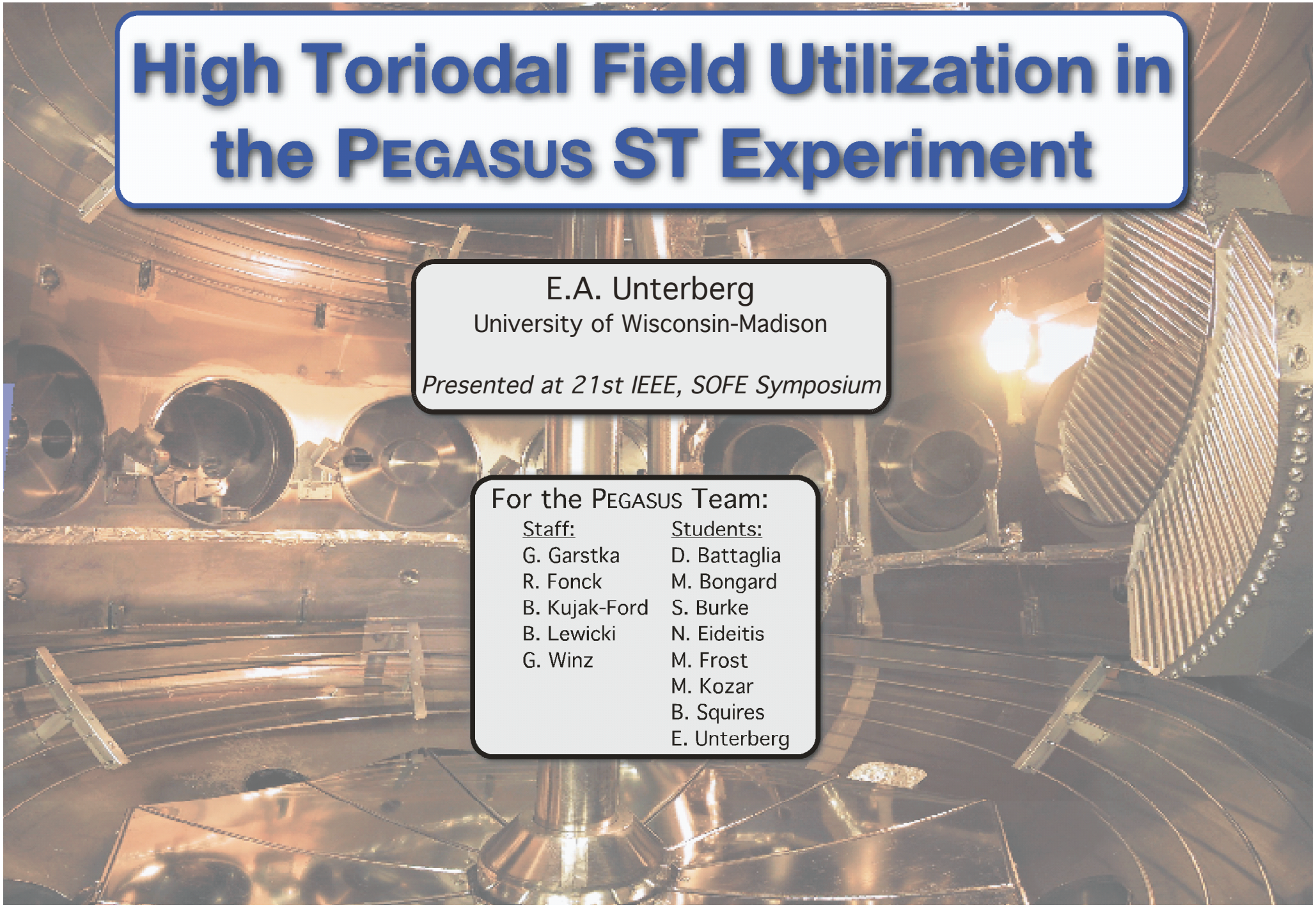


High Toriodal Field Utilization in the PEGASUS ST Experiment

E.A. Unterberg

University of Wisconsin-Madison

Presented at 21st IEEE, SOFE Symposium

For the PEGASUS Team:

Staff:	Students:
G. Garstka	D. Battaglia
R. Fonck	M. Bongard
B. Kujak-Ford	S. Burke
B. Lewicki	N. Eideitis
G. Winz	M. Frost
	M. Kozar
	B. Squires
	E. Unterberg

