Performance and Stability Limits at Near-Unity Aspect Ratio in the PEGASUS Toroidal Experiment

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The accessible parameter space at near-unity aspect ratio in the Pegasus Experiment has been increased. β_t values up to 25% (β_N ~ 5) were obtained with no evidence of a limit, while densities range up to the Greenwald limit. A toroidal field utilization factor up to 1.2 and normalized currents greater than 5 have been achieved. The stored energy is consistent with expectations from the ITER98pby2 scaling. Plasma startup is characterized by high current ramp rates (15-45 MA/s) and low internal inductance ($\ell_i \sim 0.3$). The current is usually limited by volt-seconds or a large m/n = 2/1 MHD instability, which results in a rapid decrease in dI_p/dt. The appearance of this mode is coincident with $q(0) \gtrsim 2$ and low shear across a broad region of the plasma interior. A more complete set of magnetic diagnostics was installed to better characterize these plasmas. Increased ohmic power, HHFW pre-heating, variable shaping, improved conditioning and gas handling, and transient high toroidal field during plasma formation provide new tools to control the MHD activity and move closer to near-unity beta plasmas in this geometry.

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Role of the PEGASUS Experiment

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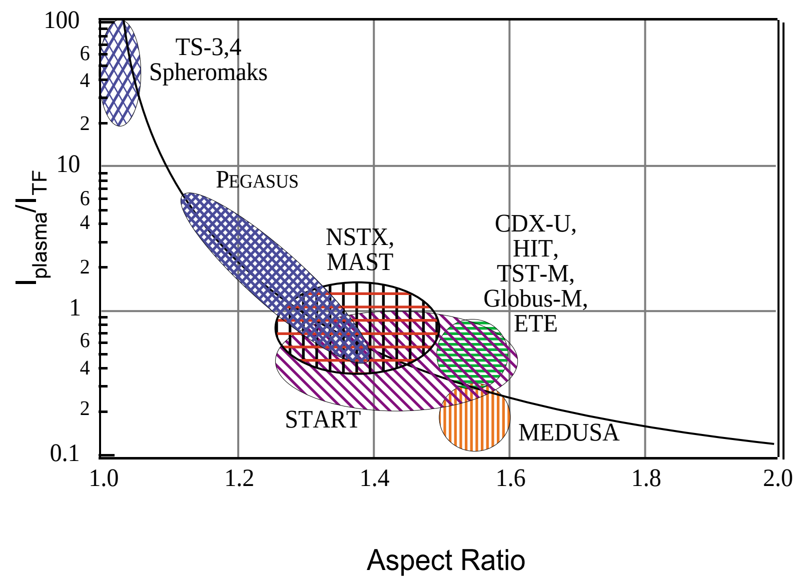
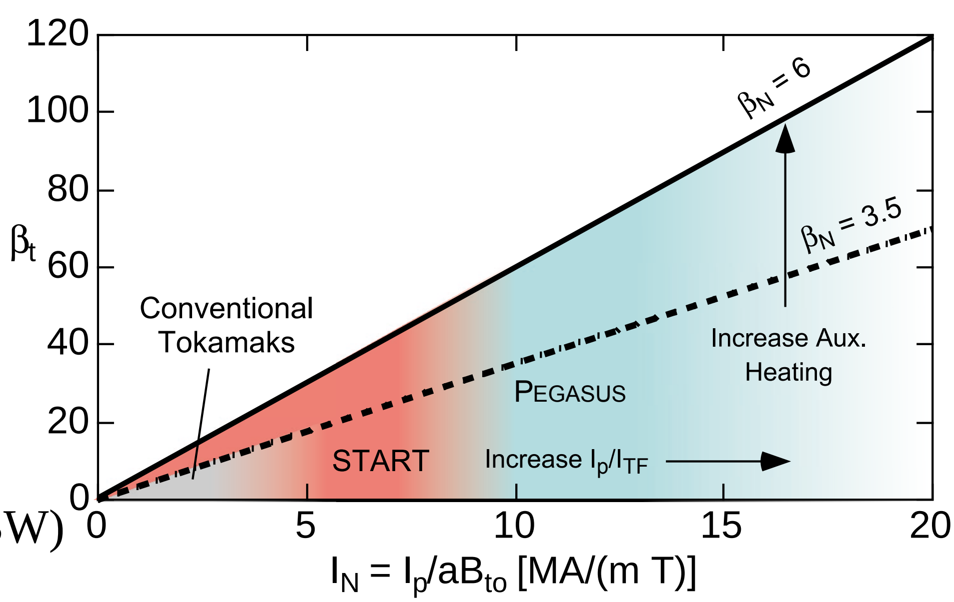
Mission Statement

An extremely low-aspect ratio facility exploring quasi-spherical high-pressure plasmas with the goal of minimizing the central column while maintaining good confinement and stability.

- **Physics of $A \approx 1$ plasmas as an Alternate Concept (low q)**
  - Extreme toroidicity ($A \rightarrow 1$)
  - Very high TF utilization (I_P/I_{TF}) > 3
  - Stability at very low TF ($\beta \sim 1$)
  - Relaxation stability at tokamak/spheromak boundary
  - RF heating and CD schemes (HHFW, EBW)
  - Trade-offs: CD, recirculating power, and $A \approx 1$, low-TF operation



- **Contribute to development of the ST (high q)**
  - Stability limits for $A \rightarrow 1$ (vs. I_p/I_{TF}, q_ψ, N_e, β_t, β_{pol}, κ, A, etc.)
  - β limit dependencies
  - Access high β_t at extreme I_N w/o conducting shell
  - Confinement A < 1.3
  - Startup schemes (e.g., Ext. induction, EBW)



PEGASUS is a Mid-Sized University ST

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Design Parameters

A	1.1 - 2.0
R	0.2 - 0.45 m
I_p	0.1 - 0.3 MA
B_t	< 0.30 T
κ	~ 1.5 - 3.7
Δt_{pulse}	30 - 40 msec
β_t	*O*(1)
β_N	> 5
I_N	> 10
Heating and Sustainment	Inductive* + RFCD (HHFW, EBW)

* NHMFL: $B_{solenoid}$ = 10 - 14 T

Program Developments in 2001 Campaign

- **Developing understanding of limits of operation at very low A and low TF**
  - Gain capability to explore high-β_t, low-q_a regimes

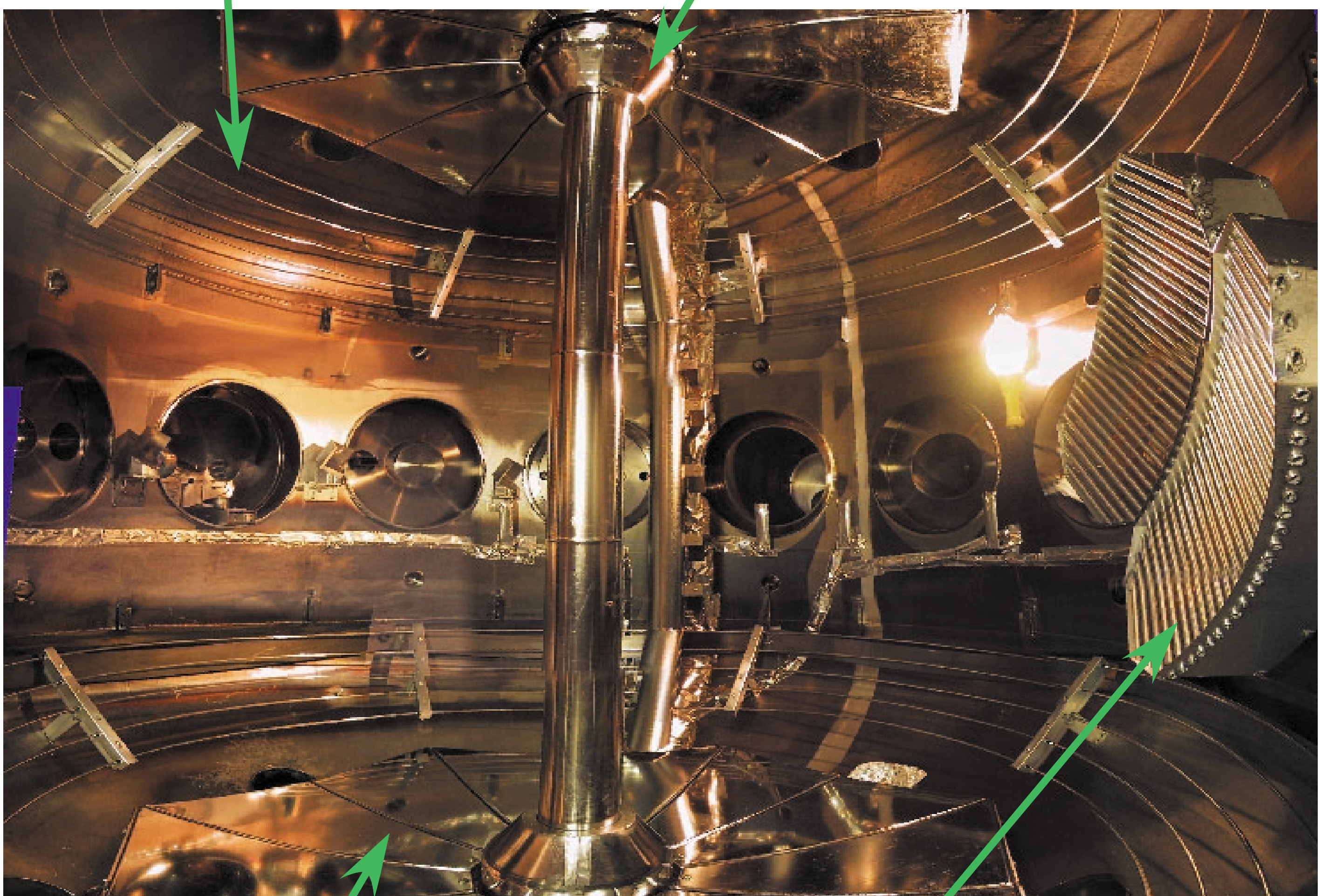
- **Facility development**
  - Increasing ohmic drive capability: I_p up to 150 kA
  - New internal hardware and pfc's
  - Diagnostics and analysis tools
  - Initial operation of HHFW heating system

