solutions (liquid metals)
3. Understand ST confinement/stability at fusion-relevant parameters
4. Develop stability control techniques for long-pulse disruption-free operation
5. Employ energetic particle beams, plasma waves, particle control, and core fueling techniques to maintain the current, control plasma profiles
6. Develop normally-conducting radiation-tolerant magnets for ST applications
7. **Extend ST performance to near-burning-plasma conditions**

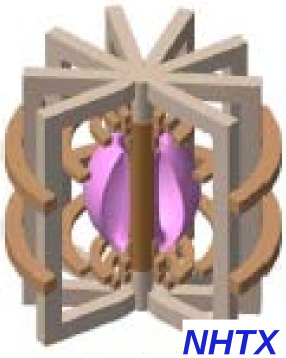
ST community formulated preliminary development path timeline during ReNeW



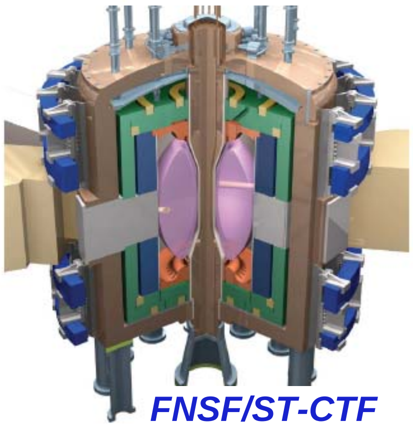
- **Much discussion revolved around appropriately colored "grey" box**
- **Near-term ST community goal is to better define next-step options**

ST facilities proposed to follow NSTX/NSTX-U emphasize preparation for fusion Demo

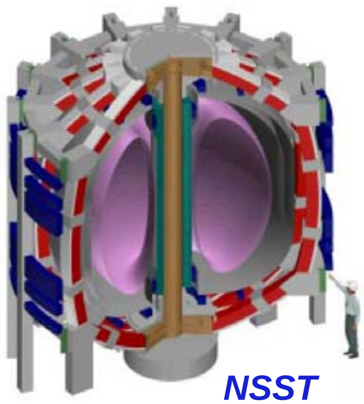
- ST Plasma Material Interface Facility (ST-PMIF)
  - Develop PMI solutions for FNSF/Demo (low and high-A)
  - Advance start-up, confinement, sustainment for ST
  - High P_{heat}/S ~1MW/m^2, high T_{wall}, τ_{pulse} ~ 10^3s



- Fusion Nuclear Science Facility ST (FNST)
  - Develop/test nuclear components for Demo
  - Sustain $W_{neutron}$ ~ 0.2-0.4→1-2MW/m^2, τ_{pulse} = 10^3 →10^6s

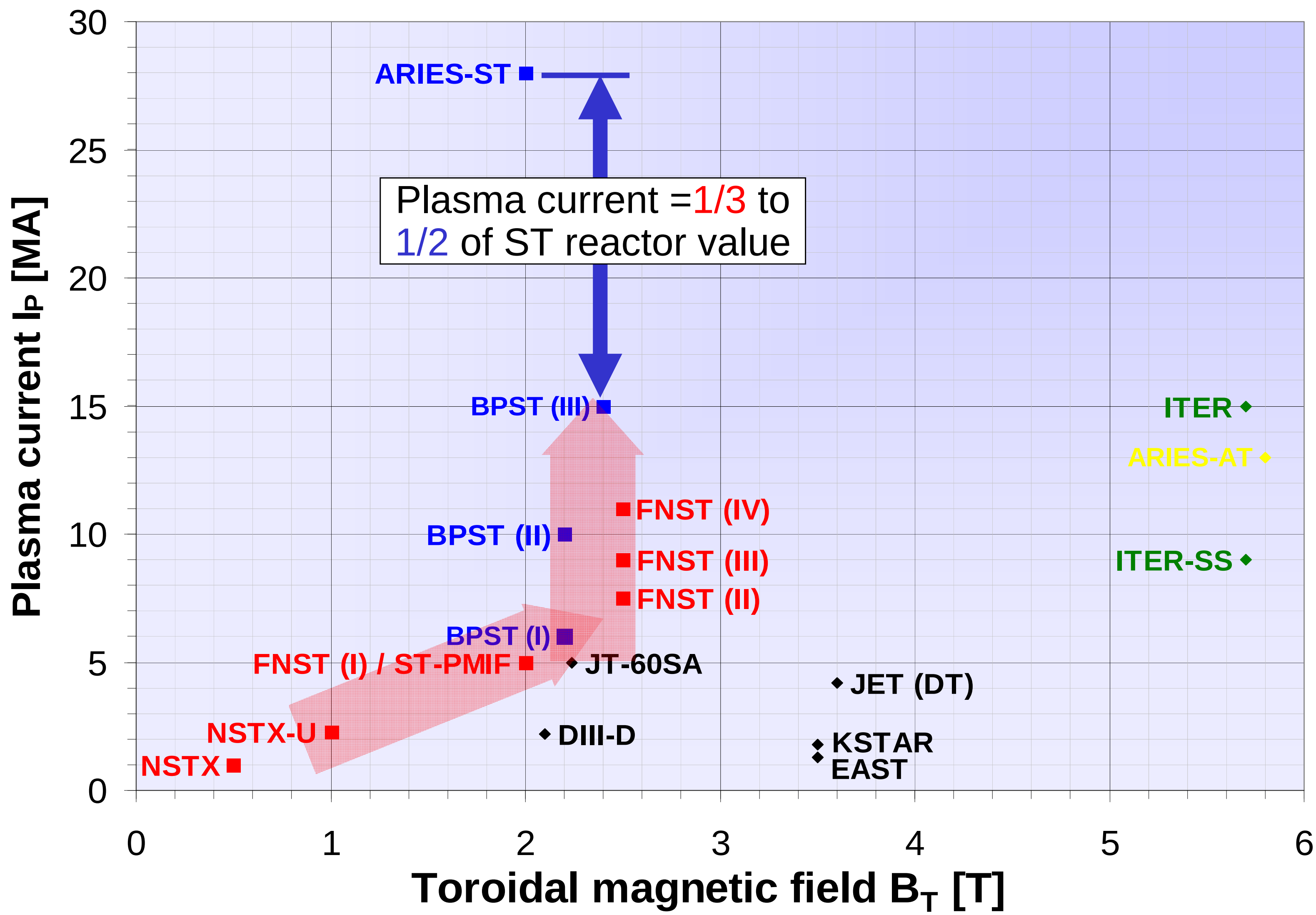


- Burning Plasma ST (BPST)
  - Burning plasma science for ST-Demo, high $W_{neutron}$ FNST
  - Advance start-up, confinement, PMI for FNST/ST-Demo
  - High β_T=20-40%, high v_{fast}/v_{Alfven}, τ_{pulse}=10^2-10^3s → ?



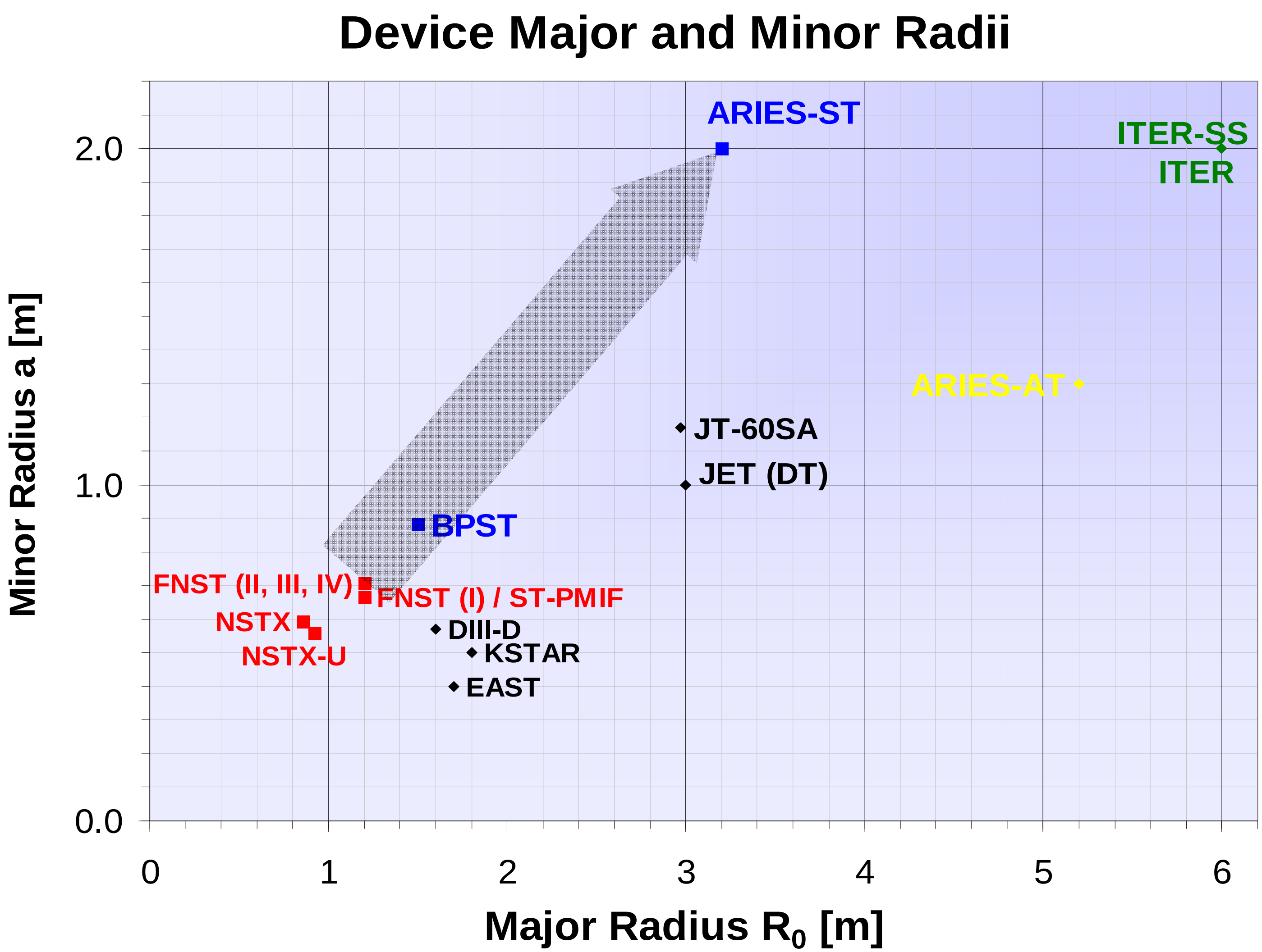
Next STs progress from plasma current I_P~4-6MA up to 10-15MA at toroidal field B_T = 2-3T

