Overview of Pellet Fueling Experiments on the Madison Symmetric Torus Reversed Field Pinch

K.J. Caspary

THE UNIVERSITY of WISCONSIN MADISON

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J.S. Sarff

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S.K. Combs

C.R. Foust

Motivation For Pellet Fueling

- The improved confinement regimes of the RFP are typically limited to low density with edge fueling alone
  - Natural targets for pellet fueling
- Highest β RFP plasmas (26%) have been obtained in pellet fueled improved confinement plasmas on MST
  - But as of yet, no observed β limit

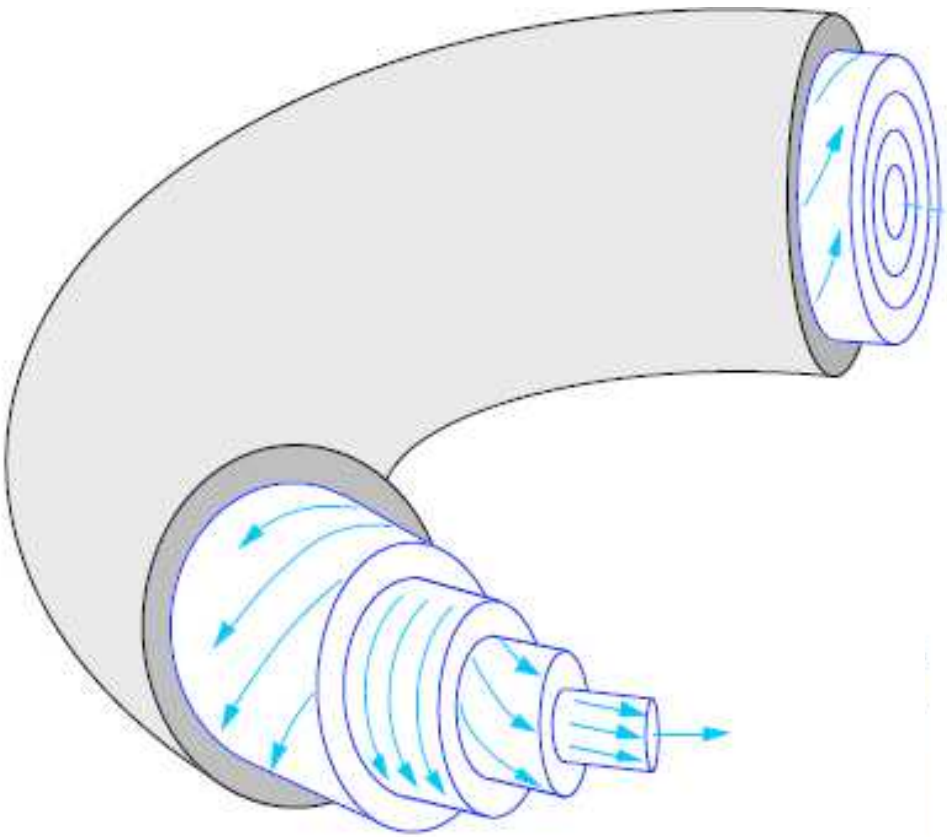
- Standard RFP plasmas limited by Greenwald density limit
  - Can exceed the limit in improved confinement discharges with pellet fueling
  - An understanding of the mechanisms which govern the density limit is important for future experiments

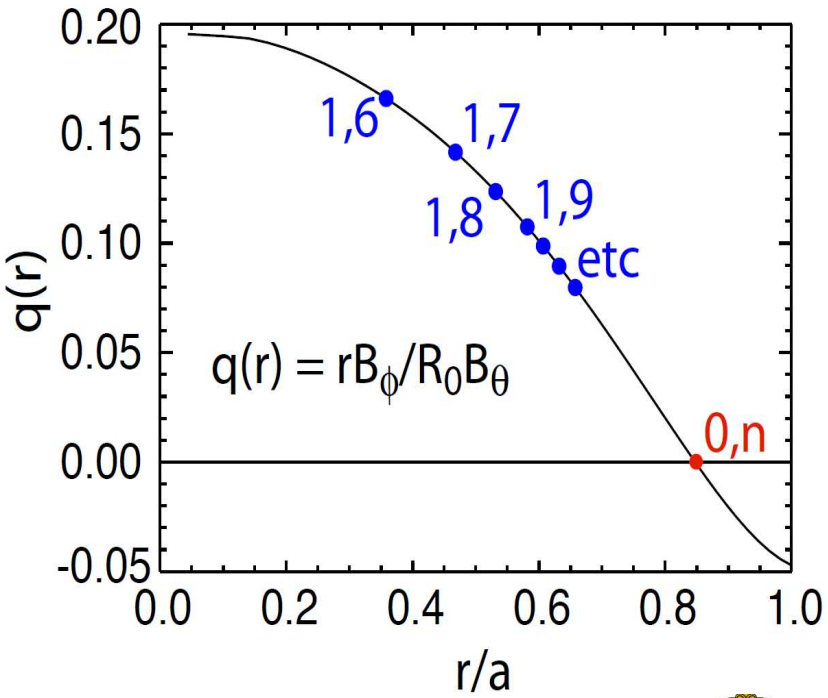
Outline

- The Madison Symmetric Torus
- Pellet Injector System
- High Beta Experiments
- Density Limit Experiments

The Reversed Field Pinch (RFP)

- $B_\theta \sim B_\Phi$ (In contrast to the tokamak where $B_\Phi > B_\theta$)
- B_Φ reverses direction in the edge
- m=0 and m=1 tearing modes resonant (q < 1 everywhere)
- Overlap of islands leads to stochasticity, aids transport





The Madison Symmetric Torus (MST)

$R = 1.5$ m

$a = 0.5$ m

$I_\phi = 0.2 – 0.6$ MA

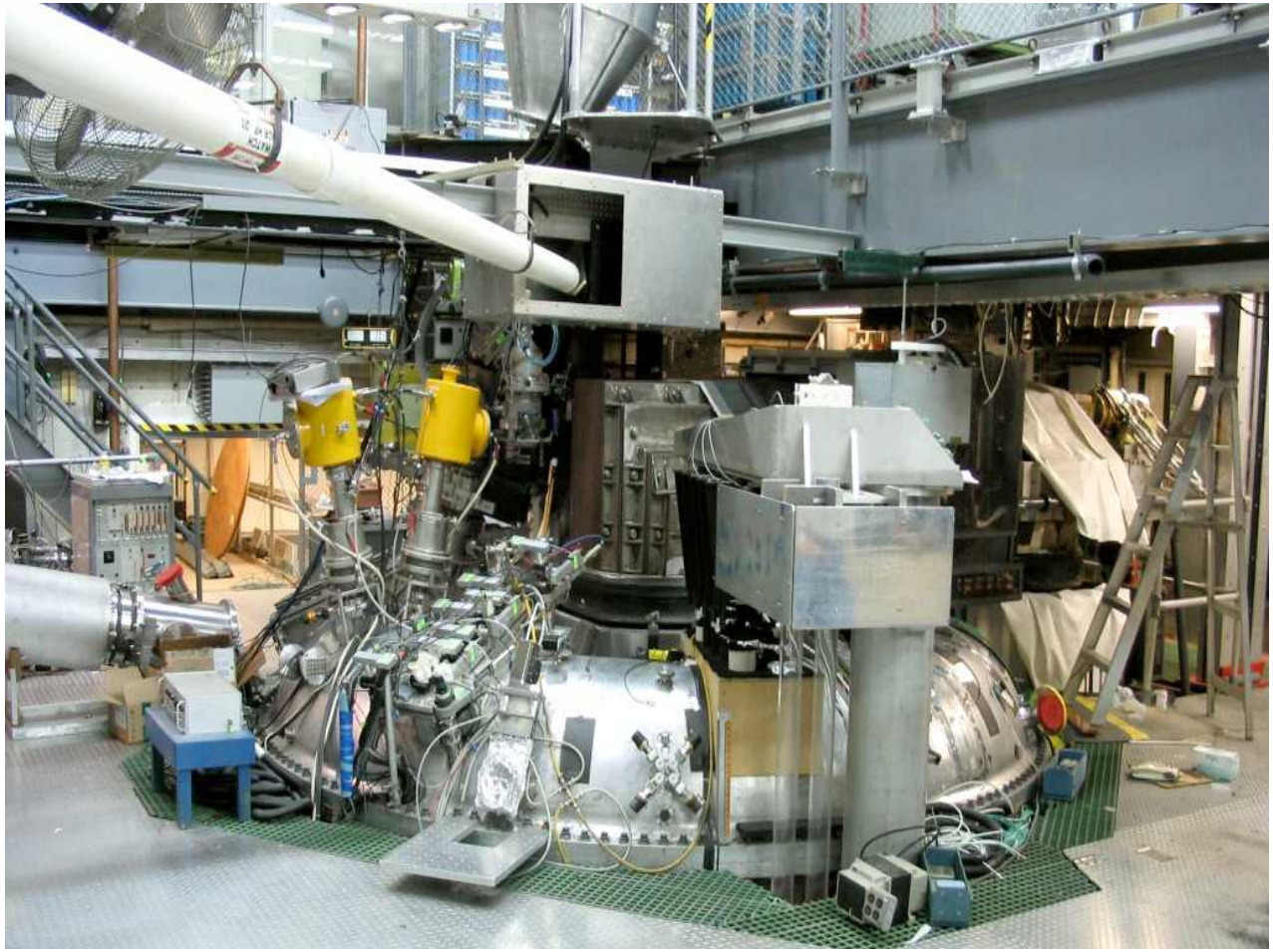
$|B| = 0.15 – 0.6$ T

$\langle n_e \rangle \sim 1 \times 10^{19}$ m^{-3}

$T_e, T_i < 2.0$ keV

Vessel doubles as toroidal winding

As few as two students needed to run experiments



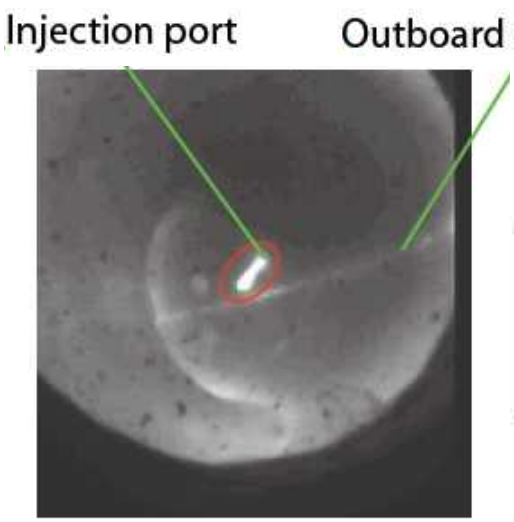
MST's Pellet Injector

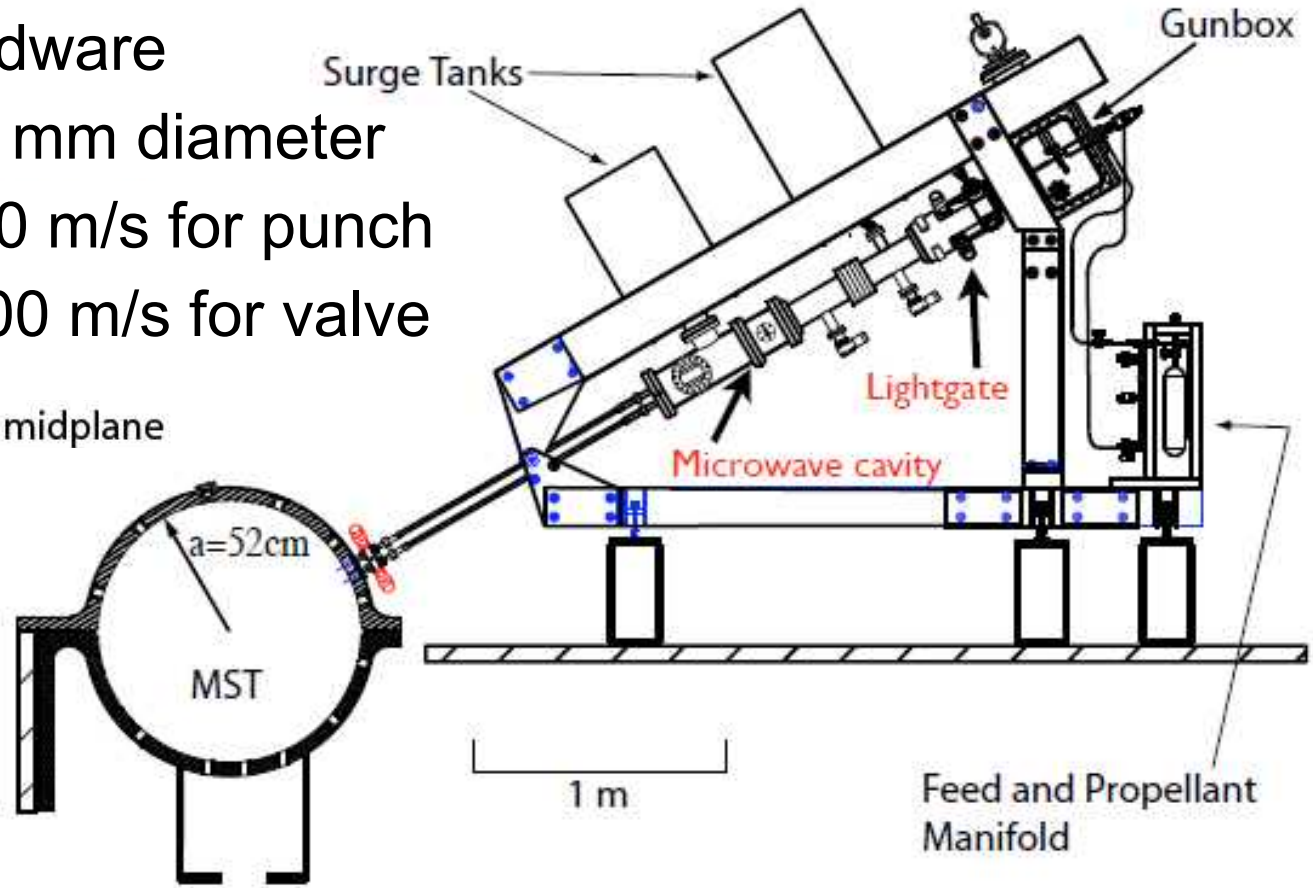
Collaboration with ORNL

4-barrel pipe gun injector

Flexible pellet hardware

- 1.0 – 4.0 mm diameter
- 100 – 400 m/s for punch
- 1100-1200 m/s for valve





Key Hardware Changes

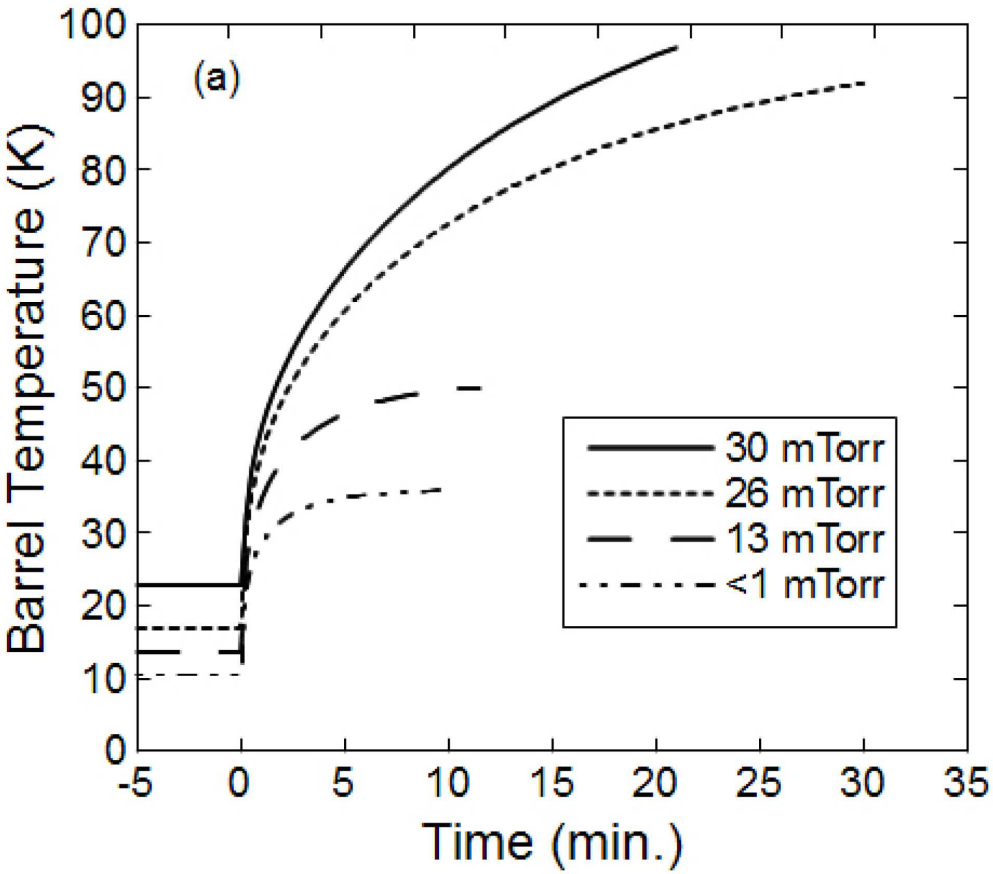
- Improved vacuum system for fuel manifold
- Switch to more purified deuterium fuel
  - Improved pellet consistency
- Gunbox modification for Methane pellet experiments
  - Measurements of carbon transport aided by methane pellet fueling
- Major Hardware upgrade to increase maximum pellet diameter to 4.0mm pellets
  - Opens up new density regimes and enables density limit experiments for full plasma current range

