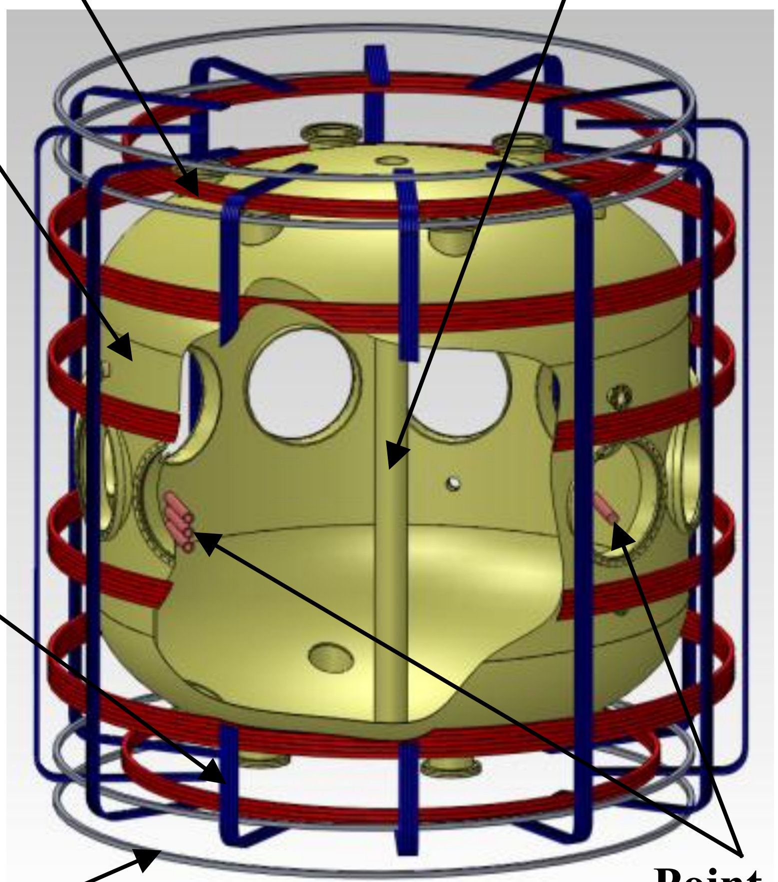
ABSTRACT

Studies on the Pegasus ultralow aspect ratio (A~1) tokamak are exploring: non-solenoidal startup using localized magnetic helicity injection; and edge peeling mode stability and dynamics. The helicity injection (HI) operating space is constrained by a balance between HI and dissipation rates and a geometric limit on I_p. Bursts of MHD activity, consistent with driving low-n kink modes line-tied to the injector, are observed during HI. These bursts correlate with rapid equilibrium changes, including inward motion of the magnetic axis and redistribution of the plasma current; preliminary observations correlate these bursts to the formation of current-carrying axisymmetric plasma rings that merge into the tokamak-like equilibrium. Internal magnetic measurements show formation of a poloidal field null prior to relaxation into a tokamak-like state, and current redistribution into the core as the plasma evolves. This MHD activity results in strong ion heating, with $T_i \sim 1$ keV, and emission line splitting indicating bi-directional flows. The impedance of a plasma arc injector is consistent with a double-layer sheath at the extraction aperture. Scaling this startup technique to larger devices will require the dominant current drive to be helicity injection, with minimal inductive drive from vertical field ramps. Demonstration discharges in Pegasus with $I_p \sim 100$ kA are formed and sustained using only helicity injection, with extrapolation to high I_p feasible with increased helicity injection. Different techniques for increasing the magnetic helicity input with a high geometric I_p limit are being evaluated scientifically, including the use of simple electrodes, gas-fed electrodes, or multiple plasma arc sources. The increased understanding developed in these studies supports the practical scalability of the HI startup technique to large devices. Operation at A~1 with high I_p/B_T allows study of peeling modes, a cause of ELMs in larger devices. Peeling modes in Pegasus appear as coherent edge-localized EM activity with low n and high m. Internal magnetics and fast framing images show the formation of current-carrying field-following filamentary structures, which briefly accelerate radially, detach from the plasma edge, and propagate radially at a constant velocity. The acceleration and propagation velocity correspond to the predictions of EM blob theory. **Work supported by US DOE Grants DE-FG02-96ER54375 and DE-SC0006928**.

THE UNIVERSITY of WISCONSIN MADISON

Pegasus is a Compact Ultralow-A ST



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)	$\leq$ .21	$\leq$ 0.30
I_N (MA/m-T)	6 – 12	6 – 20
RB_t (T-m)	$\leq$ 0.06	$\leq$ 0.1
κ	1.4 – 3.7	1.4 – 3.7
τ_{shot} (s)	$\leq$ 0.025	$\leq$ 0.05
β_t (%)	$\leq$ 25	> 40

Major research thrusts include:

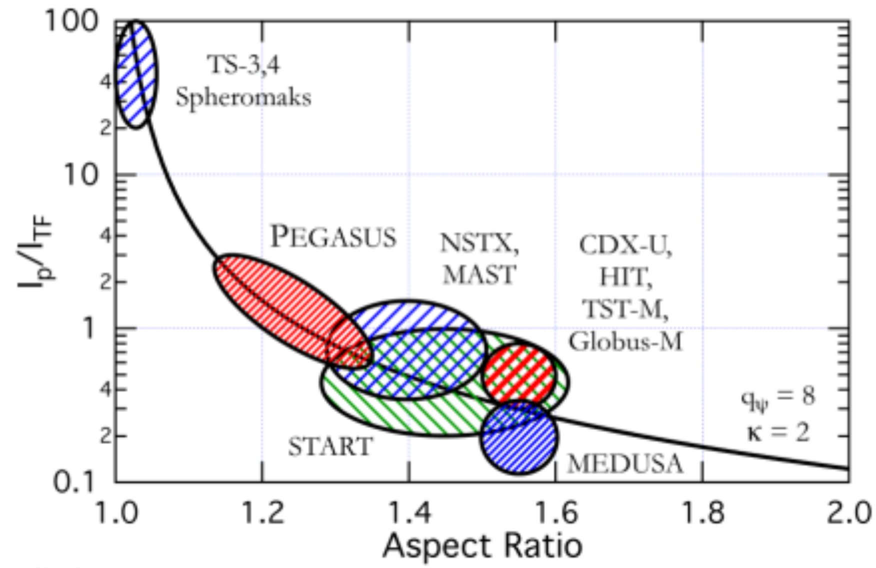
- *Non-inductive startup and sustainment*
- *Tokamak physics in small aspect ratio:*
  - *High-I_N, high-β operating regimes*
  - *ELM-like edge MHD activity*

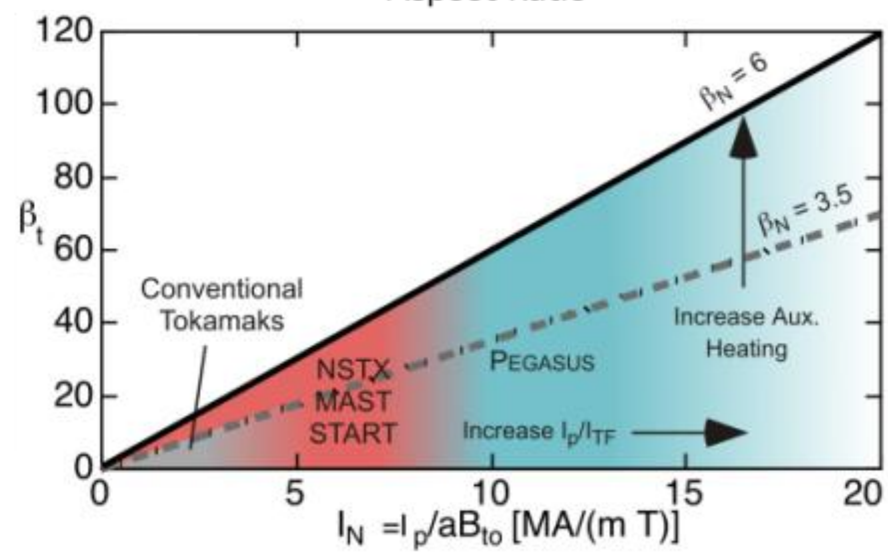
Redd et al, IAEA Fusion Energy Conference 2012

THE UNIVERSITY of WISCONSIN MADISON

PEGASUS Mission: Physics of Low A → 1

- Non-solenoidal startup
  - Local helicity injection
  - Helicity injection discharges couple to other current drive methods
- Physics of High I_p/I_{TF}
  - Expand operating space of the ST
  - Study high β_T plasmas as A→1
- Tokamak edge stability studies
  - Experimental tests of peeling-ballooning theory (ELMs)
  - H-Mode studies as A→1

