Development of Non-Solenoidal Tokamak Startup on the PEGASUS-III Experiment

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University of Wisconsin-Madison

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PEGASUS-III Toroidal Experiment

Layout Slide (Include for Posters) - Success

US Legal
8.5 x 14”

US Letter
8.5 x 11”

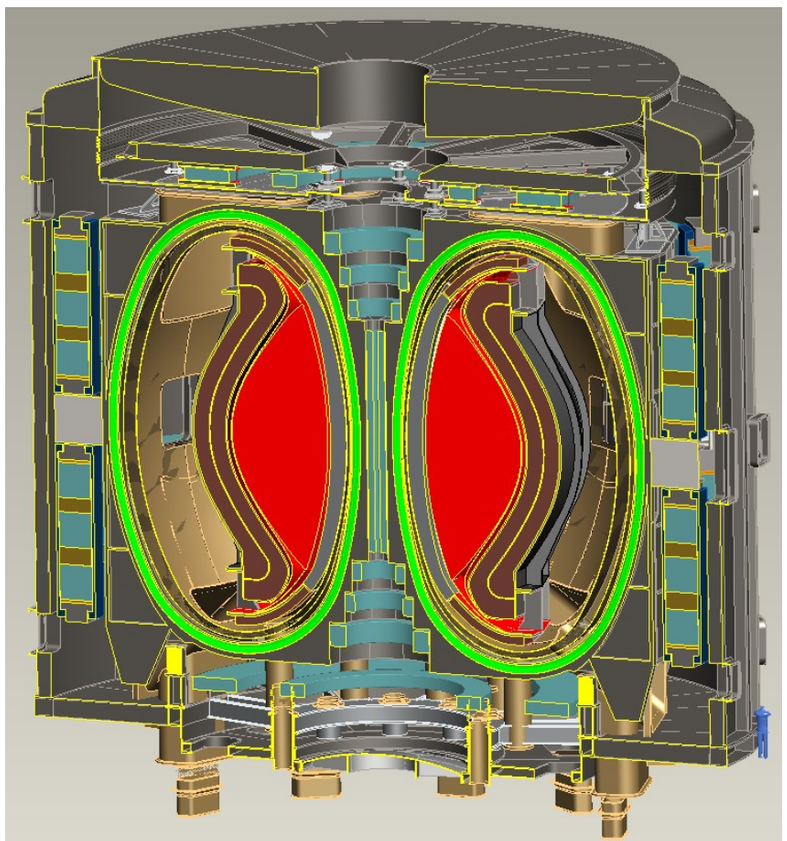
12:1 scale Panel size: 8’ x 4’

Transition from Pegasus to Pegasus-III	Non-Solenoidal Startup Techniques on Pegasus-III	Informing Injector Design for Pegasus-III	Validation of “Kama” Injector Design on Pegasus	Future of Non-Inductive Startup on Pegasus-III
The Pegasus Experiment has Established Groundwork for Non-Inductive Startup Using Local Helicity Injection (LHI)	Global Helicity Balance and Taylor Relaxation Results in I_p Limits in Helicity Injection	LHI Source Development Confirms Active Arc Injector Preferred	Non-Circular Injector Prototype Designed From Established LHI Physics	Kama Injector is Expected to Easily Achieve I_p ~ 0.3 MA on PEGASUS-III
PEGASUS-III is a Modification of the PEGASUS Experiment	LHI Utilizes Local Edge Current Injection for Tokamak Startup	Plasma Current in LHI Dominated Discharges Shows Linear Scaling with LHI Drive	Kama Injector Design Minimizes Deleterious Behaviour Along Plasma-Injector Interface	Low Ripple, Programmable $V_{inj}(t)$ from Cuk Topology Power Supplies will Enable Optimization of Helicity Input
PEGASUS-III Upgrade Highlighted by Improved Toroidal Coils	CHI Produces High-I_p Plasmas with Axisymmetric Electrodes	Favorable Scaling of I_p with Taylor Limit During Early Phase	Kama Injector Features Advanced Fueling to Stabilize Arc Fluctuations	Upgrade of PEGASUS-III is Underway
Conceptual Design for Expanded PEGASUS-III Diagnostic Suite	RF Heating and Current Drive Studies Will Focus on the EBW	PMI on Injector Surfaces Restricts Access to Large Helicity Input	Stark Broadening Measurement will Assess Uniformity of Arc Channel	Initial Physics Goals for PEGASUS-III

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Non-Solenoidal Startup is Critical for the Spherical Tokamak

- Future ST designs call for solenoid-free operation
  - Nuclear ST designs generally minimize OH due to shielding/cost
- OH solenoid removal simplifies tokamak design
  - Potential cost reduction
  - More space for inboard shielding/blanket → Critical for ST
  - Reduce PF system requirements for breakdown B_p null
  - Lower electromechanical stresses
- Solenoid-free startup techniques may offer tools for modifying $J(R)$



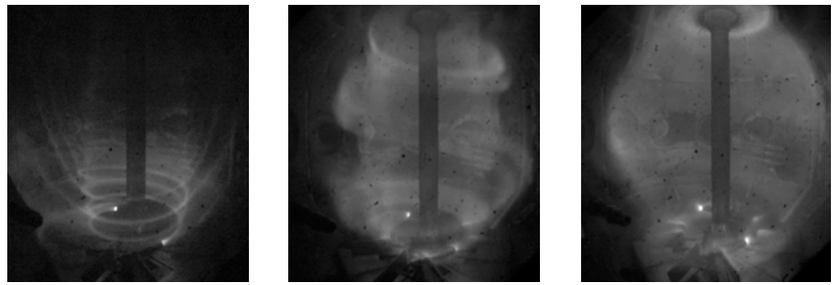
No / small OH HTS ST-FNSF / Pilot Plant

*J.E. Menard, Phil. Trans. R. Soc. A **377**, 20170440 (2019)*

Several Solenoid-Free Startup Techniques Pursued Globally

- Multiple methods have shown promise
  - Local helicity injection (LHI)
  - Coaxial helicity injection (CHI)
  - Radiofrequency plasma initiation, heating, and current drive
  - Poloidal field induction
  - Neutral beam current drive
- Need for a dedicated facility to develop understanding and scalability
  - Develop and validate predictive understanding
  - Provide sufficient runtime and experience
  - Comparative studies
  - Exploit possible synergies
  - Establish routine startup tools

PEGASUS HFS LHI



$I_p \sim N_{turns}\, I_{inj}$ $I_p \gtrsim N_{turns}\, I_{inj}$ $I_p \gg N_{turns}\, I_{inj}$



NSTX Transient CHI

RF Startup Experiments

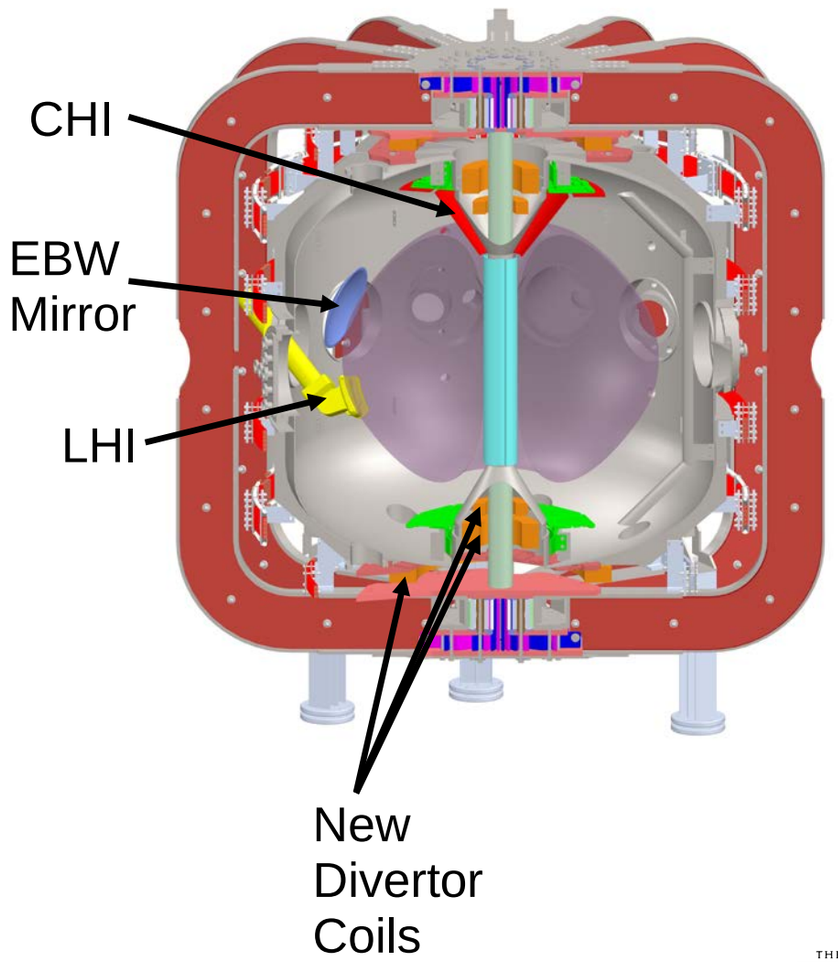
RF Method	Device	I_p [kA]
ECH + PF induction	DIII-D	166
	JT60-U	100
ECH	QUEST	70
	DIII-D	33
	KSTAR	15
ECH + LHCD	T-7	20
EBW	MAST	73
	LATE	15
LH	PLT	100
	TST-2	25
	GLOBUS-M	21

