Feasibility Study for Local Helicity Injection Startup in the NSTX Upgrade (NSTX-U) Device

A.J. Redd, R.J. Fonck, M.W. Bongard

Department of Engineering Physics

University of Wisconsin-Madison, Madison, WI USA

S.J. Jardin

Princeton Plasma Physics Laboratory

Princeton, NJ USA

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PEGASUS
Toroidal Experiment

Motivation: MA-Class Nonsolenoidal Startup on NSTX-U Using Local Helicity Injection

- Local Helicity Injection is a high-current tokamak startup technique
  - Using LHI and outer-PF induction on Pegasus, $I_p \leq 0.17$ MA
  - Using LHI-dominated startup on Pegasus, $I_p \leq 0.08$ MA

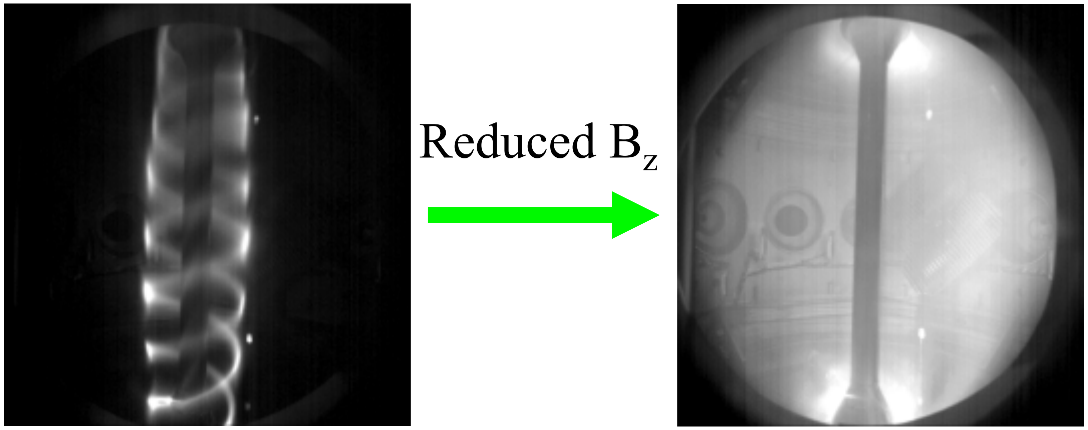
- Goal is projection to a MA-class startup system for NSTX-U

- Pre-conceptual design of NSTX-U injector evolving
  - Injector structure incorporates both an active plasma source (for startup) and a shaped electrode (to maximize the driven plasma current)
  - Injector materials and design consistent with deployment in the scrape-off region

- Validating computational tools for exploring operating scenarios
  - Validation through modeling ultralow aspect-ratio Pegasus discharges (including neoclassical effects, confinement/dissipation in LHI-driven plasmas, and quantifying the LHI current drive)

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

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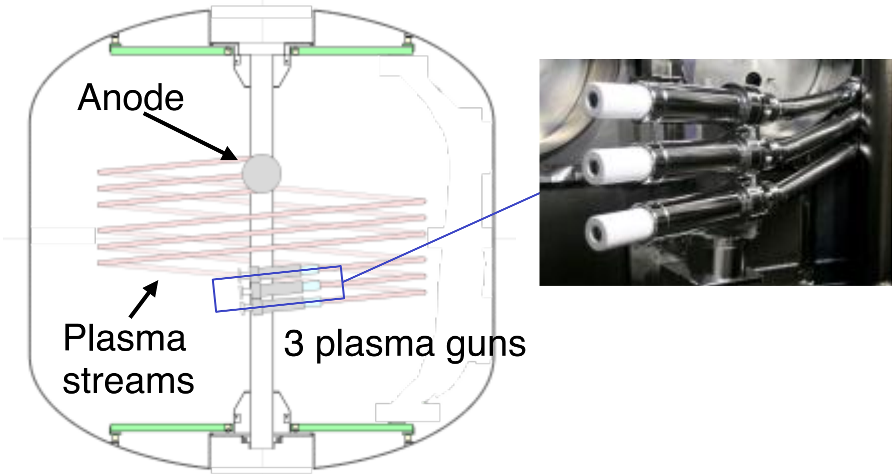
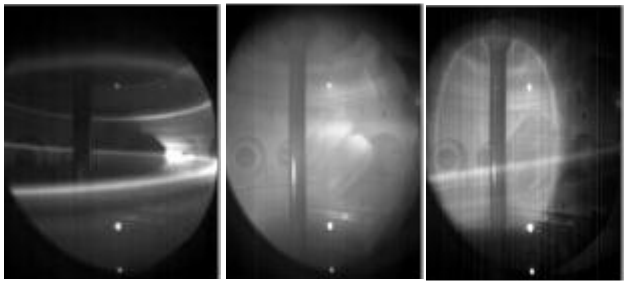
OUTER LFS INJECTION ADDS POLOIDAL INDUCTION TO HELICITY INJECTION

- Flexible geometry for injector locations
  - Outer midplane allows “port-plug” installation
- PF null via injection into helical (TF + PF) field; followed by relaxation to tokamak-like state
  - Rapid inward expansion and growth in I_p at low A
- Poloidal field induction adds to current growth



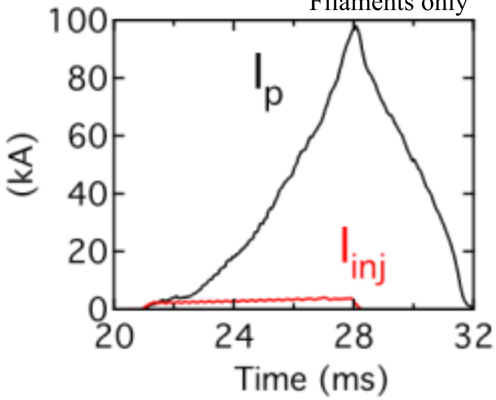
PEGASUS shot #40458: two midplane guns, outer-PF ramp



I_p=2-3 kA
Filaments only

I_p=42 kA
Driven plasma

I_p=37 kA
Guns off
Decaying



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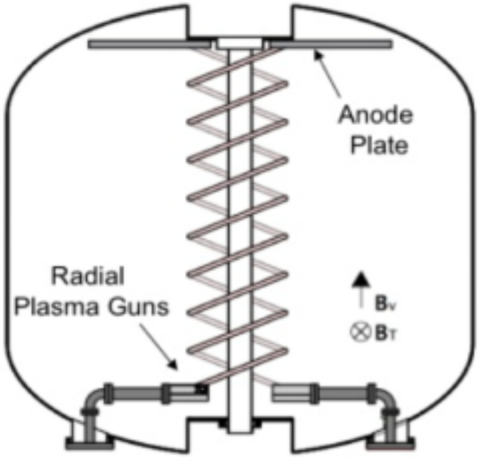
Inboard HFS Injection in Divertor Region Maximizes Helicity Input Rate

- HFS injection near centerstack maximizes helicity input rate
- Reduced plasma position control requirements
  - Static fields support easy control of position

