Local Helicity Injection Systems for Non-Solenoidal Startup in the Pegasus Toroidal Experiment

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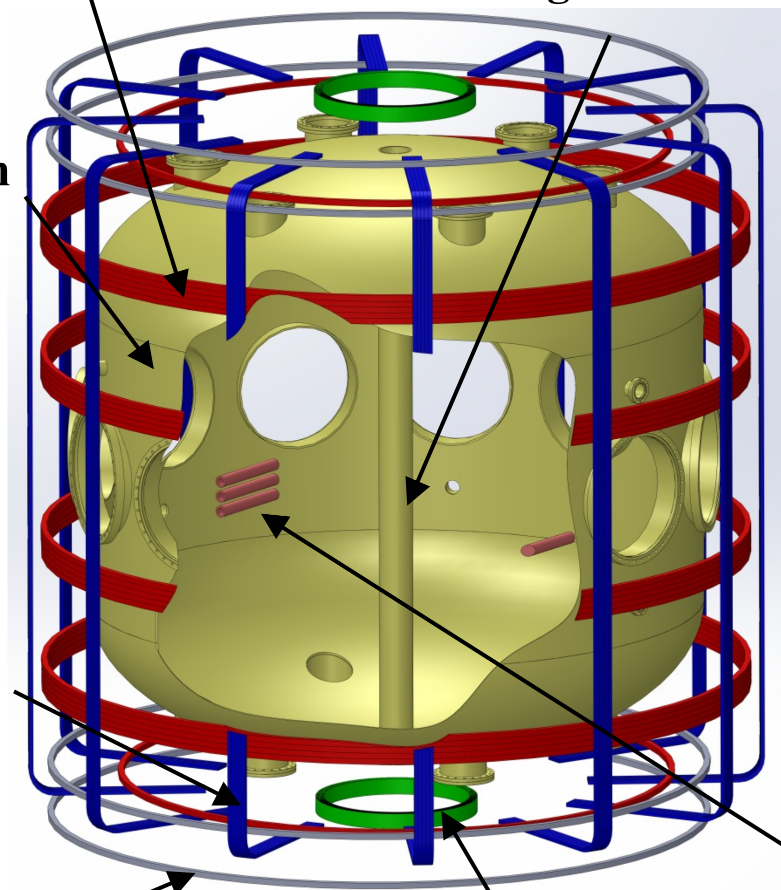
PEGASUS Toroidal Experiment

Local helicity injection is being developed in Pegasus towards viable high-current start-up of larger tokamaks

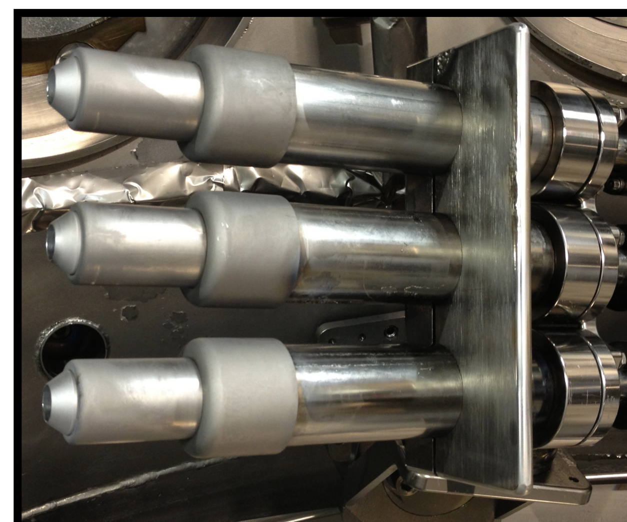
- Local helicity injection (LHI) allows non-solenoidal start-up of tokamak plasmas using localized current injectors, which provide an effective loop voltage
- Injector technology has been developed through many iterations to provide increased drive from LHI
- Demonstrating 300 kA start-up in Pegasus will test an operational regime that projects to 1 MA start-up in larger machines
- Experimental results and modeling have given the injector specifications required for 300 kA start-up, leading to the design of a compact array of 8 point-source injectors with internal arcs and gas feed

Pegasus is a compact, ultralow-A ST

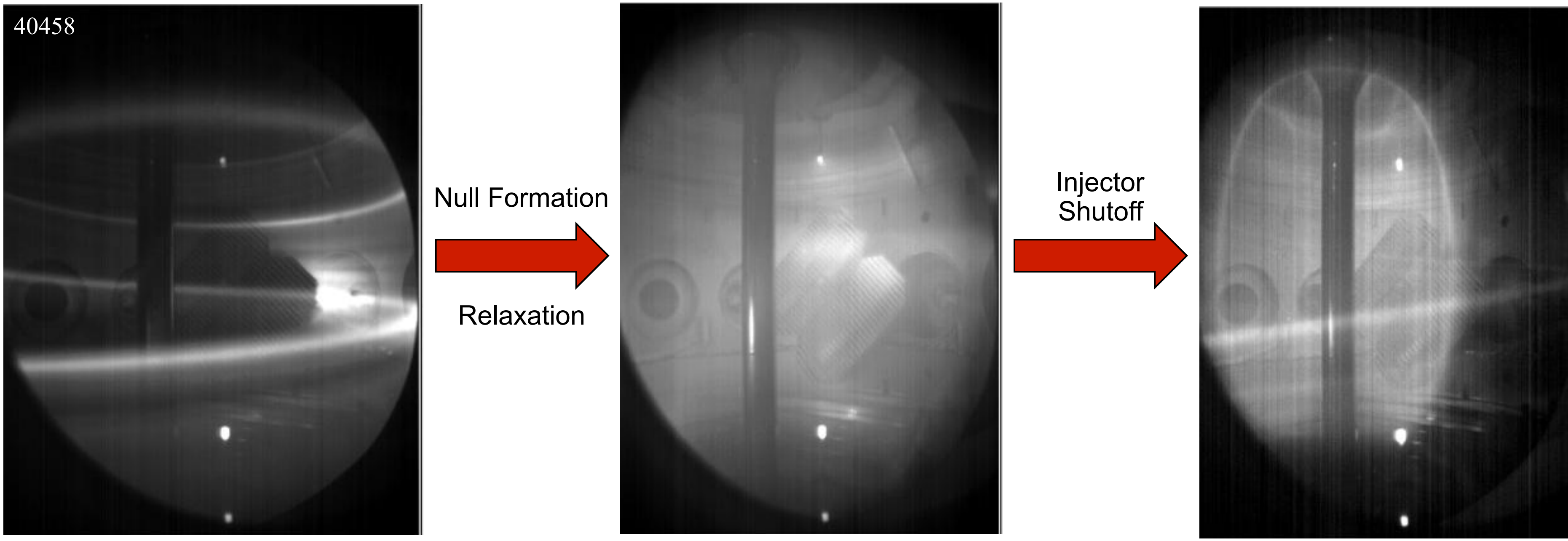


Experimental Parameters

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)	$\leq$ .23	$\leq$ 0.30
I_N (MA/m-T)	6 – 14	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



