NSTX

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Physics and Control Considerations for a Steady State High-β Spherical Torus

Stefan Gerhardt
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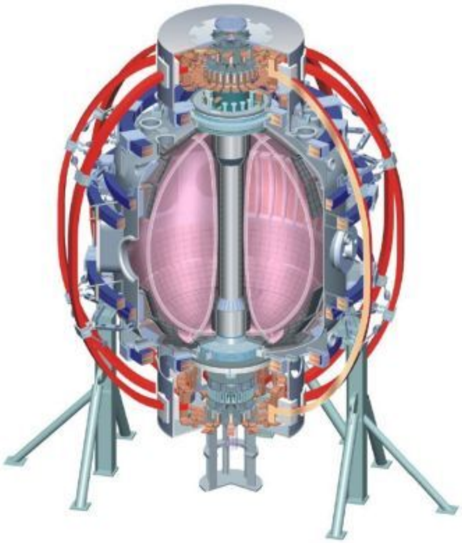

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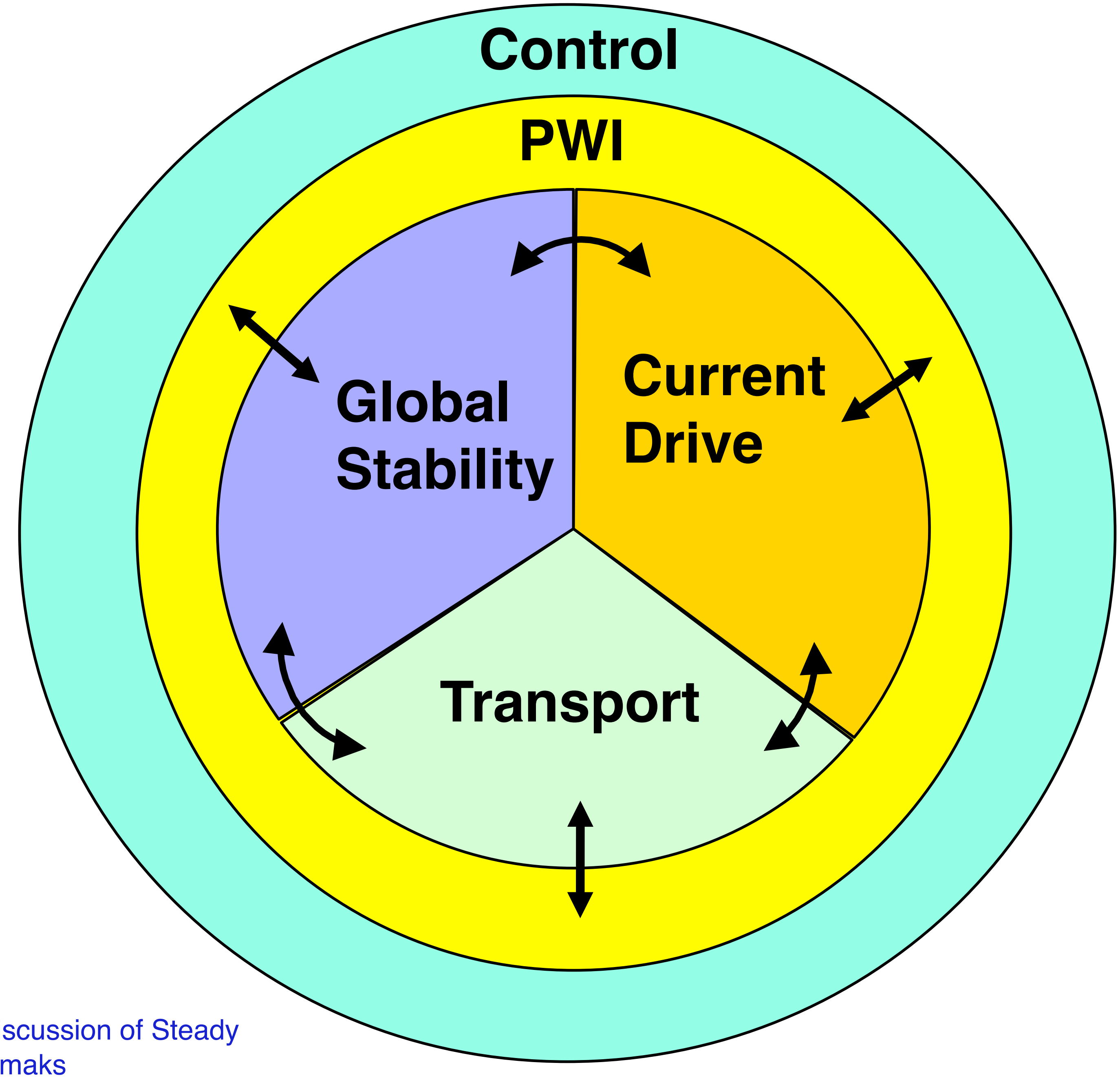
A View of High-β ST Operation (Essentially the Same as for Conventional Aspect Ratio)



Control

PWI

Global Stability

Current Drive

Transport

See T. Luce, Phys. Plasmas **18** For Discussion of Steady State Conventional Aspect Ratio Tokamaks

Overview

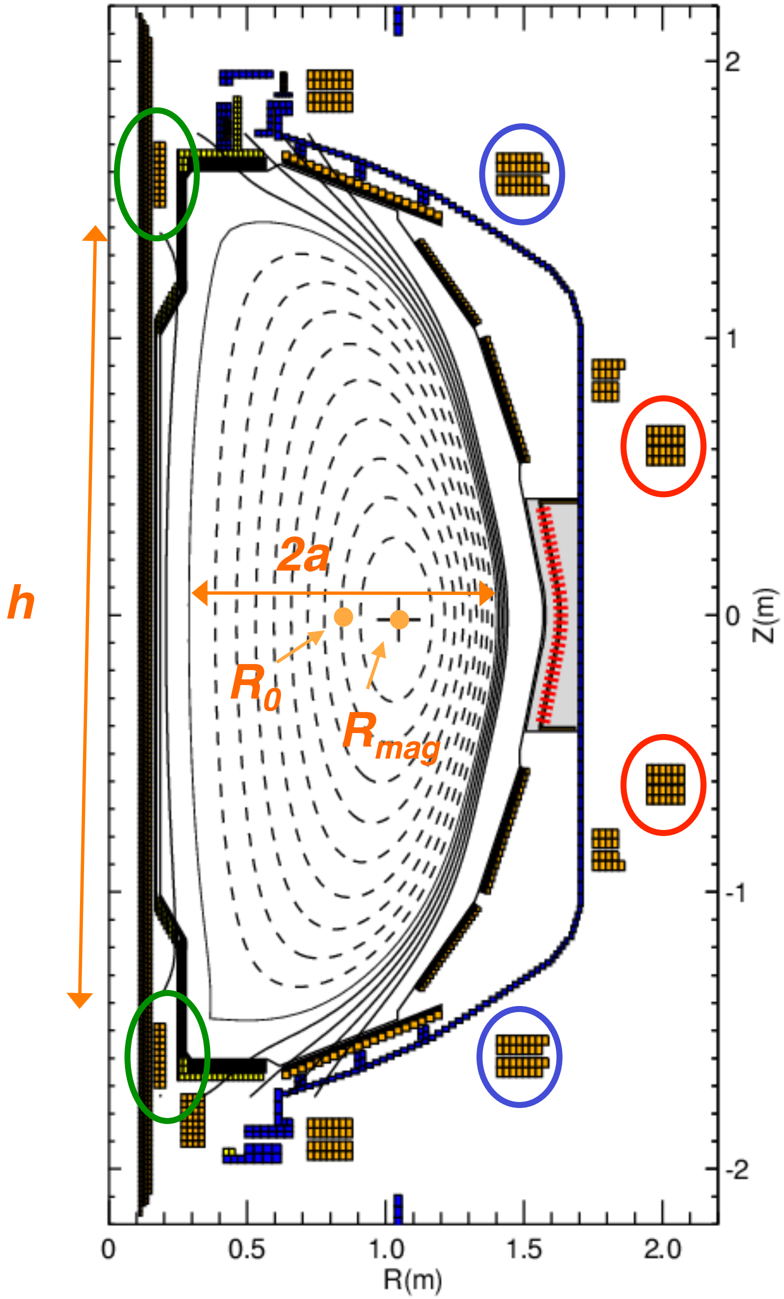
- Take a narrow view: focus on global stability, current drive, confinement…and their control.
  - Neglect critical issues of pedestal & divertor physics, PMI, energetic particle physics, plasma startup.
- Outline:
  - Basics: Historical & technical background of the ST.
  - Optimization to high β.
  - Current drive requirement.
  - How transport impacts the above.
  - Control considerations (time permitting).

Give you some sense of the interplay between, and optimization of, parameters called β_N, β_T, β_P, l_i, F_P, $A=1/\varepsilon$, κ, δ, H

Brief History of the ST

- 1980s
  - Peng and Strickler (NF, 1986) synthesized many of the important advantages of the ST in a single reference:
    - Natural high elongation, improved average field curvature & better utilization of the TF coil
- 1990s:
  - START device demonstrated high β with at low-A and strong shaping.
  - Theory studies demonstrated the existence of very attractive high-β equilibria.
- 2000s:
  - NSTX and MAST demonstrated sustained high-performance plasmas.
  - ST designs for a component test facility and a reactor appear.
- 2010s:
  - NSTX and MAST are both approved for major upgrades.

Major Components of An ST Like NSTX



Coils

Vertical Field: Anti-parallel to plasma current, counter-acts tendency for the plasma column to radially expand, controls the radius of the plasma.

$F_R \sim J_T B_Z$

Radial Field: Anti-parallel to plasma current, controls the elongation, vertical position.

Divertor: Parallel to the plasma current, “pull” an X-point, increase the elongation.

Solenoid: Current ramps through the shot, providing an inductive voltage to drive current (goal of research: eliminate this inductive current drive).

$$\kappa = \frac{h}{2a} \qquad A = 1/\varepsilon = \frac{R_0}{a}$$

$$\beta_P = \frac{2\mu_0\langle p\rangle}{B_P^2} \qquad \beta_T = \frac{2\mu_0\langle p\rangle}{B_{T,0}^2}$$

Must Have Strong Shaping and High β_N For an Efficient Reactor

- Fusion power scales as $n^2T^2 \sim B_T^2\beta_t^2$
  - B_T is limited by field at the coil, so we must maximize β_t.
- Bootstrap current scales as $f_{BS}=C_{BS}\varepsilon^{1/2}\beta_P$.
  - Want to maximize the self driven current, so maximize β_P.
- What is the requirement for them both to be large?
  - Consider definition of poloidal β:

$$\beta_P = \frac{2\mu_0\langle p\rangle}{B_P^2} = \frac{2\mu_0\langle p\rangle}{\left(\mu_0 I/l_P\right)^2}$$

  - Approximate expression of the poloidal circumference l_P:

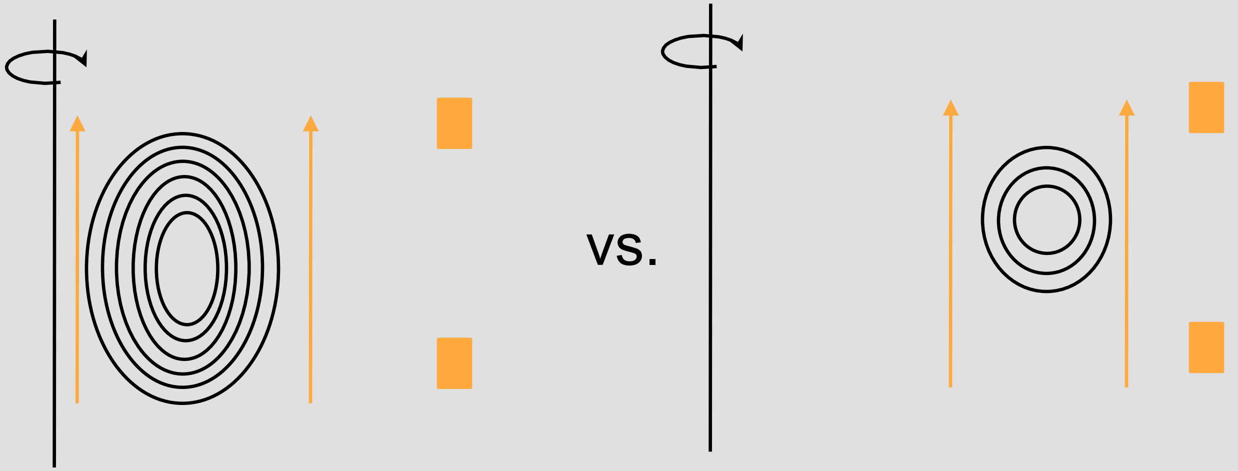
$$l_P \approx 2\pi a\sqrt{\frac{1+\kappa^2}{2}} \quad \Rightarrow \quad \begin{cases} \beta_P = \dfrac{2\mu_0\langle p\rangle}{B_P^2} = \dfrac{2\mu_0\langle p\rangle}{\left(\mu_0 I\right)^2}\left(2\pi a\right)^2\left(1+\kappa^2\right) \\ q \sim \dfrac{B_T}{B_P} \sim \dfrac{B_T}{I_P}\sqrt{1+\kappa^2} \end{cases}$$

  - Multiply β_P and β_T to get:

$$\beta_T\beta_P = 25\frac{1+\kappa^2}{2}\left(\frac{\beta_N}{100}\right)^2, \qquad \text{where } \beta_N = \frac{\beta_T}{I_P/aB_T}$$