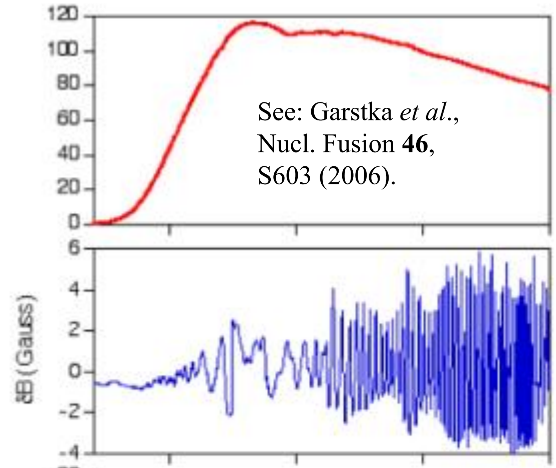




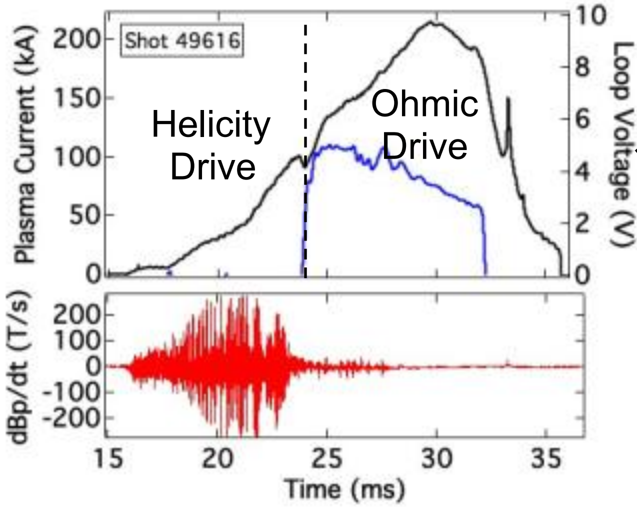
Redd et al, IAEA Fusion Energy Conference 2012

Current Drive Tools Provide Access to High Field Utilization Regime

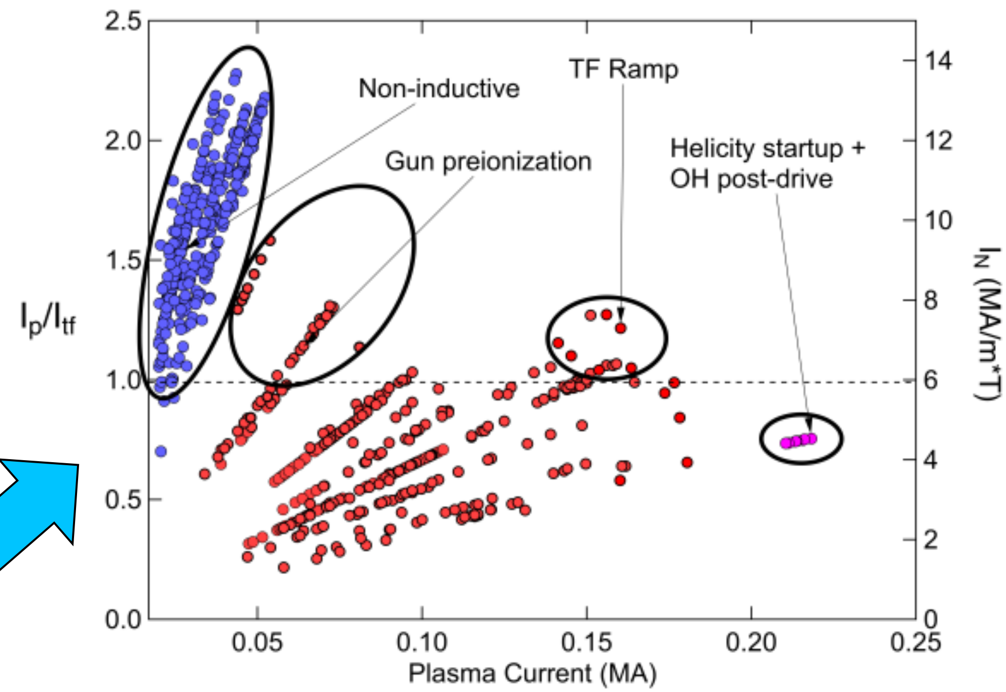
OH only = large 2/1 modes limit I_p



HI startup = MHD quiescent



Redd et al, IAEA Fusion Energy Conference 2012



- 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 $A\approx1$

Building the Physics Basis for Scaling Local Helicity Injection Startup to High Current

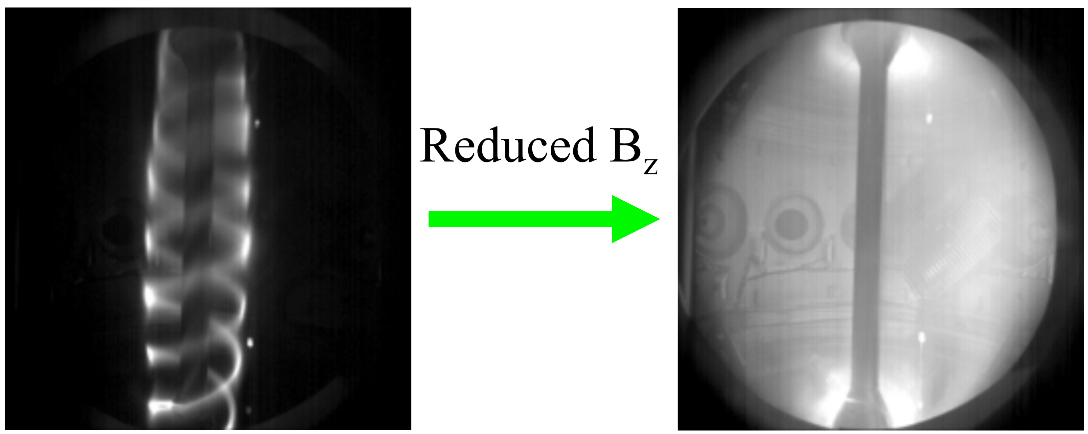
- Conceptually simple non-solenoidal startup technique
  - Compact injectors can be withdrawn after high-current startup
  - Maximum I_p set by two limits:
    - Balance of helicity injection and dissipation rates
    - Magnetic-field geometric limit set by Taylor's relaxation theory
- Extending to higher helicity injection rate, higher current, longer pulse
  - Developing theory-based understanding of injector impedance and effective area
  - Testing plasma confinement properties
  - Exploring high-I_p scenarios where helicity drive dominates over PF induction for growth
  - Evaluating injector concepts for high helicity injection with high geometric I_p limit (requires sourcing intense electron current over an extensive cross-sectional area)
- Developing physics basis for confident scaling to larger scales
  - Studying the magnetic equilibrium evolution, from formation of the axisymmetric state to the transport of driven edge current into the plasma core.
  - Exploring bursts of MHD activity in helicity injection driven plasmas, which correlate with rapid equilibrium changes and strong ion heating

Redd et al, IAEA Fusion Energy Conference 2012

THE UNIVERSITY of WISCONSIN MADISON

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

- Current is injected into the existing helical 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 turbulent tokamak-like Taylor state with high toroidal current multiplication

