The PEGASUS-Upgrade Experiment

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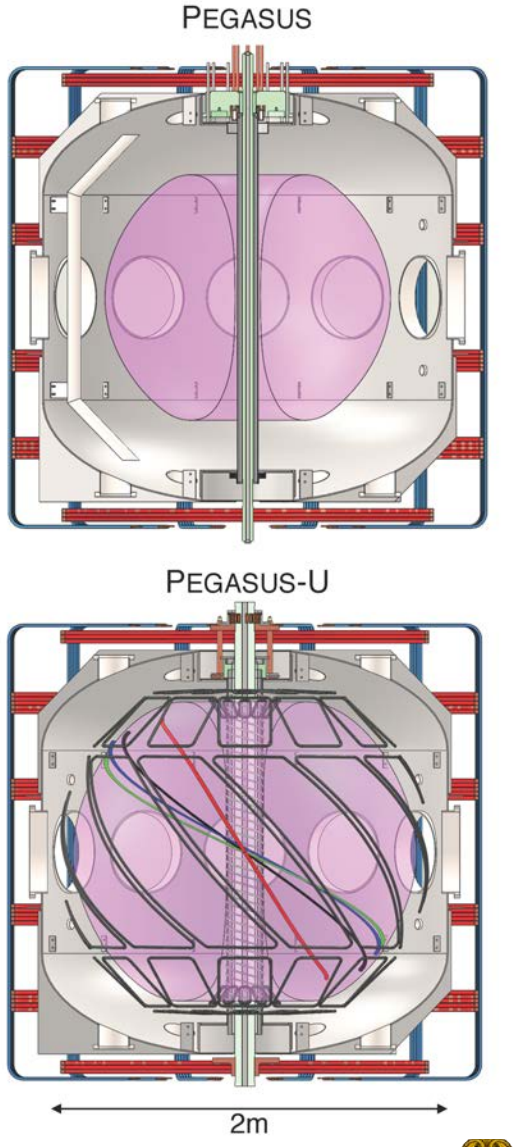
PEGASUS
Toroidal Experiment

Physics Motivation

PEGASUS-U Supports Focused Physics Mission

- Nonlinear pedestal and ELM studies
  - Simultaneous measurements of $p(R,t)$, $J(R,t)$, $v_\phi(R,t)$
    - New edge diagnostics (probe arrays, DNB)
  - Tests of Sauter neoclassical bootstrap model
- ELM Modification and Mitigation
  - Novel 3D-MP coil array
    - LFS array: 12 toroidal × 7 poloidal
    - Helically-wound HFS coils
  - LHI current injectors in divertor, LFS regions
- Physics of Local Helicity Injection Startup[1]
  - High I_p, long-pulse startup
  - Projections to NSTX-U



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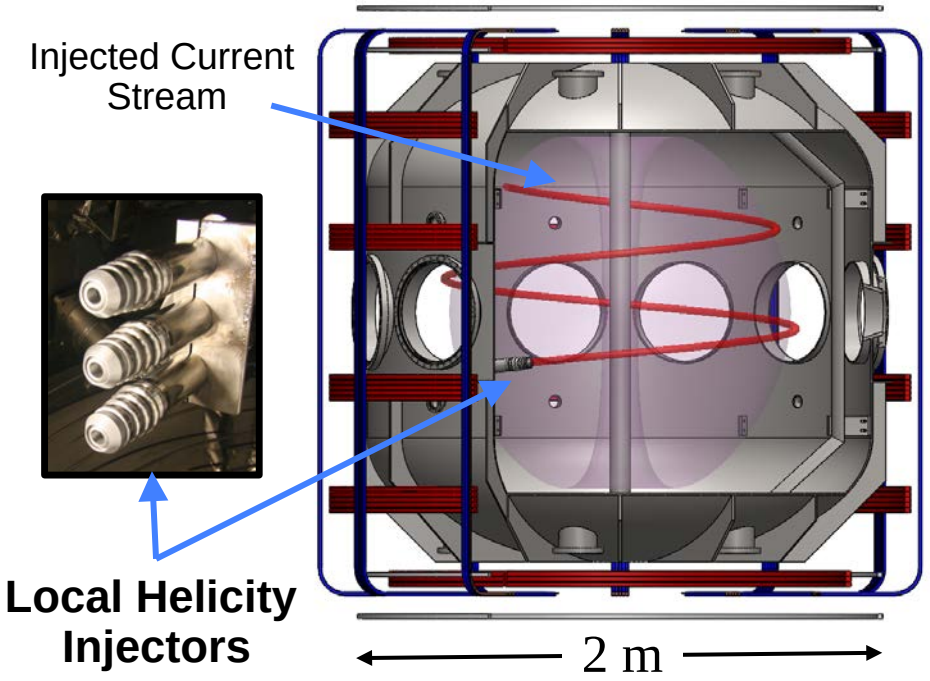
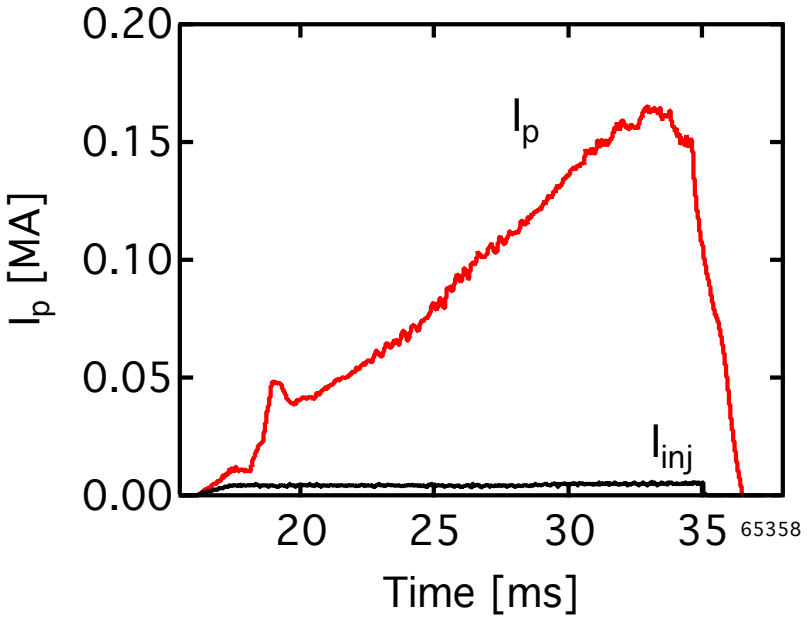
Local Helicity Injection (LHI) is a Scalable Non-solenoidal Startup Technique

Current injected from local plasma source



$I_p \leq 0.18$ MA (I_{inj} = 5 kA)

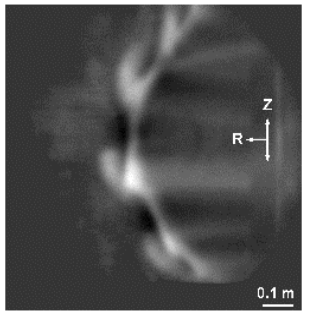


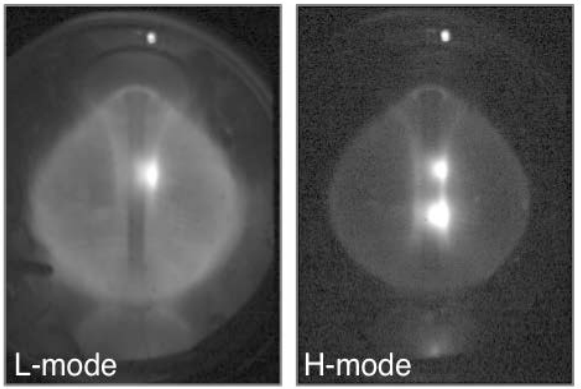
- Unstable current streams form tokamak-like state via Taylor relaxation
- Compact, modular, and appears scalable to MA-class startup

A ~ 1 Operations Provide Access to AT Physics

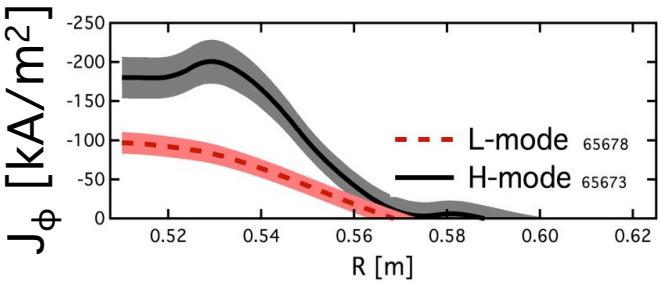
- *A* ~ 1 → high I_p at very low B_T
  - Excitation of peeling modes without J_{BS}[1,2]
  - Easy access to H-mode regime and ELMs
  - Neoclassical effects (resistivity enhancement)

PEGASUS





- Modest-sized plasma and relatively low T_e
  - Allows diagnostic access to pedestal
  - Pedestal $J_\phi(R, t)$, $p(R, t)$, and $v_\phi(R, t)$ via probes



[1] Bongard *et al.*, Phys. Rev. Lett **107**, 035003 (2011).
[2] Bongard *et al.*, Nucl. Fusion **54**, 114008 (2014).

