Abstract

The Pegasus power systems are composed of switching power supplies with active current feedback control using pulse-width modulation (PWM) controllers. The 72 MVA poloidal and toroidal field power systems use conventional IGBT switches (900V, 2.5 kHz) and analog PWMs. These systems have a flexible configuration to allow for a variety of operational scenarios. The 113 MVA OH power system uses IGCT switches (2.4 kV, 3 kHz) and a new digital PWM that was developed to avoid damaging switching events by defining minimum switching state intervals. OH switching transient suppression is achieved with RLCD snubbers and by minimizing the internal inductance of the switch structure. A passive LC filter in series with the OH solenoid provides a smooth $V_{loop}(t)$ while maintaining a sub-ms response time. IGCT switch limitations due to finite driver energy have been measured, and are used to map the operating space for present experiments.

Work supported by U.S. D.O.E. Grant DE-FG02-96ER54375

This research was performed under appointment to the Fusion Energy Sciences Fellowship Program administered by Oak Ridge Institute for Science and Education under a contract between the U.S. Department of Energy and the Oak Ridge Associated Universities.

Programmable Power Supplies on PEGASUS

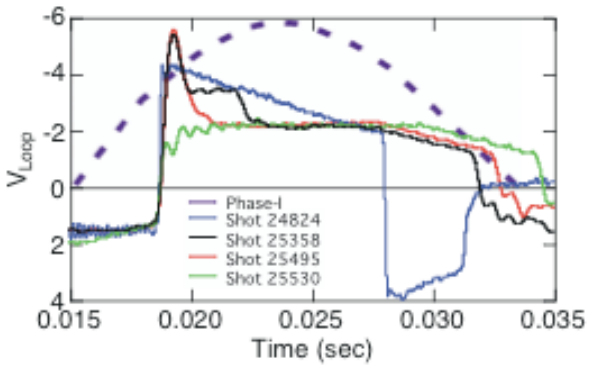
- **Current controlled by active feedback**
  - PWM with H-bridge systems
  - 900 V IGBT switches: EF/TF/Plasma Guns
  - 2.8 kV IGCT switches: Ohmic heating solenoid

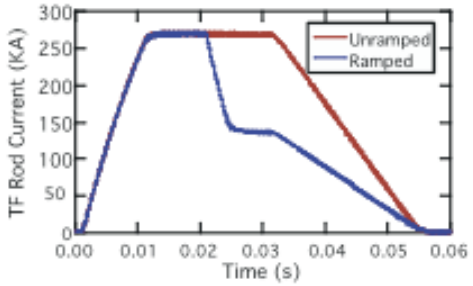
- **IGCT system operational**
  - Switching transient suppression achieved
  - Digital PWM & fault detection circuitry implemented
  - High power operations with LC line filter & solenoid
  - Operational space modeled & verified

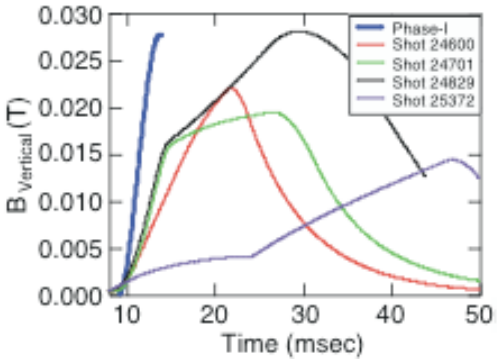
Power Supplies Aid Access to High I_p/I_{TF}

- **Approaches and tools to increase I_p/I_{TF}**
  - Manipulate current profile
    - V_{loop} control, position/shape control, $B_t(t)$
    - Plasma guns
  - Reduce η before low-order rationals appear
    - V_{loop} control, position/shape control, RF heating (HHFW)
  - Transiently increase q during startup
    - V_{loop} control, $B_t(t)$
    - Plasma guns
- **Achieved Phase-I plasma performance with ~1/3 stored energy**

(See E.A. Unterberg et. al., APS-DPP 2006)





