NSTX

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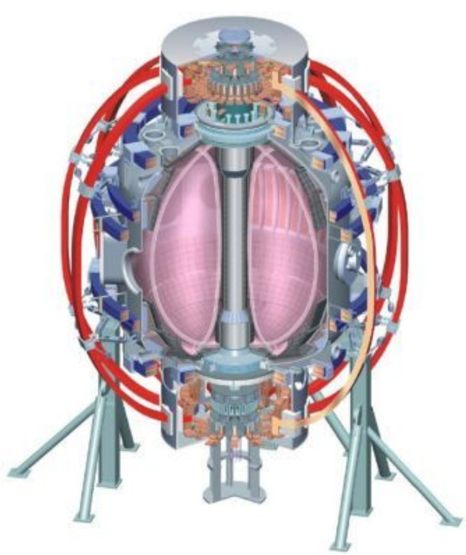
Equilibrium and Stability Modeling of NSTX-Upgrade Scenarios with Free-Boundary TRANSP and DCON

Status Report

Stefan Gerhardt

Thanks to TRANSP support (Doug, Marina, Tina, Rob) for lots of help.



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Goals of This Study

- PAC Request: "PAC recommends detailed modeling of non-inductive capability in NSTX-U", from PAC-29 debrief.
  - Of course, much has already been done, but we should show them something new next time around.
  - Also study the effect of $D_{FI}>0$ on scenarios.

- Develop reference target scenarios for NSTX-Upgrade for comparison to existing data.
  - Inform the upcoming run.

- Test free-boundary TRANSP at low-A and high-κ,β.

Outline

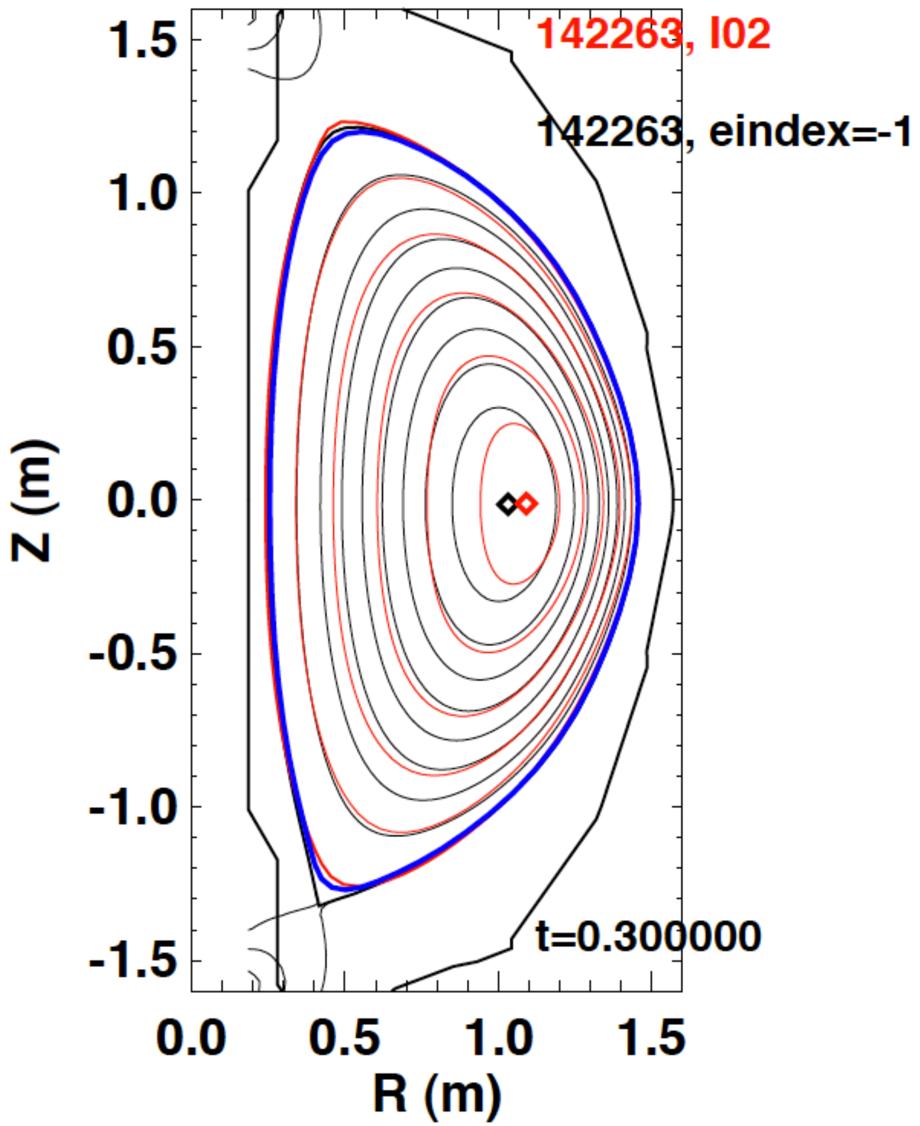
- Free-Boundary TRANSP modeling of NSTX discharges.
- Equilibrium and stability analysis of NSTX-U Scenarios.
  - Effect of outer gap on beam loss and NBCD profiles.
  - Long-pulse, ~100% non-inductive, H~1.0
    - Effect of D_{FI}=1 m^2/s.
  - Highest stored energy scenarios.
    - Including "sustained" (q_{min}>1) partial non-inductive cases.
  - Highest sustained β_T.
    - Equivalently, highest $I_N = I_p/aB_T$ with q_{min}>1.
    - Effect of D_{FI}=1 m^2/s.
- Comparison of these scenarios to existing data.

Important physics outside the scope of this modeling.
- The divertor and impurity control.
- Tearing (rotating or locked), kinetic stabilization of the RWM.
- Details (E, pitch angle dependence) of steady and/or impulsive non-classical fast ion physics.
- Pedestal physics and ELMs.
- The actual physics of electron transport.
- Much else…

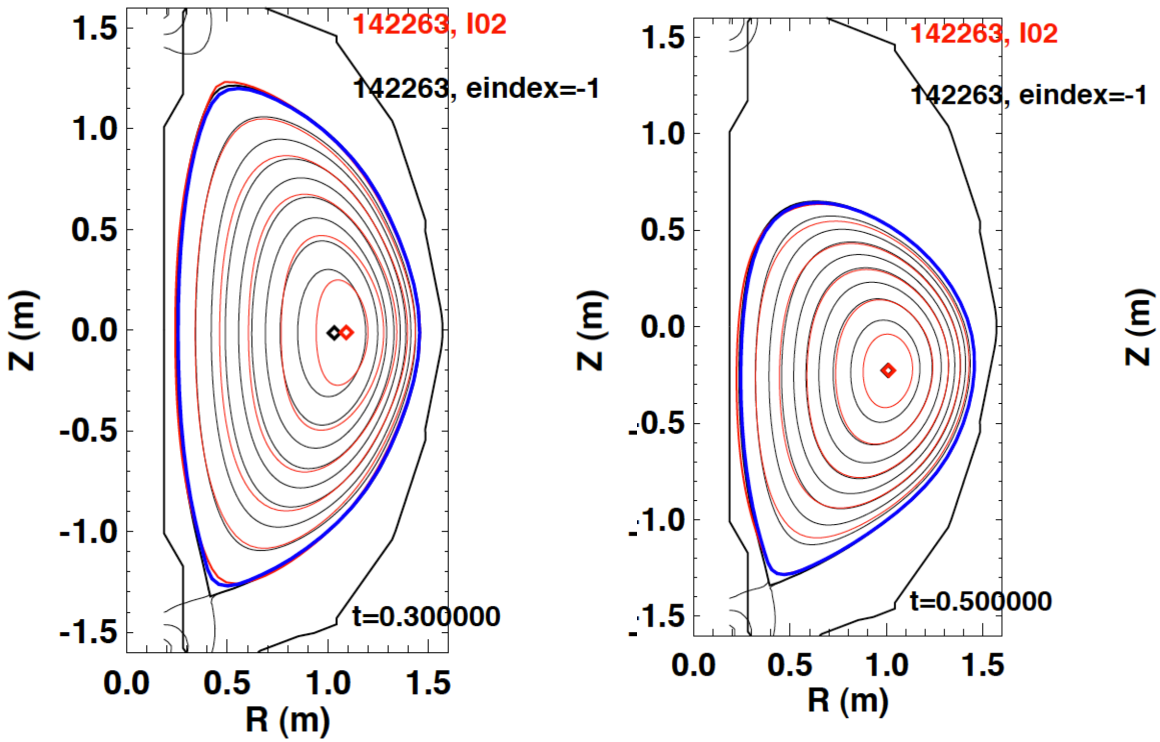
Example of Free-Boundary TRANSP Simulation of an Existing Discharge

TRANSP+ISOLVER Computes Coil Currents to Best Match a Requested Boundary, Given P and q Profiles.

- ISOLVER inputs:
  - Pressure profile: typically input thermal pressure + NUBEAM fast ion pressure.
  - q profile: Either from input equilibrium, or from current diffusion calculation.
  - Requested boundary shape (mds+ tree or a g-eqdsk file).
  - Which PF coils to use.
  - Various name list options controlling the numerics of the calculation.
- ISOLVER outputs:
  - Achieved boundary and Ψ(R,Z)
  - Coil currents for that boundary.
- Other notes:
  - No vessel currents in calculation.
  - No “inductance” in the coils
  - Can be finicky on occasion, intolerant of rapid changes in the equilibrium



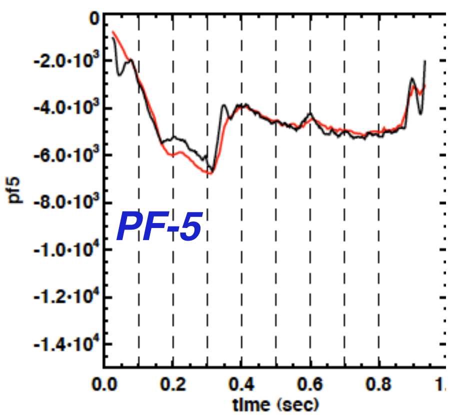
Code Can Achieve Good Matches for Coils That Strongly Impact the Plasma Shape

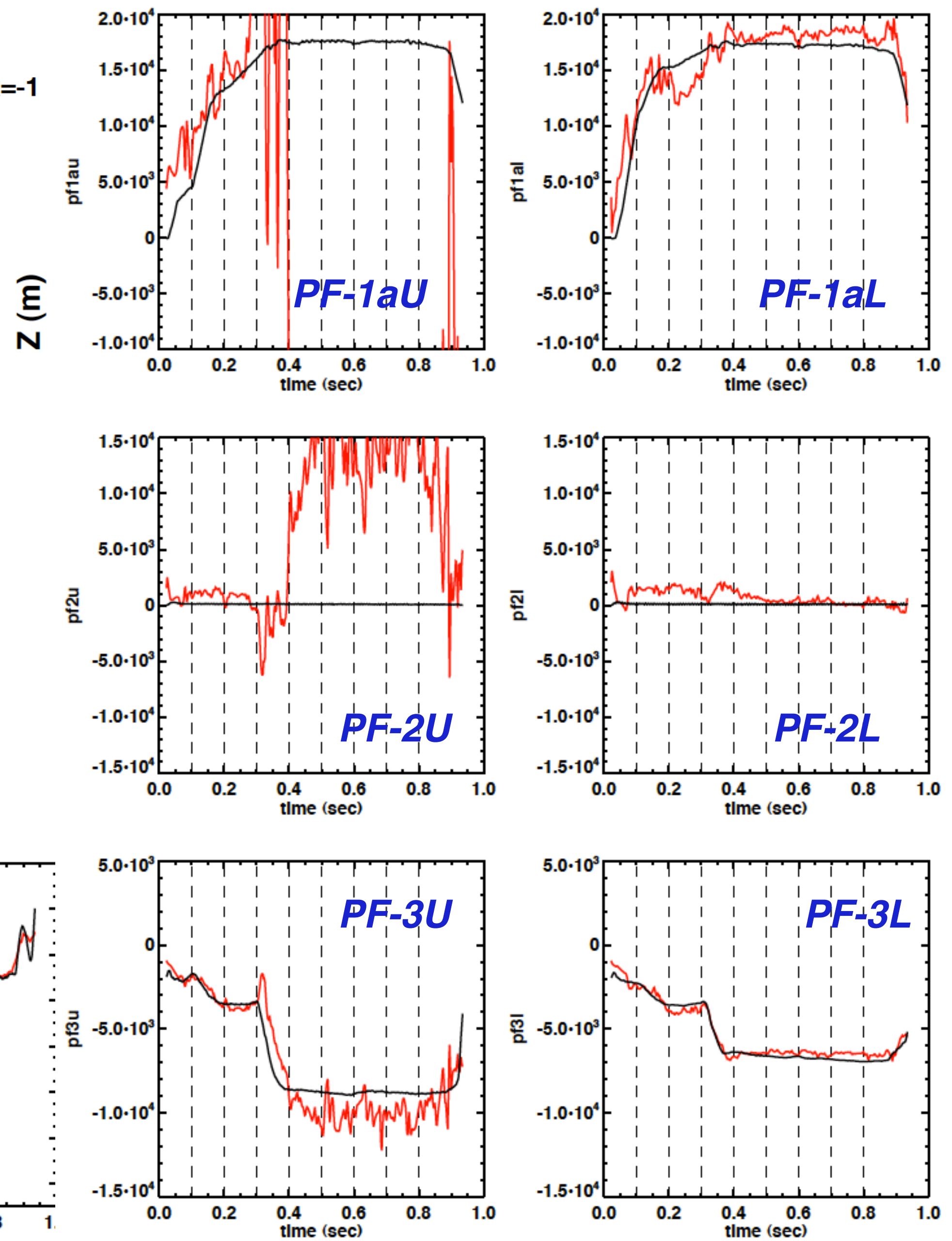


- Early mismatch in axis radius due to differences in pressure profile.
  - TRANSP more peaked than LRDFIT
- Good agreement on ALL coils until t~0.3, when plasma is shifted down.
  - Upper divertor coils then are poorly constrained.
- Similar levels of agreement found in other shots.

