Thesis Statement(s)

- High Field Utilization (I_p/I_{tf}) needed to access $\beta_t \sim 1$ and High I_N in an ultra-low-aspect-ratio torus (ULART)
- Operations in the PEGASUS ULART have shown the need for discharge evolution to obtain high performance
- Modeling & experiments confirm PEGASUS can access high I_p/I_{tf}, I_N regimes
- Recent experments in PEGASUS have given $I_p/I_{tf} \sim 1.5\text{-}2$ at $I_p < 0.1$ MA

Outline

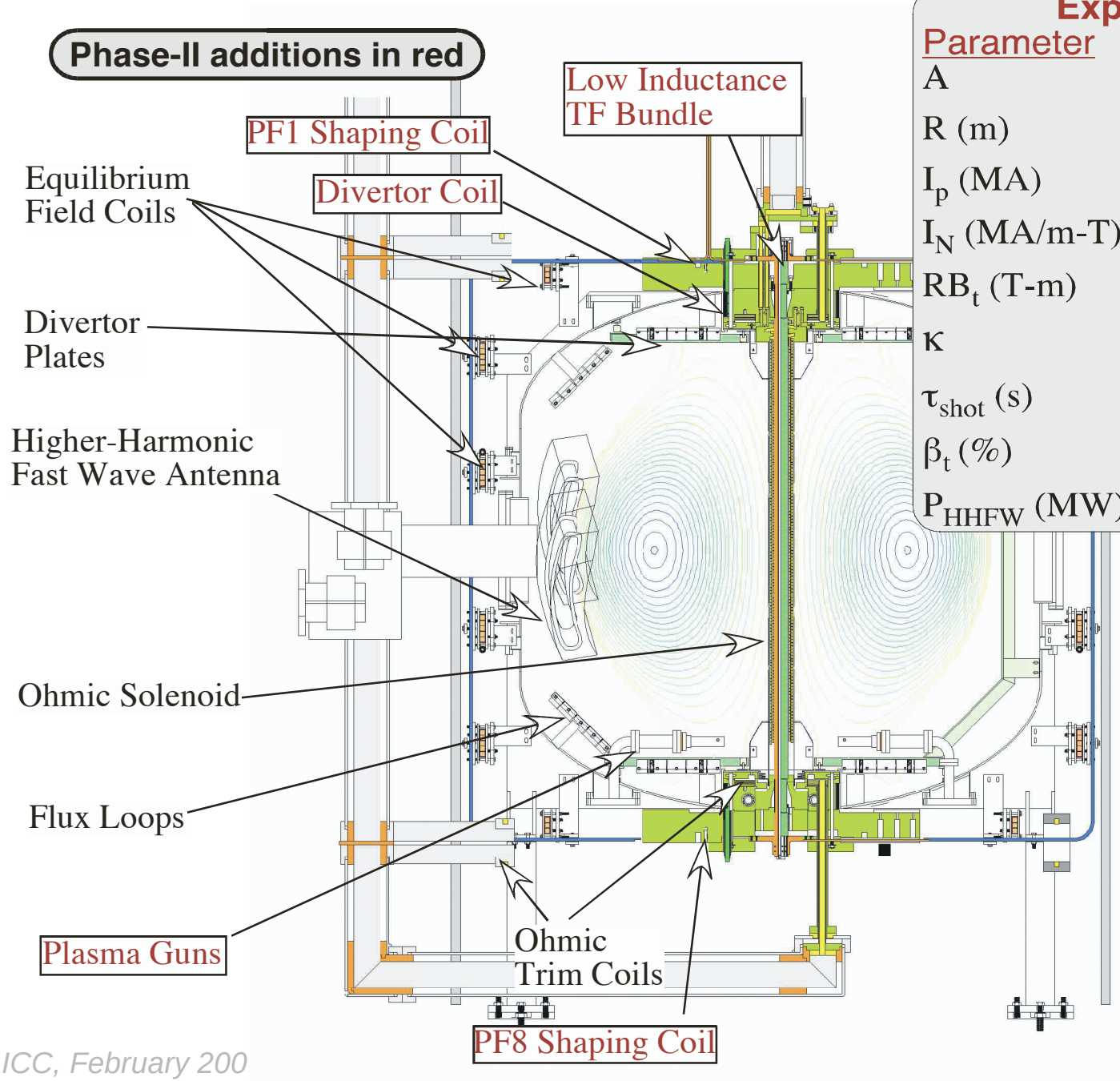
- **Achievable Performance of Initial Experiments Limited to $I_p \sim I_{tf}$**
  - Tearing modes (TM) due to ST physics and crude experimental control
  - Magnetic shear mitigates TM ⇒ external kinks were observed; all limited by hardware control

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

- **Non-Inductive and Limited-OH Experiments ⇒ I_p/I_{tf} = 1.5-2.2 Achieved**
  - 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: $I_p/I_{TF} \sim 1.5$
    - *experiments limited by flux (~ 30mV-sec; full capability = 90 mV-sec)*

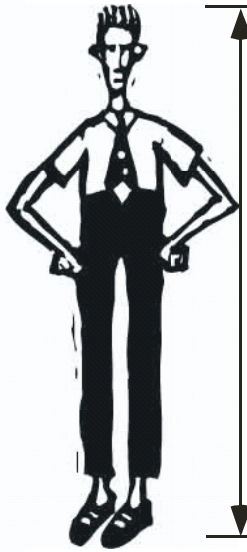
PEGASUS is a University-Scale, Mid-Sized ST

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

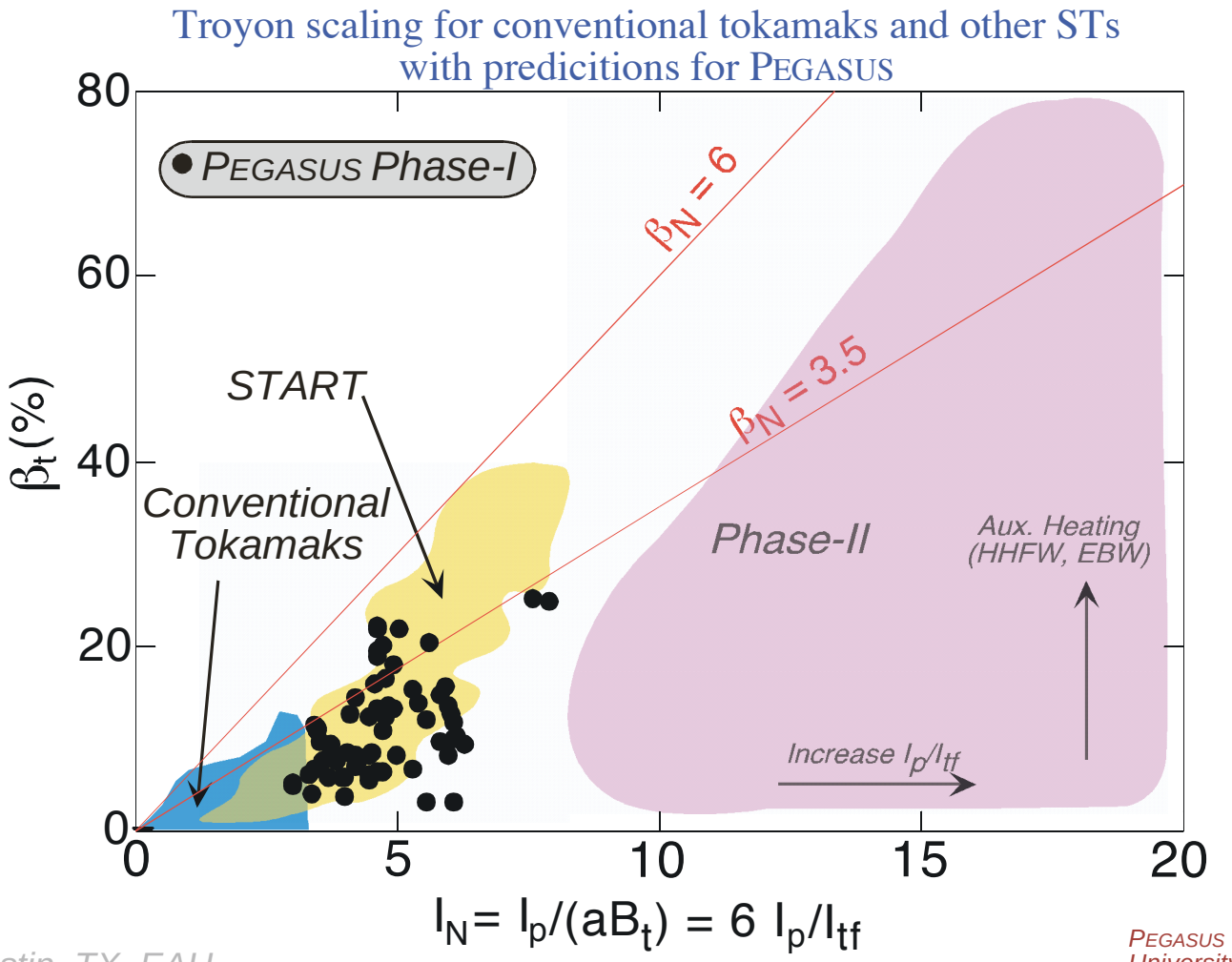


Typical PEGASUS Employee ~ 6 Feet

Main Mission: Studies at High-β_t and I_N

PEGASUS Goals

- Stability and confinement at high I_p/I_{TF} at 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*



