Response to Question 3a

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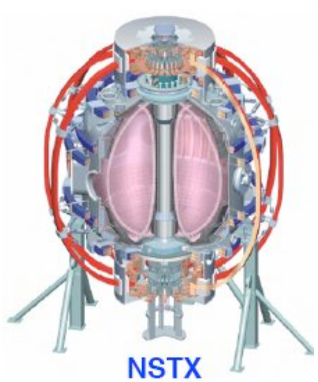
ST Goal: "To produce a sustained plasma fusion environment of high heat flux and high neutron fluence to enable the R&D that establishes a knowledge base for an attractive fusion energy source."

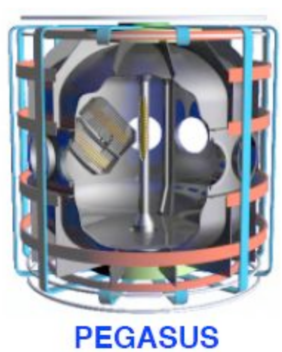
Goal addresses FESAC themes

- **Theme** B - *Taming the plasma material interface*
  - ST brings high heat and particle flux, high neutron flux and fluence to address plasma-wall interactions, PFCs, RF launchers
- **Theme** C - *Harnessing fusion power*
  - ST can contribute high duty factor and neutron fluence to address fuel cycle, power extraction, material science, safety, reliability, maintainability

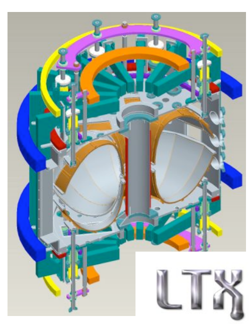
How would the ST program address and resolve the most crucial scientific questions ahead of it for the this goal - startup and sustainment, transport, boundary physics?



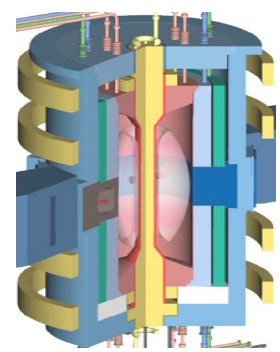
NSTX



PEGASUS

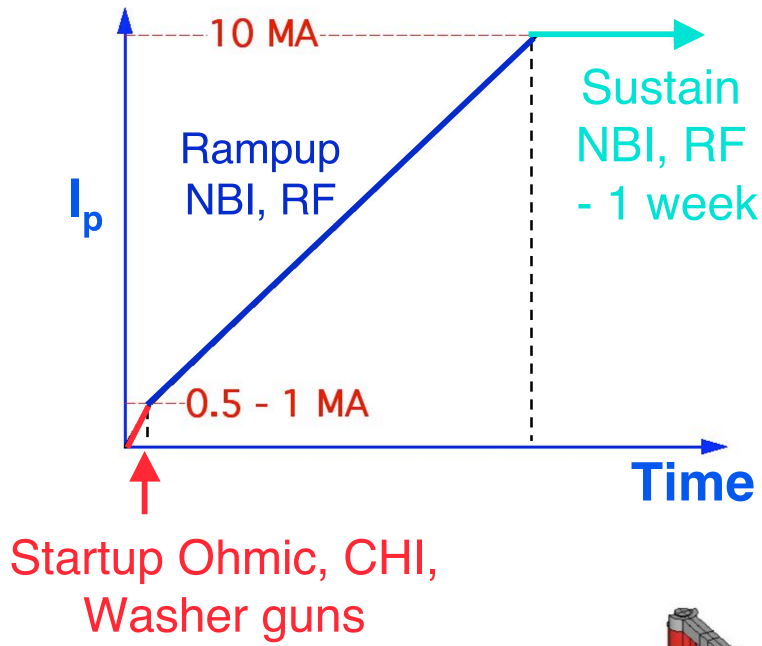


Intermediate steps
Upgrades
New Facilities



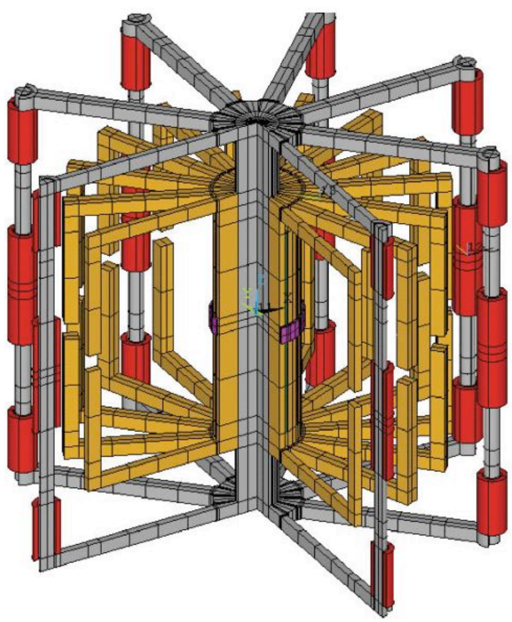
ST-CTF

Startup current requirements similar to achieved values in present experiments - but need neutron-tolerant system



- Startup phase: 1 MA
  - Startup discharge must provide sufficient fast ion, thermal confinement to support rampup phase
  - Comparable to present-generation flattop
- Candidate neutron-tolerant Ohmic options for ~1 V-sec startup:
  - Resistively-shimmed iron core
  - Air core solenoid with mineral insulated cable construction
    - » MIC tested to 10 dpa

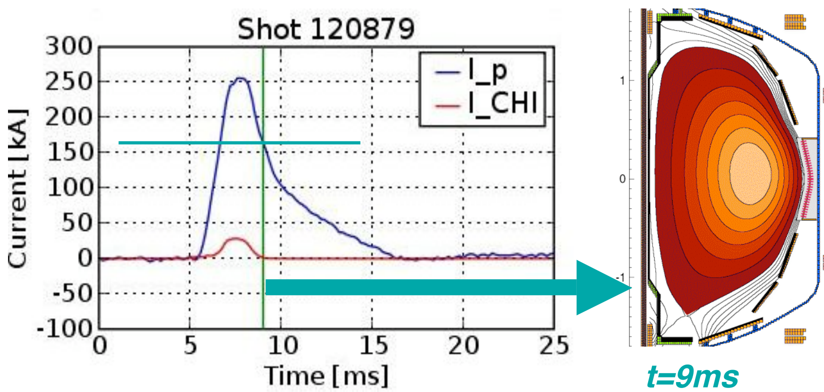
- **Full 3D ANSYS model of the iron core plus copper TF with inconel spacers**
- **Initial model has:**
  - **16 fold TF symmetry**
  - **8 fold Iron symmetry**
- **Results similar to 2D model with ~0.4V of loop voltage for ~2s for an A~1.9 device**
- **Further design work required**



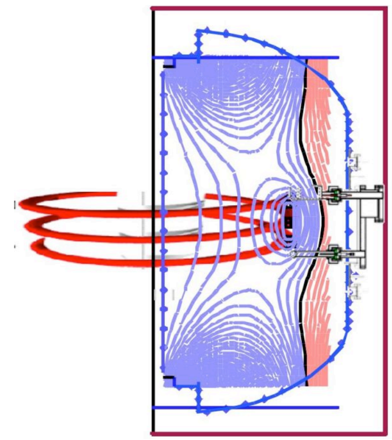
Form factors for radiation resistant mineral-insulated cable

