NSTX

Supported by U.S. DEPARTMENT OF ENERGY Office of Science

1: XP-1006: Low Current, High-f_{NI} Experiments
2: Relationship of Transport Scalings to Non-Inductive Current Drive in NSTX

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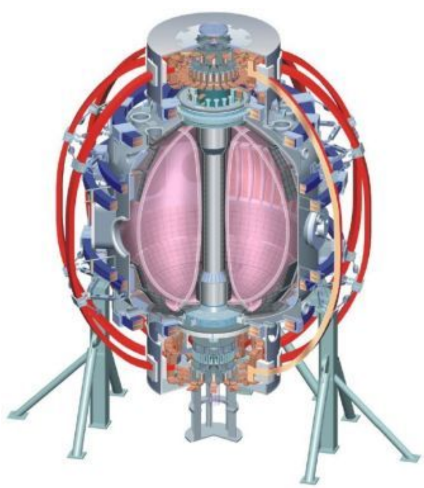
NSTX Late 2010 + Early 2011 Results Review



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Overview of Day 2 of XP-1006

- Day 1: Use impurity reduction techniques to lower Z_{eff} in 700 kA, high-β_P scenarios.
  - Largely unsuccessful.

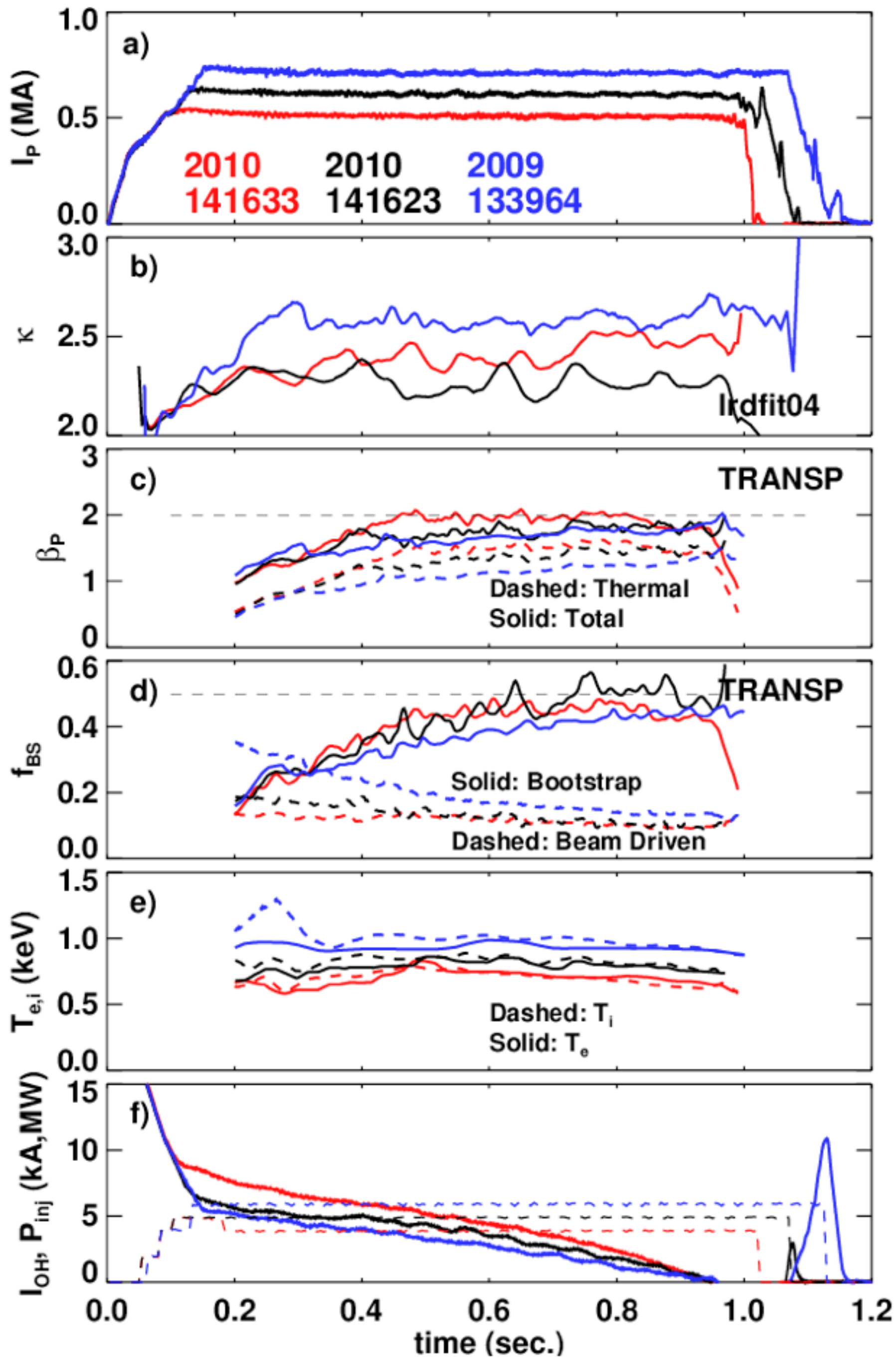
- Day 2: Test the limit of non-inductive fraction in low(er)-current plasmas.
  - Done during the "AM-Lithium" part of the run, machine not optimal.
  - Still, very productive.