Red: ISOLVER

Black: LRDFIT and measured I_{coil}.





Methodology for NSTX-Upgrade Simulations

How To Navigate Through NSTX-Upgrade Configuration Space?

Inputs

- I_P & B_T
- Thermal density and temperature profiles.
  - These map to H_{98}, f_{GW}
- Requested plasma boundary shape.
- Z_{eff}, D_{FI}
- Beam R_{tan}, voltages

Outputs

- Equilibrium properties.
  - Bootstrap fraction.
  - NBCD fraction.
  - Achieved shape & required coil currents
- Stability properties
  - q_{min}, q_0
  - F_P, l_i, β_N
  - $\delta W_{no\text{-}wall}$, $\delta W_{with\text{-}wall}$,

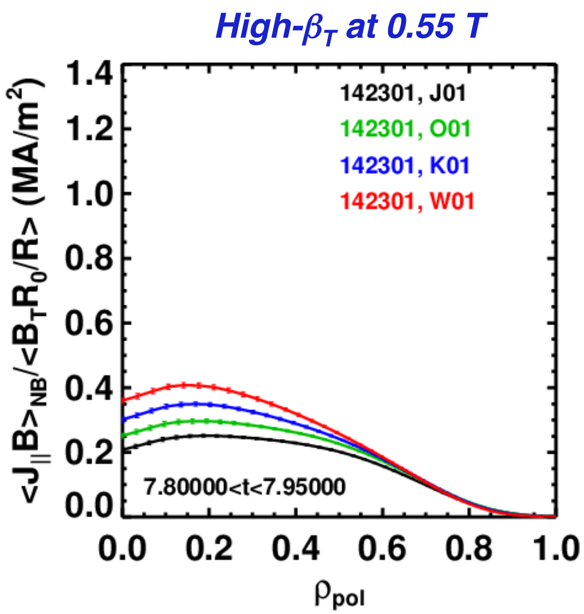
Chosen Methodology

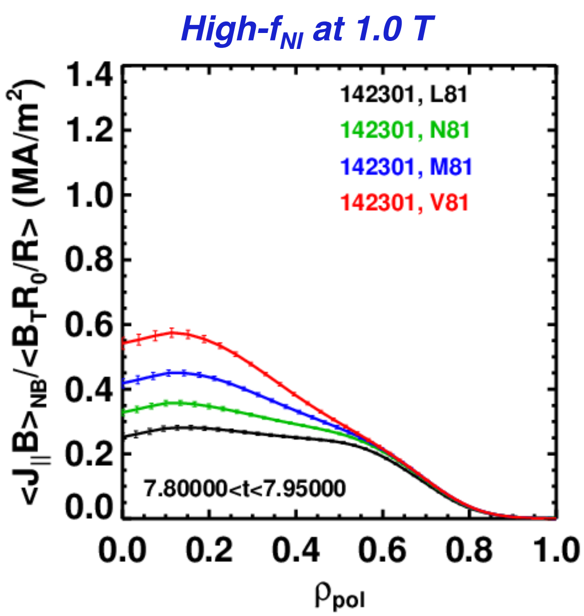
- Define a configuration:
  - I_P, B_T, Z_{eff}, D_{FI}, Beam voltages and geometry, current and field, boundary shape, multiplier on neoclassical χ_i, T_e and n_e profile shapes.
- Use neoclassical theory to predict the ion temperature.
- Over a series of free-boundary TRANSP runs, scan input electron density and temperature profile magnitudes.
  - Amounts to a scan in f_{GW} and H_{98}.
- Run resulting equilibrium through CHEASE.
  - Refine for small G.-S. error.
- Use CHEASE equilibrium to compute n=1 & 2 stability with DCON.

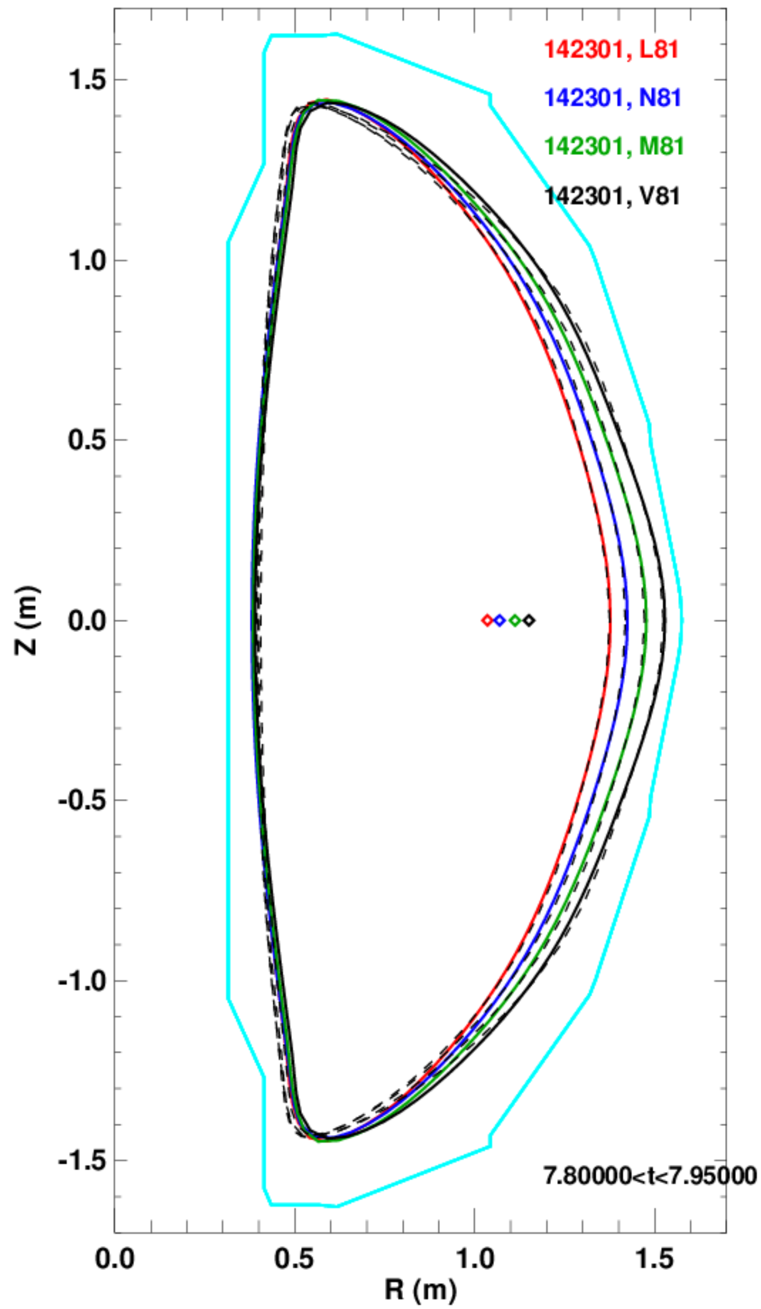
Effect of Outer Gap on Scenarios

Outer Gap Plays a Key Role in Determining NBCD Profile (& Beam Power Losses)

- Fix the plasma height, requested inboard midplane separatrix radius.
- Scan the outboard midplane separatrix radius.
  - 20 cm, 15 cm, 10 cm, 5 cm
  - This scans the aspect ratio and elongation.
- Large outer gap cases have the broadest driven current profile.
  - Though it is always MORE peaked than the Ohmic profile

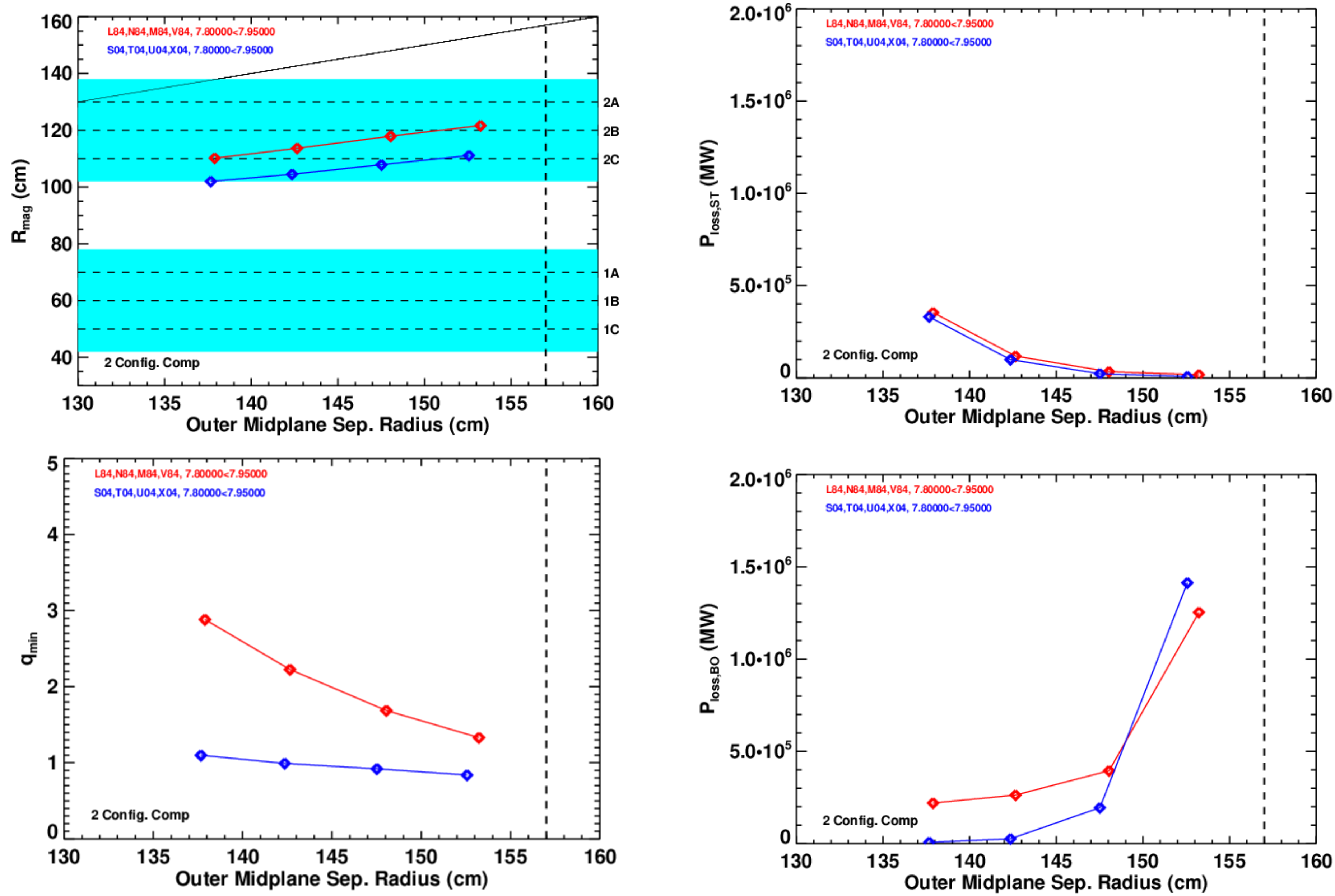






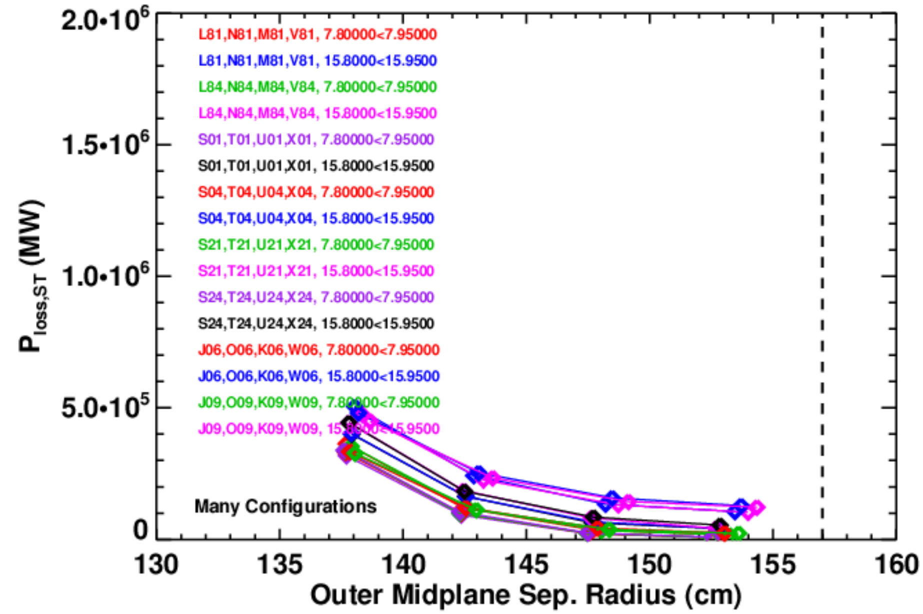
~10-15 cm Outer Gap Appears Desirable For "Sustained" Scenarios