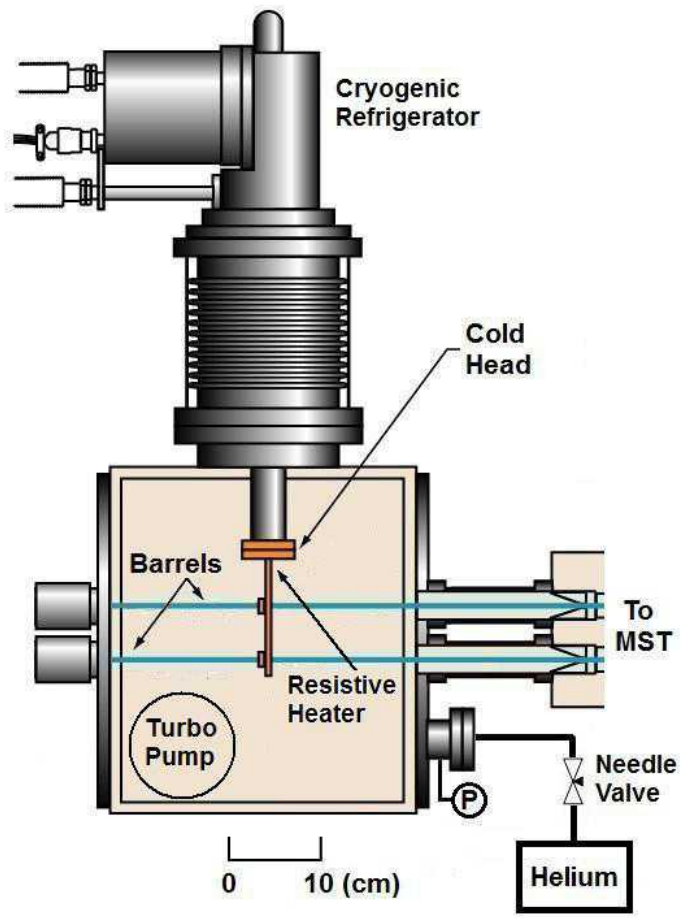
Methane Pellet Overview

- Goal: Inject methane pellets and observe impurity transport of carbon
- Problem: Methane triple point of 90.7 K outside of the operating range for our heating hardware
- Deuterium fueling is the primary use of the injector
- Ideal solution should be easily reversible or have little impact on deuterium pellet formation

Helium Gas Introduced as Heat Source

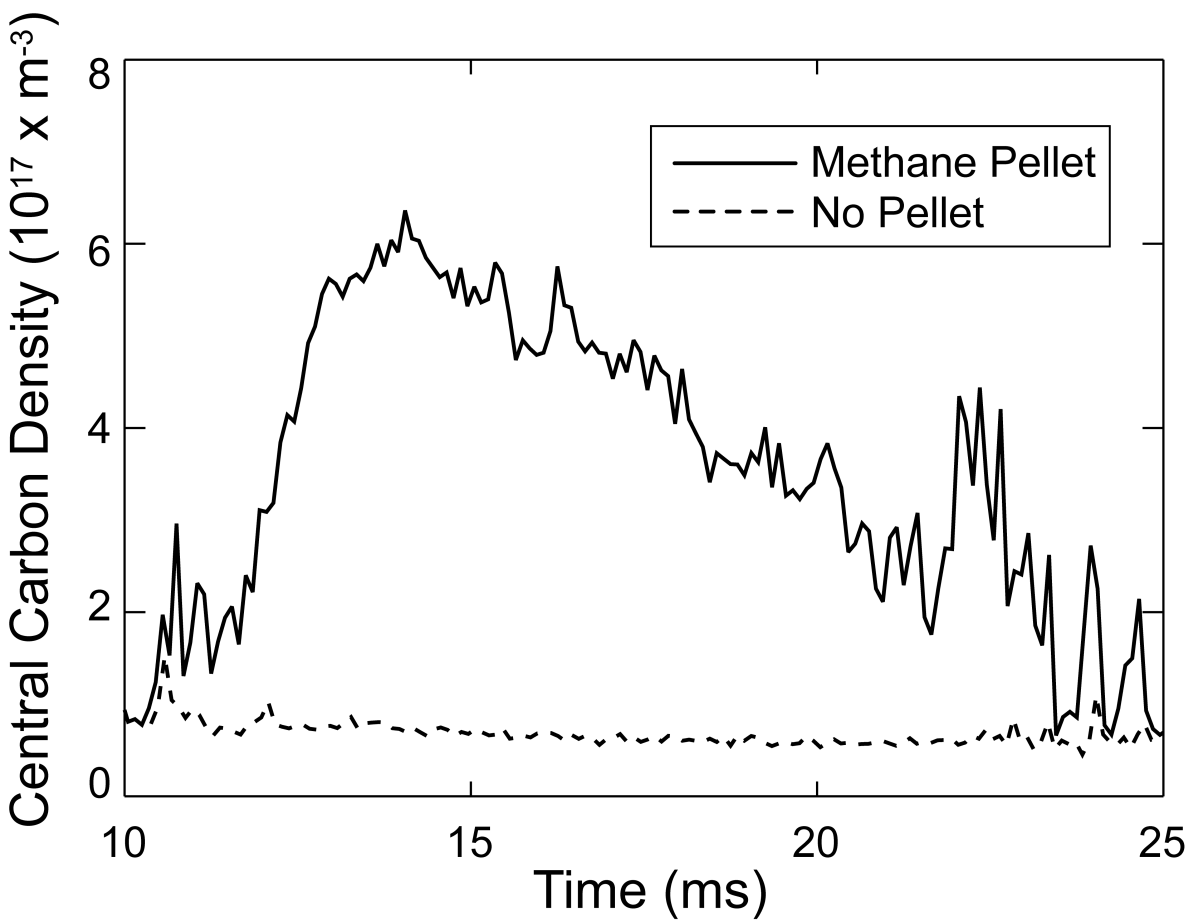
- Introduce flow of helium as controllable heat source to aid barrel heaters and raise temperature
- Expands operational range to accommodate methane pellets





Methane Pellet Injection

- 6-fold increase in core carbon density after injection 1.0mm methane pellets
- Used to study carbon impurity transport (Kumar et. al.)



Key Hardware Changes

- Improved vacuum system for fuel manifold
- Switch from bottled to purified deuterium
  - Improved pellet consistency
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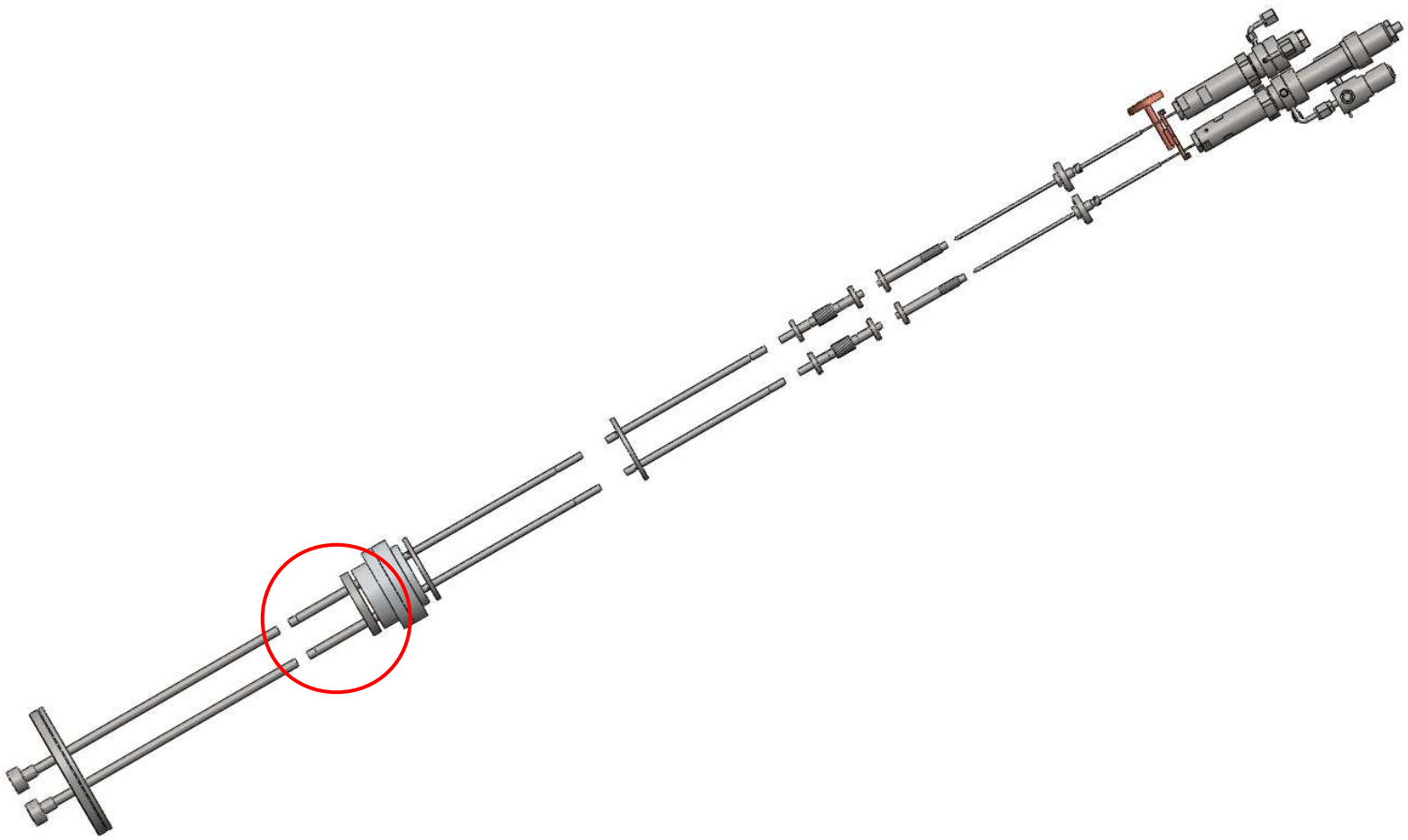
- Major Hardware upgrade to increase maximum pellet diameter to 4.0mm pellets
  - Opens up new density regimes and enables density limit experiments for full plasma current range

Why the need for the injector upgrade?

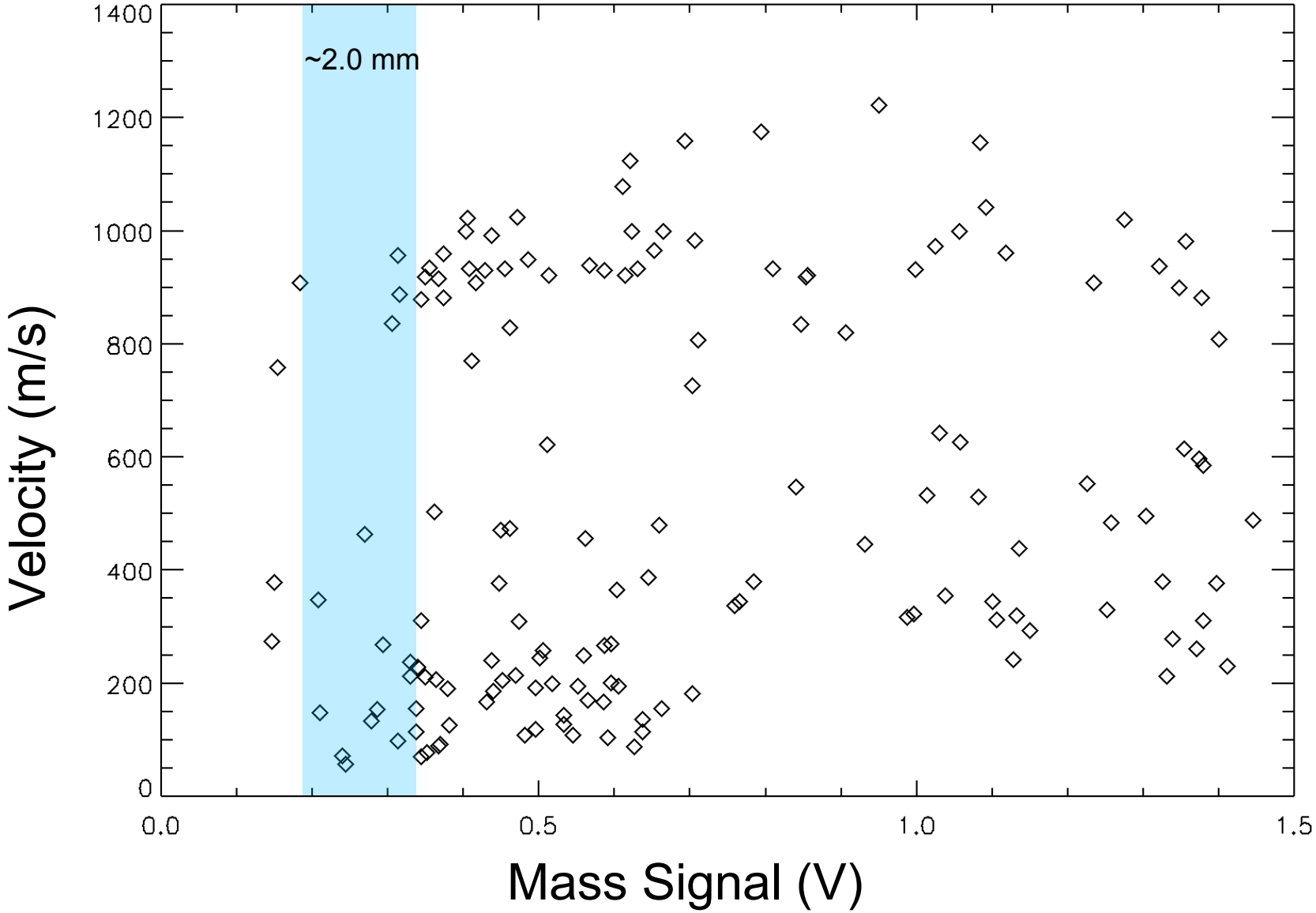
- After implementing 2.0 and 2.5 mm barrels, observed a decrease in successful pellet rate despite normal looking diagnostic signals
- Single pellet fueling as effective as multi pellet fueling but eliminates need for coordination
- Increased fueling capability to maximum conceivable density
- 2 n_{GW} @ 800 kA ~1.9e20 = $N_{max} \rightarrow D_{max}$ = 4.0mm

4.0mm Pellet Upgrade

- Required injector disassembly and modification of several of the guide tube stages as well as new barrels