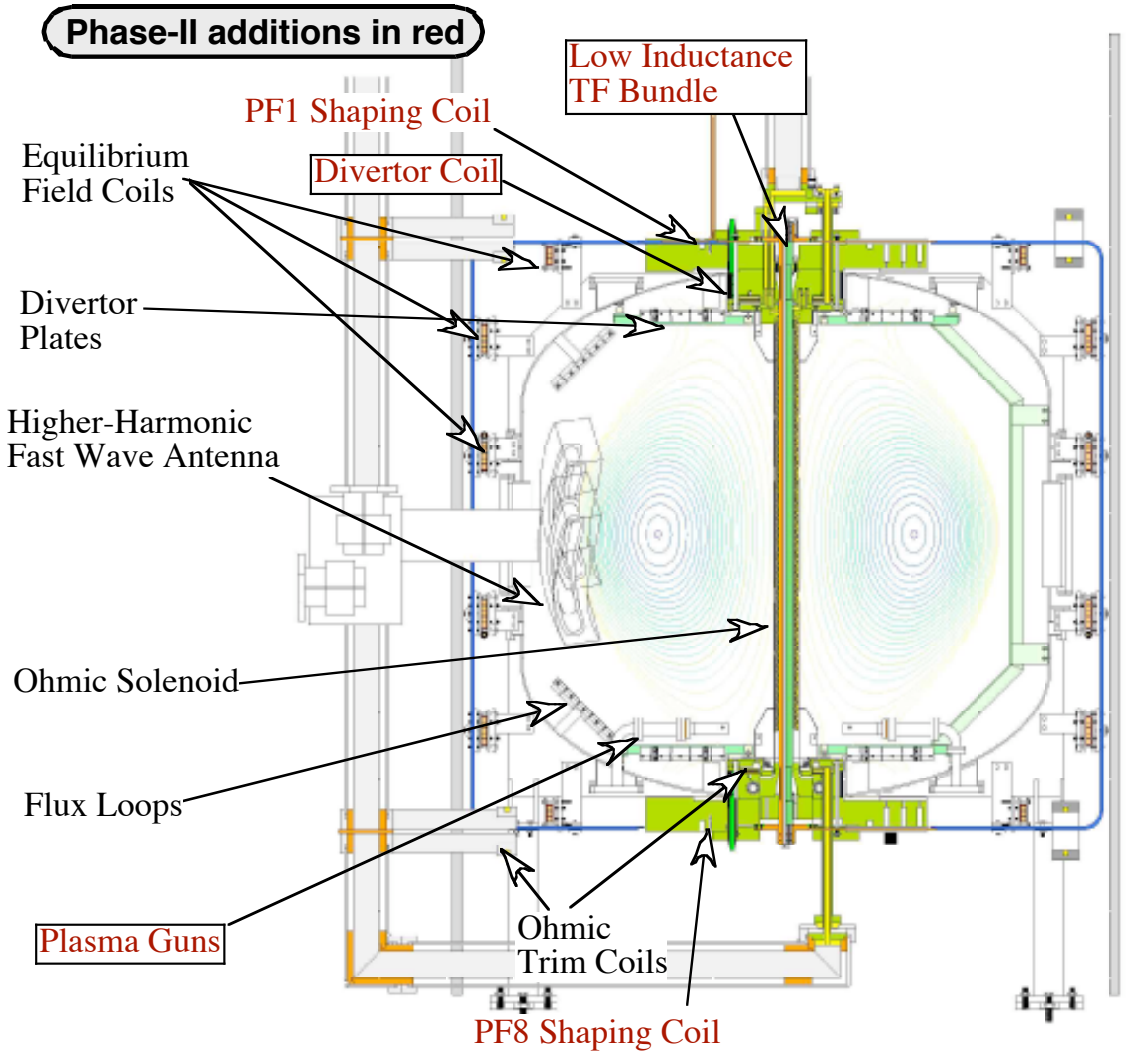


THE UNIVERSITY of WISCONSIN MADISON

The Three Pegasus Power Systems

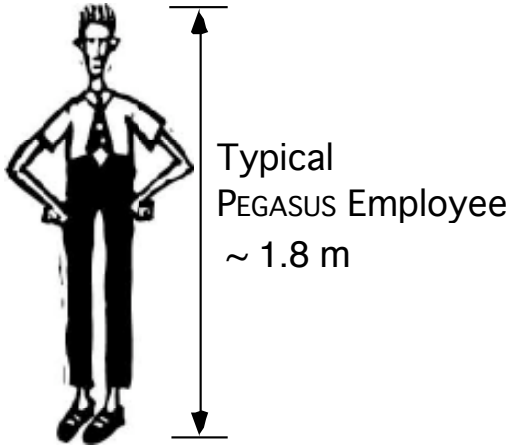
- **Ohmic Solenoid System**
  - 12 parallel 4-quad IGCT subsystems provide ±48kA @ 2.8kV
  - 270 turn double wrap solenoid (R ~ 5 cm)
- **Toroidal Field System**
  - 8 parallel 2-quad IGBT subsystems provide +38kA @ 900V
  - 12-turn low inductance coil set → rapid current ramping
- **Equilibrium Field & Plasma Guns Systems**
  - 20 IGBT H-bridges w/ ± 4.8kA @ 900V per subsystem
  - Highly flexible → up to 10 independent EF coil sets
  - Plasma gun bias supply utilizes single H-bridge

