Non-inductive plasma startup and current profile modification in Pegasus spherical torus discharges

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PEGASUS Toroidal Experiment

Talk Outline

- The Pegasus spherical torus device
- Non-inductive formation of tokamaks:
  - DC helicity injection using biased plasma guns
  - Divertor-region vs outboard midplane locations
- ELM-like MHD activity in Ohmic discharges:
  - Filamentary magnetic structures
  - Correlated with high edge current density
- Summary

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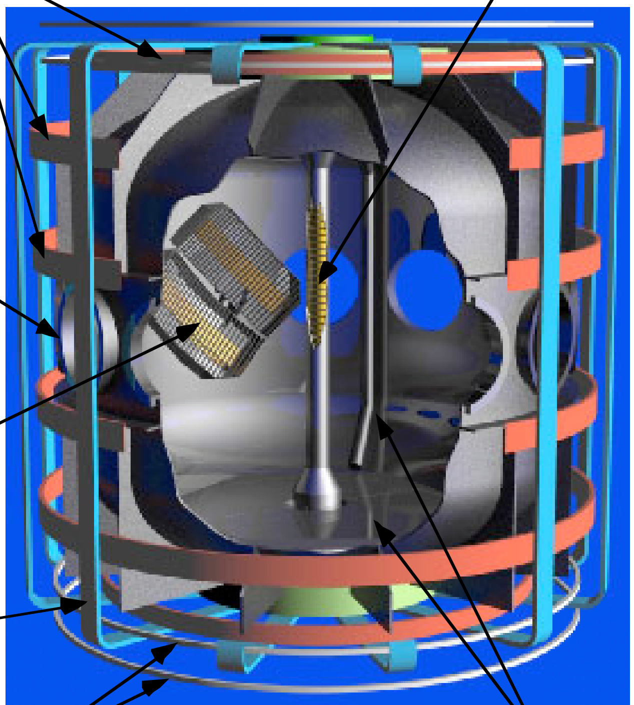
Studying ST Science and Engineering



Experimental Parameters

Parameter	Achieved	Goals
A	1.15-1.3	1.12-1.3
R (m)	0.2-0.45	0.2-0.45
I_p (MA)	≤ 0.18	≤ 0.30
I_N (MA/m-T)	6-12	6-20
RB_t (T-m)	≤ 0.06	≤ 0.1
κ	1.4–3.7	1.4–3.7
τ_{shot} (s)	≤ 0.02	≤ 0.05
β_t (%)	≤ 25	> 40
P_{HHFW} (MW)	0.2	1.0

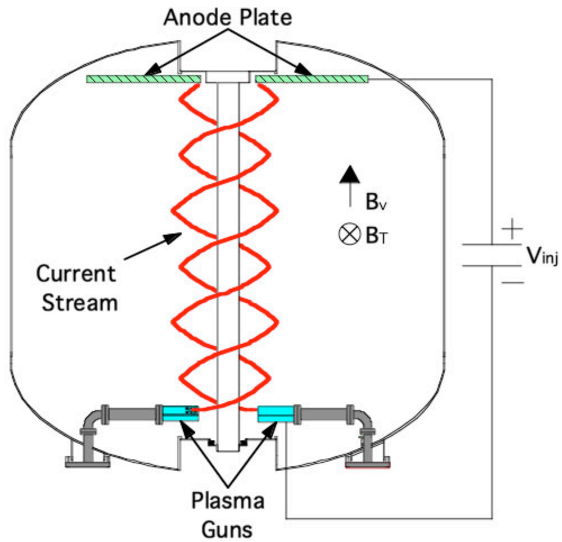
- Non-inductive startup/sustainment
- Tokamak physics in small aspect ratio:
  - –High-I_N, high-β operating regimes
  - –ELM-like edge MHD activity

Biased Plasma Guns Can Be DC Helicity Sources

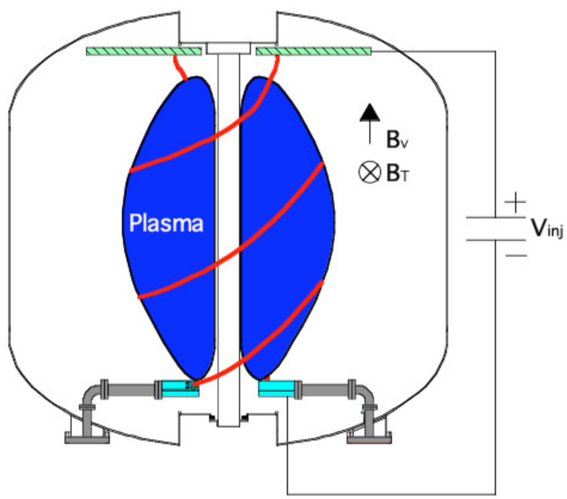
- Two divertor-mounted guns are shown.
- DC helicity injection rate is given by:

$$\dot{K}_{inj} = 2V_{inj}B_N A_{inj}$$

- The helical filaments can relax and form a tokamak if:
  1. Plasma-generated B_p greater than vacuum B_v
  2. Radial force balance is satisfied
  3. Sufficient input power
- Relaxed-plasma I_p is greater than I_{bias} multiplied by vacuum field windup.



