Exploring Transformative Startup Solutions for Magnetically Confined Fusion Plasmas


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Work supported by DOE
Why Investigate Startup for Tokamaks?

- More efficient use of main magnetic field by compact toroidal geometry
  - Reduces central induction (main startup technique) capacity
  - Spherical Tokamaks (STs) study this operation space, low-A
- Lighting a match for fusion: new PEGASUS-III Experiment to study innovations in plasma startup techniques
  - Focused on techniques to help reduce cost and complexity of future fusion reactors
- Radiofrequency waves can be used to heat, drive current in STs, synergistically enhance non-solenoidal techniques

PEGASUS-III – Research in fusion energy and plasma science, UW-Madison Engineering Physics Department
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Tokamak Plasmas Require Current Drive and Heating to Achieve Fusion

- Fusion power proportional to:
  \[ n \cdot T \cdot \tau_E \]
  - External heating required to reach temperature for ignition
  - After ignition, self-heating sustains plasma

- Several methods of external heating & current drive available
  - Electron cyclotron (EC) resonance is in microwave range of frequencies
  - At high densities, injected microwave can be reflected – requires alternative methods of coupling microwave power
Helicity Injection Techniques Can Initiate and Drive Tokamak Plasmas

- Magnetic helicity, $K \equiv \text{“linkedness” of magnetic flux in a volume}

- In a tokamak, $K_{\text{plasma}}$ results from linking $\Psi_T$ and $\psi_p$

- Increasing $K_{\text{plasma}}$ → increase in toroidal plasma current

- Two methods of adding helicity:
  - AC helicity injection – increasing flux via magnetic induction within target volume
  - DC helicity injection – potential applied along open field lines that penetrate magnetic boundary

$$K = \int_V B \cdot A \, dV$$

Schematic illustrating flux linkage in a toroidal (tokamak) geometry
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Diem – MIPSE – Dec. 2nd, 2020
The Spherical Tokamak (ST) is a Low Aspect Ratio Tokamak

- Low aspect ratio: $A = \frac{R}{a} < 2$
- Natural elongation: $k = \frac{b}{a}$ without active shaping coils
- Strong toroidicity: $B_T(R)$ varies significantly across plasma

Y.-K.M. Peng, Nucl. Fusion 26, 769 (1986)
ST Configuration Efficiently Utilizes B

- Average field line curvature optimizes MHD stability for given toroidal field
  - Also, device cost ($B_T \sim \$\$)

- Efficiency leads to high $\beta_T = \langle p \rangle / (B_T / 2\mu_0)$

KSTAR Tokamak

Tokamak
- $A \sim 4$
- $q_a \sim 4$
- $\beta_T < 10\%$
- $I_p / I_{TF} \ll 1$

Spherical Tokamak
- $A \sim 1.25$
- $q_a \sim 12$
- $\beta_T < 100\%$
- $I_p / I_{TF} \sim 1$

Diem – MIPSE – Dec. 2nd, 2020
Engineering Tradeoffs Arise at Low A

- **Low-A → small central column**
  - Little/no space for needed tokamak coils, diagnostics, cooling

- **Limited Ohmic volt-seconds**
  - Small solenoid area
  - PEGASUS: $B_{\text{sol}} < 15$ T; $R_{\text{sol}} \sim 3$ cm

- **Feasibility of reactor central column neutron shielding**
  - $I_p \sim I_{\text{TF}}$: Copper TF rod possible
    - Nonetheless, high recirculating power
  - Non-solenoidal startup preferred
Non-Solenoidal Startup is Critical for the ST

• 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
  – Reduce PF system requirements
  – Lower electromechanical stresses

• Solenoid-free startup techniques may offer tools for modifying J(R)
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Elimination of Solenoid Greatly Simplifies ST Design and Requires Non-Inductive Startup Pathway

- Future ST designs call for solenoid-free operation
  - Nuclear ST: no OH due to shielding/cost

- PEGASUS-III Mission: Solving solenoid-free startup for STs (and ATs)
  - Advanced Local Helicity Injection
  - Floating Coaxial Helicity Injection
  - RF assist, sustainment and startup
  - Compatibility with NBI heating and current drive