- Took 25 discharges.
  - 14 discharges as 600 kA
    - Warmed up the machine, power scan, played with the fuelling.
  - 11 discharges at 500 kA
    - Kappa scan, power scan.

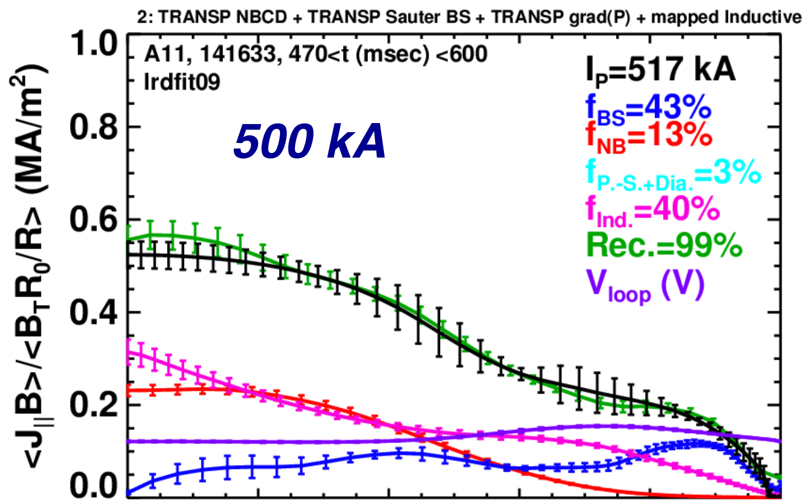
- Achievements:
  - Achieved (for first time) sustained β_P=2 during the flat-top.
  - Completed scaling of τ, f_{NI} from 0.5 to 1.3 MA.

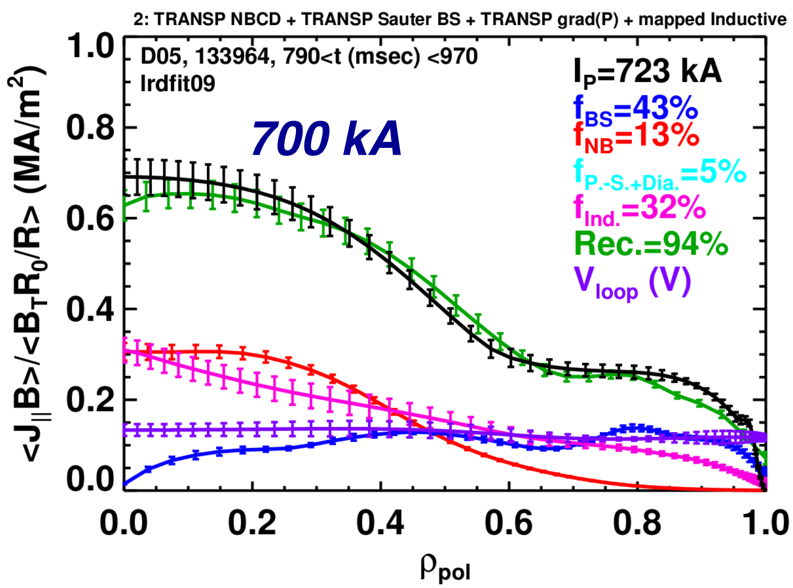
Demonstrated β_P=2 During the I_P Flat-Top.