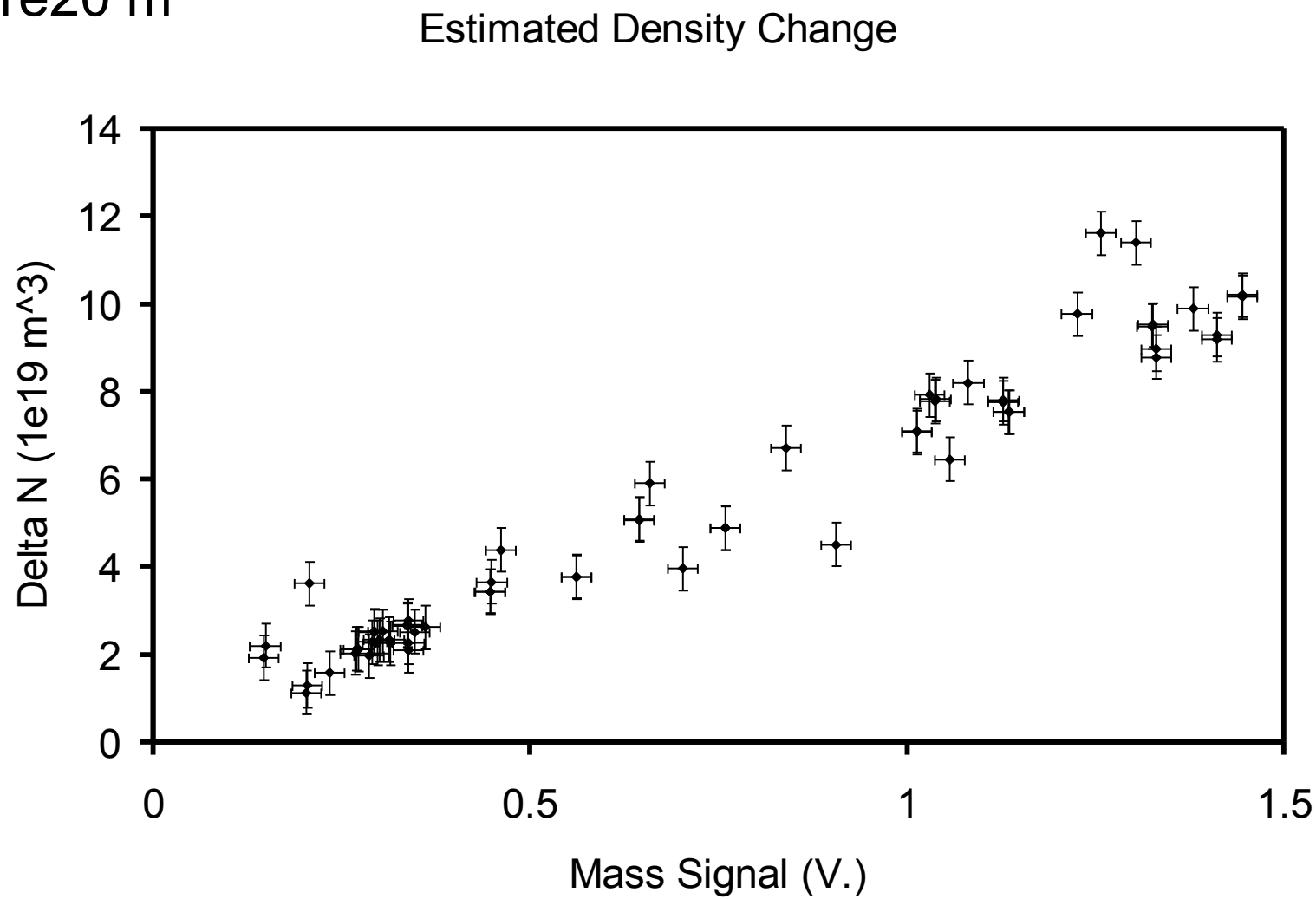


4.0mm Pellet Flexibility



Pellet Particle Content Estimates

- Largest 4.0mm pellets should be sufficient to fuel above 1e20 m^{-3}



Outline

- The Madison Symmetric Torus
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- High Beta Experiments
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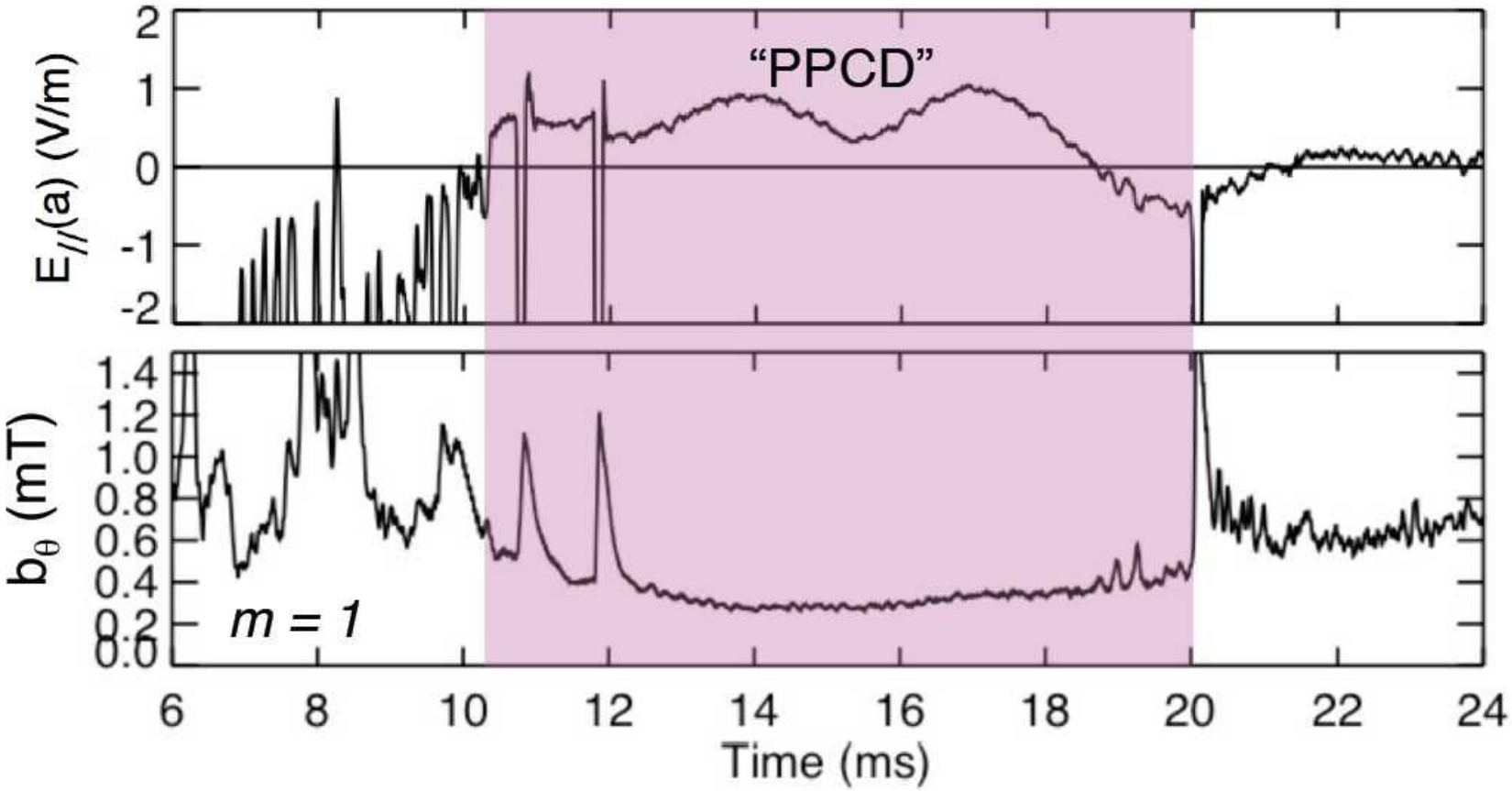
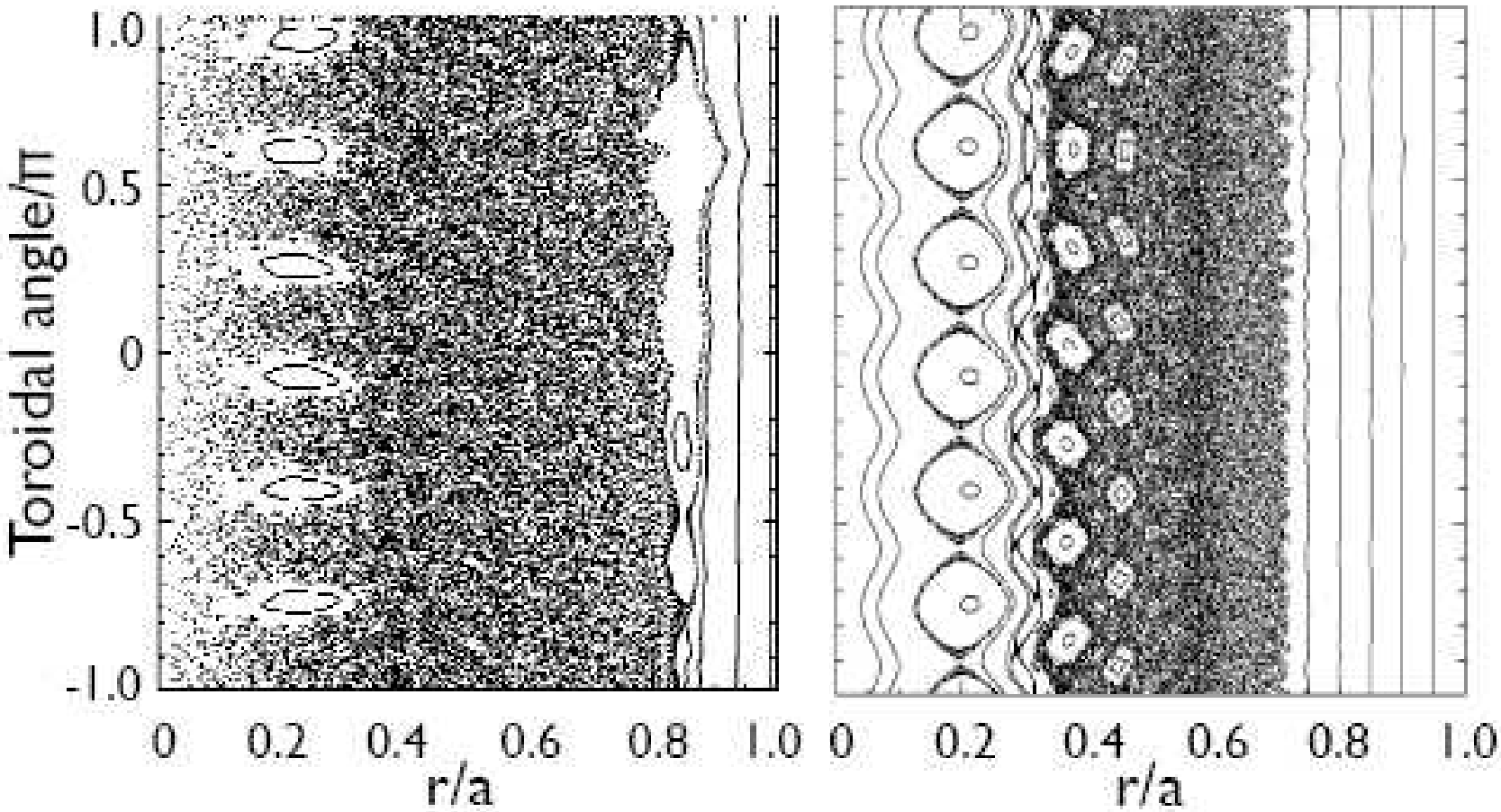
Pulsed Parallel Current Drive

- Inductively drives current in the plasma edge to flatten the current profile, reducing the tearing mode drive
- Reduction in mode activity observed for both m=1 and m=0
- Limited to low density (< 1e19 m^{-3})



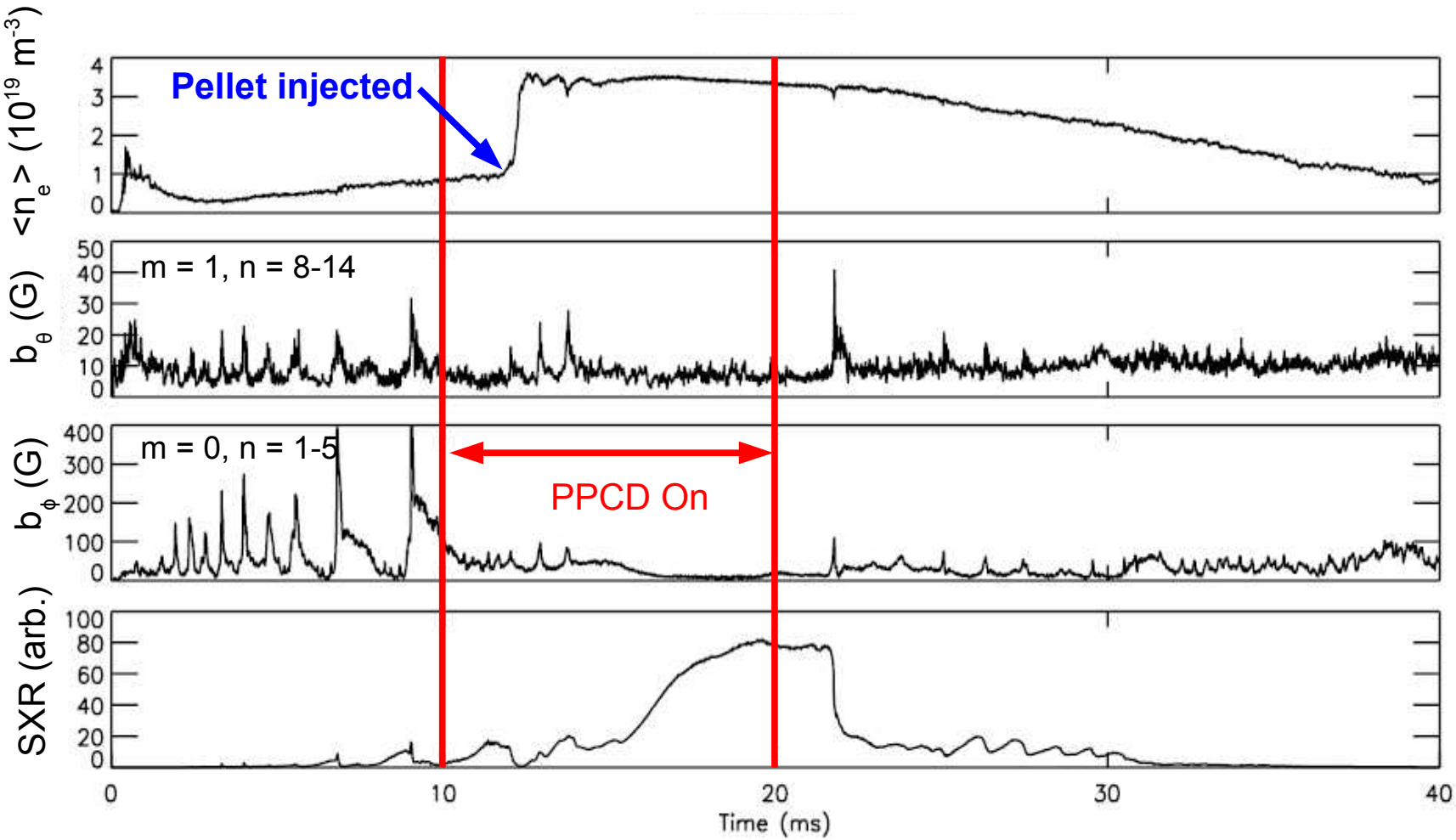
PPCD Improves Plasma Confinement

- Confinement times increase: τ = 10 ms (1ms in standard)
- β Increases to 15% in 200kA PPCD (9% in standard)
- In many ways tokamak-like



Pellet Injection into PPCD Plasmas

- Density increases by a factor of 3 or more while m = 0 and m = 1 activity reduced



Electron and Ion Temperatures Increase

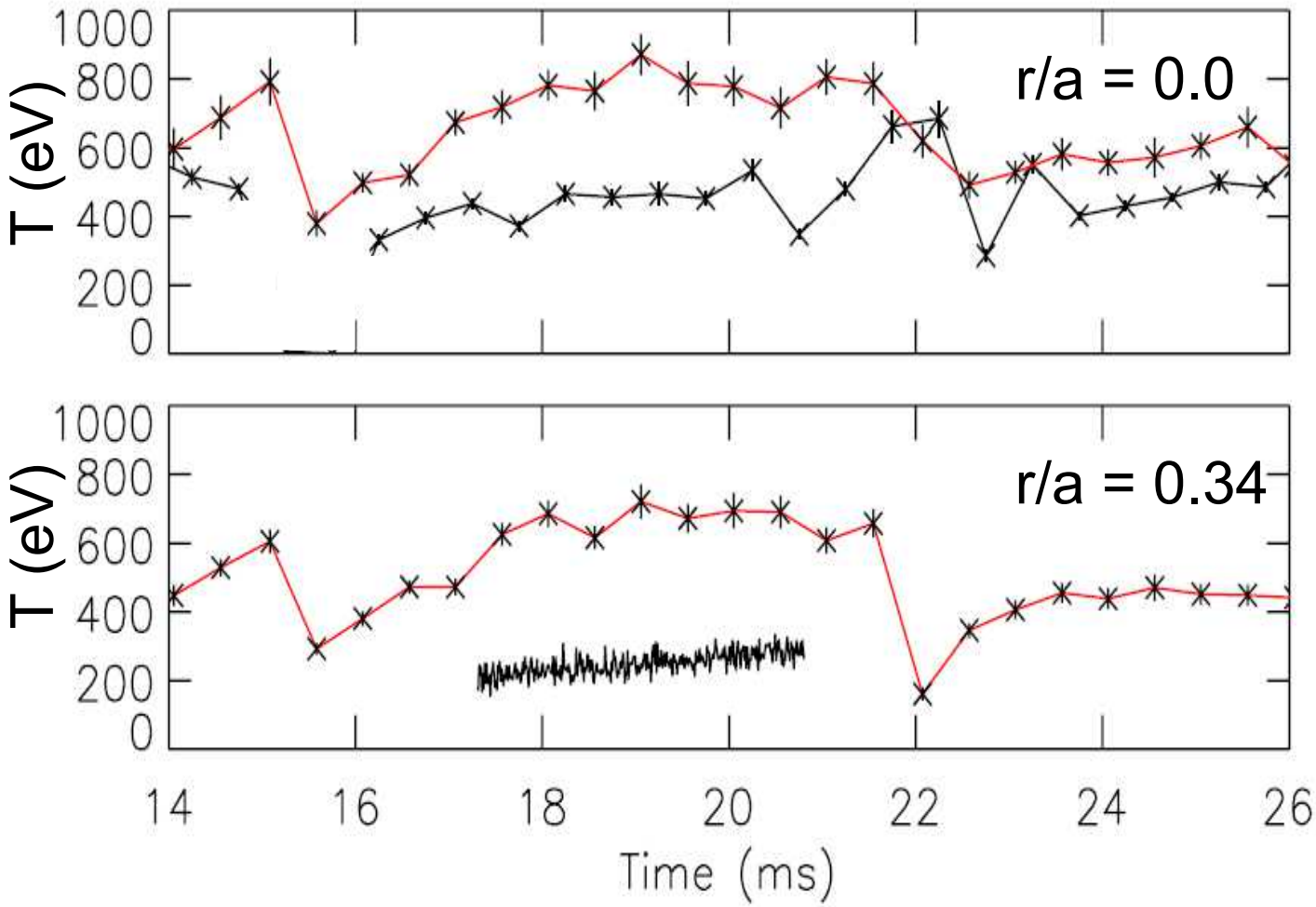
- Electron temperature increases via ohmic heating
- Collisional heating plays a role for ions (scales as $T_e^{3/2}/n_e$)

CHERS T_i

T_i

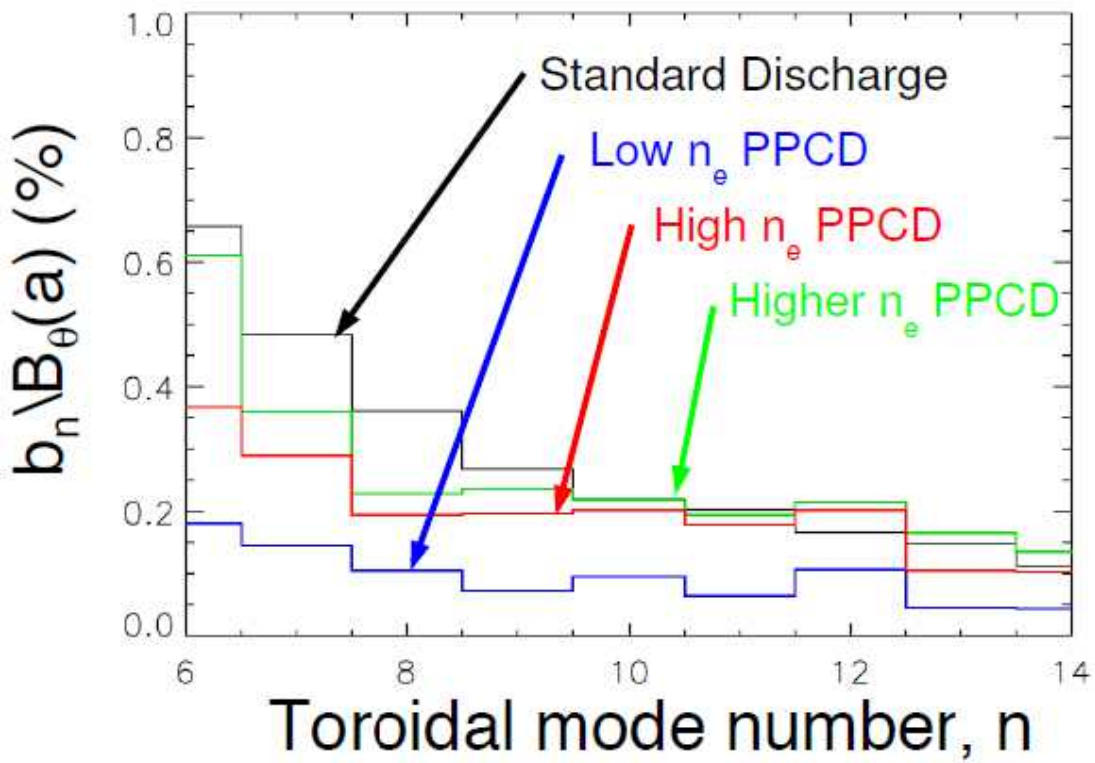
T_e

Ruth. T_i



High β plasmas on MST

- Confinement improved compared to standard but with 2-3 fold increase in plasma density
- Ion temperature increases along with electron
- Despite many attempts, maximum achieved beta still ~26%
- Combined with NBI heating in attempt to probe beta limit