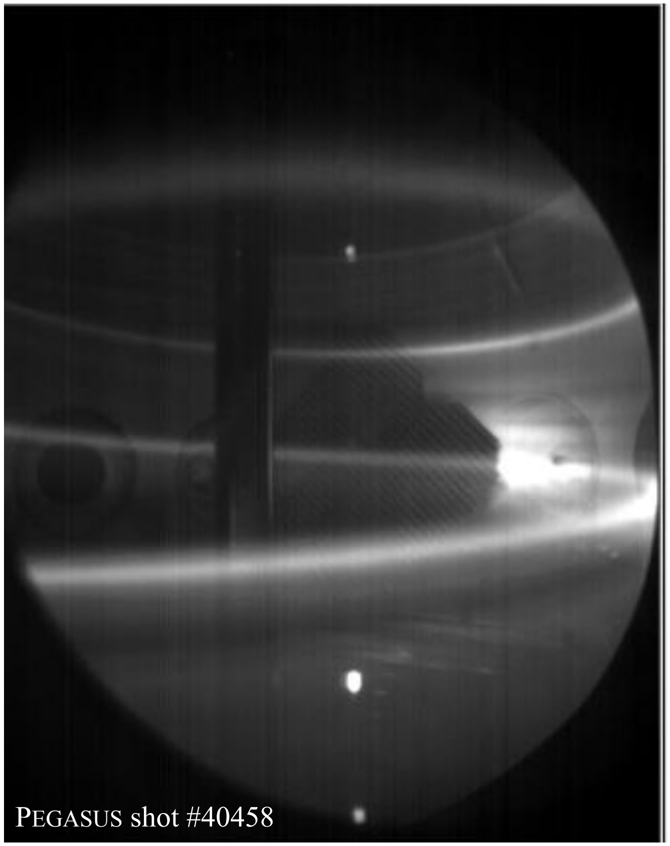


Current filaments | Relaxed tokamak

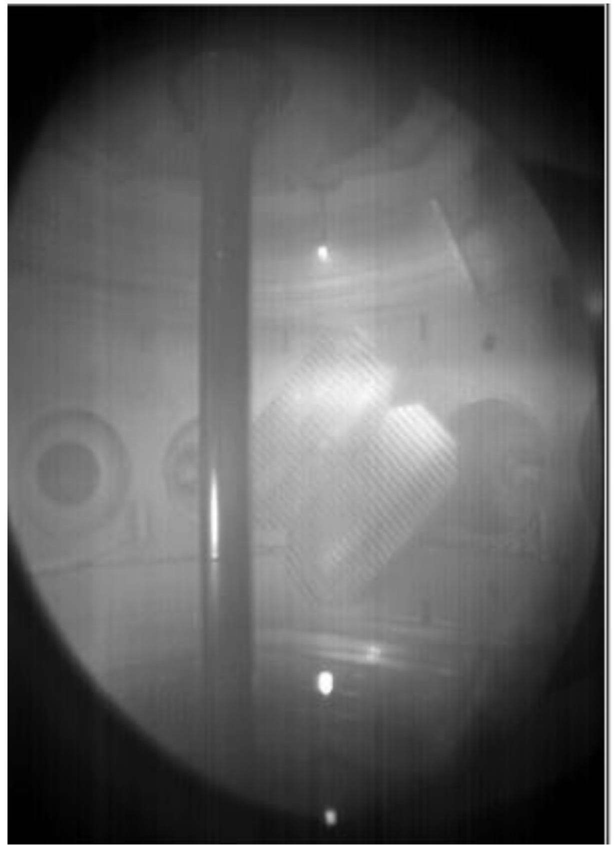
- Technical attractiveness: can remove sources after startup

Redd et al, IAEA Fusion Energy Conference 2012

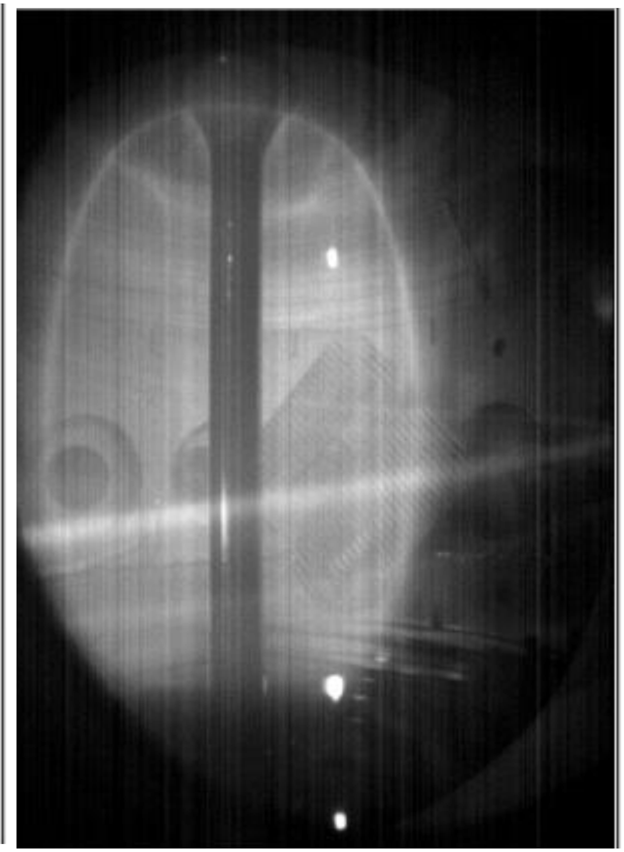
Evolution of Midplane-Gun-Driven Plasma



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

See Battaglia *et al*., Nucl. Fusion **51**, 073029 (2011)

Maximum Attainable I_p set by Helicity Balance and Taylor Magnetic Relaxation Limit

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 plasma confinement via the resistivity η

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

Taylor relaxation of a force-free magnetic equilibrium:

$$\nabla \times B = \mu_0 J = \lambda B$$

$$\lambda_p \le \lambda_{edge}$$

$$\Rightarrow \quad \frac{\mu_0 I_p}{\Psi_T} \le \frac{\mu_0 I_{inj}}{2\pi R_{inj} w B_{\theta,inj}} \quad \Rightarrow \quad I_p \le f(\epsilon, \delta, \kappa)\sqrt{\frac{\kappa A_p I_{\mathrm{TF}} I_{\mathrm{inj}}}{2\pi R_0 w}}$$

Assumptions:

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

where:
A_p is plasma cross-sectional area
Ψ_T is plasma toroidal flux
w is width of driven edge region
I_{inj} is injector bias current
I_{TF} is total TF coil current

See: Battaglia *et al*., Nucl. Fusion **51**, 073029 (2011)

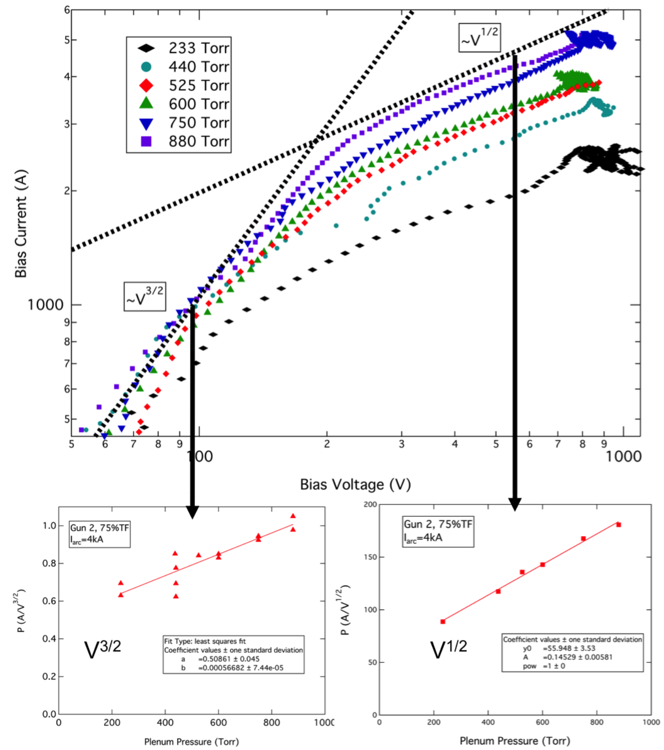
Helicity Injection Process Governed by Space Charge and Magnetic Current Limits

- Current injector impedance is a critical parameter in local helicity injection startup
  - I_{inj} sets Taylor relaxation maximum I_p and V_{inj} sets effective V_{loop}
  - Impedance couples the two to define power requirements
  - Needed to confidently project to startup systems on NSTX-U

- Double-sheath space-charge limits I_{inj} at low I_{inj} and V_{inj}
  - $I_{inj} \sim n_e V^{3/2}$

- At high I_{inj} and V_{inj} > 10 kT_e/e, the Alfven-Lawson magnetic current limit dominates
  - $I_{inj} \sim V^{1/2}$
  - The observed dependence of impedance on the gas fueling rate may be due to variations in the electron beam current profile
  - Possible that sheath expansion also contributes

- Models, supporting evidence imply impedance determined by processes local to injector, not the background plasma
  - Needs verification