The Pegasus Toroidal Experiment



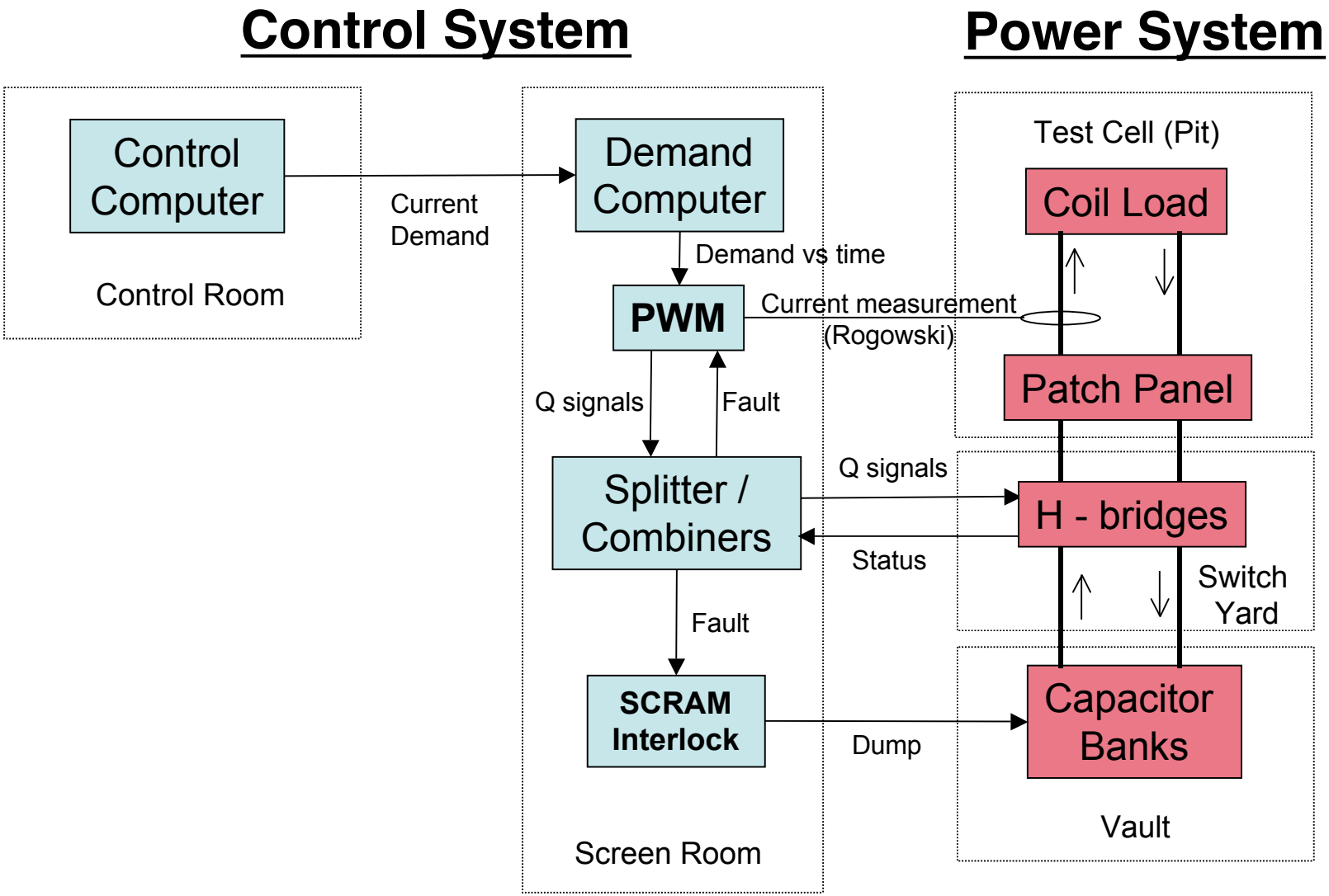
Experimental Parameters

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



THE UNIVERSITY of WISCONSIN MADISON

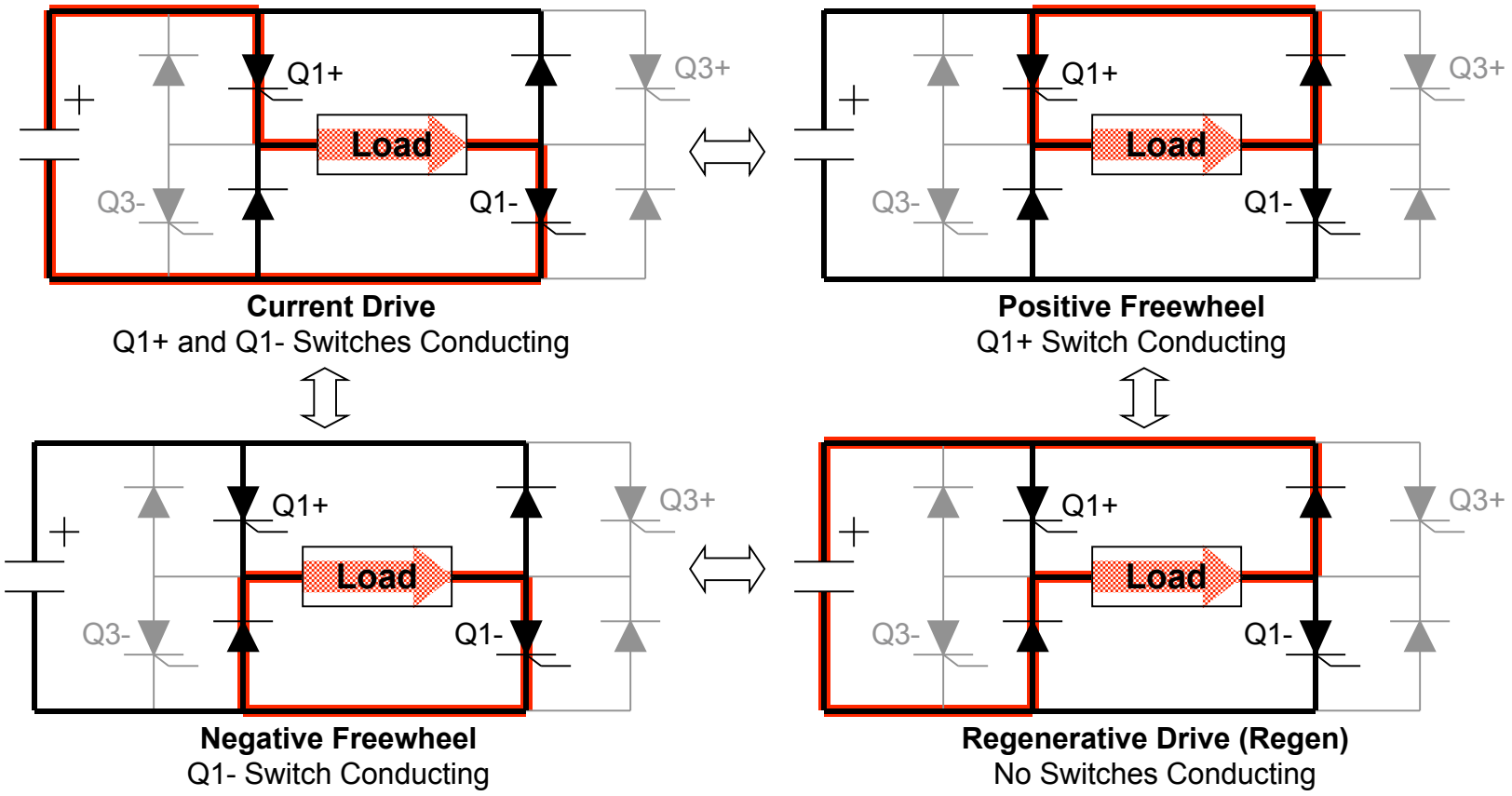
Active Current Feedback Control System



THE UNIVERSITY of WISCONSIN MADISON

Current Control using H-bridge Circuit

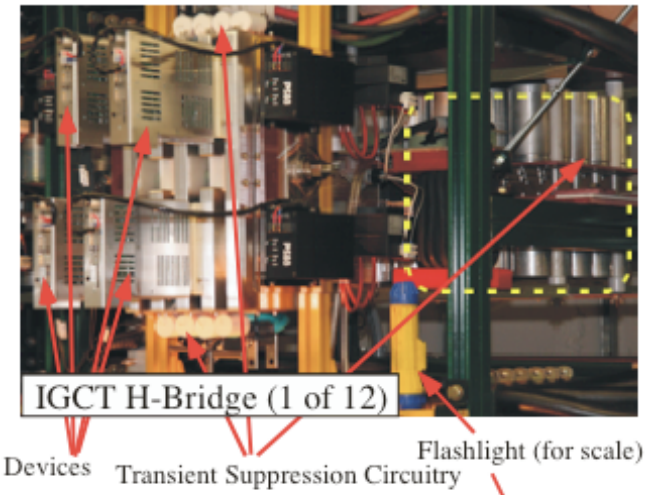
- 4 quad → positive (drive) and negative (regen) voltage and positive (Q1 switches) and negative (Q3 switches) current
- 2 quad → would not have the Q3 switches and their associated diodes



