The PEGASUS Toroidal Experiment Program

A.J.Redd, J.L.Barr, M.W.Bongard, M.G.Burke, R.J.Fonck, E.T.Hinson, D.J.Schlossberg, and K.E.Thome

2010 Annual Meeting of the APS Division of Plasma Physics

Chicago, Illinois

November 8-12, 2010



University of Wisconsin-Madison



PEGASUS Toroidal Experiment

PEGASUS Overview Abstract

The PEGASUS program is developing nonsolenoidal startup and growth techniques for tokamaks, and exploring plasma stability at near-unity aspect ratio.

Helicity injection from localized current sources (plasma guns) in the plasma periphery have produced $I_p > 0.17$ MA to date, consistent with helicity balance and Taylor relaxation constraints. Compact passive electrodes can also be used for helicity injection and I_p growth, given a tokamak discharge already formed by the plasma guns.

During helicity injection, the plasma edge exhibits bursty low-n MHD activity and ion spectroscopy shows strong ion heating, consistent with turbulent magnetic relaxation processes.

After gun shutoff, the plasmas are MHD quiescent, and I_p can be grown and sustained above 0.20 MA, due to formation of sheared magnetic profiles in the core region. Efficient handoff from helicity injection to inductive drive requires relatively slow I_p rampup during helicity injection, to build up significant core current density.

Plasma stability is dominated by peeling-like modes at large j_{edge}/B, and large-scale low-m/n=1 core activity. Probe-measured edge profiles constrain equilibrium fits, and allow direct tests of peeling-ballooning theory.

Work supported by U.S. DOE Grant DE-FG02-96ER54375

Main Physics Points

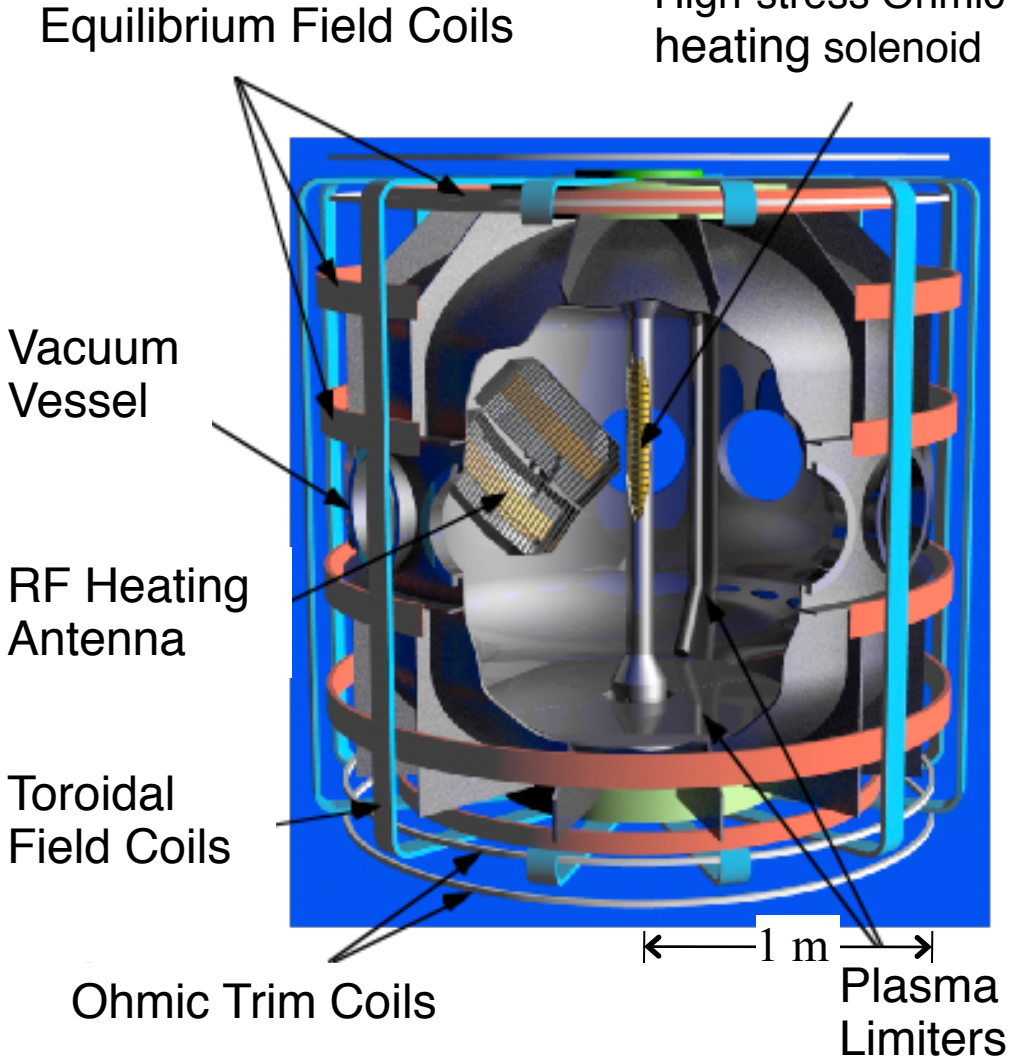
- Point-Source Helicity Injection Holds Promise as a Scalable Non-Inductive Startup Technique for STs and Tokamaks
  - Achievable I_p governed by helicity input rate and Taylor relaxation constraints
  - Measurements on PEGASUS confirm predicted scalings of maximum achievable I_p
  - Recent development suggests simpler more powerful injection system using plasma gun – passive electrode combination

- The Helicity Injection Non-Inductive Startup Technique Allows j(R,t) Control to Enable Access to high I_N, β_T

- High j_{edge}, low B_T at A ~ 1 Provides Opportunity for Detailed Peeling Mode Studies

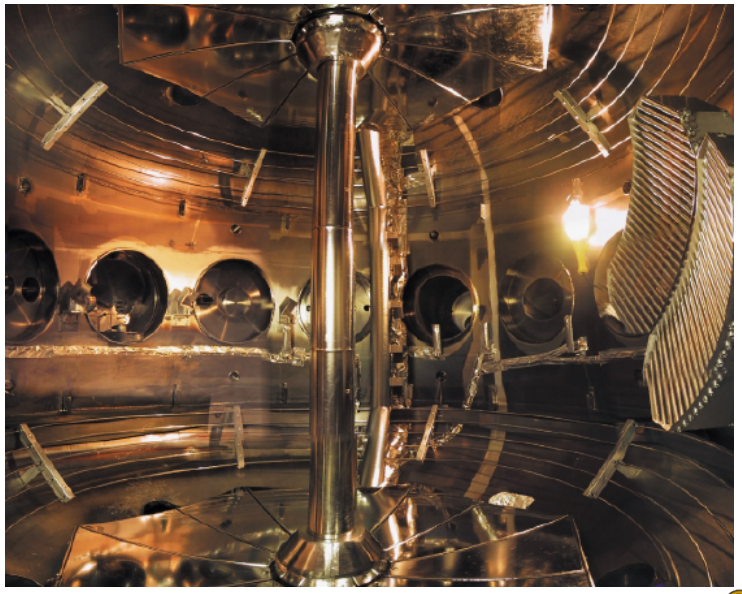
THE UNIVERSITY of WISCONSIN MADISON

Pegasus is a Compact Ultralow-A ST



Experimental Parameters

Parameter	To Date
A	1.15 – 1.3
R(m)	0.2 – 0.45
I_p (MA)	≤ .22
I_N (MA/m-T)	6 – 12
l_i	0.2 – 0.5
κ	1.4 – 3.7
τ_{shot} (s)	≤ 0.025
β_t (%)	≤ 25
P_{HHFW} (MW)	0.2



A.J.Redd et al, 2010 APS-DPP Annual Meeting, Chicago, IL, Nov 8-12, 2010

THE UNIVERSITY of WISCONSIN MADISON

DC Helicity Injection Startup on PEGASUS Utilizes Localized Washer-Gun Current Sources

- Plasma gun(s) biased relative to anode:
  - Helicity injection rate:

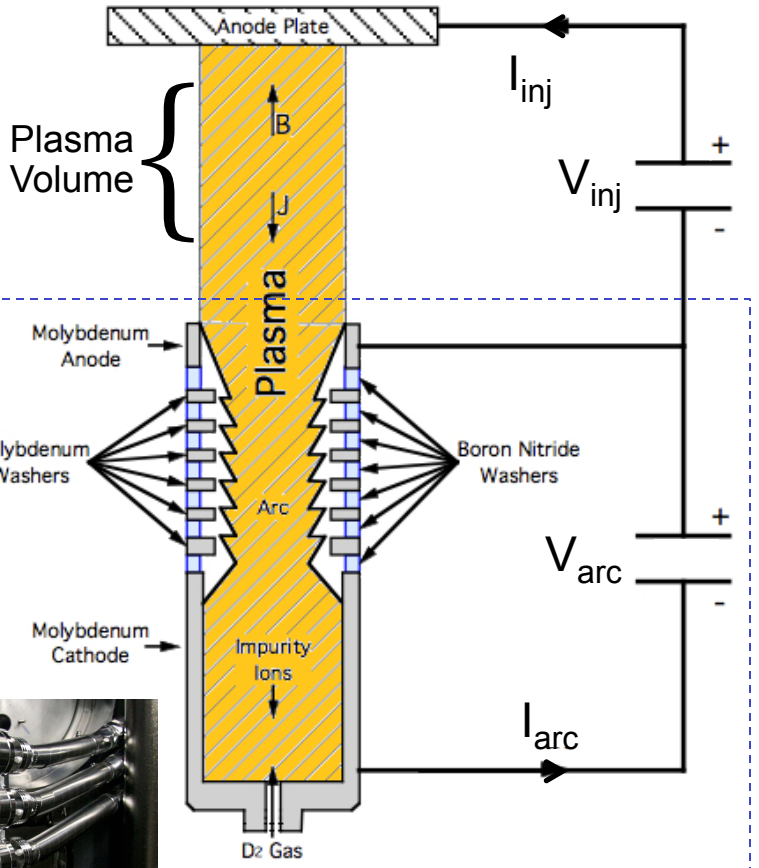
$$\dot{K}_{inj} = 2V_{inj}B_N A_{inj}$$

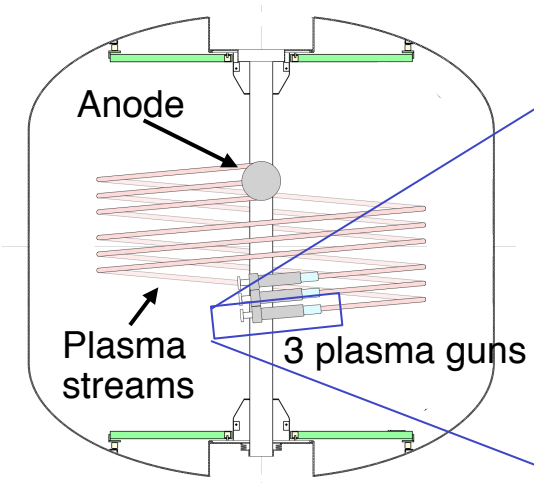
V_{inj} - injector voltage

B_N - normal B field at gun aperture

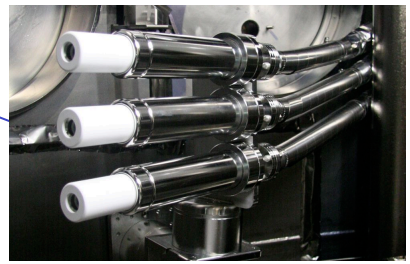
A_{inj} - injector area

Simplified illustration of a plasma gun for helicity injection *(not to scale)*





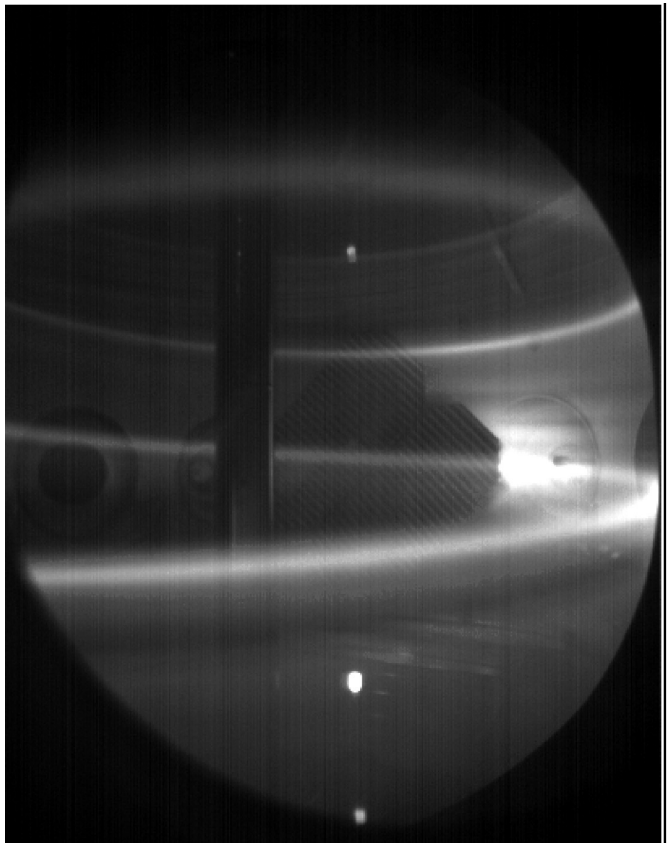
Midplane Injection



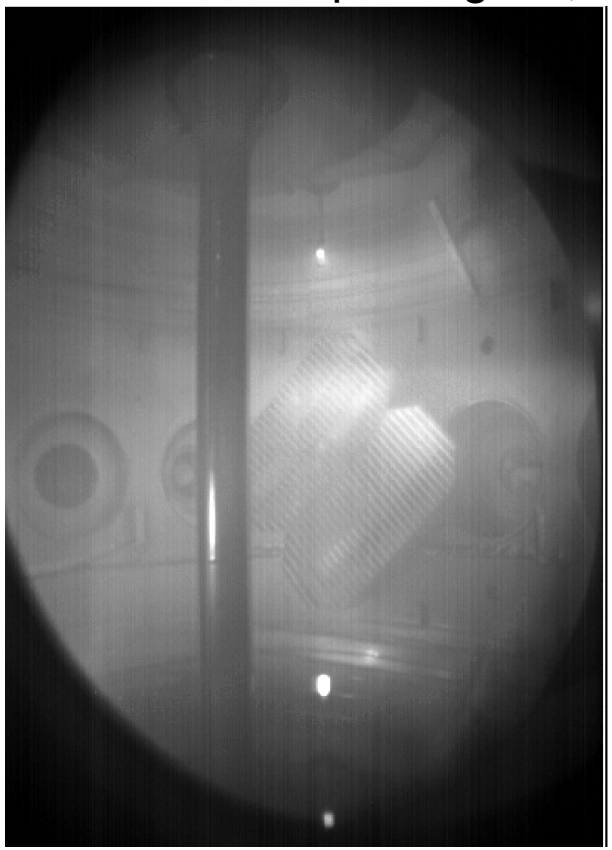
THE UNIVERSITY of WISCONSIN MADISON

Evolution of midplane-gun-driven plasma

PEGASUS shot #40458: two midplane guns, mild outer-PF ramp



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



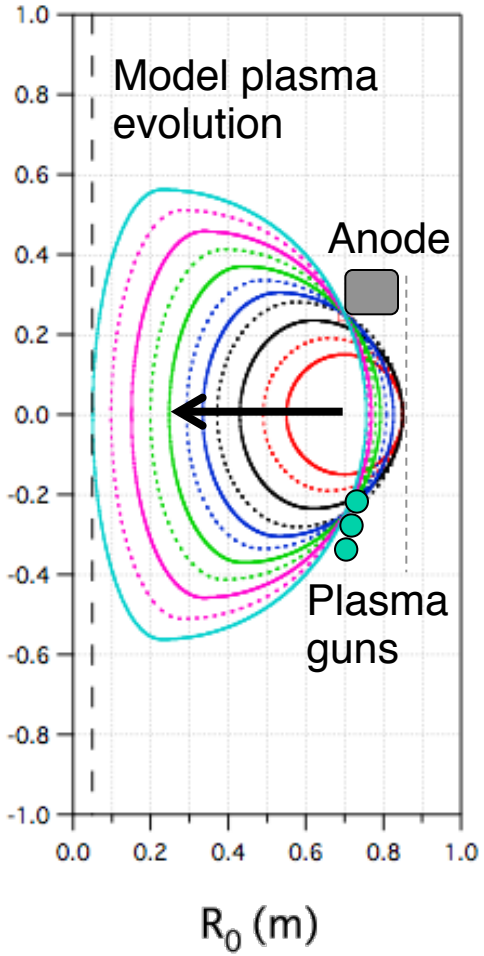
t=28.8 ms, I_p=42 kA
Driven diffuse plasma

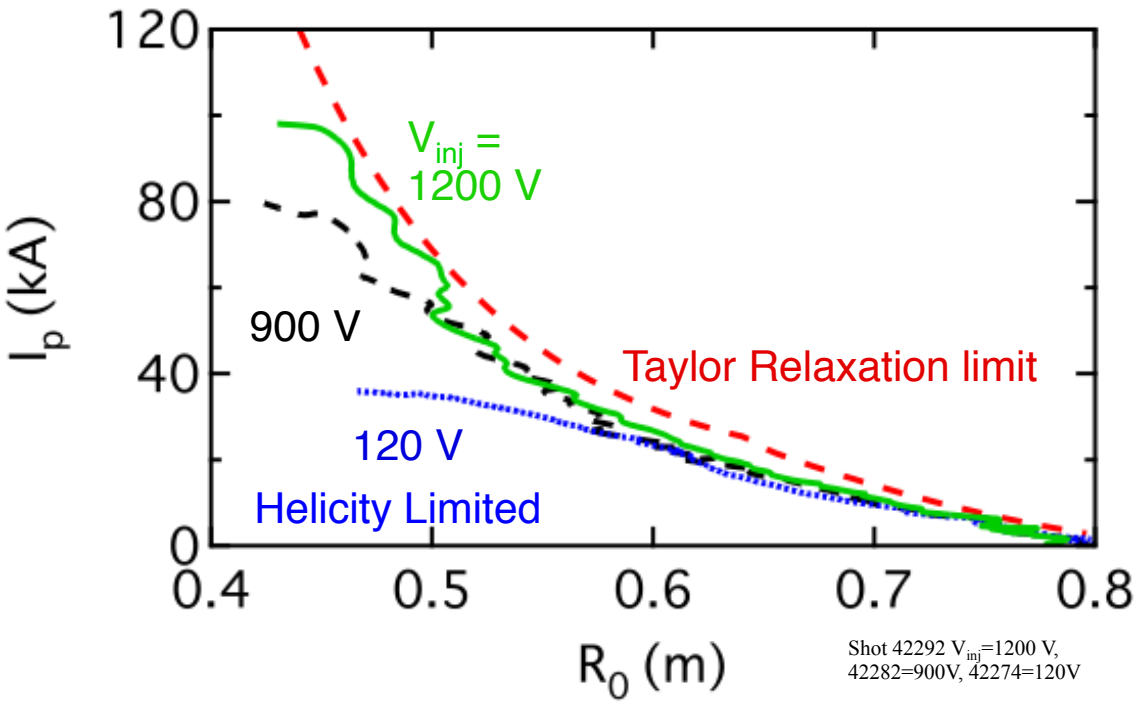


t=30.6 ms, I_p=37 kA
Guns off, Decaying

THE UNIVERSITY of WISCONSIN MADISON

Achieving the Taylor-Limit Maximum I_p Requires Sufficient Helicity Injection Input Rate





- Helicity input rate, and effective net volt-seconds, increases as V_{inj} increases
- Sufficient net V-sec needed to reach Taylor relaxation limit

THE UNIVERSITY of WISCONSIN MADISON

Driven helical filaments can relax to an axisymmetric tokamak-like state

- Driven helical filaments are strongly unstable
- Tokamak-like equilibrium satisfies a set of conditions
  - Radial force balance, helicity/power balance, kink stability (edge q > 3), and a Taylor relaxation current limit
- Max I_p determined by Taylor relaxation limit:

$$I_p \leq f_G \left[\frac{\varepsilon A_p I_{TF} I_{inj}}{2\pi R_{edge} w} \right]^{1/2}$$

Where: ε is the inverse aspect ratio,
A_p is the plasma cross-sectional area,
I_{TF} is the TF coil current,
I_{inj} is the gun bias current,
R_{edge} is the radial location of the gun(s),
w is the width of the driven plasma region,
and f_G is a scalar function ranging from 1 to 3, depending upon geometry.

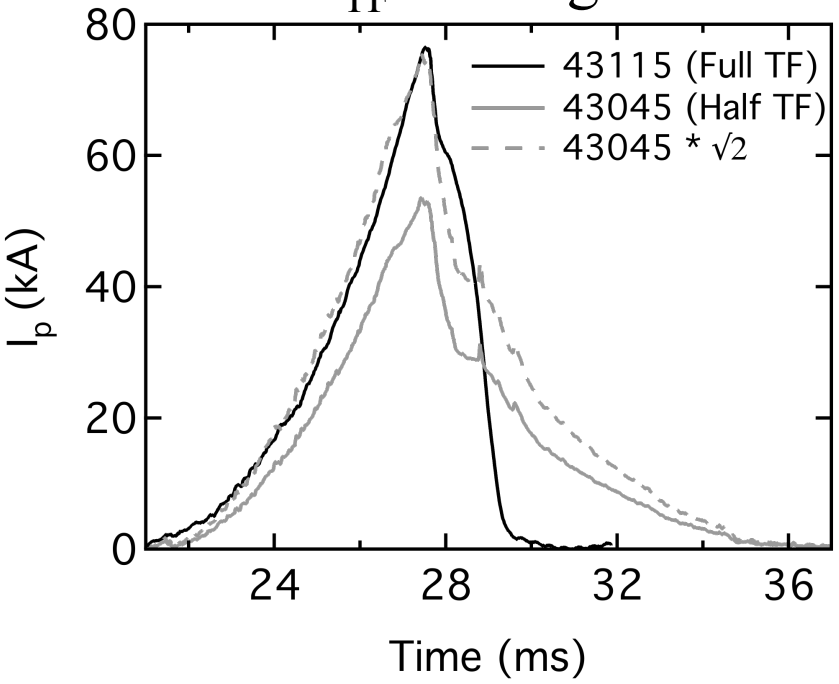
See Battaglia *et al*, Phys. Rev. Lett. **102**, 225003 (2009).