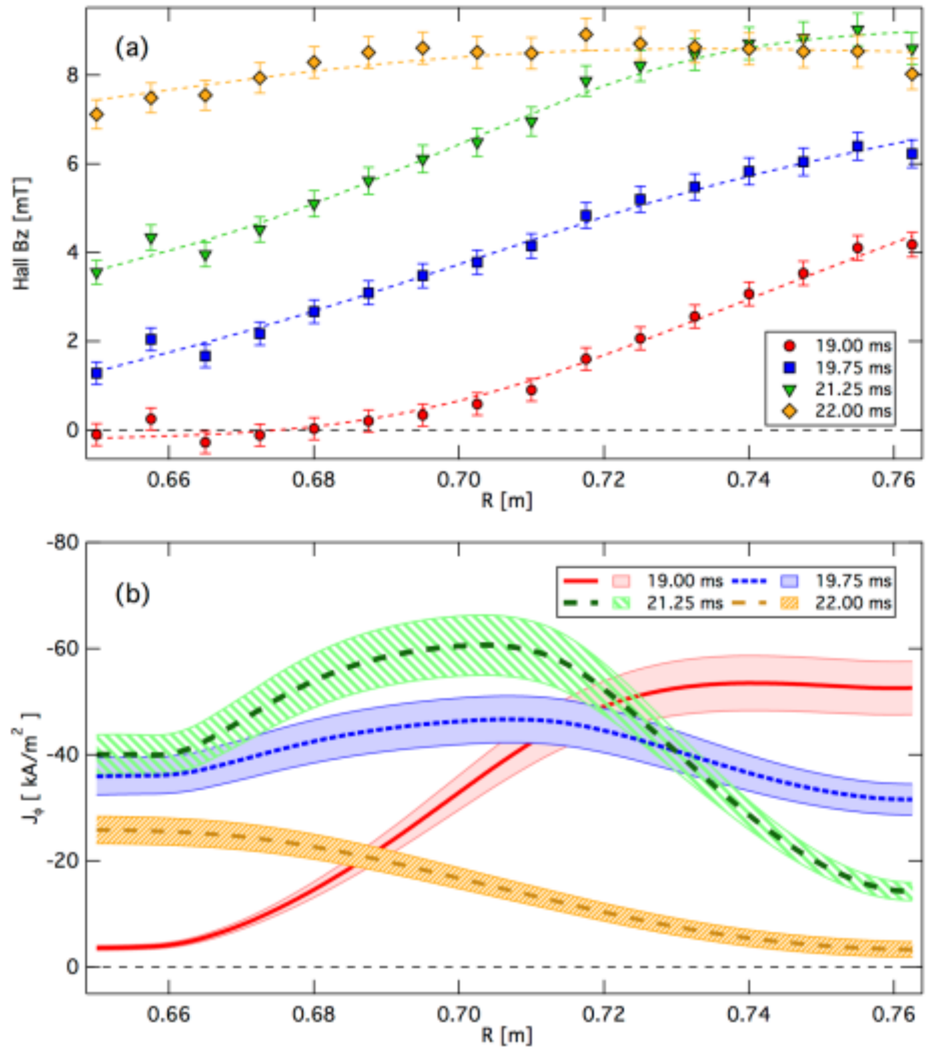


Top: I-V characteristics of arc plasma current injector for varied fueling rates. Bottom: inferred density scaling for both the scaling regimes.

Redd et al, IAEA Fusion Energy Conference 2012

Internal B(R) Shows Initial Poloidal Null and Current Profile Evolution

- (a) Measured internal B_z at four times during the early evolution of Pegasus shot #60021
  - Early B_z profile (red) shows a poloidal field null
- (b) Corresponding calculated J_T profiles at those four times
  - Steady buildup of current in the plasma core (red to blue to green)
  - Corresponding steady drop in the edge current density
  - Current profile becomes typical peaked tokamak profile after detachment

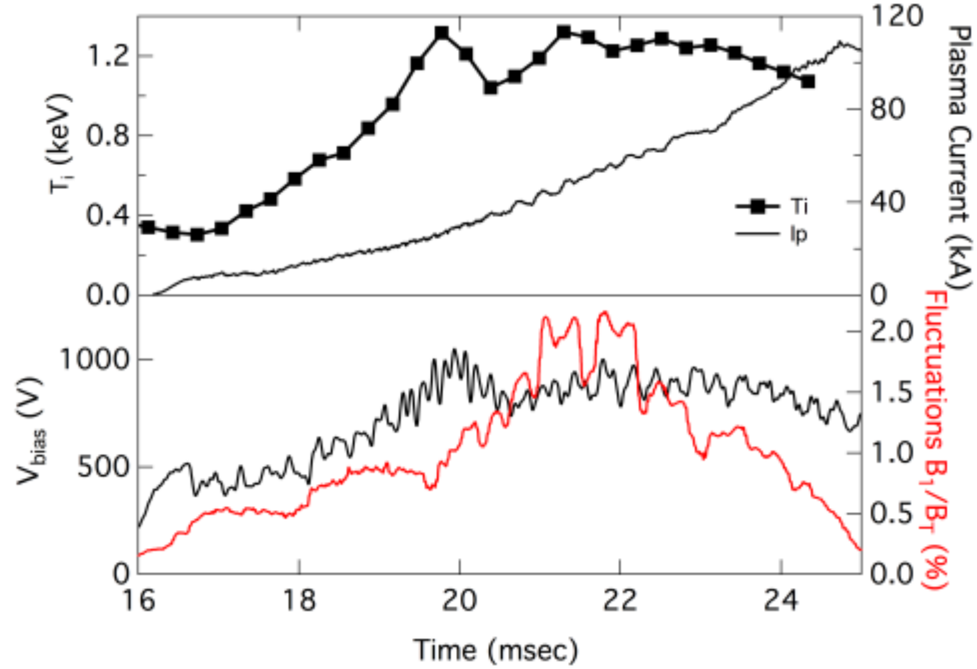


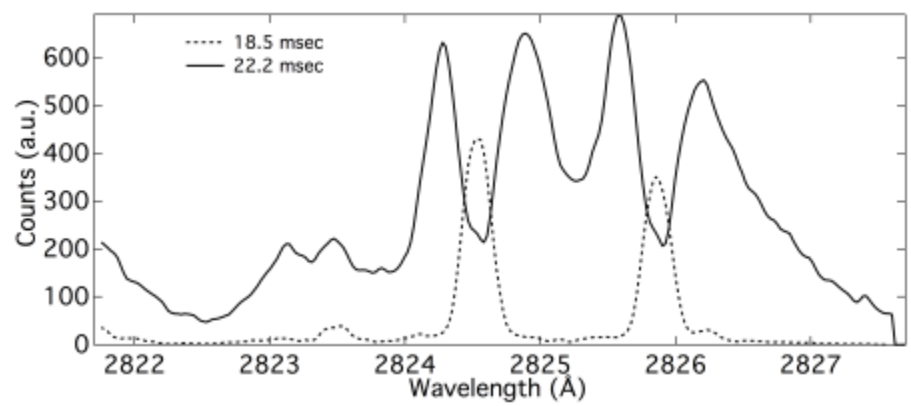
Redd et al, IAEA Fusion Energy Conference 2012

THE UNIVERSITY of WISCONSIN MADISON

Passive Ion Spectroscopy Indicates Strong Ion Heating and Emission Line Splitting

- Typical HI shot #54520
  - Ti calculated from CIII emission. Error bars comparable to marker size.
  - Strong ion heating during helicity injection drive, also correlated with the presence of MHD activity
- Line splitting from similar discharge, #51742
  - Emission from BIV doublet
  - Splitting in the presence of strong MHD activity
  - Splitting indicative of bi-directional flows, as expected from significant reconnection.



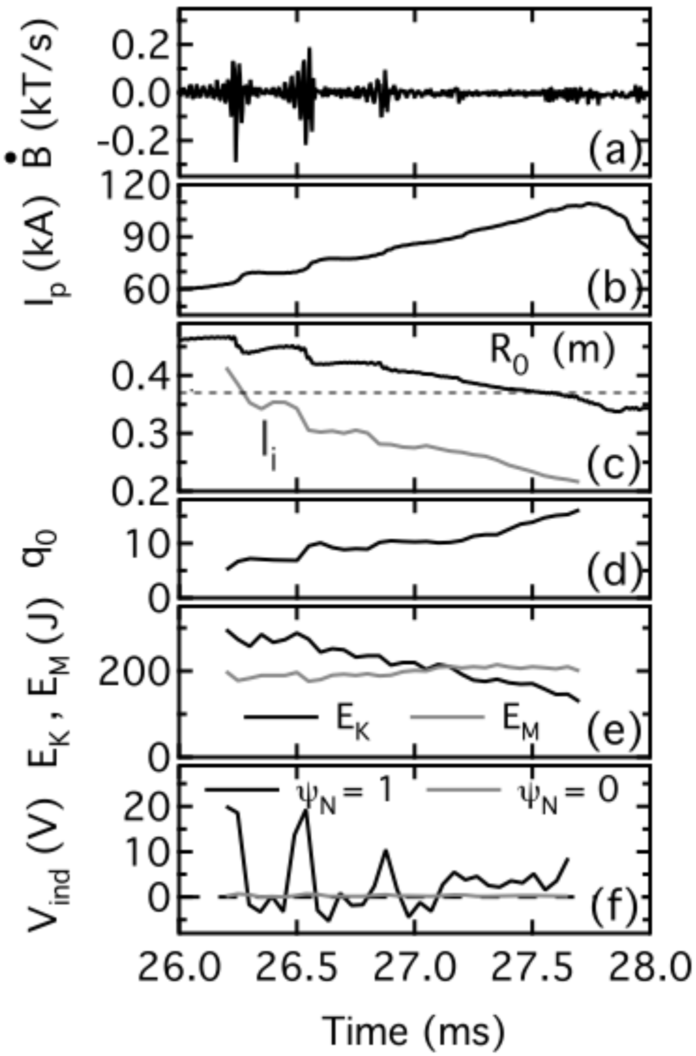


Redd et al, IAEA Fusion Energy Conference 2012

THE UNIVERSITY of WISCONSIN MADISON

Magnetic Topology Rapidly Changes with each Burst of MHD Activity

- Each burst typically ~ 0.1 ms
- With each burst…
  - l_i decreases → I_p increases
  - R_o decreases → plasma expands
  - $B_{\phi o}$ increases → q_o increases
  - Slight drop in E_k and E_m
  - Very little change in poloidal flux at plasma edge
  - Rapid decrease in the total trapped poloidal flux
- Temporally and spatially averaged V_{ind} ~ 1.5 V



See Battaglia *et al.*, Nucl. Fusion **51**, 073029 (2011)

