• High Field Utilization \( (I_p/I_{tf}) \) needed to access \( \beta_t \sim 1 \) and High \( I_N \) in an ultra-low-aspect-ratio torus (ULART)

• Operations in the PEGASUS ULART have shown the need for discharge evolution to obtain high performance

• Modeling & experiments confirm PEGASUS can access high \( I_p/I_{tf}, I_N \) regimes

• Recent experiments in PEGASUS have given \( I_p/I_{tf} \sim 1.5-2 \) at \( I_p < 0.1 \) MA
Outline

• **Achievable Performance of Initial Experiments Limited to \( I_p \sim I_{tf} \)**
  - Tearing modes (TM) due to ST physics and crude experimental control
  - Magnetic shear mitigates TM \( \Rightarrow \) external kinks were observed; all limited by hardware control

• **Modeling Points to Access to High \( I_p/I_{tf} \) Equilibrium**
  - TSC modelling confirms accessibility at full capability
  - Confinement estimates point to high-\( \beta \) w/ \( I_p/I_{TF} \sim 2 \)
  - Equilibrium & DCON calculations give stable predictions at \( I_p/I_{TF} \sim 2 \)

• **Non-Inductive and Limited-OH Experiments \( \Rightarrow I_p/I_{tf} = 1.5-2.2 \) Achieved**
  - Goal: \( I_p/I_{TF} \sim 2-3 \) (\( I_N \sim 10-20 \)) at high \( I_p \)
    - *in present experiments: OH @ 1/3 capability; prototype non-inductive source*
  - Non-inductive sources w/ OH drive coupling: \( I_p/I_{TF} \sim 2 \)
    - *central heating seen during OH drive*
  - Ultra-low-field preionization w/ OH drive: \( I_p/I_{TF} \sim 1.5 \)
    - *experiments limited by flux (~ 30mV-sec; full capability = 90 mV-sec)*
PEGASUS is a University-Scale, Mid-Sized ST

**Experimental Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Achieved</th>
<th>Phase II Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.15-1.3</td>
<td>1.12-1.3</td>
</tr>
<tr>
<td>R (m)</td>
<td>0.2-0.38</td>
<td>0.2-0.45</td>
</tr>
<tr>
<td>I_p (MA)</td>
<td>≤ 0.16</td>
<td>≤ 0.30</td>
</tr>
<tr>
<td>I_N (MA/m-T)</td>
<td>6-8</td>
<td>15-20</td>
</tr>
<tr>
<td>R_B (T-m)</td>
<td>≤ 0.03</td>
<td>≤ 0.1</td>
</tr>
<tr>
<td>κ</td>
<td>1.4–3.7</td>
<td>1.4–3.7</td>
</tr>
<tr>
<td>τ_{shot} (s)</td>
<td>≤ 0.02</td>
<td>≤ 0.05</td>
</tr>
<tr>
<td>β_t (%)</td>
<td>≤ 20</td>
<td>&gt; 40</td>
</tr>
<tr>
<td>P_{HHFW} (MW)</td>
<td>0.2</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**Diagram Details:**

- **Equilibrium Field Coils**
- **Divertor Plates**
- **Higher-Harmonic Fast Wave Antenna**
- **Ohmic Solenoid**
- **Flux Loops**
- **Plasma Guns**
- **PF1 Shaping Coil**
- **Low Inductance TF Bundle**
- **PF8 Shaping Coil**
- **Divertor Coil**
- **Phase-II additions in red**

*Typical PEGASUS Employee ~ 6 Feet*
Main Mission: Studies at High-$\beta_t$ and $I_N$

**PEGASUS Goals**

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

- Limits on $\beta_t$ and $I_p/I_{TF}$ (kink) as $A \rightarrow 1$
  
  - *Overlap between the tokamak and the spheromak*

---

Troyon scaling for conventional tokamaks and other STs with predictions for PEGASUS
Phase-I: Mode Activity Dependent on Current Profile

- Maximum $I_p \approx I_{tf}$ limit

- $q$-profile of ST conducive to TM activity
  - large region of low magnetic shear near axis $\Rightarrow$ large island widths
  - low TF operations $\Rightarrow q<2$ when highly resistivity

- Crude manipulation of $q(r)$ reduced mode amplitude
  - Increased shear, $q_0 \Rightarrow$ delay tearing onset

$\Rightarrow$ Access higher $I_p/I_{TF}$ via higher $q_0$, $T_e$, shear

ICC, February 2006, Austin, TX, EAU
Phase-I: External Kink Seen at Highest Performance

- Highest Phase-I $I_p$ often disrupt
  - $q_{95} = 5$ observed preceding disruption
    - $\ell_i=0.5$ at this time
- DCON analysis $\Rightarrow$ unstable to $n=1$ external kink
  - $m=5$ most unstable mode
- Consistent with theory expectation & high edge current

![Graph showing plasma current, $q_{95}$, and MHD amplitude over time.]

![Graph showing poloidal mode eigenfunctions.]