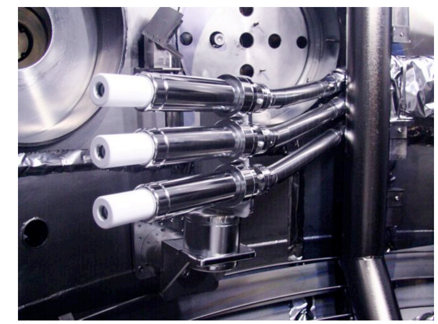
Solenoid-free startup

- BUT: OH solenoid will require ~25% of cross-sectional centerstack area
- ST concept can be enhanced with full noninductive startup
  - Coaxial helicity injection
  - Gun-injected helicity

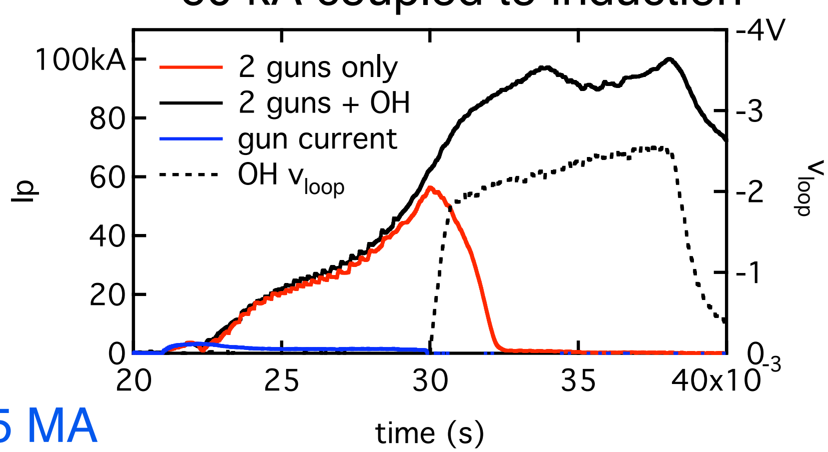


- CHI in NSTX
  - Record closed-flux (I_p=160 kA)
  - Recently coupled 100 kA to inductive H-mode discharges
- Outer PF only startup demonstrated in MAST
  - With internal coils - demonstration with external coils required





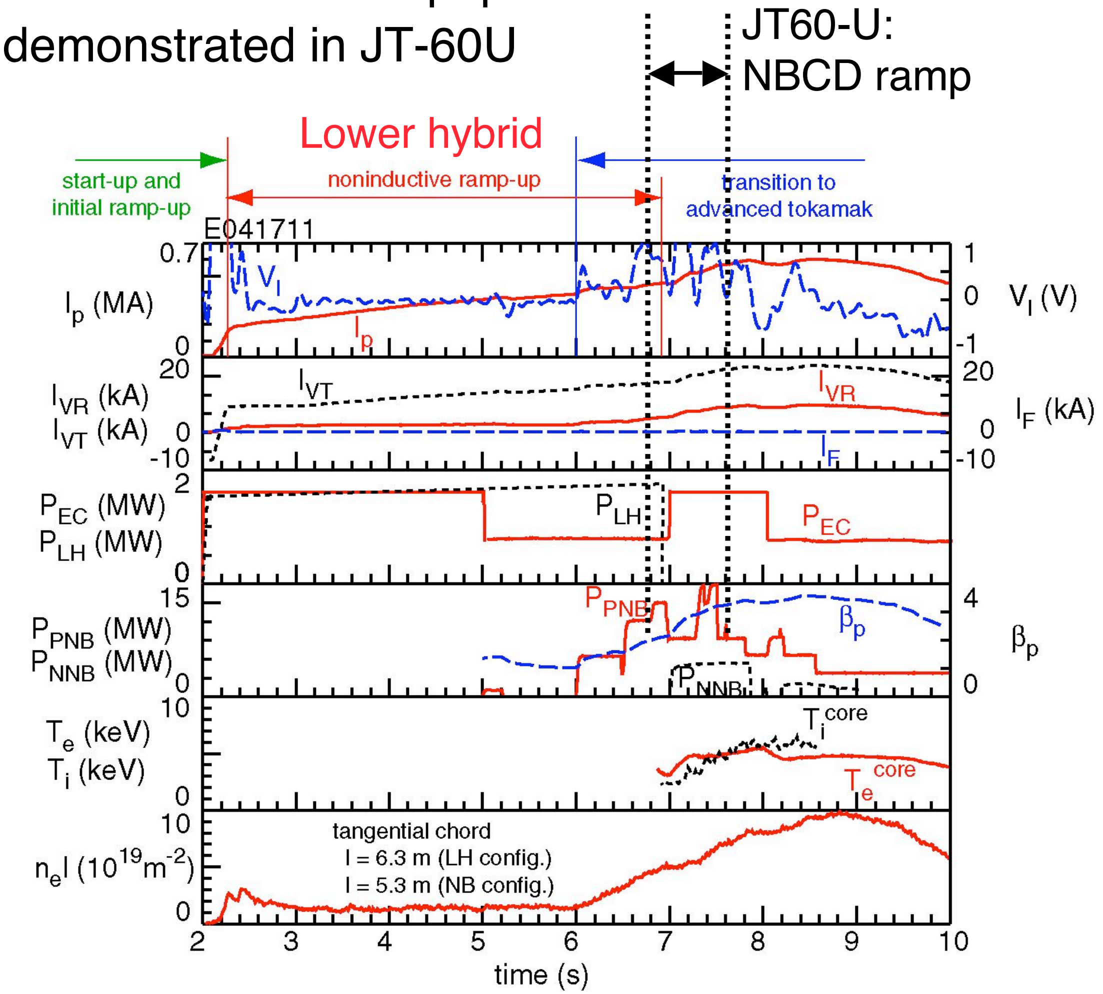
- Plasma gun startup in Pegasus
  - 60 kA coupled to induction



⇒Noninductive startup must be extended to 0.5 MA

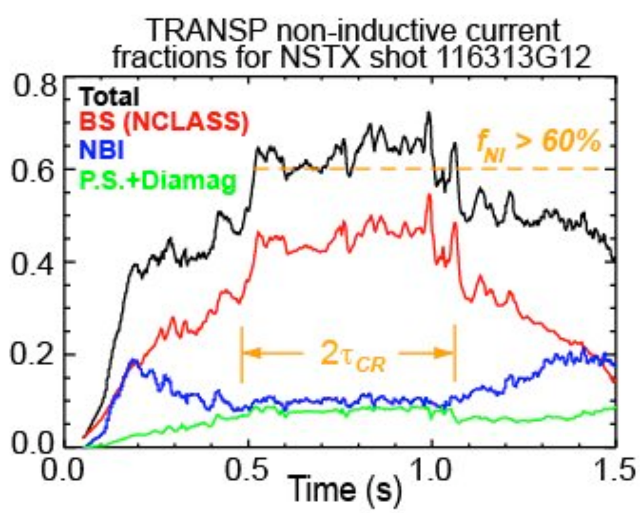
Current rampup requirements significantly extend present state-of-the-art

- Large rampup from startup discharge (0.5 - 1MA) to alpha-confining current (8-10 MA) required
  - No rampup demonstration exists for the ST
- Conceptual solution relies in part on NBCD for rampup
  - Modest NB driven rampup demonstrated in JT-60U
    - » Requires sufficient startup current to confine fast ions
    - » Requires good thermal confinement for CD efficiency
- Rampup assist possible from RF (ECH/EBW, fast wave, other?)
  - Most robust noninductive rampup in tokamaks with LHCD
  - Not tested in the ST
    - » No tests planned