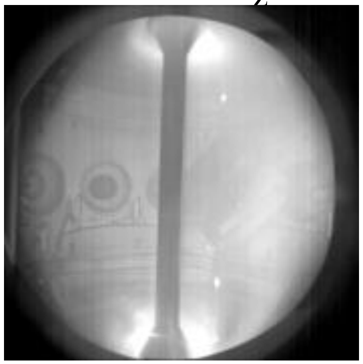
Inboard Divertor Gun Injection



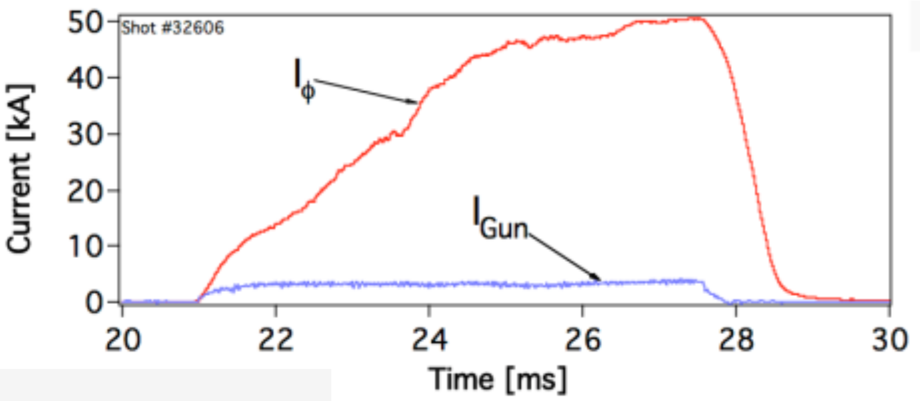
R_{gun} = 16 cm, Z_{gun} = - 75 cm

Increased I_{inj}
Reduced B_z

Current filaments



Relaxed tokamak



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Parameters of NSTX-U Startup System

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

Helicity balance in a tokamak geometry:

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

- *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:

$$\begin{gathered}\nabla\times B = \mu_0 J = \lambda B\\ \lambda_p \le \lambda_{edge}\end{gathered} \quad \Rightarrow \quad \frac{\mu_0 I_p}{\Psi_T} \le \frac{\mu_0 I_{inj}}{2\pi R_{inj} w B_{\theta,inj}} \quad \Rightarrow \quad I_p \le f(\epsilon,\delta,\kappa)\sqrt{\frac{\kappa A_p I_{\mathrm{TF}} I_{\mathrm{inj}}}{2\pi R_0 w}}$$

Maximizing the peak I_p requires:

- High helicity injection rate: **High A_{inj} and V_{inj}**
- High Taylor limit: **High I_{inj} and Low *w***

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)

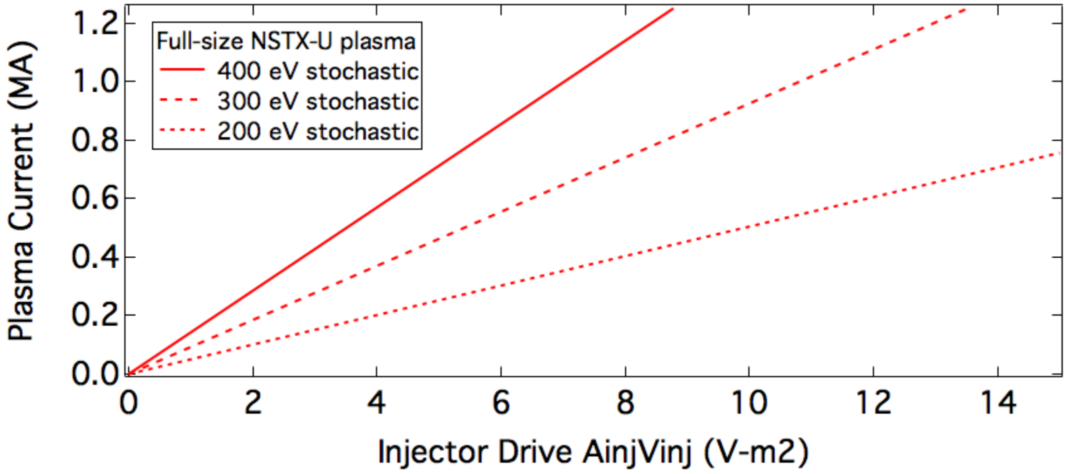
Goals for NSTX-U startup system, and constraints from Pegasus studies

- Goals for NSTX-U Local Helicity Injection startup system:
  - ~1 MA startup plasma, appropriate for OH, NBI, and/or RF sustainment
  - Well-defined startup procedures and plasma development scenarios
  - Unobtrusive and retractable injection hardware

- Parameters and constraints from Pegasus LHI studies:
  - Arc gun is needed to provide initial plasma
  - Formation of the poloidal field null, and relaxation to the turbulent tokamak-like state, can be sensitive to outboard injector location
  - Current drive from helicity injection must dominate over induction from ramping the outboard poloidal fields
  - Passive electrodes may be the optimum tool for driving the tokamak plasma to high current and large cross-sectional area
  - Local limiters mitigate impurities (Pegasus $Z_{\mathrm{eff}} \leq 2$ during HI; ~1 in OH)

Detailed projections to NSTX-U startup depend on dissipation/confinement

- Injected current density determined by Taylor limit
  - For example, 1 MA startup at full TF ➔ $I_{inj} \approx 3$ kA for $w \approx 25$ mm
- Injector cross-section determination more complicated
  - Driving voltage must be consistent with injector impedance
  - Startup performance strongly affected by nature of energy confinement (stochastic confinement requires a large injector cross-section, but more optimistic models imply much smaller necessary injector area)
  - Higher V_{inj} allows a smaller electrode for the same performance



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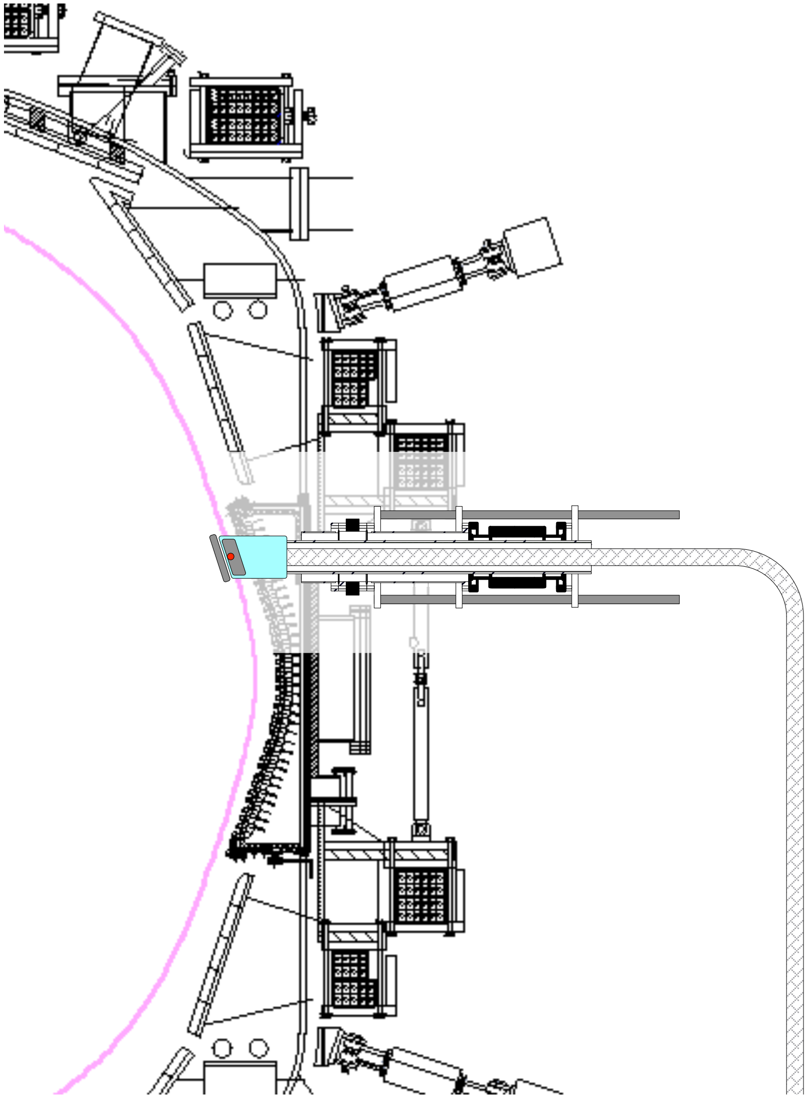
Pre-conceptual design for the NSTX-U startup system