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

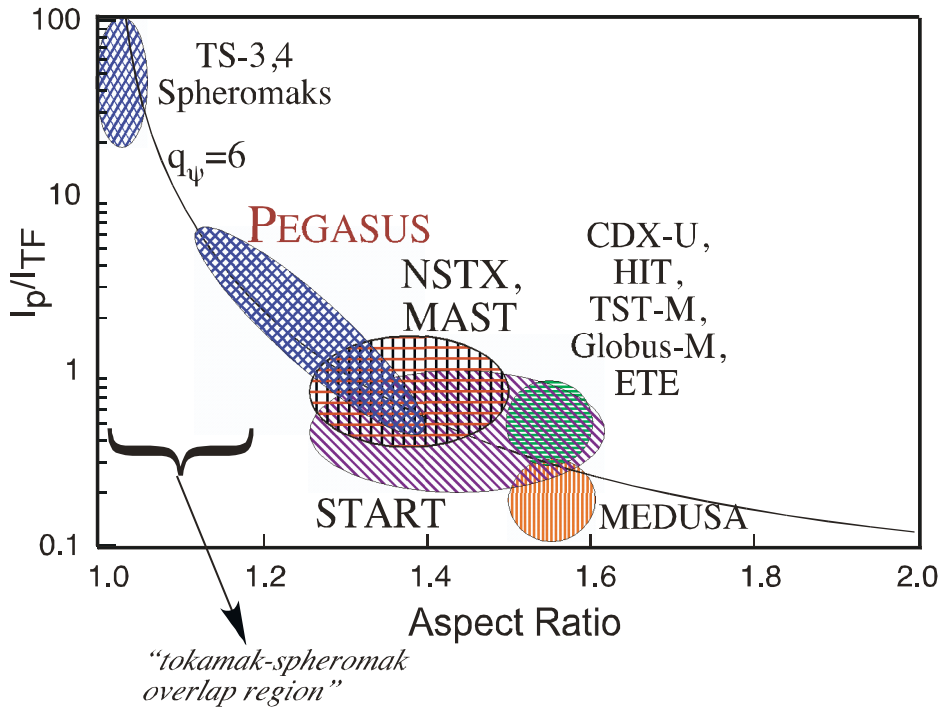
PEGASUS Goals

- 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*

Future Emphases

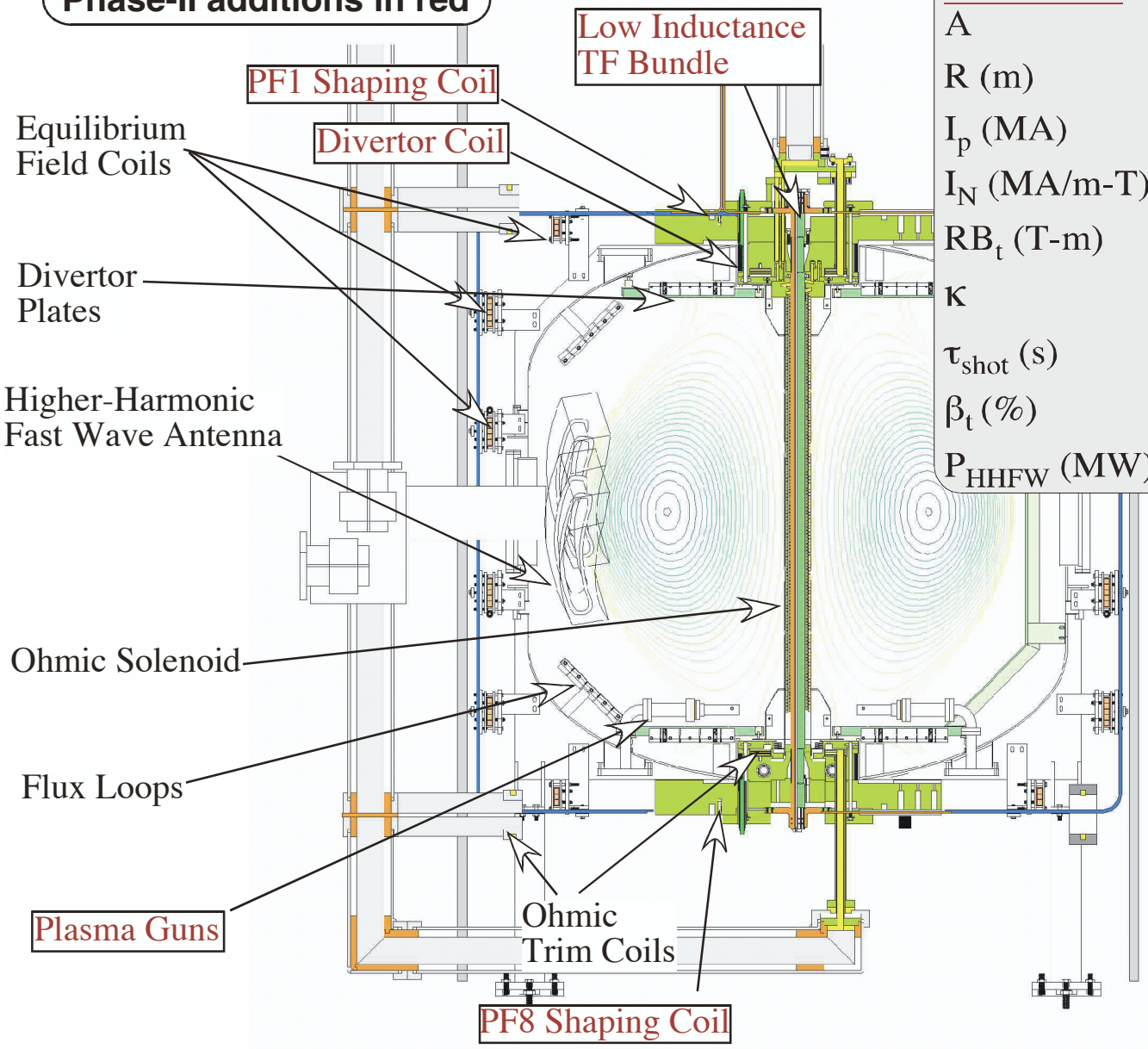
- Support ST movement to next stage
  - *EBW tests for heating and CD (w/PPPL)*
  - *Noninductive startup techniques*
  - *High pressure gas puff for deep fueling*
  - *Diagnostics*

