PLASMA STUDIES AT HIGH NORMALIZED CURRENT IN THE PEGASUS EXPERIMENT

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Explore plasma limits as $A = 1$

Pegasus is an extremely low-aspect ratio facility exploring quasi-spherical high-pressure plasmas with the goal of minimizing the central column while maintaining good confinement and stability.

Primary Pegasus Goals:

• Stability and confinement at high $I_p/I_{TF}$
  - Extension of tokamak-like studies

• Limits on $\tau$ and $I_N \sim 6I_p/I_{TF}$ (kink) as $A = 1$
  - Overlap between the tokamak and the spheromak

Planned Future Emphases:

• Support ST program movement to next stages
  - Noninductive startup tests
  - EBW tests for heating & CD (w/PPPL)
  - Novel divertor design tests (w/UT)
Phase I demonstrated low-A characteristics

- $A \sim 1.1$ via OH
  - High field/stress solenoid
  - Very low TF (< 0.1 T)
  - HHFW available

- Low field, ohmic only
  - high $I_N$ & $t$

- Resonant L-C power systems
  - Fixed waveform evolution
  - Low $I_I$, low shear

$n_e$ up to density limit

Measured low-shear $q(r)$
Phase I: An $I_p/I_{TF} \approx 1$ soft limit observed

Large resistive MHD instabilities as TF

- low $B_t$ and fast $dI_p/dt$ early appearance of low-order $q=m/n$ at low $T_e$
- ultra-low $A$, low $l_i$ low central shear

Rapid growth of 2/1, 3/2 tearing modes and large saturated island widths

- $I_p/I_{TF} \approx 1$ $q_0 \approx 1.5 - 2$
- plus reduction of V-sec as TF

$\rho_N \approx 6 I_p/I_{TF}$
Phase II: PEGASUS Facility has been Completely Rebuilt

- **New Tools Enhance Study of Plasma Stability Boundaries**
  - All coil power systems upgraded to programmable waveform control
  - Active shaping and position programming
  - **Increased V-sec** (2 - 2.5x) and control
  - Low inductance, higher $B_T$ (3x) Toroidal Field bundle for rapid TF ramp
  - Divertor coils for separatrix operation
  - **Plasma Guns** for plasma startup and current drive

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Power systems offer path to high $I_p/I_{tf}$ operation

- Suppress tearing modes early in discharge evolution
  - Transiently manipulate $q$ during discharge:
    - Increased TF at startup
    - Variable $I_p$ and $R_0$
  - Reduce resistivity before low-order rationally appear
    - Maximize $J$
    - Increase ohmic flux
    - Use HHFW system
- Explore edge kink boundary at high field utilization
  - Manipulate edge shear
  - Decrease edge currents
  - Manipulate plasma shape
  - Manipulate current profile
- Begin operations with reduced OH power
  - 900V IGBT H-bridges for low-power OH (120 MVA)
  - Near-future: 2700V IGCT bridges for full OH ops (130 MVA)
Phase II: Earlier Results Recovered; Extending Operation Space

- Comparable characteristics to Phase I plasma achieved
  - $I_p$ ramp rate, maximum $I_p$

- Mode activity: similar qualities
  - frequency, $B$

- Initial tests to lower $I_p$ ramp-rate
  - Envelop function of Mirnov signal decreases with decreased $dI_p/dt$
New Capability Widens Operating Space

• Higher TF allows extension of operation space

• Limited OH flux and control during shakedown
  - 2/1 mode still evident with high $dI_p/dt$
  - Full OH will allow challenge to high $I_N$, $I_p/I_{TF}$
Present Status - Integrating New Capabilities towards $I_p/I_{tf} > 1$

• Summer-Fall ‘04: Shakedown & Commissioning
  - 1st plasma in late May
  - Shakedown campaign
    • Transient suppression and PS stabilization
    • New facility tests and systems shakedown
    • Effects of wall currents with new waveforms
    • Low power startup studies
    • Phase I operation space recovered
  - New power systems stabilized and working as desired
    • Robust to major failures

• Recent upgrades to enhance operations
  - New diagnostics
  - Plasma guns installed for tests of CD and fueling
  - $V_f(t)$ control -> $dI_p/dt$ control

• Fall ‘04: Installation of first High-V OH power supplies

• Campaign in Winter 2004-2005: Use New Tools
  - Commission new OH system for high-power ops
  - Access to $I_p/I_{tf} > 1$, low-q, high $I_N$, high $I_e$ regime
  - Introduce separatrix
    - Tearing mode suppression
    - Characterize ext kink limits
    - Use gun for startup assist
Plasma Guns Being Tested for Startup and Fueling

