Outline

- **Achievable Performance of Initial Experiments Limited to $I_p \sim I_{TF}$**
  - Tearing modes (TM) due to fast dI_p/dt and large regions of low magnetic shear
  - Increased magnetic shear mitigates TM $\Rightarrow$ external kinks were observed

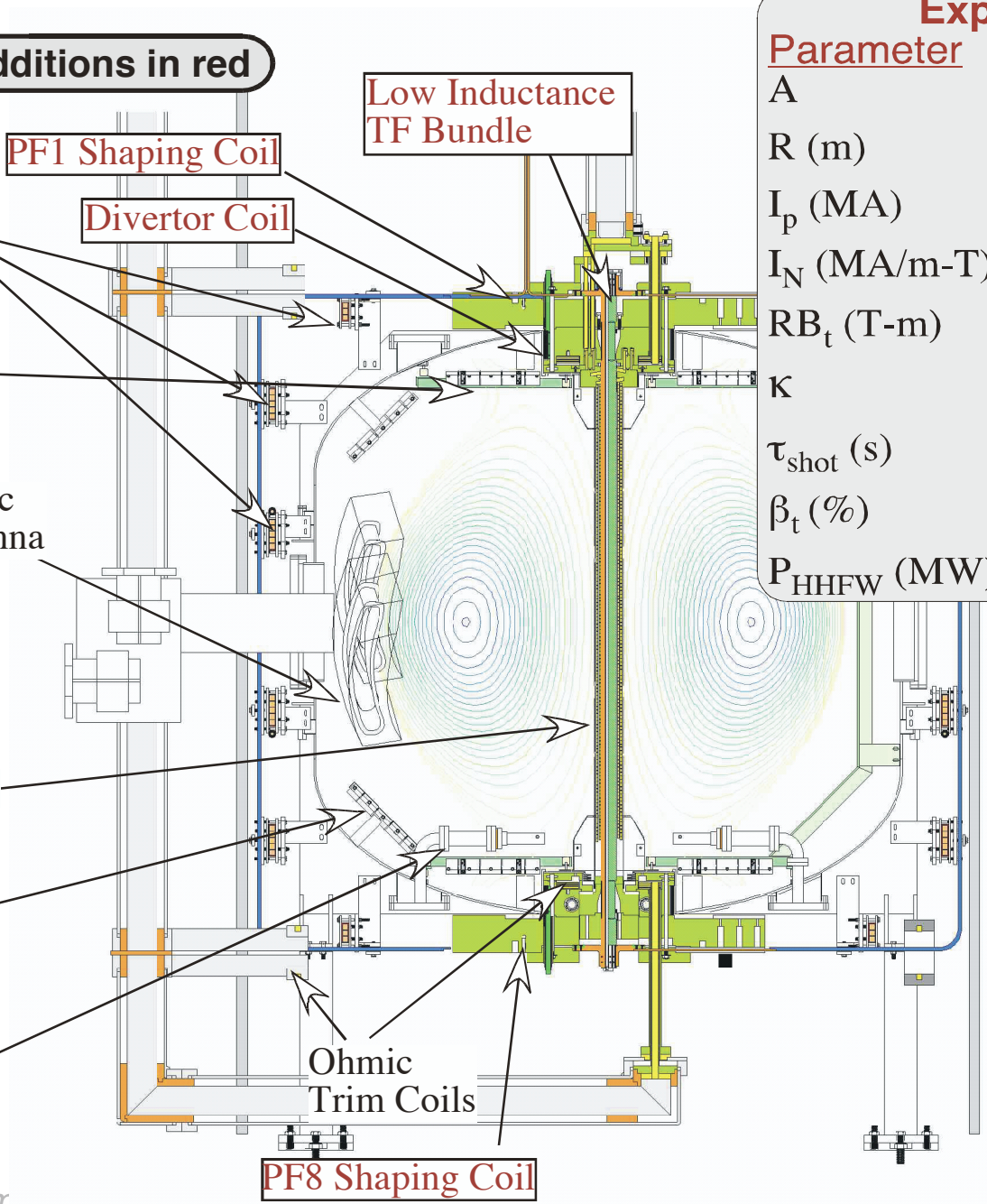
- **Modeling Points to Access of High I_p/I_{TF} Equilibrium**
  - TSC modeling confirms accessibility at full capability
  - Confinement estimates point to high-β_t w/ $I_p/I_{tf} \sim 2$
  - Equilibrium & DCON calculations give stable predictions at $I_p/I_{tf} \sim 2$

- **Plasma Gun and TF Rampdown Experiments $\Rightarrow$ I_p/I_{TF} = 1.3-2.2**
  - Goal: $I_p/I_{TF} \sim 2$-3 ($I_N \sim 10$-20) at high I_p
    - *in present experiments: OH @ 1/3 capability; prototype non-inductive source*
  - Non-inductive sources w/ OH drive coupling: $I_p/I_{TF} \sim 2$
    - *central heating seen during OH drive*
  - Ultra-low-field preionization w/ OH drive: $I_p/I_{TF} \sim 1.5$
  - TF Rampdown $\Rightarrow$ $I_p/I_{TF} \sim 1.3$ and $I_p \sim 0.18$ MA

PEGASUS is a University-Scale, Mid-Sized ST

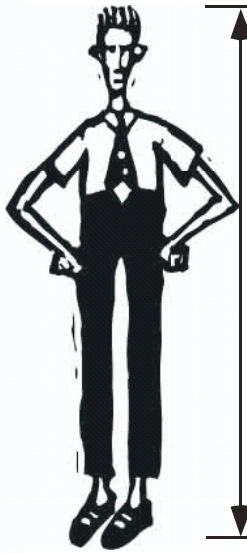


Phase-II additions in red



Experimental Parameters

Parameter	Achieved	Phase II Goals
A	1.15-1.3	1.12-1.3
R (m)	0.2-0.38	0.2-0.45
I_p (MA)	≤ 0.16	≤ 0.30
I_N (MA/m-T)	6-8	15-20
RB_t (T-m)	≤ 0.03	≤ 0.1
κ	1.4–3.7	1.4–3.7
τ_{shot} (s)	≤ 0.02	≤ 0.05
β_t (%)	≤ 20	> 40
P_{HHFW} (MW)	0.2	1.0