ICC, February 2006, Austin, TX, EAU
Facility Modifications to Access High $I_p/I_{TF}$

- Extensive modifications to facility to allow access to higher $I_p/I_{TF}$ operations

- Approaches and tools to increase $I_p/I_{TF}$
  - Manipulate current profile
    - $V_{loop}$ control, position/shape control, $B_t(t)$
  - Reduce $\eta$ before low-order rationals appear
    - $V_{loop}$ control, position/shape control, RF heating (HHFW)
  - Transiently increase $q$ during startup
    - $B_t(t)$, $V_{loop}$ control

- Main facility modifications
  - Power Supplies
    - OH: effective V-s $\uparrow$ w/ increased waveform control
  - Coil Sets
    - Lower inductance TF set: 60 turns $\Rightarrow$ 12 turns
    - PF Set: monolithic set $\Rightarrow$ 8 independent sets
    - Divertor coil set installed
Programmable Power Supplies give Highly Flexible Experiment

- **250 MVA programmable power**
  - Economical, high-power, solid-state switches
  - Impedence matched for each coil
  - Allows more effective power with less stored energy

- **Large degree of coil arrangement flexiblity**
  - Up to 40 independent subsystems @ 4 kA available
    - 28 @ 900V → IGBT systems
    - 12 @ 2700V → IGCT systems
  - PWM feedback gives msec time response (U.Wash)

- **Allows easy integration to active PCS system**
  - Real-time control under development with GA
Discharge Control Seen with Pre-Programmable Coil Sets

- Large array of new capabilities developed; deployed into routine use
  - Pre-programmed coil currents
  - New wall conditioning and fueling
  - Variable PF configurations
  - Increased TF with time-variability
  - Divertor coils

- Integration of these capabilities led to discharge control

![Graph showing varied Ip & respective |δB| over time](image_url)
Tools for High $I_p$ Studies: Plasma Control System

- Studies at high $I_p/I_{\text{tf}}$ known to need fine discharge control
  - Highly shaped discharges
  - Possible disruption mitigation

- Active control system based on DIII-D PCS
  - GA PCS Team collaborating
  - System commissioning planned mid-2006

**KEY**

- Pre-Existing Component
- New Component
- Information Flow

**Power Supply Control (PWMs)** → **Power Supplies** → **Coils** → **Plasma** → **Diagnostics** → **Data Acquisition System**

**Outputs**
- 16 Analog channels

**“Real-Time” Computer**
- Control Algorithms

**Digitizer**
- ~120 channels
- 0.1-1MHz simultaneous
- 12 bit

**Digitizer**
- 96 channels
- 500 kHz simultaneous
- 16 bit
Modeling Confirms Access to High $I_p/I_{TF}$

- Modeling done to verify access to interesting regimes

- **TSC: Full ohmic flux (90 mV-s)**
  - Flux consumption calculations indicate 300 kA $I_p$ attainable
  - Simulations corroborate
    - $I_p/I_{tf} = 2$
    - $I_N \sim 12$ MA/m-T
  - Effects of resistive MHD unclear

- **Confinement modeling:**
  - $I_p/I_{tf} = 2 \Rightarrow \beta_t = 40-70\%$
    - Sufficient to assess stability boundaries
    - Similar calculations confirmed in Phase-I with data
DCON Used to Develop High $I_p/I_{tf}$ Operating Scenerios

- Stable equilibria found with $I_p/I_{tf} = 1.93$
- DCON predicts equilibria stable
- Effects of pressure profile on stability still needed

"zero"-\(\beta\) Equilibria

Flux Plot

Equil. Paramters

- $I_p = 290000$
- $I_N = 12$
- $I_p/I_{tf} = 1.93$
- $\epsilon_i = 0.59$
- $q_0 = 1.5$
- $R_0 = 0.39$
- $a = 0.34$
- Elongation $= 2.2$
- $q_{95} = 4.8$

DCON predicts equilibria stable
Modeled $I_p \sim 3I_{tf}$: Approaches Goals and Physics Limits

- Equilibria at $I_p \sim 3I_{tf}$ found
- DCON predicts possible resistive instability
- $q < 1$ over $\sim 0.5$ of minor radius
- Suggests $I_p \sim 3I_{tf}$ may be upper bound on stability

High-$I_p/I_{tf}$, “zero”-$\beta$ Equilibria

Flux Plot

Equilibria Parameters

- $I_p$ = 296000
- $I_{tf}$ = 90000
- $I_N$ = 18.9
- $i$ = 0.68
- $q_0$ = 0.91
- $R_0$ = 0.41
- $a$ = 0.36
- Elongation = 1.98
- $q_{95}$ = 2.3

DCON Output

- $D_I D_R > 0 \Rightarrow$ Unstable
- Mercier Criterion
- $q$ Profile
- GGJ Resistive Criterion
- ArcSinh $D_I(A, U) \times 10^1$
- ArcSinh $D_R(A, U) \times 10^1$
- $\rho$
- $\psi_N$

ICC, February 2006, Austin, TX, EAU
Modeling: Current & Pressure Profiles Studies Underway