Using NBI to probe for β limits

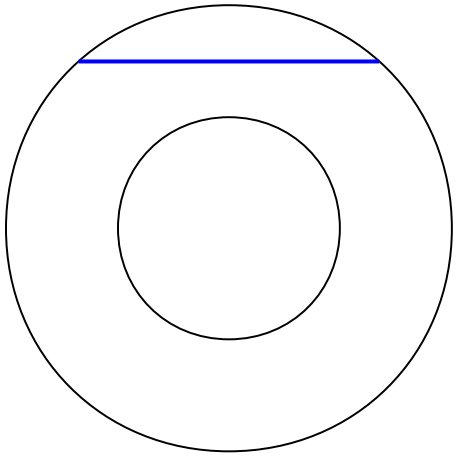
- 1 MW, 25keV neutral beam for up to 20 ms duration
- Additional NBI heating power should boost β, but by how much?
- How does NBI deposition vary with plasma density?
- What is the optimal density to maximize beam deposition?
- What fraction of the beam power is deposited in the core?
- Pellet fueled plasma ideal for equilibration of electrons and ions as well as for slowing down of fast ions

A Simple Deposition Calculation

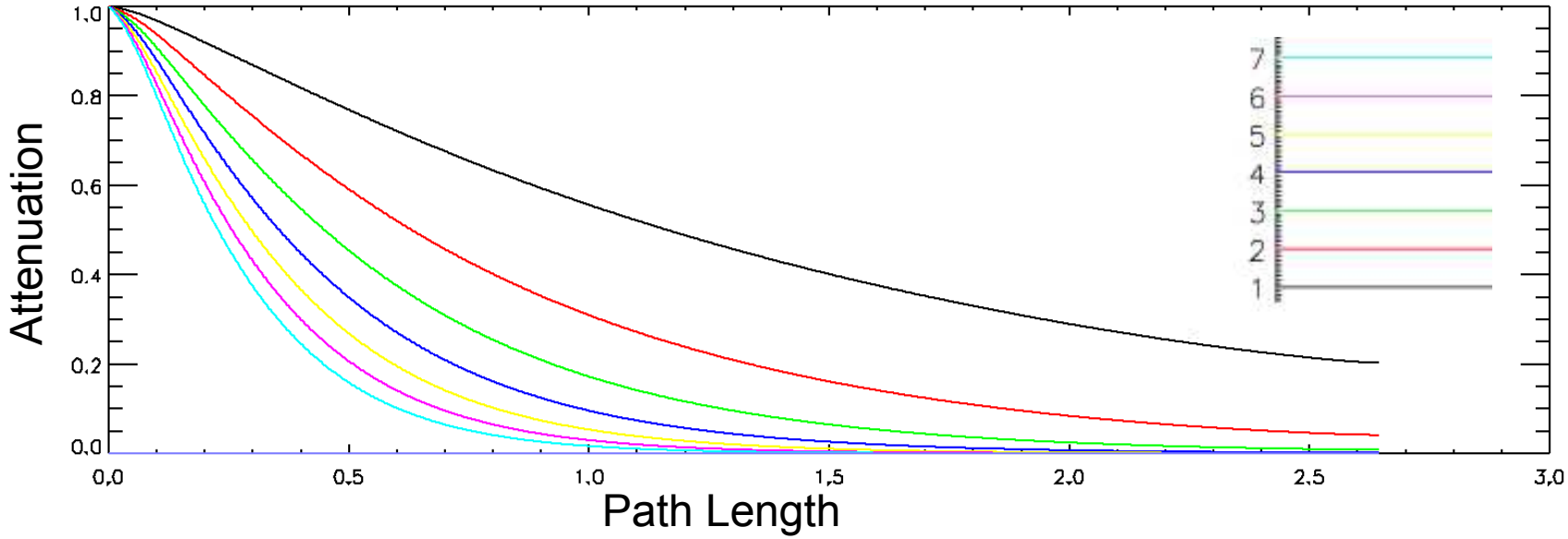
- Look at beam attenuation along a 1-D tangential injection line through r/a = 0

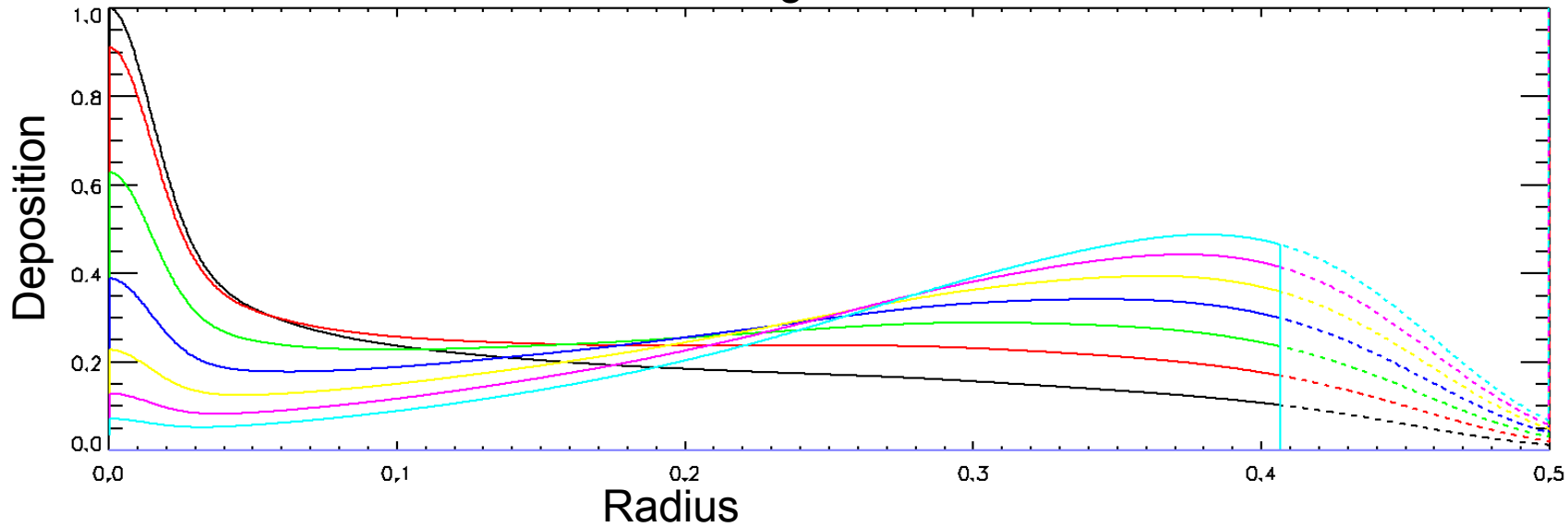
$$I(l) = I(0)\exp\left[-\int_0^l n_e\left(\langle \sigma \nu_e \rangle / v_b + \sigma_i + \sigma_{cx}\right) dl\right]$$

- Cross sectional plasma parameters based on experimental measurements
- Deposition weighted by attenuation and mapped to radial coordinate based on beam path



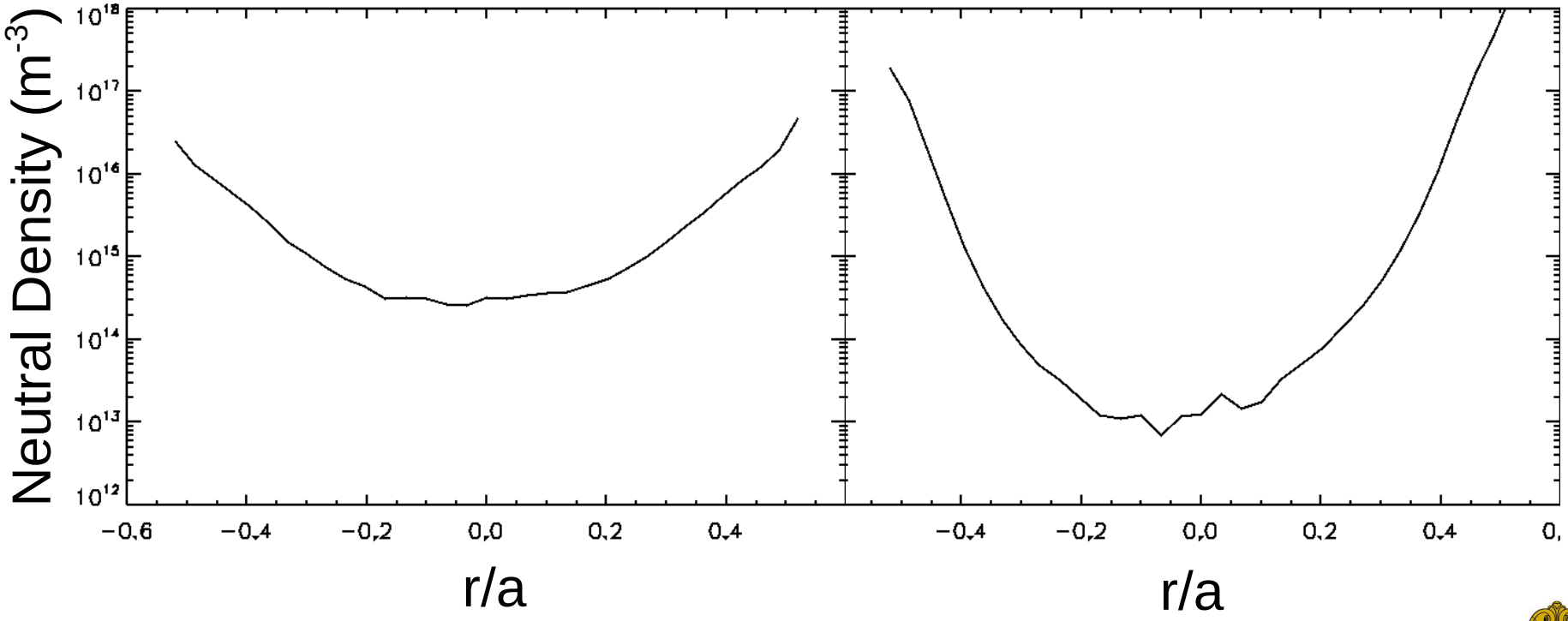
Density Dependence of Fast Ion Deposition





Investigating Loss Mechanisms

- Estimations of prompt loss
- CX loss from interactions with neutrals
- NENE simulations show a decrease in core neutral density for pellet fueled plasmas



Fast Ion Slowdown

- Using Classical Collision Rate

$$\frac{1}{E_{fi}}\frac{dE_{fi}}{dt}=\frac{-Z_{fi}^{2}e^{4}n_{e}m_{fi}^{1/2}\ln\Lambda}{4\sqrt{2}\pi\epsilon_{0}^{2}m_{e}E_{fi}^{3/2}}\left[\frac{4}{3\sqrt{\pi}}\frac{m_{e}}{m_{fi}}\left(\frac{E_{fi}}{T_{e}}\right)^{3/2}+\sum_{i}\frac{m_{e}n_{i}}{m_{i}}\frac{Z_{i}^{2}}{n_{e}}\right]$$

τ_{Efi} $\langle n_e \rangle$

T_e	1	2	3	4	5	6	7
200	5	2.5	1.7	1.3	1	0.8	0.7
400	14	7	4.6	3.5	2.8	2.3	2
600	24	12	8	6	5	4	3.5
800	36	18	12	9	7	6	5
1000	47	24	16	12	9.5	8	7
1200	59	30	20	15	12	10	8
1400	70	35	23	18	14	12	10

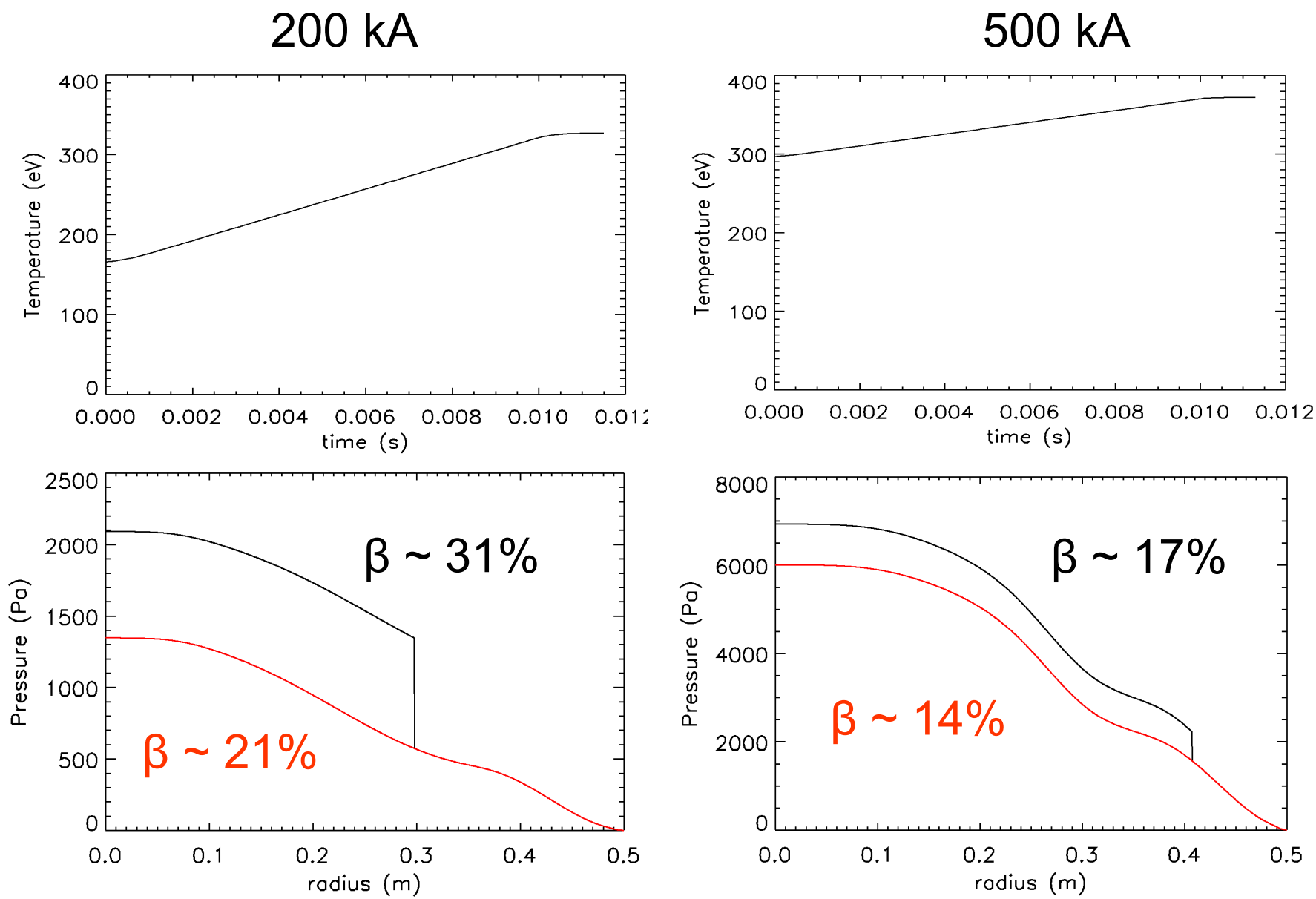
Pellet Fueled 500 kA PPCD

Low Density 500 kA PPCD

Pellet Fueled 200 kA PPCD

Low Density 200 kA PPCD

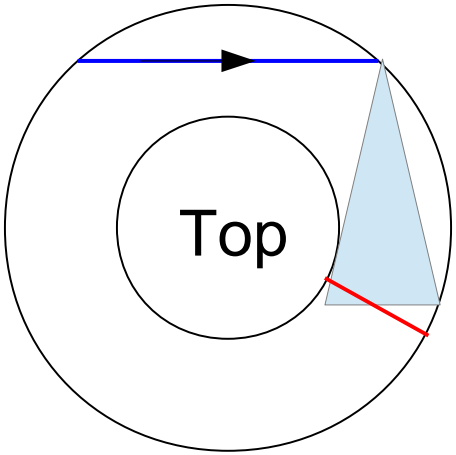
Estimated Effect on β (Optimistic)



No observed β limit but...