Local helicity injection offers scalable non-solenoidal startup



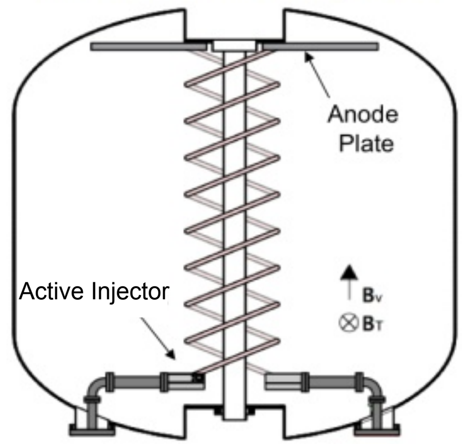
- Current injected along helical vacuum field
  - Local, active current sources
- MHD relaxation, tokamak-like state
  - Constrained by helicity, Taylor relaxation limits
- Tokamak plasmas produced after injector shut off
  - Couples to alternative current drive sources

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

Helicity input provided by edge-localized sources

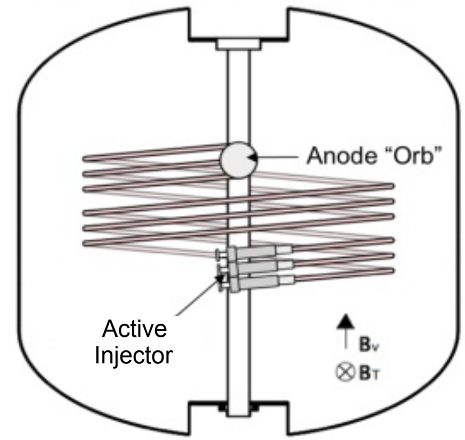
- Flexible injector geometry:
  - Inboard / divertor region
  - Outboard midplane
- Biased injectors at plasma edge source DC helicity
  - Injectors source current, I_{inj}
- Produces robust plasmas with $I_p >> I_{inj}$
  - Can hand off to other current drives

Inboard Injection *

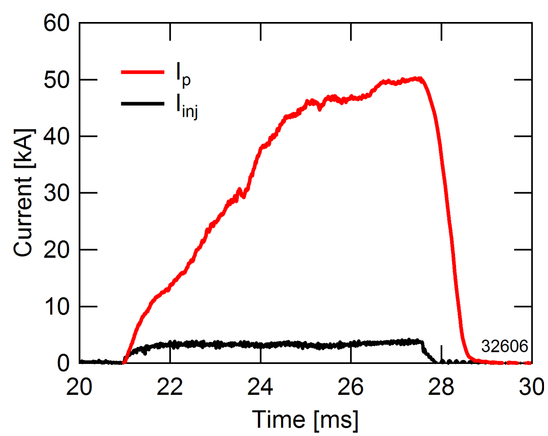


R_{inj} = 16 cm, Z_{inj} = -75 cm

Outboard Injection**



R_{inj} = 70 cm, Z_{inj} = -20 cm



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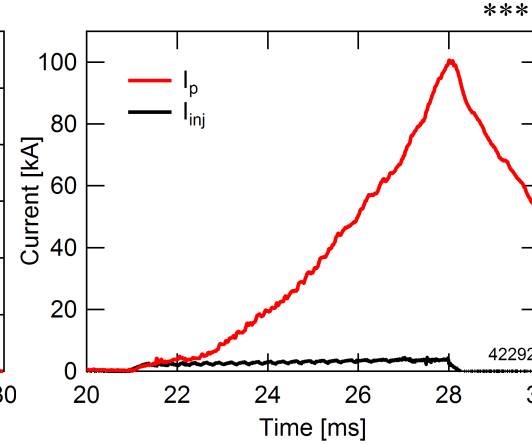

*: Eidietis *et al.,* J. Fusion Energ. **26**, 43 (2007)
: Battaglia *et al.*, Nucl. Fusion **51, 073029 (2011)
***: Battaglia *et al.,* Phys. Rev. Lett. **102**, 225003 (2009)

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Helicity conservation motivates key parameters to boost current drive

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

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

Resistive dissipation — Inductive drive — DC helicity injection

$$\dot{K}_{DC} = -2\int_A \Phi \mathbf{B} \cdot d\mathbf{s} = 2V_{inj} B_\perp A_{inj} \Rightarrow V_{eff} \approx \frac{A_{inj} B_{\phi,inj}}{\Psi} V_{inj}$$

- Injector area (A_{inj}) and injector bias voltage (V_{inj}) drive V_{eff} for fixed TF and plasma geometry
  - Motivates an injector with a large area sourcing the injected current
  - Injector bias voltage, not magnitude of injected current, is relevant to helicity injection

Taylor relaxation criterion also limits the total sustainable I_p for a given plasma geometry

- Considering force-free equilibrium:

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

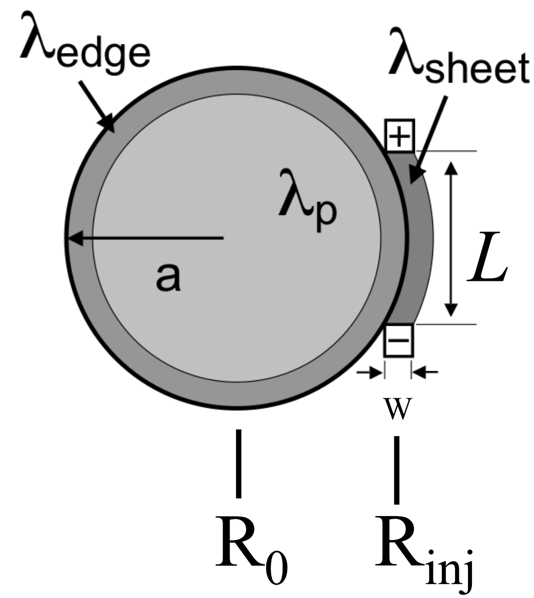
- Current penetration via Taylor relaxation requires:

$$\bar{\lambda}_{edge} > \bar{\lambda}_{plasma}$$

- Averaging $\bar{\lambda}_{edge}$ over the plasma surface area gives Taylor relaxation current limit[1]:

$$I_p \leq \left[\frac{C_p}{2\pi R_{inj}\mu_0} \frac{\Psi I_{inj}}{w} \right]^{1/2}$$

- Current limit increased by high I_{inj}, low injector width
  - Informs injector design



A_p, A_{inj} : Plasma, injector area
C_p : Plasma circumference
Ψ : Plasma toroidal flux
w : Edge current channel width