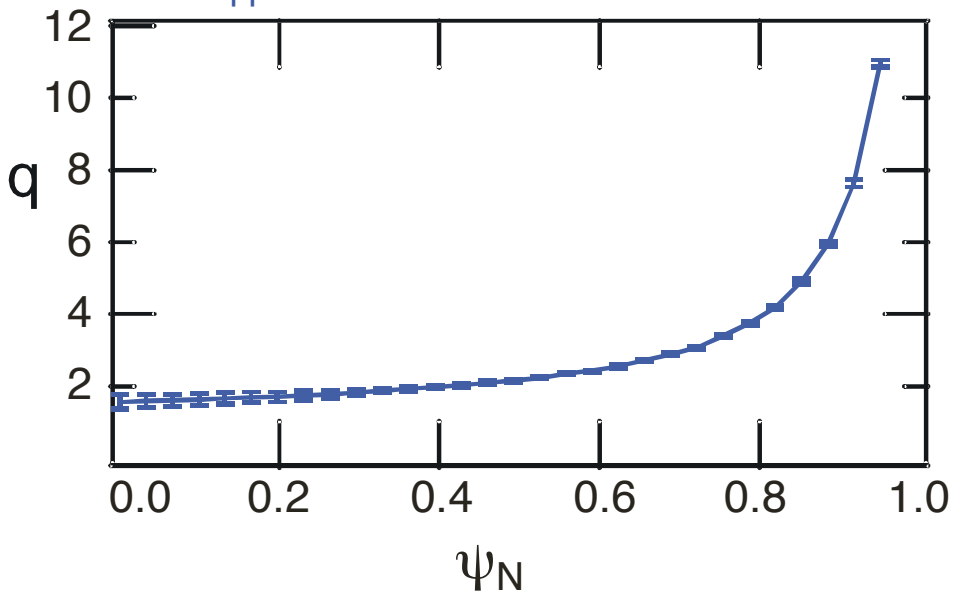
PEGASUS Toroidal Experiment
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Phase-I: Mode Activity Dependent on Current Profile

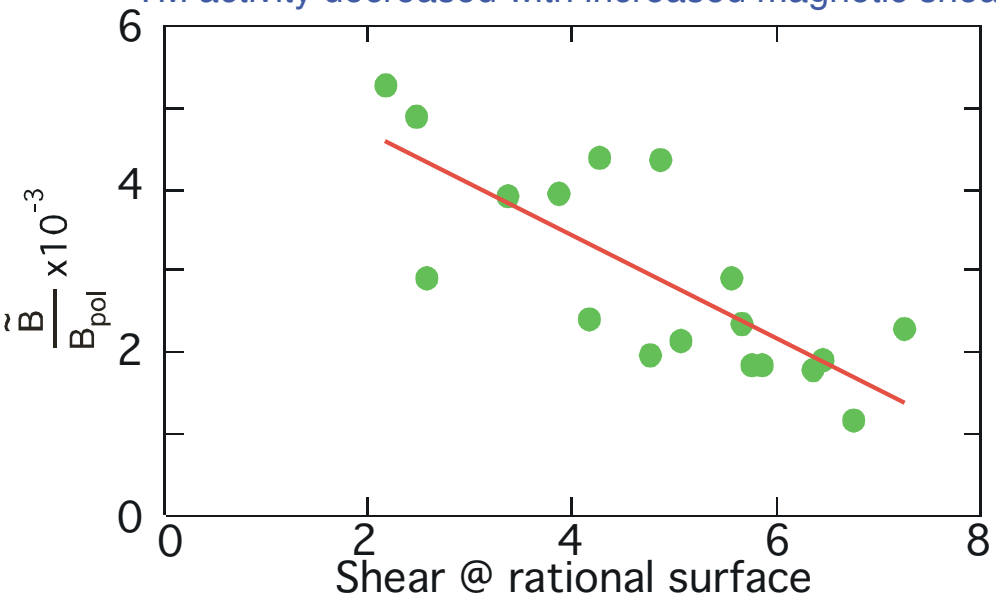
- **Maximum $I_p \approx I_{tf}$ limit**

- **q-profile of ST condusive 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

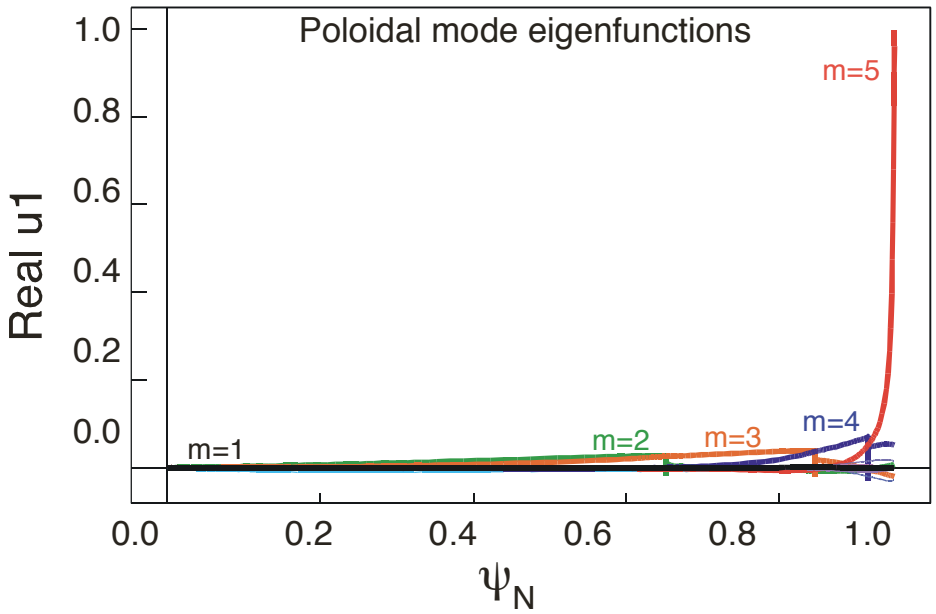


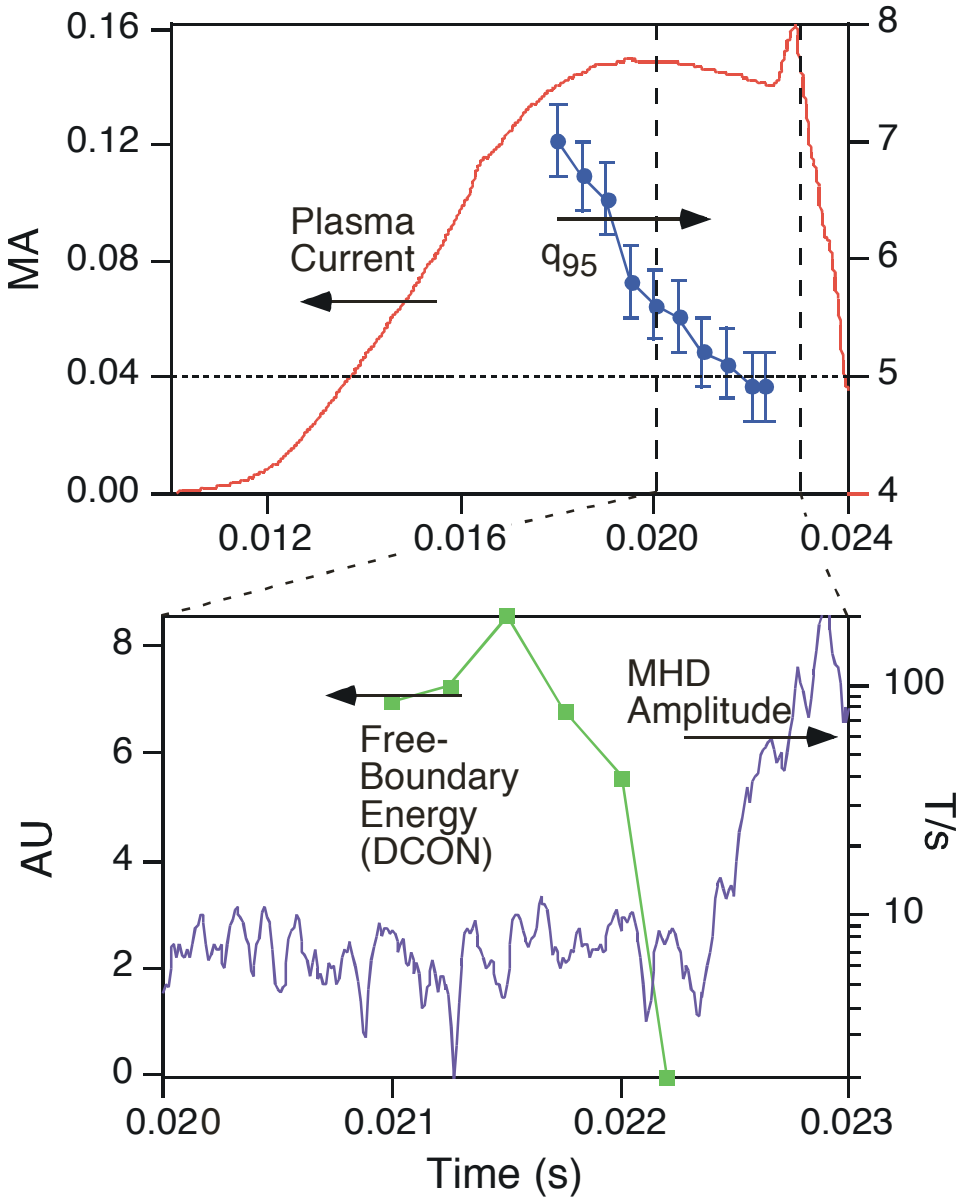
- **Crude manipulation of q(r) reduced mode amplitude**
  - *Increased shear, q_0 ⇒ delay tearing onset*