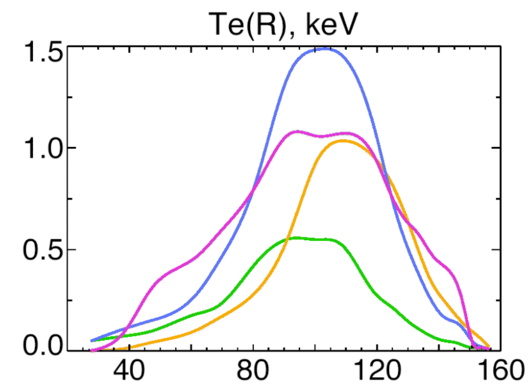


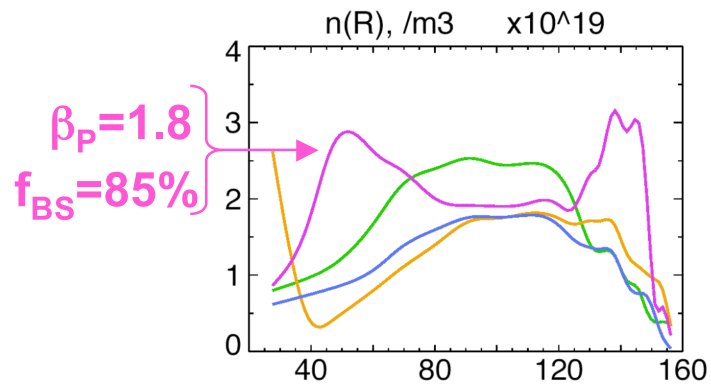
Current sustainment required for very long pulses (~ week, or two)

- Available techniques similar to rampup
  - Baseline approach: NBCD
    - Good efficiency requires low density operation (n_e/n_{GW}~0.3-0.5)
  - Sustained target overdense - limits RF options for current drive
    - ECH ⇒ EBW
    - FWCD
    - LHCD limited to edge



- HHFW heating in NSTX
  - T_e to 1 keV in 200 kA target plasma
  - f_{BS}=85%



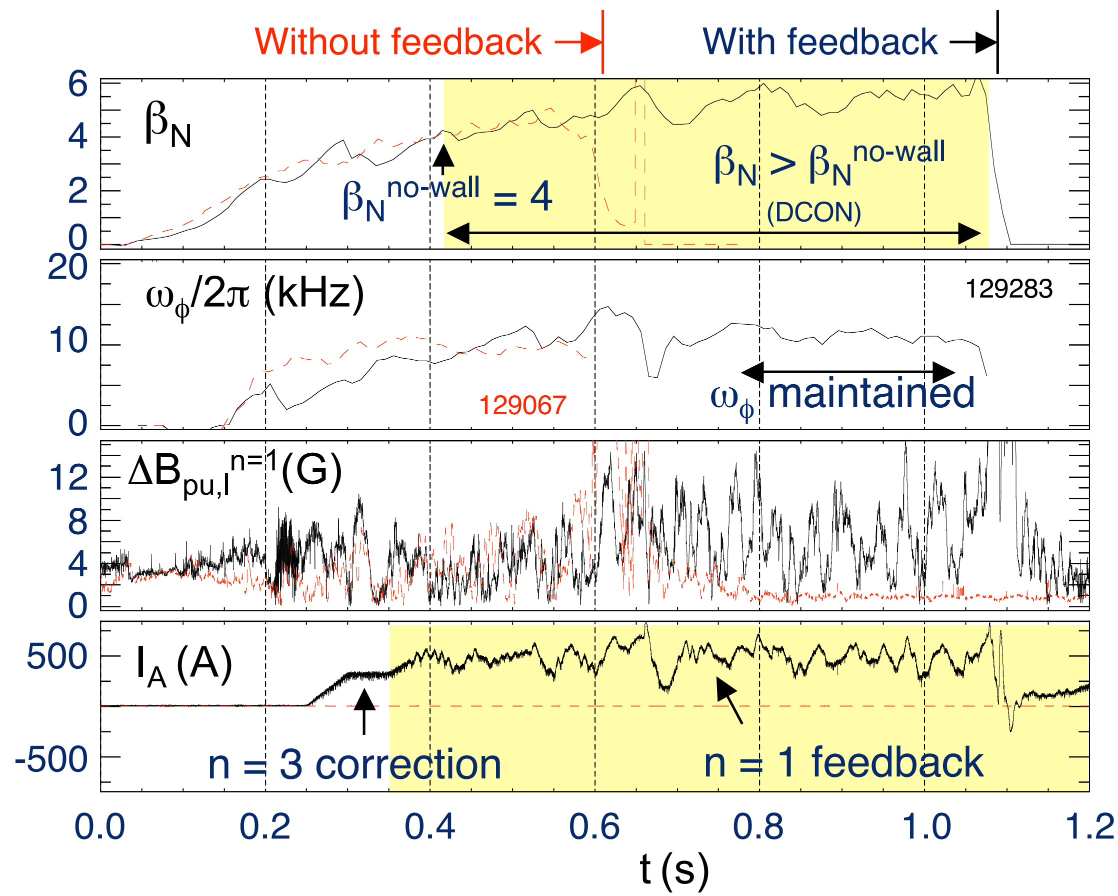


- NBCD in NSTX
  - f_{NI} > 60%

Successfully sustained discharge requires routine achievement of high, stable β_N with high reliability

- NSTX pulse duration ~ τ_{CR}, not steady-state
- Key modes critical to tame
  - Disruptions: global kink, RWM, NTM
  - Beta collapse/decay: internal kink, NTM, ELMs
  - Loss of plasma rotation: NTM, stable RWM (RFA)
- ST program lacks a long-pulse (many τ_r) device to study sustainment and control
  - ⇒ Unclear if science gained from long pulse operation of superconducting ATs at β~5-6% is can guarantee successful operation of a CTF at β~15-20%

Long pulse NSTX discharge with reduced recycling (lithium), n = 1 feedback, n = 3 correction

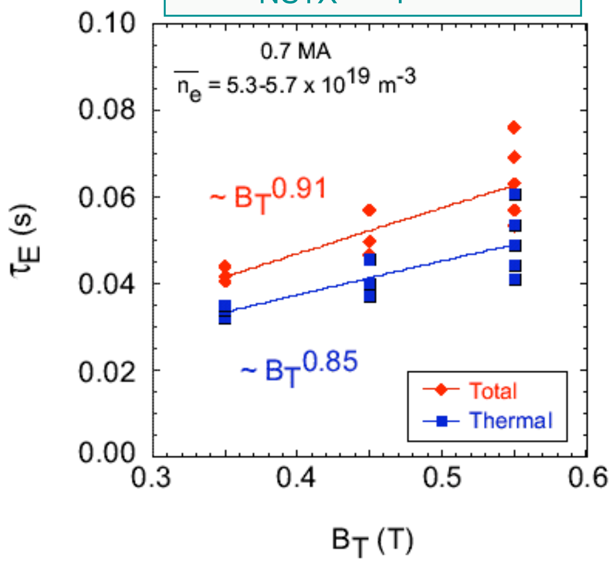


Transport: Scalings in ST H-mode Plasmas are Different Than Those at Higher Aspect Ratio

