Abstract

The PEGASUS Toroidal Experiment explores ST plasma behavior focusing on q and beta limits as the aspect ratio approaches unity. Typical plasma parameters are $A = 1.15 - 1.4$, $R = 0.2 - 0.4$ m, $I_p < 0.16$ MA, $B < 0.07$ T, and toroidal beta $< 20\%$. A 1 MW HHFW system has begun operation and injected 0.2 MW into plasma. Plasma performance is constrained by power supply limitations and low-order resistive instabilities associated with low central shear. Edge kink instabilities have been observed for $q_{95} = 5$ with low internal inductance (0.2-0.4). The magnetic field set power systems are being upgraded to allow for improved waveform control and plasma performance. These upgrades include: 1) increased V-s and loop voltage control for higher plasma current and suppression of observed internal and edge modes; 2) increased toroidal field with fast-ramp capability for improved startup and subsequent access to the low-q, high toroidal beta regime; and 3) improved equilibrium field and waveform control for radial position and modest shape control.
Overview of PEGASUS Results and Facility Upgrades

• Introduction
  - Mission statement for experiment, experiment facility overview

• PEGASUS Results Summary
  - High $t$ via Ohmic Heating, Soft $I_p/I_{TF}$ limit, MHD

• Major Upgrades in progress
  - Experimental Facility, Toroidal Field Centerstack Assembly, Equilibrium Field compensation coils

• Magnet Coil Power Systems
  - Pulse Width Modulated (PWM) coil supplies, HIT power system collaboration

• Summary
Mission Statement for the PEGASUS Toroidal Experiment

• The PEGASUS Toroidal Experiment is a university based plasma magnetic confinement experiment designed to study high-pressure plasmas in a low aspect ratio axisymmetric toroidal geometry.
• **PEGASUS discharges exhibit low-A characteristics**

  - \( t > 10\% \), \( N > 4 \), \( I_p/I_{TF} \sim 1 \), \( \beta > 2 \), high edge-q at low TF
  - highly paramagnetic: \( \beta_p = 0.3 \) at \( \beta = 0.83 \); \( F/F_{vac} \sim 1.5 \) on axis

• **\( I_p/I_{TF} \) ‘soft’ limit due to combination of internal tearing modes and limited OH flux**

  - internal tearing modes arise when low-order rational surfaces appear
  - low magnetic shear allows large radial extent
  - low TF allows onset early in discharge when \( \alpha \) is high

• **External kink accessed at \( q_{95} \sim 5 \)**

  - theoretical predictions indicate stable \( q \) increases at low-A
  - exacerbated by low-\( \ell_1 \) in Pegasus
PEGASUS Routinely Accessing High-$t$, High $I_N$ via Ohmic Heating

- High $t$ attained at high density, low-TF
  - Ohmic heating constant TF
  - Highest $t$, $I_N$ at low TF

![Graph showing the data for Conventional Tokamaks with lines $N = 6$ and $N = 3.5$. The data points are marked as PEGASUS data.](image-url)
\[ I_p/I_{TF} \] ‘Soft’ Limit Observed

- Limit manifests as plasma current roll over, not disruption
- Internal tearing modes and V-s limitation contribute to limit
  - extending to \[ I_p/I_{TF} >> 1 \] regime requires tools to suppress/manipulate MHD
**Pegasus MHD Summary**

- **Large scale resistive internal kinks limit** $I_p \sim I_{TF}$
  - mode growth correlates with appearance of low order rational surface in broad region of low magnetic shear

- **External kink observed at** $q_{95} \sim 5$

- **Exploration of high** $I_p / I_{TF}$, high $t$ regime requires suppression of this MHD
  - increase $T_e$, lower
  - crude control of $q(\ )$
  - increase $V$-s and $I_p(t)$
  - allow edge/separatrix control
PEGASUS Experiment is in a Major Upgrade Phase

• Major Laboratory Reconfiguration
  - Facility damaged in fire following power diode failure
  - Improved experiment safety and access in experimental area
  - All major energy storage capacitor banks relocated to vault outside building

• Adding new tools to enhance study of plasma stability boundaries
  - All coil power systems being upgraded to programmable waveform control
  - Independent Equilibrum Field coils to provide active shaping and position control
  - Increased V-sec (2 - 2.5x) and control during all phases of plasma evolution
  - Low inductance Toroidal Field return bundle being installed for establishing higher \( B_T (4x) \) and allowing rapid current ramping capability
  - Divertor coils being activated for separatrix operations
  - Compensation coil provides additional DC bias field prior to startup

• Enhance Poloidal Field System to Include Stray Field Reduction
Old PEGASUS Experiment Facility

• Crowded Experimental Area

- All high energy coil power systems locate within the experiment hall taking up more than 60% of the usable experiment area.

  - Close proximity of power systems to each other and the machine experiment could lead to high collateral damage.

  - Resonant systems required more stored energy and high power coupling comments to give desired current waveforms
Old PEGASUS Experiment Facility

All coil power system capacitor banks and switching located in experiment area
Improved PEGASUS Experiment Facility

• Facility Upgrades

- No energy storage capacitor banks in experiment area
- High power PWM switching located in room adjacent to the experiment area
- Removed all outdated interference from past facility.
- Diagnostic transmission lines completely replaced for better RF shielding and grounding
- All oil-dielectric/insulated components replaced with aluminum-electrolytic or dry, self-healing type technology.
- Increased machine capability includes additional Poloidal Field coil to compensate for increased stray field in public areas.
Improved PEGASUS Experiment Facility