- **Experimental Campaign**
  - Improved plasma formation control
  - Extension to higher Ip capability
  - Documentation of equilibrium parameters at very low A
  - Identification of factors hindering access to low B_t, high I_p
    - V-sec availability
    - Large-scale internal MHD activity
  - Demonstrate access to external kink limit at low β_N

- **Identify paths for next campaign**
  - Increased V-sec and CD capability
  - High power RF heating
  - Increased B_t with fast rampdown

Facility Upgrades Installed in Major Opening in Fall/Winter 2001

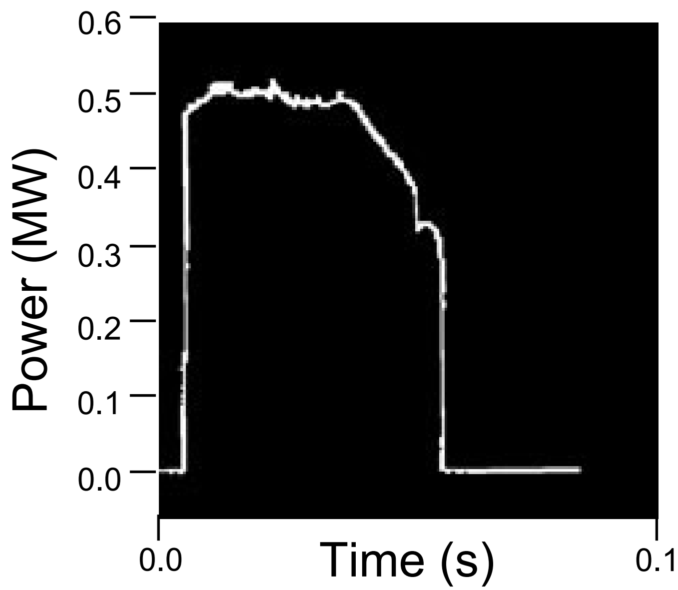
- Internal diagnostics installed
  - Flux loops; B_{pol} arrays; Centerstack magnetics; New Rogowski coils



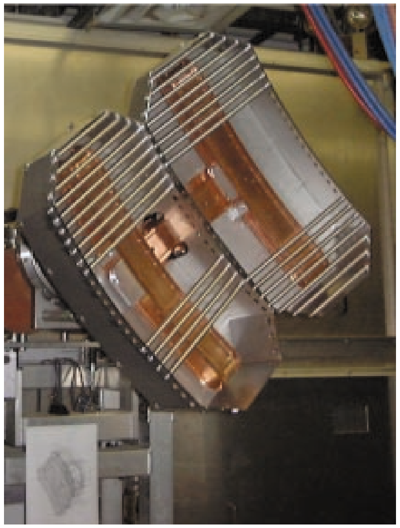
- Improved plasma facing components
  - Divertor plates
  - High-power outer limiter
  - New centerstack shield / cone structure
- HHFW and EBW antennae
  - $P_{RF\text{-}HHFW} \approx 1$ MW
  - Steerable EBW/ECH antenna

Initial Operation of HHFW Heating System

- **HHFW system installed and heating tests underway**
  - *P_{RF} = 1-2 MW available; sufficient to access high β_t regime*
  - Initial loading tests give an impedance of about 1 Ohm
  - Up to 100 kW injected into vessel



RF forward power results from
~ 50 ms test into dummy load



- **HHFW Startup and CD applications:**
  - Startup assist via preheating and/or current profile "freezing"
    - *Startup plasma phase: 40% single pass absorption*
    - *High β plasma phase: 100% single pass absorption*
  - CD possible with present power supply and new antenna

Diagnostics on Pegasus

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- Presently operating diagnostics

Diagnostic	Capability	Measures
Core Flux Loops	(6)	V_L , Ψ_{pol}
Wall Flux loops	(6)	Vessel currents
Int. Flux loops	(20)	Ψ_{pol}
Rogowski Coils	(2)	I_p
Diamagnetic Loop	(2)	Φ_{tor} / β_p
B_p, Mirnov Coils	(56)	B_r , B_z / MHD activity
VUV (SPRED)	central chord	Impurity monitor
Filterscopes	central chord	Oxygen, Carbon, D_α
Interferometer	single chord	$N_e l$
High Res. Camera	1000 fps	Plasma shape/position
2-D SXR Camera		Internal Shape/ j(R)

- Analysis and modeling tools

Equilibrium code	R, a, l_i , β, K, etc.
DCON	Stability Analysis
TSC	New tool designs; n=0 analysis
Wall currents model	Coil design, run guidance

- Near-future diagnostics

Diagnostic	Capability	Measures	When?
Poloidal SXR Diode Array	(19)	MHD Activity	Winter 2001
Tangential CCD PHA	single chord	$T_e(t)$	Winter 2001
Tangential Bolometer Array	~20 chords	P_{rad}	Winter 2001
Ross Filters	single chord	$T_{e0}(t)$	Winter 2001
2-Color X-ray	single chord	T_e	Winter 2001
Tangential VB Array	~20 chords	$Z_{eff}(R,t)$, $N_e(R,t)$	Summer 2002
DNB		$N_e(R,t)$, $T_e(R,t)$, j(R)	Proposed
EBW Radiometer		$T_e(t)$	Proposed

Diagnostics on PEGASUS

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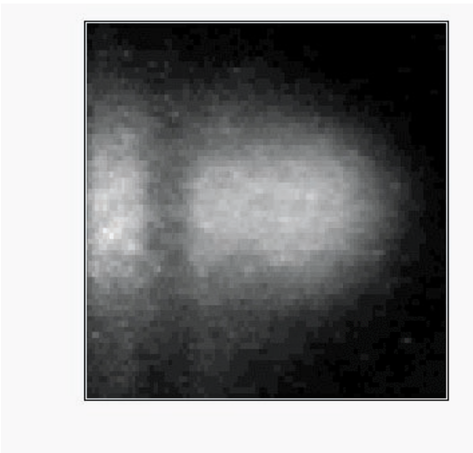
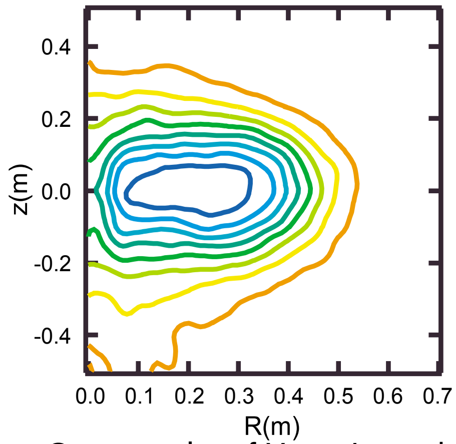
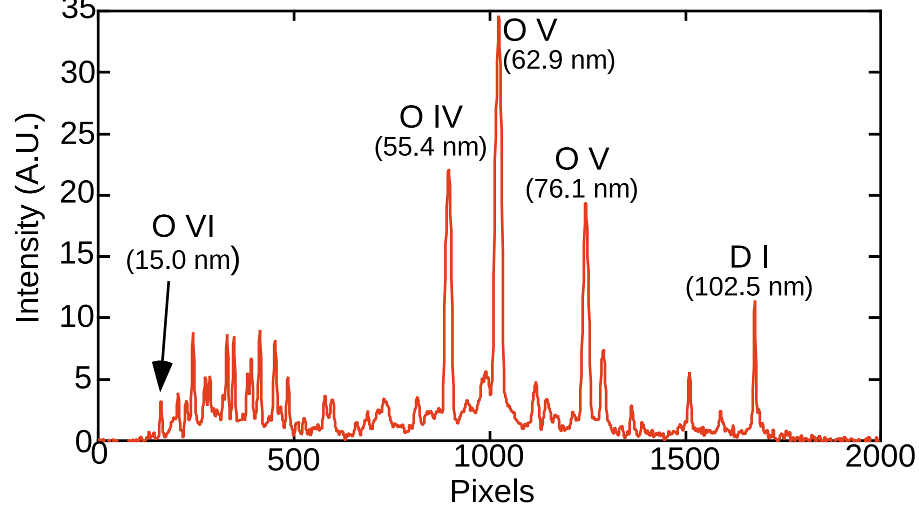
Pinhole SXR Camera