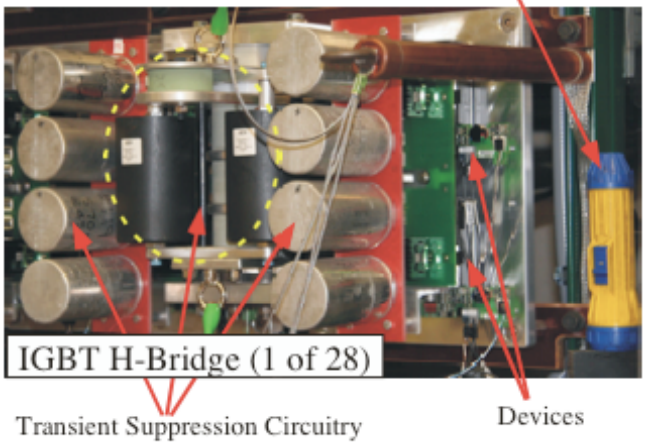
THE UNIVERSITY of WISCONSIN MADISON

IGBT & IGCT High Power Switches

- **Insulated Gate Commutable Thyristor**
  - CW: 2.8 kV, 3.8 kA, 1 kHz
  - Pulsed: 2.8 kV, 3.8 kA, 3 kHz
  - Pulse length and switching frequency limited by available driver energy
  - External fault detection circuitry needed



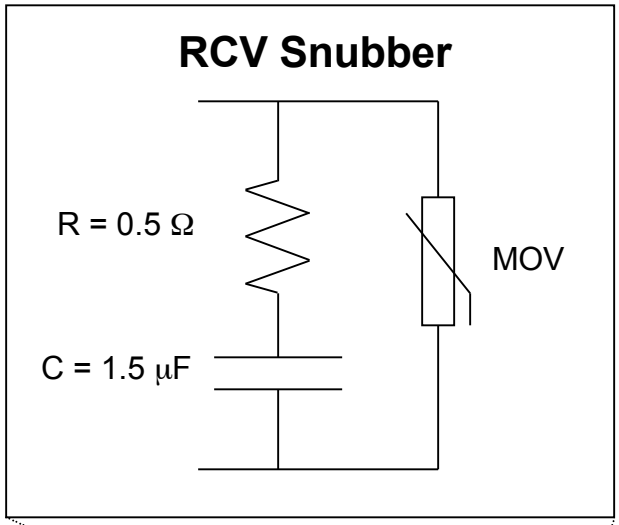
- **Insulated Gate Bipolar Transistor**
  - CW: 900 V, 2.4 kA, 1 kHz
  - Pulsed: 900 V, 4.8 kA, 2.5 - 24 kHz
  - Pulse length limited by heating from conduction losses (only TF system)
  - Onboard controller fault detection

