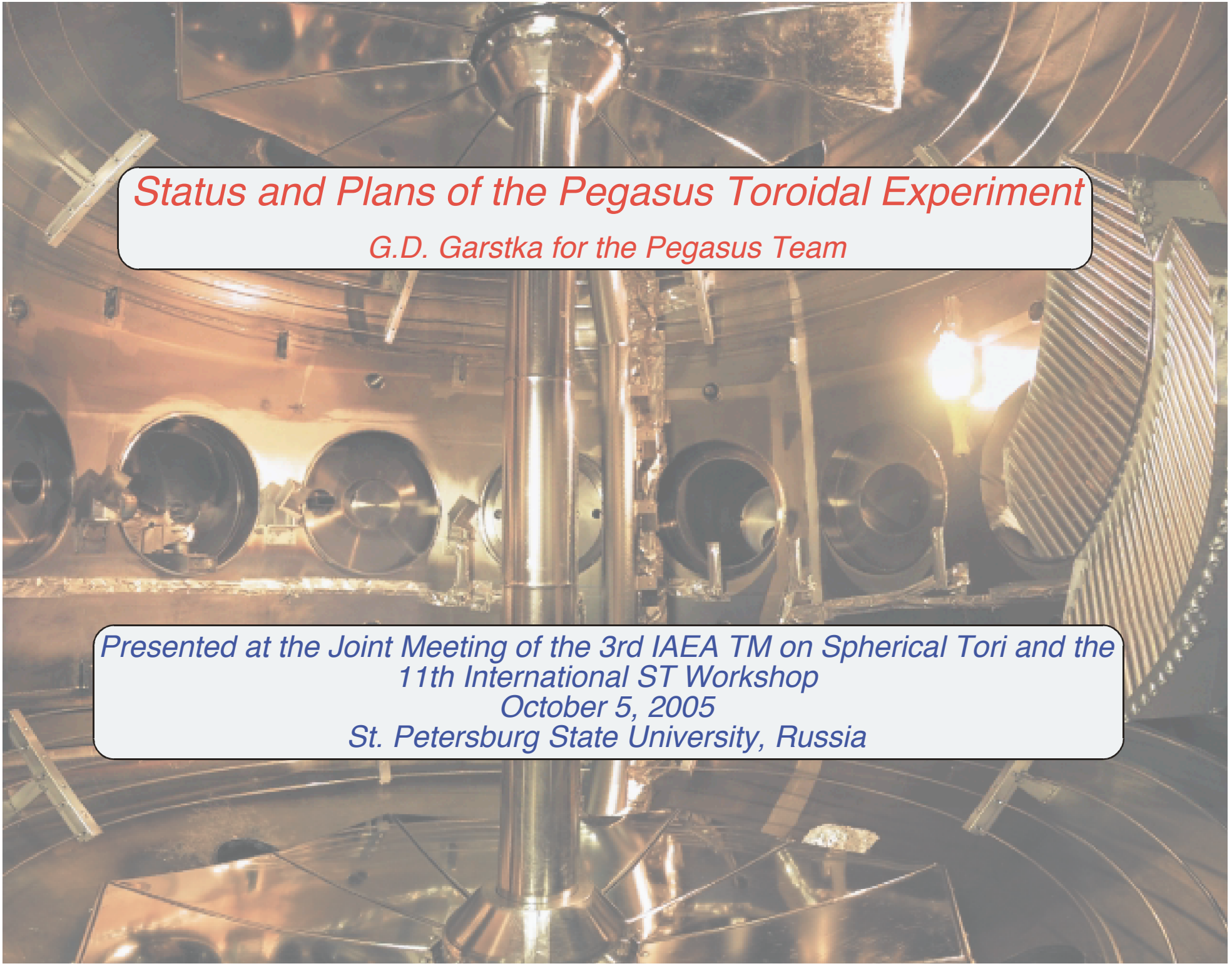


Status and Plans of the Pegasus Toroidal Experiment

G.D. Garstka for the Pegasus Team

Presented at the Joint Meeting of the 3rd IAEA TM on Spherical Tori and the 11th International ST Workshop
October 5, 2005
St. Petersburg State University, Russia

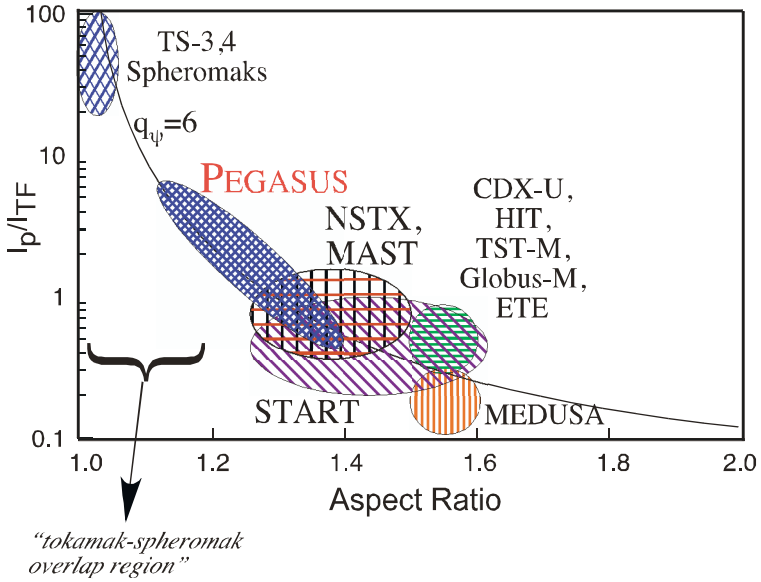
Mission: Explore plasma limits as A→1

Pegasus is 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

Original Goals:

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

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

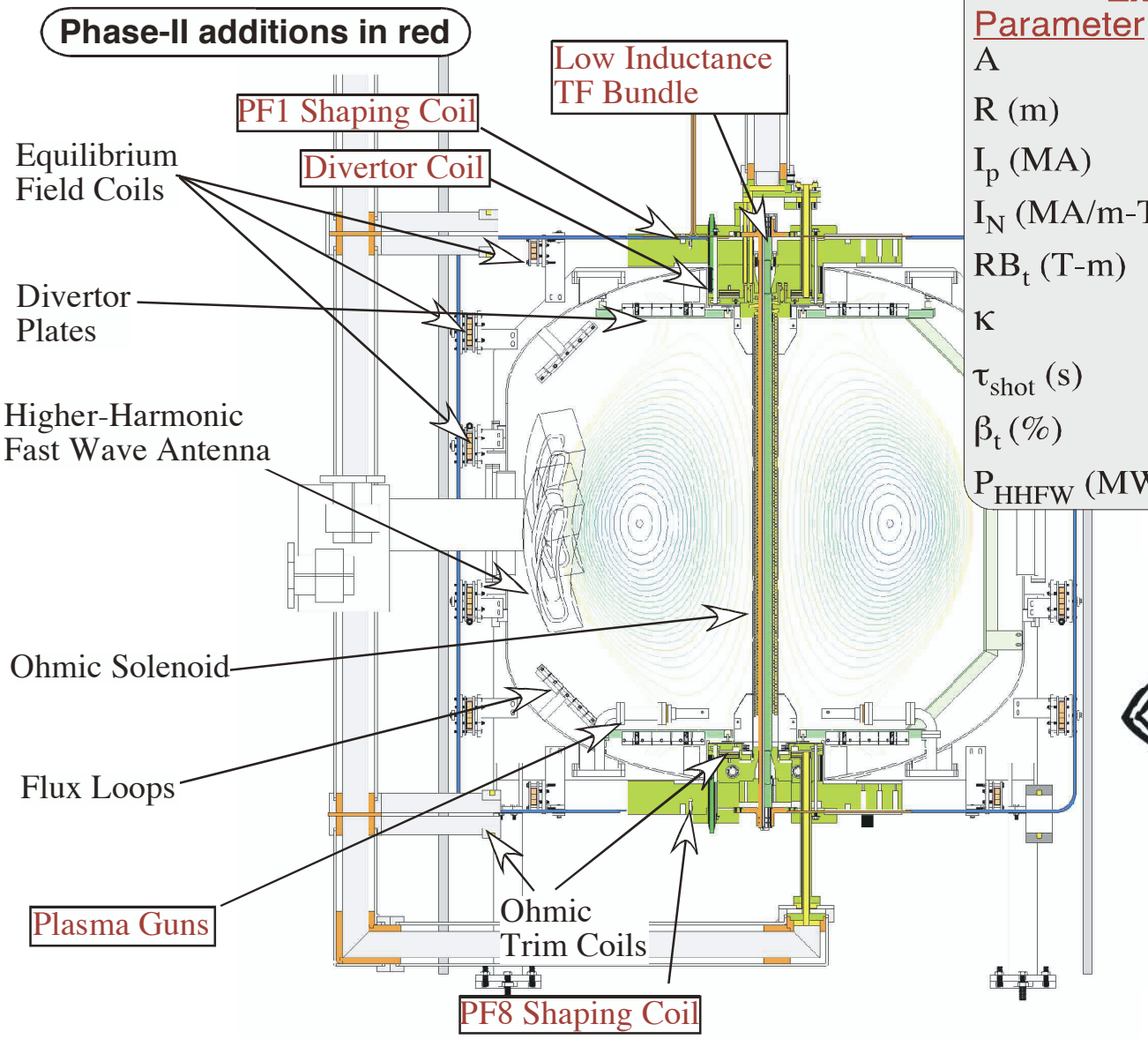


Future Emphases:

- Support ST program movement to next stages
  - *EBW tests for heating & CD (w/PPPL)*
  - *Noninductive startup & CD tests*

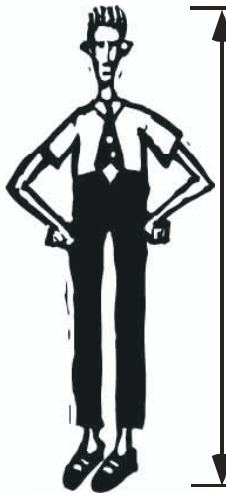
  } *Discussed in this talk*
  - *Diagnostic development*
  - *High-pressure gas puff for deep fueling*