- Pellet fueled PPCD consistently shows an increase in β compared to low density
- Tearing mode activity increases as density increases
- No observed β limit with added NBI heating, nor any significant increase in observed β

- During NBI heating experiments, observe toroidal deflection of the pellet in direction of NBI
- Toroidal deflection consistent with asymmetric ablation due to fast ion population



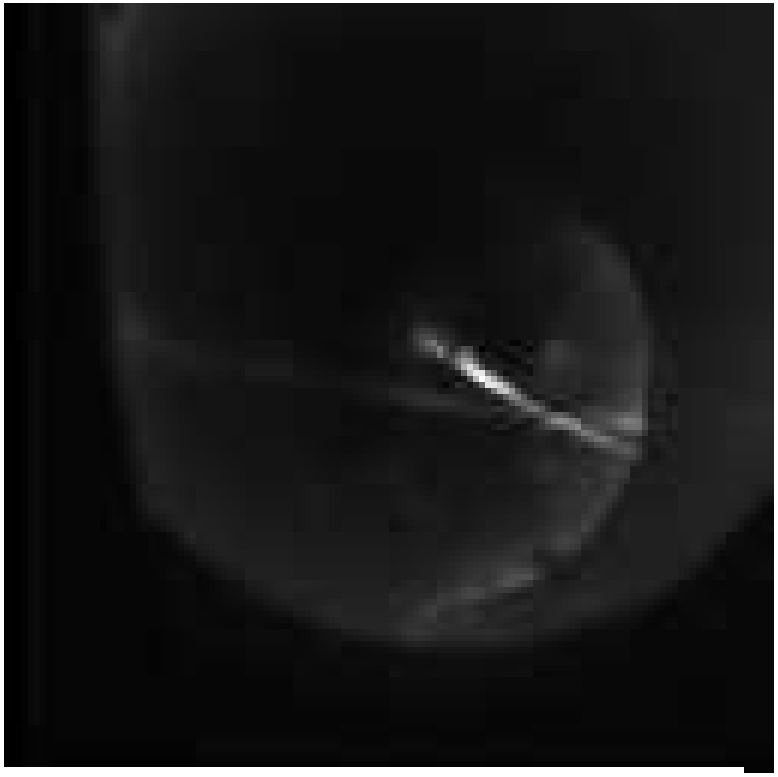
Pellet deflection by fast ions

Beam Off

Beam On

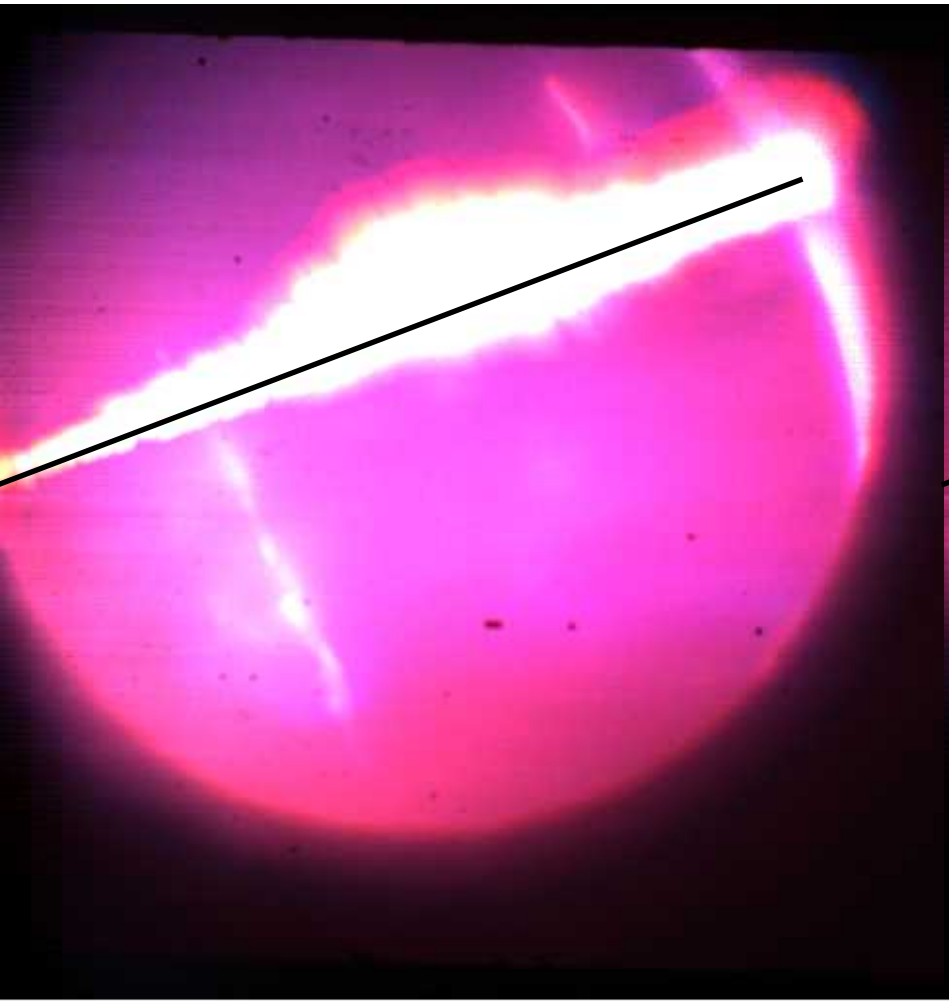
Pellet deflection by fast ions

Beam Off

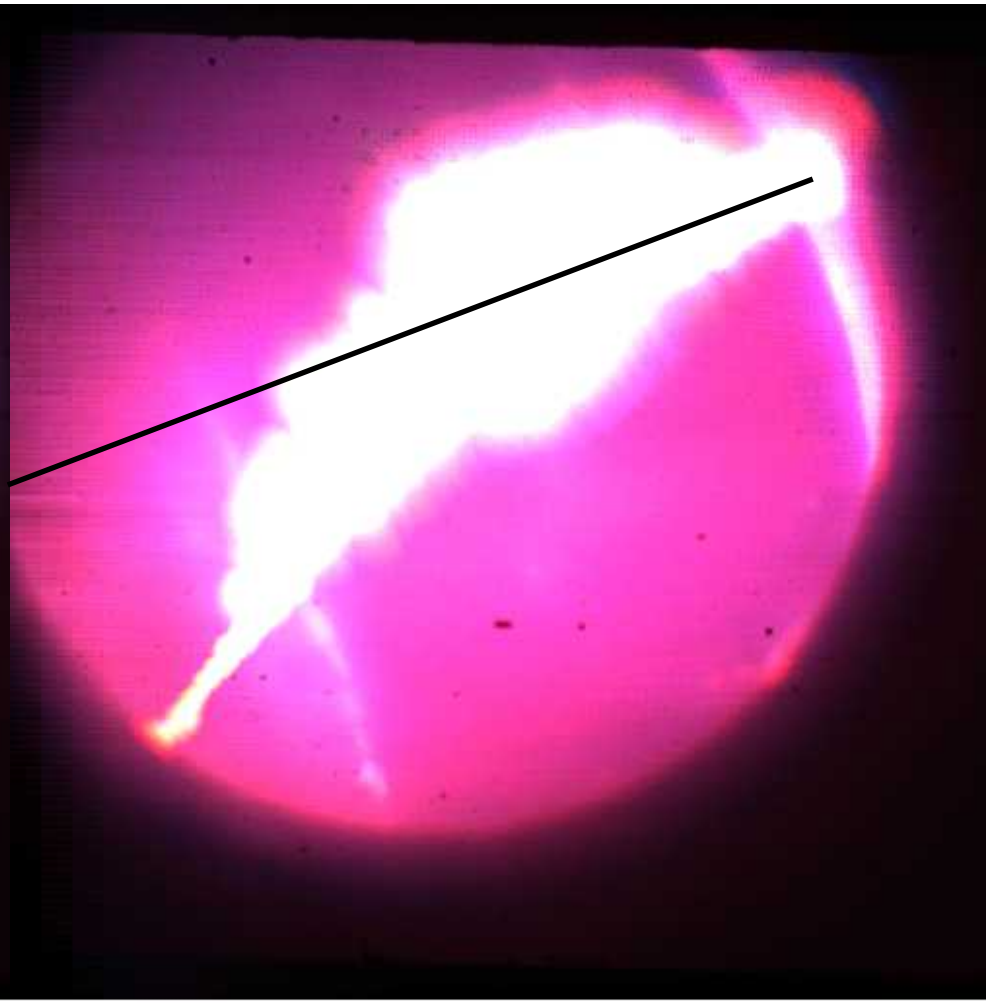


Beam On

Pellet Deflection by Fast Ions



Beam Off



Beam On

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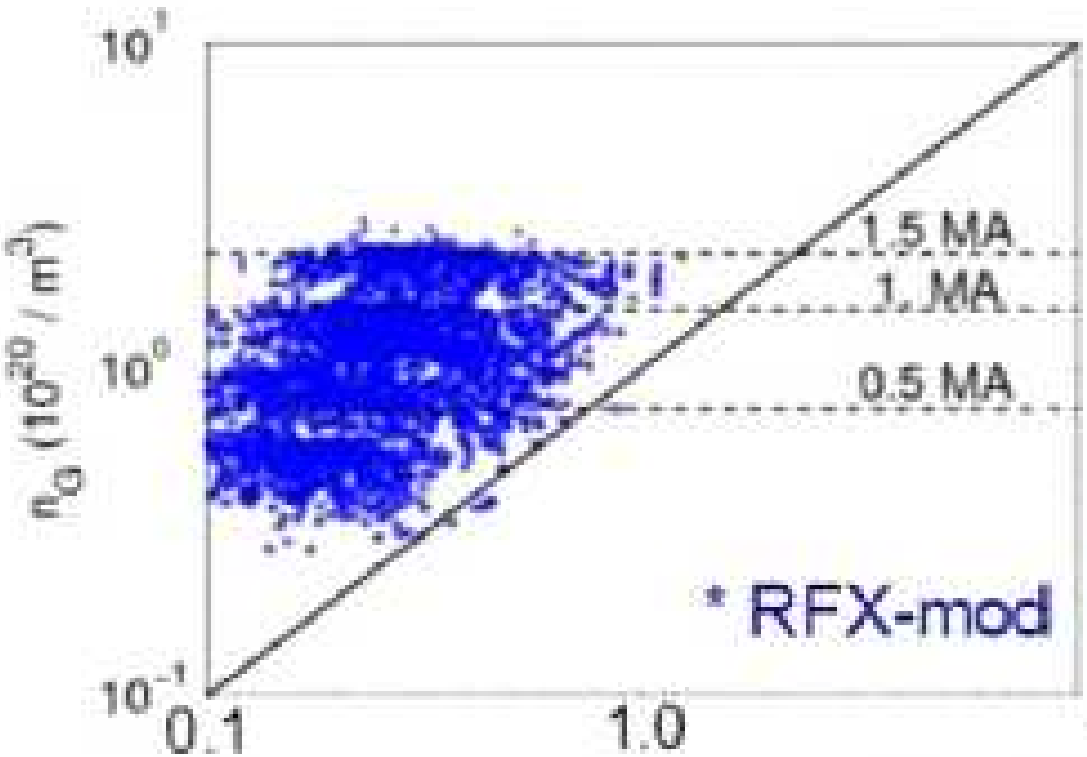
RFP Density Limits

- Greenwald limit for Tokamaks and RFP experiments with circular cross sections:

$n_{GW} = I/\pi a^2$

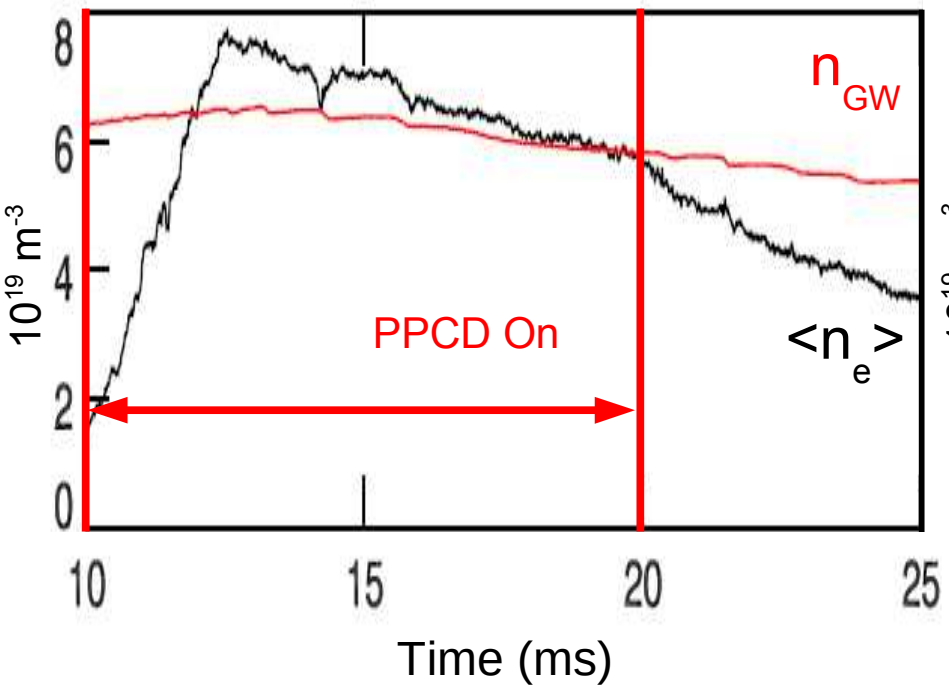


- Symptoms include:
  - Increase in radiation
  - Edge cooling
  - MHD activity
  - Thermal quench

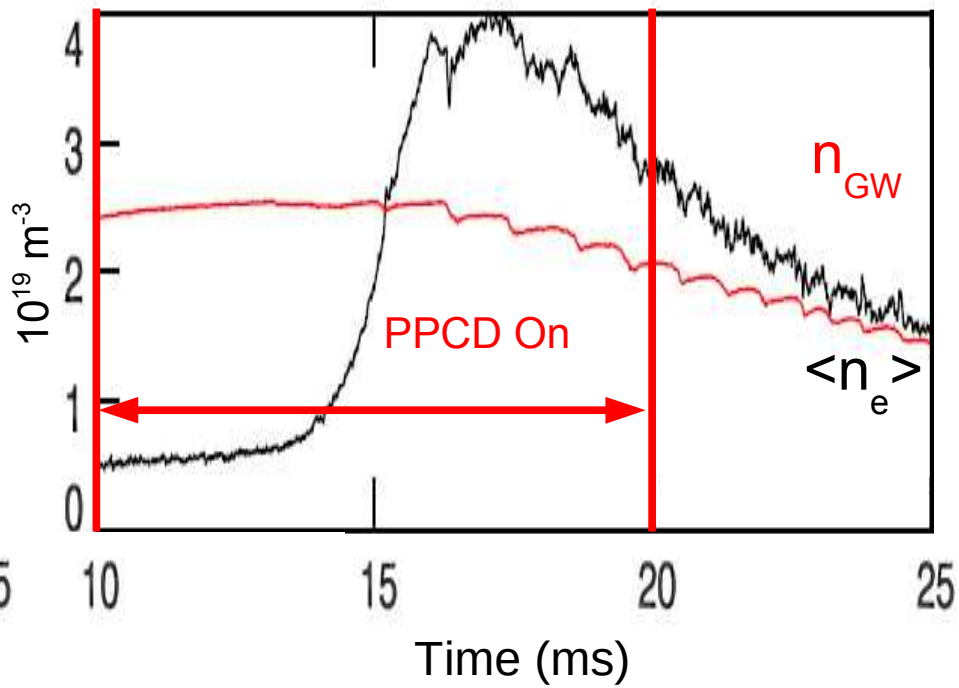
Exceeding the Density Limit on MST

- Injecting pellets during PPCD can achieve densities above the Greenwald limit without termination
- 4.0 mm pellets greatly expand achievable density