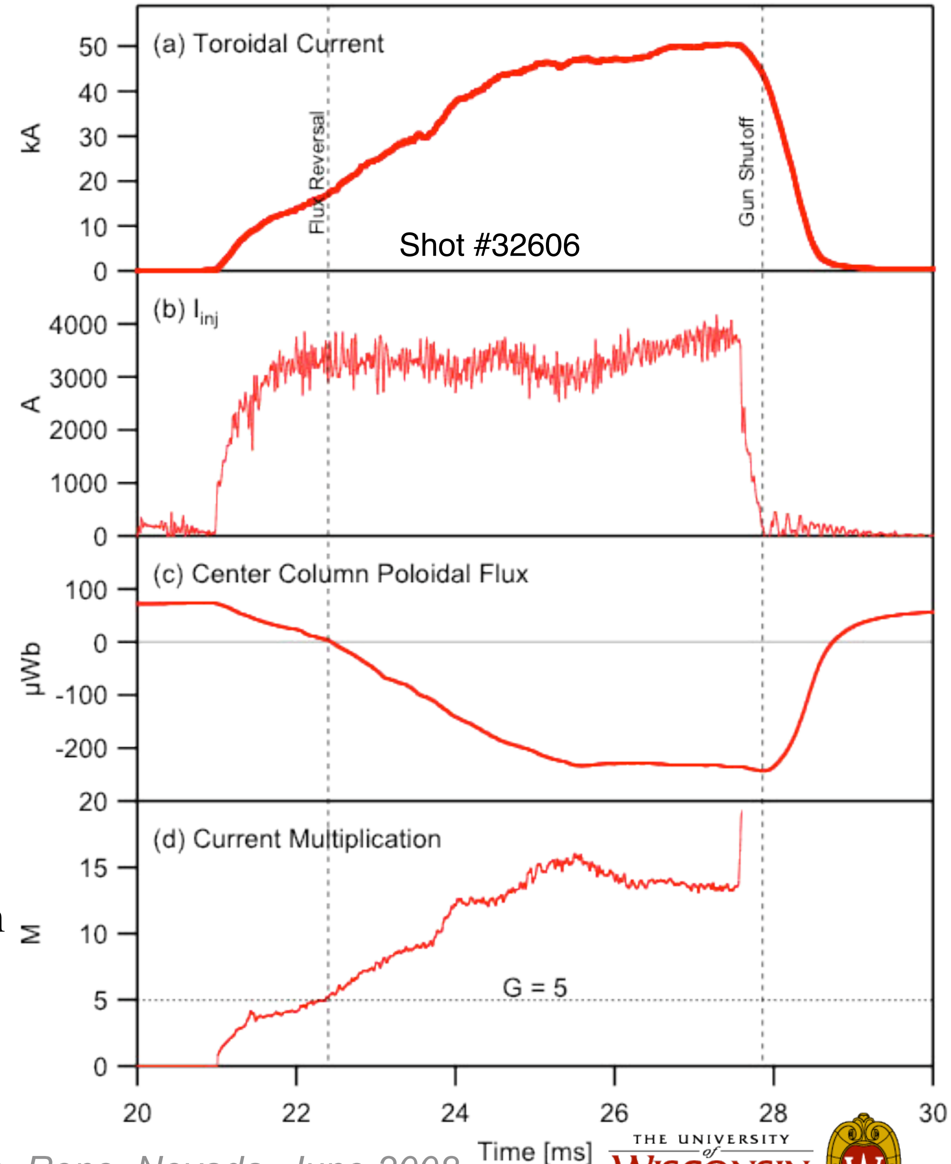
Filaments



Relaxed State

Relaxation Enhances the Driven Current Beyond the Vacuum-Field Windup

- I_p > 50 kA driven by I_{bias} ≤ 4 kA:
  - Plasma current persists after $I_{bias}=0$
  - Coil currents static (no ramps)
  - B_T = 11 mT at plasma magnetic axis
  - Vacuum vertical field is 7 mT
- Poloidal flux reversal on column is hallmark of significant relaxation:
  - Occurs when I_p/I_{bias} exceeds windup
- Current multiplication (I_p/I_{bias}) up to 15:
  - Consistent with poloidal flux amplification
  - Vacuum-field windup of only 5



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Maximum I_p Set by Helicity Balance

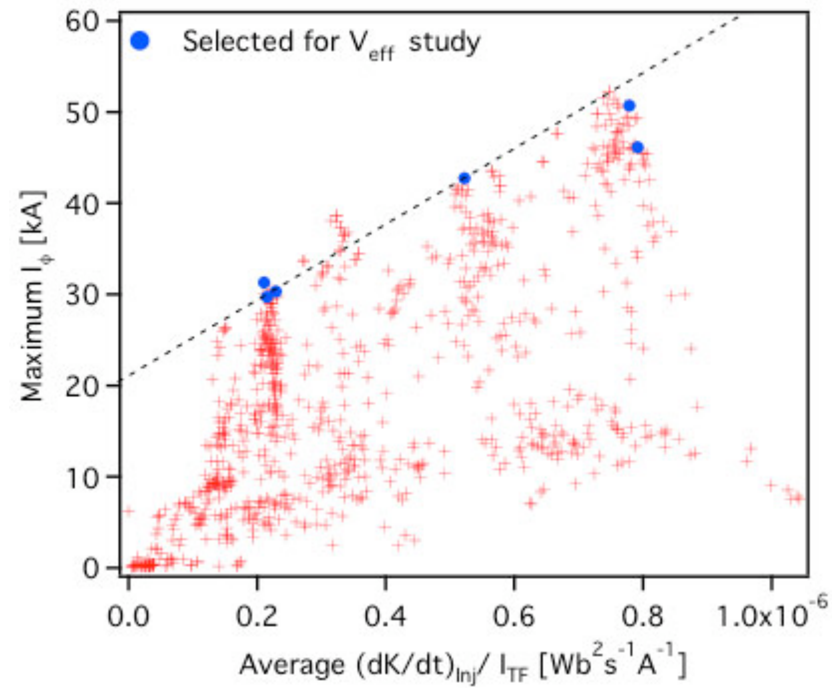
- Maximum I_p is consistent with the helicity injection rate:
  - –Offset-linear relationship

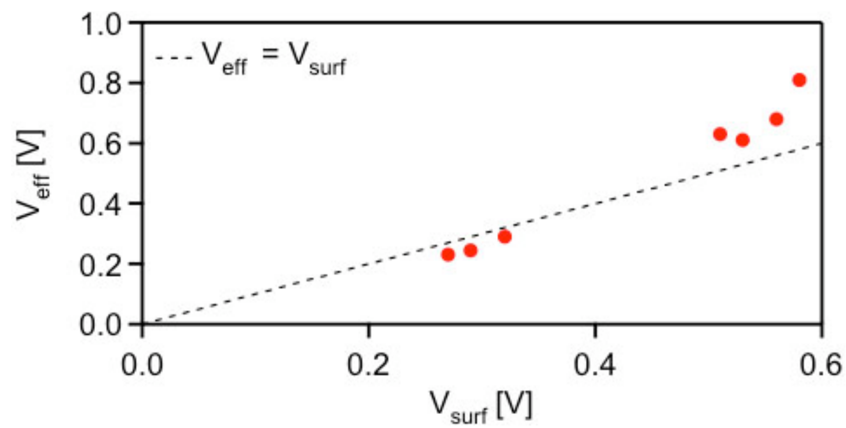
- Maximum I_p can be increased by
  - –Increasing number of guns
  - –Increasing gun aperture(s)
  - –Increasing bias voltage

- At peak current I_p, helicity injection rate is equal to measured dissipation:
  - –Dissipation voltage V_{surf} measured with central-column flux loop
  - –Effective drive voltage V_{eff} is:

$$V_{eff} \approx V_{inj} \frac{N_{inj} A_{inj} B_{Tinj}}{A_p B_{Tp}}$$

See Eidietis *et al.*, JFE **26**, 43 (2007).





Point-Source Injectors can be Placed Anywhere

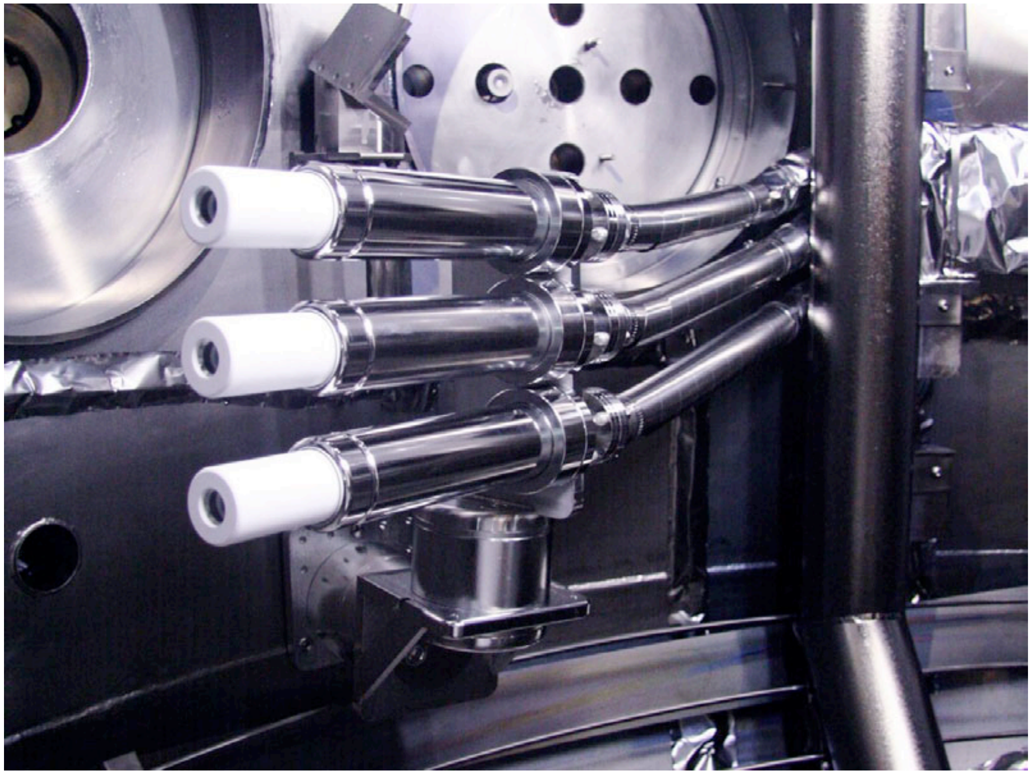
- Divertor-gun-driven tokamaks couple to Ohmic drive, but require significant coil-current ramps:
  - To maintain radial magnetic stability.
  - To reach typical Ohmic operating parameters (*e.g.*, increased TF to maintain kink stability).