1 Holcomb, C.T. et. al., Phys. Plasmas **13**, 2006

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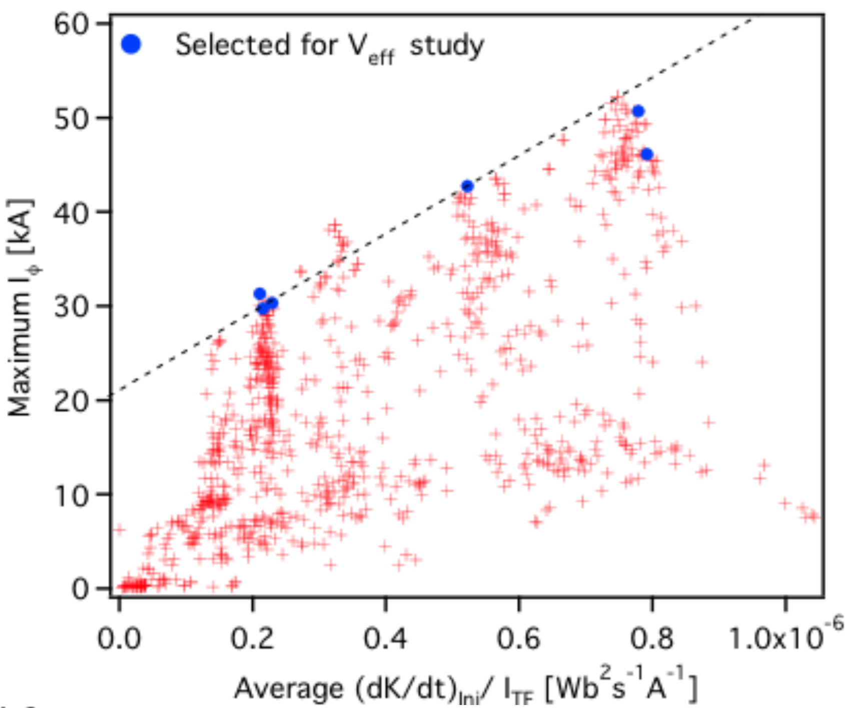
Experimental results support the formulation of V_{eff}

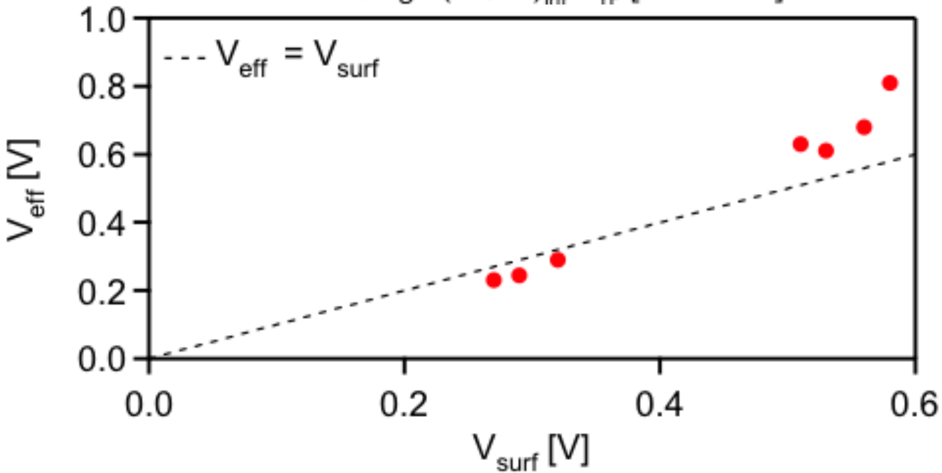
- Inboard injector geometry, no PF induction
- Max I_{ϕ} offset linear to injected dK/dt
  - dK/dt limiting I_{φ}

- Compare V_{eff} & decay V_{loop}
- Decay V_{loop} estimated by V_{surf}
  - Measured by center column flux loop

- $V_{eff} \approx V_{surf}$ indicates:

  1. Helicity efficiently transported into plasma
  2. Current drive limited by helicity injection rate

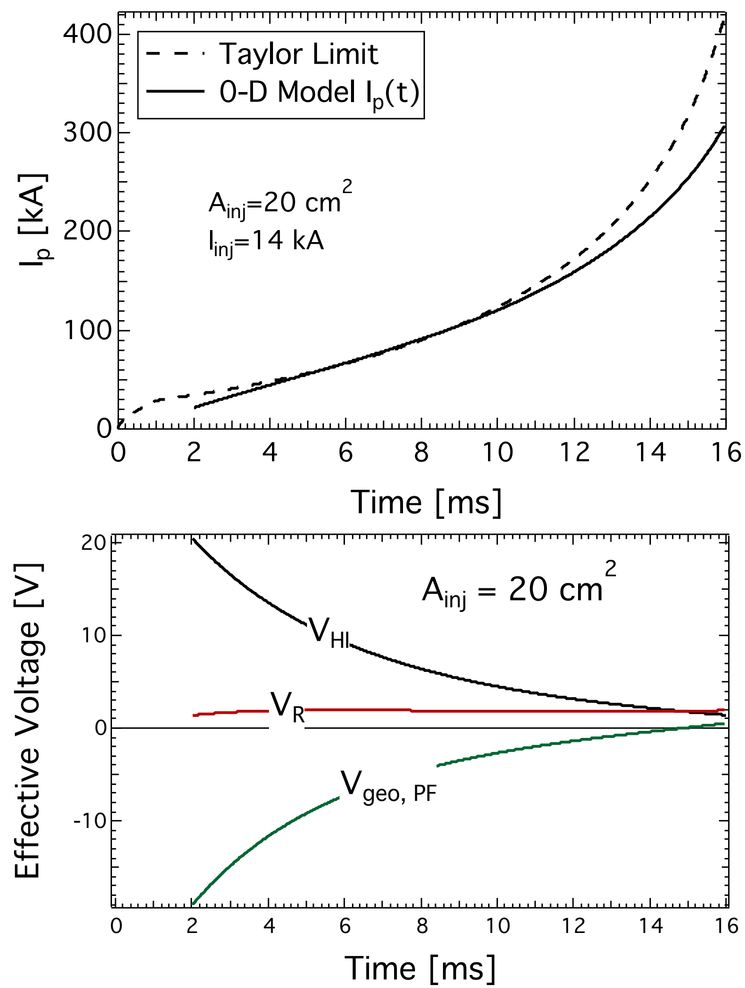




Maximum plasma current must be increased to reach the physics regime relevant to NSTX-U, FNSF

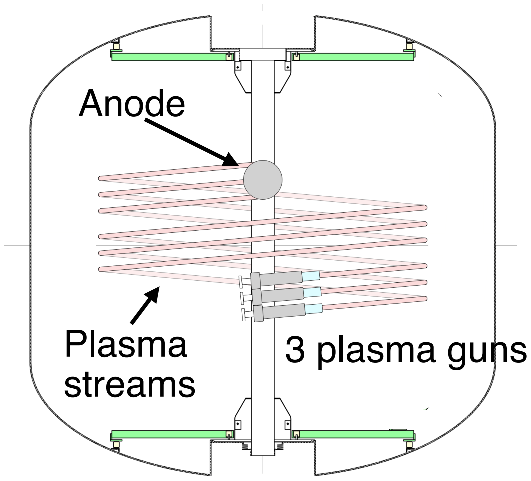
- Goal is scalability to 1 MA startup in a larger ST
  - Drive from LHI exceeds drive from PF/geometric induction
- 300kA needed in Pegasus to enter this regime
  - Discharges to date dominated by PF induction
  - More V_{eff} needed to reach this regime
- A power balance model for LHI predicts 20cm² of injector area with V_{bias}=1kV is needed to achieve I_p=300kA
  - See Poster **TP8.00018 by** Jayson Barr for detail