Typical PEGASUS Employee ~ 6 Feet

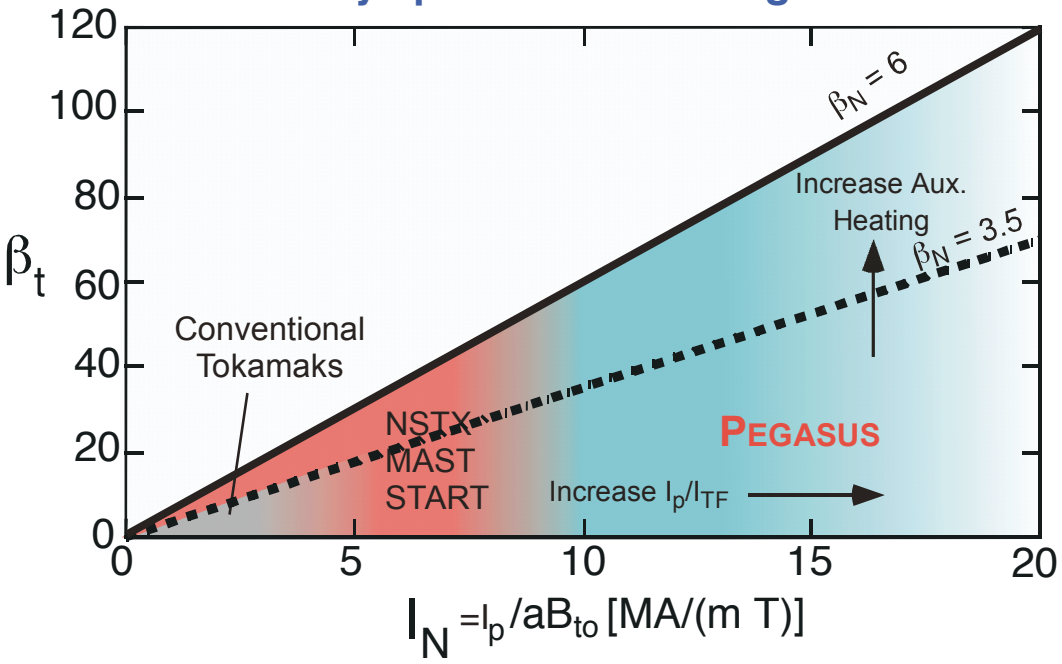


Focus Area: Studies of Plasma Limits as A → 1

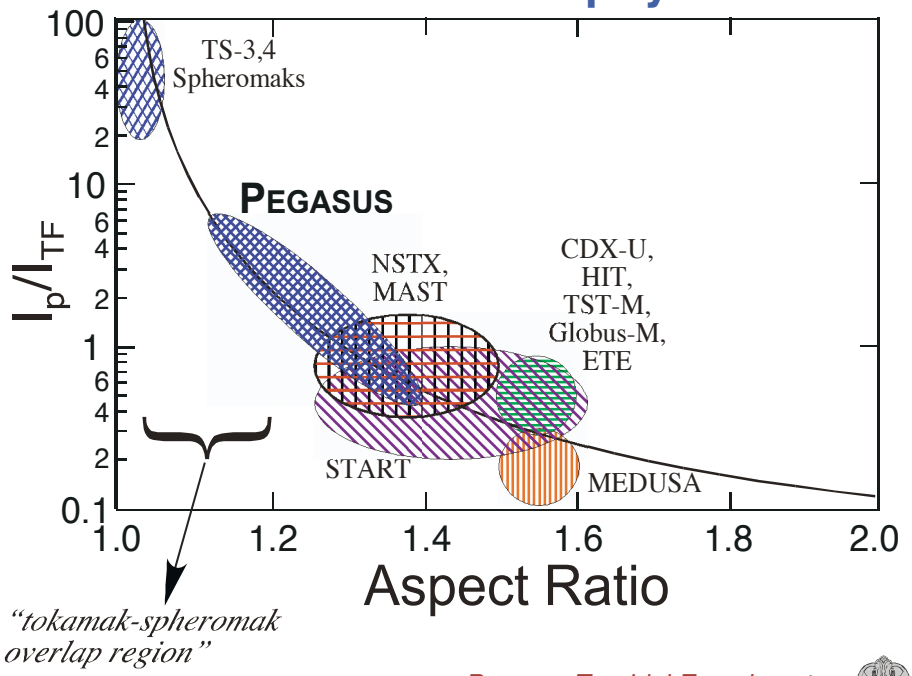
Goals of Focus Area

- Stability and confinement at high I_p/I_{TF} and high I_p
  - *Extension of tokamak studies*
- Limits on β_t and I_p/I_{TF} (kink) as A→1
  - *Overlap between the tokamak and the spheromak*

Stability space for wide range of A



I_p/I_{tf} → figure of merit for access to low-A physics



Expanded Capability for High I_N Access



Phase I		Phase II
- Limited current profile control - *coils controlled with simple LRC resonant circuits*	⇒	- Manipulate current profile - *V_{loop} & position/shape control, $B_t(t)$, Electrostatic current sources*
- Low-order rationals appear early - *large low magnetic shear regions*	⇒	- Reduce η before low-order rationals appear - *V_{loop} & position/shape control, $B_t(t)$*
- TF: steady state compared to discharge - *high L_{tf} from 60 turn coil set*	⇒	- Transiently increase q during startup - *$B_t(t)$, V_{loop} control*

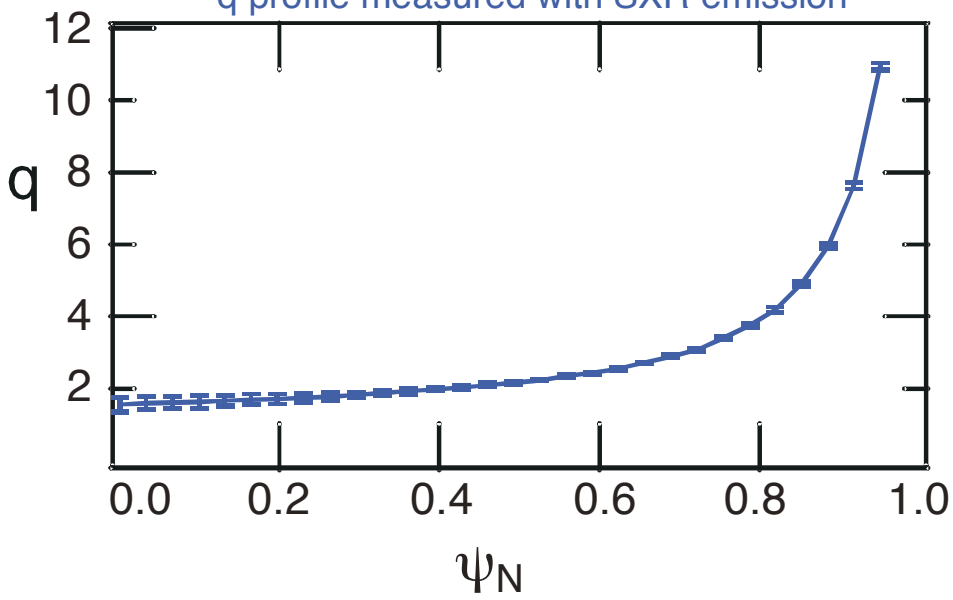
- **Facility modifications for expanded capability**
  - Power Supplies
    - *OH: effective V-s ↑ w/ increased waveform control*
  - Coil Sets
    - *Lower inductance TF set: 60 turns ⇒ 12 turns*
    - *PF Set: monolithic set ⇒ 8 independent sets*
    - *Divertor coil set installed*
  - Electrostatic Current Sources in Lower Divertor Region