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



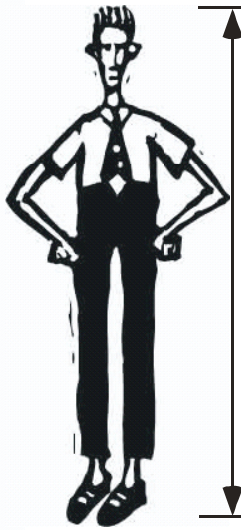
PEGASUS is a University-Scale, Mid-Sized ST

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

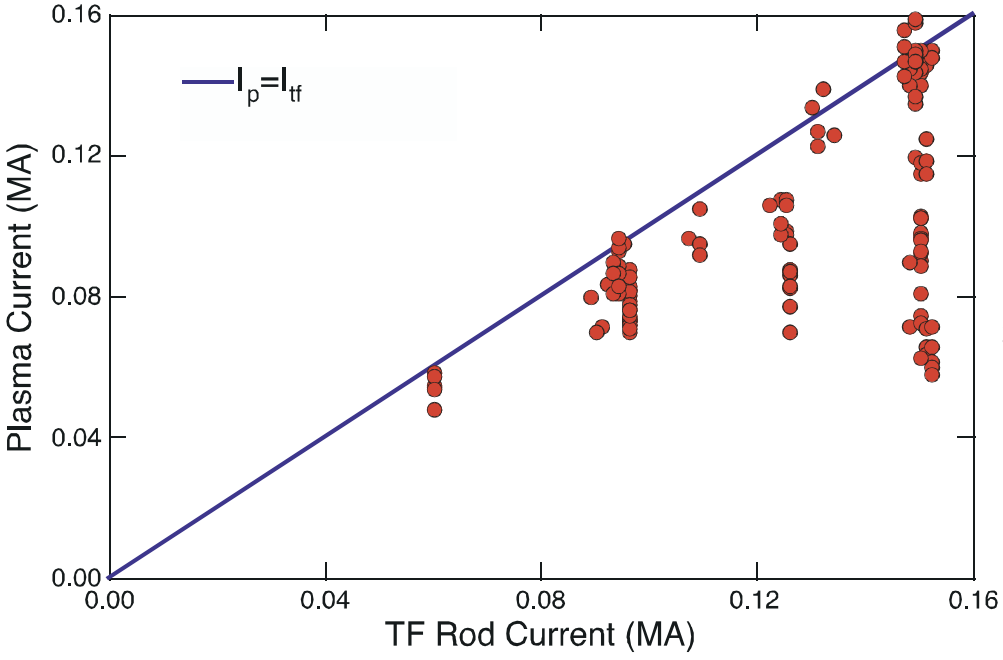


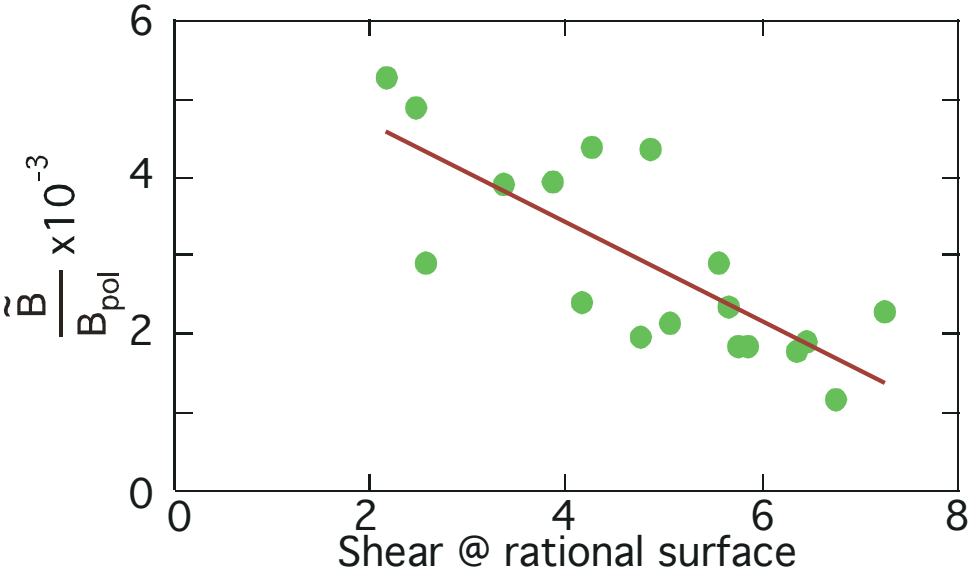
Typical PEGASUS Employee ~ 6 Feet

Performance in Phase-I Exhibited a "Soft Limit"

- Maximum $I_p \approx I_{TF}$
- Soft limit due to 2 factors:
  - *Internal tearing modes with rapid growth and large island widths*
  - *Reduced V-sec as TF decrease*
- Manipulation of q(r) reduced mode amplitude
  - *Increased shear, $q_0 \Rightarrow$ delay tearing onset*
  - *Discharge tailoring $\rightarrow$ reduced MHD activity $\rightarrow$ increased W, I_p*