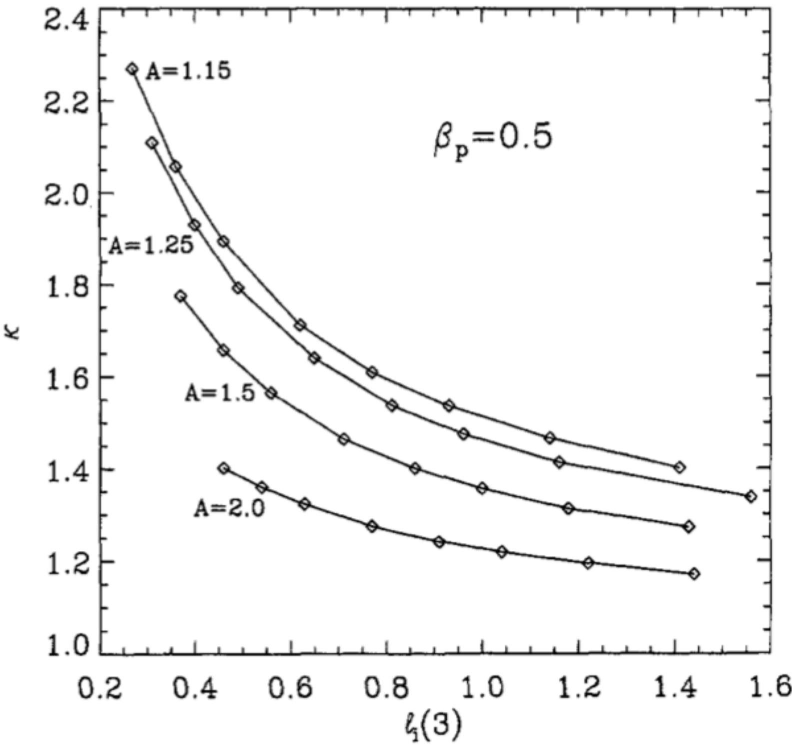
  - *Must have simultaneously high elongation and β_N.*

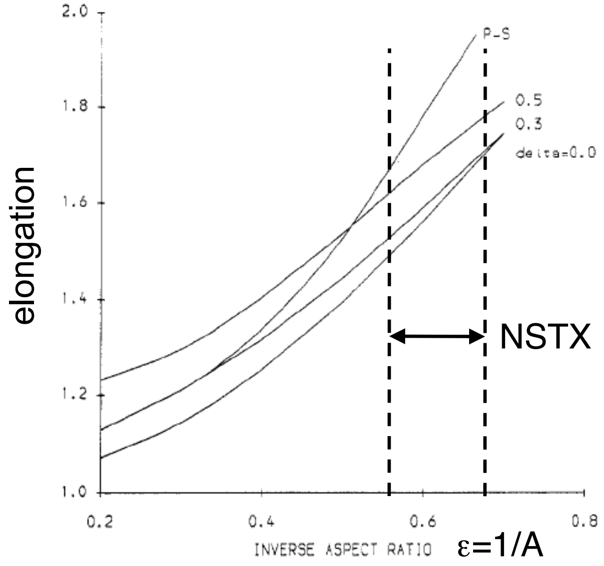
ST Plasmas are “Naturally Elongated”… …and it Depends on the Current Profile



“Natural Elongation” is the boundary elongation with a straight equilibrium field.

J.E. Menard, et al, Nuclear Fusion **37**





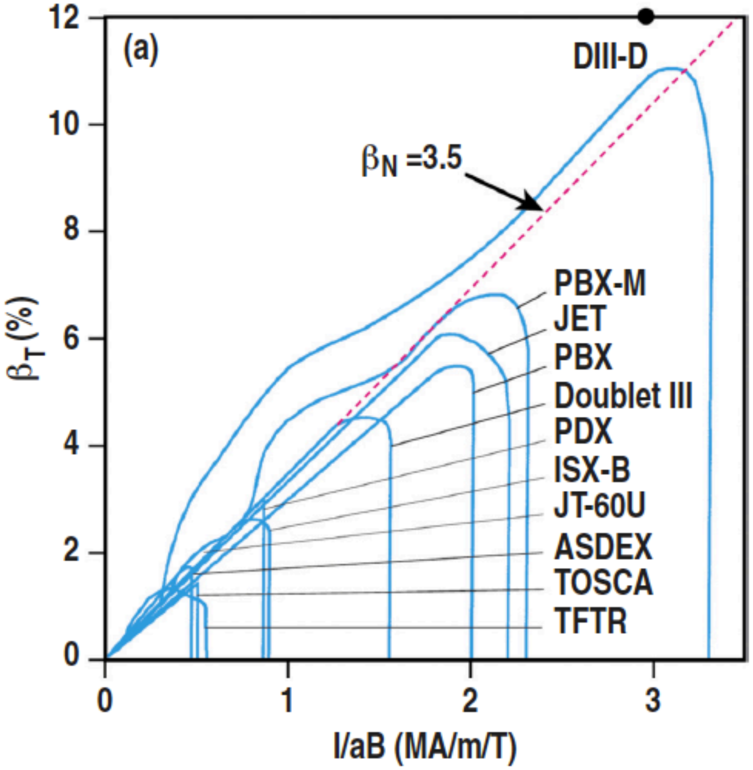
Roberto & Galvao, Nuclear Fusion **32**

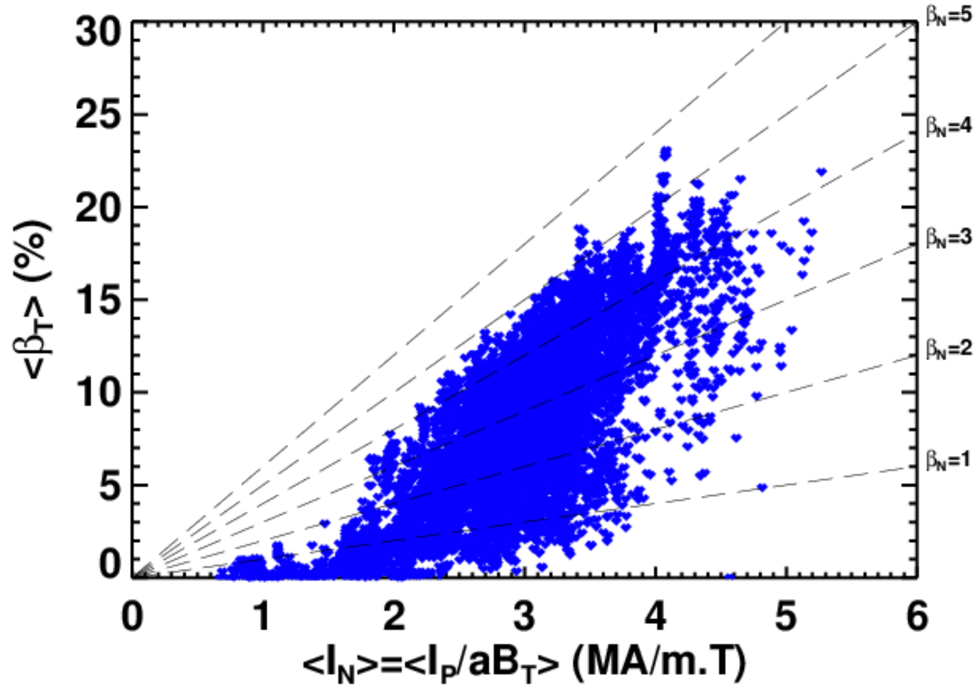
l_i indicates “peakedness” the current profile.
“low-l_i” means broad current profile.

$$l_i(1)=\frac{l_p^2 \iiint B_P^2 dV}{V\left(\mu_0 I_P\right)^2}$$

To Lowest Order, β_N Controls Ideal Stability

- Troyon, others, showed that the β_T limit scales as I_P/aB_T.
  - Based on calculations of low-n kink stability, high-n ballooning stability.
  - Said another way, if you want high-β_T, must increase I_P/aB_T.



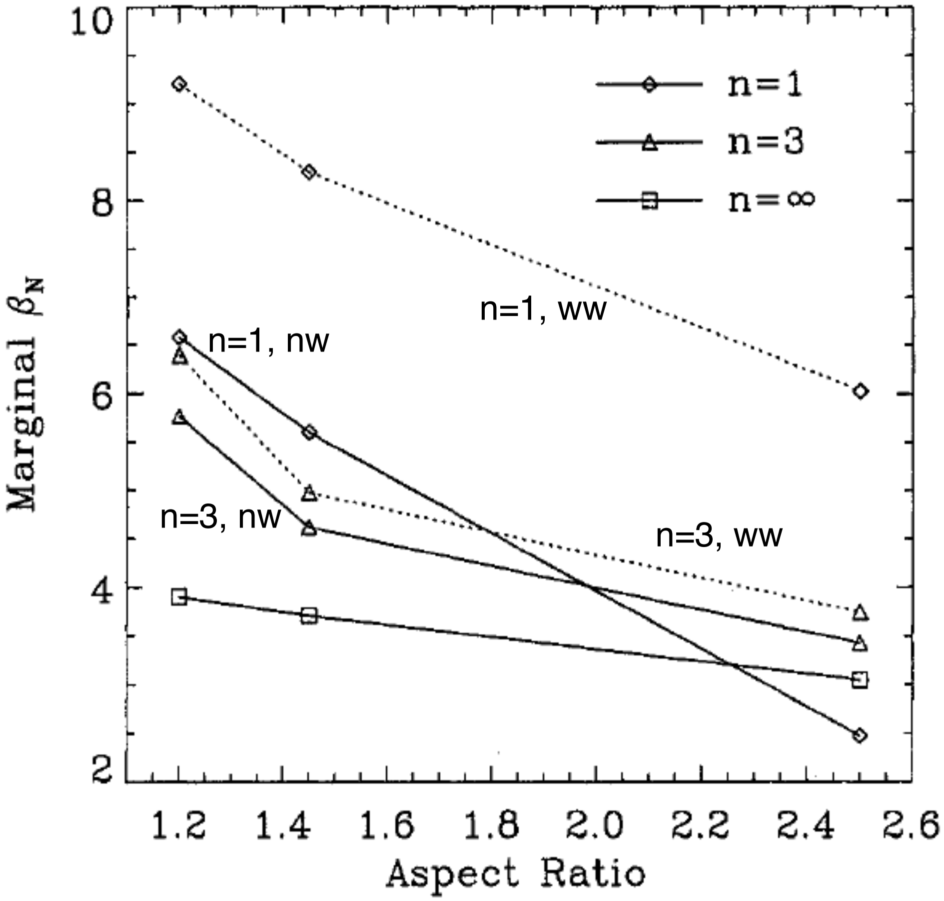


T. Luce, Phys. Plasmas **18**

The β_N Limit Can Be Modified by Changes to the Plasma Shape….

- Three important degrees of freedom in axisymmetric plasma boundary shaping.
  - Aspect ratio (A): Better utilization of the good-curvature, high-TF region, increased safety factor.

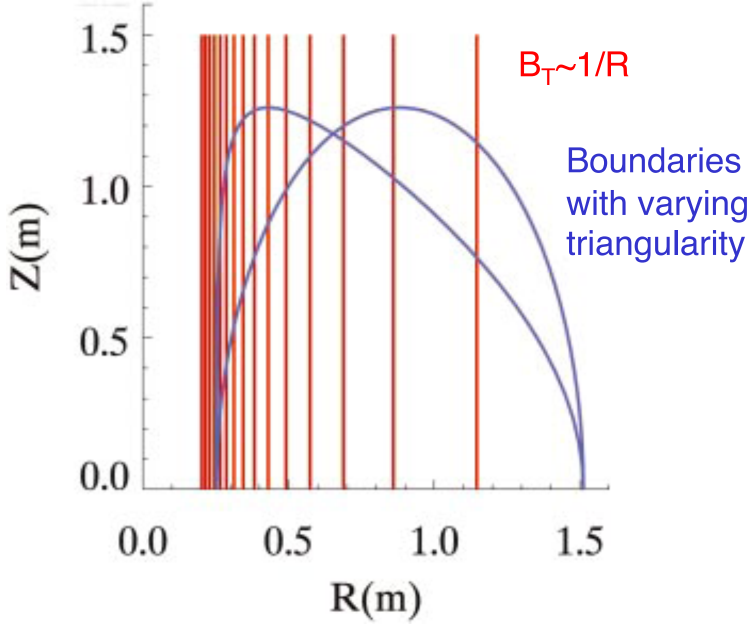
J.E. Menard, et al, Nuclear Fusion **37**

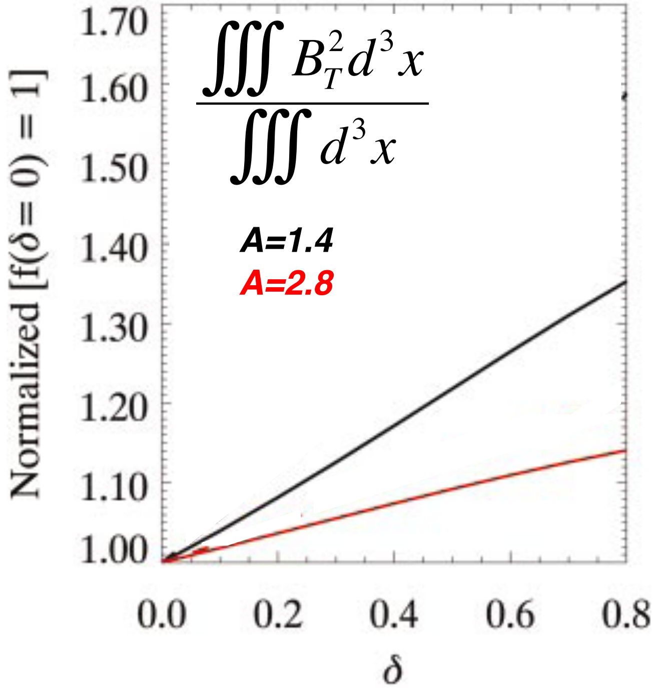


Solid: No Wall (nw)
Dashed: Conformal Wall 0.4a from Plasma (ww)

The β_N Limit Can Be Modified by Changes to the Plasma Shape….

- Three important degrees of freedom in axisymmetric plasma boundary shaping.
  - Aspect ratio (A): Better utilization of the good-curvature, high-TF region, increased safety factor.
  - Elongation (κ): Increasing elongation increases q, improving the *kink stability* & increasing *bootstrap currents*.
  - Triangularity (δ): Increasing the triangularity causes fields lines to spend more time in the *high-field good-curvature* region.





D. Gates, et al, Phys. Plasmas **10**

The β_N Limit Can Be Modified by Changes to the Plasma Shape….