- Use MST-style gun current sources to inject helical current in divertor region
  - $I_{\text{gun}} \approx 300 - 600\, \text{A}$, $N_e \sim 10^{20}\, \text{m}^{-3}$
- Vary TF, EF fields to control current path
- Diverse potential applications
  - Ionized plasma fueling source in SOL
  - Ease OH V-sec needs
  - Provide PF-only startup path
  - Non-inductive startup path

Gun installed in lower divertor region
Current Filaments Merge Above Threshold

- Current amplification up to ~ 20
- Clear merging or reconnection(?) above a threshold in power
- Closed flux surfaces requires field, gun optimization

SN 24434 Vbias = 50 V
Low current
=> Filaments Maintained
No amplification

SN 24438 Vbias = 400 V
High current
=> Filaments Merge
Net amplification
Gun Startup Compatible with OH or EF Inductive Drive

- I scales linearly with # of guns
- Vloop added to gun plasma
  - *No preionization or null required*
  - *via OH or dEF/dt*
- I ~ 60 kA (OH) and ~ 20 kA (EF)
- Closed flux surfaces next target
  - Optimize field, Igun evolution
  - ~ 2x increase needed (?)

**Guns + dEF/dt**

- Toroidal Current [A]
  - Shot 25731
  - Shot 25752

- EF Coil Current [A]
  - 0 to 12,000

**Guns + dOH/dt**

- Plasma Current [A]
  - 1 Loop Volt OH
  - 2 Loop Volt OH
  - 2 Loop Volt, Highest Ip

- Time [s]
  - 0 to 20

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Economical Tests of EBW Possible on PEGASUS

EBW heating and current drive of interest for ST regime
- Plasma startup, sustainment
- Applicable to low-field, overdense plasmas
- Of interest to future NSTX development

Basic principles tested on W-7S and CDX
- Need to be tested at significant power levels

Pegasus good candidate for EBW development
- Low-cost 2.45 GHz technology
- Klystrons and waveguide available from PLT
- Need to demonstrate good target plasma control

Working with PPPL to develop best approach
- Modeling
- Hardware
- Experiments

(a) EBW ray tracing calculations for a 250 kA PEGASUS equilibrium, central density of ne(0) = 10^{13} \text{ cm}^{-3}. (b) n_{||} along the ray path, showing the upshift depends upon launch position. (c) Power deposition profiles corresponding to the rays in (a) and (b).
SUMMARY

• Phase I ops up to Spring 2002
  - \( \frac{I_p}{I_{tf}} = 1.1 \)
  - \( t \leq 25\% \)
  - Factors found limiting plasma current:
    + internal resistive modes
    + V-s limitations
    + external kinks

• Facility completely rebuilt and upgraded to provide increased plasma control
  - New switching power supplies (final OH installation now)
  - New divertor and shaping PF coils
  - New TF centerstack
  - etc.

• Phase II experiments have begun
  - Switching systems and infrastructure debugged
  - Low power OH demonstrating increased control
    • Phase I results readily reproduced
    • Fine control of OH, TF, and PF fields being established
    • Modest feedback control developing
  - Plasma gun tests suggest non-OH startup capabilities
  - High power operations to challenge low-q, high-\( A \) \( \rightarrow 1 \)
PEGSUS Poster Session: Thursday Afternoon

PP1.015  Stability Studies          [Unterberg]
PP1.016  Diagnostic Measurements   [Kozar]
PP1.018  Control & DAS Systems      [Burke]
PP1.019  Facility and Power Systems [Lewicki]
PP1.020  Plasma Gun Experiments     [Eidietis]
PP1.021  Potential EBW Experiments  [Garstka]

Related - Weds morning:

HP1.074  NIMROD MHD modelling       [Sovinec]
Low Current/Power --> Linear Scaling; Filament Maintained

- Current channel follows field line
  - Maintains helical nature

- Total toroidal current ~ 5 x gun current
  - $I_p/I_g \approx constant$

![Graph showing current and time relationships](image)
High Current/Power --> Nonlinear Scaling; Filaments Merge

- Current channels merge/reconnect
  - Generates extended plasma
- Total toroidal current > 5 x gun current
  - $I_p/I_g$ increases

![Graph showing current and amplification over time](image_url)