Extending Helicity Injection Startup on Pegasus to High Plasma Currents

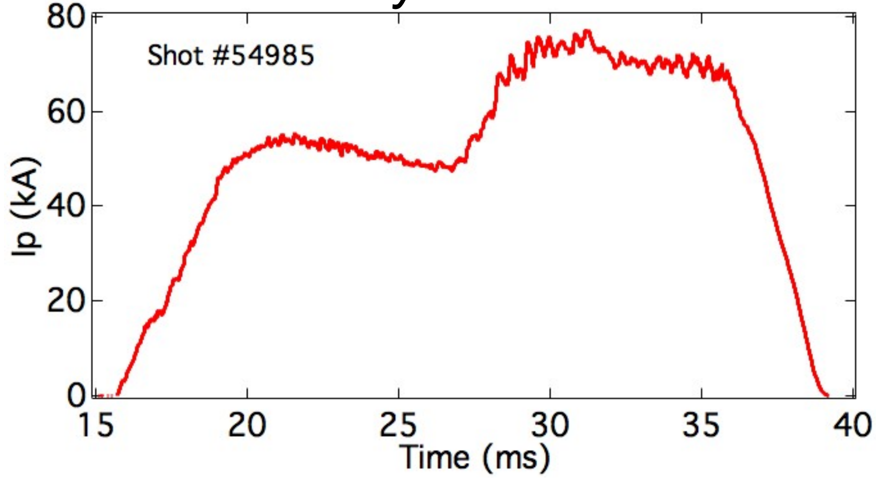
- Need to grow I_p using helicity injection as dominant drive
  - Inductive flux from an outer poloidal field ramp is limited
- Demonstrated plasma sustainment without PF induction
  - Scale discharges to high I_p with more helicity injection
- Higher plasma current available with shaped electrodes
  - Shaped electrode can be optimized with respect to the two I_p limits: large cross-sectional area for high helicity injection rate and drive, but narrow *w* for a high Taylor limit
  - Preliminary experiments show equivalence between plasma guns and passive electrodes of similar cross-section for driving the discharge
  - Focusing on improving understanding of injector physics for different hardware configurations and in varying parameter regimes

Redd et al, IAEA Fusion Energy Conference 2012

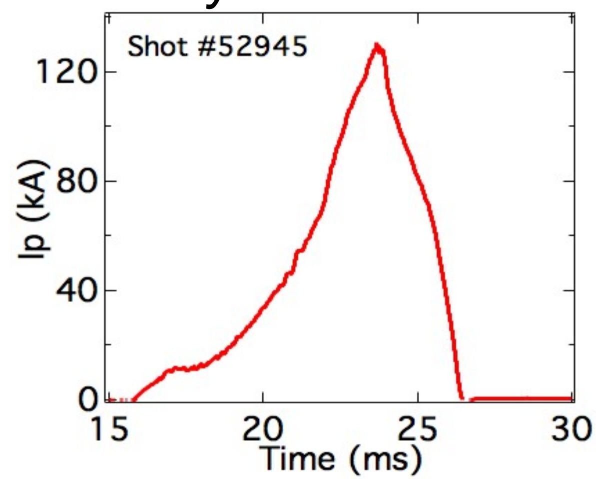
THE UNIVERSITY of WISCONSIN MADISON

Pegasus Discharges Formed and Sustained by Majority Helicity Injection

Helicity-Driven



Helicity & PF-Induction



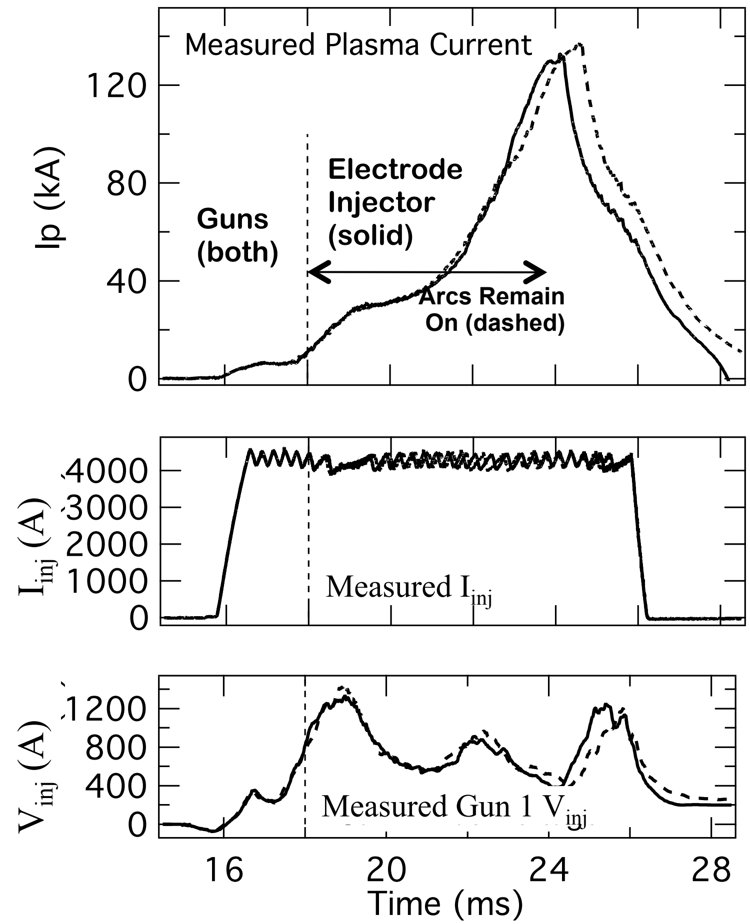
- Demonstration has distinct gun and electrode phases
  - Early part of discharge is driven using plasma gun sources (I_{bias} ~ 4 kA)
  - Later part of discharge driven using extensive electrode (I_{bias} ~ 10 kA)

- No intrinsic limit on driving plasmas with helicity injection
  - In principle, arbitrarily high Ip is achievable by increasing the drive and scaling the vertical field as the plasma evolves
  - Increasing the drive requires a more capable injector

Redd et al, IAEA Fusion Energy Conference 2012

Pegasus Experiments Show Equivalence Between Gun and Electrode Drive

- Electrode shots have two phases:
  - 1. Form initial tokamak-like state with minimal active arc gun
  - 2. Grow to much larger I_p with passive electrodes of similar cross-section, fed by gas flow through the arc channel.
- Compare to gun-only discharges with the same programming and conditions
- First tests were promising
  - Arc current off after relaxation and formation of tokamak-like state
  - I_p rise is virtually the *same,* whether arc discharge or gas-fed electrode provide the charge carriers

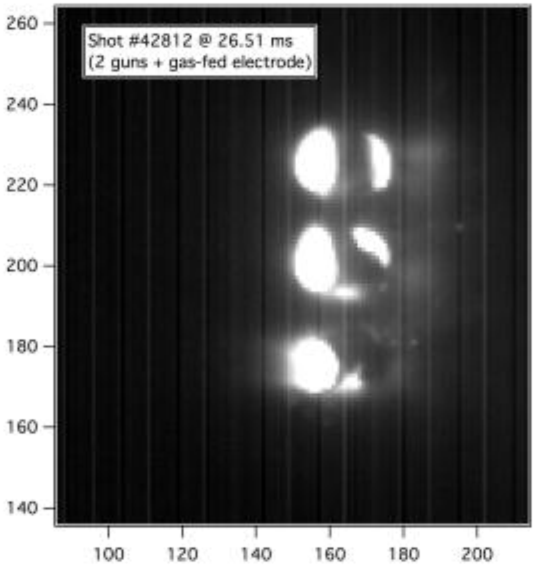


Redd et al, IAEA Fusion Energy Conference 2012

Continuing the Evaluation of Injector Concepts with Gas-fed Electrodes

- Finding the simplest possible approach that scales to NSTX-U and beyond
  - Bare unfueled electrodes: electron current drawn from electrode in discrete sub-millimeter-scale cathode spots
  - See also Fonck *et al.*, FTP/P1-19, this conference

- Next step: evaluating gas-fed electrodes
  - Pegasus has previously used a gas-fed electrode to replace an active plasma gun injector
  - Neutral gas is broken down by nearby plasma, local discharge sustained by conduction of the bias current
  - Empirically, electrode impedance found similar to gun



- Near-term planned variations:
  - Footprint of gas-fed area, via the number and placement of the holes
  - Flow rate through apertures, via gas feed rate and total conductance through holes