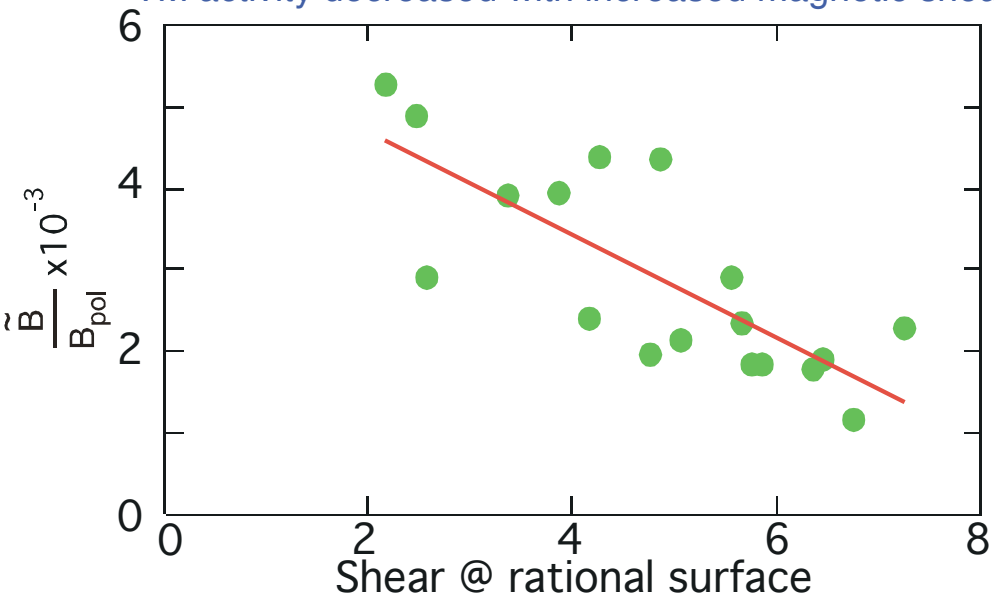
Phase-I: Mode Activity Dependent on Current Profile

- Maximum $I_p \approx I_{tf}$ limit
- q-profile of ST conducive to TM activity
  - *large region of low magnetic shear near axis ⇒ large island widths*
  - *low TF operations ⇒ q<2 when highly resistivity*