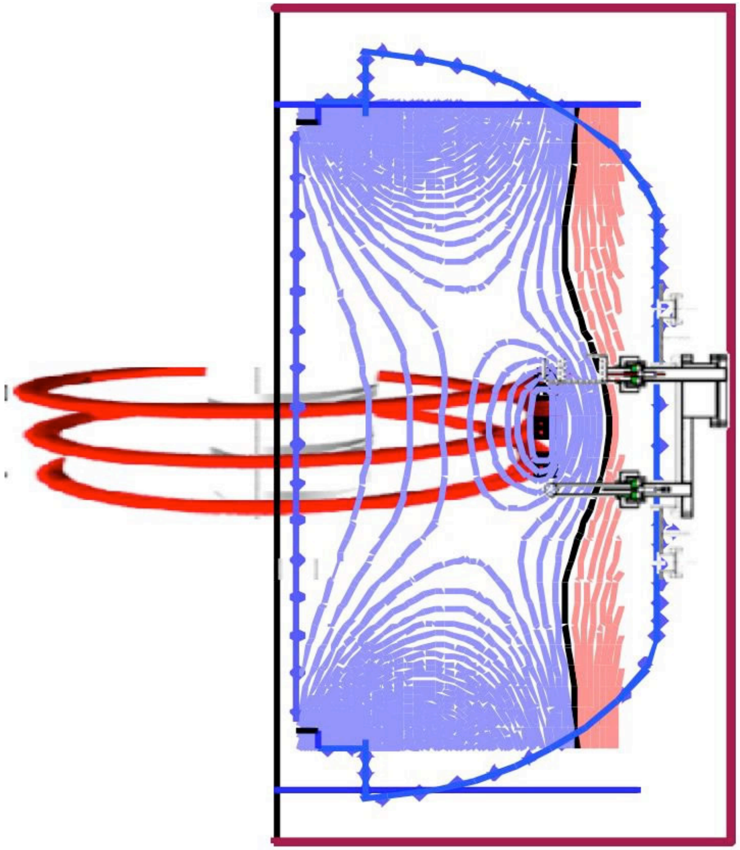
- Tokamaks formed by outboard midplane guns would:
  - Form with typical Ohmic parameters (relatively high TF).
  - More easily couple to outer-PF induction.
  - Be more accessible to diagnostics
  - Have longer L/R decay timescales

- Studies using these two extreme geometries can be used to determine the optimum injector configuration.

Outboard Midplane Gun Array Deployed

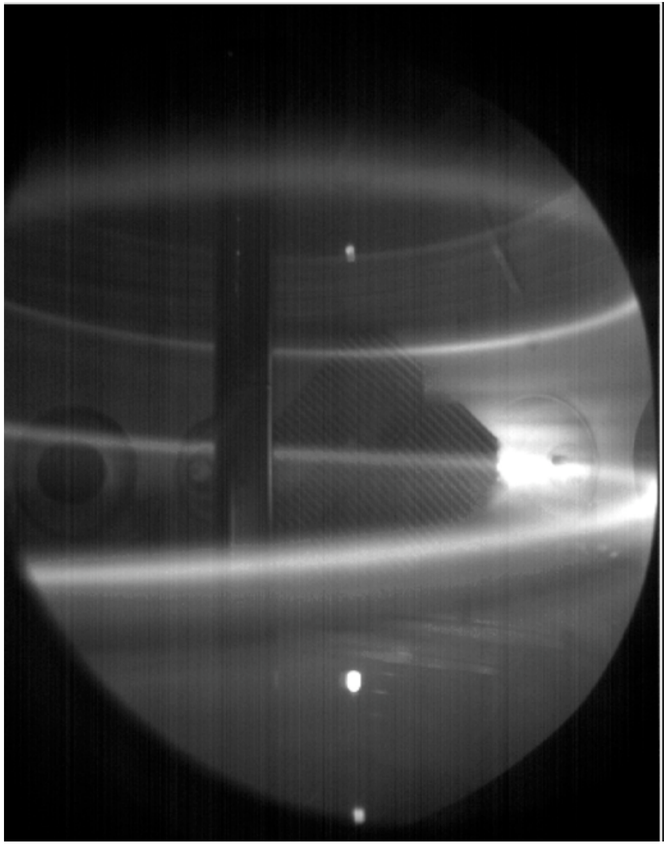
- Three guns, stacked as shown, below the Pegasus midplane.
- Single anode is at same major radius, above the midplane.