PEGASUS is a university-scale, very-low-A ST



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 ~ 2 meters

Overview

- Phase I of operations: Tearing modes dominate plasma performance
- Transition: Lab rebuilt with many improvements; power supplies dramatically upgraded
- Phase II of operations: Plasma ops resumed, new control exercised
- Stability investigations: High β_t and l_N, and external kink stability
- Noninductive startup: Plasma guns as startup and current drive technique
- Electron Bernstein Waves: Pegasus as testbed for high-power EBW physics

Phase-I plasma operation limited by tearing mode activity

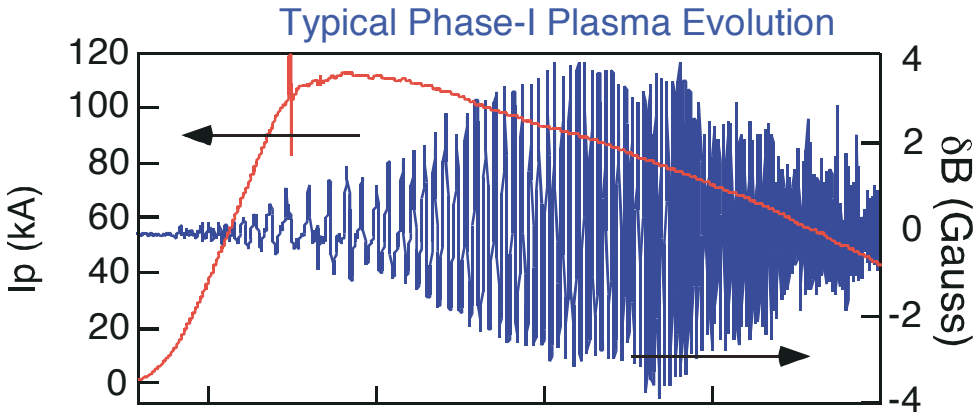
- High I_p/I_{tf} required to obtain high β_t and achieve program goals

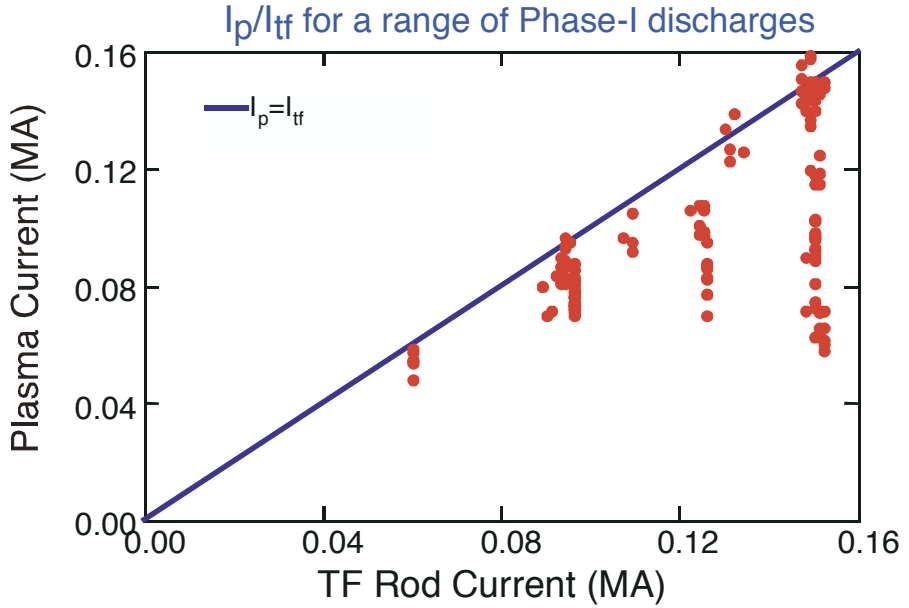
- Plasma current observed to roll over after tearing mode appears
  - w_{sat} estimated to be ≤ a/2

- Resulted in "soft limit" over a range of values of toroidal field:

$$I_p \lesssim I_{tf}$$

  - $I_p = I_{tf}$ roughly correlated with appearance of m/n=2/1 mode near plasma center

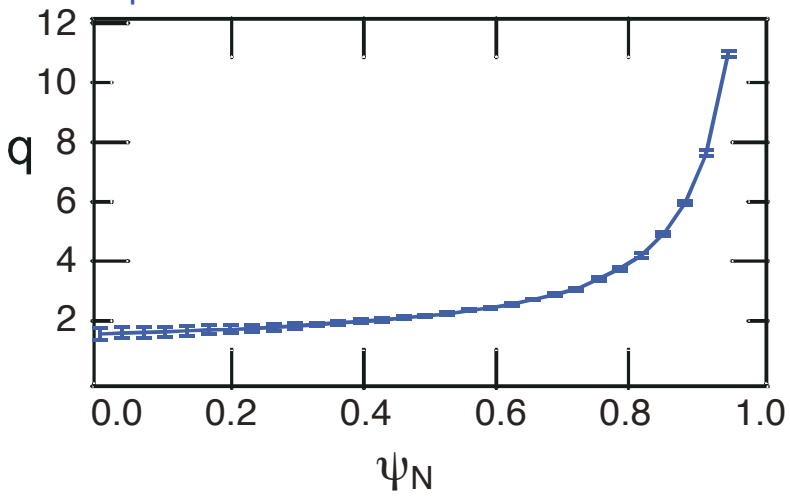




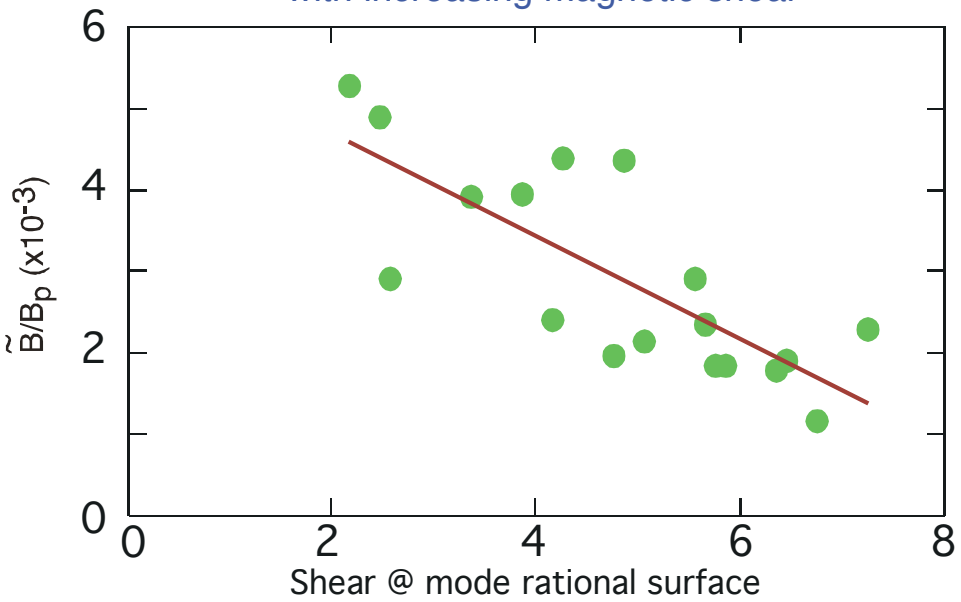
Tearing mode amplitude shown to be controllable

- Measured q-profiles have large region of low magnetic shear near axis
  - Naturally leads to large w_{sat} and increased losses
  - Fast current ramp implies hollow J(r)
- Highest performing discharges ($I_p = I_{tf}$) pushed through m/n=2/1
- Equilibrium analyses:TM amplitude a function of local magnetic shear
- Suggests current profile manipulation will mitigate tearing modes
  - Little profile variation available with simple OH power supply

q Profile measured with SXR emission

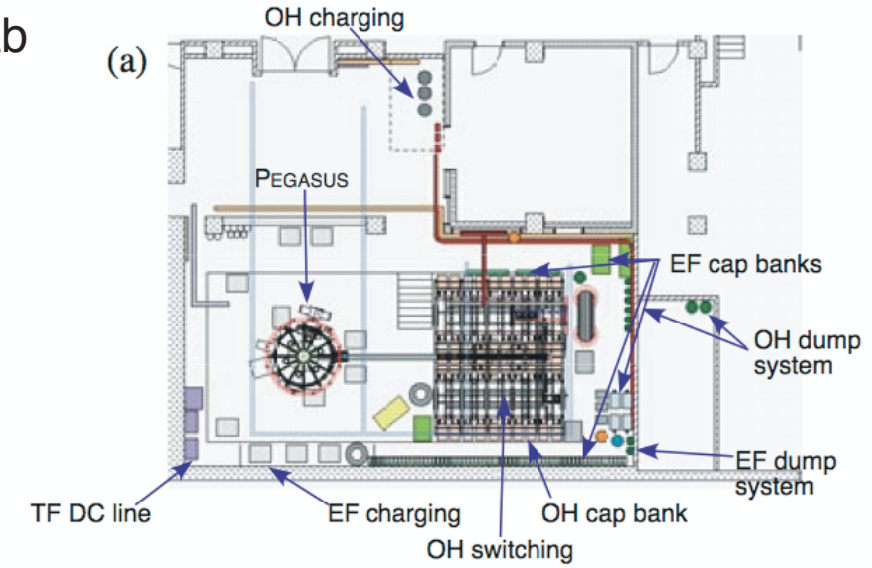


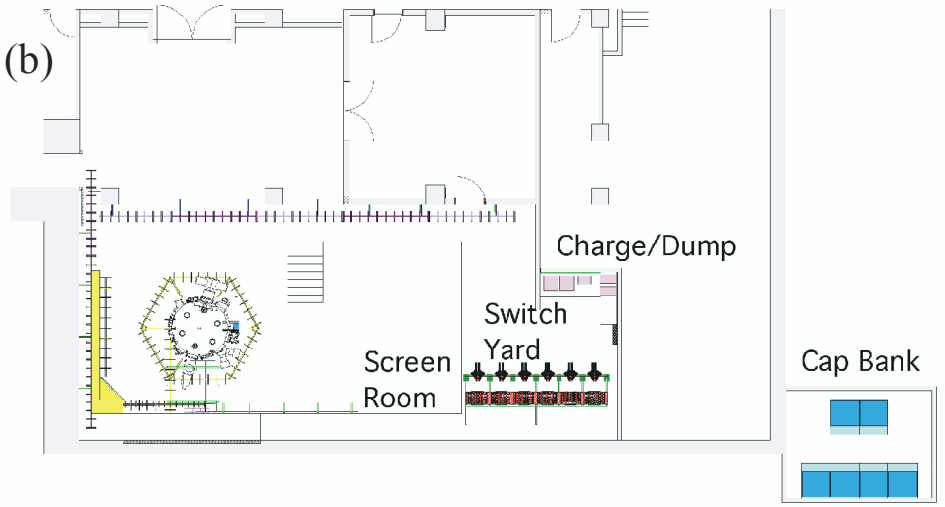
Decrease in TM amplitude
with increasing magnetic shear