⇒ 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**



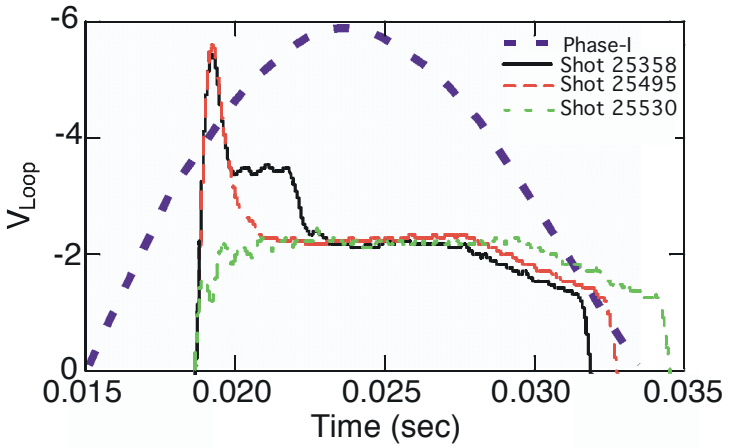


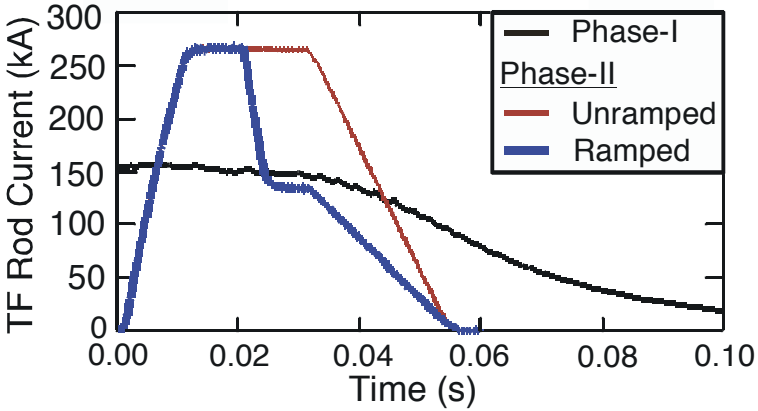
Facility Modifications to Access High I_p/I_{TF}

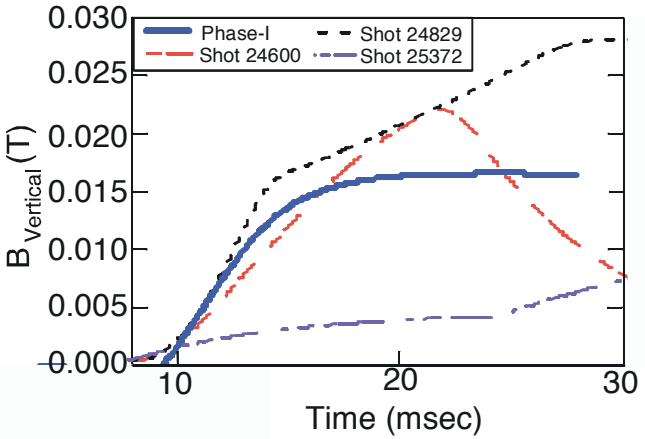
- **Extensive modications to facility to allow access to higher I_p/I_{TF} operations**

- **Approaches and tools to increase I_p/I_{TF}**
  - Manipulate current profile
    - *V_{loop} control, position/shape control, $B_t(t)$*
  - Reduce η before low-order rationals appear
    - *V_{loop} control, position/shape control, RF heating (HHFW)*
  - Transiently increase q during startup
    - *$B_t(t)$, V_{loop} control*

- **Main facility modifications**
  - 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*







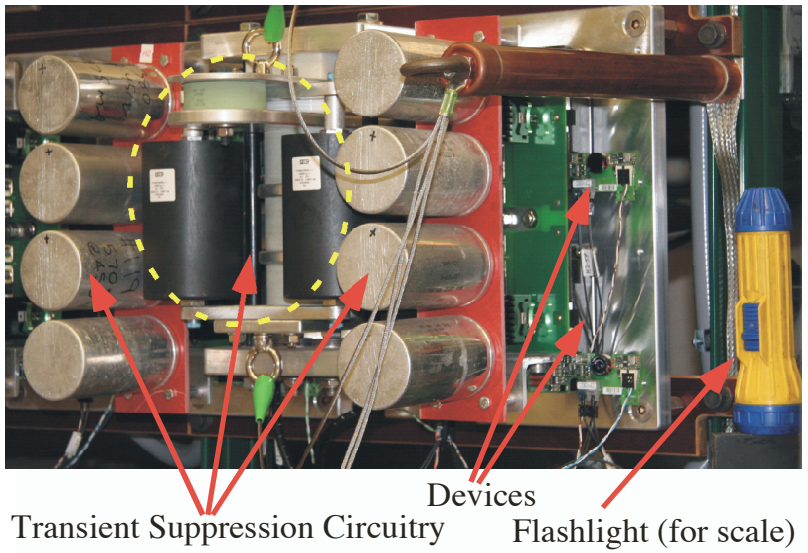
Programmable Power Supplies give Highly Flexible Experiment

- **250 MVA programmable power**
  - Economical, high-power, solid-state switches
  - Impedence matched for each coil
  - Allows more effective power with less stored energy
- **Large degree of coil arrangement flexiblity**
  - Up to 40 independent subsystems @ 4 kA available
    - *28 @ 900V* → IGBT systems
    - *12 @ 2700V* → IGCT systems
  - PWM feedback gives msec time response (U.Wash)
- **Allows easy integration to active PCS system**
  - Real-time control under development with GA

Switchyard with the 40 subsystems



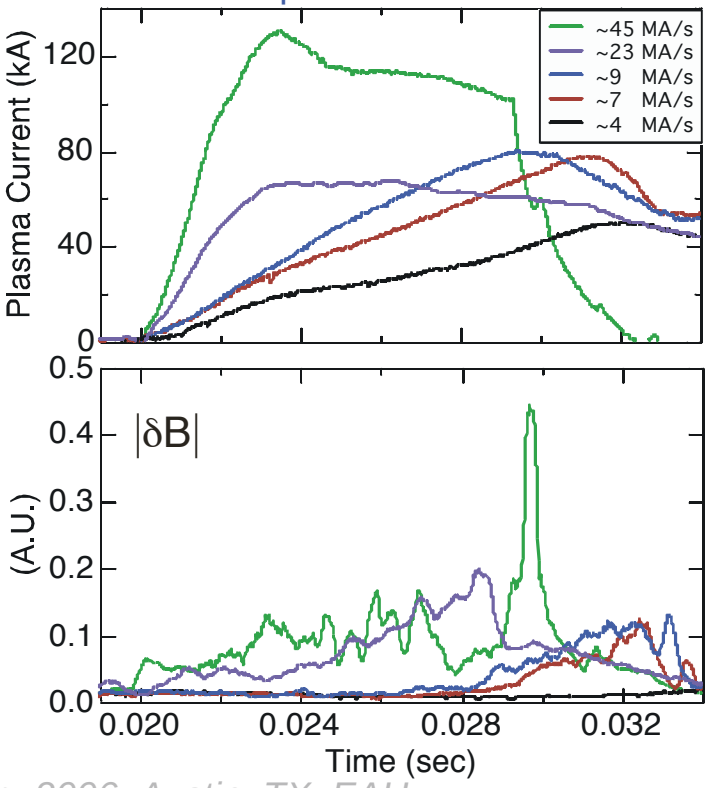
IGBT H-Bridge (1 of 28)



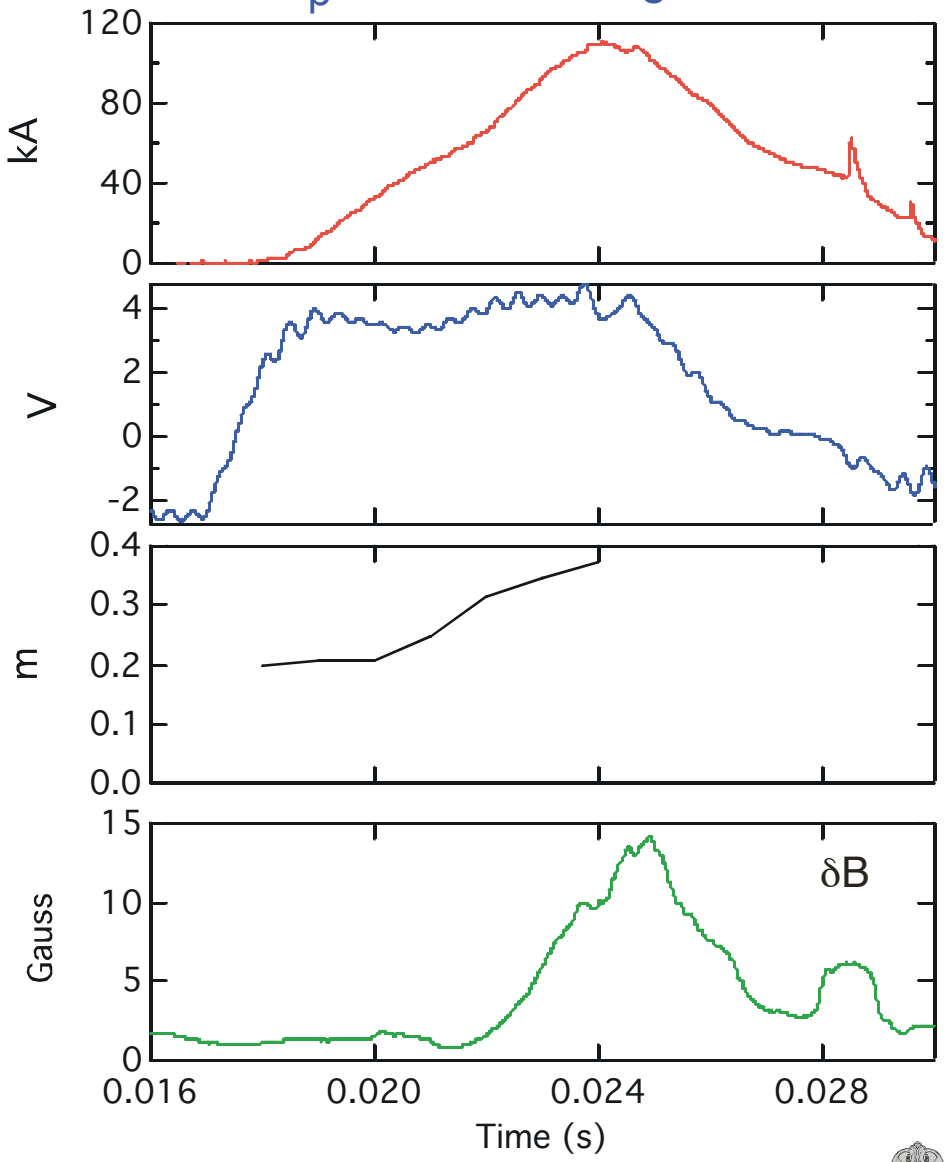
Discharge Control Seen with Pre-Programmable Coil Sets

