Engineering Design of a Coaxial Helicity Injection System for Non-Solenoidal Startup Studies on PEGASUS-III

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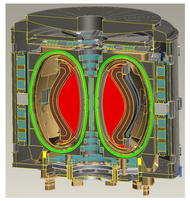
PEGASUS-III Experiment

Department of Engineering Physics, UNIVERSITY OF WISCONSIN–MADISON

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
  - 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 Pilot Plant**

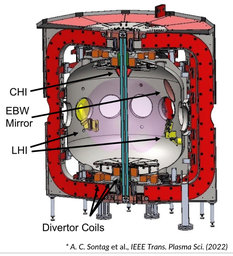


*J.E. Menard, Phil. Trans. R. Soc. A **377**, 20170440 (2019)

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
  - See M.W. Bongard CP11.00040

CAD Model of PEGASUS-III



* A. C. Sontag et al., *IEEE Trans. Plasma Sci.* (2022)

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

- Current drive increases poloidal flux ψ_p linked with toroidal flux Ψ_T from external coils (magnetic helicity K)

$$K = \int_V \boldsymbol{B}\cdot\boldsymbol{A}\,dV\,; \quad \frac{dK}{dt} = -2\frac{\partial\psi_p}{\partial t}\Psi_T - 2\int_S \Phi B\cdot dS - 2\int_V \eta\boldsymbol{J}\cdot\boldsymbol{B}dV$$

AC Helicity Injection | DC Helicity Injection | Helicity Dissipation

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

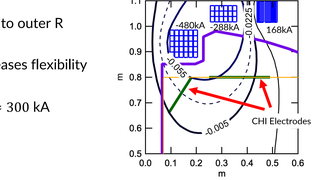
$$V_{HI} = \frac{\oint_S \Phi\,\vec{B}\cdot d\vec{s}}{\Psi_T} = \frac{V_{inj}A_{inj}B_{inj}}{\Psi_T}$$

- 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

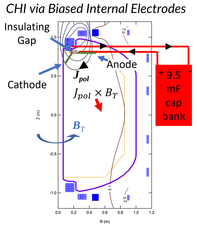
$$\lambda \equiv \frac{\vec{J}\cdot\vec{B}}{B^2} \qquad \bar{\lambda}_{plasma} \le \bar{\lambda}_{edge} \;\rightarrow\; \boxed{I_p \le I_{inj}\frac{\Psi_T}{\psi_{inj}}}$$

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

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



CHI via Biased Internal Electrodes

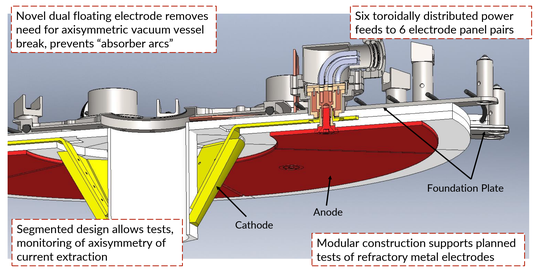


Two techniques

- Transient (T-CHI):
  - Stretch ψ_{inj}, force reconnection for 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 flux generation

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

PEGASUS-III Will Advance CHI Design With a Novel Segmented Dual Electrode



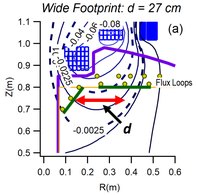
- CHI system supports science mission of PEGASUS-III
  - Capable of transient and sustained CHI operation
  - Flexible divertor coil flux geometry + modular electrode design enables exploring importance of flux distribution across electrodes
  - System capable of CHI-driven plasmas to PF limits (I_p~0.3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

New Divertor Coil Set Enables CHI Physics Studies

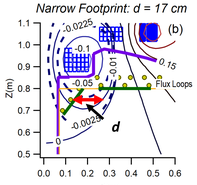
- New high power divertor coil triplet allows for high current CHI
  - 30/18/14 turn coil set from inner to outer R
  - 480/288/224 kA-turn capability
  - Multiple taps (1/3, 2/3 ratio) increases flexibility
  - Can provide > 50 mWb ψ_{inj}
  - At 1.15 MA I_{TF}, ample flux for $I_p \approx 300$ kA

Divertor Coil Configuration Producing ψ_{inj} = 50 mWb

Wide Footprint: d = 27 cm

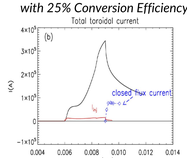


Narrow Footprint: d = 17 cm

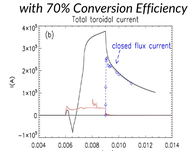


- HIT-II, NSTX : flux conversion efficiency (T-CHI), flux amplification (S-CHI) scale with "d"
  - "d" is radial separation of flux footprint midpoints
  - Two-point comparison
  - Insufficient data to date to generate scaling
- High power divertor coils enable variation in flux distribution at high connected flux
  - Allows test of scaling via coil current variation
  - $I_{inj,BB}$ and Taylor limit scale strongly with d, ψ_{inj}
- NIMROD simulations qualitatively agree with NSTX results*
  - Indicated higher conversion efficiency possible with narrower footprints
- d is 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