THE UNIVERSITY of WISCONSIN MADISON

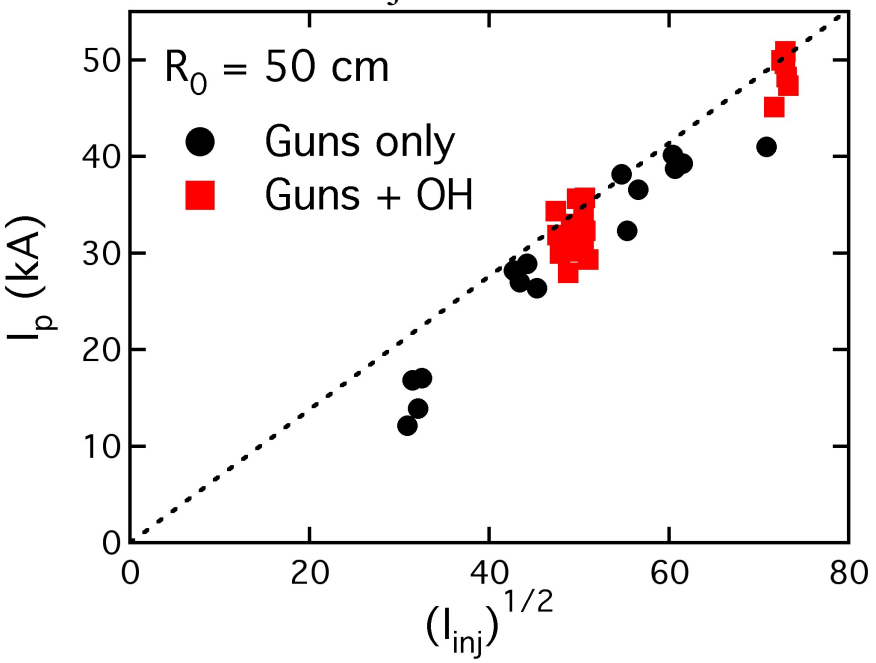
Experiments Confirm Relaxation Limit Scalings with I_{TF} and I_{inj}

- The relaxation limit I_p scales with: $$I_p \propto \left[\frac{I_{TF} I_{inj}}{w}\right]^{1/2}$$
- Maximum achieved I_p support these scalings:

I_{TF} Scaling:



I_{inj} Scaling:

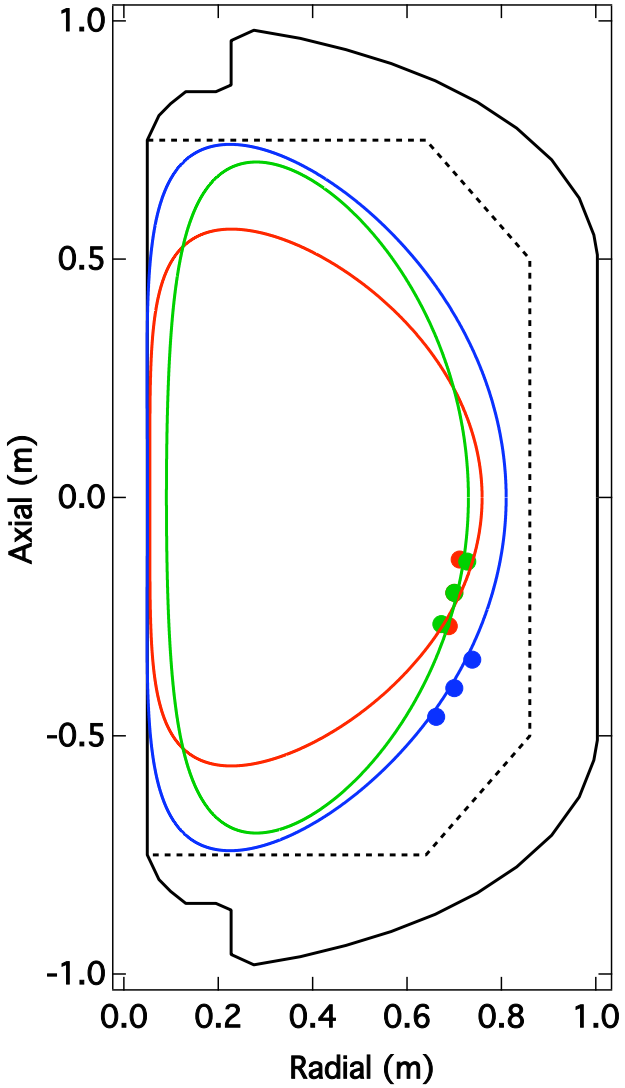


The addition of Ohmic drive did not raise I_p beyond the Taylor limit

THE UNIVERSITY of WISCONSIN MADISON

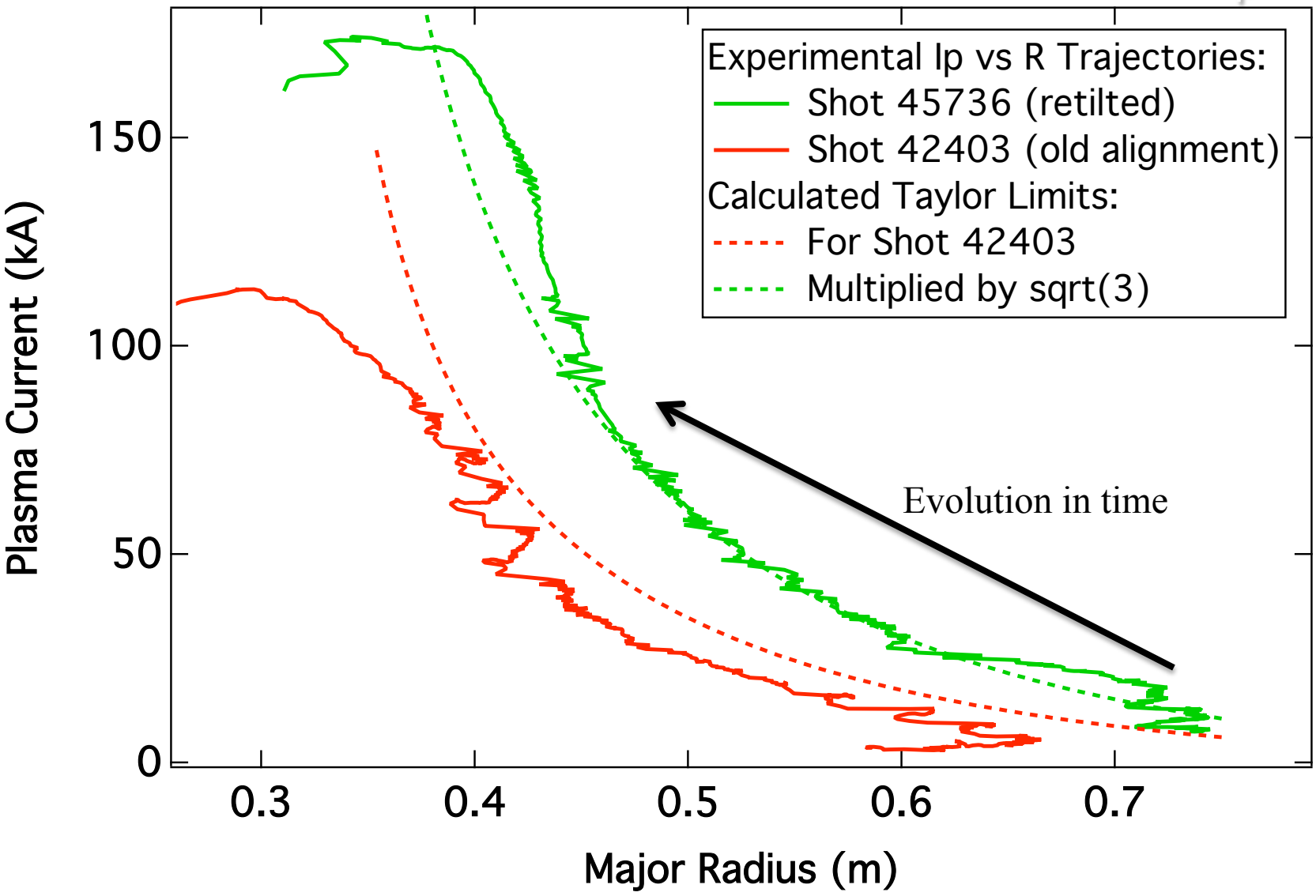
Gun array was realigned to reduce *w*, which increased the relaxation limit

- Gun array was nearly vertical (in red):
  - Driven width *w* scaled with # of guns
  - Red contour is approximate LCFS for best gun-driven I_p of 0.11 MA.
- Changed the gun array tilt (in green):
  - Green contour is reconstructed LCFS for best gun-driven I_p of 0.17 MA.
  - Maximum observed I_p has increased by a factor of 1.5-1.7, implying a factor-of-3 change in *w*., consistent with changing the projected width at midplane.
- Gun array has been moved away from midplane and tilted further (in blue):
  - Blue contour corresponds to a projected full-size PEGASUS discharge