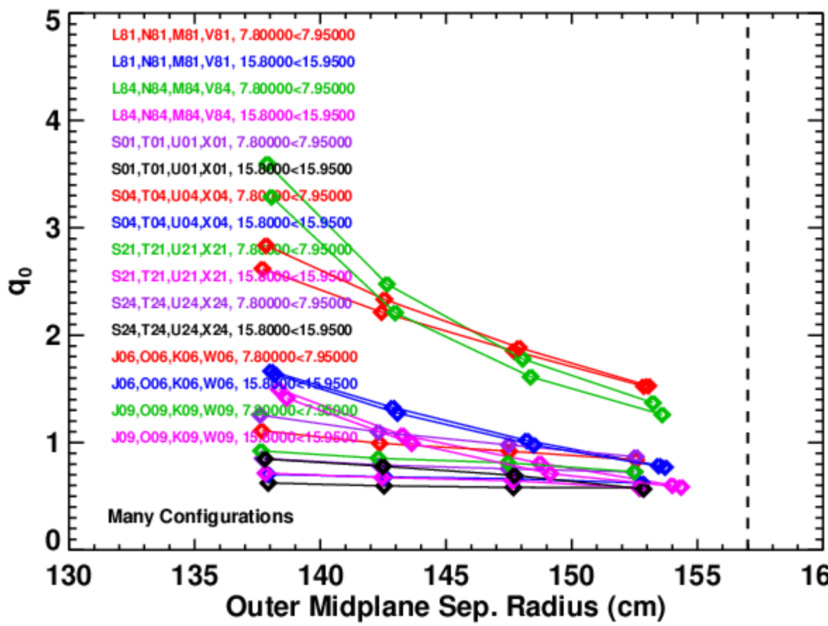
1 MA, 1T, 6-Source @ 90 kV, targeting f_{NI}~1   *1.2 MA, 0.55 T, R_{tan}=[50,60,70,130] @ 90 kV, targeting sustained high-β_T*

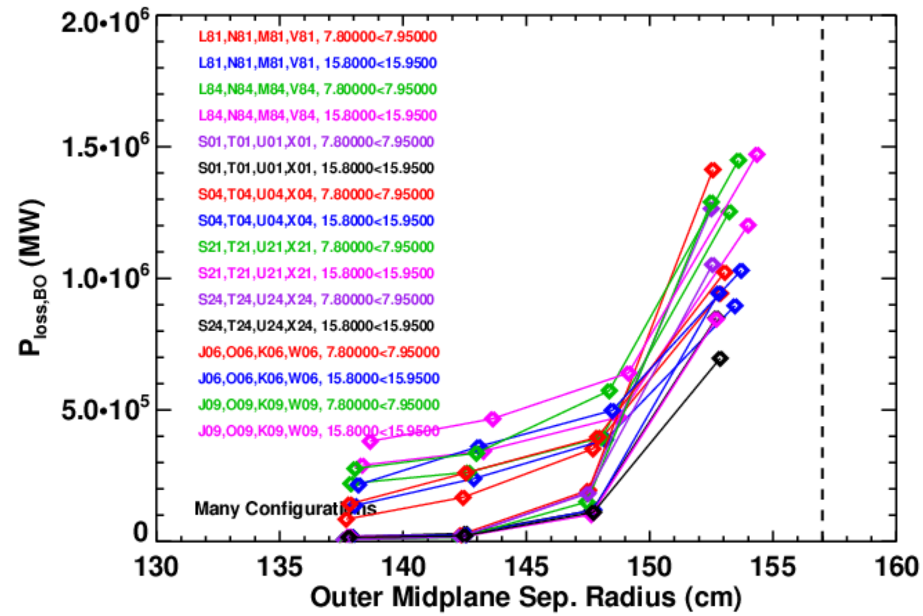


~10-15 cm Outer Gap Appears Desirable For "Sustained" Scenarios

- Some cases with 4 sources, others with 6.
  - But always includes 1C and 2A.
- 90 kV, 1-1.2 MA, $0.55<f_{GW}<1.0$
- What sets the power limit?
  - Energy on the antenna or beam armor?
    - MSE calibrations do 2 MW for 0.4 sec.
  - Or when impurity generation ruins the shot?





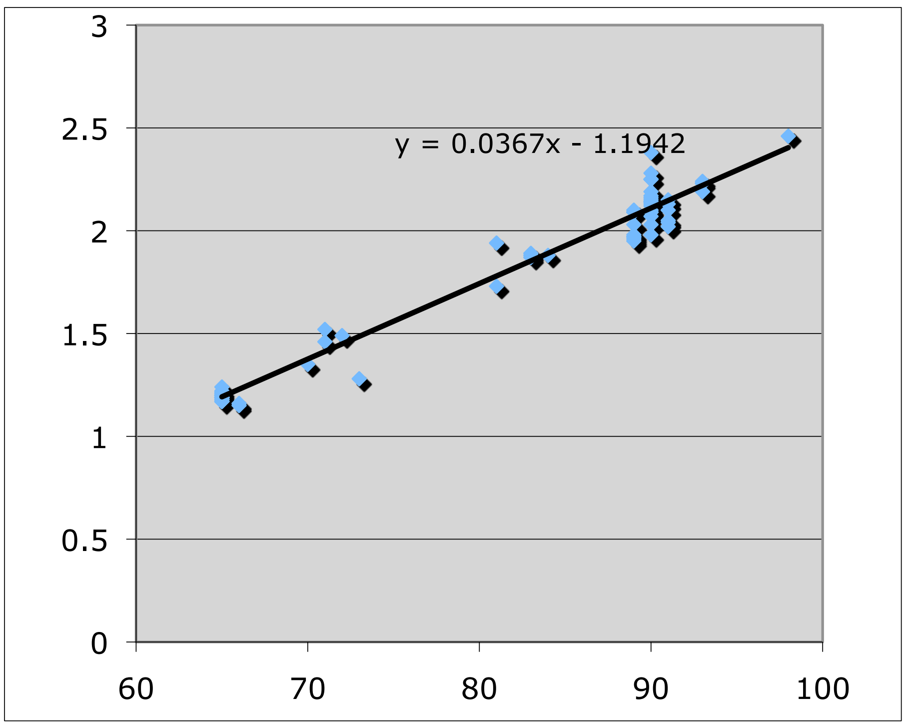


Study of ~100% Non-Inductive Scenarios in High-δ DN Shapes

From Beam GRD

Pulse length (sec)	Power to Plasma (MW)
5	5.0
4	5.4
3	6.0
2	6.8
1.5	7.5
1.25	8.2
1	9.0

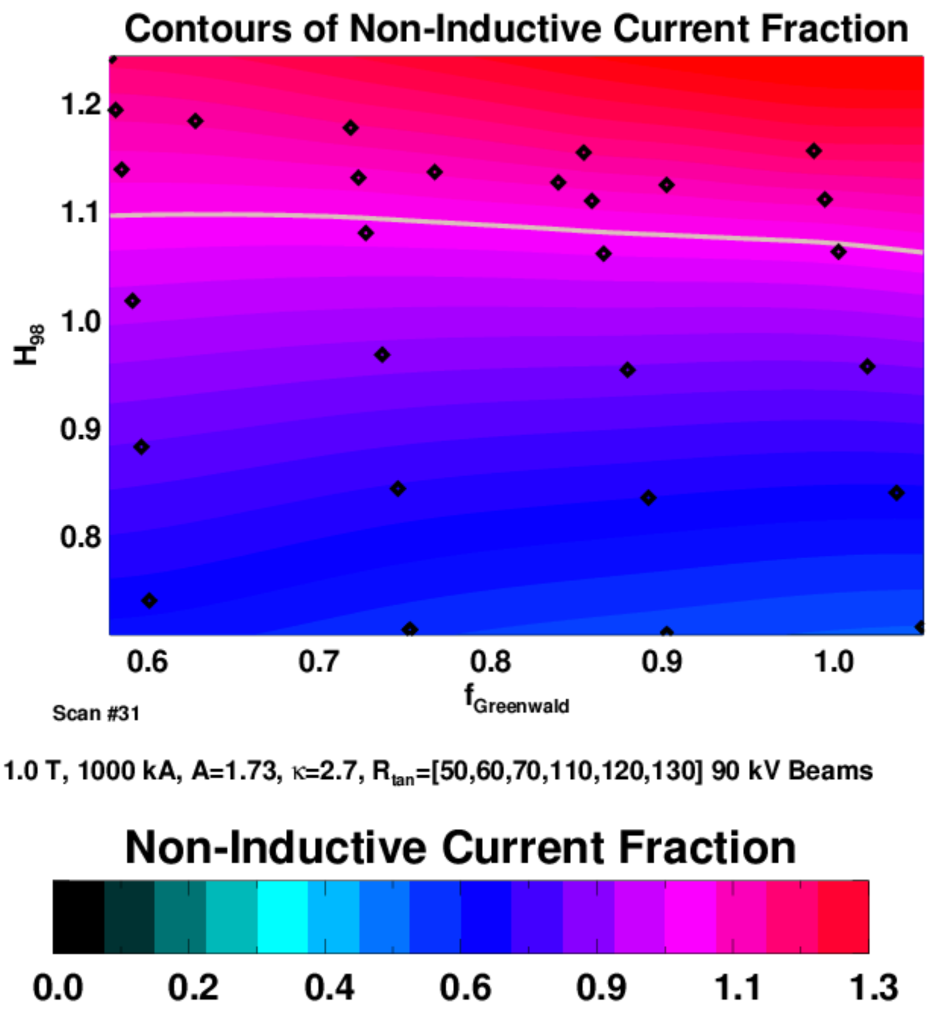
Source Power vs. Voltage (from E. Fredrickson)



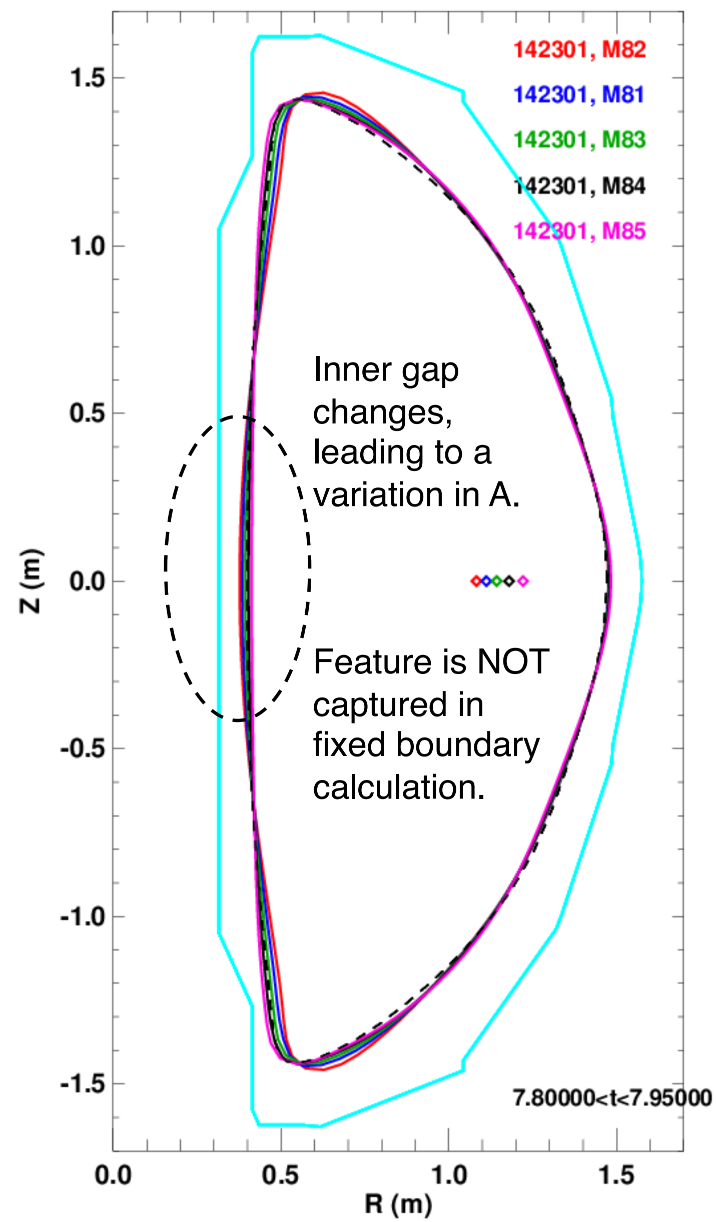
Source Voltage	Source Power	Source Duration
80	1.75	4.5
90	2	3
95	2.25	2
100	2.5	1.5
110	2.8	1.25

Vessel-Filling Plasmas at 1.0 MA Can Be Fully Non-Inductive With Modest Confinement Multipliers