Bongard et al., APS-DPP-CPP Initiative (2019)

PEGASUS-III Provides a Dedicated Facility for Non-Solenoidal Startup Research

- LHI:
  - Investigation of B_T, I_p scaling of physics and technology
  - Efficacy of reconnection current drive at high B_T
- CHI:
  - Operation requires increased B_T
  - Refractory metal floating electrodes to avoid vacuum break
- RF Heating and Current Drive:
  - EBW used for over-dense ST
  - Increased B_T aids coupling and sustainment
- Enhancement to toroidal field needed for PEGASUS-III
  - I_p goal of ~ 0.3 MA
  - Increased pulse length
  - Enhanced diagnostic capabilities

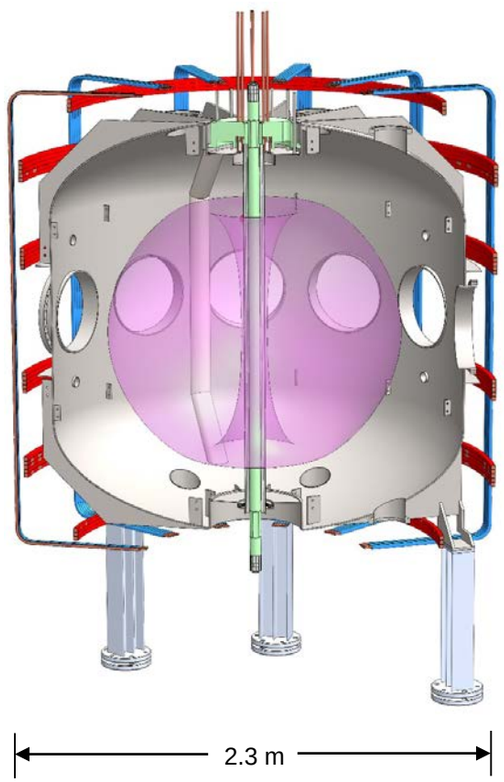
PEGASUS-III: US Startup Development Station



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PEGASUS-III is a Modification of the PEGASUS Experiment

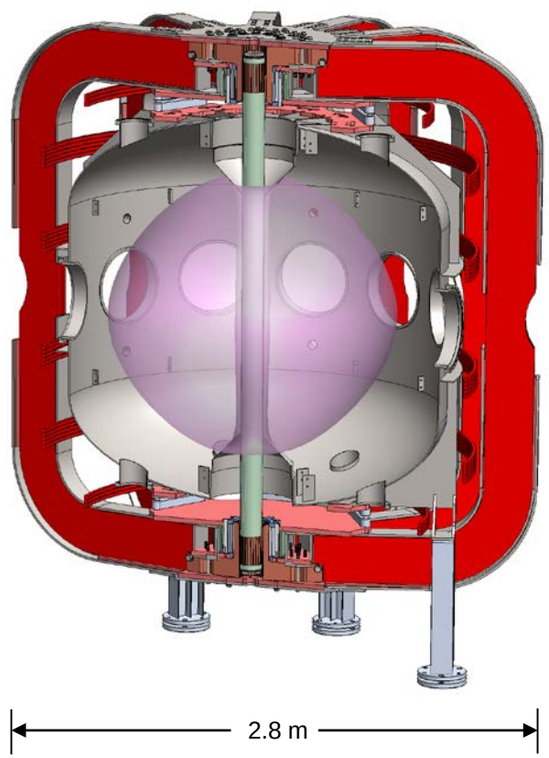
PEGASUS



- New, high B_T coil assembly
  - no OH solenoid
- New divertor coils and CHI electrodes
- Additional power systems for TF and CHI
- New, low V_{inj} LHI system
- Expanded diagnostics

Parameter	PEGASUS	PEGASUS-III
I_{TF}	0.288 MA	1.15 MA
N_{TF}	12	24
ψ_{sol} (mWb)	40	0
R_{inner} [cm]	5.5	7.0
TF Conductor Area [cm^2]	13.2	72
$B_{T,max}$ [T] at R_0~0.4 m	0.15	0.58
B_T Flattop [ms]	25	50-100
A	1.15	1.18

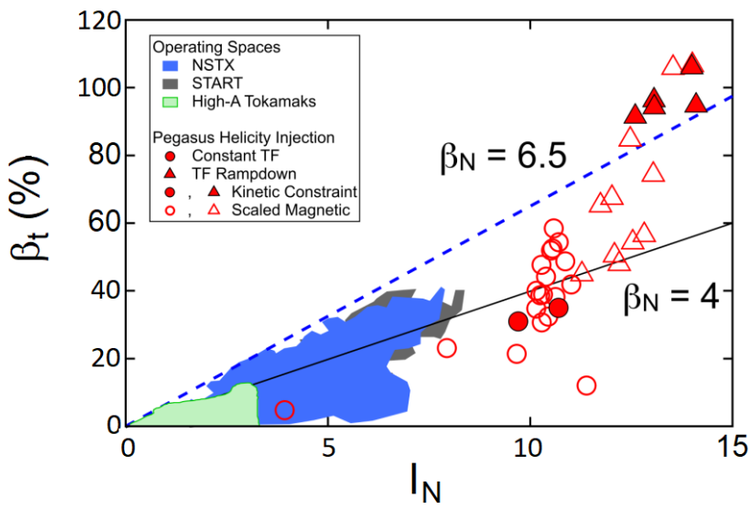
PEGASUS-III



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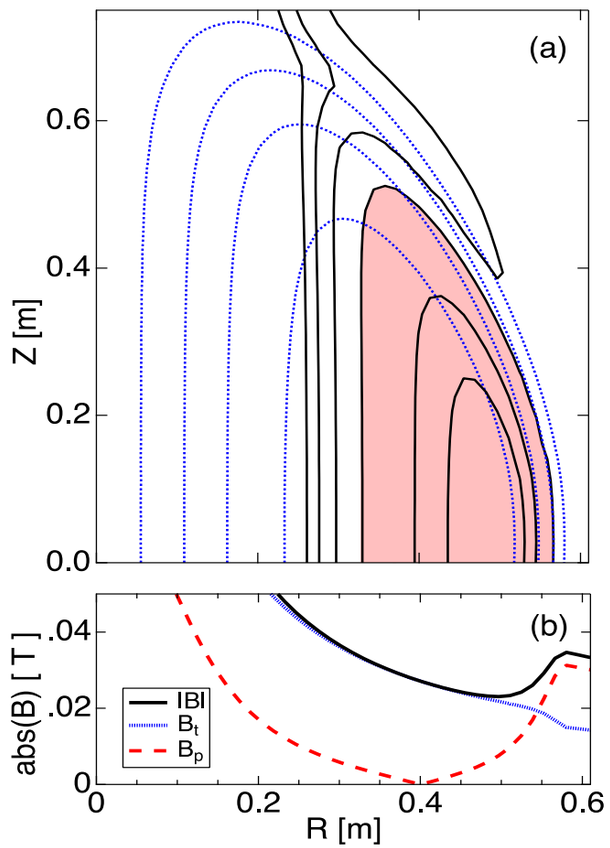
PEGASUS-III Machine Design Maintains Access to Low *A*

- Minimal increase to central column size
  - Diameter: $11\ cm \rightarrow 14\ cm$
- Relaxed edge diagnostic requirements
  - Insertable probe access at low B_T
- High β_T operation
  - Min $|B|$ well configuration
  - MHD limits at high toroidicity



