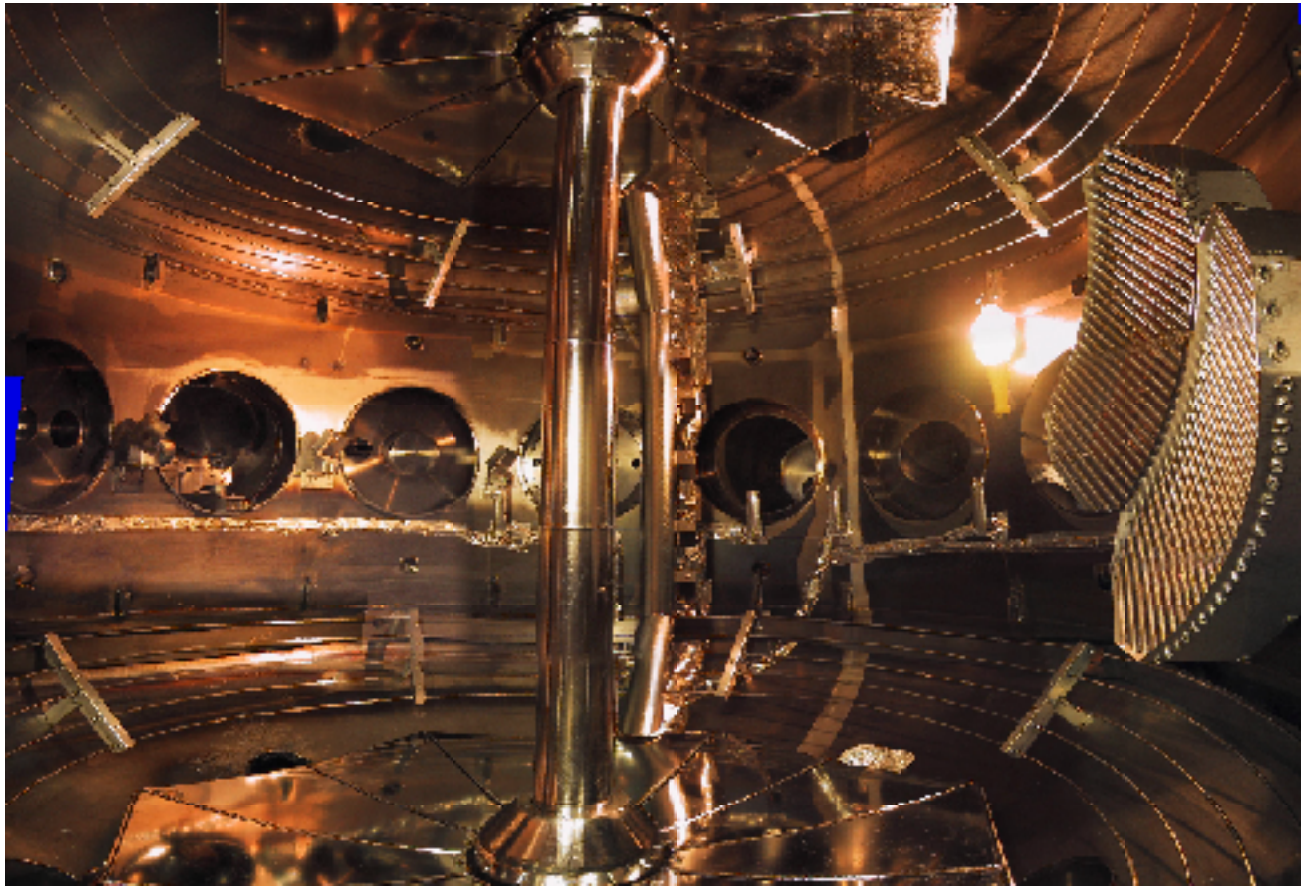
PLASMA STUDIES AT HIGH NORMALIZED CURRENT IN THE PEGASUS EXPERIMENT

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presented to the
46th Annual Meeting
of the APS Division of
Plasma Physics
Savannah, GA
Nov. 15-19, 2004



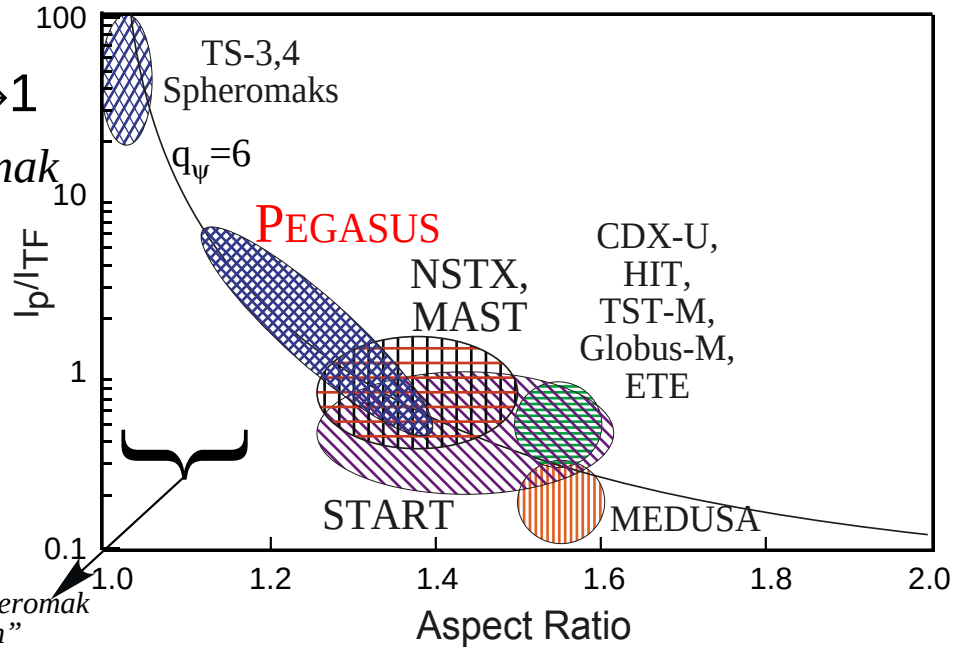
Explore plasma limits as A→1

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

Primary Pegasus Goals:

- Stability and confinement at high I_p/I_{TF}
  - *Extension of tokamak-like studies*
- Limits on β_t and $I_N \sim 6I_p/I_{TF}$ (kink) as A→1
  - *Overlap between the tokamak and the spheromak*