Lab totally rebuilt beginning late 2002

- Power supply fire damaged much of lab
- Rebuild incorporated many upgrades:
  - Programmable power supplies
  - Cap banks moved outside building
  - Increased toroidal field
  - Improved signal handling
    = Shielded screen room &
    conduits for control/data signals
  - Improved wall conditioning
    (between-shot Ti gettering)
  - Improved gas handling
  - Rebuilt star ground system
- Low-power operations resumed mid-2004



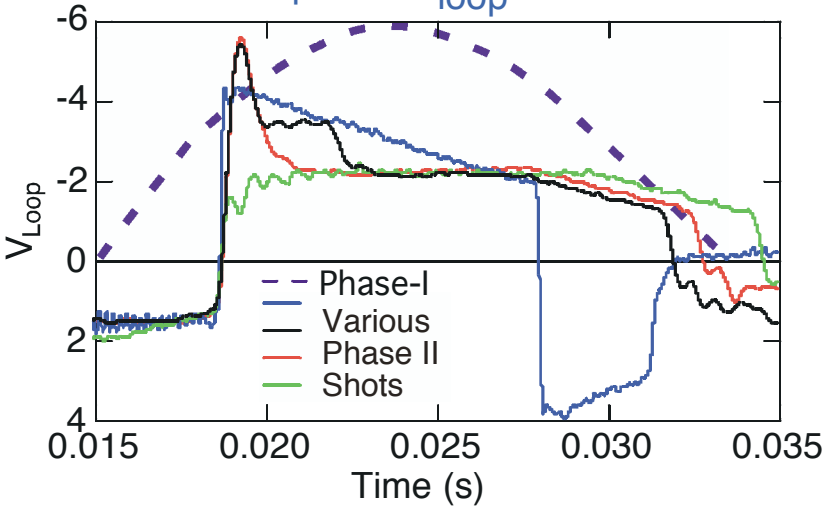


a) Phase I lab layout
b) Phase II lab layout

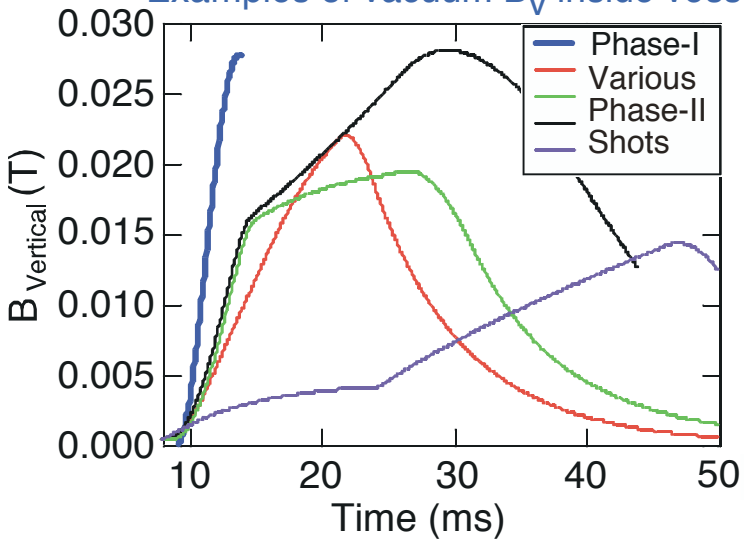
Coil current programming greatly broadens range of operating scenarios

- Phase-I currents: resonant LRC circuits
  - Limited range of V_{loop}, B_v, B_ϕ
- Phase-II currents: highly variable
  - Allows significant variations in plasma evolution
  - OH: V_{loop} control up to 5 V (130 MVA)
    = *OH supplies now coming up to full power*
  - TF: 2x increase in B_ϕ & fast-ramp (35 MVA)
  - EF (85 MVA)
    = *Individual coil control*
    = *Divertor coils*
    = *Strong drive to force field through conducting vessel*

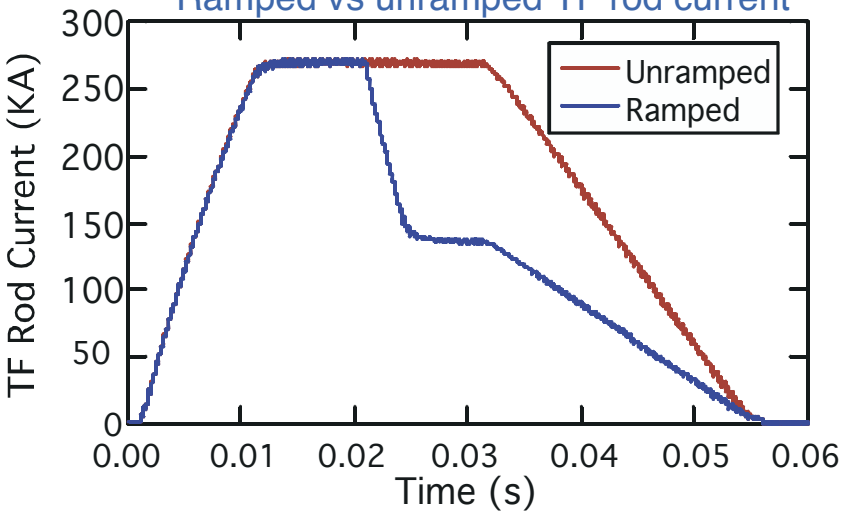
Examples of V_{loop} waveforms



Examples of vacuum B_V inside vessel



Ramped vs unramped TF rod current

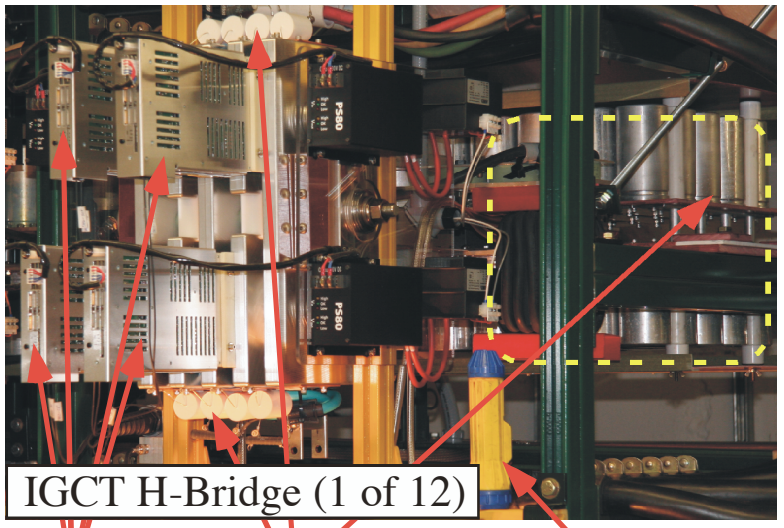


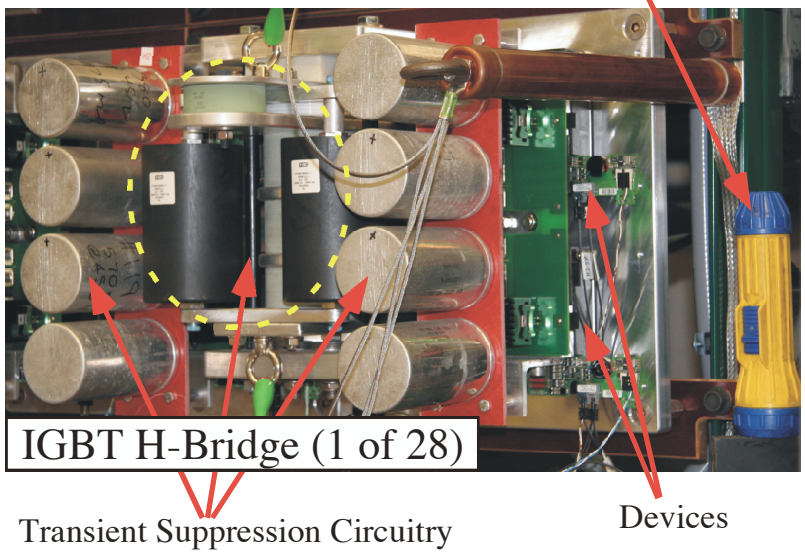
New power supplies vastly superior to Phase-I supplies

- Modulated solid state switches provide programmable current for all coils
  - Switching devices in "H-bridge" configuration
  - Highly reliable and controllable
  - Control via pulse width modulation (PWM)

- IGBT switches: low-power systems
  - Insulated-Gate Bipolar Transistor
  - Established technology
  - Fault detection & interruption capability
  - Each device: 4.8 kA @ 900 V (4.3 MVA)

- IGCT switches: OH system
  - Integrated Gate-Commutated Thyristor
  - Higher power to match OH solenoid:
    Each device: 4 kA @ 2700 V (10.8 MVA)
  - Newer technology without interruption capability
    = *has required significant debugging time*

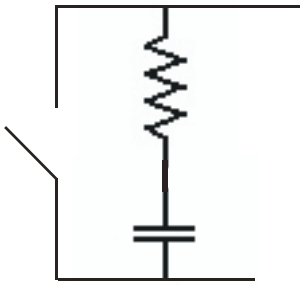




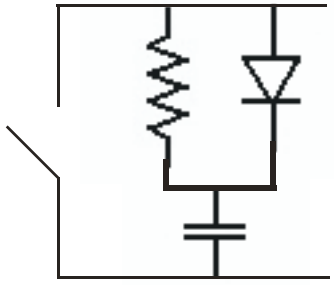
Transient suppression crucial with H-bridge switches

