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XP-901: Exploration of Fast Discharge Shut-Down Using Coaxial Helicity Injection

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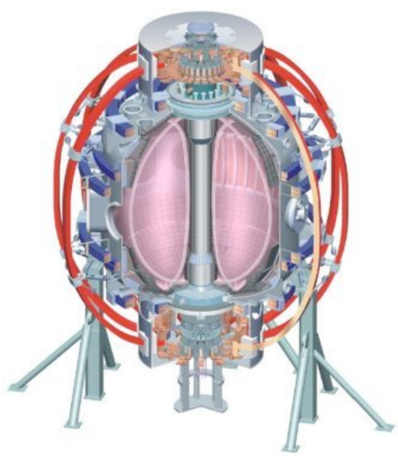
NSTX Team Review

1: Motivation and Goal for XP
2: Some technical considerations, including resolution of "chits" from group review.
3: Shot Plan for a 1 day XP.



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Questions to Explore in a First XP in NSTX

- Can CHI injection in NB heated plasma lead to fast shutdown?
  - Can VDE motion, and associated halo currents and localized thermal loading, be avoided? *(Highest Priority Question)*
  - What is the time delay between CHI initiation and plasma shutdown?
  - How much gas is required? What gas is best?
  - How does the CHI bank energy or the plasma stored energy influence the shutdown?

- Does the fast, centered shutdown require CHI?
  - LDGIS system contains ~15 times the gas inventory of the plasma, so verify that the electromagnetic effects are important.

- Does the lower divertor magnetic topology modify the effectiveness?
  - Different divertor geometries link the LOBD and LIBD in different ways (or not at all), allowing different current paths.
  - Which geometries are optimal for rapid-shutdown with CHI.

"Chits" From The Group Review

- D.M.: You need to avoid absorber arcs.
  - Agree: Modify equilibrium to put X-point at the upper OBD-IBD Gap
- M.B.: The magnetics may be corrupted during the CHI phase.
  - Agree: Define diagnostics that can be useful during CHI
- Many People: Need a proposed physical mechanism of mitigation.
  - Agree: X-point reconnection allows impurities to flow in.

Each of these is addressed in more detail later in the presentation

In MGI, Heavier Gasses Are Better At Radiating a Large Fraction of the Stored Energy

Need to radiate, not conduct, the plasma energy, so that walls are uniformly loaded.

*From E.M. Hollmann et al, Nuclear Fusion **48** (2008) 115007*

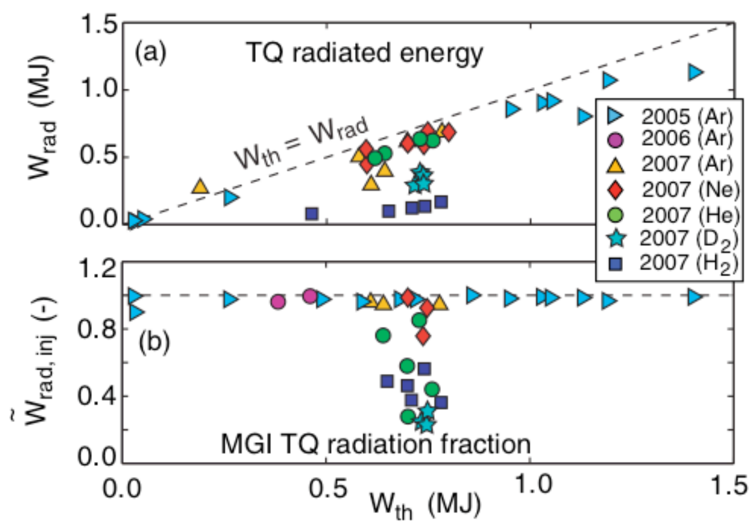


Figure 16. (*a*) TQ radiated energy for different MGI experiments from AXUV photodiodes and (*b*) TQ radiation fraction for injected gas species from UV spectrometer, all as a function of initial thermal energy W_{th}.

Start with He, and then use Ne if time permits and it seems worthwhile

*From R. Granetz et al, Nuclear Fusion **46** (2006) 1001*

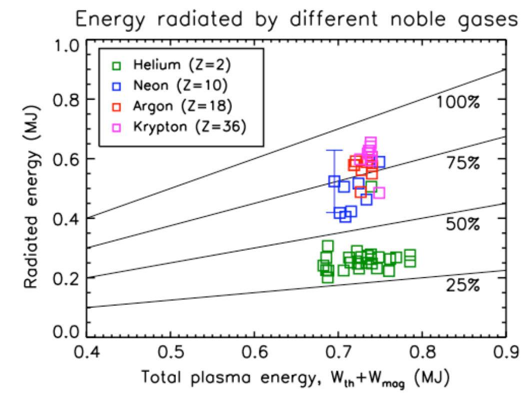


Figure 12. The higher Z gas jets convert most of the plasma energy into benign radiation. This leaves less energy to heat the divertor strike surfaces.

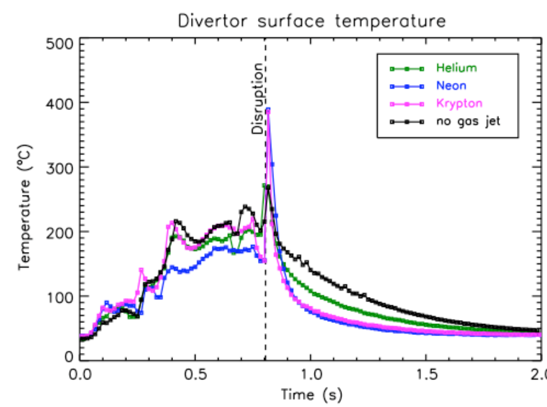


Figure 14. IR-derived temperature of the divertor surface during several different gas jet disruptions. From the data after $t = 0.9$ s it is apparent that the helium gas jet has reduced the divertor surface temperature compared with an unmitigated disruption. The neon and krypton gas jets do even better.