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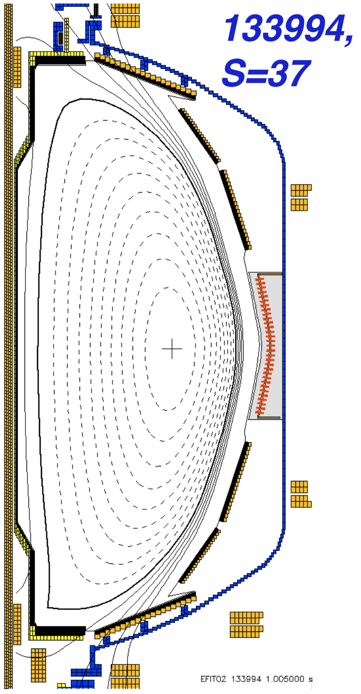
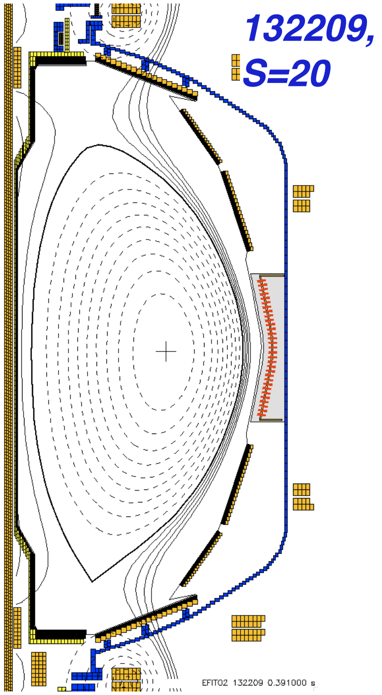
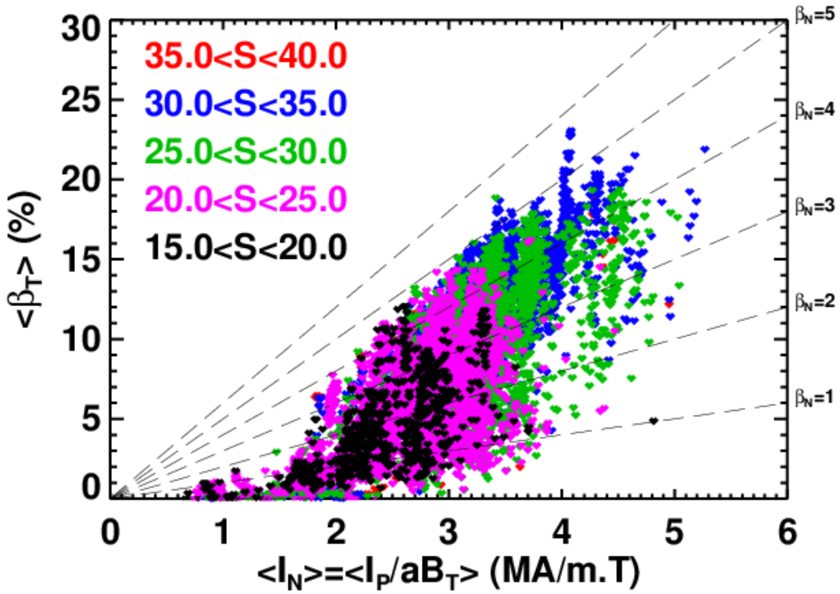
  - Triangularity (δ): Increasing the triangularity causes fields lines to spend more time in the *high-field good-curvature* region.
  - Many more degrees of freedom are possible with non-axisymmetic shaping…*this is a stellarator!*
- “Shape Parameter” S encapsulates shape effects.

$$S = \frac{q_{95} I_P}{a B_T} \propto \varepsilon\left(1+\kappa^2\right) f(\kappa,\delta,\varepsilon,\ldots)$$



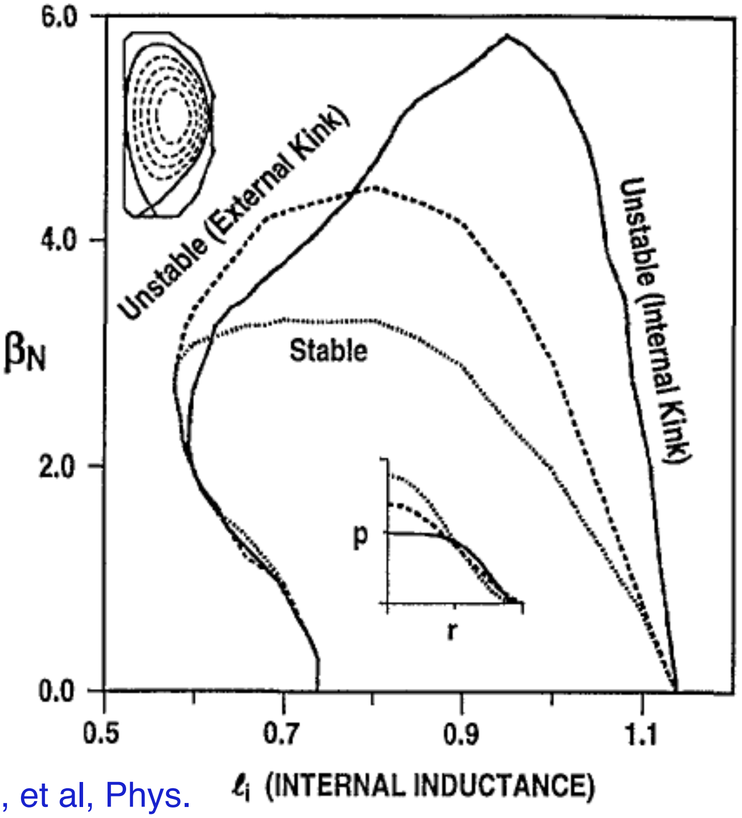




The β_N Limit Can Be Modified by Changes to the Plasma Shape….and the Profiles

- Broad pressure profiles align the pressure gradient with region of large magnetic shear.
  - Highest stability psooible with broadest profiles.
- Instability predicted at both high & low l_i.
  - High-l_i -> Internal kinks, low-l_i ->external kinks.

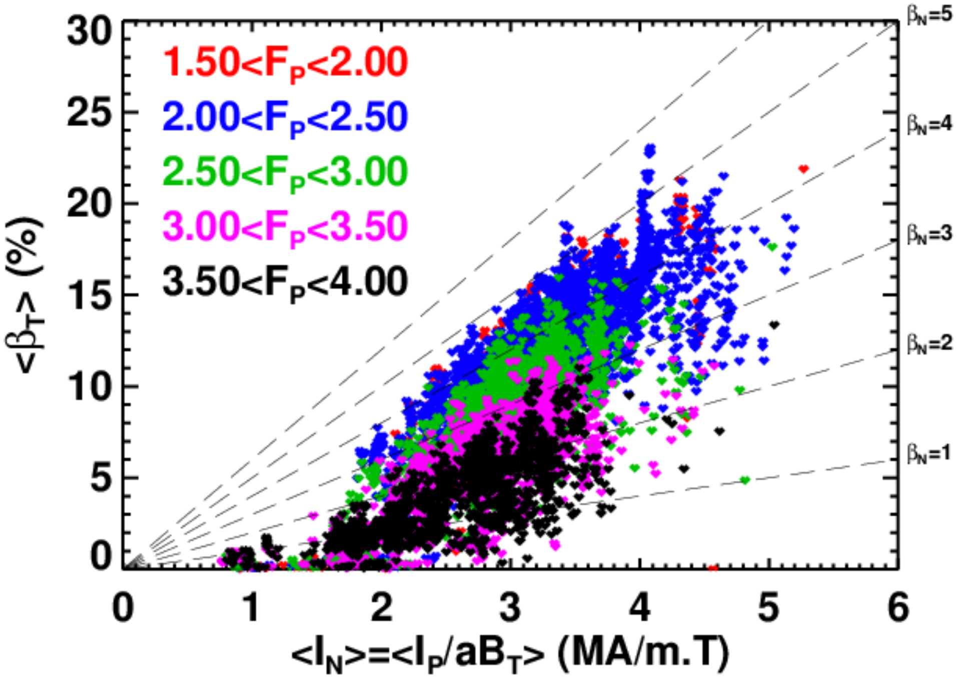
$$F_P = \frac{p_0}{\frac{1}{V}\iiint p\,d^3V}$$



E.J. Strait, et al, Phys. Plasmas **5**

<β_N> vs. <F_P> in NSTX

Low pressure peaking required for high-β_N.



Theoretical Studies in the Late 1990s Showed the Promise of the ST

Both cases stable to kink and ballooning instabilities, ~99% bootstrap driven
Strong shaping and broad pressure profiles are key.

J.E. Menard, et al, Nuclear Fusion **37**
β_T=45%

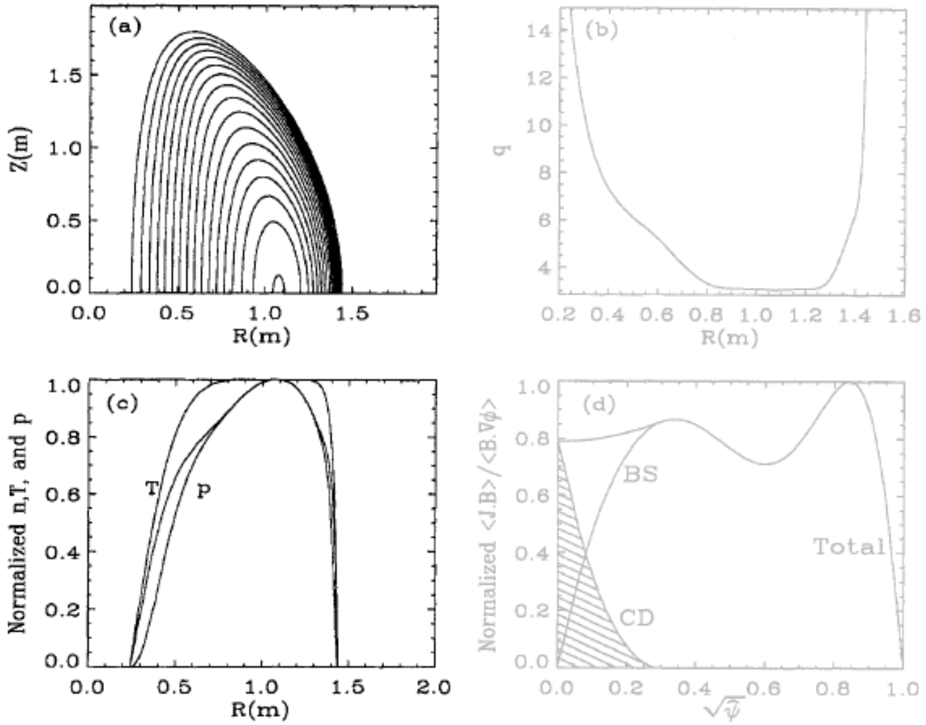


FIG. 17. Details of an $A = 1.40$, $\kappa = 3.0$, $\delta = 0.45$ equilibrium with $\beta = 45\%$ and $f_{\nabla p} = 99.3\%$ that is stable to ballooning and $n = 1$–4 kink modes with a conducting wall: (a) poloidal flux contours, (b) safety factor profile, (c) pressure, temperature and density profiles, (d) total current, bootstrap current and external current drive profiles.

R.L. Miller, et al, Physics of Plasmas **4**
β_T=54%

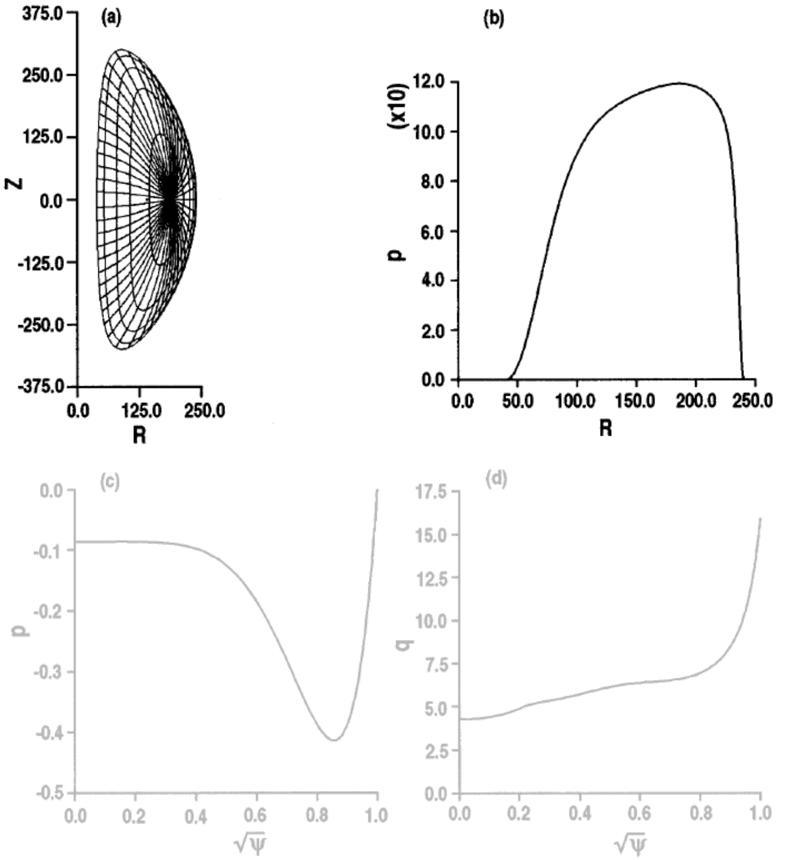


FIG. 1. High beta equilibrium: κ=3.0, δ=0.5, L_p/L_T=0.5. (a) Flux contours; (b) pressure profile across the midplane as a function of major radius; (c) p' as a function of $(\bar{\psi})^{1/2}$; (d) q as a function of $(\bar{\psi})^{1/2}$.

START Studies Demonstrated Highest-Ever β_T in a Tokamak-Like Device.