CCD Pinhole camera Image

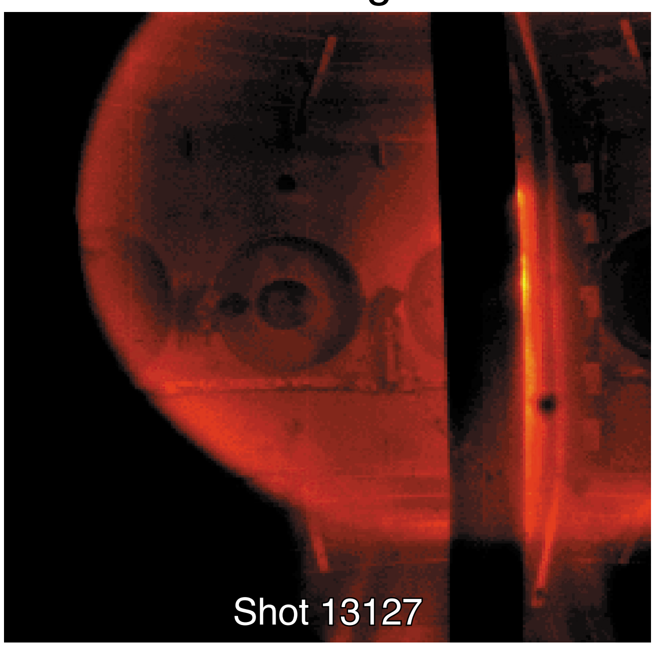


Contour plot of X-ray Intensity

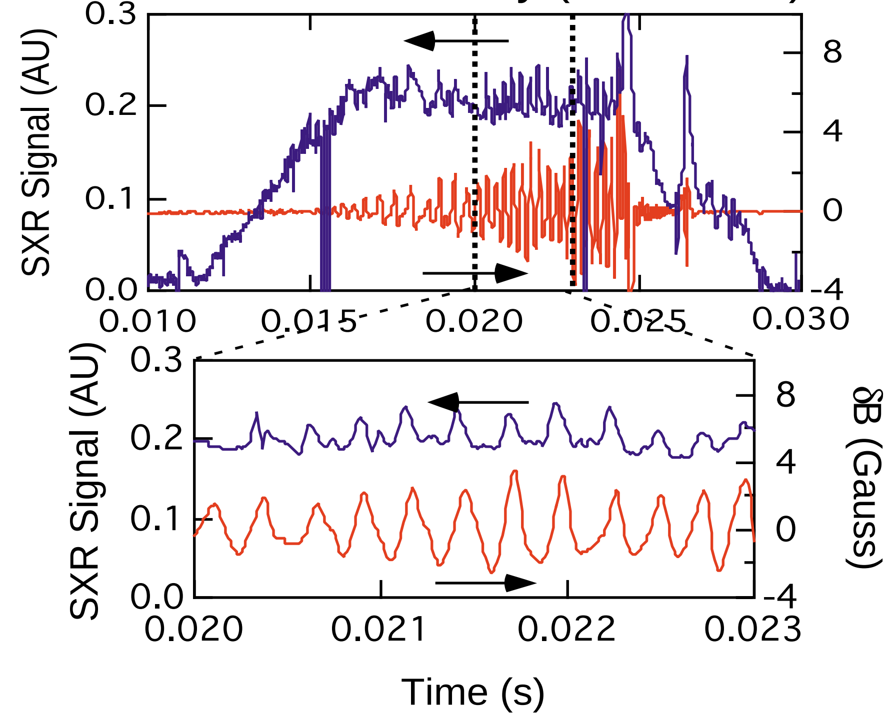
VUV Spectroscopy (SPRED)



Fast Framing Camera



Poloidal SXR Array (Channel 8)



Addition of Magnetic Diagnostics

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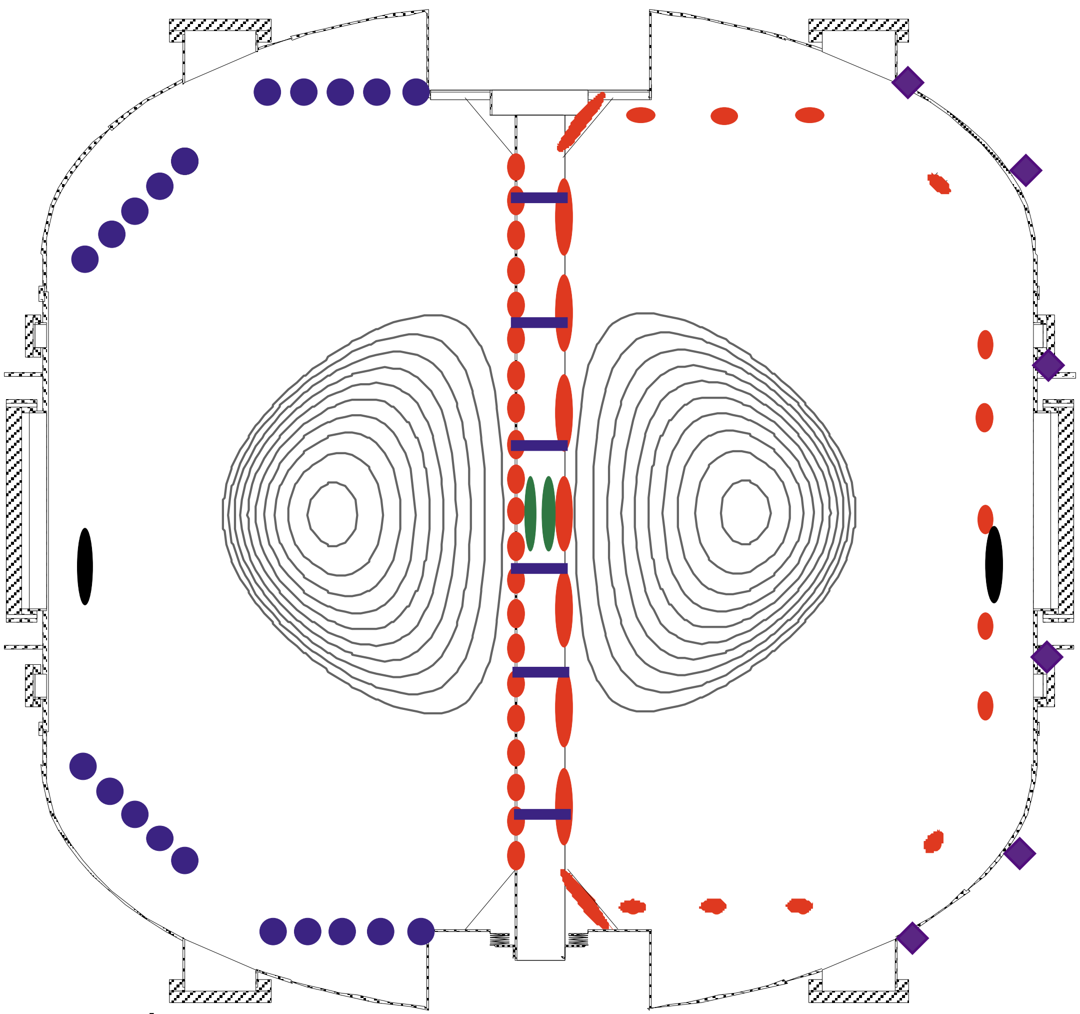
Current Magnetics Arrangement



Not shown:
- Plasma Rogowski Coils (2)
- Diamagnetic Loops (2)
- Diamagnetic Compensation Loop
- Internal B_{tan} Coils (15) [constrain wall currents]

Before Upgrade

- Poloidal Mirnov Coils	(13)
- Flux Loops	(6)
Total	(19)

After Upgrade

Flux Loops	(26)
Poloidal Mirnov Coils	(22 + 21)
LFS Toroidal Mirnov Coils	(6)
HFS Toroidal Mirnov Coils	(7)
External Wall Loops	(6)
Total	(88)