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

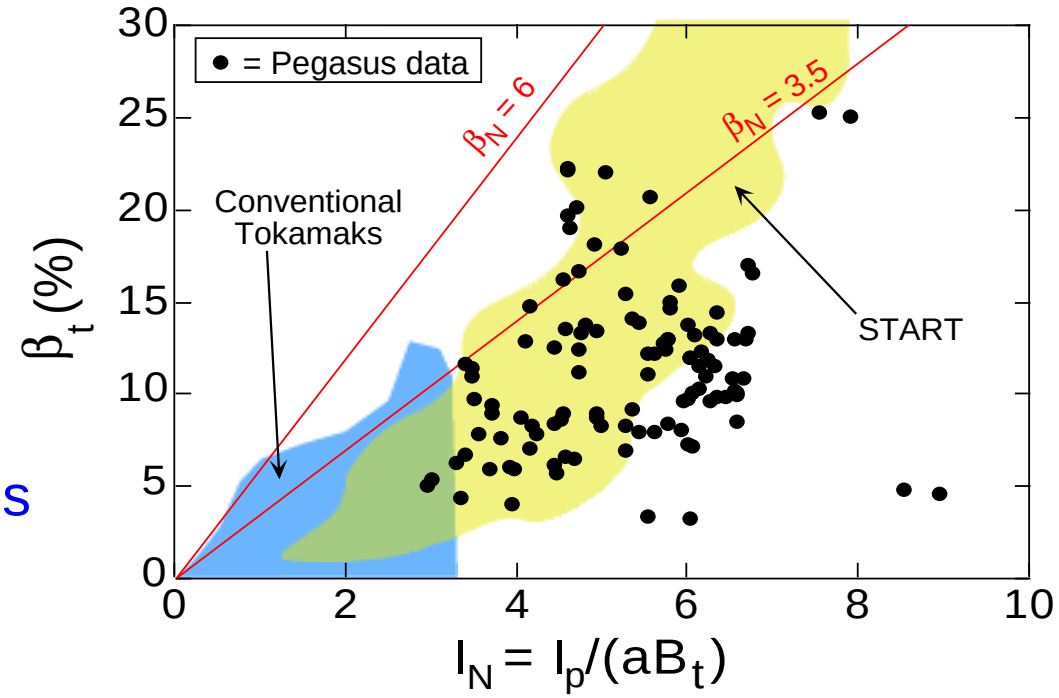


Planned Future Emphases:

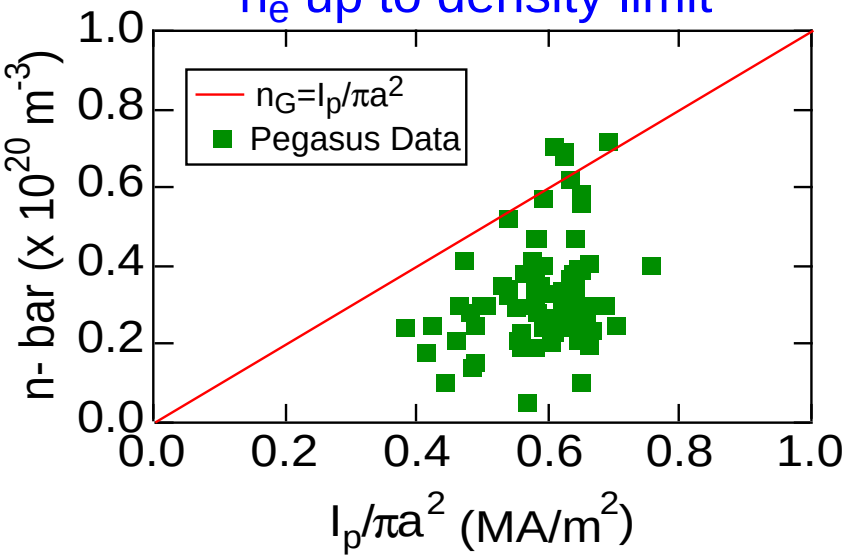
- Support ST program movement to next stages
  - *Noninductive startup tests*
  - *EBW tests for heating & CD (w/PPPL)*
  - *Novel divertor design tests (w/UT)*

Phase I demonstrated low-A characteristics

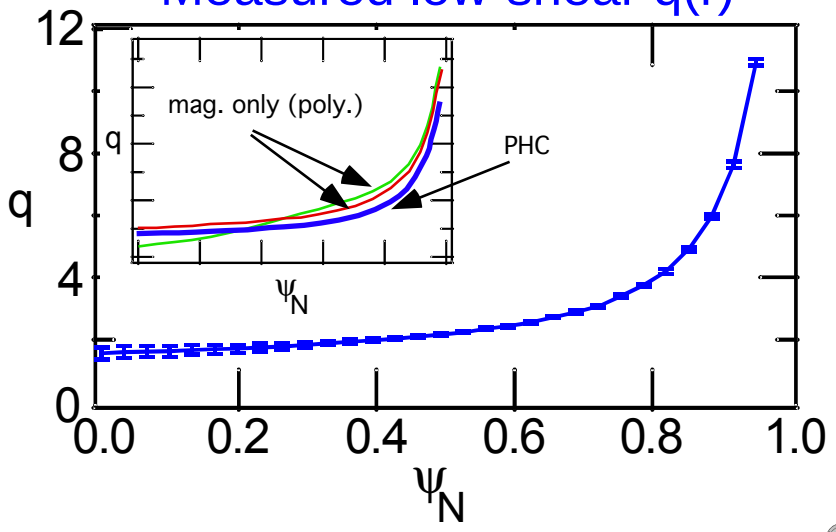
- A ~ 1.1 via OH
  - High field/stress solenoid
  - Very low TF (< 0.1 T)
  - HHFW available
- Low field, ohmic only
  → high I_N & β_t
- Resonant L-C power systems
  - Fixed waveform evolution
  - Low l_i, low shear



$\bar{n}_e$ up to density limit



Measured low-shear q(r)



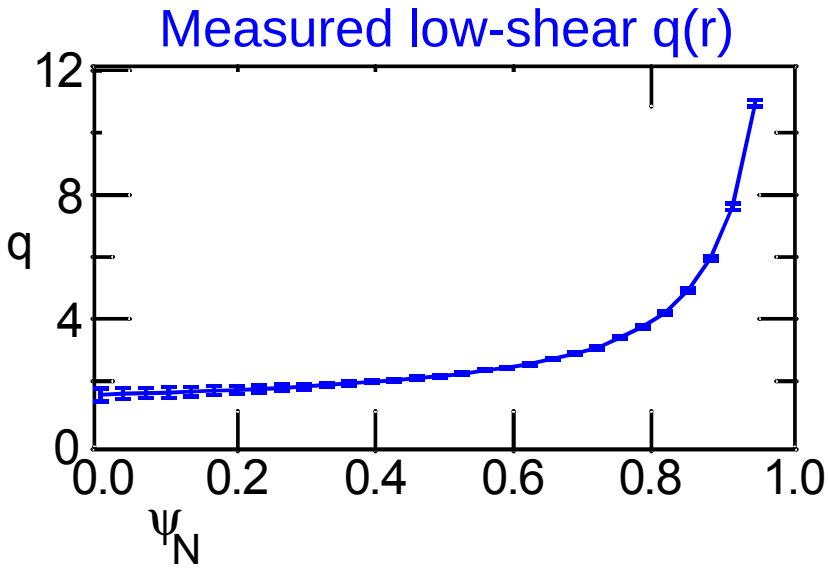
Phase I: An $I_p/I_{TF} \approx 1$ soft limit observed