- Switching events produce inductive voltage transients
  - -V=LdI/dt
  - Fast switch-turn-off ⇒ voltage spikes
    - = *Some transients < 80 ns*
- Transients can be damaging
  - Switch diodes especially sensitive
    - = *Can lead to switch failure*
  - Joint & transmission line arcing
- High-power snubbers required for operation
  - R-C or R-C-Diode across components
  - Set time scale to match spikes
  - Absorb transient energy

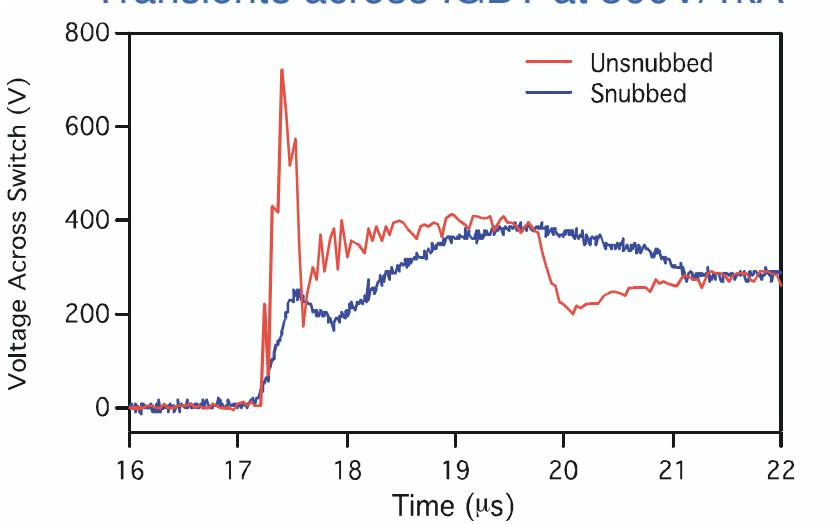
RC



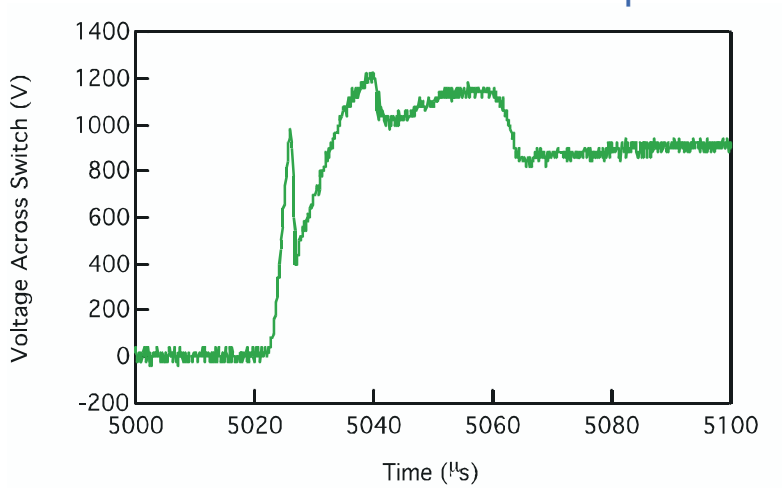
RCD



Transients across IGBT at 300V/1kA

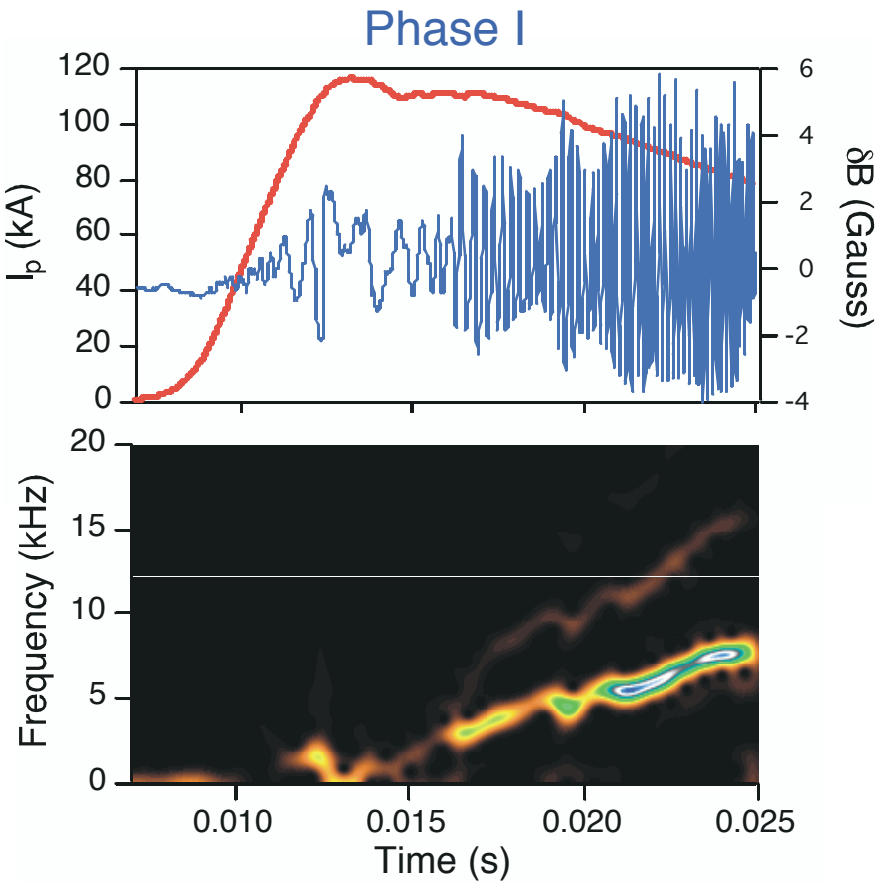


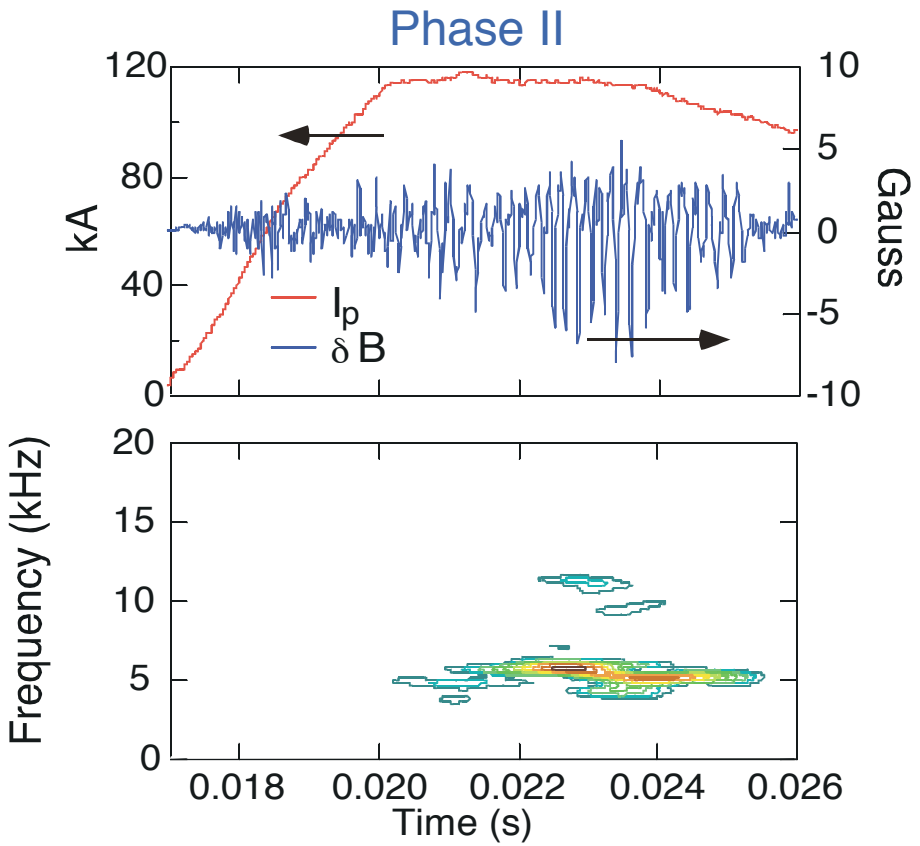
Snubbed Transients at full power



Phase I operating space recovered

- Phase I plasmas reproduced in Phase II
  - Similar density, shape, MHD, etc.
- Limited V-s have proscribed high I_p/I_{tf} experiments
  - IGCT power supplies coming up to full power late 2005