Magnetic Equilibrium Reconstruction Used as Primary Analysis Tool

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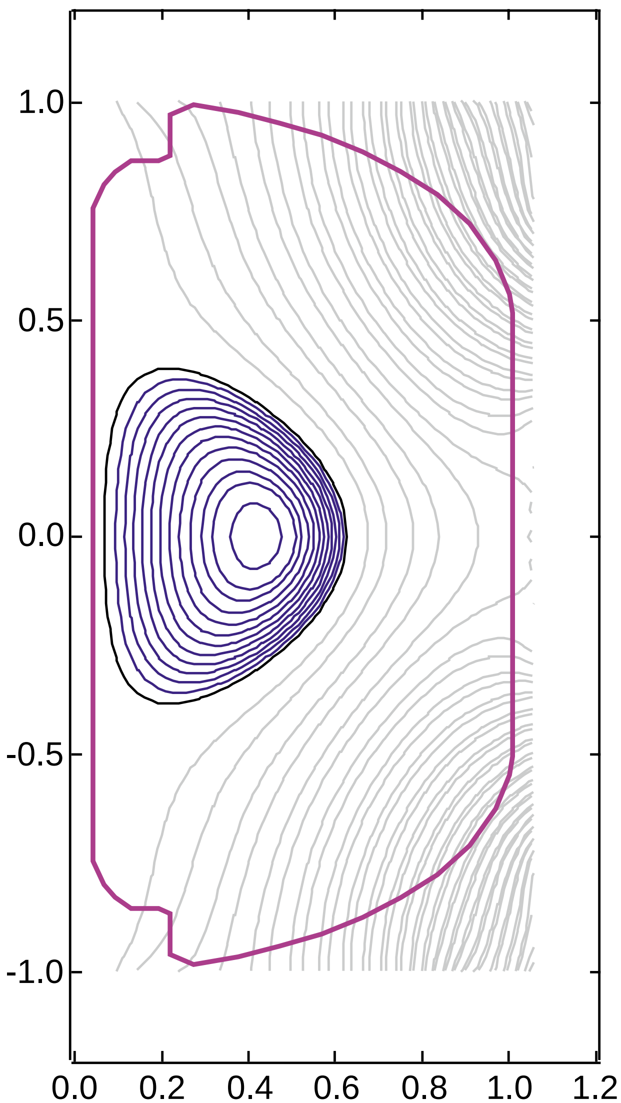

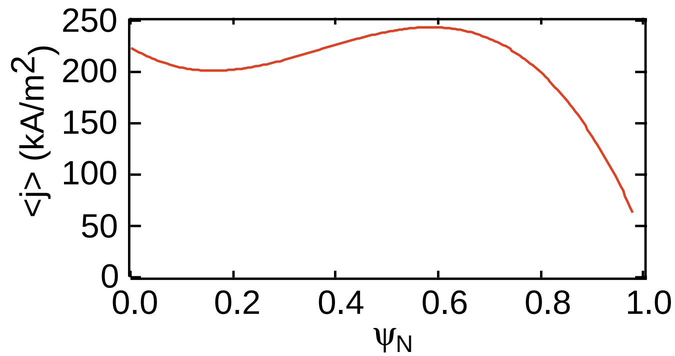

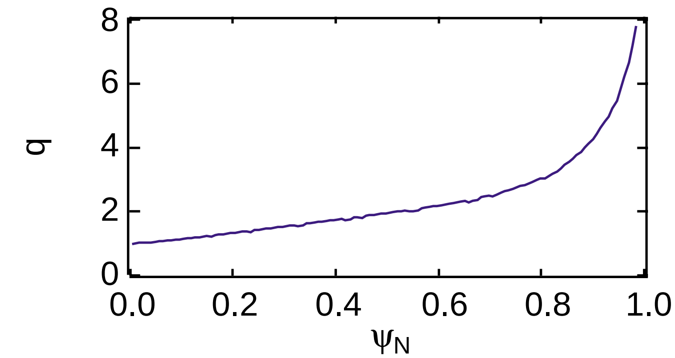

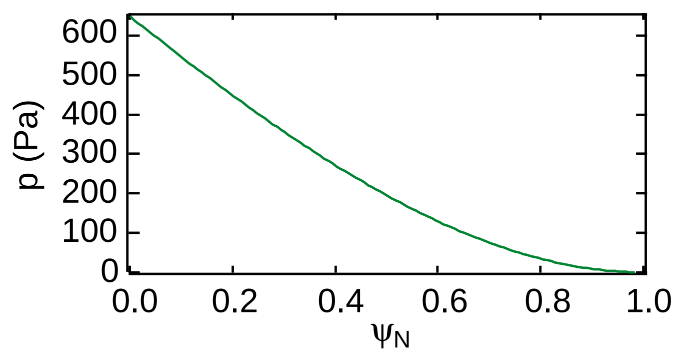

Shot 12445

I_p	78.3 kA
B_t (axis)	0.048 T
R_0	0.337 m
β_t	18%
a	0.282 m
ℓ_i	0.40
A	1.20
q_0	0.98
κ	1.4
q_{95}	5.9

Constraints:

- Rogowski Coil
- 18 Flux Loops
- 3 B_p Coils
- Diamagnetic Loop

OH Access to Interesting Low-A Regime

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- **Routine high-stress solenoid operation**

- **Startup at low B_t in presence of conducting walls**
  - Induced wall currents modeled
  - Wall currents routinely included in equilibrium runs

- **Plasmas show low-A characteristics**

- *Low-A*	$A \sim 1.16$
- *High* β_N	$\beta_N \sim 5$
- *High TF utilization factor*	$I_p/I_{TF} \sim 1.2$
- *High normalized current*	$I_N \sim 8$
- *High density*	$n_e \sim n_{GW}$
- *MHD*	*2/1, 3/2, IREs, double tearing modes, external kinks*

- **Extension of operating space**
  - Increasing ohmic drive capability; I_p up to 150 kA
  - Density control and fueling (fast gas puffing)
  - Pulse length extension (up to 30 ms)
  - Wall conditioning (Ti gettering, DC GDC)

PEGASUS is Accessing High-β_t ST Regime

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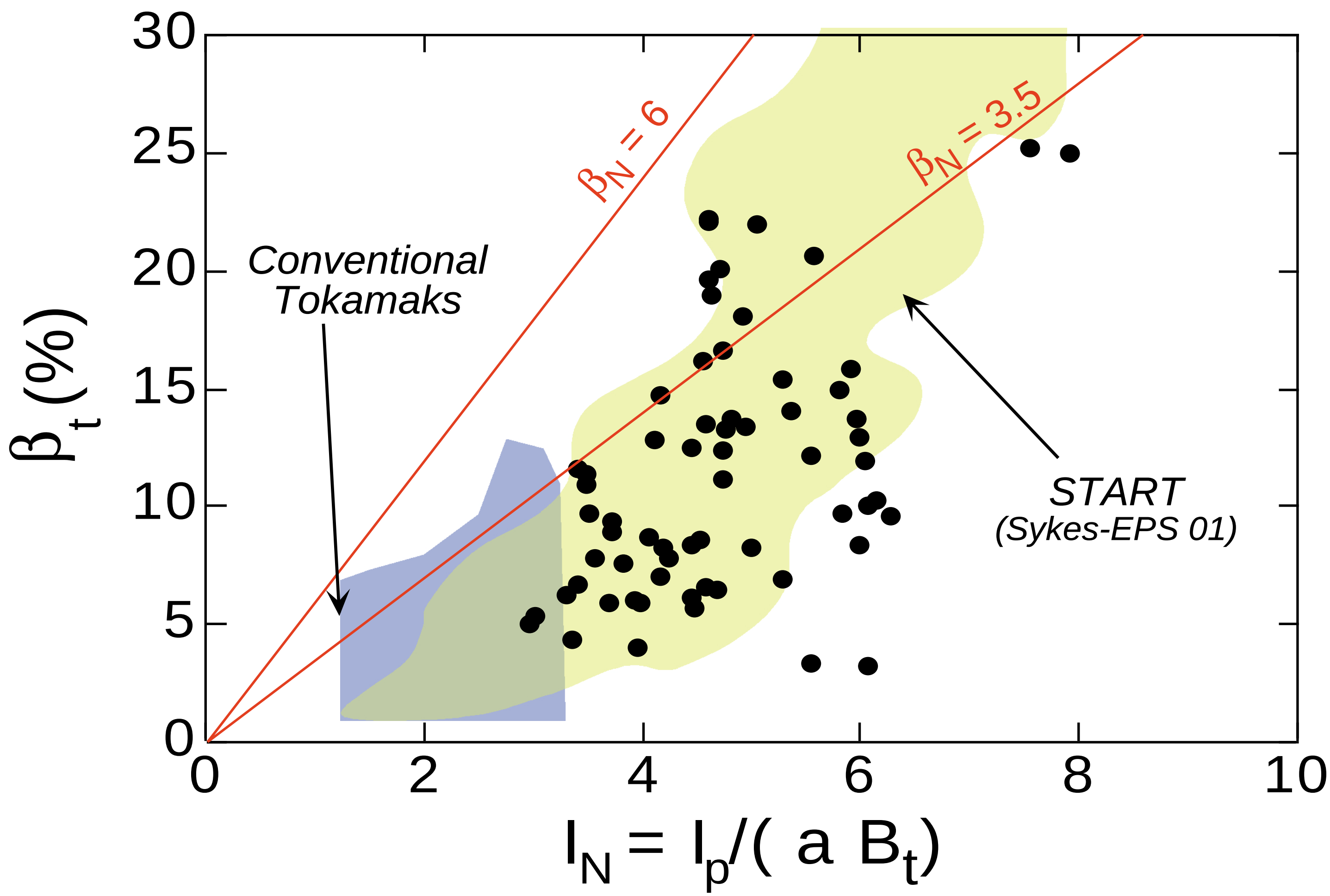
- **High β_t attained at high density, low-TF**
  - *Ohmic heating only; constant TF*
  - *Highest β_t, I_N at low TF*