Available Gas is Minimal Compared to that in a Typical MGI System

- For DIII-D MGI (From Hollmann et al, NF 48 (2008) 115007)
  - "2005" system: 1000 Torr·l in 15 msec long pulse
    - 50 x the plasma inventory
  - "2006" system: 10000 Torr·l in 10 msec long pulse
    - 500 x the plasma inventory
  - "2007" system: 1000 Torr·l in 3 msec long pulse
    - 50 x the plasma inventory
- For Alcator C-MOD (from Granetz et al, NF **46** (2006) 1001)
  - 0.3 liters, 70atm=52kTorr, implies 15000 Torr·l (!)
    - 300 x the plasma inventory
  - Typically open valves for only 2.0 ms
- For NSTX Branch 5 :
    - 1.3cc=.0013 l, 2400 Torr ->3 Torr·l, or 0.3 x the plasma inventory.
  - Large plenums:
    - 4*16.5cc=0.07 l, 2400 Torr -> 158 Torr·l, or 15 x the plasma inventory.
    - Inject into the organ pipes, with ~6" if 0.5" tubing, ~8' of 1.5" tubing, 2 90° bends.
  - Neither of these is even remotely similar to MGI systems on other tokamaks.
  - The large plenums can surely cause a slow, cold-edge disruption, but maybe not a *rapid, vertically-centered* shutdown of the plasma…hence CHI!

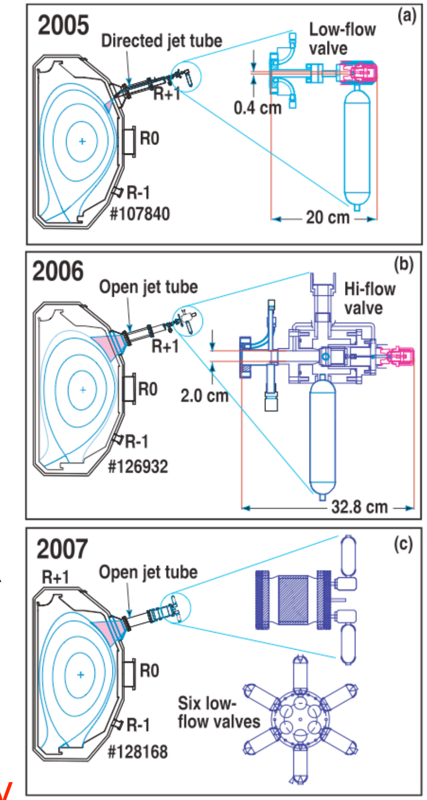
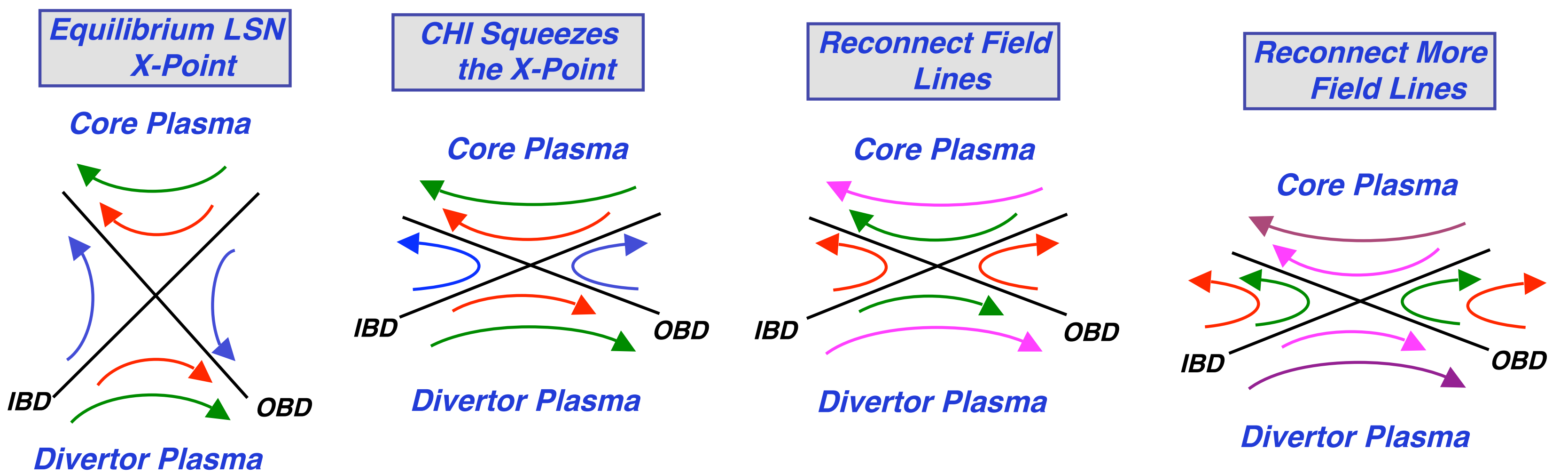


Figure 2. Schematics of different MGI geometries showing (*a*) 2005 geometry with single low-flow valve and directed jet tube, (*b*) 2006 geometry with high-flow valve and open jet tube and (*c*) 2007 geometry with six low-flow valves and open jet tube.

How might it physically work: X-Point Reconnection Allowing Rapid Transport of Impurities to Core

Goal: Radiate the thermal and magnetic stored energy of the plasma.