- **Large array of new capabilities developed; deployed into routine use**
  - Pre-programmed coil currents
  - New wall conditioning and fueling
  - Variable PF configurations
  - Increased TF with time-variability
  - Divertor coils
- **Integration of these capabilities led to discharge control**

Varied $\dot{I}_p$ & respective |δB|



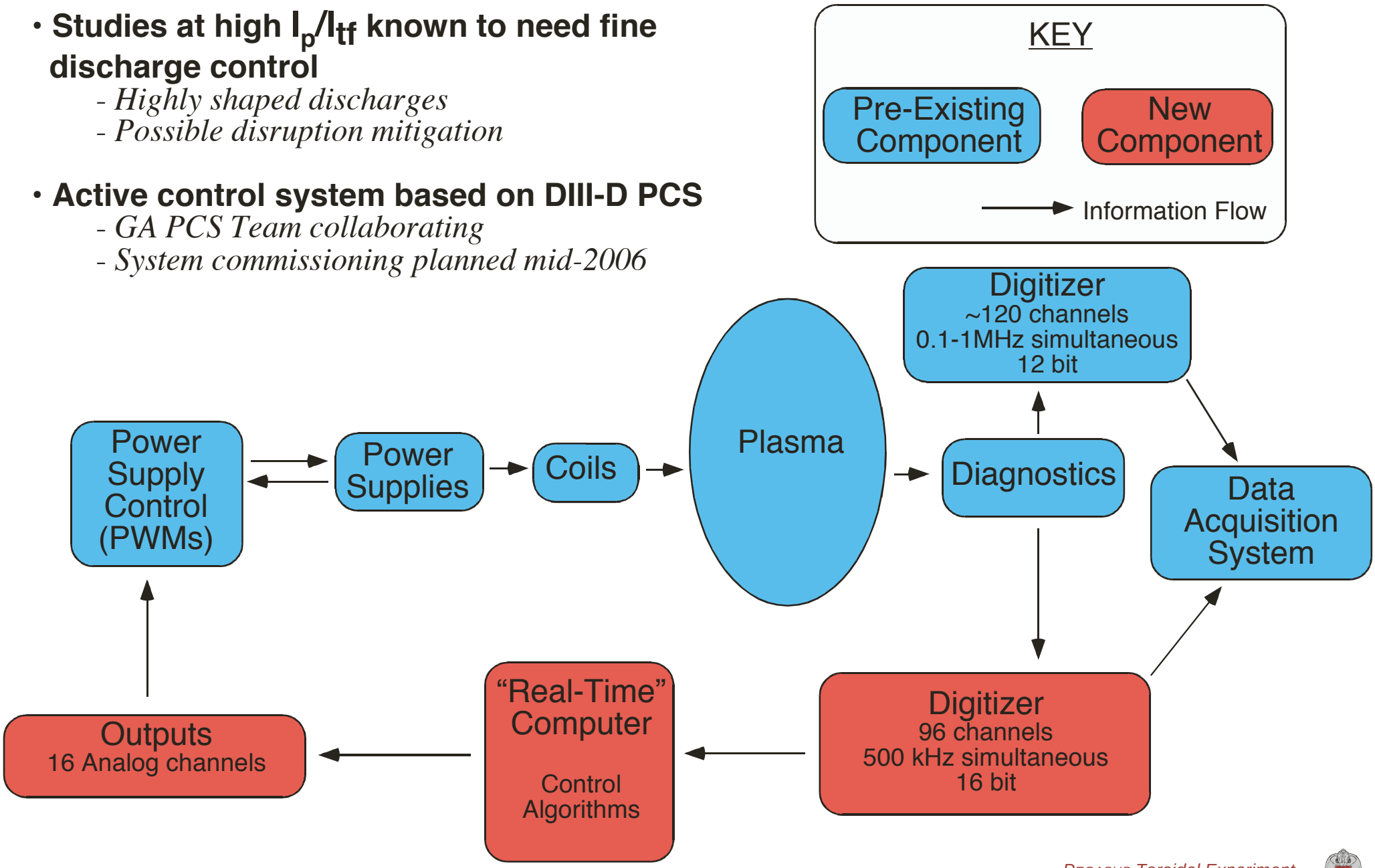
I_p-dot held through TM



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Tools for High I_p Studies: Plasma Control System

- **Studies at high I_p/I_{tf} known to need fine discharge control**
  - *Highly shaped discharges*
  - *Possible disruption mitigation*
- **Active control system based on DIII-D PCS**
  - *GA PCS Team collaborating*
  - *System commissioning planned mid-2006*



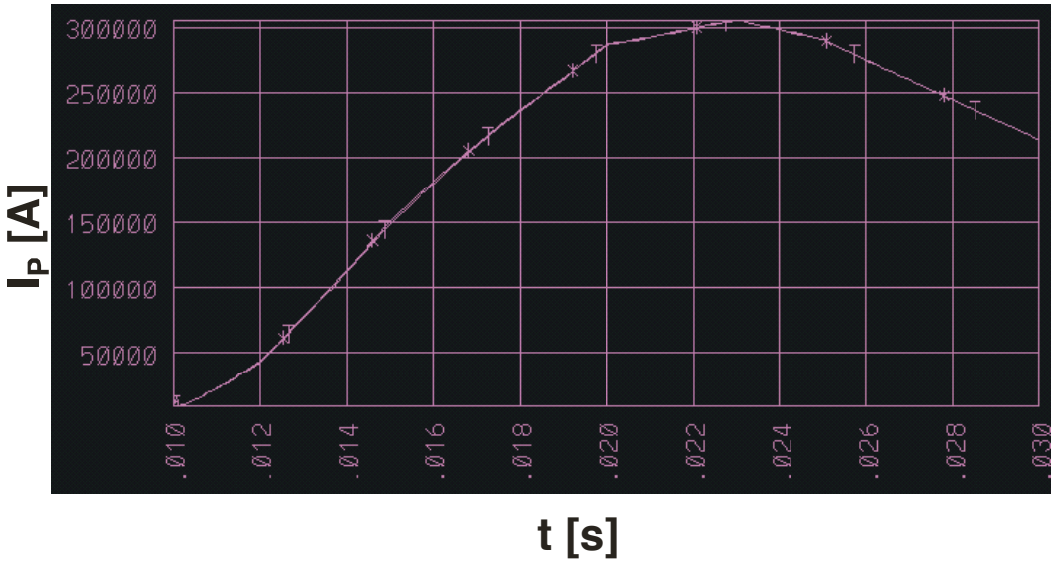
Modeling Confirms Access to High I_p/I_{TF}

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

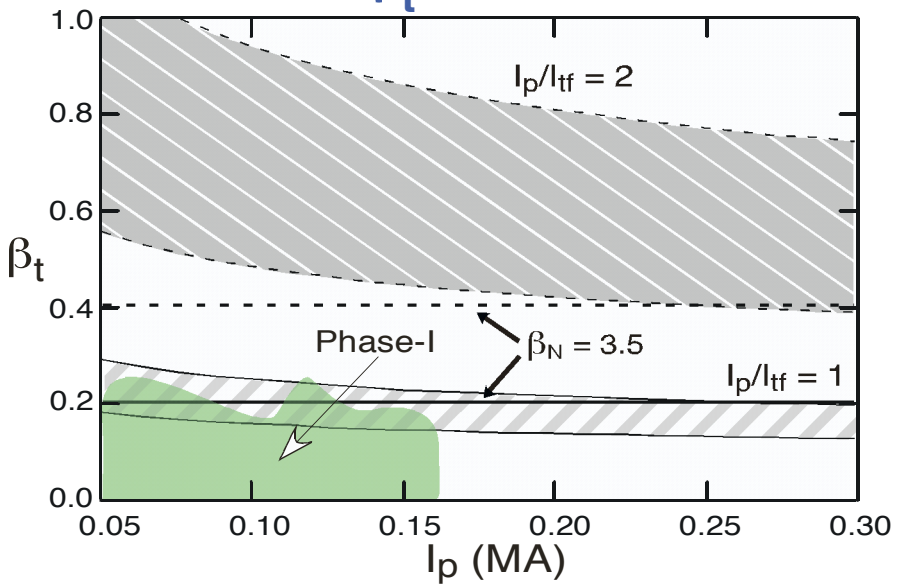
- **TSC: Full ohmic flux (90 mV-s)**
  - Flux consumption calculations indicate 300 kA I_p attainable
  - Simulations corroborate
    $= I_p/I_{tf} = 2$
    $= I_N \sim 12$ MA/m-T
  - Effects of resistive MHD unclear