q profile measured with SXR emission



TM activity decreased with increased magnetic shear

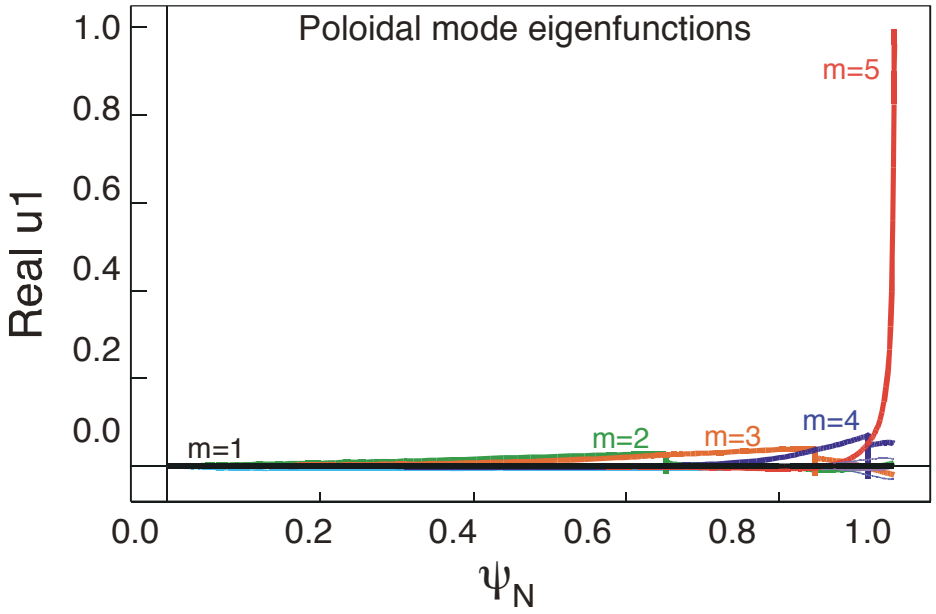


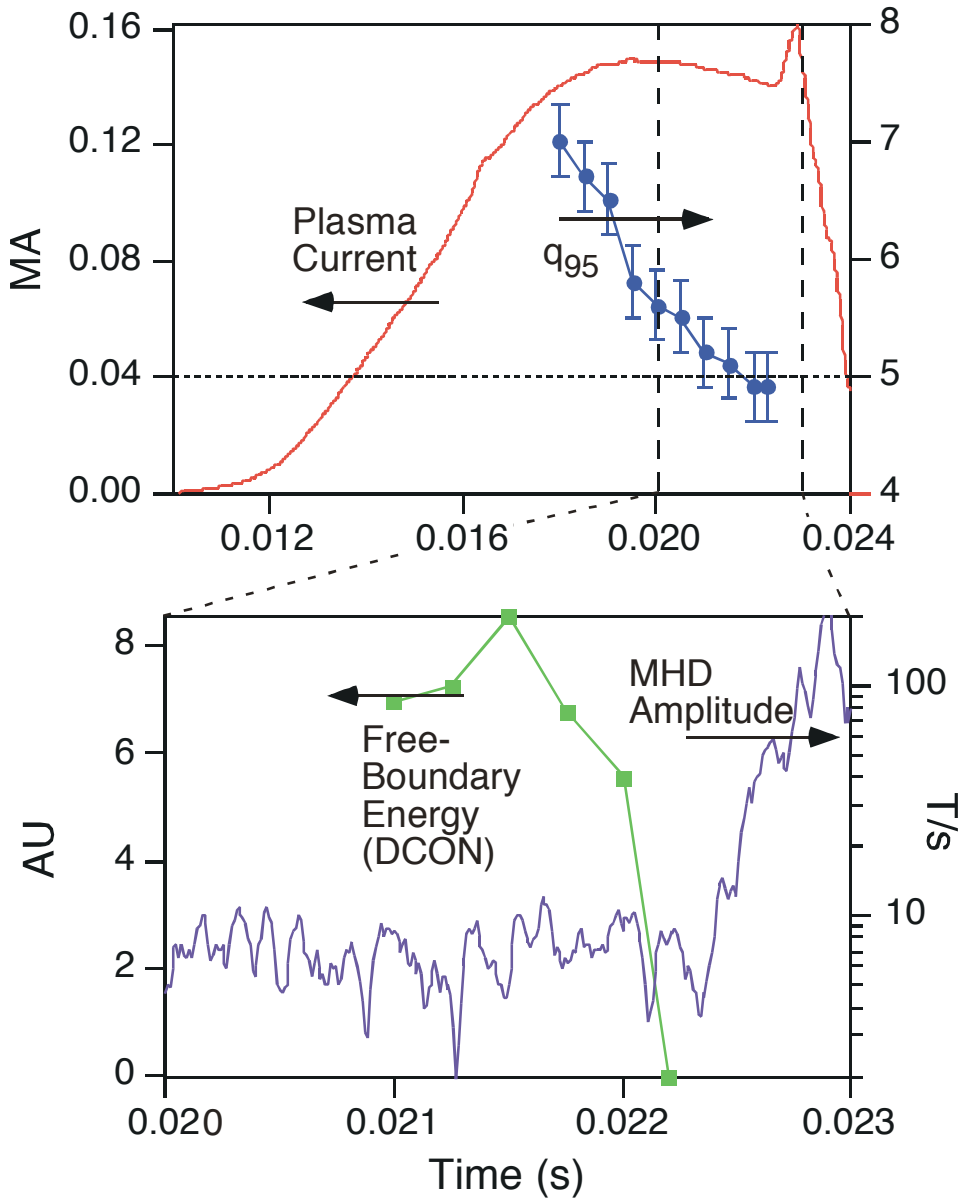
- Crude manipulation of q(r) reduced mode amplitude
  - *Increased shear, q_0 ⇒ delay tearing mode onset*

⇒ Access higher I_p/I_{TF} via higher q_0, T_e, shear

Phase-I: External Kink Seen at Highest Performance

- Highest Phase-I I_p often disrupt
- q_{95} = 5 observed preceding disruption
  - ℓ_i=0.5 at this time
- DCON analysis ⇒ unstable to n=1 external kink
  - m=5 most unstable mode
- Consistent with theory expectation & high edge current





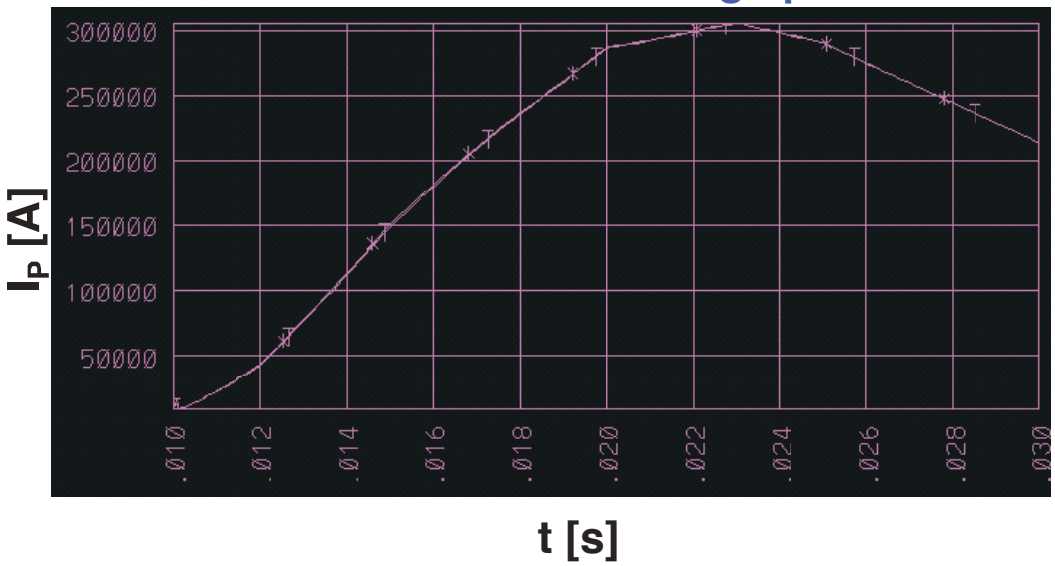
Modeling Confirms Access to High I_p/I_{tf}

- **Modeling done to verify access to interesting regimes**

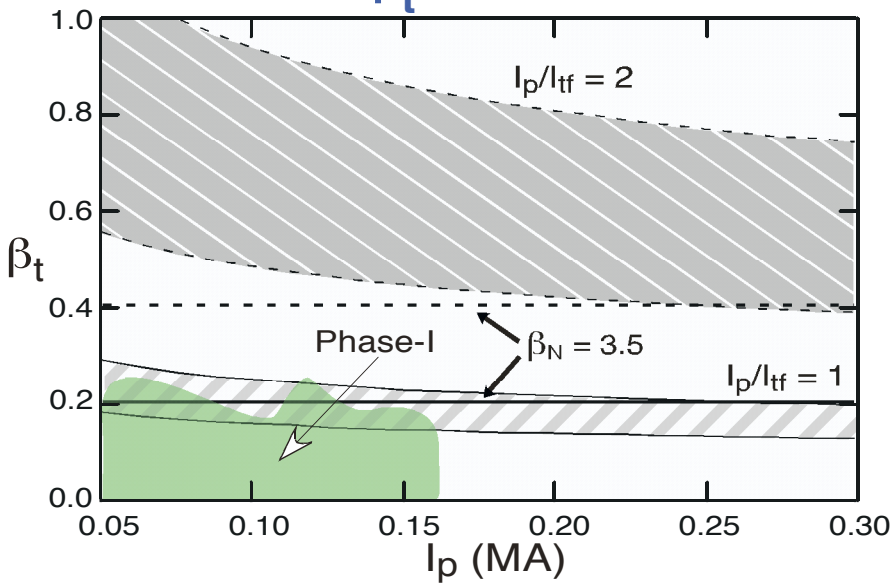
- **TSC: Full ohmic flux (90 mV-s)**
  - Flux consumption calculations indicate 300 kA I_p attainable
  - Simulations corroborate
    $= I_p/I_{tf} = 2$
    $= I_N \sim 12$ MA/m-T
  - Effects of resistive MHD unclear