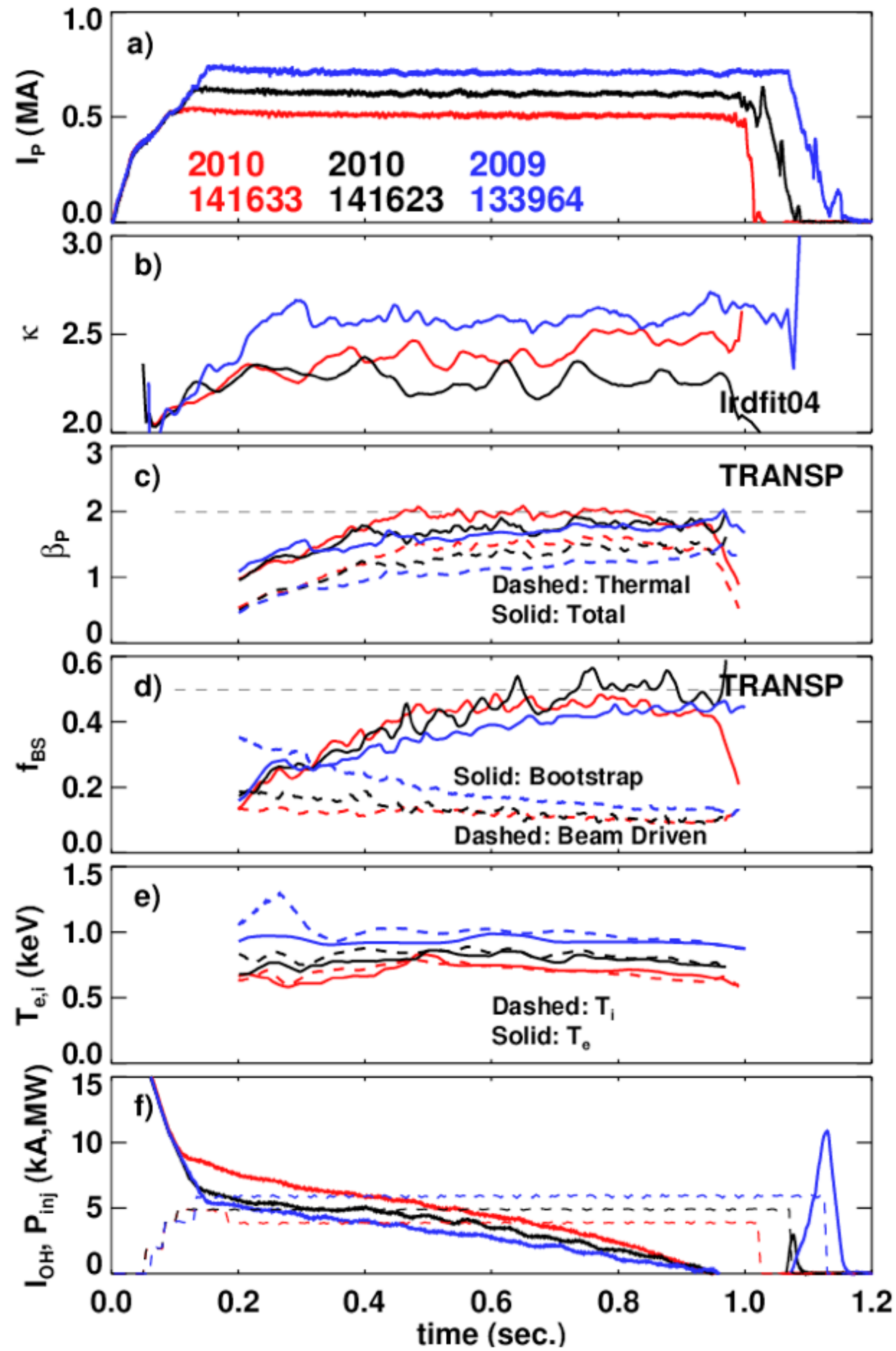
- 500, 600, and 700 kA examples.
  - 700 kA 133964 has lowest V_{surf} of an H-mode NB shot.
- Reduced beam power with I_P.
  - TRANSP shows that the loss power is about constant.
- Low current shot goes to β_P=2
- Beam fraction is much higher at 700 kA.
  - More power, higher T_e.
- Bootstrap fraction is highest at 600 kA.
  - 500 kA shot falls beneath $f_{BS}=0.44\varepsilon^{1/2}\beta_P$ scaling (due to collisionality?)
- Ohmic current fraction is roughly constant.
  - I_{OH}~I_P, but T_e increases with I_P so, V_{surf} is lower at higher I_P.