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

TSC simulations with full design parameters



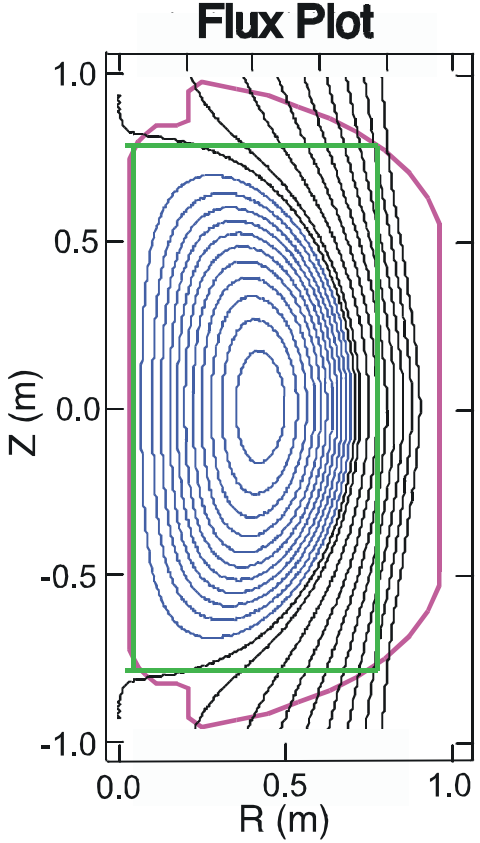
β_t Projections



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**

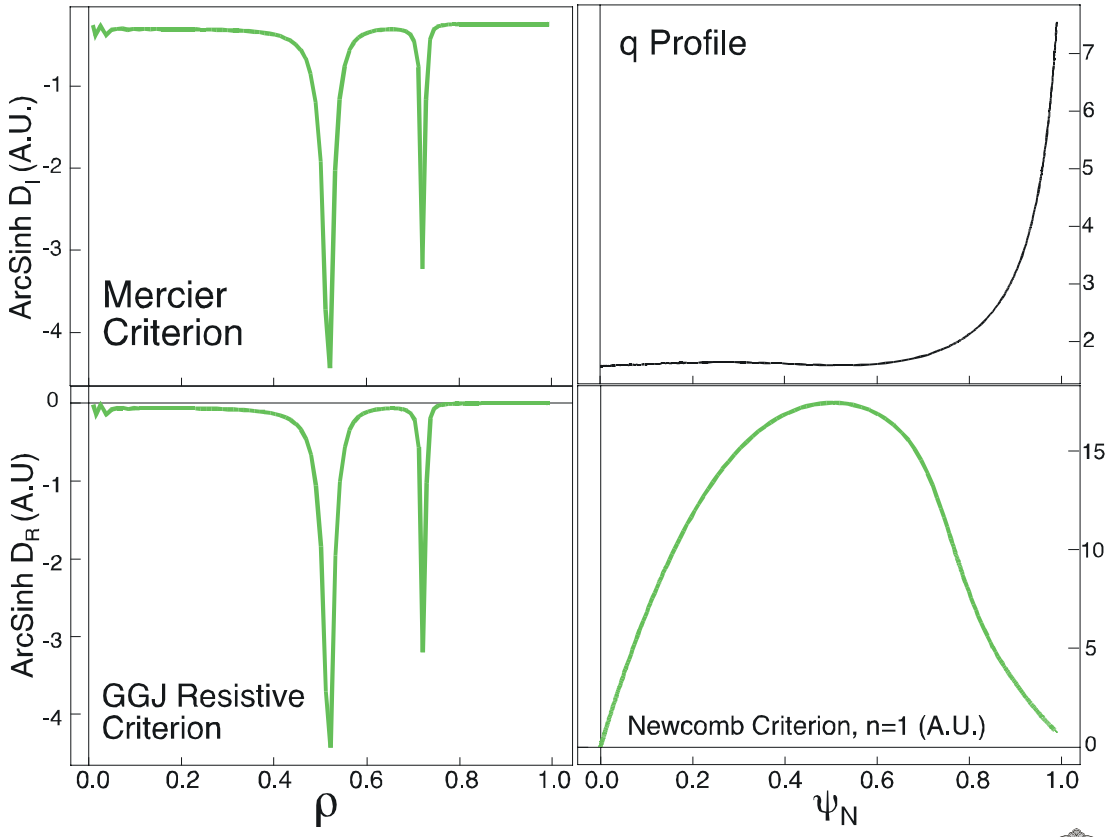
"zero"-β Equilibria



Equil. Paramters

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

DCON predicts equilibria stable

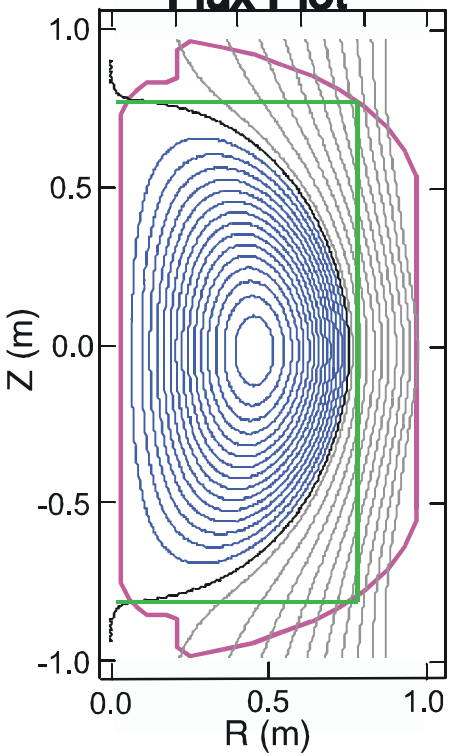


Modeled $I_p \sim 3I_{tf}$: Approachs Goals and Physics Limits

- **Equilibria at $I_p \sim 3I_{tf}$ found**
- **DCON predicts 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