- Goal: To determine optimal parameters for external kink stability at high $I_p/I_{tf}$

- Base cases with $I_p/I_{tf} = 2$ and 3 used as starting points for further study
  - Varying profiles and shapes studied done to determine possible stability boundaries

- Studies are ongoing to determine possible stability boundaries; key parameters for high $I_p/I_{tf}$ operations
  - Initials indications show need for broad current profiles & high elongation for stability

![External kink stability from DCON](chart.png)
Phase-II: Mitigate TM Activity en route to High $I_p/I_{TF}$

- **Phase-I operational space recovered and extended**
  - Higher TF allowed: $I_p \rightarrow \sim 140 \text{ kA}$; $I_p/I_{TF} \rightarrow \sim 1$
  - $m/n = 2/1$ mode activity observed with $\sim$ same characteristics as Phase-I

- **Discharge utilizing all available V-s as OH goes to full power**
  - $\sim 30 \text{ mV-s}$ available vs. Phase-I $60 \text{ mV-s}$ ($90 \text{ mV-s full design}$)

- **Tearing mode mitigation experiments are ongoing**
  - Optimizing startup to navigate through MHD activity $\rightarrow I_p/I_{TF} > 1$
  - Approaches: variable ramp-rate; plasma shape; gas handling; impurity injection

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Focus of experimental operational space (Winter 2006)

- Phase-II flux consumption estimate with given V-s

---
Starting to Access $I_p > I_{tf}$ Regime

- $I_p \sim 1.5-2I_{tf}$ achieved by operation at low TF
  - Significantly above Phase-I operating space of $I_p \sim I_{tf}$
- Low TF operations made available using plasma guns
  - Tokamak-like MHD characteristics quite different from OH driven discharges
  - Gun as preionization source: MHD similar to Phase-I
- Higher $I_p$ comes with higher power plasma guns and/or full power OH

![Graph showing the relationship between $I_p/I_{tf}$ and Plasma Current (MA)]
\( I_p \approx 1.5 I_{tf} \) Attained Using Gun Preionization Source

- **Allows OH startup @ ultra-low TF**
  - Using PF power supplies; gives \( \sim 20 \text{ mV-sec} \)
  - Phase-I experience: more V-sec will allow extend discharge length and magnitude

- **\( I_p \approx 1.5 I_{tf} \) achieved to date**
  - MHD behavior similar to high-\( I_p \);
    high-field discharges
  - High ramp rates known to limit performance

- **Significance: No intrinsic limit in \( I_p/I_{tf} \)**
  - Depends on discharge evolution and current profile
Plasma Guns Produce Tokamak-like Plasmas

- Central flux reversal indicates formation of tokamak-like plasmas

- Evidence for relaxation to tokamak-like flux surfaces:
  - Increased $I_\phi$ amplification
  - Visual change in plasma
  - Strong B-dependence
  - Flux reversal on center column
  - Appearance of n=1 mode

Toroidal Current

Central flux

Mode Spectrogram

Unrelaxed plasma

Formation of relaxed plasma

Strongly relaxed
Helicity Injection Discharges Produced $I_p \sim 2 I_{tf}$

- $I_p/I_{tf} \sim 2$ w/ vastly different MHD evolution
  - $n=2$ mode activity vs $n=1$ Phase-I
  - TM's die away at end of discharge

- Gun injection fundamentally different drive source vs OH drive

- Substantial current modification
  - Changes $q$-profile; possible reverse shear
  - Broad current profile

- Suggest guns may be useful in high $I_N$ campaigns

ICC, February 2006, Austin, TX, EAU
Beginning: Non-inductive startup + OH Discharges

- Low $V_{\text{loop}}$ added to end of gun discharges
  - Modest increase in $I_p$
  - Prototype guns: limited to very low $TF$
- SXR emission shows heating when $V_{\text{loop}}$ applied

- Full handoff from non-inductive sources
  $\Rightarrow$ OH under study
  - low field $\Rightarrow$ poor confinement $\Rightarrow$ requires more input power

- Approach: increase helicity & power from guns; increased $V_{\text{loop}}$
  - allows higher field ops
  - better matching of applied field to equilibrium field
  - added V-sec from full power OH should help
Summary

• High Field Utilization in PEGASUS Needed to Access High $\beta_t$; $I_N$ Regimes

• Modeling Confirms Access to this Regime; Modifications Give Tools
  - TSC & confinement calculations confirm high $I_p/I_{tf}$; $\beta_t$ access
  - DCON analysis predicts stability up to $I_p \sim 3I_{tf}$
  - New tools integrated; demonstrate discharge control

• $I_p > I_{tf}$ Attained Using Plasma Gun Sources
  - Goal: $I_p/I_{tf} \sim 2-3$ ($I_N \sim 10-20$) @ high $I_p$
  - $I_p \sim 2I_{tf}$ w/ guns as a non-inductive startup source
  - $I_p \sim 1.5I_{tf}$ w/ guns as a preionization source
  - $I_p \sim I_{tf}$ not an intrinsic limit