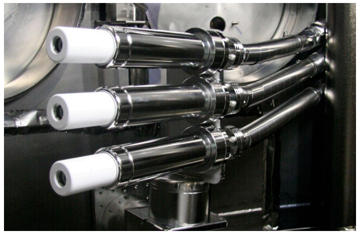
Power balance model for a 300kA plasma

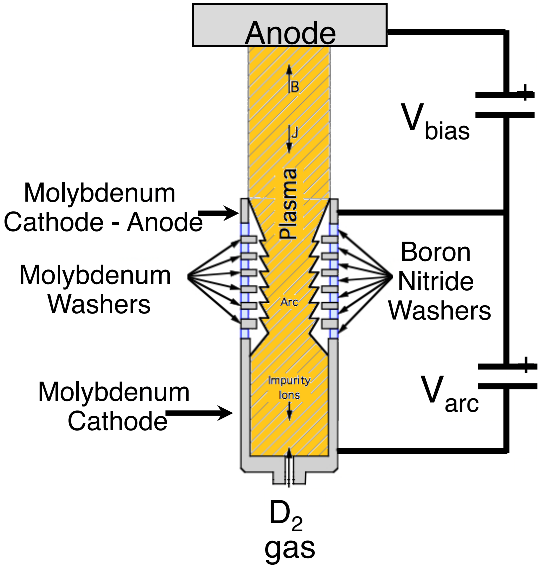


Requirements for an injector system

- LHI physics and engineering constraints set injector properties:
  - Large A_{inj}, uniform J_{inj}
  - Applied $V_{inj} > 1\text{kV}$
  - Multi-MW power system
  - $\tau_{pulse} \sim$ 10-100 ms
  - Minimize PMI
  - Must survive/function in tokamak plasma edge region
- Basic implementation is a gas fed, internal arc plasma source



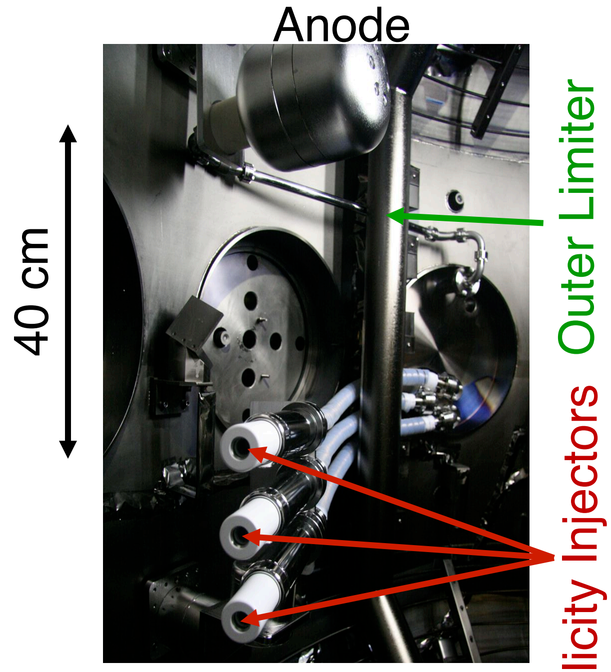


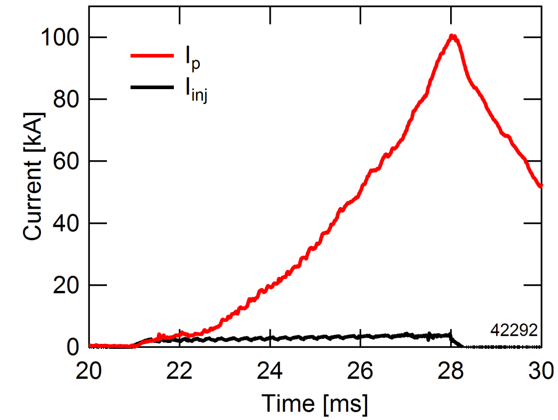


Redd *et al*, J. Fusion Energy **28**, 203 (2009)

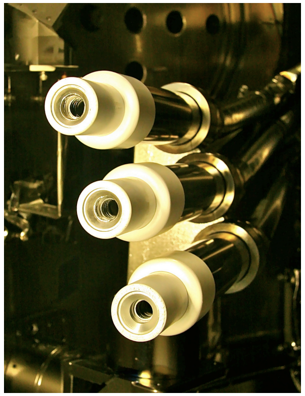
Group of 3 injectors below outboard midplane showed success, with limitations

- Plasma currents >100kA achieved
  - PF induction used on top of helicity drive
  - A good proof of principle, but did not enter the desired physics regime where LHI drive dominates
- Impurity fueling from PMI presented a major problem
  - A principal driver for changes in injector design, especially of cathode face
  - Plasma limiting on the injectors caused outgassing from BN insulators
    - Local scraper limiter added
  - Cathode spots began to source current from injector cathode for high I_{inj}
    - Spots concentrate I_{inj}, lowering helicity input





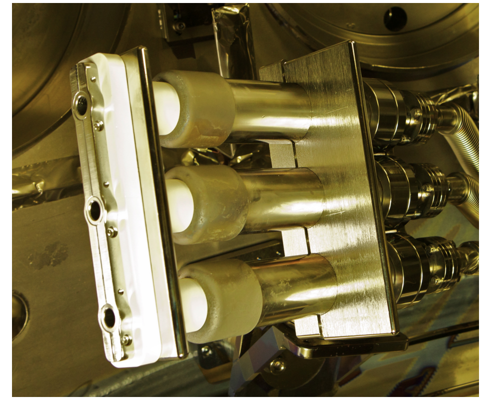
Injector technology evolved to increase helicity injection capabilities, mitigate PMI



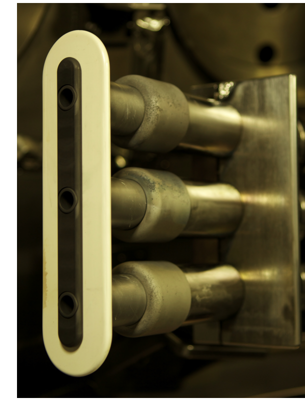
1. Circular beveled Mo faces

2. “Slot” Mo faces with BN caps

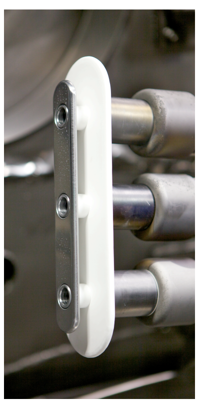
3. “Slot” caps with BN raised ~1 cm Above Mo faces



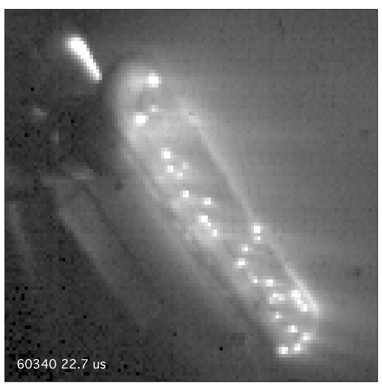
4. 3-Gun, two-piece Mo electrode with ***local scraper limiters***