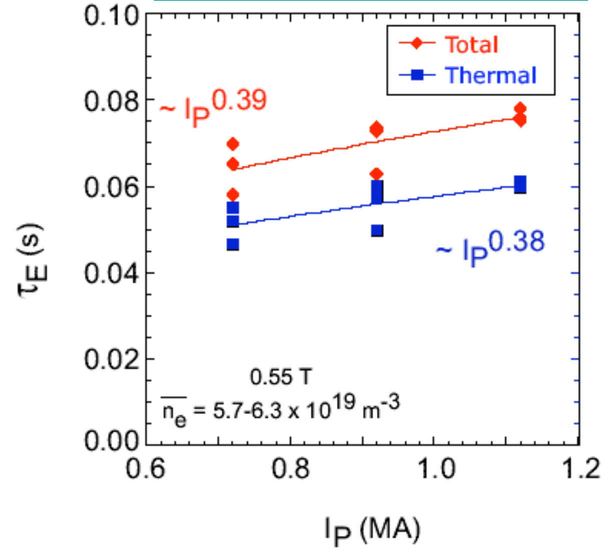
- Global transport: stronger B_T, weaker I_p dependence
  - Important to establish B_T, I_p dependence over extended range

> ⇒ ρ^* in present STs is within ~ factor of 2 of next step STs
> ⇒ ν^* gap is 1-2 orders of magnitude

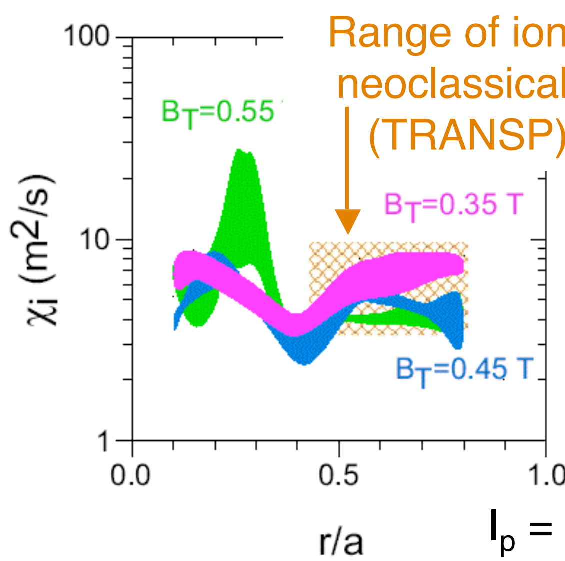
$\tau_{E,98y,2} \sim B_T^{0.15}$
$\Rightarrow \tau_{NSTX} \sim B_T$

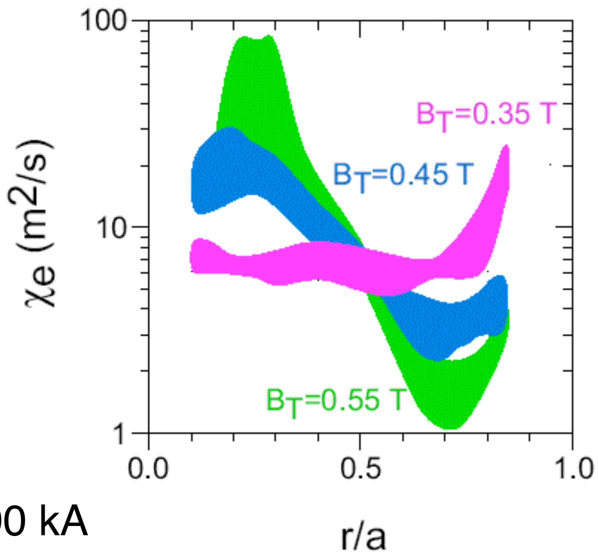


$\tau_{E,98y,2} \sim I_p^{0.93}$
$\Rightarrow \tau_{NSTX} \sim I_p^{0.4}$



- Ions often neoclassical, electrons anomalous
- Increased I_p would reduce neoclassical transport
  - Enhance relative importance of anomalous transport
  - Provide insight into momentum transport

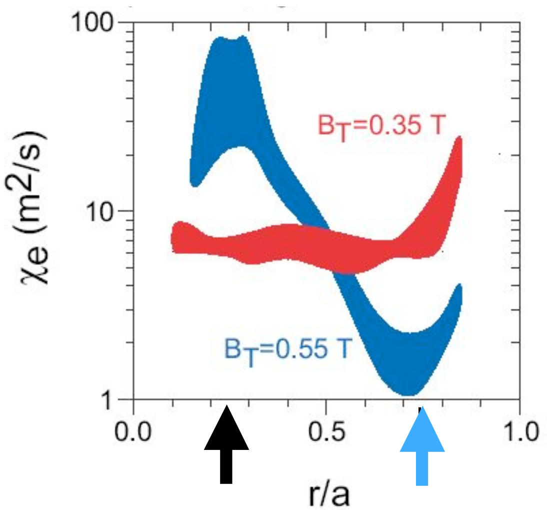


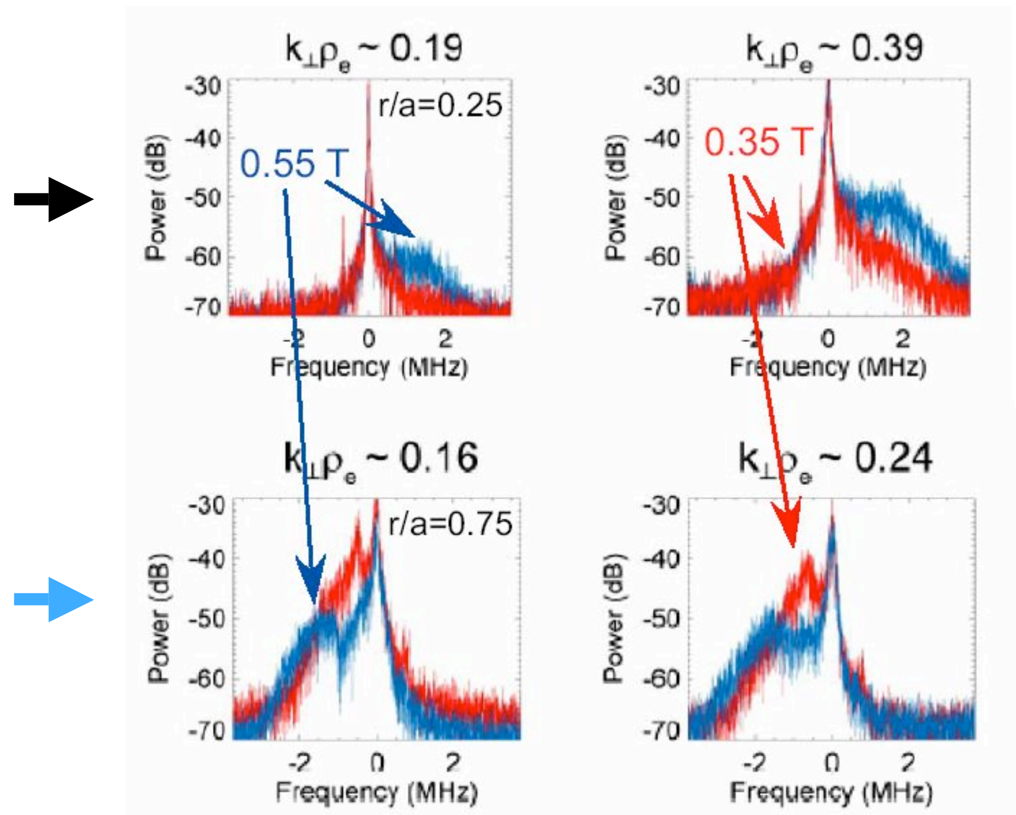


I_p = 700 kA

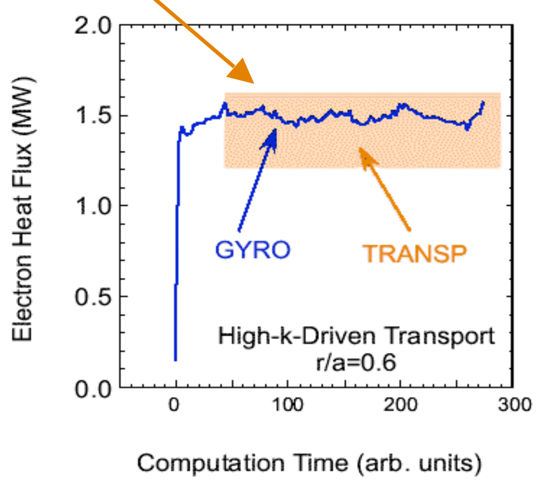
High-k electrostatic modes appear to contribute to electron transport