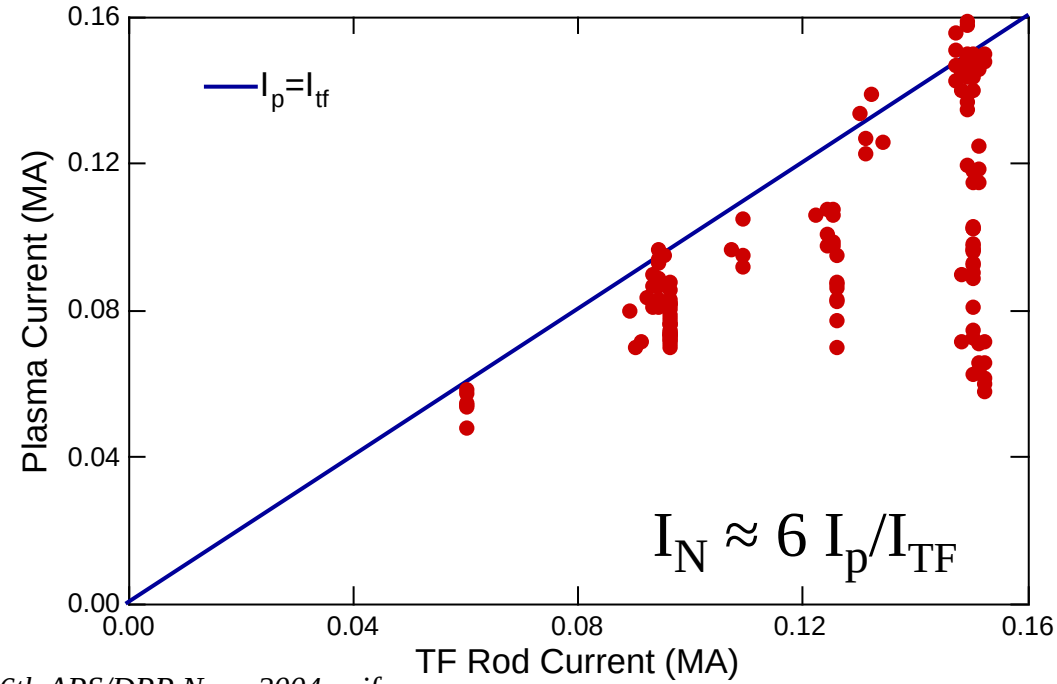
Large resistive MHD instabilities as TF ↓

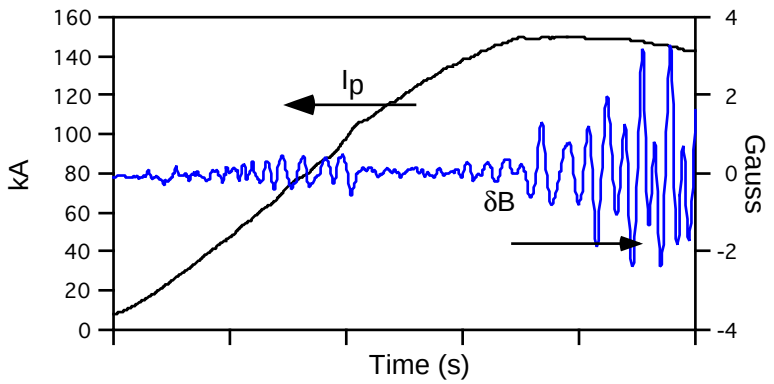
- low B_t and fast $dI_p/dt \rightarrow$ early appearance of low-order q=m/n at low T_e
- ultra-low A, low $l_i \rightarrow$ low central shear

$\Rightarrow$ Rapid growth of 2/1, 3/2 tearing modes and large saturated island widths

- $I_p/I_{TF} \approx 1 \Rightarrow q_0 \approx 1.5$ - 2
- plus reduction of V-sec as TF⇓