5. One-piece C electrode with local limiters



6: Mo electrode raised off the BN limiter



7: 1 Gun / Mo Electrode with ***piezoelectric gas control***

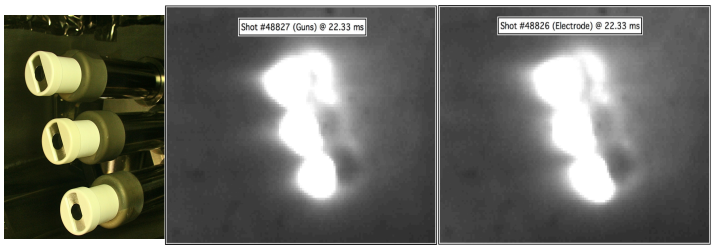
8: Mo backing plate: impurity control

9: ‘***Volcano’ guns*** + 1st generation ***gas-effused electrode***

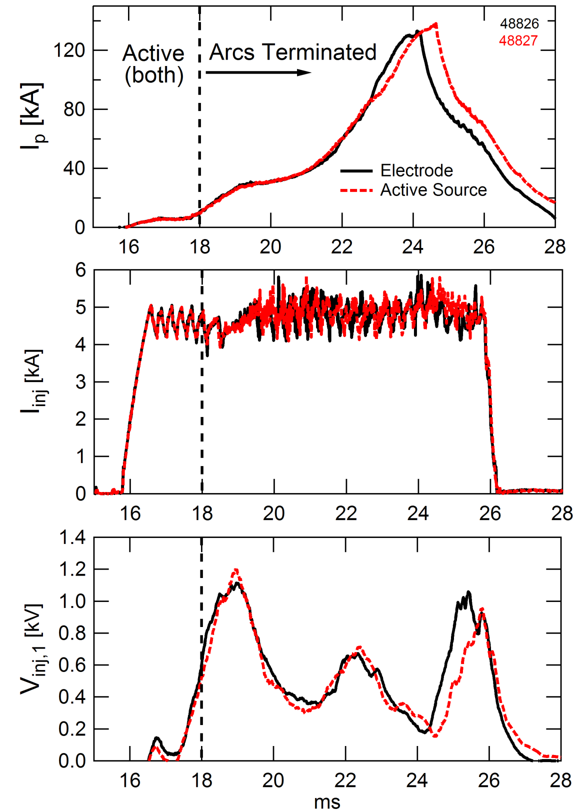
Tested: ‘Volcano’ guns + ***large area gas-effused electrode***

Early indications pointed towards passive electrodes as a simpler large area injector

- Passive electrode seemed an easier way to high area
  - Arc injectors used to form initial relaxed plasma, then arcs shut off
  - I_{inj} continues to flow from passive electrode surface



- Solid plate electrode integrated around existing arc sources
  - Order of magnitude increase in area



Electrode showed plasma performance equal to that of the active arc injectors.

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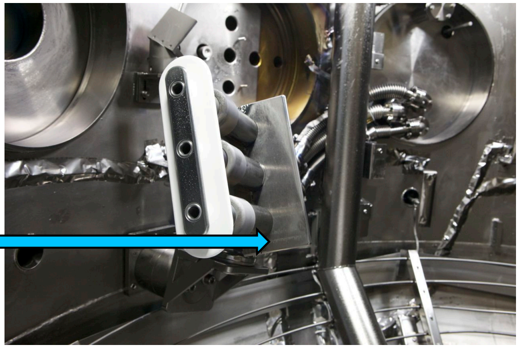
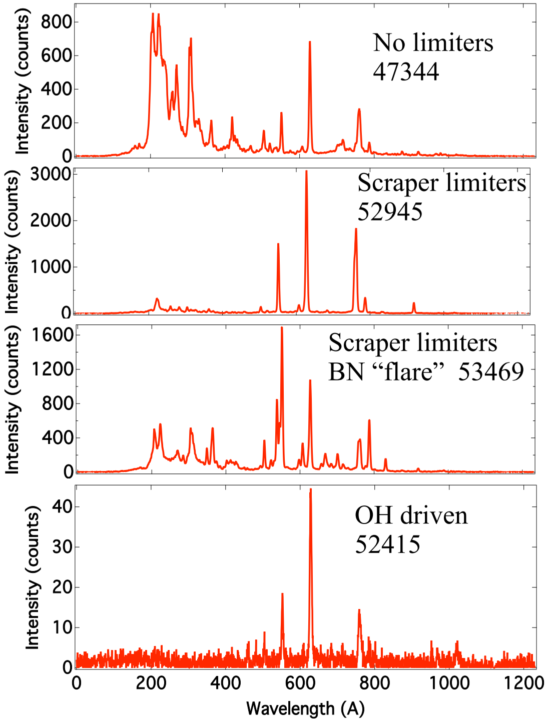
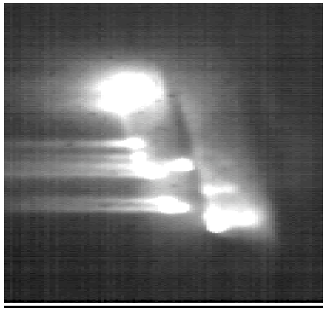
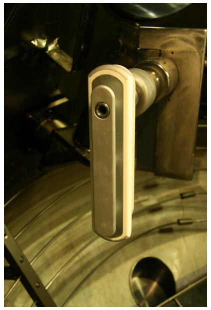
Electrode systems evolved to mitigate deleterious plasma-material interactions

- N dominant impurity with unprotected gun assembly
  - $Z_{eff} \sim 2.2. +/- 0.8$ 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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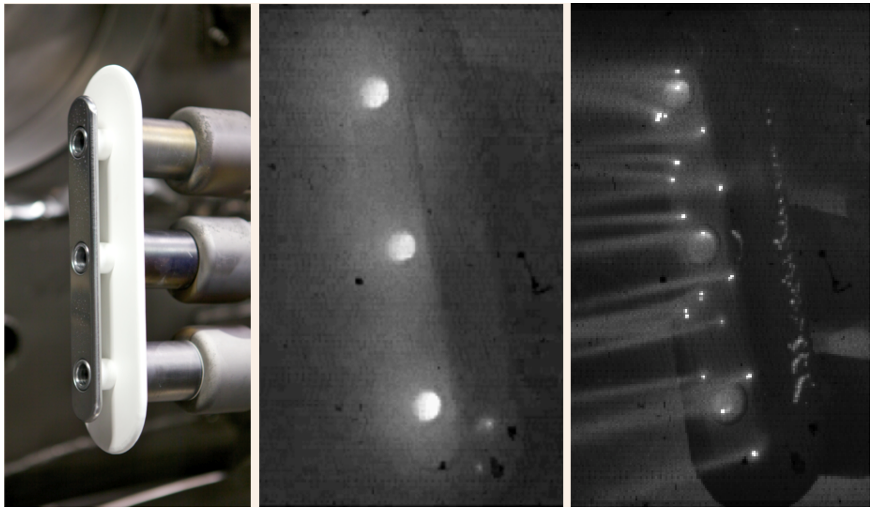
Ultimately, passive electrodes failed to achieve higher V_{eff}, due to poor area utilization