Troyon Stability Diagram for Tokamaks, STs

Min $|B|$ Well in $\beta_t \sim 100\%$ Plasma



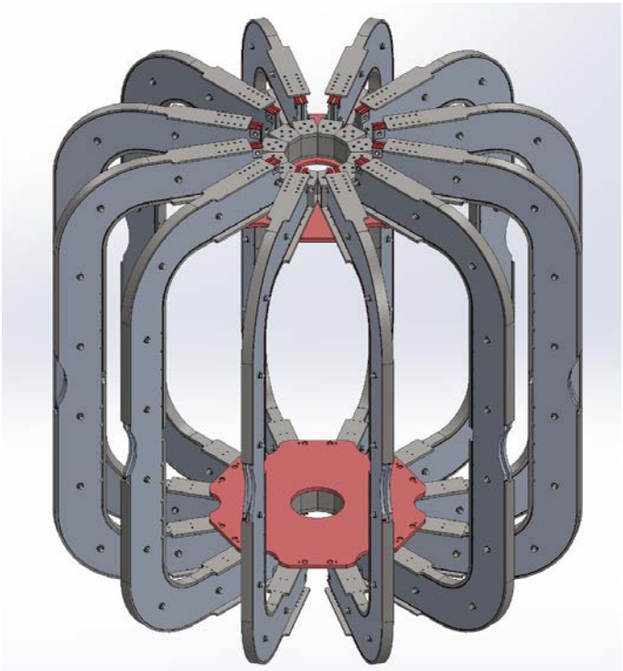
Schlossberg et al., Phys. Rev. Letters **119 035001(2017)*
Reusch et al., Phys. Plasmas **25 056101 (2018)*

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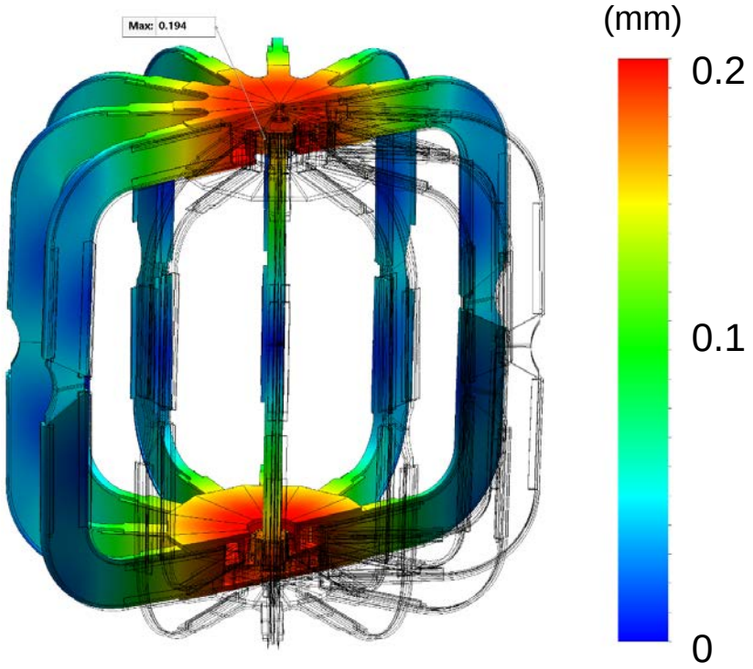
PEGASUS-III Upgrade Highlighted by Improved Toroidal Field Coils

- New, 24 turn toroidal field bundle and center column *without* central Ohmic solenoid
- 4x B_T operation results in 16x magnetic stress
  - Novel flex and compression joint designs based on implementation on PEGASUS
  - Comprehensive electro-mechanical analysis has been done to insure safe, reliable operation - ***A.C. Palmer - GP10.00.00126***

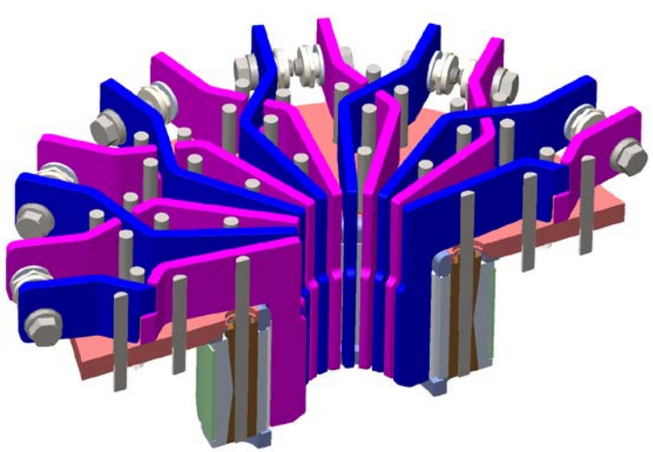
PEGASUS-III TF Return Model



Displacement at $B_T \sim 0.6T$



Upper Compression Joint



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PEGASUS-III Power Systems to Supply ~300 MVA of Programmable Power

- Optically isolated H-bridges
  - Most at 900V, 4 kA per bridge
  - Full digital feedback control and safety monitor
- PF – expansion for new DIV and vertical position control
- TF – new 48 kA power system
  - I_{TF} buildup system: 16 repurposed PEGASUS IGCTs
  - I_{TF} sustain system: 2-quadrant H-bridges built with new IGBTs
- LHI, S-CHI – 32MVA programmable $V_{inj}(t)$ control
- RF, DNB – resonant converter (e.g. ~ 80kV, ~ 4A for DNB)



PEGASUS H-bridge Inventory



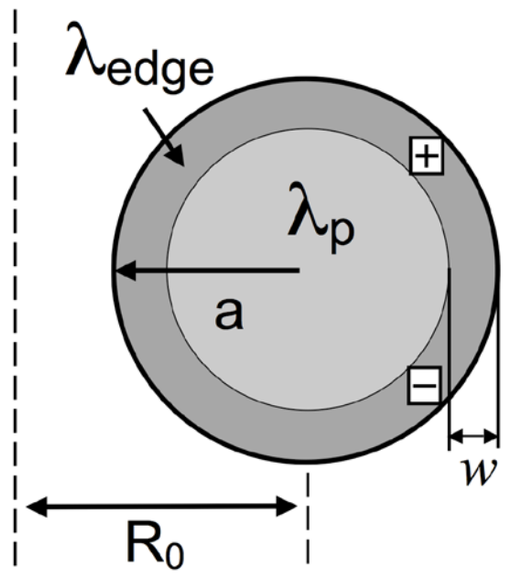
Resonant Supply

Global Helicity Balance and Taylor Relaxation Results in I_p Limits in Helicity Injection

- Current drive occurs as a result of global helicity balance:

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

- Absolute I_p limit from Taylor relaxation: $\left\langle \frac{\mu_0 J_{||}}{B} \right\rangle \equiv \lambda_p \leq \lambda_{edge} \rightarrow I_p \leq \frac{I_{inj}\Psi_T}{\psi_{inj}}$



- Schematic illustrating Taylor relaxation in DC helicity injection.

LHI

- I_p limit from balancing helicity drive and dissipation:

$$I_p \leq \frac{A_p}{2\pi R_0 \langle \eta \rangle}(\cancelto{0}{V_{IND}} + V_{LHI})$$

$$V_{LHI} \equiv \frac{A_{inj}B_{inj}}{\Psi_T}V_{inj} \approx \frac{A_{inj}}{A_p}\frac{R_p}{R_{inj}}V_{inj}$$

- LHI Taylor limit: $I_{p,TL} \sim \sqrt{\frac{I_{TF}I_{inj}}{w_{inj}}}$

CHI

- Relaxation occurs based on the "Bubble Burst" criteria:

$$I_{inj} \geq \frac{C\psi_{inj}}{{\mu_0}^2 d^2 I_{TF}}; C \sim O(1)$$

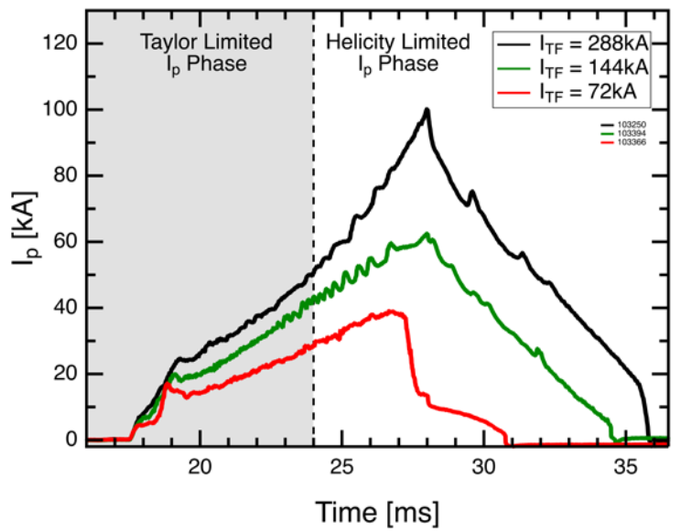
- CHI flux conversion: $\psi_{pol} \leq \psi_{inj}$