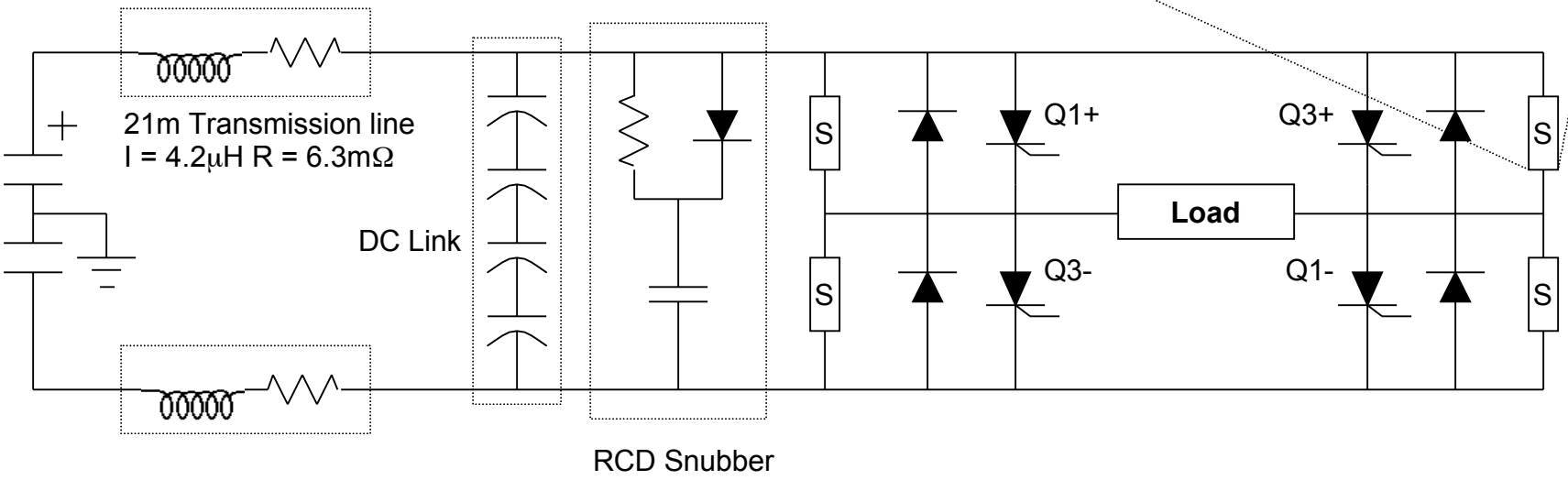


THE UNIVERSITY of WISCONSIN MADISON

IGBT H-bridge Transient Suppression

- **DC Link**
  - Decouples line inductance from H-bridge
- **RCV and RCD Snubbers**
  - Limits switching transients < 1.7 kV

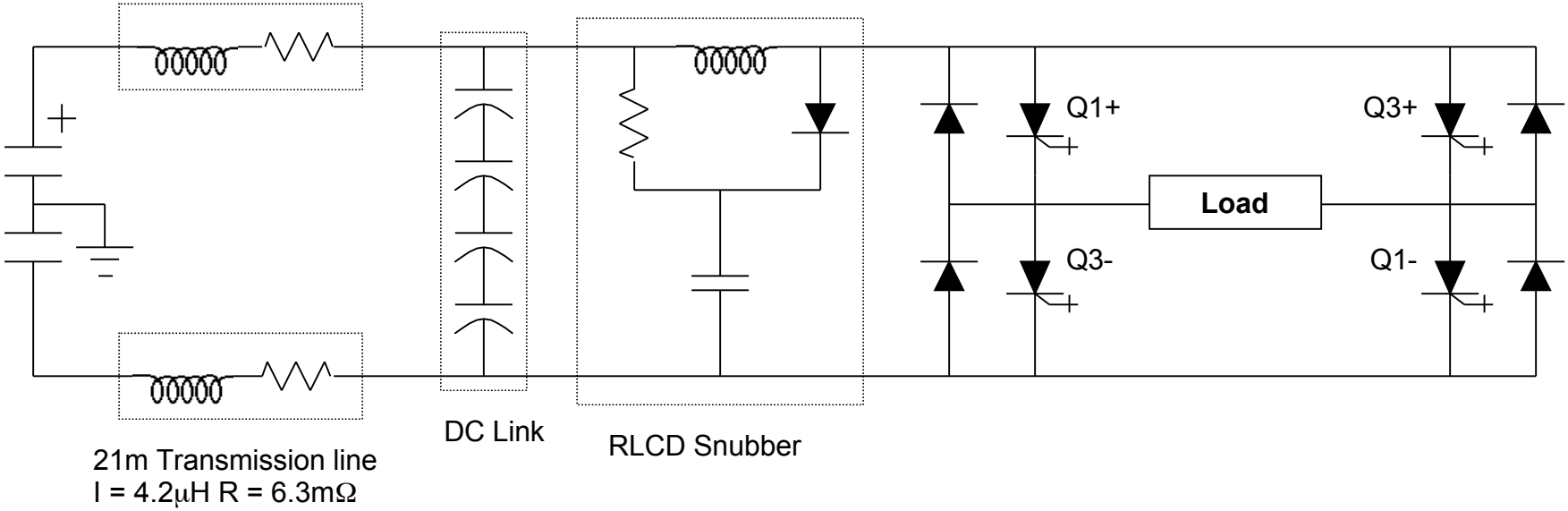




THE UNIVERSITY of WISCONSIN MADISON

IGCT H-bridge Transient Suppression

- **DC Link**
  - Decouples line inductance from H-bridge
- **RLCD Snubber**
  - Limits switch transients < 4.5 kV
  - Provides a zero voltage diode turn-off condition