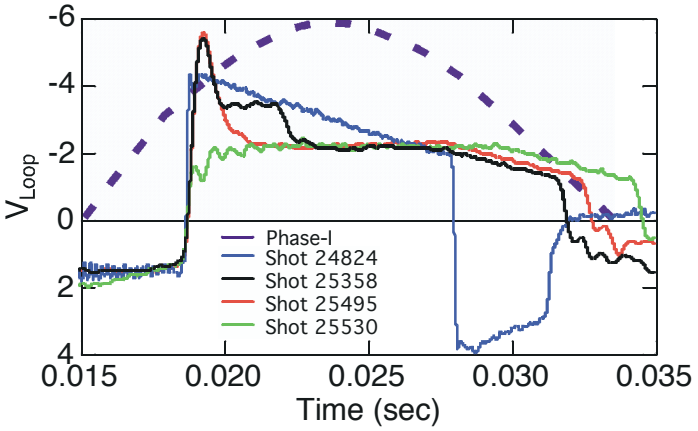
$\Rightarrow$ Access higher I_p/I_{TF} via increased plasma control (i.e. higher q_0, T_e, shear)



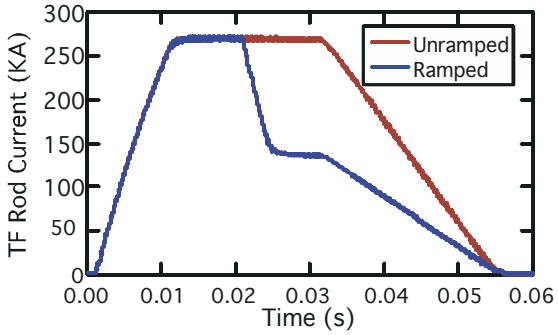


All Coil Sets Upgraded for Phase-II Ops

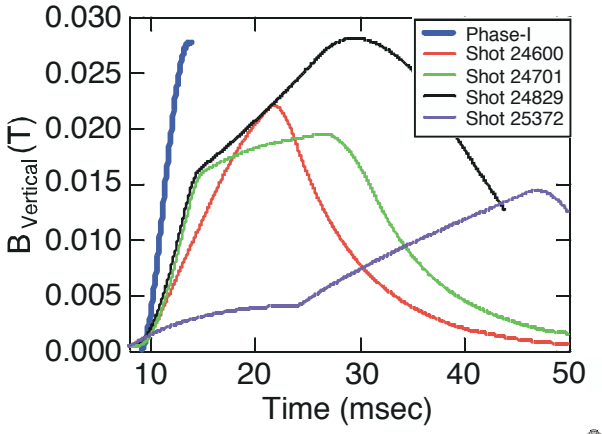
- **Powered with Modular, Parallel DC-Subsystems**
  - *Uses Insulated Gate Bipolar Transistor (IGBT) and and Insulated Gate Commutable Thyristor (IGCT) technology*
  - *4 IGBTs or 4 IGCTs arranged in "H-bridge" layout per subsystem*
  - *Total of 250 MVA programmable power*



- ***Ohmic Heating (OH) [130MVA]***
  - *12 parallel IGCT subsystems provide ±48kA @ 2.7kV*
  - *Efficient utilization of up to 100 mV-sec Ohmic Flux*
  - *Phase-I: Half-Sine Wave, LRC Resonant Circuit; ±40kA @ 14kV*



- ***Toroidal Field (TF) [35MVA]***
  - *8 parallel IGBT bridges provide +38kA @ 900V*
  - *12-turn low inductance coil set → rapid current ramping; 450 kA-t max*
  - *Phase-I: High inductance 60-turn coil set; 150 kA-t max*