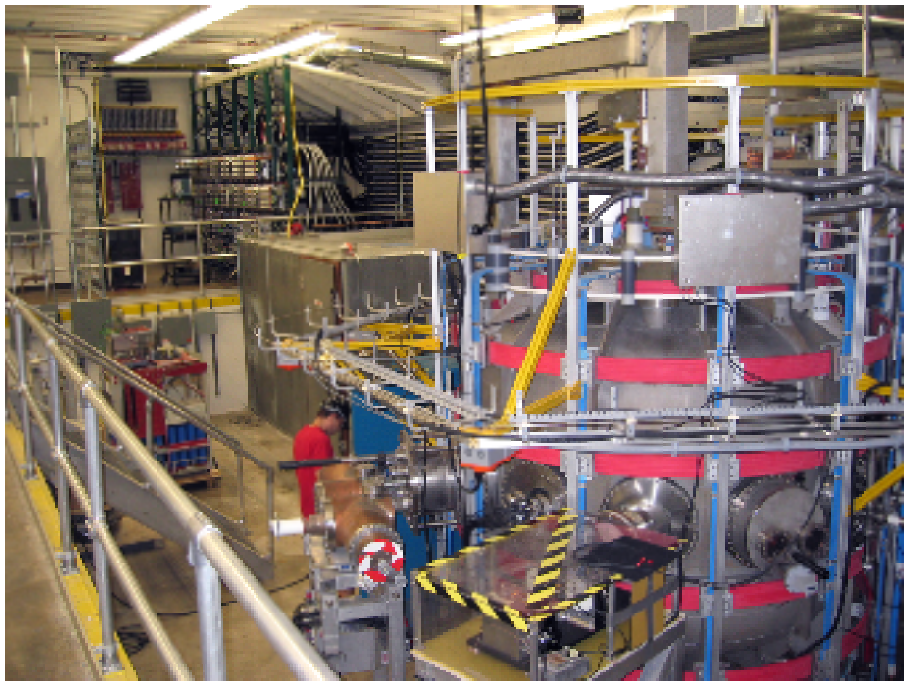


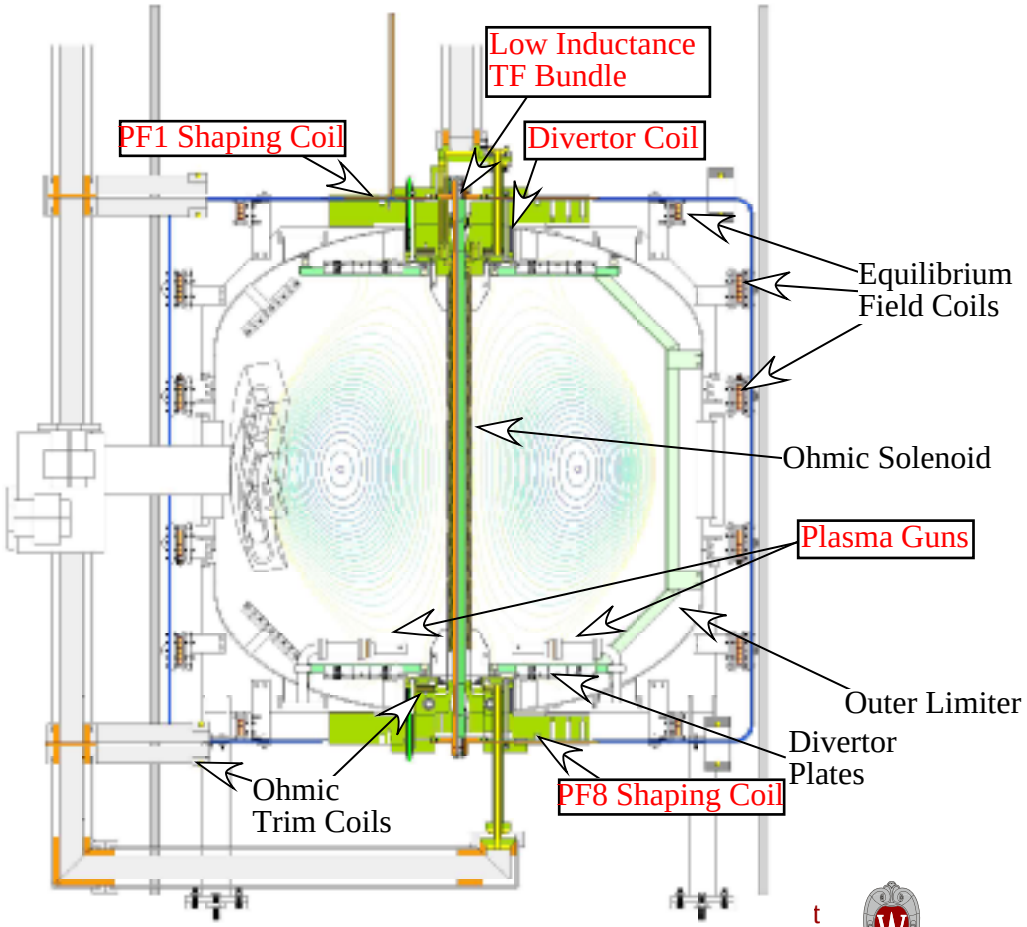


- 2/1, 3/2 modes observed
- island size ≈ a

Phase II: PEGASUS Facility has been Completely Rebuilt

- **New Tools Enhance Study of Plasma Stability Boundaries**
  - All coil power systems upgraded to programmable waveform control
    - Active shaping and position programming
  - Increased V-sec (2 - 2.5x) and control
  - Low inductance, higher B_T (3x) Toroidal Field bundle for rapid TF ramp
  - Divertor coils for separatrix operation
  - Plasma Guns for plasma startup and current drive

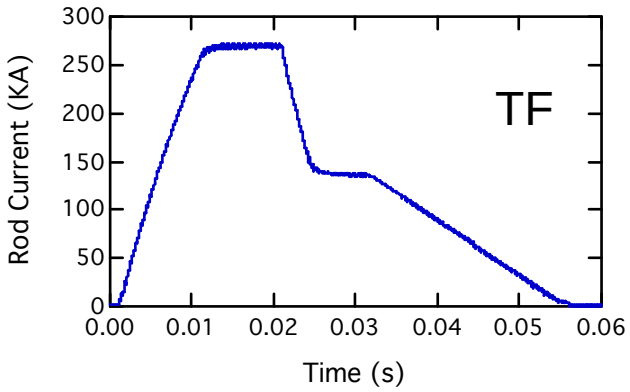


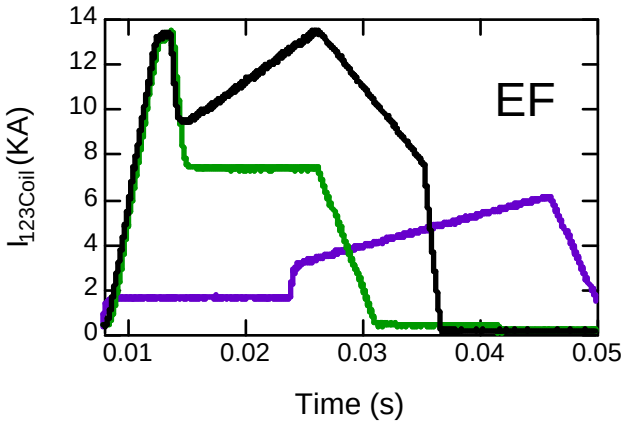


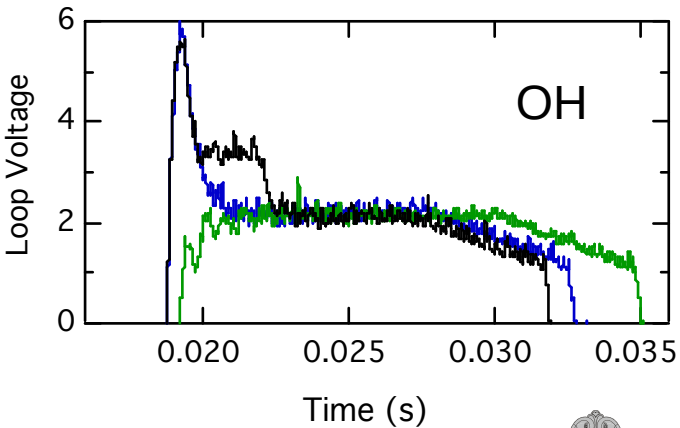
Power systems offer path to high I_p/I_{tf}, β_t operation

- Suppress tearing modes early in discharge evolution
  - = Transiently manipulate q during discharge:
    - Increased TF at startup
    - Variable I_p and R_0
  - = Reduce resistivity before low-order rationals appear
    - Maximize J
    - Increase ohmic flux
    - Use HHFW system
- Explore edge kink boundary at high field utilization
  - Manipulate edge shear
  - Decrease edge currents
  - Manipulate plasma shape
  - Manipulate current profile
- Begin operations with reduced OH power
  - 900V IGBT H-bridges for low-power OH (120 MVA)
  - Near-future: 2700V IGCT bridges for full OH ops (130 MVA)

