Non-solenoidal Startup through Local Helicity Injection in the Pegasus Toroidal Experiment

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PEGASUS Toroidal Experiment

Layout

Title Banner

Build. Phys. Basis scale LHI Startup to High Current, Expl. Low-A Physics	LHI Injection Offers Scalable NS Startup	HI Process Governed by Space Charge, Mag Limits	Int Field Meeas confirm features of HI model	Exploring passive injectors to increase HI rates	H-mode access: more detailed ELM tests, Possible Post HI CD Enhance	Recent device Upgrd. Supprt Expanded HI, Edge phys studies
Peg = compact, ultralow-A ST	Helicity Input Provided by Edge-local. sources	Density scale in inj Impedance reflect e beam	Mag Topology Rapidly Changes with Bursts of MHD during HI	Large electrode deployed for development of large-are source technology	Toroidal flow reverses at L-H transition	TS System uses new tech for visible wavelength system
Peg mission low A--1	Taylor Relaxation constrains Achievable Ip	Robust switching power supplies deployed	MHD Burst Spatial Struc. Consistent with n=1 line-tied kink	Electrode systems evolved to mitigate deleterious PMI	Edge Current Pedestal observed in H-mode	Summary: Sig. Progress w N-S startup of ST, Extend. Edge Phys studies
CD tools provide access to high FU Reg	Active & Passve elec. inj. systems used to provide hel.	Powr Sys. provide program. Iinj, helicity	Strong anisotropic ion heating obs. during HI	Gas-Fed, Large-area elec. may mitigate required arc source systems	Jedge ELM Dynamics Observed	Reprints

Submitted Abstract

Non-solenoidal plasma startup via local helicity injection is governed by helicity balance and Taylor relaxation constraints. Local helicity injection capabilities at Pegasus have been increased, supporting an expansion of the existing operational space towards $I_p \sim 0.3$ MA and characterization of helicity dissipation mechanisms during plasma startup, growth, and sustainment. After discharge initiation with an active current source, helicity injection may be provided by passive electrodes to continue its evolution and extend pulse length. Local magnetic measurements confirm that a local field null is transiently created by injected current streams prior to relaxation into a tokamak-like state and sustained helicity injection. Bursts of MHD activity during the growth phase are correlated with rapid equilibrium changes, redistribution of the toroidal current density, and observations of strong ion heating ($T_i \sim 1$ keV). The impedance of active injectors and thereby their helicity input rate appears constrained by a double-layer space charge limit at low currents and the Alfvén-Lawson limit for intense electron beams at high currents. Facility and diagnostic upgrades include an expanded poloidal field coil system for improved plasma control, new divertor coils, new plasma gun-electrode injector assemblies, a Thomson scattering system, expanded gas fueling techniques, and support for doubling the toroidal field.

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Building Physics Basis to Scale Local Helicity Injection Startup to High Current, Exploring Low-A Physics

- Local Helicity Injection (LHI) for MA-class non-solenoidal startup
  - DC edge current injection produces tokamak plasmas constrained by:
    - Helicity injection and resistive dissipation
    - Relaxation towards Taylor minimum-energy state
  - LHI-produced plasmas couple to consequent current buildup and drive mechanisms
    - OH V-sec savings in Pegasus → access to high I_N, high-β operating regime
  - Injectors may be withdrawn after high-current startup in next-step devices

- Developing physics, technology basis for LHI
  - Verification of null formation, edge current drive
  - MHD activity and anisotropic T_i heating
  - Injector impedance physics → well-defined power supply requirements
  - Advanced electrode injectors to optimize Taylor, helicity injection limits

- Initial exploration of H-mode at ultralow A → 1
  - Ohmic H-mode achieved via central column fueling
  - $J_{edge}(R,t)$ evolution measured during ELM cycle

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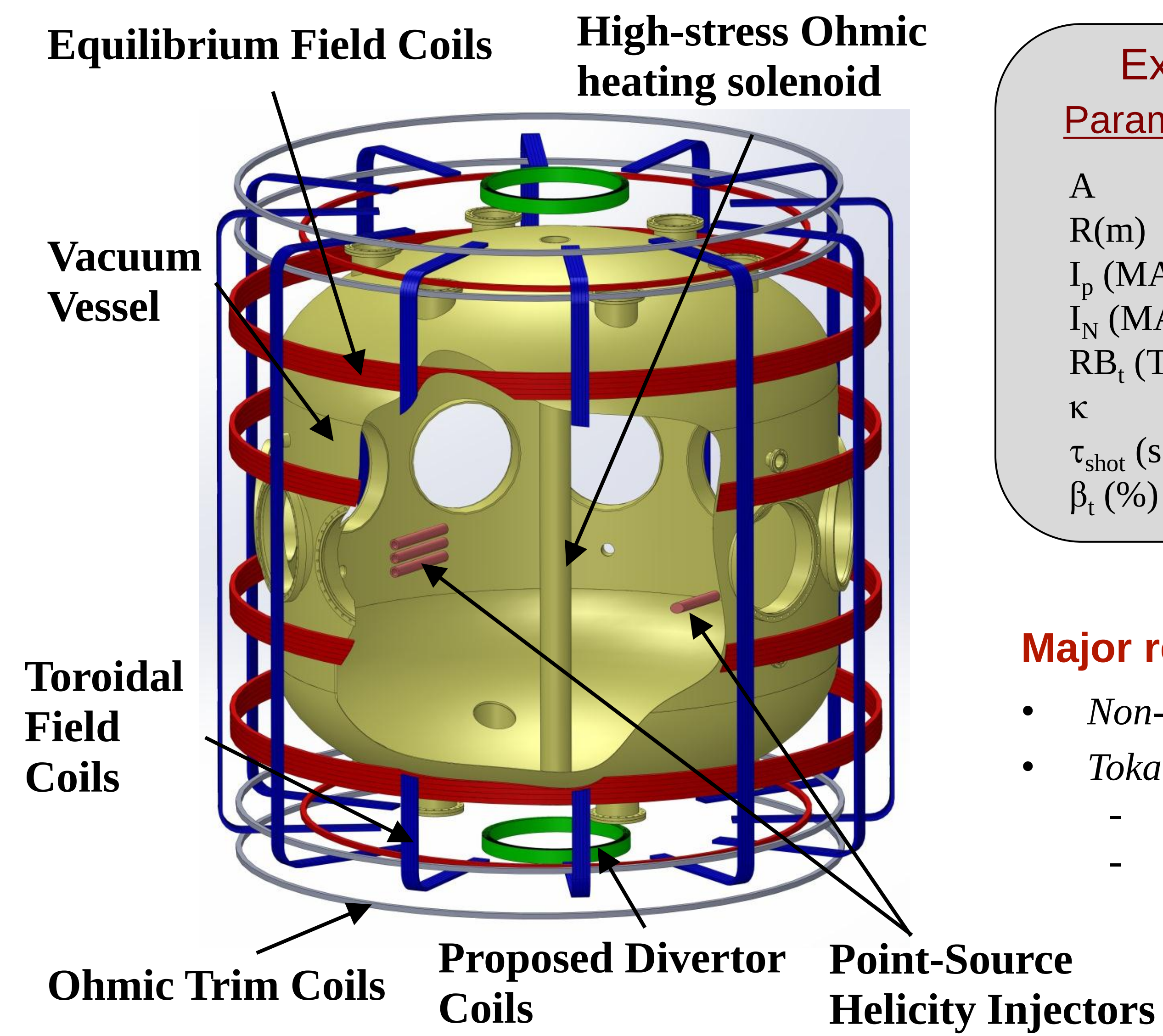
Pegasus is a Compact, Ultralow-A ST



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-relevant edge MHD activity*

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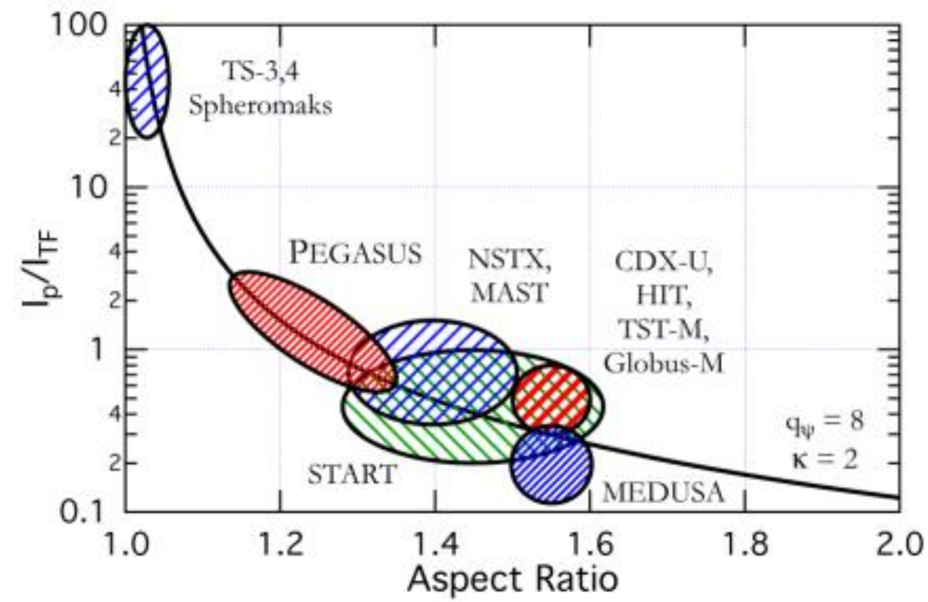
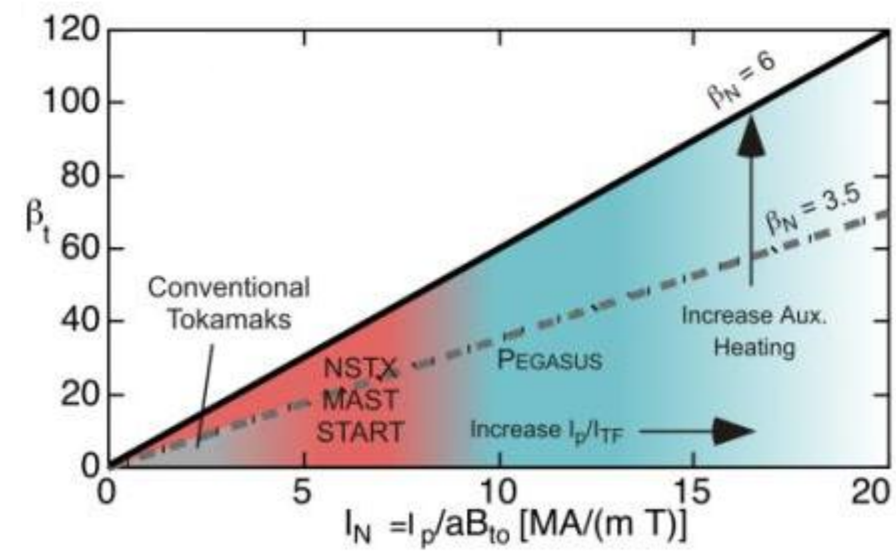
Pegasus Mission: Physics of Low A → 1

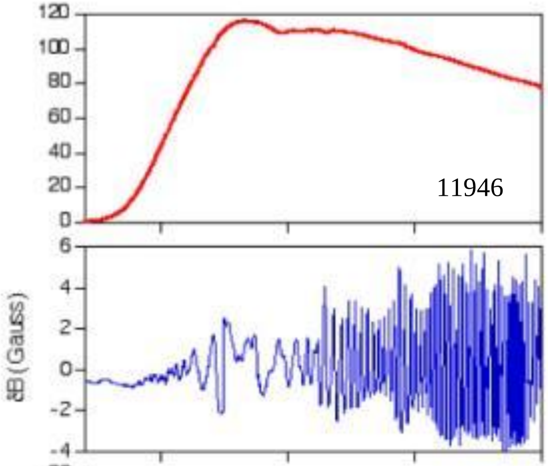
- Non-solenoidal startup
  - Local helicity injection
  - Helicity-initiated discharges readily couple to other current drive methods
- Physics of High I_p/I_{TF}
  - Explore limits of ST operating space
  - Study high β_T plasmas as A → 1
- Tokamak edge stability
  - Tests of peeling-ballooning theory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