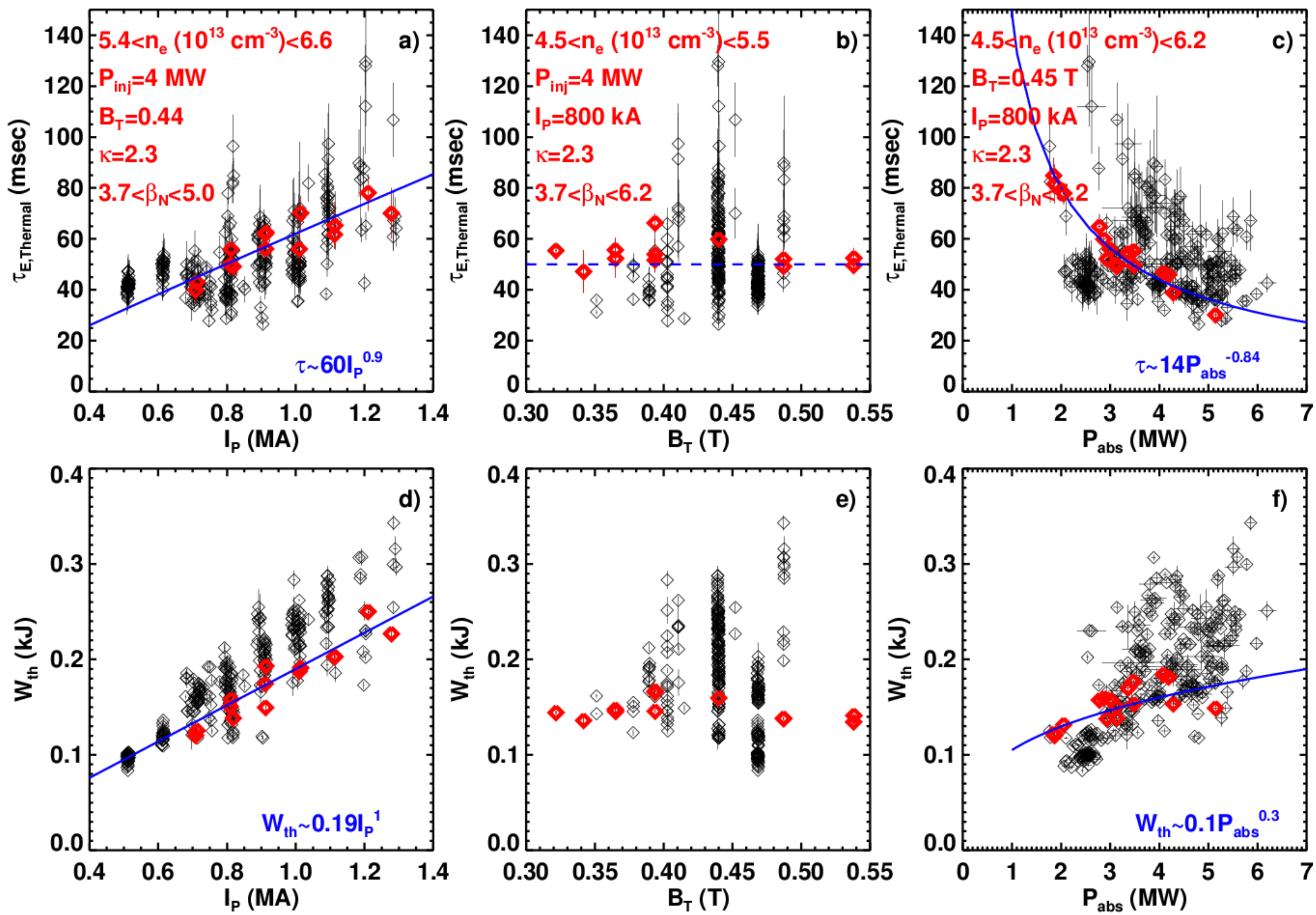
Demonstrated β_P=2 During the I_P Flat-Top.



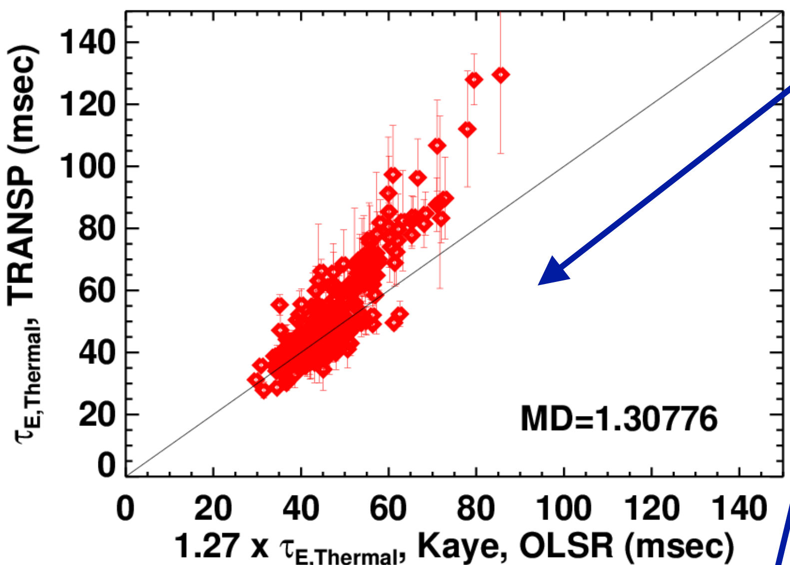




Reminder: XP-1041 Showed Different Confinement Scaling Than Previous ST Results…Due to Lithium?