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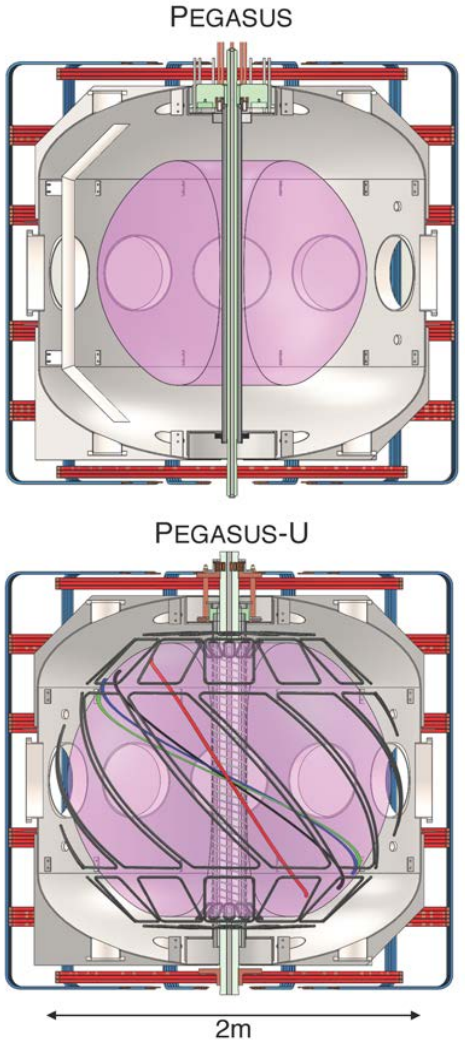
Motivates PEGASUS-Upgrade Proposal

	PEGASUS	PEGASUS-U
ψ_{SOL} (mWb)	40	138 /170
$B_{T,max}$ (T) at R_0	0.14	~ 0.4
$I_{p,max}$ (MA)	0.15	0.3
Δt (ms)	15	> 50
A	1.15	1.22

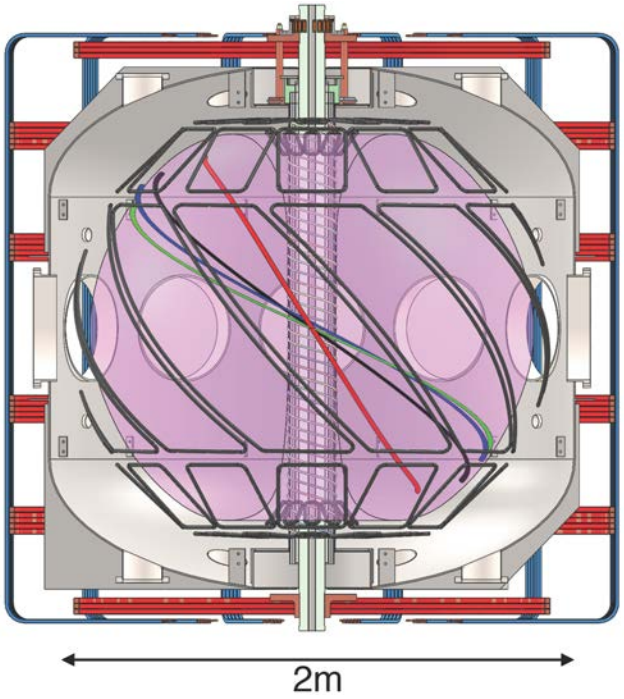


- Nonlinear pedestal and ELM studies
  - Simultaneous measurements of p(R,t), J(R,t), v_φ (R,t)
    - New edge diagnostics (probe arrays, DNB)
  - Tests of Sauter neoclassical bootstrap model
- ELM Modification and Mitigation
  - Novel 3D-MP coil array
  - LHI current injectors in divertor, LFS regions

Upgrade Elements

Aggressive, Low-Cost Upgrade to Present Facility Proposed to Create Pegasus-U

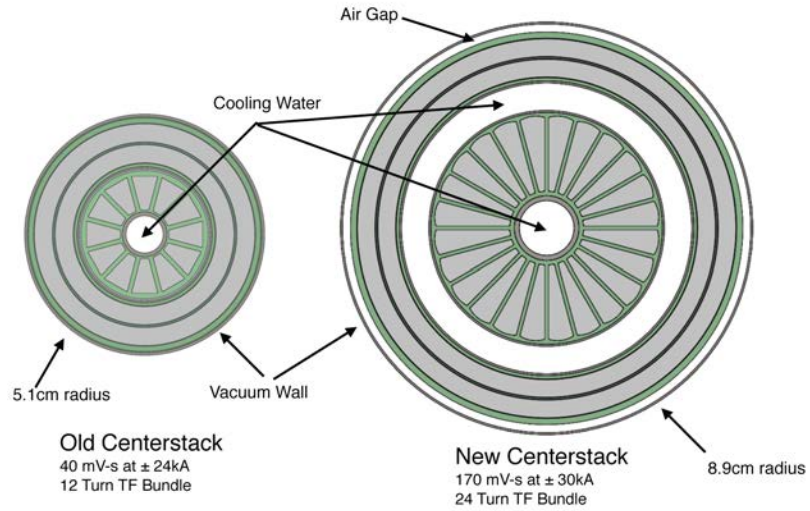
	PEGASUS	PEGASUS-U
R_{sol}(cm)	4.9	8.4
I_{sol}(kA)	±22	±24/30
ψ_{SOL} (mWb)	40	138 / 170
$B_{T,max}$ (T) at R_0	0.14	~ 0.4
$I_{p,max}$ (MA)	0.15	0.3
Δt (ms)	15	50 - 100
A	1.15	1.22



- New Centerstack
  - Extended pulse length; Increased TF; noise-immune diagnostics
- Increased Ip
- Midplane, Divertor large-area LHI current injectors
- Upgraded OH power switches
- New TF and expanded PF power supplies

Larger Centerstack, Maintaining A ~ 1.22

- New centerstack assembly
  - OH solenoid via PPPL collaboration
    - $\Delta\Phi\downarrow OH$:40→170 mV-s
  - TF bundle: 0.15 → 0.40 T
  - Pulse length: 15 → 50–100 ms



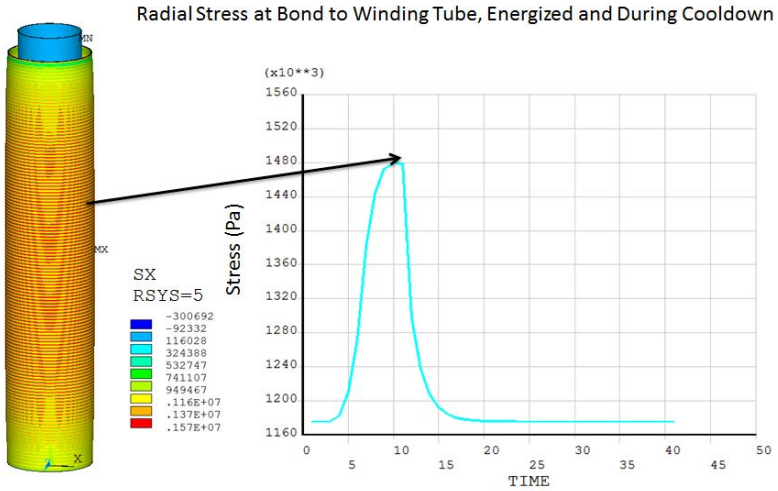
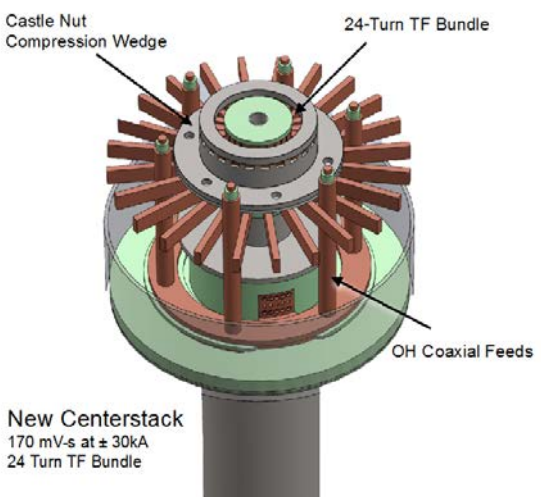