- **Confinement modeling:**
  $I_p/I_{tf} = 2 \Rightarrow \beta_t = 40\text{-}70\%$
  - Sufficient to assess stability boundaries
  - Similar calculations confirmed in Phase-I with data

TSC simulations with full design parameters



β_t Projections

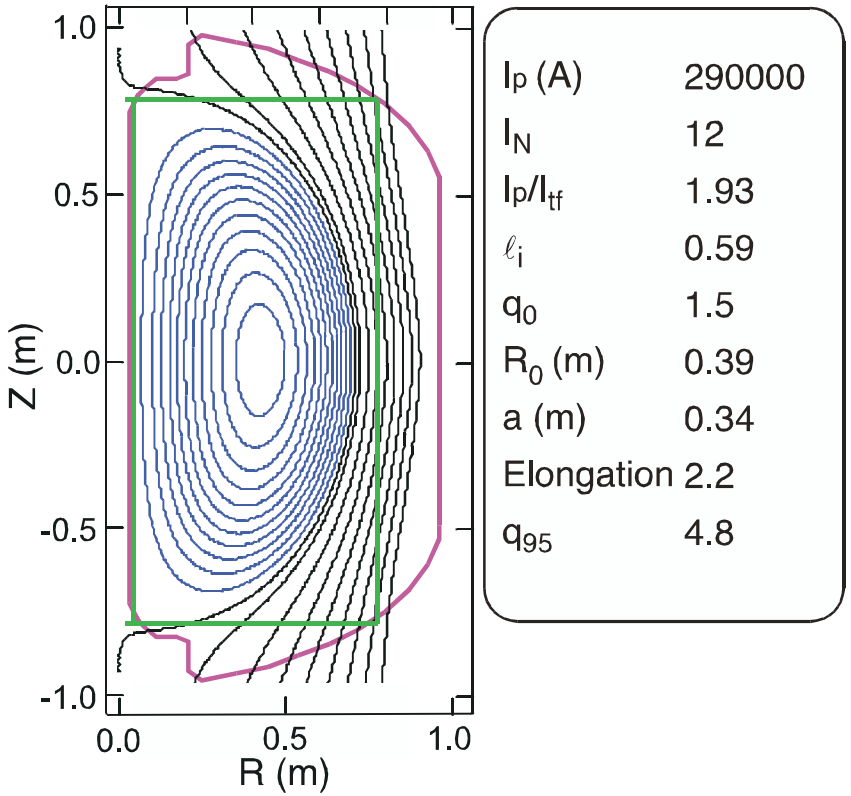


DCON Used to Develop High I_p/I_{tf} Operating Scenerios

- **Stable equilibria found with I_p/I_{tf} = 1.93**
- **DCON predicts equilibria stable**
- **Effects of pressure profile on stability still needed**

"zero"-β Equilibria

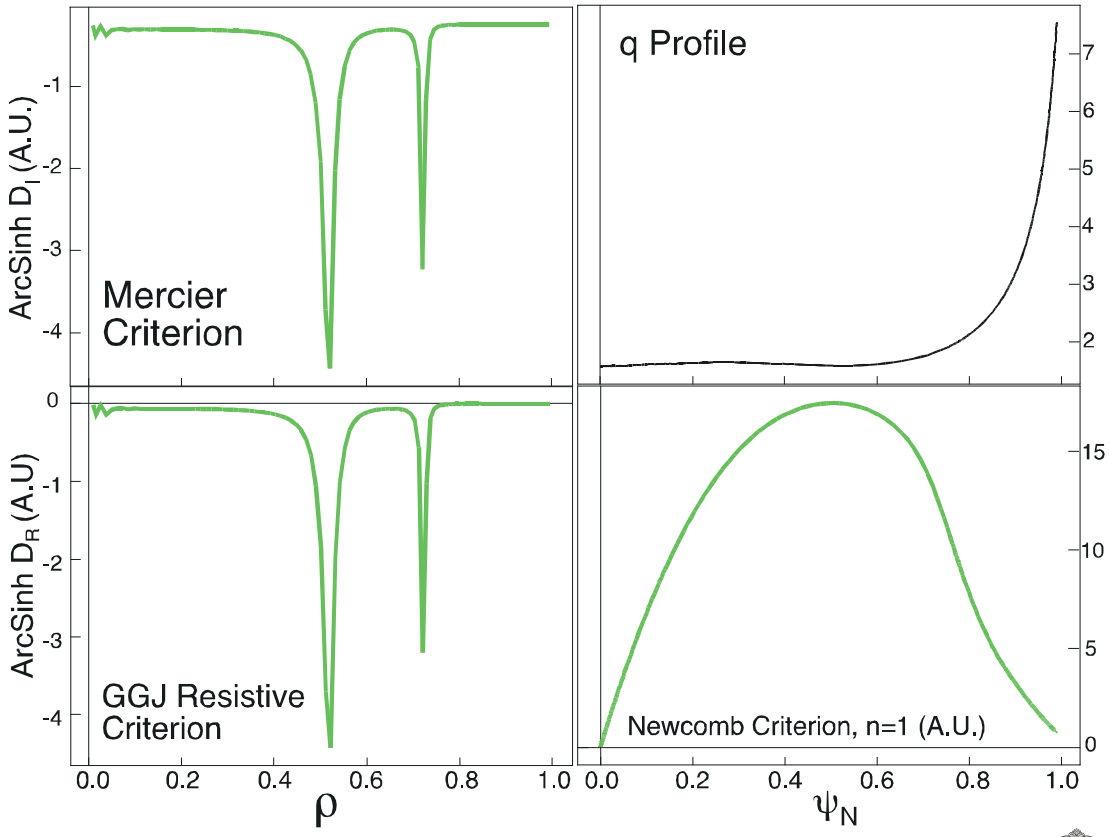
Flux Plot



Equil. Parameters

I_p (A)	290000
I_N	12
I_p/I_{tf}	1.93
ℓ_i	0.59
q_0	1.5
R_0 (m)	0.39
a (m)	0.34
Elongation	2.2
q_{95}	4.8