- Research program will provide a predictive understanding of these solenoid-free techniques
  - Extrapolatable techniques to next-step devices
PEGASUS-III is a Major Upgrade of the PEGASUS Experiment

PEGASUS-III features:

- No solenoid
- 4x toroidal field
- Advanced control
- Expanded diagnostics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PEGASUS</th>
<th>PEGASUS-III</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{TF}$ (MA)</td>
<td>0.288</td>
<td>1.15</td>
</tr>
<tr>
<td>$N_{TF}$</td>
<td>12</td>
<td>24</td>
</tr>
<tr>
<td>$\psi_{sol}$ (mWb)</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>$R_{inner}$ [cm]</td>
<td>5.5</td>
<td>7.0</td>
</tr>
<tr>
<td>TF Conductor Area [cm$^2$]</td>
<td>13.2</td>
<td>72</td>
</tr>
<tr>
<td>$B_{T,max}$ [T] at $R_0 \sim 0.4$ m</td>
<td>0.15</td>
<td>0.58</td>
</tr>
<tr>
<td>$B_T$ Flattop [ms]</td>
<td>25</td>
<td>50-100</td>
</tr>
<tr>
<td>$A$</td>
<td>1.15</td>
<td>1.18</td>
</tr>
</tbody>
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Phases of PEGASUS Toroidal Field Coil

PEGASUS-III
Local Helicity Injection
Local Helicity Injection is a Promising Non-Solenoidal Startup Technique

- Edge current extracted from injectors
  - Relaxes to tokamak-like state
- Used routinely for startup on PEGASUS

Battaglia et al., Nucl. Fusion 51 073029 (2011)
Perry et al., Nucl. Fusion 58, 096002 (2018)
Bongard et al., Nucl. Fusion 59, 076003 (2019)
Projecting LHI to High-Performance Facilities Requires Tests at Increasing $B_T$

• Critical physics issues:
  – Confinement tests: linear (OH), saturated (L-mode), open field line
  – Turbulence-driven dynamo current drive mechanisms

Taylor Limit

$$I_p \leq I_{TL} = I_{inj} \Psi/\psi_{inj}$$

• Utilize two injector configurations
  – Two arrays of 2x4 cm$^2$ circular injectors
  – Advanced non-circular “Kama” injector – monolithic port mounted injector

• Goal: routine experiments at $\sim$ 0.3 MA

LHI Produces High-$I_p = 0.2$ MA Tokamak Plasma ($I_{inj} \leq 8$ kA)

Monolithic LHI Injector

Power balance projections for Pegasus-III ops

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Coaxial Helicity Injection
Coaxial Helicity Injection: Axisymmetric Electrodes Drive Poloidal Current into a “Magnetic Bubble”

Two techniques:
• Transient (T-CHI): stretch connected flux and quickly force reconnection to create closed flux by terminating injection
• Sustained (S-CHI): build up connected flux by continued current drive

“Bubble burst” condition requires threshold $J \times B$ stress across the current layer to overcome field line tension

$$I_{inj} = \frac{C \psi^2_{inj}}{\mu_0 d^2 I_{TF}}$$

R. Raman et al., Nucl. Fusion 53 (2013)
Comparative Studies of Helicity Injection Techniques will be Explored at Increased $B_T$ PEGASUS-III

- Novel, flexible CHI system in dedicated experiment
- Address critical physics
  - Flux conversion efficiency
  - Role of footprint in efficiency
  - Comparison and synergies with other methods
  - Role or advantages of non-axisymmetric current flows & structures

- Validate projection to $\geq 1$ MA system
  - Test bubble burst and Taylor limit up to 0.3 MA
  - Vary flux distribution across electrodes

- CHI requires auxiliary heating to raise $T_e(0)$

"Bubble burst" criterion

\[
I_{inj} \geq \frac{C \psi_{inj}^2}{\mu_0 d^2 I_{TF}}; C \sim O(1)
\]
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Radiofrequency Wave Injection

PEGASUS-III

CHI

EBW

LHI

Divertor Coils
RF Waves Resonate with Natural Frequencies in the Plasma Can Provide Heating/CD