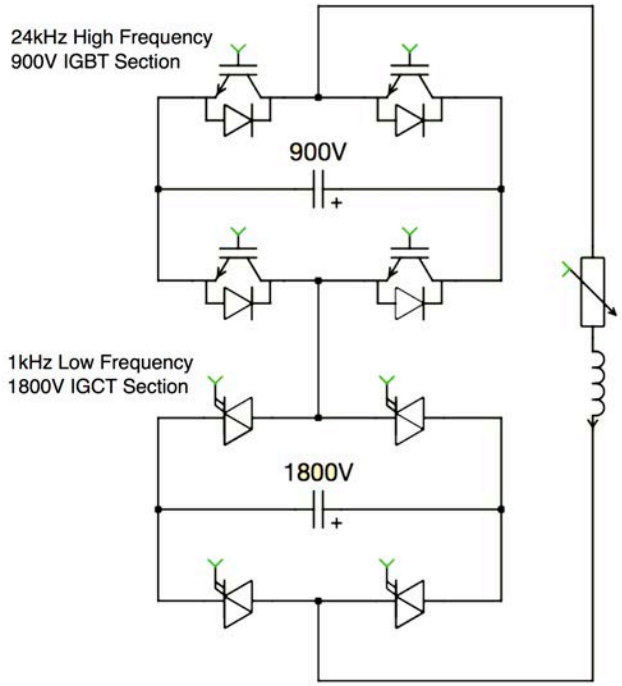
Fig. 4-10 (right). Thermal and electromechanical stress estimates.

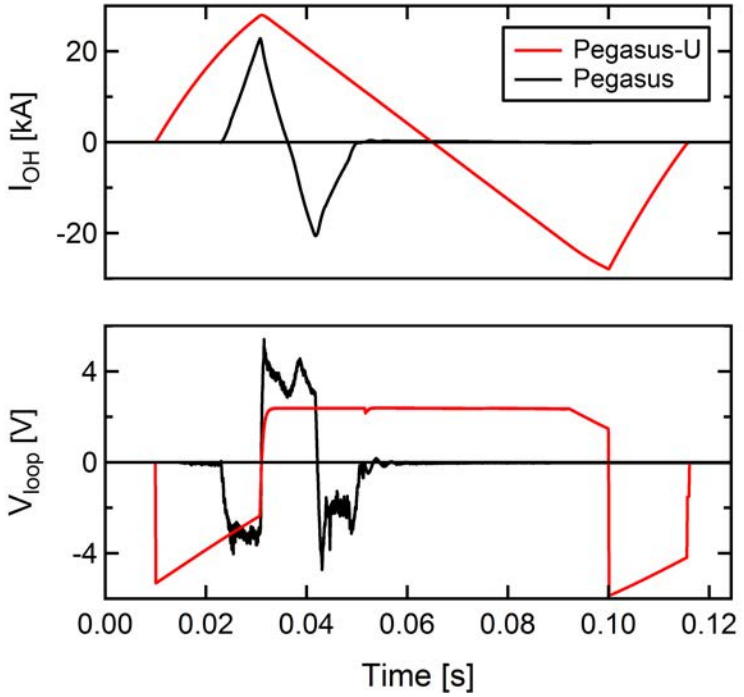


Present Centerstack detail:
Castel Nut & Coaxial Feeds

"Castle Nut" compression wedge in proposed, present assemblies.

OH Cascaded Multilevel Inverter for Long-Pulse OH Operation, Improved V_{loop} Control





- Optimizes use of existing switches and energy storage
  - Existing IGCT silicon at low-frequency to maximize switch-events
  - High-frequency IGBT “corrector” provides waveform refinement
  - Employs multichannel FPGA logic control

- Design matched to new central solenoid

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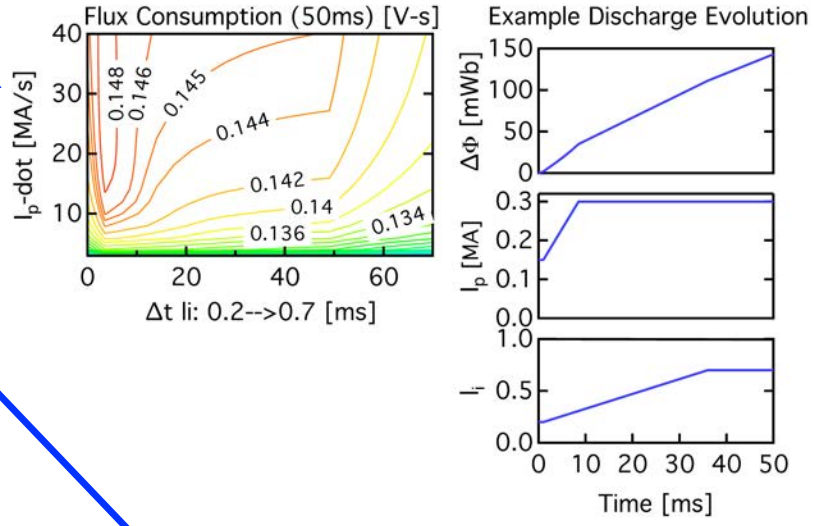
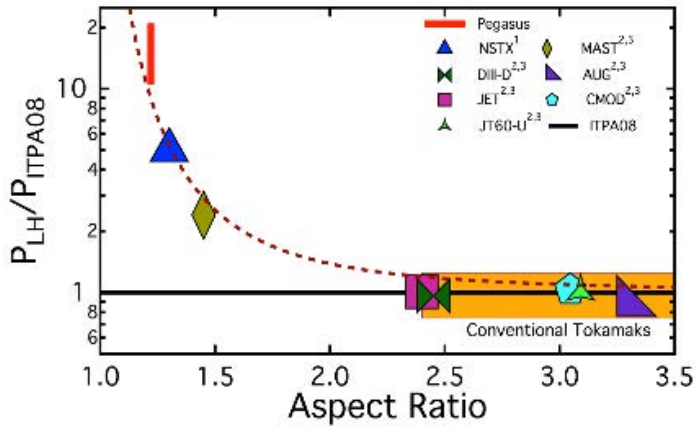
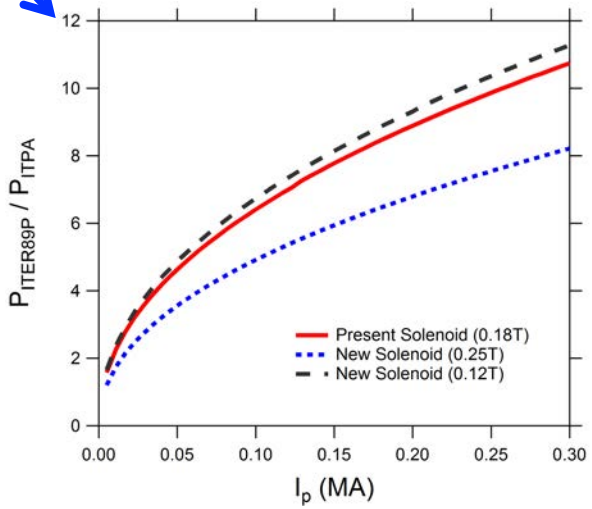
Maintains Access to A ~1 Operating Space

- Centerstack design provides sufficient V-sec to maintain 0.3 MA for 50-100 msec
- P_{OH} maintains access to H-mode
- A ~ 1.22 remains in anamolous P_{LH} regime:



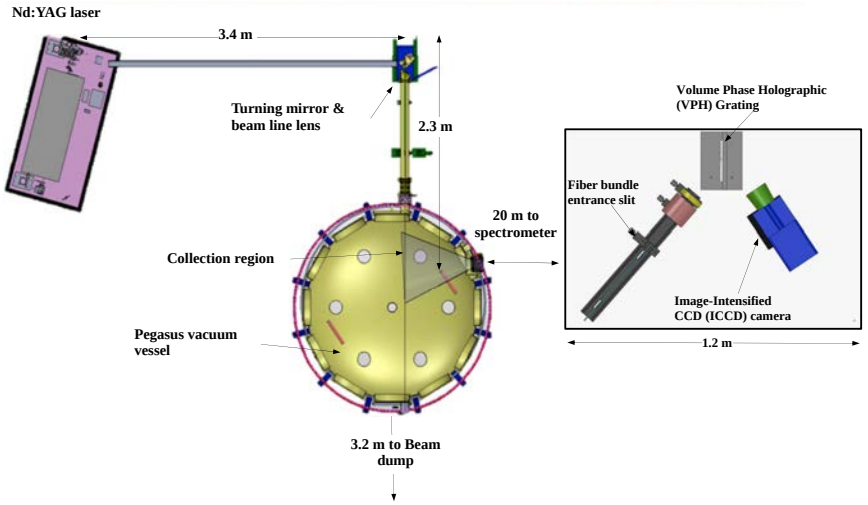




R.J. Fonck, APS-DPP 2015

Core Profile and High-Resolution Edge Diagnostic Upgrades Planned

- Thomson scattering
  - 12-24 spatial points
  - Variable radial position sampling
  - ARRA-funded
- Diagnostic neutral beam
  - $T_i(R,t)$, $v_\phi(R,t)$, $N_Z(R,t)$
  - 80 keV, 2-3 A, H^0, $\leq$ 100 ms
  - Part separately supported diagnostic development project
- New centerstack magnetics
- Insertable Probes across Pedestal
  - Langmuir probe array
  - B(R,t) array
  - Mach probes
- Soft X-ray imaging for LHI current streams



Thomson scattering diagnostic layout on PEGASUS facility.

DNB in refurbishment for turbulence diagnostic devleopment

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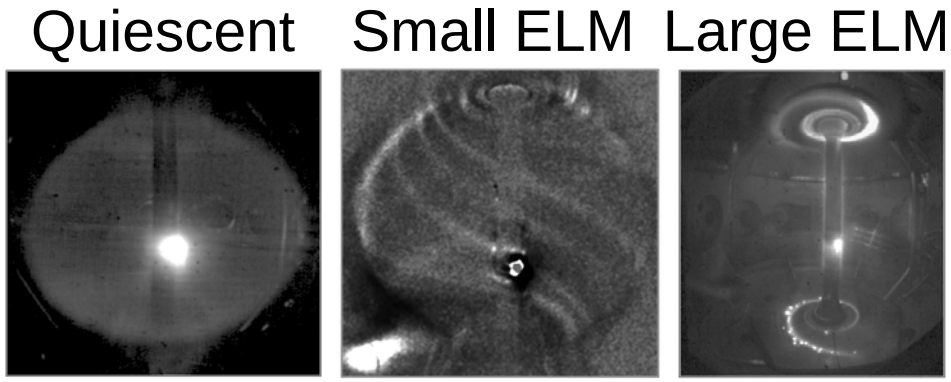
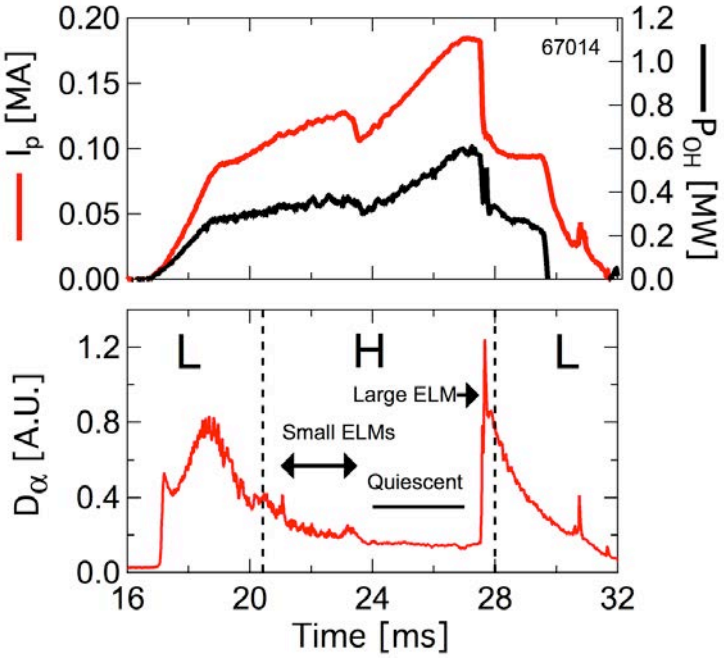
H-mode, Pedestal, ELM Mission Elements

A ~ 1 Enables Nonlinear ELM Studies

- Small and Large ELMs observed in Pegasus H-mode
- ELMs evolve nonlinearly on Alfvén timescales
- Perform fast, localized measurements of all critical fields:
  - n, T, J, v, …
  - More feasible at some scales than others
- To truly test nonlinear models, data at various A, ν, S, η, etc. needed
  - Both high- and low-performance plasmas relevant to theory-experiment comparison





K.E. Thome, GP 12.00115 D.M. Kriete, GP 12.00120

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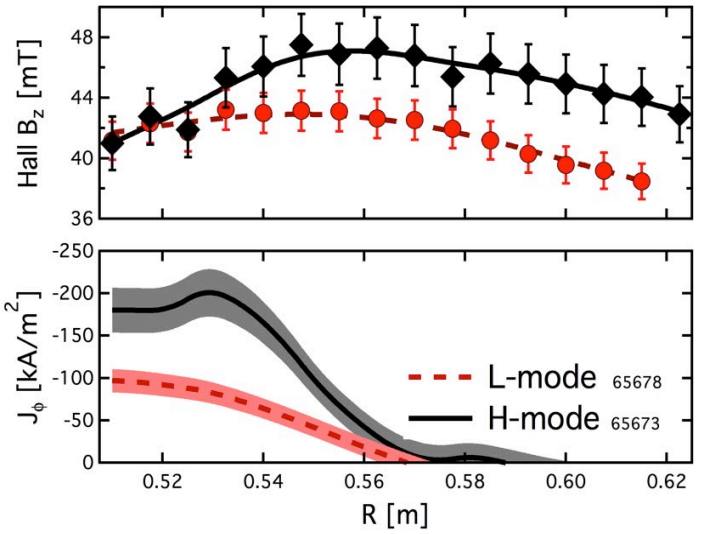
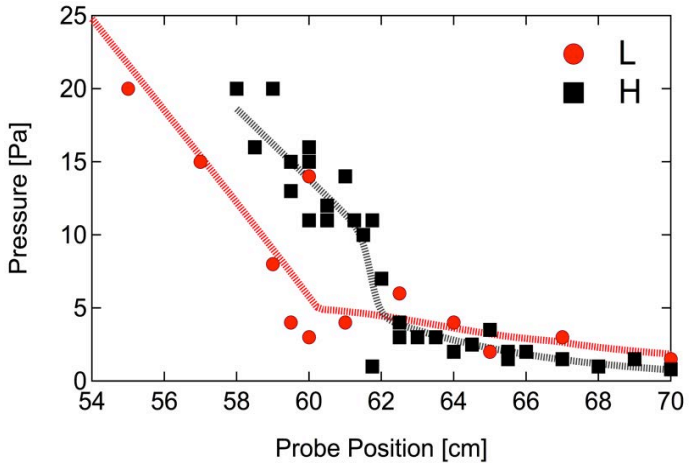
Edge Pedestals Measured Between ELMs in H-mode

- Short pulse, low edge T_e permit detailed edge measurements
  - $J_\phi(R,t)$ via multichannel Hall probe[1,2]
    - High spatial, temporal resolution
  - p(R) via triple Langmuir probe
    - Single point, high temporal resolution
- Clear current pedestal observed
  - L → H scale lengths: 4 → 2 cm
- Multi-shot Langmuir probe scans indicate pressure pedestal
  - Some edge distortion present from MHD





[1] M.W. Bongard *et al.*, *Rev. Sci. Instrum.* **81**, 10E105 (2010)
[2] M.W. Bongard *et al.*, *Phys. Rev. Lett.* **107**, 035003 (2011)