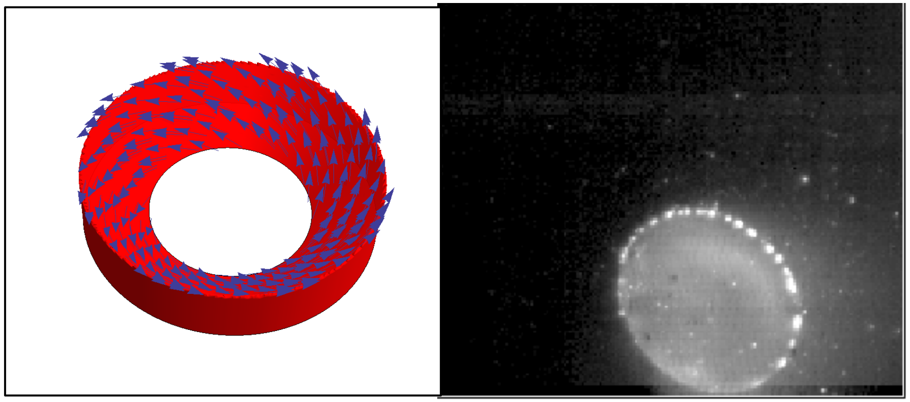
- Cathode spots sourced the injected current from the electrode surface
  - 30-50 cathode spots (200-400A per spot)
  - $A_{spot} < 1mm^2$
  - Total area utilized for injection:
    - $A_{inj} < 1\ cm^2$
- Low area utilization is a fatal flaw for passive electrodes
  - Need a way to source current more uniformly from a large area injector
  - Nonetheless, experience gained with PMI control in plasma edge



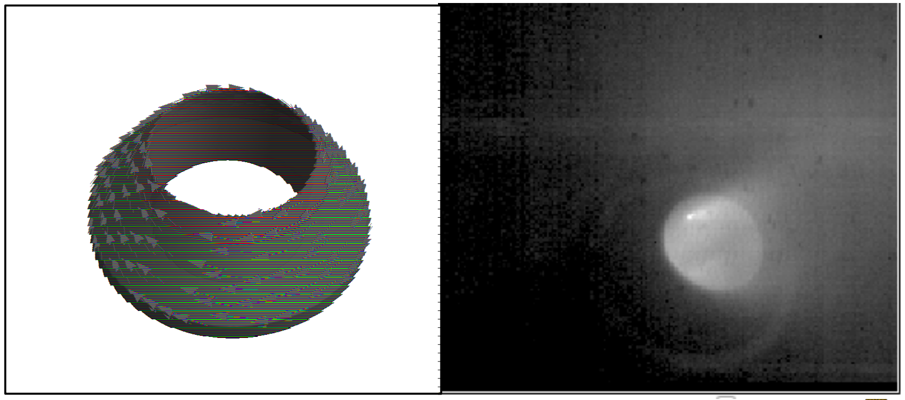
Improved cathode design for arced injectors reduces impurity fueling due to cathode spots

- Previous injectors are prone to generation of cathode hot spots
  - Concave cathode face results in cathode spot drift outward to junction with BN insulator
  - Causes severe impurity fueling, loss of bias voltage
- Cathode spot effects mitigated by geometry of new frustum cathode
  - Convex cathode face results in cathode spot drift up the cone toward cathode lip, where spots die out
  - Significant reduction in impurity fueling ($Z_{eff} < 1.5$) during LHI

Concave Electrode



Convex Electrode

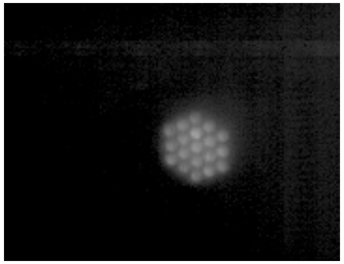


Attempts to use hollow cathode effect to utilize full area of gas-effused electrodes

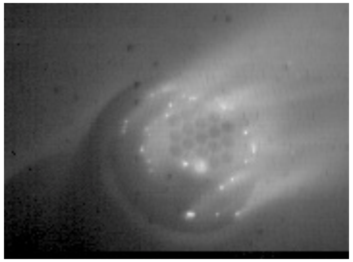
- Perforated electrode surface allows gas-fed hollow cathode effect to source charge carriers in place of active arc

- HC effect tested by a “pepper-shaker” cap on an injector (without arc current)
- Fast imaging showed uniform glow at low current densities
  - Small area meant V_{eff} was hard to measure
- At high injected current cathode spots emerge
  - Results in very small effective area