Device Field and Current

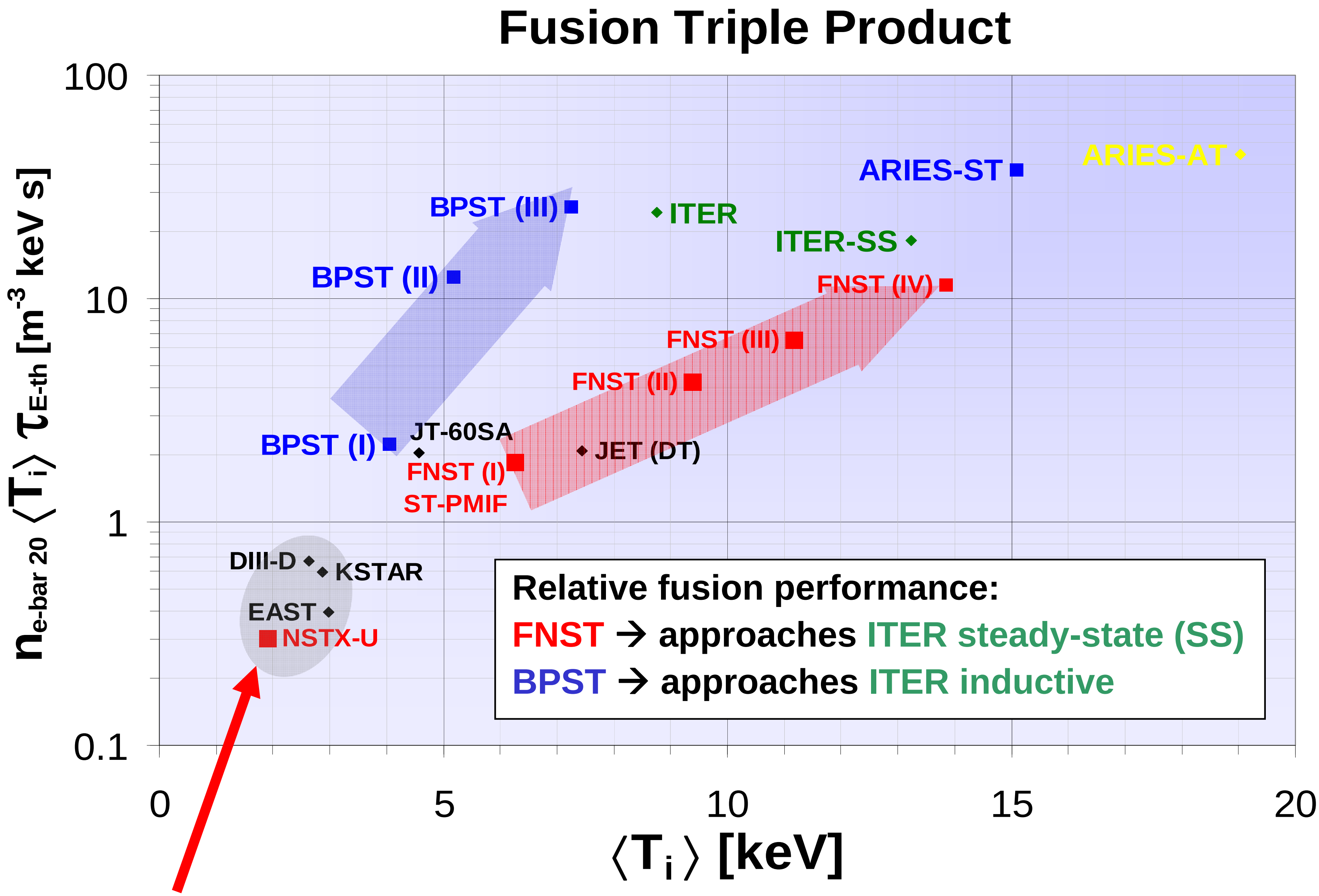


Next STs remain modest in size: $R_0 \leq 1.5m$, a < 1m

- FNST/BPST would be ~1/3 to 1/2 size scale of ST reactor
  - Similar size extrapolation from JET/JT-60SA to ITER

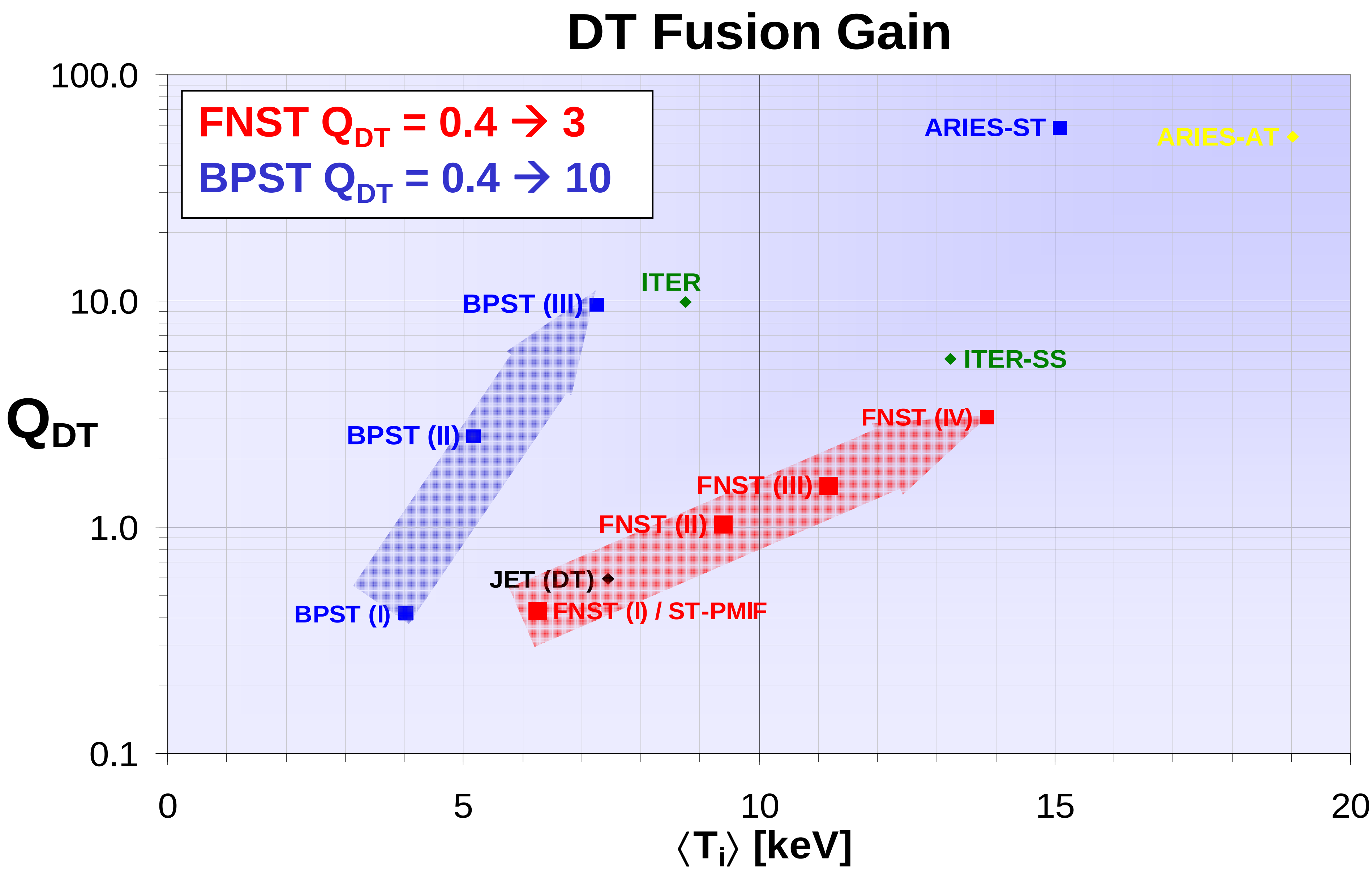


Next major ST facilities target baseline fusion performance at or above JET/JT60-SA levels



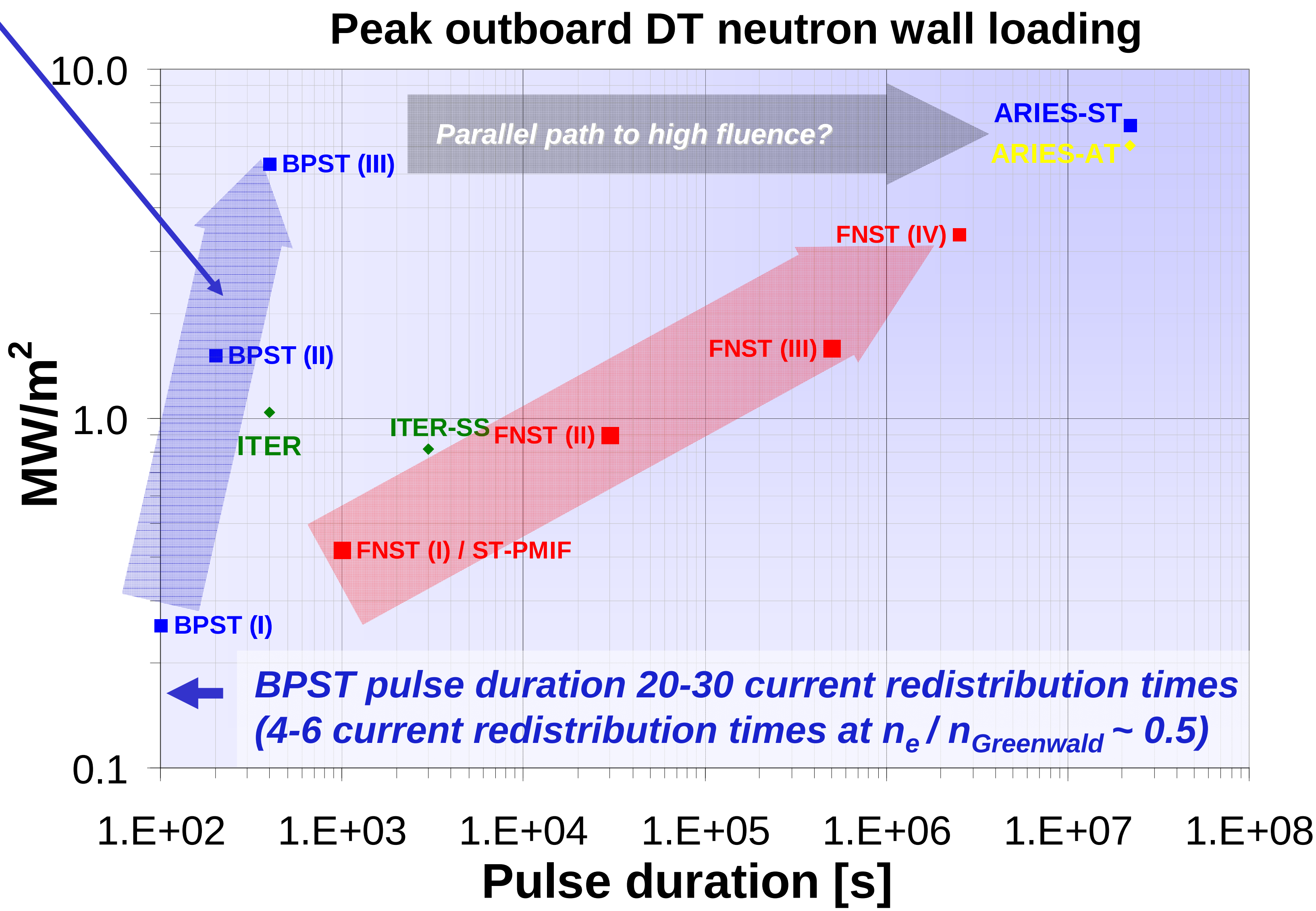
NSTX-U will increase ST fusion performance 10-fold to near EAST/KSTAR/DIII-D

Next major DT ST facilities extend fusion gain from JET levels toward ITER levels



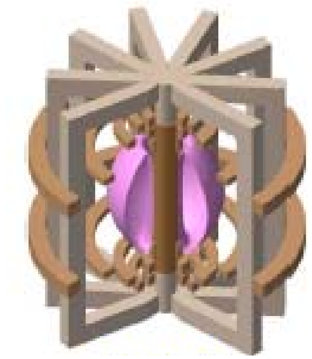
FNST progressively accesses wall loading and pulse-durations approaching Demo values

- **BPST would access ITER → Demo wall loading for ITER-level pulse durations**

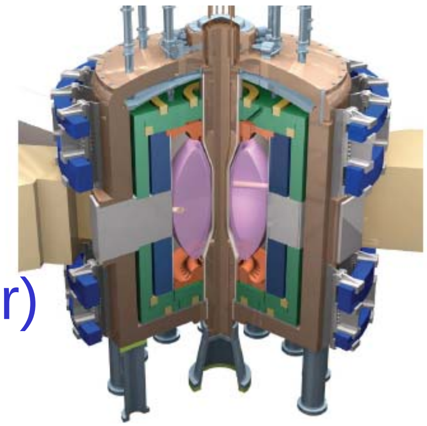


Potential Risks

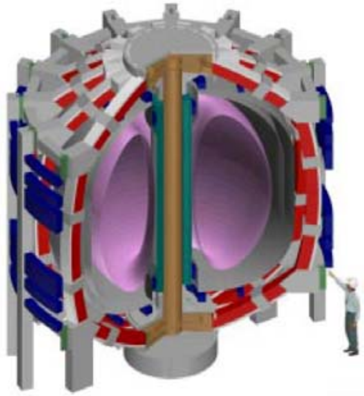
- ST Plasma Material Interface Facility (ST-PMIF)
  - Unclear what parameters/criteria to use for designing and operating "scale-model" of FNSF/Demo divertor
    - Unclear matching P/R and P/S of Demo is sufficient
    - What SOL/divertor physics is most important? role of turbulence?