Redd et al, IAEA Fusion Energy Conference 2012

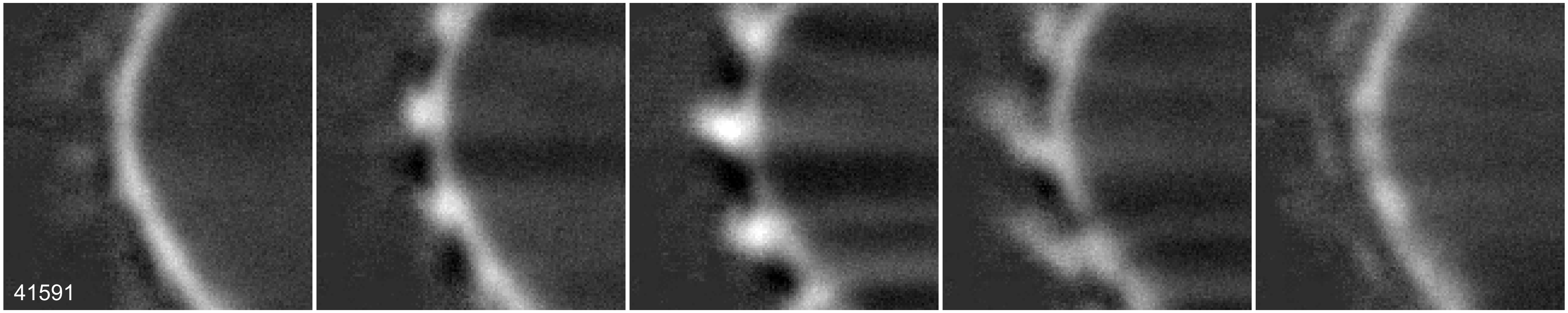
Peeling Mode Onset and Dynamics Studied in Pegasus Ohmic Plasmas

- Direct measurements of J_{edge} conducted with Hall probe
  - Direct analysis, equilibrium reconstruction
  - J_{edge} controllable with dI_p/dt
- Characteristics of peeling modes consistent with theory
  - Macroscopic features: Electromagnetic low-n, high-m edge-localized mode
  - Onset consistent with ideal MHD, analytic peeling stability theories
  - Observed MHD scales with measured J/B peeling drive
  - Coherent, propagating filaments
- J_{edge} dynamics supports current-hole & EM blob hypotheses
  - Nonlinear filaments generated from current-hole J_{edge} perturbation
  - Transient magnetostatic repulsion
  - Constant-V_R propagation in agreement with available EM blob theory

Redd et al, IAEA Fusion Energy Conference 2012

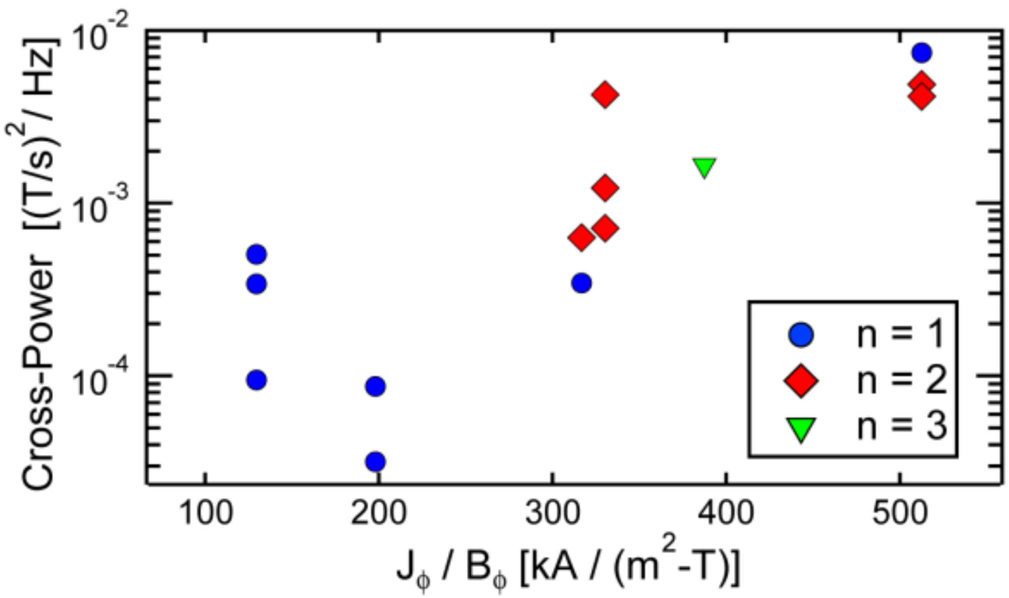
THE UNIVERSITY of WISCONSIN MADISON

Pegasus Peeling Mode Features Match Empirical and Theoretical Expectations



0-9 μs | 11-20 μs | 22-31 μs | 33-42 μs | 44-53 μs

- Short lifetimes with high poloidal coherence
- Detachment, radial propagation of filaments
- High-m, low-n structure
- Mode amplitude increases with theoretical drive J/B



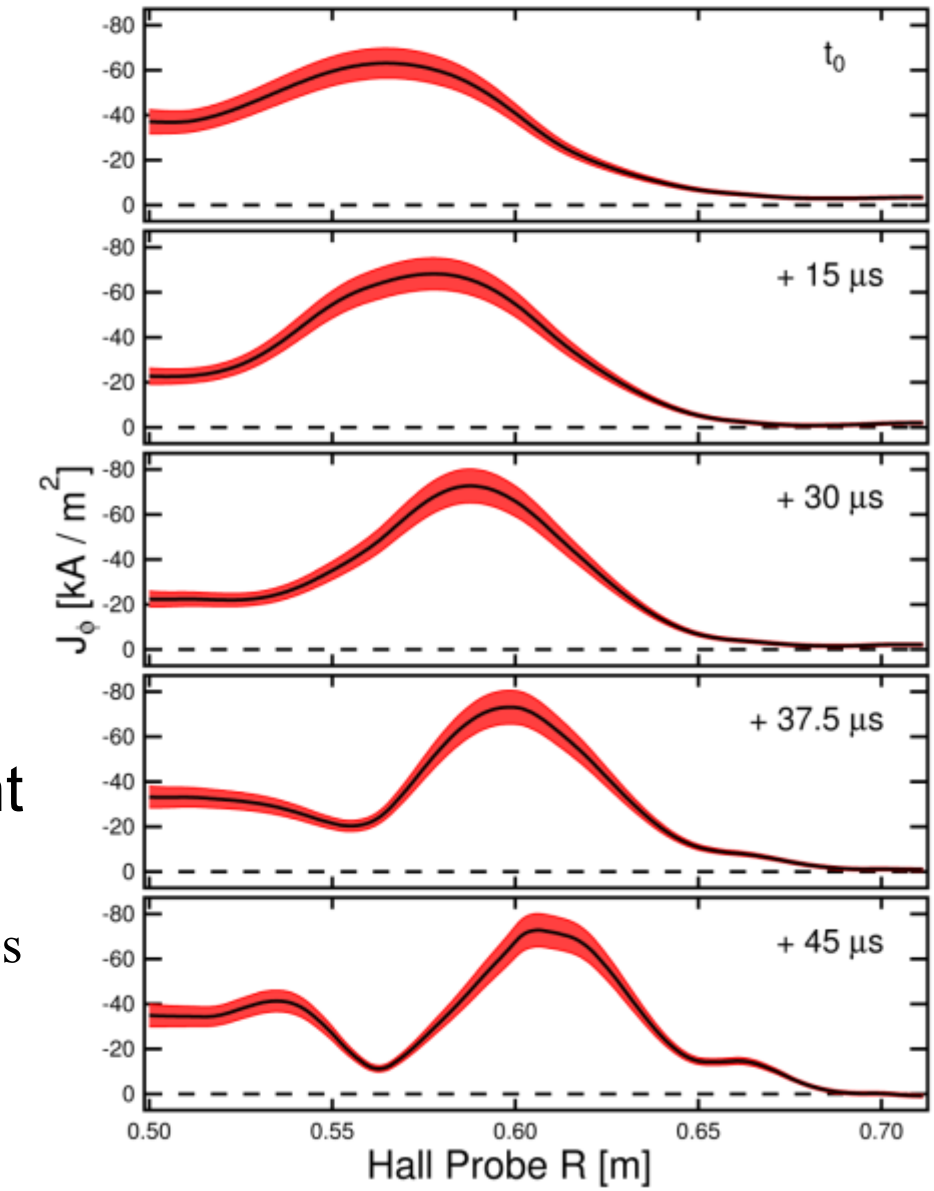
See Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)

Redd et al, IAEA Fusion Energy Conference 2012

J_{edge} Dynamics Measured on ELM Timescales

- J_{edge} resolved during peeling filament generation
- Propagating filament forms from initial "current-hole" J_{edge} perturbation
  - Validates formation mechanism hypothesized by EM blob transport theory
- Filament carries toroidal current $I_f \sim 100–220$ A
  - Comparable to MAST ELM estimates
  - $I_f < 0.2$ % of I_p