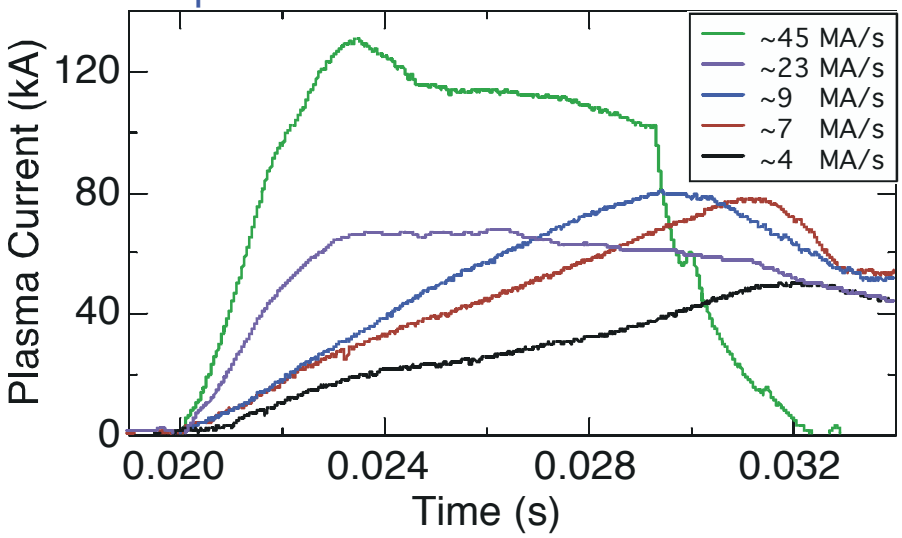




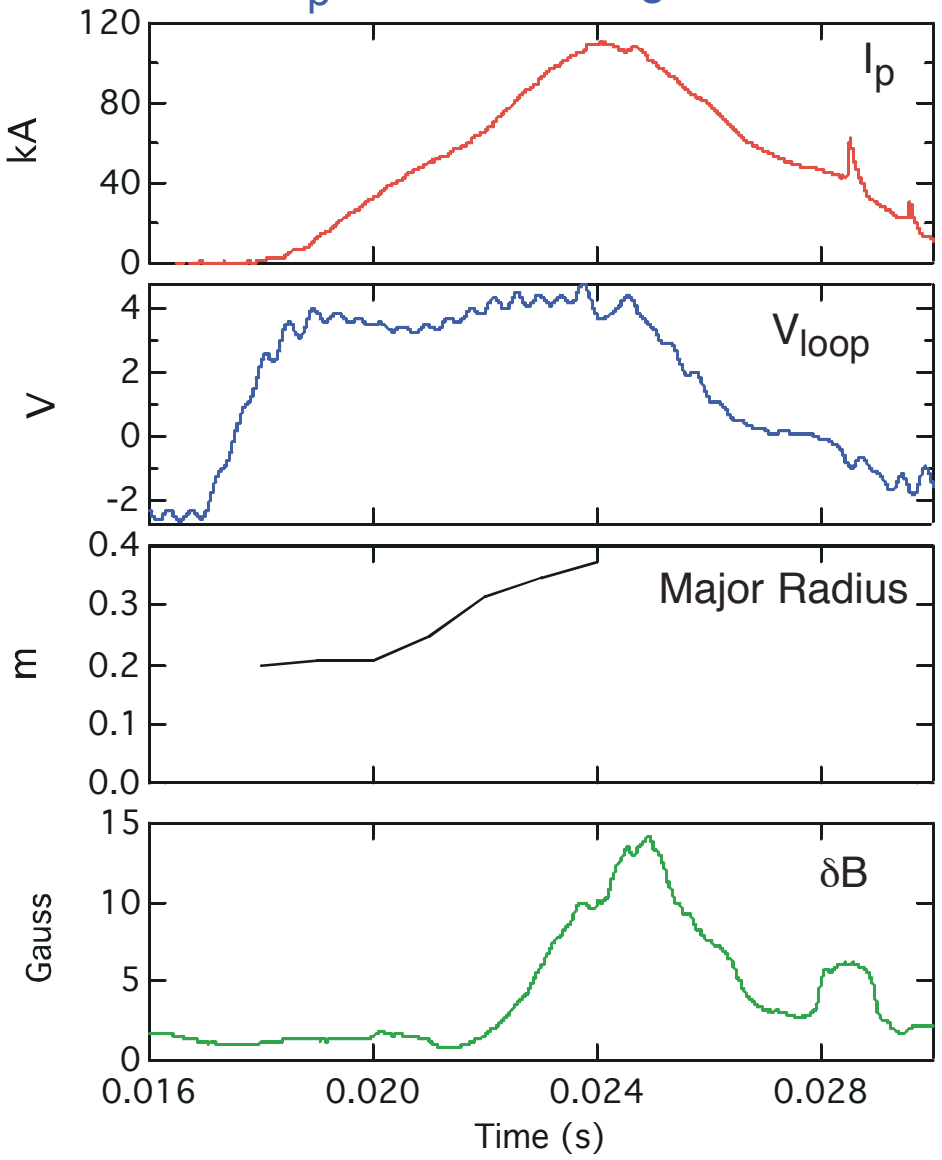
Pre-programmmed control being established

- Control tools coming into routine use
  - Gas puffing to peak J(r)
  - Reduced dI_p/dt
  - Radial position control
  - Increased V_{loop}
- Plots on right: control tools used to maintain current ramp through TM
  - V_{loop} control runs out @ 23.5 ms
  - Radial position evolved as desired

I_p ramp rate control demonstration

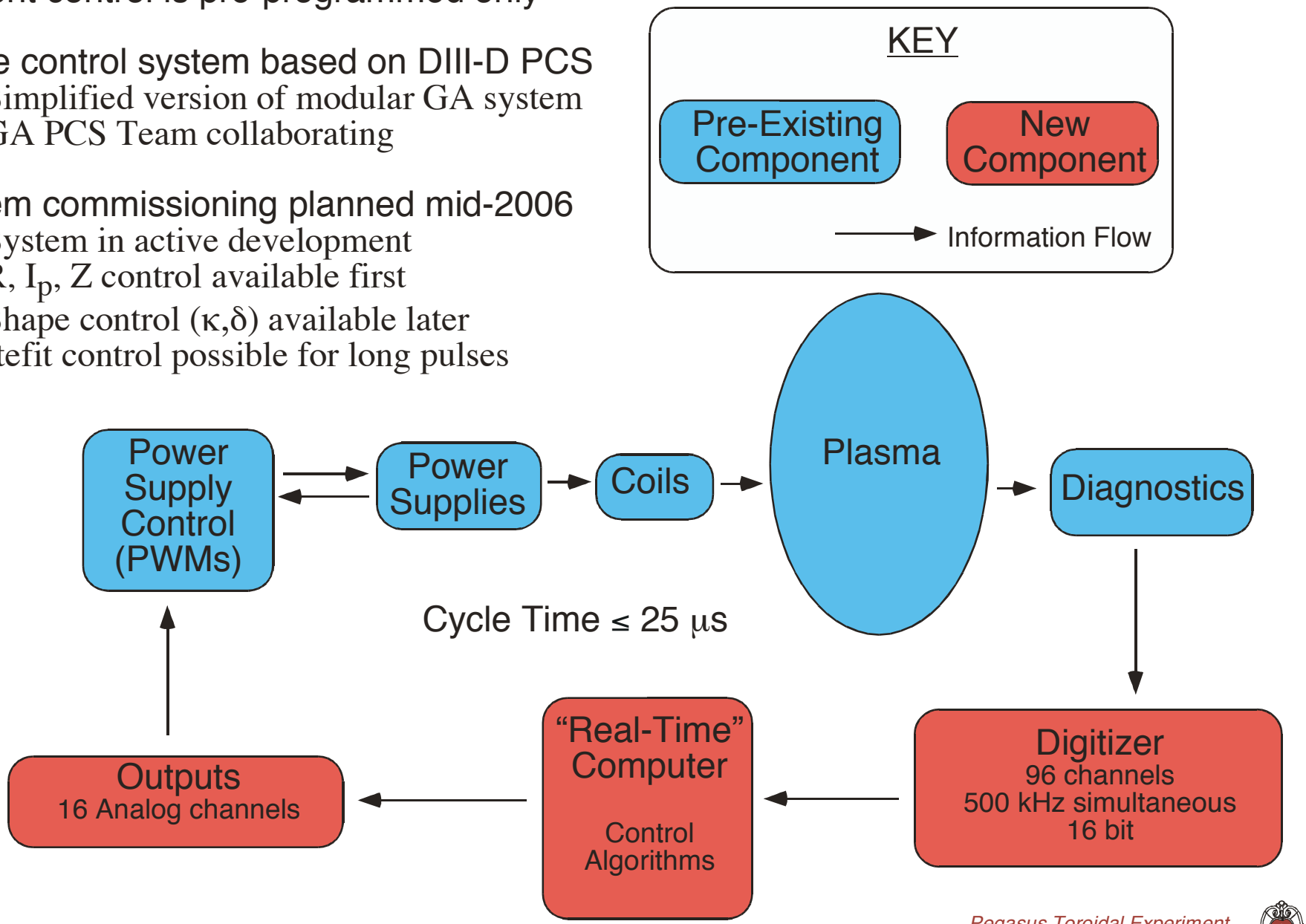


I_p-dot held through TM



Active plasma control system being implemented

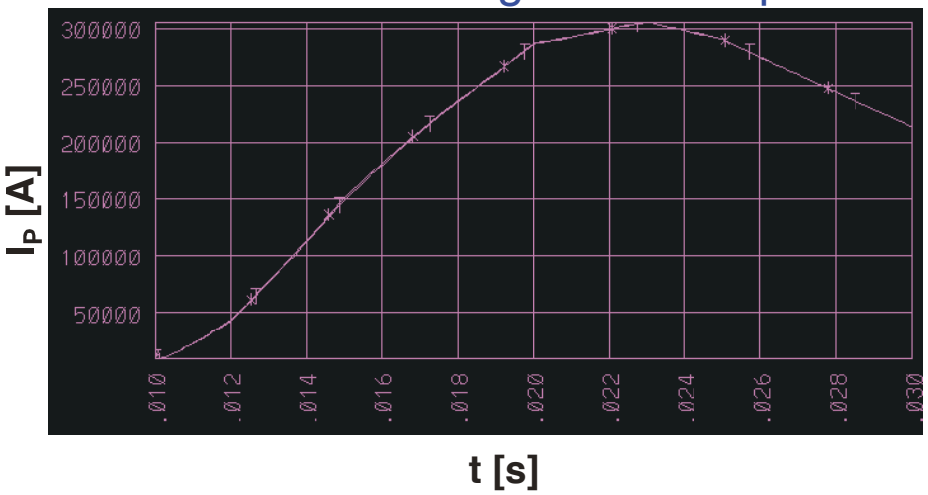
- Present control is pre-programmed only
- Active control system based on DIII-D PCS
  - Simplified version of modular GA system
  - GA PCS Team collaborating
- System commissioning planned mid-2006
  - System in active development
  - R, I_p, Z control available first
  - Shape control (κ,δ) available later
  - rtefit control possible for long pulses