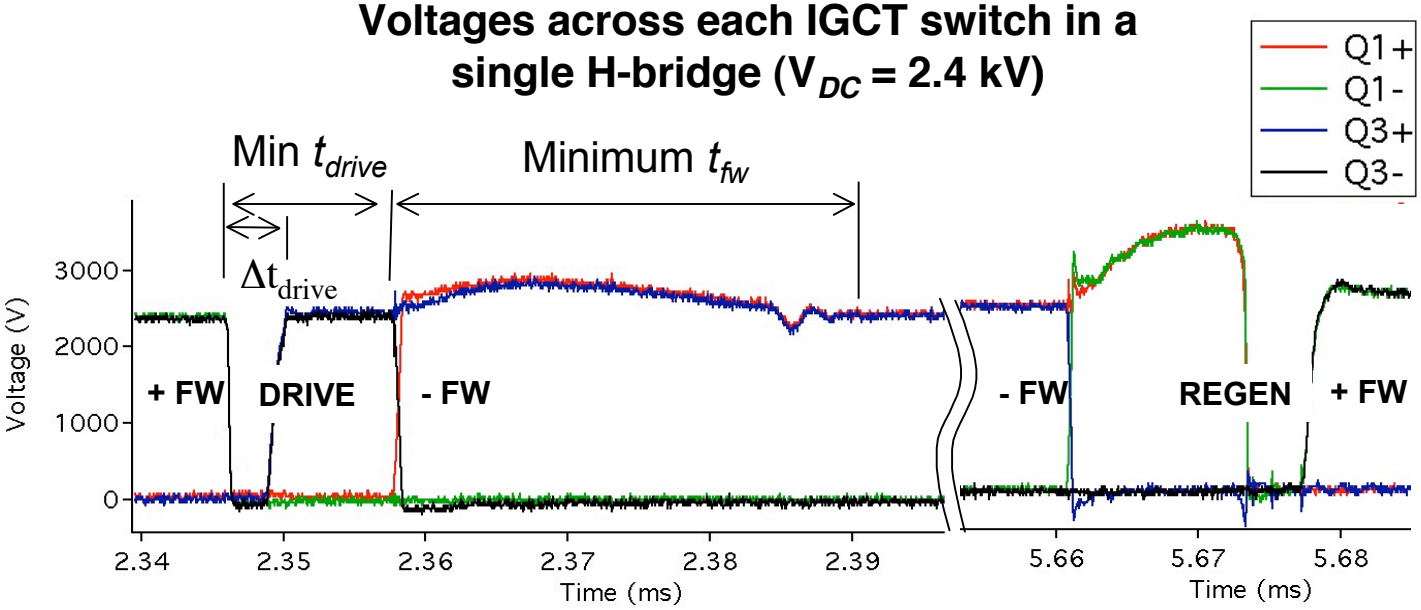


THE UNIVERSITY of WISCONSIN MADISON

Effect of RLCD Snubber

- **Shortens effective drive time**
  - Drive delay depends on load current $\Delta t_{drive} \propto I_{load}$
  - Min safe drive + drive delay at max current = min drive time (~12μs)
- **Enhances effective regen voltage $V_{load} > V_{DC}$**
- **Must define minimum freewheel time**
  - $L_{RLCD} \rightarrow 0$ in ~ 35 μs

Voltages across each IGCT switch in a single H-bridge (V_{DC} = 2.4 kV)



THE UNIVERSITY of WISCONSIN MADISON

IGCT System Requires Digital PWM

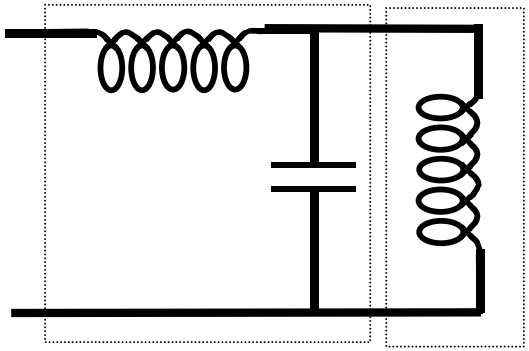
- **IGBT systems use analog PWMs**
  - Can define minimum t_{fw}
  - More than one switch event can occur per clock cycle → potentially damaging to IGCT switches
- **IGCT system uses digital PWM**
  - Can define minimum t_{fw} (*necessary for RLCD*)
  - Can define minimum t_{drive} & t_{regen}
    - Min t_{drive} & t_{regen} decoupled → compensate for drive delay
    - Drive & regen events skipped when appropriate
    - Saves driver energy & improves control
  - Clocks drive/regen decision
    - Insures one switch event per clock cycle
    - Permits "quadrant switching" → deactivates inactive switches