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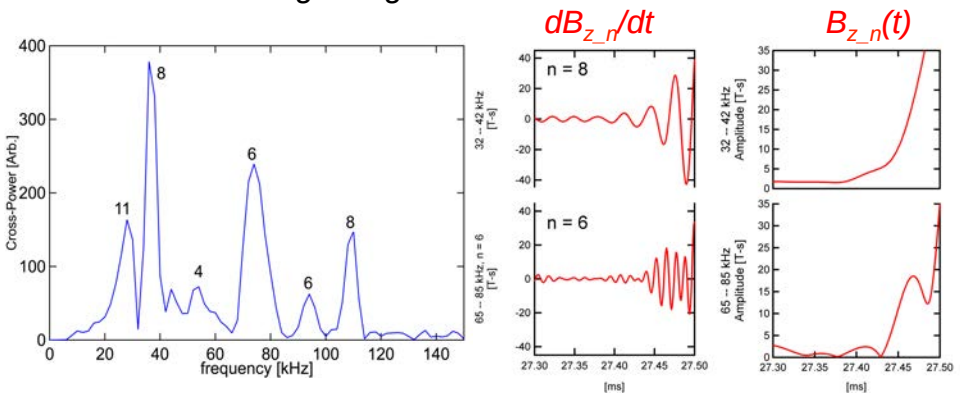
Fast-time Evolution Measurements of Pedestal Region Accessible

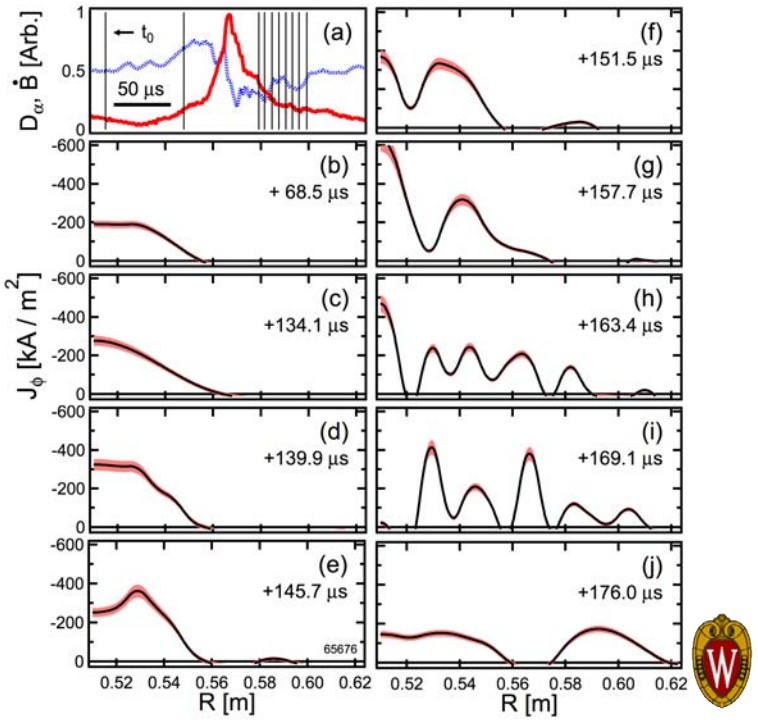
- Simultaneously unstable toroidal modes present during ELM
  - Detectable only within ~ cm of LCFS
  - Nonlinear energy exchange

Edge Magnetic Probes on PEGASUS:



Large ELM Magnetic Structure *ELM mode growth*

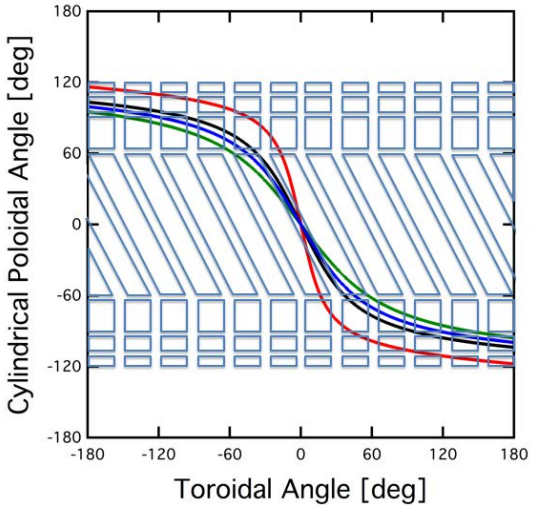
- Complex, multimodal $J_{edge}(R, t)$ collapse
  - High Δt ~ 6 μs through single large ELM
  - Current filament ejection

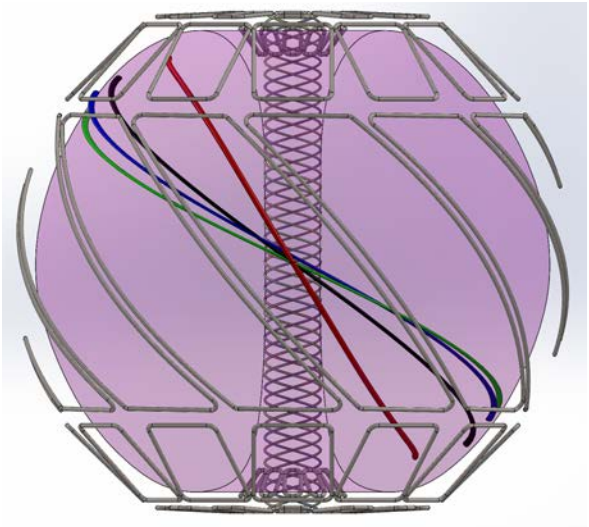


- **Goal:** studies of nonlinear ELM dynamics at Alfvénic timescale
  - Comparisons to nonlinear models

3D-Magnetic Perturbation System Planned

- Design study, fabrication as proposed work
- Comprehensive 3D-MP system
  - LFS coils, spaced with ~equal-PEST angle from model equilibria
    - 12 toroidal x 7 poloidal array
    - Initial DC power systems for n=3 control
  - HFS 4-fold helical coil set
- Uniqueness
  - Widest spectral range
  - Active and Passive control capabilities
  - Local pedestal plasma response measurements





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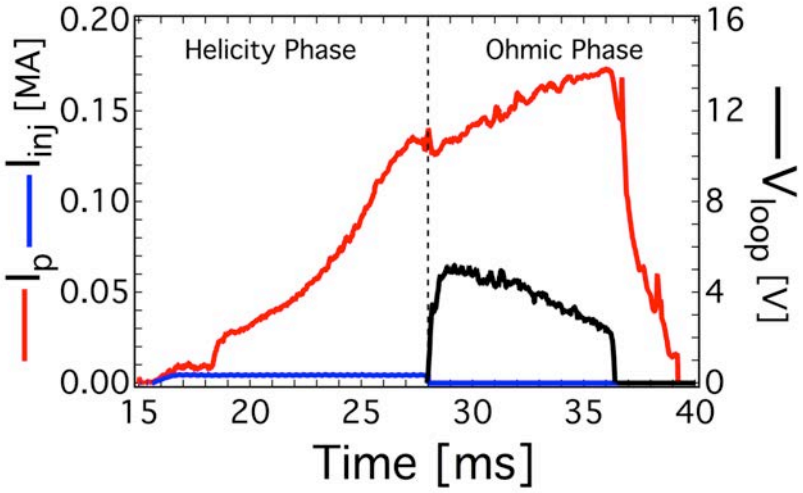
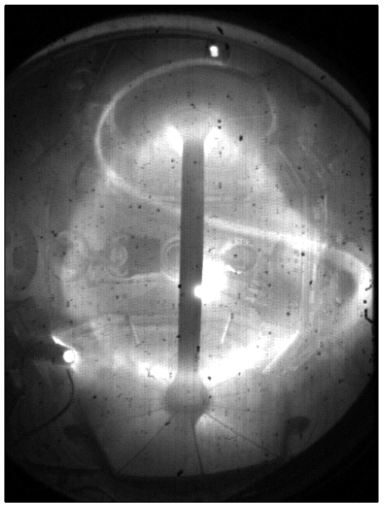
3D Edge Current Injectors Support ELM Studies

- Local helicity injection system provides 3D SOL current injection
  - $I_{inj} \leq 5$ kA, J_{inj} ~1 kA/cm^2



- LHI use with H-mode studies
  - Pulse extension and J(R) control

- LHI system affects edge plasma
  - Strong 3D edge current perturbation
    - Similar to LHCD on EAST[1]
  - Edge biasing to modify rotation profiles