- Fusion Nuclear Science Facility ST (FNST)
  - Inadequate knowledge-base for ~10MA start-up/ramp-up
  - No high-power/long-pulse power/particle exhaust solution
  - Confinement understanding inadequate (impacts size, power)
  - High-current radiation-tolerant magnets undeveloped



- Burning Plasma ST (BPST)
  - Confinement understanding inadequate (impacts size, power)
  - High-power power/particle exhaust solutions not mature
  - Advanced performance for high Q_{DT} inaccessible
  - Limited auxiliary current-drive options



Prospects for start-up/ramp-up and PMI solutions

- Start-up and ramp-up
  - Pegasus, NSTX, DIII-D have demonstrated ~150-200kA non-OH start-up
  - Aim to achieve ≥ 0.5MA start-up in NSTX-U → project to ≥ 1MA in FNST
  - **Need non-inductive ramp-up from ~1MA to ~10MA in FNST**
  - NSTX-U will provide first (critical) test of NBI ramp-up in ST
  - If ramp-up behaves as predicted (or better), could take "leap" to FNST
    - This is high-risk approach given present knowledge base/environment
    - Substantial predictive capability for thermal, fast-ion confinement needed
  - Non-inductive **ramp-up** test to ~1/3-1/2 FNST current would reduce risk

- PMI
  - Partial divertor detachment has reduced peak heat flux factor of 2-5
  - NSTX will test LLD particle pumping - first liquid metal tests with divertor
  - MAST-U will test Super-X, NSTX/NSTX-U will test high flux expansion
  - NSTX-U plausibly upgradable to "warm" (~350C) walls
    - Test hydrogenic retention with high-Z wall + low-recycling Li-wall concept
  - Dedicated PMI facility would strongly benefit ST, especially if low-A

Prospects for transport and stability

- Transport
  - Next STs (& ATs) require confinement well above ITER H-mode scaling
  - NSTX-U will improve understanding of transport causes and scalings
    - Will extend ν^* scaling factor of 3-6 lower
    - The ν^* scaling most important for FNST, β and ρ^* scalings for BPST
    - Electron transport most important given high χ_e observed in STs
  - **Need tools to improve confinement → motivation for Li research**
    - Primary goal of LTX program

- Stability
  - Increased CD and profile control capability of NSTX/MAST-U expected to provide access to high-β regimes w/ full non-inductive current drive
    - Need to characterize trade-offs between high β_N and low disruptivity
  - NSTX-U/MAST-U → Normalized pulse-lengths limited to ~3-10τ_{CR}
  - ST has unique β, ρ^*, ν^*, parameter regime, profile/control requirements
    - No other long-pulse/steady-state high-performance ST devices are planned
    - Long-pulse high-performance ST PE or BP would substantially lower risk

Prospects for plasma sustainment and magnet development

- Sustainment and profiles
  - NBI-CD will be utilized/exploited on NSTX/MAST, HHFW on NSTX
  - EC/EBW should be developed for ramp-up/sustainment: MAST, QUEST?
  - Core fueling development also needed if Li-wall concept is successful

- Magnets
  - Requirements will depend on scale of next-step
    - ST-PMIF, BPST (initially) could use OH (BPST ½ swing OH → 10MA)
    - FNST nuclear phase must operate w/o OH – ut what about initial phase?
  - CS (and other) shielding requirements for BPST must be determined
    - Will depend on fluence goal of device
  - Could develop single-turn TF in ST-PMIF/BPST if FNST is not next step

Other risks and considerations for ST development path

- There is risk in having too narrow a range of operating scenarios for fusion nuclear science/burning plasma goals

- There is risk in designing a device which cannot study or exploit scenarios with very high performance, even if the base device mission does not depend on high performance.

- Above risks motivate re-examination of device optimization
  - Example: Modest increase in size and/or current could significantly enhance fusion performance
    - Might reduce risks in achieving nuclear testing mission of FNSF/CTF
    - But would increase cost
  - Need to explore broader range of operating scenarios
    - Higher density and higher bootstrap fraction scenarios
    - What do scenarios with reduced confinement look like?
    - High confinement likely essential for compact/efficient device

0D (XL spreadsheet) model of operating points developed

(Similar to C. Neumeyer version developed for ST-CTF/NHTX, but simpler)

- **Special attention given to NBI-CD and fast-ion (NBI + alpha) pressure contribution**

- **NBI CD efficiency estimated including all trapping and slowing-down effects**
  - D.F.H. Start et al., Plasma physics, Vol. 22, pp. 303 to 316

Normalized current drive efficiency

$$\frac{I_T}{P}=\frac{\tau_s v_0 K_1 Z_b}{2\pi R(1+\alpha^3)\varepsilon_0}(1-Z_b/Z_{\text{eff}}+1.46\varepsilon^{1/2}AZ_b/Z_{\text{eff}})$$
$$\times[1+(3-2\alpha^3\beta_1)(1+\gamma)\delta/(1+\alpha^3)^2]$$
$$\times\int_0^1 x^{3+\beta_1}\left(\frac{1+\alpha^3}{x^3+\alpha^3}\right)^{1+\beta_1/3}\mathrm{d}x$$

$$\alpha^3=0.75\pi^{1/2}m_e v_e^3\left(\sum n_i Z_i^2/n_e m_i\right)\Big/ v_0^3$$

$$\beta_n=m_i Z_{\text{eff}} n(n+1)/2m_b,\ \delta=T_e/2\varepsilon_0,\ \rho=n_b/n_e$$

$$\tau_s=3m_e v_e^3 m_b/(16\pi^{1/2}e^4 Z_b^2 n_e \ln\Lambda)$$

- **NBI and alpha pressure derived from energy moment of slowing-down f(E)**
  - T.H. Stix, Plasma Physics, Vol. 14, pp. 367 to 384

Energy loss rate — *i-collisions* — *e-collisions*

$$\left\langle\frac{\mathrm{d}W}{\mathrm{d}x}\right\rangle=-\frac{\alpha}{W}-\beta W^{1/2},$$

$$\alpha\equiv 1{\cdot}30\times 10^{-13}AZ^2\ln\Lambda\sum_j\frac{n_j Z_j^2}{A_j}$$

$$\beta\equiv 2{\cdot}28\times 10^{-15}\frac{Z^2}{A^{1/2}}\frac{n_e\ln\Lambda}{(kT_e)^{3/2}},$$

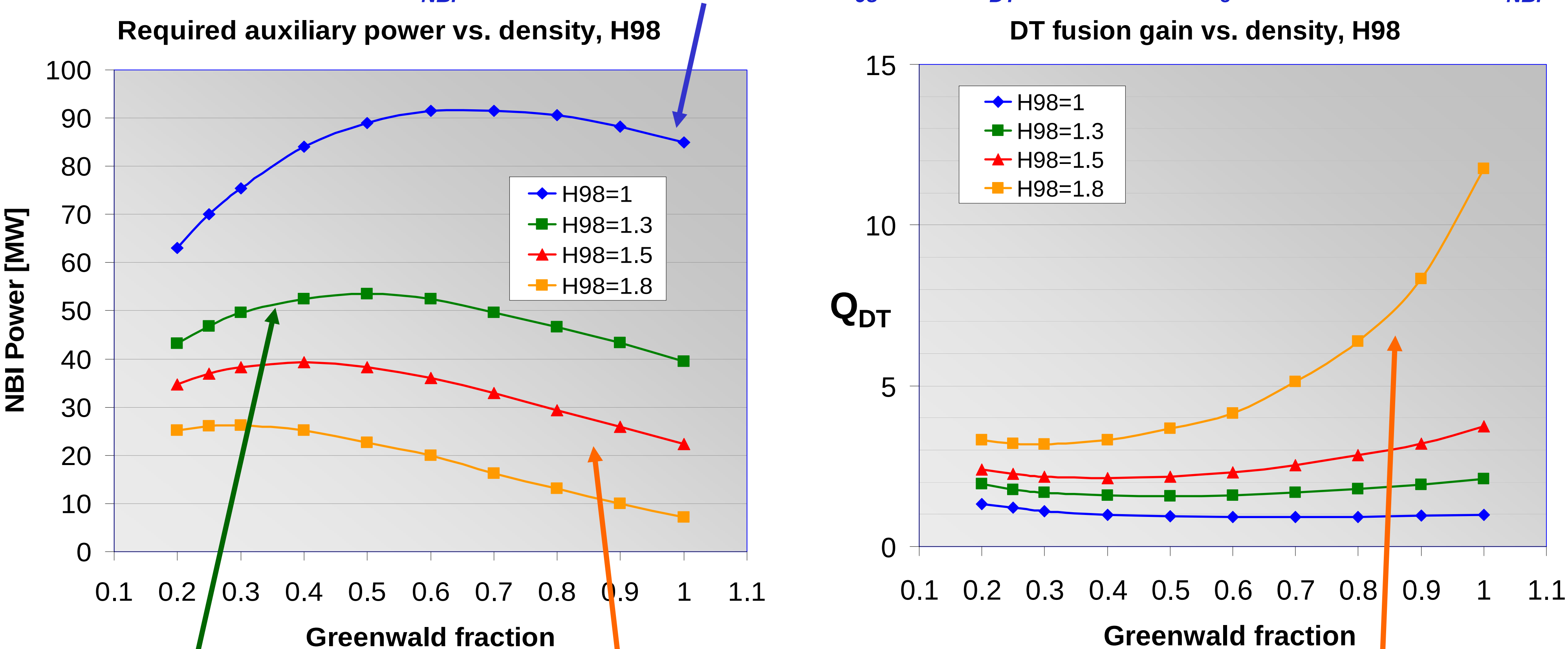
$$\left\langle\frac{\mathrm{d}W}{\mathrm{d}t}\right\rangle=\left\langle\frac{v\,\mathrm{d}W}{\mathrm{d}x}\right\rangle=1{\cdot}39\times 10^6\left(\frac{W}{A}\right)^{1/2}\left\langle\frac{\mathrm{d}W}{\mathrm{d}x}\right\rangle$$

$$\tau=-\int_0^W\frac{\mathrm{d}W}{\mathrm{d}W/\mathrm{d}_t}=\frac{t_s}{3}\ln\left[1+\left(\frac{W}{W_{\text{crit}}}\right)^{3/2}\right]$$