Low Current Data Adds To Large Confinement Database in Lithiumized Data

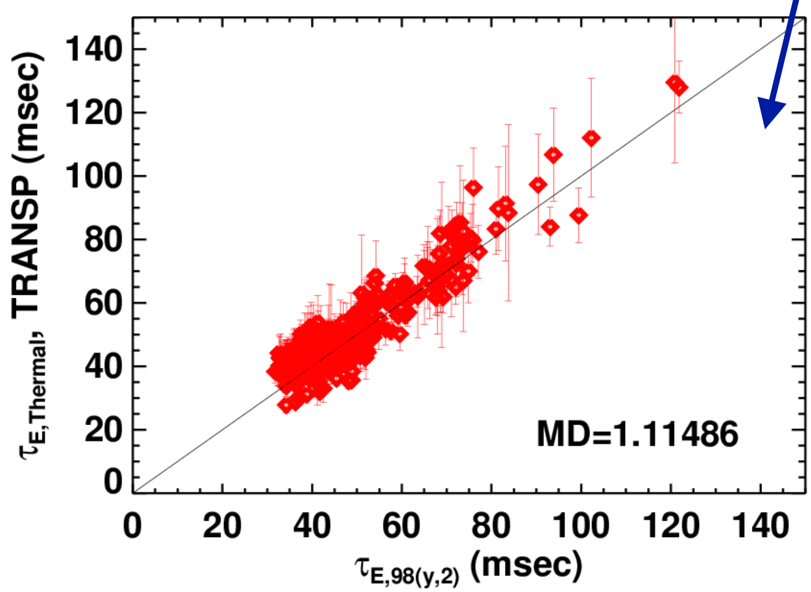


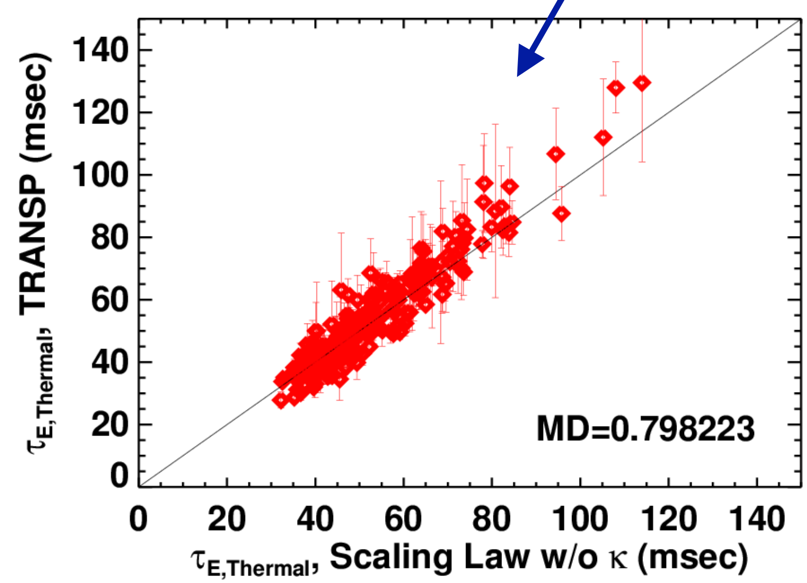
Previous NSTX Scaling (No Lithium!)
Systematic error at high confinement (high I_P)

ITER-98$_{y,2}$ Scaling Looks OK

New MLR Fit: Marginally better than ITER-98$_{y,2}$

$$\tau_{E,thermal} \propto I_P^1 B_T^{0.3} n_e^{0.35} P_{abs}^{-0.9}$$





Bootstrap Current Scaling is Consistent With Thermal Confinement Scaling

- Envelope of the f_{BS} vs. I_P curve looks like $1/I_P$.
- Bootstrap fraction scales mostly as $\varepsilon^{1/2}\beta_P$.
- Do linear regression on the bootstrap fraction against engineering variables.