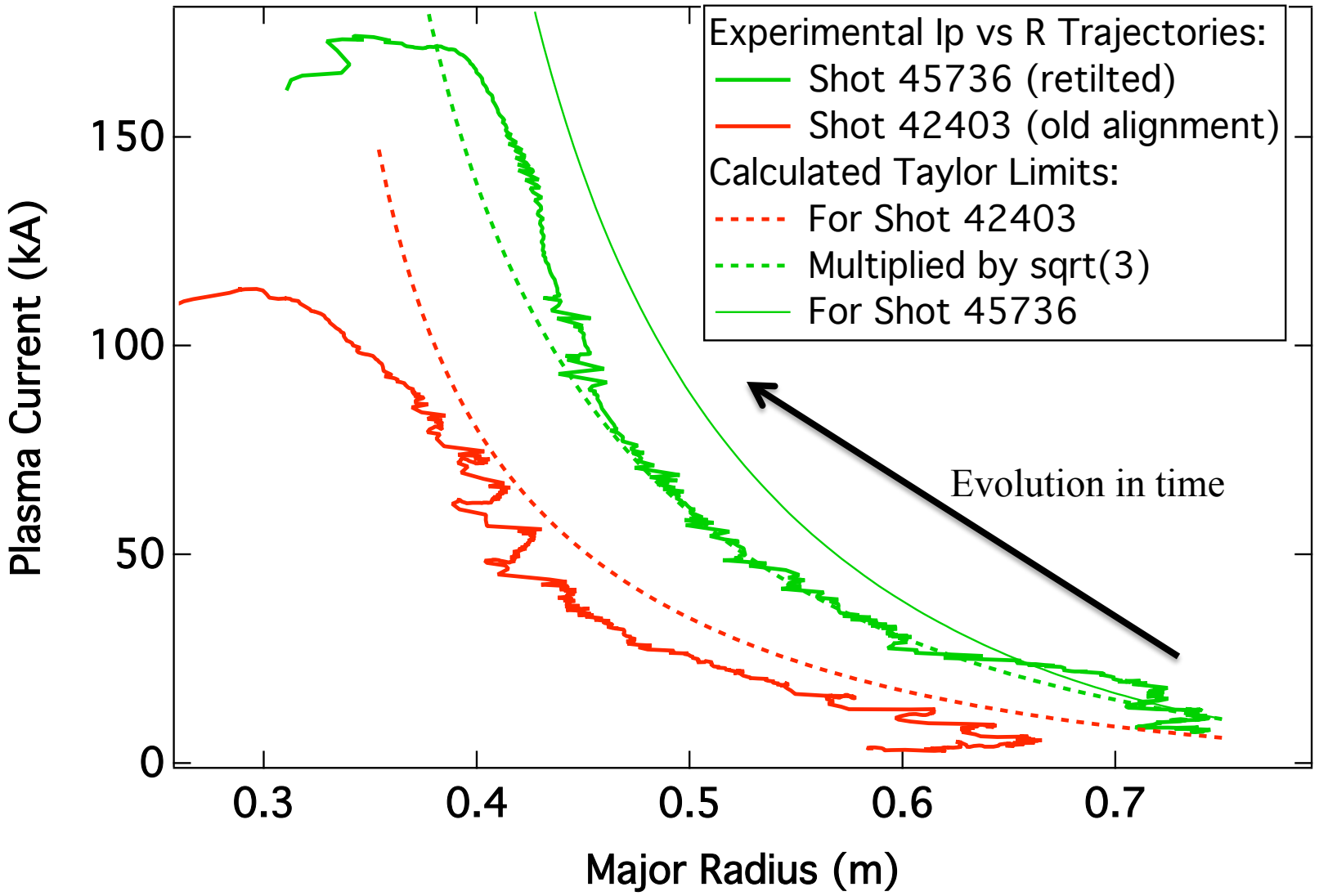
THE UNIVERSITY of WISCONSIN MADISON

Gun array tilt change increased Taylor limit and allowed higher gun-driven I_p



THE UNIVERSITY of WISCONSIN MADISON

Gun array tilt change increased Taylor limit and allowed higher gun-driven I_p

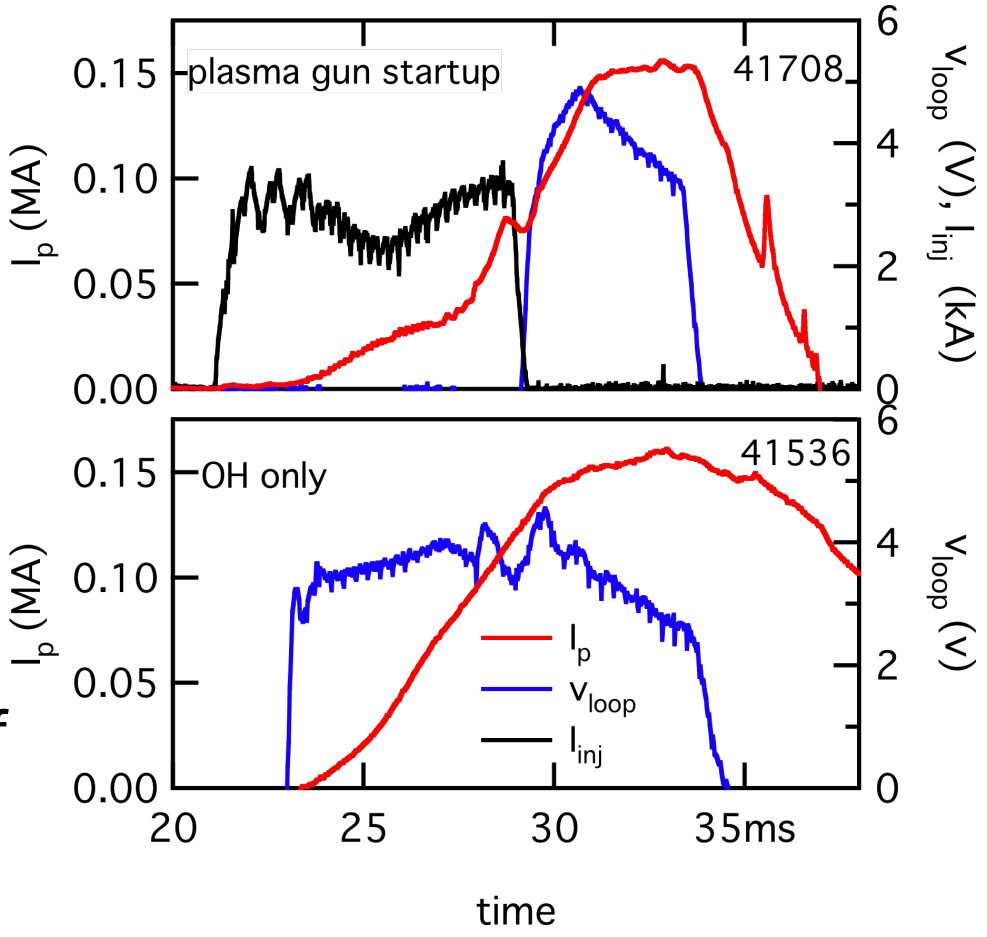


A.J.Redd et al, 2010 APS-DPP Annual Meeting, Chicago, IL, Nov 8-12, 2010

THE UNIVERSITY of WISCONSIN MADISON

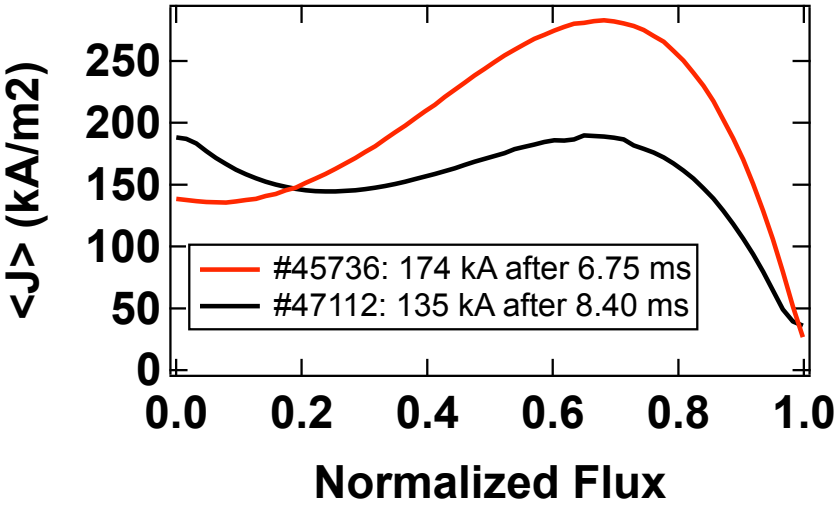
Poloidal flux generated by HI startup is equivalent to Ohmic flux generation

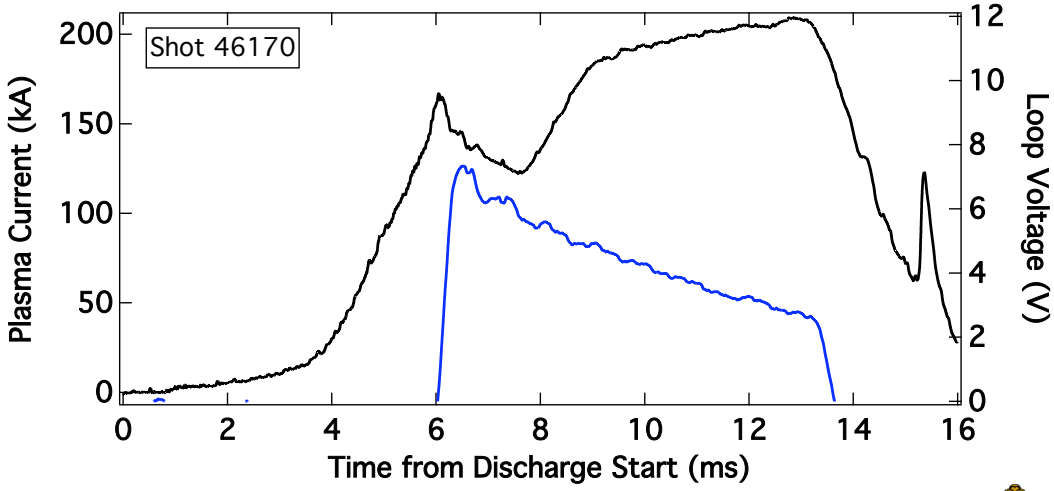
- Compare two scenarios:
  1. Handoff of 80 kA gun-driven target to single-swing Ohmic
  2. Pure-Ohmic double-swing
- Handoff discharge reaches same peak I_p using half the Ohmic flux
  - Implies ~ 50% flux savings
- Will assess the efficiency of helicity injection combined with other CD techniques
  - *e.g.*, 0.8 MW PEGASUS HHFW



Slowly-evolved Gun-driven Plasmas Hand Off Most Efficiently to Ohmic Drive

- Efficient handoff requires careful tailoring of gas fuelling, bias current, and outer-PF ramping
- Typical slowly evolving case (black J_T curve, below left):
  - Smooth handoff to Ohmic inductive drive; handoffs shown in other slides (current density profiles from external-only equilibrium reconstructions)
- Typical rapidly evolving case (red J_T curve, below left):
  - Does not hand off efficiently to Ohmic drive (below right)



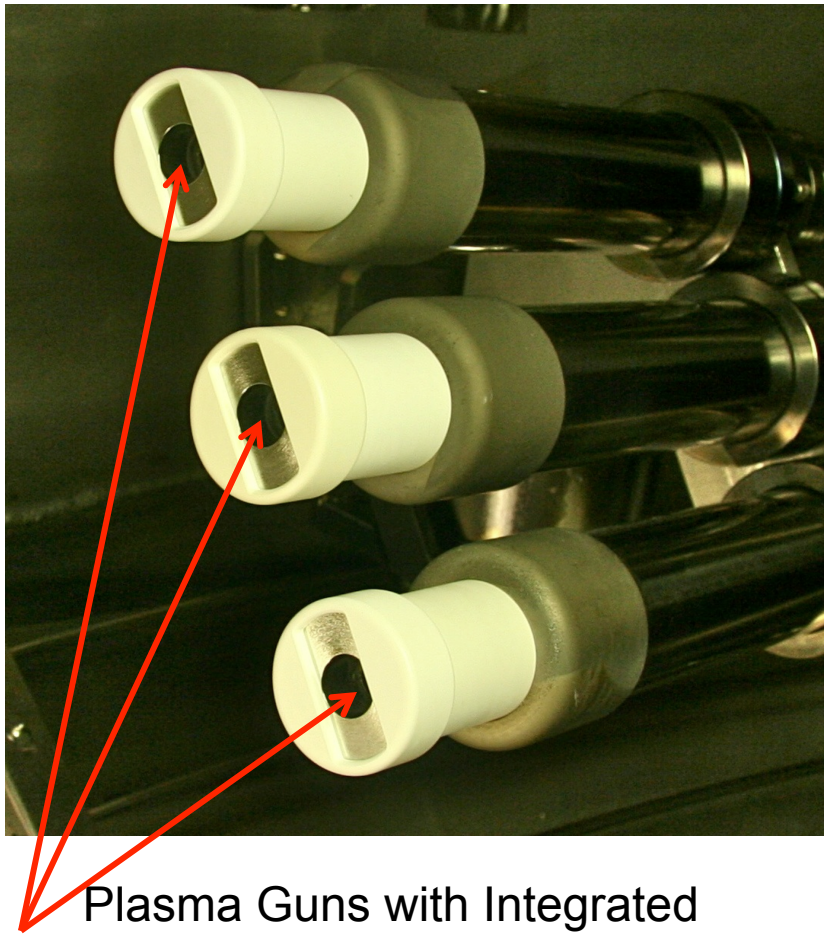


A.J.Redd et al, 2010 APS-DPP Annual Meeting, Chicago, IL, Nov 8-12, 2010

THE UNIVERSITY of WISCONSIN MADISON

Active Gun / Passive Electrode Assembly Points to Simpler, Higher I_p Operation

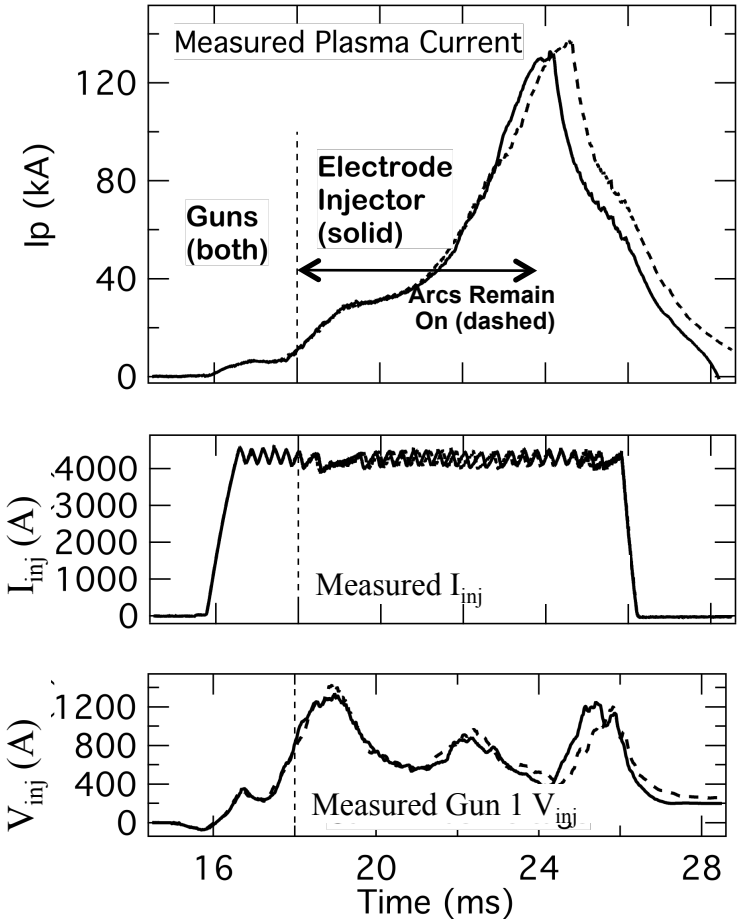
- Potential for much higher I_{inj} without need for either more plasma guns or larger guns.
- Helicity injection physics is agnostic to the exact source of the edge charge carriers.
- Passive electrodes allow arbitrary shaping:
  - Can optimize both helicity input (large cross-sectional area) *and* the Taylor limit on I_p (narrow in radial direction)



