Stellarator program vision

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DoE Budget Planning meeting

April 30, 2018

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Outline

- Program Vision
- Role of Stellarators in the US program
- Program Enhancements
  - National Stellarator Optimization Initiative
  - International Stellarators
  - Domestic Experiments
  - Theory and Modeling
- National Program Priorities

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Program Vision for Stellarator Research in the US

- Strategic goal: position the US as a leader in quasi-symmetric stellarator research
  - Exploit international collaborations to verify the physics of current optimization strategies
  - Develop concepts based on advanced optimization for high performance maintainable fusion confinement
  - Implement a select design at the mid-scale and verify the physical assumptions underlying the optimizations
  - Prepare for a major experimental initiative in ITER era

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How stellarator research addresses "FES: A Ten-Year Perspective"

- The natural disruption immunity of the stellarator directly addresses
  - "Elimination of transient events that can be deleterious to toroidal fusion plasma confinement devices"
- International collaboration on the W7-X stellarator in Germany
  - "Strengthens our partnerships with international research facilities,"
  - serves as a test-bed for development of successful international collaboration on ITER.
- Materials science as it relates to plasma and fusion sciences, another critical research area, can be carried out effectively in a stellarator
  - inherent steady state operation
- Additionally, significant advances along two of the Research Directions outlined in the report;
  - "Burning Plasma Science: Foundations - Next-generation research capabilities"
  - "Burning Plasma Science: Long pulse - Sustainment of Long-Pulse Plasma Equilibria"

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Stellarator Research is an excellent scientific investment

- W7-X collaboration is supporting 34 different personnel
  - 3 long term staff assignments during OP1.2 (~2 years each)
  - 2 shorter term staff assignments (during run only)
  - Up to 15 on-site personnel at one time
- 36 US authored papers Jan 2016- Jul 2017
- Numerous diagnostics and major equipment provided and operated
  - X-ray Imaging Crystal Spectrometer (XICS), Phase Contrast Imaging (PCI), Edge cameras, Trim coils and power supplies, Scraper element, IR cameras, Filter-scopes, Divertor Penning gauges, Divertor Helium Beam
- US domestic stellarator program has trained many of the leading scientists in the US program

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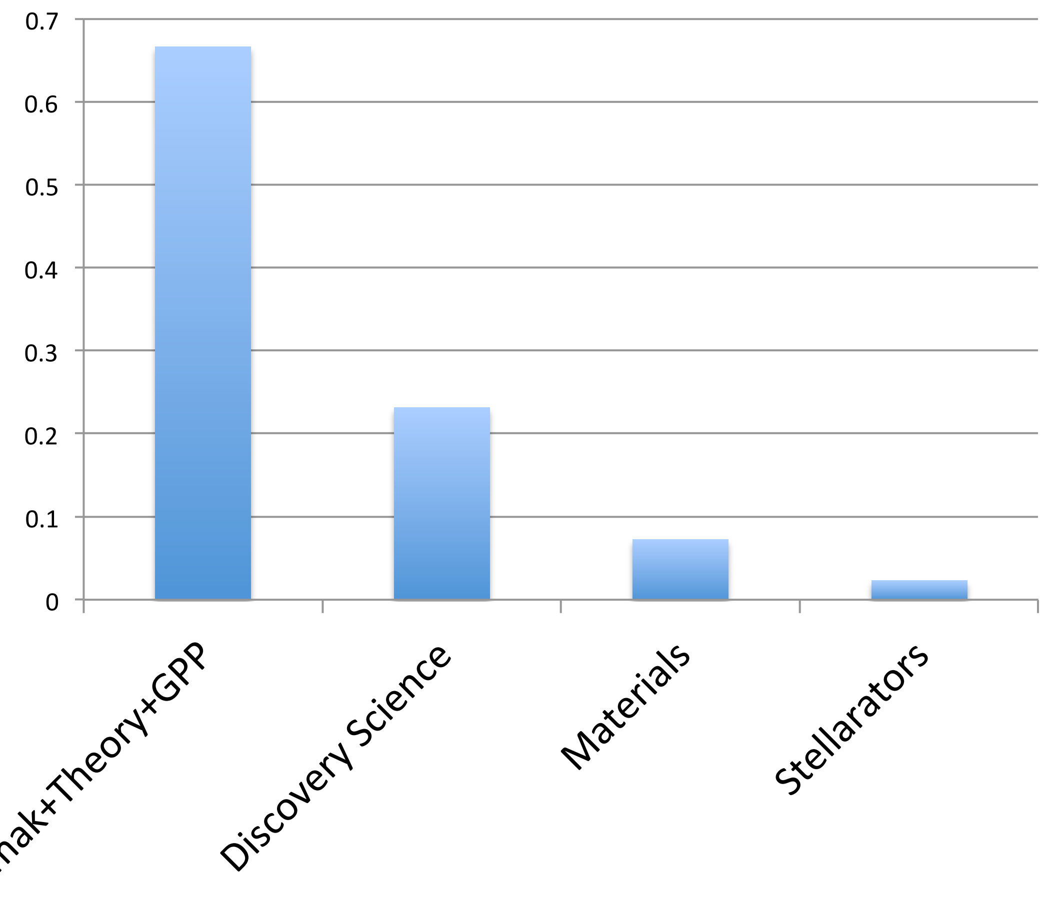
The current role of stellarators in the US program