Magnetically confined plasma

Toroidal magnetic field

\[ F = q(E + v \times B) \]

Cyclotron motion

Magnetic field

Coil current
Launched Microwaves Absorbed Near Cyclotron Resonances

- Tuned to either electron or ion cyclotron motion
- RF source frequency can be chosen to be absorbed at precise location
  - Can provide heating or drive current
- For tokamas, STs, $B_t \propto \frac{1}{R}$
- Inject either:
  - Ordinary mode (O-mode), $E \parallel B$
  - Extra-ordinary mode (X-mode), $E \perp B$
EC Wave Injection Provides Plasma Heating and Current Drive – in Certain Conditions

- For plasmas with relatively low $B_T$, high density, O-mode & X-mode reflected near plasma edge
  - Happens in ST, RFP, stellarators
  - Refer to these plasmas as being “overdense”

$$f_{pe} > f_{ce}, \text{ where } f_{pe} = \sqrt{\frac{n_e e^2}{\pi m_e}}$$

- Alternative heating method required
Electron Bernstein Waves Can Propagate in Overdense Plasmas

• Electron Bernstein waves (EBW) are hot plasma waves:
  – Perpendicularly propagating, $k_\parallel = 0$
  – Do not experience a density cutoff in the plasma
  – Longitudinal, electrostatic waves

Electrons
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  – Cannot propagate in vacuum
  – Absorbed near cyclotron harmonics

\[
1 - 2 \sum_s \frac{4\pi n_s m_s c^2}{\lambda B_0^2} \sum_s e^{-\lambda} I_n \left( \frac{\lambda}{\omega / \Omega} \right) \left( \frac{n^2}{\omega / \Omega - n^2} \right) = 0
\]

As wave frequency approached EC harmonic, $\omega = n\Omega$, wave is strongly absorbed

Where: $\lambda = \frac{k^2 \kappa T_e}{m\Omega^2}$
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EBW coupling efficiency depends on plasma parameters near plasma edge
- Density gradient
- Magnetic field pitch

$X_0 = O$-mode cutoff
$\nabla n_e$
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RF Heating/CD to be Explored as Component of Non-Solenoidal ST Startup Program

• RF auxiliary heating and CD system will enable long-term scientific campaigns
  – Synergistic effects for improving helicity injection and RF current drive efficiency
  – Comparative tests of most major non-solenoidal startup techniques
  – Current profile tailoring
  – Handoff from non-solenoidal startup to non-inductive sustainment utilizing reactor-relevant non-inductive sustainment tools

• Initial experimental campaigns focus on RF coupling to overdense plasmas
  – EBW heating capability may synergistically enhance LHI induced $I_p$ current by lowering resistivity

• Long term develop RF-only startup
Initial EBW Program Seeks to Explore Synergies

- Relative low $B_T$, high $n_e$ of STs necessitates use of EBWs for fundamental absorption
  - $500 \text{ kW EBW RF, 8 GHz}$
- EBW heating: synergistically enhance LHI induced $I_p$ current by lowering resistivity
- $T_e$ increases compatibility with non-inductive sustainment (i.e. NBCD)
- $T_e$ control as test of confinement models
Demonstration of EBW CD for Future Sustainment Studies

• 8 GHz absorption at fundamental EC
  – ~400 kW injected into decaying HI-produced plasma
    (B_T = 0.339 T)
  – Poloidal launch angle of 30 above midplane
    • n || = -0.55 to -0.45
  – Increasing T_e can increase current drive efficiency

• Modeling shows current drive peaked off-axis
  – I_{EBW} ~ 30 kA comparable to j(0) from LHI
  – Perform current profile tailoring
  – Varying B_T can be used to change absorption location
2\textsuperscript{nd} Phase RF: Add ECH/ECCD for Helicity Injection
Synergies and Direct RF Startup

- Heating during post-CHI decay phase
  - Significantly increase $T_e^*$

- LHI coupling:
  - $T_e$ heating during LHI for increased CD efficiency
  - Post-LHI heating for subsequent heating and CD