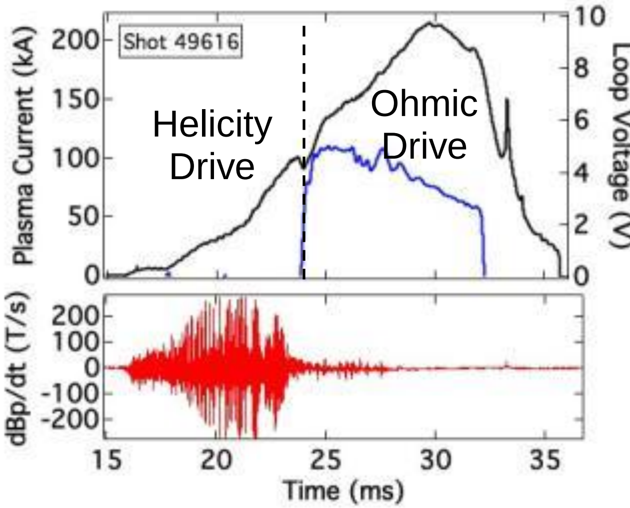
Current Drive Tools Provide Access to High Field Utilization Regime

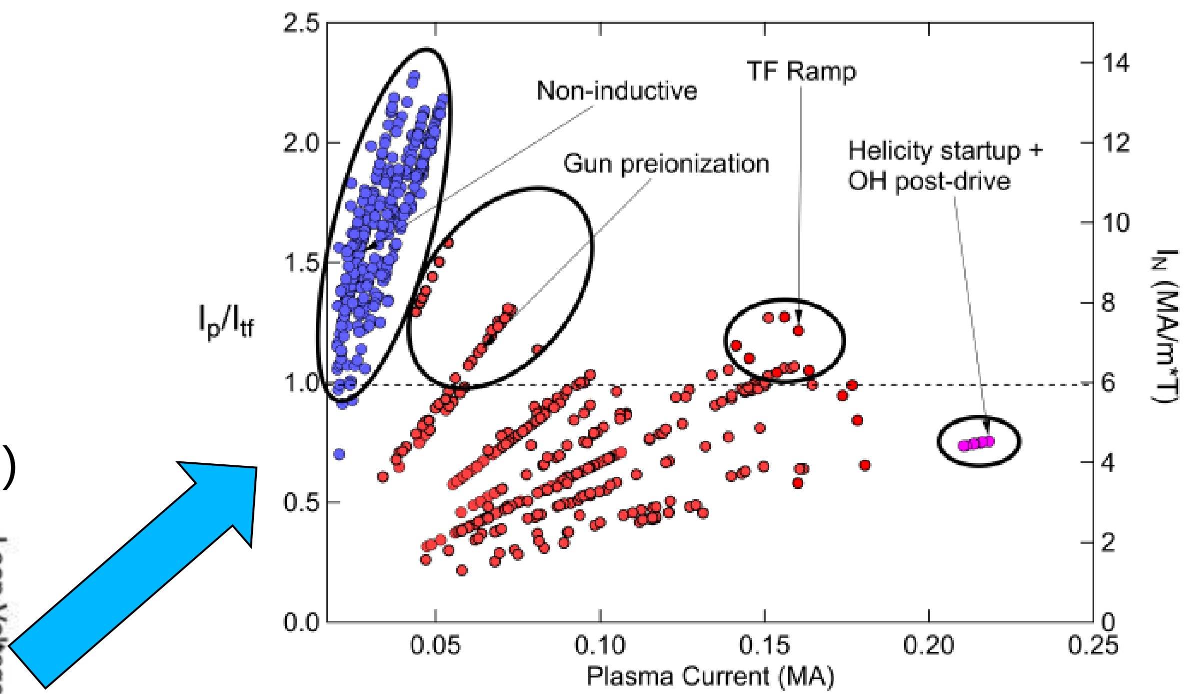
OH only = large 2/1 modes limit I_p



Garstka *et al*., Phys. Plasmas **10**, 1705 (2003)

Post-HI = MHD quiescent J(R)





- 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 $A \approx 1$

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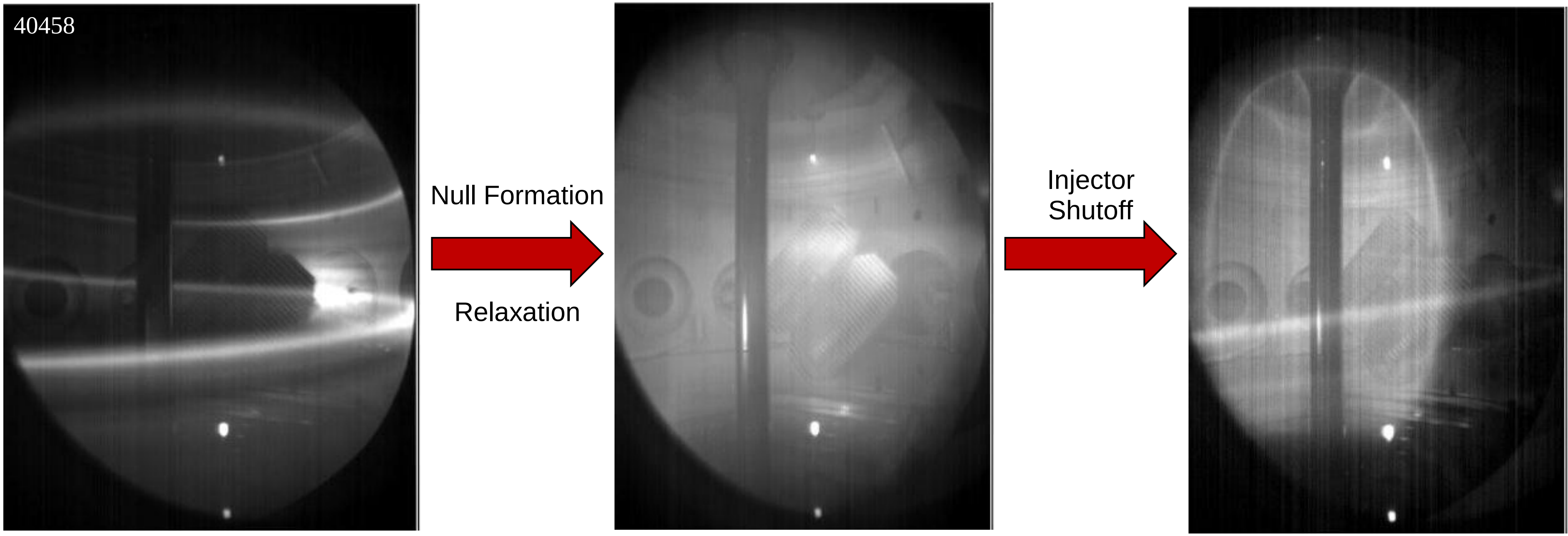
Local Helicity Injection Offers Scalable Non-Solenoidal Startup



- Current injected along helical vacuum field
  - Local, active current sources
  - Geometric current multiplication
    $M = I_p / I_{inj} \sim G$
- MHD relaxation, tokamak-like state
  - Onset via local PF null
  - Current multiplication
    $M >> G$
  - Constrained by helicity, Taylor relaxation limits
- Tokamak plasmas produced after injector shut off
  - Couples to alternative current drive sources

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

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Helicity Input Provided by Edge-Localized Sources

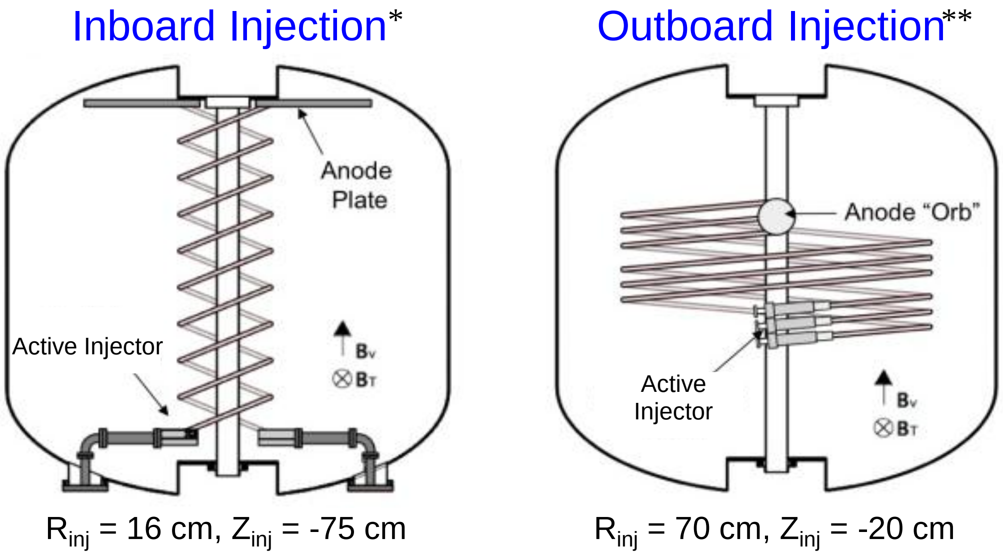
- Biased injectors at plasma edge source DC helicity
  - Helicity balance leads to I_p limit:

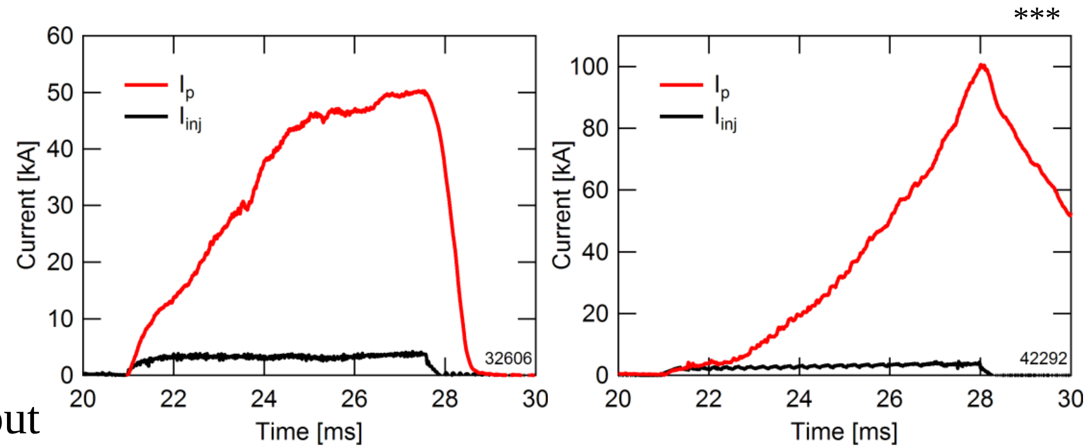
$$I_p \leq \frac{A_p}{2\pi R_0 \langle\eta\rangle}\left(V_{ind} + V_{eff}\right),$$

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

    - A_p, A_{inj} : Plasma, injector area
    - V_{ind} : inductive loop voltage
    - V_{inj} : injector bias voltage
    - Ψ : plasma toroidal flux
  - Helicity dissipated through plasma resistivity η

- Flexible injector geometry
  - Inboard: minimize position control requirements, maximize helicity input
  - Outboard: "port-plug" installation, optimize V_{ind} through PF induction





*: Eidietis *et al.*, J. Fusion Energ. **26**, 43 (2007)
: Battaglia *et al.*, Nucl. Fusion **51, 073029 (2011)
***: Battaglia *et al.*, Phys. Rev. Lett. **102**, 225003 (2009)

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Taylor Relaxation Constrains Achievable I_p