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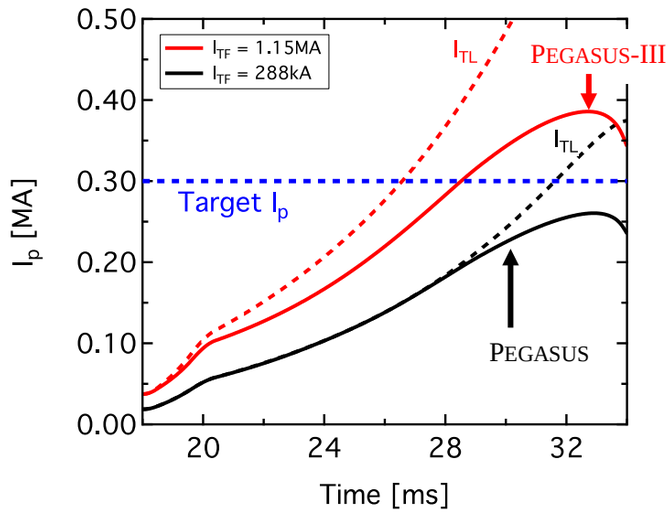
Projecting LHI to Larger Facilities Requires Tests at Increasing B_T

- Increasing B_T is a path to high I_p for LHI startup
  - I_p constrained by Taylor limit: $I_{TL} \sim \sqrt{I_{TF}}$
  - Increasing initial Taylor limit leads to strong I_p gains
- Physics variations with B_T
  - OH or stochastic scaling of core confinement
  - Magnetic reconnection and current drive mechanisms
  - Effects of stochastic edge on transport properties
  - Current stream stability and edge properties
  - Demonstration of achieving increased I_p
  - B_p null formation and tokamak relaxation
- Technology implications
  - Optimized geometry for reduced V_{inj}
  - Current channel uniformity
  - PMI mitigation
  - Long-pulse capabilities

PEGASUS B_T Scaling Experiment: Varying Initial I_{TL} Raises Final I_p



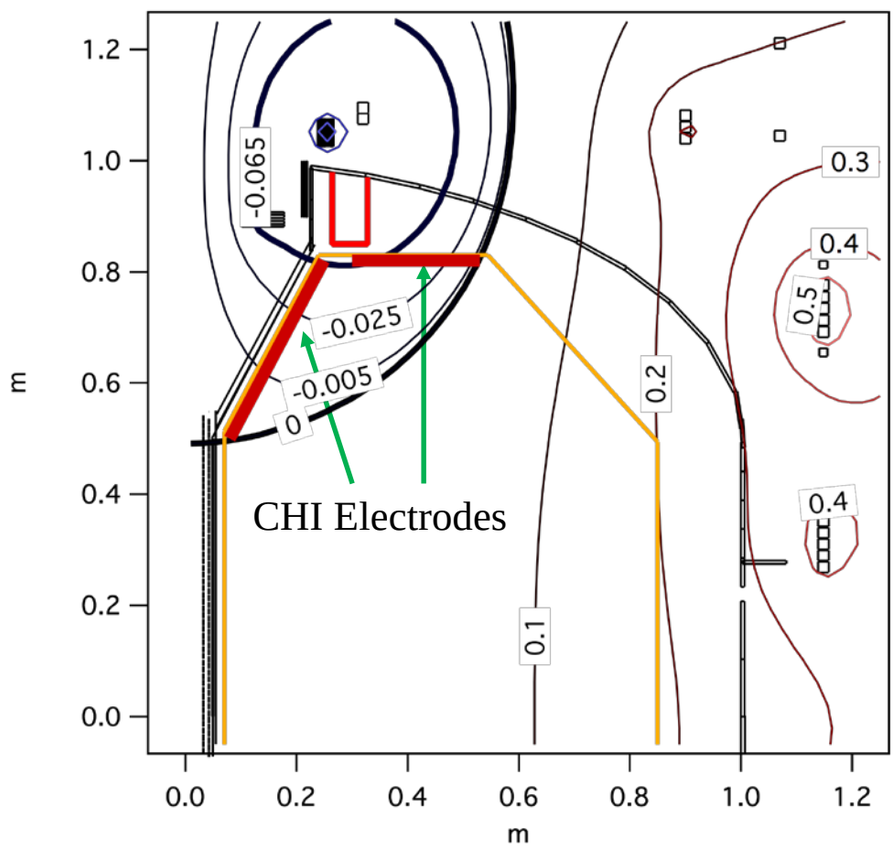
0-D Power-Balance Projections for LHI on PEGASUS-III



Two-Electrode CHI System to be Implemented on PEGASUS-III

- CHI system targets I_p = 0.3 MA
  - Segmented floating electrodes
  - B_T ~ 0.6 T for increased Taylor limit and decrease I_{inj}
  - Ψ_{inj} ~ 35 mWb to reach 0.3 MA Taylor limit
- Explore CHI physics at B_T = 0.6 T
  - Optimization of T-CHI and/or S-CHI scenarios
  - 2D axisymmetry vs 3D effects
  - Flux conversion efficiency
  - Validation of MHD simulations
  - Comparison and synergies w/other methods (LHI, RF, etc.)
- UW collaboration team (Raman, Nelson, Rogers)

65 mWb Connecting Simple CHI Electrodes

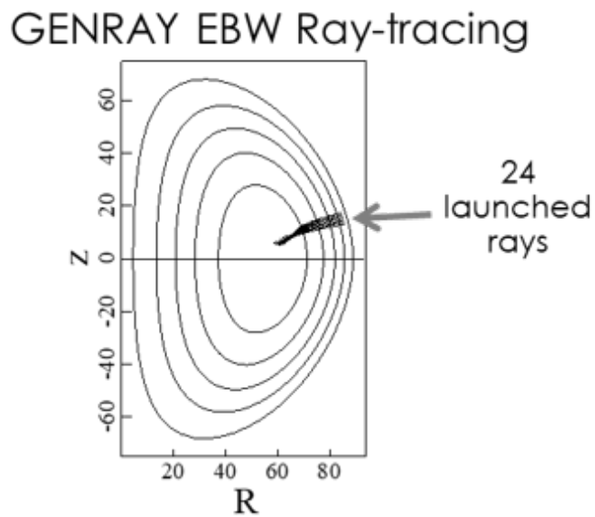


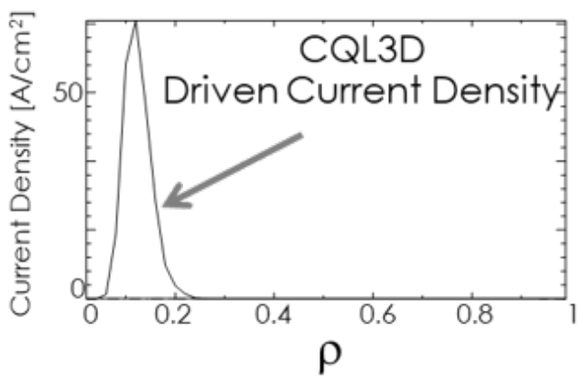
R Raman and V F Shevchenko, Plasma Phys. Control. Fusion ***56,*** *103001 (2014)*

R. Raman - GP10.00.00128

RF Heating and Current Drive: Synergies with LHI; Handoff/Startup

- Initial focus on EBW heating and current drive:
  - Heating for increased LHI/CHI efficiency
    - Classical helicity dissipation scaling: $\dot{K} \sim I_p R_p \sim {T_e}^{-3/2}$
  - Efficiency and localization
  - EBW CD as potential current sustainment
- ORNL collaboration team (Diem, Bigelow, Lau)
  - Loan agreement for the 8 GHz, 500 kW FTU system from Frascati in progress
  - Modeling of scenarios (GENRAY, CQL3D) ongoing
  - Implementation: Steerable O-mode mirror on LFS
- Possible expansion: add ECH and ECCD
  - Direct RF startup: Trapped electron precession → ECCD (see M. Ono (2019))
  - Explore proposed NSTX-U startup scenario (Poli et al.): HI + electron heating





S.J. Diem et al., 2018 US-EU-JP RF Technology Workshop
F.M. Poli et al., Nucl. Fusion ***55****, 123011 (2015)*

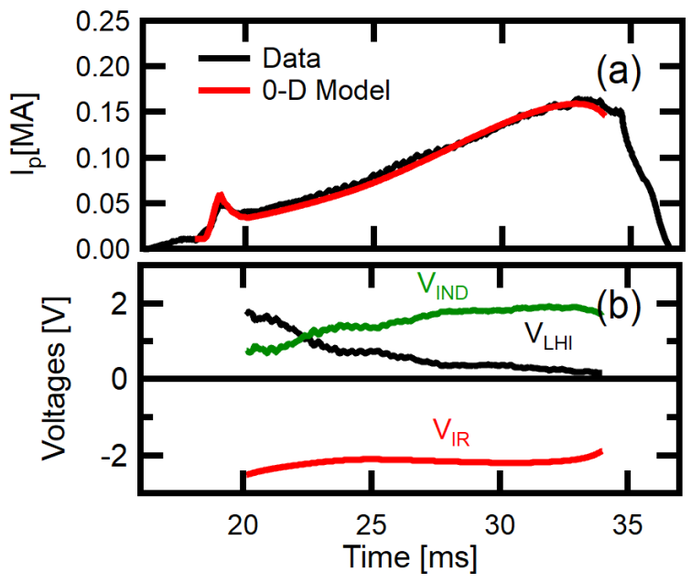
Modeling of LHI Experiments Defines Advantages of Different Injector Configurations