M. Gryaznevich, et al, PRL 1998

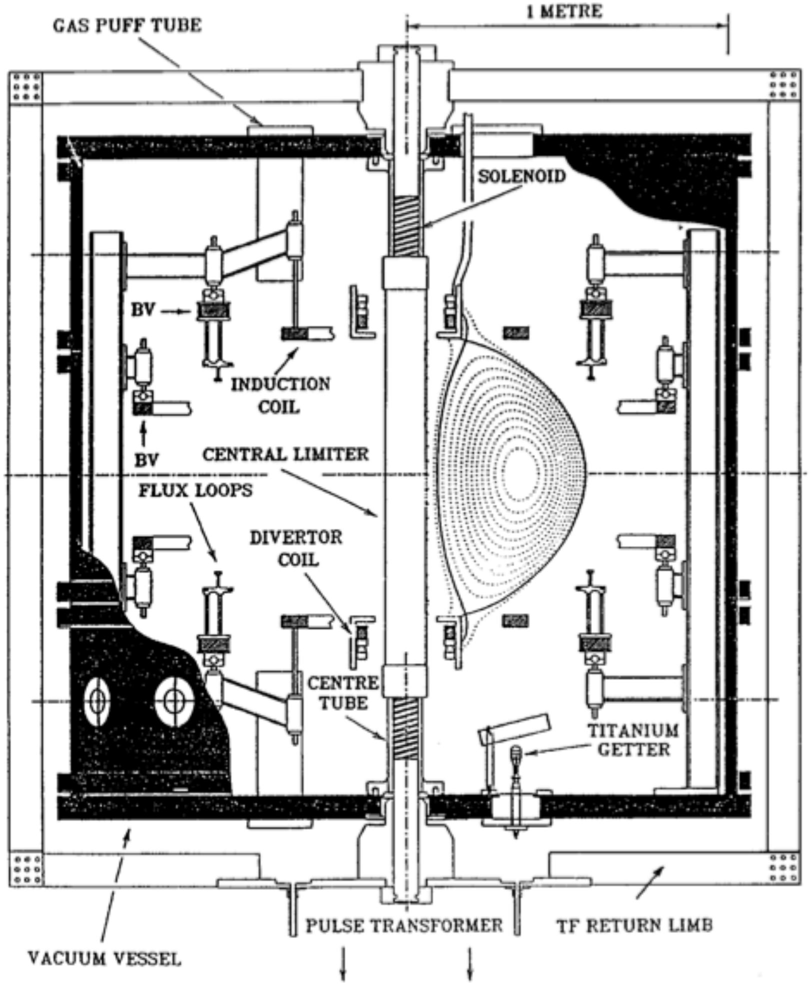


FIG. 1. Cross section of the START device (April, 1997) showing an equilibrium reconstruction of high-β shot #32993.

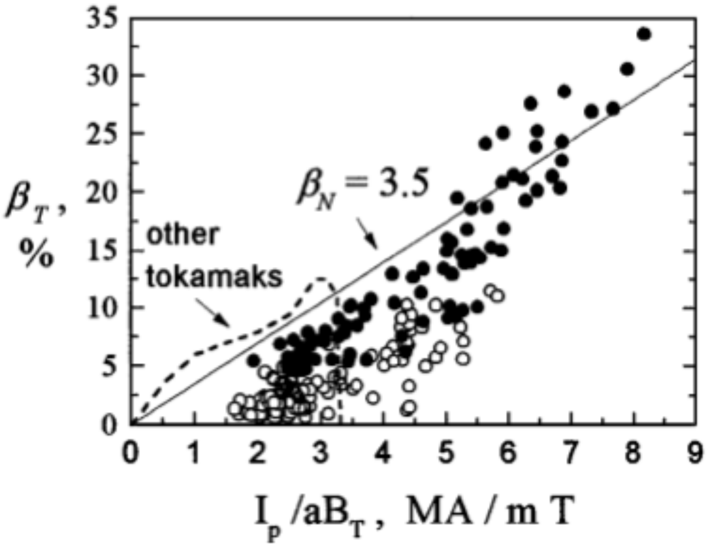
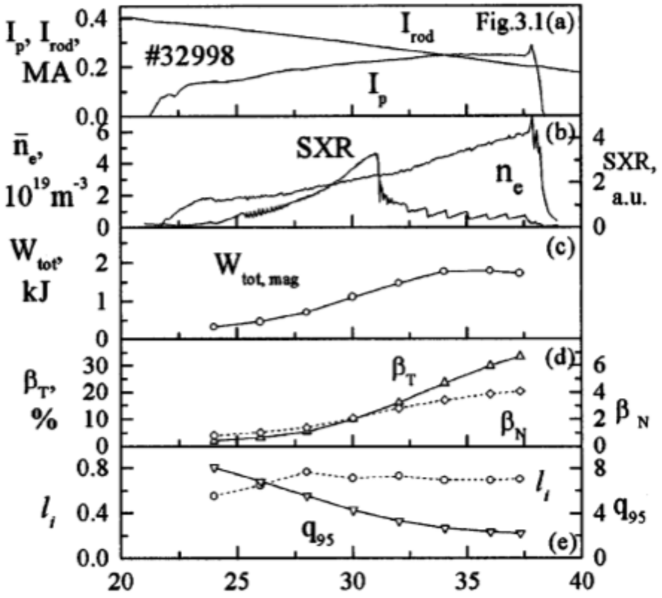


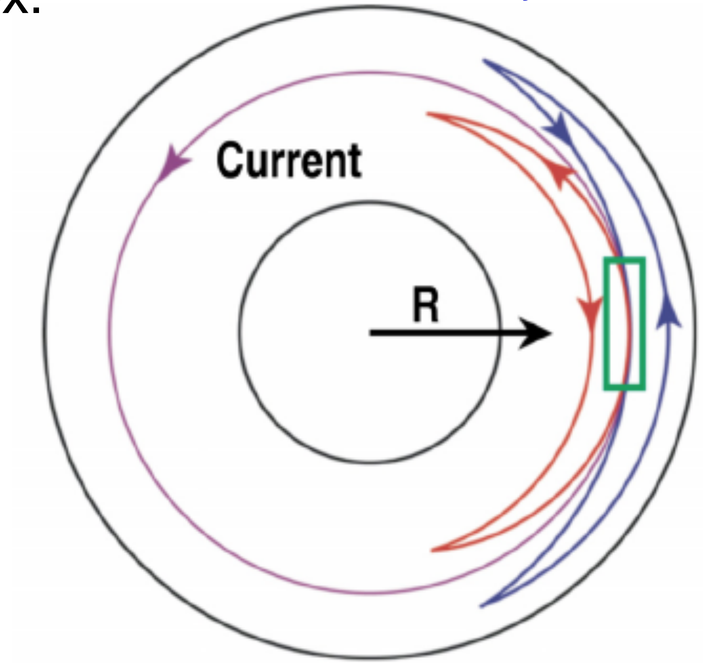
FIG. 2. β_T vs I_p/aB_T in START; high-β operation limits for other tokamaks are shown for comparison.



Plasmas Have the Ability To Drive Their Own Toroidal Current

- Consider the trapped particle orbits in the green box.
- Net counter-clockwise current if:
  - There is a density gradient:
    - More particles on the red orbit.
  - There is a temperature gradient:
    - Particles on red orbit more faster.
- Trapped particles do not make net current.
  - But collisions with passing particles transfer the asymmetry…and a net current flows.

T. Luce, Phys. Plasmas **18**



Simple Expression For Current Density

$$J_{BS} \approx \sqrt{\varepsilon}\,\frac{c}{B_P}\frac{dP}{dr}$$

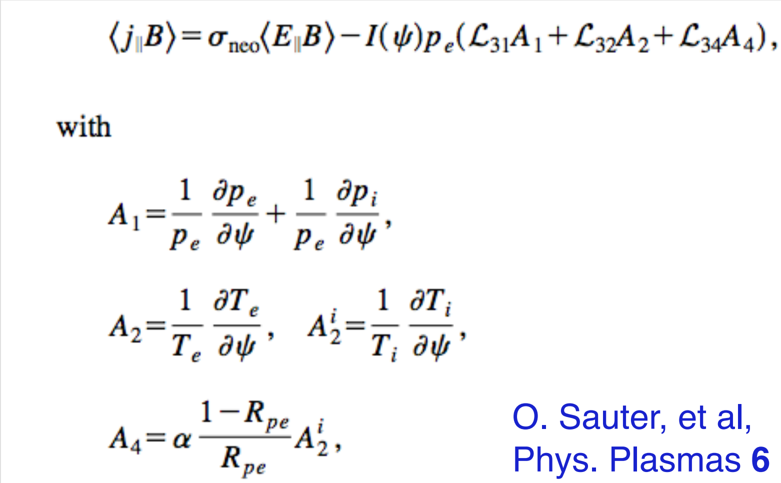
Convert to Toroidal Current

$$I_{BS} \sim \iint \sqrt{\varepsilon}\,\frac{c}{B_P}\frac{dP}{dr}\,r\,dr\,d\theta \sim \sqrt{\varepsilon}\,\frac{caP}{B_P}$$

Convert to Fraction of Total Current

$$f_{BS} \equiv \frac{I_{BD}}{I_P} \approx \sqrt{\varepsilon}\,\frac{caP}{I_P B_P} \sim \sqrt{\varepsilon}\,\frac{cP}{B_P^2} = C_{BS}\sqrt{\varepsilon}\,\beta_P$$

More General Expression:



$$\langle j_{\|}B\rangle = \sigma_{\mathrm{neo}}\langle E_{\|}B\rangle - I(\psi)p_e(\mathcal{L}_{31}A_1 + \mathcal{L}_{32}A_2 + \mathcal{L}_{34}A_4),$$

with

$$A_1 = \frac{1}{p_e}\frac{\partial p_e}{\partial\psi} + \frac{1}{p_e}\frac{\partial p_i}{\partial\psi},$$

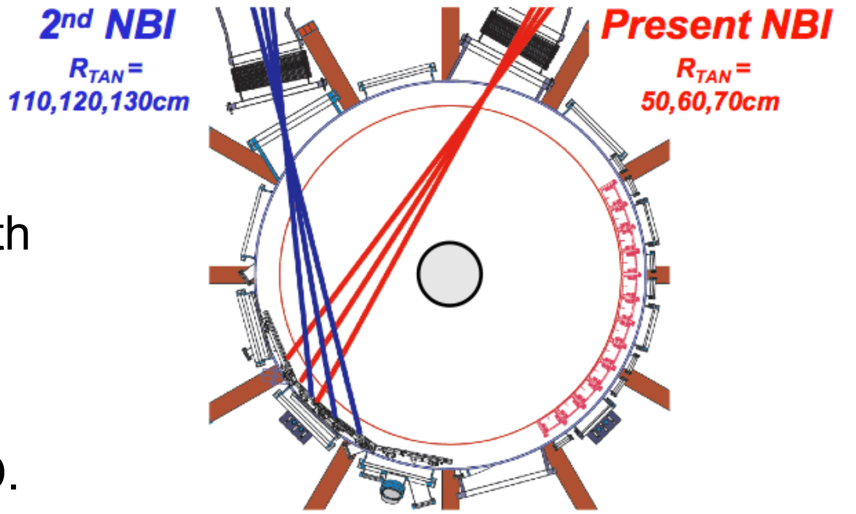
$$A_2 = \frac{1}{T_e}\frac{\partial T_e}{\partial\psi}, \quad A_2^i = \frac{1}{T_i}\frac{\partial T_i}{\partial\psi},$$

$$A_4 = \alpha\frac{1-R_{pe}}{R_{pe}}A_2^i,$$

O. Sauter, et al,
Phys. Plasmas **6**

Neutral Beam Current Drive Typically Invoked to Supplement the Bootstrap Current

- Neutral beams are the work-horse heating source for present and proposed STs.
  - Can also inject momentum and drive current.
- Current is due to the circulating fast ions.
- Collisions would generally bring electrons along with ions, cancelling the current.
  - Impurity ions and electron trapping impede this canceling current.
- Remember, reduces plant efficiency to drive NBCD.



$$\left\langle j_{\parallel}B\right\rangle = \underbrace{\left\langle j_{\parallel,f}B\right\rangle}_{} \underbrace{\left[1-\frac{Z_b}{Z_{eff}}\left(1-G\left(Z_{eff},\varepsilon\right)\right)\right]}_{}$$

- Fast ion current.
- Computed via Monte Carlo methods for NSTX.
- Increases when the slowing down time is longer:

$$I_{NBCD} \propto C_{NBCD}\frac{\overline{T}_e^{3/2}}{\overline{n}_e}P_{inj}$$

- Correction due to electron response, including neoclassical effects.
- Computed analytically, for instance:

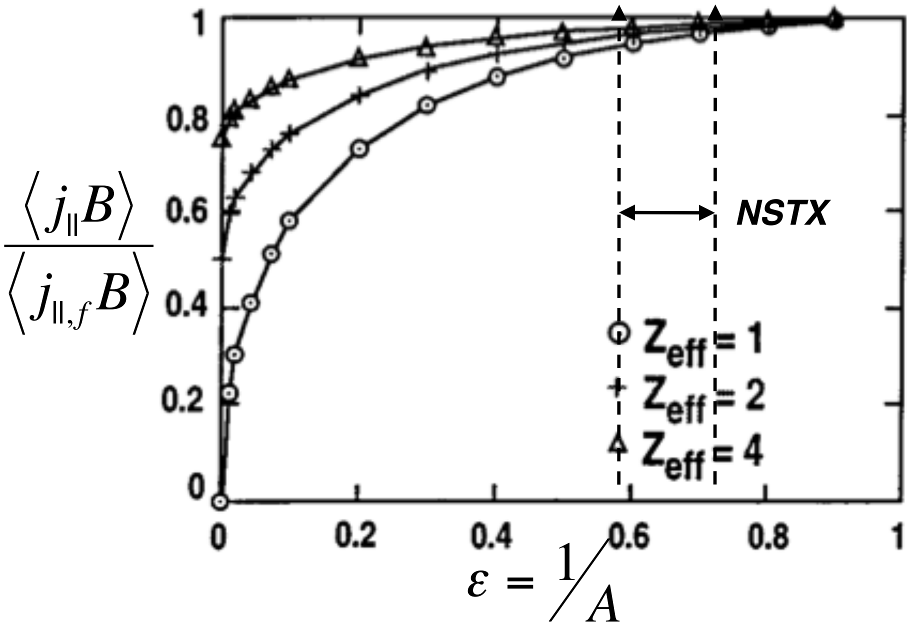
$$G\left(Z_{eff},\varepsilon\right)=\frac{x}{D}\left[\begin{array}{l}\left(0.754+2.21Z_{eff}+Z_{eff}^2\right)\\ +x\left(0.348+1.243Z_{eff}+Z_{eff}^2\right)\end{array}\right]$$

$$D=1.414Z_{eff}+Z_{eff}^2+x\left(0.754+2.657Z_{eff}+2Z_{eff}^2\right)$$

$$+x^2\left(0.348+1.243Z_{eff}+Z_{eff}^2\right)$$

$$x=f_t/\left(1-f_t\right)$$

Lin-Liu & Hinton, Phys Plasmas **4**



NSTX Studies Show Good Agreement Between Calculated Current Sources and Total Current Profile