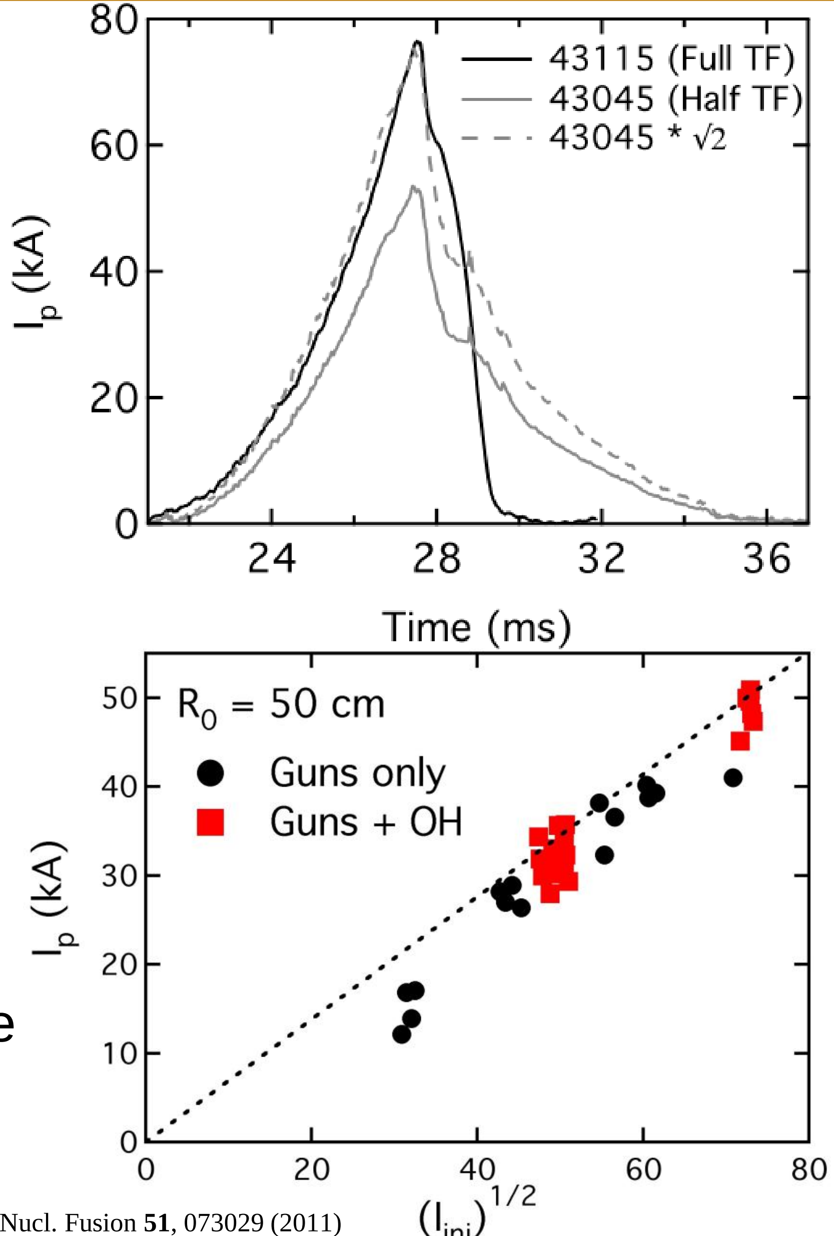
- Maximum I_p via DC helicity injection when relaxed to Taylor equilibrium

$$\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{J} = \lambda \boldsymbol{B} \quad \lambda_p \le \lambda_{inj} \rightarrow \frac{\mu_0 I_p}{\Psi} \le \frac{\mu_0 I_{inj}}{2\pi R_{inj} w B_{\theta,inj}}$$

$$I_p \le f(\epsilon, \kappa, \delta) \sqrt{\frac{\kappa A_p I_{TF} I_{inj}}{2\pi R_0 w}}$$

  - I_{inj}, I_{TF} is {injector bias, total TF coil} current
  - w is width of driven edge region
- – Assuming
  - Driven edge current mixes uniformly
  - Edge fields average to tokamak-like structure

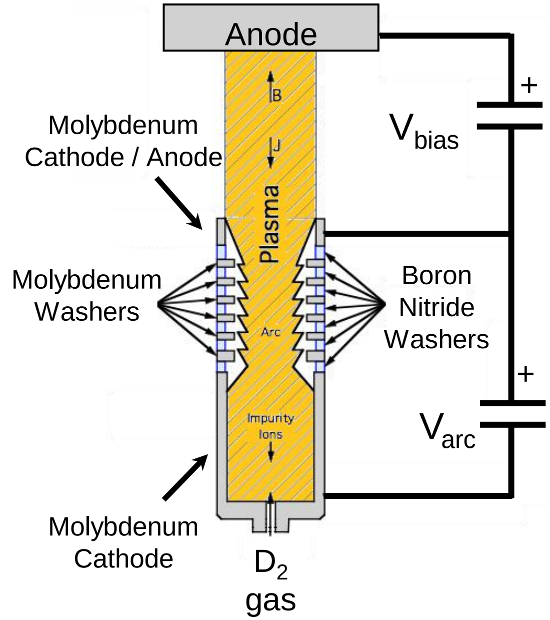
- Experimental plasma currents follow these scalings

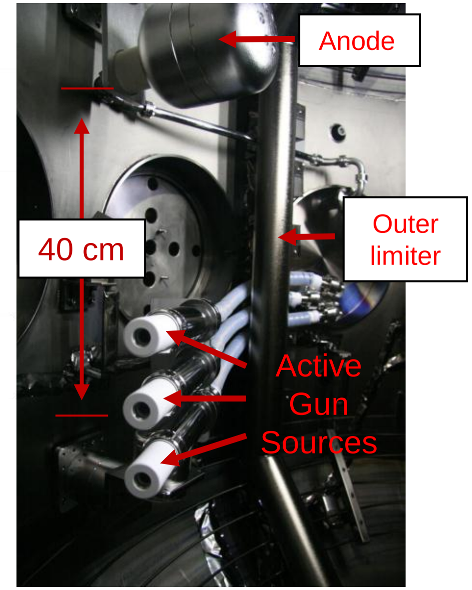


Battaglia *et al.*, Nucl. Fusion **51**, 073029 (2011)

Active and Passive Electrode Injector Systems Used to Provide Input Helicity

- Maximizing I_p requires
  - High Taylor relaxation limit
    - High I_{inj}, low *w*
  - Large helicity input rate
    - High A_{inj}, V_{inj}, B_{inj}
  - Satisfying initial relaxation criteria



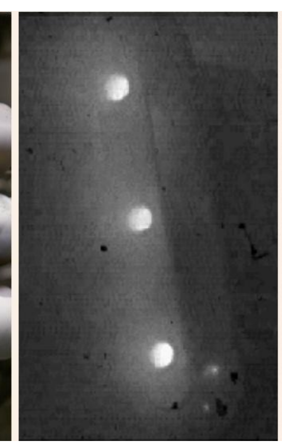


A.J. Redd *et al*, J. Fusion Energy **28**, 203 (2009)

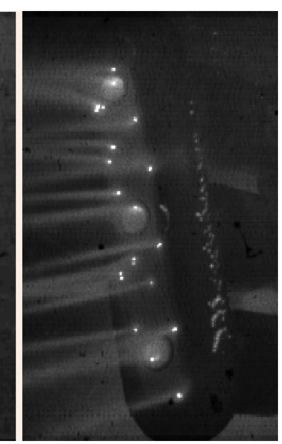
- Active sources used for initial relaxation, sustainment
  - Arc plasma created in coaxial washer gun
  - Electron current extracted from arc

- Passive electrode-based systems may offer scalable path forward
  - Goal: simultaneously optimize helicity injection, Taylor relaxation constraints
    - Large $A_{inj} >> A_{inj,gun}$, high I_{inj}, low *w*
  - Requires initial startup with active source(s)

Gun / Electrode assembly



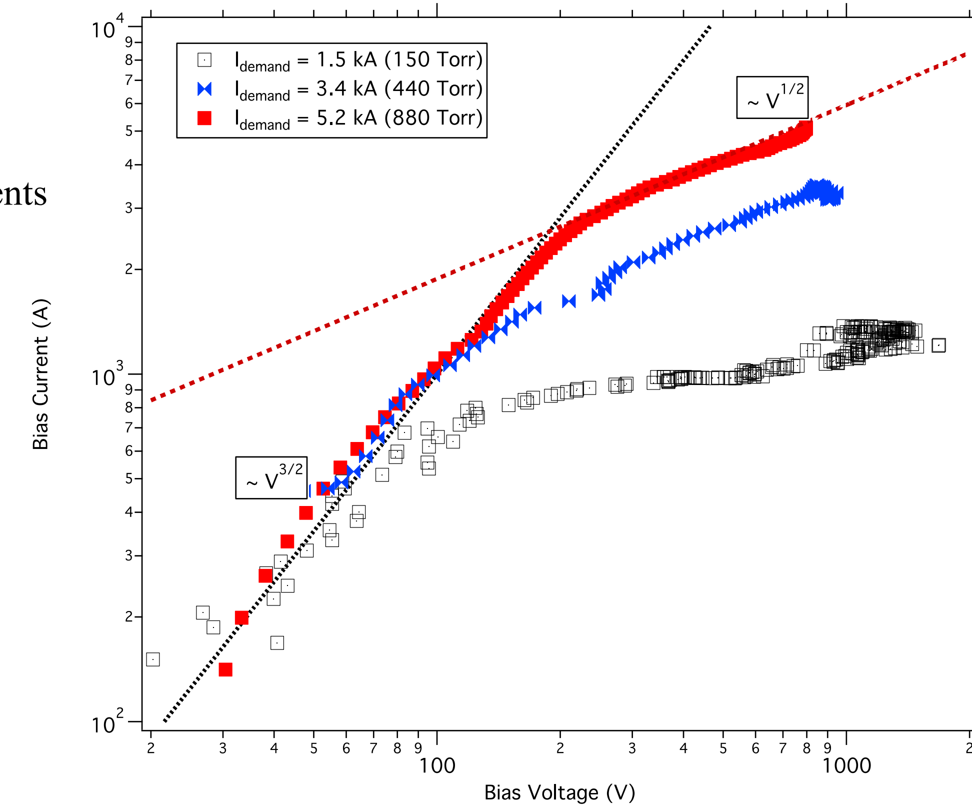
Active Source Operation



Electrode Operation

Helicity Injection Process Governed by Space Charge and Magnetic Current Limits

- Predictive impedance models required to project towards future startup systems
  - Taylor limit $\propto \sqrt{I_{inj}}$
  - Helicity input $\propto V_{inj}$
  - Impedance couples $I_{inj}, V_{inj} \rightarrow$ power requirements
- Active source I-V characteristics obtained during plasma startup
  - Two distinct regimes evident
- Double-sheath space-charge limits I_{inj} at low I_{inj} and V_{inj} in initiation phase
  - $I_{inj} \propto n_e V^{3/2}$
- Alfvén-Lawson magnetic current limit dominates at high $I_{inj} > I_A$ and $V_{inj} > 10\ kT_e/e$
  - $I_{inj} \propto V^{1/2}$
  - Possible that sheath expansion also contributes here



I-V characteristics of arc plasma current injector for varied fueling rates.

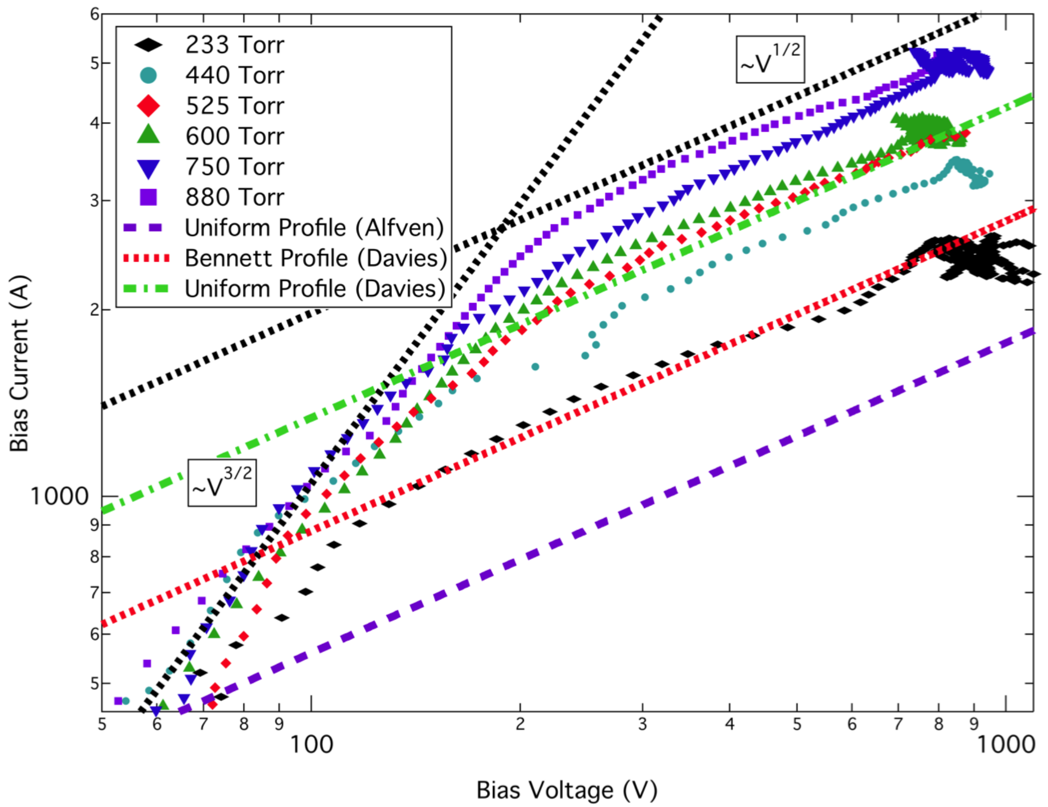
E.T. Hinson, NP8.00062, this session

Density Scaling in Injector Impedance May Reflect e- Beam Profiles?