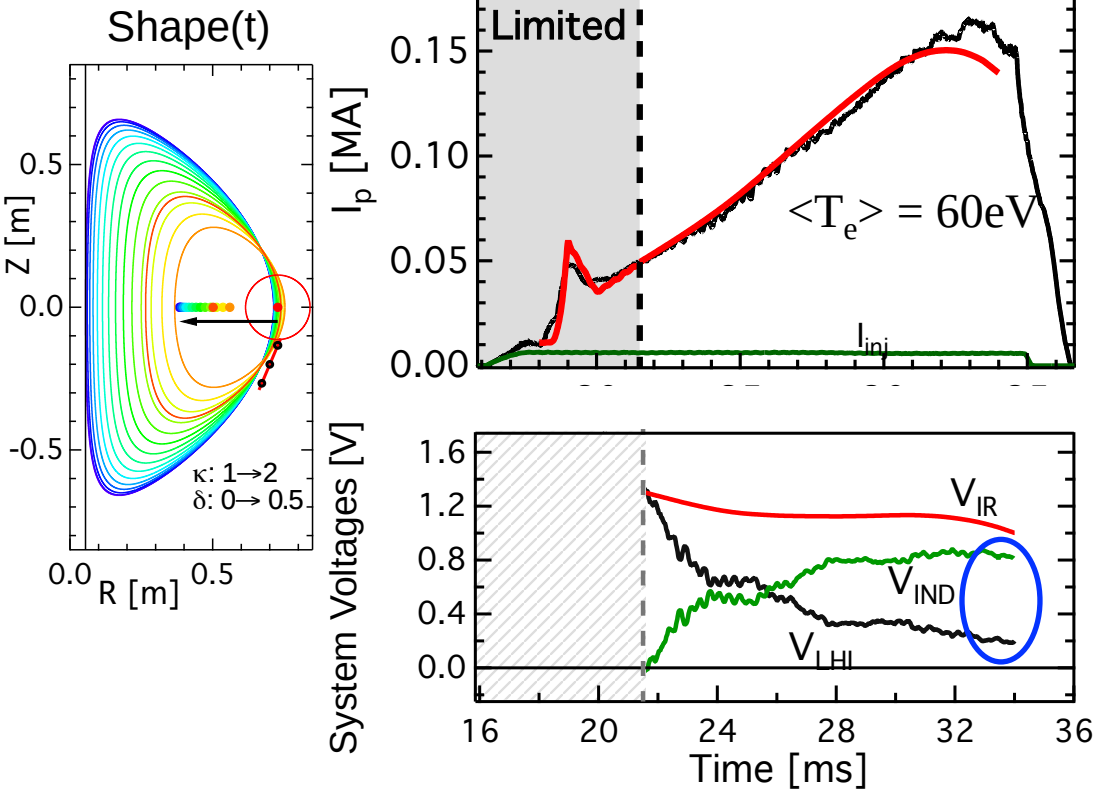
1: Liang *et al.*, Phys. Rev. Lett. **110**, 235002 (2013)

Non-solenoidal LHI Startup Mission Elements

0-D Power Balance Model Describes Relative Strengths of LHI and Inductive Current Drives

- Model elements:
  - Inputs: <η(t)>, $R_0(t)$, shape(t), $V_{inj}(t)$, $\ell_i(t)$
  - Confinement model under development for <η(t)>

$$I_p \left[V_{LHI} + V_{IR} + V_{IND} \right] = 0; \; I_p \le I_{TL}$$

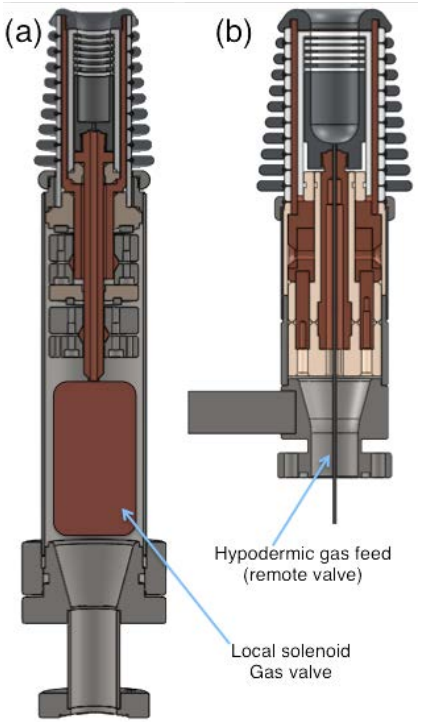


- With LFS injection and compression, induction povides significant V-sec
  - Tradeoffs between inductive contributions, transport, and geometry

- See J.L. Barr GP12.00116

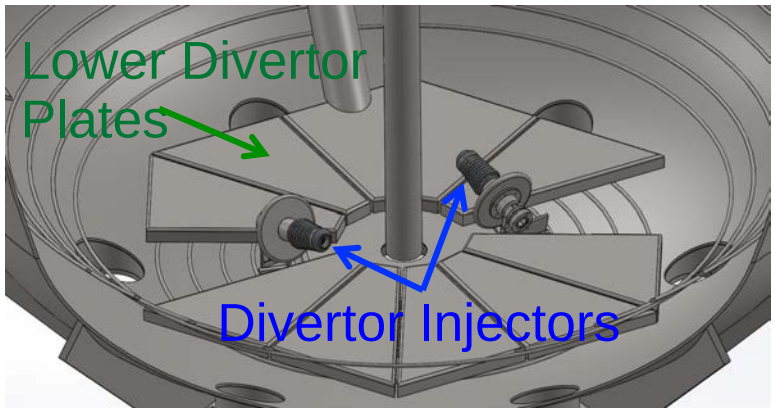
Divertor Injection: Vary Injector Geometry to Separate Inductive and Helicity Drive Effects

- Addresses issues for extrapolation to NSTX-U
  - Accesses higher I_p startup via 3-4x increase in V_{LHI}
- Minimal V_{IND}: ~ fixed geometry
  - Separates effects: edge reconnection Vs. inductive drive
- Larger injector at low R_{inj}
  - Increased B_{TF} tests

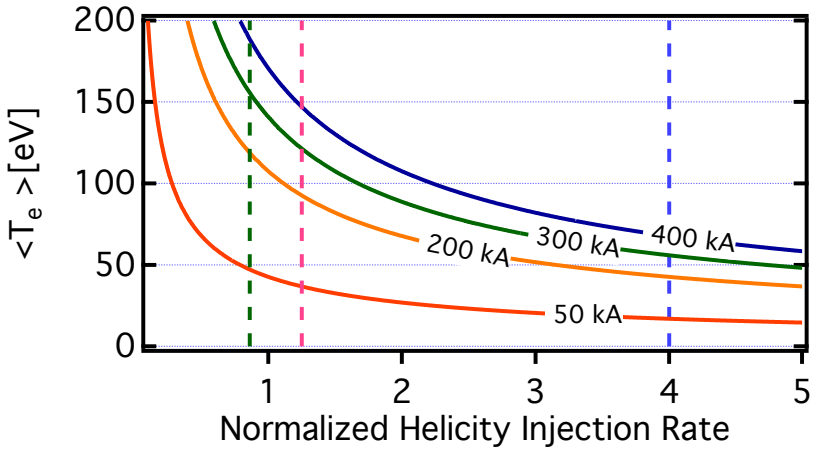


(a) Present injector cross-section; (b) proposed new injector design.