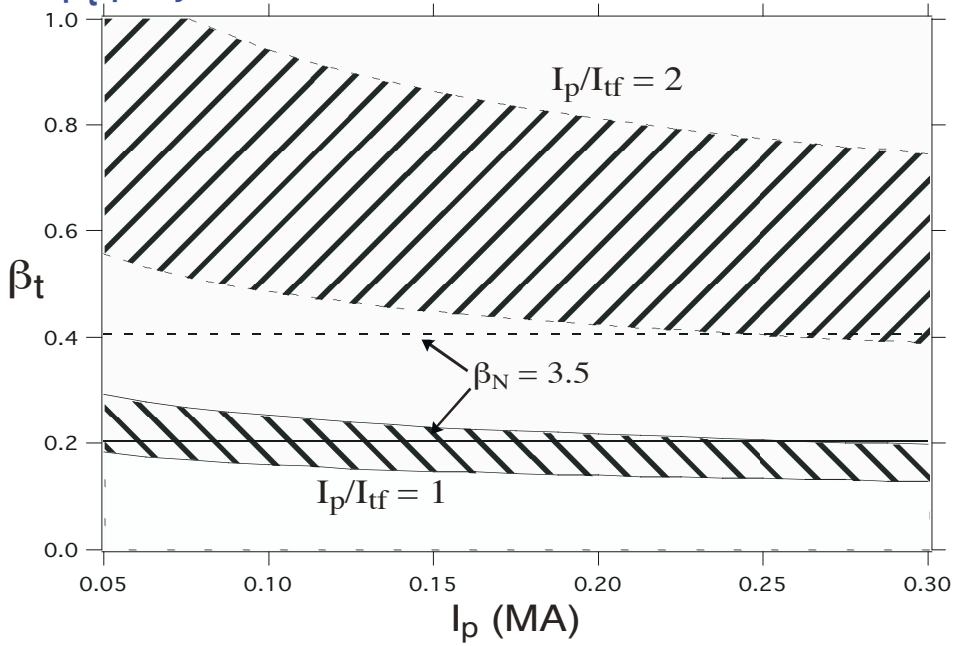
Near-term goal: attain high I_N, β_t

- Pegasus main goal: explore stability & confinement in this region
- Full ohmic flux: 90 mV-s
  - Flux consumption calculations indicate 300 kA I_p attainable
  - TSC modeling corroborates
    $= I_p/I_{tf} = 2$
    $= I_N \sim 12$ 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

TSC model of Pegasus startup



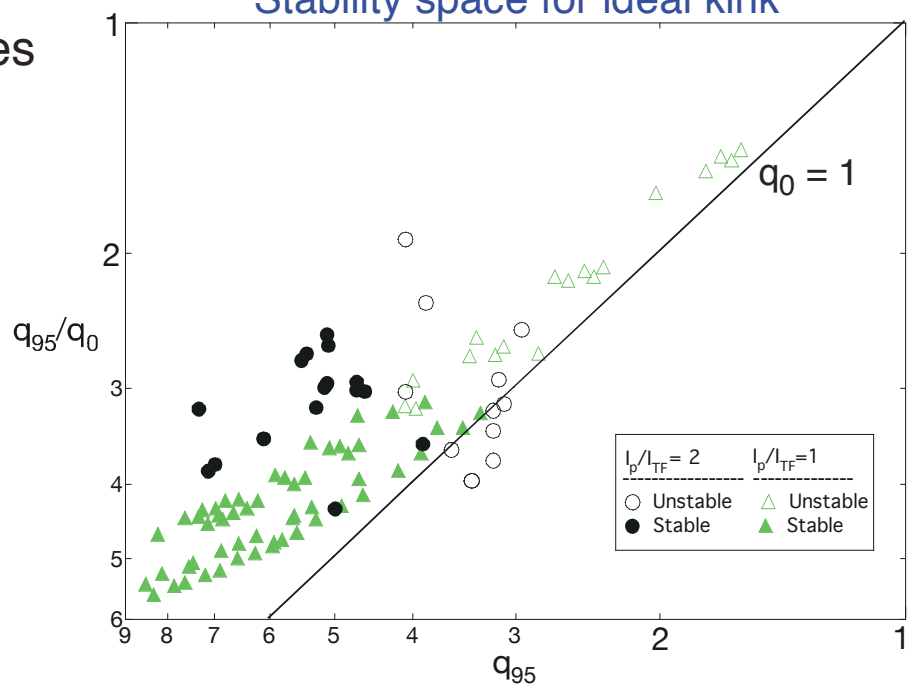
β_t projections based on confinement models



Modeling of ideal stability space ongoing

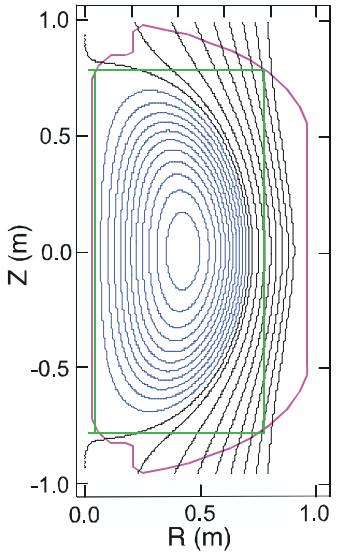
- DCON used to find ideal stability boundaries
  - External kink is likely limiting instability
  - $q_{95} > 4$ indicated as kink limit
- Stable equilibria found with $l_p/l_{tf} = 2$

Stability space for ideal kink



Stable equilibrium with $l_p/l_{tf} = 2$ (DCON)

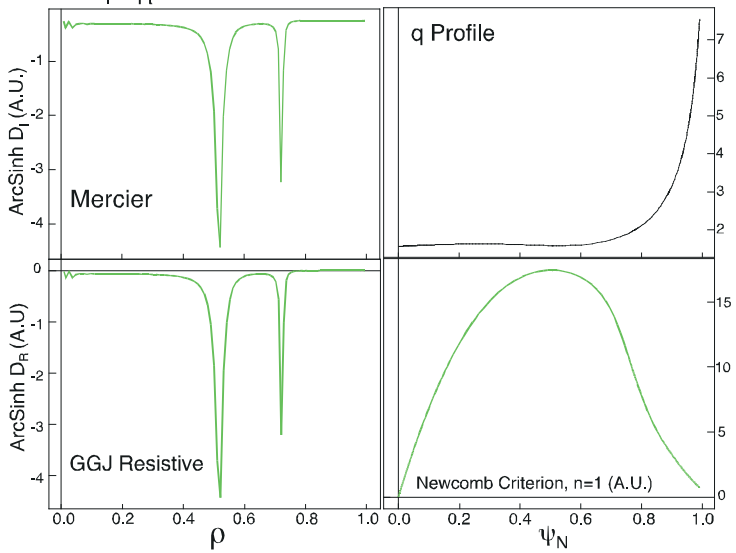
Flux Plot



Equil. Parameters

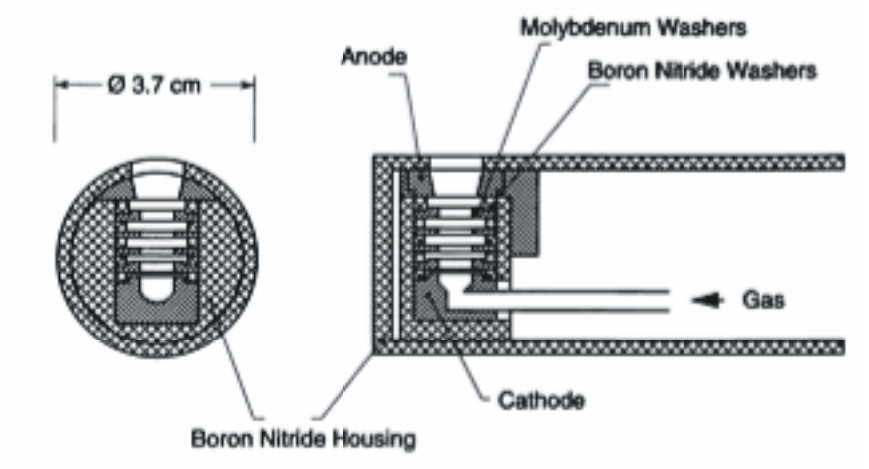
I_p	290000 A
I_N	12
I_p/I_{tf}	1.93
l_i	0.59
q_0	1.5
R_0	0.39 m
a	0.34 m
κ	2.2
q_{95}	4.8

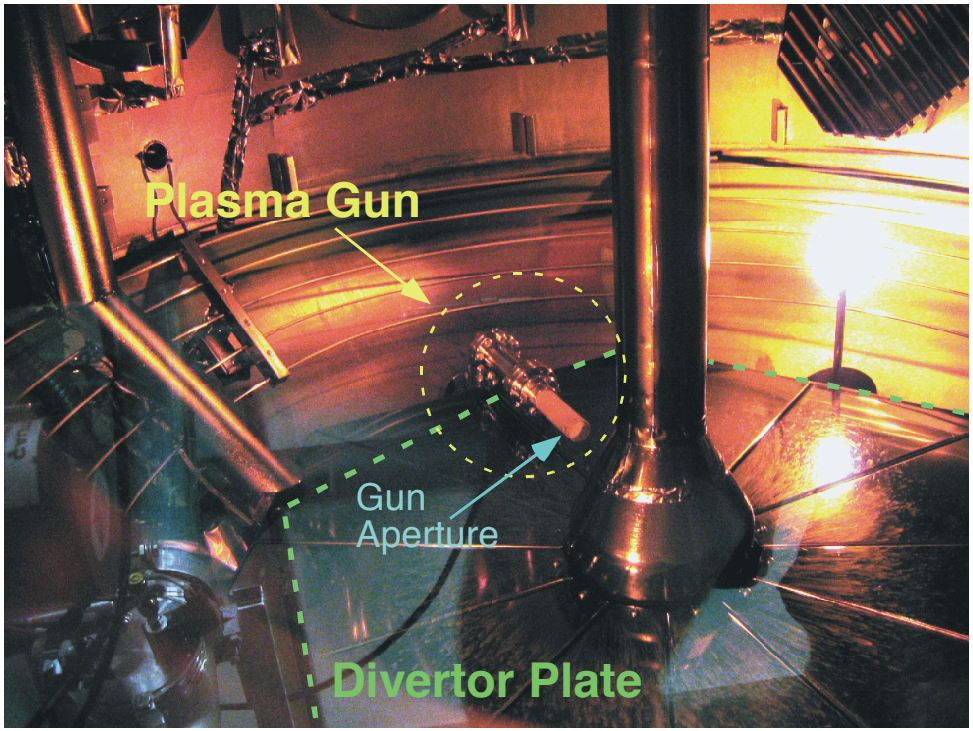
$D_I, D_R > 0$ => Unstable



Plasma injectors being used to study noninductive startup

- Limited OH flux provides impetus to investigate other CD techniques
- Use high-current, low-impurity washer guns
  - $I_{gun} \sim 1$ kA
  - $T_e \sim 10$-20 eV
  - $n_e \sim 2 \times 10^{20}$ m^{-3}
- Two guns presently located in lower divertor region
- Operation is straightforward
  - Guns biased up to -900 V wrt vessel
  - Helical field lines established by operating vertical & toroidal fields
  - Plasma injected onto field lines and flows to top divertor plate
  - Net toroidal current is produced