- I-V characteristics at varied fueling rates suggests a scaling with arc density
- Density variation may reflect changes in beam current density profile
  - Alfvén: uniform J with backward particle flow

$$I_{AL}^{e} = 1.65\frac{4\pi m_e v_e}{e\mu_0} \equiv 1.65 I_A = 56\sqrt{V_{inj}}$$

  - Davies: Uniform profile and Bennett profile for J(r)
    - Derived from energy conservation



$$I_{uniform}^{e} = 4.0\frac{4\pi m_e v_e}{e\mu_0} = 134\sqrt{V_{inj}}$$

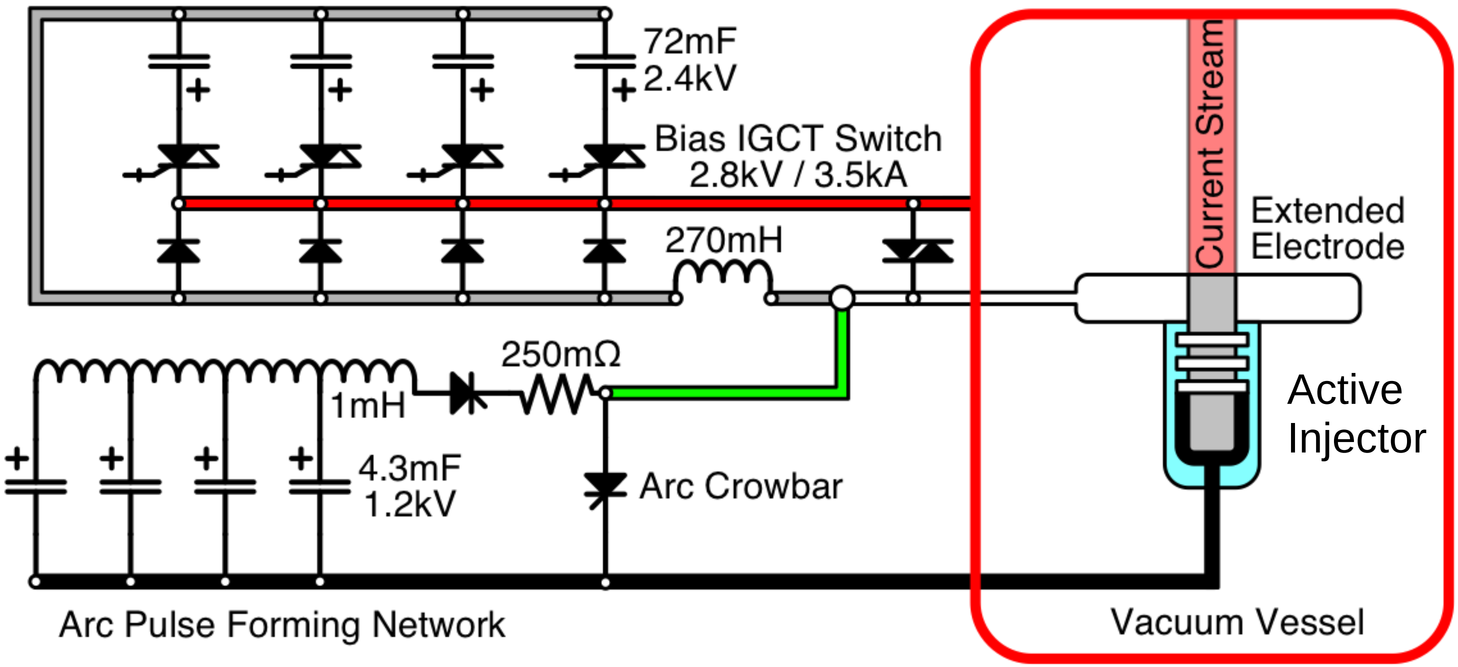
$$I_{Bennett}^{e} = 2.9\frac{4\pi m_e v_e}{e\mu_0} = 88\sqrt{V_{inj}}$$

- Data shows inferred trends but detailed measurements needed

E.T. Hinson, NP8.00062, this session

Robust Switching Power Supplies Deployed for Arc & Injection

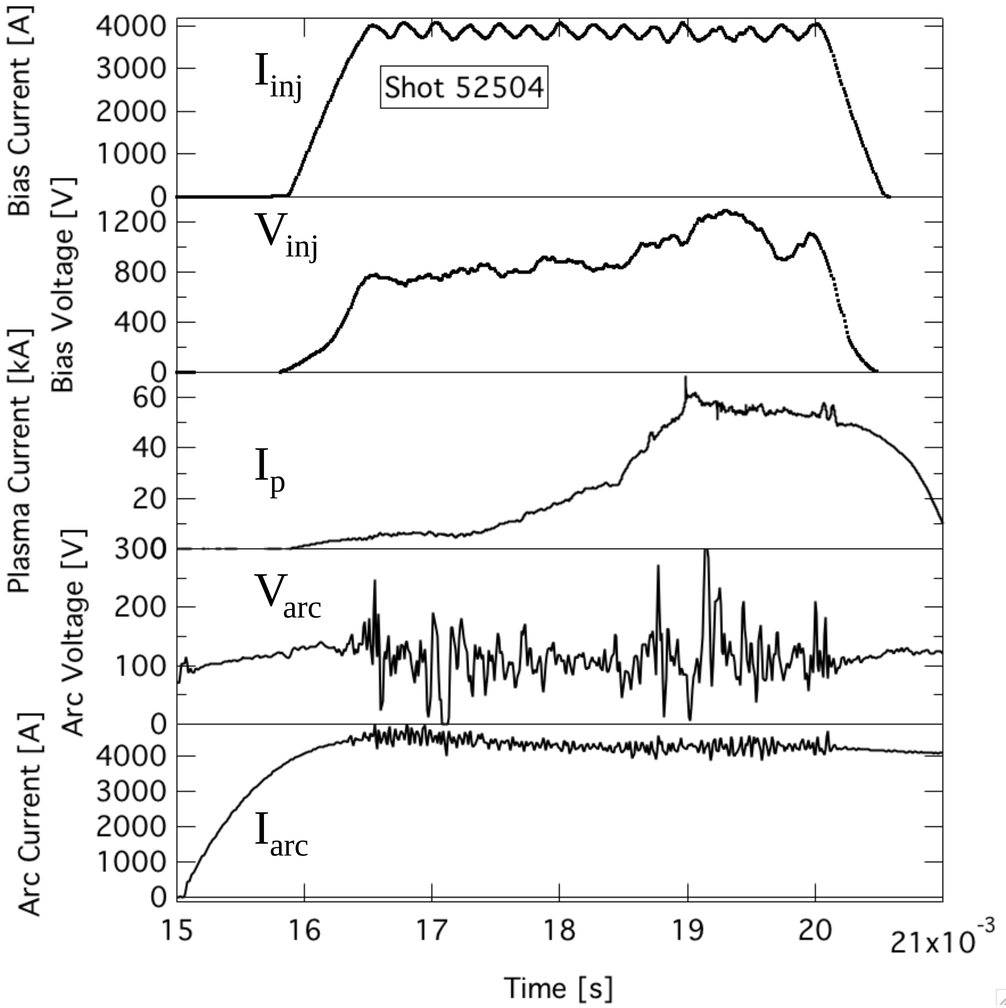
- Active source plasma arc supply is a simple pulse forming network
  - Once arc is established: I_{arc} = 1–2 kA @ V_{arc} = 100–200 V
  - SCR terminates arc on demand
- High-voltage injection (bias) circuit uses 4 IGCT switches in parallel
  - Total: $I_{inj} \leq 14$ kA @ $V_{inj} \leq 2.2$ kV
  - Augments or replaces additional 900 V IGBT bias system
  - Preprogrammed current control via stabilized PWM feedback controller



J.M. Perry, NP8.00068, this session

Power Systems Provide Routine Programmable Injected Current and Helicity

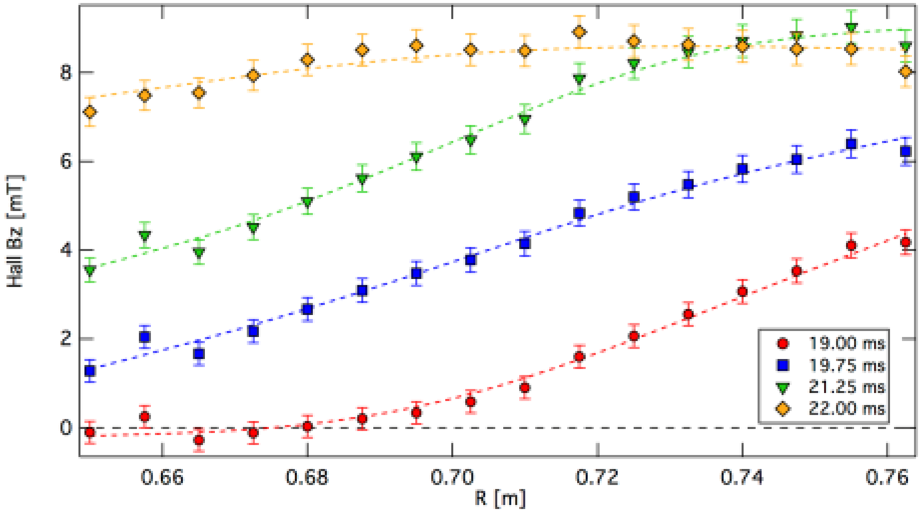
- Injection circuit current regulated with proportional feedback control
  - Impedance varies with injector, tokamak parameters
    - Consequence: V_{inj} variable in-shot
  - Future upgrade: voltage feedback control
    - Active control of helicity injection rate
- Arc circuit fully ionizes injected gas
  - I_{arc} ~ 2–4 kA @ V_{arc} ~ 150 V
- Simple initiation technique
  - Inject gas flow into arc chamber
  - Strike arc current (~ 1ms)
  - Bias injector to extract I_{inj}

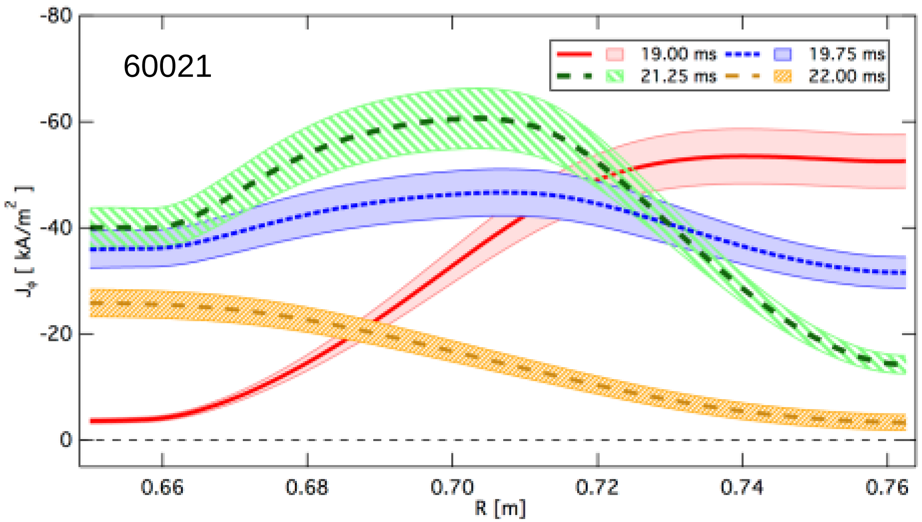


J.M. Perry, NP8.00068, this session

Internal Field Measurements Confirm Features of Helicity Injection Model

- Hall probe* provides internal $B_Z(R,t)$ throughout discharge
  - No significant plasma perturbation
- Local field null (red) from I_{inj} generated prior to relaxation
- $J_\phi(R)$ evolution consistent with injection paradigm, I_p trajectory
  - Initial midplane concentration outside injectors due to perturbed fields (red)
  - Current builds near injector radius while dropping outside (blue → green)
  - Plasma detaches from injector after I_{inj} termination (yellow)
    - Inward propagation as I_p decays