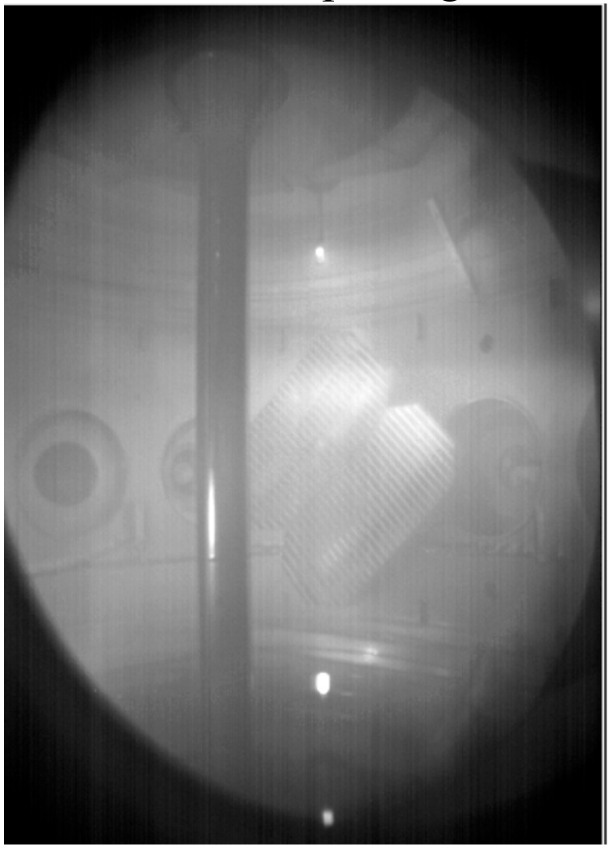


Evolution of Midplane-Gun-Driven Plasma

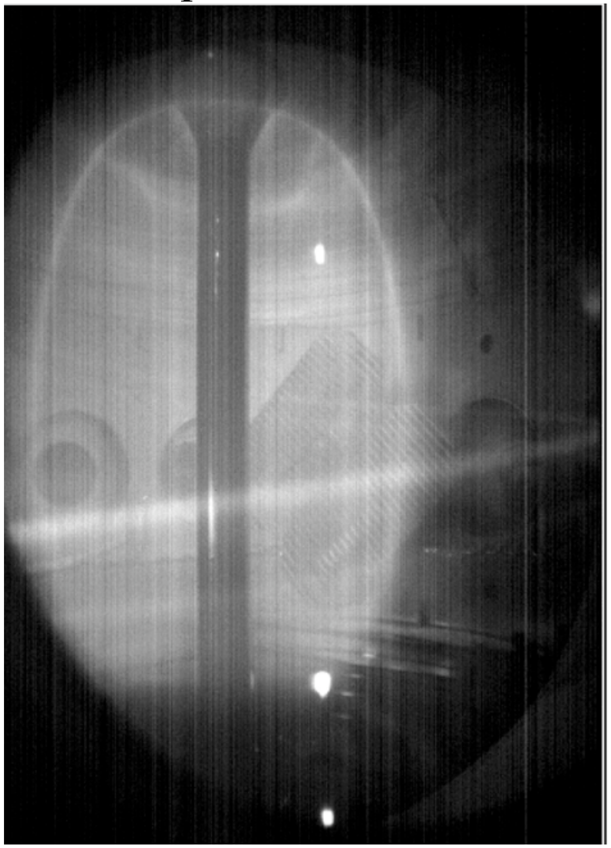
Pegasus shot #40458: Two midplane guns, outer-PF ramp



t=21.1 ms, I_p=2-3 kA
Filaments only



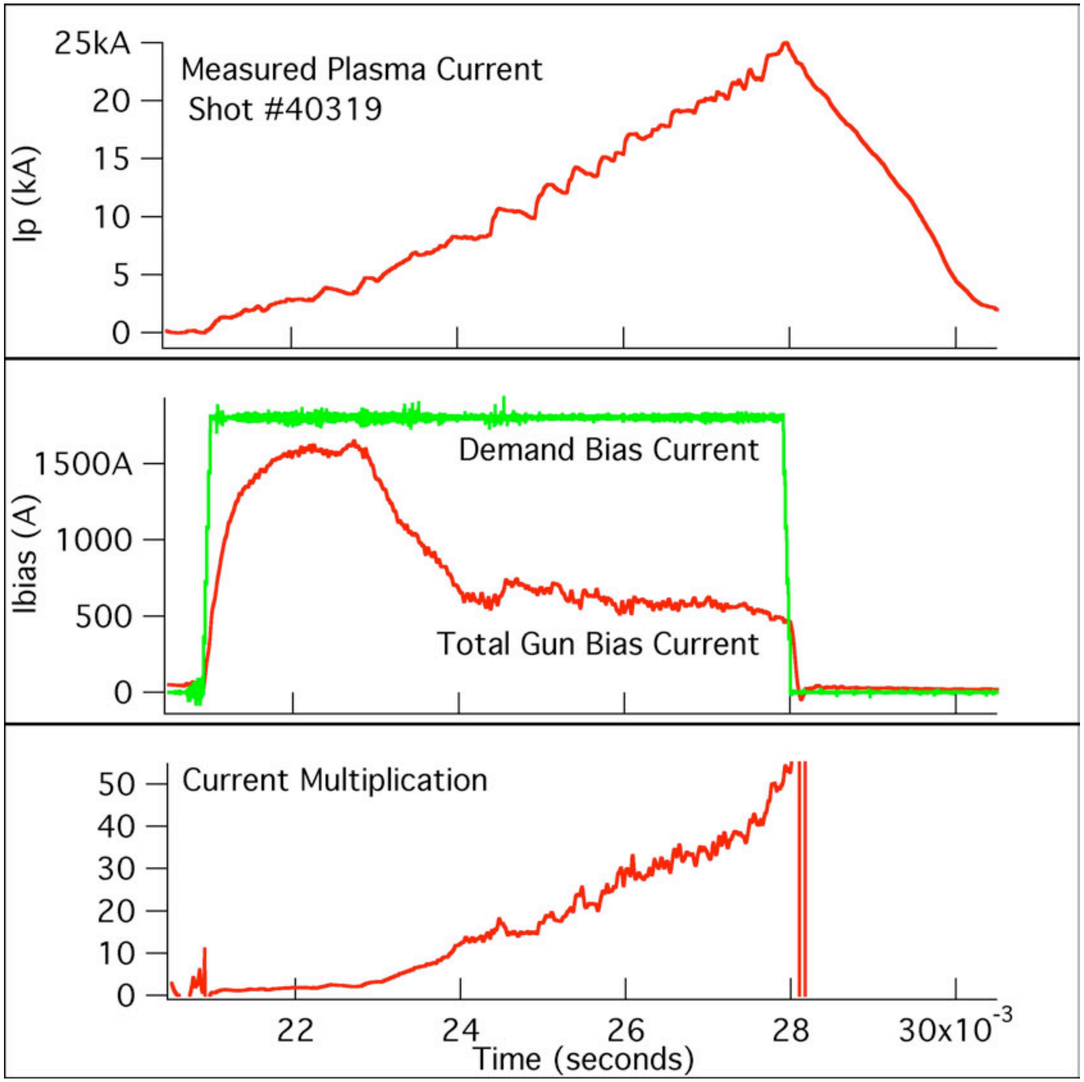
t=28.8 ms, I_p=42 kA
Driven diffuse plasma



t=30.6 ms, I_p=37 kA
Guns off, Decaying

High Current Multiplication with Midplane Guns

- Single-gun discharge with no PF ramps.
- Current multiplication above 50 at gun shutoff.
- Sharp rises in I_p during rampup may correspond to low-order rational values for the edge-q.