Current Profile Reconstructed from…

Pressure-Driven Currents: *Bootstrap, Pfirsch-Schlueter+Diamagnetic*

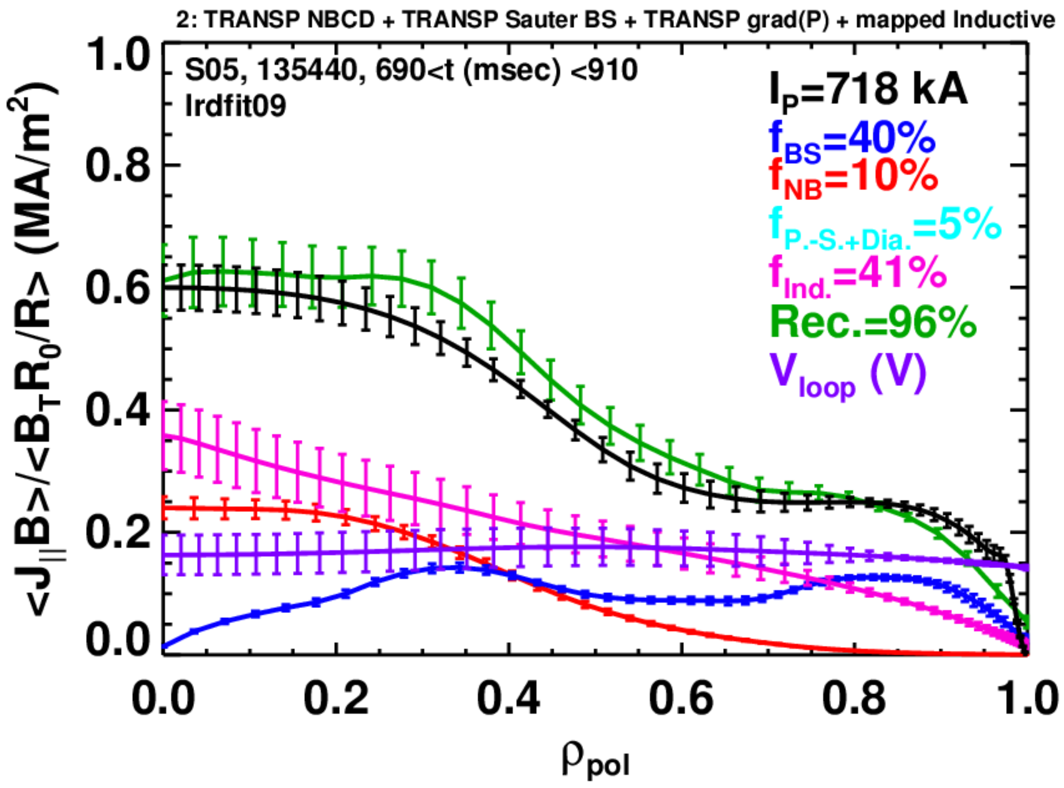
Inductive current: *time derivatives of reconstructed equilibria + neoclassical resistivity*

Neutral Beam Current Drive *from NUBEAM, with classical beam physics*

Compare to…

Reconstructions *constrained by MSE and T_e isotherm constraint*

Choose time with no EP MHD or low-frequency kink/tearing

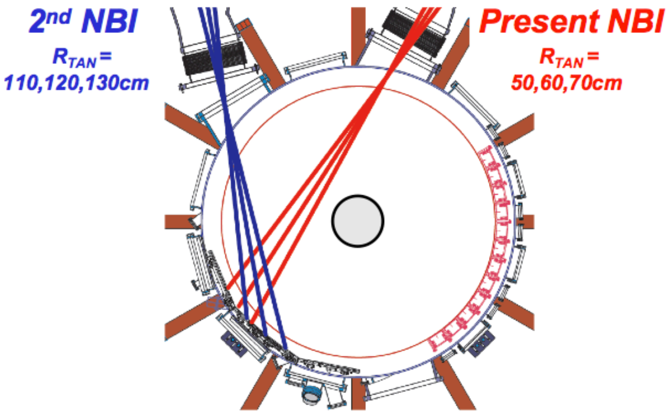


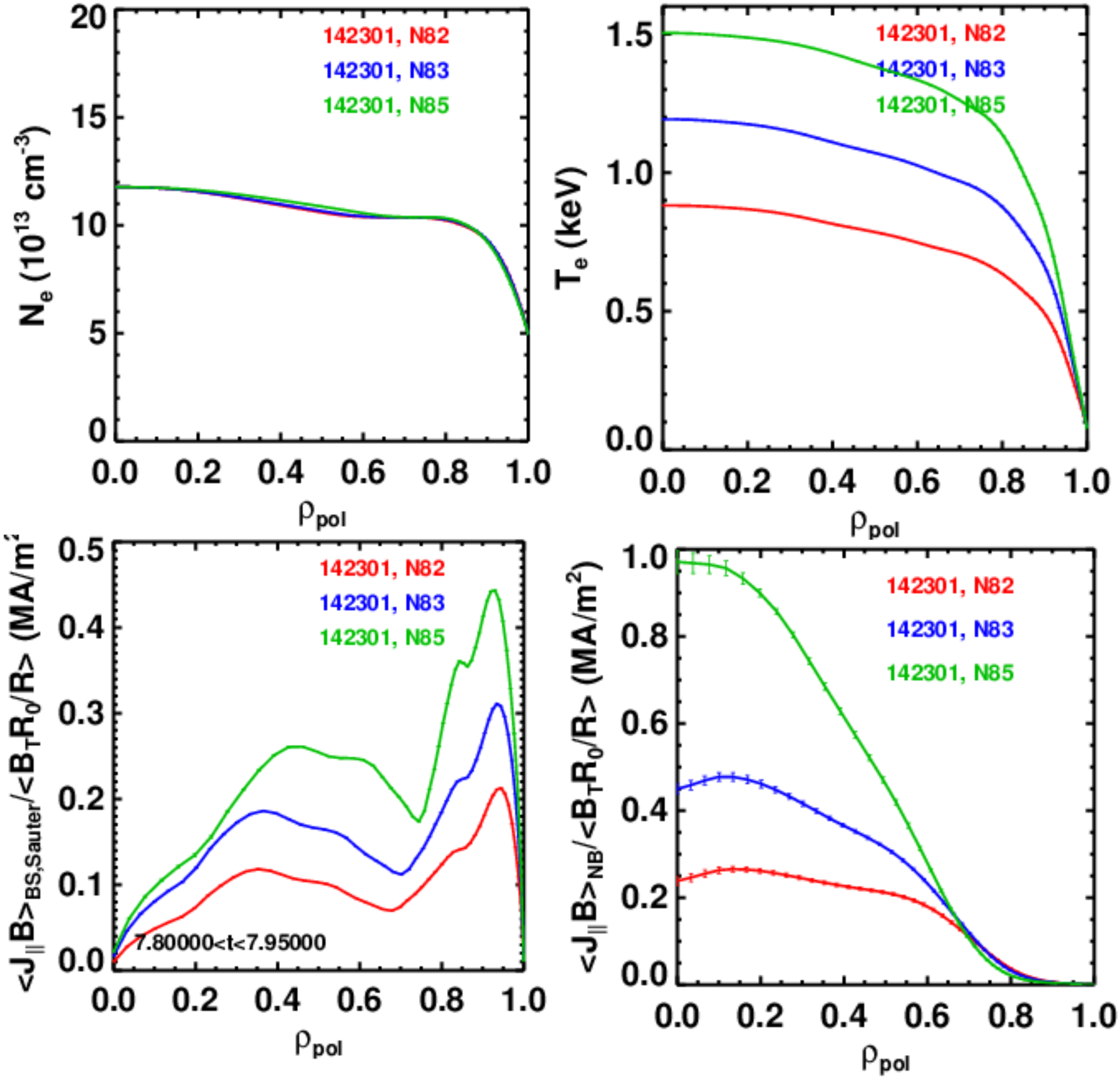
S.P. Gerhardt, Nuclear Fusion

Non-Inductive Current Profiles Depend on the Electron Temperature (and others profiles as well).

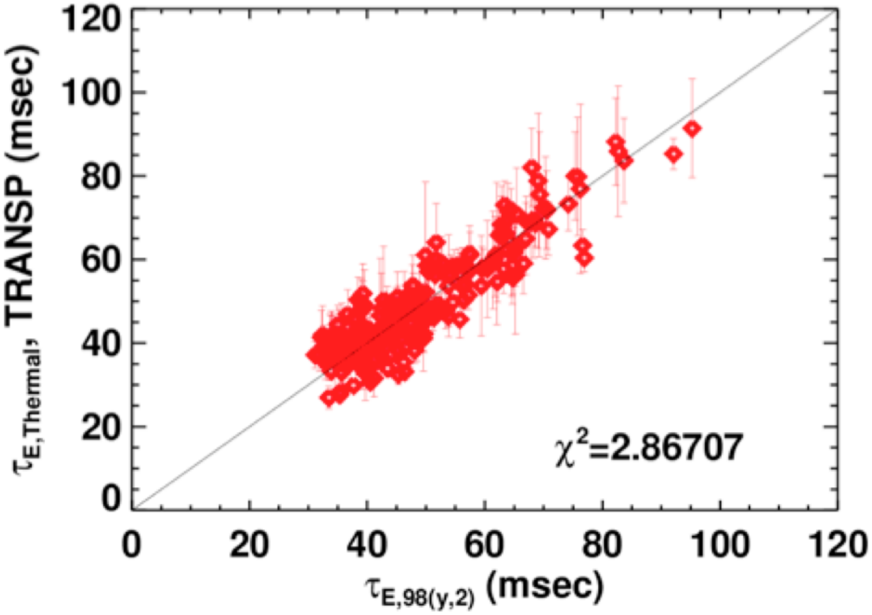
- Fix the electron density, Z_{eff} and scale T_e & T_i.
- Calculations from TRANSP
  - Sauter model for Bootstrap currents
  - NUBEAM for NBCD
- Beam currents tend to be centrally localized for these parameters.
- Bootstrap currents tend to be edge localized in H-mode -> low-l_i

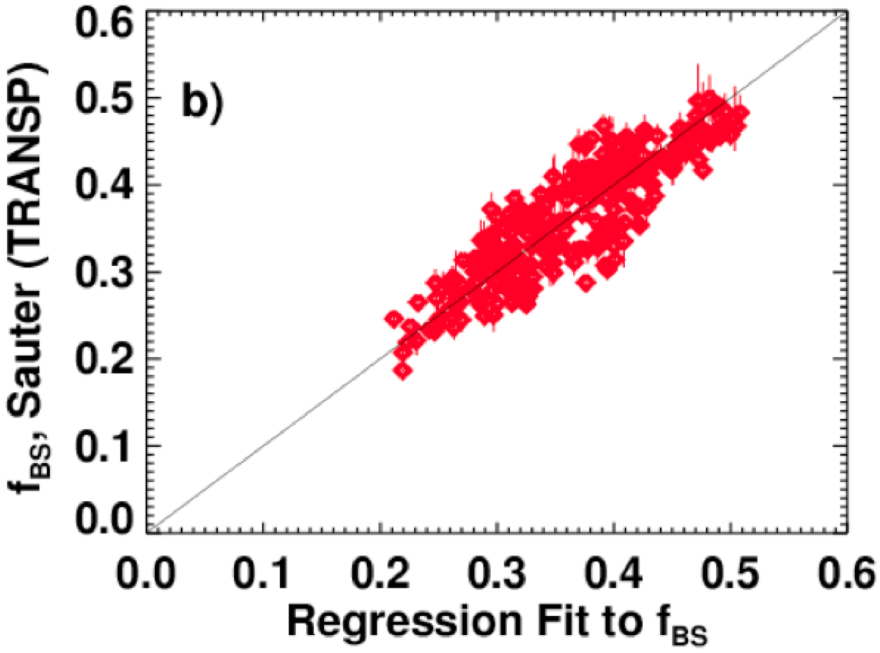
Simulations use all 6 Sources





Plasma Transport Determines The Achievable Level Of Bootstrap Current (when stability is not violated)





Experimental Confinement Scaling

$$\tau_{E,ITER-98} \propto I_P^{0.93} B_T^{0.15} n_e^{0.41} P_L^{-0.69}$$

$$H_{98} = \tau_{E,achieved} \Big/ \tau_{E,ITER-98}$$

Bootstrap Fraction From Confinement Scaling

$$f_{BS} \propto \beta_{P,th} \propto \frac{P\tau_{E,th}}{I_P^2}$$

$$f_{BS} \propto \frac{P I_P^{0.93} B_T^{0.15} n_e^{0.41} P^{-0.69}}{I_P^2} \approx \frac{n_e^{0.4} B_T^{0.2} P^{0.3}}{I_P}$$