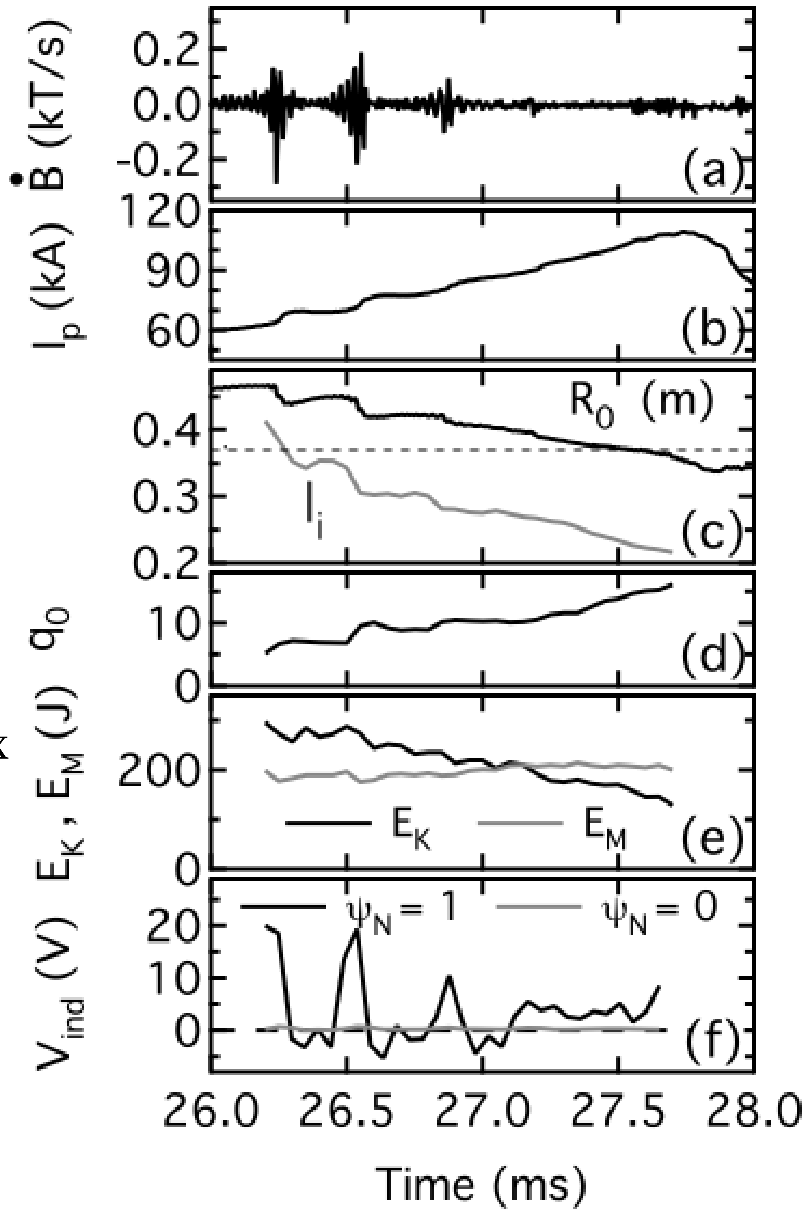


*: M.W. Bongard *et al.*, Rev. Sci. Instrum. **81**, 10E105 (2010)

J.L. Barr, NP8.00061, this session

Magnetic Topology Rapidly Changes with Bursts of MHD Activity During Helicity Injection

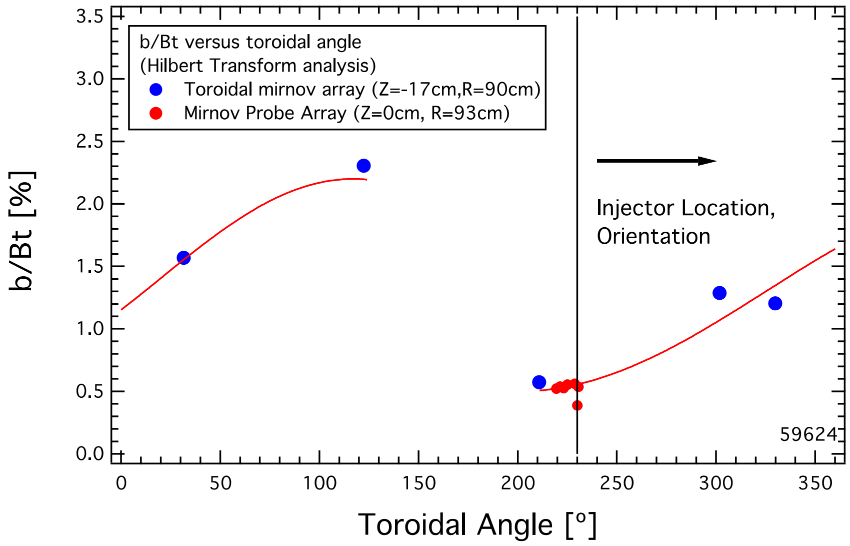
- Each burst typically ~ 0.1 ms
- With each burst…
  - ℓ_i decreases → I_p increases
  - R_0 decreases → plasma expands
  - $B_{\phi,0}$ increases → q_0 increases
  - Slight drop in E_k and E_m
  - Little change in poloidal flux at plasma edge
  - Rapid decrease in the total trapped poloidal flux
- Temporally and spatially averaged V_{ind} ~ 1.5 V

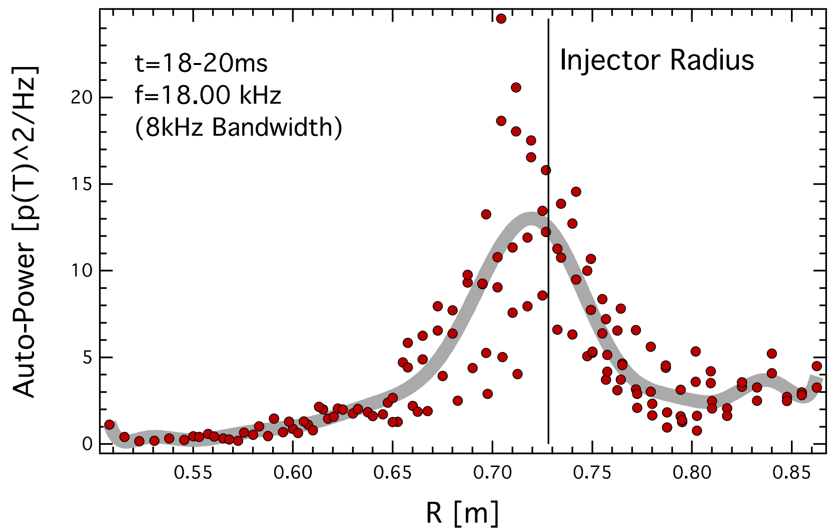


Battaglia *et al*., Nucl. Fusion **51**, 073029 (2011)

MHD Burst Spatial Structure Consistent with n = 1 Line-Tied Kink

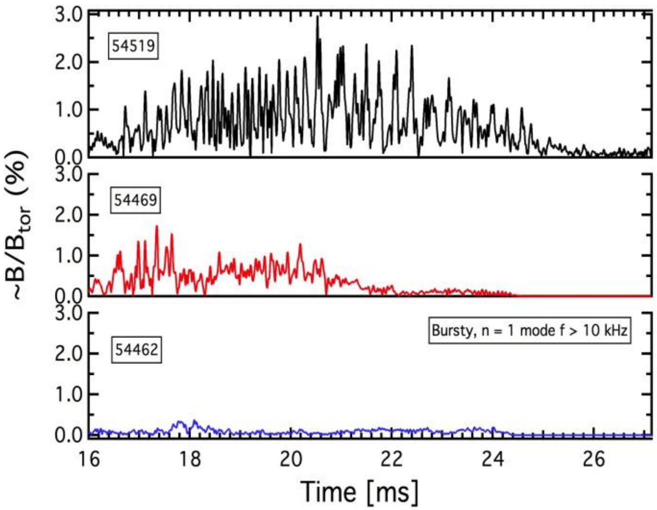
- MHD mode structure investigated
  - Toroidally distributed Mirnov coils
  - Radial $B_Z(R)$ from Hall probe
- Bursts have two main spectra
  - High-frequency 10–20 kHz n = 1
  - Low-frequency < 5 kHz n = 0
- n = 1 mode consistent with line tying
  - Radial localization to injectors
  - Toroidal asymmetry in $\tilde{b}/B$
- n = 0 mode localized to plasma
  - Inward radial motion

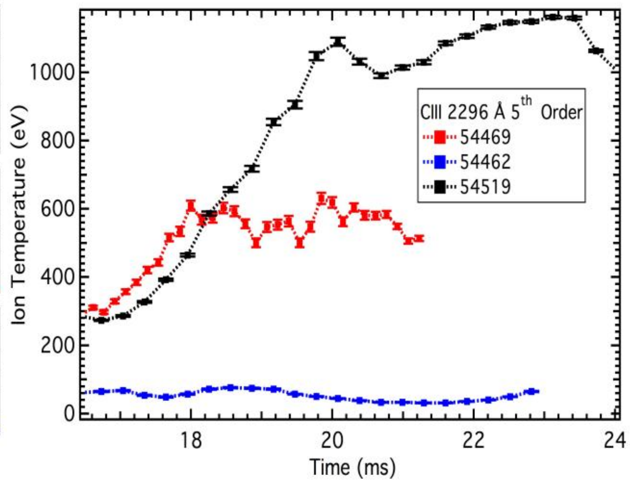


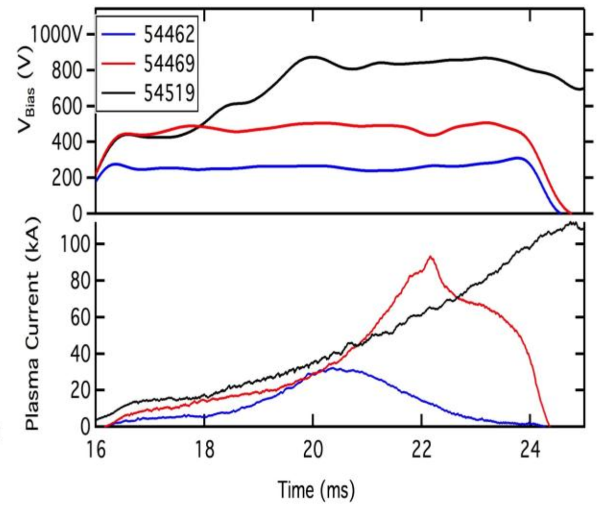


J.L. Barr, NP8.00061, this session

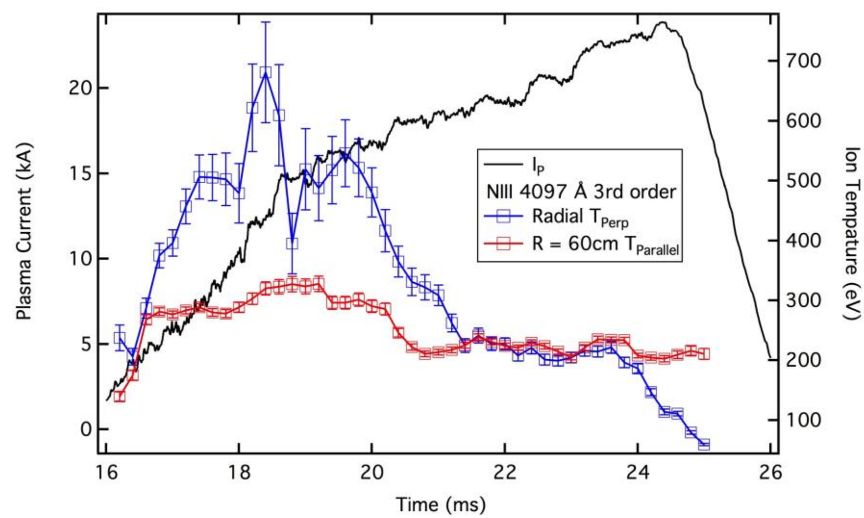
Strong, Anisotropic Ion Heating Observed During Helicity Injection







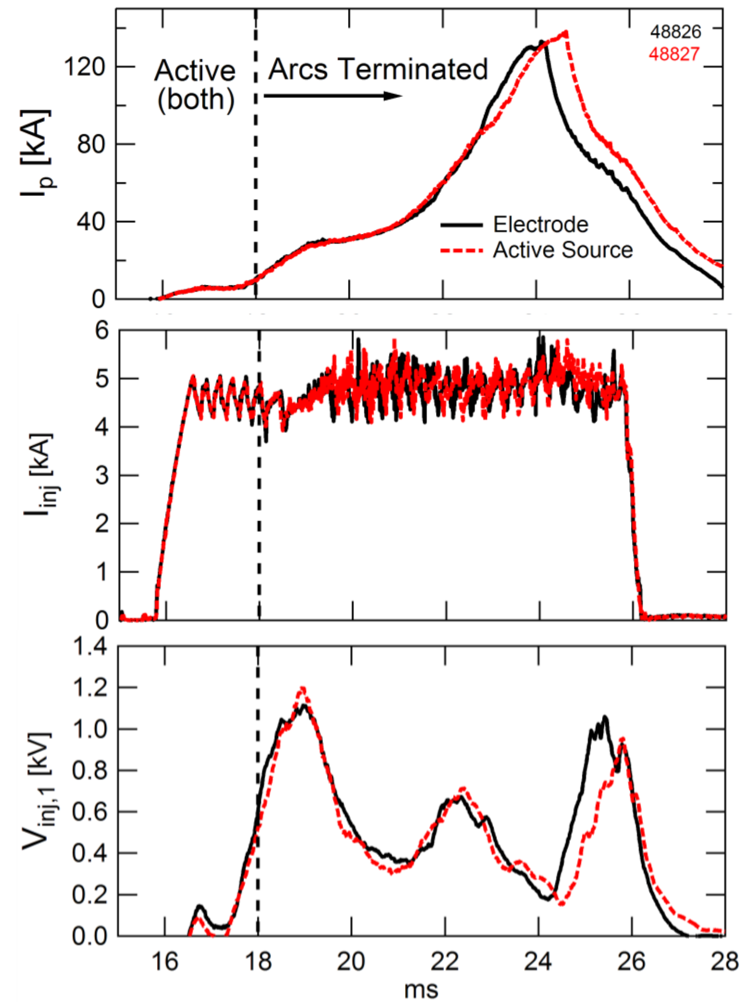
- Strong ion heating correlated with n = 1 burst activity on multiple line species
  - T_i correlated with both MHD $\tilde{b}/B$, V_{bias}
- Ion $T_\perp > T_\parallel$ observed
  - Similar phenomenon observed in MST during sawtooth crash