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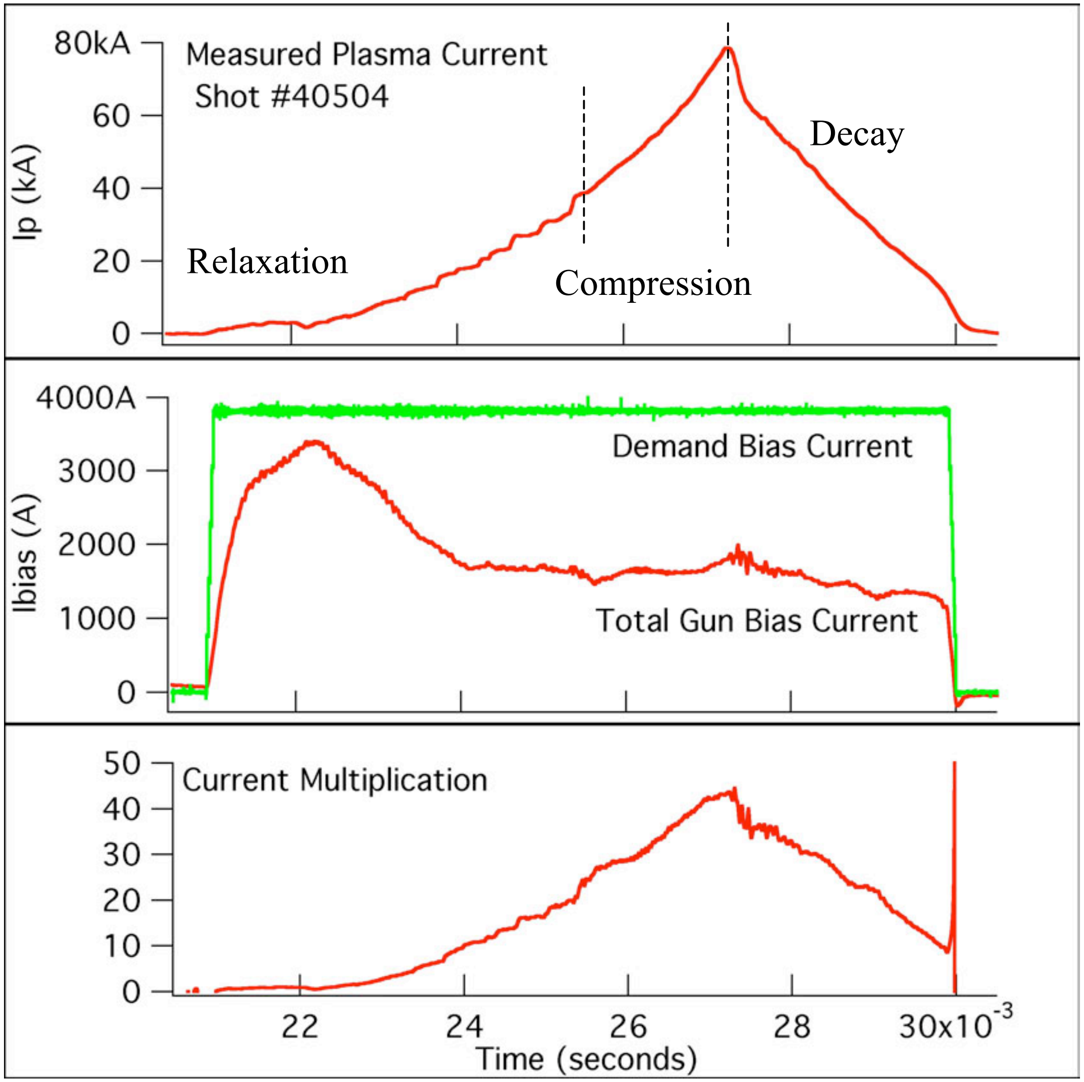
Outer-PF Ramps Further Enhance I_p

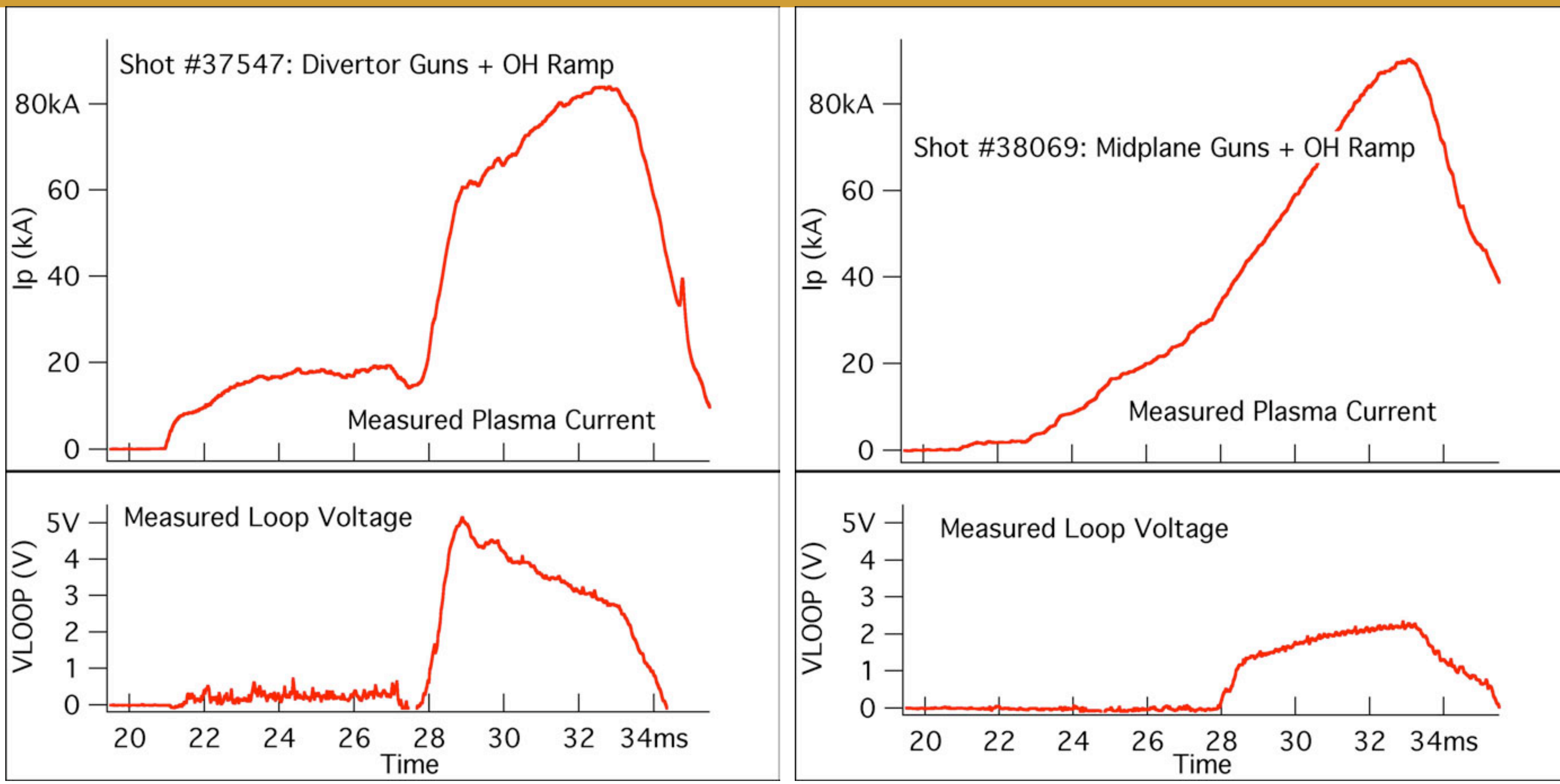
- Current multiplication through relaxation and outer-PF ramp.
- I_p evolves through three stages:
  1. Relaxation of gun-driven plasma +outer-PF ramp
  2. Radial compression of detached tokamak
  3. Tokamak decay, limited on the central-column