- FES investment in W7-X collaborations has strengthened the US stellarator program
  - Thank you
- However, the stellarator is a 2.3% fraction of the current US program
- The 2017 Community Workshops identified the quasi-symmetric stellarator as a potential “game-changer” for fusion



From the 2019 DoE budget request to congress
FY2017 enacted (doesn’t include ITER construction)

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Stellarator role in the World Program

- The stellarator plays a major role in the European Roadmap
- Identified as solving many of the problems associated with MFE
  - Modern optimization strategies and investment in facilities can bring the stellarator to parity with the tokamak in the DEMO time frame
- Both the German and Japanese programs are roughly 50-50 tokamak and stellarator
  - Germany is considering a stellarator replacement for ASDEX-U
- China is importing H1 from Australia, building CFQS in Chengdu, and planning a 3rd stellarator in Hangzhou

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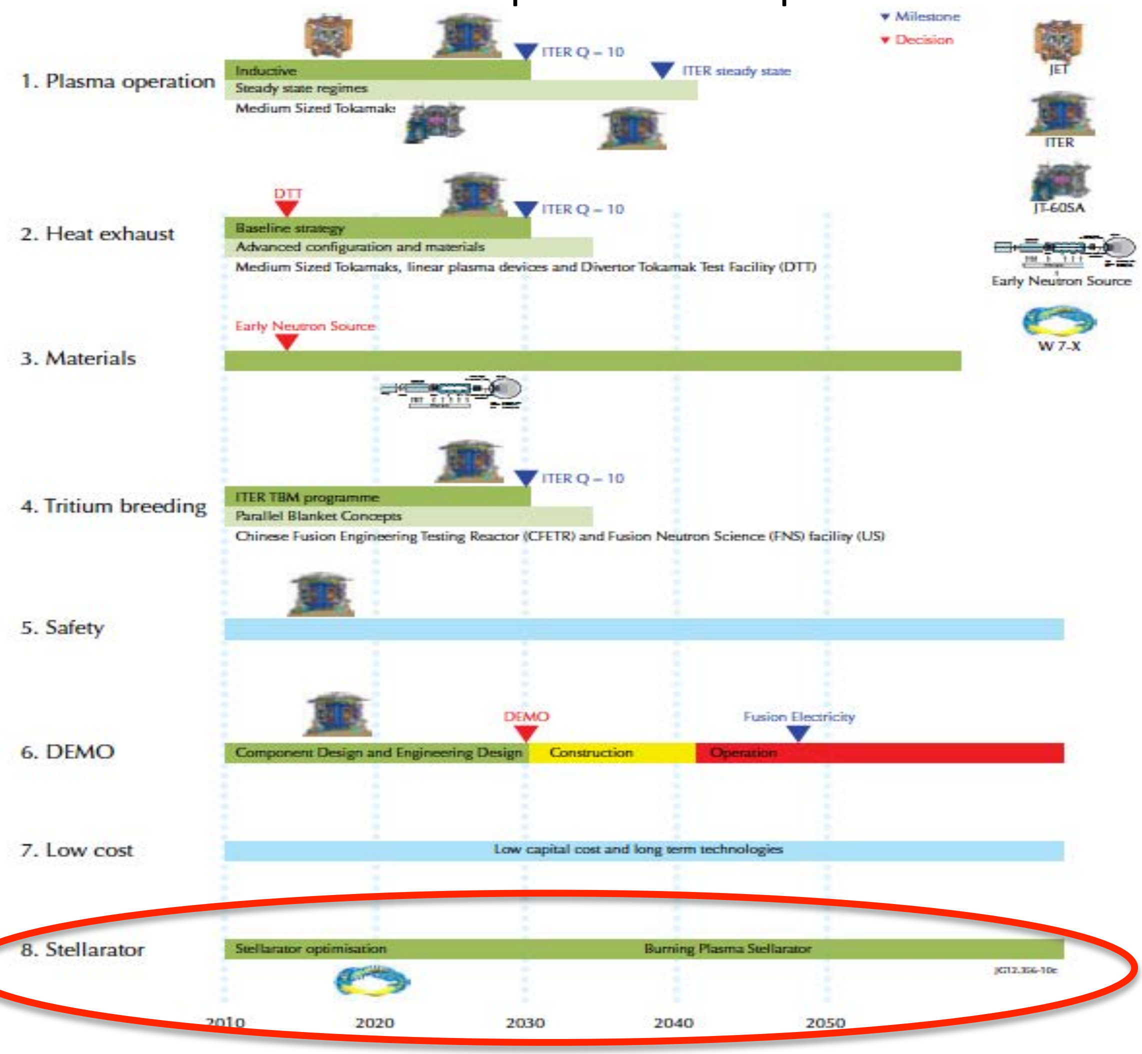
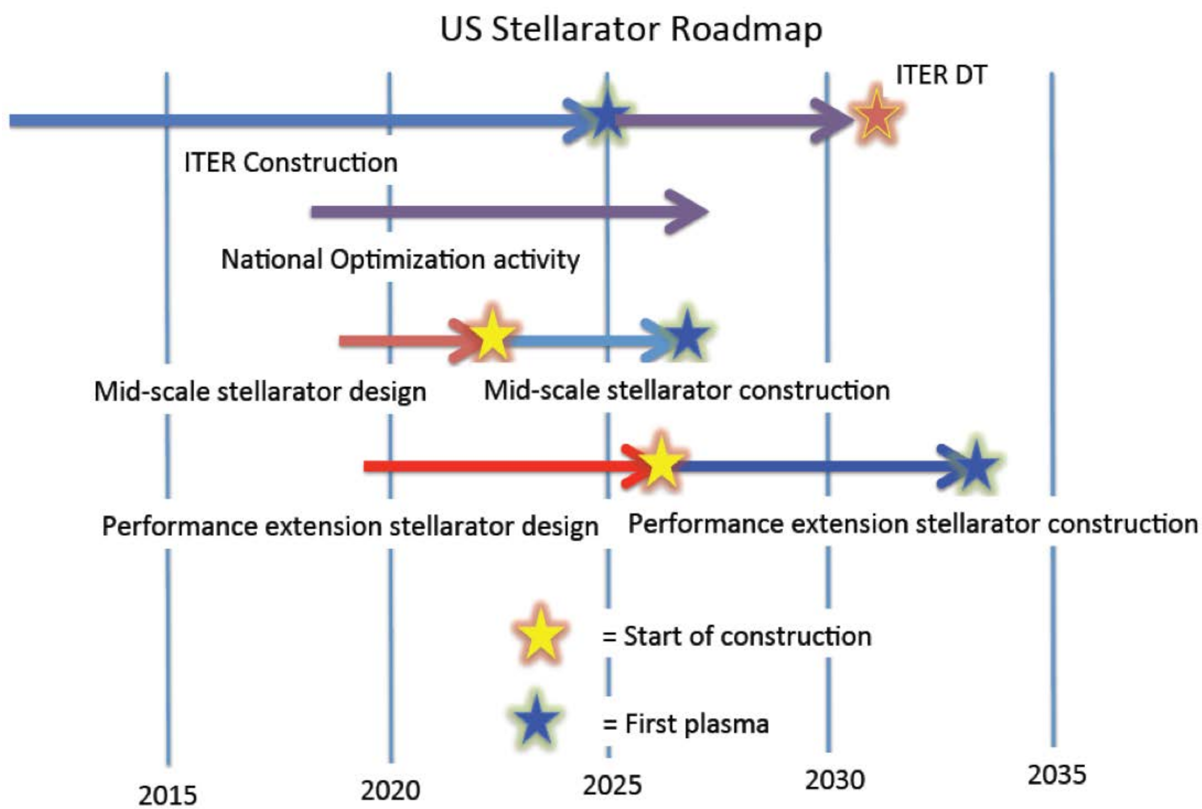
The European Roadmap