Example Waveforms



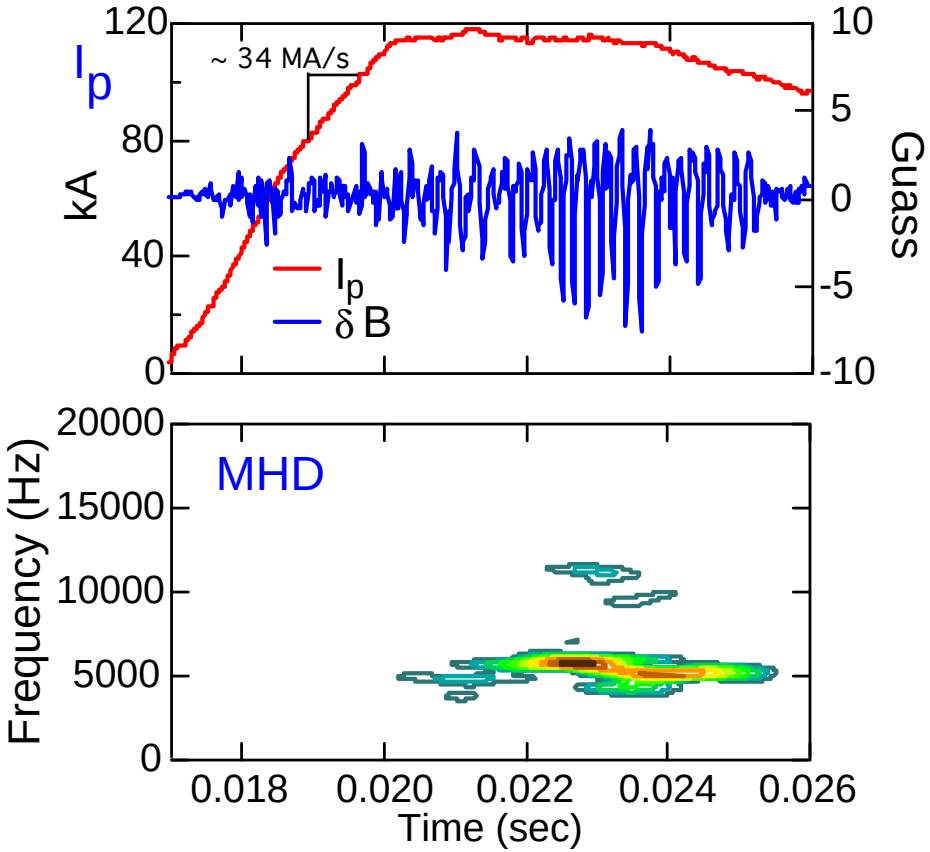




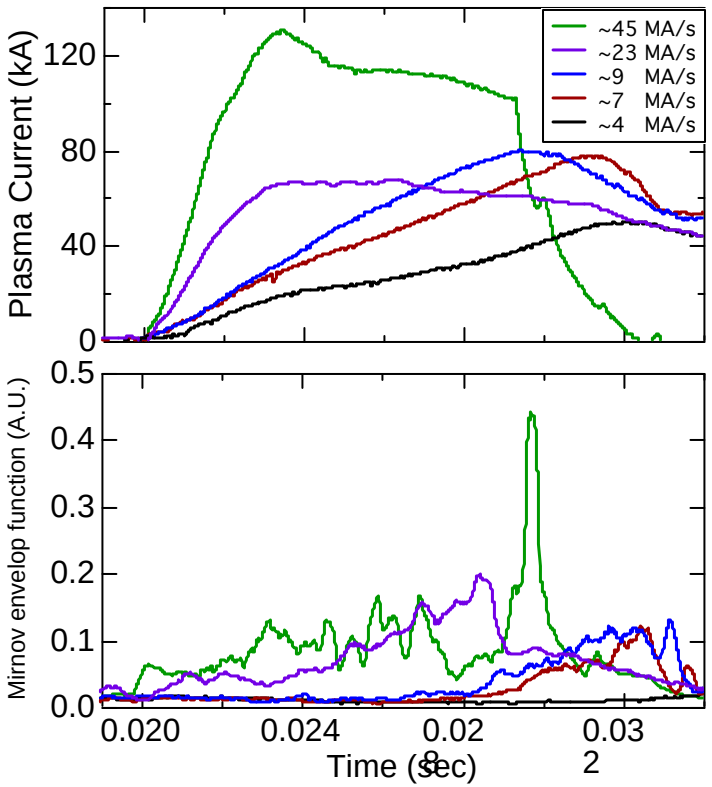
Phase II: Earlier Results Recovered; Extending Operation Space

- Comparable characteristics to Phase I plasma achieved
  - *I_p ramprate, maximum I_p*

- Mode activity: similar qualities
  - *frequency, δB*



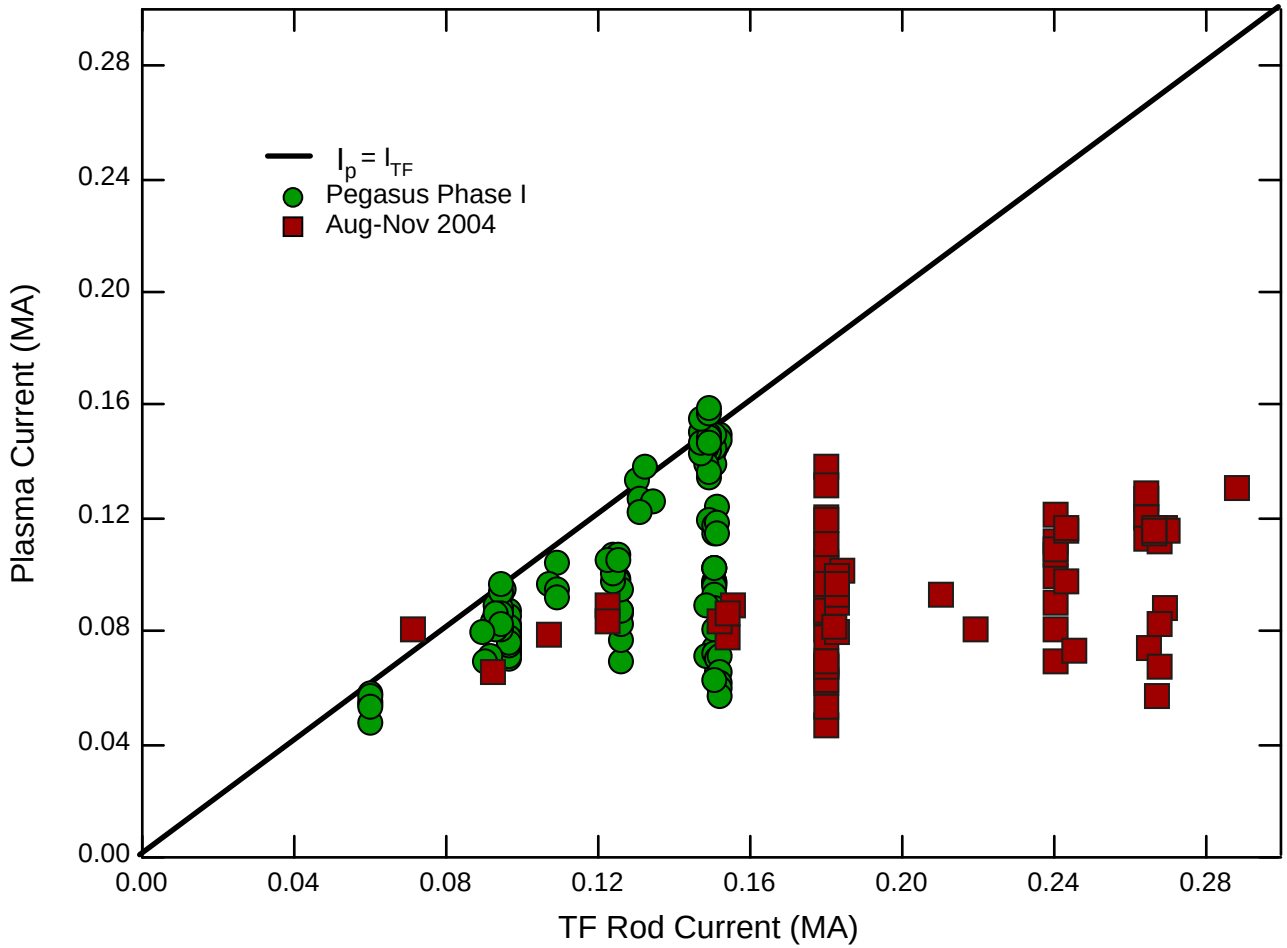
Varied I_p ramprates & respective envelop functions



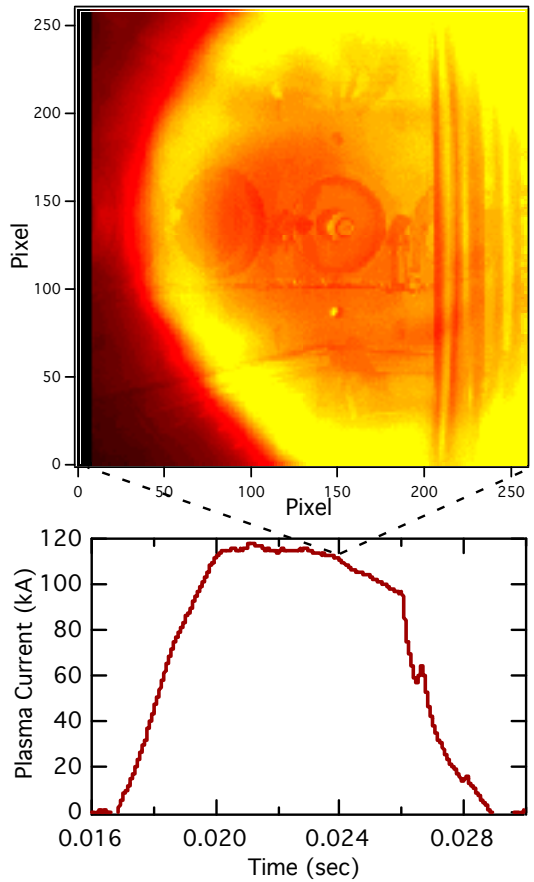
- Initial tests to lower I_p ramp-rate
  - *Envelop function of Mirnov signal decreases with decreased dI_p/dt*