- Gun/electrode injector:
  - Single port access for injector
  - Retractable behind gate valve
  - Active gun and large electrode
  - Piezoelectric gas control
  - Local limiter structure

- Power supplies:
  - Bias supply comparable to Pegasus (1-2 kV; 15 kA; Δt ~ 1 ms)
  - Arc provided by simple PFN supply



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Plasma Arc Sources

Compact Plasma Arc Sources Provide Dense Plasma for Electron Current Extraction

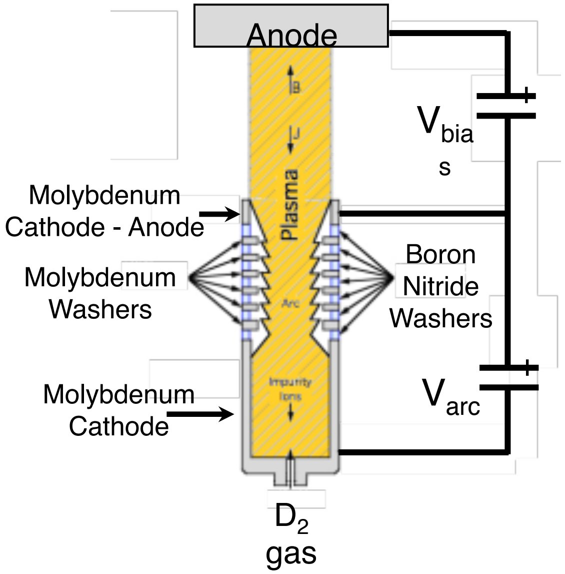
- Plasma arc(s) biased relative to anode:
  - Helicity injection rate:

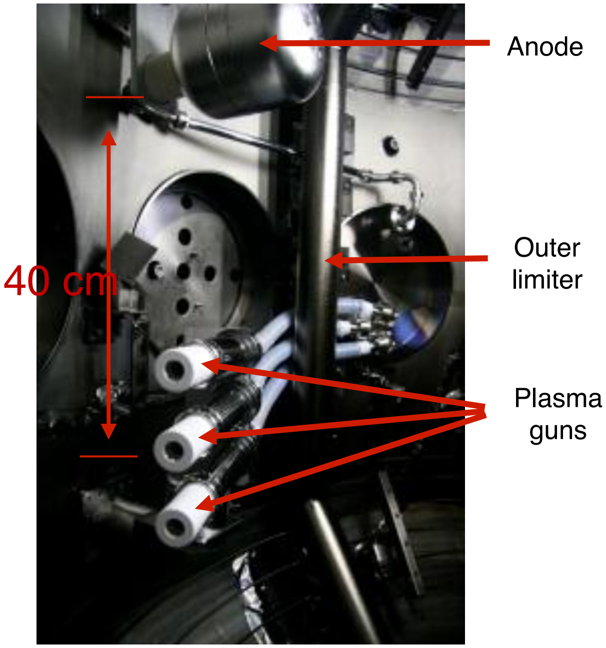
$$\dot{K}_{inj} = 2V_{inj}B_N A_{inj}$$

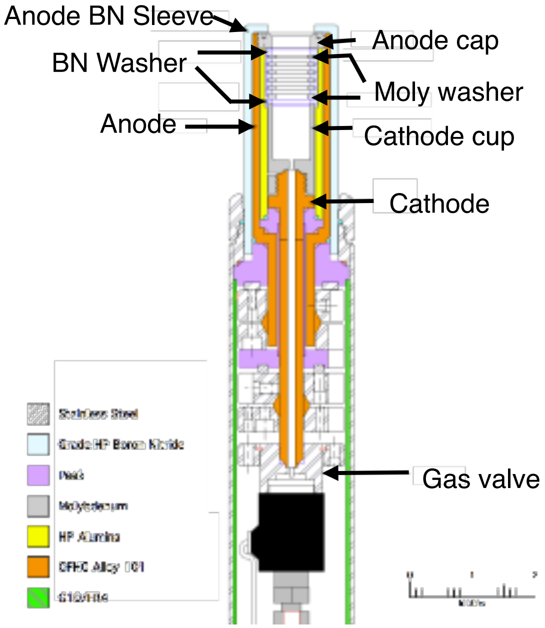
V_{inj} - injector voltage

B_N - normal B field at gun aperture

A_{inj} - injector area







- Arc plasma fully ionized
  - $N_e \sim 10^{20}\ m^{-3}$
  - $T_e \sim 10$ eV
  - Dia = 1.6 cm
  - $I_{arc} \sim 2$ kA

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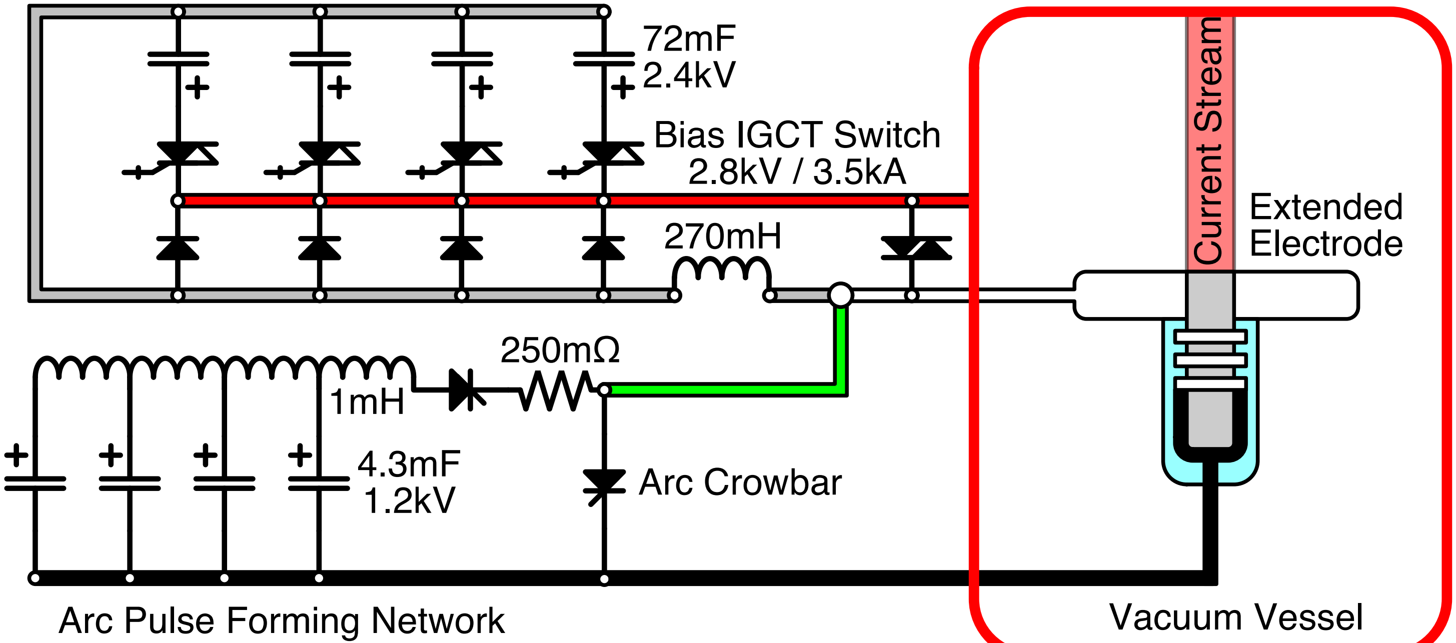
1 Fiksel, G, et. al., Plasma Sources Sci. & Tech. **5** (1996) 78.