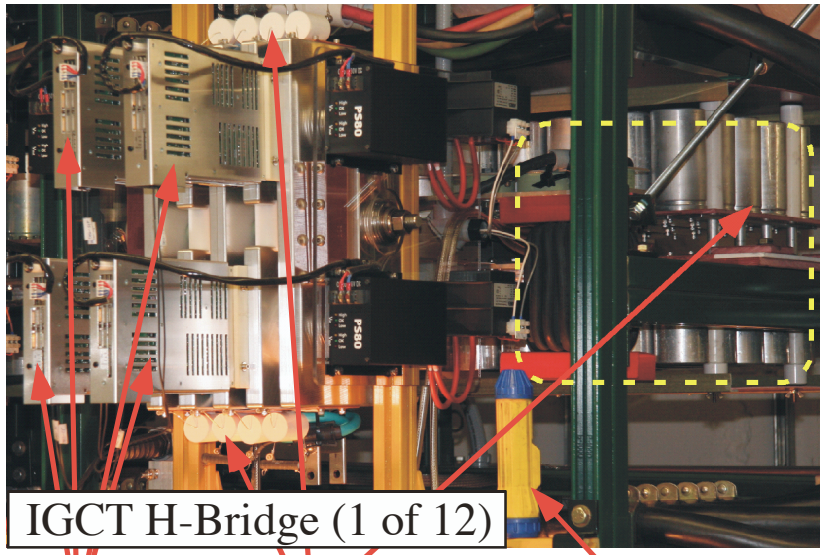


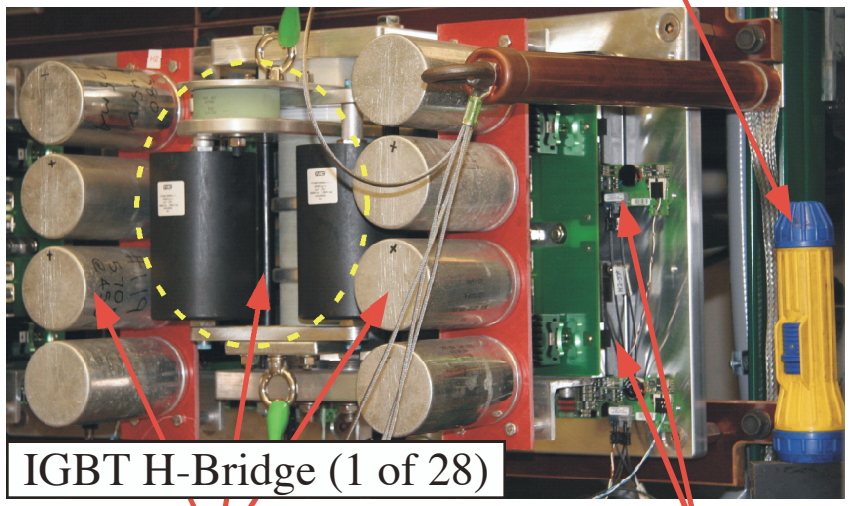
- ***Equilibrium Field (EF) [85MVA]***
  - *20 IGBT subsystems; ±4.8kA @ 900V per subsystem*
  - *Allows up to 10 independent coil sets → position and shape control*
  - *Phase-I: monolithic coil set, 2 resonant capacitor banks*

Phase-II Coil-Current-Control Superior to Phase-I

- **System provides more reliability and control with less stored energy**
  - H-Bridge configuration provides regeneration mode to minimizes heating of coil sets
  - Pulse-Width Modulation (PWM) feedback allows:
    - *$-I_{Coil}$ tailoring to match desired plasma evolution*
    - *-Fault detection and interruption capability*

- **IGBT vs. IGCT: each have unique considerations**
  - Single IGBT Device
    - *Full power ops = 4.8 kA @ 900V*
    - *Switching freq. = 5kHz; depends on controller*
    - *Primary heating from conduction losses; minimized with reduced voltage*
  - Single IGCT Device
    - *Full power ops = 4 kA @ 2800V*
    - *Switching freq. = 5kHz; depends on switched power*
    - *Primary heating from switching losses; minimized with reduced current*

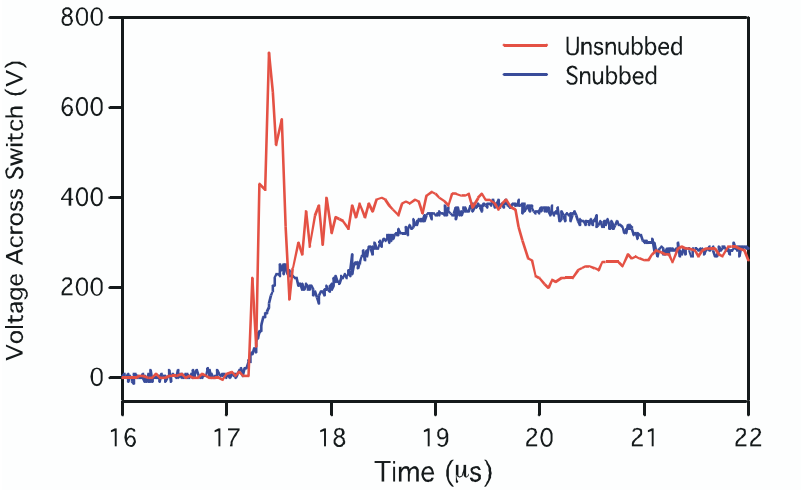




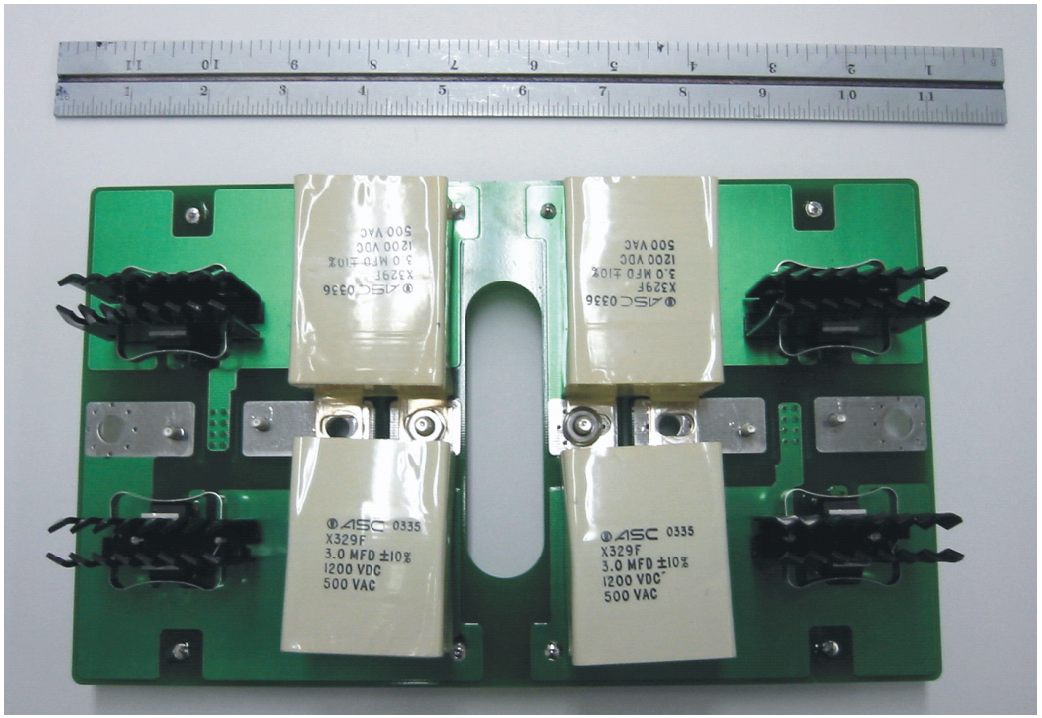
H-Bridge Optimized to Reduce Switching Transients