- ETG/high-k TEM (∇T, f_T, ν^*)





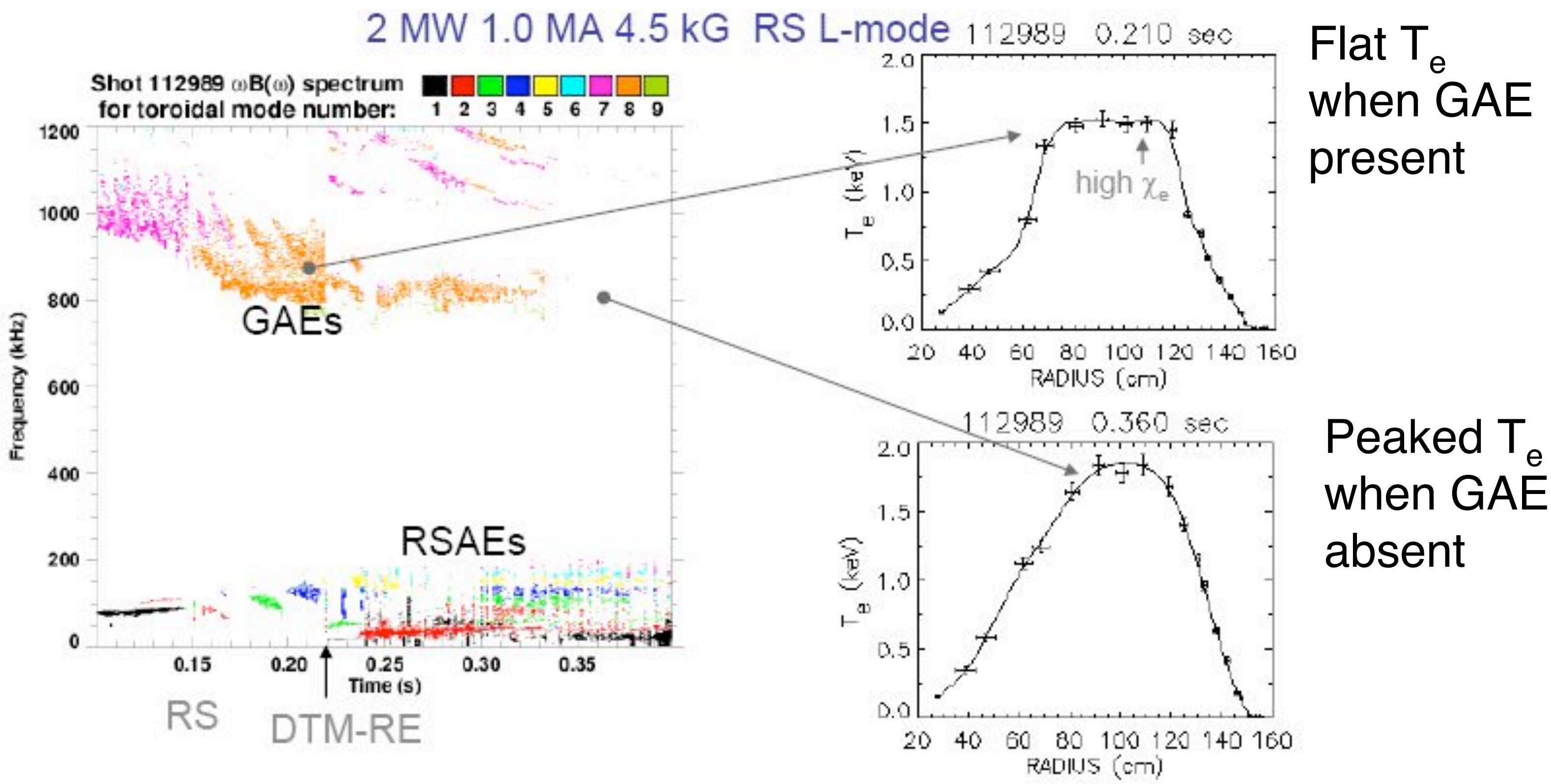
Observed transport consistent with ETG for some discharges



- Increased electron thermal diffusivity correlates with increased high-k fluctuations in space, vs. field

Magnetic fluctuations may also contribute to electron transport

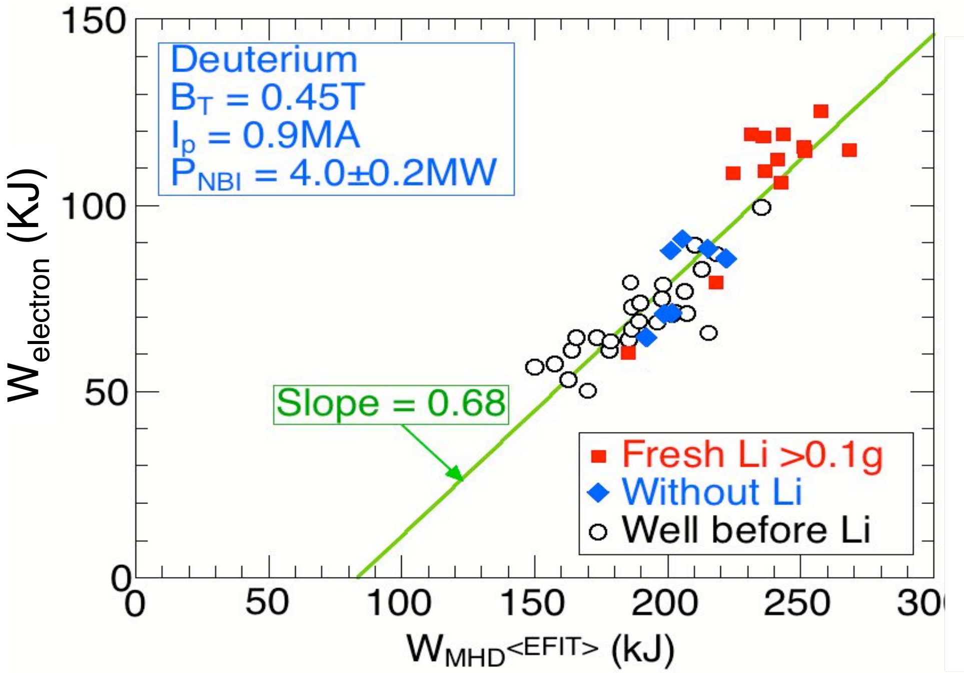
- Global Alfvén Waves (fast ions, thermal e^-) - high frequency magnetic fluctuations