Plasma Guns with Integrated Slotted Electrodes

Initial Tests of Gun/Electrode Helicity Injection System Are Promising

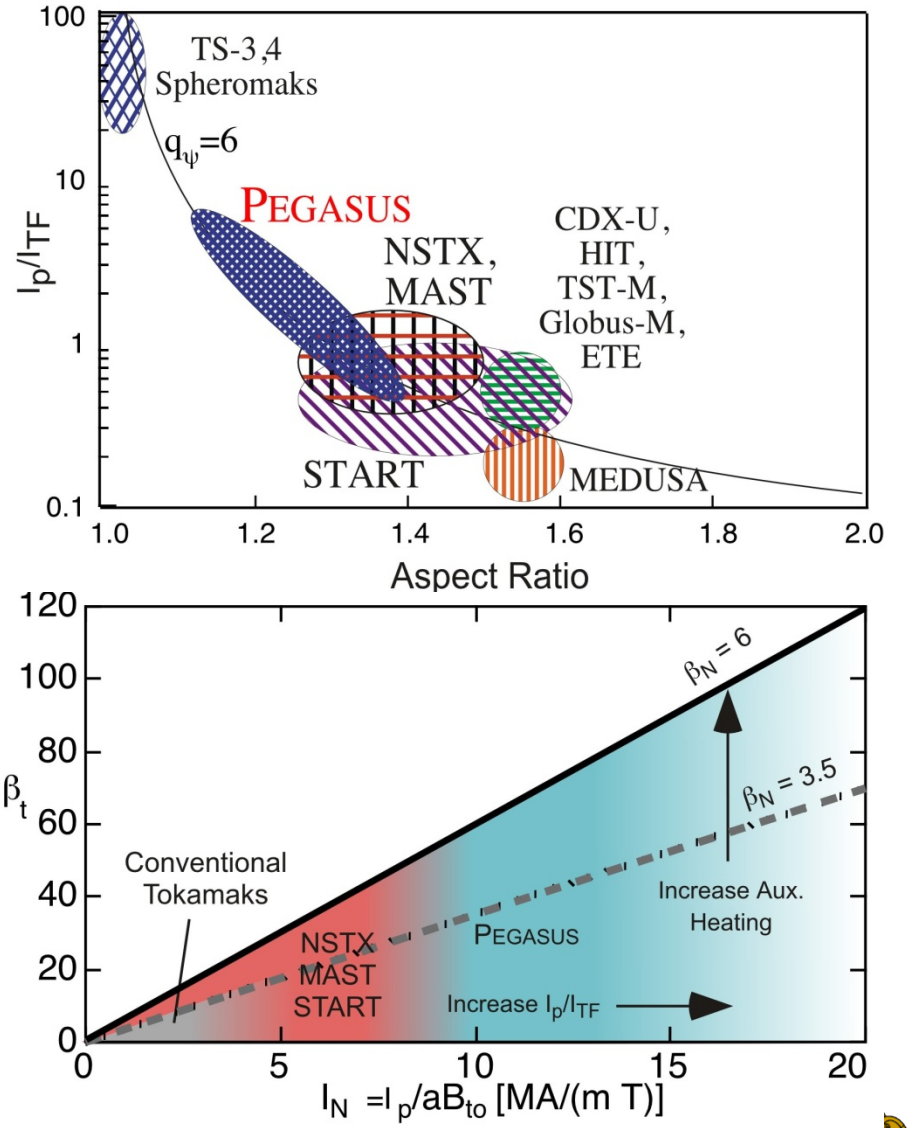
- Operations use two steps:
  - 1. Form initial tokamak-like state with minimal active arc gun
  - 2. Grow to much larger I_p with passive electrodes fed by charge carriers in tokamak edge region.
- First tests are promising
  - Arc current off after relaxation and formation of tokamak-like state
  - I_p rise is virtually the *same,* whether arc discharge or tokamak edge losses provide the charge carriers



THE UNIVERSITY of WISCONSIN MADISON

PEGASUS Mission: Physics of Low A → 1

- University-scale, Low-A ST
  - $R_0 \leq 0.45$ m, a ~ 0.40 m
- Physics of High I_p/I_{TF}
  - Expand operating space of the ST
  - Study high β_T plasmas as A→1
- Non-solenoidal startup
  - Point-source DC helicity injection
  - Helicity injection discharges couple to other current drive methods
- Peeling-mode studies
  - Experimental tests of peeling-ballooning theory



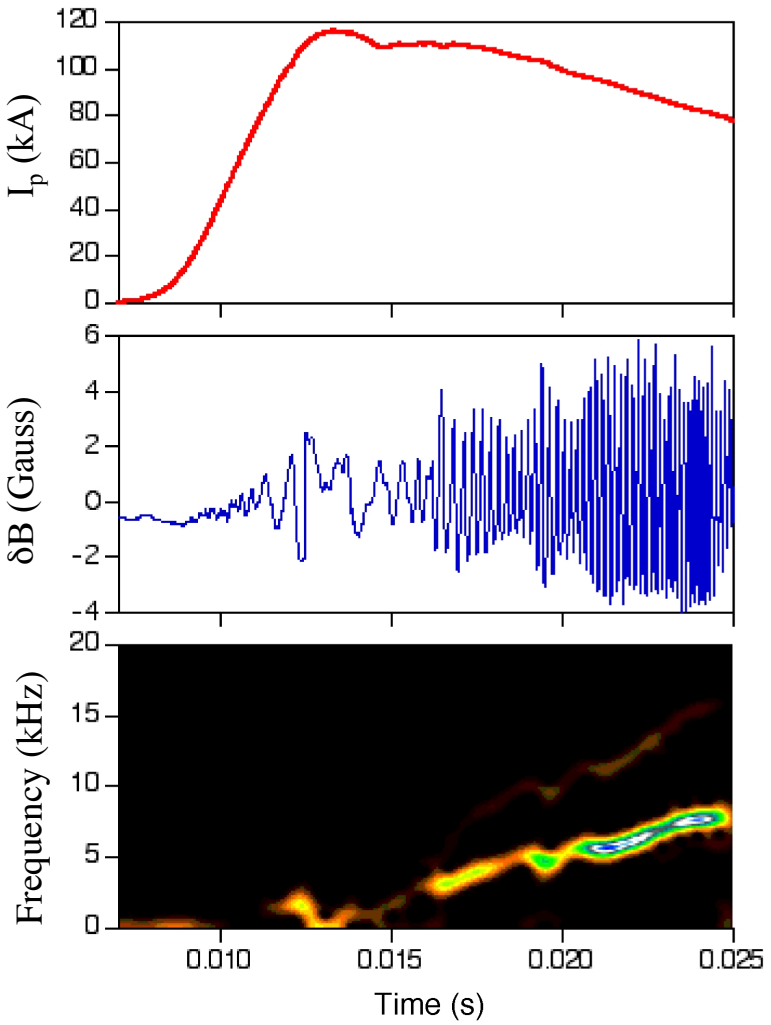
A.J.Redd et al, 2010 APS-DPP Annual Meeting, Chicago, IL, Nov 8-12, 2010

THE UNIVERSITY of WISCONSIN MADISON

Initial Phase of Operations had $I_p/I_{tf} \sim 1$, $I_N \sim 5$ Limit

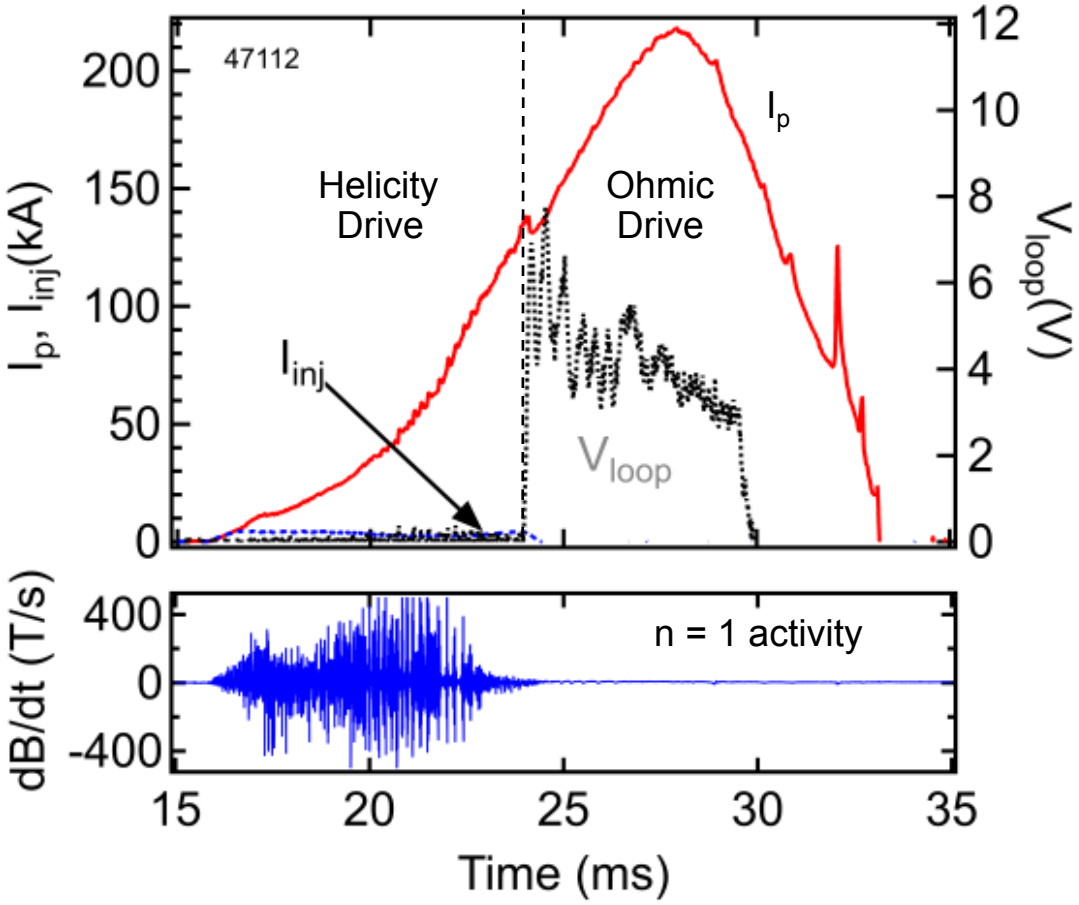
- OH discharges experienced large tearing modes
  - Low-order rational q-surfaces in regions of low magnetic shear
- Modes saturated I_p, W
  - Inefficient use of available power
- Need better control over discharge evolution and additional source of current!
  - All ST's need non-solenoidal startup; Tokamaks could use it too
  - Approach: *Point-source DC helicity injection* for current startup

I_p rolls over and decays with onset of large n =1 modes



THE UNIVERSITY of WISCONSIN MADISON

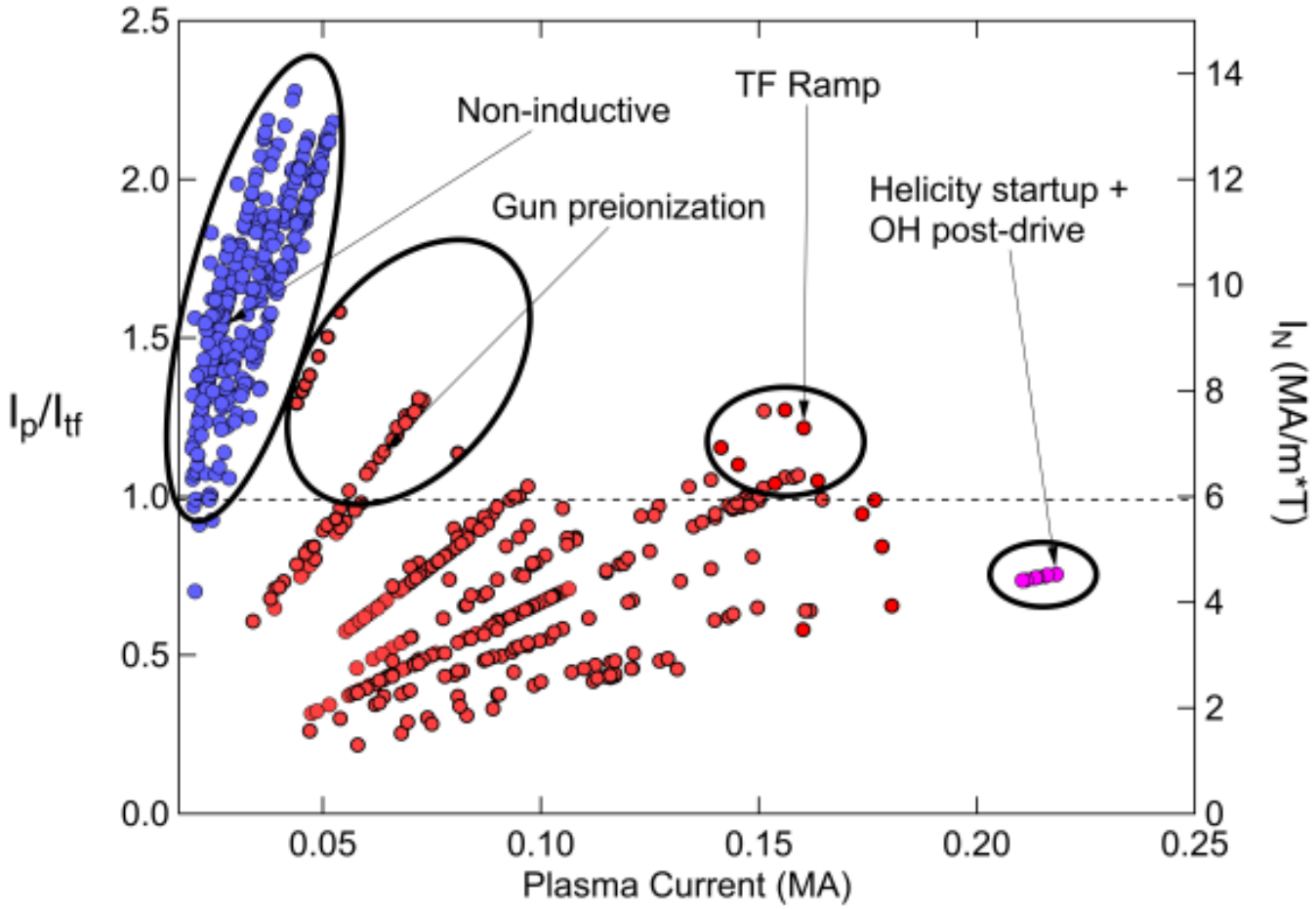
Ready Handoff to OH; MHD activity strongly reduced after gun bias shutoff