$I_{inj} = 0.5$ kA

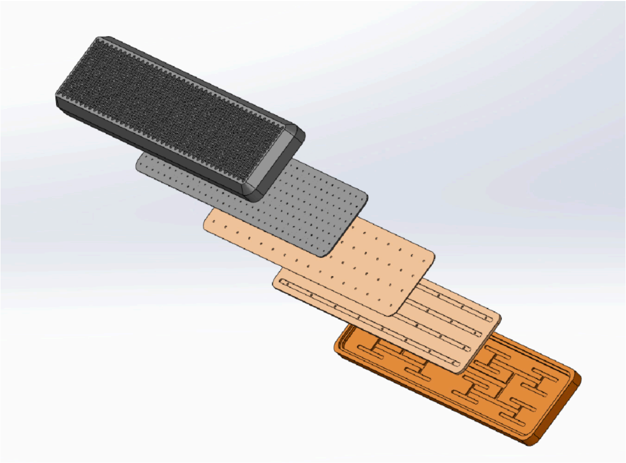


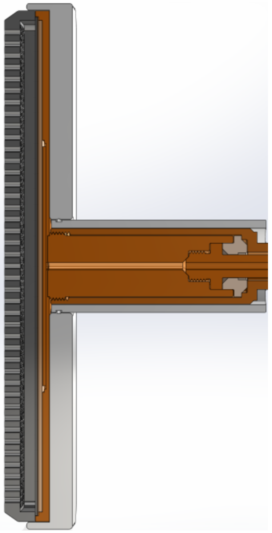
$I_{inj} = 2$ kA



Showerhead: a large area gas effused electrode

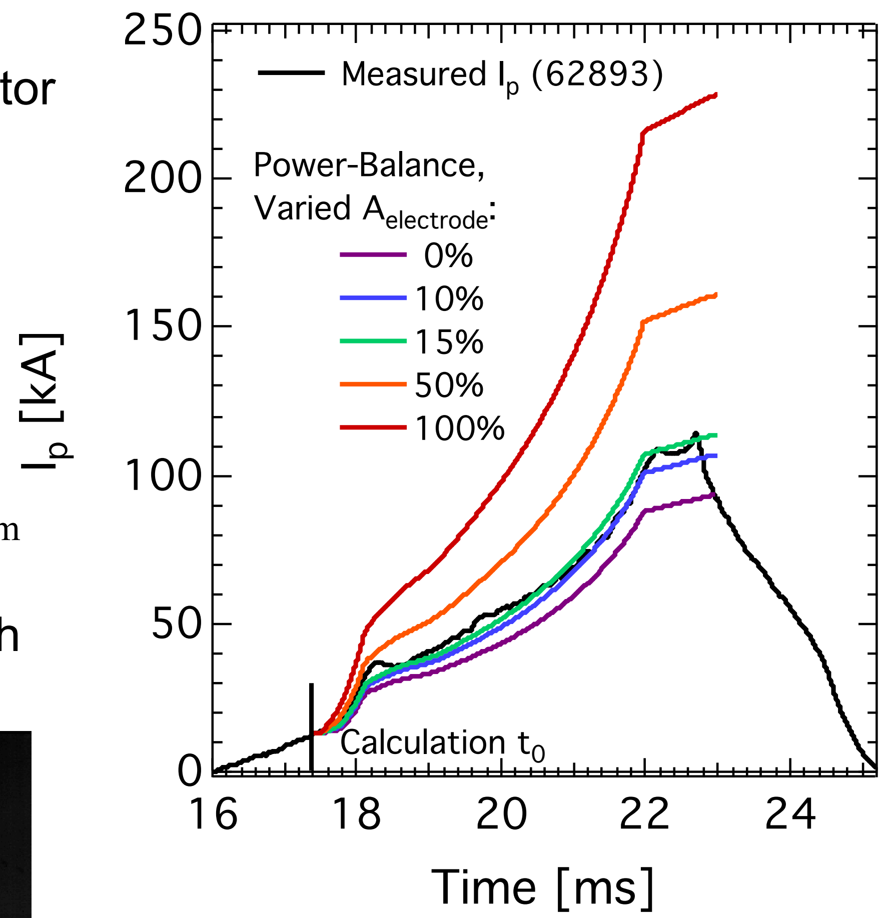
- "Pepper-shaker" results motivated a 50 cm^2 gas effused "showerhead" electrode
- 1161 holes x 4.5mm^2 = 52cm^2 hole area
  - HC effect used to source current uniformly from all holes
- Complex gas manifold feeds showerhead surface uniformly from a single piezo-electric gas valve

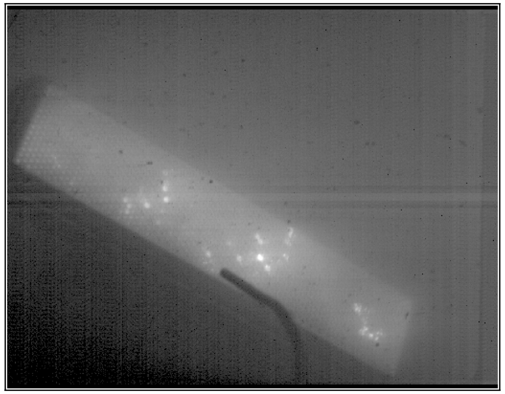


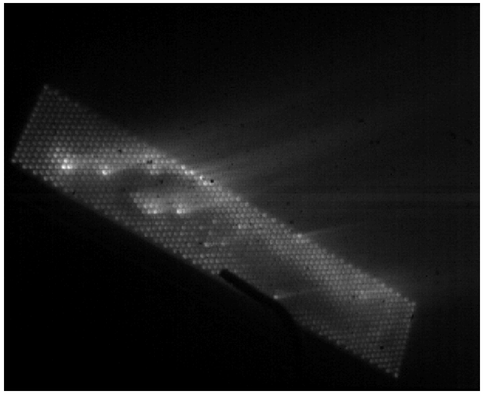


Power balance model indicates only a small fraction of the showerhead area was utilized

- The best showerhead discharges produced only incremental improvements over 3-injector discharges
  - Results were consistent with a low V_{eff} due to low area utilization
- The operational space for uniform hollow cathode operation was narrow
  - Through most of each discharge, areas of light and dark were mixed across the face of the showerhead
  - Presence of random cathode spots suggested non-uniform current emission
- Conclusion: not useful as robust tool for high helicity injection rate

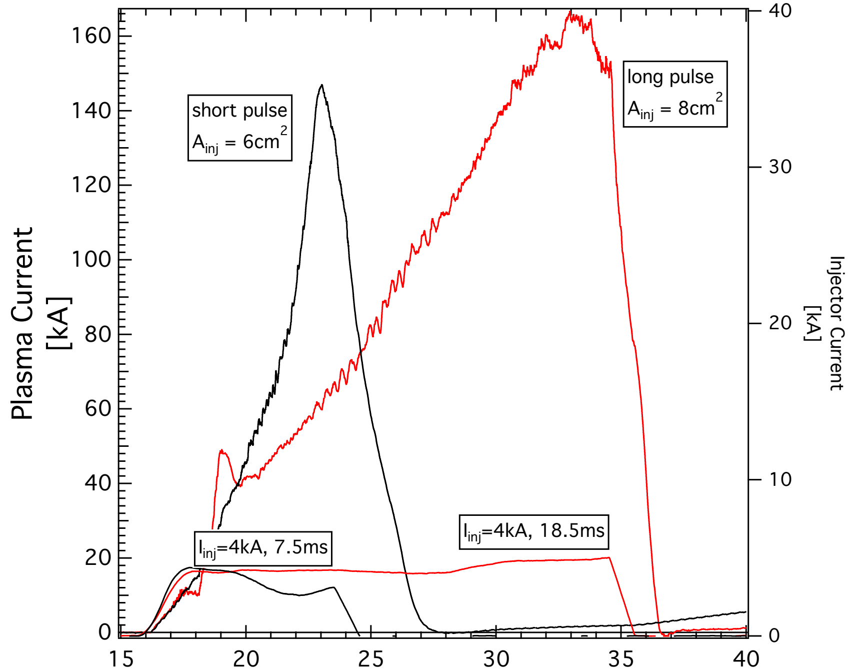


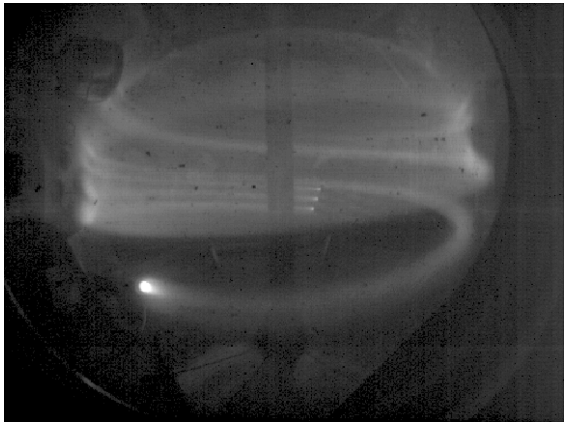




Arc-source power supply upgrades makes longer pulse discharges possible

- Arc injector upgrades support pulse extension
  - IGBT switched arc power supplies to minimize heat load and extend pulse length
  - Programmable Piezo-valve gas injection
- Enabled doubling of startup pulse length
  - Varied I_p ramp rate for enhanced stability
  - A modest increase in inductive drive terms
- Discharges carried out with 4 injectors (3-injector array + single injector toroidally opposite)
  - Proves viability of monolithic bias supply for separate injectors
  - Marks the limits of operation with present hardware