High Density, Low-ℓ_i, Low-TF Operation

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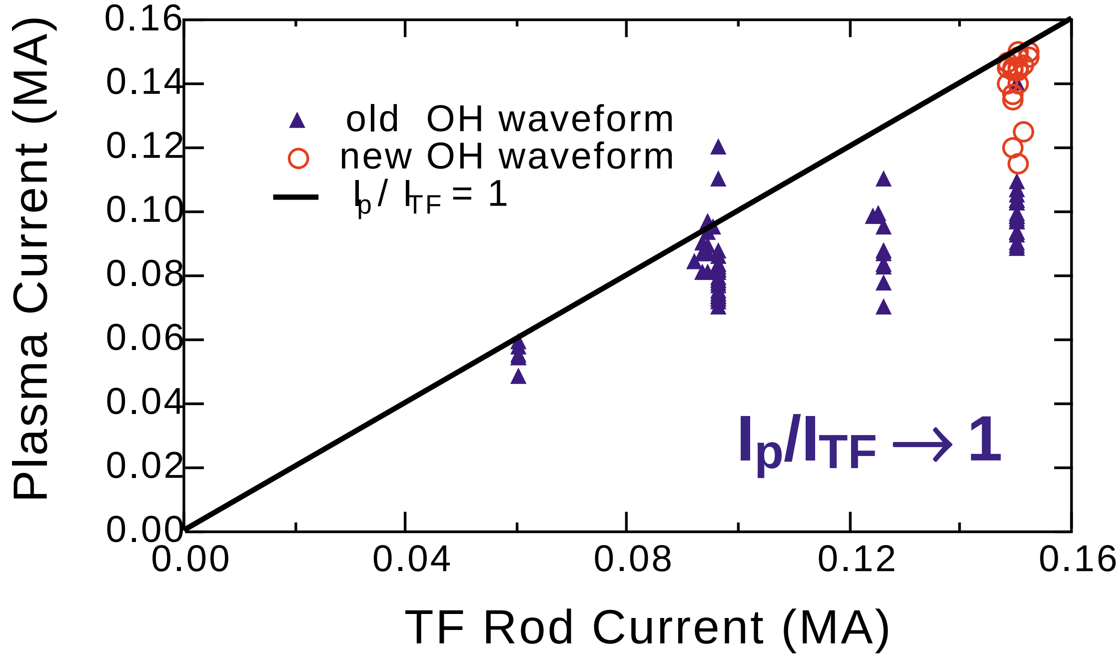
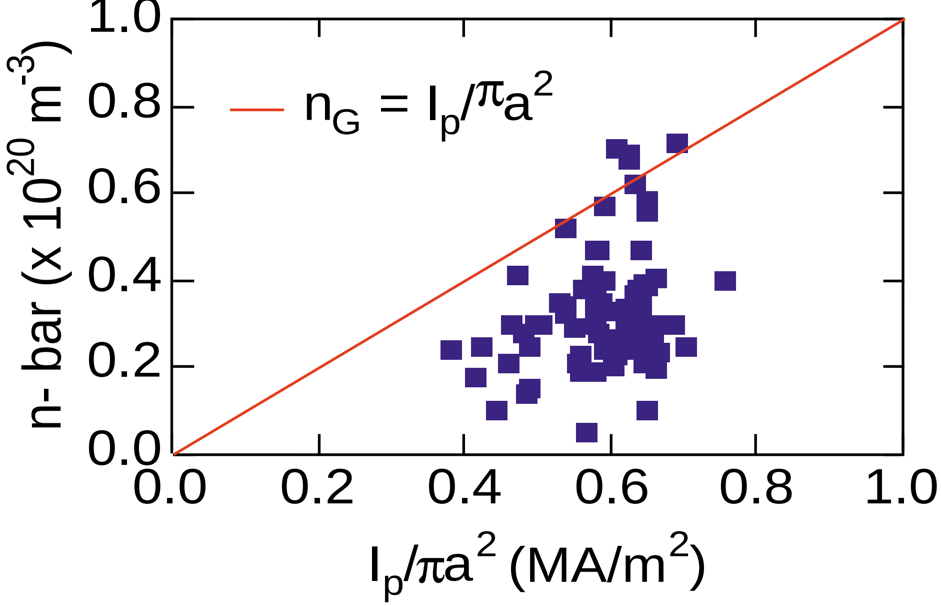
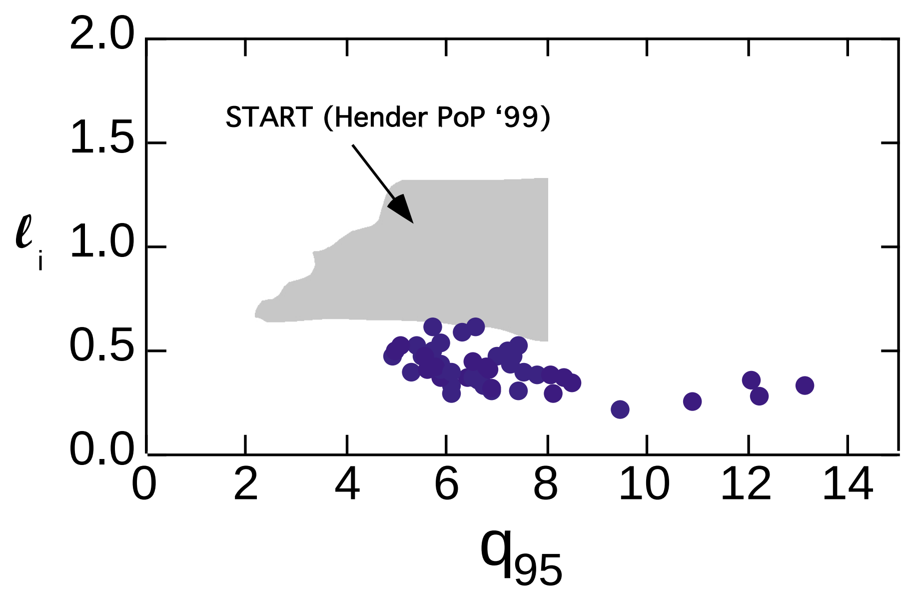


Density up to the Greenwald Limit



Low ℓ_i; increases during current relaxation



Estimates of β_t Consistent with START Confinement

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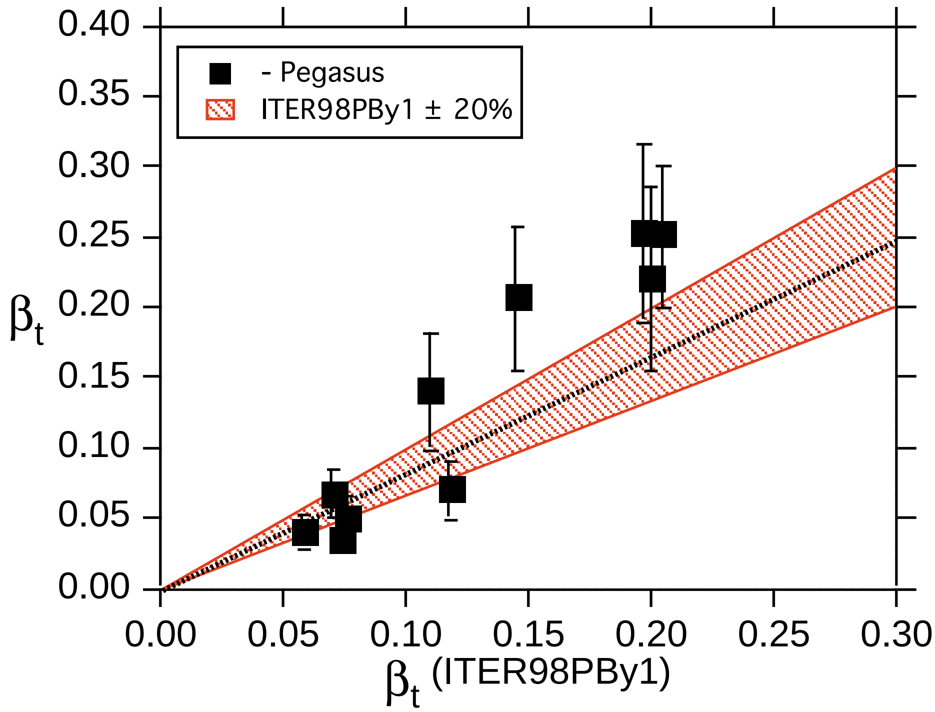
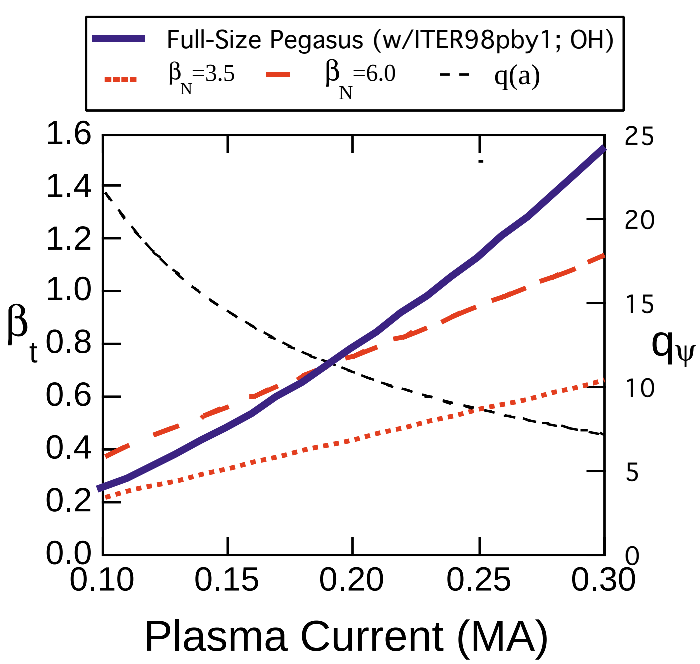
- **β_t estimated from magnetic equilibrium reconstruction**