New Capability Widens Operating Space

- Higher TF allows extension of operation space
- Limited OH flux and control during shakedown
  - *2/1 mode still evident with high dI_p/dt*
  - *Full OH will allow challenge to high I_N, I_p/I_{TF}*



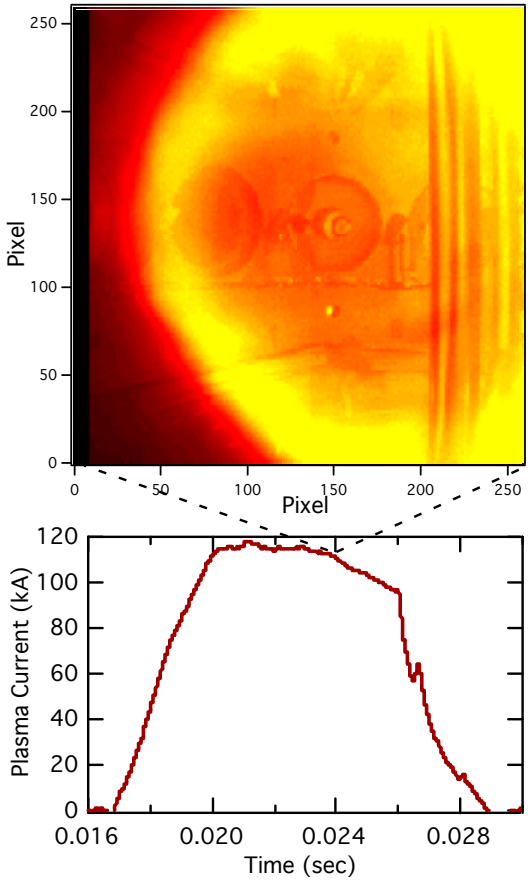
Shot 24825: Sample Plasma



Present Status - Integrating New Capabilities towards $I_p/I_{tf} > 1$

- Summer-Fall '04: Shakedown & Commissioning
  - 1st plasma in late May
  - Shakedown campaign
    - *Transient suppression and PS stabilization*
    - *New facility tests and systems shakedown*
    - *Effects of wall currents with new waveforms*
    - *Low power startup studies*
    - *Phase I operation space recovered*
  - New power systems stabilized and working as desired
    - *Robust to major failures*

Shot 24825: Full-sized Plasma



- Recent upgrades to enhance operations
  - New diagnostics
  - Plasma guns installed for tests of CD and fueling
  - $V_l(t)$ control => dI_p/dt control

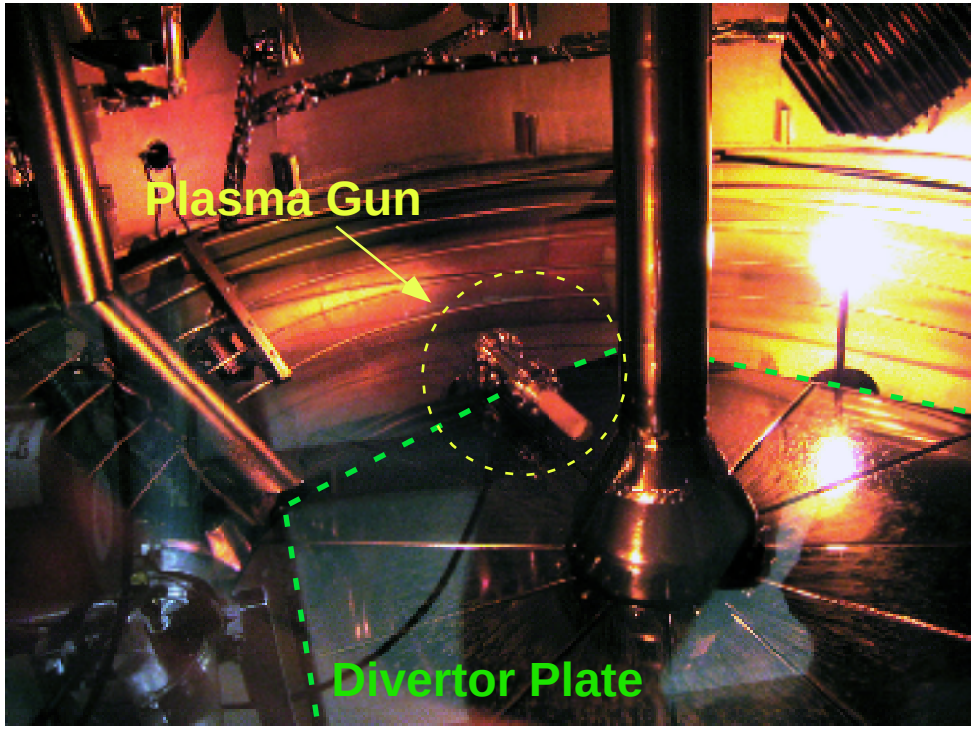
- Fall '04: Installation of first High-V OH power supplies

- Campaign in Winter 2004-2005: Use New Tools
  - Commission new OH system for high-power ops
  - Access to $I_p/I_{tf} > 1$, low-q, high I_N, high β_t regime
  - Introduce separatrix
  - Tearing mode suppression
  - Characterize ext kink limits
  - Use gun for startup assist

Plasma Guns Being Tested for Startup and Fueling

- Use MST-style gun current sources to inject helical current in divertor region
  - $I_{gun} \approx 300 - 600A$, $N_e \sim 10^{20}\ m^{-3}$
- Vary TF, EF fields to control current path
- Diverse potential applications
  - *Ionized plasma fueling source in SOL*
  - *Ease OH V-sec needs*
  - *Provide PF-only startup path*
  - *Non-inductive startup path*