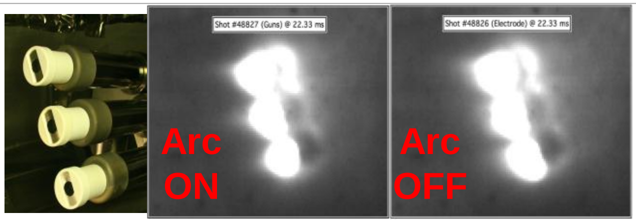
M.G. Burke, NP8.00063, this session

Exploring Passive Injectors to Increase Helicity Injection Rates

- Maximizing helicity input (current drive) requires large area electron emitters
- Two possible paths to large A_{inj}
  - Large area, active, high-density plasma sources
  - Passive electron emission through driven electrodes
- To mitigate cost/effort of producing electron current, simpler passive current sources without arc pursued
  - Form initial relaxed plasma with minimal active source
  - Continue I_p growth with passive electrode(s)
  - Critical feature is how to diffuse the current extracted from metallic electrode
- Initial concept tests with arc-passivated injector motivated further development
  - Arc current extinguished after formation of tokamak-like state
  - Gas fueling through injector continued
  - Achieved I_p is virtually the *same*, whether plasma arc or passive electrode provides charge carriers



"Slot" Mo faces with BN caps



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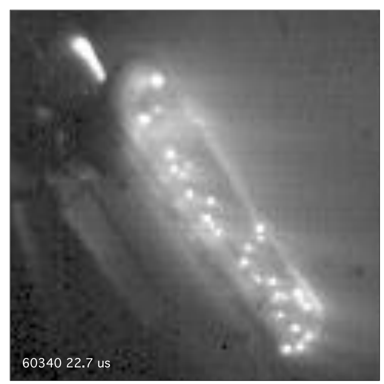
Large Electrode Deployed for Development of Large-Area Source Technology

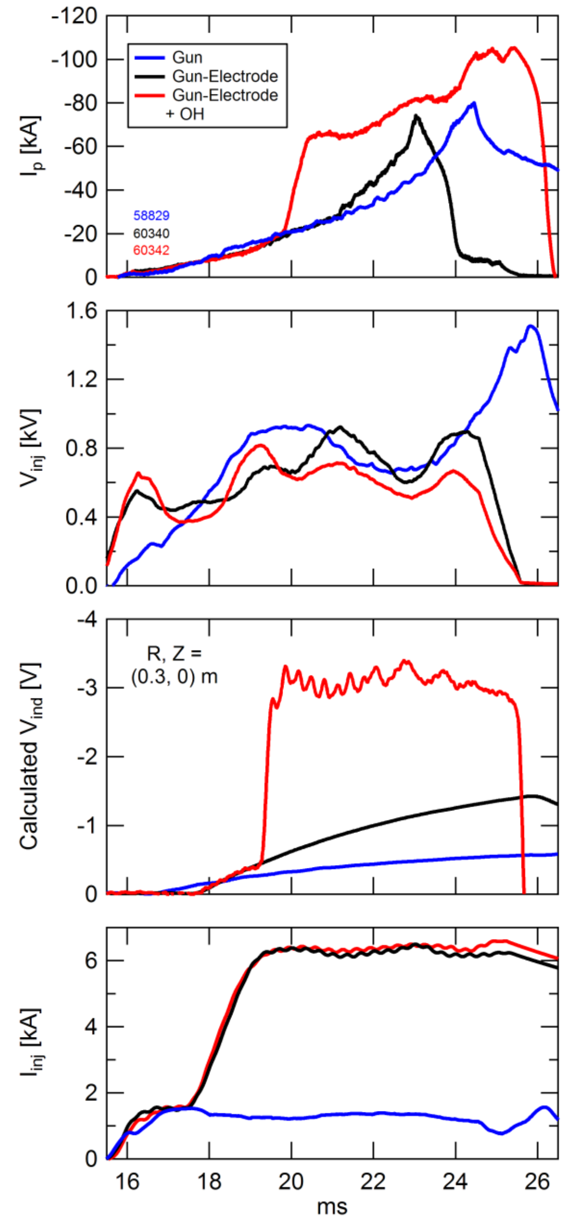
- Tests of current distribution on metallic electron emitter
  - Minimal active injector + large-area Mo electrode
    - No gas feed through electrode; expected to be dominated by cathode spot emission
  - Current in presence of plasma emitted from localized cathode spots
    - Similar to emission in vacuum; ~200-400 A per spot
    - For I_{inj} ~ 6kA, max effective area < 0.3 cm^2 ~ $A_{arc}/4$
  - Both single arc source and large passive electrode give similar I_p, well below the relaxation limit
    - Limit demonstrated with additional OH V_{loop}
  - Nonetheless, useful for development of insulator and arc-mitigation techniques

- Need integrated gas fueling to spread I_{arc} across large area
  - Tests with single arc source cap underway to confirm and optimize

Single arc source with integrated large-area passive electrode

Small cathode spots emit current from simple metallic electrode





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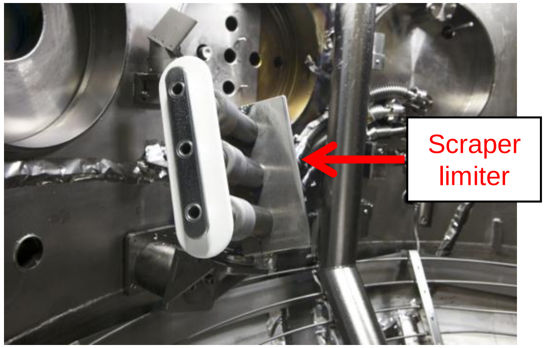
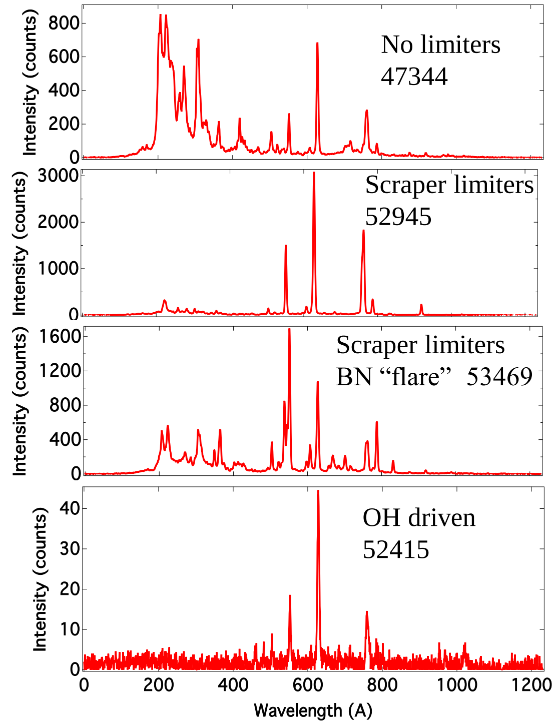
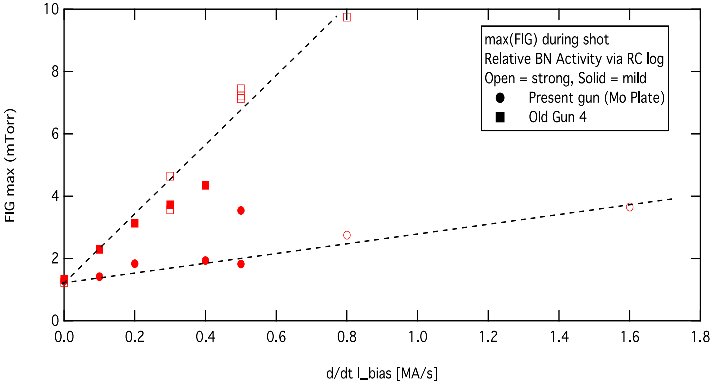
Electrode Systems Evolved to Mitigate Deleterious Plasma-Material Interactions

- N dominant impurity with unprotected gun assembly
  - Z_{eff} ~ 2.2 ± 0.8 during, ≤ 1.4 after injection
- Local scraper limiters reduce N from unprotected gun case
  - Also controls local edge N_e and injector impedance
  - O dominant impurity in OH and “well-behaved” helicity-driven plasmas
- Mo backing plate reduces BN interactions and undesired gas emission
  - Arc-backs to limiter still occur at times







Electrode with Mo Plate

Limiter Arc-back

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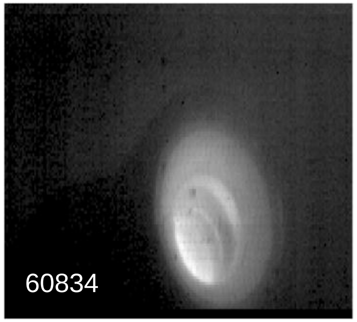
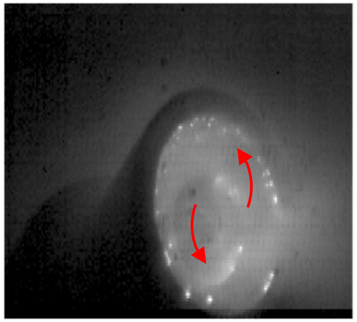
Gas-Fed, Large-Area Electrode May Mitigate Required Arc Source Systems

- Need to spread I_{inj} across large area
  - Small-area cathode spots extract current from bare metallic electrode → low A_{eff} → low HI rate
  - Cathode spot migration leads to BN interaction, unacceptable impurity generation
- New gas-fed electrode appears to operate in hollow cathode mode to provide required large-area source of charge carriers
  - Performs similarly to active source of equivalent area
  - Uniform emission with $J < 0.5$ kA/cm^2
    - Adequate for Pegasus, NSTX-U deployment
  - Beveled electrode surface controls spot migration

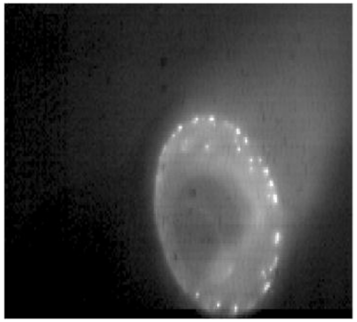
Perforated electrode (no plasma arc) with beveled edge