1.0 T, 1.0 MA, κ=2.7, A=1.73, *10 cm outer gap*, 90kV, 12 MW

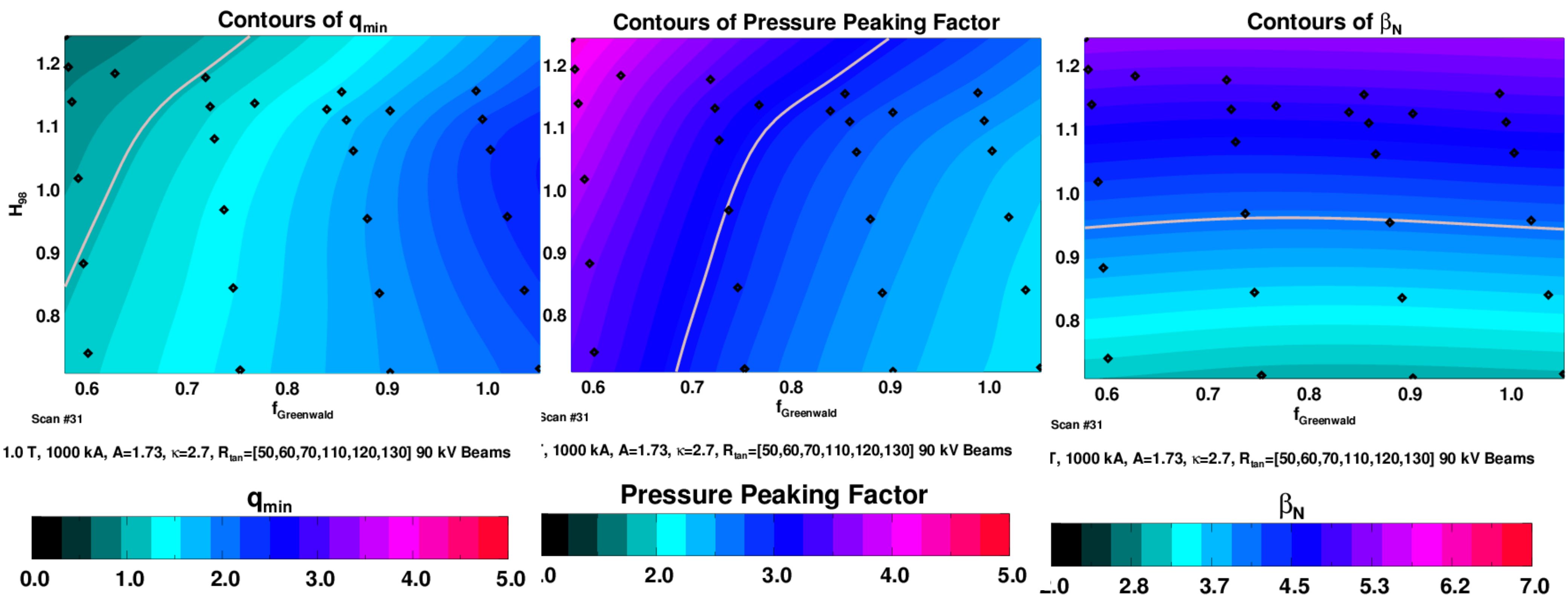


Changes to shape as confinement changes at $0.85<f_{GW}<0.9$



Significant Changes in Profiles Over This Parameter Range

1.0 T, 1.0 MA, κ=2.7, A=1.73, *10 cm outer gap*, 90kV, 12 MW

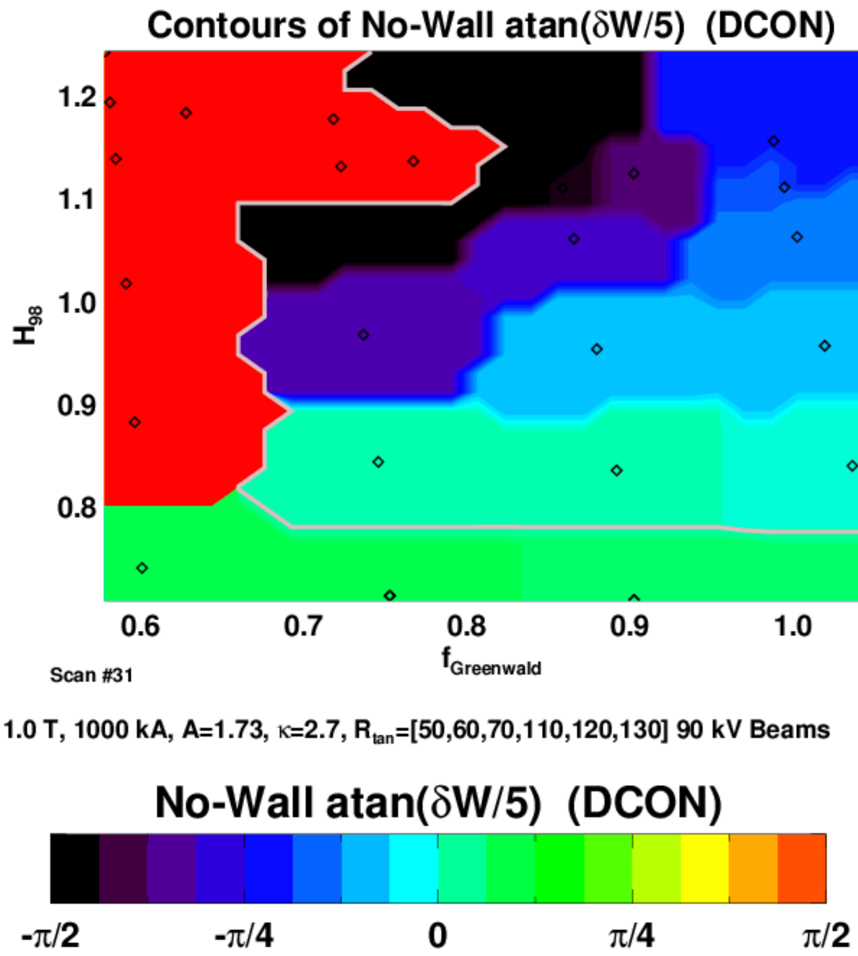


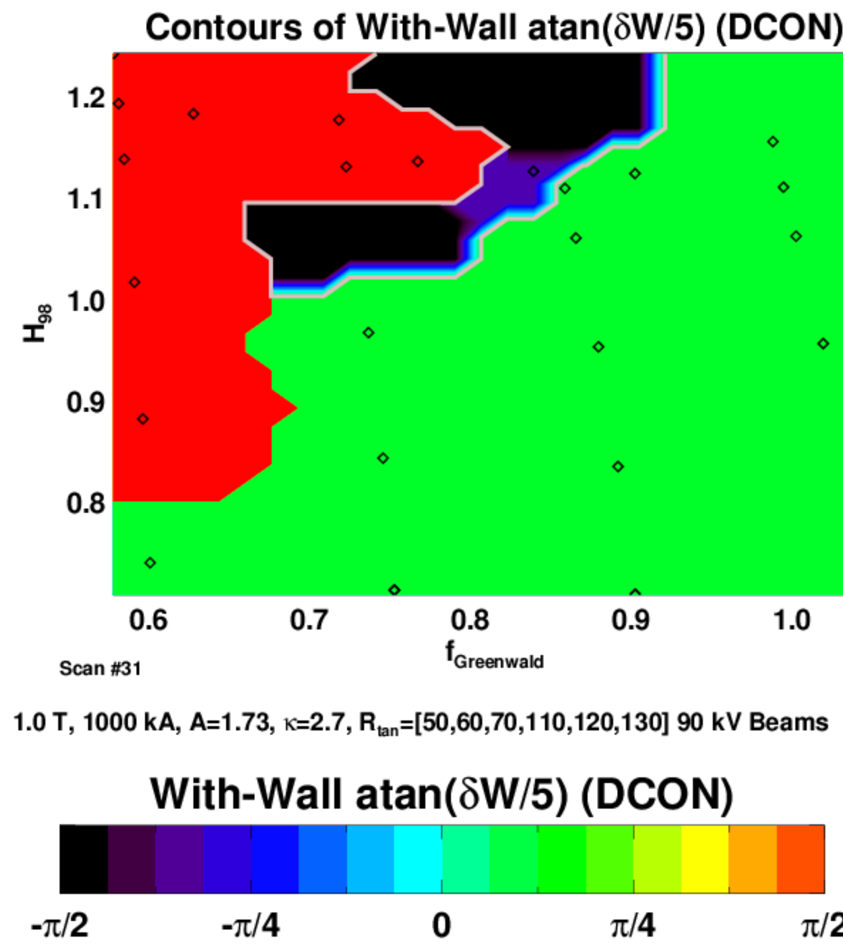
- Low density, high confinement region has 30-40% fast ion pressure fraction.
  - Drives down q_{min}.
  - Increases F_p

$$F_P = \frac{p_0}{\iiint p\,dV}$$

Stability Properties May Render This Scenario Problematic

1.0 T, 1.0 MA, κ=2.7, A=1.73, *10 cm outer gap*, 90kV, 12 MW



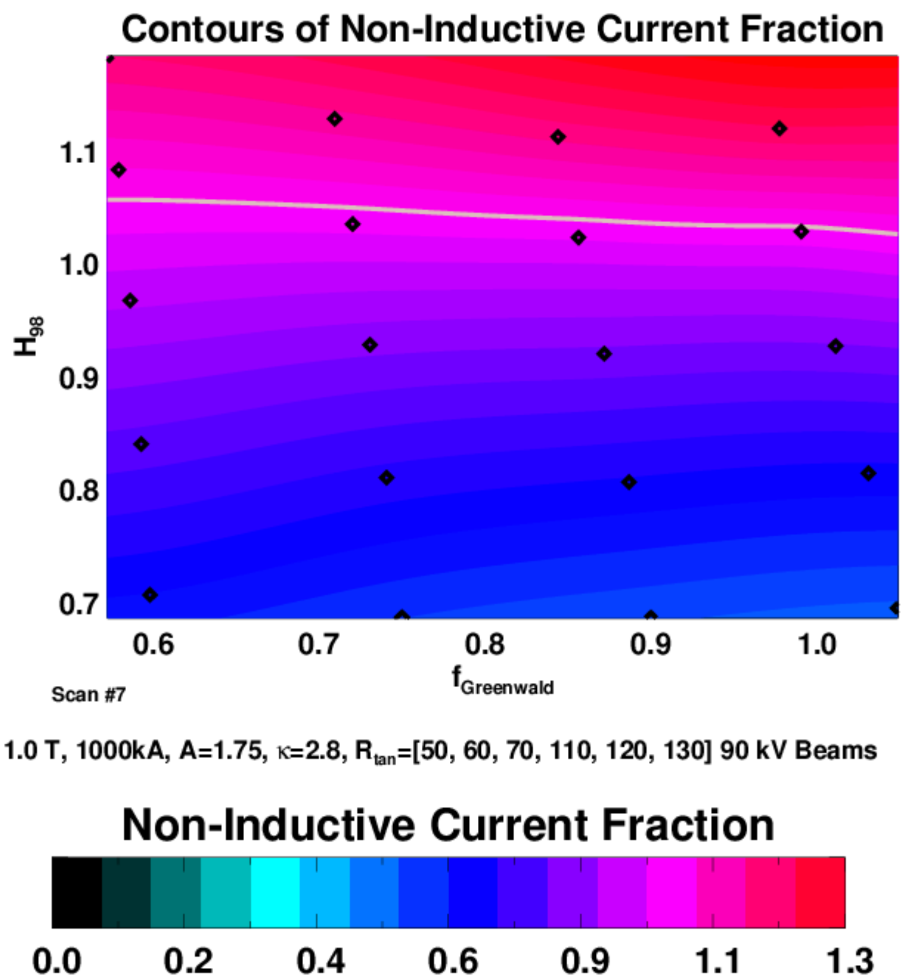


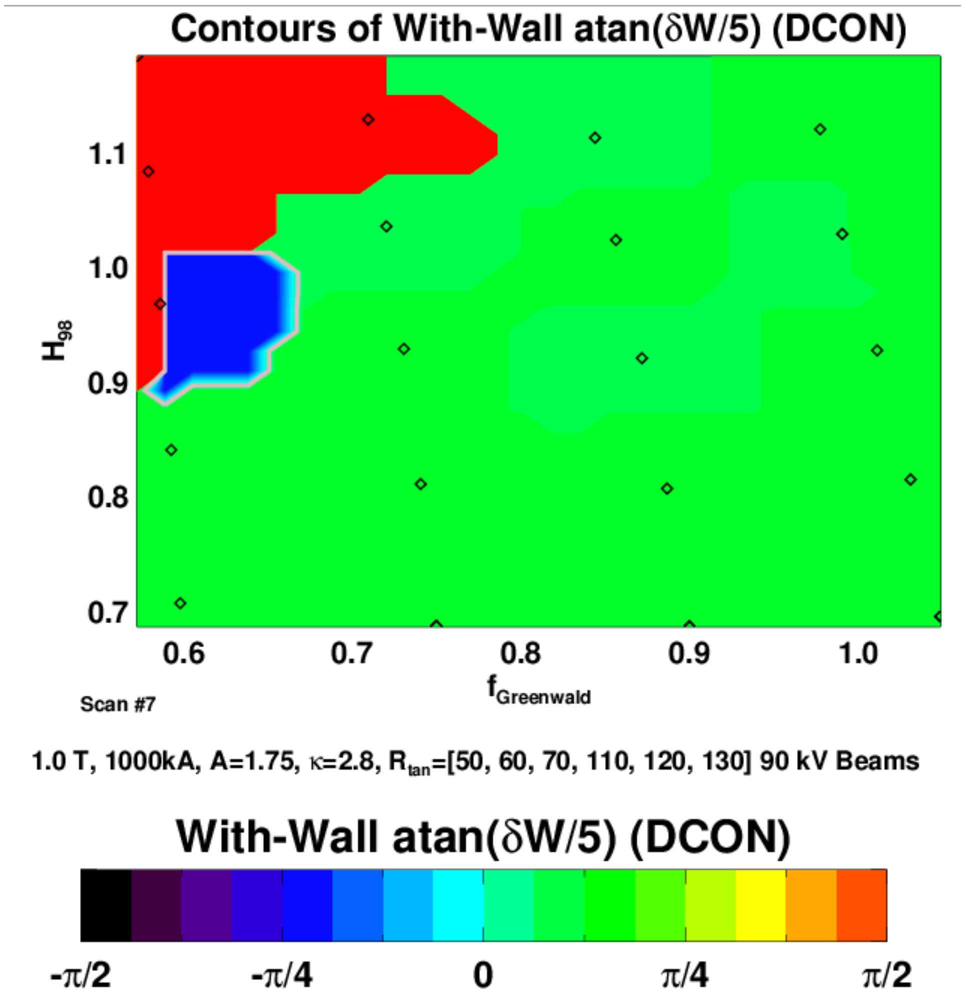
Problems: *1)Too much central NBCD (drives down q_{min})*
2) too much fast particle pressure on axis (drives up F_P)

Solutions: *1) Increase the outer gap to make source 2A, 2B more off-axis.*
2) Invoke some fast-ion diffusivity.