.5 MA $\langle n_e \rangle / n_{GW} > 1.2$

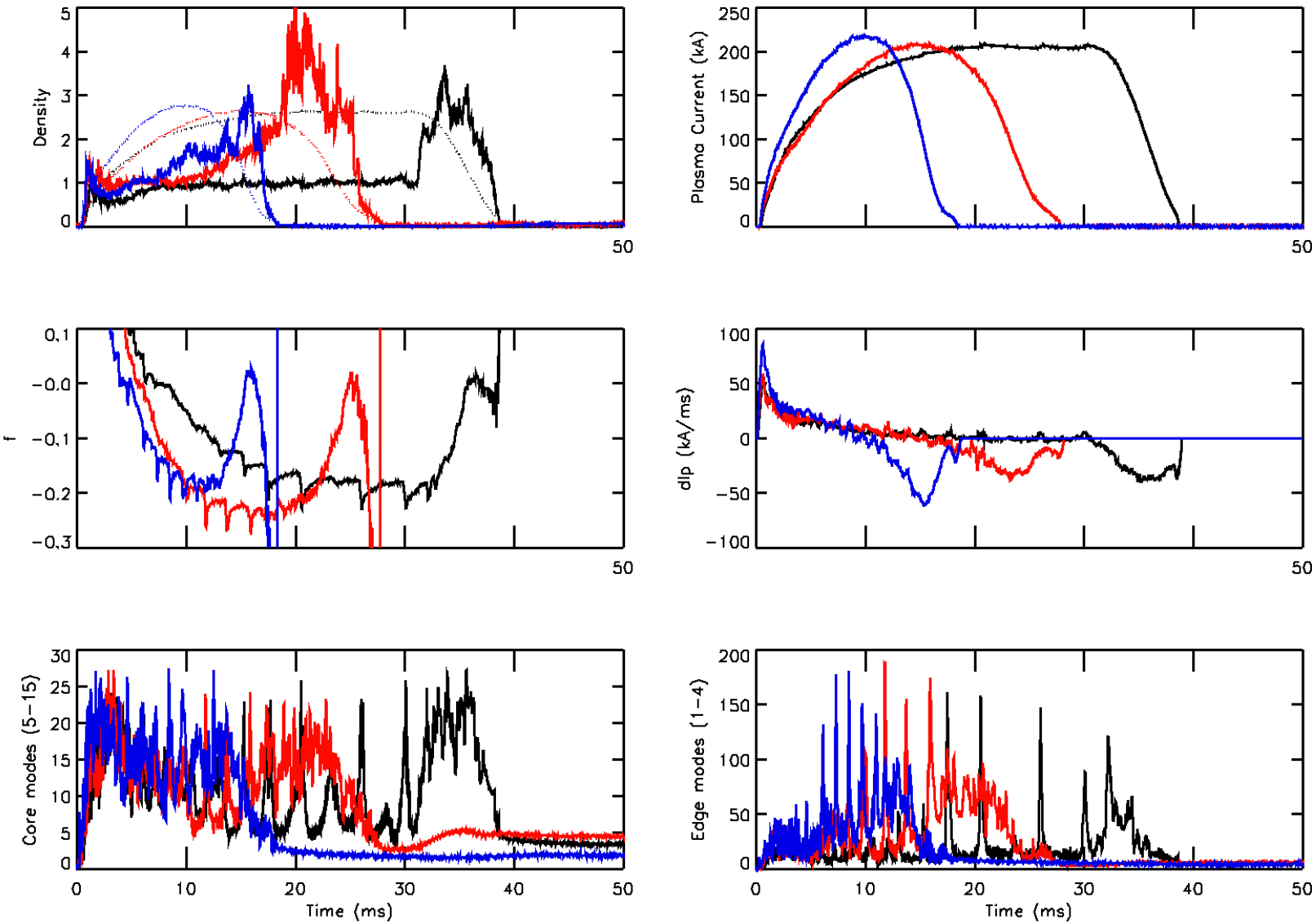


.2 MA $\langle n_e \rangle / n_{GW} > 1.5$



Comparing Density Limit Events

Pellet Gas Valve Excursion

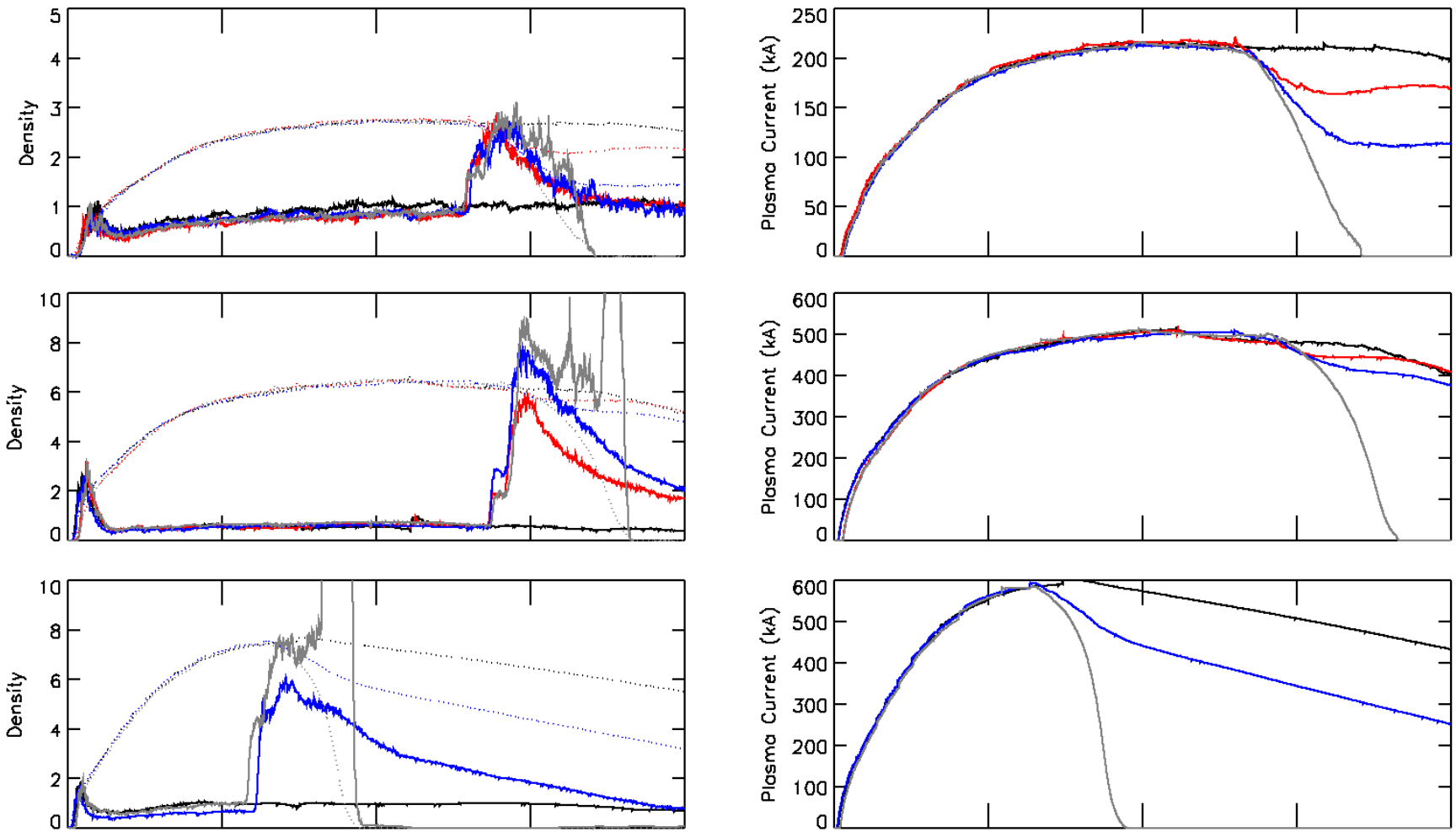


Using Pellets to Trigger Termination

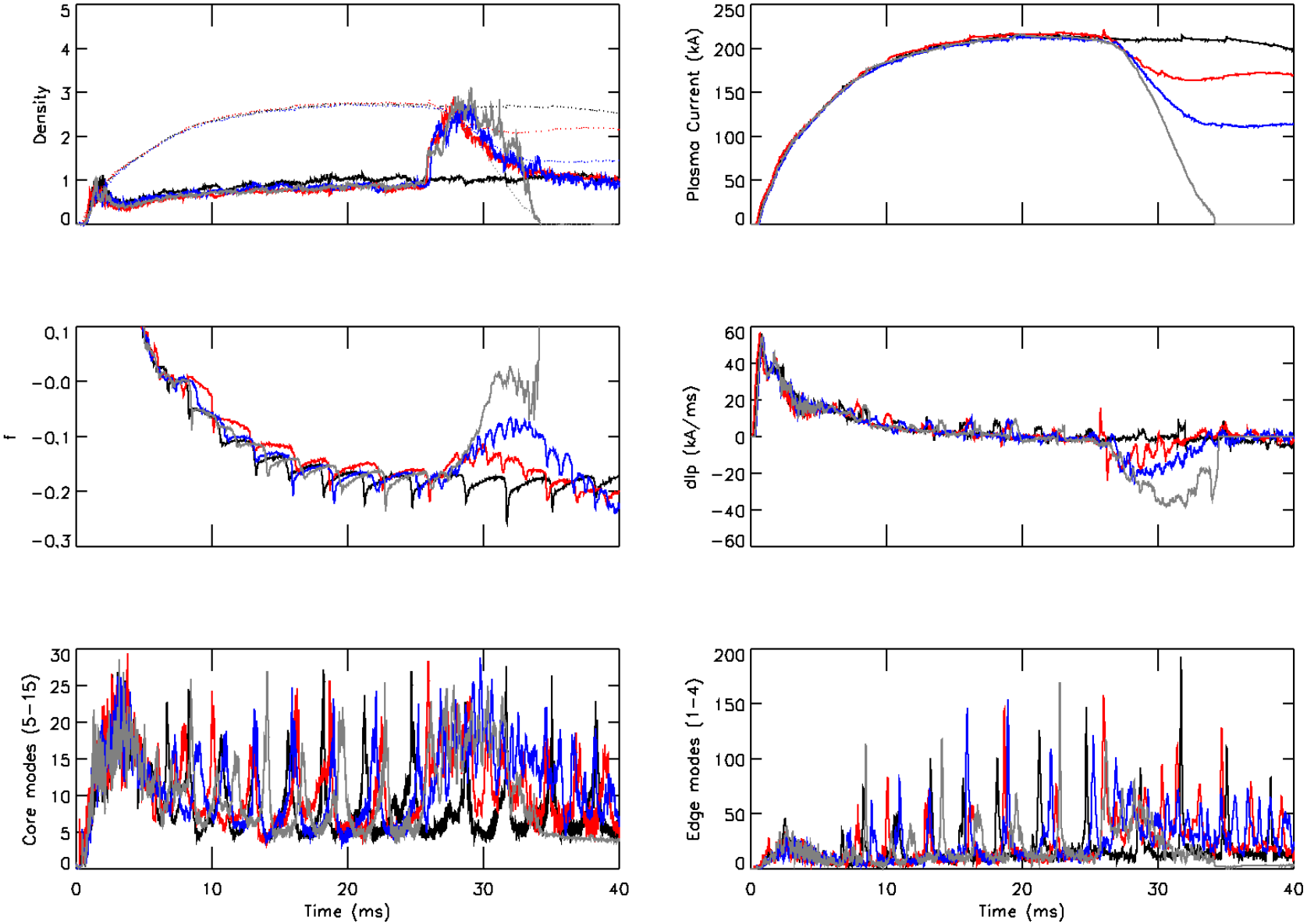
- Goal was to trigger density limit terminations for all plasma currents as well as look for changes based on the value of q at the wall
  - $q(a) < 0$ for standard operation
  - $q(a) = 0$ for non-reversed
- Use large, fast deuterium pellet to provide a large edge fueling source when it collides with the far wall
  - 2.0 mm pellets used for 200kA
  - 4.0 mm pellets used up to 600 kA
- By adjusting pellet size, can probe impact of over fueling
- Utilizing the full complement of available diagnostics including:
  - Thomson Scattering, FIR, Langmuir probes, etc.

Density Limit Terminations Up to 600 kA

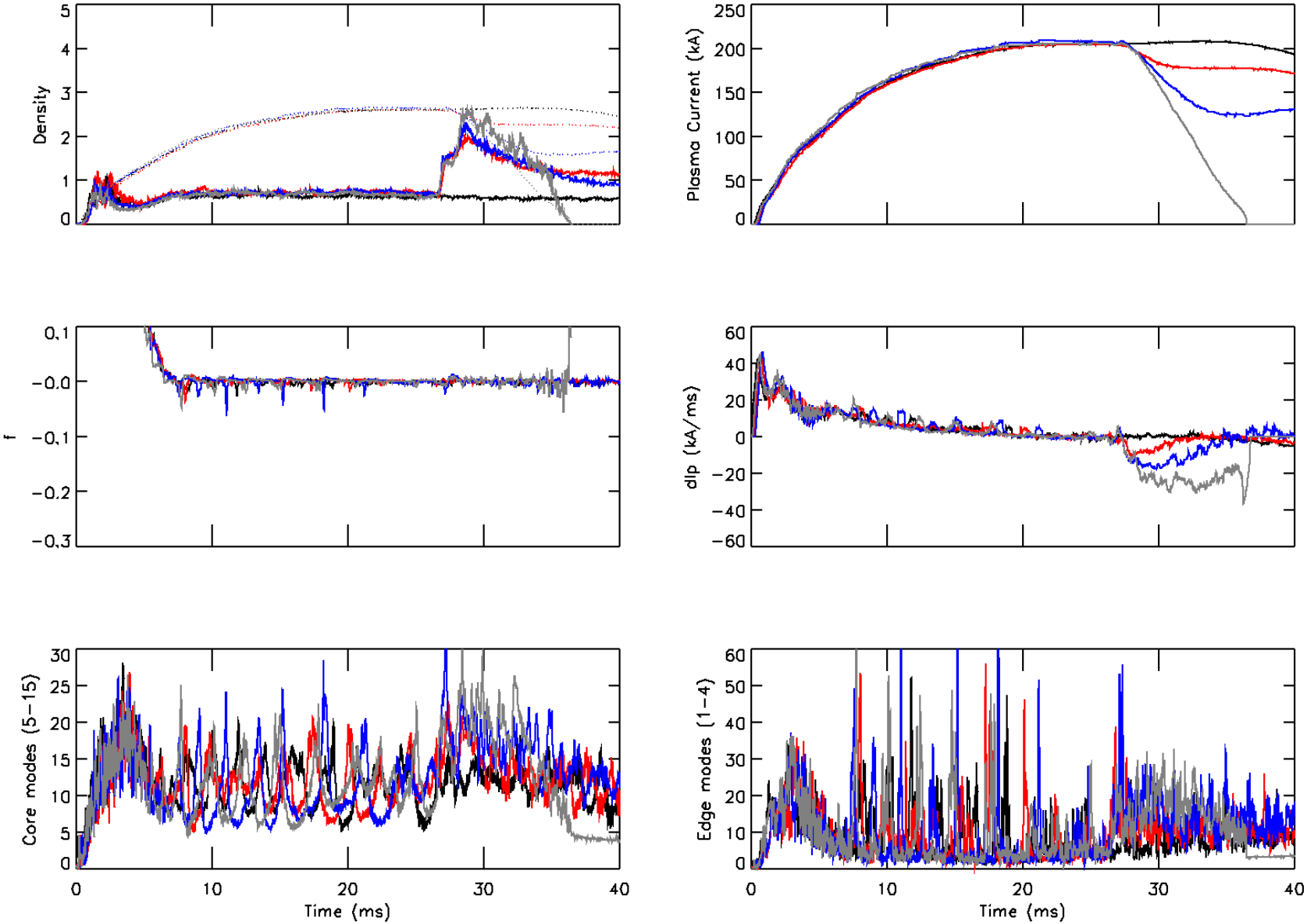
- High Current terminations require large 4.0 mm pellets



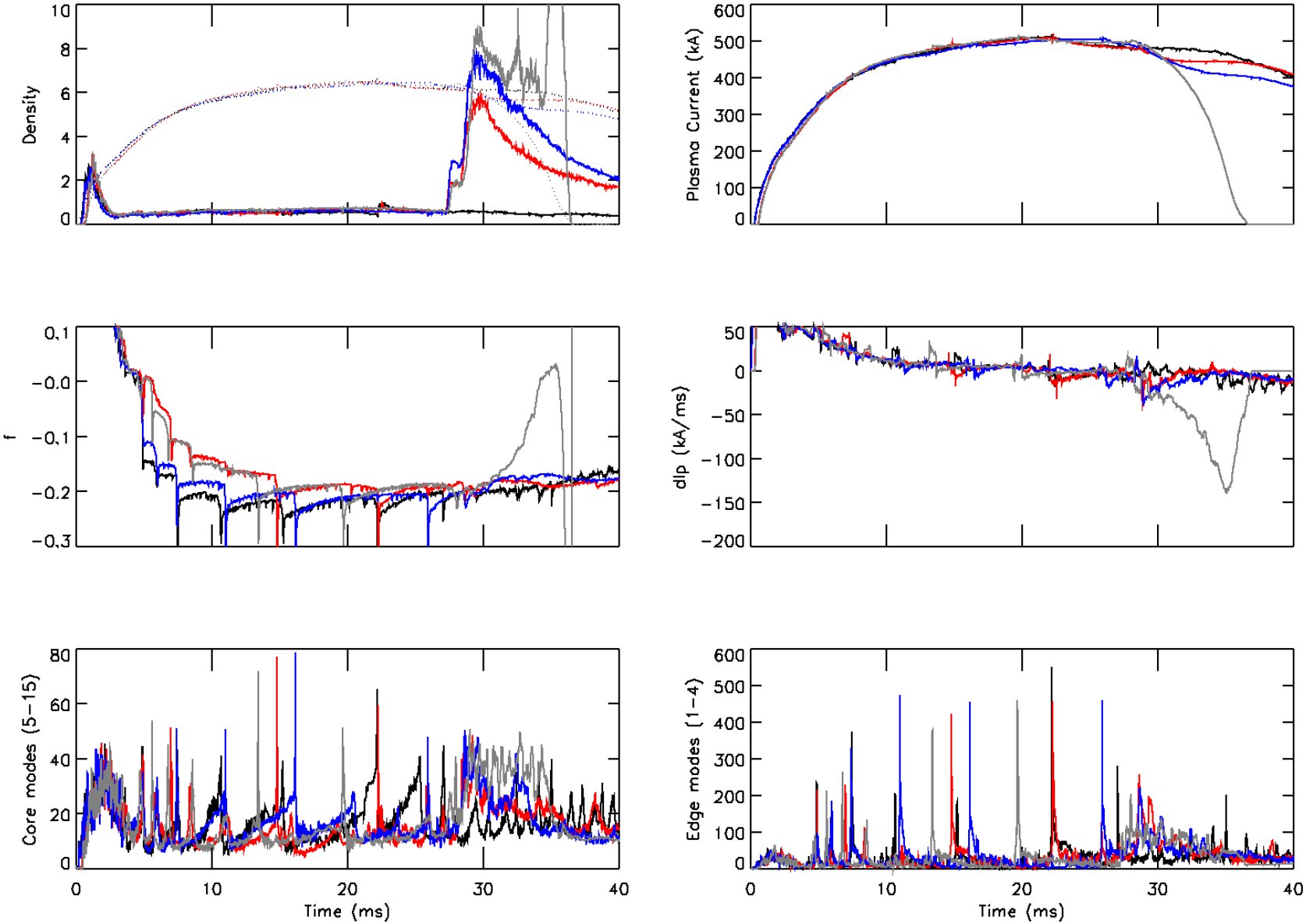
200 kA q(a) < 0


Density
Plasma Current (kA)
f
dIp (kA/ms)
Core modes (5–15)
Edge modes (1–4)
Time (ms)
Time (ms)