Gun-Driven Plasma Studies Ongoing

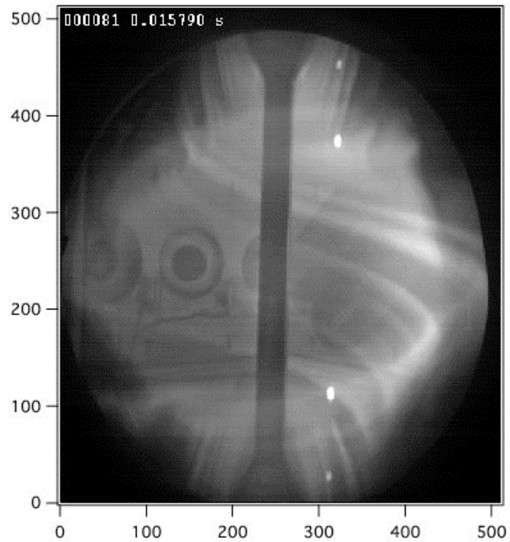
- Divertor-gun-driven plasma evolution is relatively simple:
  - Guns in high-field region sustained plasmas in low-field region.
  - Plasma current I_p evolved relatively smoothly with time.
  - Maximum I_p is primarily determined by the helicity injection rate.
- Plasma evolution for outboard guns is more dynamic:
  - Discharges must "grow" from the low-field region near the guns into the higher-field confinement region.
  - "Bursts" of MHD activity correspond to rapid increases in I_p; these "bursts" may also correlate with low-order rational edge-q.
  - Maximum I_p is related to the helicity injection rate, radial force balance, and the Taylor relaxation condition ($\lambda_{inj} > \lambda_{tok}$).
- For more details, see poster by D. Battaglia *et al*.

Midplane-Driven Plasmas Couple More Easily to Ohmic

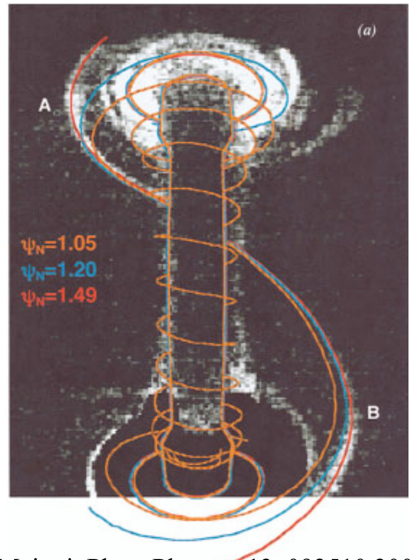


- Both discharges had guns, outer-PF ramps, and applied OH drive.
- The midplane-driven discharge required less Ohmic flux and applied loop voltage to reach the same peak plasma current (90 kA).

ELM-like Edge Filaments Observed

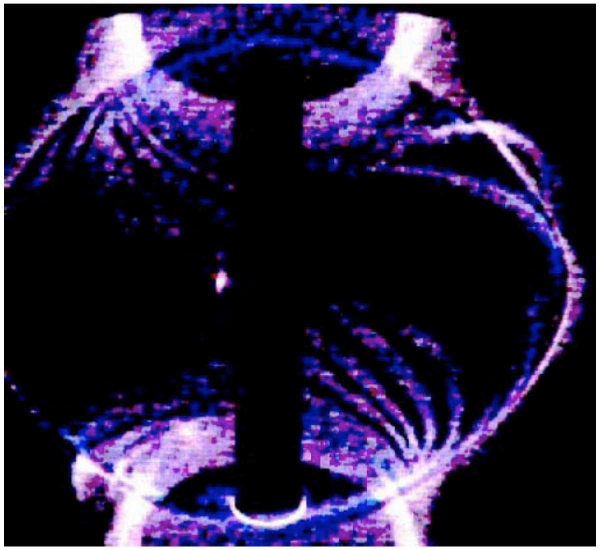


Pegasus



Maingi, Phys. Plasmas **13**, 092510 2006

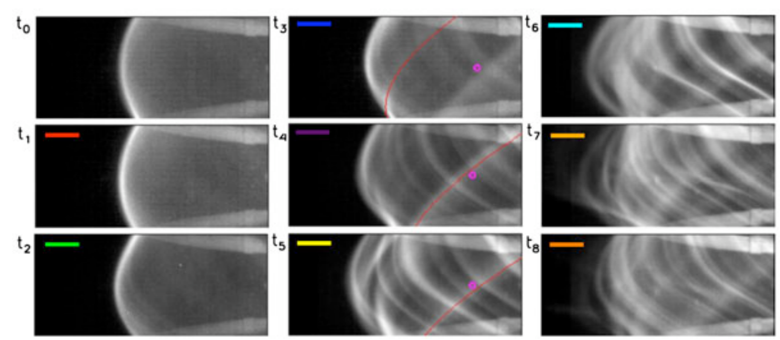
NSTX



Kirk, 2004 Proc. 20th Int. Conf. on Fusion Energy 2004

MAST

- Filaments follow field lines, and correlate with high edge current density.
- Pegasus filaments are continuous in time, unlike "bursty" strong ELM behavior:
  - Pegasus likely has an L-Mode edge
  - But, may be same physical mechanism as ELMs



Scannell, Plas. Phys. Controlled Fus. **49**, 2007

High $(j_{||}/B)_{edge}$ Typical in Pegasus

- Key parameter for peeling-mode stability is the ratio $j_{||}/B$, related to the usual magnetic inverse length scale λ.

- Edge $j_{||}/B$ (or λ) in Pegasus Ohmic plasmas is comparable to that in larger devices, suggestive of strong peeling drive:
  - Pegasus: $j_{||}/B \sim 1\text{x}10^6$ A/(m^2-T), or $\lambda \sim 1.2\ m^{-1}$
  - DIII-D*: $j_{||}/B \sim (0.5\text{-}1)\text{x}10^6$ A/(m^2-T), or $\lambda \sim 0.6\text{-}1.2\ m^{-1}$