STELLCON report – potential US stellarator roadmap

- In order to impact stellarator research for the burning plasma era we need to start now
- STELLCON report lays out a coherent national strategy for achieving this goal
  - Next step: National Optimization Initiative

Gates *et al.*, JOFE **37** (2018) 51



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Stellarator optimization group formed at UW-Madison

- Primary optimization team (STELLOPT) --- A. Bader, J. Schmitt (Auburn U.), B. Faber
  - Four working groups:
    - Turbulence optimization (Faber, Hegna, Terry, McKinney)
    - Coil Design (Schmitt, Bader, Kruger)
    - Energetic Particles (Bader, Schilling)
    - Edge and Divertor (Schmitz, Bader, Frerichs)
- Weekly group meetings --- dedicated website (archived presentations, configuration repository, codes, …)
  - Broad UW representation including: Anderson, Talmadge, Hegna, Fonck, Forest, Sarff, Schmitz, Terry
- Strong collaboration with world stellarator theory program
  - Optimization [STELLOPT (PPPL),…]
  - Coils [REGCOIL(Md), FOCUS (PPPL),…]
  - Turbulence [GENE(IPP), U. Texas-Austin, NIFS,…]

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Stellarator Optimization group formed using PPPL LDRD

- Team consists of:
  - STELLOPT development: S. Lazerson, J. Breslau, M. Landreman (U. Maryland), J. Schmitt (Auburn), B. Faber (UW-Madison)
  - Equilibrium database: P. Porazik, C. Zhu
  - Coils: C. Zhu, J. Breslau, J. Schmitt (Auburn), N. Pomphrey (ret.)
  - Fast particle optimization: S. Lazerson
  - Divertor optimization: O. Schmitz (UW-Madison)
  - Turbulent transport optimization: H. Mynick (ret.)
- Monthly team meetings to discuss progress
- Initial focus on developing a database of 2 period and 3 period QA plasmas with simplified coils
- Support other US STELLOPT users (UW) as required