15 cm Outer Gap Case Has Better Properties

- 1.0 T, 1.0 MA, κ=2.7, A=1.73, *15 cm outer gap*, 90kV, 12 MW
- Elevated q_{min} is maintained





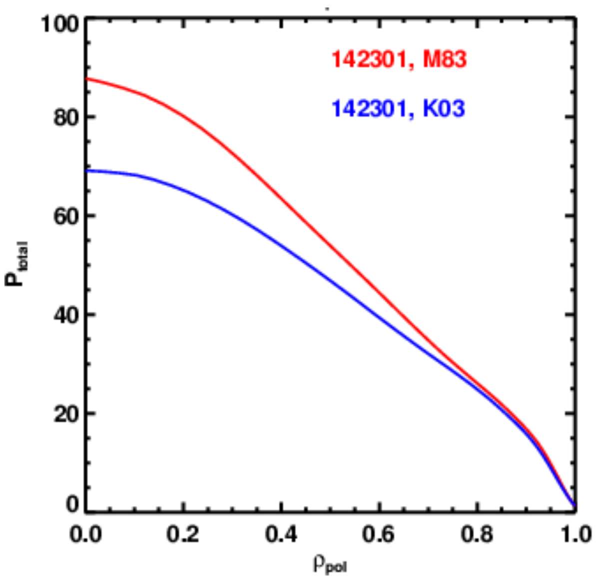
Invoking Anomalous Fast Ion Diffusivity Helps Elevate q_{min} and Reduce F_P in 10 cm Outer Gap Case

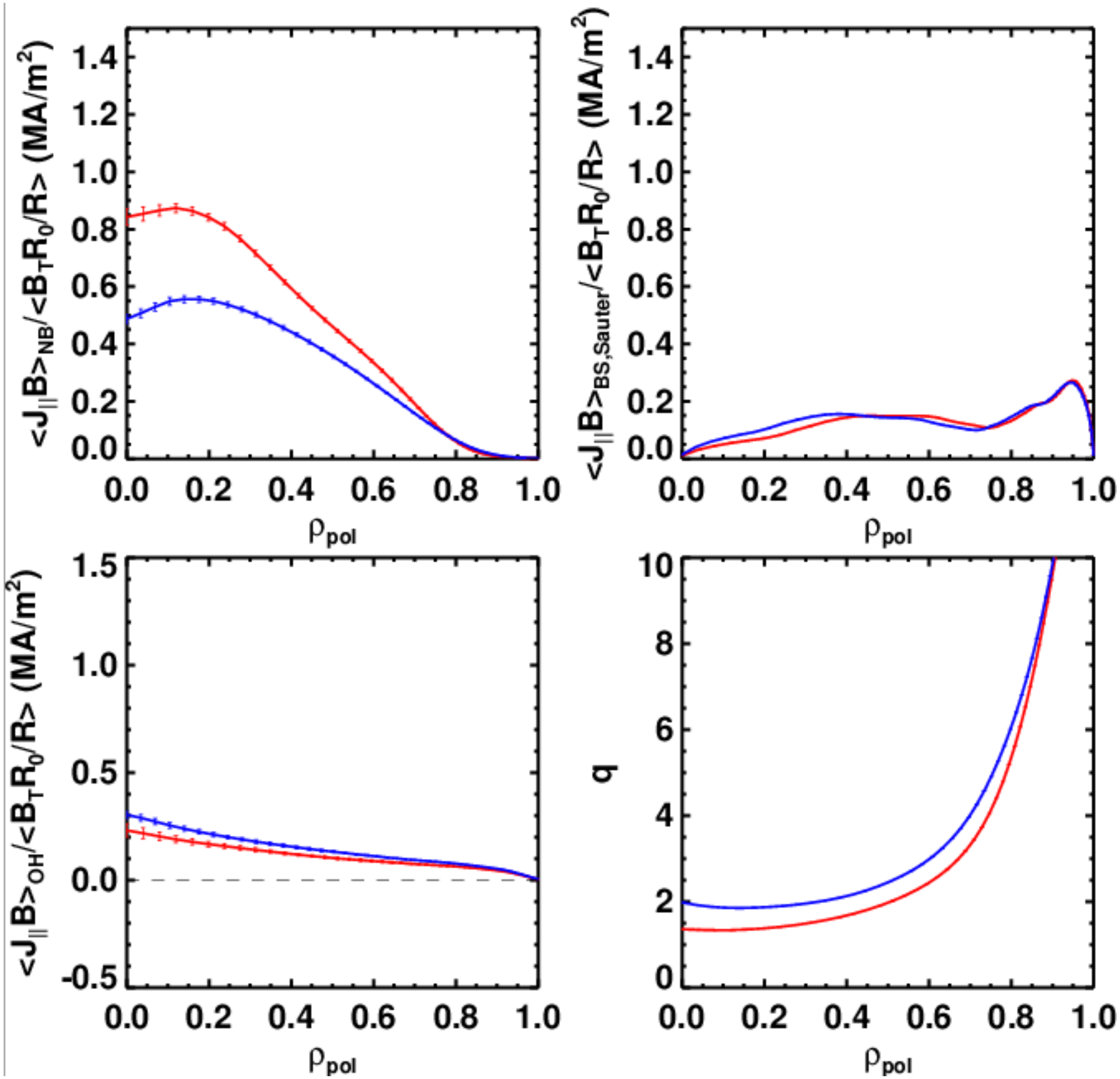
$H=1$, $f_{GW}=0.7$

$D_{FI}=0\ m^2/s$

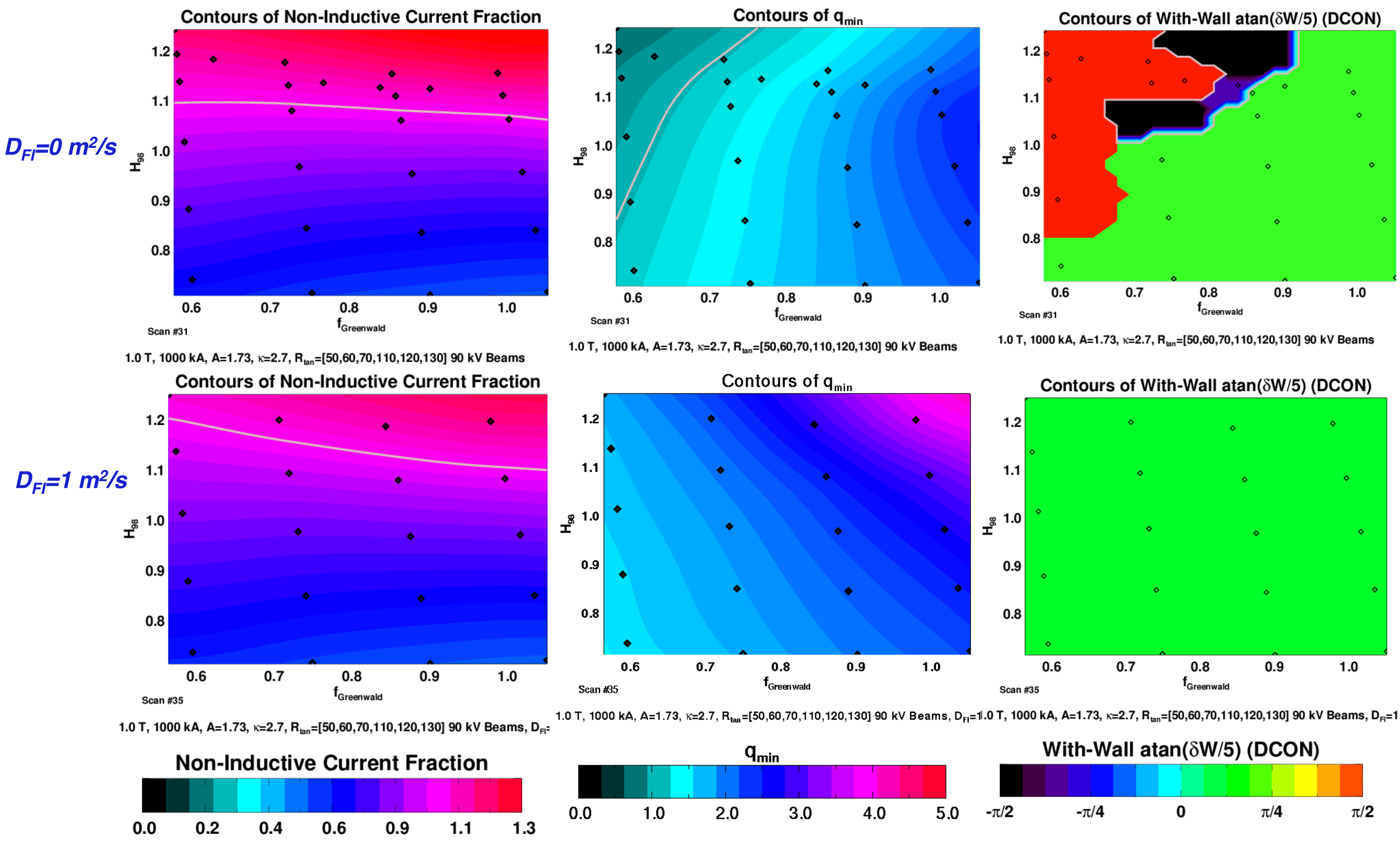
$D_{FI}=1\ m^2/s$

Note: Ohmic current profile is broader than NBCD profile

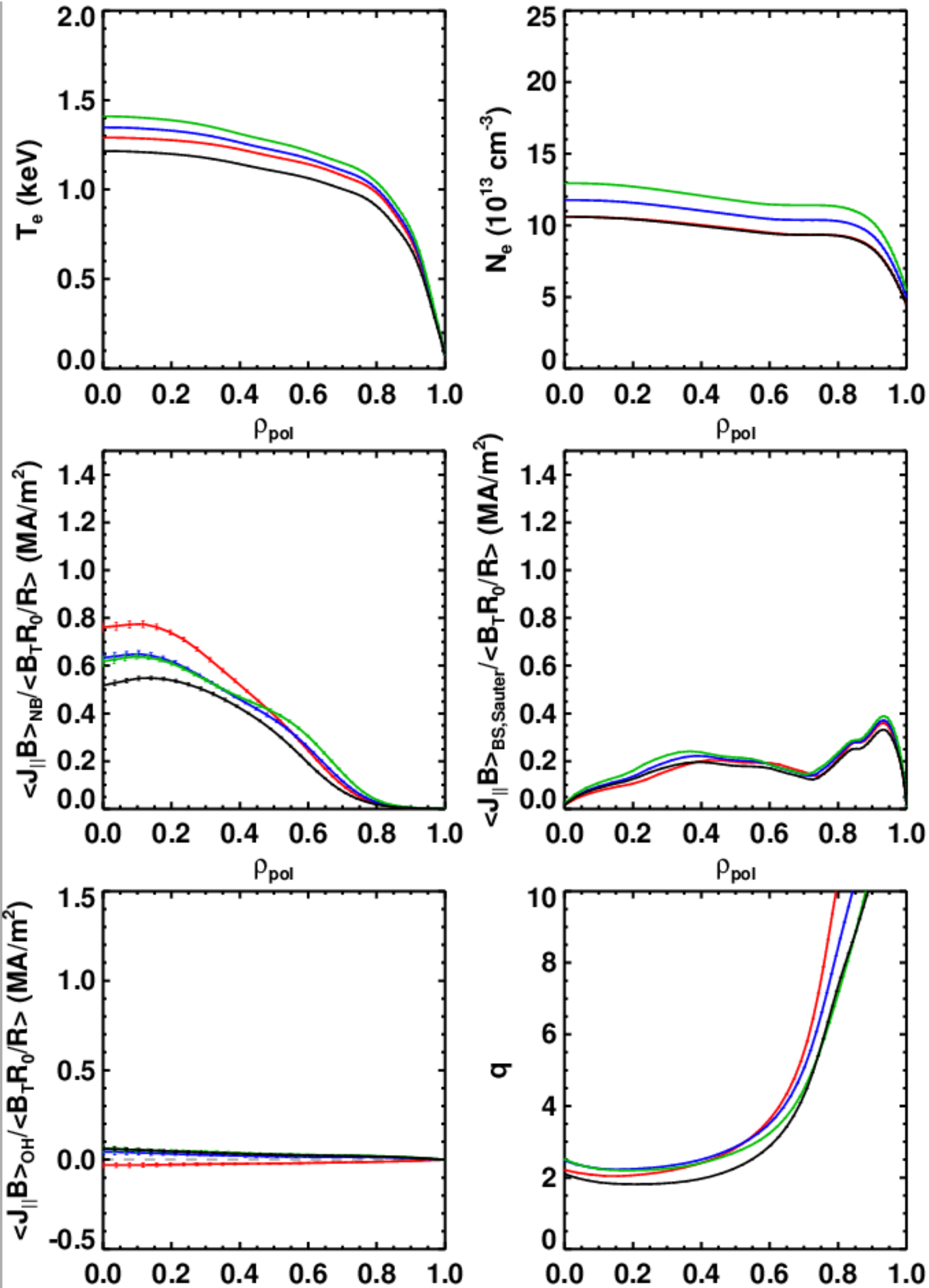




Elevated q_{min} and Reduced F_P with D_{FI}=1 Improves the Ideal Stability (but required higher H_{98} at low f_{GW})



Changing Beam Voltage Raises or Lowers The Non-Inductive Current Level



- TRANSP is run with predetermined constant I_P.
  - This is how the experiment is typically operated.
  - Must guess profiles and beams perfectly to achieve exactly 100% non-inductive.
  - Small changes in confinement or plasma current would lead to f_{NI}=1.
- Previous NSTX-U modeling was done with pre-determined constant V_{surf}=0.
  - Plasma current relaxes to the non-inductive value.
  - Hard to know the confinement level beforehand.
  - Running TRANSP this way with ISOLVER crashed 100% of the time.