Bootstrap Fraction From Direct Regression

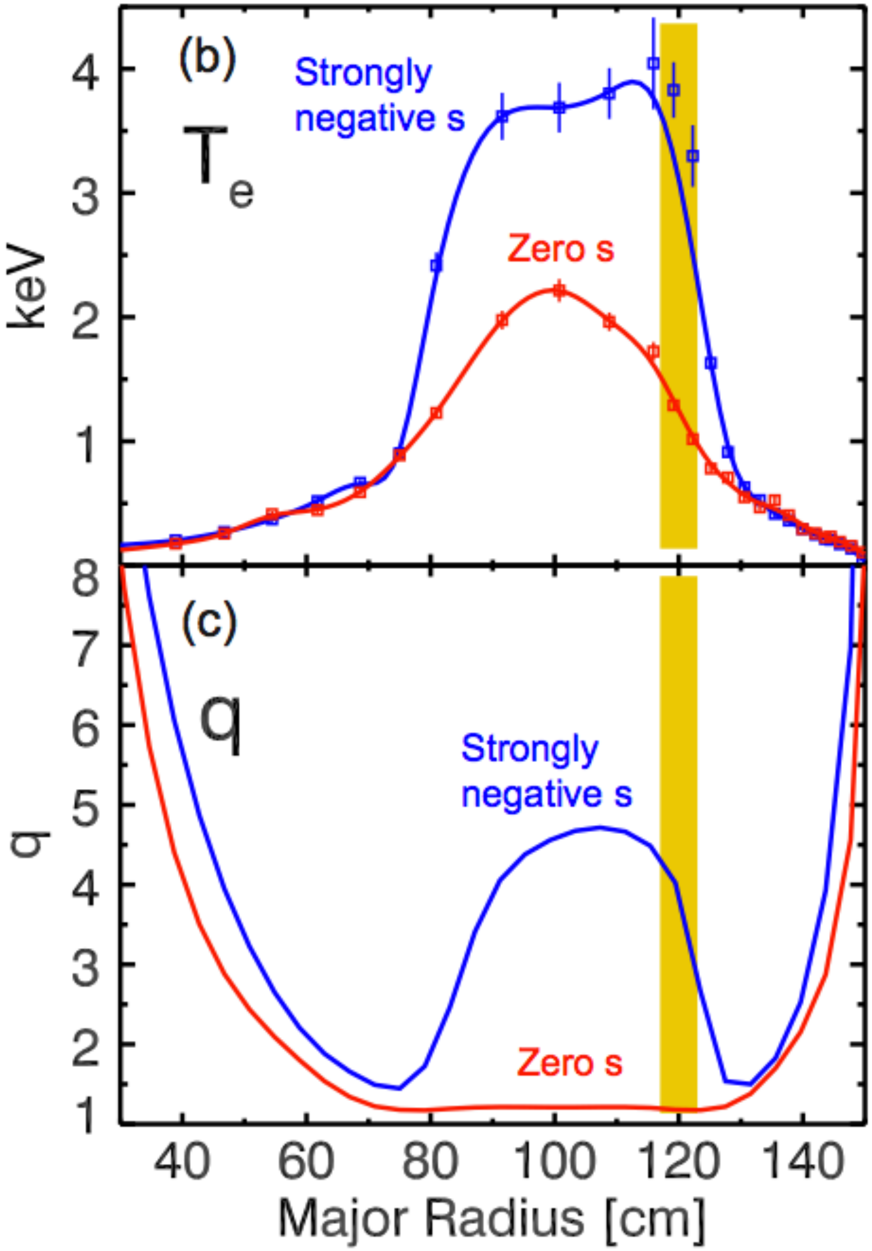
$$f_{BS} \approx \frac{n_e^{0.4} B_T^{0.25} P^{0.2}}{I_P}$$

S.P. Gerhardt, submitted to Nuclear Fusion

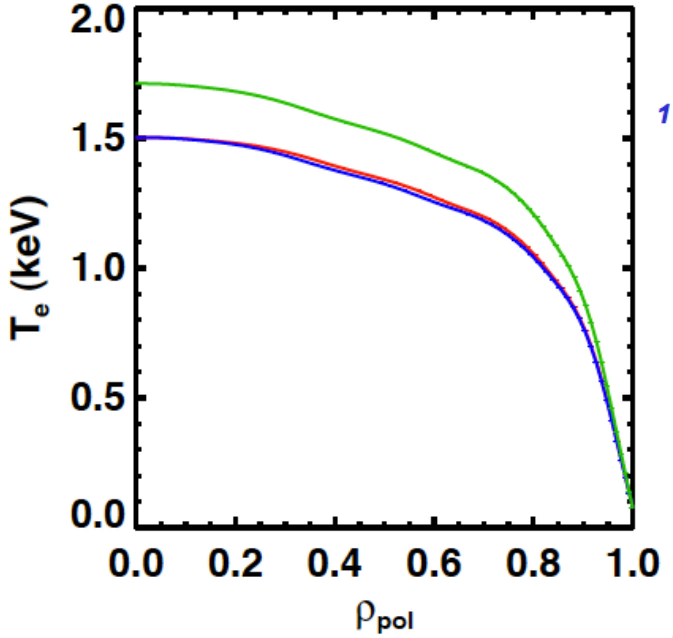
Internal Transport Barrier Formation is a More Complicated Interaction Between the Thermal and Current Profiles

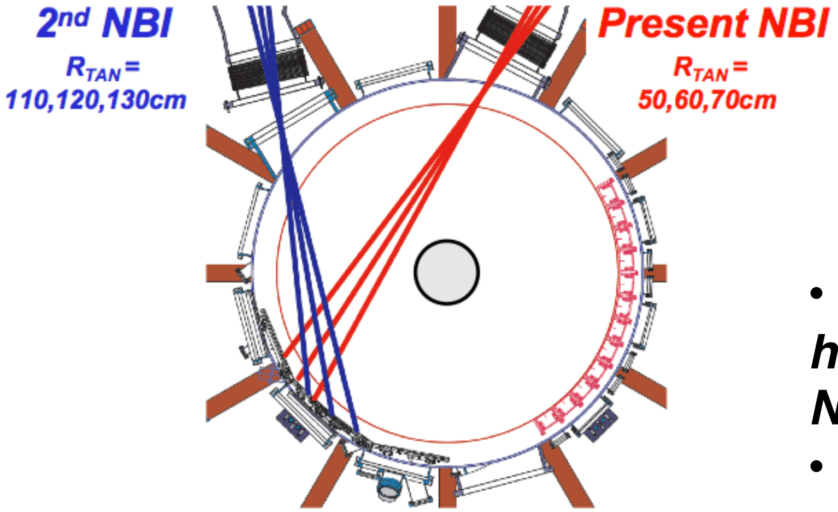
- Confinement depends on magnetic shear.
  - Peak electron temperature typically occurs near location of most negative magnetic shear (in NSTX).
- Strong gradient can produce strong bootstrap current.
  - Modifies the q-profile…necessary to have current profile carefully “aligned” with the pressure profile.
- Resulting configuration has a higher pressure peaking factor.
  - is the ideal MHD stability acceptable in this scenario?
  - Double tearing can also be unstable.

H. Yuh, Phys. Plasmas **16**



Changing Beam Sources Can Modify the Current Profile Shape





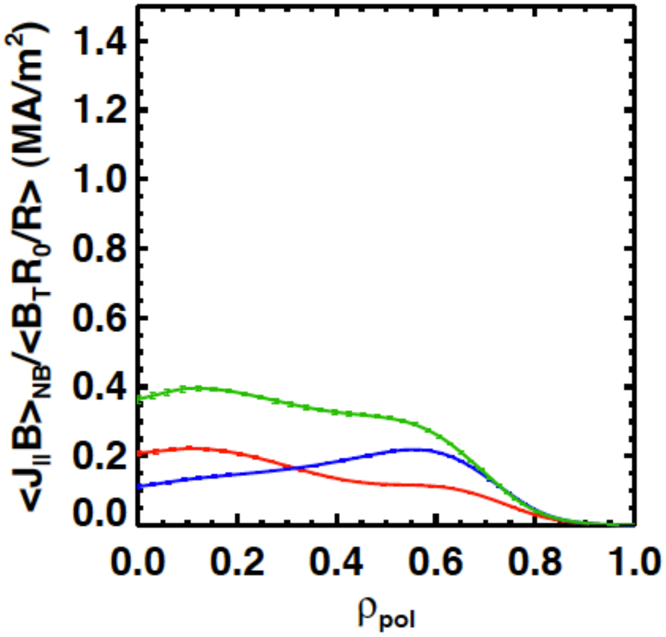
50, 60, 70, 130

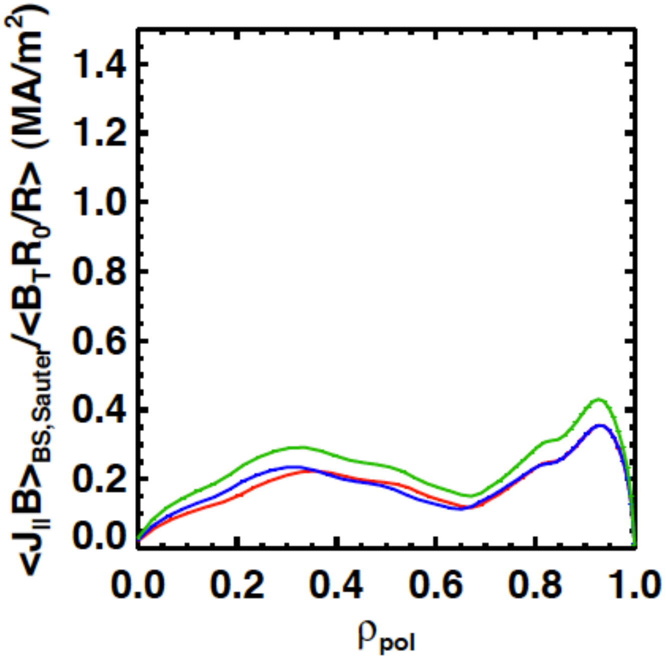
50, 60, 120, 130

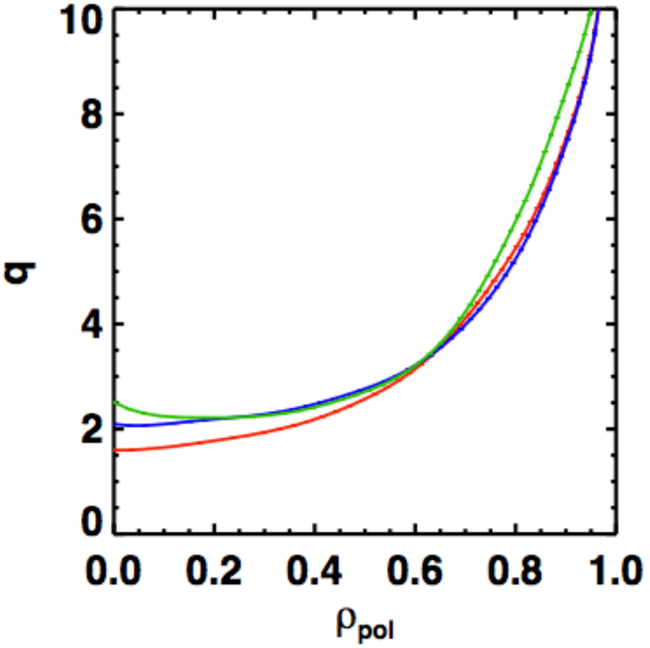
All 6 Sources

- *Higher power case has higher T_e, and better NBCD efficiency.*
- *Keeps q_{min} above 2, avoiding possibility of 2/1 tearing.*

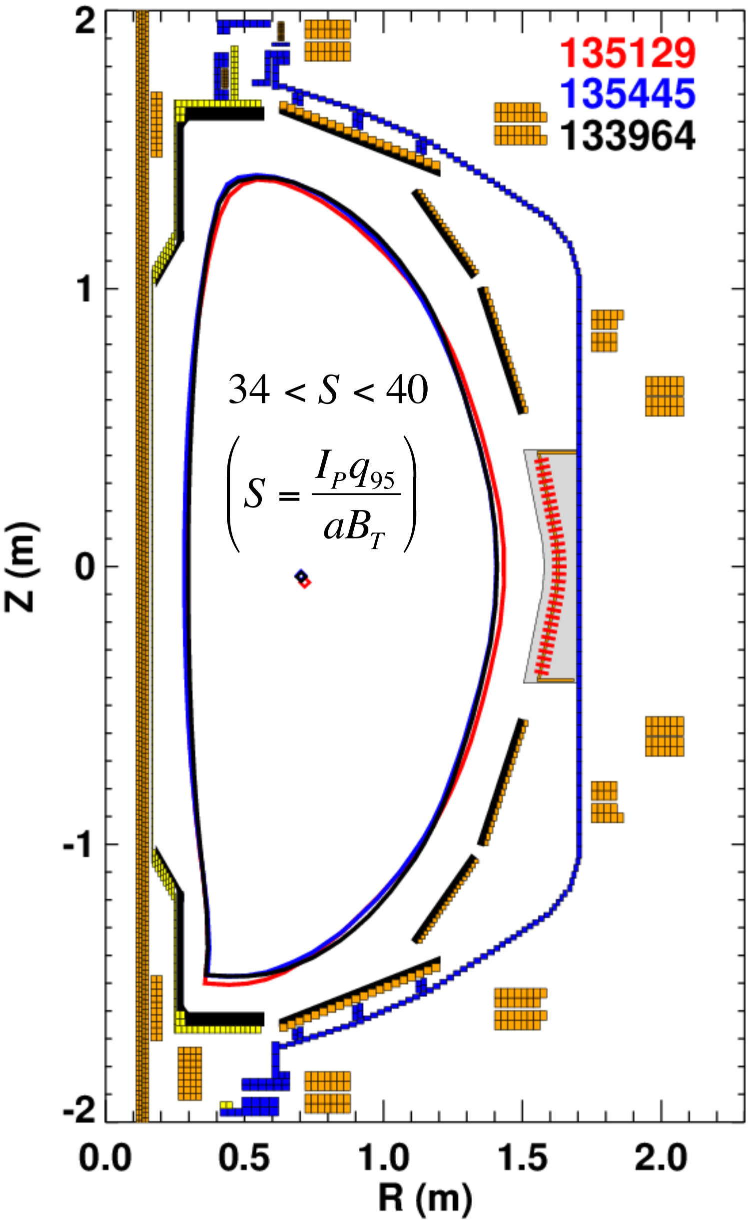
A=1.8, I_P=1300 kA, B_T=1.0







Best NSTX Discharges Combine Strong Shaping, Good Confinement, and Large Non-Inductive Currents