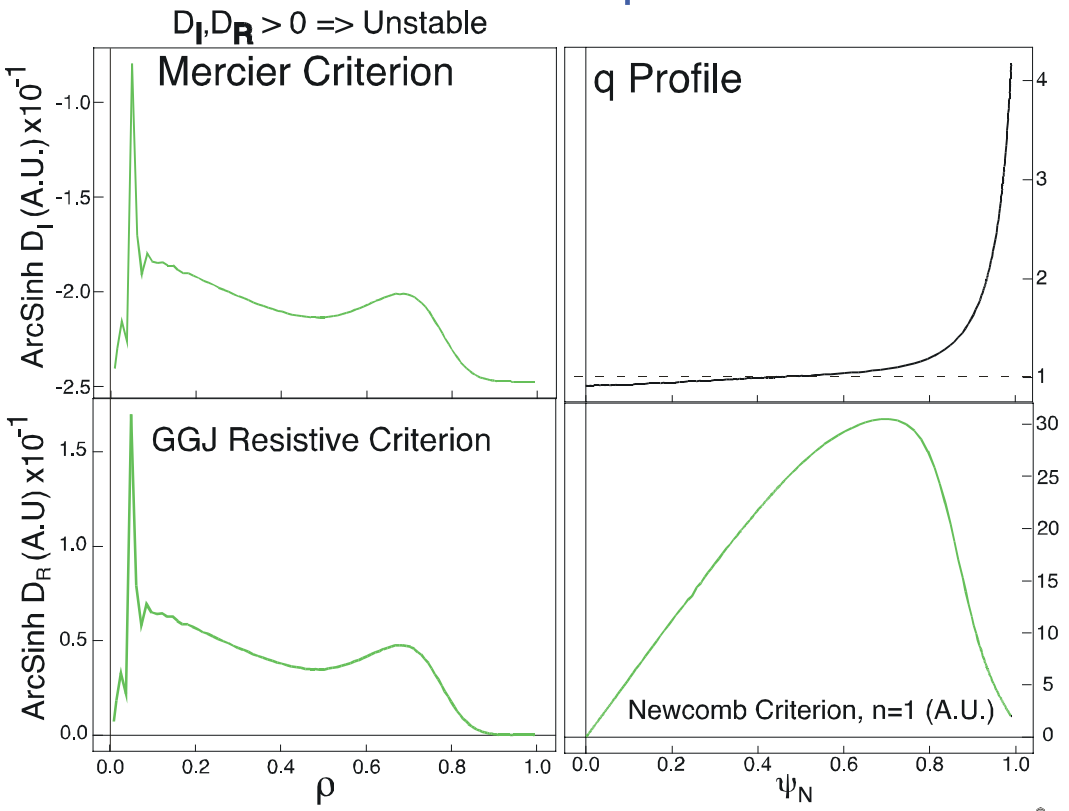
Flux Plot



Equilibria Parameters

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

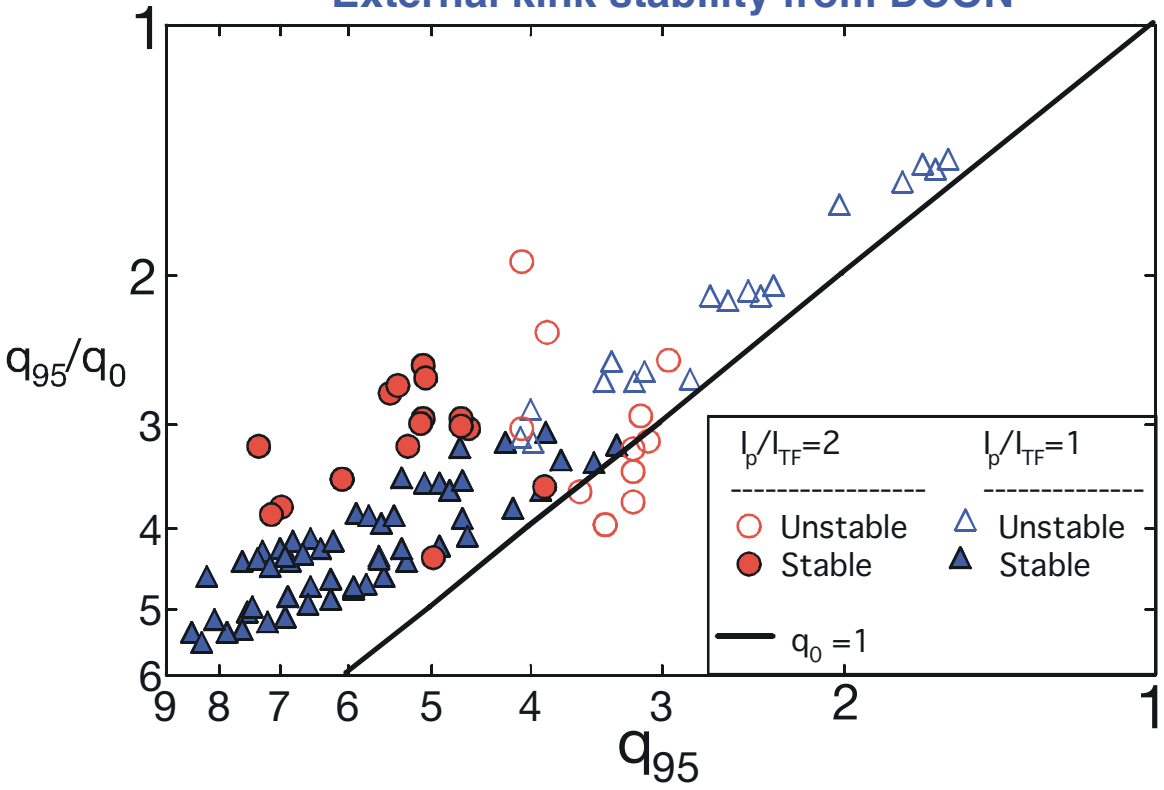
DCON Output



Modeling: Current & Pressure Profiles Studies Underway

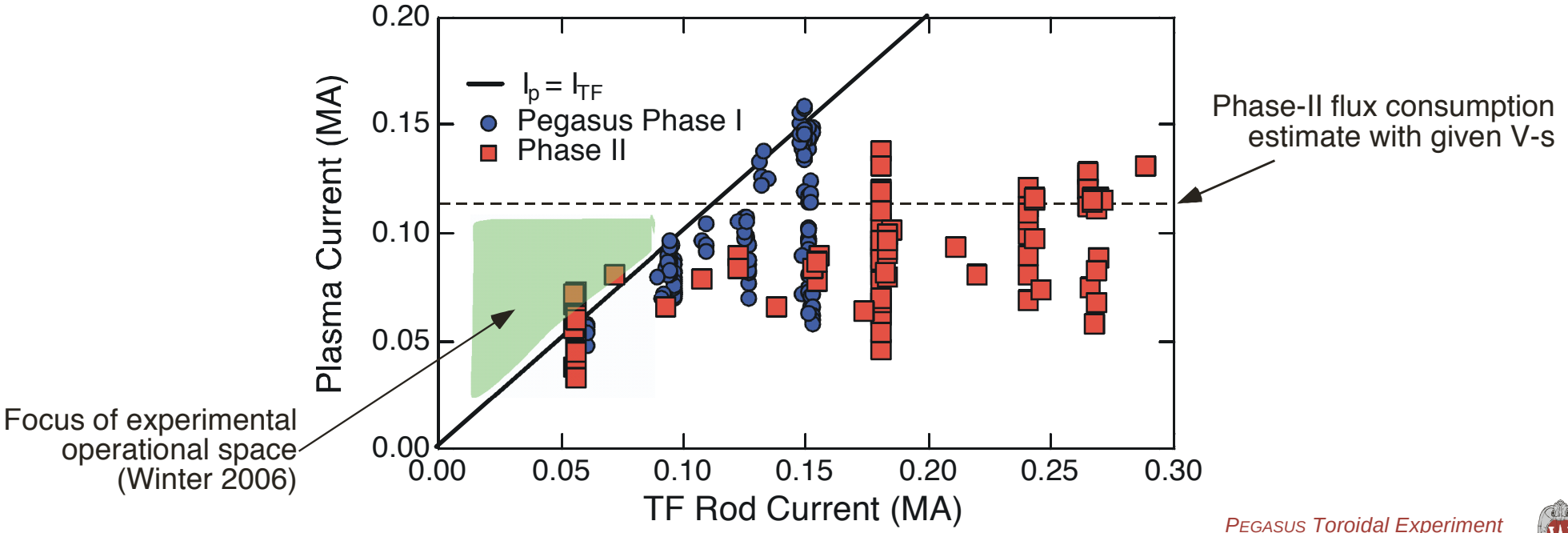
- **Goal: To determine optimal parameters for external kink stability at high I_p/I_{tf}**
- **Base cases with I_p/I_{tf} = 2 and 3 used as starting points for further study**
  - *Varying profiles and shapes studied done to determine possible stability boundaries*
- **Studies are ongoing to determine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

External kink stability from DCON



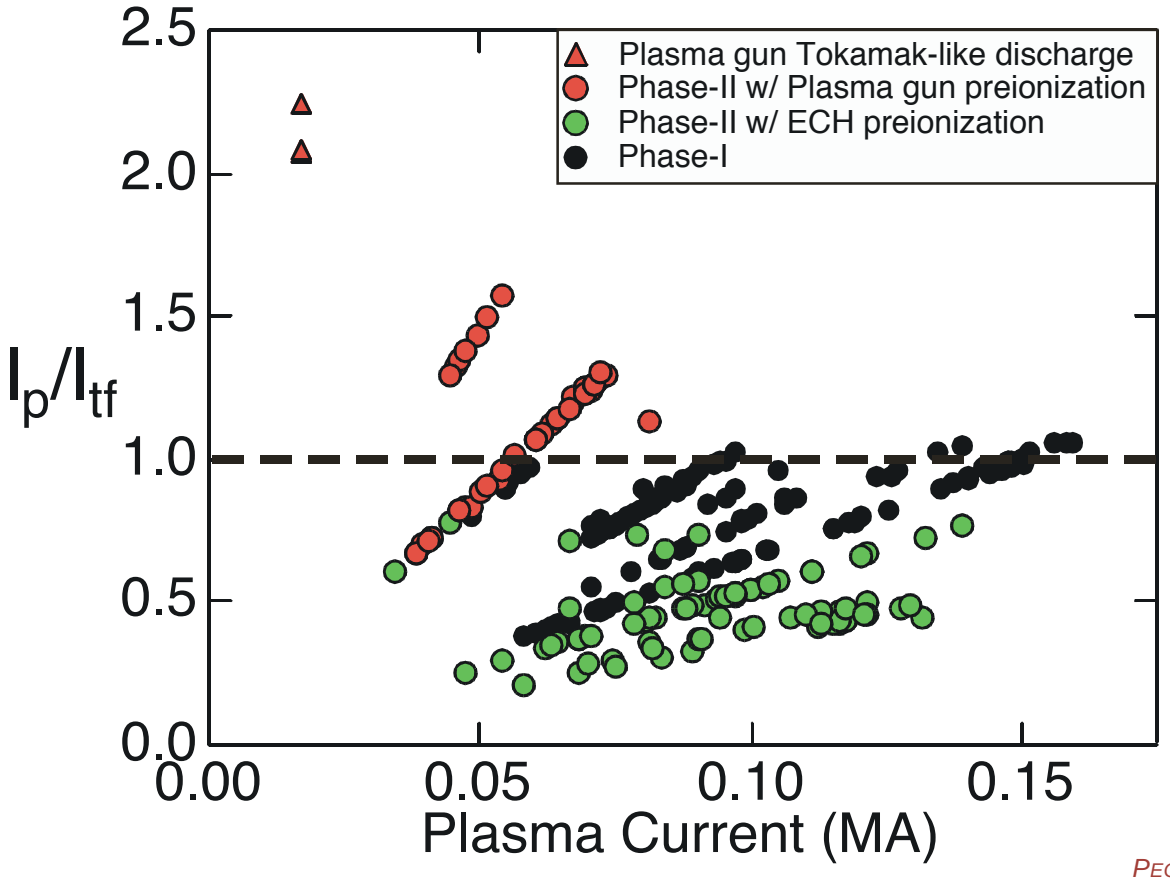
Phase-II: Mitigate TM Activity en route to High I_p/I_{tf}

- **Phase-I operational space recovered and extended**
  - Higher TF allowed: $I_p \rightarrow$ ~140 kA ; $I_p/I_{TF} \rightarrow$ ~1
    - *m/n =2/1 mode activity observed with ~ same characteristics as Phase-I*
- **Discharge utilizing all available V-s as OH goes to full power**
  - ~ 30 mV-s available vs. Phase-I 60 mV-s (90 mV-s *full design)*
- **Tearing mode mitigation experiments are ongoing**
  - Optimizing startup to navigate through MHD activity $\rightarrow I_p/I_{TF} > 1$
  - Approaches: variable ramp-rate; plasma shape; gas handling; impurity injection



Starting to Access $I_p > I_{tf}$ Regime

- **I_p ~ 1.5-2I_{tf} achieved by operation at low TF**
  - *Significantly above Phase-I operating space of $I_p \sim I_{tf}$*
- **Low TF operations made avaiable using plasma guns**
  - *Tokamak-like MHD characteristics quite different from OH driven discharges*
  - *Gun as preionization source: MHD similar to Phase-I*
- **Higher I_p comes with higher power plasma guns and/or full power OH**