Robust Switching Power Supplies Deployed for Arc & Injection

- Plasma Arc uses simple Pulse Forming Network
  - Once arc is established: I_{arc} = 1-2 kA @ V_{arc} = 100-200 V
  - SCR terminates arc on demand

- Injection (Bias) circuit uses 4 IGCT switches in parallel
  - Total: $I_{inj} \leq 14$ kA @ $V_{inj} \leq 2.2$ kV
  - Preprogrammed current control via stabilized PWM feedback controller
  - Series inductance stabilized, sometimes with parallel stabilizing capacitor and ballast resistor



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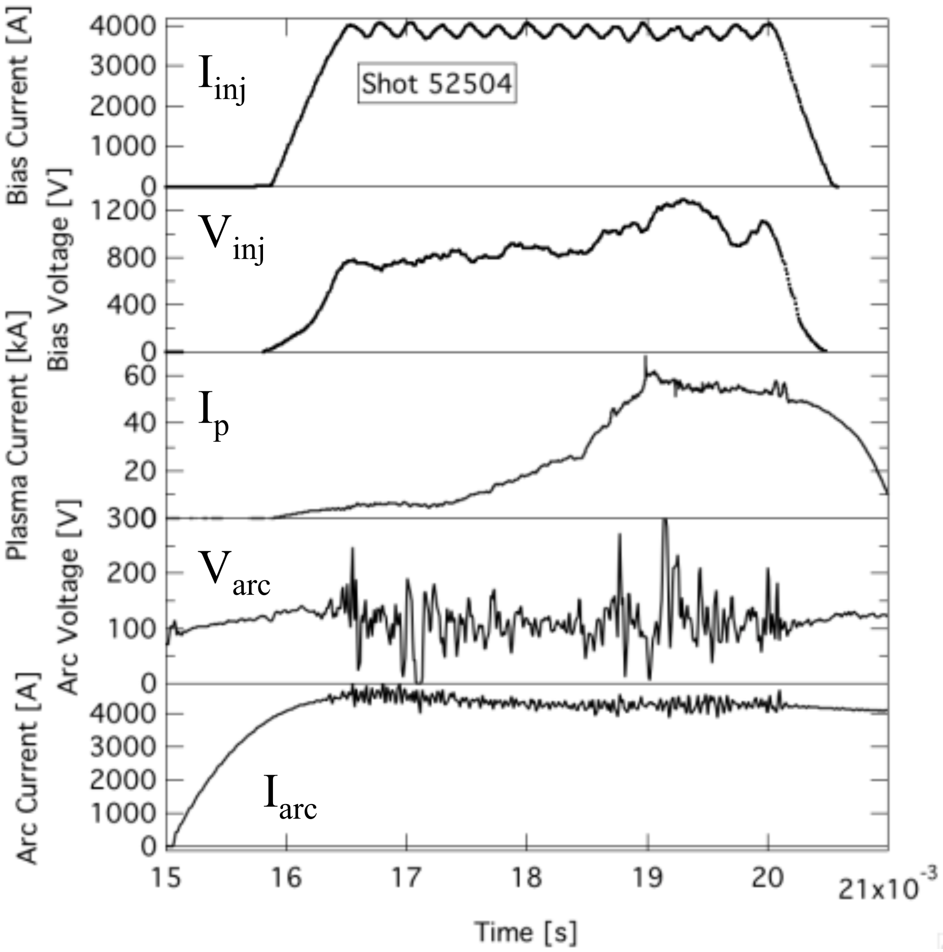
Power Systems Provides Routine Programmable Injected Current and Helicity

- Injection circuit provides current feedback control
  - Impedance varies with resulting tokamak plasma so that V_{inj} varies through shot
  - Future upgrade: go to voltage feedback control
    - Active control of helicity injection rate

- Arc circuit fully ionizes injected gas
  - $I_{arc} \sim$ 2-4 kA @ $V_{arc} \sim$ 150 V
  - With 1.6 cm diameter arc chamber, routine operation at 2 kA, with reduced lifetime at 4 kA

- Shot sequence
  - Inject gas flow into arc chamber
  - Strike Arc current; allow ~ 1ms to establish arc
  - Extract I_{inj}; usually with $I_{inj} < I_{arc}$



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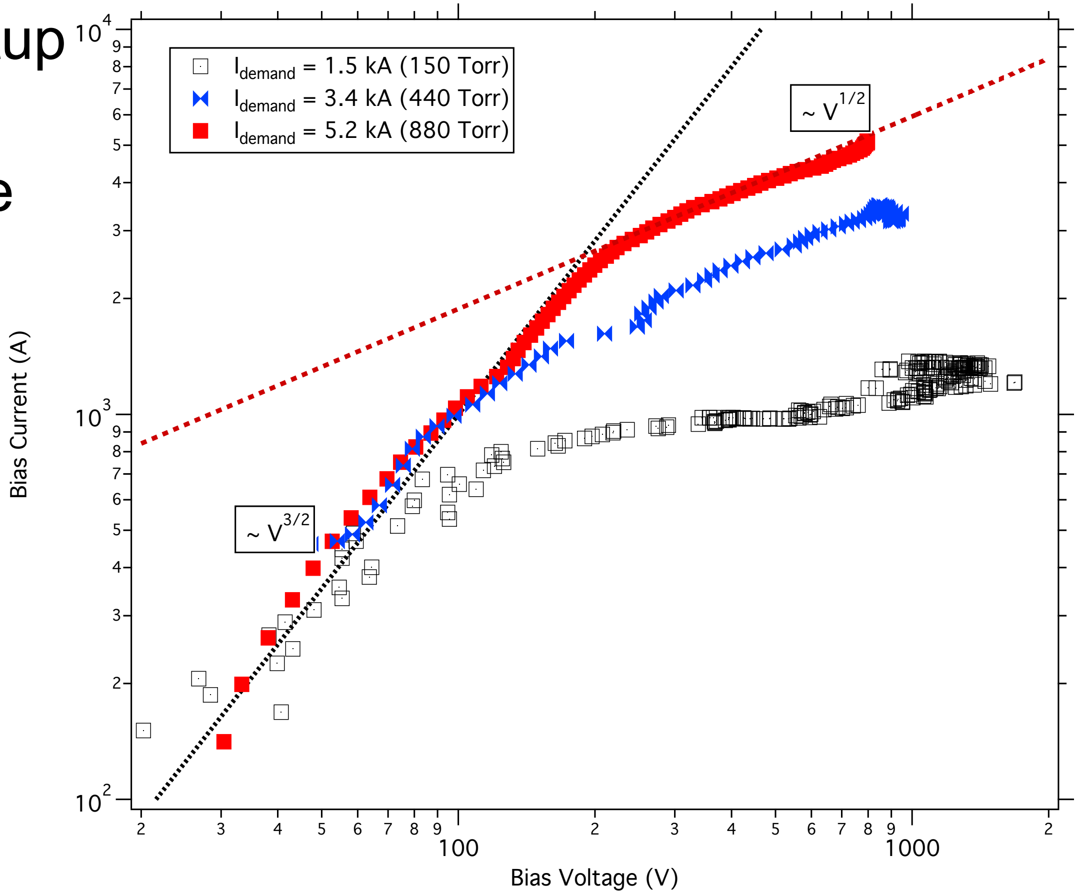
Arc Source Impedance