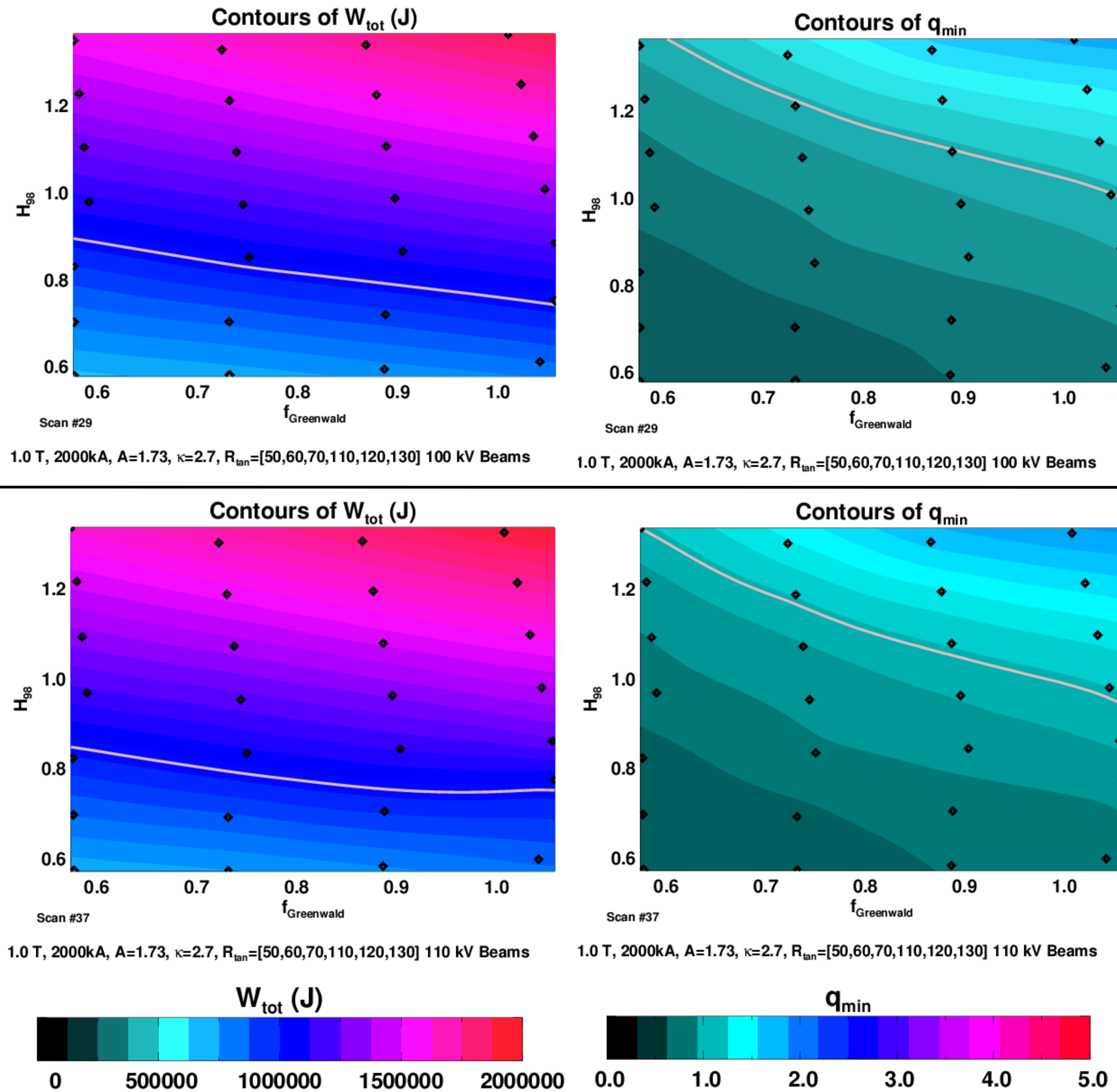
Near Non-Inductive Current Levels for 5 & 6 Source Scenarios at Various Beam Voltages, 15 cm Outer Gap

Run	I_P, B_T	Source Voltage	H_{98}/f_{GW}	Source Duration
O09	900, 1.0	80	1.04/0.85	4.5
N84	1000, 1.0	90	1.02/0.85	3
O64	1100, 1.0	100	0.99/0.86	1.5
Q39	**900, 0.75**	**90 (5 sources)**	**1.04,0.85**	**3**

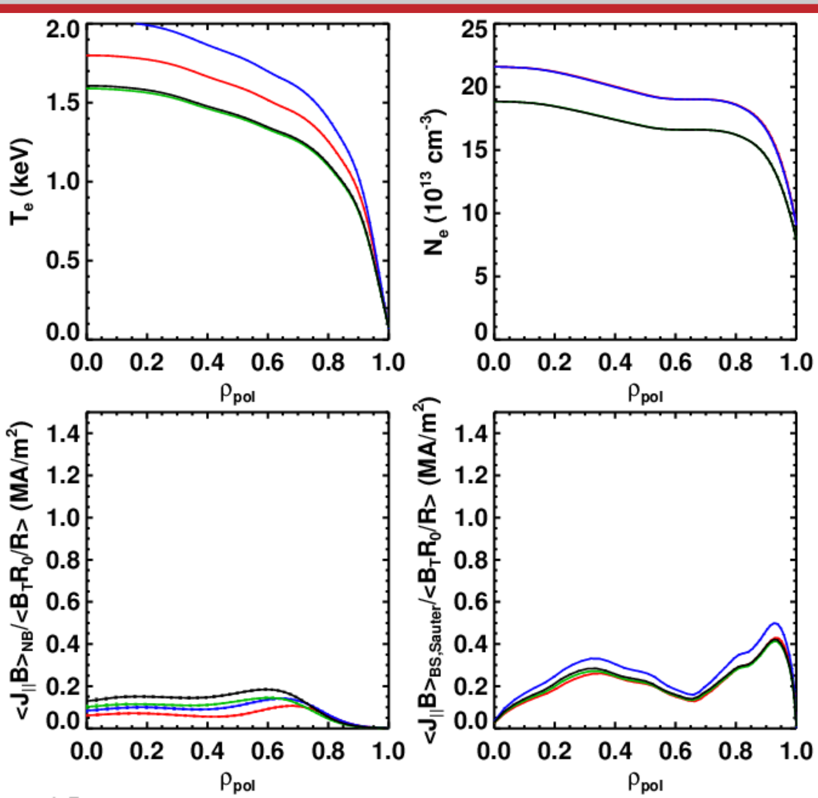
Maximum Achievable and Sustainable Stored Energies.

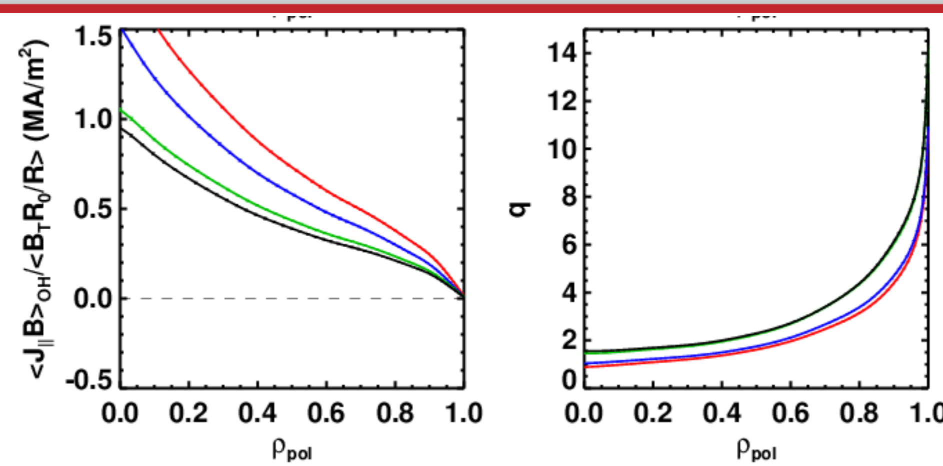
Plasmas With up to 1.5 MJ (or more) May Be "Transiently" Possible

- 2 MA, 1 T, 10 cm outer gap
- 110 & 100 kV beam cases shown.
- Equilibrates to q_{min}<1.
  - Probably OK since the beams have only ~1.2 sec pulse duration at this voltage.
- 1 stick of dynamite = 2MJ.
  - What sort of machine protection/operational development will we required before we try this?
  - Tendency for q_0->1 will tend to increase disruptivity.



Should be Possible to *Sustain* Configurations with ~1000 kJ with H_{98}~1.





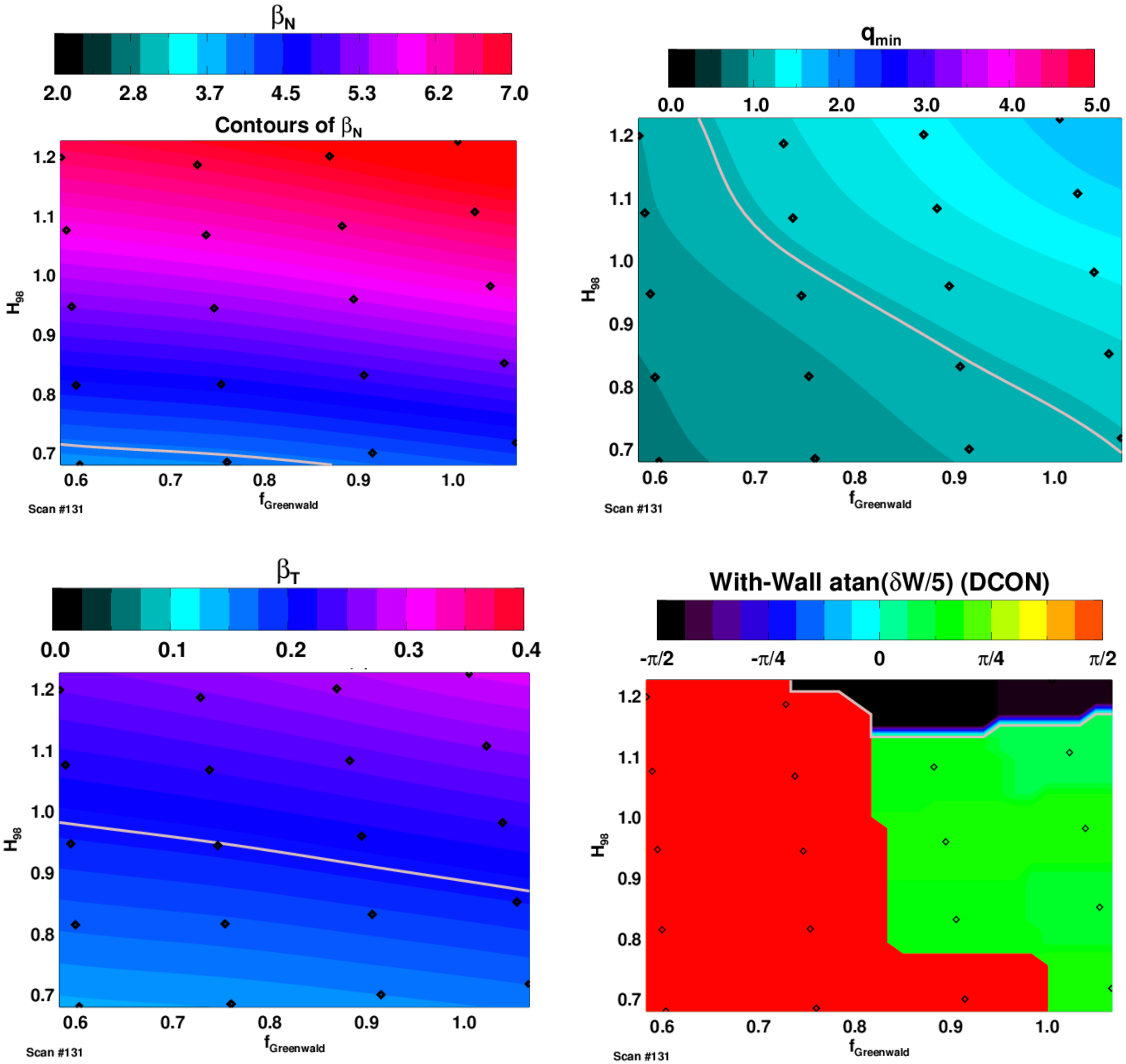
6-Source High-Current Partial Inductive Cases Short beam duration and long τ_{CR} imply that relaxed q_{min} may not be relevant.

Run	Plasma Current	Source Voltage	H_{98}, f_{GW}	W_{tot}	Relaxed q_{min}	V_{surf}
M79	2000	100	0.99, 0.89	1200	0.88	0.217
K54	2000	110	1.05, 0.88	1440	1.03	0.148
O96	1800	100	0.99, 0.88	1080	1.2	0.172
O84	1600	90	1.02, 0.88	917	1.45	0.129
?	?	80	?	?	?	?