- **High β_t accessible at full OH power; higher T_e with aux heating**



MHD Activity Appears to Hinder Access to low-TF, high-β_t regime

- **Access to high I_p/I_{TF}, low-q_{95}, high β_t regimes requires identification and suppression**

- **Evaluating role of MHD on access to low-TF OH regime**
  - Correlate appearance with estimated q(0,t) evolution
  - Use flux consumption analysis for quantitative comparison
    - Ejima Coefficient, C_e = high $\Rightarrow$ poor use of Ohmic V-sec
    - Ejima Coefficient, C_e = low $\Rightarrow$ efficient use of V-sec

- **Large Scale Internal Resistive MHD $\Leftrightarrow$ Reduced I_p, $C_e \sim 1$**
  - Internal modes appears to limit I_p in these cases
  - Mode is a large 2/1; observed when q_0 drops below 2
  - Appears to correlate with a large low-shear interior region with $q \leq 2$

- **External Kink Observed $\Leftrightarrow$ max I_p, $C_e \sim 0.5$**
  - External kink and/or V-sec limit at highest I_p, B_t cases
  - Appears as q_{95} approaches 5; higher than typical tokamak

Significant MHD is Observed During Discharge Evolution

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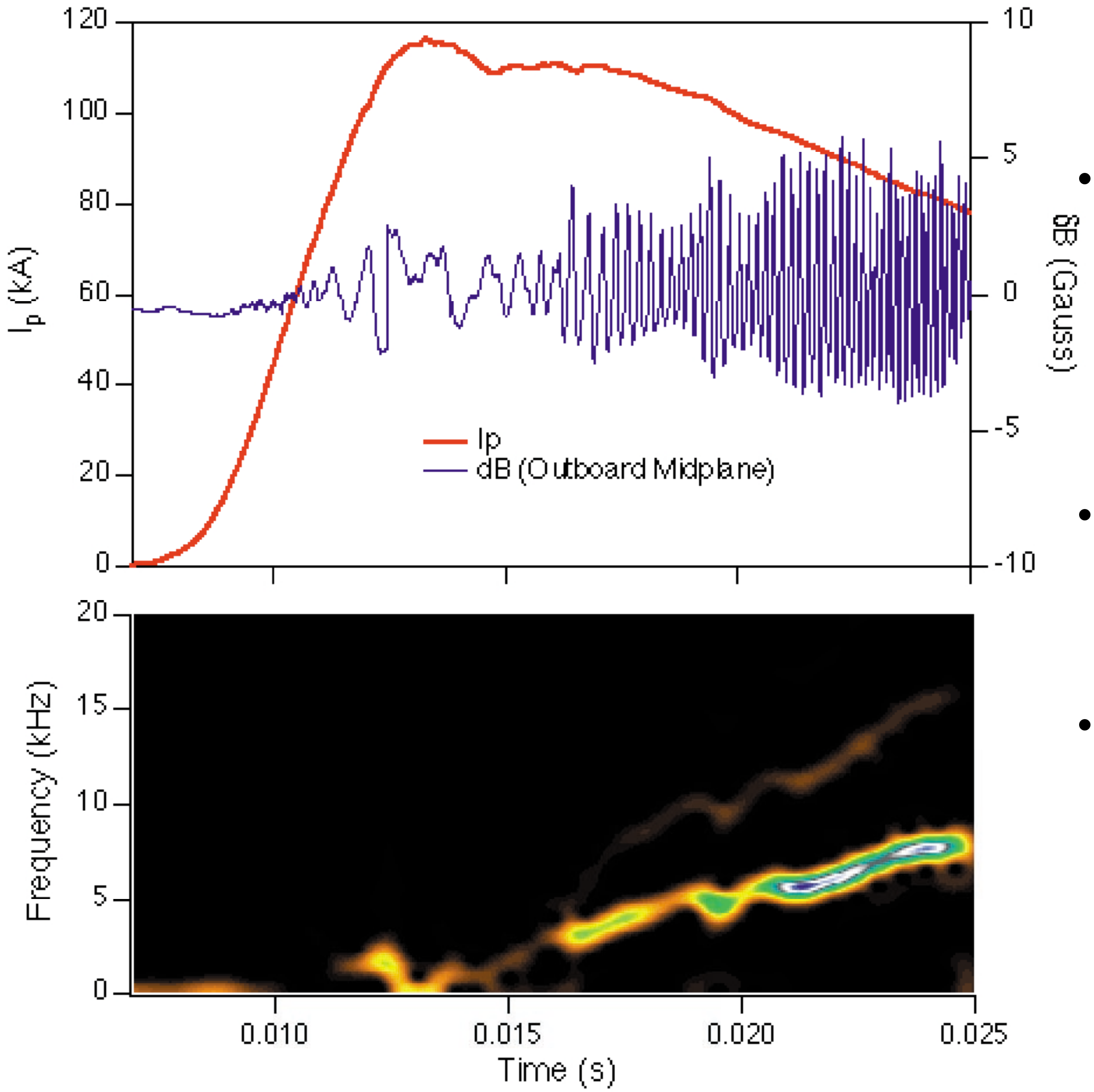
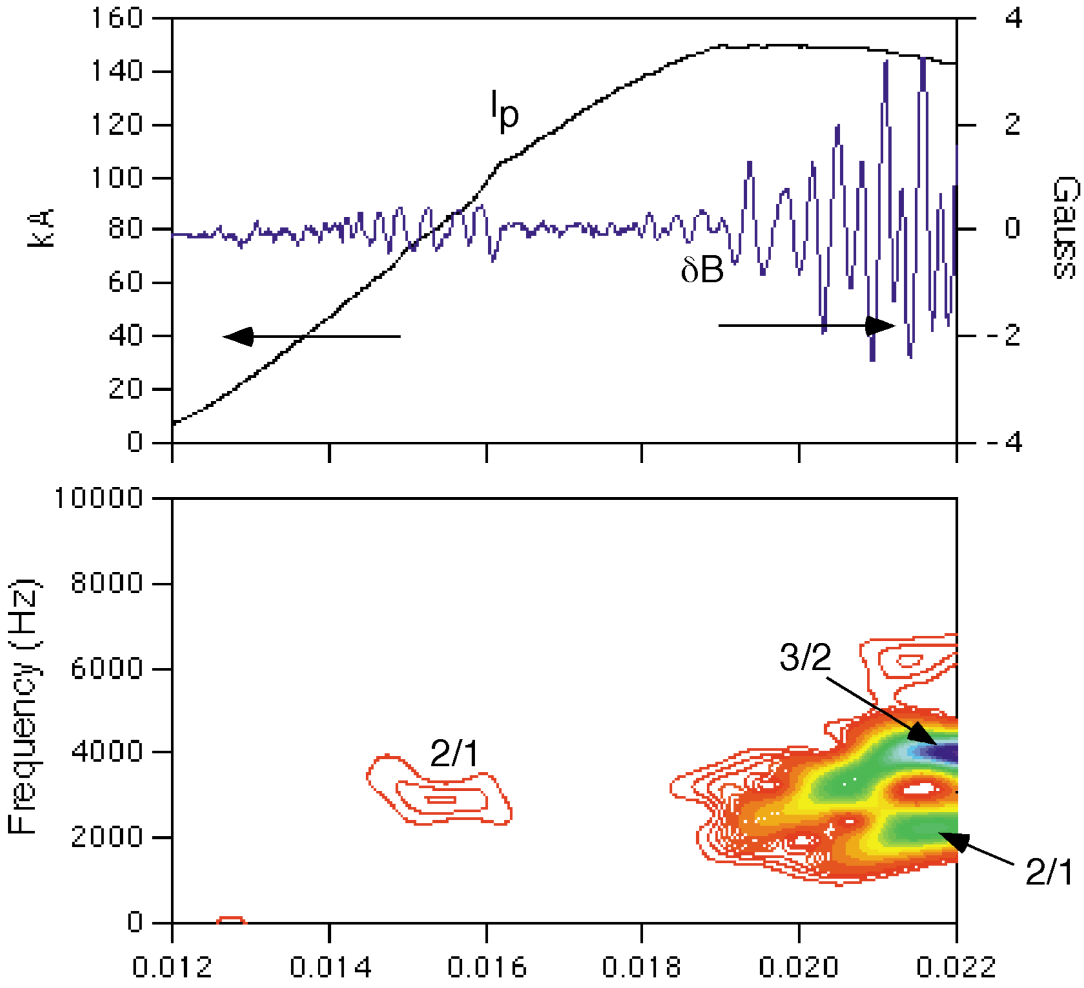