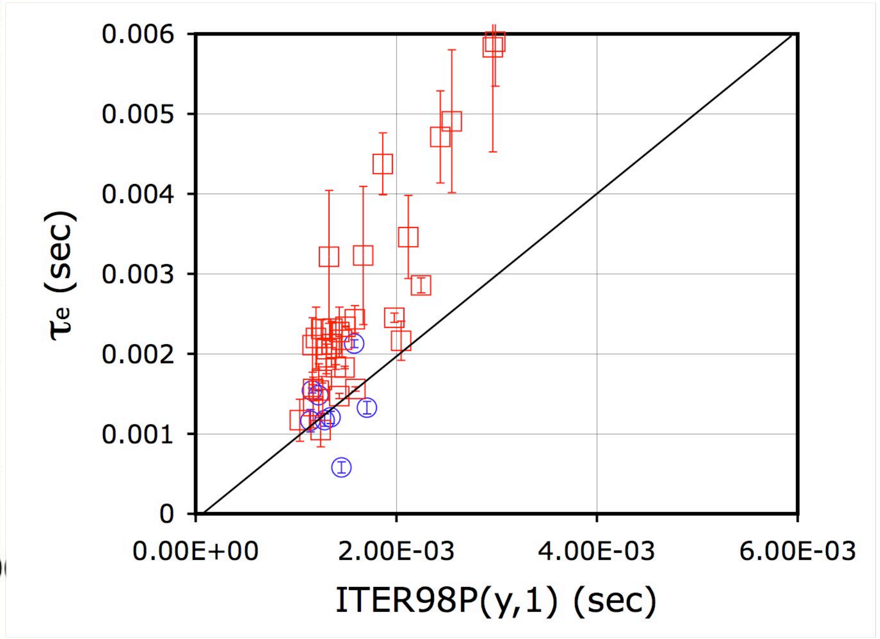
- Also a candidate: microtearing (∇T, high-β, ν^*) - low frequency magnetic fluctuations
  - $\chi_{e,NSTX}$(r/s~0.4 - 07) ~ $\chi_{microtearing}$ in low shear H-modes
- Higher B_T, I_p, lower $\nu^* \Rightarrow$ suppression of microtearing modes
- Higher B_T reduces fast ion instability drive $\Rightarrow$ suppression of GAEs
  - Higher B_T, I_p allow for isolation of ETG/TEM modes
- EPM also redistribute fast NB ions, affect current drive profile and efficiency

Transport: Reduced electron transport observed with lower recycling

- ◆NSTX: Use of between-shots lithium coatings increases stored energy
- ◆Increase primarily in electron channel
  - –Confinement increase limits NBI power
- ◆Other effects: ELM suppression
  - –Longer discharges
  - –Limited now by TF, OH capabilities

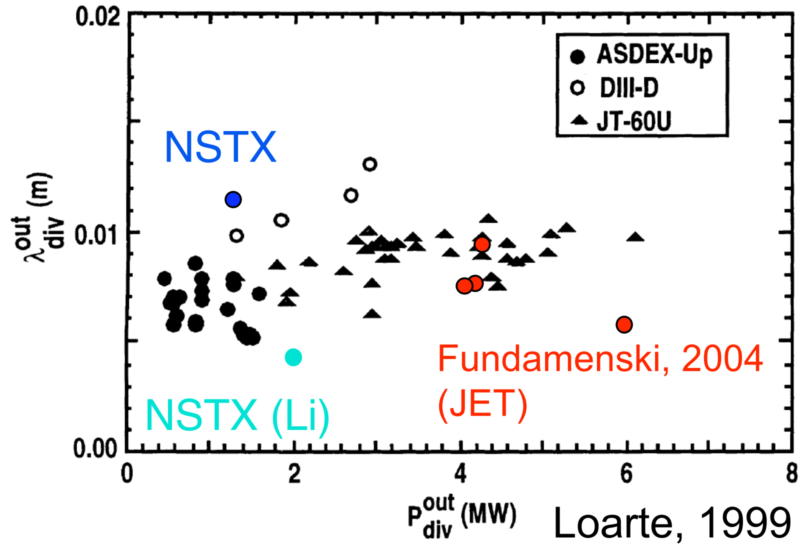


- ◆CDX-U: Use of liquid lithium PFCs increases τ_e
  - –Reduction in anomalous electron transport implied
    - »Low density, ohmic tokamak
    - »Decoupled electrons, (cold) ions

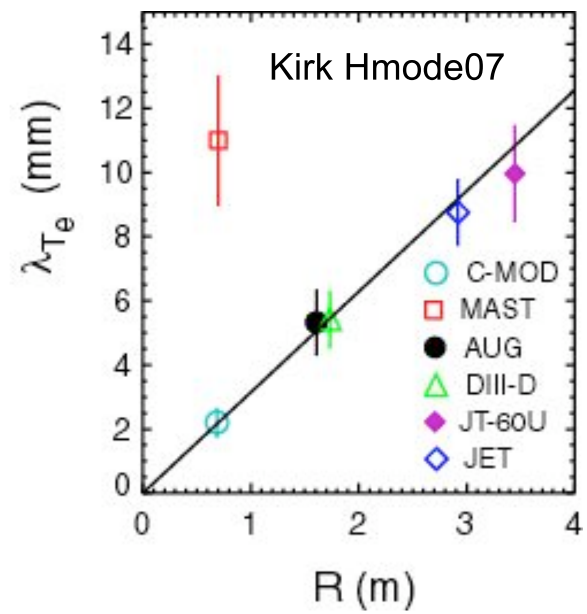


Edge and SOL transport rates not well understood
Extrapolation of pedestal and SOL widths uncertain

- Detailed transport analysis of pedestal and SOL transport scarce in STs
  - Ideal MHD stability probably limits P′ ($\nu_e^* \geq 1$)
  - Pedestal T_e, P_e generally lower than at high aspect ratio: B_t, β, or inherent R/a dependence?
- Generally SOL cross-field transport rates (to match data) higher than in high aspect ratio tokamaks
  - Extrapolation to future STs uncertain by factors of 2-5
  - Measured SOL power width in NSTX comparable to other devices, despite shorter $\ell_{||}$
- Need to understand pedestal and SOL *widths* at high P/R, $q_{||}$; low ν_e^*