Sustained High-β_T Scenarios

Or, what is the highest I_P/B_T possible with q_{min}>1?

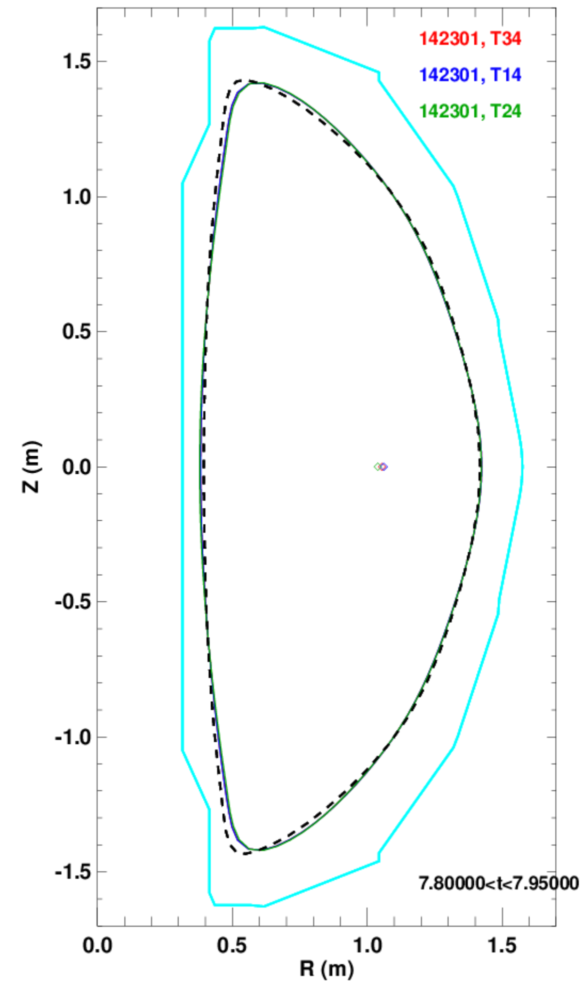
Limit Operating Space with β_t~25% is Possible?



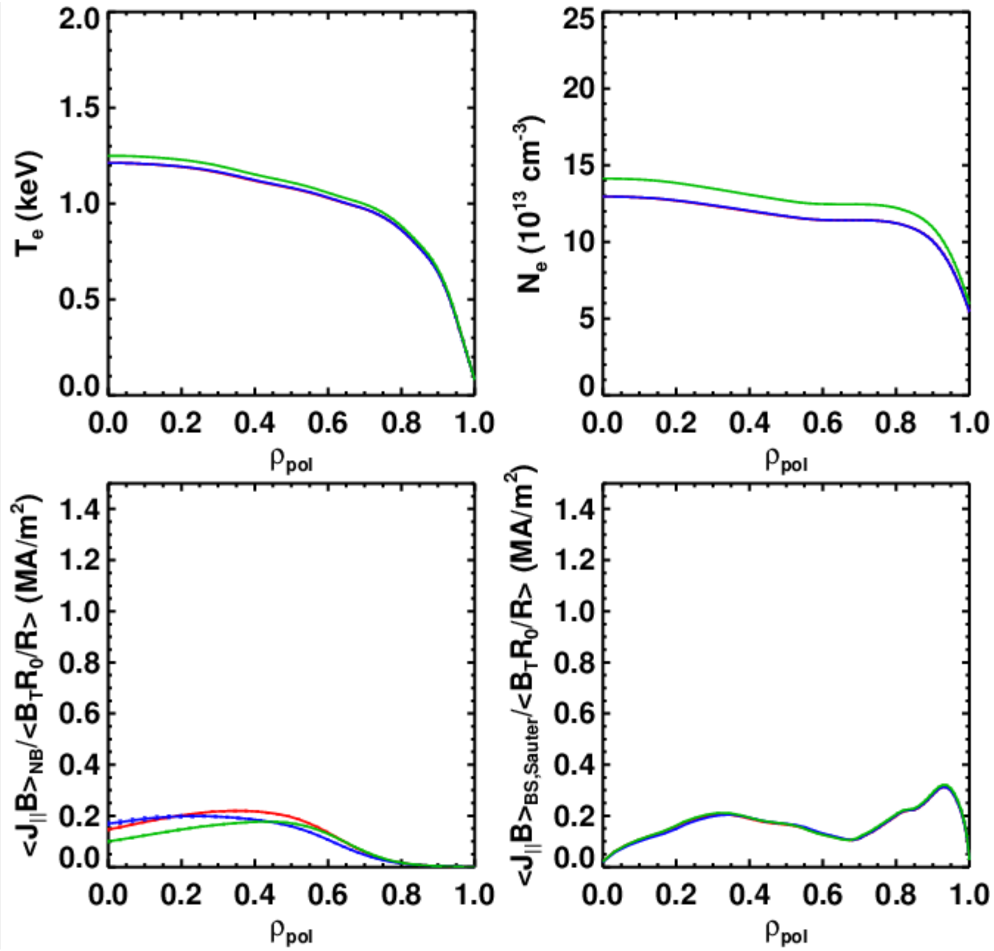
B_T=0.55 T, I_P=1100 kA

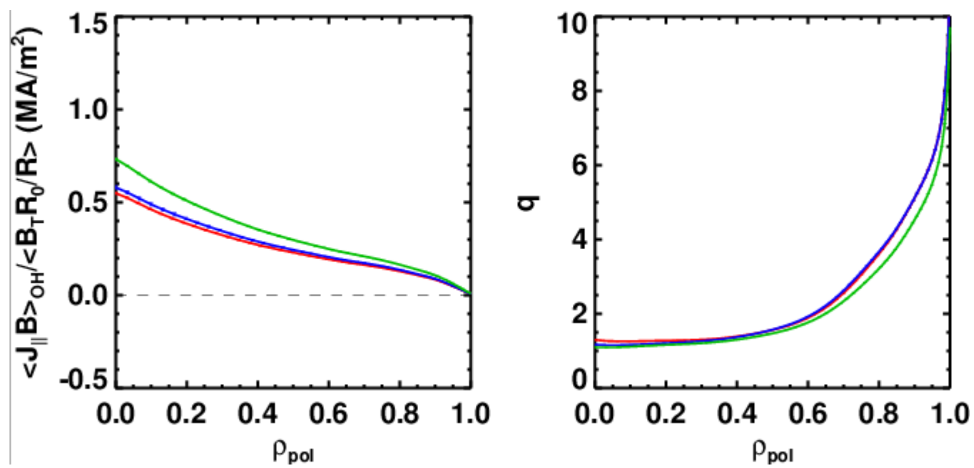
R_{tan}=[50, 60, 120, 130] 90 kV

15 cm outer gap



Sustained Scenarios With β_T~25% @ B_T=0.55 T Appear Feasible





4 Source Elevated q_{min}, high-β_T Cases with B_T=0.55 T

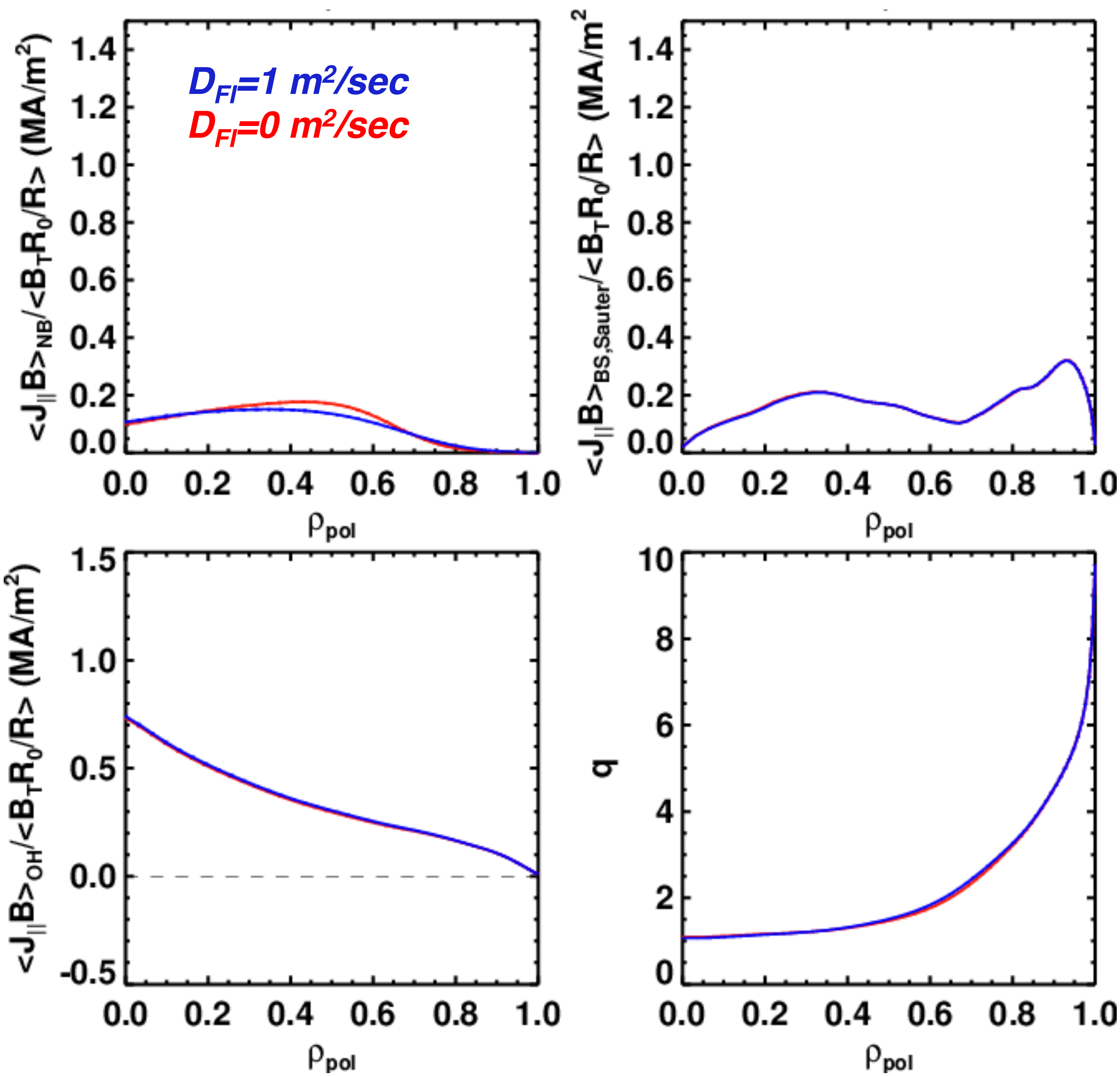
Challenging to find beam configurations which result in q_{min}>1 and large I_N.

T64?

Run	Plasma Current	Source Voltage	R_{Tan}	H_{98},f_{GW}	β_N,β_T	q_{min}	V_{surf}
T34	1100	90	50,60,120,130	1.08, 88	6.3, 24%	1.29	0.11
T14	1100	90	50,60,70,120	1.08, 0.88	6.2, 23%	1.17	0.12
T24	1200	90	50,60,120,130	1.08, 0.88	6.3, 26%	1.1	0.14

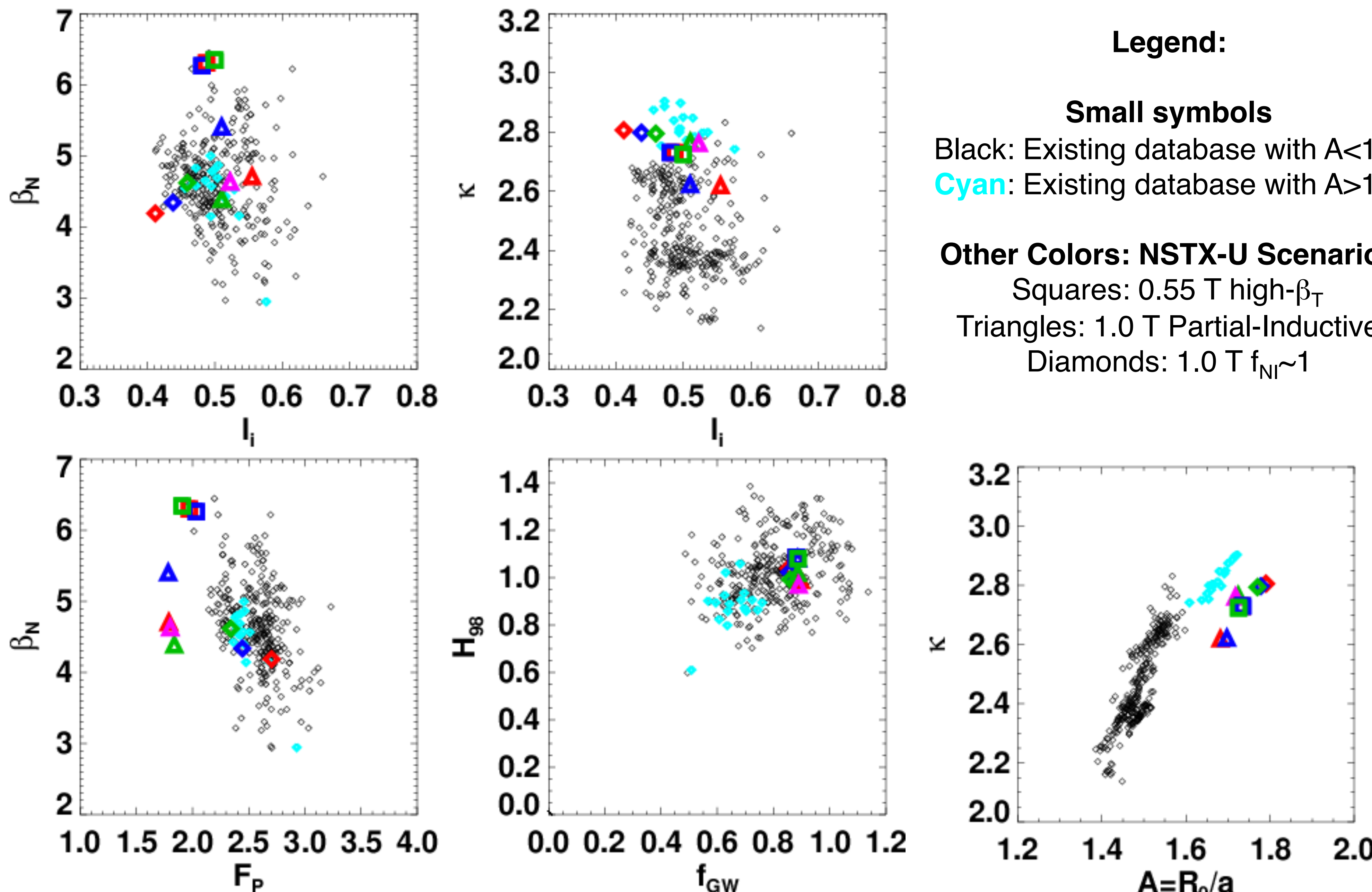
Additional Fast Ion Diffusion (D_{FI}=1m^2/s) Has Little Impact on the Scenario

- Example is the 1200 kA, R_{tan}= [50,60,120,130] case.
- D_{FI}~1 m^2/sec is the upper bound for values in quiescent discharges.
- Has little discernable effect on the scenario.