DCON predicts equilibria stable

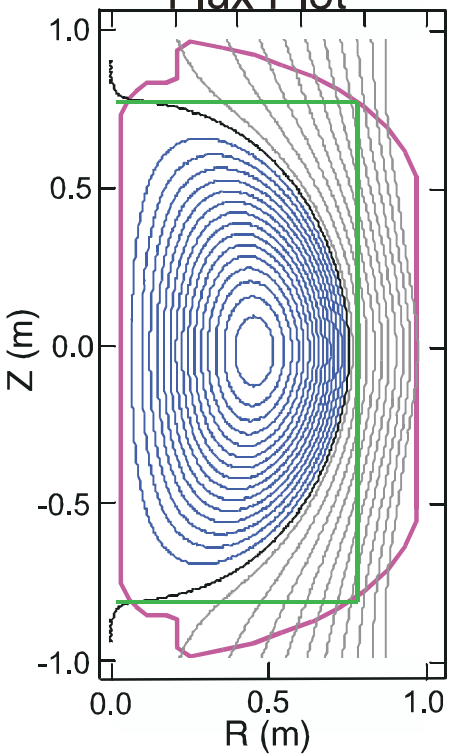


Modeled $I_p \sim 3I_{tf}$: Approachs Goals and Physics Limits

- **Equilibria at $I_p \sim 3I_{tf}$ found**
- **DCON predicts instability due to resistive interchange**
  - *possible resistive instability*
- **$q < 1$ over ~ 0.5 of minor radius**
- **Suggests $I_p \sim 3I_{tf}$ may be upper bound on stability**

High-I_p/I_{tf}, "zero"-β Equilibria

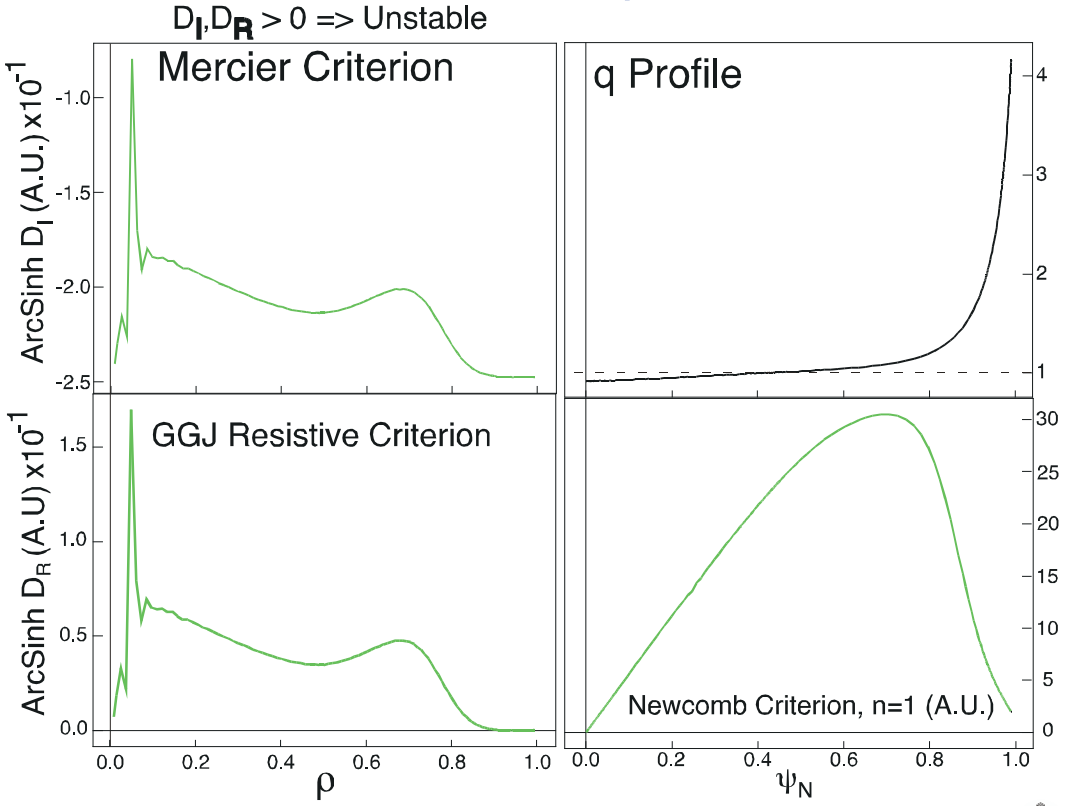
Flux Plot



Equilibria Parameters

I_p (A)	296000
I_N	90000
I_p/I_{tf}	18.9
ℓ_i	0.68
q_0	0.91
R_0 (m)	0.41
a (m)	0.36
Elongation	1.98
q_{95}	2.3