Gun installed in lower divertor region



Time-integrated plasma image

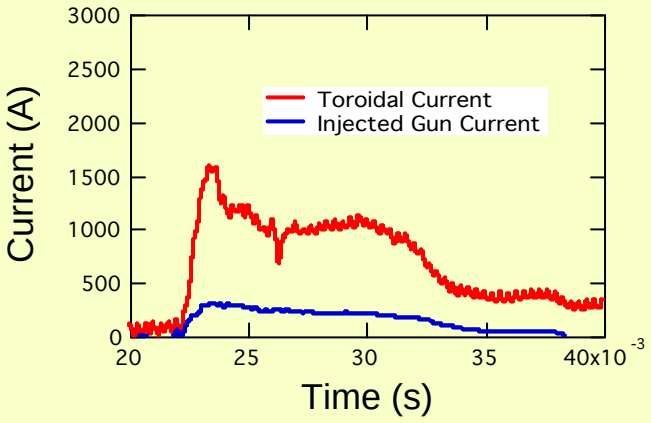


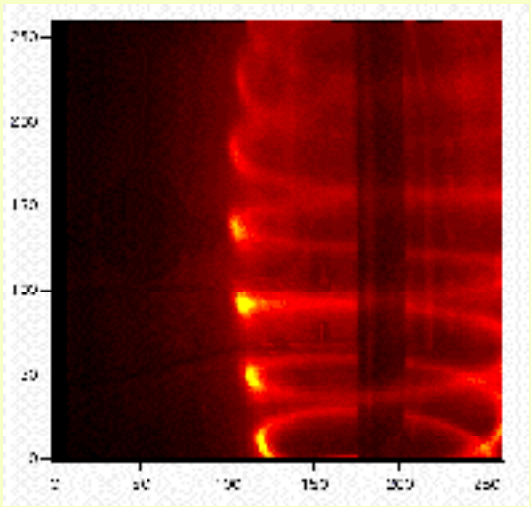
Current Filaments Merge Above Threshold

SN 24434 Vbias = 50 V

Low current

=> Filaments Maintained
No amplification



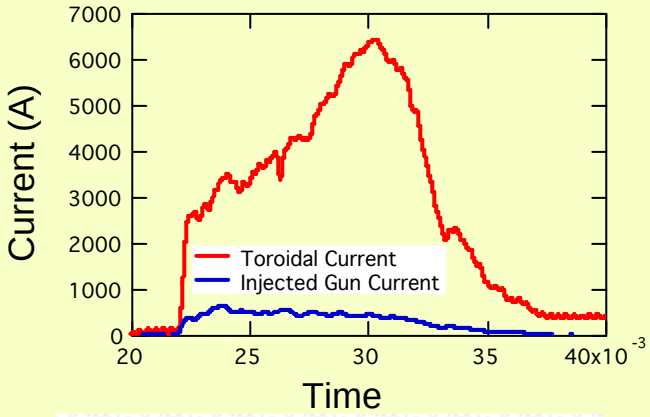


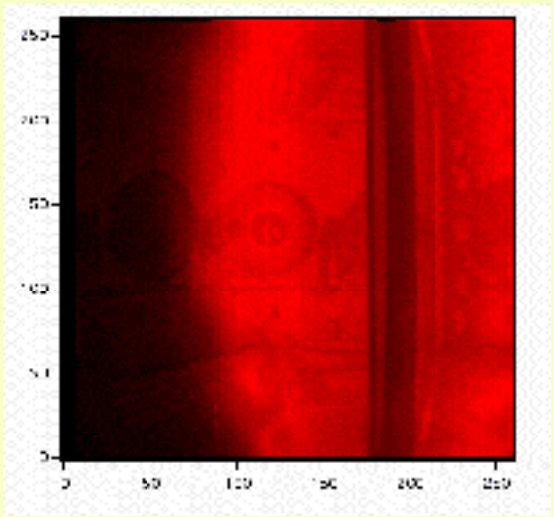
- Current amplification up to ~ 20
- Clear merging or reconnection(?) above a threshold in power
- Closed flux surfaces requires field, gun optimization

SN 24438 Vbias = 400 V

High current

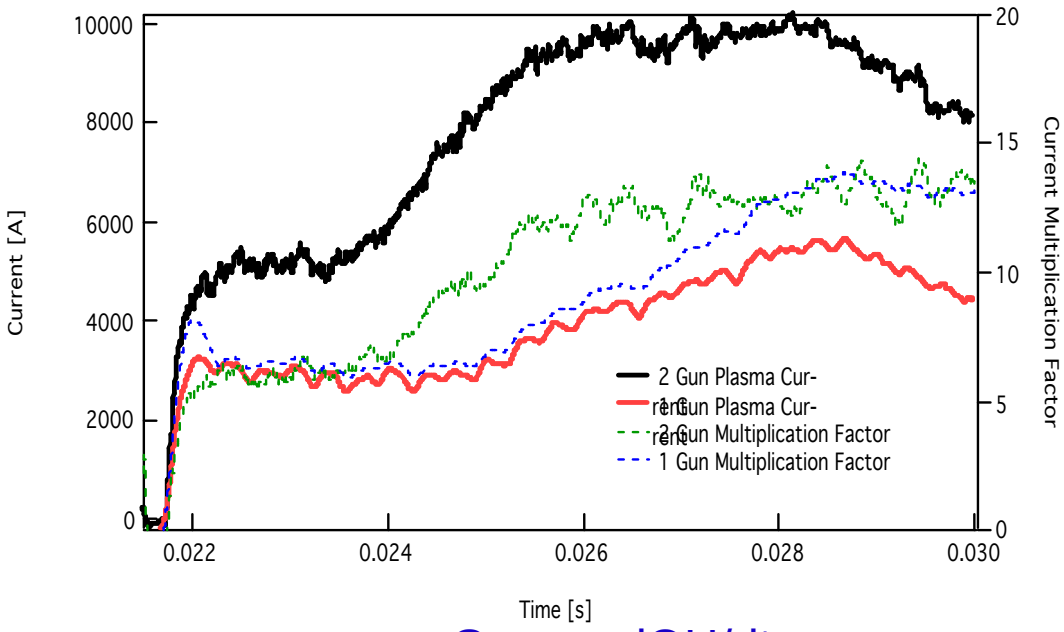
=> Filaments Merge
Net amplification



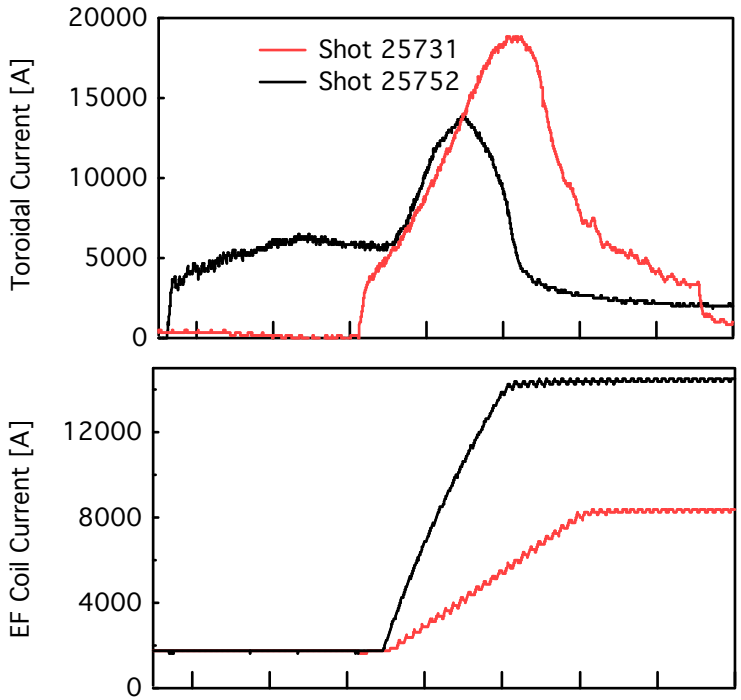


Gun Startup Compatible with OH or EF Inductive Drive

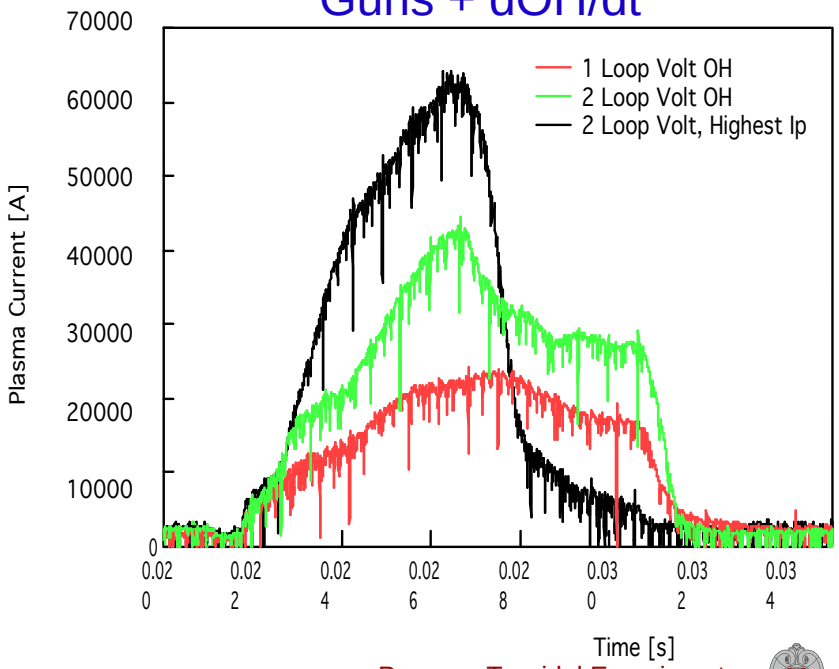
- I_ϕ scales linearly with # of guns
- V_{loop} added to gun plasma
  - *No preionization or null required*
  - *via OH or dEF/dt*
- I_ϕ ~ 60 kA (OH) and ~ 20 kA (EF)
- Closed flux surfaces next target
  - Optimize field, I_{gun} evolution
  - ~ 2x increase needed (?)