- After helicity injection, OH phase of discharges are *stable* to low-n tearing modes
  - In contrast to most OH-driven startup plasmas

THE UNIVERSITY of WISCONSIN MADISON

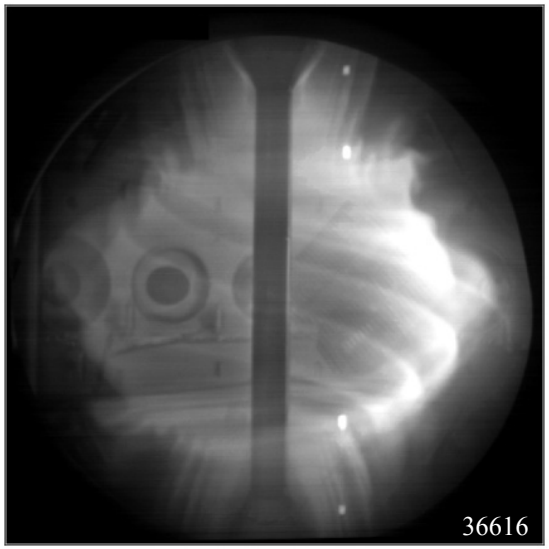
Current Drive Tools Providing Access to High Field Utilization Regime



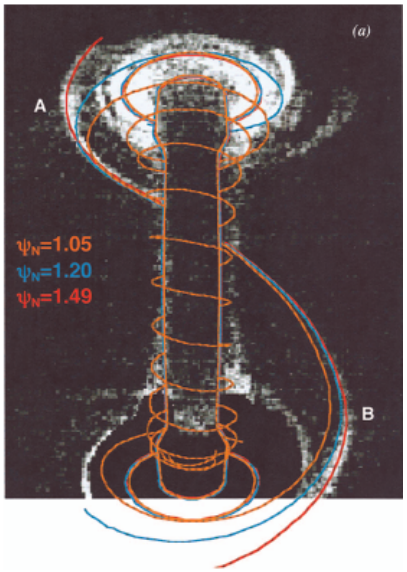
- Helicity injection startup and Ohmic sustainment provides MHD-stable profiles at $I_p/I_{TF} < 1$
- Need to extend to higher I_p, then to low I_{TF} for high I_N and high β_T as A≈1

THE UNIVERSITY of WISCONSIN MADISON

PEGASUS: ELM-like Structures Observed

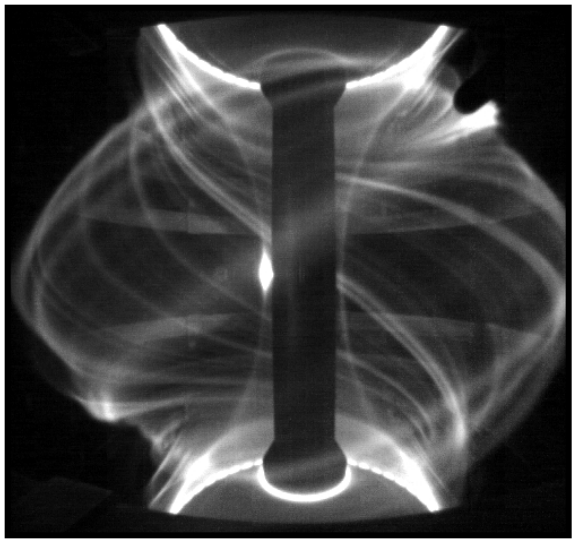


PEGASUS



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

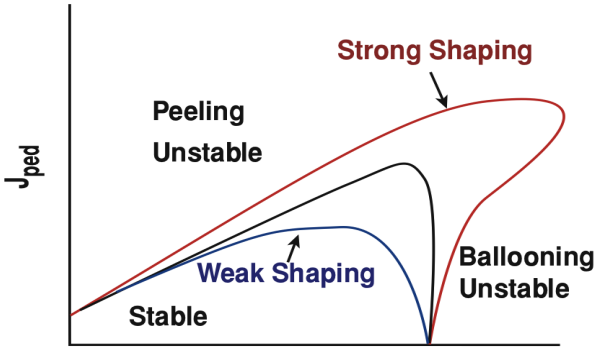
NSTX



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

MAST

- ELMs take form of filamentary, field-aligned structures
  - Peeling-ballooning theory: trigger mechanism
- PEGASUS: L-mode edge assumed
  - Peeling instability candidate mechanism



Snyder, Phys. Plasmas **12**, 056115, 2005;
see also Hegna, Phys. Plasmas **3**, 584, 1996

THE UNIVERSITY of WISCONSIN MADISON

Near-unity A Enhances Peeling Drive

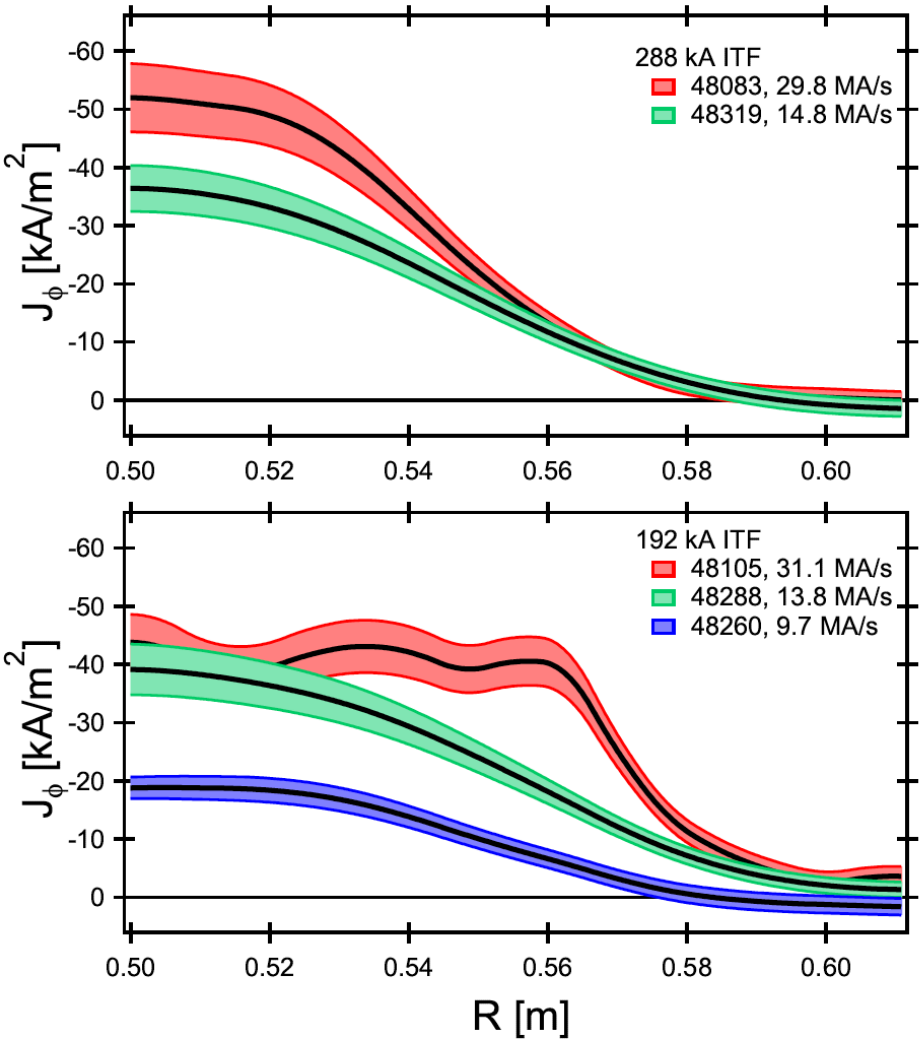
Device	J_{edge} (MA/m^2)	$B_{\varphi,0}$ (T)	J_{edge}/B	R_0 (m)	q_{95}
PEGASUS	~ 0.1 – 0.2	0.1	**~ 1**	**~ 0.45**	**< 25**
DIII-D	1 – 2*	2	**0.5 – 1**	**~ 1.50**	**< 5**

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

- PEGASUS operations at A → 1 lead to naturally high J_{edge}/B
- However, *source* of J_{edge} differs
  - Large machines: H-mode p' → J_{BS}
  - PEGASUS: Large dI_p/dt (≤ 50 MA/s) → transient skin current
- Additional geometric effects: modest drive from Rq_a possible
  - Increased edge shear competes with this effect

THE UNIVERSITY of WISCONSIN MADISON

J(R) Structure Strongly Influenced by dI_p/dt



- Data supports hypothesis of skin current drive

A.J.Redd et al, 2010 APS-DPP Annual Meeting, Chicago, IL, Nov 8-12, 2010

THE UNIVERSITY of WISCONSIN MADISON

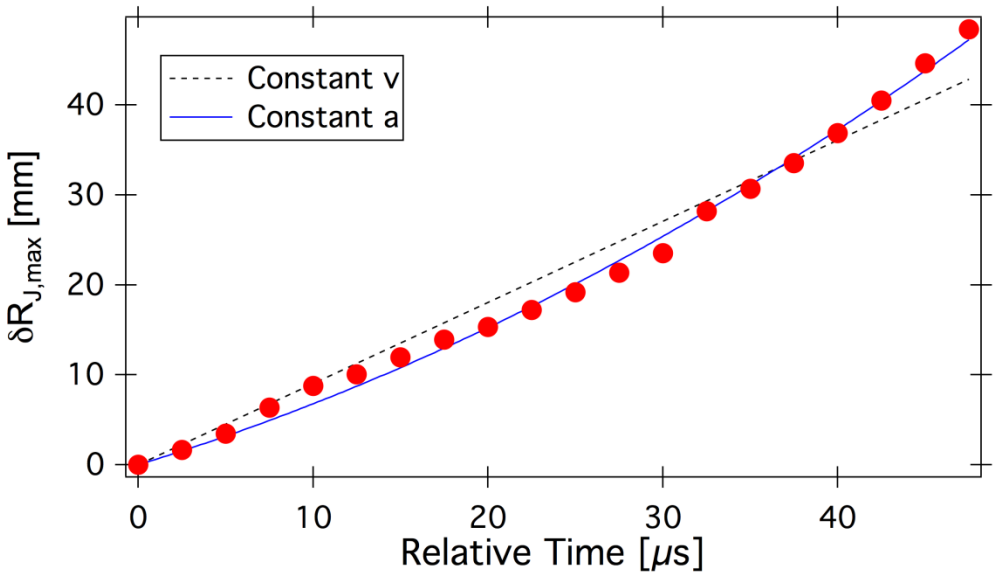
Edge Dynamics Consistent with ELM models