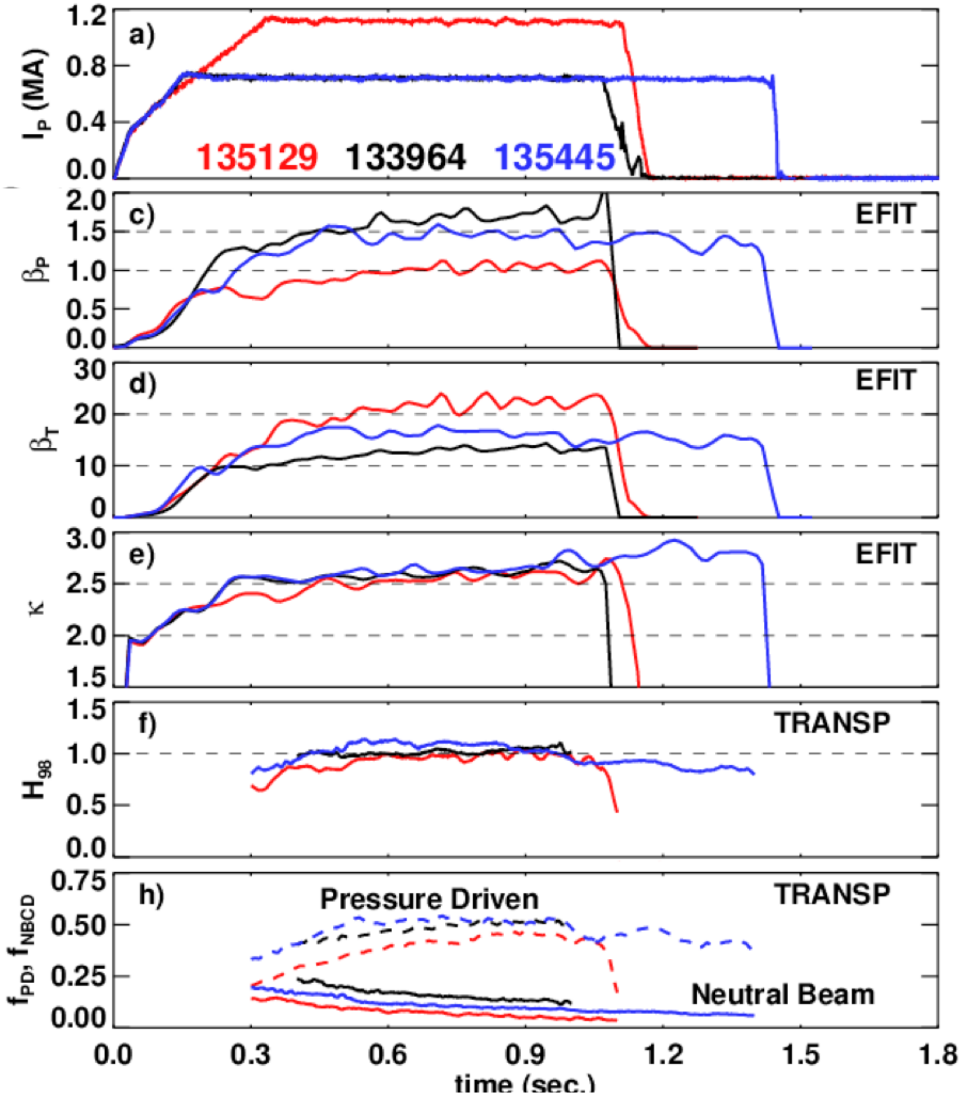
$34 < S < 40$

$$\left(S = \frac{I_P q_{95}}{a B_T} \right)$$

Aspect Ratios 1.45-1.55

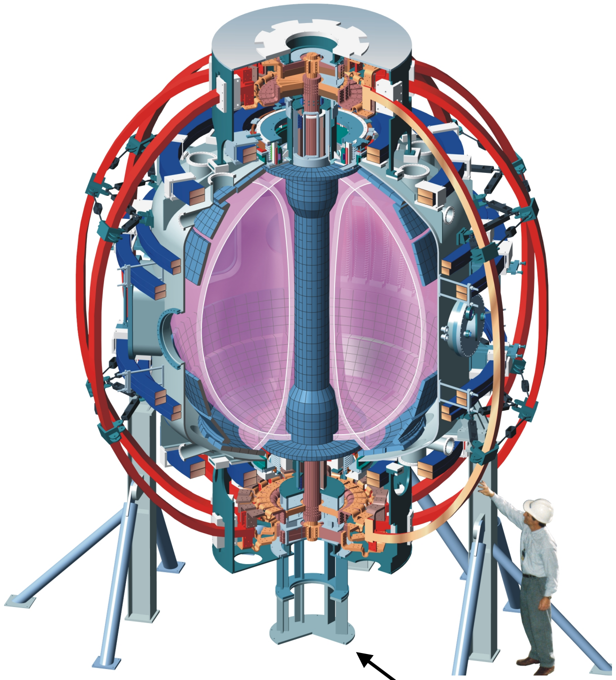
Optimized For:

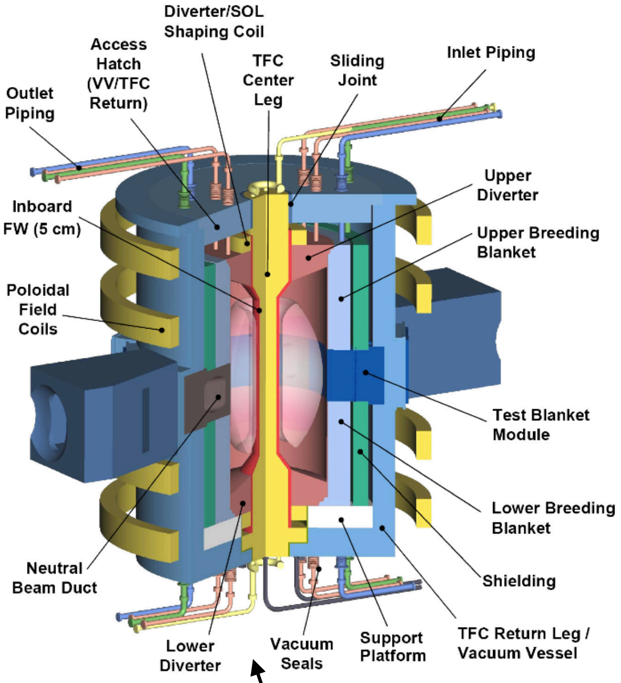
High sustained β_T high non-inductive fraction longest-pulse

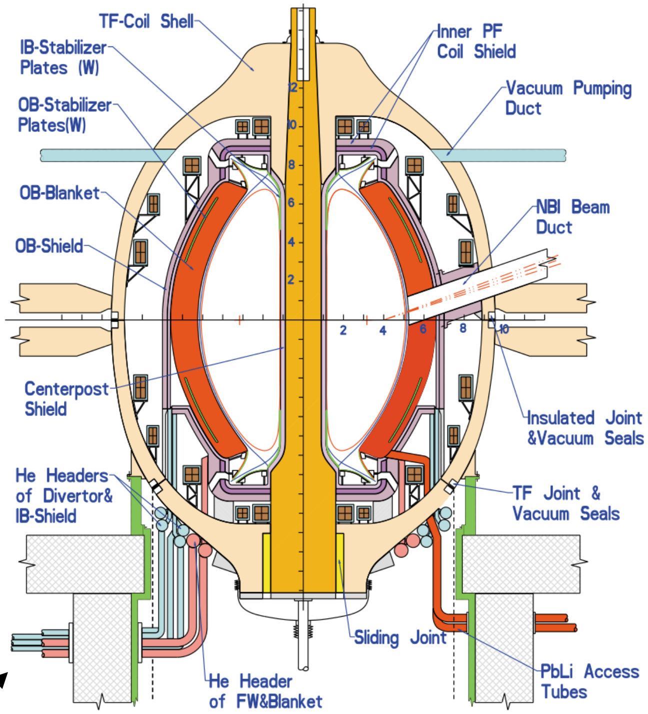


S.P. Gerhardt, submitted to Nuclear Fusion

Large Steps Still Required For Next-Step Devices







	NSTX[1]	ORNL CTF[2]	ARIES-ST[3]
R_0 (m)	0.85	1.2	3.2
I_P/B_T (MA/T)	1.0/0.55	8.2/1.13	29/2.1
β_N	5.0	3.8	7.4
κ	2.8	3.1	3.5
f_{BS} (%)	50-60	50	96
P_{fusion} (MW)	0	75	3000

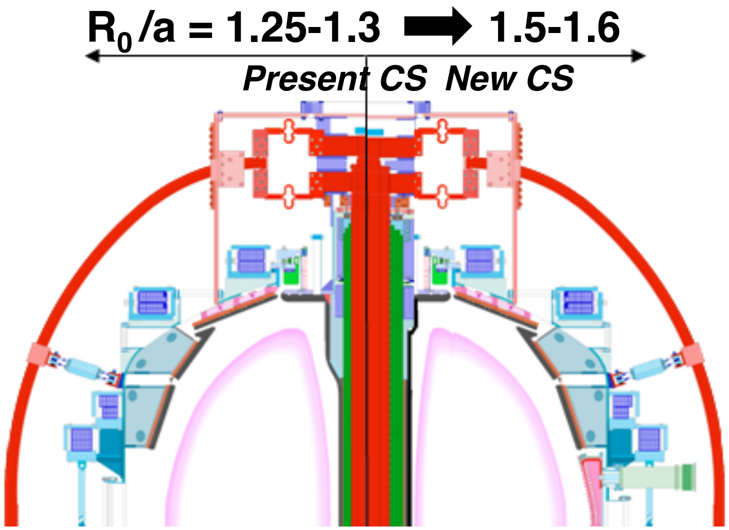
[1] S.P. Gerhardt, et al., EXS/P2-08, IAEA FEC 2010.

[2] Y.K.M. Peng, et al., FT/P3-14, IAEA FEC 2008. WL= 1 MW/m^2

[3] F. Najmabadi, et al., Fusion Engineering and Design, 2003.

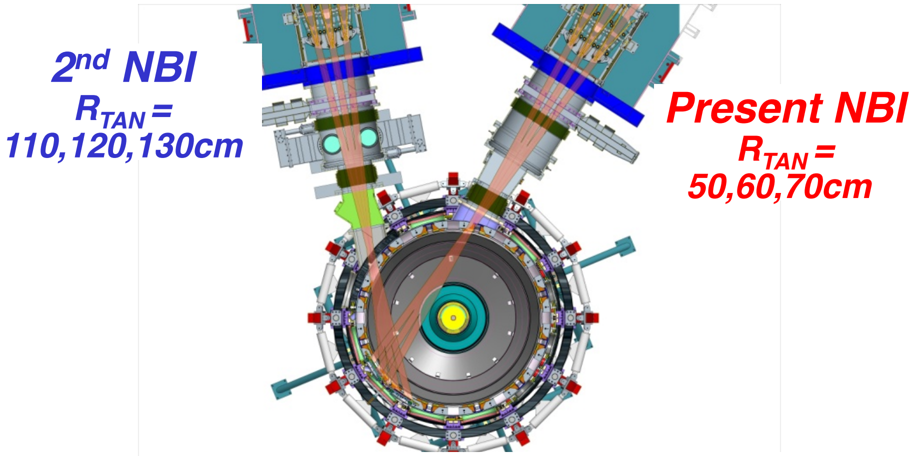
NSTX (and MAST) Are Planning Substantial Upgrades

New center stack for 1T, 2MA, 5s

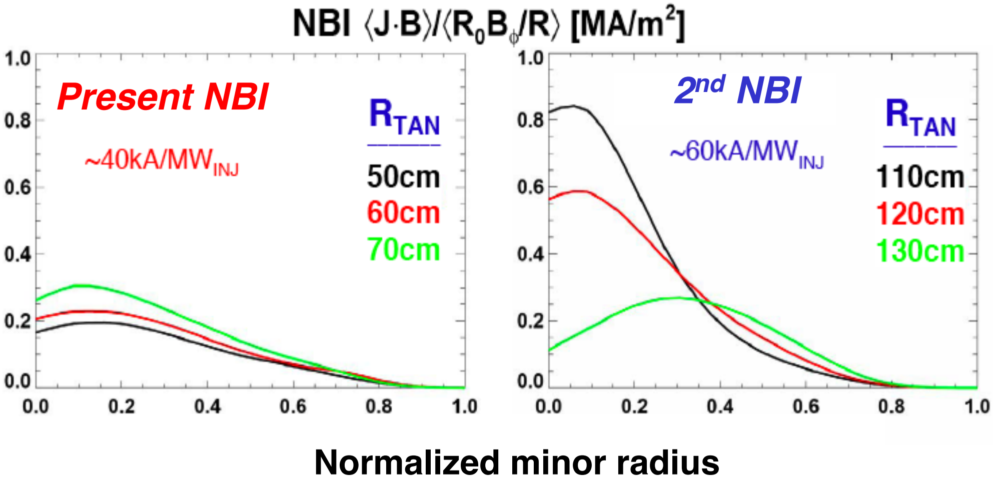


- New center column:
  - 1 MA -> 2MA,
  - 0.5T ->1T, 1.4 sec ->5.0 sec.
- 1 additional beamline with three sources.
- Study transport, stability, current drive
  - in low-collisionality plasmas with 100% non-inductive current drive.