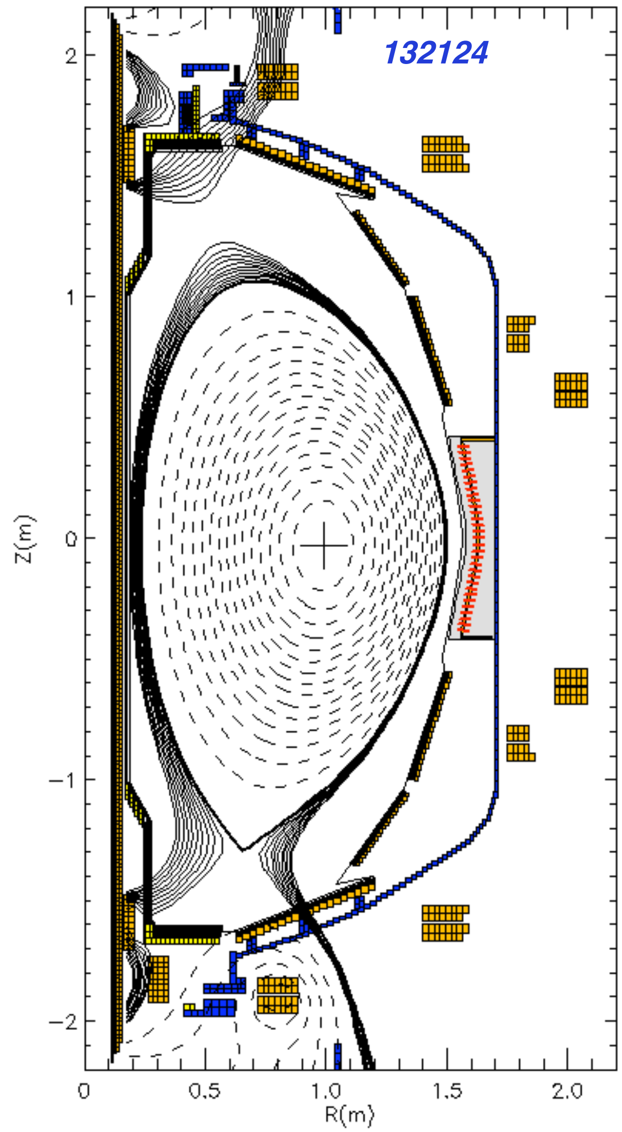
- CHI drives the private region flux toward the main plasma, compressing the X-point and driving (guide-field) reconnection.



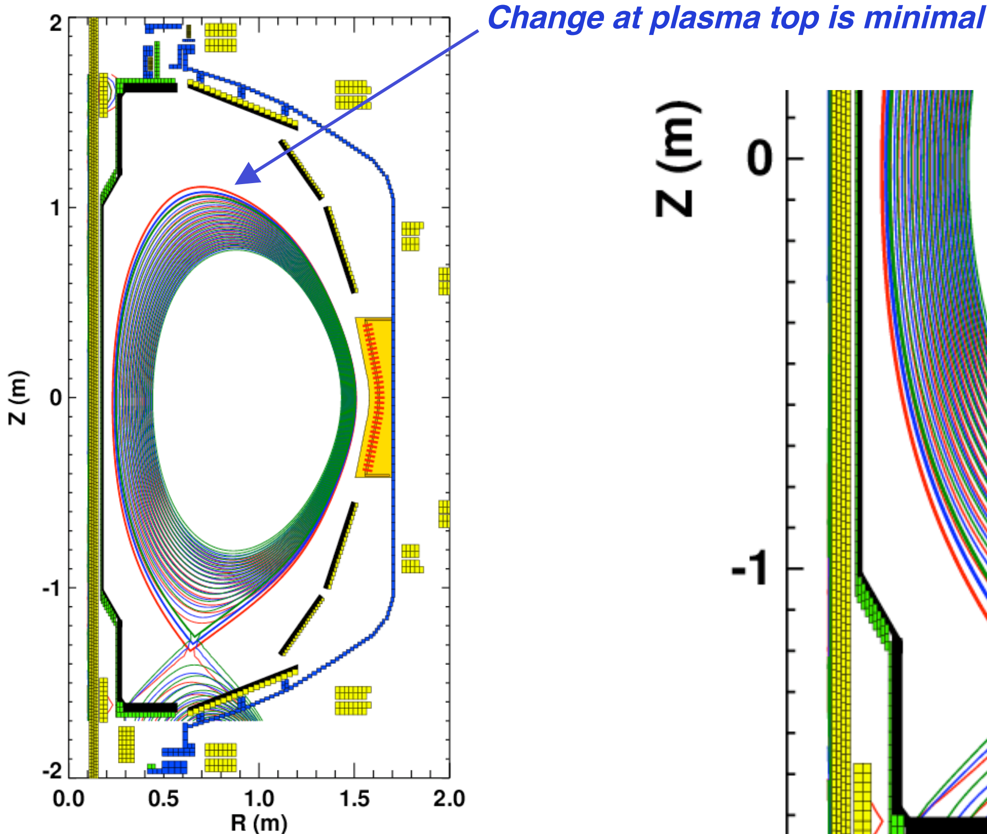
- Reconnection connects main plasma field-lines to those of the private flux region:
  - Field lines previously inside the separatrix (red, then green above) are now connected to the divertor plate
  - Impurities can free-stream into the (previously) core plasma: ***good***.
  - Heat can stream out of the core plasma to the divertor: ***bad.***
- In NSTX, (impurity) gas from the LDGIS comes up the organ-pipes, appearing in the bottom left of these cartoons.