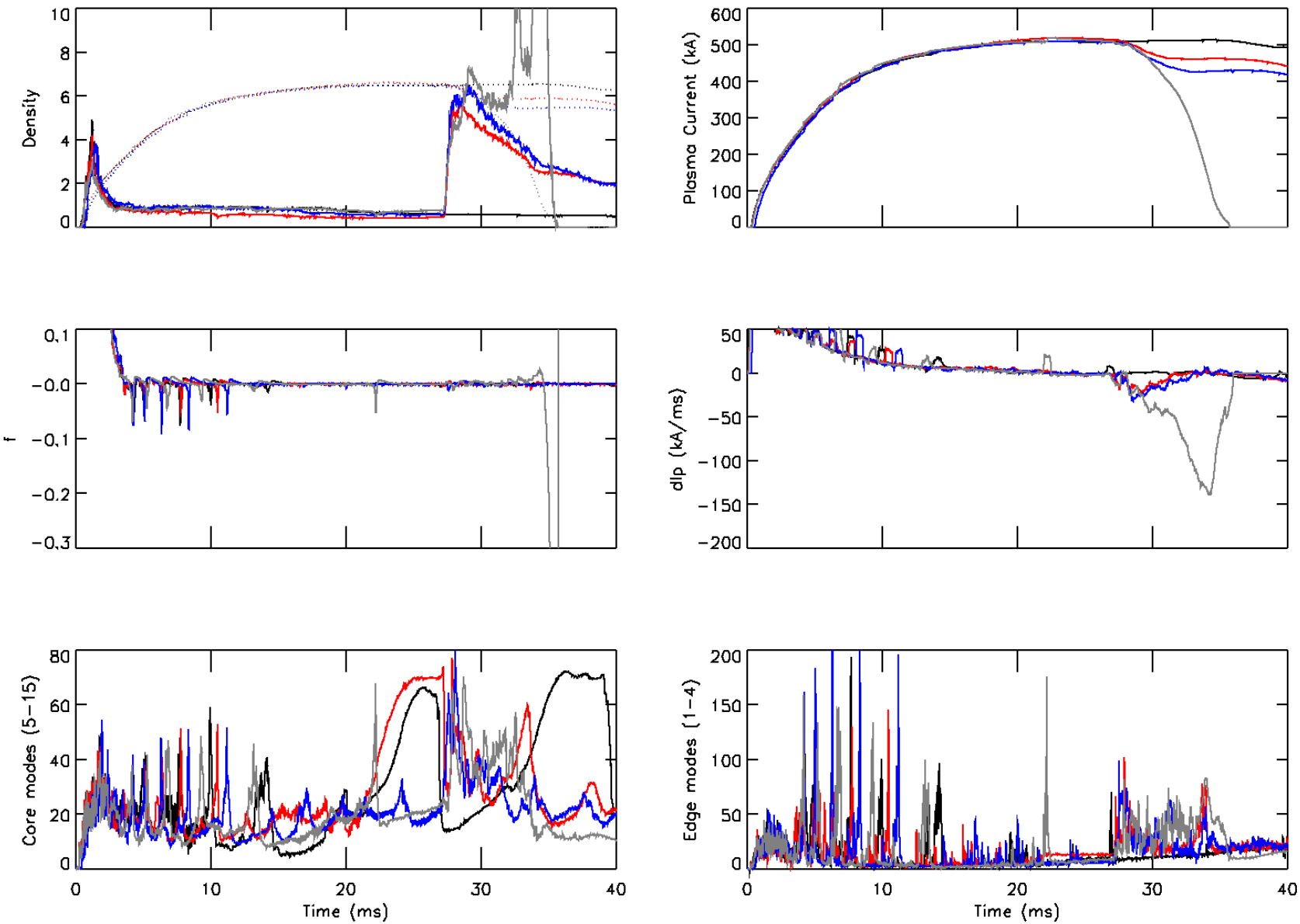
200 kA q(a) = 0


Density
Plasma Current (kA)
f
dIp (kA/ms)
Core modes (5–15)
Edge modes (1–4)
Time (ms)
Time (ms)

500 kA q(a) < 0

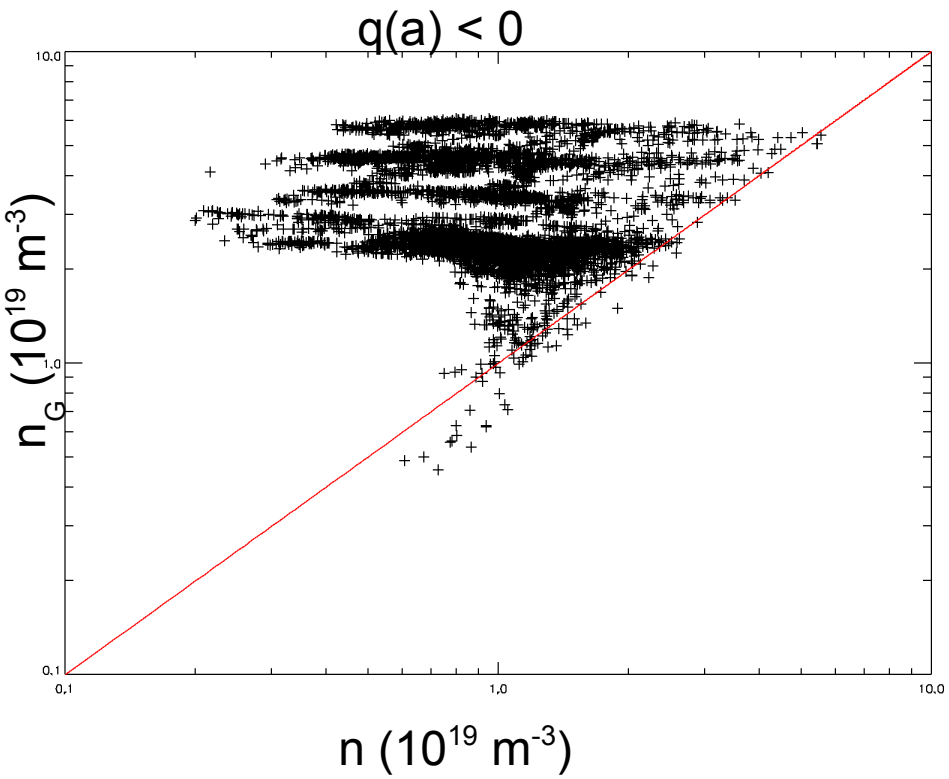

Density
Plasma Current (kA)
f
dIp (kA/ms)
Core modes (5–15)
Edge modes (1–4)
Time (ms)
Time (ms)

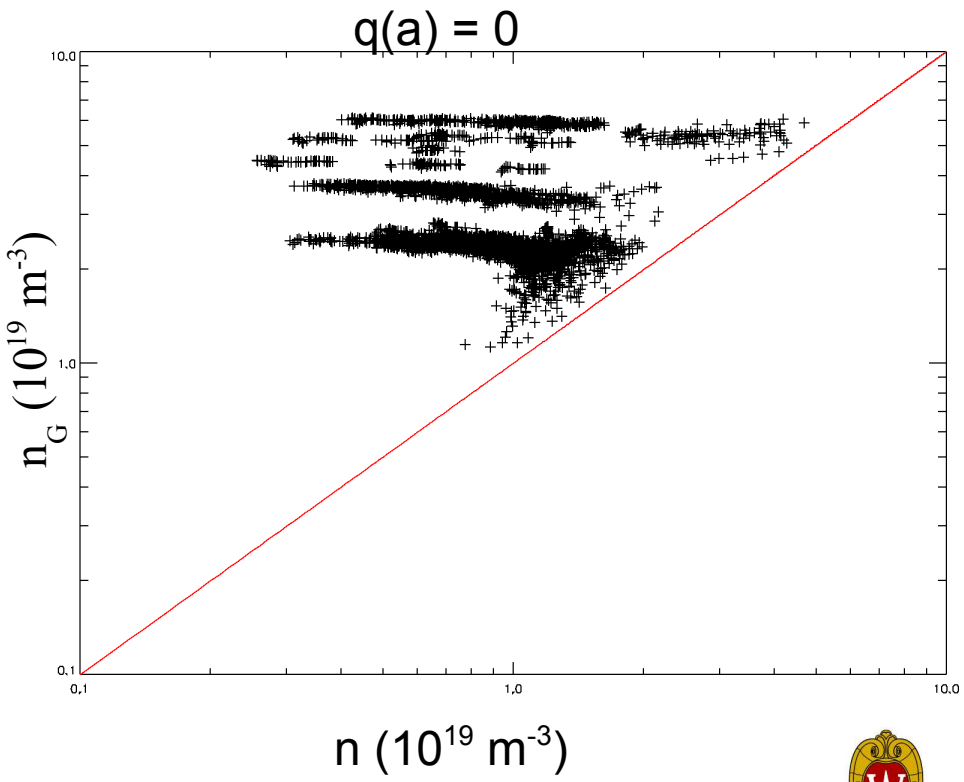
500 kA q(a) = 0


Density
Plasma Current (kA)
f
dIp (kA/ms)
Core modes (5–15)
Edge modes (1–4)
Time (ms)
Time (ms)

MST Operational Density

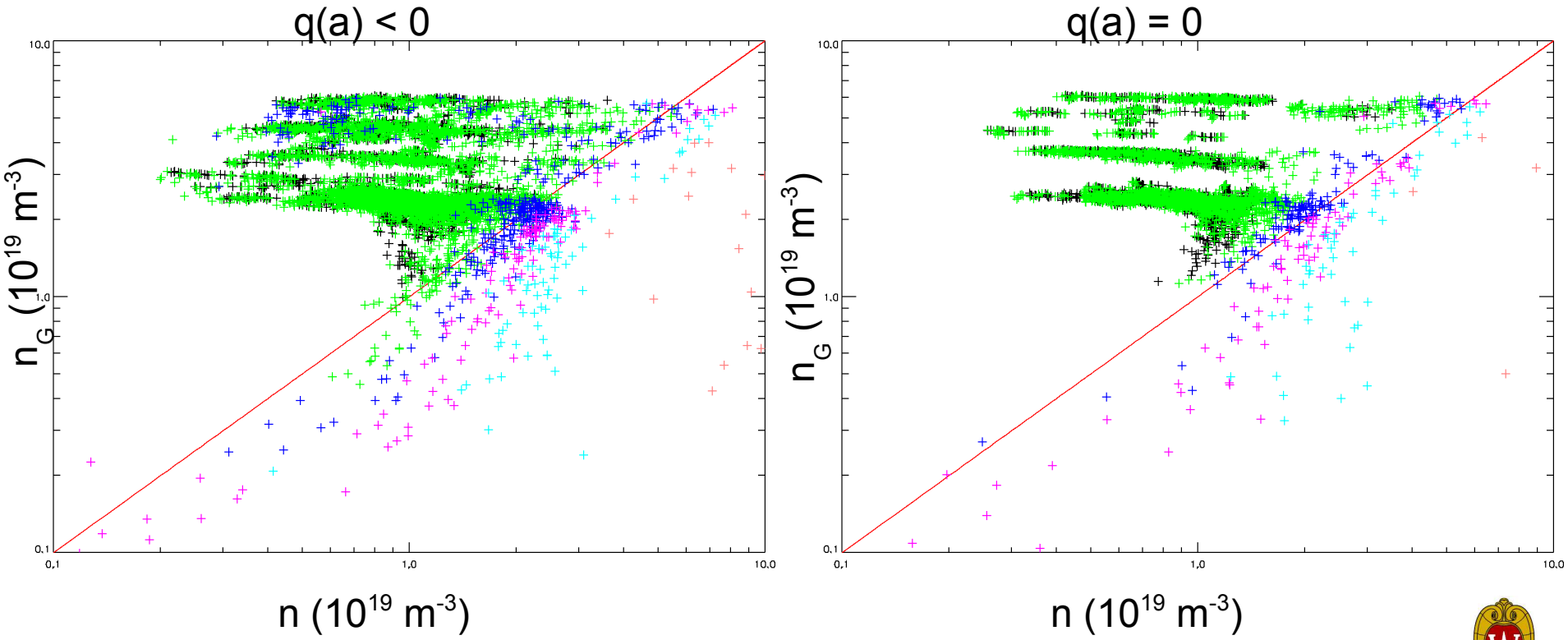
- dI/dt > 0 kA/ms
- Greenwald limit constrains density
- Small change based on reversal parameter
  - Or potentially based on differing plasma conditions



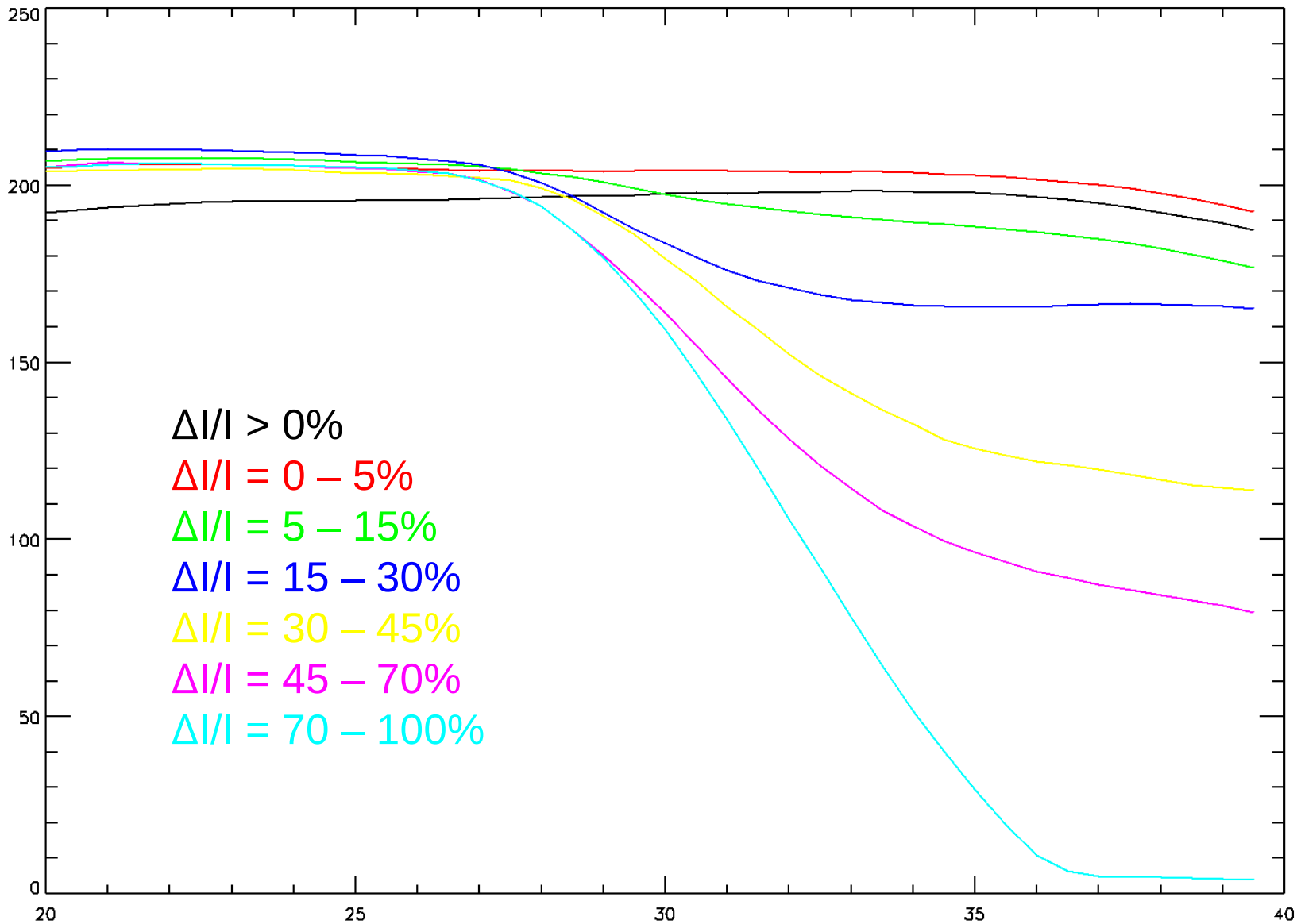


Operational space (density)

dI/dt > 0
0 < dI/dt > -10
-10 > dI/dt > -20
-20 > dI/dt > -30
-30 < dI/dt < -50
dI/dt < -50