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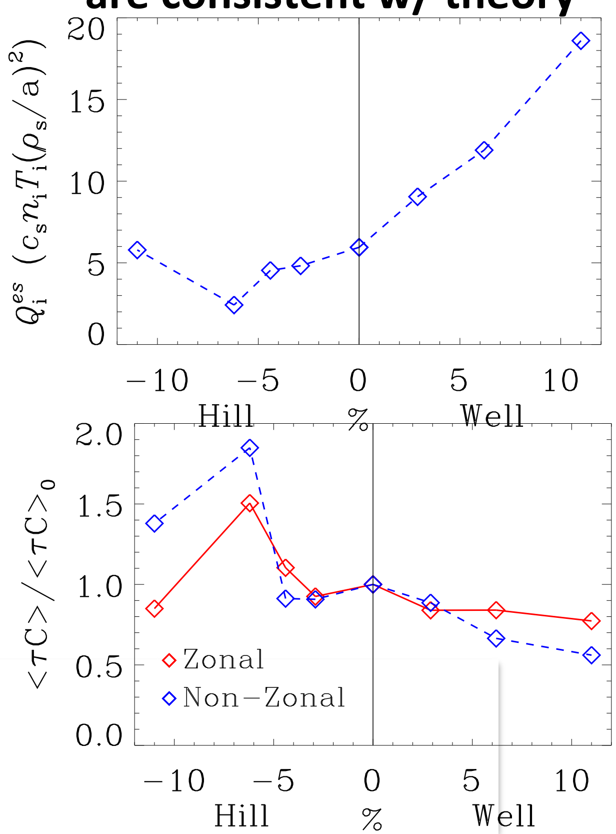
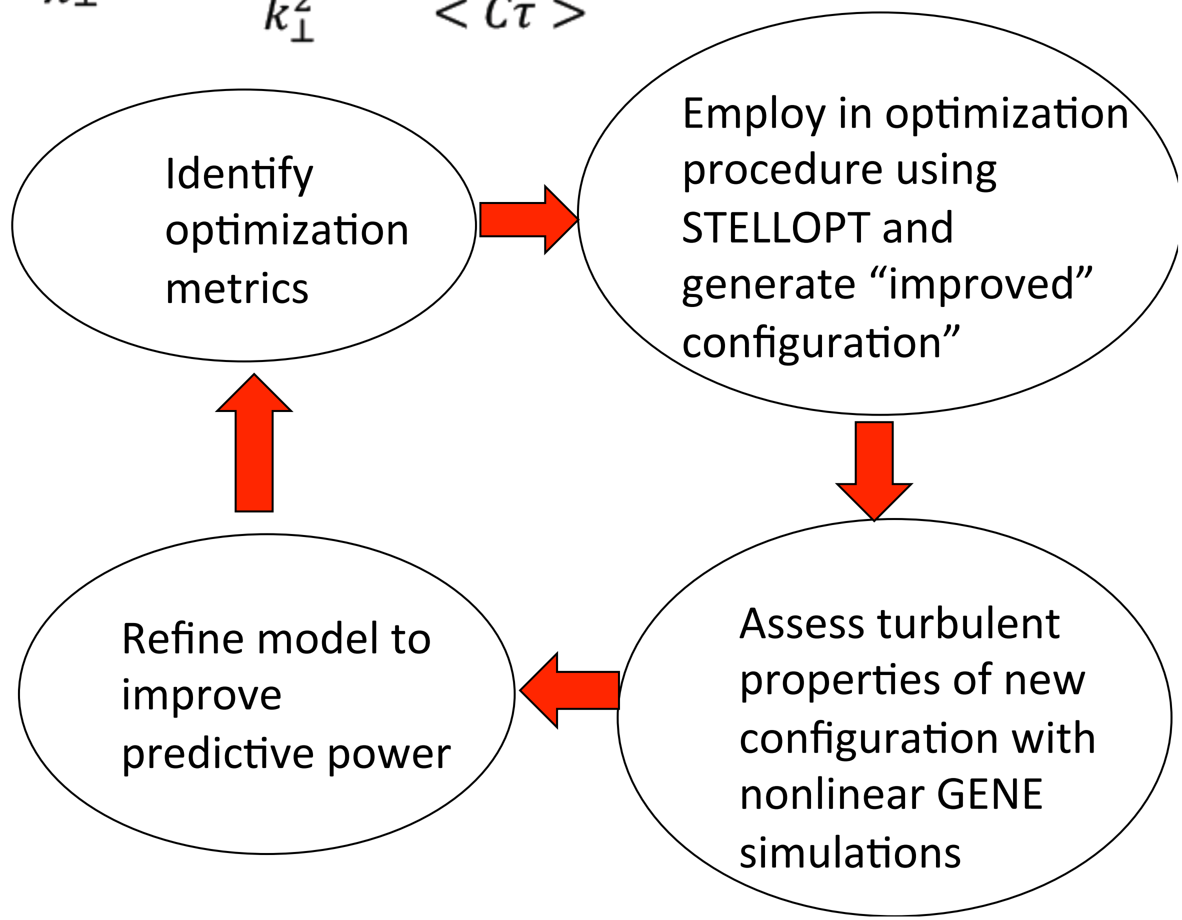
New ideas in turbulent transport optimization motivate optimization initiative