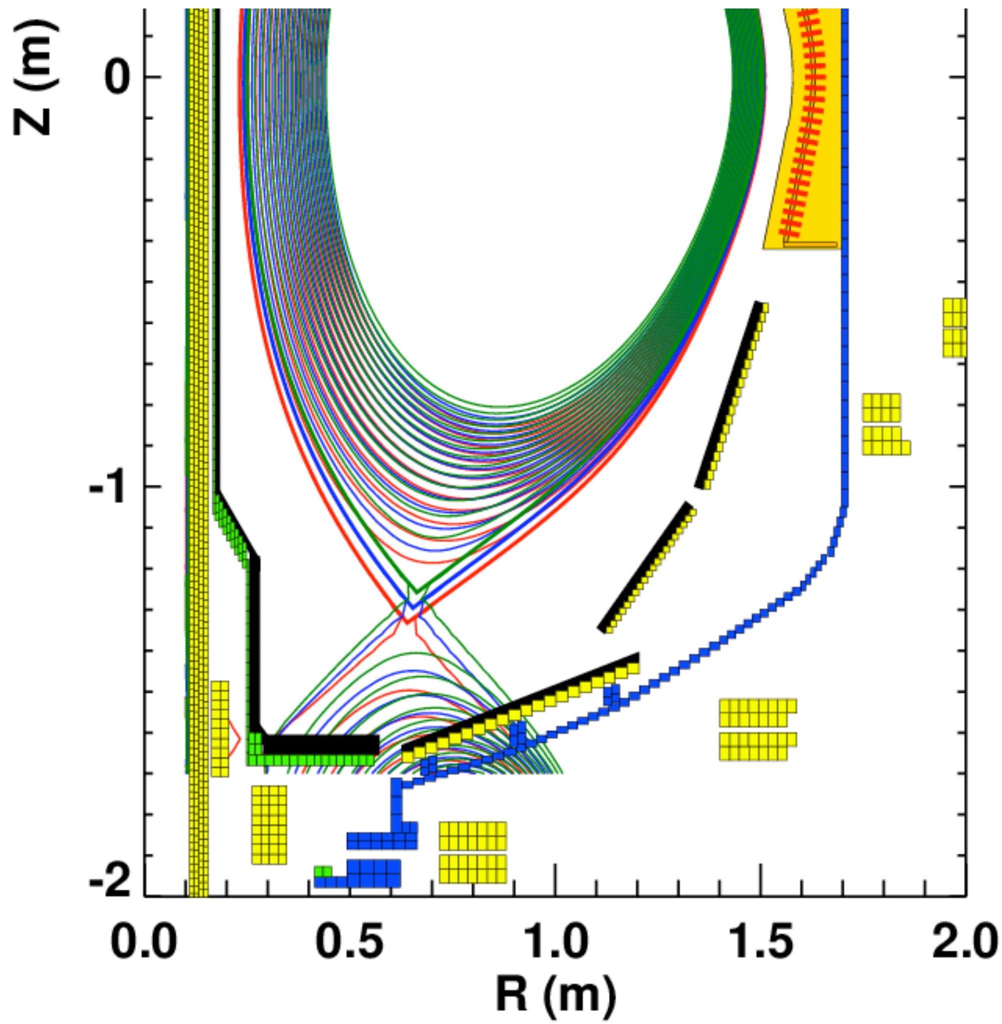
Possible Low-δ Target Discharge Developed Early in This Run

- 600kA, LSN, Isoflux
- Desirable characteristics:
  - Uses PF2, so divertor flux links OB and IB divertors.
  - Runs with P_{inj}=2MW, D_2 with no LFS,that the LDGIS is free for arbitrary injected gas.
  - Maximum loop voltage during ramp of 3.8 V, and only very briefly.
- Undesirable characteristics:
  - Too much poloidal flux at the absorber?
  - Might like more poloidal flux linking OBD and IBD?
  - Not H-mode.
  - Prone to locked modes.
  - Hasn't been tested at higher power.
- Possible development steps:
  - Increase the PF2L current (next slides)
  - Attempt 3 or 4 MW injected power.
  - Modify flux in absorber region (next slides).



Increasing the PF2L Current Does Increase the Linked Flux





PF2L:2.7 kA (reference shot)

PF2L: 3.7 kA

PF2L: 4.7 kA

Increasing PF2L provides more flux that can reconnect with the main plasma poloidal flux