Helicity Injection Process Governed by Space Charge and Magnetic Current Limits

- Arc source I-V characteristics obtained during plasma startup

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

- At high $I_{inj} > I_A$ and $V_{inj} > 10\ kT_e/e$, the Alfven-Lawson magnetic current limit dominates
  - $I_{inj} \sim V^{1/2}$
  - Possible that sheath expansion also contributes here



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

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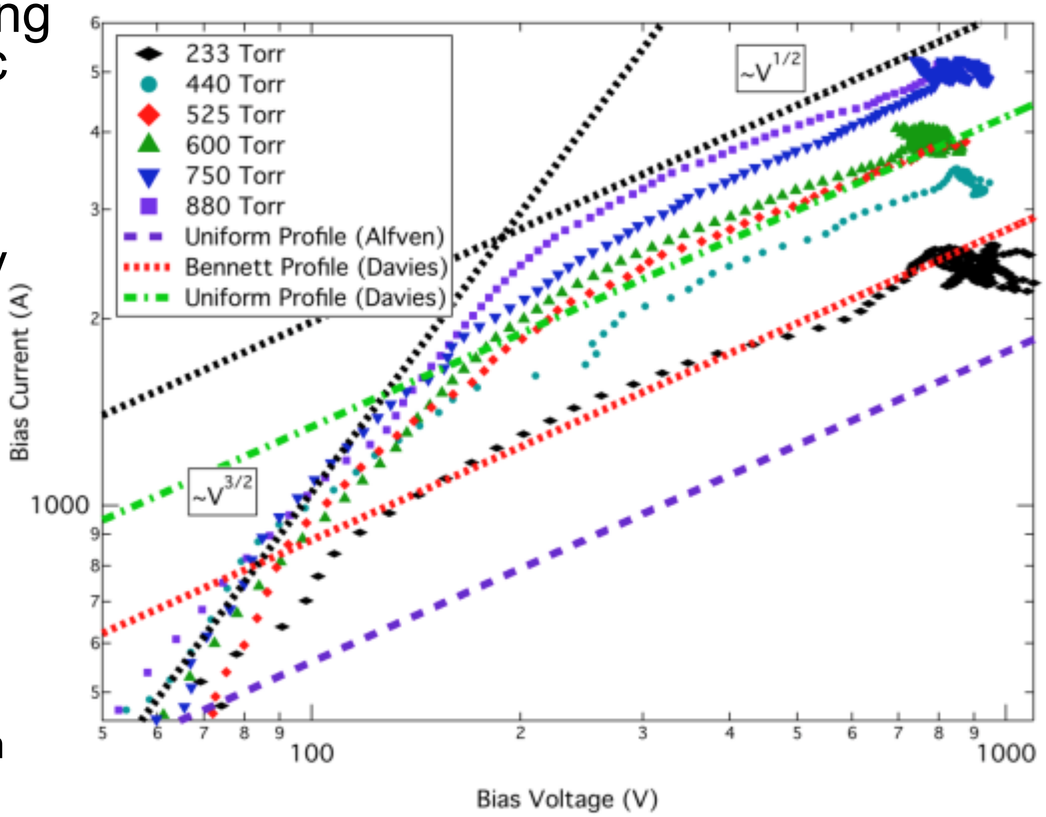
Density Scaling in Injector Impedance May Reflect e^- Beam Profiles

- I-V characteristics at varied fueling rates suggests a scaling with arc density



- Density variation may reflect changes in beam current density profile
  - Alfven: uniform j with backward particle flow

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

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

$$I^e_{uniform} = 4.0\frac{4\pi m_e v_e}{e\mu_o} = 134\sqrt{V_{inj}} \qquad I^e_{Bennett} = 2.59\frac{4\pi m_e v_e}{e\mu_o} = 88\sqrt{V_{inj}}$$

- Data shows inferred trends but detailed measurements needed

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Large Area Electrode Development/Tests

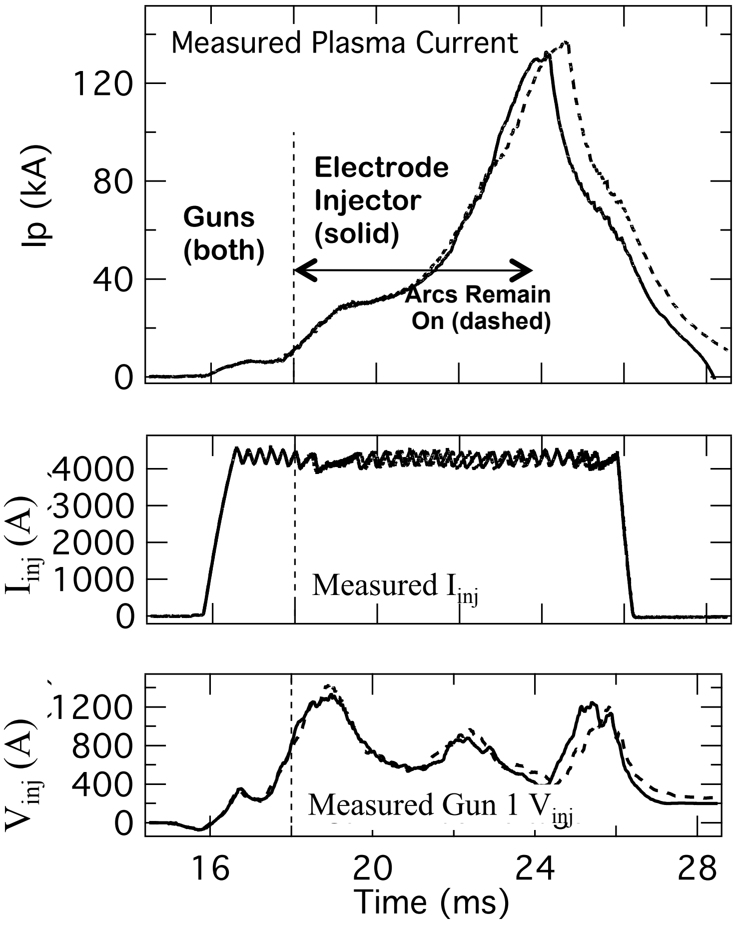
Exploring Passive Injectors to Increase Helicity Injection Rates

- Maximizing Helicity (i.e., current drive) requires large area electron emitters

- Two possible paths
  - Large area active high-density plasma sources
  - Passive electron emission through driven electrodes

- To mitigate the effort in producing electron current, it is worthwhile to explore simple passive (i.e., no plasma arc) current sources
  - Form initial tokamak-like state with minimal active arc gun
  - Increase I_p with passive electrodes.
  - Critical feature is how to diffuse the current extracted from metallic electrode

- First tests were promising
  - Arc current cut off after relaxation and formation of tokamak-like state
  - Gas fueling through chamber continued
  - I_p rise is virtually the *same,* whether arc discharge or passive electrode provide the charge carriers
  - Suggests continuing development of electrode emitters