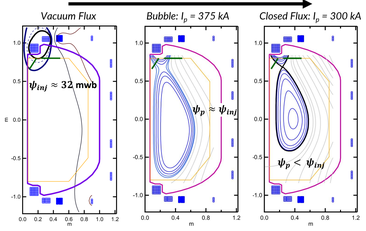


*Ebrahimi, Phys. Plasmas **26**, 092502 (2019)
Redd, et al., Phys. Plasmas **15, 022506 (2008)

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

Constant PF Coil Programming

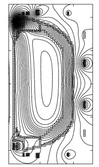


Parameter	Value
"d" [cm]	17
ψ_{inj} [mWb]	32
BB I_{inj} [kA]	37
Bubble $\psi_{p,pol}$ [mWb]	32
Closed Flux $\psi_{p,pol}$ [mWb]	27
Bubble $\Psi_{T,pol}$ [mWb]	390
Closed Flux $\Psi_{T,pol}$ [mWb]	260
Flux Conversion [%]	84
Bubble TL [kA] (I_{inj} = 30kA)	410
Closed Flux TL [kA] (I_{inj} = 30kA)	300

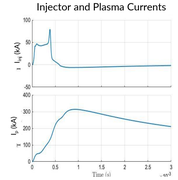
TSC Simulations Indicate 300 kA Achievable with Planned System

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

Poloidal flux @ 3ms



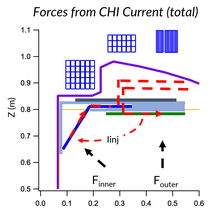
Injector and Plasma Currents



*Sontag, *et al.*, Nucl. Fusion **48** (2008) 095006
**Raman, *et al.*, Fusion Sci. and Tech. (2022)

CHI Structures See Significant Electromechanical Force

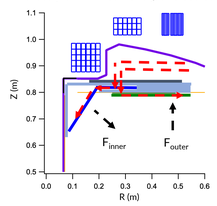
Forces from CHI Current (total)



For I_{inj} = 40 kA, $F_{outer} \sim F_{inner} \sim$ 6.4 kN
$F_{phi,inner} \sim$ -4 kN, $F_{phi,outer} \sim$ -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
- Local Helicity Injection (LHI): localized current return
  - LHI is a separate startup system on PEGASUS-III (see A.C. Sontag, CP11.00045)
  - Produces high current localized electron beam
  - Up to 16 kA for 25 ms could return to any single electrode
  - Force on inner electrode put structure in tension, outer electrode in compression
- LHI: most challenging electromechanical, thermal stress for the CHI electrodes

Forces from LHI Current (per electrode)

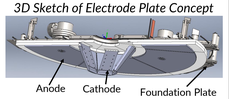


For I_{inj} = 16 kA, $F_{outer} \sim F_{inner} \sim$ 2.5 kN
$F_{phi,inner} \sim$ 1.4 kN, $F_{phi,outer} \sim$ -1 kN

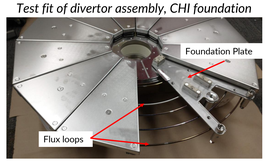
CHI Electrodes and Power Feeds Are In Design, Power Supplies Are Built

- Electrode mechanical structure for CHI is in design
  - Electrodes located in upper divertor region
  - Physics, engineering requirements fully specified
  - Electrodes capable of transient, sustained injection
  - 6 segments powered by 6 feeds
  - Stainless steel electrodes initially, Mo or W in future

3D Sketch of Electrode Plate Concept



Test fit of divertor assembly, CHI foundation

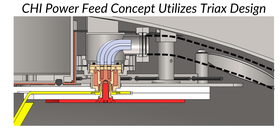


- CHI electrodes/insulators will mount off divertor "foundation plates"
- Power feed from top on high field side
  - Optimizes $J \times B$ forces
- Diagnostics integrated into assembly

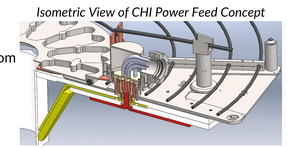
Power Fed Through Six Toroidally Distributed Umbilicals

- Large copper cross section minimizes 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
  - 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 cap bank: 4.13 kJ, 2.1 kV, 22 kA
- S-CHI bank: 3.5 MJ, 2.7 kV, 16 kA MLBC
  - Sub-ms voltage, current control

S-CHI, LHI Bias MLBC Power Supply



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 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 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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