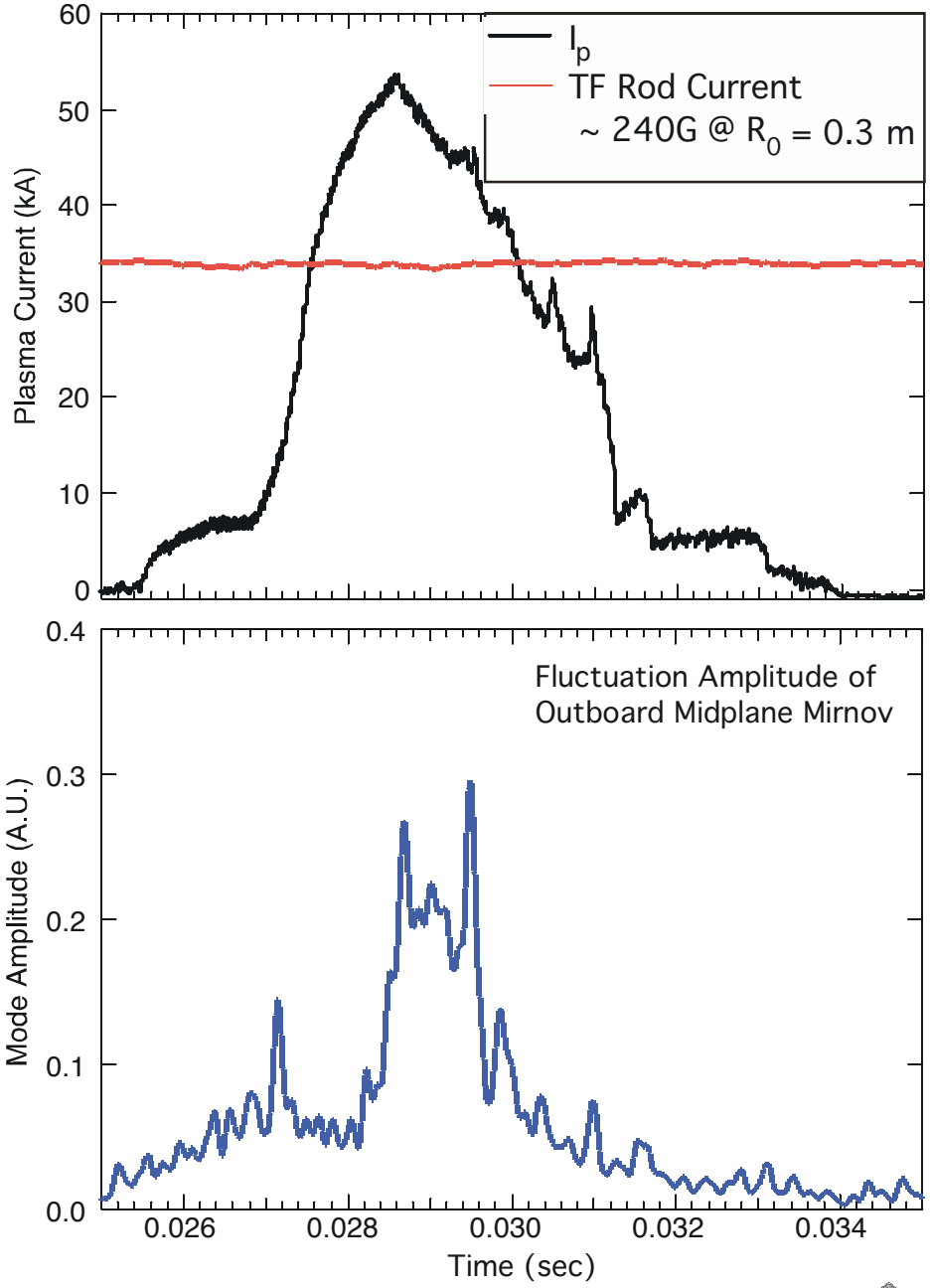


$I_p \sim 1.5 I_{tf}$ Attained Using Gun Preionization Source

- **Allows OH startup @ ultra-low TF**
  - *Using PF power supplies; gives ~ 20 mV-sec*
  - *Phase-I experience: more V-sec will allow extend discharge length and magnitude*

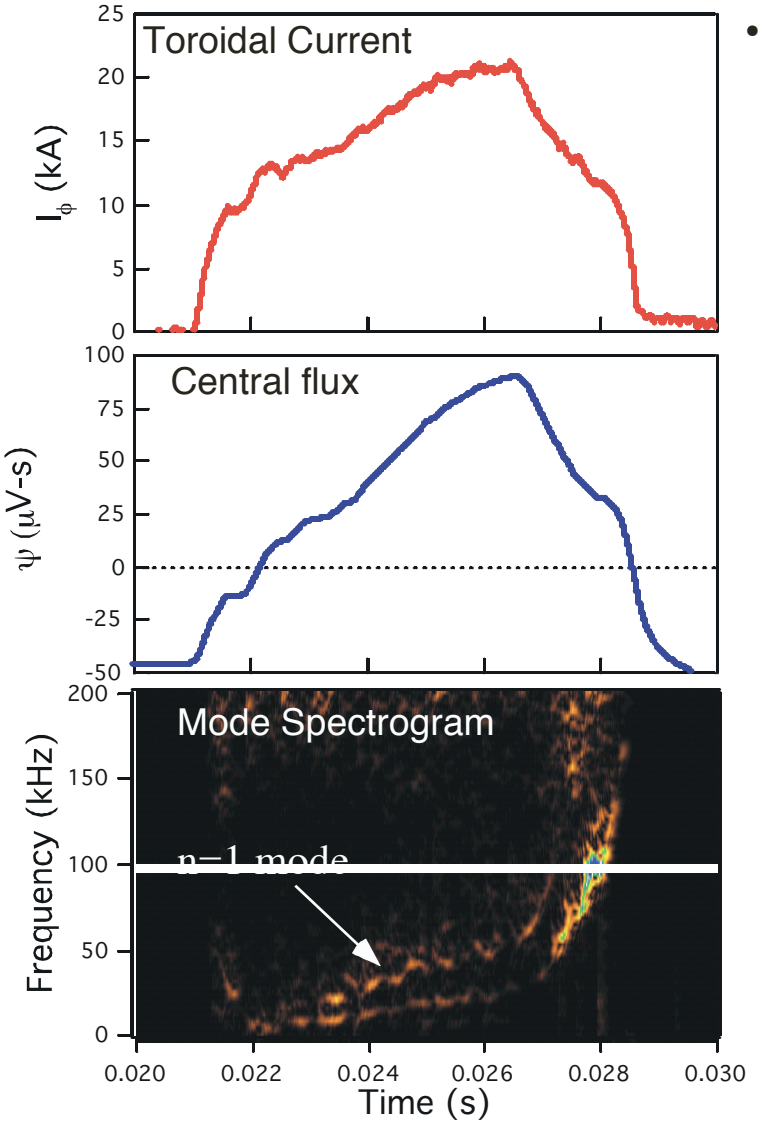
- **$I_p \sim 1.5 I_{tf}$ achieved to date**
  - *MHD behavior similar to high-Ip; high-field discharges*
  - *High ramprates known to limit performance*

- **Significance: No intrinsic limit in I_p/I_{tf}**
  - *Depends on discharge evolution and current profile*

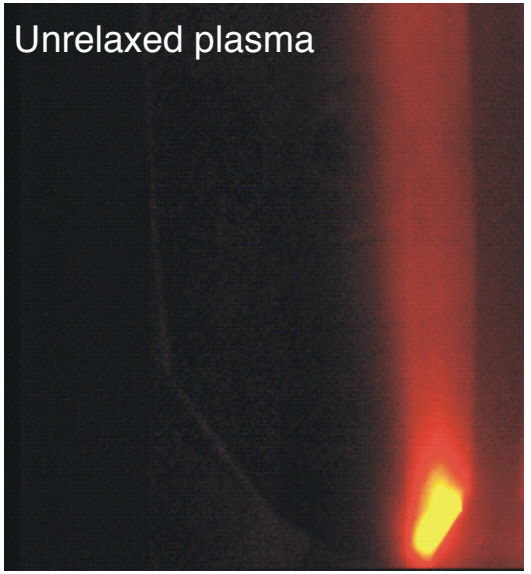


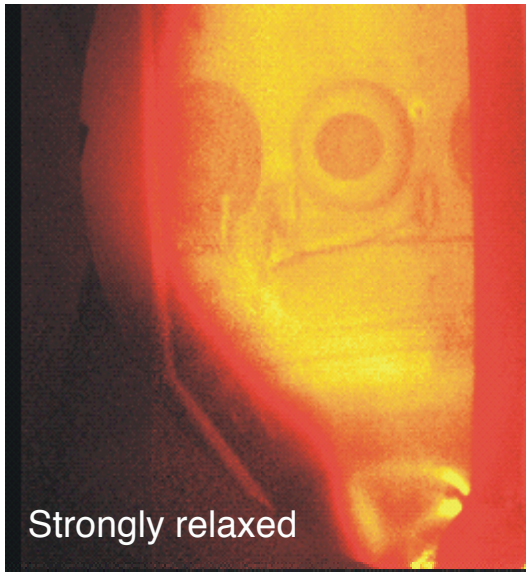
Plasma Guns Produce Tokamak-like Plasmas

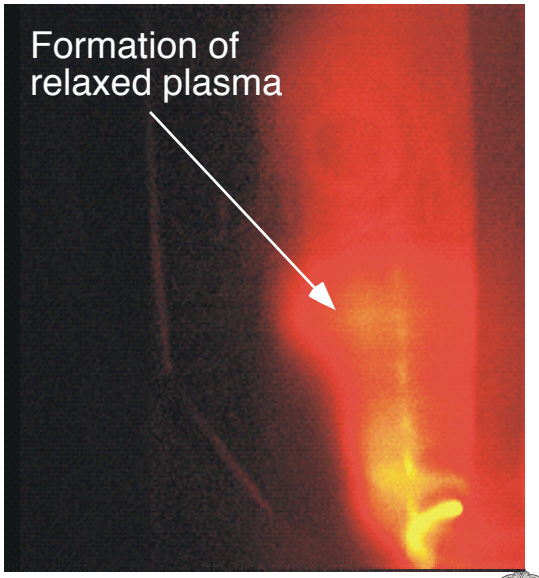
- **Central flux reversal indicates formation of tokamak-like plasmas**