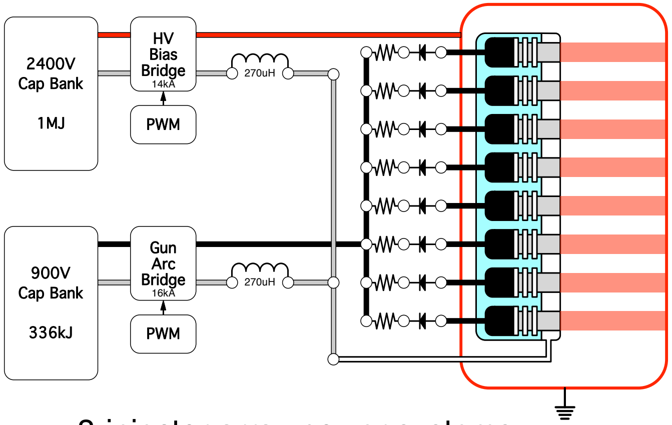


Improvements in injector technology have opened a new way forward

- Key technologies have been developed over the course of LHI research:
  - Programmable monolithic IGBT arc power supply simplifies the creation of a large number of arc sources
    - Previously used a pulse-forming network (PFN), not programmable
  - Monolithic IGCT bias system reduces power supply requirements for multiple injectors
  - Gas manifold from Showerhead enables many channels to be fed from a single piezo-controlled gas valve
  - Frustum injector cathodes reduce impurity fueling, rendering arced injectors more effective
- With these improvements in technology, a compact array of many injectors with internal arc plasma sources becomes a viable way to achieve high injector area.
  - This solution was untenable with the original injector technology

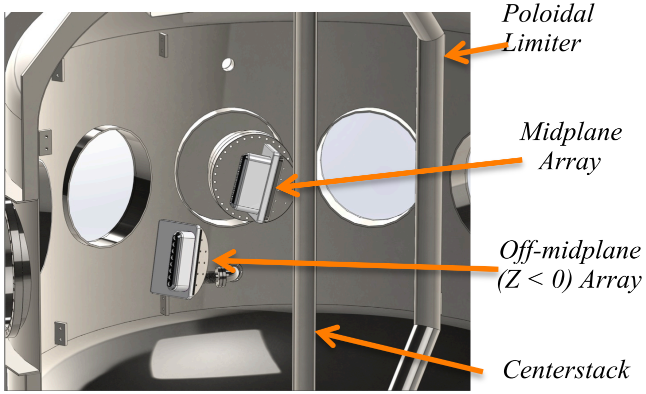
Large area injector via compact integrated arc injector array for high-I_p startup

- Simple monolithic power systems support multi-injector array
  - Single power systems for internal plasma arcs and extraction bias
  - Tested with 3-gun assembly on Pegasus
  - Programmable IGBT controlled Arc current demonstrated for active heat and current control
- Integrated 8-injector array presently in fabrication
  - 8 arc chambers in monolithic assembly
  - Gas distribution using staggered-hole plate array in base
  - 16 cm^2 array will prototype NSTX-U design

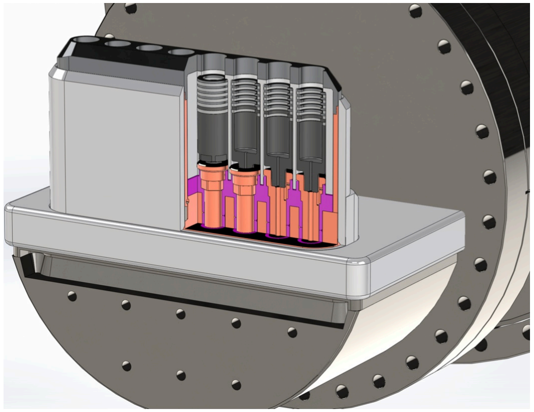


8-injector array power systems

Variable Array Locations



Integrated 8-injector Assembly



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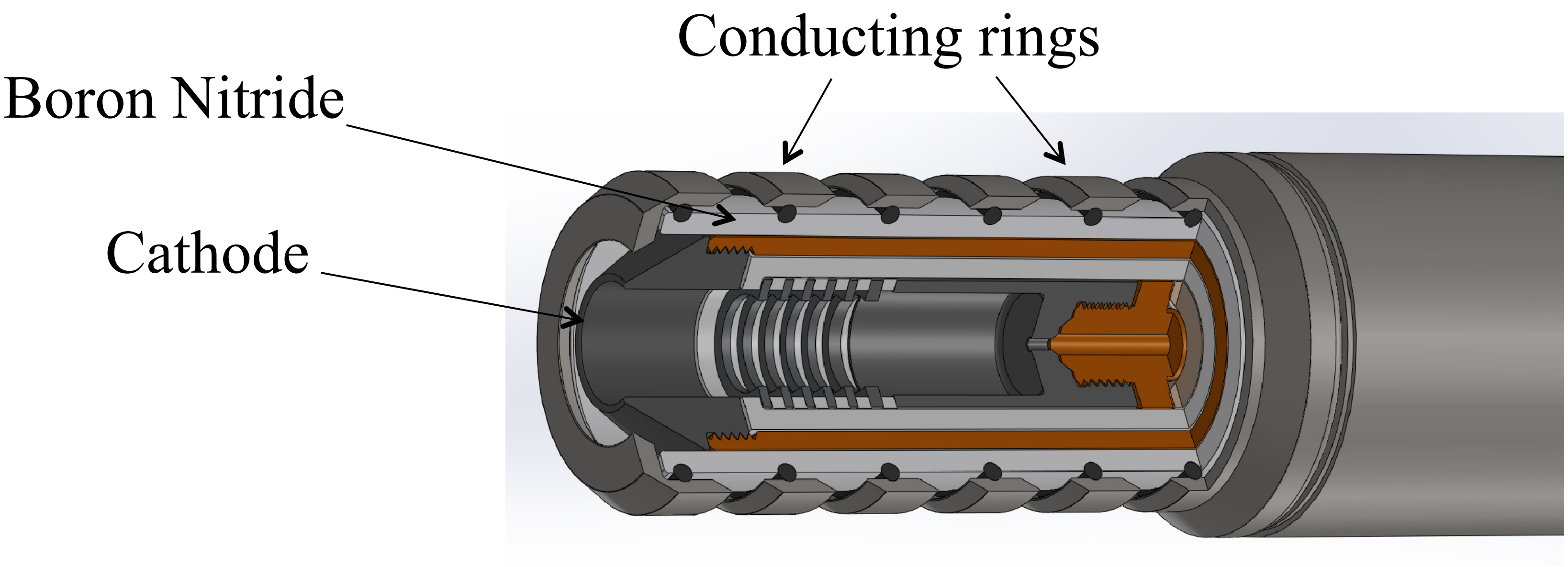
Improved injector insulation system may enable higher voltage standoff, reduced impurity fueling

- Conducting rings added along outside of boron nitride gun sleeve to increase voltage standoff from ground
  - Shield insulator from Ti gettering
  - Creates an effective voltage divider between cathode and ground
  - Aim is to reduce surface currents on the insulator, which cause impurity fueling



Summary

- LHI provides non-solenoidal startup in Pegasus
  - But the physics regime for high current start-up in larger machines requires HI drive comparable to inductive drive from PF/geometry
  - This requires higher V_{eff}, which means larger injector area and/or higher injector bias voltage
- Injector technology has been improved over several generations of LHI in Pegasus
  - Injector materials and geometry tailored to minimize PMI / impurity fueling
  - Power supply and gas feed technologies have advanced to provide greater flexibility and control in LHI operations
- A compact array of injectors with internal gas-fed arcs should provide the HI drive to reach higher Ip, show scalability to 1 MA start-up in NSTX-U, FNSF