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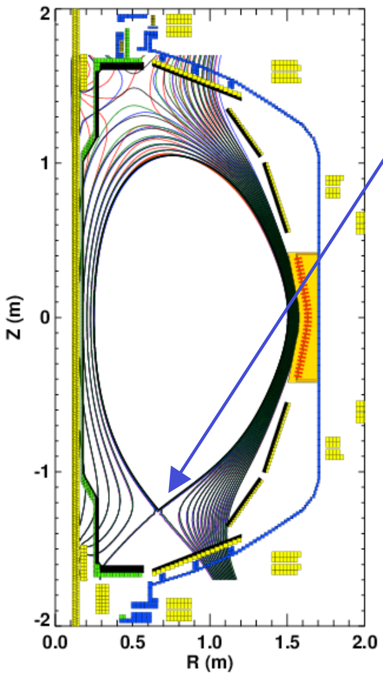
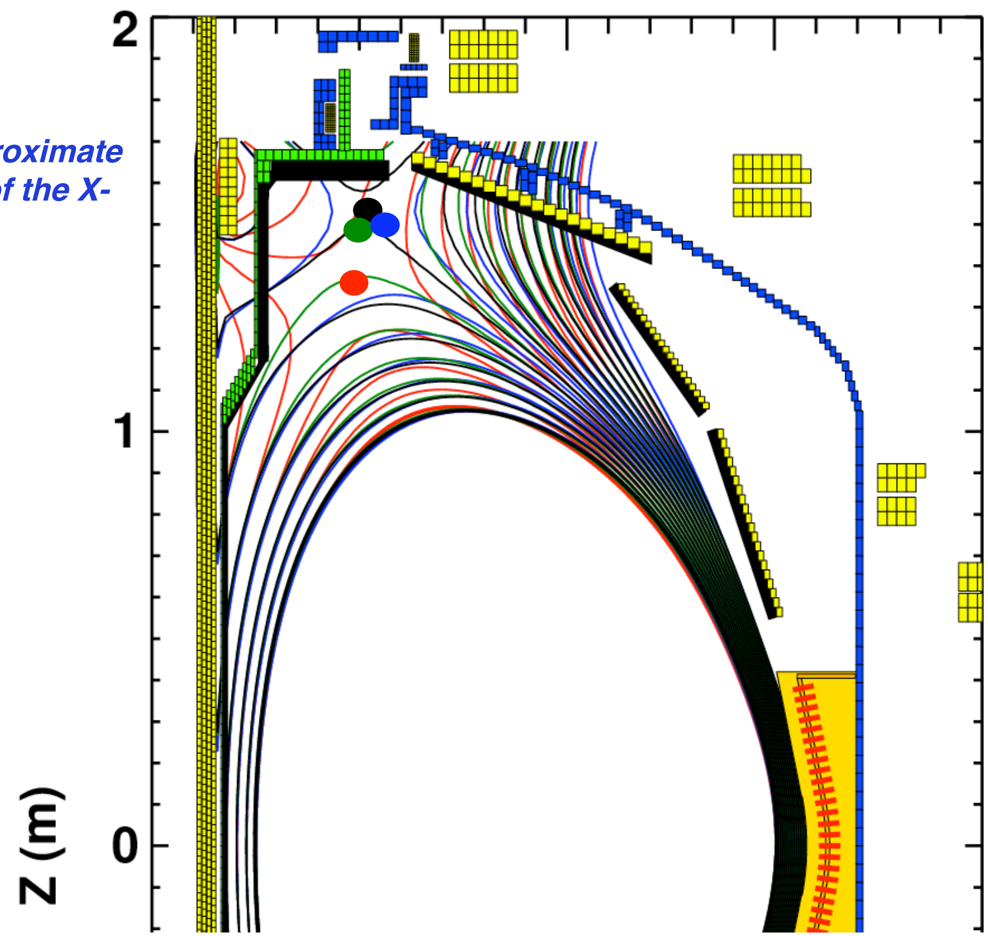
Move the Upper X-Point Over and Up by Reducing PF1AU

Needed to Avoid Absorber Arcs

Change at plasma bottom is minimal



Dots are approximate locations of the X-point.



These with PF2L=4700A

PF1AU:7500 kA (reference shot)

PF1AU: 2500 kA

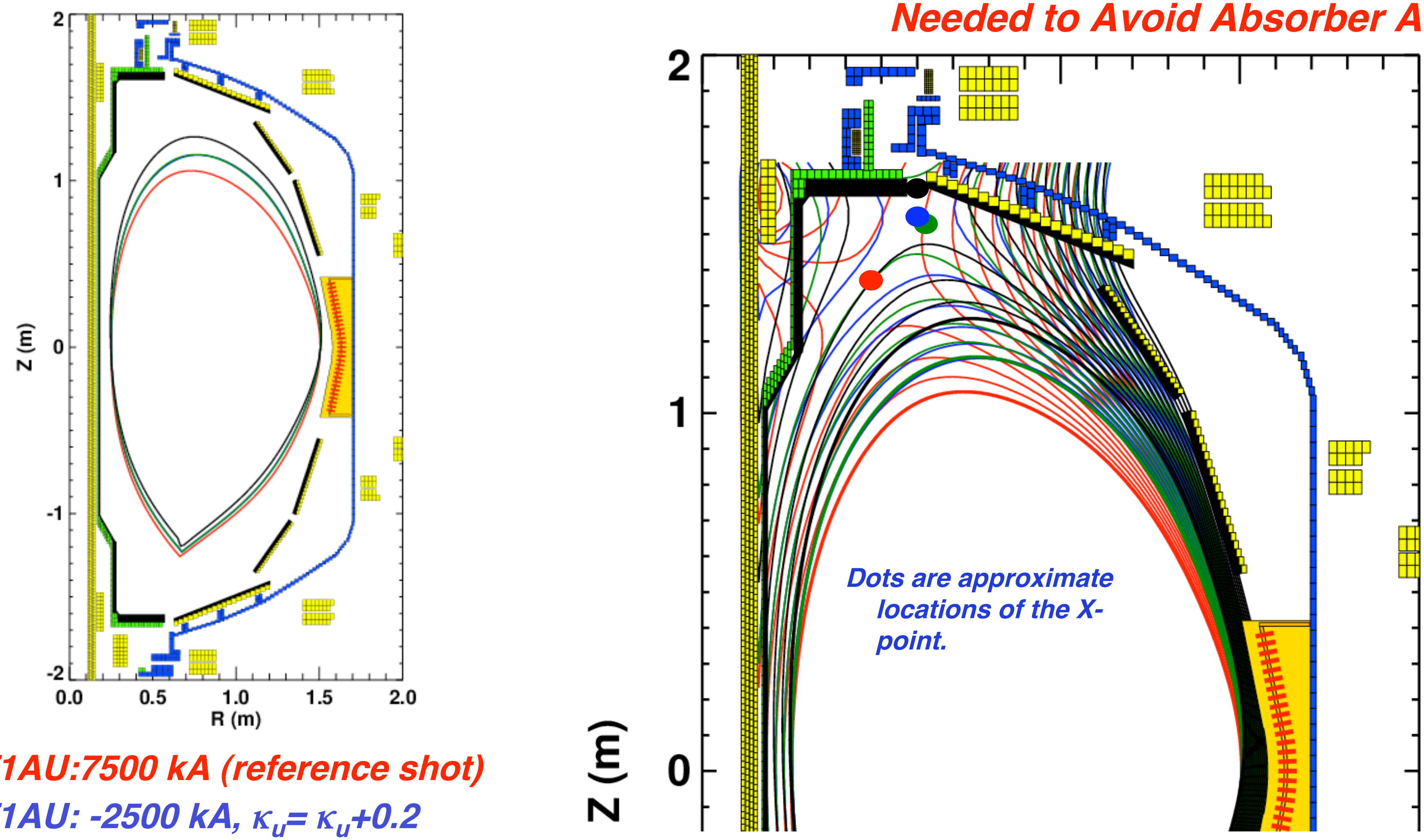
PF1AU: 0 kA

PF1AU: -2500 kA

ISOLVER

Final Shape Achieved By Increasing Kappa By 0.4

Needed to Avoid Absorber Arcs



PF1AU:7500 kA (reference shot)

