A Coaxial Helicity Injection System for Non-Solenoidal Startup Studies on the PEGASUS-III Experiment

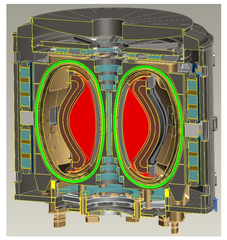
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*Work Supported by US DOE grants DE-SC0019008, DE-SC0020402, and DE-SC0019415

Non-Solenoidal Startup Critical for Spherical Tokamak and May Benefit Advanced Tokamaks

- Future ST designs call for solenoid-free operation
  - Nuclear STs 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
  - Lower electromechanical stresses
- Solenoid-free startup techniques may offer tools for modifying $J(R)$

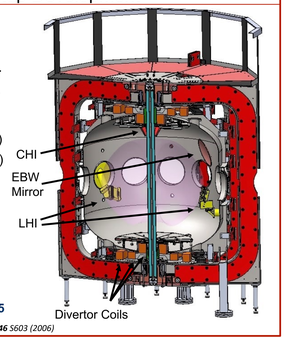


*No / small OH HTS ST-FNSF / Pilot Plant**

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

PEGASUS-III Will Provide a Dedicated US Platform for Solenoid-Free Startup Development

- Major facility upgrade to PEGASUS*
- Compare / contrast / combine concepts for solenoid-free startup in a dedicated facility
  - Local Helicity Injection
  - Coaxial Helicity Injection (Transient, Sustained)
  - RF assist and sustainment (EBW, ECH, ECCD)
  - Assess compatibility with RF/NBI heating and current drive
- Goal: develop validated physics and technology basis for MA-class startup on NSTX-U and beyond



See also A. Sontag, Poster Session 121, ID 535

Garstka et al., Nucl. Fusion **46 S603 (2006)*

Coaxial Helicity Injection can Initiate and Drive Tokamak Plasmas with Axisymmetric Electrodes

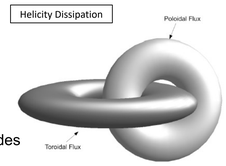
- Current drive increases the amount of poloidal flux ψ_p linked with the toroidal flux created by external coils (magnetic helicity)

$$K = \int_V \boldsymbol{B}\cdot\boldsymbol{A}\,dV\,;\quad \frac{dK}{dt} = -2\frac{\partial\psi}{\partial t}\Psi - 2\int_S \Phi\boldsymbol{B}\cdot d\boldsymbol{S} - 2\int_V \eta\boldsymbol{J}\cdot\boldsymbol{B}dV$$

AC Helicity Injection | DC Helicity Injection | Helicity Dissipation

- DC helicity injection can be represented by an effective loop voltage:

$$V_{HI} = \frac{\oint_S \Phi\,\vec{B}\cdot d\hat{s}}{\Psi} = \frac{V_{inj}A_{inj}B_{inj}}{\Psi}$$



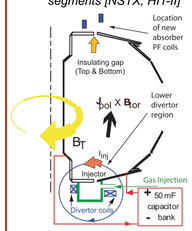
- CHI: Large area (A_{inj}) biased (V_{inj}) coaxial electrodes drive open field line current (I_{inj})
- Taylor relaxation limits I_p to lowest energy state that conserves K

$$\lambda \equiv \frac{\vec{J}\cdot\vec{B}}{B^2} \qquad \bar{\lambda}_{plasma} \le \bar{\lambda}_{edge} \quad\rightarrow\quad \boxed{I_p \le I_{inj}\frac{\phi_p}{\psi_{inj}}}$$

- ψ_{inj} provided by divertor coils, ϕ_p toroidal flux enclosed by plasma
- "Bubble burst" condition: $J\times B$ stress overcomes field line tension

$$\boxed{I_{inj} = \frac{C\psi_{inj}^2}{\mu_0^2 d^2 I_{TF}}}$$

*CHI via biased vacuum vessel segments [NSTX, HIT-II]**



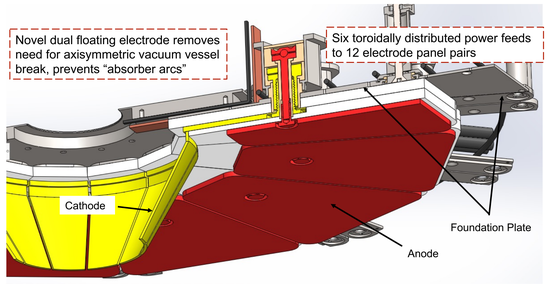
Two techniques

- Transient (T-CHI):
  - Stretch connected flux and quickly force reconnection to create closed flux
  - High poloidal flux conversion efficiency important
  - $\psi_p/\psi_{inj} = 50-80\%$ demonstrated**
- Sustained (S-CHI):
  - Build up connected flux by continued current drive
  - Requires dynamo/reconnection for closed flux current