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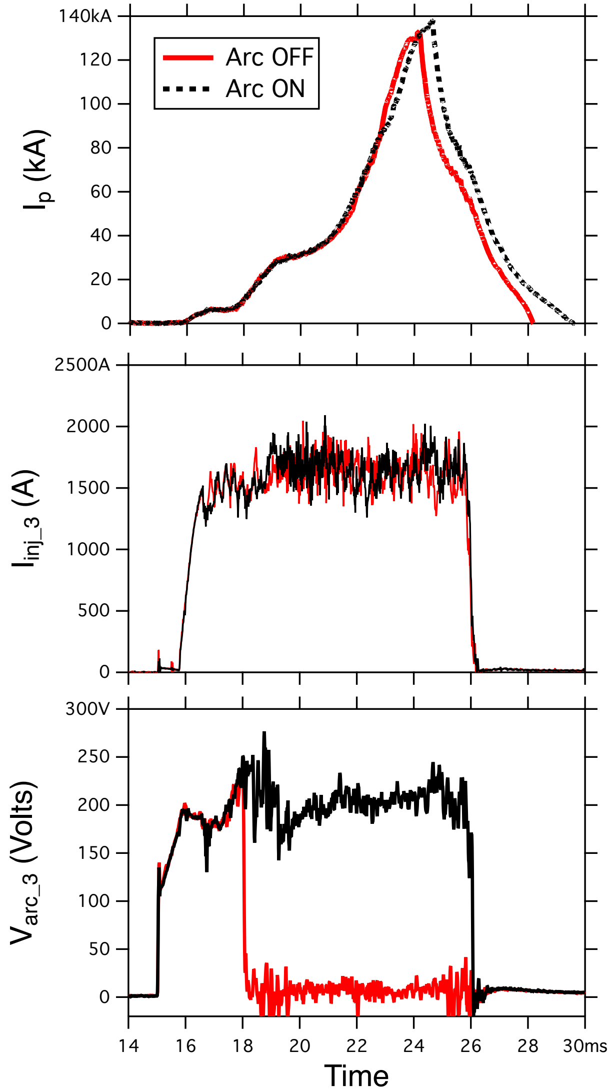
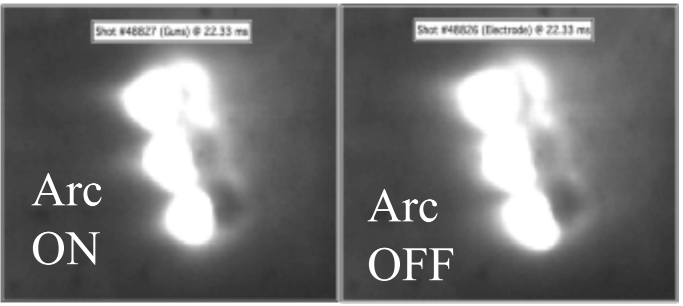
Identical Discharge Evolution Seen with Plasma Arc Turned Off

- Arc crowbarred out after tokamak discharge established to transition from arc plasma source to driven electrode system
  - Keep electrode widths narrow to maintain Taylor limit
  - Some limitations from PMI interactions at Mo/BN interface

- Demonstrated transition from active gun drive to passive electrode drive
  - Same extracted current whether arc is on or off, with same gas flow
  - Driven I_p virtually identical
  - Camera (low-res) images suggest similar current source regions



“Slot” Mo faces with BN caps



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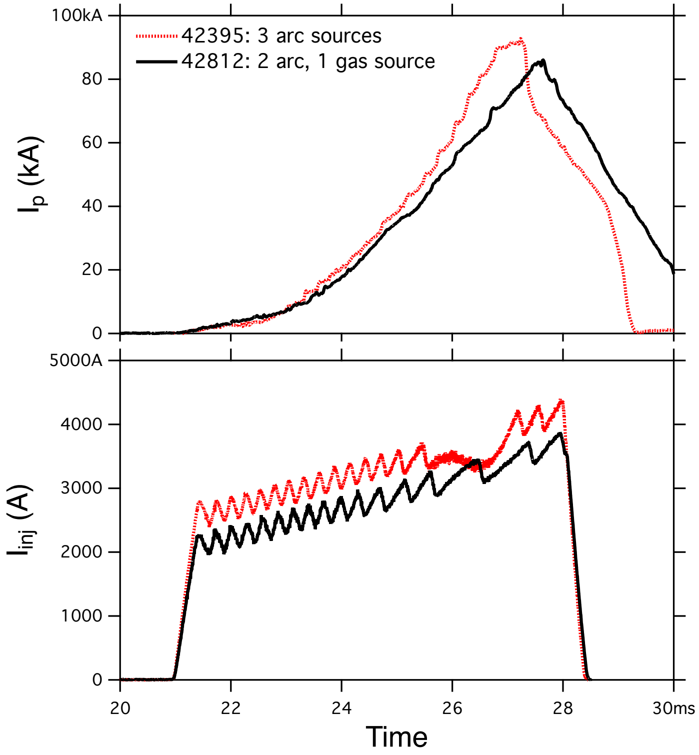
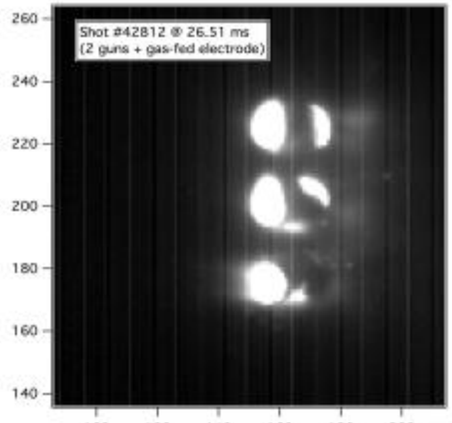
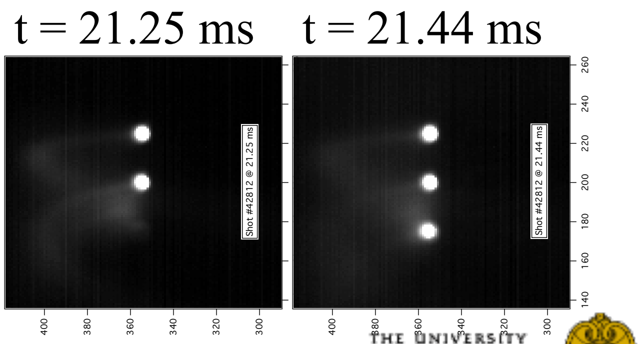
Electrode with Integrated Gas Feed Behaves Similarly to Arc Source

- Simple gas-fed electrode replaced a single arc source to test electrode concept
  - Passive electrode turns on spontaneously after 2 arc sources establish discharge
  - Discharge evolution to similar 3-arc source plasma
    - Suggests effective area of ~ size of gas source region
- Current ~ equally shared amongst 3 injectors