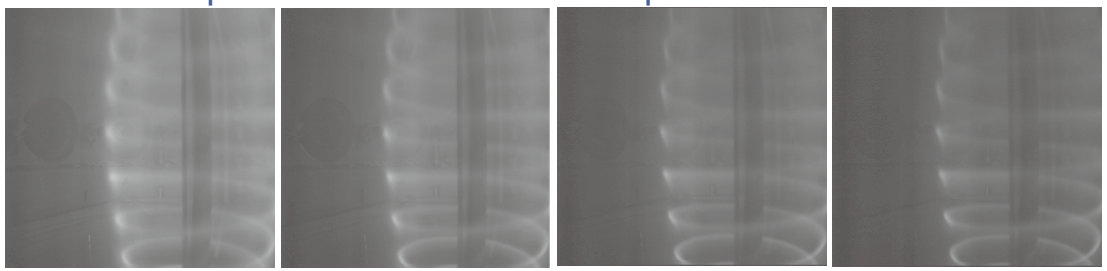




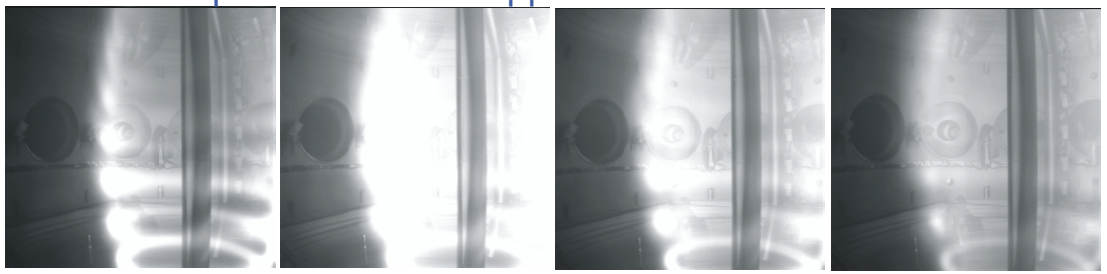
Current streams merge if input power high

- Nature of produced plasma changes as bias increased:
  - Low bias voltage:
    - = $I_{toroidal} = (I_{gun})$ x (geometric windup)
    - = plasma appears as separate streams
  - High bias voltage:
    - = $I_{toroidal} = (I_{gun})$ x (geometric windup) x (additional multiplication)
    - = streams merge into uniform-appearing plasma
- No evidence yet of closed flux surfaces
- Two guns found to add to $I_{toroidal}$ linearly

50 V bias: plasma streams remain separate

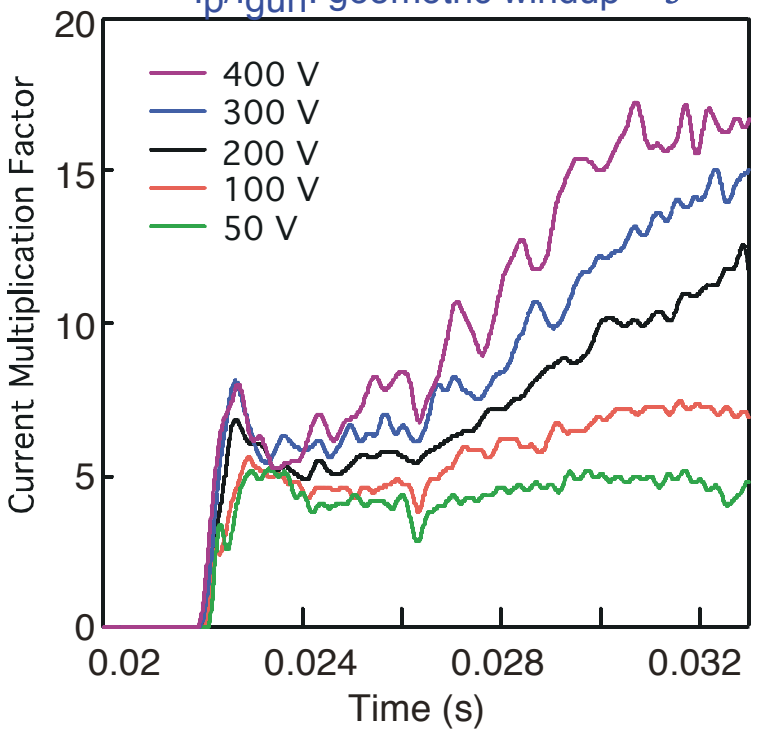


400 V bias: plasma streams appear to reconnect



1 ms per frame

I_p/I_{gun}: geometric windup ≈ 5

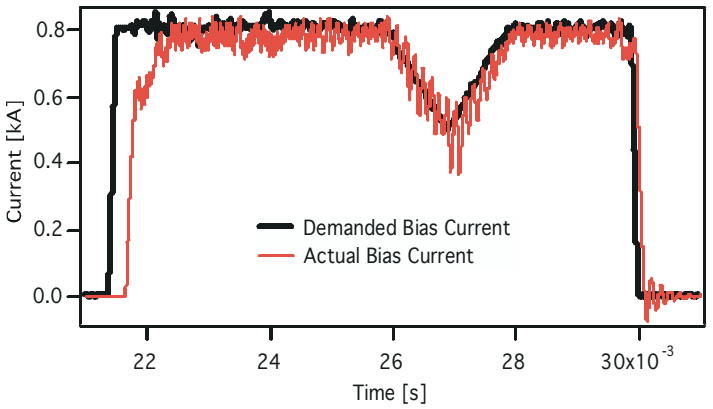


Gun-driven non-inductive startup will be a main thrust

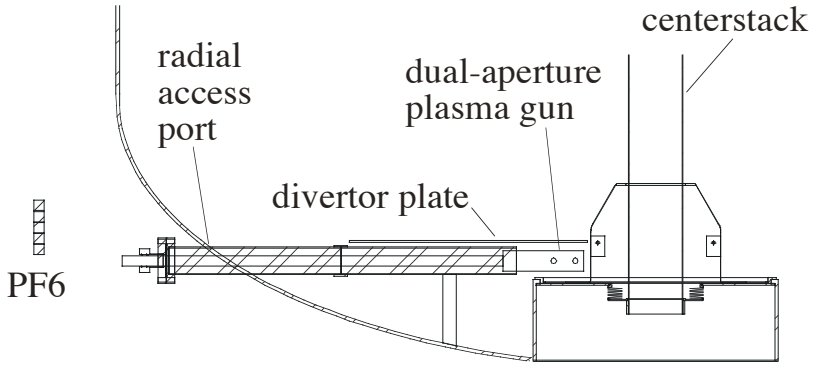
- Short-term aims:
  - Establish reliable feedback control of I_{gun} with PWM circuit
  - Determine conditions necessary for flux surface closure
    = *possibly install 3rd gun*
  - Establish reliable handoff to ohmic current drive

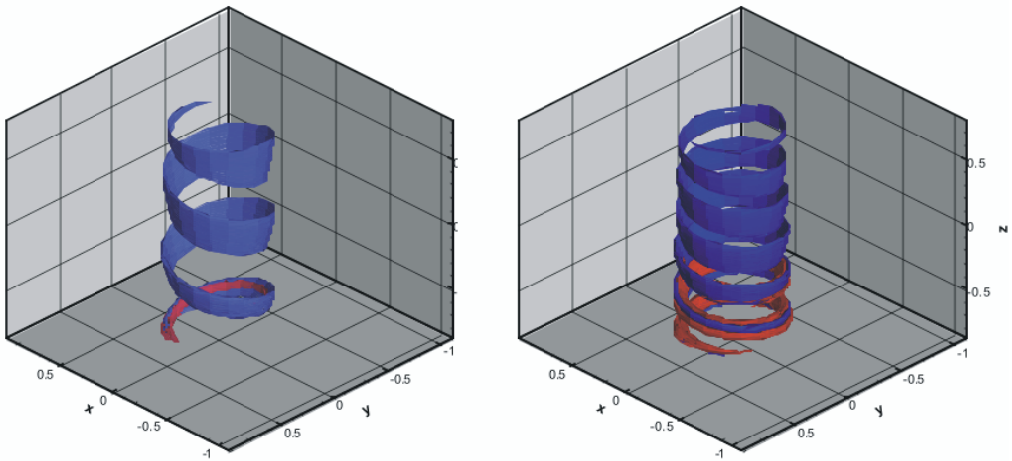
- Longer-term aims:
  - Install 12-gun array (6 x 2-gun assemblies)
    = *theoretically can drive up to 100 kA $I_{toroidal}$*
    = *significant savings in V-s (30-40%) possible*
  - Model evolution beyond helicity balance arguments
    = *use NIMROD code*
    = *mean poloidal field structures vs true flux closure?*
    = *role of global tearing instabilities?*