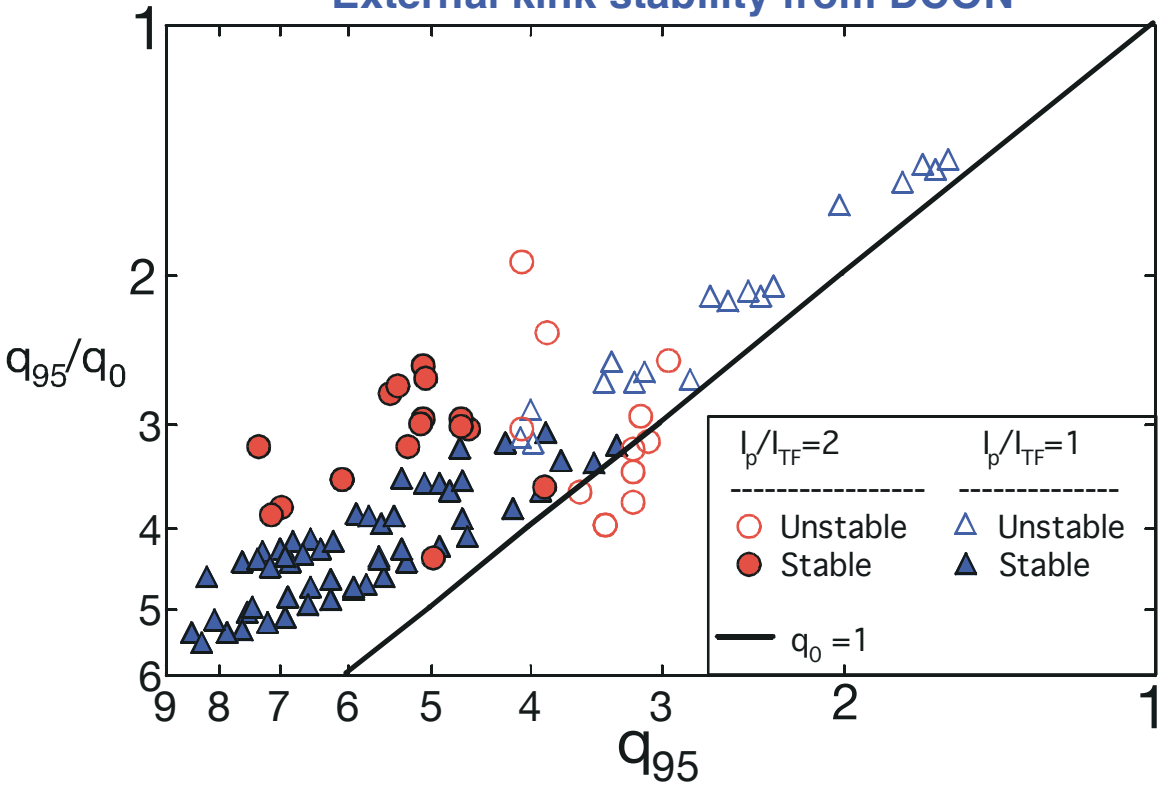
DCON Output



Modeling: Current & Pressure Profile Studies Underway

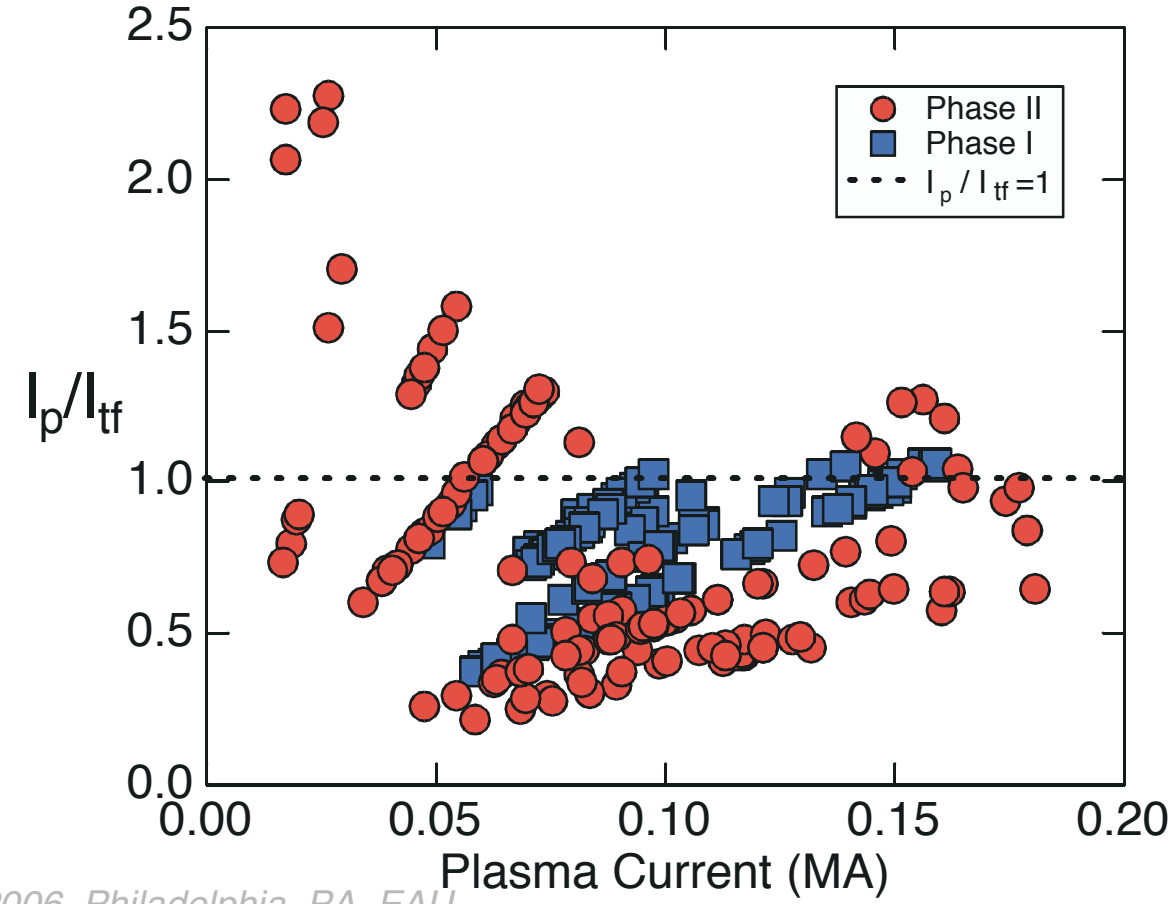
- **Goal: To determine optimal parameters for external kink stability at high l_p/l_{tf}**
- **Base cases with l_p/l_{tf} = 2 and 3 used as starting points for further study**
  - *Variety of profiles and shapes studied to determine possible stability boundaries*
- **Studies ongoing to determine possible stability boundaries; key parameters for high l_p/l_{tf} operations**
  - *Initial indications show need for broad current profiles & high elongation for stability*

External kink stability from DCON



Access $I_p > I_{tf}$ with J(r) manipulation

- **Significantly above Phase-I $I_p \approx I_{tf}$ "soft-limit"**
  - *New ops space: plasma guns & $B_t(t)$ used to vary J(r)*
- **$I_p \sim 1.5\text{-}2I_{tf}$ using guns**
  - *Tokamak-like MHD characteristics different from OH drive*
  - *Gun preionized discharge have similar MHD to Phase-I*
- **Gives evidence that $I_p \sim I_{tf}$ is not an intrinsic limit**



3 Unique Paths to $I_p > I_{tf}$

- **Fast TF rampdown, $\tau_{ramp} << \tau_{discharge}$**
  - *Simultaneously high I_p & high I_p/I_{tf}*
  - *Allows access to high I_N, β_t plasmas*
  - *Adds edge current ⇒ develop hollow current profile during ramp*