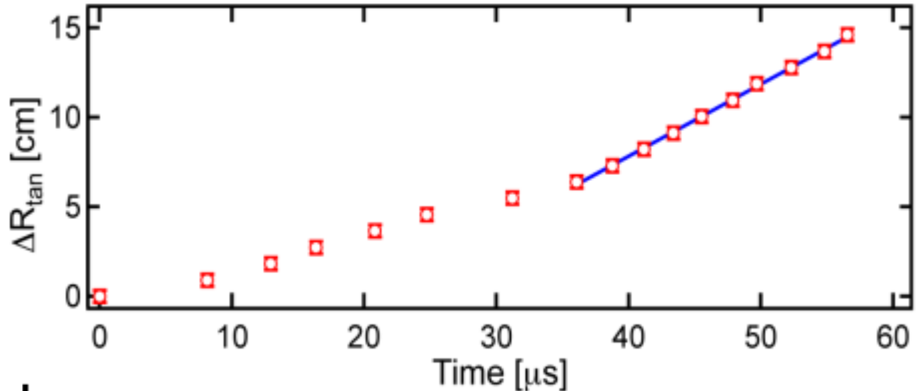
Redd et al, IAEA Fusion Energy Conference 2012



Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)

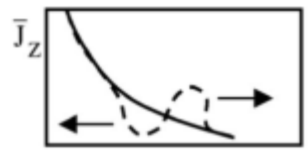
Filament Radial Motion Qualitatively Consistent with Electromagnetic Blob Transport

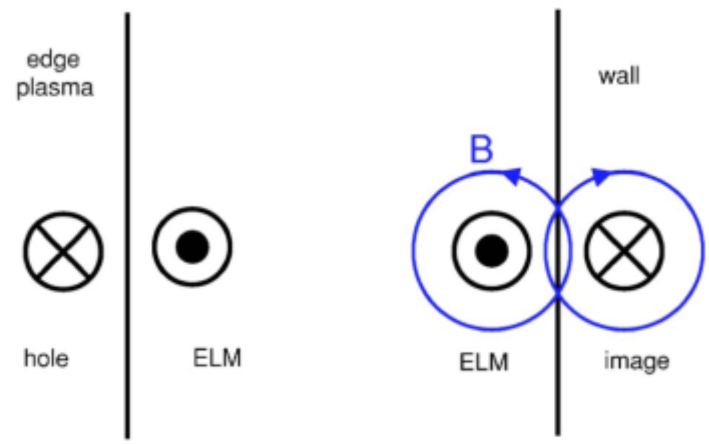
- Trajectory of detached filament tracked with 275 kHz imaging
  - Radially accelerates, followed by constant velocity motion



Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)

- Magnetostatic repulsion* plausibly contributes to dynamics
  - Current-hole $\boldsymbol{J} \times \boldsymbol{B}$ drives a_R
  - Transition at ~ 35 μs comparable to healing time of current-hole





- Measured V_R comparable to available EM blob models**
  - $V_R \sim 4$ km/s; $V_{R,IB} \sim 8$ km/s
  - Agrees to O(1) accuracy of theory

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

: Myra *et al.*, Phys. Plasmas **12, 092511 (2005)

Redd et al, IAEA Fusion Energy Conference 2012

THE UNIVERSITY of WISCONSIN MADISON

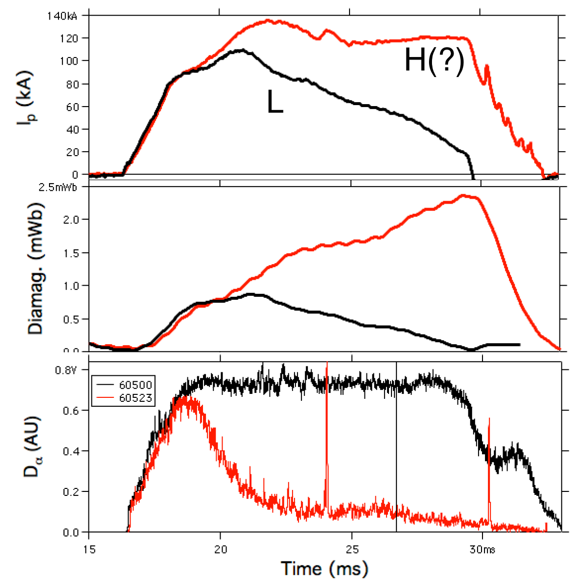
Summary: Progress on Non-Solenoidal Startup via Local Helicity Injection and ELM Studies

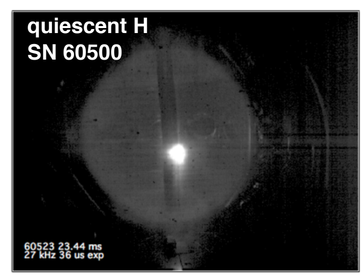
- Significant progress with non-solenoidal startup of ST
  - $I_p \sim 0.17$ MA with helicity injection and outer-PF ramps; ~ 0.08 MA with HI only
  - Increased understanding of helicity balance, relaxation current limit, and injector physics has guided hardware and operational changes
    - HI-only driven plasma points to long-pulse, high I_p startup
    - Evaluating injector concepts to find the simplest hardware that scales for a feasible local helicity injection startup system on NSTX-U and beyond
  - Goal ≈ 0.3-0.4 MA non-solenoidal I_p to extrapolate to next level/NSTX-U
    - Developing physics understanding: λ_{edge}, Z_{inj}, confinement, *etc.*
  - Deploying plasma control tools and new diagnostics to better understand processes

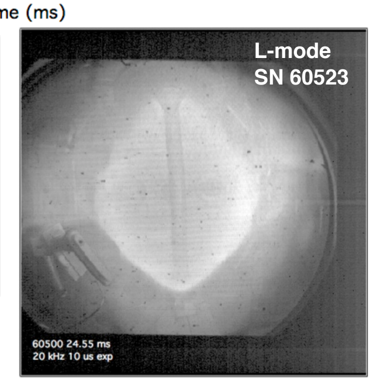
- Peeling mode dynamics studied experimentally
  - Peeling-mode filaments studied with high-speed imaging and magnetic measurements
  - Filament ejection dynamics compare well to theory
  - ELM-like dynamics, even with L-Mode Ohmic discharges
  - Peeling-ballooning studies will now be extended to H-mode Pegasus plasmas

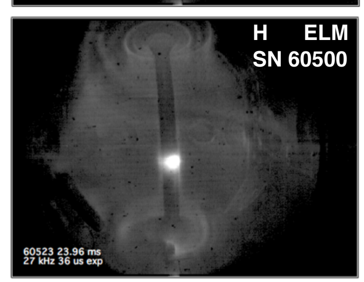
H-mode Access: More Detailed ELM Tests and Possible Helicity Injection Enhancement

- Ohmic H-mode apparently achieved with centerstack (high–field–side) fueling
  - Low recycling via Ti gettering
  - Standard L-mode with low-field-side external fueling; very poor fueling
  - HFS fueling appears very efficient
- Standard H-mode signals seen
  - Reduced D_α emission
  - Quiescent edge between ELM events
  - Type I and III ELMs suggested
  - Improved confinement inferred
    - Increased diamagnetic flux signal
    - Improved V-sec consumption; increased T_e suggested
- New divertor coils = separatrix operation
  - Full H-mode ELM simulation and measurements
  - Access to high-β stability studies at A ~ 1.
  - Coil set installation Nov. 2012.