R. Raman et al., Nucl. Fusion **53 (2013)*

***R. Raman et al., Fusion Sci. Tech. **68** (2015)*

PEGASUS-III will Advance CHI Design with a Novel Segmented Dual Electrode

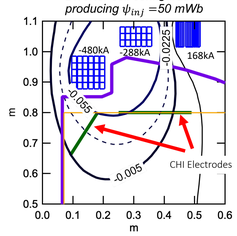


- Coupled with toroidal field and divertor coil system upgrades, CHI electrodes supports science mission of PEGASUS-III
  - Capable of both transient and sustained CHI operation
  - Flexible divertor coil flux geometry + modular electrode design enables exploring importance of flux distribution across electrodes
  - System capable of CHI-driven plasmas to PF limits (I_p~0.3 MA)

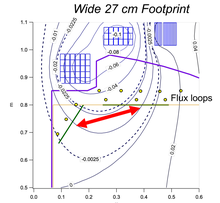
New Divertor Coil Set Enables CHI Physics Studies

- New high power divertor coil triplet allows for high current CHI
  - 30/18/14 turn coil set from inner to outer R
  - 480/288/224 kA-turn capability
  - Each coil multi-tapped at 1/3, 2/3 ratio for increased flexibility
  - Can provide over 50 mWb poloidal flux connecting electrodes
  - At 1.15 MA TF rod current, provides ample flux for 300 kA plasma current

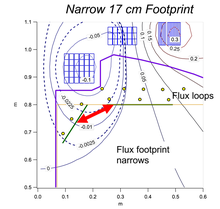
Divertor coil configuration producing ψ_{inj} =50 mWb



Wide 27 cm Footprint

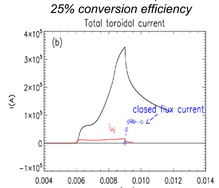


Narrow 17 cm Footprint

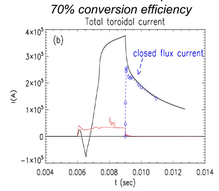


- HIT-II and NSTX found flux conversion efficiency (T-CHI) and flux amplification (S-CHI) scale with footprint separation "d"
  - Two point comparisons
  - Insufficient data to date to generate scaling
- High power divertor coils enable variation in flux distribution at high connected flux
  - New system allows tests of scaling with simple coil current variation
  - Predictions of injector current at bubble burst and Taylor limit scale strongly with d, ψ_{inj}
- NIMROD simulations qualitatively agree with NSTX results*
  - Indicated still higher conversion efficiency possible with narrower footprints
- Likely also important for generation of flux amplification in S-CHI**
  - Data to date indicate threshold but not scaling or efficiency information

Simulated "Wide" footprint with 25% conversion efficiency



Simulated "Narrow" footprint with 70% conversion efficiency



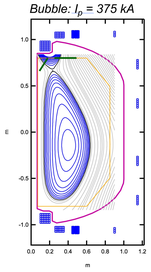
Ebrahimi, Phys. Plasmas **26, 092502 (2019)*

***Redd, et al., Phys. Plasmas **15**, 022506 (2008)*

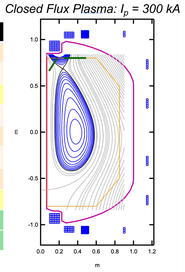
T-CHI System Design Projections Indicate 300 kA Readily Achievable

- T-CHI discharge forms in ~1 ms, expected full pulse ~5 ms
  - Too short for plasma shape control with external coils
  - Requires vacuum fields, ψ_{inj} consistent with full formed high I_p plasma
- Steady state magnetic equilibria provided by KFIT Grad-Shafranov solver*
  - Vacuum fields connect electrodes with over ~30 mWb of poloidal flux
  - Expected closed flux current ~300 kA
  - Peak predicted open field line current ~375 kA
  - Divertor, poloidal field coil currents held constant

Bubble: I_p = 375 kA → *Constant PF Coil Programming* → *Closed Flux Plasma: I_p = 300 kA*

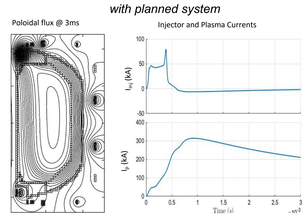


Parameter	Value
"d" [cm]	17
ψ_{inj} [mWb]	32
BB I_{inj} [kA]	37
Bubble $\psi_{p,poi}$ [mWb]	32
Closed Flux $\psi_{p,poi}$ [mWb]	27
Bubble $\Psi_{T,poi}$ [mWb]	390
Closed Flux $\Psi_{T,poi}$ [mWb]	260
Flux Conversion [%]	84
Bubble TL [kA] (I_{inj} = 30kA)	410
Closed Flux TL [kA] (I_{inj} = 30kA)	300



- Initial simulations with Tokamak Simulation Code (TSC) support equilibrium analysis**
  - Simulations evolve plasma current distribution self consistently
  - Indicate 300kA achievable
  - Poloidal field coil currents still need to be optimized