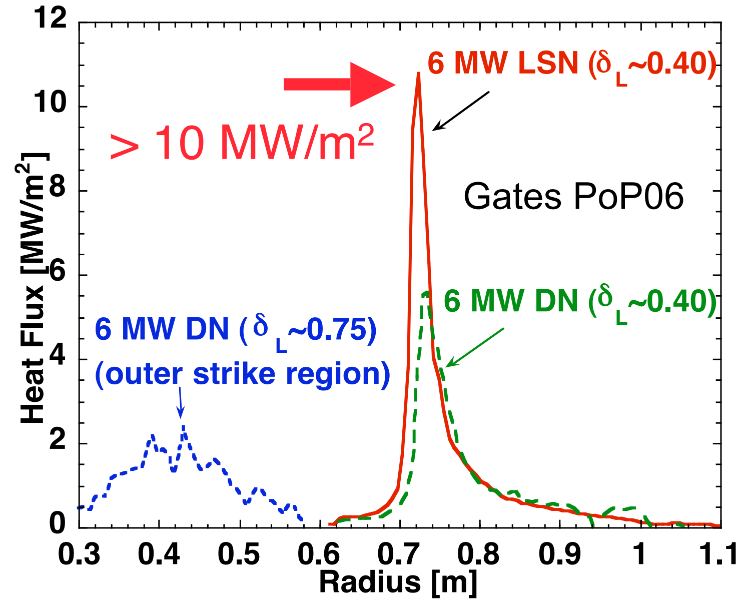


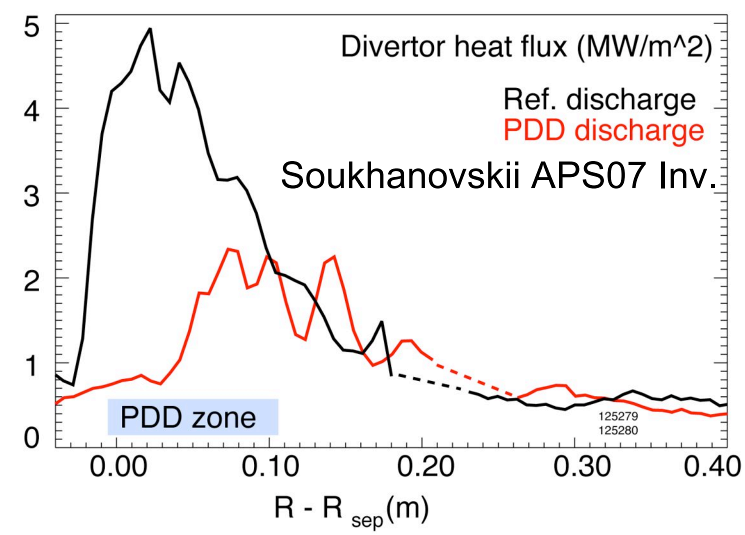
Loarte, 1999



Boundary: Combination of high flux expansion, double-null, and detachment will be needed for power handling

- STs have very high *measured* heat flux
  - Power density in excess of 10 MW/m^2 in NSTX is record
- Next step devices will have higher still heat flux, longer pulse
- Solid divertor targets (tungsten) exhibit surface exfoliation under helium bombardment
  - Less tolerant of high heat flux
  - Tritium retention in solids uncertain
- Heat flux management through plasma shaping (upper panel) and detachment with good confinement (lower panel) shows promise in NSTX
- But: detachment may be incompatible with low n_e, high P/R in STs (short $\ell_{||}$ - limited radiation volume)
  - Novel divertors can increase $\ell_{||}$ and decrease detachment n_e threshold
- Need test of detachment at high P/R
- Need test of novel divertor schemes

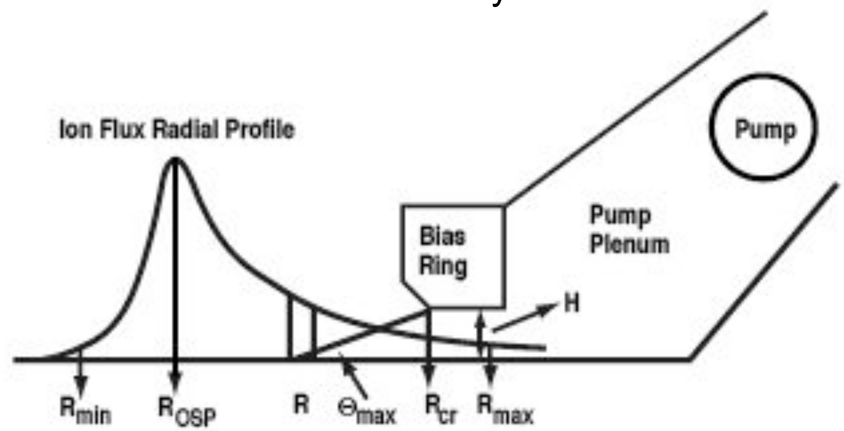


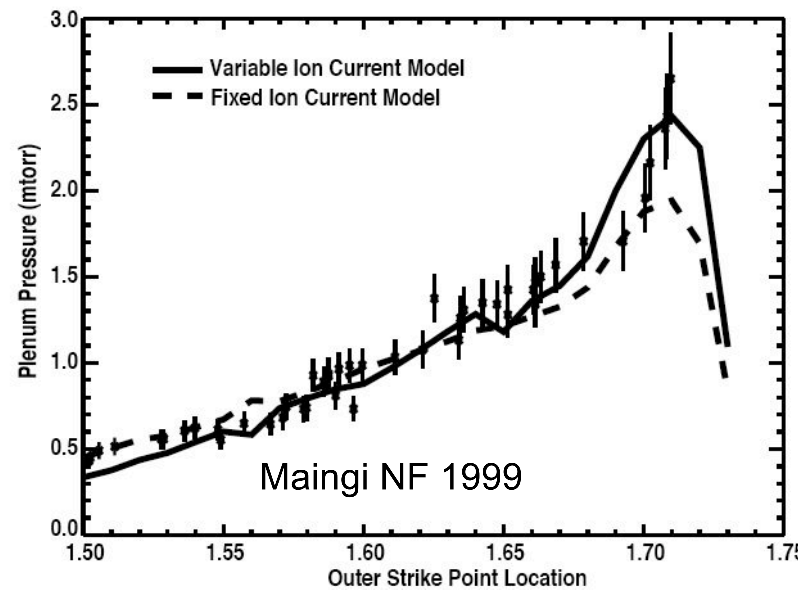


Cryopump advantages and disadvantages

- Operatio at n_e/n_{GW}~0.3-0.5 required
- Cryopumps are a proven technique for density control
  - Plenum exhaust understood with simple models
- Cryopump exhaust rate depends on plasma/plenum geometry
  - Must be optimized for particular configuration, i.e. less experimental flexibility
    - » Unclear if density control can be maintained during 1 - 10 MA rampup
  - Reduced pumping efficiency at high flux expansion
    - » Far removed from plasma in nuclear environment
- Possible loss of pumping speed for long pulse lengths if ice gets too thick
- Full testing requires long pulses

DIII-D study





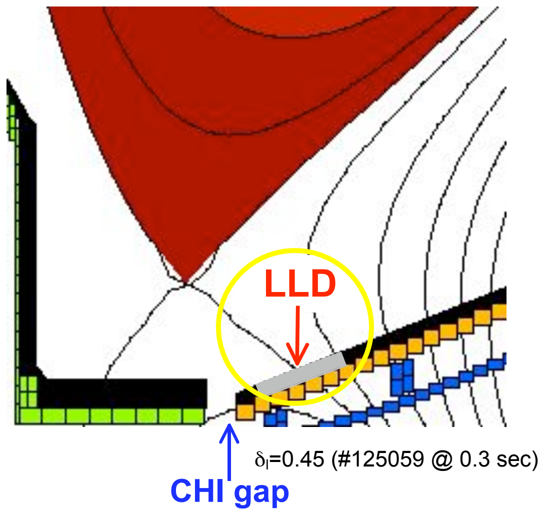
Maingi NF 1999

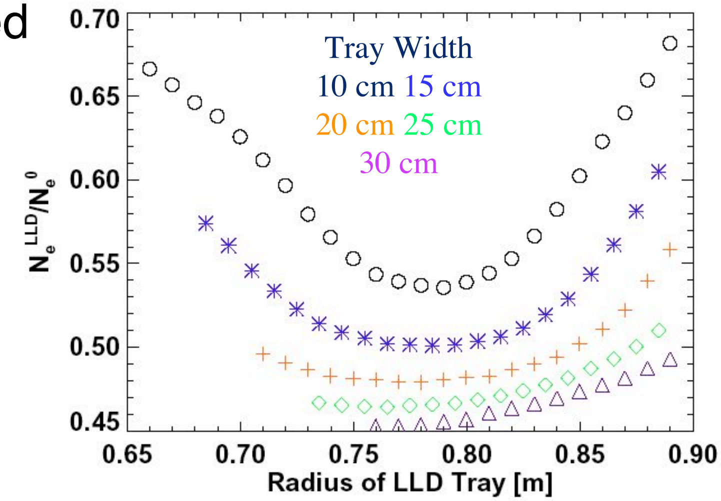
Liquid Li pumping advantages and disadvantages