Divertor Injector CAD



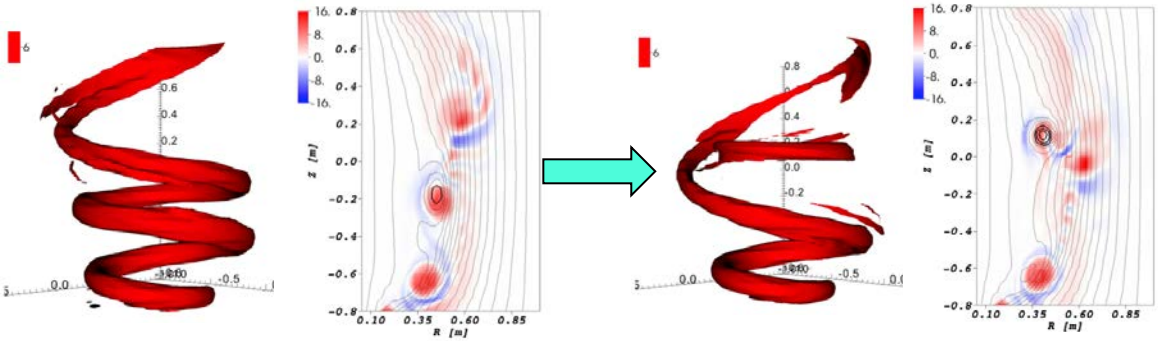
Projected I_p with Divertor Injection



See J.M. Perry PO6.00001 and J. A. Reusch GP12.00113

Unstable Current Streams in Edge Consistent with NIMROD Modeling

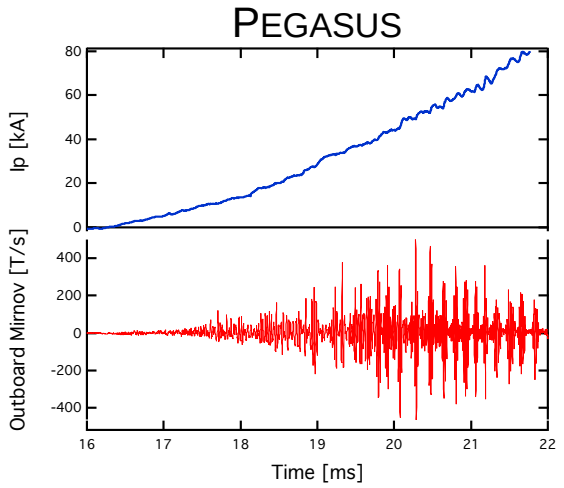
- Internal MHD amplitude and correlation analysis of bursts consistent with interacting streams in plasma edge*
  - Coherent streams persist and intermittently reconnect at high I_p, consistent with NIMROD:

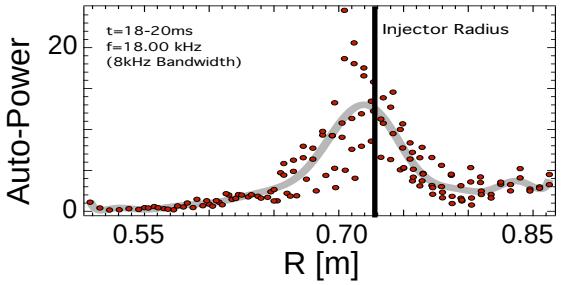


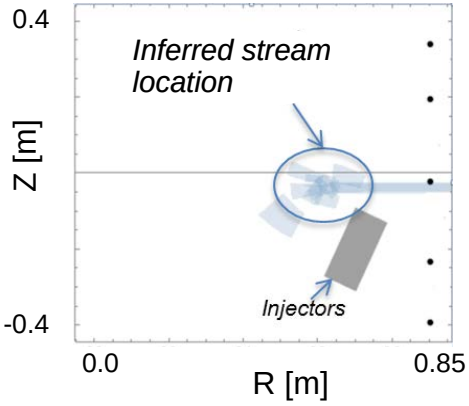
** J. O'Bryan, et al., Physics of Plasmas, **19**, 080701 (2012)*

- Confinement degradation from stochasticity may be localized to edge

** E.T. Hinson GP12.00117*



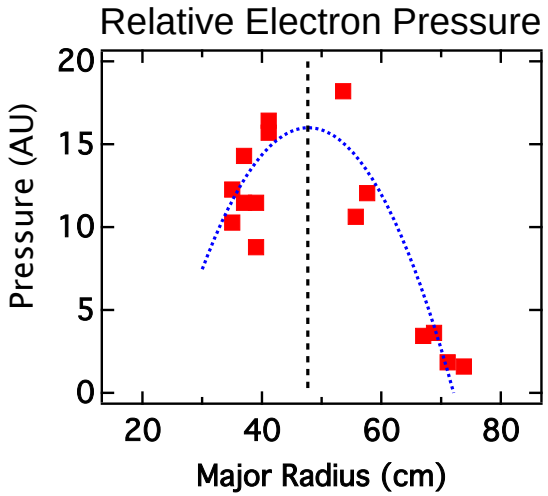


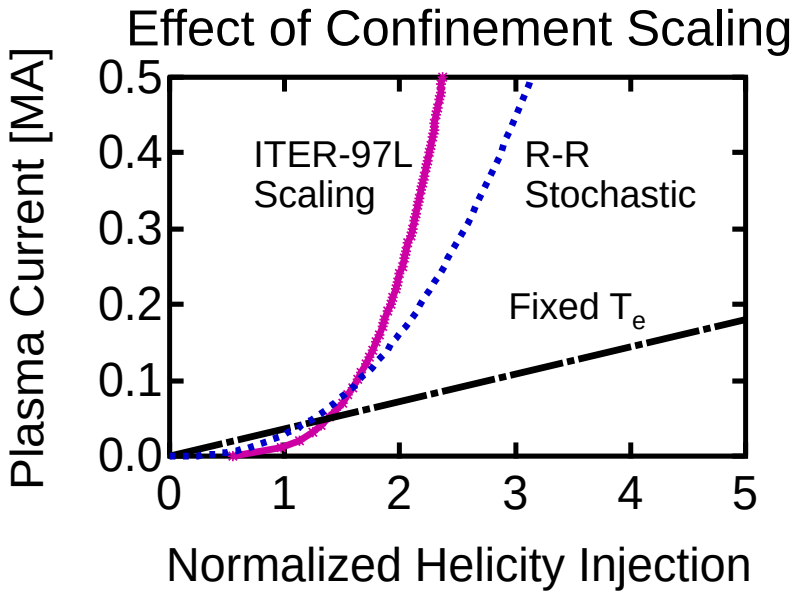


Confinement Behavior Critical for Projections to Larger Experiments

- Peaked T_e and P_e indicate suggest good core confinement
  - Not highly stochastic across profile
  - $T_e(0)$ comparable to 80 kA Ohmic L-mode
  - Larger high T_e volume: lower injector requirements
  - May indicate two zone confinement
    - Drive: V_{IND} (across plasma), V_{LHI} (edge)

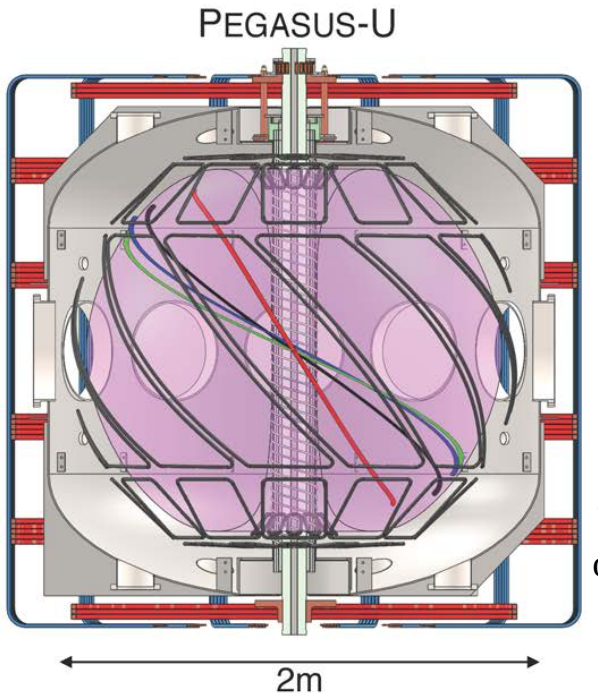
- Experiments at higher Helicity Injection rate and varied geometry will inform projections



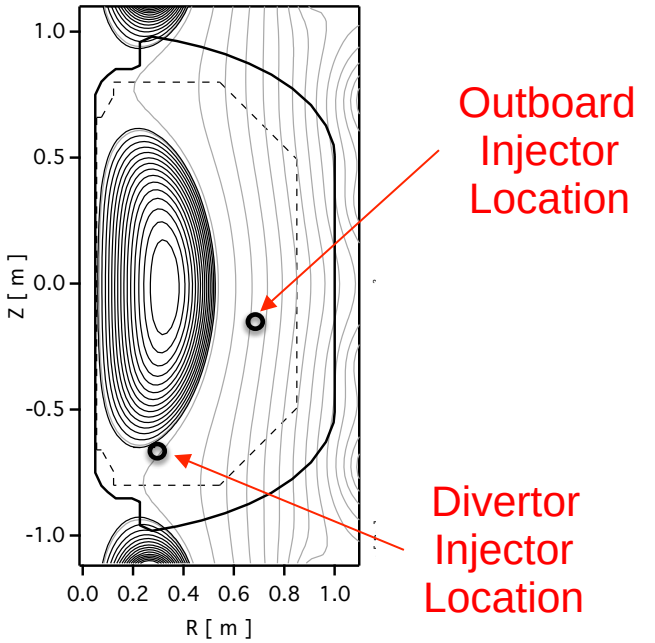


See D. Schlossberg GP12.00118 and G. BodnerGP12.00119

Critical Issues for LHI Predictive Understanding Addressed by Pegasus-Upgrade



Projected LHI Equilibrium



- Increased B_{TF}, t_{pulse} extends scalings to NSTX-U relevant levels
  - Injector B_{TF} ~ 0.8T: reconnection current drive; poloidal null formation; injector physics
  - Increased V_{eff}: confinement scalings
  - Pulse length ~100 ms: variable inductive drive; injector integrity
  - Injector geometry: roles of HI vs Inductive current drive
  - Diagnostics: CHERS via DNB; multi-point probe arrays, SXR camera