PF1AU: -2500 kA, $\kappa_u = \kappa_u + 0.2$

PF1AU: 0 kA, $\kappa_u = \kappa_u + 0.2$

PF1AU: 0 kA, $\kappa_u = \kappa_u + 0.4$ (X-point in IBD-OBD gap!)

Note change upper squareness request by 0.4*0.02/0.1=0.08

ISOLVER

GR #3: Concern about CHI corrupting the Magnetics Diagnostics / Analysis

- **Halo Current Detection.**
  - Both magnetic detection and new instrumented tile array.
  - Should see the CHI currents, but hopefully NOT disruption HCs
  - May have trouble during CHI period
- **USXR Measurements**
  - h-top in bolometry, h-bottom in 10 μm, vtop in 10μm
  - Should allow a measurement of the cooling time, independent of magnetics
- **Thomson Scattering**
  - May vary the Thomson scattering trigger time, for instance to be +0.5, +1 and +1.5ms after CHI trigger.
  - Be wary of background light issues during shutdown.
  - Should allow a measurement of the cooling time, independent of magnetics
- **Phantom Cameras.**
  - One viewing toriodally into X-point region, for details of interaction.
  - One viewing from top.
  - Typically work during CHI
- **Fast Equilibrium Reconstruction.**
  - 1 msec EFITs between shots.
  - May have trouble during CHI period
- **IR Thermography.**
  - New fast camera viewing lower divertor. New capability for 2009.
  - Slow cameras viewing upper and lower divertor, for up-down imbalance of total divertor energy deposition.
  - Lithium may complicate interpretation.
  - Unclear to SPG how these will tolerate CHI
- **Color Camera in Fish-Eye View.**
  - Critical for observing absorber arcs.
- **Hard X-rays**
  - Look for formation of runaways.

NSTX Device Configuration

- Source A set for 2 MW, B for 1 MW, and C for 1MW
  - Allows 1,2,3,4 MW cases to be achieved easily.
- CHI Bank Connections:
  - Bank 1: 2 Capacitors
  - Bank 2: 3 Capacitors
  - Bank 3: 5 Capacitors
- LDGIS configured in “puff” mode at 2400 T He.
  - Start with He, then possibly switch to Ne
  - Use both small and large plenums.
- RWM Coils/SPAs in odd configuration for “standard” n=1+3 EF correction, if necessary (but pick configurations where high-β physics isn’t too important).
- PF2 configured in the normal configuration, as a pulling coil.
- OH coil configured for 4kV operation:
  - Standard is 6kV, so maximum breakdown loop voltage limited to (4kV/6kV)*7=4.7 V
  - Reference shot is below that threshold.

Shot List (1)

Step 0: Establish Gas Valve Timing in He and Ne

- Done during an evening proceeding the experiment.
- Branch 5: He at 1200 & 2400 Torr
- LDGIS: He at 1200 & 2400 Torr

Step 1: Establish Reference Discharge *(3 Shots)*

- Reload Shot 132124
- Attempt 4MW version
- Increase PF2L current (0.005 kA/kA -> 0.0078 kA/kA)

Step 2: Low-Energy CHI (Safety Check) *(4 Shots)*

- Reference Shot is 132122, or 132124 without the NBI
  - 132122 is an OH-only shot developed for C. Skinner's D_2 Retention Study
- Use 2 capacitors (0.9 kV), 2400 Torr He in Branch 5, T_{CHI}=250 msec. ($T_{gas}=T_{CHI}$-13ms (?))
- Use 2 capacitors (1.8 kV), 2400 Torr He in Branch 5, T_{CHI}=250 msec. ($T_{gas}=T_{CHI}$-13ms (?))
- If absorcer arcs are apparent, go to "Upper X-Point Location Optimization" steps.

Upper X-Point Location Optimization (if necessary) *(3 Shots)*

- Reduce flat-top PF1AU (to as close to zero as possible)
- Increase upper elongation (by increasing the upper-outer squareness by 0.8(?))

Total: 7

Shot List (2)

Step 3: Shutdown Experiment, CHI Timing Scan ***(5 Shots)***

- Go back to beam shot 123124
- Use 4-Plenum system 2400 Torr He, Bank 3, 1800V
- Test optimum CHI firing time with respect to Gas Injection
  - Optimum: Discharge is terminated rapidly, with minimal vertical motion
- Take one discharge with LDGIS injection, but no CHI

Step 4: Shutdown Experiment, CHI Energy Scan ***(5 Shots)***

- Use 4 Plenum system at 2400 Torr He, Optimum CHI/gas timing.
- Test different combinations of capacitors, energy.
  - Banks 1,2,3, 1800 V
  - Banks 1,2 1800V
  - Bank 3 only, 1200 V
- Repeat discharge with LRDGIS injection, but no CHI
- If no fast shut-down is observed at more that 1.5 hours left in day, then go to Neon Contingency

Step 5: Shutdown Experiment, Plasma Thermal Energy Scan ***(5 Shots)***

- Use optimal configurations from steps #4 and #5
- Repeat with injected powers of 0,2,3,4 MW

Step 6: Documentation of Most Interesting Case ***(5 Shots)***

- Take single case from steps #4, #5, #6, and repeat.
- Change timing of the MPTS lasers.
- Change USXR filters.