Confinement well above ITER scaling very important to achieve attractive FNST with acceptable auxiliary power

Peak outboard neutron wall loading = $1 MW/m^2$

P_{NBI} = 60-90MW required for H_{98}=1 → Q_{DT} ~ 1 – lower n_e requires lowest P_{NBI}



Required power lowest for high H_{98} = 1.5-1.8 (and achieves high fusion gain)

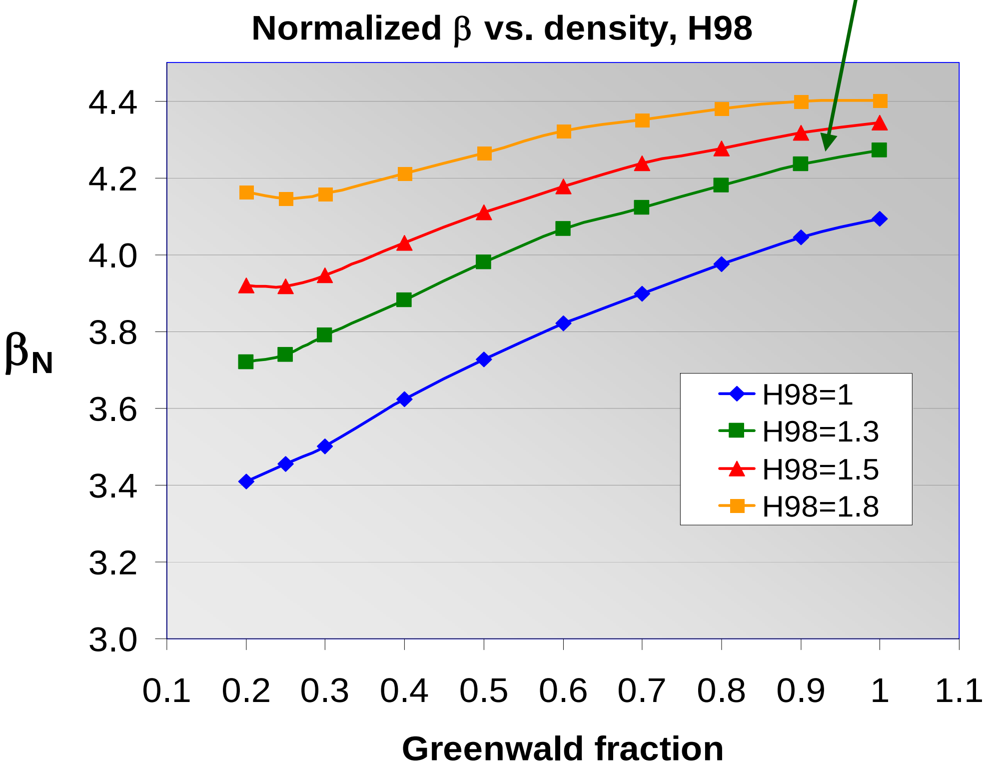
Required power not strongly dependent on density for H_{98} = 1.3-1.5

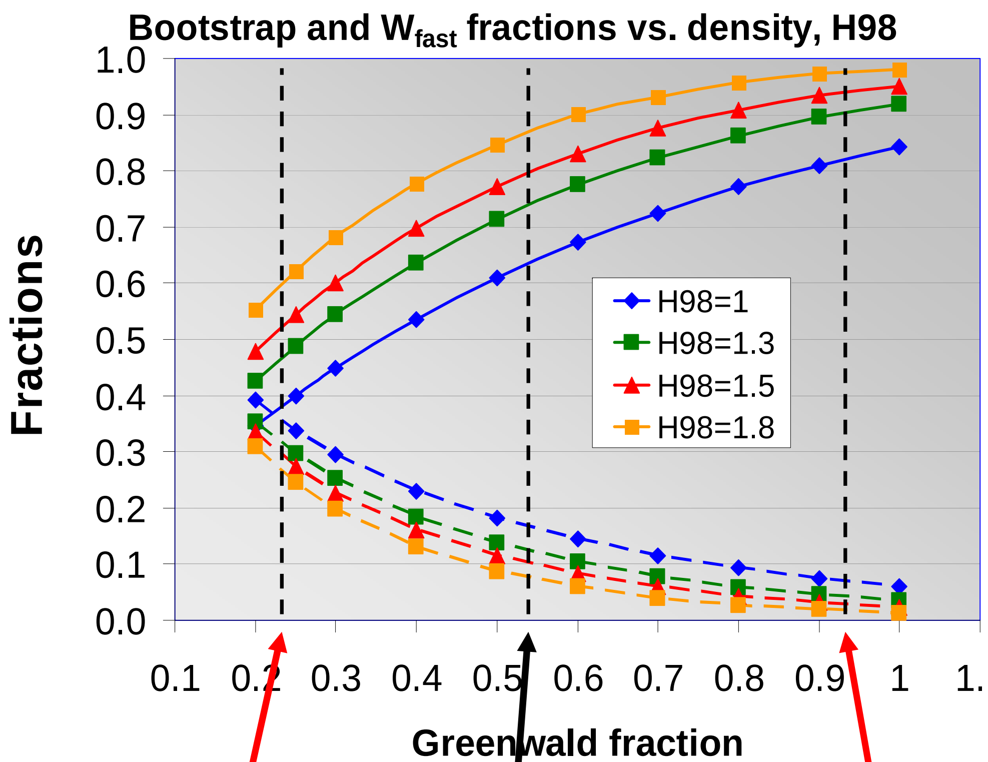
A=1.7, κ=3.3, R_0 = 1.5m, B_T=2.4T, I_P=9-12MA, E_{NBI}=0.5MeV, ITER-98 H-mode scaling

Total plasma beta depends weakly on density, but bootstrap fraction and fast-ion content depend strongly on density

Peak outboard neutron wall loading = $1 MW/m^2$

Less than 15% variation in total β_N with density for $H_{98} > 1.3$





Low n_e: Good NBI profile control, but strong *AE activity?

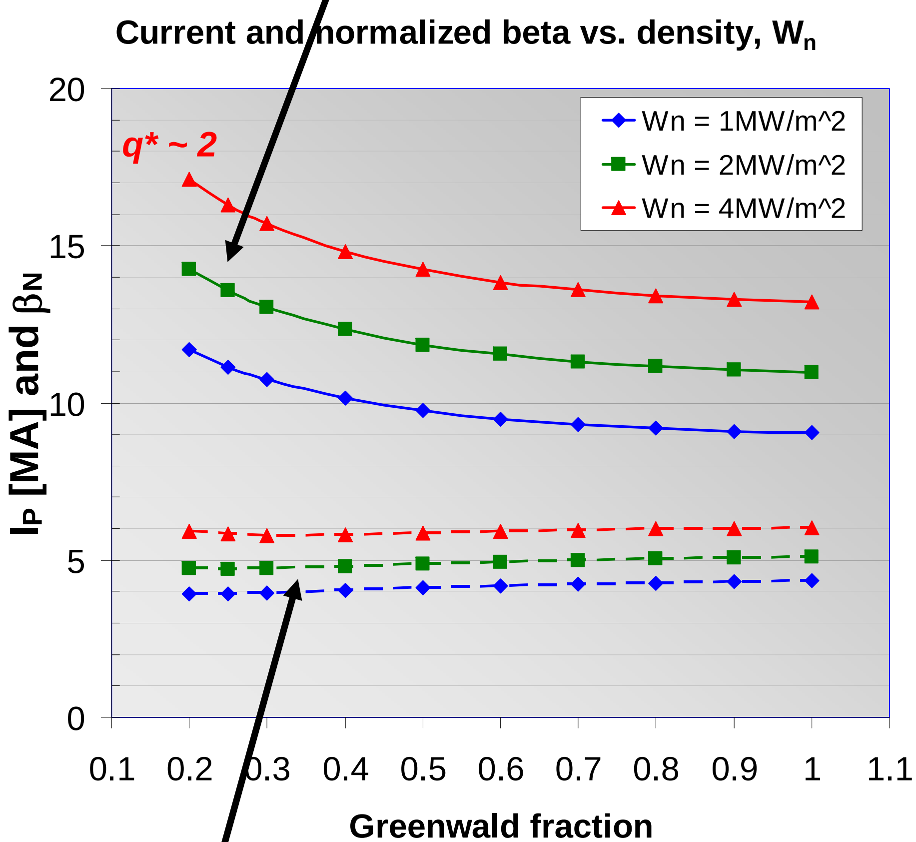
Moderate n_e: Acceptable (perhaps optimal) *AE activity + control?

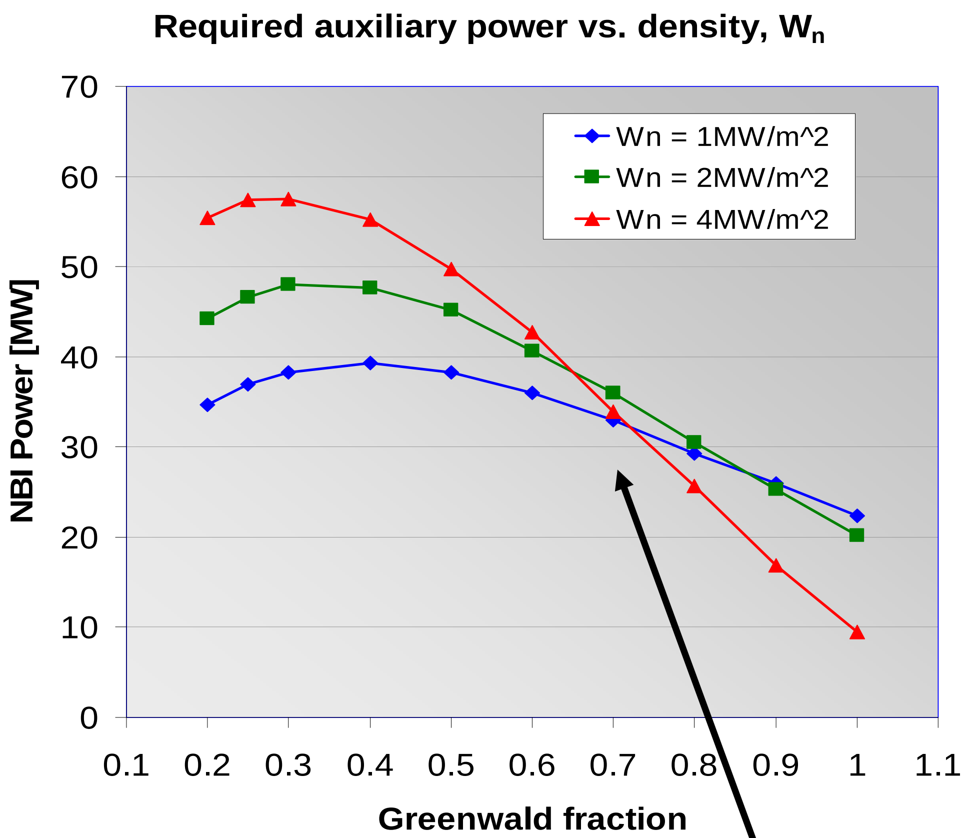
High n_e: lower *AE activity?, but challenging plasma control (like ST-Demo)?