- Significant progress in understand ITG turbulent saturation physics [Hegna, et al PoP '18] → theory identifies metrics for use in turb. optimization.

$$\chi_{\perp}^{turb} = \alpha \frac{\gamma}{k_{\perp}^{2}} \quad \alpha \sim \frac{1}{< C\tau >}$$

Nonlinear GENE simulations are consistent w/ theory

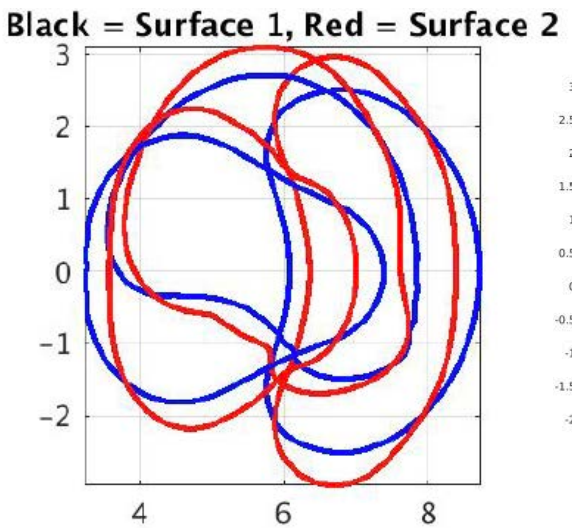


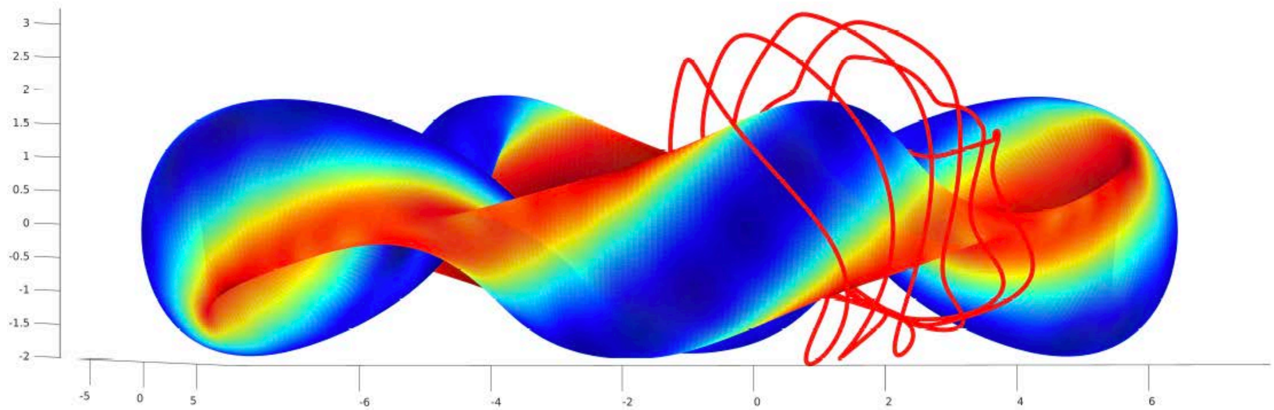


Improved coil design techniques can improve the stellarator concept

- Recent improvements to coil design are implemented ---- REGCOIL, FOCUS

REGCOIL/STELLOPT used to optimize winding surface[Schmitt, Landreman, Bader]





