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

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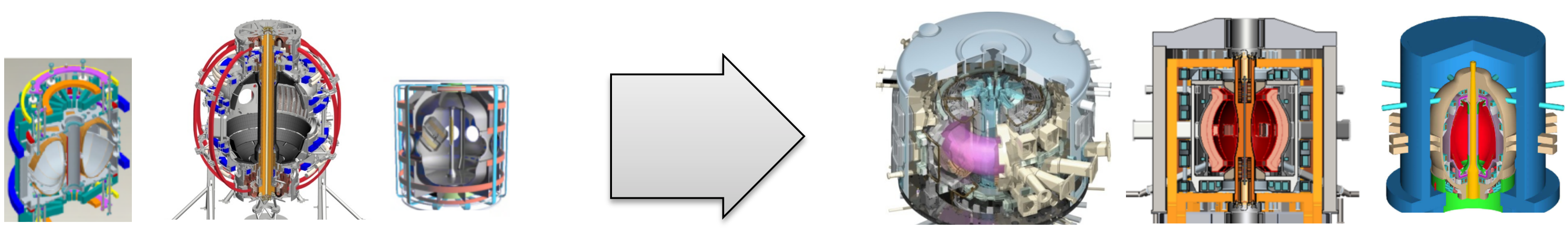
PEGASUS Toroidal Experiment

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

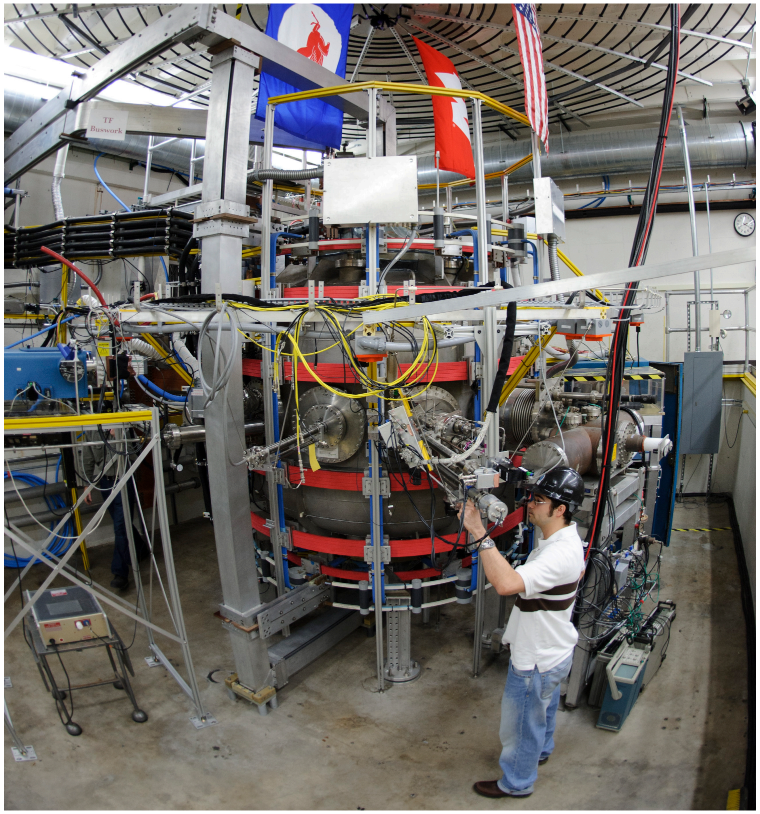
- **Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond**
  - PEGASUS-U, NSTX-U: high β, toroidicity, MHD / transport validation, ELMs
  - NSTX-U: non-linear Alfvénic modes, electromagnetic turbulence



LTX NSTX-U PEGASUS ITER FNSF-ST ST DEMO

Tokamak Physics at Low A → 1: Advancing Fusion Energy Sciences

- PEGASUS: Ultra-Low-A ST
  - $R_0 \leq 0.40$ m, a ~ 0.35 m, B_{TF} ~ 0.15 T, $I_p \leq 0.25$ MA, Δt_{pulse} ~ 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