- Pure-RF startup scenarios
  - ECH/ECCD initiation and current channel formation
  - Subsequent EBW heating and CD for full $I_p$, $n_e$ growth

- Exploit 2\textsuperscript{nd} harmonic EC resonance
  - Significant EC absorption can occur at 2\textsuperscript{nd} harmonic
  - Density cutoff $< 5 \times 10^{18}$ m$^{-3}$, accessible during startup

\begin{center}
\begin{tabular}{|c|c|c|c|c|c|}
\hline
\textbf{Mode} & \textbf{X1} & \textbf{X2} & \textbf{O2} & \textbf{X3} \\
\hline
\textbf{Frequency} & $\Omega_{ce}$ & $\Omega_{ce}$ & $2\Omega_{ce}$ & $2\Omega_{ce}$ & $3\Omega_{ce}$ \\
\hline
\textbf{Density} & $n_{01}$ & $2n_{01}$ & $2n_{01}$ & $4n_{01}$ & $6n_{01}$ \\
\hline
\end{tabular}
\end{center}
LHI-produced targets are accessible to ECH
- Wide range of $<n_e>$ available

Peak 15% first pass absorption possible for $T_e(0) = 15$ eV
- Single ray launch injection angle scan via GENRAY
- Launcher at $z = 5.5$ cm, poloidal angle $= -15^\circ$, toroidal angle $1^\circ$
- Applicable to CHI targets

First pass absorption reaches 70% for $T_e(0) = 300$ eV
- Efficacy of ECH dependent on confinement scaling of $T_e(0)$ with $B_T, n_e$, etc.

Initial ECH modeling shows promising capabilities
28 GHz ECH Feasible at Full $B_T$ in PEGASUS-III

Poloidal Cross Section

Toroidal Cross Section

Absorption region

Absorption surface

GENRAY 48-ray bundle trajectory shown for $T_e(0) = 150$ eV, 42% first pass absorption
Long term: 28 GHz, 8 GHz RF Systems Can Be Used Simultaneously for Scenario Development

• ECH can be used during active helicity drive to significantly increase $T_e(0)$, improving EBW CD efficiency
  – EC resonant locations with significant absorption obtained for both systems with $B_T = 0.4$ T

• First pass absorption 0% for 3$^{rd}$, 4$^{th}$ EC harmonic
  – 28 GHz, X2 absorbed near $R = 0.3$ m

• Assuming ECH during HI provides significant increase in $T_e$, 1 keV, EBW current drive increases by $\sim 2x$
RF Systems Can be Used Simultaneously to Study Synergistic Effects, Study Scenario Optimization

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**ECH during HI**

**Handoff to EBWCD**

**Driven Current (CQL3D)** $I_{EBW} \sim 50$ kA

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Diagnostics Required to Verify RF Heating, Current Drive

CQL3D modeling of SXR

SXR Energy Flux [ergs/cm$^2$·s·ster·eV]

- No RF
- 100 kW, 8 GHz EBW
- 400 kW, 8 GHz EBW

SXRD Channel

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Long Term Plans for RF Seek to Enhance Non-Solenoidal Tools on PEGASUS-III Experiment

• Bold tests of non-solenoidal ST startup using reactor relevant techniques
  – Local Helicity Injection
  – Coaxial Helicity Injection (transient, sustained)
  – EBW assist and sustainment
  – Future: EC heating and current drive

• RF auxiliary heating and CD system will enable long-term scientific campaigns
  – Synergistic effects for improving helicity injection and RF current drive efficiency
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  – Current profile tailoring
  – Handoff from non-solenoidal startup to non-inductive sustainment utilizing reactor-relevant non-inductive sustainment tools

• Also allows unique studies of near unity $\beta_T$, low-A physics
PEGASUAS-III is Under Construction

Complete electromechanical design & analysis of TF system

PEGASUS decommissioned

TF center rod, conductors, & return structures delivered

Assembly of 240 MVA power systems underway

New cascaded inverter in fabrication to drive LHI, S-CHI systems

DNB supporting new diagnostics (PPPL loan)

https://pegasus.ep.wisc.edu