Demonstration of gun current control



Conceptual design of dual-gun assembly

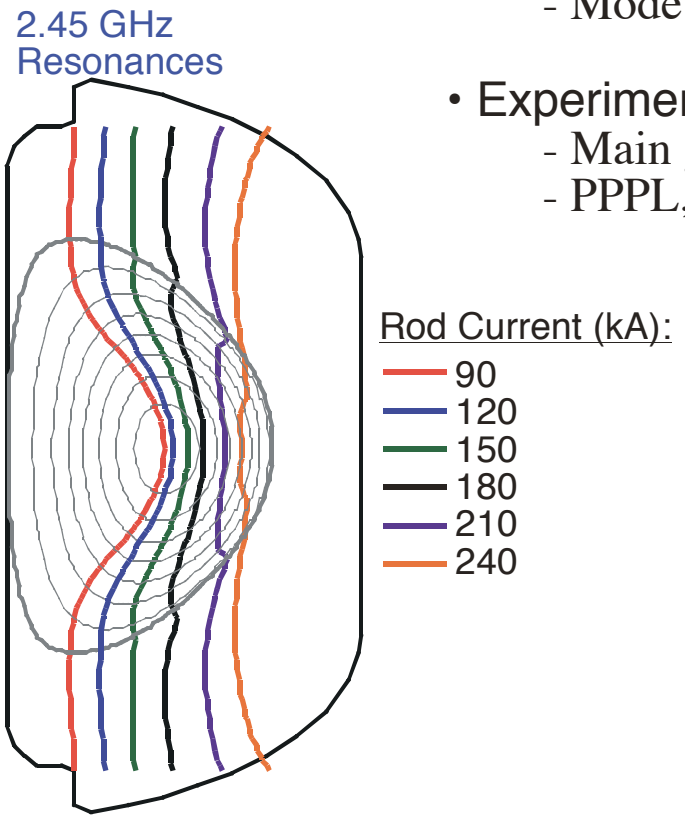


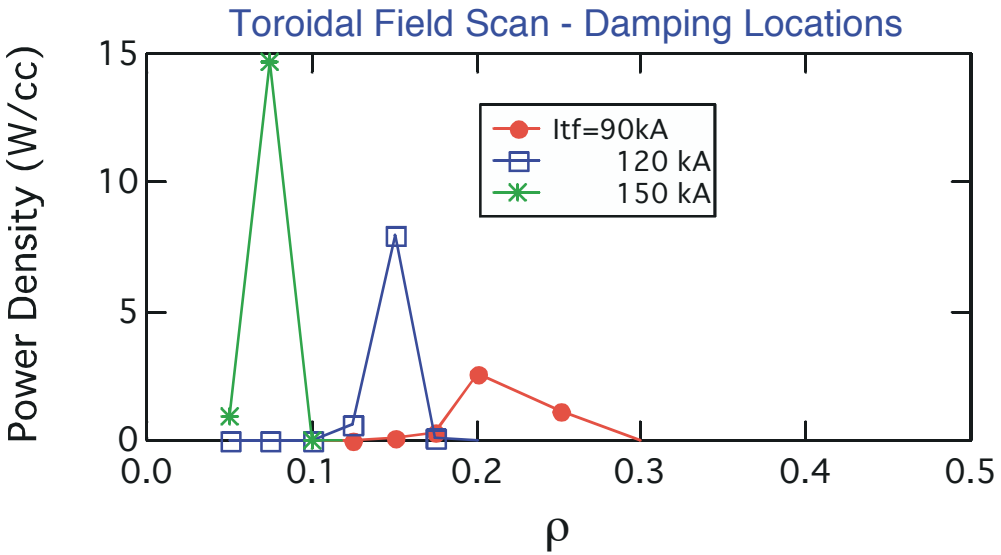


NIMROD models of $J_{||}$ iso-surfaces (C. Sovinec)

High-power EBW tests are planned

- Pegasus provides a convenient test bed for EBW physics tests
  - Toroidal field a good match for existing 2.45 GHz sources
  - Plasma control system to provide good edge coupling
  - Moderate machine size provides great experimental flexibility
- Significant physics can be performed at this scale
  - Validation of raytracing/power depostion/CD models
  - Effects of nonlinear parasitic instabilities
  - Mode conversion studies
- Experiments will be a collaborative effort
  - Main goal is support of NSTX experiments
  - PPPL, ORNL, CompX involved to date

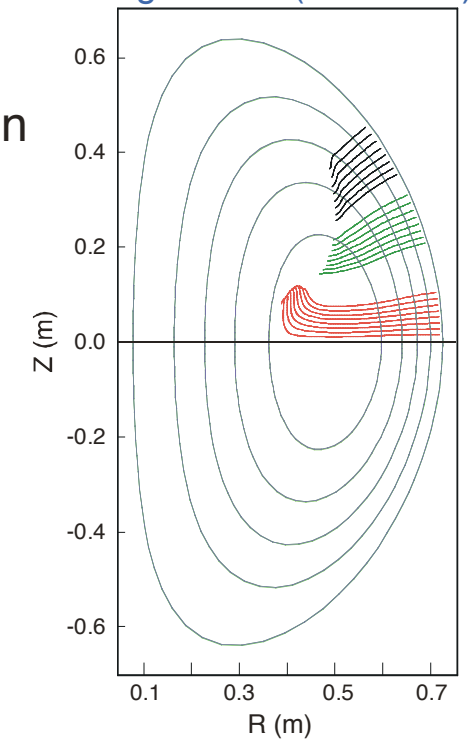




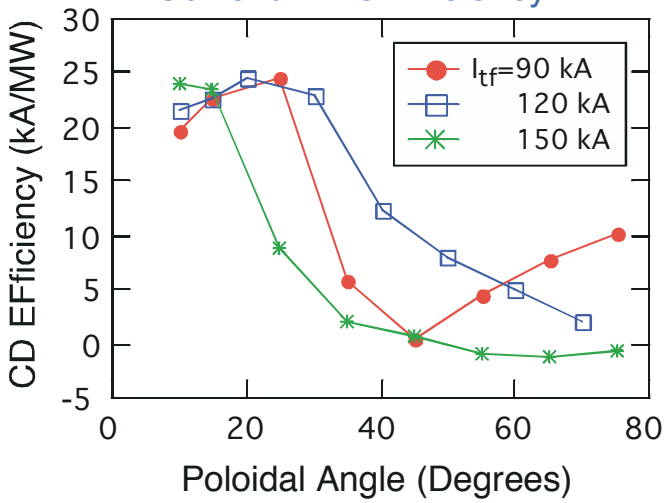
EBW modeling underway in support of heating & current drive experiments

- Focus primarily on O-X-B conversion scenario
- GENRAY/CQL3D used primarily for raytracing & power deposition
  - S. Diem & G. Taylor (PPPL) chief collaborators
- First studies have concentrated on accessibility & scope
  - Near-midplane antenna found to be optimal
  - Waves propagate for a wide range of B, n_e, and T_e
- Current drive primarily by Fisch-Boozer mechanism
  - No studies of Ohkawa effect have ben performed
  - Dimensionless CD efficiencies up to 0.5 predicted

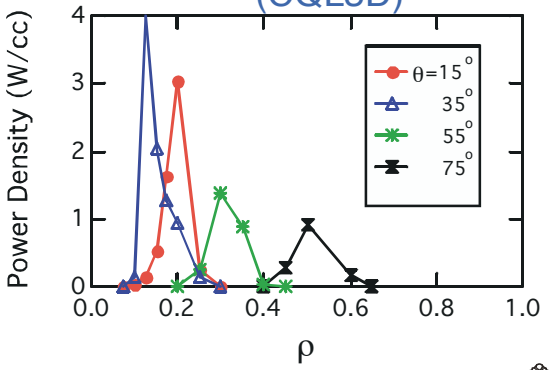
Injection Angle Scan (GENRAY)



Current Drive Efficiency



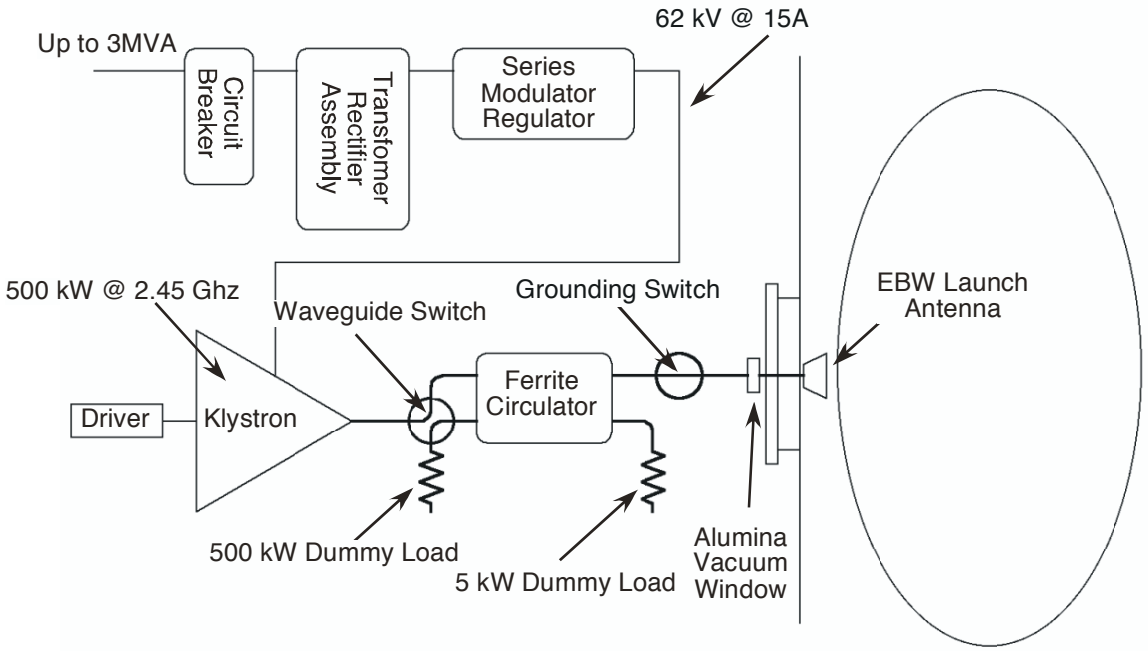
Power Deposition from Injection Angle Scan (CQL3D)



Up to 1 MW of RF power is planned for EBW experiments

- Significant hardware has been made available
  - PPPL: supplying PLT LH system components
    = *klystrons, recirculators, arc detectors, etc.*
  - ORNL & LANL: offered high-voltage klystron power supplies
- Hardware scheduled to begin arriving late 2005
- First heating experiments planned late 2007

Conceptual system schematic



500 kW, 2.45 GHz Klystron



Summary

- Phase I plasma physics dominated by persistent low m/n tearing modes
- Lab rebuilt for Phase II with significant upgrades
- Increased power & control will allow completion of program goals
  - To date, plasma performance matches Phase I & improved control demonstrated
- Future plans fulfill Pegasus original mission and extend it:
  - Stability and confinement studies at high I_N and β_t
  - Noninductive startup & sustainment via plasma guns
  - High-power EBW heating and current drive tests