Comparison to Existing Data

Identified Scenarios are a Small Change In Some Parameters…



Legend:

Small symbols

Black: Existing database with A<1.6

Cyan: Existing database with A>1.6

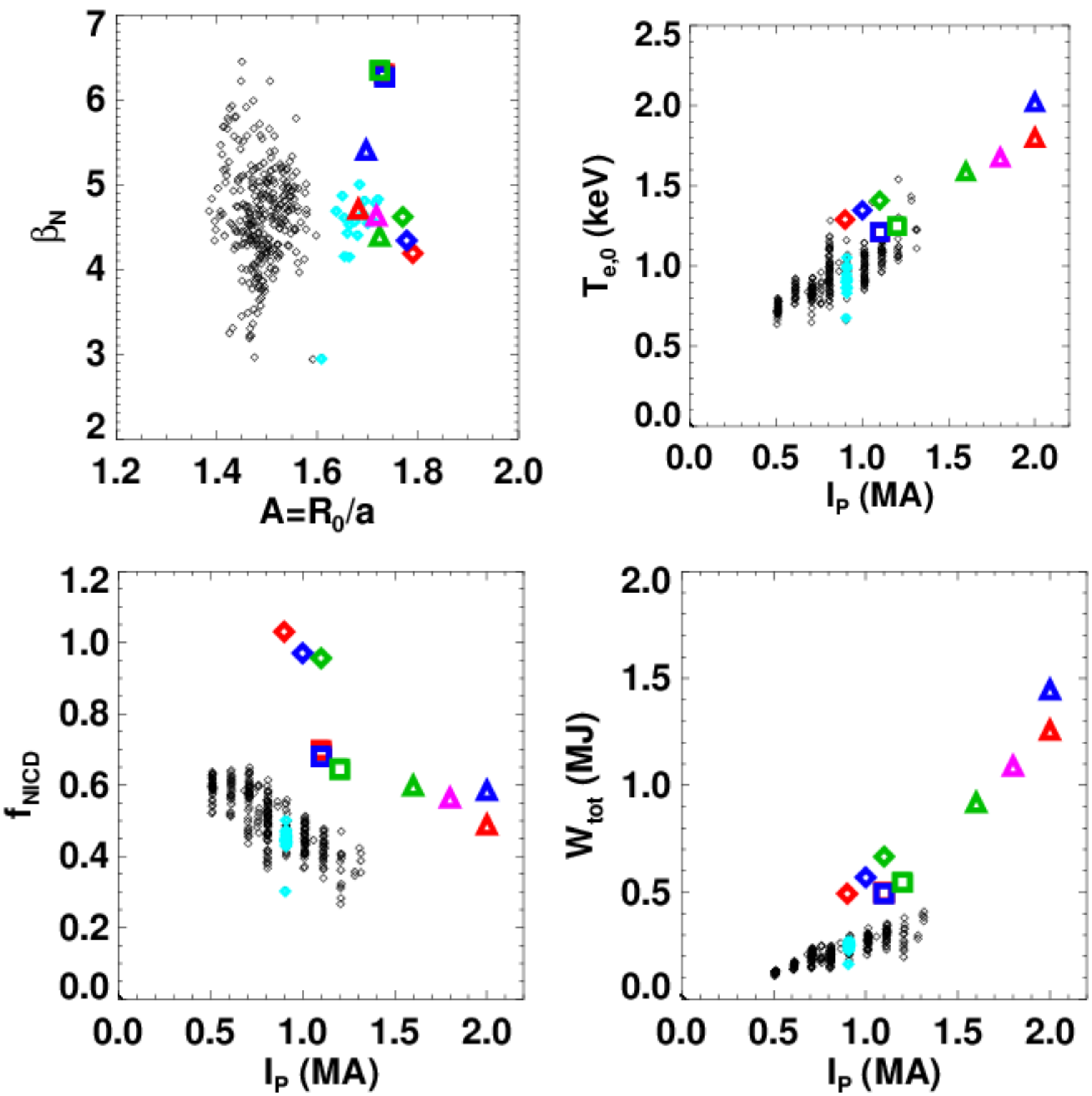
Other Colors: NSTX-U Scenarios

Squares: 0.55 T high-β_T

Triangles: 1.0 T Partial-Inductive

Diamonds: 1.0 T f_{NI}~1

Identified Scenarios are a Small Change In Some Parameters…and a Big Change in Others



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Other Colors: NSTX-U Scenarios

Squares: 0.55 T high-β_T

Triangles: 1.0 T Partial-Inductive

Diamonds: 1.0 T f_{NI}~1

Summary

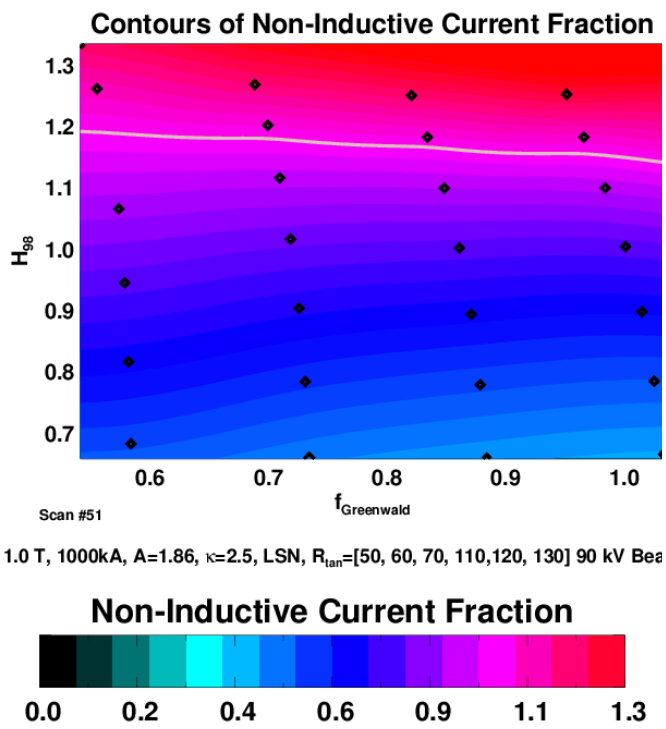
- Free-Boundary TRANSP simulations are working fine for NSTX and NSTX-U.
  - But can be tricky…see R. Andre of S. Gerhardt before trying it.
- 10-15 cm outer gaps appear to be optimal with respect to off-axis NBCD and beam power loss.
- f_{NI}=1 scenarios are available over a range of currents and beam powers.
- Stored energies up to 1.5 MJ may be possible.
- Sustained configurations with β_T~25% may be possible.
- Moderate levels of anomalous fast ion diffusion may be beneficial for some scenarios, irrelevant to others.
  - Large levels of D_{FI}, like for TAE avalanches, not simulated, but likely to matter a lot more.
- Biggest extrapolation appears to be high β_N and higher-A.
  - We will work on this as part of R11-2.

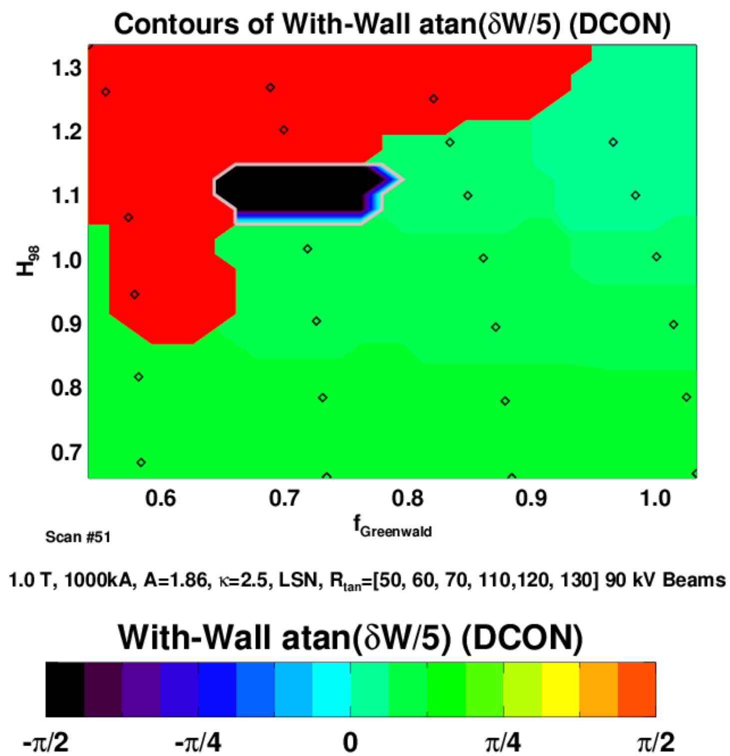
- Near term things to do:
  - Continue to look for elevated q_{min} scenarios at high-β_T.
  - Look for scenarios where the variation in NB sources results in the largest changes in the q-profile…these optimal for current profile control.
- Long term:
  - Need a validated electron transport model.

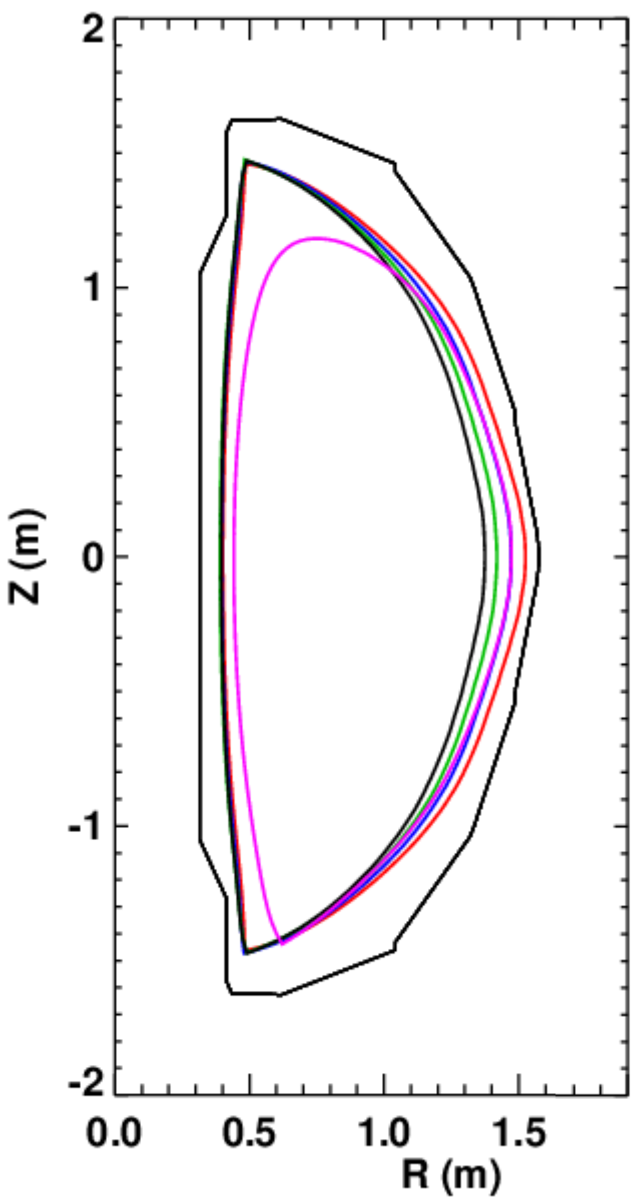
Study of 100% Non-Inductive Scenarios in LSN Shape

LSN Shape Requires Excellent Confinement for f_{NI}=1 @ 1 MA, and Stability May be a Problem

- LSN shape with 10 cm outer gap.
  - Elongation is 2.5
  - A=1.86 due to the larger inner gap.
- Might be typical of a shot with power on the LOBD.







Dropping Plasma Current and Source 2C Results in a Sustainable Scenario, if Confinement is Good.

12 MW, 800 kA
6 Sources
R_{tan}=[50,60,70,110,120,130]
Too much central NBCD drives down q_0.

10 MW, 800 kA
5 Sources
R_{tan}=[50,60,70, 120,130]