A=1.7, κ=3.3, R_0 = 1.5m, B_T=2.4T, I_P=9-12MA, E_{NBI}=0.5MeV, ITER-98 H-mode scaling

Higher normalized beta operation enables enhanced neutron wall loading for fusion nuclear science/technology

Plasma current increases at lower density and higher wall loading





β_N depends weakly on density, increases from 4 → 5 → 6 for higher wall loading

Aux power required increases with wall loading at low density, decreases at higher density

A=1.7, κ=3.3, R_0 = 1.5m, B_T=2.4T, E_{NBI}=0.5MeV, ITER-98 H-mode scaling, H_{98}=1.5

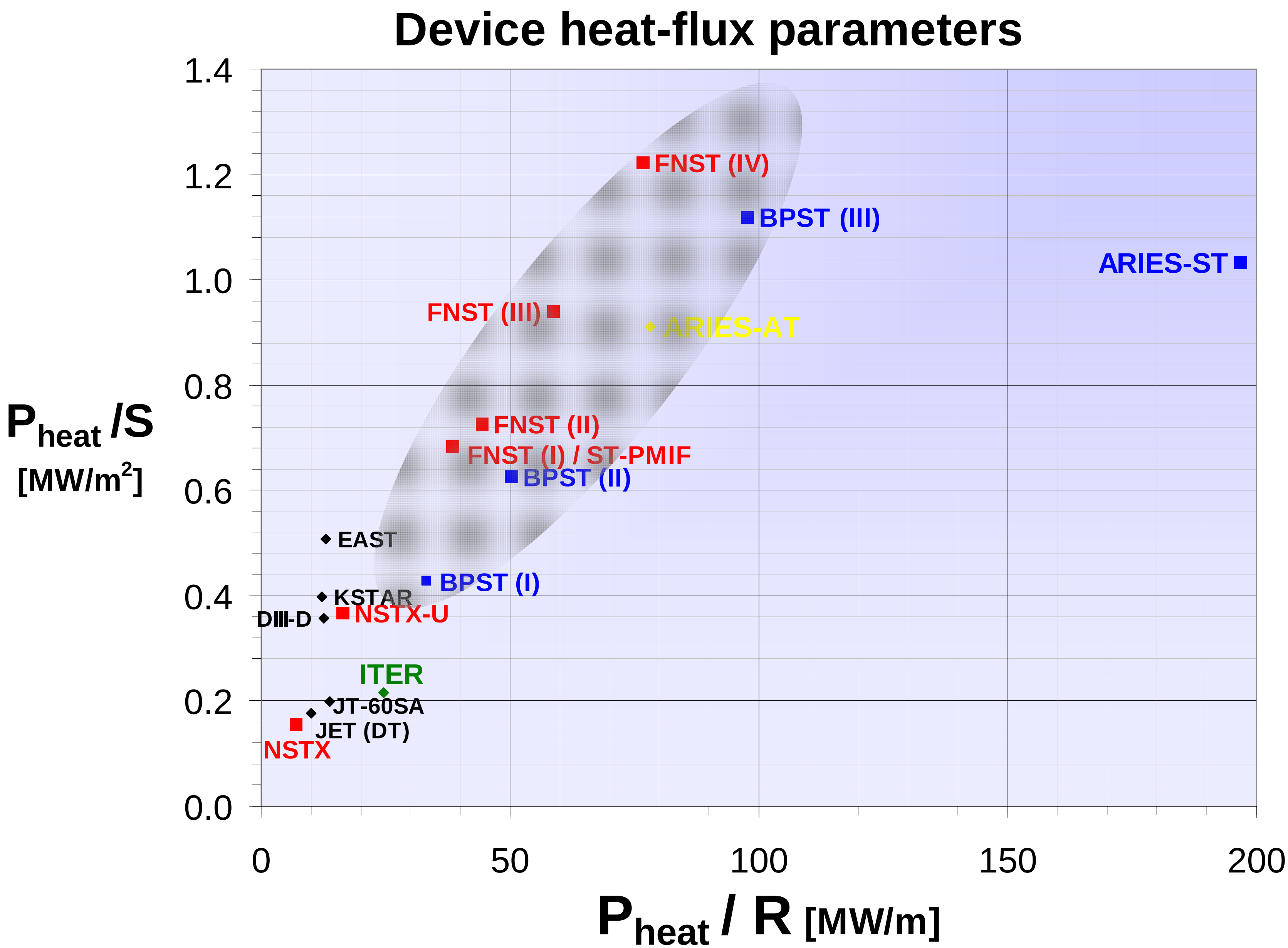
Summary

- Issues, gaps, needs, goals for ST are clearly defined
  - Major upgrades + world program will narrow many gaps

- Next-step ST should have range of operating scenarios to achieve fusion nuclear science missions
  - Essential to access and understand very high confinement
    - Is high-recycling wall good enough, or will a low recycling be needed?
  - Plasma density likely critical parameter in scenario physics
    - Will impact CD and J(r) control, Alfvénic instabilities, divertor regime
    - 0D studies suggest Greenwald fraction ~0.5-0.6 could be attractive
  - High $\beta_N = 4 \rightarrow 6$ could increase neutron wall loading 4-fold
    - But must be weighed against increased control demands, disruptivity

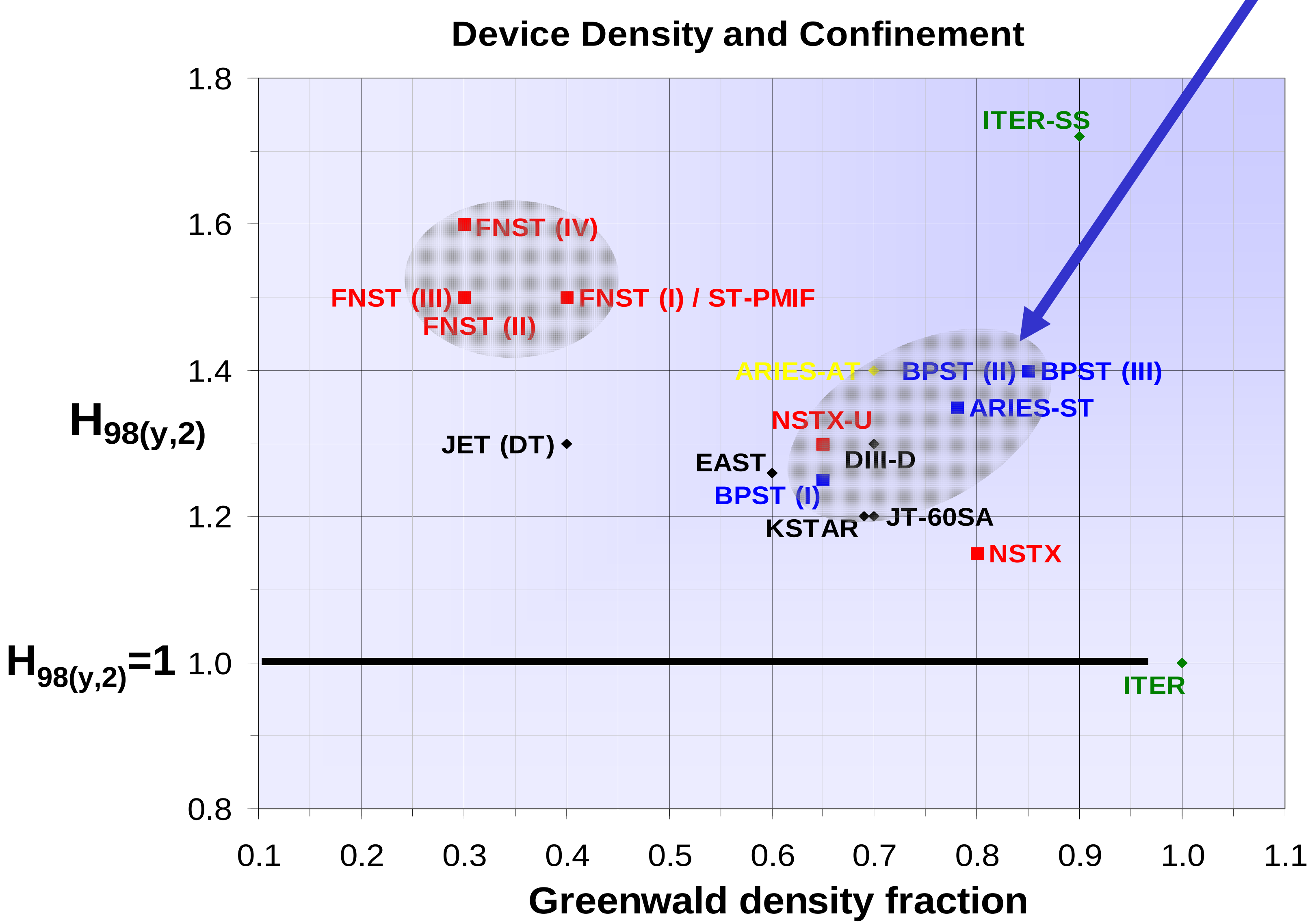
Backup

Next STs push well beyond divertor and first-wall heat-loads accessible in present fusion devices

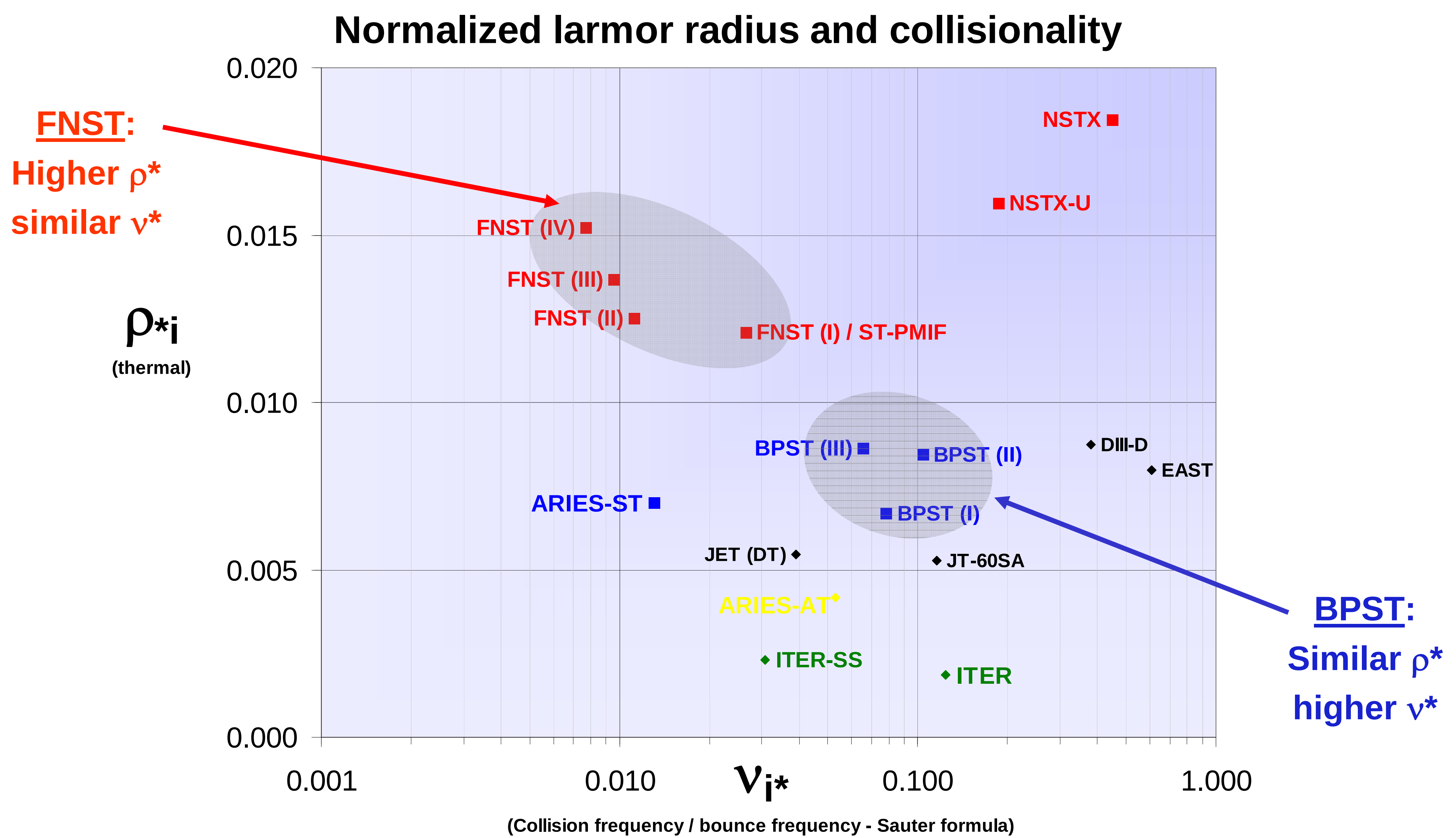


FNST scenarios optimize at high normalized H-mode confinement and reduced density (for NBI-CD)