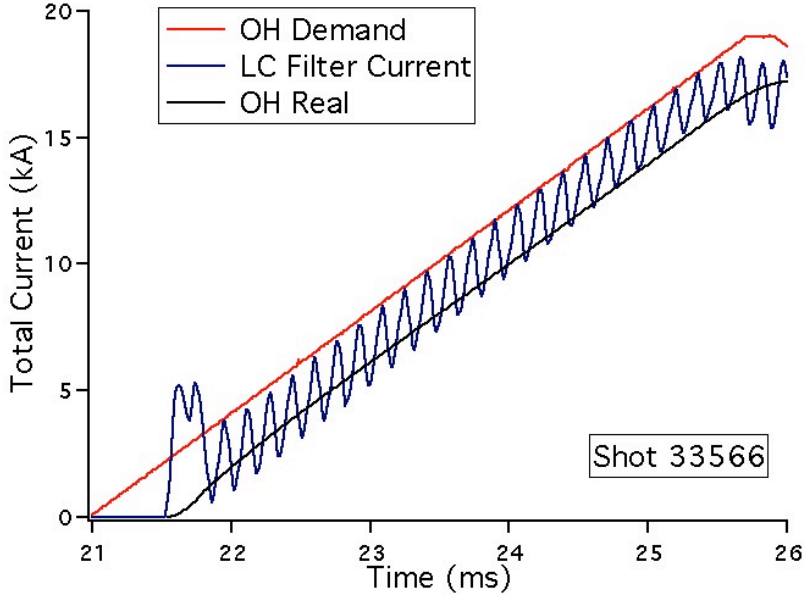
Splitter/Combiner Modules

- **Fiber communication with switches**
- **Fan-out of PWM commands to switches**
- **Fan-in of switch status**
  - IGBT controller
    - Active fault detection
    - Acknowledges switch events & reports a fault
  - IGCT controller
    - Reports status → fault detection done in S/C module
    - S/C modules confirm status of switch before sending it a command to close
- **Fault detection propagation**
  - All PWM commands disabled
  - Cap banks are dumped

Switch Event Filtering

- **TF/EF: Vessel walls provide effective filtering**
- **OH and plasma guns: LC line filter**
  - Small resistive loss
  - Feedback on LC filter current, not load (OH solenoid or gun) current
  - Sub μs time response





THE UNIVERSITY of WISCONSIN MADISON

IGCT Driver Limitation Model

- **Driver pulse energy: $E_{open} >> E_{close}$**
- **E_{open} depends on: I_{open} , V_{DC}, T_{switch}**

With constant V_{DC}, T_{switch} , energy depletion of driver given by:

$$E_D(t) = \gamma \sum_{i=1}^{n} I_{open} + n E_{off} - \gamma \beta t + \gamma \delta$$

γ : driver energy discharged per kA of current switched off

I_{open} : current switched off at each transition i

n : number of turn-off events ($= f t$)

$\gamma\beta$: recharging rate of the onboard capacitor bank

E_{off} : energy used by the driver to initiate turn-off event

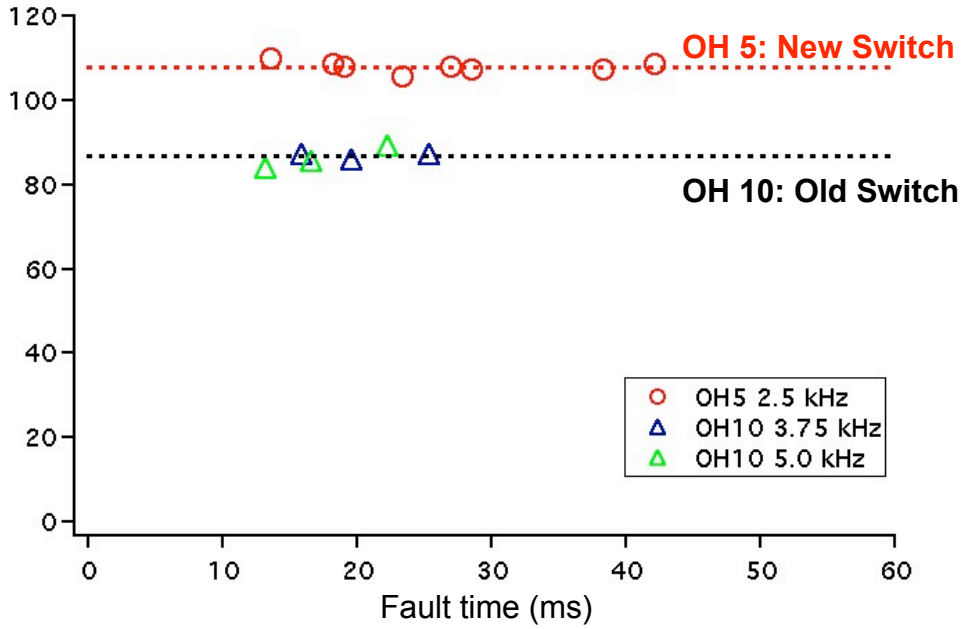
$\gamma\delta$: steady state energy loss of the driver

THE UNIVERSITY of WISCONSIN MADISON

IGCT Driver Limitation Data

- **When $E_D < E_{thresh}$, switch faults out**
- **E_{thresh} / γ same for every driver $\therefore \delta$ depends on the IGCT switch**

$$\left[\frac{E_{thresh}}{\gamma} - \delta\right](kA)$$

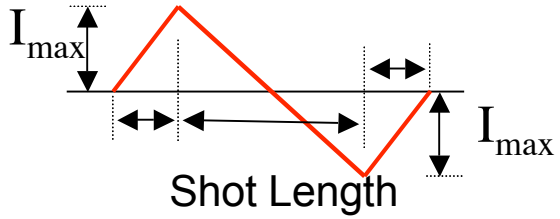


δ is a figure of merit for the IGCT devices

THE UNIVERSITY of WISCONSIN MADISON

Mapping Ohmic Operational Space

- **Model frequency limits for typical ohmic ops**
- **Conservative model → no drive/regen skips**