Initial winding surface is a uniform distance from LCFS

Reconstructions show Magnetic Spectrum has QHS

Optimized surface opens up space for flexible divertor solutions

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Stellarator optimization group is poised to substantially expand activities

- Dedicated optimization funds at UW ($236k/year) and PPPL LDRD funds ($360k/year) are insufficient to fully pursue this exciting activity
  - High level of enthusiasm amongst the fusion community
  - High level of collaboration within national stellarator program
- Number of exciting research opportunities:
  - Turbulence --- develop and refine turbulence metrics, employ turbulence suppression in optimization, test against GENE simulations, …
  - Energetic ion --- Is QS sufficient? test energetic ion metrics (Nemov), quantify improvement with better coil solutions
  - Divertor/edge --- novel divertor possibilities, assess advantages of improved coil designs, develop metrics for optimization
  - Coils --- take advantages of advances in coil design
  - MHD --- consistency of good ballooning stability properties with self-consistent bootstrap and excellent confinement
  - Expansion of STELLOPT code capabilities
- We can make substantial progress on all of these areas with uptick in resources

  → Critical effort needed to access scope of proposed experimental facility

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Proposal: National Optimization Initiative

- Funding at the level of ~$2.5M/year
  - $1.25M managed by PPPL, $1.25M managed by UW-Madison (operate as a national team)
  - UW to focus on needs of near term midscale facility with a focus on divertor design and turbulent transport
  - PPPL to develop database of equilibria and identify attractive high-beta potential reactor configurations
- In addition to neoclassical transport and MHD stability, focus on the four topics identified in STELLCON:
  - Coil simplification
  - Integrated divertor design
  - Fast particle optimization
  - Turbulent transport optimization
- Goal is position the US as a leader in quasi-symmetric stellarator research
  - Developing improved configuration is the next step towards this goal

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W7-X "OP1.2" Campaign: A One-Year Window of Opportunity for Large Advances in 3D Physics Understanding

Major Scientific Topics

- **Optimization of confinement in W7-X ion-regime.**
  - High density; strong ion-electron coupling
  - Heating, fueling, density limit
- **Confinement and core transport**
  - Anomalous versus neoclassical transport
  - Role of radial electric field
  - Impurity transport
- **Qualifying the island divertor as steady state exhaust concept**
  - Detachment and control
  - Scraper element campaign
  - Model validation
- **Scenarios (with a view to steady-state in OP2)**
  - High density heating with ECH
  - Ion heating & energetic ion generation (NBI, ICRF)

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Possible W7-X Enhancements

- The following slides list proposals for enhancements to existing collaborations of W7-X
- The relative priorities of these specific enhancements to W7-X have not yet been vetted by the collaborators
  - We have done this in the past and we will do it again on the near future
- Priorities so far
  1. Optimization Initiative
  2. Pellet project
  3. Additional W7-X enhancements