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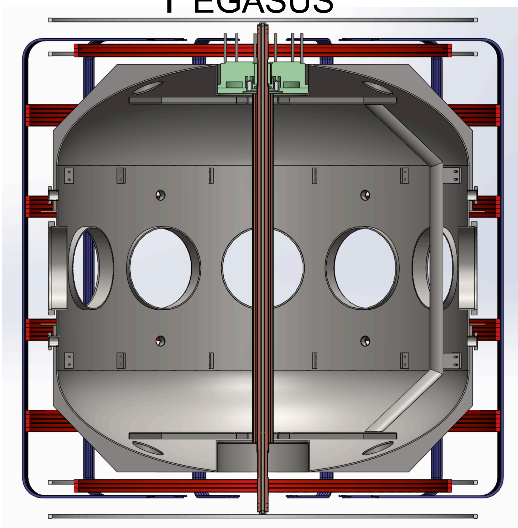
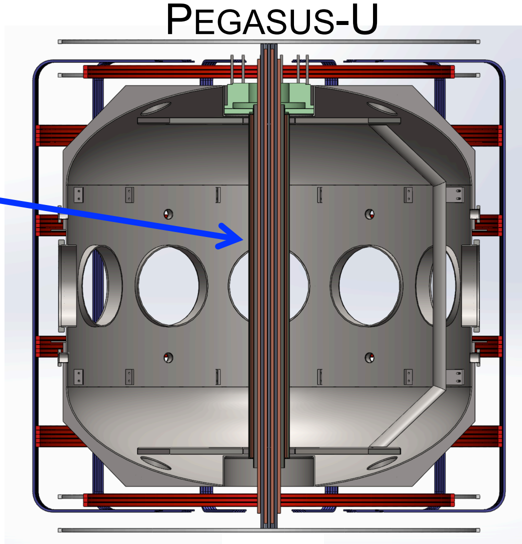
PEGASUS-U Initiative: Advancing Non-Solenoidal Startup and AT Physics

- Mission
  - Physics and technology of LHI
    - For NSTX-U and beyond (FNSF)
  - Nonlinear ELM dynamics, H-mode physics
  - Tokamak stability limits: A~1 high β_T regime
- Facility enhancements
  - New centerstack assembly
    - B_{TF} increases 5x
    - Δt_{pulse} ~ 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

PEGASUS



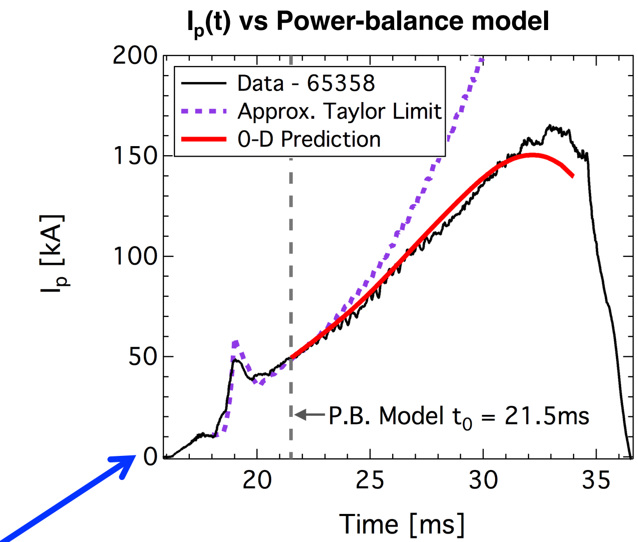
PEGASUS-U



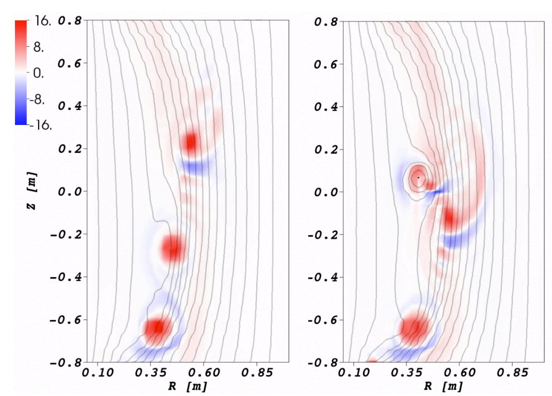
2 m

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 $I_{inj} \sim 6$ 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