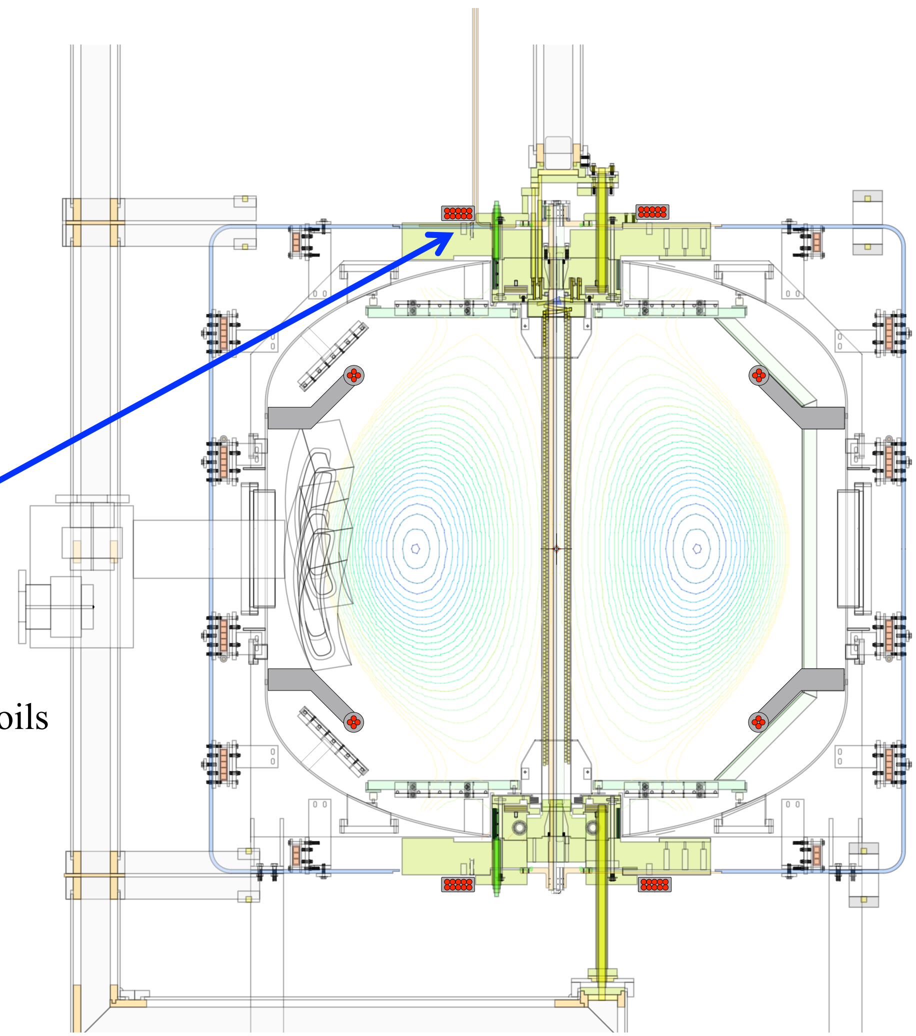


Redd et al, IAEA Fusion Energy Conference 2012

THE UNIVERSITY of WISCONSIN MADISON

Medium-Term Upgrades Will Allow Further Tests of Point-Source Helicity Injection

- Gun-electrode Evolution
  - Gas-feed and electrode material variations
    - *Stand-off Mo electrode w/gas effusion suggested*
    - *Expand to large-area plasma injectors as needed*
  - Separate plasma and injector fueling
    - *Centerstack gas injection for main plasma*
- Power Supplies, Heating, Fueling
  - New helicity injection power: *2.2 kV, 14 kA*
  - Double TF current: *Taylor limit increase*
  - Centerstack and close-flux surface gas injectors
- Expanded PF Coil Set and control
  - Enhanced PF coils for radial position control
  - New external divertor coils, separate vertical position coils
  - Implement GA Plasma Control System
- Diagnostic Additions
  - Multipoint Thomson Scattering
  - High-speed $T_i(r,t)$: *Anomalous reconnection heating*



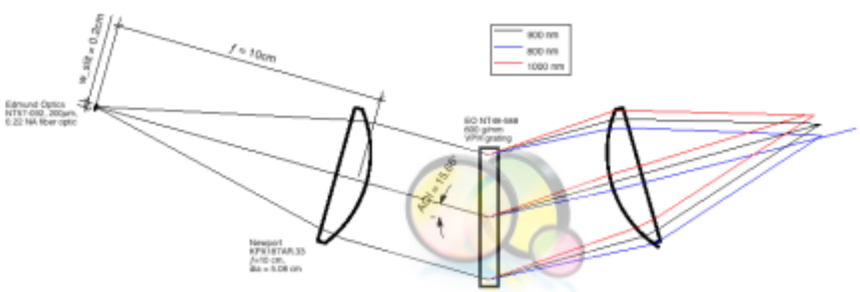
Redd et al, IAEA Fusion Energy Conference 2012

THE UNIVERSITY of WISCONSIN MADISON

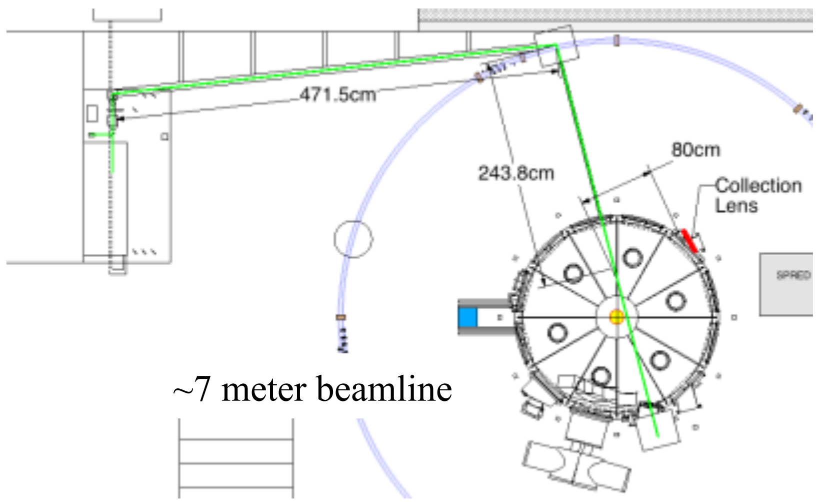
Thomson Scattering system uses new technologies for visible wavelength system

- Frequency doubled Nd:YAG laser provides ~10^{18} photons
- For typical PEGASUS plasma, $n_{scattered}$ ~ 10^4 photons
- VPH grating efficiency >85% for λ_{inc} = 532 - 632 nm
- Gen III image intensifiers ~50% efficient in visible region
- ~ 6 ns ICCD gating provides easy detector technology

Laser Specifications	Value
Output Energy at 532 nm	≥ 2000 mJ
Beam diameter at head	12 mm
Beam diameter at waist	3 mm
Pointing stability	≤ 50 μrad
Divergence	≤ 0.5 mrad
Repetition Rate	≤ 10 Hz
Pulse length	≥ 10 ns



Volume Phase Holographic (VPH) Grating



~7 meter beamline

Redd et al, IAEA Fusion Energy Conference 2012

Local Helicity Injection Startup and Edge Stability Studies in the Pegasus Toroidal Experiment

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

Department of Engineering Physics

University of Wisconsin-Madison

IAEA Fusion Energy Conference

October 8-13, 2012
San Diego, California USA

University of Wisconsin-Madison

PEGASUS Toroidal Experiment

Initial Phase of Helicity Injection Startup Utilizes Compact Washer-Gun Current Sources

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

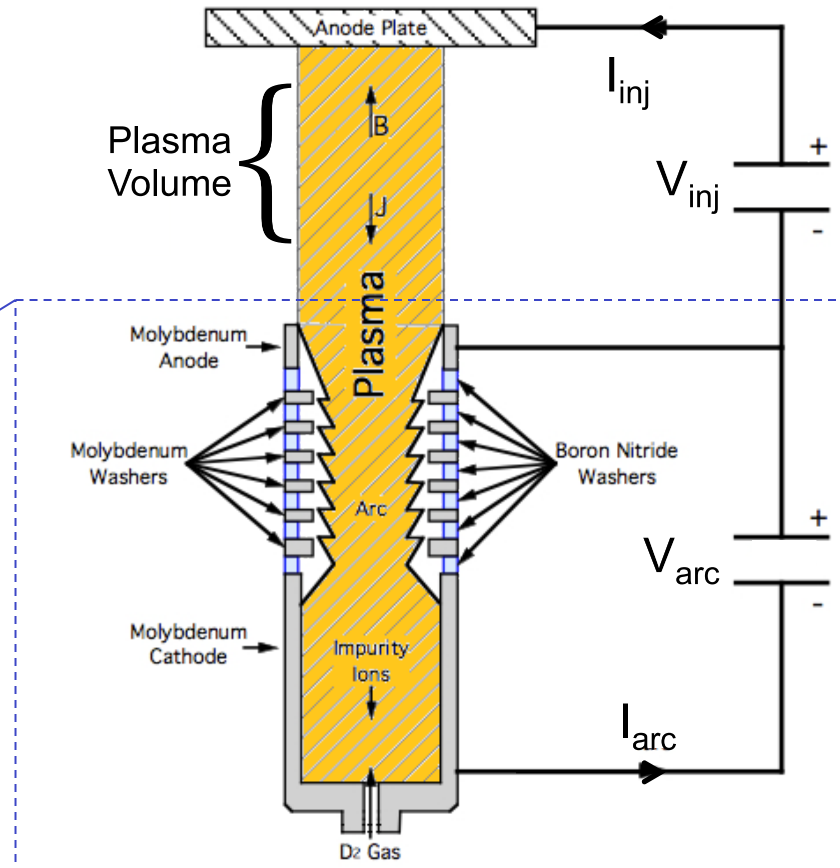
$$\dot{K}_{inj} = 2V_{inj}B_N A_{inj}$$

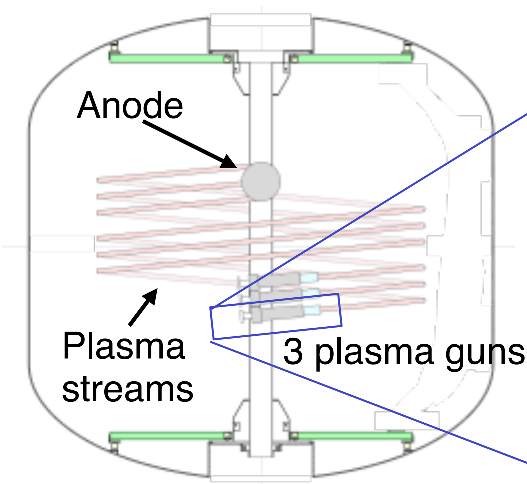
V_{inj} - injector voltage

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

Redd et al, IAEA Fusion Energy Conference 2012

See Redd *et al*, J. Fusion Energy **28**, 203 (2009)