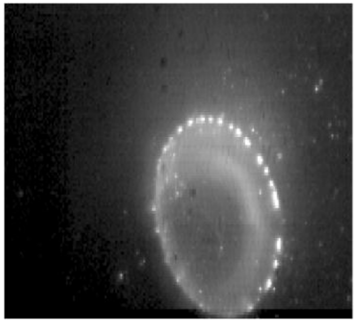
Active Phase



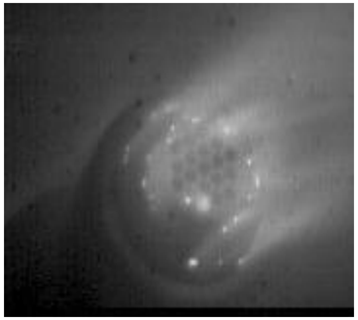
Spot Birth, Migration



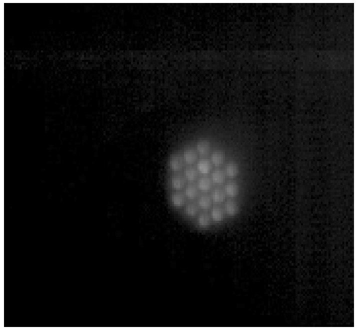
Heating BN Lip



BN Flare, Ejecta



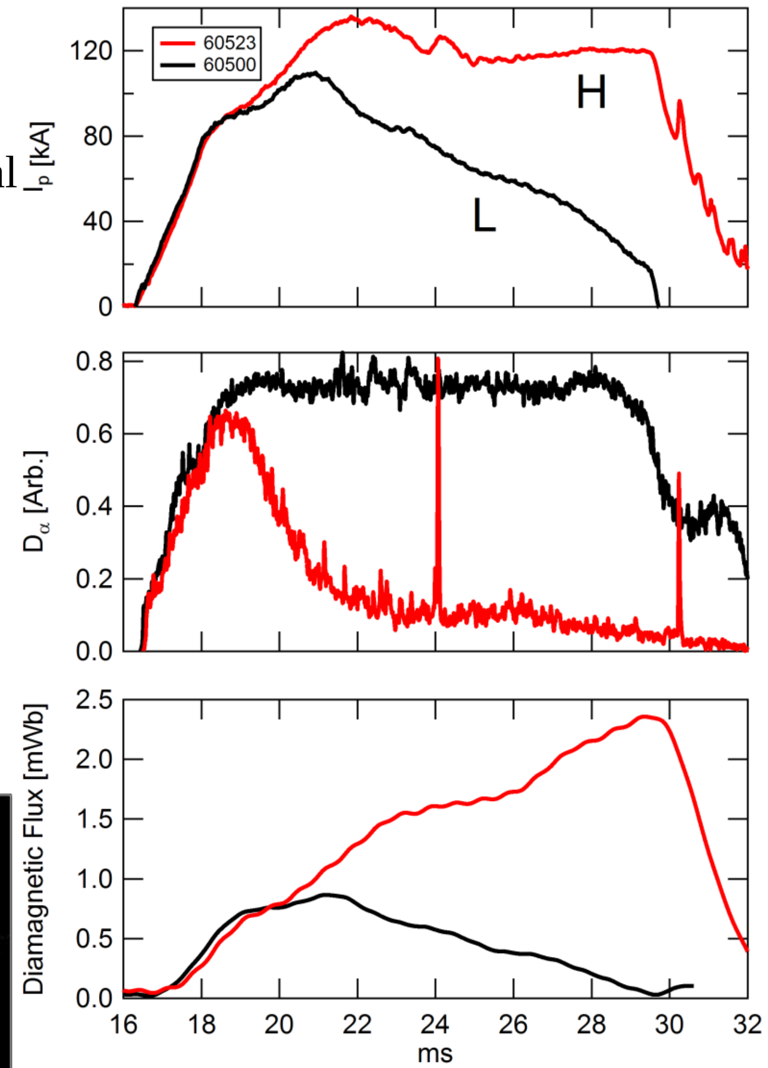
$I_{inj} = 2$ kA

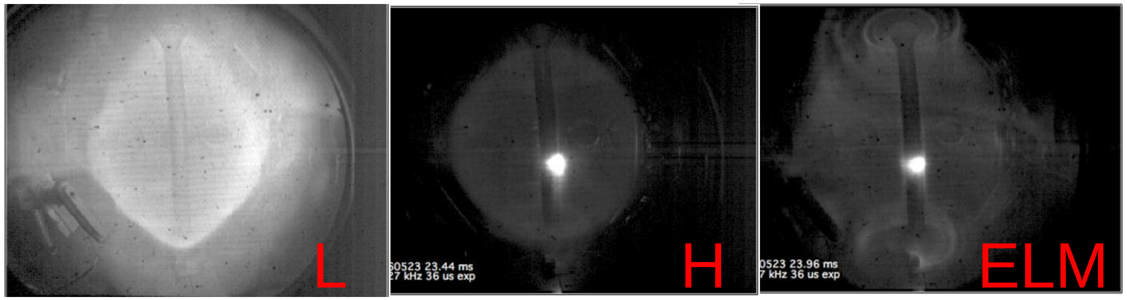


$I_{inj} = 0.5$ kA

H-mode Access: More Detailed ELM Tests and Possible Post-HI Current Drive Enhancement

- Ohmic H-mode achieved with new central column (high–field–side) fueling system
  - Low recycling via Ti gettering
  - Standard L-mode with strong 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



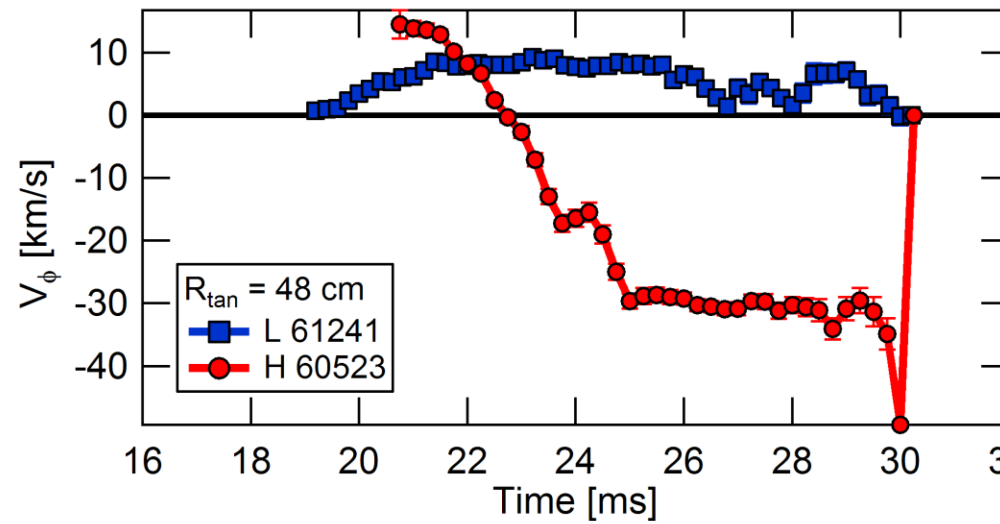


M.W. Bongard,54th APS-DPP, Providence RI, Oct. 2012

K.E. Thome, NP8.00064, this session

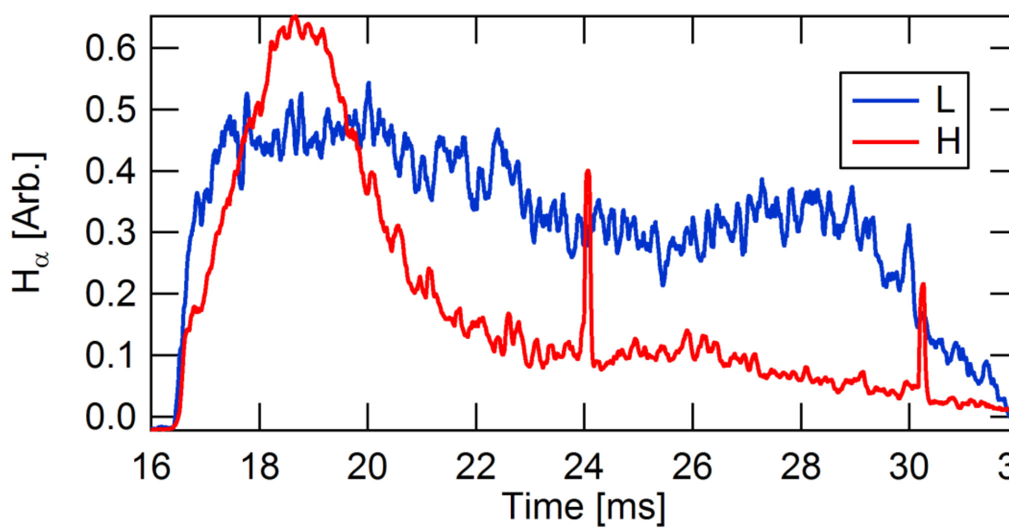
Toroidal Flow Reverses at L–H Transition

- Toroidal rotation measured via T_i spectrometry* in L, Ohmic H-mode discharges
  - No external momentum input



- L-mode flows are in the counter-current direction

- H-mode shots reverse rotation at L→H transition
  - Effect seen on MAST** and NSTX during HFS fueling



*: M.G. Burke, *et al.*, Rev. Sci. Instrum. **83**, 10D516 (2012)

: H. Meyer *et al.*, J. Phys.: Conf. Ser. **123, 012005 (2008)

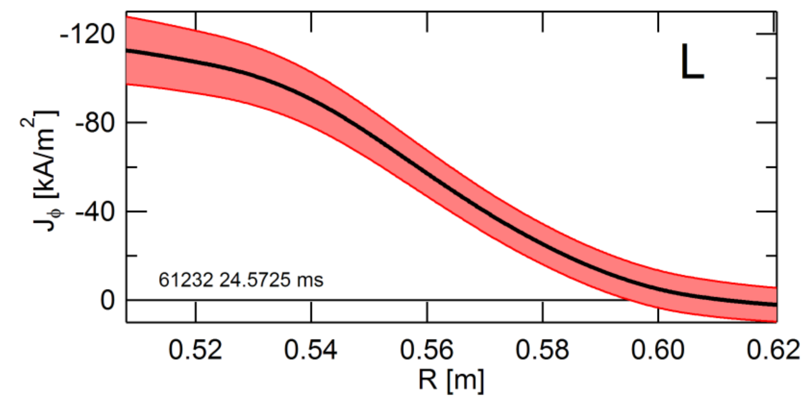
M.G. Burke, NP8.00063, this session

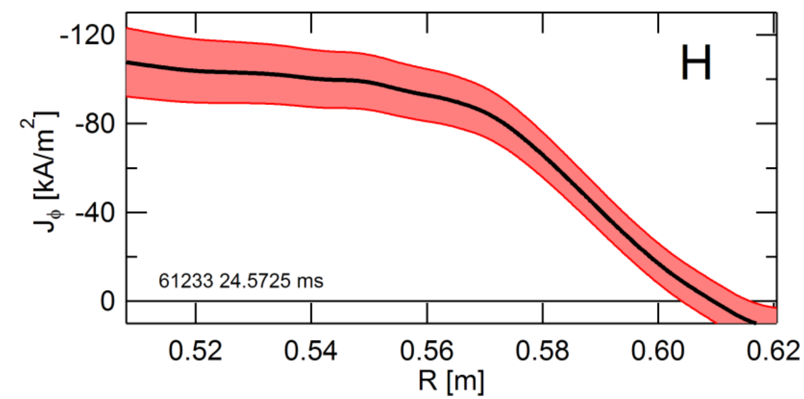
Edge Current Pedestal Observed in H-Mode

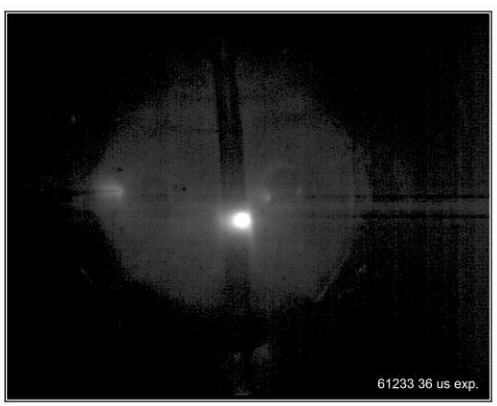
- Internal B measurements from Hall array* yield local $J_{\phi}(R,t)$**

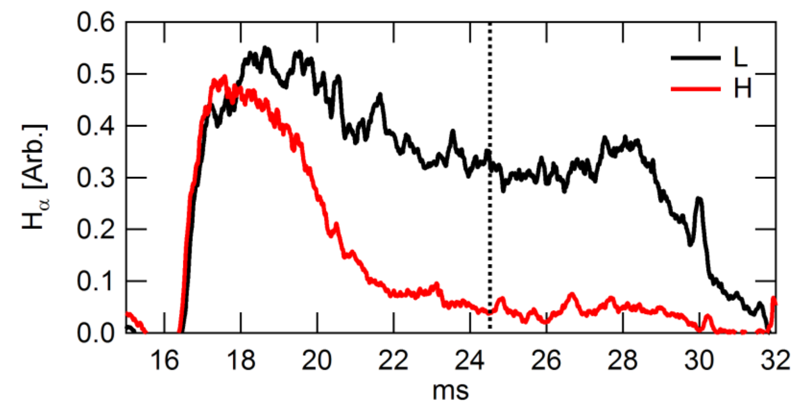
- Current gradient scale length significantly reduced in H-mode
  - $L \rightarrow H$: $6 \rightarrow 2$ cm

*: M.W. Bongard *et al.*, Rev. Sci. Instrum. **81**, 10E105 (2010)
: C.C. Petty *et al.*, Nucl. Fusion **42, 1124 (2002)