- **H-Bridge Transient Suppression**
  - Transmission lines have inductive stored energy
  - RCD snubber for overall H-Bridge
  - RCD snubber for individual switching components
  - Local electrolytic capacitors (DC Links)

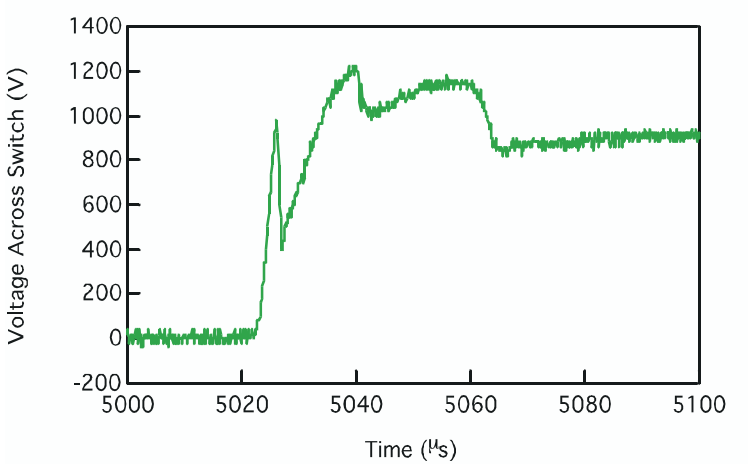
Transients across IGBT at 300V/1kA



IGBT H-Bridge RCD Snubber Board



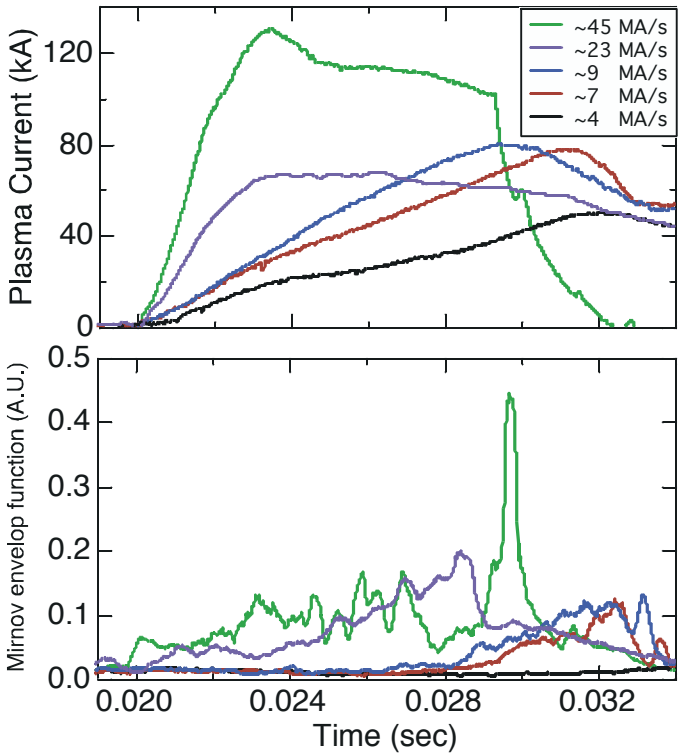
Snubbed Transients across IGBT at Full Power



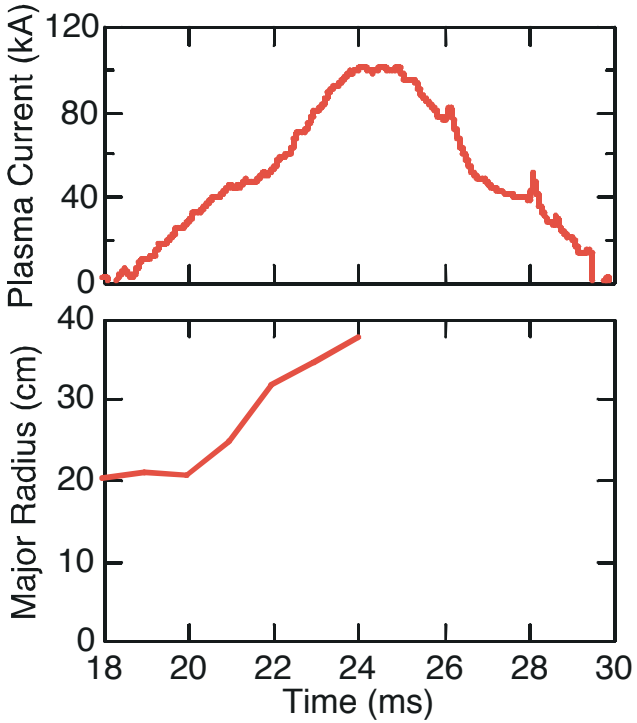
Upgrades Allow Increased Discharge Control