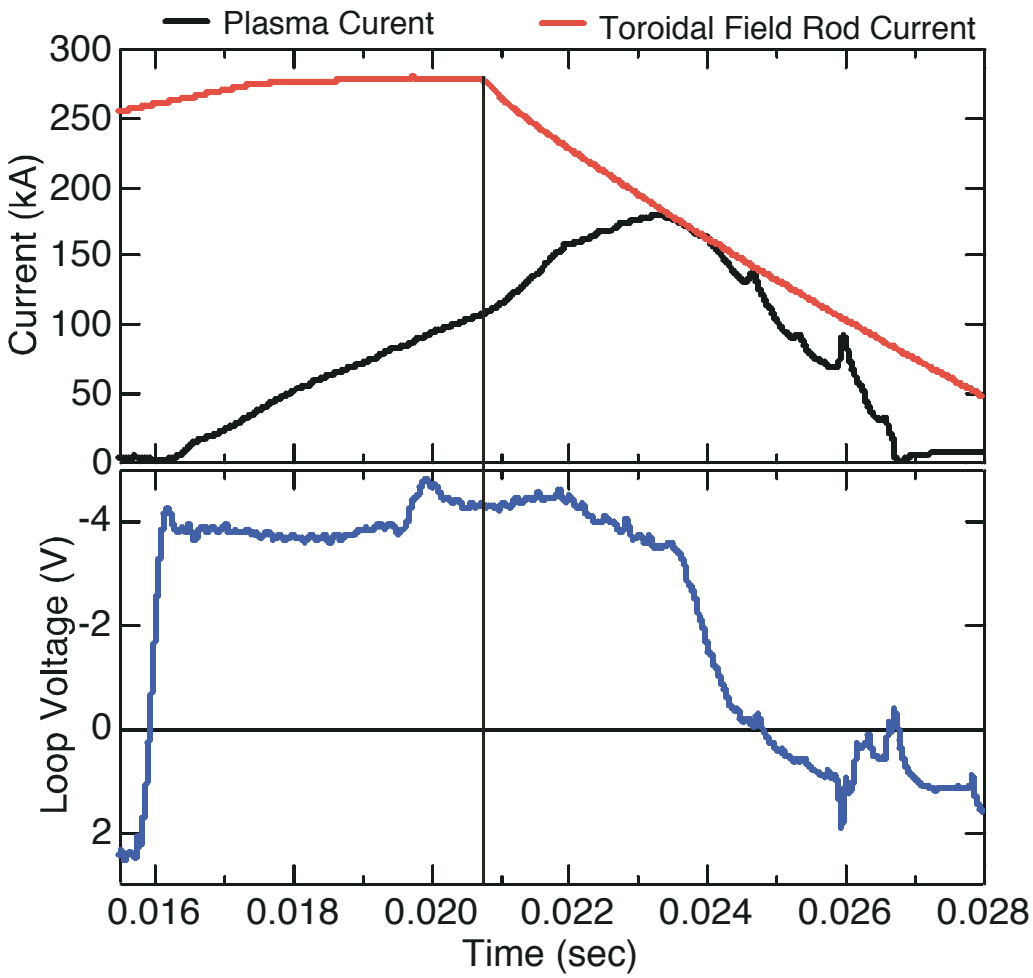
- **Non-inductive startup with electrostatic current injection**
  - *Gives highest I_p/I_{tf}(~2.2)*
  - *MHD activity characteristically different from OH driven discharges*
  - *Adds J(r) relaxes from hollow profile ⇒ reverse shear early*

- **Ultra-low TF with preionization gun**
  - *Efficient OH driven discharges; $V_{loop} < 4V$*
  - *MHD activity simialr to high TF discharges*
  - *Expands operating space; Ultra-low TF = no ECH resonance for breakdown assist*

TF Rampdowns used in Ip > Itf Studies

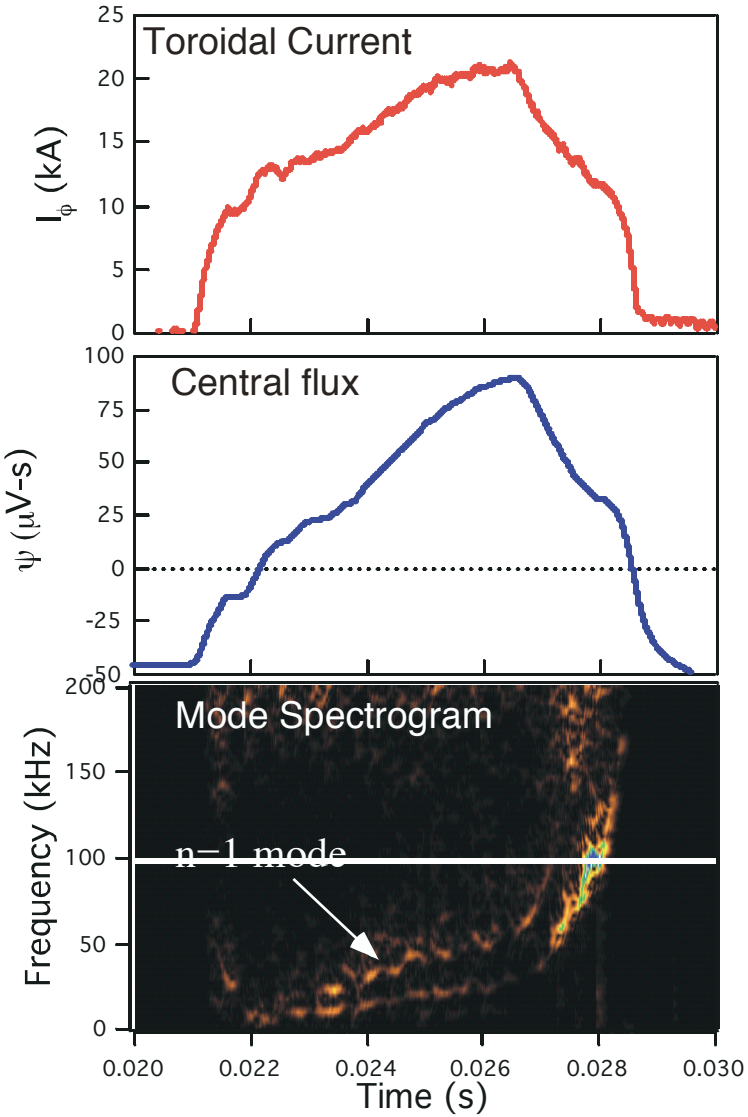
- **New TF coil set allows fast ramprates**
  - *Phase-I → 60 turn, high inductance set*
  - *Phase-II → 12 turn, $dI_{tf}/dt \sim 50$ MA/sec*
- **Current amplification seen during ramp**
  - *$dI_p/dt \sim 25$ MA/sec before ramp*
  - *$dI_p/dt \sim 35$ MA/sec after ramp*
  - *V_{loop} help ~ constant in beginning of discharge*
- **Fast ramp occurs at end of typical discharge**
  - *Ramps begin after ~2 msec of high TF flattop*
  - *Allows high q in low resistance phase of discharge*

Example of TF rampdown



Plasma Guns Produce Tokamak-like Plasmas

- **Central flux reversal indicates formation of tokamak-like plasmas**



- **Evidence for relaxation to tokamak-like flux surfaces:**
  - Increased I_ϕ amplification
  - Visual change in plasma
  - Strong B-dependence
  - Flux reversal on center column
  - Appearance of n=1 mode
  - Increased L/R decay time