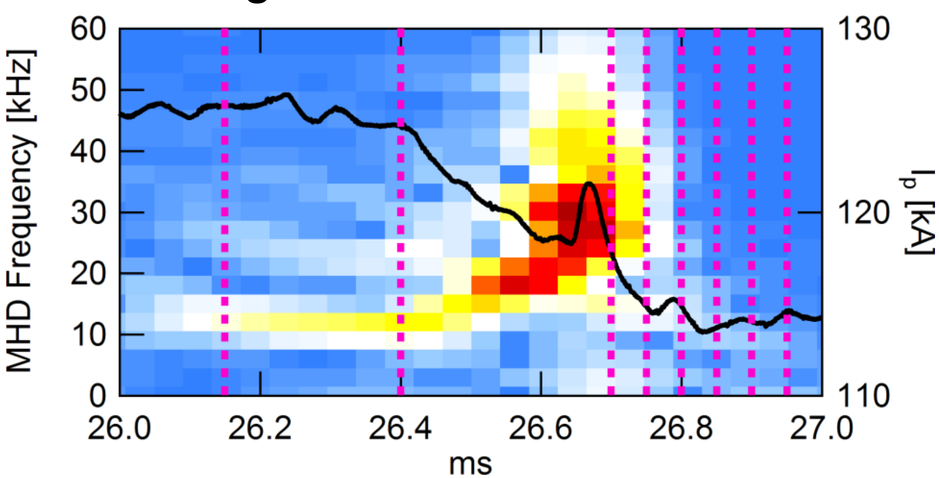




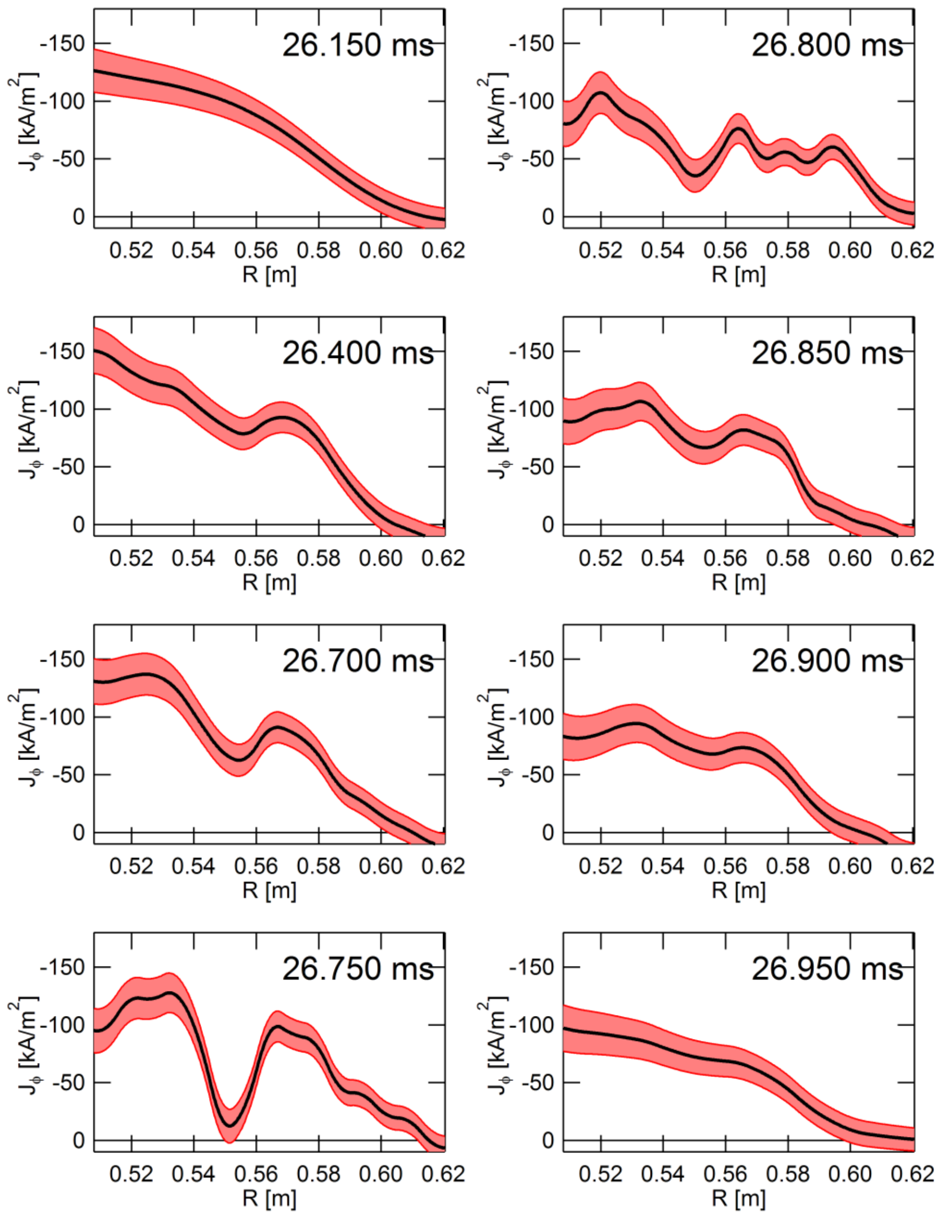


J_{edge} ELM Dynamics Observed

- J(R,t) profiles measured throughout single Type III ELM
  - n = 1 EM precursor
  - ~10% I_p loss, negligible $\Delta\Phi$
- Current-hole perturbation accompanies pedestal crash
  - Similar to peeling modes in Pegasus*
- Rapid recovery to H-mode pedestal following event

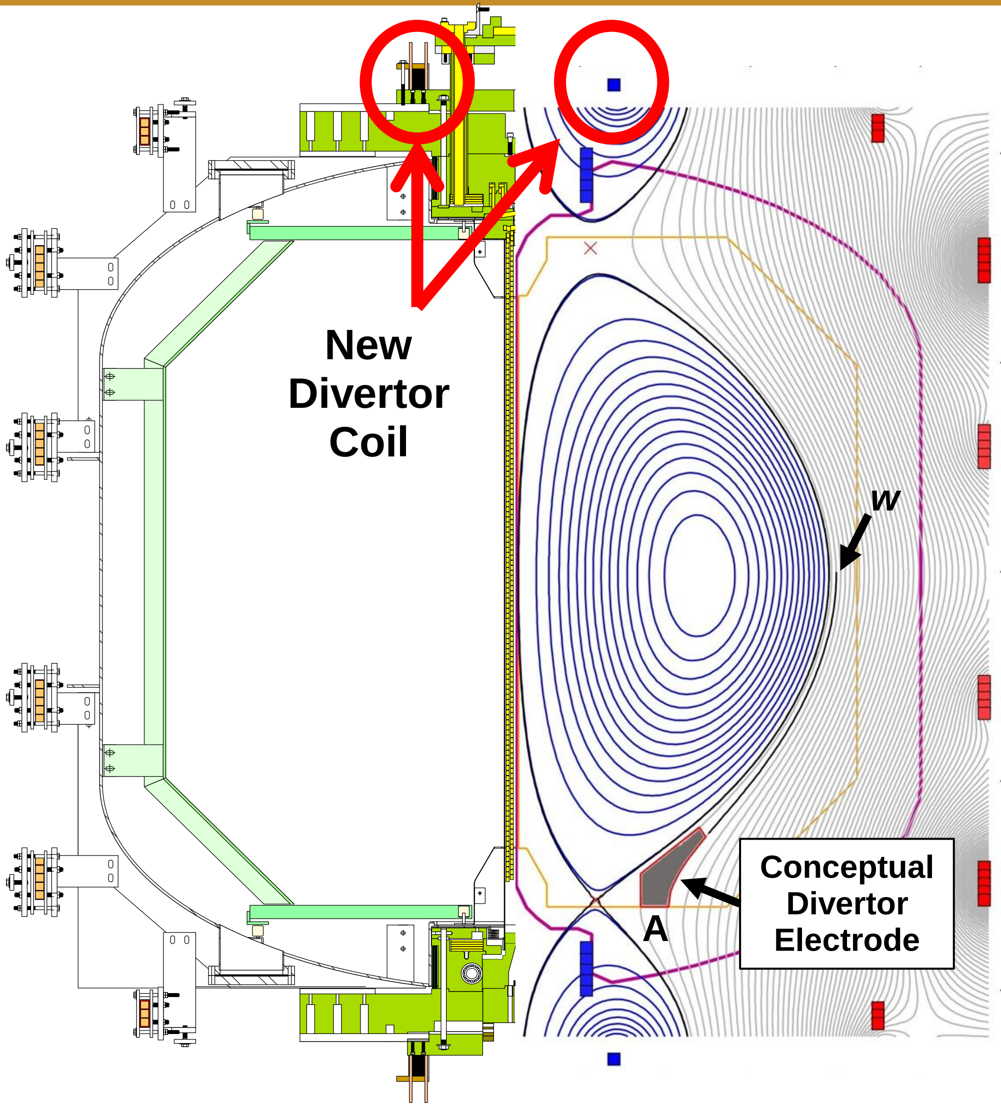


*: Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)



Recent Device Upgrades Support Expanded Helicity Injection, Edge Physics Studies

- Helicity Injection Systems
  - Piezoelectric injector fueling: *improved V_{bias} control*
  - Injector materials, geometry optimization: *reduced PMI*
  - Large-Area electrode injectors for high-I_p startup
- Power Supplies, Heating, Fueling
  - New helicity injection power: *2.2 kV, 14 kA supply*
  - Centerstack & Internal fueling: *H-mode access*
- Expanded PF Coil Set and Control
  - New PF coils, power systems: *radial position control*
- Diagnostic Deployment and Improvements
  - Multipoint Thomson Scattering
  - High-speed $T_i(R,t)$: *Anomalous reconnection heating*
- New divertor coils → *separatrix operation*
  - Flux expansion to optimize LHI startup
  - Exploit H-mode operating regime



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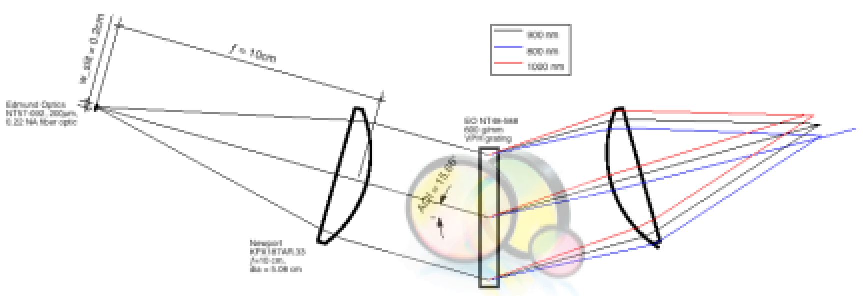
Thomson Scattering System Uses New Technologies for Visible Wavelength System

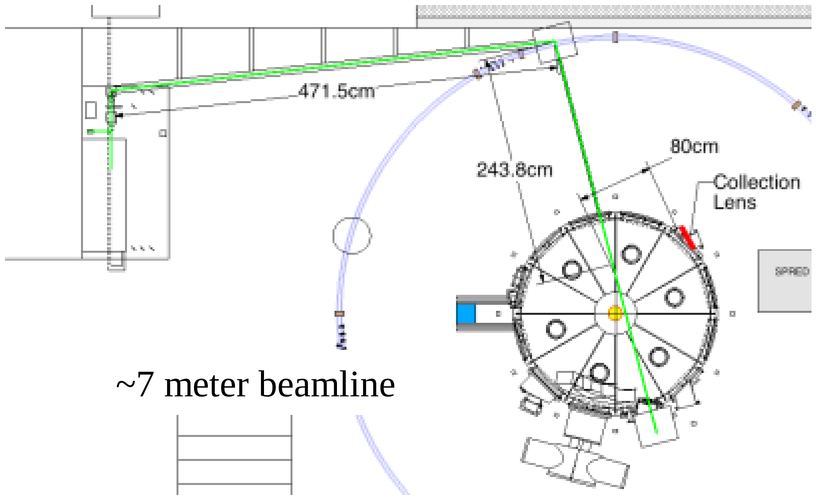
- Frequency doubled Nd:YAG laser provides ~10^{18} photons
- For typical Pegasus plasma, $n_{scattered}$ ~ 10^4 photons
- VPH grating efficiency >85% for l_{inc} = 532 - 632 nm
- Gen III image intensifiers ~50% efficient in visible region
- ~ 6 ns ICCD gating provides easy detector technology

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

N.L. Schoenbeck, NP8.00066



~7 meter beamline

D.J. Schlossberg, NP8.00065

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Summary: Significant Progress with Non-solenoidal Startup of ST, Extending Edge Physics Studies

- Increasing understanding of HI physics to project towards MA-class non-solenoidal startup in future devices
  - Null formation, $J_{edge}(R,t)$ agree with expectations
  - Reconnection-driven ion heating and global plasma evolution
  - Sheath and magnetic current limits dominate injector impedance
    - *Further tests needed to understand apparent density scaling*

- Developing edge current sources for helicity injection
  - Large area with narrow radial current channel
    - *Flux expansion with new divertor system*
  - Gas-fed "hollow cathode" electrodes may support drive to high I_p
  - Requires PMI understanding and mitigation

- H-mode access supports pursuit of high-β regimes, edge physics
  - Central column fueling → Ohmic H-mode
  - Detailed $J_{edge}(R,t)$ evolution during ELMs

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