- BPST/reactor scenarios optimize at somewhat lower H_{98} and higher density



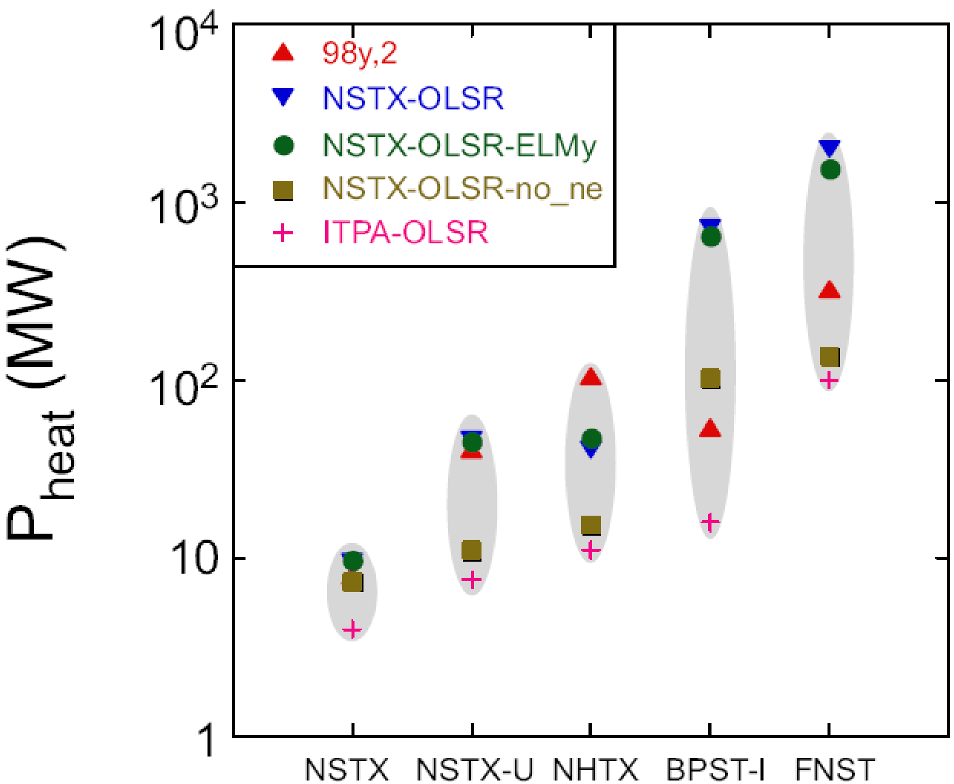
FNST and BPST scenarios approach ST reactor ρ*, ν* from complementary directions



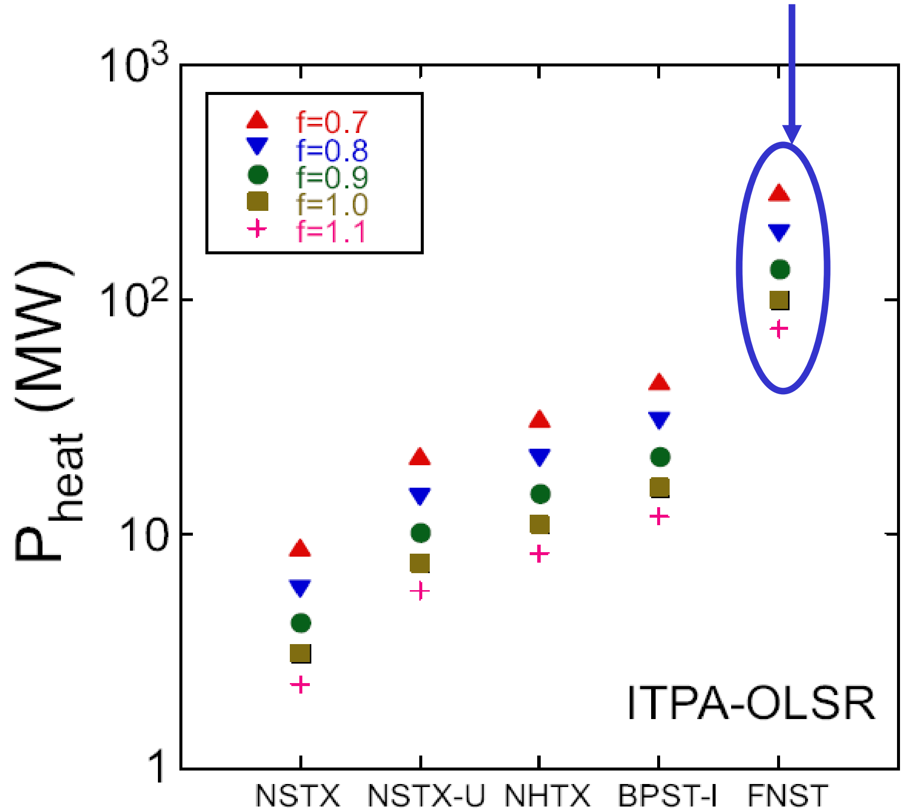
Confinement and the ST development path

- How much would the uncertainty in confinement extrapolation to FNST and a BPST be reduced by NSTX-U, and by an intermediate step?
  - We are still working on answering this one…
- How might this impact the choice of device size, auxiliary power, etc.

Predicted heating power to achieve target W_{TOT} shows wide variation for next-steps