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Implementation Status

Status: Awaiting Funding Decision

- Centerstack components ready for bids
  - Solenoid designed by PPPL
  - TF rod assembly ready for bids
  - New castle nut and coil feeds designed
  - New torque plate needed
- Power systems
  - Cascaded inverter conceptual design
    - Need IGBT 2nd stage silicon
  - New TF power supply silicon and cap bank in house (ARRA funded)
  - FPGA control software under development
- TF & PF coil modifications identified
  - Upgraded Divertor coils to be integrated into centersatck
- Next-gen LHI injectors fabricated; installation Winter 2015
  - 1st DIV (HFS) injector pair scheduled
  - Lower Divertor plates to be redesigned
- Diagnostics
  - Langmuir probe tested to pedestal top
  - DNB in fabrication (free to project)
  - Thomson Scattering expansion in progress (ARRA funded)

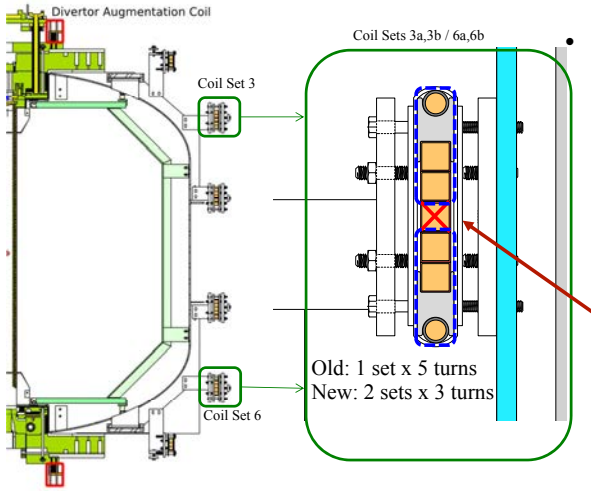

Fig. 7-46. New divertor coils and augmented poloidal field coils (PF3 and PF6)

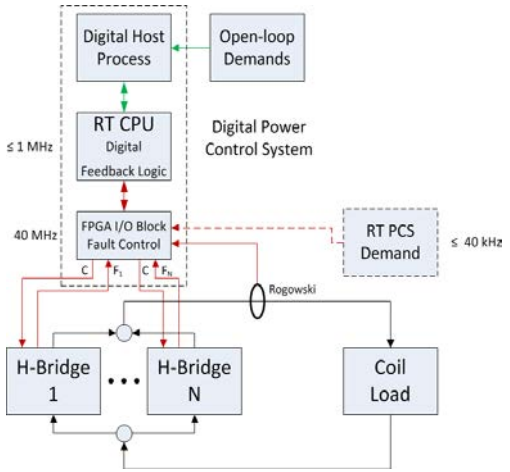

Fig. 7-52. Logical schematic of FPGA interface instrumentation.

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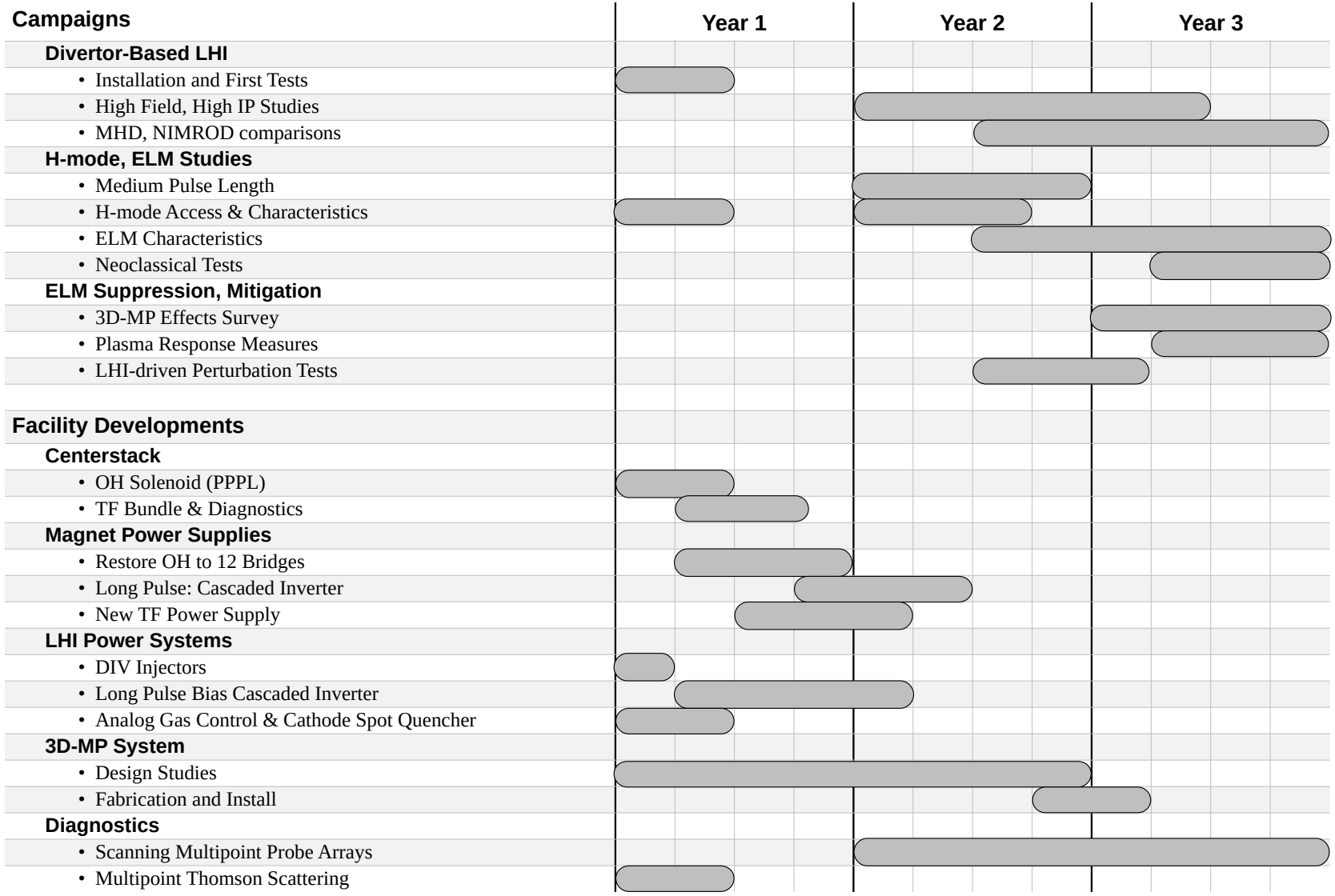
R&D Timeline Staged to Balance Budget Load



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Unique AT Physics Studies Facilitated at $A \sim 1$ in Pegasus-U

- H-mode plasmas with pedestal diagnostic access
  - High spatio-temperal resolution across pedestal
  - Nonlinear ELM dynamics & mitigation, incl. j_{edge} mod.
  - Plasma response in pedestal region with 3-D MP coils
  - Potential tests of neoclassical theory

- Non-solenoidal startup via Local Helicity Injection
  - Divertor-LHI confinement scaling
  - NSTX-U issues: high B_{TF}; long pulse; hi I_p confinement
  - MHD characteristics and NIMROD modeling tests

- Pegasus-U addresses physics, technology issues
  - Multi-field documentation of Pedestal and ELM dynamics
  - Initial studies of 3D-MP effects on H-mode and ELMs
  - Extension of LHI to NSTX-U relevant conditions