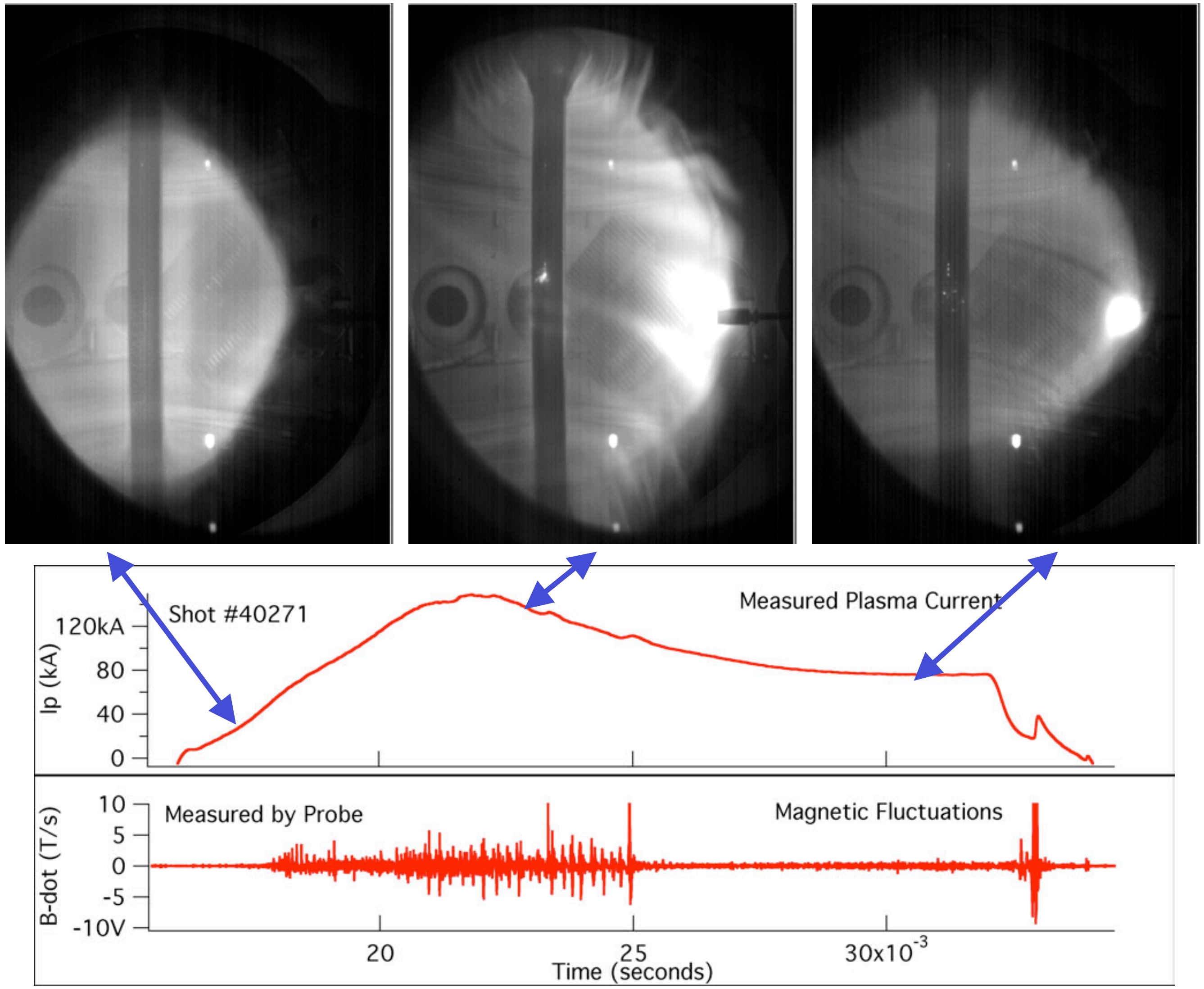
- Pegasus edge $j_{||}/B$ can be manipulated with loop voltage variations in time, or by using the midplane plasma guns.

*: Thomas, Phys. Plasmas **12**, 056123 2005

Reducing Edge $J_{||}$ Suppresses Filaments

Fast camera images of Ohmic shot #40271 at:

- 17.5 ms: current rise, filament onset.
- 23.1 ms: near current peak, vigorous filaments.
- 30.6 ms: current flattop/decay, filaments strongly suppressed.



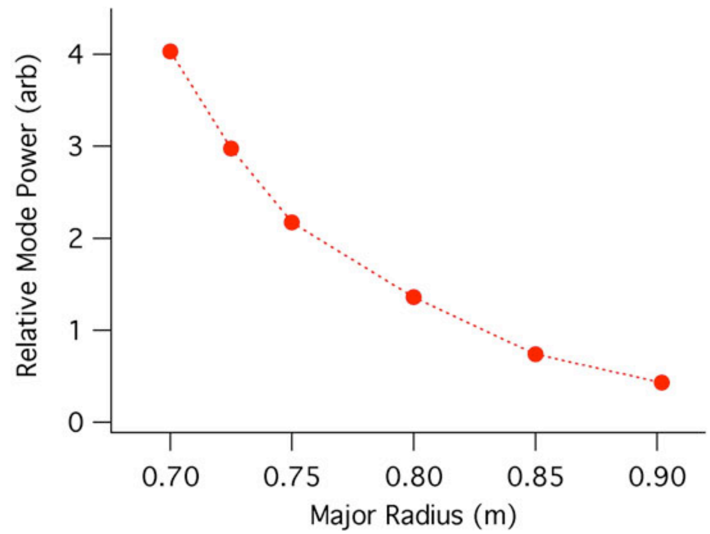
Pegasus Diagnostics Are Improved for Filament Study

Determining the magnetic structure of these edge filaments requires diagnostics with good spatial and temporal resolution.

Pegasus DAS electronics have been upgraded: anti-aliasing up to 400 kHz; common-mode noise rejection.

Two internal magnetic probes are deployed, and a finely-spaced toroidal array will be installed.

Taking initial data, after completing Ohmic-bank upgrade.



Relative power radial structure for a low-frequency edge mode, for a series of identical shots. The relative power for this n=1 mode falls as $(R-R_{edge})^{-2}$, as expected for the 2/1 tearing mode.

Similar scans for high-frequency modes are now possible for Pegasus.

Summary

- The Pegasus device is a valuable testbed for exploring tokamak- and ST-related physics and engineering:
  - Non-inductive startup, MHD studies, high-I_N high-β operations.
- Non-inductive Pegasus discharges (with I_p up to 80 kA) can be formed with biased point current sources:
  - DC helicity injection with point current sources (vs CHI electrodes).
  - Midplane-driven plasmas will be further optimized, including the optimum coupling to Ohmic or other current drive methods.
  - Gun startup + upgraded Ohmic may extend high-β operations.
  - Physical understanding of the relaxation and its geometric dependence will enable design of a future optimum source configuration.
- Ohmic Pegasus discharges have high edge λ, and exhibit continuous instabilities similar to peeling modes:
  - Internal probes are being used to characterize these modes.
  - Control of these modes may be possible by manipulating the edge λ.

PEGASUS Team and References

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- Unterberg *et al*., Journal of Fusion Energy **26**, 221-225 (2007).
- Eidietis *et al*., Journal of Fusion Energy **26**, 43-46 (2007).
- Garstka *et al*., Nuclear Fusion **46**, S603 (2006).
- Garstka *et al*., Physics of Plasmas **10**, 1705 (2003).

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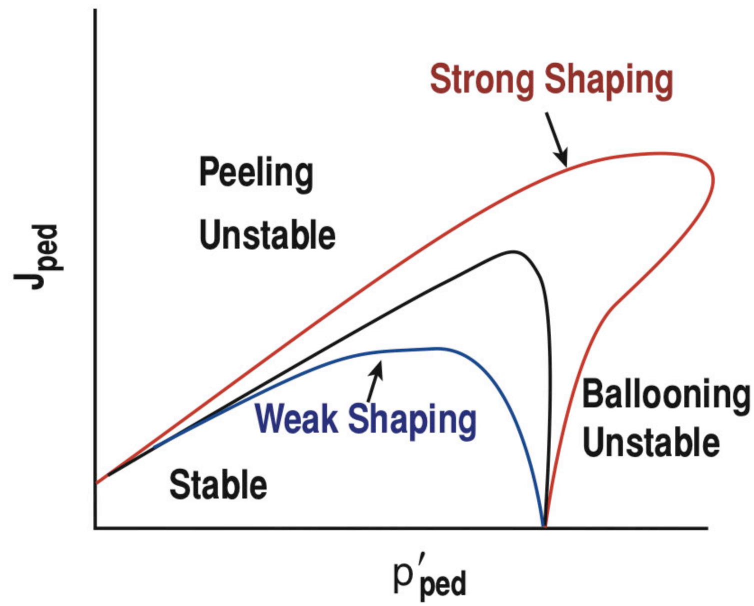
Near-Term Plasma Gun Research