- A rotating 2/1 mode is present
  - Observed in most discharges
  - Mode rotates in electron diamagnetic direction
  - Frequency is 5-10 kHz
- A lower frequency mode is often observed during the current ramp
- IREs and double tearing modes also observed

Higher-Current Discharges Exhibit a Variety of MHD activity

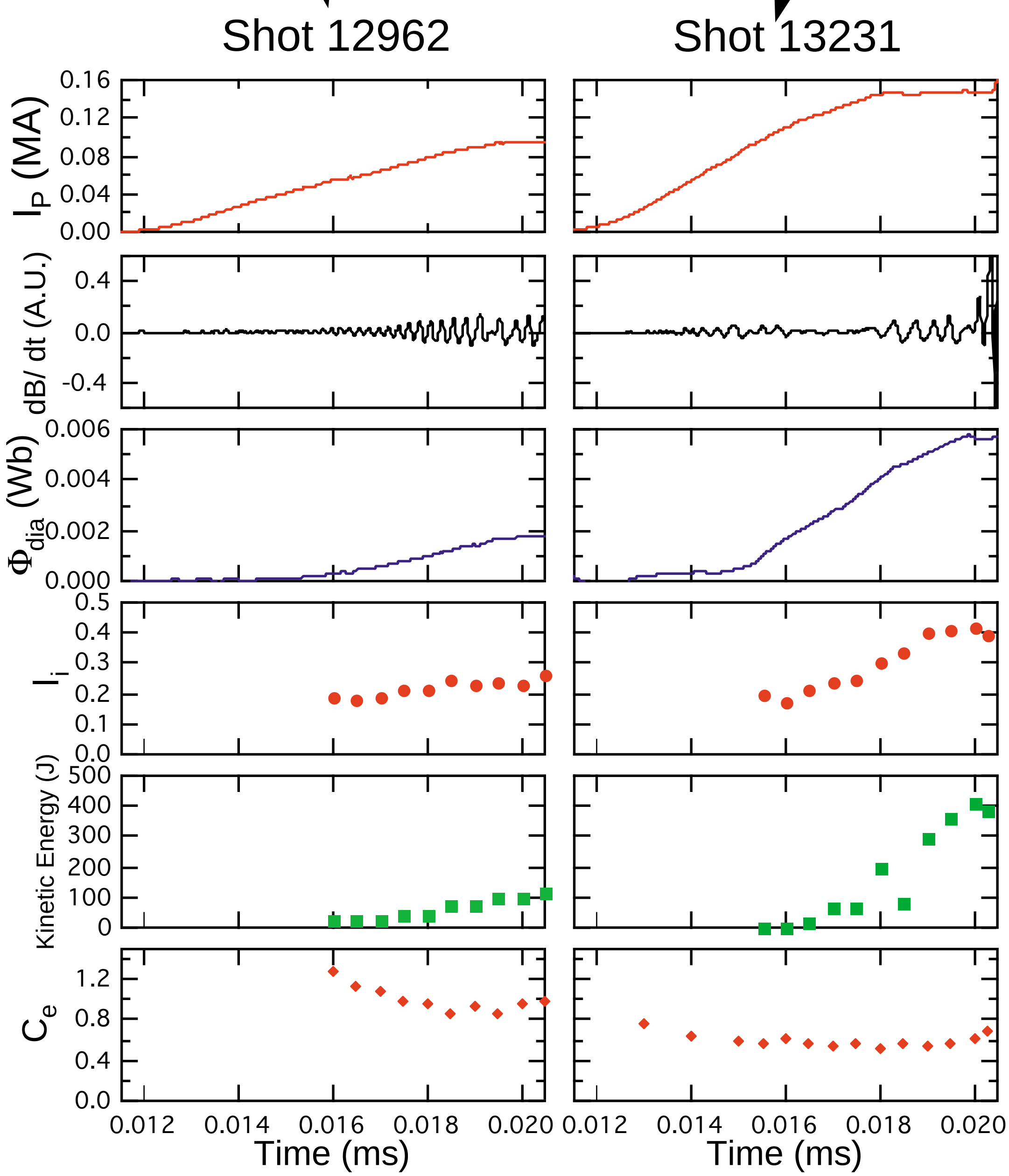
- 2/1 mode is observed but disappears
  - Pass through $q(0) \approx 2$ region
- A 3/2 mode appears after a quiescent period
  - Correlated with $q(0)$ dropping below 1.5



- Higher I_p accessed by discharge tailoring
  - Increased loop voltage
  - Edge cooling through aggressive gas puffing

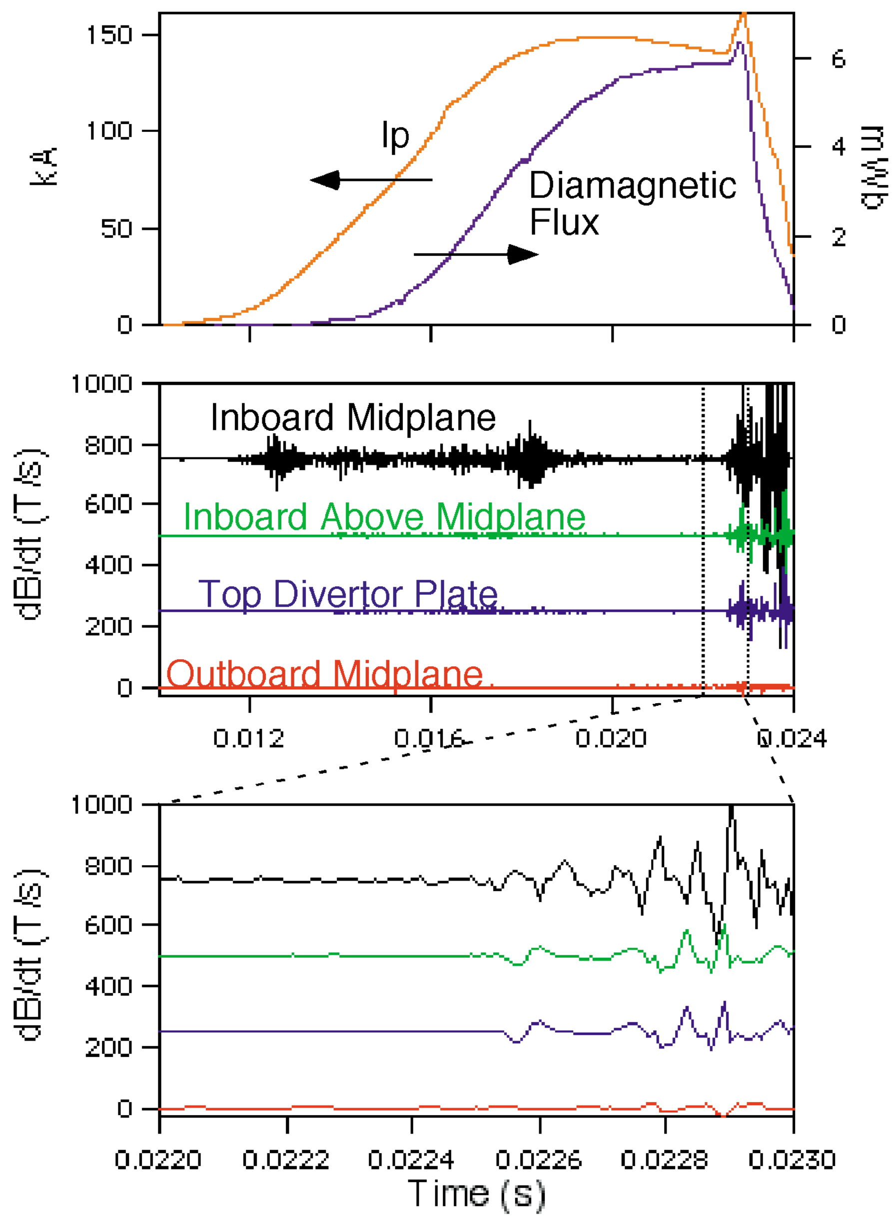
Large 2/1 MHD Activity Degrades Plasma Evolution