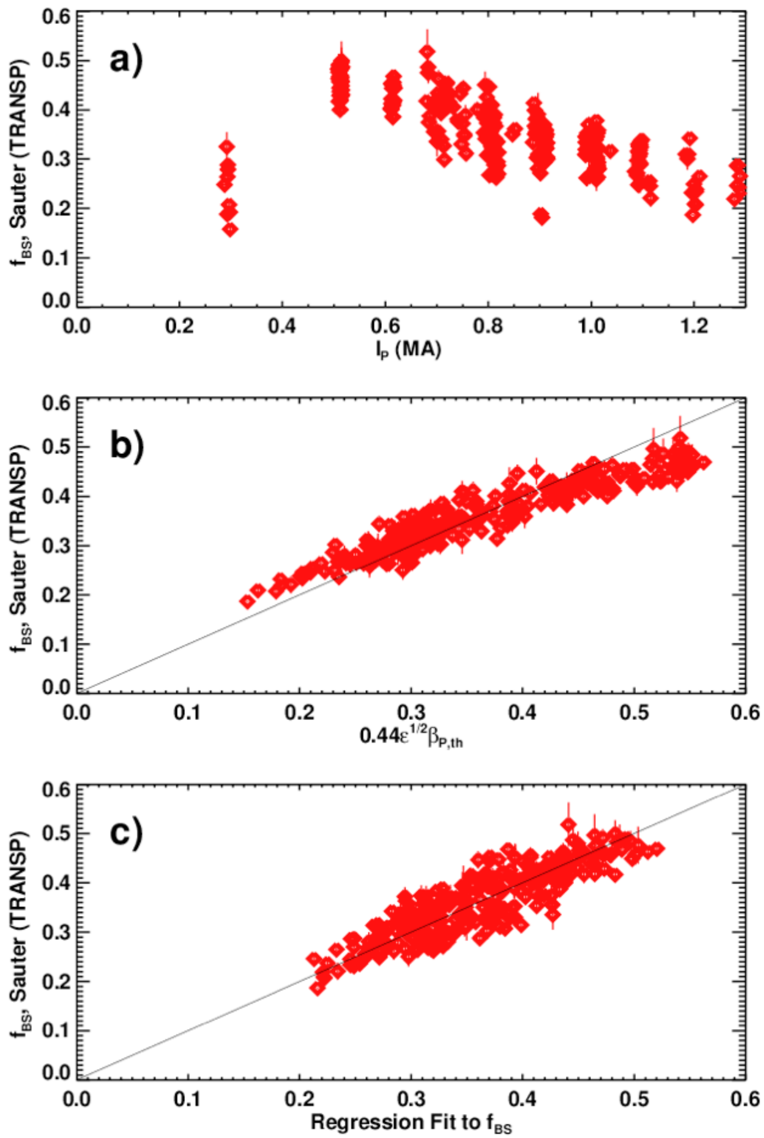
$$f_{BS} = C I_P^{-1} B_T^{0.3} n_e^{0.4} P_{inj}^{0.15} \varepsilon^{-1}$$

- Aspect ratio strongly coupled to elongation… ε^{-1}=A~κ.
- Is this consistent with confinement scaling?...essentially yes!

$$f_{BS} \propto \sqrt{\varepsilon}\beta_P \propto \sqrt{\varepsilon}\,\frac{l_P^2 P_{abs}\tau}{V I_P^2}$$

$$\tau_{E,thermal} \propto I_P^1 B_T^{0.3} n_e^{0.35} P_{abs}^{-0.9}$$

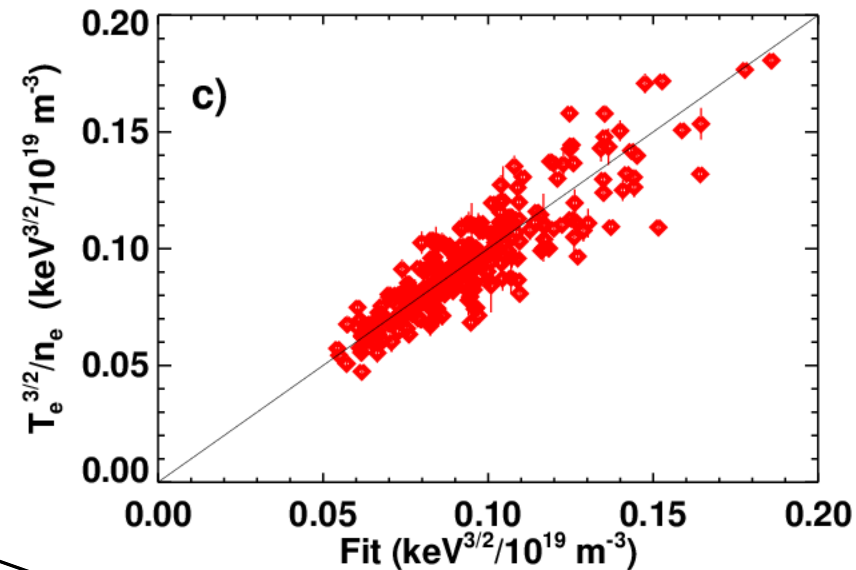
$$\frac{\sqrt{\varepsilon} l_P^2}{V} \propto \frac{\sqrt{\varepsilon} a^2 \kappa^2}{a^3 \kappa A} \propto \frac{\sqrt{\varepsilon}\kappa}{aA} \propto \frac{\sqrt{\varepsilon}}{a} \propto \varepsilon^{-1/2}$$



Need to Predict the Electron Temperature (Slowing Down Time) for Beam Current Drive

- Slowing down time depends on $T_e^{3/2}/n_e$.
- Do regression analysis on this quantity.

$$\frac{\bar{T}_e^{3/2}}{n_e} \propto I_P^{1.1} B_T^{0.25} n_e^{-1.6} P_{abs}^{0.06}$$



- This implies (roughly):