- Li pumps over large area, raises τ_E, lowers Z_{eff}
  - 0-D models (e.g. NSTX design work) predict good density control with less geometric dependence than for cryopumps
- Liquid surfaces -> self-healing, no dpa damage
  - Combined pump/heat flux target solution - potentially elegant solution
  - Potential for high heat flux (>50 MW/m^2 in spot e-beam tests
- High tritium retention can provide for controlled tritium recovery
- Low-z -> higher fatal fraction in plasma

But:

- Li must be replenished for long pulses
- Surface temp. limit < 400 ^{0}C-500 ^{0}C
- Resilience to MHD j X B forces required
- Liquid lithium divertor requires testing



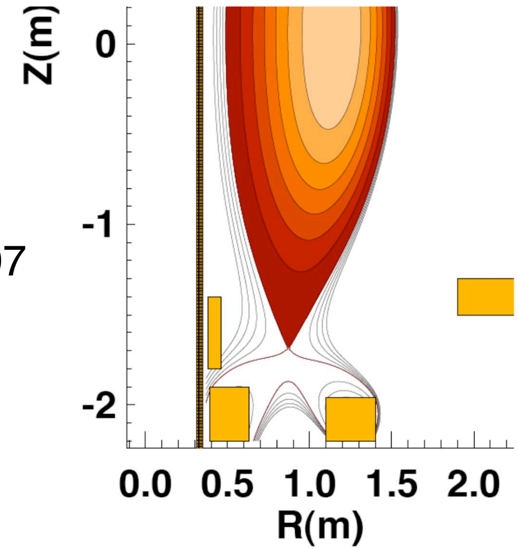


Strong density reduction
Expected for Li divertor target

Novel divertors can increase flux expansion and $\ell_{||}$

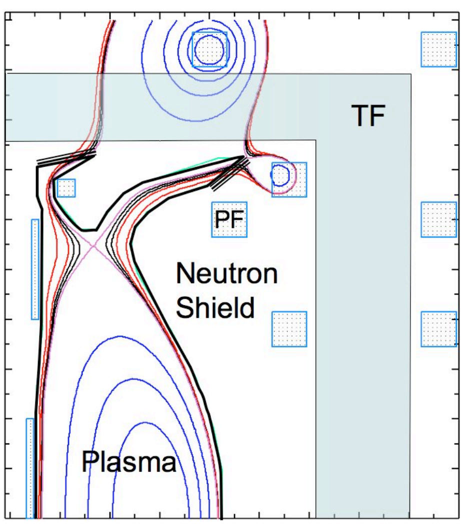
Snowflake(plus) divertor

Ryutov
PPCF 2007



Super X-Div at Large R

Valanju
APS 2008



- Snowflake (plus) divertor - uses higher order null to create large area of high flux expansion
  - Radiation volume increased
  - Shear profile near X-point changed
- Super-X divertor adds second X-point to increase outer strike point to high major radius, R
  - R_{strike} can be increased by 100%
  - $\ell_{||}$ doubled or tripled, increasing radiation volume
  - Divertor target can be removed from high neutron area
- Novel divertors need to be tested at high P_{heat}/R

Startup/sustainment, transport, boundary research needs and gaps

- Startup, rampup, and sustainment
  - Design, engineering, testing (including nuclear) of candidate ohmic systems
    - Determine available flux
  - RF current drive techniques at higher TF
    - Several "standard" RFCD techniques untested in the ST
  - Integrated tests, modeling, demonstrations of candidate startup, rampup, sustainment systems
    - Large startup current for adequate NB ion confinement
    - Very large current ramp required compared to present experiments
    - Adequate testing includes wall/divertor and fueling effects for long-term evolution of recycling, impurities, etc
    - Stringent control requirements for equilibrium, MHD stability
- Transport studies require larger ranges in important external, internal parameters
  - B_T, I_p, ρ^*, especially υ^*
  - Modeling, diagnostics
- Boundary studies require multiple experimental tests
  - Flux expansion at high P/R (requires higher P, B_T, I_p)
  - Novel divertor geometries
  - Extensive tests of novel liquid lithium solutions
  - Solid wall solutions at high temperature
  - Steady state particle control and fueling, over a range of global recycling
  - Pulse lengths of several wall equilibration times required for adequate testing

Backup

Question 2

Response to Question 2

Aaron Sontag

What features make the ST preferable for this goal; what challenges need to be overcome to achieve it?

The following strengths make the ST an attractive option for creating a high heat flux, high neutron fluence environment:

1) Common physics basis with the tokamak
2) Increased margins to known stability boundaries
3) Favorable ion transport scaling
4) Strongly shaped plasma edge and SOL
5) Compact configuration & simplified engineering

The following challenges must be overcome to realize the ST goal:

1) Startup and steady-state operation
2) Electron turbulence and transport
3) Macroscopic stability
4) Disruption mitigation and divertor design
5) Energetic particle instabilities and impact
6) Extrapolation to the very low collisionality regime

ST Strengths (1)

- Common physics basis with the tokamak
  - allowed rapid advance to high-β at low-A
  - projection to future devices with low physics risk
- Increased margin to stability boundaries
  - transient demonstration of stable high-β operation
  - aided by:
    - » natural high shaping
    - » high rotation w/NBI due to low moment of inertia
    - » increased ion banana width
      - low ρ^* scale up (~x2) to reach ST goal
- High fraction of pressure driven currents
  - near-fully bootstrapped equilibria with realistic profiles

ST Strengths (2)

- Favorable ion transport scaling
  - strong rotation & E x B shear stabilize ion scale instabilities
  - near neoclassical ion thermal diffusivity
    - » decreases with increasing field and current
    - » different transport mechanism than electrons
  - only factor of 2 scale up in ρ^* to ST goal
- Strongly shaped plasma edge and SOL
  - increased peeling/ballooning stability expected
    - » larger margin in pedestal ∇p
  - increased trapped particle instabilities lead to greater SOL width
  - high flux expansion of SOL at divertor

ST Strengths (3)

- Compact configuration & simplified engineering
  - Demo-relevant heat flux and neutron fluence at modest size and field for divertor testing
  - efficient use of PF & TF leading to I_{PF}, $I_{TF} \sim I_P$
  - reduced size, fusion power, tritium inventory, cost
  - full remote maintainability

ST Challenges (1)

- Startup and steady-state operation
  - startup options exist but have yet to achieve full current
  - non-inductive sustainment has yet to be demonstrated
- Electron turbulence and transport
  - needs to be more fully understood (similar to tokamaks)
- Macroscopic stability
  - need simultaneous demonstration of:
    - » reliable, sustained high-β operation
    - » maintenance of stabilizing plasma rotation
  - required to avoid disruptions
- Disruption mitigation and divertor design
  - large uncertainties remain (similar to tokamak)
  - high heat flux & neutron fluence require divertor capability far beyond that for ITER

ST Challenges (2)

- Energetic particle instabilities and impact
  - NBI experiments show:
    - » increased ratio of fast ion speed to Alfven speed
    - » increased ratio of fast ion beta to total beta
  - indicates possible increased level of *AE activity in ST goal
  - could lead to additional fast ion redistribution/loss
- Extrapolation to very low collisionality regime
  - ~2 orders of magnitude scale down of ν^* expected
  - requires effective particle control compatible with:
    - » long pulse
    - » high temperature walls