- 0-D power balance model predicts I_p(t) and quantifies contributions

$$I_p[V_{LHI} + V_{IR} + V_{IND}] = 0\,;\, I_p \leq I_{TL}$$

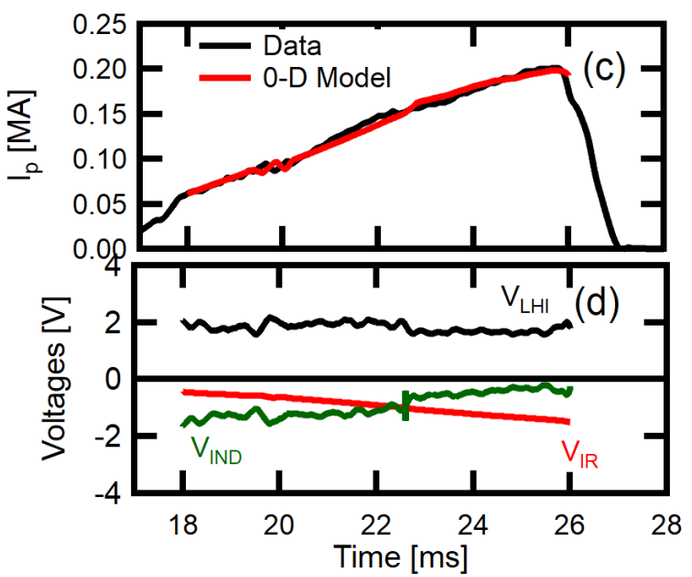
- Physics trade-offs balance out between two methods
  - Injector position based on engineering merits
- LFS geometry offers reactor-relevant design options
  - Port mounted injector assembly
  - Avoids difficulty of construction in divertor region

LFS: Non-solenoidal Induction



- Low-field-side (LFS) injection
  - Injectors on outboard midplane
  - High R_{inj} → weak V_{LHI}
  - Dynamic shape → strong V_{IND}

HFS: Helicity Injection

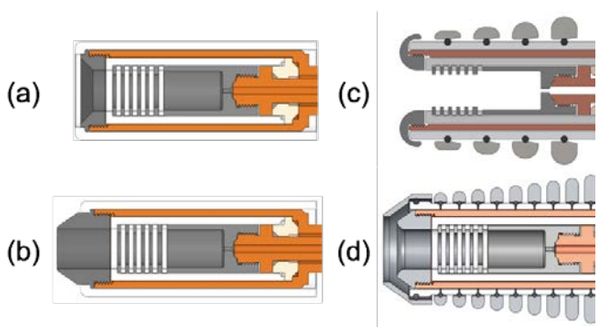


- High-field-side (HFS) injection
  - Injectors in lower divertor
  - Low R_{inj} → strong V_{LHI}
  - Static shape → weak V_{IND}

*J.A. Reusch, et al., Phys. Plasmas **25** 056101 (2018)*

LHI Source Development Confirms Active Arc Injector Preferred

- Helicity injector source design criteria
  - I_{inj} and w set $I_{TL} \geq I_p$
  - $N_{inj} A_{inj} V_{inj}$ to attain/sustain I_p
  - Armoring, limiters to minimize PMI
- Injector system geometry constraints
  - Provide initial relaxation via near-PF null
  - Conformal to desired plasma shape
  - Port access
- Cathode, shield ring features evolved to limit PMI
  - Concave → convex cathode: cathode spot control (PMI)
  - Shield rings, frustum shield: reduce PMI frequency



- Shaped electrode sources evaluated

Passive



High I_{inj}

$A_{inj} << A_{elec}$

high PMI

Active gas-fed



High I_{inj}

$A_{inj} \leq 10\% A_{elec}$

high PMI

- Active arc sources maximize V_{inj}, minimize PMI



V_{inj} ~ 400 V

high PMI



V_{inj} ~ 1000 V

medium PMI



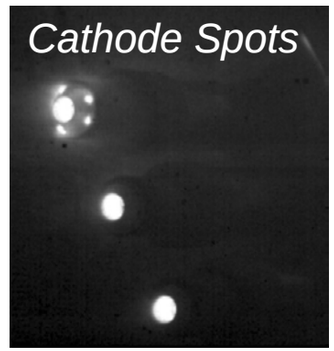
V_{inj} ~ 1500 V

low PMI

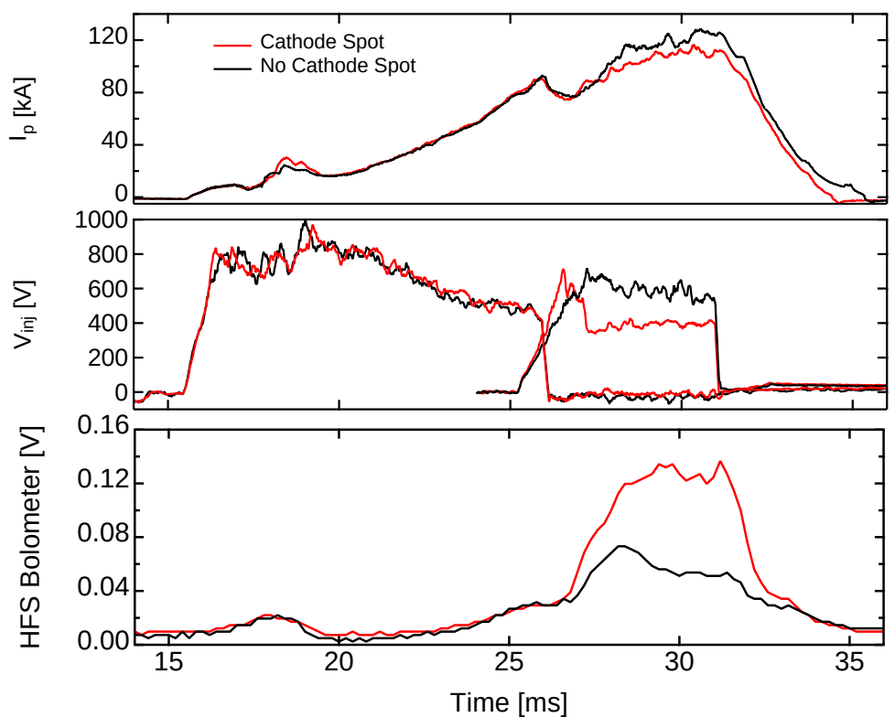
M.W. Bongard, et al., Nuclear Fusion ***59****, 076003 (2019)*

PMI on Injector Surfaces Restricts Operation at High V_{inj}

- Cathode spots occur at a critical electric field at the injector surface:
  - $E \sim \frac{V_{inj}}{\lambda_{De}} > E_{crit}$
  - Need to minimize n_e at bias surfaces
  - Lowering operating voltage is also helpful
- Onset of cathode spots abruptly decreases A_{inj} as current is sourced from spots
  - Significant drop in V_{LHI} as a result
  - May lead to craters formed on injector surface, enhancing likelihood of future PMI
  - Sources strong, irreducible impurities
- LHI operation on a MA class machine must minimize cathode spots



- LHI injector with cathode spots on the injection cathode surface



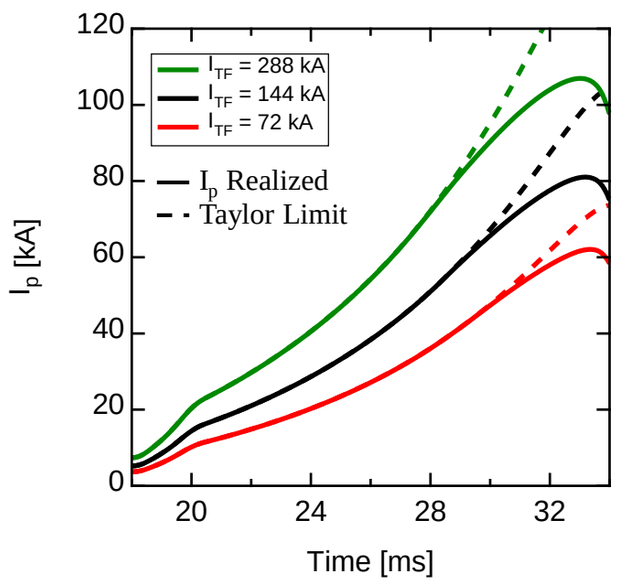
- Effects of a cathode spot on discharge evolution

