Initiatives in Non-Solenoidal Startup and Edge Stability Dynamics at Near-Unity Aspect Ratio

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U.S. ST Goal: Accelerate Fusion Development

- **Advance ST as Fusion Nuclear Science Facility**
  - NSTX-U: physics + scenario basis for FNSF-ST (also ST DEMO)
  - PEGASUS-U, NSTX-U: non-solenoidal start-up: helicity injection, EBW, +…

- **Develop solutions for plasma-material interface**
  - LTX, NSTX-U: liquid Li for very high confinement, liquid metal PFCs
  - NSTX-U: novel divertors: snowflake/X, detachment, vapor shielding

- **Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond**
  - PEGASUS-U, NSTX-U: high $\beta$, toroidicity, MHD / transport validation, ELMs
  - NSTX-U: non-linear Alfvénic modes, electromagnetic turbulence
Tokamak Physics at Low A → 1: Advancing Fusion Energy Sciences

- **PEGASUS: Ultra-Low-A ST**
  - \( R_0 \leq 0.40 \) m, \( a \sim 0.35 \) m, \( B_{TF} \sim 0.15 \) T,
  - \( I_p \leq 0.25 \) MA, \( \Delta t_{pulse} \sim 25 \) ms
  - Grad student operated and maintained

- Non-solenoidal startup
  - Local helicity injection

- Advanced Tokamak Physics
  - ELM / H-mode / Neoclassical

- Physics of High \( I_p/I_{TF} \)
  - Toroidicity limits of stability
PEGASUS-U Initiative: Advancing Non-Solenoidal Startup and AT Physics

• Mission
  – Physics and technology of LHI
    • For NSTX-U and beyond (FNSF)
  – Nonlinear ELM dynamics, H-mode physics
  – Tokamak stability limits: A~1 high $\beta_T$ regime

• Facility enhancements
  – New centerstack assembly
    • $B_{TF}$ increases 5x
    • $\Delta t_{\text{pulse}} \sim 100$ msec
    • V-sec increases 6x (solenoid from PPPL)
    • Improved separatrix operation
  – NSTX-U relevant LHI injector arrays
    • Helicity input rate increases 2x
  – Diagnostics: multipoint TS; CHERS via DNB
Local Helicity Injection (LHI) Uses Strong Current Sources in SOL to Inject Helicity & Drive $I_p$

- Unstable streams relax to “tokamak”
  - Taylor relaxation, helicity conservation limit $I_p$
  - To date: $I_p \sim 0.18$ MA with $I_{\text{inj}} \sim 6$ kA
  - Extensive current source technology development

- Approaching predictive $I_p(t)$ model
  - Energy conservation; lumped parameter model

- Details of LHI dynamics emerging
  - NIMROD: Reconnecting current streams inject axisymmetric current rings into core plasma

- Technique scales to NSTX-U, FNSF
PEGASUS-U Initiative: Develop & Validate LHI-Startup for NSTX-U and Beyond

- Critical physics issues
  - Confinement behavior and helicity dissipation
  - Edge $\lambda=J/B$, J penetration processes
  - Injector geometry optimization

- Technology development
  - Long-pulse, large-area injectors in high $B_{TF}$

- Models & predictive understanding
  - 0-D Power Balance $I_p(t)$ model
  - NIMROD
  - TSC

“Pagoda-style” injectors sustain $V_{inj} \leq 1.5$ kV, $I_{inj} \sim 2$ kA with no PMI effects within 1-2 cm of LCFS
• Low $B_{TF} \Rightarrow$ very low $P_{L-H}$
  – With unique diagnostic access

• Ohmic H-mode plasmas
  – $H_{98} \sim 1$; 5-10x predicted $P_{L-H}$
  – Measured pedestal in $J_{\text{edge}}(R,t)$

• ELM physics studies
  – $J(R,t)$ evolution through ELM collapse
  – Type I: $n = 5-15$; Type III: $n \sim 1$
    • Opposite high-$A$ plasmas
PEGASUS-U Initiative: Nonlinear ELM Studies and H-mode Physics

- $P(r,t), J(r,t), v_\phi(r,t)$ through ELM cycles
  - Nonlinear evolution of magnetic structures

- ELM, H-mode modification and mitigation
  - Vary $J_{\text{edge}}(r)$, modify edge $v_\phi$ and shear via LHI

- Synergistic studies with BES on NSTX-U, DIII-D
  - Entry point for grad students to large facilities

- Models to test
  - NIMROD
  - BOUT++
  - EPED

Comparison of $J(r,t), N_e(r,t), T_e(r,t)$ on Pegasus to detailed $N_e(r,t)$ on NSTX-U will aid interpretation of BES ELM studies on NSTX-U & DIII-D
• Non-solenoidal startup
  – **PEGASUS-U, NSTX-U LHI program** for ~ 1 MA startup demonstration
  – New non-solenoidal startup studies: Stellarator windings; Iron core, EBW…

• **Current sustainment with LHI** via MHD control
  – Passive or active injector feedback system

• ELM modification and mitigation
  – C-pellet injection for tests of models for ELM-pacing (w/ORNL)

• Neoclassical physics tests
  – $J_{BS}$ model tests: Test Sauter model if sufficient edge pressure achieved

• High $\beta_t$ plasma studies at $I_p/I_{TF} \geq 3$
Modest Staff and Budgets with Collaborations Enable an Aggressive Program

- **Pegasus-U requires ~ $1.5M/yr**
  - Equipment and supplies funding
  - 2 Scientists; Full-time support staff
  - 1-3 more grad students; undergrad team

- **Present staffing is sub-critical**
  - 1/3 Faculty; 1 scientist
  - 2/3 Engr; 1 tech; 2/3 instrument tech
  - 6 graduate students; 2-4 undergrads

- **Growing collaborations**
  - PPPL: Solenoid; DNB; LHI; Iron core*
  - ORNL: $H_\alpha$ diag.; Pellet pace &/or EBW*
  - U Tokyo: Magnetics probe array
  - DIII-D & NSTX-U: BES programs
  (* = future?)

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![Recent PEGASUS Funding History](chart.png)

*X = not supported by PEGASUS grant*
Primary Areas of Contribution

- **Thrust 16: Develop the spherical torus**
  - Range of V&V activities in parallel with LHI startup, ELM, and high-β studies
  - Further initiatives in new nonsolenoidal startup, sustainment, ELM pacing, etc.

- **Thrust 18: Achieve high performance with minimal field**
  - Stability limits at extreme toroidicity and high \( l_p/l_{TF} (>2) \)

Additional Areas of Contribution

- **Thrust 2: Transient events in burning plasmas**
  - Edge stability studies; nonlinear ELM dynamics

- **Thrust 9: Unfold the physics of boundary-layer plasmas**
  - Pedestal evolution
  - Peeling-ballooning studies and experimental verification of models

- **Thrust 6: Develop predictive models for fusion plasmas**
  - Potential for detailed tests of Sauter neoclassical model

- **Thrust 10: Technology of plasma-surface interactions**
  - Development of LHI injectors for high-performance plasma edge
Studies at A~1 in PEGASUS-U will Advance Fusion Energy Sciences

- Significant progress with non-solenoidal startup of ST
  - Increasing understanding of LHI physics to project towards MA-class startup
  - Developing advanced edge current sources

- Leveraging low-A regime to test edge stability theory
  - Peeling mode characteristics consistent with theory
  - Tests of ELM physics

- Many possibilities for further initiatives
  - e.g., LHI J(R,t) control and H-mode support high-β studies at tokamak limits

- A cost-effective, strong platform for student education in fusion science and technologies