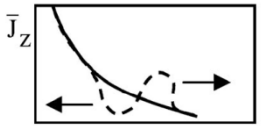
- Tracking $J_{max}(R,t)$ allows determination of filament velocity, acceleration

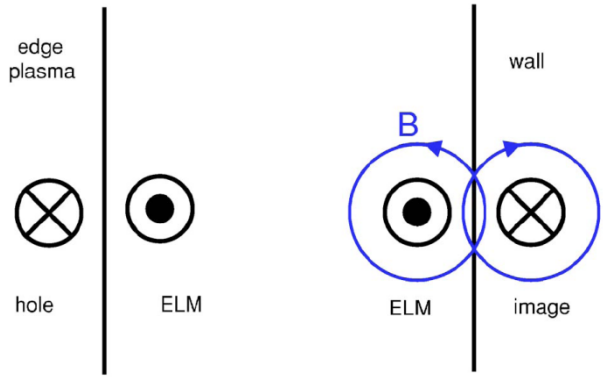
- This particular filament has
  - $v_{r,0} \sim 600$ m/s, $a_r \sim 1.7 \times 10^7$ m/s^2
  - Fast imaging results comparable

- Filament / Hole creation, propagation qualitatively consistent with ELM dynamics models*
  - Current-carrying ELM filaments repelled by magnetostatic forces

*: Myra, Phys. Plasmas **14**, 102314, 2007

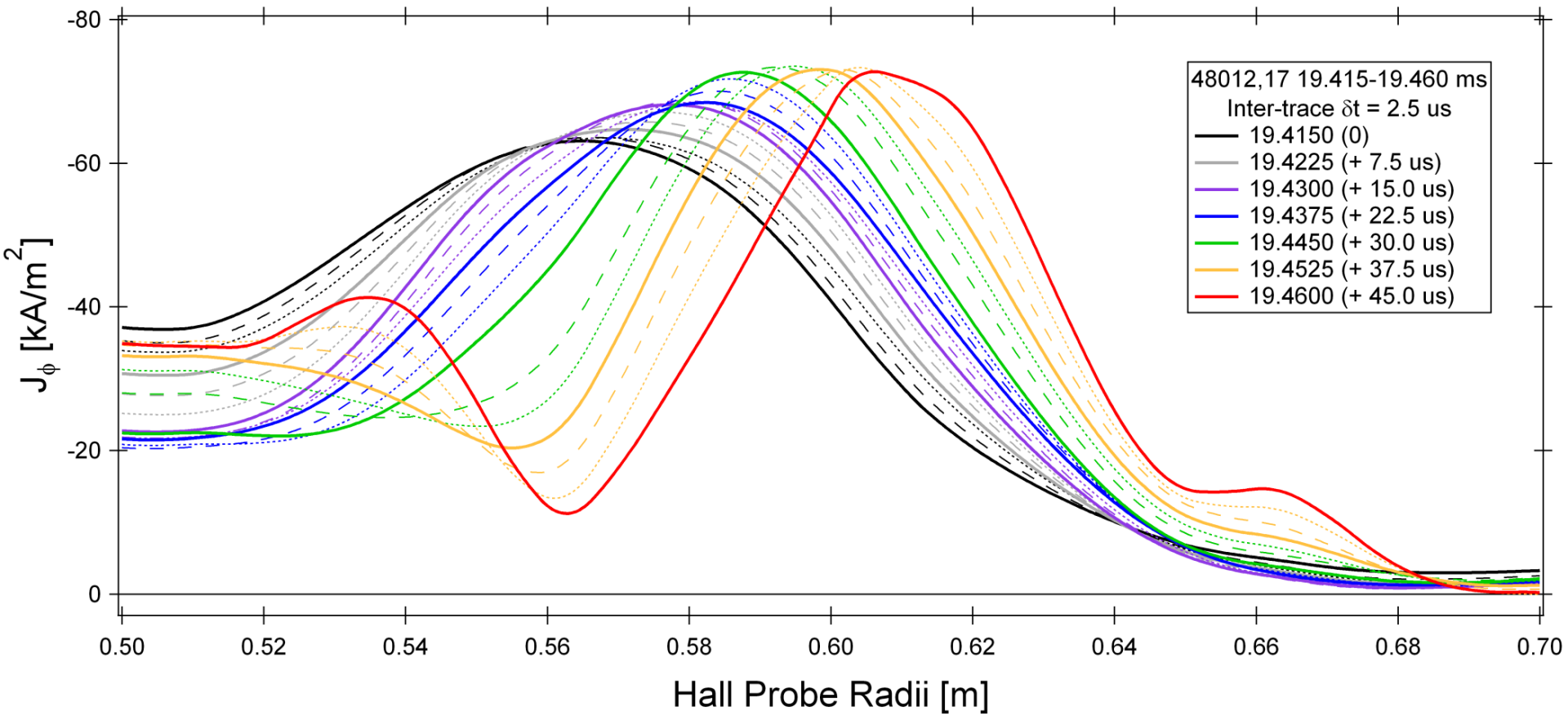






THE UNIVERSITY of WISCONSIN MADISON

J_{edge} Dynamics Resolved on ELM Timescales



- J(R) evolution tracked over filament burst
- Filament carries $|J_{edge}|$ prior to instability outward
- Outboard δJ acceleration, radial localization

A.J.Redd et al, 2010 APS-DPP Annual Meeting, Chicago, IL, Nov 8-12, 2010

THE UNIVERSITY of WISCONSIN MADISON

PEGASUS Summary: High-I_p Non-Solenoidal Startup Development; High I_N; Unique Edge Stability

- Significant progress with non-solenoidal startup of ST
  - Maximum achievable I_p is determined by helicity input and Taylor limit
  - Observed scalings of Taylor limit consistent with simple theory-based model
  - Have achieved $I_p \sim 0.17$ MA using helicity injection and outer-PF rampup
  - Demonstrated helicity injection with passive electrodes instead of plasma guns
    - Possibility of a simpler, more powerful helicity injection startup system
  - Goal $\approx$ 0.3-0.4 MA non-solenoidal I_p to extrapolate to next level/NSTX
    - Outstanding physics questions: λ_{edge}, Z_{inj}, confinement, *etc.*
- Exploration of high I_N, β_T space facilitated by j(r) tools
  - $I_p/I_{TF} > 2$, $I_N > 14$ achieved; extend operation to high I_p, n_e for high β_t
- Possibility of tests of Peeling / Peeling-Ballooning theory
  - Can compare stability calculations to experimental observations

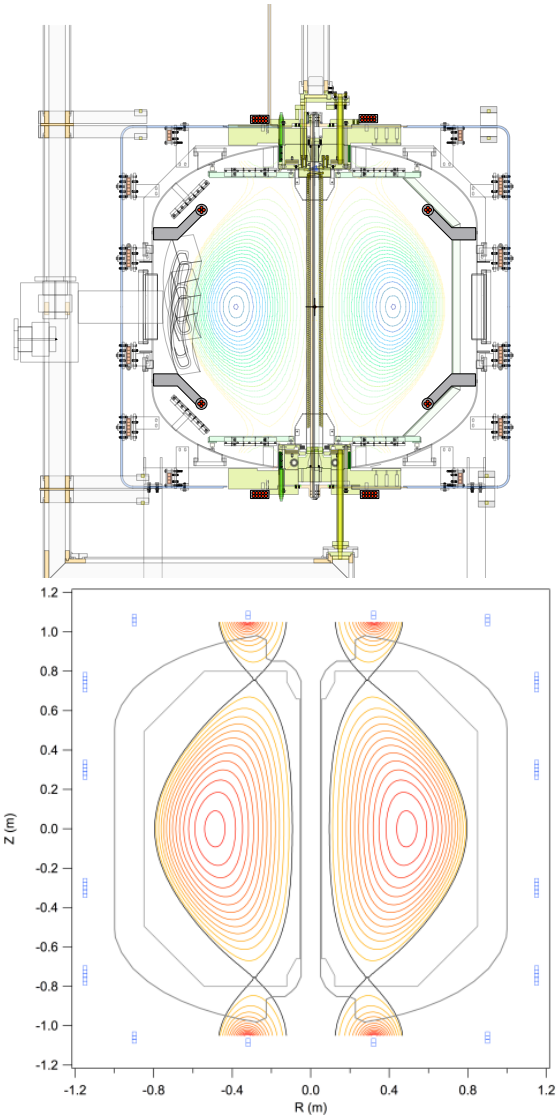
A Reprint of this poster will be available at http://pegasus.ep.wisc.edu/

A.J.Redd et al, 2010 APS-DPP Annual Meeting, Chicago, IL, Nov 8-12, 2010

THE UNIVERSITY of WISCONSIN MADISON

Long-Term PEGASUS Physics Studies Will Be Enabled by Medium-Term Upgrades

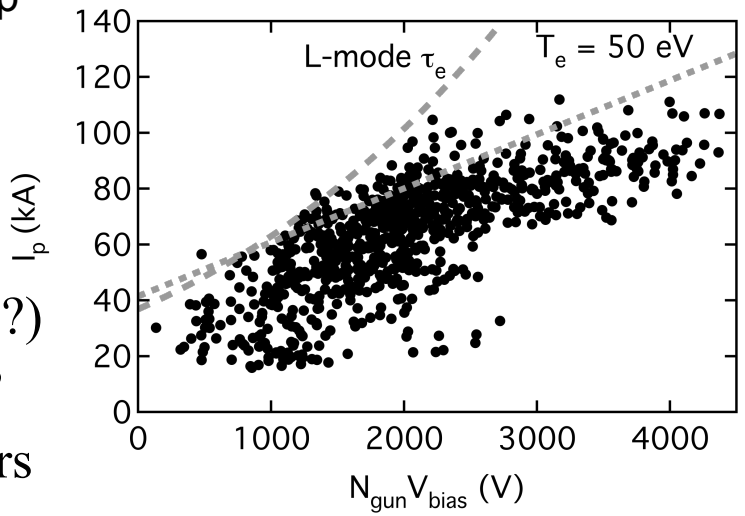
- Power/Heating Upgrades
  - Dedicated helicity injection power supplies and control
  - Double TF current
  - Commission 800 kW HHFW system
- Expanded PF Coil Set
  - New external divertor coils
  - Internal coils for radial position control
- Activate feedback PCS
  - GA Plasma Control System technology
- Diagnostic Additions
  - Multipoint Thomson Scattering
  - Poloidal SXR Arrays



THE UNIVERSITY of WISCONSIN MADISON

Near-Term PEGASUS Physics Studies

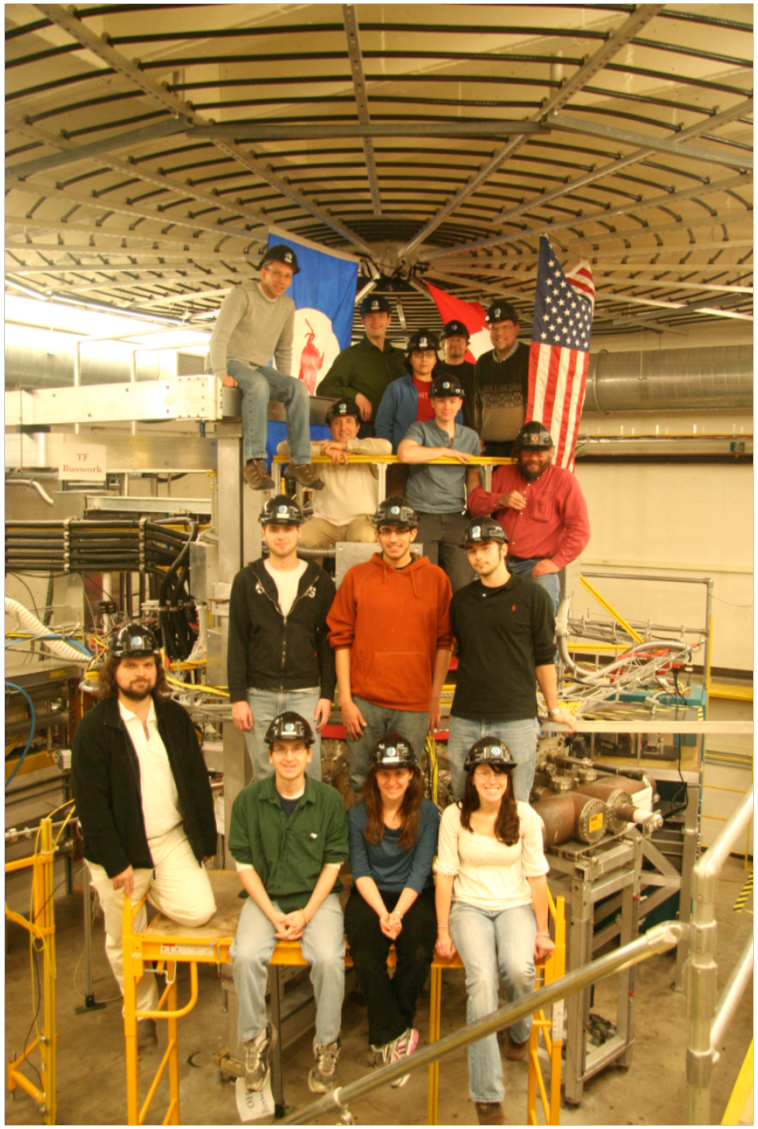
- Near-term Helicity Injection goal is I_p = 0.3-0.4 MA to address relaxation physics issues:
  - What sets the bias impedance Z_{inj}?
  - Confirm Taylor-limit parametric scalings
  - Is the confinement/dissipation stochastic? (What physical processes determine $T_e(R,t)$?)
  - What sets the width *w* of the driven region?
  - Confidently extrapolate to NSTX parameters