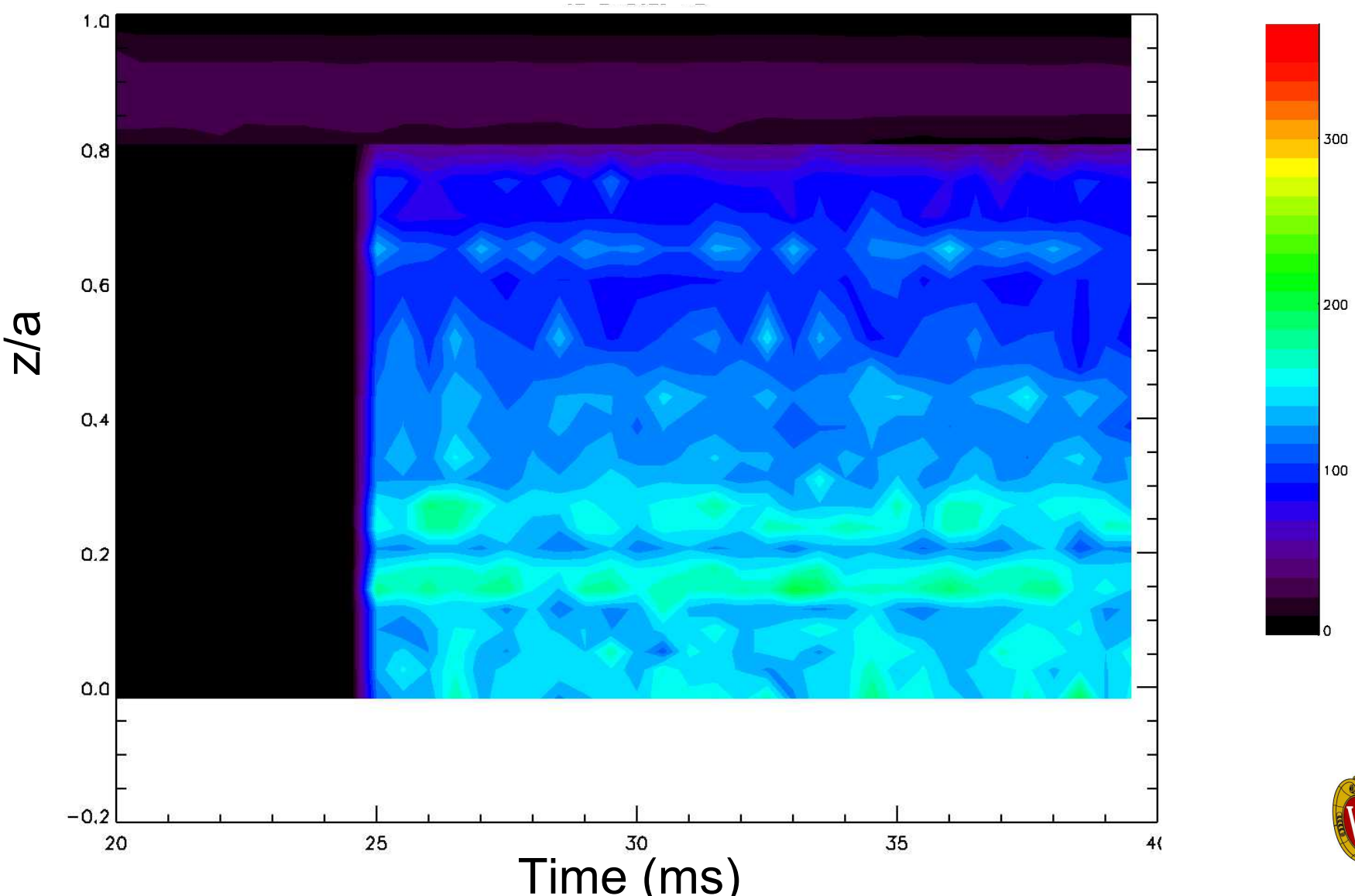


What Changes as Current Decays



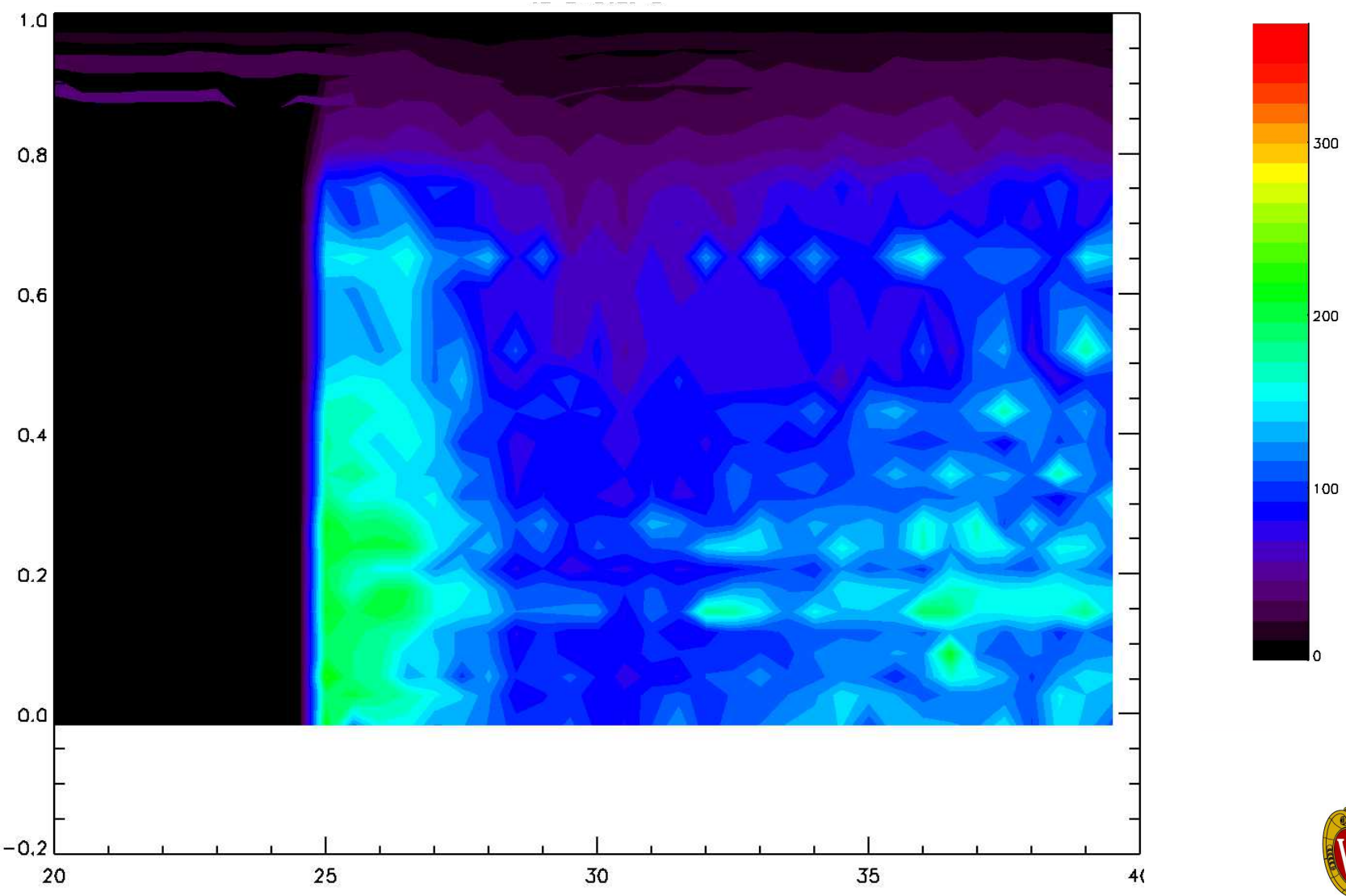
200 kA q(a) < 0 Discharges

$\Delta I/I = 0 - 5\%$



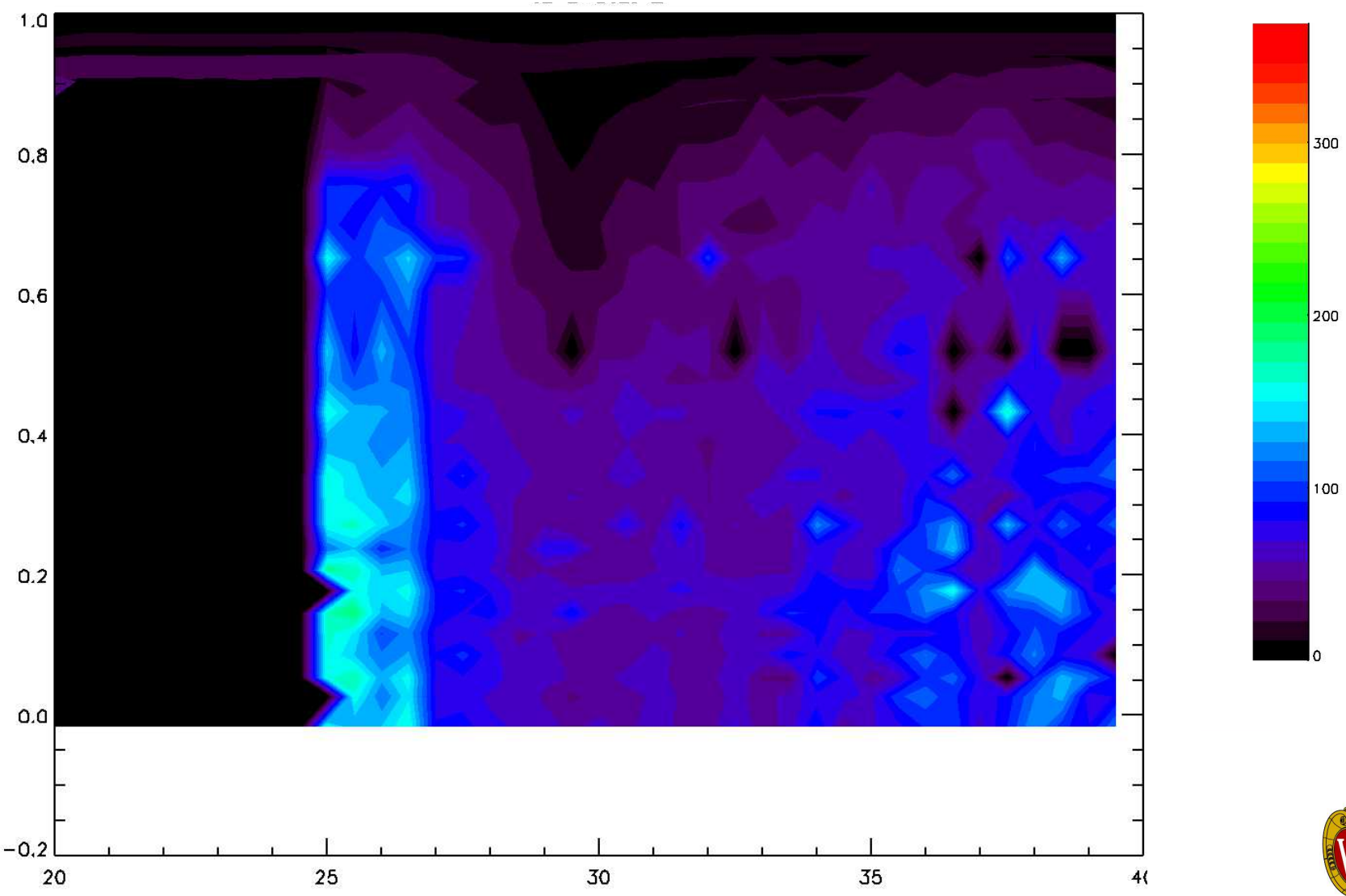
200 kA < 0 Discharges

$\Delta I/I = 5 – 15\%$



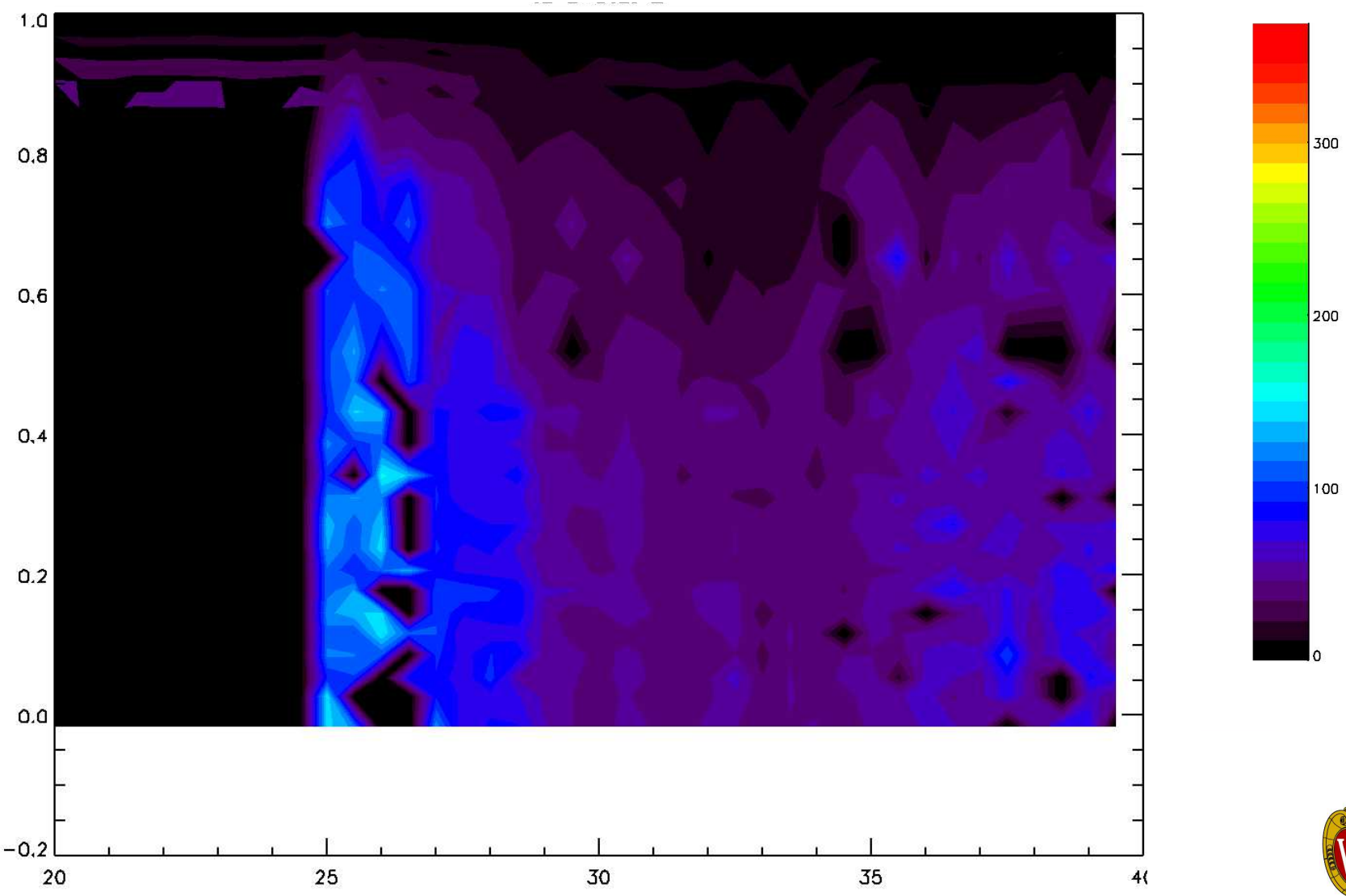
200 kA q(a) < 0 Discharges

$\Delta I/I$ = 15 – 30%



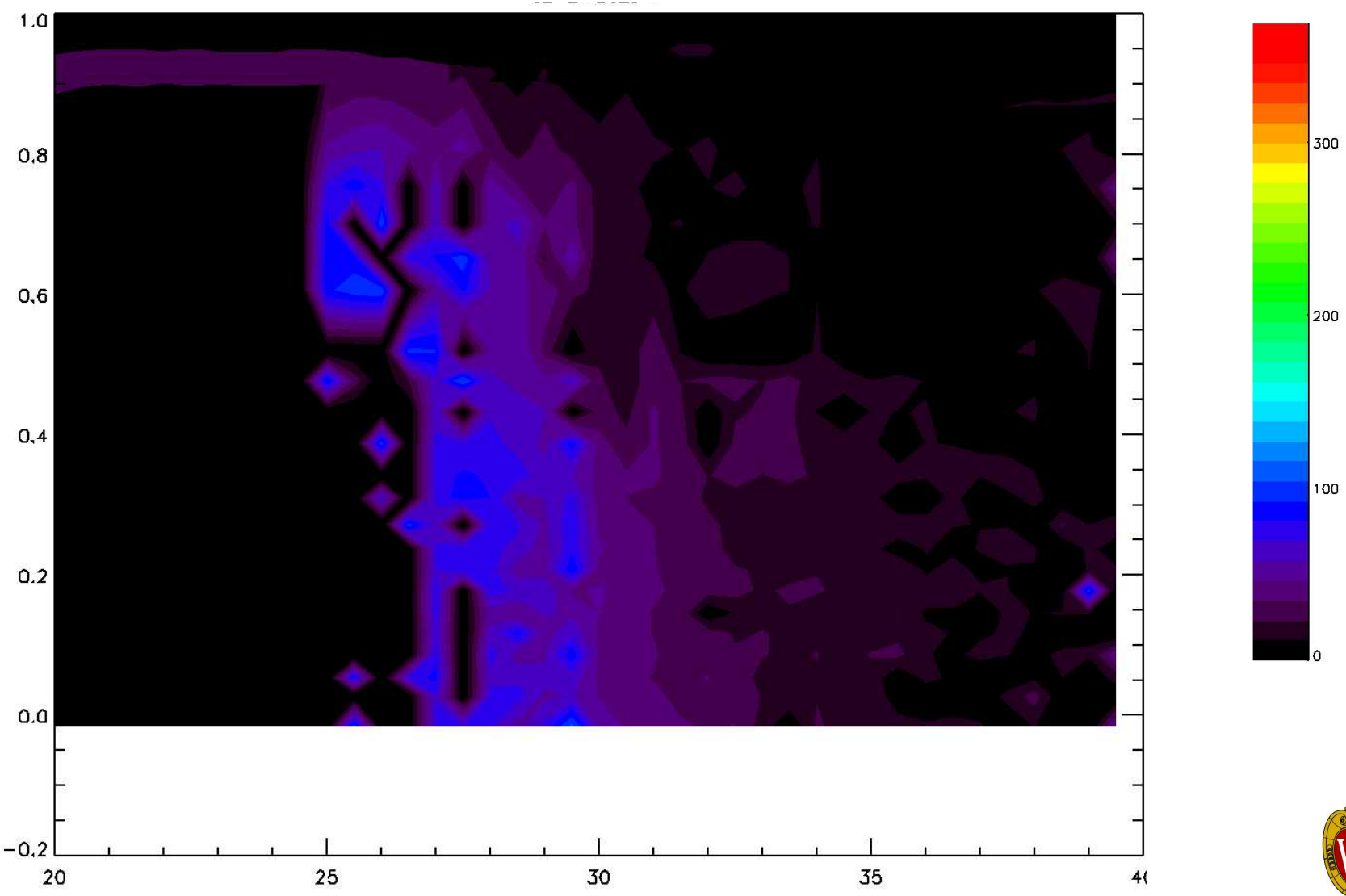
200 kA q(a) < 0 Discharges

$\Delta I/I$ = 30 – 45%



200 kA q(a) < 0 Discharges

$\Delta I/I$ = 45 – 70%



Density Limit Wrapup

- Further analysis of density limit terminations is underway
- Many of the diagnostics struggle with the extreme low temperature and high density of these experiment
- Pellet triggered terminations are reproducible and display many of the signature symptoms
  - Edge cooling
  - Possible shrinking of the current channel
  - Highly radiative
- Varying q(a) has an effect on the apparent density limit

Conclusions

- Pellet fueling on MST has proved to be a valuable tool for investigating and probing the potential limits of the RFP
  - High beta experiments
  - Density Limits

- Many important upgrades have been made to expand the operational capabilities of the injector
  - Expanded pellet size capability
  - Alternate fuels