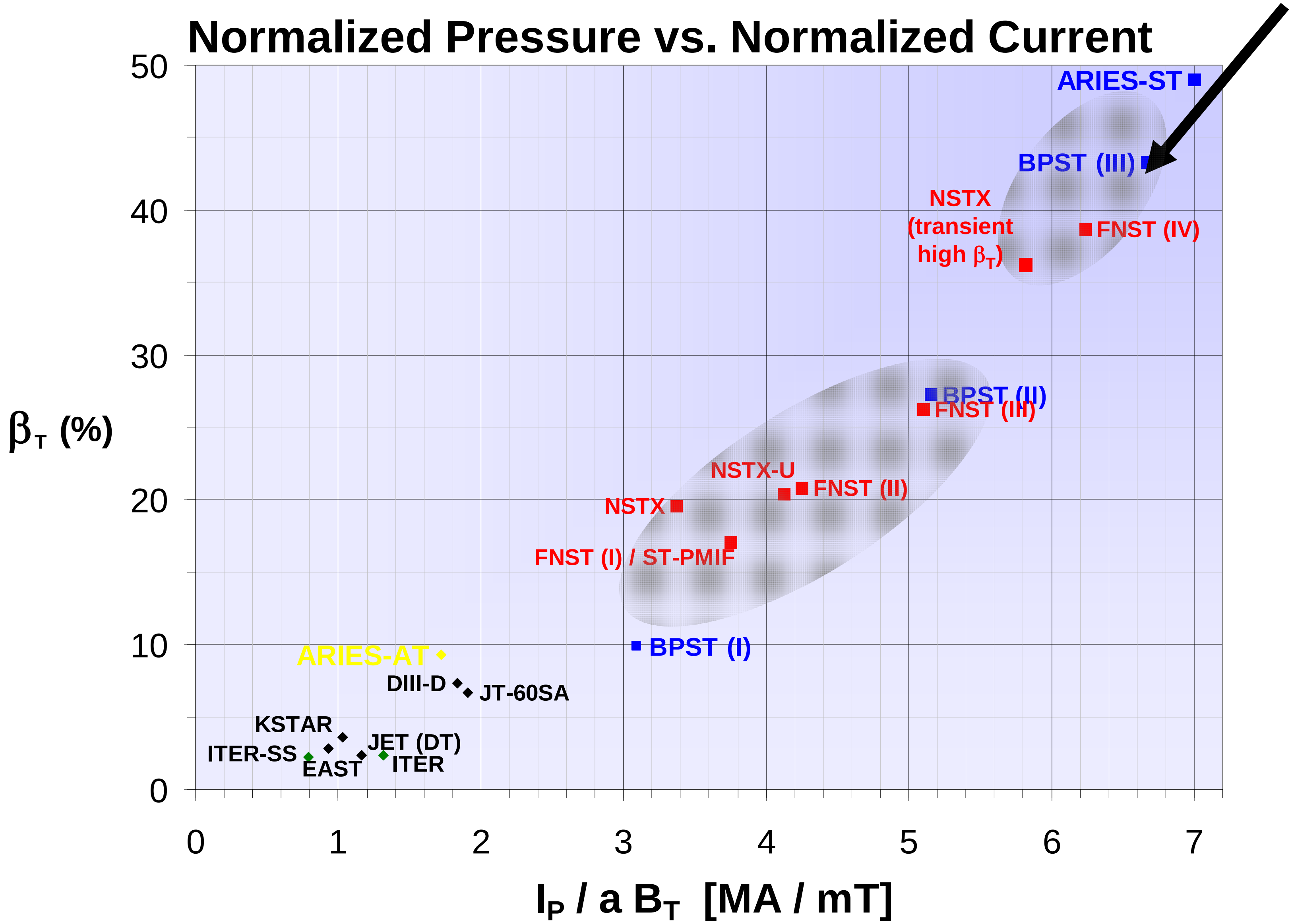


FNST requires favorable scaling and/or high multiplier to keep P_{heat} < 100MW



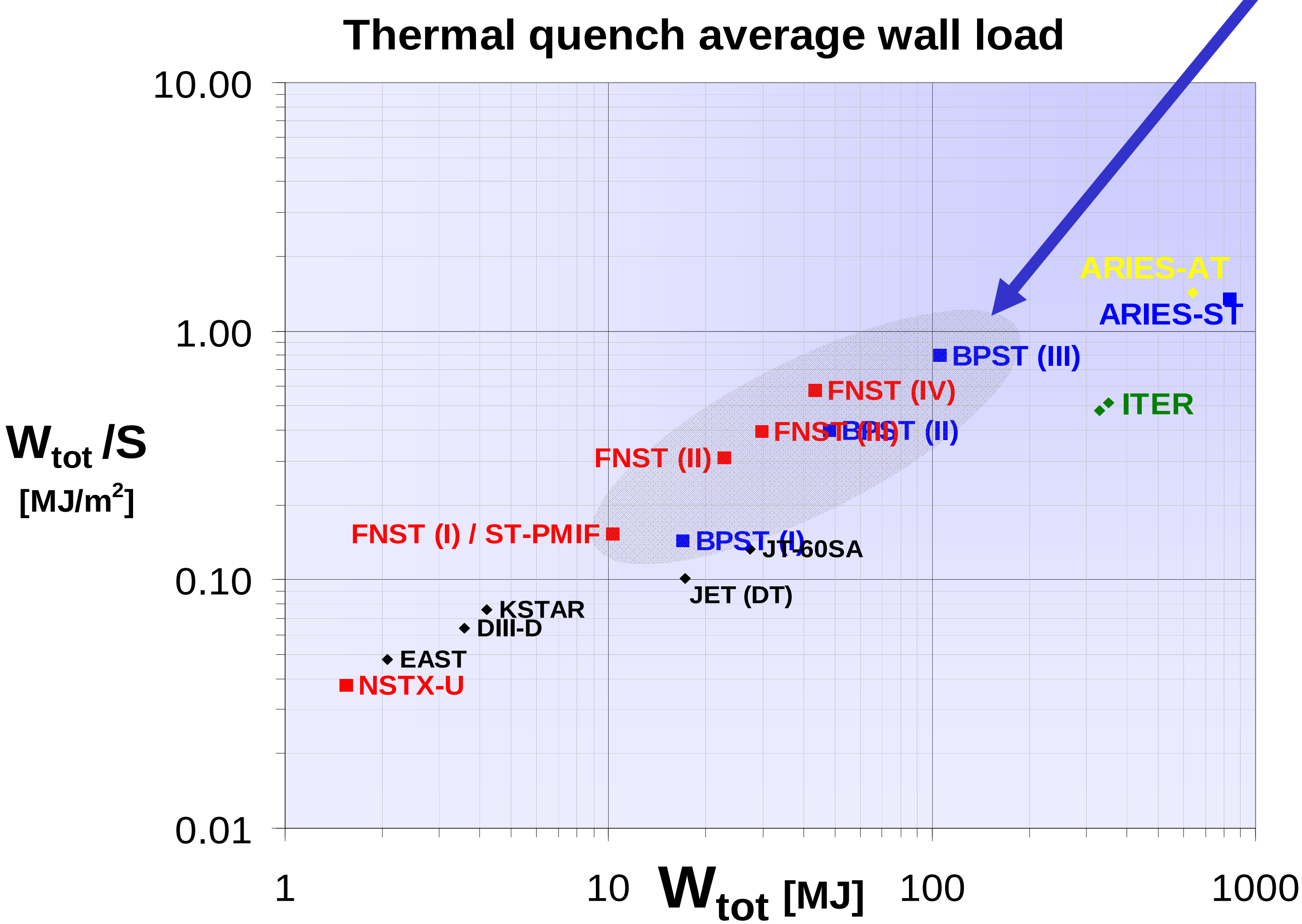
Next ST facilities operate with normalized stability parameters comparable to NSTX/NSTX-U

- **But further research needed to sustain high β_T~30-40% for BPST (III), FNST (IV)**



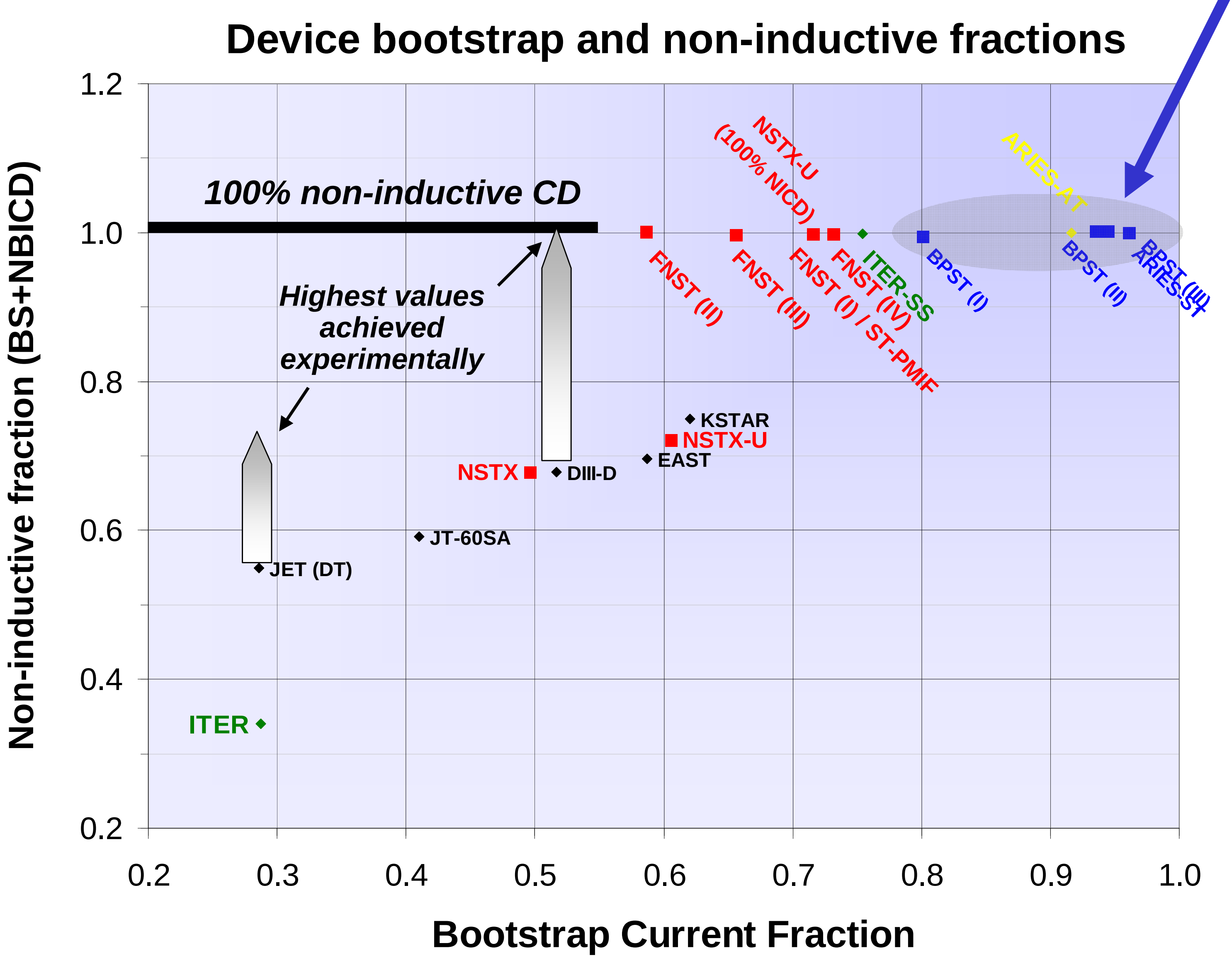
Next STs have disruption thermal quench wall loads extending from JET/JT-60SA to ITER values

- High-Q_{DT} BPST (III) would have wall loading above ITER, approaching reactor
  - Is disruption mitigation developed for/on ITER sufficient for STs?
  - What is role of liquid walls for disruption survivability?



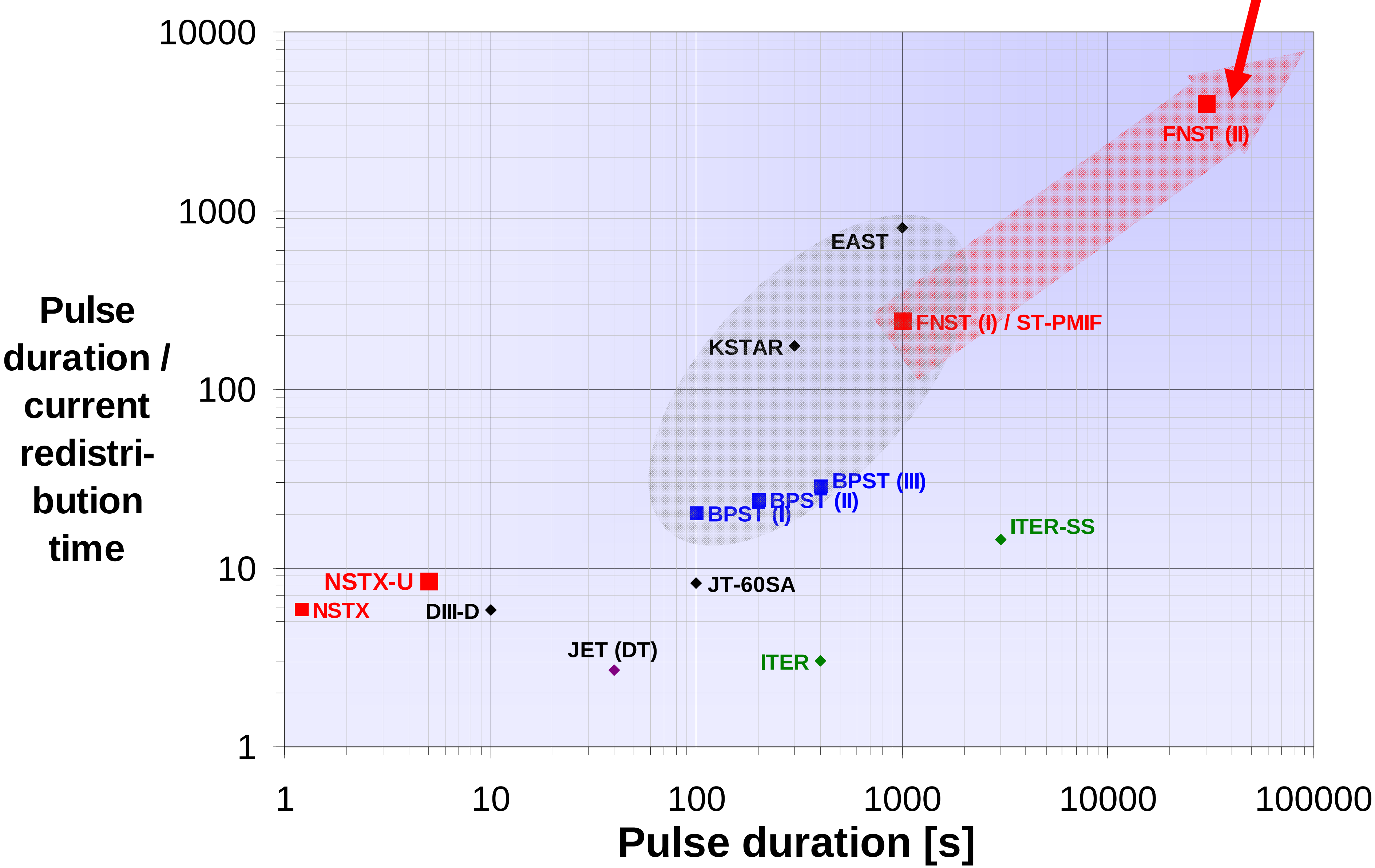
Next STs operate fully non-inductively with current provided by the bootstrap effect + NBI-CD