Guns + dEF/dt



Guns + dOH/dt



Economical Tests of EBW Possible on PEGASUS

EBW heating and current drive of interest for ST regime

- Plasma startup, sustainment
- Applicable to low-field, overdense plasmas
- Of interest to future NSTX development

Basic principles tested on W-7S and CDX

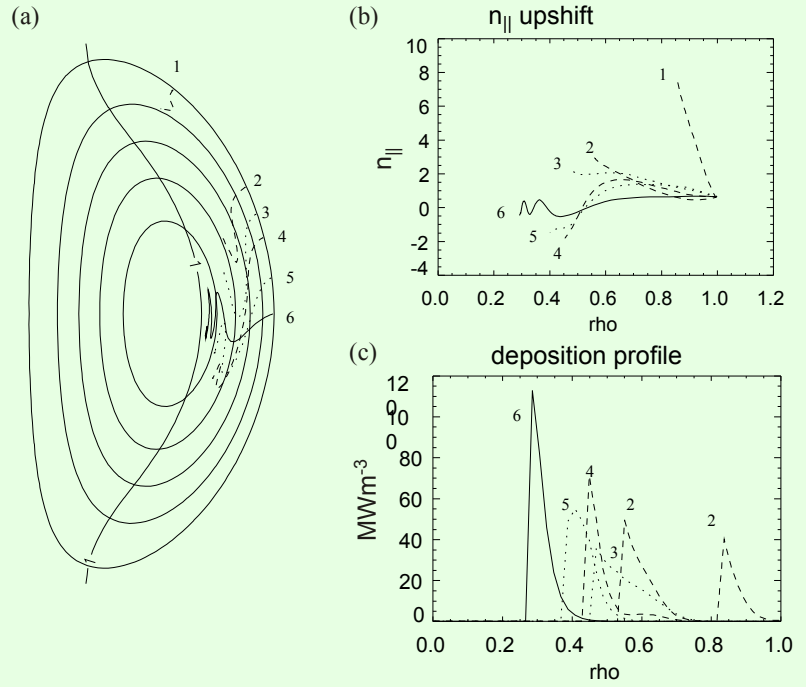
- Need to be tested at significant power levels

Pegasus good candidate for EBW development

- Low-cost 2.45 GHz technology
- Klystrons and waveguide available from PLT
- Need to demonstrate good target plasma control

Working with PPPL to develop best approach

- Modeling
- Hardware
- Experiments



(a) EBW ray tracing calculations for a 250 kA PEGASUS equilibrium, central density of ne(0) = 10^{13} cm^{-3}. (b) $n_{||}$ along the ray path, showing the up-shift depends upon launch position. (c) Power deposition profiles corresponding to the rays in (a) and (b).

SUMMARY

- Phase I ops up to Spring 2002
  - $I_p/I_{tf} = 1.1$
  - $\beta_t \leq 25\%$
  - Factors found limiting plasma current:
    - + *internal resistive modes*
    - + *V-s limitations*
    - + *external kinks*

- Facility completely rebuilt and upgraded to provide increased plasma control
  - New switching power supplies (final OH installation now)
  - New divertor and shaping PF coils
  - New TF centerstack
  - etc.

- Phase II experiments have begun
  - Switching systems and infrastructure debugged
  - Low power OH demonstrating increased control
    - *Phase I results readily reproduced*
    - *Fine control of OH, TF, and PF fields being established*
    - *Modest feedback control developing*
  - Plasma gun tests suggest non-OH startup capabilities
  - High power operations to challenge low-q, high-β as A -> 1

PEGASUS Poster Session: Thursday Afternoon

PP1.015	Stability Studies	[Unterberg]
PP1.016	Diagnostic Measurements	[Kozar]
PP1.018	Control & DAS Systems	[Burke]
PP1.019	Facility and Power Systems	[Lewicki]
PP1.020	Plasma Gun Experiments	[Eidietis]
PP1.021	Potential EBW Experimemts	[Garstka]

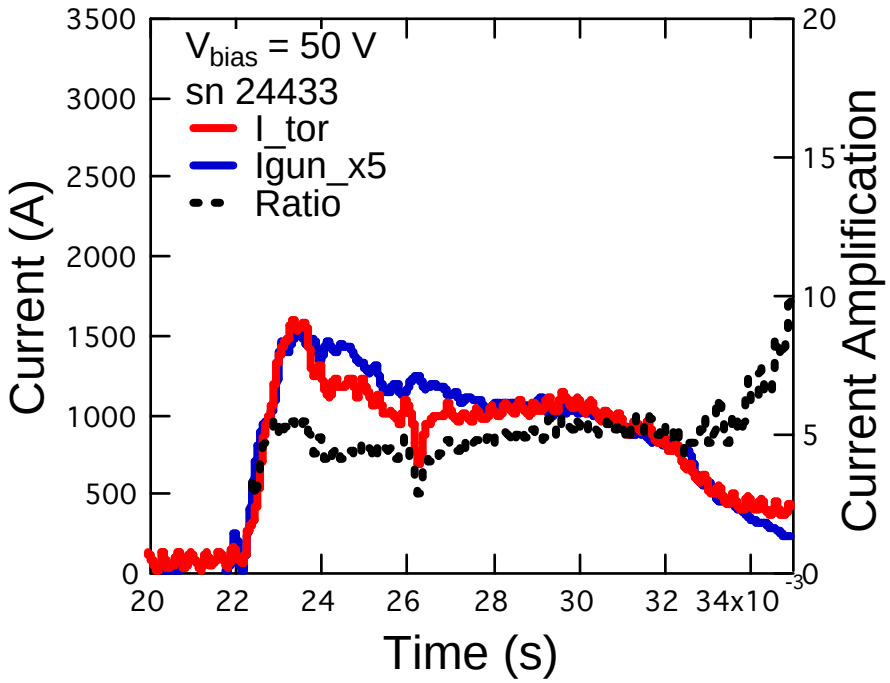
Related - Weds morning:

HP1.074	NIMROD MHD modelling	[Sovinec]

Low Current/Power --> Linear Scaling; Filament Maintained

- Current channel follows field line
  - *Maintains helical nature*

- Total toroidal current ~ 5 x gun current
  - $I_p/I_g \approx$ *constant*



HIgh Current/Power --> Nonlinear Scaling; Filaments Merge

- Current channels merge/reconnect
  - *Generates extended plasma*

- Total toroidal current > 5 x gun current
  - *I_p/I_g increases*