- Sustained high I_N operations requires HI high-I_p startup, double-swing Ohmic sustainment, at low I_{TF}
  - High β_T accessible at $I_p/I_{TF} > 2$
- Hardware upgrades may enable H-mode access
  - Diverted operation and auxiliary heating to reach power threshold
  - Edge instabilities will more closely resemble ELMs in larger devices

THE UNIVERSITY of WISCONSIN MADISON

The PEGASUS Research Team



Faculty/Staff:

Raymond J. Fonck (PI)
Benjamin A. Kujak-Ford
Benjamin T. Lewicki
Paul Probert
Aaron J. Redd
David J. Schlossberg
Greg R. Winz

Graduate Students:

Jayson L. Barr
Michael W. Bongard
M. Galen Burke
Edward T. Hinson
Kathreen E. Thome
Nathan R. Woodruff

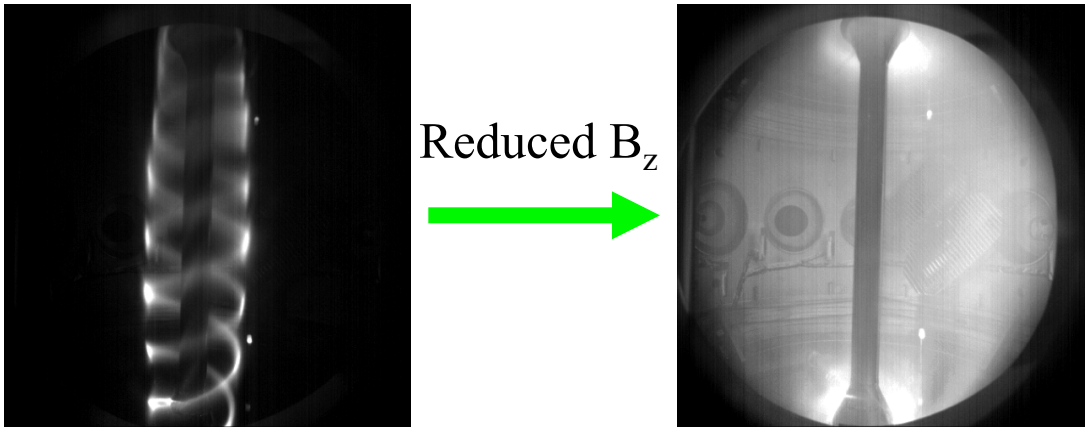
Undergraduates:

Grant M. Bodner
Jonathan A. Cole
Austin S. Dowd
Amir E. Jaber
Jonathon I. Moritz
Shane M. Swager

THE UNIVERSITY of WISCONSIN MADISON

Local Plasma Current Sources + Helical Vacuum Field Give Simple DC Helicity Injection Scheme

- Current is injected along helical vacuum magnetic field
- High I_{inj} & modest B $\Rightarrow$ filaments merge into current sheet
- High I_{inj} & low B $\Rightarrow$ current-driven B_θ overwhelms vacuum B_z
  - Relaxation via MHD activity to tokamak-like Taylor state w/ high toroidal current multiplication



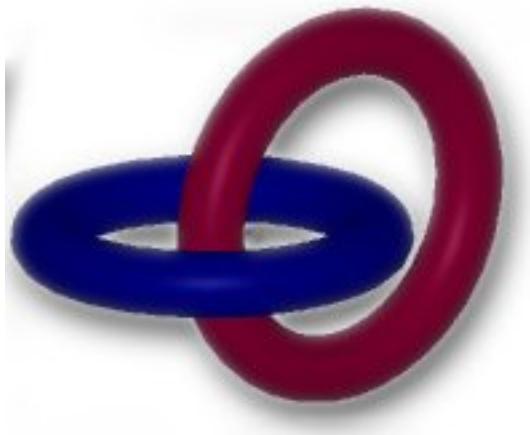
Current filaments Relaxed tokamak

THE UNIVERSITY of WISCONSIN MADISON

Magnetic helicity in tokamak plasmas

Magnetic helicity is a measure of the linkage between magnetic fluxes (or, equivalently, the currents that generate those fluxes).
The general definition of magnetic helicity is an integral over a volume that encompasses the linked fluxes:

$$K \equiv \int \mathbf{A} \cdot \mathbf{B} \, dV$$



Magnetic helicity is the best-conserved constant of motion in magnetized plasma, decaying on resistive timescales.

In the case of two linked but distinct fluxes ϕ and ψ, similar to the rings shown, the total magnetic helicity of the volume is $K=2\phi\psi$.

In a tokamak, the magnetic helicity K is proportional to the product $I_{TF}I_p$, with I_{TF} determined by the TF coil power supply. Increases in the helicity K correspond to increases in the toroidal plasma current I_p.

Tokamak Current Drive is Helicity Injection

Total helicity K in a tokamak geometry: $K = \int_V (\mathbf{A} + \mathbf{A}_{vac}) \cdot (\mathbf{B} - \mathbf{B}_{vac})\, d^3x$

$$\frac{dK}{dt} = -2\int_V \eta \mathbf{J} \cdot \mathbf{B}\, d^3x - 2\frac{\partial \psi}{\partial t}\Psi - 2\int_A \Phi \mathbf{B} \cdot d\mathbf{s}$$

- Resistive Helicity Dissipation
  - $\mathbf{E} = \eta \mathbf{J} \rightarrow$ much slower than energy dissipation ($\eta \mathbf{J}^2$)
  - Turbulent relaxation processes dissipate energy and conserve helicity

- AC Helicity Injection: $\dot{K}_{AC} = -2\frac{\partial \psi}{\partial t}\Psi = 2V_{loop}\Psi$
  - Ψ is toroidal flux, ψ is poloidal flux (*e.g.*, current drive through solenoid induction)

- DC Helicity Injection $\dot{K}_{DC} = -2\int_A \Phi \mathbf{B} \cdot d\mathbf{s} = 2V_{inj}B_{\perp}A_{inj}$
  - Φ is electrostatic potential

Taylor Relaxation Criteria Sets the Maximum I_p for a Given Magnetic Geometry

Helicity balance in a tokamak geometry:

$$\frac{dK}{dt} = -2\int_V \eta \mathbf{J}\cdot\mathbf{B}\, d^3x - 2\frac{\partial\psi}{\partial t}\Psi - 2\int_A \Phi\mathbf{B}\cdot d\mathbf{s} \quad \Rightarrow \quad I_p \le \frac{A_p}{2\pi R_0\langle\eta\rangle}\left(V_{ind} + V_{eff}\right)$$

- *Helicity injection can be expressed as an effective loop voltage*
- I_p limit depends on the scaling of plasma confinement via the η term

$$V_{eff} \approx \frac{A_{inj}B_{\phi,inj}}{\Psi_T}V_{bias}$$

Taylor relaxation of a force-free equilibrium:

$$\nabla\times B = \mu_0 J = \lambda B \qquad \lambda_p \le \lambda_{edge} \quad \Rightarrow \quad \frac{\mu_0 I_p}{\Psi_T} \le \frac{\mu_0 I_{inj}}{2\pi R_{inj} w B_{\theta,inj}} \quad \Rightarrow \quad I_p \le \left[\frac{C_p}{2\pi R_{inj}\mu_0}\frac{\Psi_T I_{inj}}{w}\right]^{1/2}$$

Assumptions:

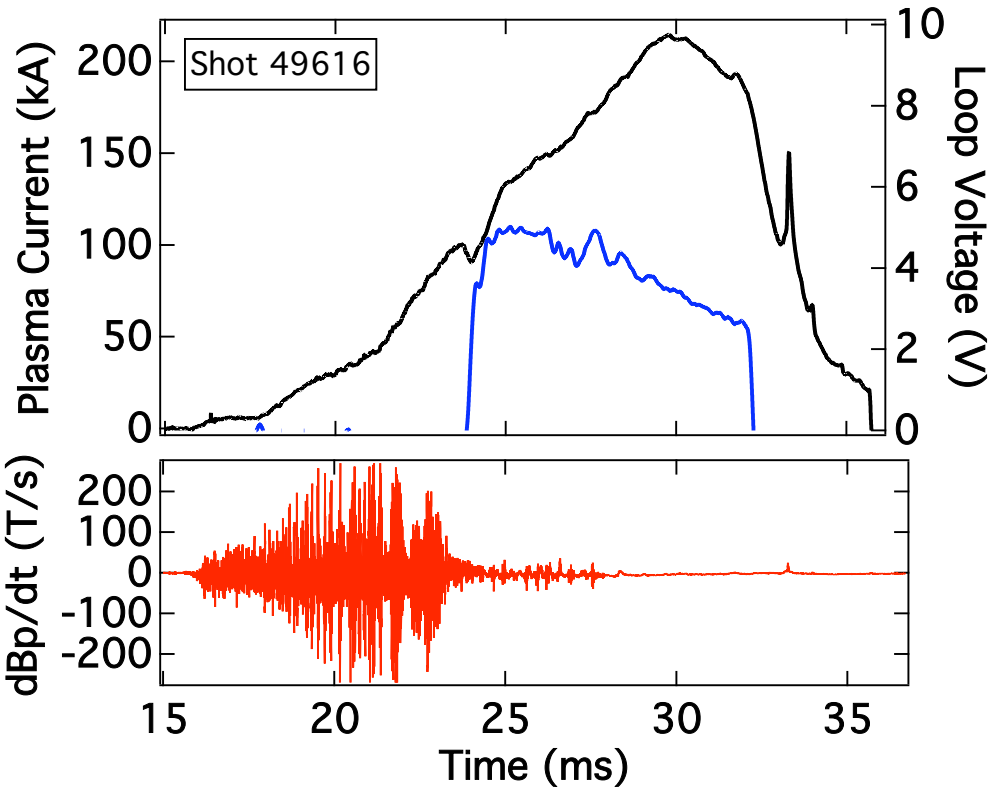
- Driven edge current mixes uniformly in SOL
- Edge fields average to tokamak-like structure

A_p Plasma area
C_p Plasma circumference
Ψ_T Plasma toroidal flux
w Edge current channel width

THE UNIVERSITY of WISCONSIN MADISON

Electrode-driven discharges have been coupled to Ohmic double-swing

- Double-swing ramp:
  - Longer Ohmic drive duration
  - Demonstrates feasibility for high-bT scenario development
- This particular shot had:
  - Only two guns: low handoff I_p
  - Non-optimal handoff target: best available electrode-driven target plasma at the time. During helicity injection phase, the limiter material and location has a profound effect on plasma performance. This is an area of active research.
  - Ohmic-phase plasma fills the PEGASUS confinement region.



THE UNIVERSITY of WISCONSIN MADISON