- With 2/1 Mode
  - *I_p reduced*
  - *High C_e*
  - *Low stored energy*
- Without 2/1 Mode
  - *Max I_p achieved*
  - *Lower C_e*
  - *Kinetic energy high*
  - *Onset of 3/2 mode*



Starting to Challenge External Kink Limits

- Higher-I_p discharges often terminate in abrupt disruptions
  - Precursor fluctuations observed on Mirnov coils
  - Lower-I_p shots have IREs, followed by gradual plasma termination



- Observed disruptions are associated with edge q-limits
  - Oscillations not observed until $q_{95} \approx 5$

- Consistent with theoretical understanding of ideal kink stability
  - DCON & VACUUM: Plasma-vacuum energy $\rightarrow$ 0 as fluctuations begin
  - As $A\rightarrow1$, stable q_a increases

Facility Upgrades Will Increase Access to low-q_{95}, high β_t Plasmas

Goals:

- **Increased control of plasma conditions**
  - *Density control, reproducibility, improved equilibrium field control*

- **Suppression of large internal resistive MHD modes**
  - *Increased I_p ramp time*
  - *Attain higher $T_e(0)$ during formation*
  - *Maintain $q(0) > 2$ during formation*

- **Control onset of suspected external kink modes**
  - *Maintain I_p ramp time*
  - *Maintain high q_{95} during formation*
  - *Edge control: edge cooling, shear, etc.*

- **Access to very high β_T regime**
  - *Increase I_p, N_e, T_e*
  - *Improved access to low-B_t regime*

Tools to achieve goals in near future:

- *Between-shot gettering and controlled gas puff*
- *Increased V-sec via external induction coil set(?)*
- *Increased B_T w/fast-rampdown*
- *Increased RF power*
- *Energize divertor coils*

- **Proposed long-term improvements to add control flexibility**
  - *Programmable internal radial position coils and divertor coils*
  - *Internal induction/compression coil set*
  - *EBW heating and startup tests*

Proposed Future Campaign: Access and Document Very High β_t Regime

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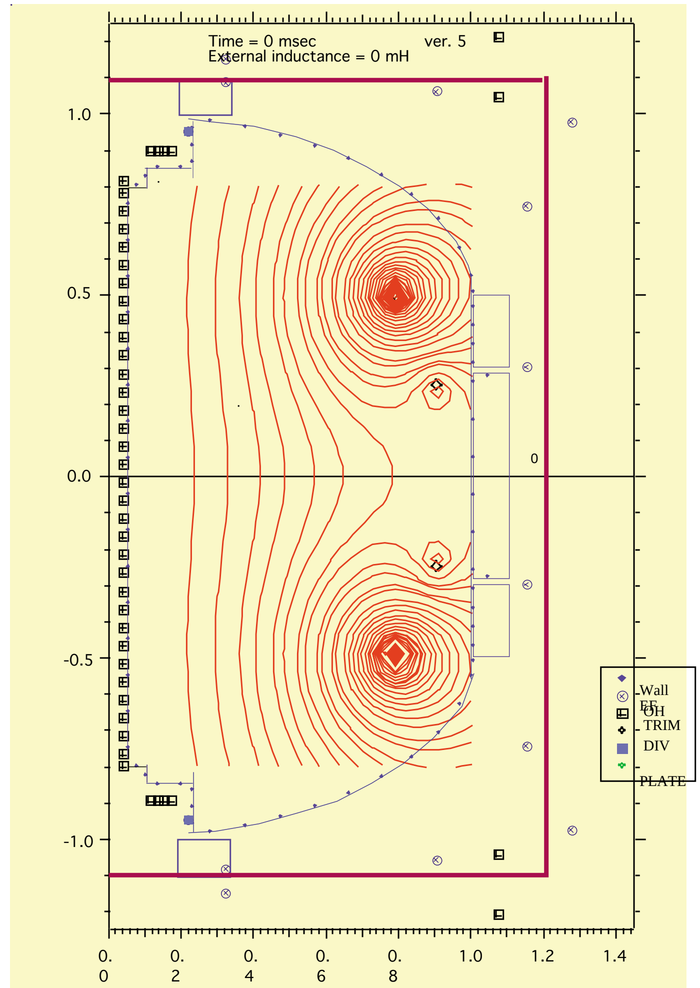
- **Access very high β_t, I_p/I_{TF} regime by increasing I_p**
  - *Reduce MHD in hotter plasma*
  - *Increased V-sec with* ***internal induction coil set***
- **Variable TF for MHD suppression**
  - *Hardware in fabrication*
  - *TSC modeling underway*
- **Test heating and current-drive via EBW**
  - *≥ 200 KW @ 2.45 GHz with PPPL/ORNL help*
  - *multi-grid launcher from PLT under evaluation*
- **Internal and profile diagnostics as needed**
  - *Diagnostic station proposal for profile measurements pending @ DOE*

Vacuum field structure for candidate internal induction coil set:



TF Coils with Rapid Ramp-down and Increased B_t in Fabrication

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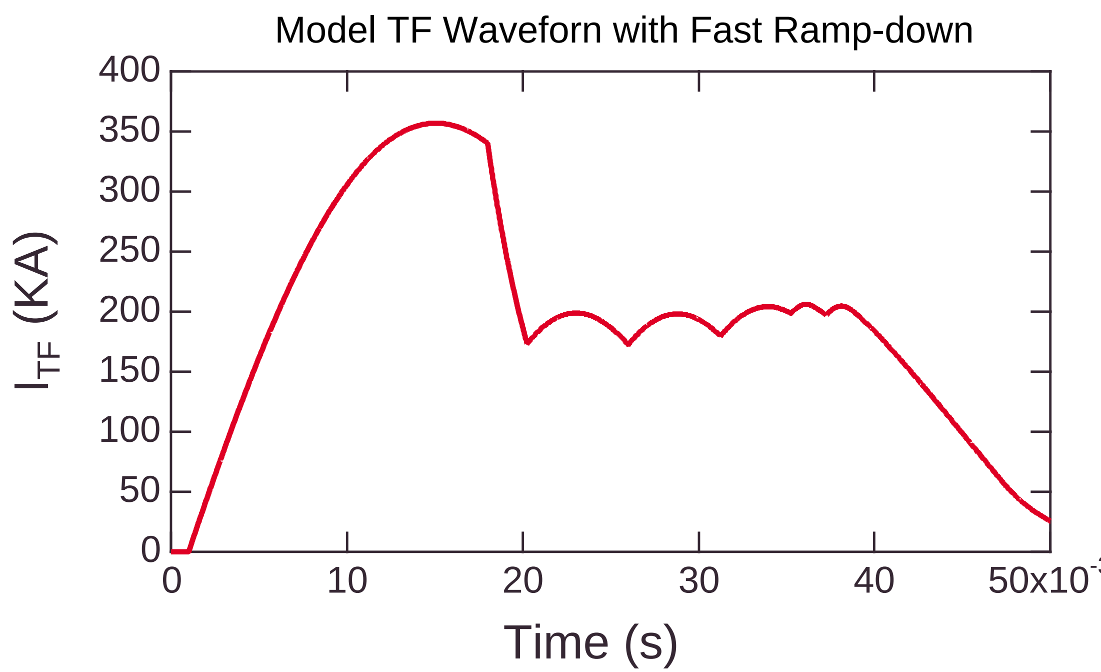
- **Provide B_T increase of 2-3 (0.15 - 0.3T) during formation**
  - *Support faster I_p ramp w/o large-scale MHD*
  - *Improved T_e evolution for lower resistivity*

- **Allow rapid decrease in B_t during shot**
  - *Access low-q_{95} and/or high β_t regimes starting with well-formed, hot plasma*
  - *New 12-turn low-inductance TF center rod assembly fabricated*

New 12-Conductor TF Center-rod Assemblies



Summary: Progress in Development and Understanding Plasmas at Very Low A & B_t

- **Facility and analysis developments ⇒ increased capability**
  - Internal hardware, wall conditioning, field programming
  - Magnetics diagnostic array and equilibrium analysis

- **Plasma equilibria show low-A characteristics**
  - *$\beta_t \sim 25\%$* *$\beta_N \sim 5$*
  - *$I_p/I_{TF} \sim 1.2$* *$I_N \sim 8$*
  - *$n_e \sim n_{GW}$* *$A \approx 1.16$*
  - *2/1, 3/2, double tearing modes, IREs, external kink*

- **Access to low-B_t, low-A operation: configuration and physics**
  - V-sec capability can limit access to interesting physics
  - Large internal modes (2/1, 3/2) degrade plasma evolution
    - *Susceptible due to large, low shear region and low Te?*

- **Evidence of access to external kink emerging**

- **Next campaign: focus on MHD control and challenge limits**
  - Begin power RF heating
  - Increased B_t with slow rampdown

- **Proposed directions to access & document high β_t @ A →1**
  - Characterize tokamak-spheromak overlap regime
  - Increased Ip with induction/compression coils
  - Increased TF with time-variation
  - Separatrix operation for edge q control and possible H-mode
  - Test high power EBW heating & CD