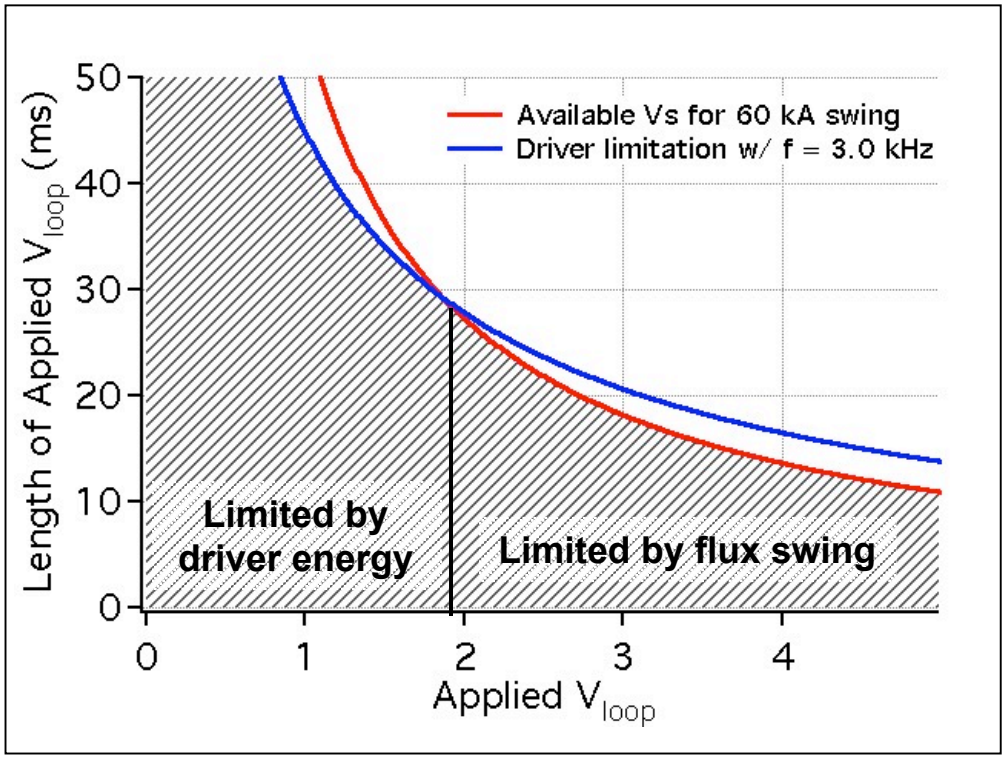


12 IGCT switches

δ = 86 (OH 10 limit)

dI/dt pre & post: 4.4 kA/ms

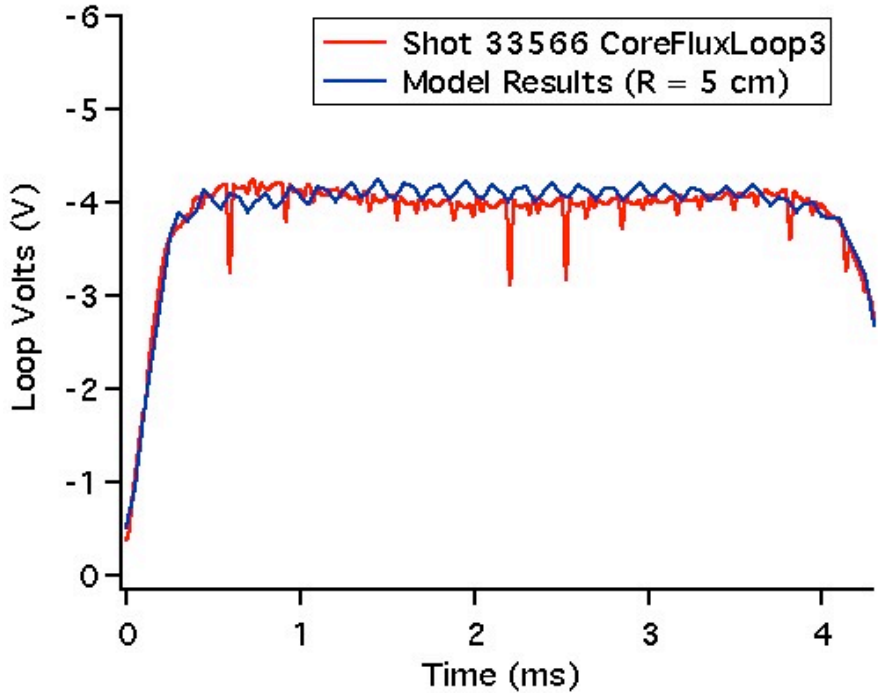
dI/dt during shot: 1.1 kA/mVs



THE UNIVERSITY of WISCONSIN MADISON

Predictive Model for Experiments

- **Iterative circuit model**
  - Two pole load: Solenoid & LC filter
  - PWM logic
  - RLCD effects
  - Wall currents
- **Future development**
  - Use model to optimize LC filter & f_{PWM}
  - Integrate into PCS model



THE UNIVERSITY of WISCONSIN MADISON

Conclusion

- **IGCT Ohmic Power Systems Operational**
  - Transient suppression achieved
  - Routinely used in high power operations
  - LC line filter provides smooth V_{loop}
- **New digital PWM and fault detection circuitry implemented**
  - Insures safe and consistent operation of IGCT switches
- **Ohmic power system models verified**
  - Driver energy limitation model
  - Ohmic power systems/wall model

Reprints