Total: 7+20=30

Shot List, Neon Contingency (3)

If He shutdown has failed and time permits, take controlled access to switch for Ne CHI

Step 7: Shutdown Experiment in Ne, CHI Timing Scan *(5 Shots)*

- Go back to beam shot 123124
- Use 4-Plenum system 2400 Torr Ne, Bank 3, 1800V, Ne
- Test optimum CHI firing time with respect to Gas Injection
  - Optimum: Discharge is terminated rapidly, with minimal vertical motion
- Take one discharge with LDGIS injection, but no CHI

Step 8: Shutdown Experiment in Ne, CHI Energy Scan *(5 Shots)*

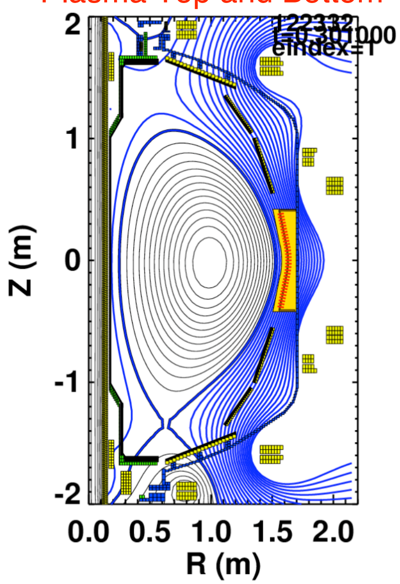
- Use 4 Plenum system at 2400 Torr Ne, Optimum CHI/gas timing.
- Test different combinations of capacitors, energy.
  - Banks 1,2,3, 1800 V
  - Banks 1,2 1800V
  - Bank 3 only, 1200 V
- Repeat discharge with LRDGIS injection, but no CHI

Backup or Group Review Slides

Possible Targets With Difference Field Line Characteristics Linking Lower Divertor, Different Control Capabilities

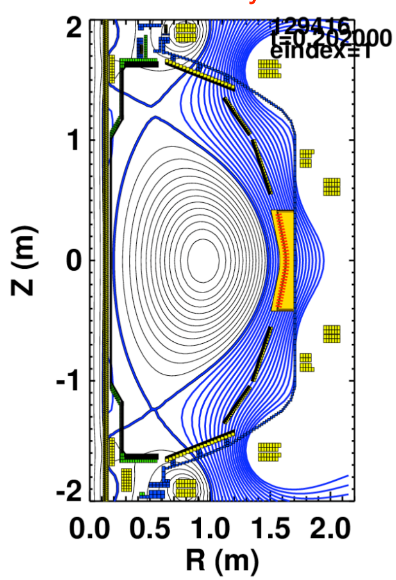
- Goal: Avoid Shot Development
- Gap Control Algorithm
  - Feedback control only the vertical position, R_0, gaps (bad).
  - Has capability for freezing of vertical position control (good).
- rt-EFIT (SPG prefers to use these, save deliberates VDE studies for next year)
  - Control above + κ (through squareness), dr_{sep} (good)
  - No vertical position freeze. (bad)

122332, Gap Control
Used in XMP-48
IBD and OBD Linked Over Plasma Top and Bottom



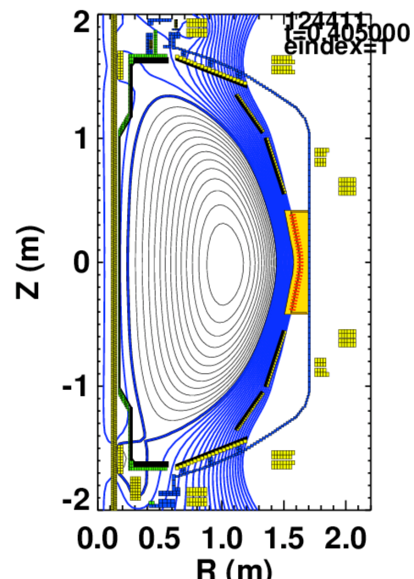
Over/Under Linkage

129415, Gap Control
Used in Δz_{max} XP, 2008
IBD Linked to OBD at Bottom Only



Under Linkage

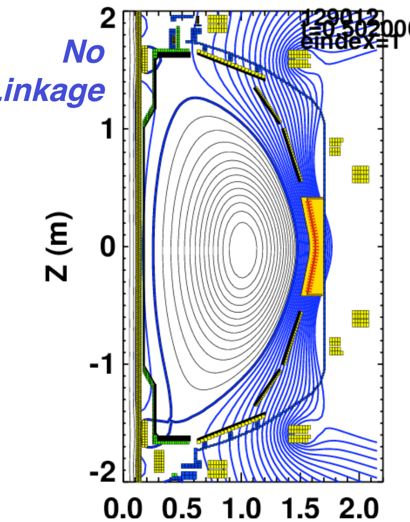
124411, Gap Control
High-κ, high-δ
JEM Shot last used 2007
No IBD/OBD Linkage