- **BPST would utilize scenarios with higher (80-95%) bootstrap fraction**



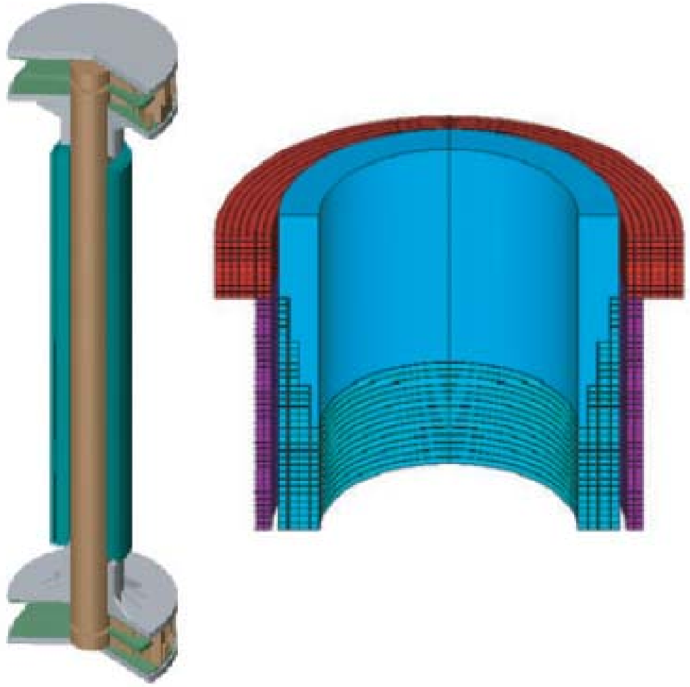
Next STs have baseline pulse durations between JT60-SA and KSTAR/EAST

- **FNST would target extension to much longer pulse durations**



Magnets and the ST development path

- How much single-swing solenoid flux is available for I_P ramp-up in a BPST or the break-in phase of an FNST? What are achievable plasma currents?
- Are insulated multi-turn TF/OH coils viable in BPST fusion environment?

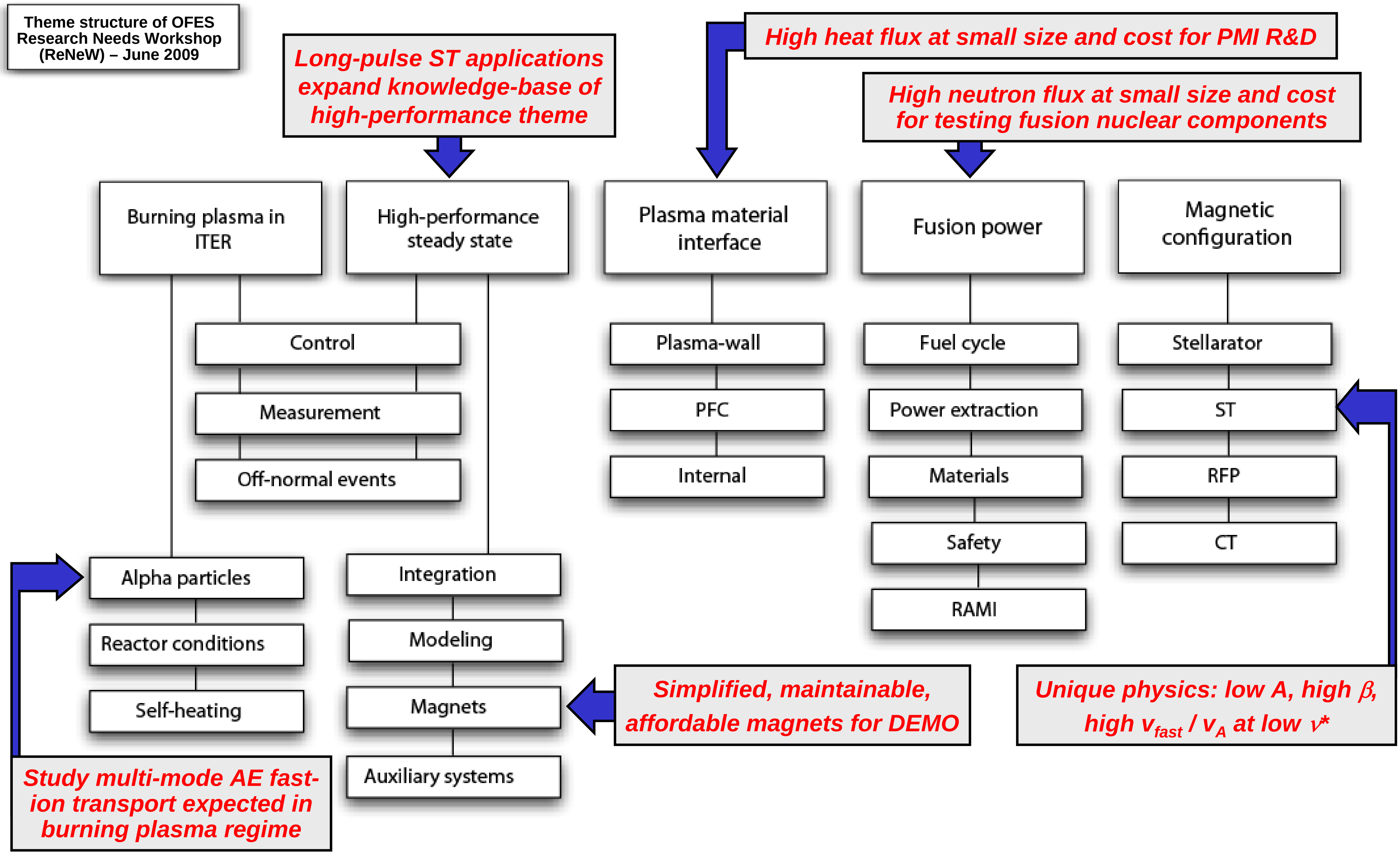


- NSST 2-layer OH design: OFHC for outer, BeCu for inner + LN_2 cooling
  - 9T OH field limit combined with NBI + H-mode in ramp-up for lower C_{Ejima} →
  - BPST: **OH single-swing to ~10MA** (7Wb ½ swing OH) – sufficient for Q_{DT}~2
  - FNST: **OH single-swing to ~7MA** (4Wb ½ swing OH) – sufficient for Q_{DT}~1
  - Allowable dpa and shielding requirements = work in progress…
- **Also still need to address/develop single-turn central TF**
  - **BPST could test NI ramp-up to ~10MA – could also test single-turn TF w/o OH?**

Is an ST-based pilot plant possible?

- Answer: possibly, but would require ***aggressive*** approach
- Example calculation:
  - BPST-III at 15MA, β_N = 7, Q_{DT} = 10 → ~500MW fusion power
  - Use ARIES-ST power conversion assumptions:
    - Total thermal power ~13% above P_{fusion}, conversion efficiency = 45%
    - Electricity production = 245MWe (need to recover every Watt!!!)
    - Estimated total TF power for 2.4T = 330MW
    - Minimize PF power consumption (assume SC PF coils as for ARIES-ST)
    - Assuming P_{AUX} = 50MW, 35% wall-plug efficiency → 140MWe
    - TF + auxiliary heating = 470MW → Q_{ENG} ~ 0.5
  - **BUT**, with A=1.6→1.7, B_T=2.4T → 2.2T, **H_{98} = 1.4 → 1.7**
    - P_{AUX} = 20MW → TF + auxiliary heating ~ 250MW → Q_{ENG} ~ 1
    - Also reduces mid-plane port space required for auxiliary systems
  - **Improved confinement, high β critical → motivates Li & stability research**
- **BPST-III is ½ size of ARIES-ST – would larger BPST do better?**

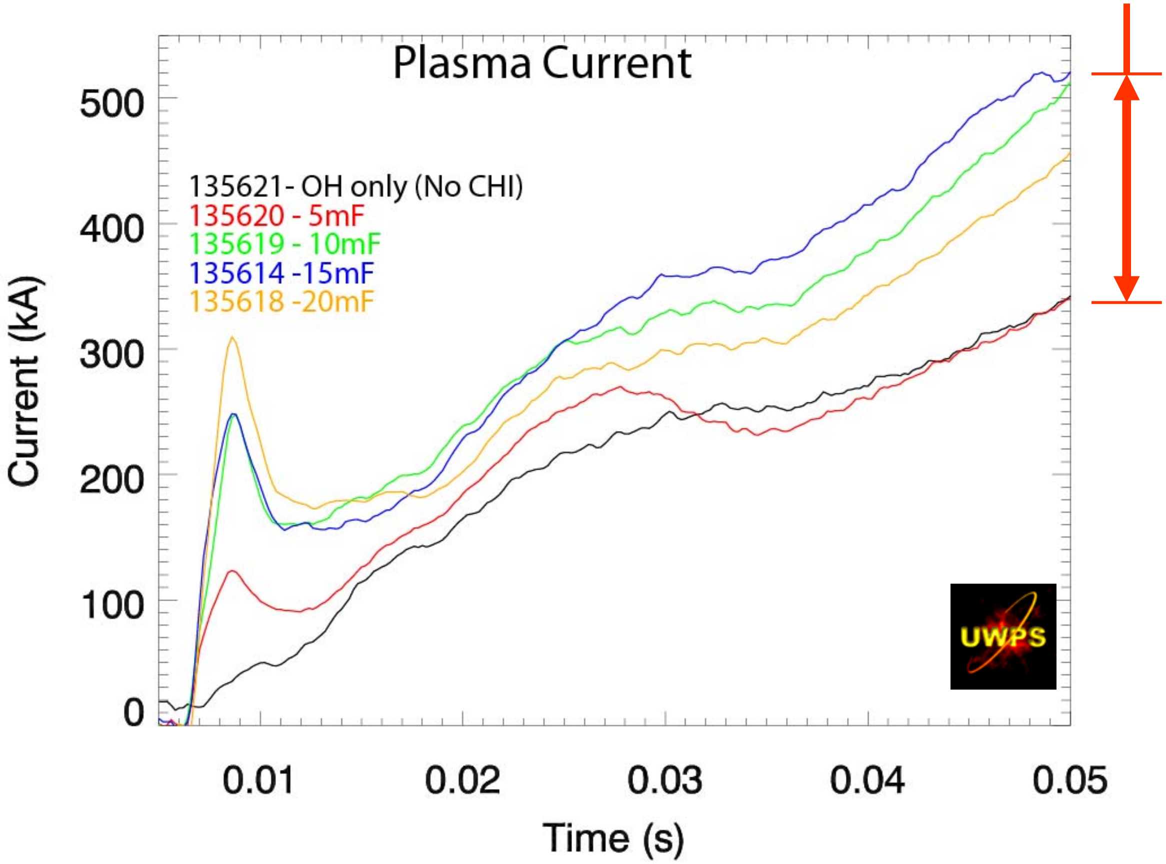
The ST provides unique contributions to all magnetic fusion research needs – for the ITER era and beyond



CHI has been coupled to induction and NBI-heated H-mode in NSTX with substantial sustained current savings

- **Extensive conditioning improved divertor conditions for successful CHI → OH coupling**
  - Upper divertor conditioned with NBI-heated USN plasmas
  - Lower divertor conditioned with sustained CHI plasma
  - Li evaporation used to reduce oxygen, increase D pumping
  - CHI voltage duration (absorber arcs) reduced

180kA current savings



- 300kA (or higher) current savings is goal for NSTX
  - Should be possible w/ additional improvements
- 400kA needed to absorb 2nd NBI in NSTX-U
- Higher TF expected to increase I_P (CHI) in NSTX-U