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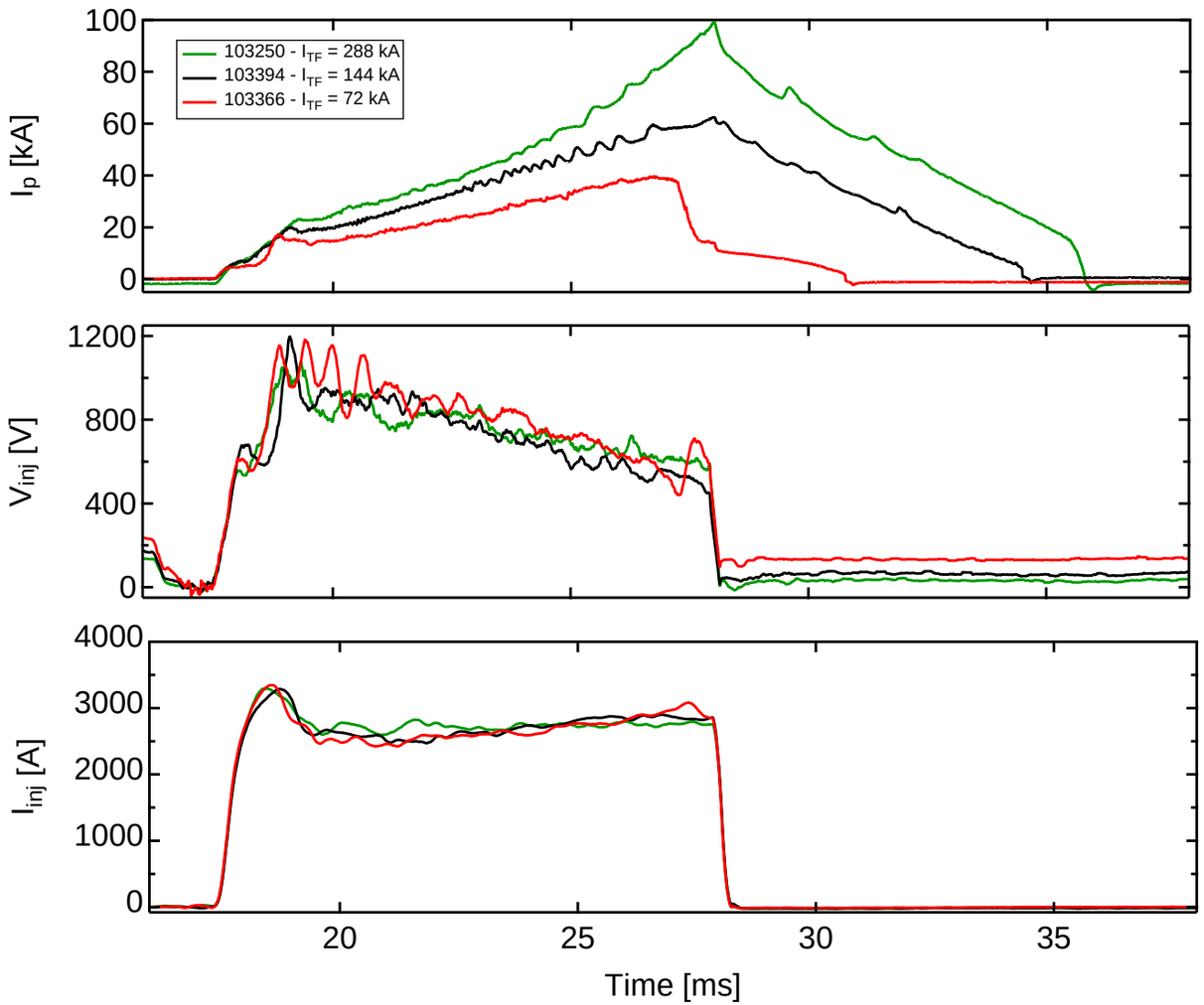
Favorable Scaling of I_p with Increasing Initial Taylor Limit

- Higher performance achieved as early Taylor limit is increased
- Behavior similar to model expectations
  - Modify early phase I_p Taylor limit via I_{TF}
  - Shape evolution and V_{inj} consistent between cases
  - Higher performance at end of discharge

A_{inj} = 4cm^2 , V_{inj} = 1kV , I_{inj} = 3.5kA , W_{inj} = 2.83cm



- 0-D Power balance model of varying Taylor limits



- Experimental results of model discharges

A.T. Rhodes, APS DPP 2019

Non-Circular Injector Provides Low V_{inj}, High A_{inj}, High Taylor Limit

- Non-circular “Kama” injector presents an attractive solution for LHI
  - Increased I_{inj} capability while maintaining low w_{inj} to increase Taylor limit
  - Large A_{inj} allows for high V_{LHI} operation at low V_{inj}

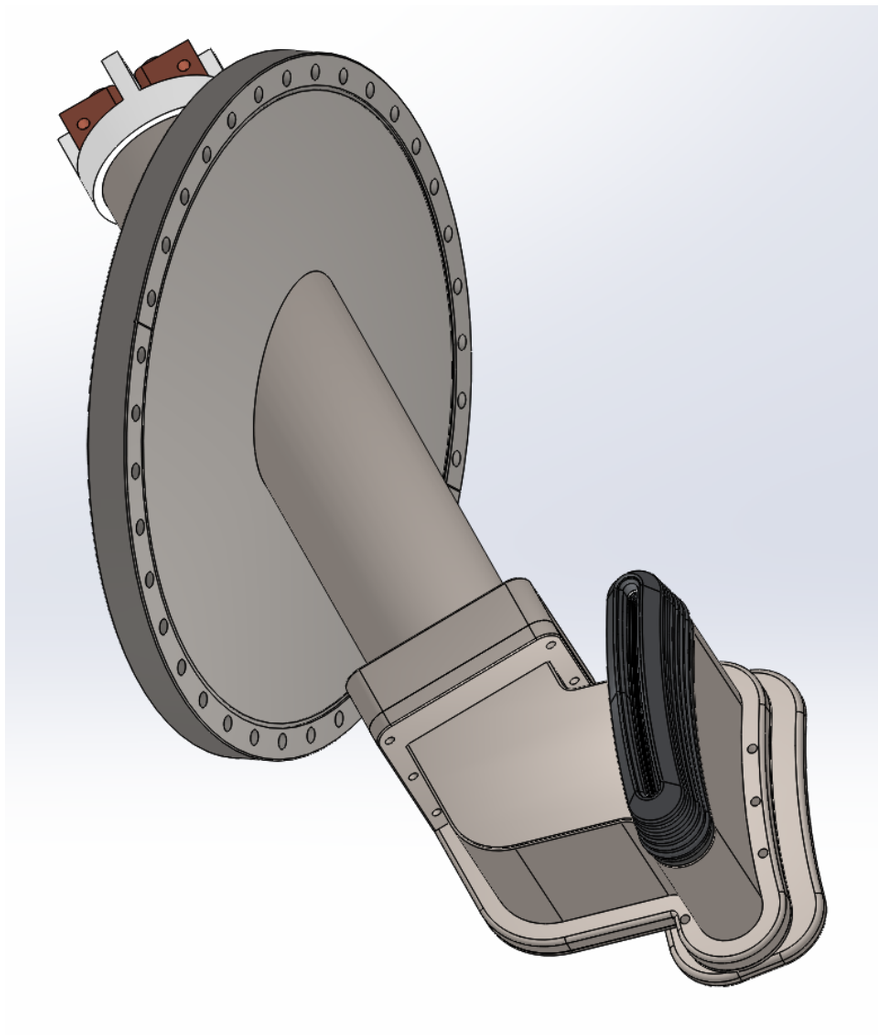
Taylor limit

$$I_p \leq I_{TL} \sim \sqrt{I_{TF} I_{inj} / w}$$

Helicity limit

$$I_p \leq V_{LHI} / R_p \sim A_{inj} V_{inj}$$

- Injector shape conforms to flux surfaces to improve coupling
- Re-entrant port-mounted design applicable for larger facilities, such as NSTX-U
- Prototype “Kama” fabricated for testing on Pegasus



Model of Kama Assembly

Kama Injector Design Minimizes PMI Along Plasma-Injector Interface

- A fraction of injected current will back-stream along shield rings through the SOL plasma