- **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

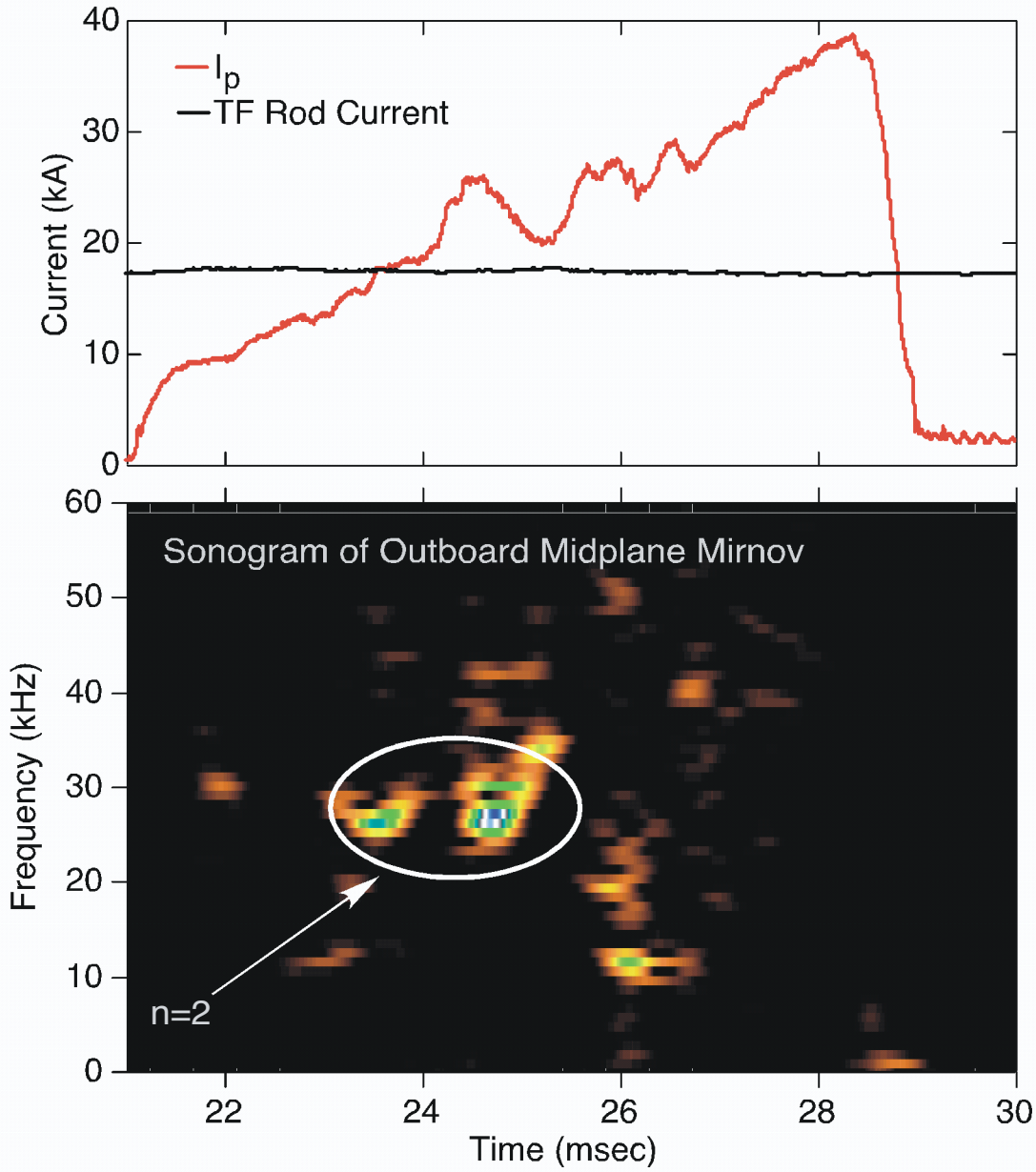






Helicity Injection Discharges Produced $I_p \sim 2\ I_{tf}$

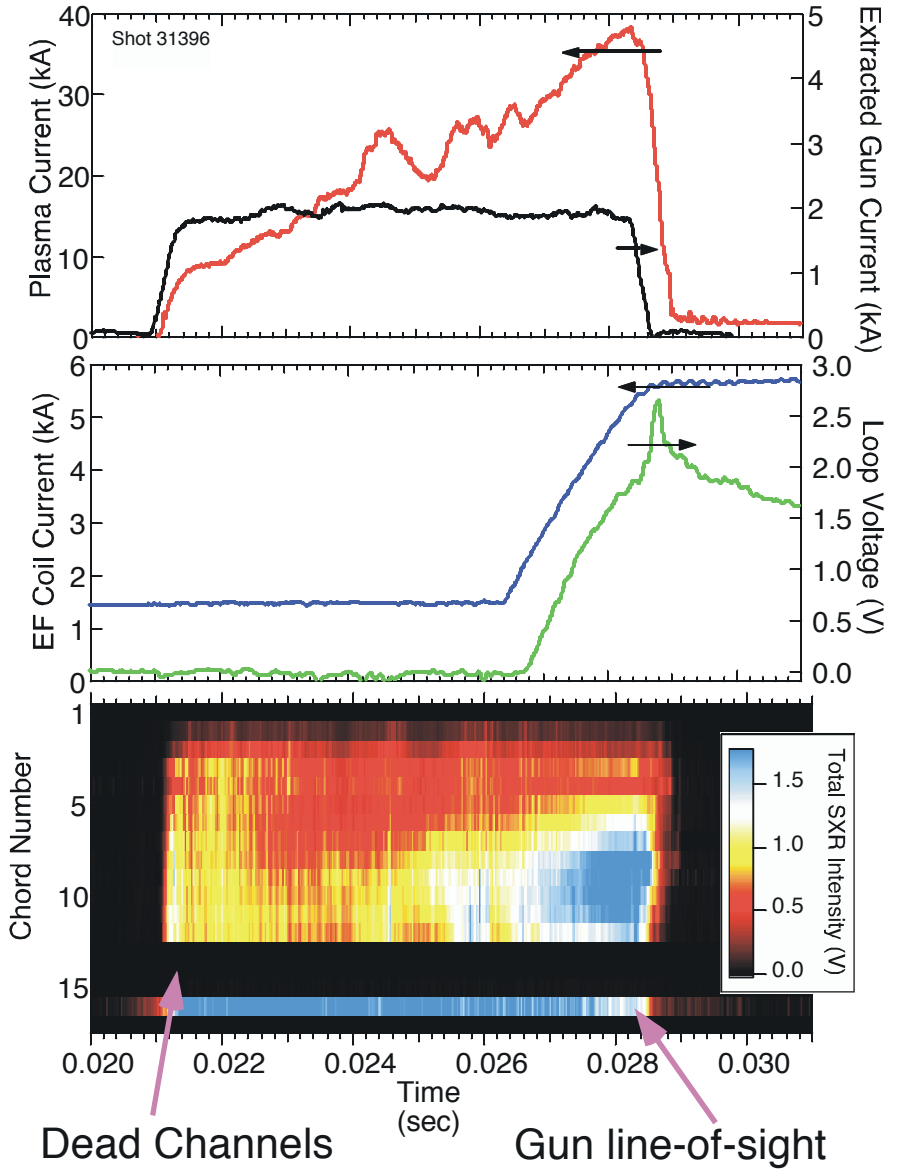
- **$I_p/I_{tf} \sim 2$ w/ vastly different MHD evolution**
  - *n=2 mode activity vs n=1 Phase-I*
  - *TMs die away at end of discharge*
- **Gun injection fundamentally different drive source vs OH drive**
- **Substantial current modification**
  - *Changes q-profile; possible reverse shear*
  - *Broad current profile*
- **Suggest guns may be useful in high I_N campaigns**



Beginning: Non-inductive startup + OH Discharges

- **Low V_{loop} added to end of gun discharges**
  - *Modest increase in Ip*
  - *Prototype guns: limited to very low TF*
- **SXR emission shows heating when V_{loop} applied**
- **Full handoff from non-inductive sources ⇒ OH under study**
  - *low field ⇒ poor confinement ⇒ requires more input power*
- **Approach: increase helicity & power from guns; increased V_{loop}**
  - *allows higher field ops*
  - *better matching of applied field to equilibrium field*
  - *added V-sec from full power OH should help*

V_{loop} added to tokamak-like discharge



PEGASUS Toroidal Experiment
University of Wisconsin-Madison

Summary

- **High Field Utilization in PEGASUS Needed to Access High β_t; I_N Regimes**

- **Modeling Confirms Access to this Regime; Modifications Give Tools**
  - TSC & confinement calculations confirm high I_p/I_{tf}; β_t access
  - DCON analysis predicts stability up to $I_p \sim 3I_{tf}$
  - New tools integrated; demonstrate discharge control

- **$I_p > I_{tf}$ Attained Using Plasma Gun Sources**
  - Goal: $I_p/I_{tf} \sim 2$-3 ($I_N \sim 10$-20) @ high I_p
  - $I_p \sim 2I_{tf}$ w/ guns as a non-inductive startup source
  - $I_p \sim 1.5I_{tf}$ w/ guns as a preionization source
  - $I_p \sim I_{tf}$ not an intrinsic limit

Reprints