NIMROD:Reconnecting current streams

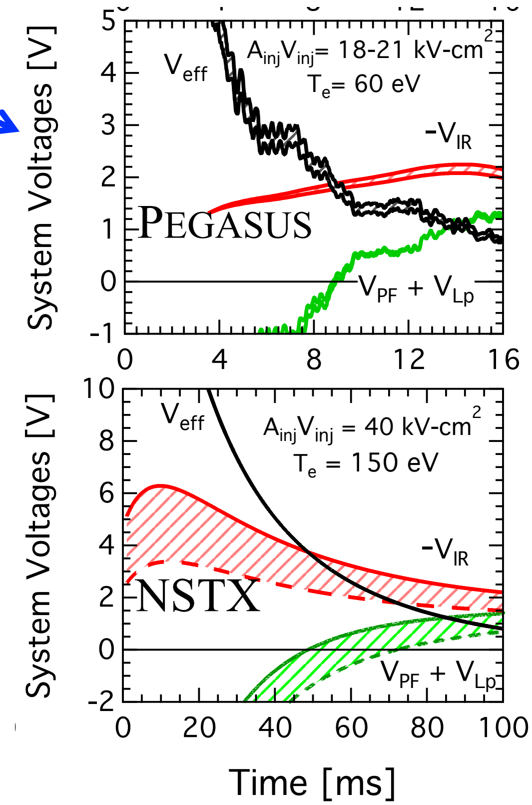


[O'Bryan Phys Plas.**19**, 2012]

PEGASUS-U Initiative: Develop & Validate LHI-Startup for NSTX-U and Beyond

- Critical physics issues
  - Confinement behavior and helicity dissipation
  - Edge λ=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

PEGASUS @ 0.3 MA = same regime as NSTX-U @ 1MA:



"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

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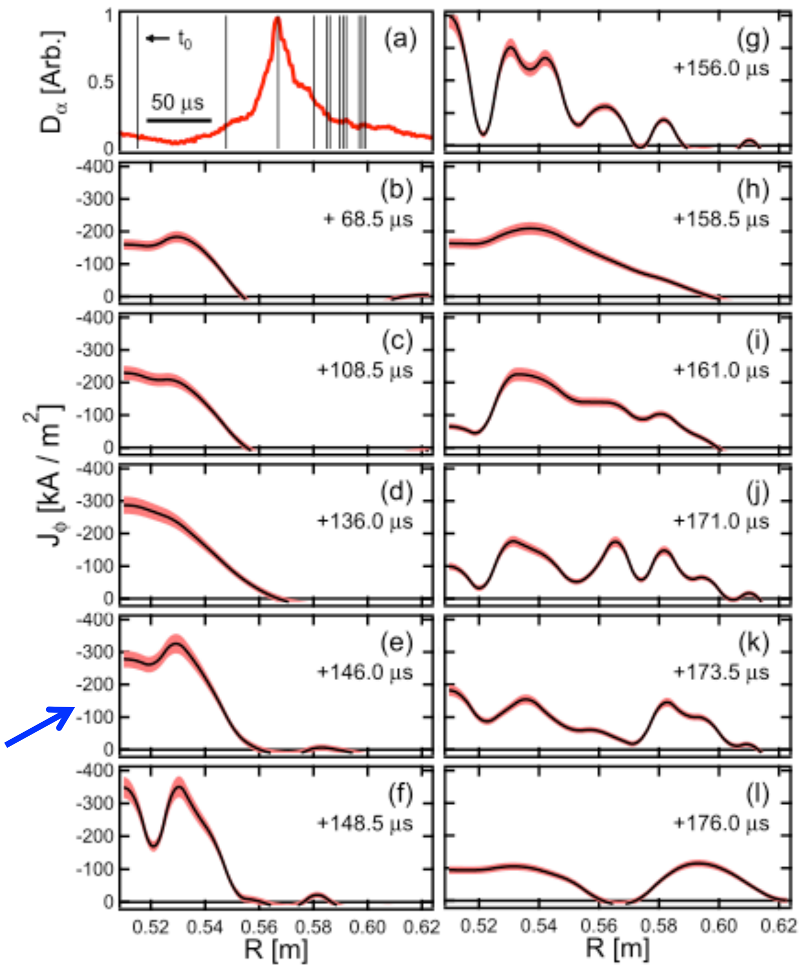
A~1 Access to AT Physics: H-mode, J_{edge} Dynamics, High-β, etc.