No coil power systems located in main experiment

Vacuum & Machine Prep Area

Power Supply Switch Yard

RF Screen Room

Capacitor Bank Vault
Proposed Pulse Width Modulated (PWM) Power Systems

• Ohmic Heating (OH)
  - Operates up to ±50kA @ 2700V/3500kJ - Four Quadrant Control
  - Ohmic Trim provides high order vacuum null for plasma formation
  - Allows full controlled utilization of up to 100mV/sec Ohmic Flux
  - Regenerative nature of H-bridge allows for resonant termination of Ohmic Current to minimize heating of Ohmic Solenoid

• Toroidal Field (TF)
  - Operates up to +50kA @ 900V/584kJ - Two Quadrant Control
  - Will allow rapid current ramp down during the shot
  - Will allow up to 600kA of TF rod current (up from 150kA)

• Equilibrium Field (EF)
  - 5 independent systems operate up to +20kA @ 900V/146kJ - Two Quadrant Control
  - Provides positioning and shaping fields with active feedback control
  - Coil set is adaptable for shaping and positioning concerns
Helicity Injected Torus Power Systems Collaboration

• Motivation

- Need better control coil power systems to tailor the current waveform to match the needs of the plasma with active feed back control.

- Use PWM Controlled modern IGCT/IGBT semiconductors

- More reliability and control with less overall stored energy

- Fault detection and interruption capability

- HIT has developed and utilizes a CAMAC based, optically isolated PWM controller for IGBT semiconductors

ABB IGCT Presspack with Gate Unit
Steady State - 2.8kV@4kA

Integrated Gate Commutated Thyristor

Eupec IGBT
Steady State - 900V@2.4kA

Insulated Gate Bipolar Transistor
• Ohmic Heating (OH)
  - Solenoid provides primary heating for the plasma
  - Ohmic Trim provides high order vacuum null for plasma formation
  - Operates up to 3kV at ±60kA

• Toroidal Field (TF)
  - Coil Set provides main confining field
  - New, low inductance 12 turn return bundle
  - Operates up to 900V at 50kA (600kA rod current)

• Equilibrium Field (EF)
  - Provides positioning and shaping fields
  - Coil set is adaptable for shaping concerns
  - Operates up to 900V at 20kA
Ohmic Power System Upgrades

• Motivation
  - Need better control over formation and growing stages of the plasma.
  - Need to minimize Ohmic solenoid heating while maximizing loop volt utilization.

• PWM IGCT H-Bridge
  - 2700V/3500kJ Electrolytic Cap-Bank
  - Full four quadrant switching capability
  - ABB 5SHY 35L4510 IGCT capable of switching 2800V @ 6000A at up to 25kHz
  - Feedback control via applied loopvolts with possible future control via plasma current
  - Ohmic H-Switch requires 8 parallel modules each with 4 IGCTs per module
New TF Bundle and Waveform

- **Motivation & Design**
  - Provide High-TF for improved plasma startup and MHD control
  - Rapid TF ramp down during shot to provide access to High-$B$, Low-$Q$ regime.

- **New TF Bundle**
  - 12 turn high current, low inductance
  - Installation without venting machine
  - Will allow access to high $I_TF (>500kA)$ rod current - increased from present 150kA
  - Low inductance allows ~2msec current ramp down during shot

- **PWM IGCT Half-Bridge**
  - 900V/584kJ Electrolytic Cap-Bank
  - Two quanrant switching capability
  - ABB 5SHY 35LA510 IGCT capable of switching 900V @ 12000A at up to 25kHz
  - Feedback control via applied current
  - H-Switch requires 4 modules each with 2 IGCTs per module
Coil Systems

- Coils 1, 2, 7, & 8 provide shaping and n=0 stability and operate up to +20kA w/ 2msec control - operate as a series connected set

- Coils 3 & 6 provide Up/Down symmetry and operate up to +20kA w/ 2msec control - operate as two independent coils

- Coils 4 & 5 provide additional shape and position control and operates up to +20kA w/ 2msec control - operate as series connected set

- Compensation coils provide bias field and stray field compensation and operate up to -20kA w/ 2msec control - operate as series connected set
Equilibrium Field Stray Field Compensation

- Motivation & Design
  - The desired increased Equilibrium Field capability would raise stray B-field in public areas.
  - The addition of a symmetric set of actively controlled 'bucking' coils and passive coil set mounted above the machine reduce the stray B-field to less than 5 Gauss in public exposure areas.
Summary

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  - Improved diagnostic infrastructure to be ready for high power RF operations

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  - Compensation coil provides additional DC bias field prior to startup

• PWM controlled Magnet Coil Power Systems
  - HIT power system collaboration greatly reduced development time
  - Allows for precise current waveform with feedback control

• Enhance Equilibruim Field System to Include Stray Field Reduction
  - Compensation coil provides additional DC bias field prior to startup
Abstract

Overview of PEGASUS Results and Facility Upgrades*

University of Wisconsin-Madison

The PEGASUS Toroidal Experiment explores ST plasma behavior focusing on q and beta limits as the aspect ratio approaches unity. Typical plasma parameters are $A=1.15-1.4$, $R=0.2-0.4$ m, $I_p<0.16$ MA, $B<0.07$ T, and toroidal beta $<20\%$. A 1 MW HHFW system has begun operation and injected 0.2 MW into plasma. Plasma performance is constrained by power supply limitations and low-order resistive instabilities associated with low central shear. Edge kink instabilities have been observed for $q_{95}=5$ with low internal inductance (0.2-0.4). The magnetic field set power systems are being upgraded to allow for improved waveform control and plasma performance. These upgrades include: 1) increased V-s and loop voltage control for higher plasma current and suppression of observed internal and edge modes; 2) increased toroidal field with fast-ramp capability for improved startup and subsequent access to the low-q, high toroidal beta regime; and 3) improved equilibrium field and waveform control for radial position and modest shape control.

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