- **"Soft-limit" mitigation experiments begun**
  - *Ramp-rate control to vary J(r)*
    $\Rightarrow$ *less hollow J(r)*
  - *Radial position control demonstrated*
  - *Discharges use full flux swing; I_p ~120 kA*

Varied I_p ramp-rates & respective envelop functions



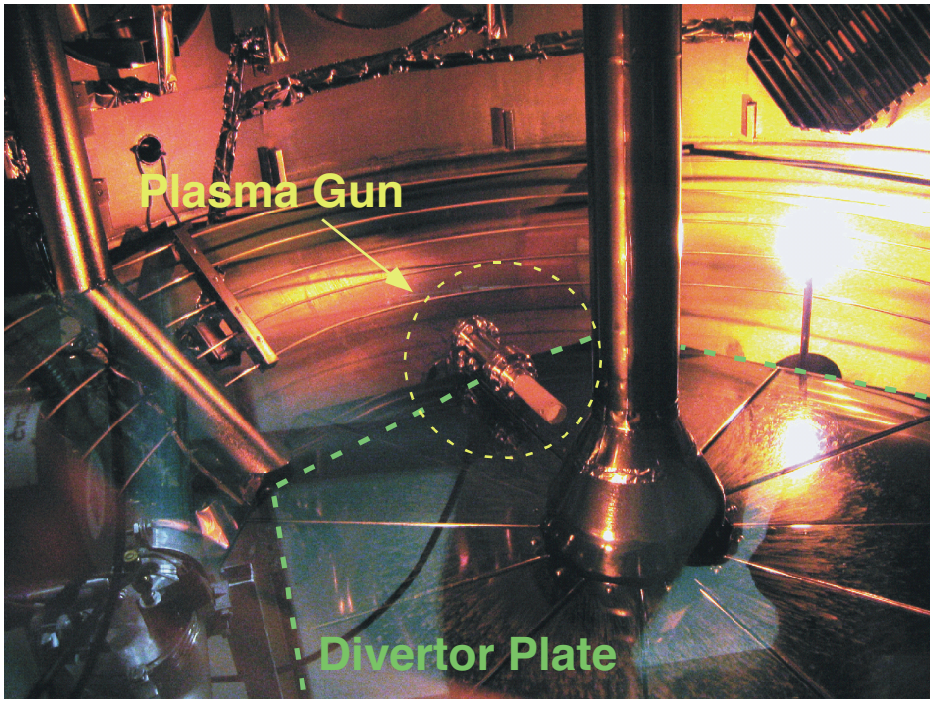
Plasma major radius evolution



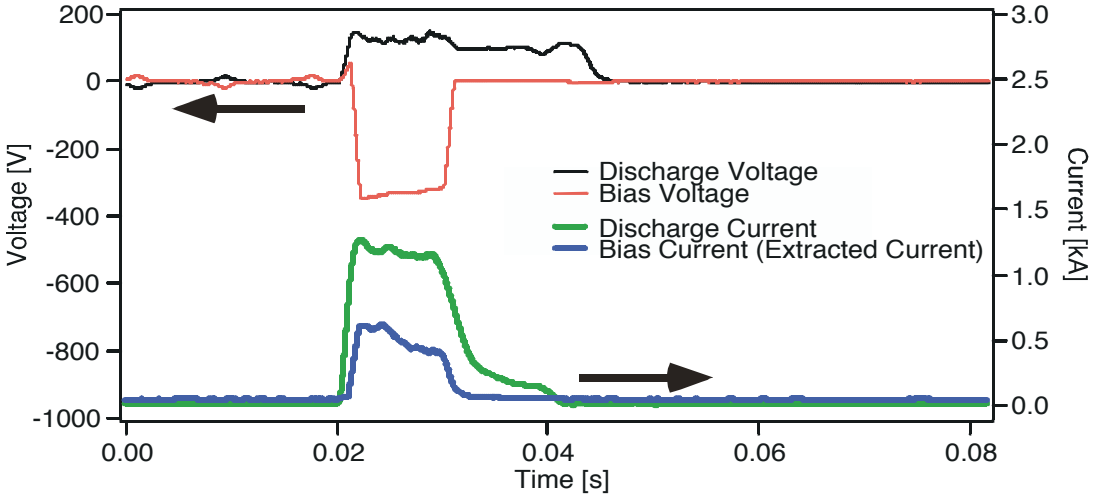
- **Near-term ops to concentrate on mode supression**
  - *Continued drive capability as OH-PS $\Rightarrow$ full pwr*
  - *Ne impurity experiments for J(r) manipulation*
  - *PCS coming online for plasma feedback*

Electrostatic-Current-Injection Sources Used for Noninductive Startup and Current Drive Experiments