t = 21.25 ms

t = 21.44 ms

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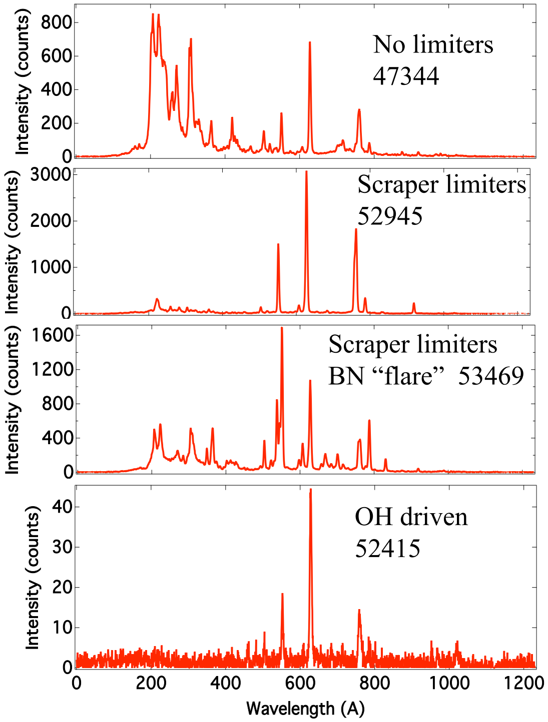
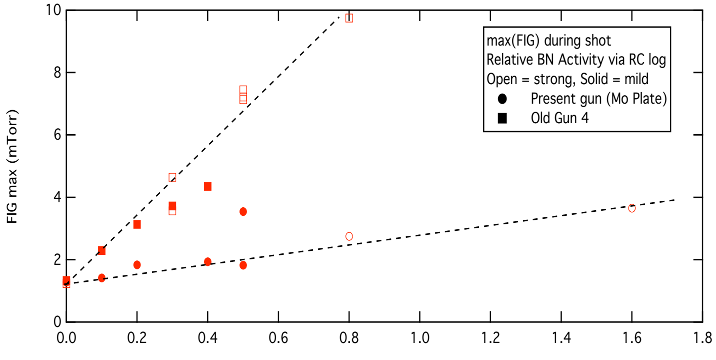
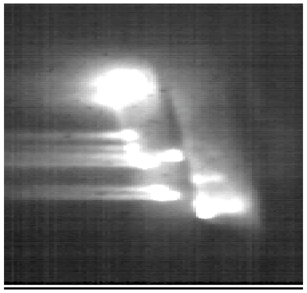
Electrode Systems Evolved to Mitigate Deleterious Plasma-Material Interactions

- 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







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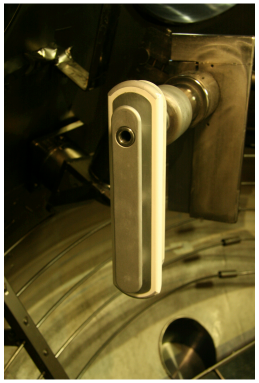
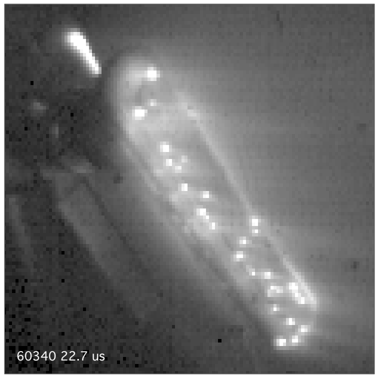
Gas-Fed, Large-Area Electrode May Mitigate Requirement for Arc Sources

- Need to spread I_{inj} across large area
  - Effective area of metallic electrode = small → low HI rate

Single arc source with integrated large-area passive electrode



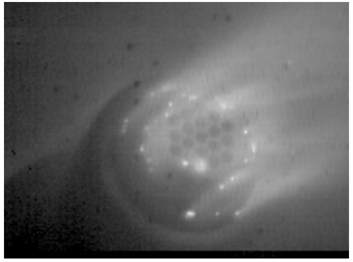
Small cathode spots emit current from simple metallic electrode



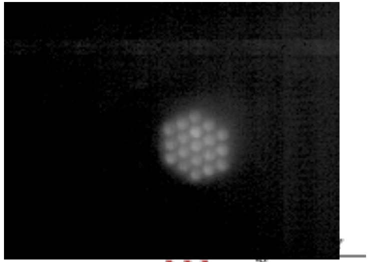
- Gas-fed hollow cathode electrode to provide required large-area source of charge carriers
  - In edge of tokamak plasma

Perforated electrode (no plasma arc) with beveled edge to avoid electrode-BN arcing

$I_{inj} = 2$ kA



$I_{inj} = 0.5$ kA



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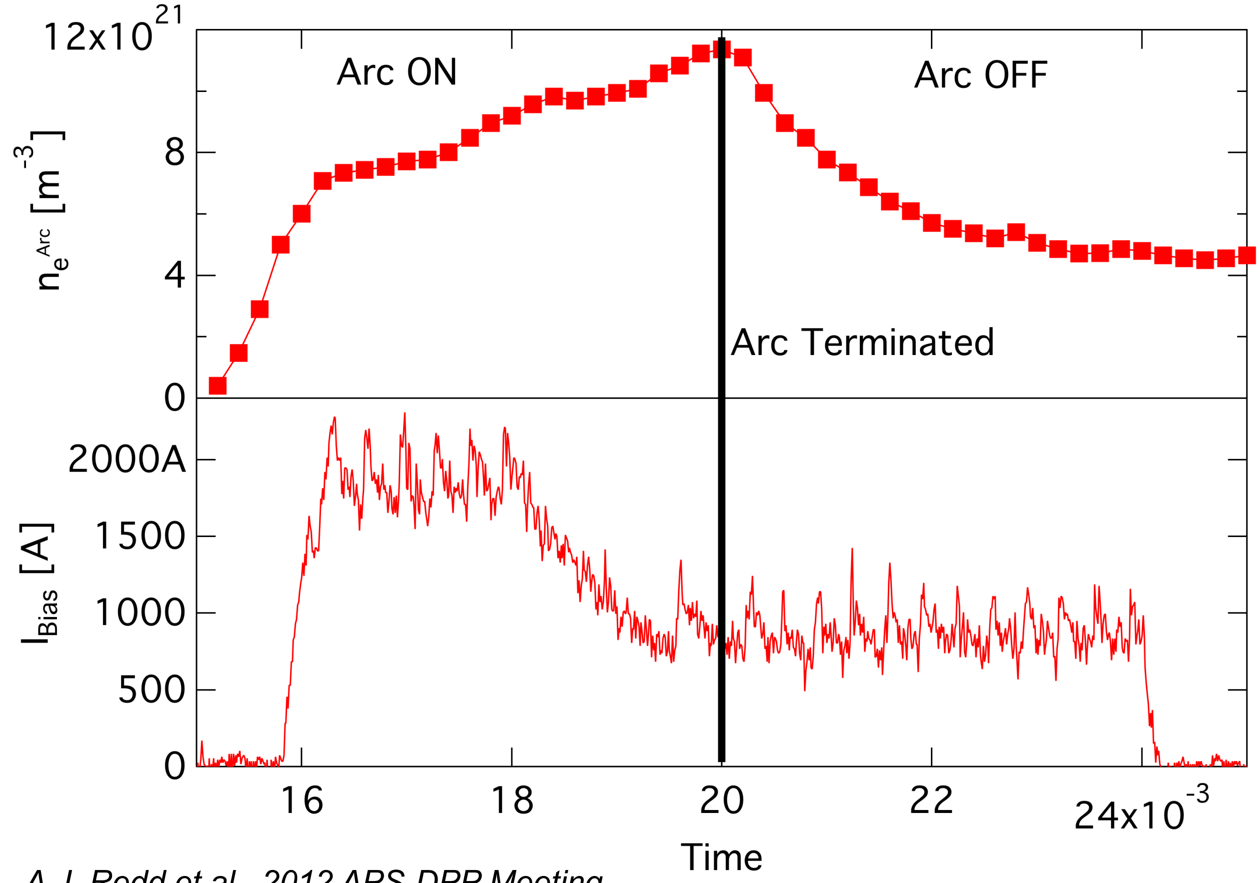
H_δ Broadening Arc Plasma Density Measurements Support Hollow Cathode Injection Concept

- Continuing gas injection after arc appears to suppress cathode spots for up to ~1kA bias current from injector
- Density measurements continue to indicate high ‘arc’ density



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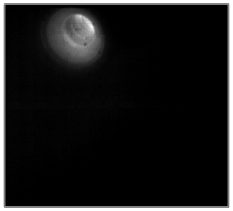
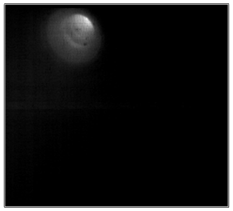
Arc+Gas+Bias:



Gas+Bias:

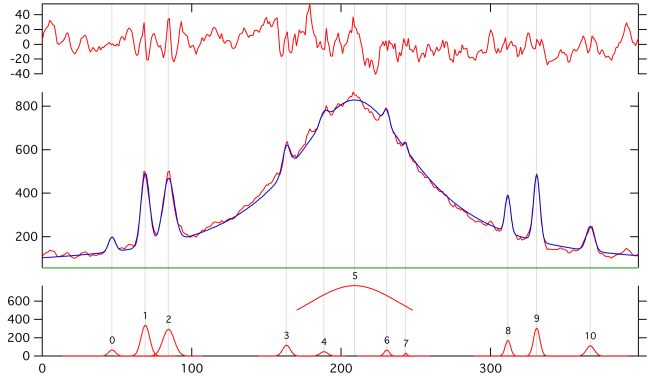


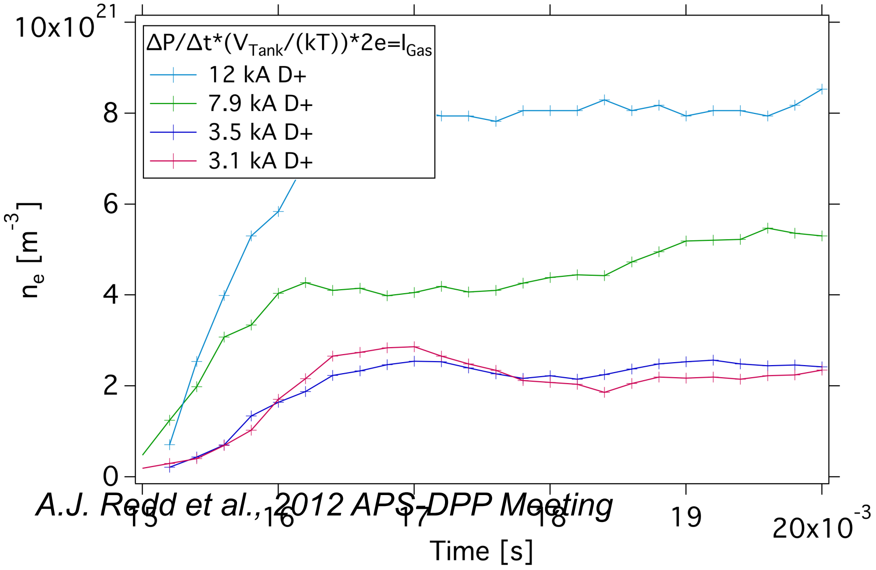
Stark Broadening of H_δ Shows Arc Source Plasma Density is Linear in Fueling

- H_δ profile obtained with view down center of gun
- Peak arc source plasma density is order $10^{21}m^{-3}$ for Pegasus' operating space

$$\Delta\lambda_{H-\delta}^{FWHM} = 0.92\left(n_e^{20}\right)^{2/3}[\mathrm{A}]$$

$$n_e^{20} \approx 10 \Rightarrow \Delta\lambda_{H-\delta}^{FWHM} \sim 4\ \mathrm{A}$$





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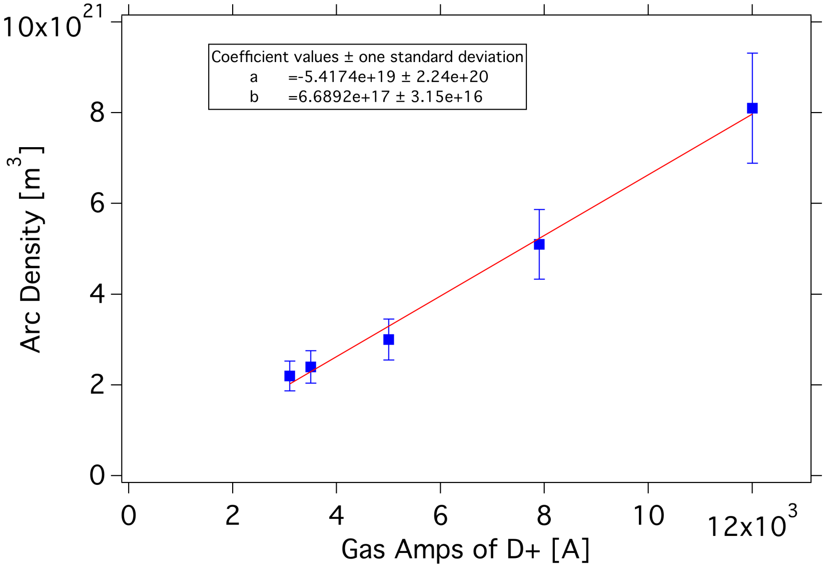

Summary: Significant Progress in Developing Local Helicity Injection and Operating Scenarios

- Local Helicity Injection is an attractive means of nonsolenoidal startup
  - Very flexible geometry, low impurity content
  - Technical attractiveness: can remove sources and anode after startup

- No fundamental obstacle to 1 MA LHI startup in NSTX-U
  - Optimum injector will have a large cross-sectional area with narrow width
  - Computational studies will develop LHI operating scenarios for NSTX-U, and test models of the detailed physics as they become available

- Injector conceptual design evolving due to Pegasus studies
  - Injector design requires PMI mitigation features
  - Arc source impedance, and helicity injection rate, appears to be governed by sheath effects and magnetic current limits

Near-term Work

- Continue Pegasus injector hardware studies
  - Evaluate use of gas-fed electrode as helicity injector
  - Improve understanding of the injector impedance
  - Demonstrate high performance with low impurity influx
- Expand simulation efforts
  - Improve the simulation platform for Pegasus (e.g, neoclassical models)
  - Include more of the detailed physics (e.g., quantifying LHI current drive)
  - More detailed cross-checking with data and reconstructions
- Develop final conceptual design for NSTX-U startup system

Operational Scenario Development

Scenario Development via the Tokamak Simulation Code (TSC)

- Detailed development of LHI operating scenarios needed
  - Necessary component of XP proposal of LHI experiments on NSTX-U
  - Simulations, especially of null formation and startup, will determine some of the boundaries of the injector design (*e.g.*, injector location)
  - Simulated scenarios will inform the conceptual injector design (*e.g.*, if the LHI drive is inadequate, then injector area must be increased)

- TSC simulations of LHI plasmas must be validated
  - Goal is confident extrapolation to NSTX-U operating scenarios
  - Integrated modeling of NSTX-U LHI discharges must include the initial poloidal null formation, relaxation to the turbulent tokamak-like state, and growth of the plasma current to ~1 MA.
  - Simulation of Pegasus LHI discharges will test theory-based models for the confinement/dissipation, LHI current drive, and the impact of SOL parameters on the injector impedance

TSC Used to Simulate Pegasus Experimental Discharges

- Pegasus discharge TSC simulations evolving
  - Ultralow aspect-ratio discharges are a computational challenge
  - Neoclassical effects can be large as A ~ 1, so TSC models may need to be updated to match Pegasus experimental observations
  - Matching experimental results is clearly requiring some “tuning” of the TSC simulation parameters (*e.g.*, neutral influx)
  - Can cross-check TSC simulation progress against raw measurements and equilibrium reconstructions

- Some physics is presently excluded from simulations
  - Null formation and the transition to tokamak-like equilibrium
  - Helical current stream from the injector
  - Detailed injector impedance model
    (instead, effective toroidal loop voltage is simply imposed)