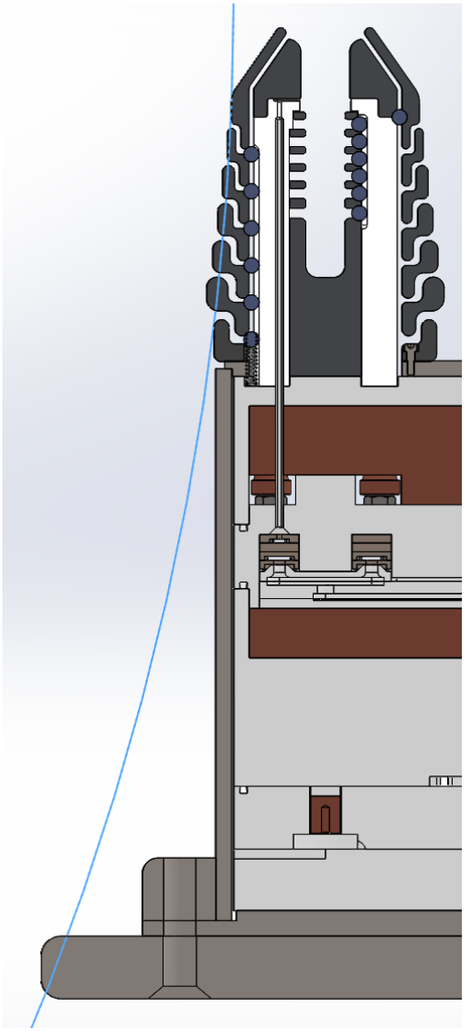
- Shield ring structure allows line-of-sight along field lines to only pass from one ring to the next
  - Illustrated by cross-section view of injector (right), with frustum shield field line in blue

- For ambipolar space charge layers, the back-streaming current density is given by:

$$J_a = \frac{4 n_0 e}{9(1 + 0.8{\Phi_N}^{3/4})^2} \frac{{\Phi_N}^{3/2}}{(1 + {\Phi_N}^{-3/2})^{2/3}} \sqrt{\frac{2T_e}{m_e}} \; ; \; \Phi_N = \frac{eV_{inj}}{N_{rings} T_e}$$

- Kama injector design results in:

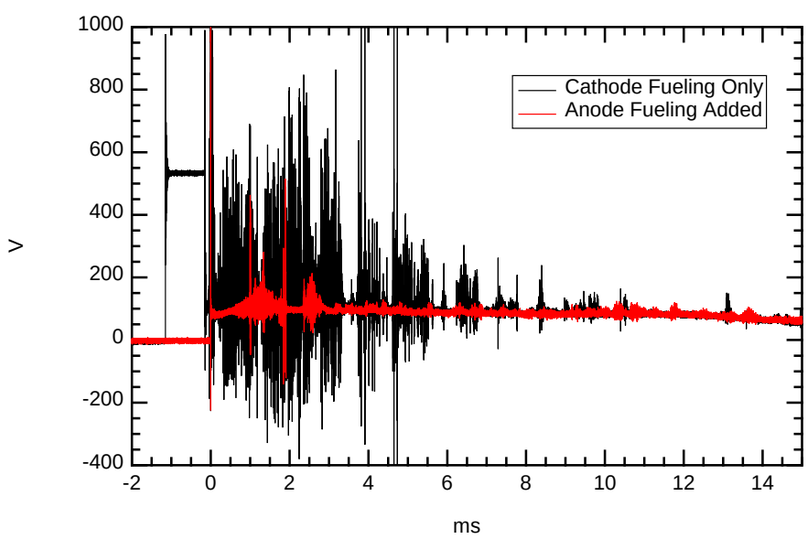
$$\frac{J_a}{J_{inj}} = 3.3\% \text{ ; for } J_{inj} = 1 \; kA/cm^2 \text{ - typical LHI sources}$$



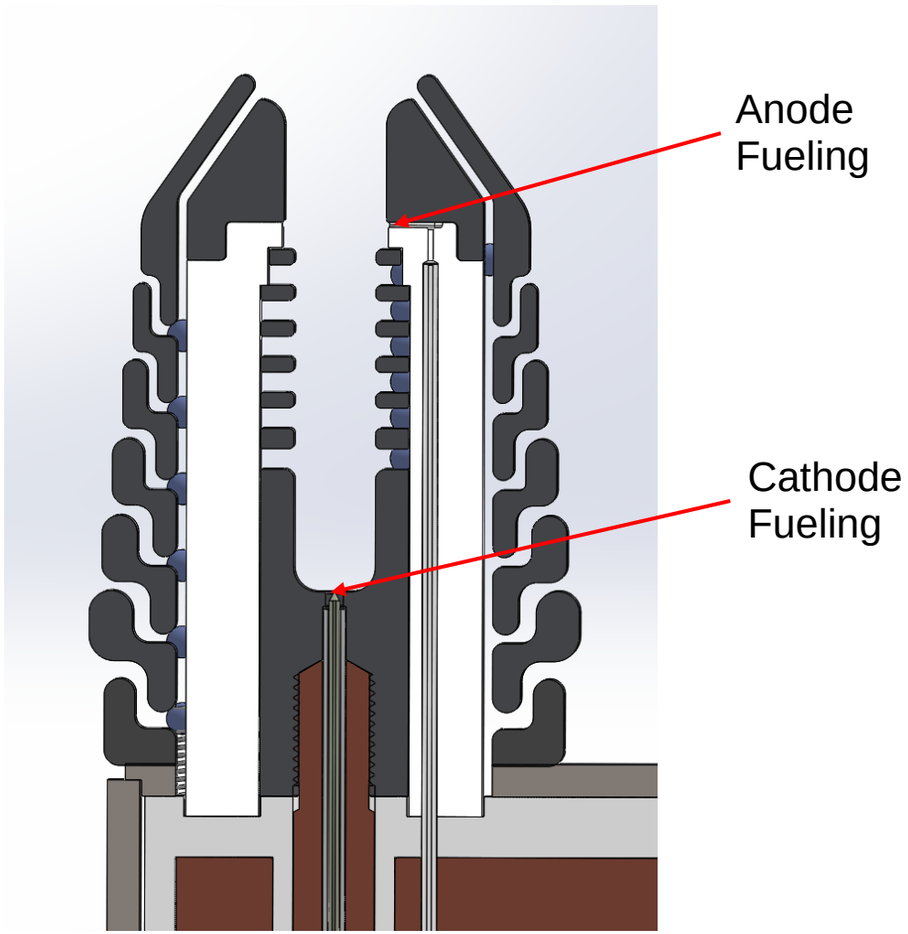
Takamura, et al. Contrib. Plasma Phys. (2004)

Kama Injector Features Advanced Fueling to Stabilize Arc Fluctuations

- "Kama" Injector will feature separate fueling at arc cathode and anode
  - Independent gas valves for either fueling location
- Lab tests show stabilization of arc plasma due to anode fueling



- Arc voltage waveforms with reduced fluctuations from anode fueling

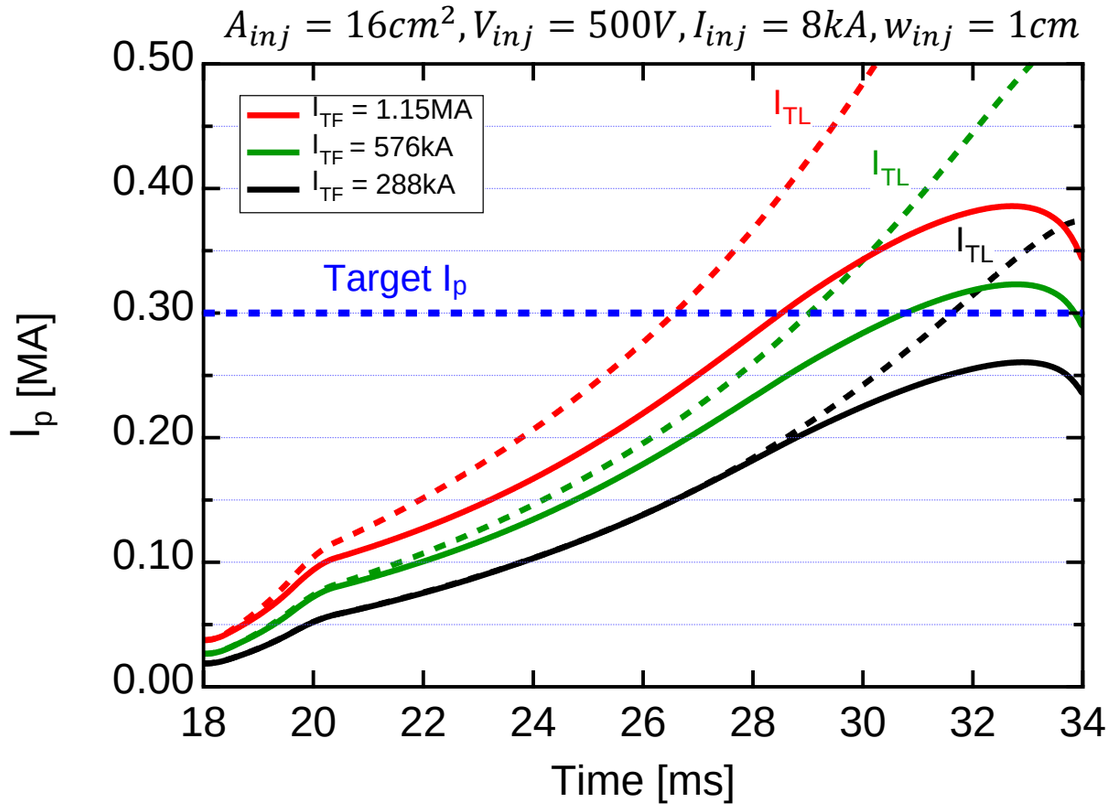


- Cross-section of "Kama" injector showing gas outlet channels for arc fueling

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Kama Injector Should Access I_p ~ 0.3 MA on PEGASUS-III