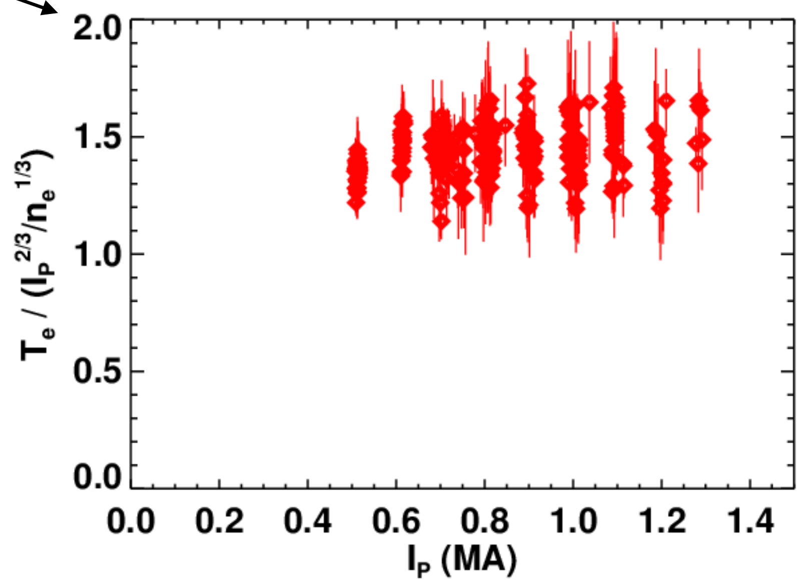
$$\frac{\bar{T}_e}{I_P^{2/3} / n_e^{1/3}} = Const.$$

- Is it consistent with transport scaling?
  - Roughly, yes.

$$T \propto \frac{P_{abs}\tau_{th}}{n}, \quad \tau_{Th} \propto I_P B_T^{0.25} P_{abs}^{-0.9} n_e^{0.4}$$

$$\frac{T^{3/2}}{n} \propto \frac{P_{abs}^{3/2}\tau_{th}^{3/2}}{nn^{3/2}} \propto \frac{P_{abs}^{3/2}}{n^{5/2}} I_P^{3/2} B_T^{0.4} P_{abs}^{-3/2} n_e^{0.6}$$

$$\frac{T^{3/2}}{n} = I_P^{3/2} B_T^{0.4} n_e^{-1.9}$$



Confinement Scalings Mean Density Determines the Neutral Beam Fraction

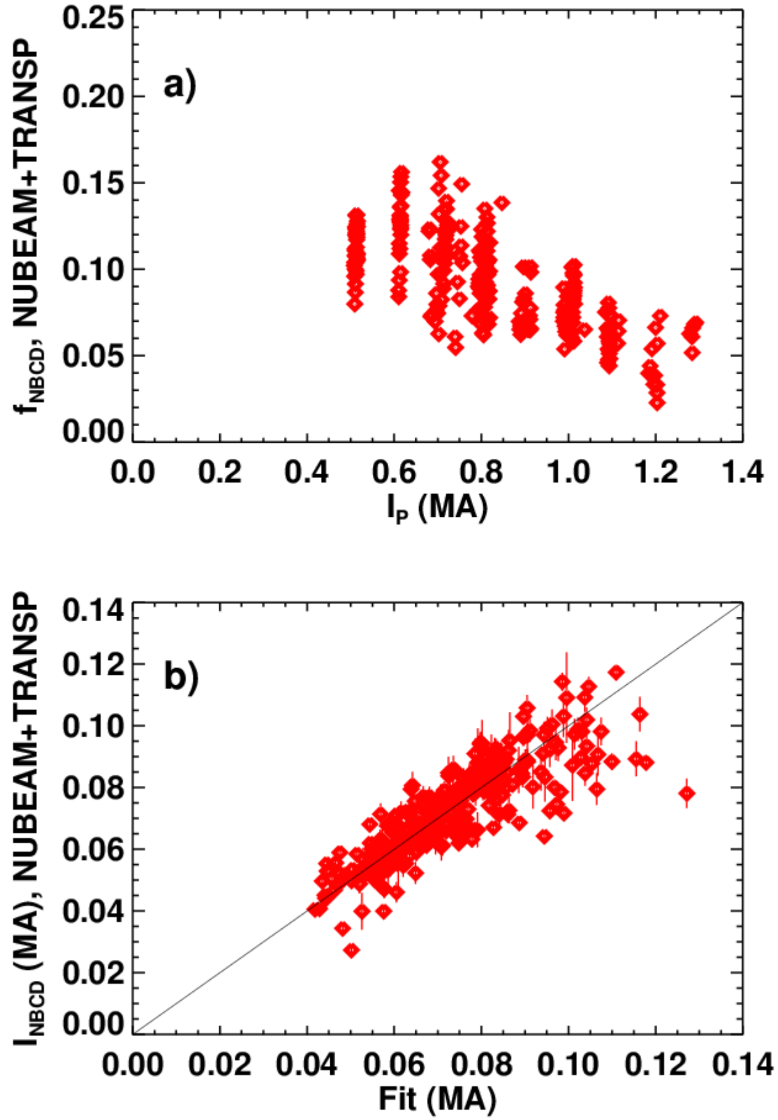
- Neutral beam current fraction increases at lower current…is this $1/I_P$? No!
- Dominant terms in the NBCD:
  - Slowing down time
  - Injected powers
- Fit beam driven current with a simple formula:

$$I_{NBCD} = C_{NBCD} \frac{\overline{T}_e^{3/2}}{\overline{n}_e}\left(P_{inj,A} + 0.85P_{inj,B} + 0.7P_{inj,C}\right)$$

  - Factors of 0.85 & 0.7 from TRANSP
- Use regression for $T_e^{3/2}/n_e$ ($\sim I_P/n_e^{3/2}$).
- Find that the dominant scaling is:

$$f_{NBCD} = C_{NBCD}\overline{n}_e^{-3/2}\left(P_{inj,A} + 0.85P_{inj,B} + 0.7P_{inj,C}\right)$$

  - Apparent $1/I_P$ dependence in a) comes from the confinement scaling with I_P and variation of n_e and T_e with I_P



Summary:

- Day 2 of XP-1006 was very useful.
  - Completed a nice set of scans at 600 & 500 kA.
  - Achieved sustained β_P=2 for a range of parameters.
  - Didn't achieve lower loop voltage (lower T_e).
- Developed a Consistent Picture of How Confinement Scalings Impact the Non-Inductive Current Drive
  - Thermal confinement in lithiumized plasmas has a weak B_T scaling, strong I_P scaling, and strong power degradation.
  - Bootstrap fraction scales mostly with $1/I_P$, weakly on n_e and B_T, essentially independent of P_{inj}.
  - Average temperature increases with $I_P^{2/3} n_e^{-1/3}$, so beam fraction scales as $n_e^{-3/2} P_{inj}$…consistent with global scaling.
  - Need to assess how these may impact upgrade scenarios.
    - In any case, need to expand these results over the wider range available in NSTX-Upgrade.

Comparison of Lithium vs. No Lithium Scalings
B_T and P_{inj} Matter More With the Old Scaling

General Scaling Law

$$\tau_{E,thermal} \propto I_P^{\beta_I} B_T^{\beta_B} n_e^{\beta_n} P_{abs}^{\beta_P} \varepsilon^{\beta_\varepsilon}$$

$$f_{BS} \propto I_P^{\beta_I - 2} B_T^{\beta_B} n_e^{\beta_n} P_{abs}^{\beta_P + 1}$$

$$f_{NB} \propto I_P^{\frac{3}{2}\beta_I - 1} B_T^{\frac{3}{2}\beta_B} n_e^{\frac{1}{2}(3\beta_n - 5)} P_{abs}^{\frac{3}{2}(\beta_P + 1) + 1}$$

"Lithium" Scaling Law

$$\tau_{E,thermal} \propto I_P^{0.9} B_T^{0.3} n_e^{0.3} P_{abs}^{-0.9}$$

$$f_{BS} \propto I_P^{-1.1} B_T^{0.3} n_e^{0.3} P_{abs}^{0.1}$$

$$f_{NB} \propto I_P^{\frac{3}{2}0.9 - 1} B_T^{\frac{3}{2}0.3} n_e^{\frac{1}{2}(3*0.3 - 5)} P_{abs}^{\frac{3}{2}(-0.9 + 1) + 1} = I_P^{0.35} B_T^{0.5} n_e^{-2} P_{abs}^{1}$$

"Kaye" Scaling Law

$$\tau_{E,thermal} \propto I_P^{0.5} B_T^{1} n_e^{0.3} P_{abs}^{-0.6}$$

$$f_{BS} \propto I_P^{-1.5} B_T^{1} n_e^{0.3} P_{abs}^{0.4}$$

$$f_{NB} \propto I_P^{\frac{3}{2}0.5 - 1} B_T^{\frac{3}{2}1} n_e^{\frac{1}{2}(3*0.3 - 5)} P_{abs}^{\frac{3}{2}(-0.6 + 1) + 1} = I_P^{-0.25} B_T^{1.5} n_e^{-2} P_{abs}^{1.6}$$

f_{BS} & β_P Didn't Change with κ (within range tested).

- 500 kA plasmas, 4 MW.
- Aspect ratio and elongation strongly coupled in scan.
  - See talk on XP-1071.
- All shots achieve β_P~2.
  - Bootstrap fractions of ~50%.
- l_i is kept quite low.