2nd NBI with 5 MW, 5s at larger R_{TAN}



NBI current drive profiles [MA/m²]



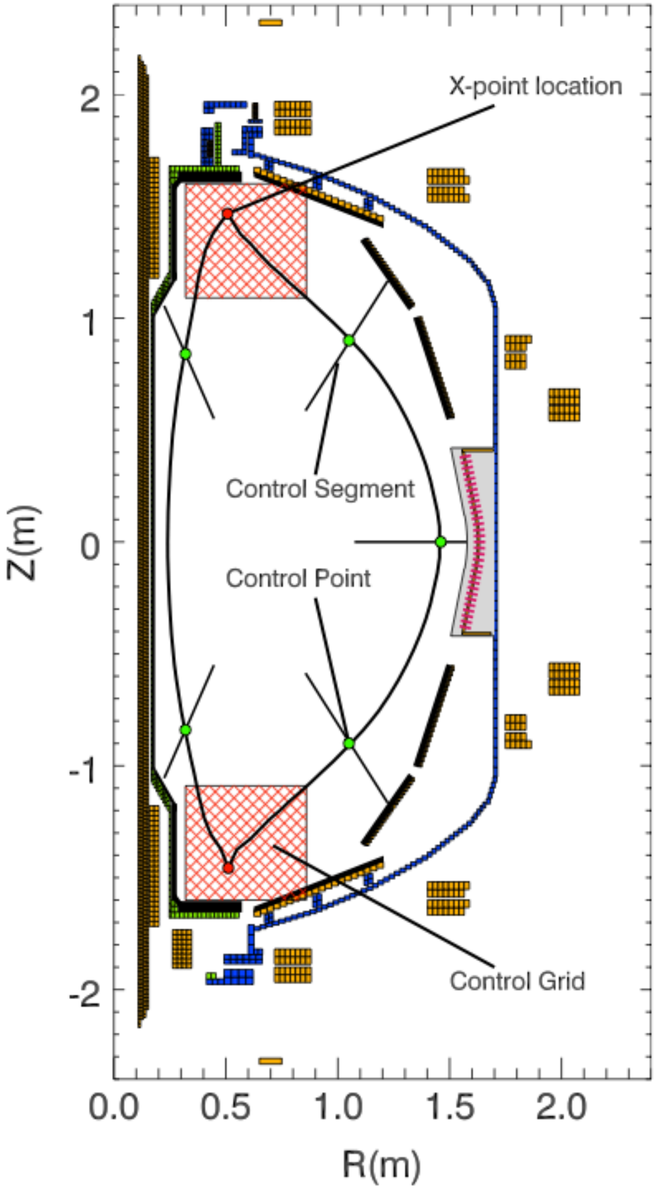
Up to 2 times higher NBI current drive efficiency, and current profile control

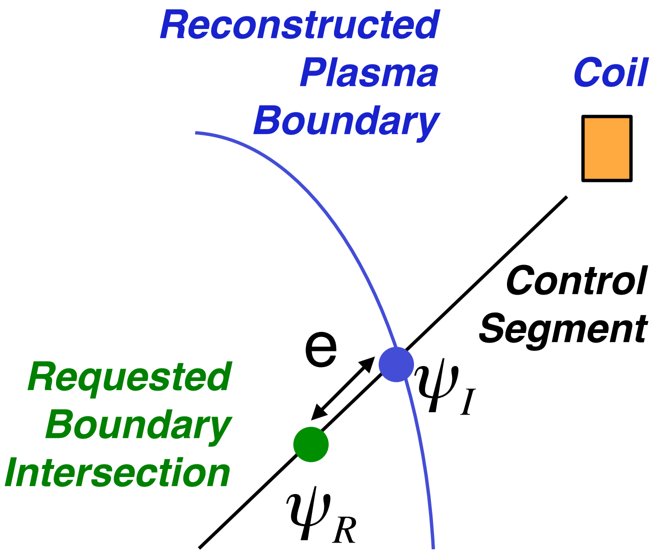
Summary

- Sustained, economical tokamak fusion power requires simultaneous high β_N and κ.
- ST offers a potential route to maximizing these parameters.
  - Strong shaping, profile optimization lead to further improvements.
- Bootstrap and neutral beam current drive are the common non-inductive currents sources in present and future STs.
  - Theory of these current drive sources is (mostly) verified.
- Transport determines the level of these non-inductive currents, as well as the profile magnitudes and shapes…
  - …which in turn determine the stability.
- Best NSTX discharges optimize this physics for high-performance, but large steps are required for next-step devices.
  - NSTX and MAST upgrades will help bridge the gap.

Control The Plasma Shape in With Realtime Grad-Shafranov Equation Solutions

Specify intersections of Control Segments with Desired Boundary





- Compute a solution to the Grad-Shafranov equation solution.
- Compute the flux on control segment at intersection with boundary (ψ_I).
- Compute the error

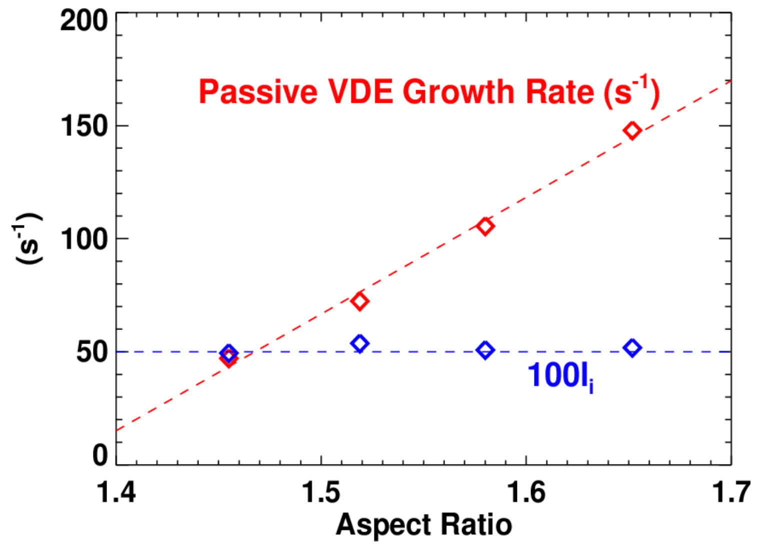
$$e = \psi_R - \psi_I$$

- Adjust coil voltage as

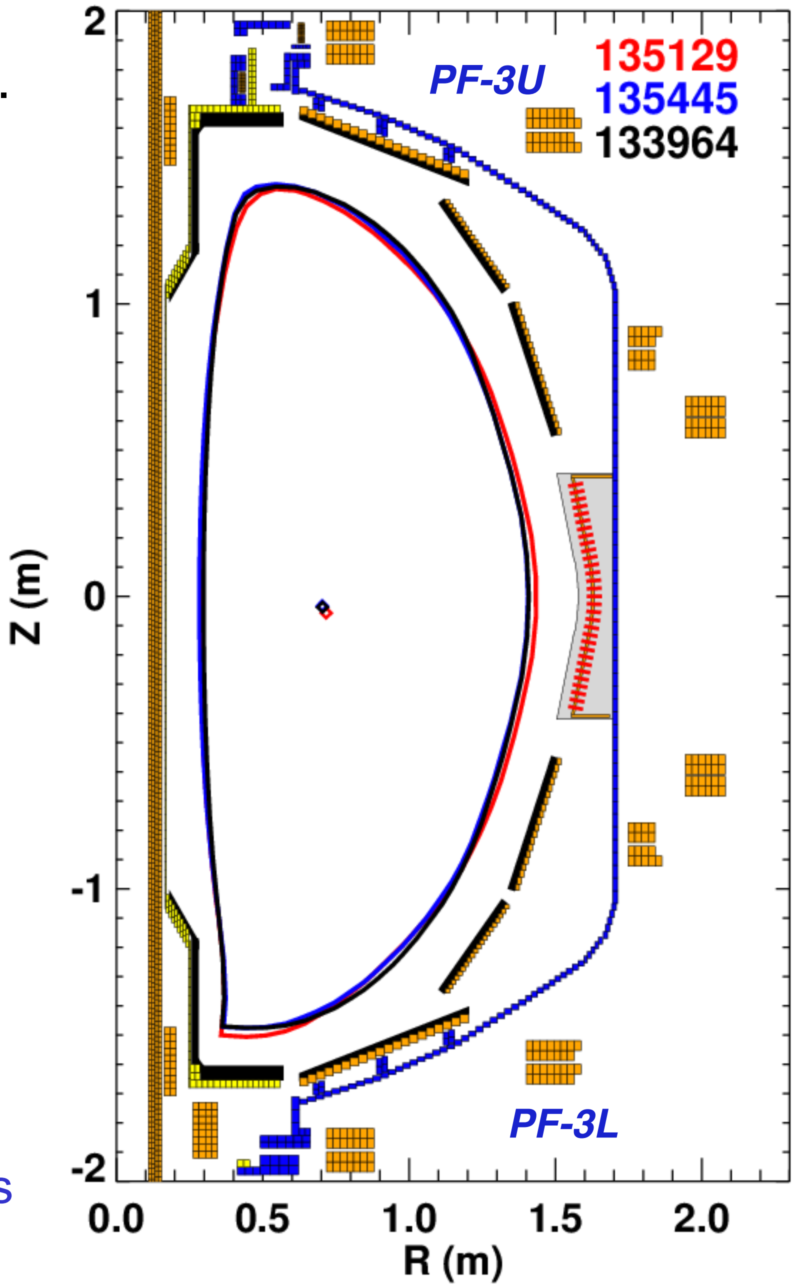
$$V_{coil} = Pe + D\frac{de}{dt} + I\int edt$$

Simplest "Fast Feedback" System in NSTX: Vertical Position Control (I)

- Large natural elongation of the ST stabilizes the "Vertical Displacement Event" (VDE)…to a point.
  - VDE growth rate increases with A.



- Fast vertical position control is required to keep plasma centered in vessel.
- Internal inductance plays an important role. Higher-l_i means:
  - The natural elongation is reduced.
  - Current is farther from the coils, making them less effective for control.



Simplest "Fast Feedback" System in NSTX: Vertical Position Control (II)

- VDE is too fast to be captured by the shape controller.
  - Use an additional feedback system, based on the plasma velocity.
- Two flux-loops are usually sufficient for control.

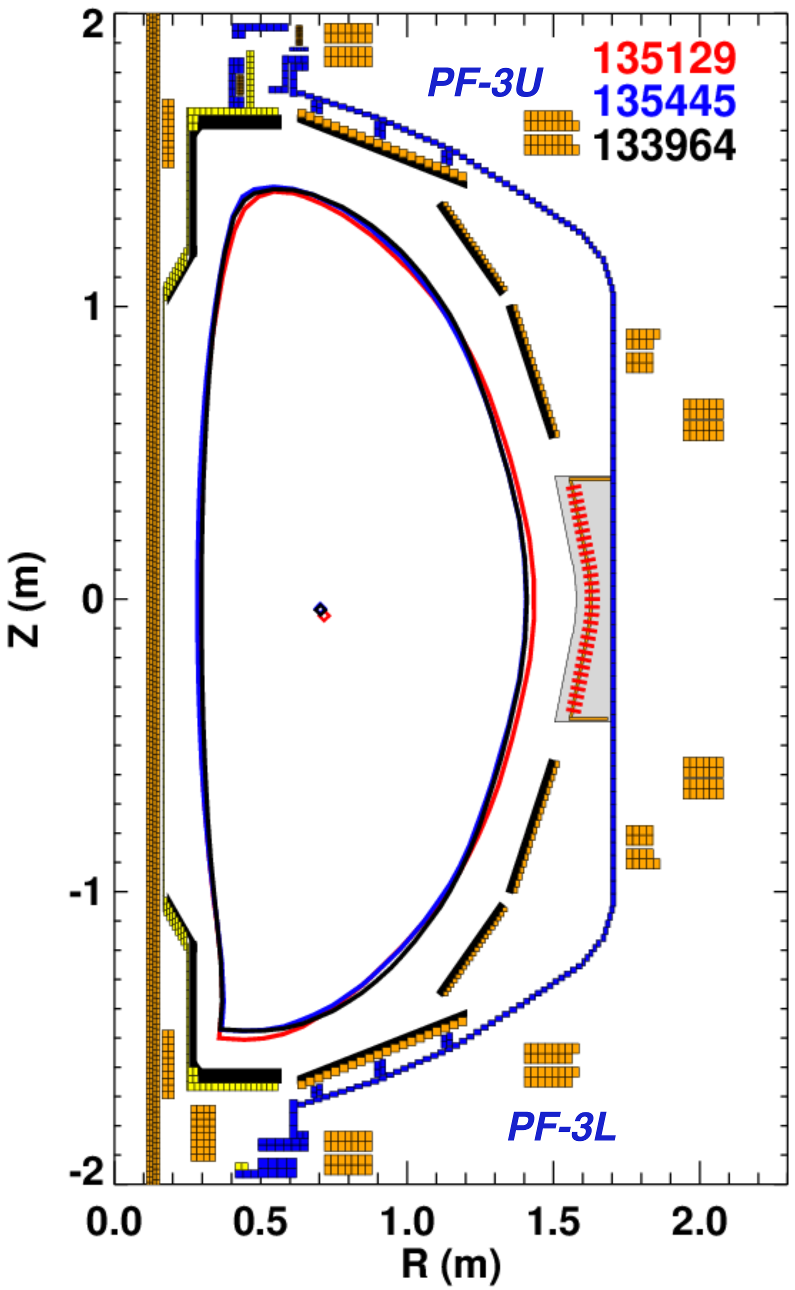
$$Z_P \approx C\left(\psi_U - \psi_L\right)$$

$$\frac{dZ_P}{dt} \approx C\left(\frac{d\psi_U}{dt} - \frac{d\psi_L}{dt}\right) = C\left(V_U - V_L\right)$$

- Apply a voltage to the "Radial Field" coil proportional inferred velocity.

$$V_{PF-3U} = V_{PF-3U,ISOFLUX} - D\left(V_U - V_L\right)$$

$$V_{PF-3L} = V_{PF-3U,ISOFLUX} + D\left(V_U - V_L\right)$$



Many Other Quantities are Under Feedback Control in NSTX…But Is this Feasible in Future Devices?

- Other examples of control in NSTX:
  - Slowly-growing n=1 kinks (resistive wall modes) are suppressed.
    - Magnetic detection of kink-perturbation using 48 sensors, feedback with midplane coils.
    - Key for providing reliable operation at high-β…big research program at NSTX.
  - The plasma β_N is regulated.
    - Use rtEFIT to measure β_N, modulate the heating sources.
  - The plasma rotation will (soon) be controlled .
    - Measure V_f with realtime CHERS, control with NB torque changes and magnetic braking.
- Next-step devices pose many challenges for control:
  - Can the appropriate real-time measurements be made in a neutron environment?
    - e. g., neutron streaming limits available sizes of ports?
  - Will we have the actuators available?
    - e. g., internal coils for non-axisymmetric fields may not be available?
- This is a key issue going to next-step devices.

NSTX Shows a β_N Limit, Not a β_T Limit

- Show β_N and β_T averaged over the pulse duration, and plotted against the pulse duration.
  - But, what sets the β_N limit? Why is is 5 and not 3?