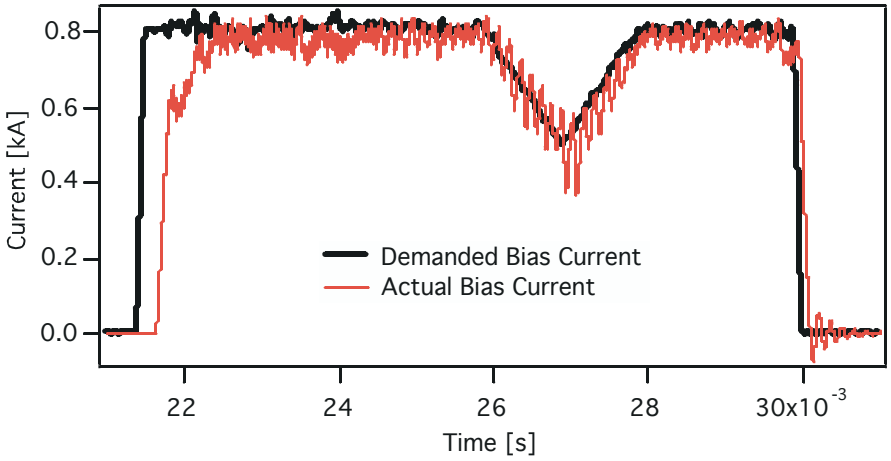
- **Plasma source clean and tested technology**
  - Uses MST-style gun current to inject helical current from divertor region
    - *Each gun; $I_{Extract} \sim 0.8$-1 kA; $n_e \sim 10^{20}$ m^{-3}*
  - Diverse potential applications
    - *Ionized plasma fueling source in SOL*
    - *Ease OH V-sec needs*
    - *Provide PF-only startup path*
    - *Non-inductive startup path*
- **Closed flux surfaces near-term target**
  - Optimize field, $I_{Extract}$ *evolution*
    - *H-bridge subsystem used to aid optimization*
  - ~ 2x increase needed (?)



Source Performance Determined by Bias Voltage



Full Injection Current Controlled with IGBT Subsystem



PEGASUS Toroidal Experiment
University of Wisconsin-Madison

High-power proof-of-principle tests of EBW heating and current drive are planned

- PEGASUS is an ideal test bed for EBW physics
  - Toroidal field good match for 2.45 GHz
  - Plasma control will provide good mode coupling
  - University scale allows ready access to experiment
  - Several physics issues can be addressed at this scale
    - = *Validation of raytracing/power depostion/CD models*
    - = *Effects of nonlinear parasitic instabilities*
    - = *Mode conversion studies*

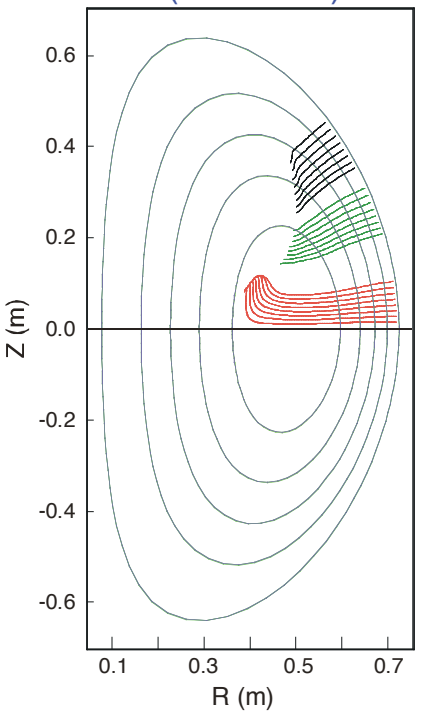
- Significant hardware exists in the community
  - PLT lower hybrid system produce & transmit RF power
    - = *Up to 1 MW of microwave power available*
  - Power supplies available from ORNL, LANL

- A collaborative R&D effort is planned
  - PPPL, ORNL, UW are already involved

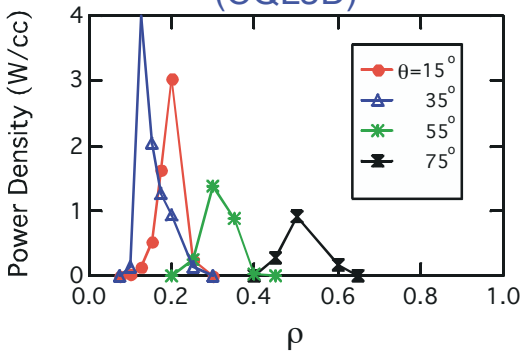
500 kW, 2.45 GHz Klystron



Sample Raytracing (GENRAY)



Power Deposition Profiles (CQL3D)



Summary

- **PEGASUS is a mid-size ST built to explore A → 1**

- **Phase-I limits necessitated H-bridge upgrade**
  - Coil sets upgraded to use IGBT/IGCT H-bridge technology
  - H-bridges have been optimized for each coil set and for transient suppression
    - *250 MVA total programmable power*
    - *I_{Coil} tailoring to match desired plasma evolution*
  - Upgrades have allowed experiments to begin in discharge evolution control
    - *Discharges utilizing full flux-swing capability; I_p ~ 120 kA*

- **Experiments planned in high I_P/I_{TF} ops, electrostatic current injection, and EBW physics**
  - I_P/I_{TF} limit in ops found due to ST physics and lack of discharge control
    - *Upgrades allow for increased discharge control*
    - *To-date experiments have demonstrated ability to evolve discharge*
    - *Near term goal to suppress performance limiting mode activity*
  - Injection sources used to test noninductive startup and CD on an ST
    - *Currently focused on demonstrating closed flux surfaces*
  - PEGASUS economical test bed for EBW physics
    - *Collabortive R&D effort planned with PPPL & ORNL*