- High power design for PEGASUS-III
  - Refractory metal electrodes (Mo/W)
  - Programmable $V_{inj}(t)$ power systems
  - Active gas control
  - $I_{inj} \leq 16$ kA
- 0-D Model Predicts I_p ~ 0.3 MA with modest injector parameters
  - LFS injection scenario with dynamic shape evolution
  - I_{inj} = 8 kA used in modeling is only half of injector capability
  - Strictly helicity limited at $B_{TF} \sim 0.6$T
  - Kama parameters ($A_{inj}, V_{inj}, w_{inj}$) sufficient to achieve projections
- Operation at enhance B_T compatible with CHI/RF



Model projection for "Kama" LHI system on PEGASUS-III

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Prototype Kama Injector will Assess Viability of a Large-Area Injector for PEGASUS-III

- Kama injector prototype will be tested with lower power
  - Non-refractory electrodes to simplify fabrication

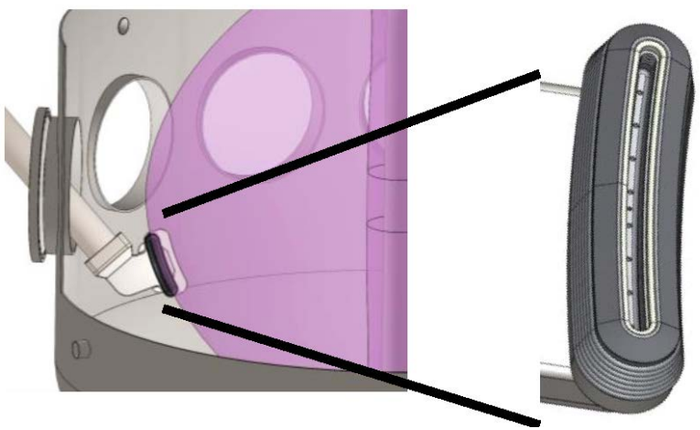
- Physics and operational issues:
  - Uniform arc breakdown and current extraction
    - Non-uniform current extraction results in reduce effective A_{inj}
  - Extracted beam stability
    - ability to drive magnetic reconnection
  - Geometry and current density requirements for null formation
  - Impact of neutral gas load on injector impedance

Prototype Kama in Fabrication for Tests on PEGASUS

- Operational parameters:
  - Arc channel dimensions: 1 cm x 16.2 cm
  - $A_{inj} = 16\ cm^2$
  - $R_{inj} = 70\ cm$
  - $Z_0 = -20\ cm$
  - Arc channel to LCFS: 1.8 cm
- Power supplies for test offer $V_{inj} \leq 1\text{kV};\ I_{inj} \leq 8kA$
- Injector hardware and contained within single, port-mounted assembly



Stainless steel Kama prototype components



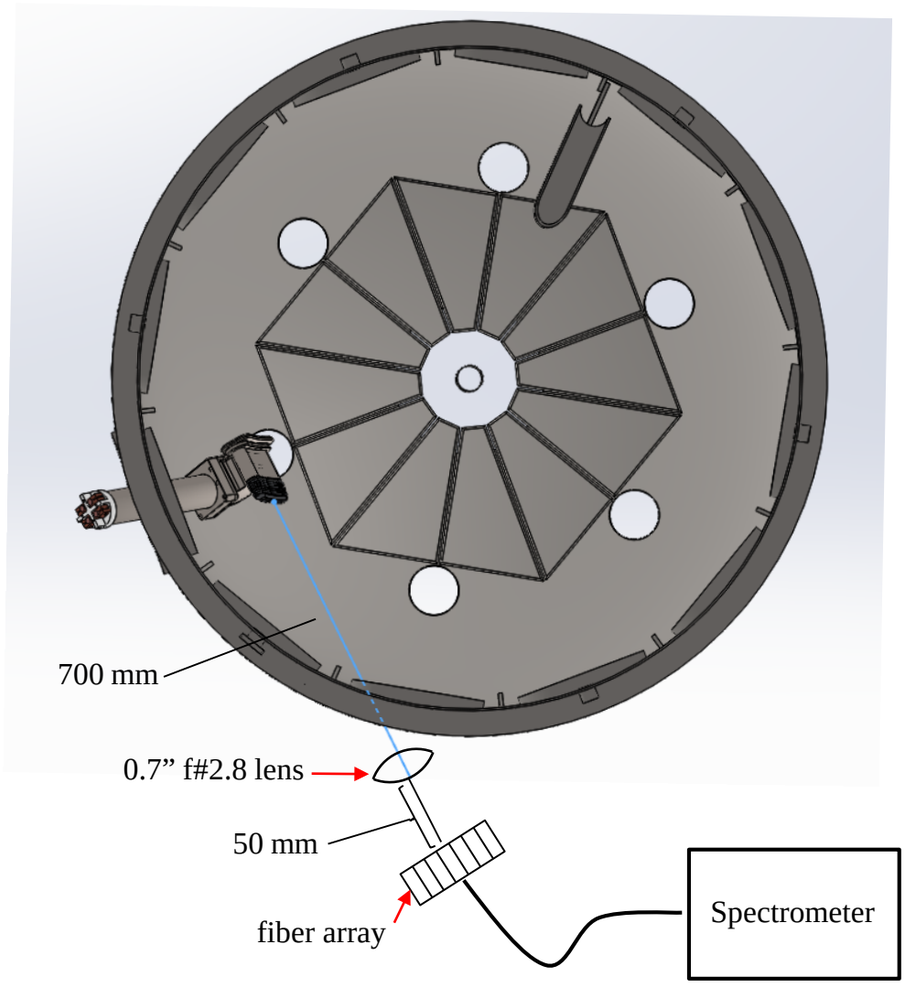
Model of Kama in PEGASUS vacuum vessel

Several Criteria Needed for Successful Kama Prototype Test

- Arc breakdown achieved throughout channel
  - Lower power with non-refractory electrodes
- Beam current uniformly extracted from arc plasma
- Demonstration of capability for relaxation and current drive
  - Test at low injected current and low field
- Efficacy of anode gas fueling
  - Does not impede current extraction or enhance PMI

Stark Broadening Measurement will Assess Uniformity of Arc Channel

- Uniformity of gas breakdown in the arc tube is critical for Kama injector success
- Arc density measured using D_γ line at 434 nm
  - $n_e[m^{-3}] = 10^{23}\left(\frac{FWHA\,(nm)}{4.668}\right)^{1.45826}$
- Light is collected by a 0.5 meter Acton 2500 SpectroPro Czerny-Turner spectrometer and an Andor iXon 358 emCCD camera
  - A fiber bundle of eight 1100 μm fibers provides a spatial scan of the injector arc channel
- A similar diagnostic has been used to measure arc density in LHI sources in the past – *Hinson. PhD Thesis, UW-Madison. 2015.*



- Schematic of arc density measurement

Upgrade to PEGASUS-III is Underway

- PEGASUS-III will compare/contrast/combine multiple non-inductive startup techniques in a single facility
  - Local Helicity Injection (LHI)
  - Transient and Sustained Coaxial Helicity Injection (CHI)
  - EBW radiofrequency heating and current drive
- Toroidal field magnet construction is in progress
- Kama injector prototype is in fabrication for testing
- Configuration of coil power supplies for PEGASUS-III is in progress
- Operational in 2020

Unified Non-Solenoidal Startup Mission

Transitioning from Pegasus to PEGASUS-III



Non-Solenoidal Startup Techniques on PEGASUS-III



Informing Injector Design for PEGASUS-III

New “Kama” Injector Under Development



Future of Non-Solenoidal Startup on PEGASUS-III