- Low B_{TF} => 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 $J_{edge}(R,t)$
- ELM physics studies
  - J(R,t) evolution through ELM collapse
  - Type I: n = 5-15; Type III: n ~1
    - Opposite high-A plasmas



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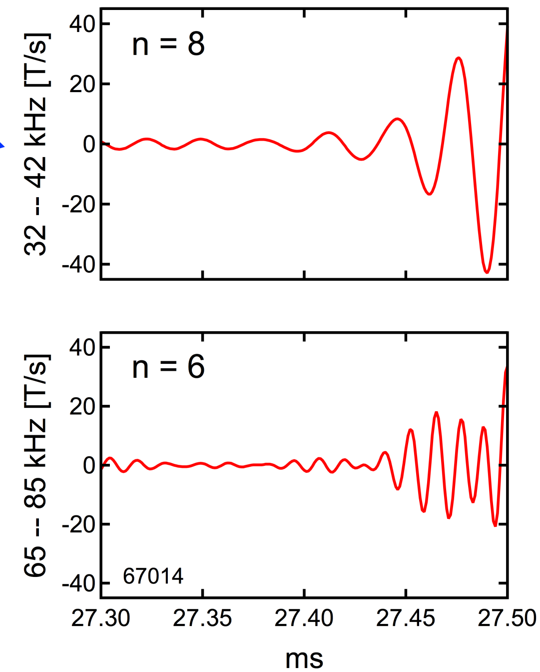
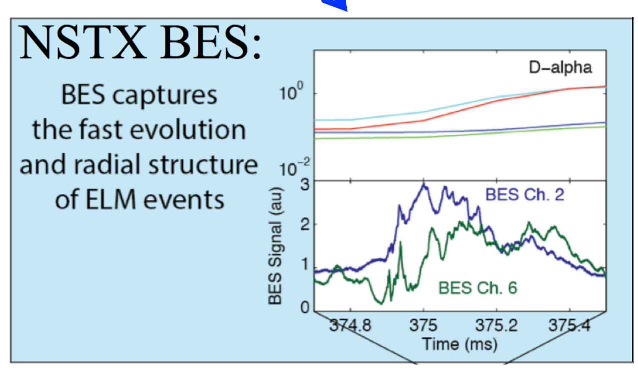
PEGASUS-U Initiative: Nonlinear ELM Studies and H-mode Physics

- P(r,t), J(r,t), v_ϕ(r,t) through ELM cycles
  - Nonlinear evolution of magnetic structures
- ELM, H-mode modification and mitigation
  - Vary J_{edge}(r), modify edge v_ϕ 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

Nonlinear Evolution of ELM Magnetic Toroidal Modes in PEGASUS:





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

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PEGASUS-U Enables Further Initiatives for Latter Part of Decadal Period

- 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 β_t plasma studies at $I_p/I_{TF} \geq 3$

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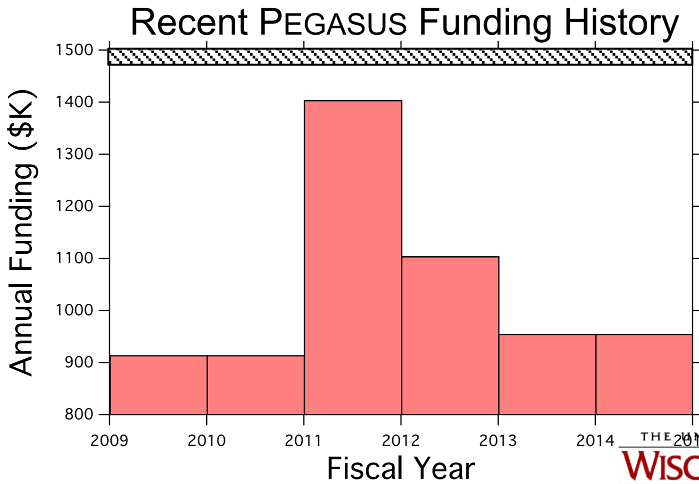
Modest Staff and Budgets with Collaborations Enable an Aggressive Program

- 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_α diag.; Pellet pace &/or EBW*
  - U Tokyo: Magnetics probe array
  - DIII-D & NSTX-U: BES programs

  (* = future?)

X = not supported by PEGASUS grant



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PEGASUS-U Initative Contributes to Many ReNeW Research Thrusts

- 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
    - Stabilitylimits at extreme toroidicity and high I_p/I_{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

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