TSC simulations indicate 300 kA achievable with planned system

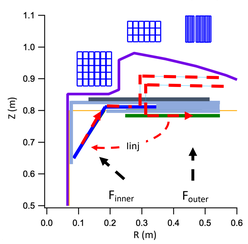


*Sontag, et al., Nucl. Fusion **48** (2008) 095006

**Raman, Proceedings of the 63rd annual APS-DPP meeting, BP11.00005

Electromechanical Forces on CHI Structure Non-trivial

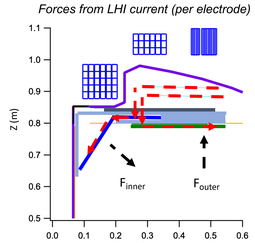
Forces from CHI current (total)



For I_{inj} = 40 kA, F_{outer} ~ F_{inner} ~ 6.4 kN
$F_{phi,inner}$ ~ -4 kN, $F_{phi,outer}$ ~ -3 kN

- Electrodes see significant $I_{inj} \times B$ forces
  - Two cases of interest: CHI and LHI
- CHI: axisymmetric current distribution
  - Up to 33 kA total injected current
  - Current is distributed on 6 power feeds
  - Current sharing reduces force per electrode
  - Forces put entire structure in compression → easily manageable
- Second case of interest is Local Helicity Injection (LHI) return current case
  - LHI is a separate startup system on PEGASUS-III (see Sontag Poster ID 535)
  - Produces high current localized electron beam
  - Up to 16 kA for 25 ms could return to any single electrode
  - Forces on inner electrode put structure in tension, outer electrode in compression
- LHI most challenging electromechanical, thermal stress for the CHI system

Forces from LHI current (per electrode)

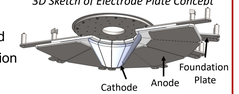


For I_{inj} = 16 kA, F_{outer} ~ F_{inner} ~ 2.5 kN
$F_{phi,inner}$ ~ 1.4 kN, $F_{phi,outer}$ ~ -1 kN

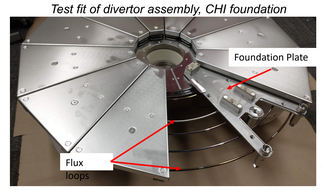
CHI Electrodes and Power Feeds are in Design, Power Supplies are Built

- Electrode mechanical structure for CHI is in design
  - Electrodes to be located in upper divertor region
  - Physics and engineering requirements fully specified
  - Electrodes capable of transient and sustained injection
  - 12 segments powered by 6 feeds
  - Primary challenge is handling large unbalanced LHI current

3D Sketch of Electrode Plate Concept



Test fit of divertor assembly, CHI foundation

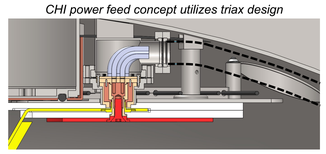


- CHI electrodes/insulators will mount off divertor "foundation plates"
- Power feeds will enter from top on high field side
  - Optimizes $J\times B$ forces
- Diagnostics integrated into assembly

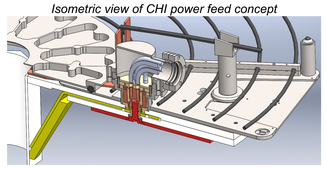
Power Fed Through Six Toroidally Distributed Umbilical Structures

- Large copper cross section needed to minimize heating
  - Required capability: 16 kA for 25 ms with < 20 °C rise per shot
  - Vacuum break close as possible to CHI electrodes on high field side
  - Allows air cooling of cabling
- Latest design iteration utilizes 4 x 6 AWG wires per electrode
  - Limits heating to 12 °C per shot
  - Utilizes standard conflat flanges with custom peek insulators
  - Coaxial feed with outer grounded shell (~triax design)
  - 4 O-rings provide vacuum break
  - Structural connection helps support electrodes

CHI power feed concept utilizes triax design

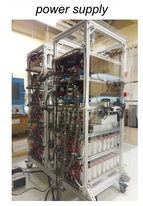


Isometric view of CHI power feed concept



CHI I_{inj} Supplied by Two New Power Systems

Low Inductance T-CHI power supply



- Power supplies for T-CHI and S-CHI constructed
- T-CHI uses 4.13 kJ, 2.1 kV, 22 kA cap bank
  - 1ms pulse
  - Relies on L and R of plasma for pulse shape
- S-CHI uses 2 MJ, 2.7 kV, 16 kA MLBC supply*
  - Sub-ms voltage, current feedback control

S-CHI, LHI bias MLBC power supply



See also M. Bongard, Poster Session 311, ID 481

Pegasus-III will Enable Exciting New CHI Studies

- Develop and test a double biased electrode configuration
  - First test of novel electrode geometry
  - Supports transient, sustained CHI experiments
- First CHI studies on will establish and optimize T-CHI scenarios
  - I_p up to external PF coil limits as B_T is raised (goal: 0.15 → 0.3 MA)
  - Quantify impact of parameter "d", flux shaping, and CHI insulator location and gap width on the closed flux conversion efficiency
  - Compare CHI discharge to MHD simulations
- Future:
  - Sustained CHI studies
  - T-CHI-to-LHI sustainment scenarios
  - RF auxiliary heating of T-CHI discharges
  - Impact of non-axisymmetry on performance

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