- Further optimize gun-driven plasma performance:
  - Three guns, higher bias voltage: peak I_p well over 100 kA
- Couple gun-driven discharges to Ohmic drive:
  - Single-swing and double-swing ramps
  - Separate Ohmic upgrade: more flux, longer duration
  - Gun-driven startup may extend high-I_N, high-β operations
- Edge probing: what is the relaxation mechanism?
- Development of a complete model, including:
  - Plasma current limits versus geometry and other parameters
  - Optimum gun-array design and running scenarios for Pegasus and other toroidal devices, such as NSTX or ITER

Candidate Instability: The Peeling-Ballooning Mode

- Proposed ELM mechanism, supported by experimental and computational studies:
  - Medium-n MHD instability
- Peeling-mode branch
  - Edge current, current gradient drive
  - Stabilized by increasing edge p', for a range in edge current density
  - Weakly stabilized by strong shaping
- Ballooning-mode branch
  - Normal pressure gradient drive
  - Stabilized by increasing shear
  - Strongly stabilized by shaping



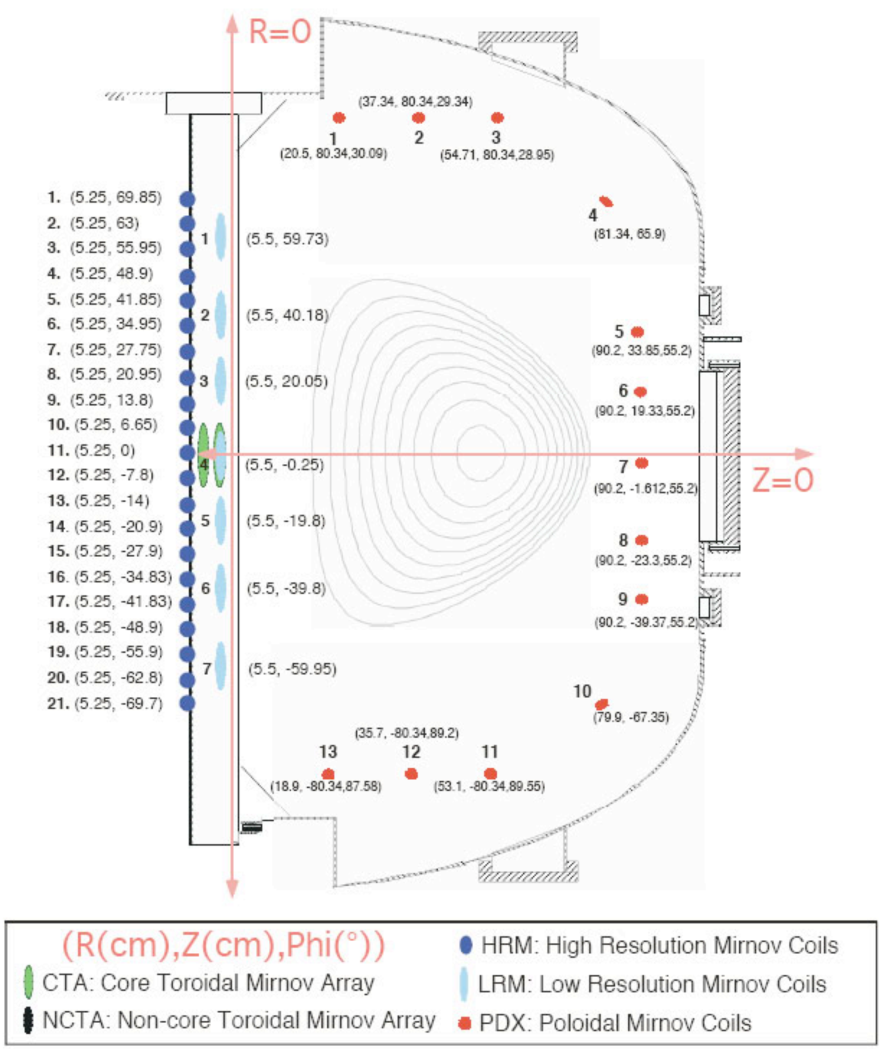
Snyder, Phys. Plasmas **12**, 056115, 2005

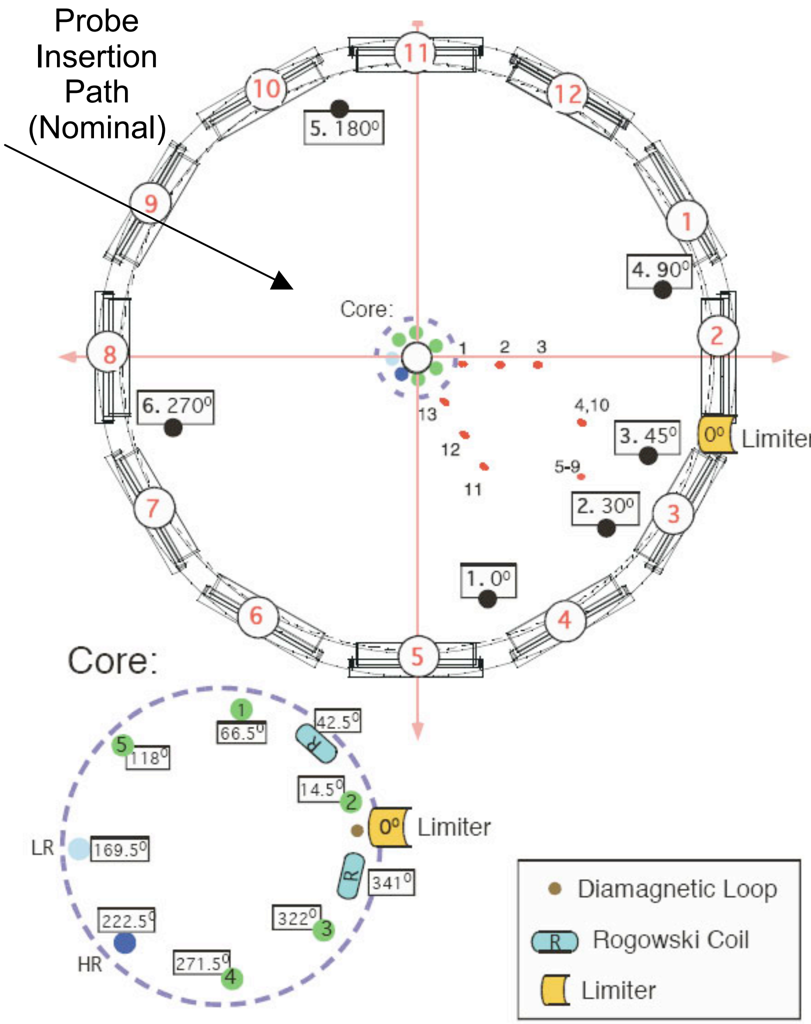
Is the Pegasus Edge Peeling-Unstable?

- Pegasus plasma edge is compatible with probes
  - Two midplane single-winding magnetic probes deployed
  - Midplane toroidal array being implemented
  - Triple langmuir probes being designed

- Internal probe analysis:
  - Confirm that the filaments have a magnetic signature
  - Correlation studies and mode analysis to determine structure
  - Measured internal fields improve equilibrium reconstructions, for stability analysis or comparison to theoretical models

Pegasus Mirnov Locations





A.J. Redd and the Pegasus Team, 2008 ICC Workshop, Reno, Nevada, June 2008

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