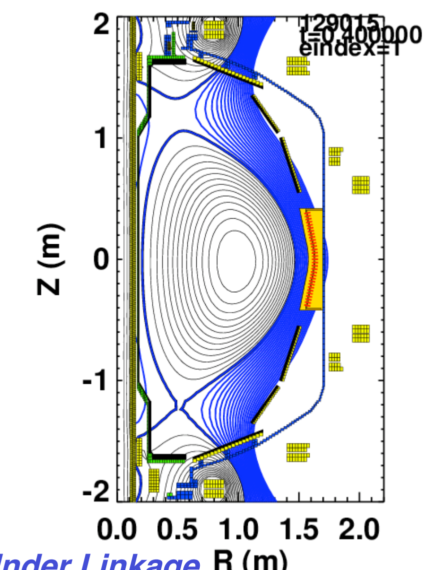


No Linkage

Liter Day 1&2, rt-EFIT

No Linkage





Under Linkage

Disruptions Have Many Adverse Consequences For Tokamaks Reactors

- Eddy Currents Driven by the Current Quench
  - Cause overturning moment on conducting components inside the vessel.
- Halo Currents During Vertical Motion
  - Vertical position typically lost after β-collapse or thermal quench.
  - Large current (10-30% I_P) flow between plasma and PFCs, causing large forces of those PFCs.
- Impulsive Heat Loading
  - Entire thermal energy of plasma lost in <1ms.
  - If it all goes to divertor, can exceed melting/ablation threshold (~40 $MJ/m^2s^{1/2}$).
- Runaway Electron Beam Formation
  - Three mechanisms can drive runaway formation.
  - Can be mitigated if the runaway loss rate is increased.
  - Can result in very localized damage to PFCs.
- Often Little Warning of Immanent Disruption
  - Especially true of ITB ∇p disruptions.
  - Only very short time to initiate shutdown before disruption starts.

If unsolved, the disruption problem will prevent tokamak fusion.

CHI-Based Fast Shutdown Scheme Might Help Alleviate Many of These Concerns

- Thermal Quench Heat Loading :
  - CHI plasma can bring impurity gas into main discharge.
  - Thermal energy is radiated away, instead of conduction to divertor.
  - Impurity gas is toroidally distributed, so that, in contrast to MGI, there is no localized radiation burst.
- Halo Currents :
  - If shutdown is sufficiently fast, the VDE motion cannot occur before shutdown is done…no possibility for halo currents.
- Runaway Formation:
  - It is believed that stochastic fields can prevent runaway formation (see Granetz APS contributed oral).
  - Flowing CHI currents could assist in making fields stochastic.
- Look Ahead Time:
  - Impurities are electromagnetically forced into the main plasma, potentially reducing the time to shutdown compared to gas flowing down a tube.

If an ST reactor has a CHI system for startup, then it is useful to explore the capabilities of the system for shutdown as well.

Fast Visible Imaging May Help Reveal This Process

He MGI in DIII-D (From Hollmann et al, NF 48 (2008) 115007)

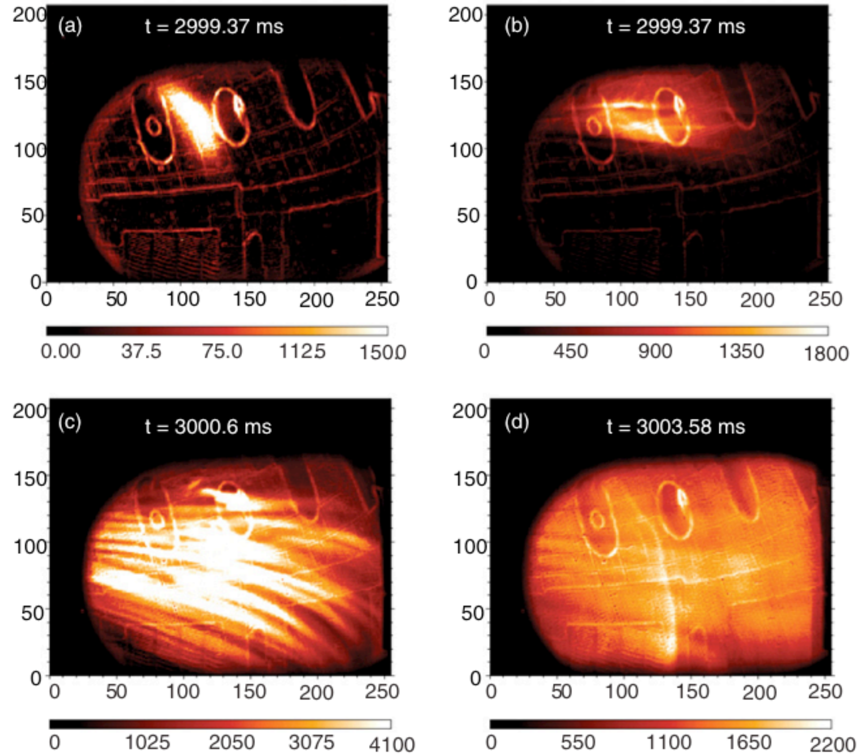


Figure 3. He I emission measured with fast-framing visible camera during He MGI (2007 geometry). (*a*) and (*b*) are taken at times before TQ, (*c*) is during TQ and (*d*) is during CQ. Note that the brightness scale varies frame-to-frame. Illumination of edge features on wall is enhanced artificially to help provide image fiducials.

JxB Force Much Larger than Force Between CHI Current and PF2, so CHI Arc Should go Up

$$\frac{F_{up}}{L} = I_{CHI}B_T + \frac{\mu_0 I_{CHI} I_P}{2\pi d_1}$$

$$\frac{F_{down}}{L} = \frac{28\varsigma\mu_0 I_{CHI} I_P}{2\pi d_2}$$

$$\varsigma = I_{PF2}/I_P$$

$$\frac{F_{up}}{F_{down}} = \frac{2\pi d_2 d_1 B_T + \mu_0 d_2 I_P}{28 d_1 \varsigma \mu_0 I_P}$$

$$\frac{F_{up}}{F_{down}} = \frac{3.76 B_T + 5\times 10^{-7} I_P}{4.2\times 10^{-7} I_P}$$

$$\frac{F_{up}}{F_{down}} = \frac{1.7 + 0.35}{0.3} > 1$$

Top View of NSTX

LSN, δ_r~0.4