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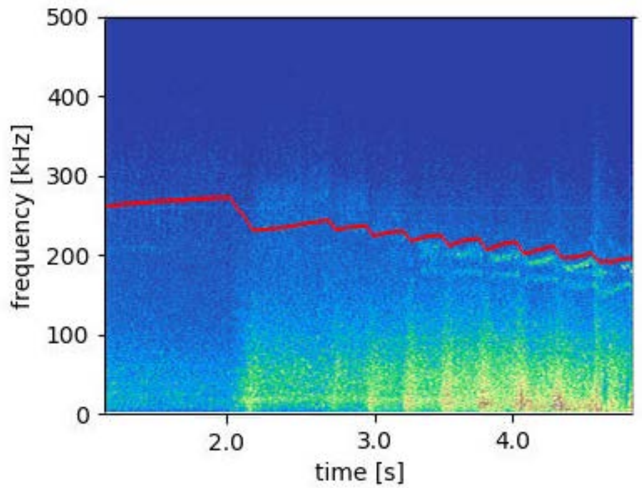
Phase Contrast Imaging on W-7X

Miklos Porkolab, PI, MIT PSFC

Eric Edlund, SUNY Cortland, Key Collaborator

Major Milestones from years 1-3:

- PCI design completed in 2016
- Hardware installation began in January 2017
- Installation completed August 2017 in time for OP1.2a
- PCI diagnostic ran throughout the OP1.2a campaign
- An upgrade to a 2-detector system is underway
- Improvements to optics for better performance in OP1.2b



Alfvén waves observed during pellet injection.

Red trace is the Alfvén frequency, based on mean density.

Possible program extensions:

- Upgrade to a combined PCI-Interferometer system for $65k (similar to recent DIII-D upgrade) that would extend measurements to the ITG range ($k < 2.0\ cm^{-1}$)
- Additional funding for student involvement from SUNY Cortland and MIT

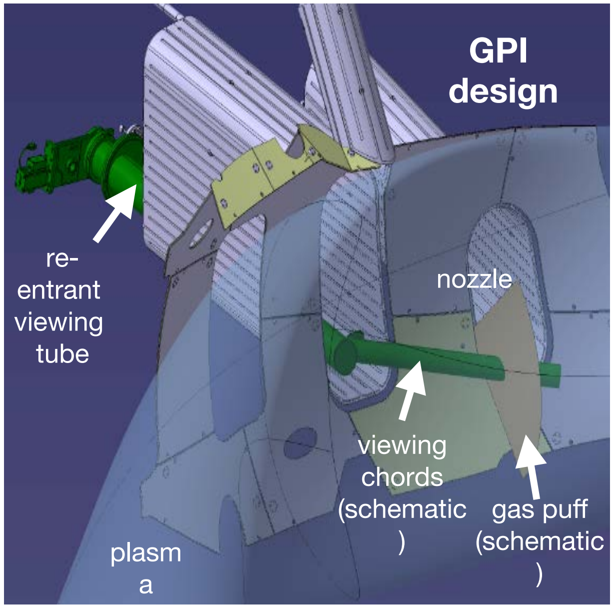
Gas-Puff Imaging (and fast camera exps.) on W7-X

PSFC Plasma Science and Fusion Center Massachusetts Institute of Technology

IPP Max-Planck-Institut für Plasmaphysik

Funded 2016-2018 to provide fast camera for operation in OP 1.2 & to provide design for (OP 2) GPI diagnostic:

- Installed & operated fast-framing camera for OP1.2a, operation will continue for OP 1.2b
- Identified quasi-coherent fluctuation in divertor emission and evidence for change in edge-fueling efficiency for $n_e > 4\times10^{19}$ m^{-3}
- Will be presenting these fast-camera results at the international PSI meeting (June 2108)
- Submitted exp. proposal for additional OP 1.2b edge turbulence experiments
- Identified ports for GPI installation for OP 2 (1 port for gas puff, one port for observing the puff)
- Designed gas injection system, including 1st-time use of de Laval nozzle for GPI
- Modeled with finite-element code the gas flow thru 2m–long capillary and out of nozzle
- Designed re-entrant viewing tube (water-cooled with shutter)
- Designed optics to bring image to coherent fiber-optic bundle outside of cryostat
- Modeled this GPI design on W7-X using neutrals code DEGAS 2 & validated DEGAS 2 results using C-Mod GPI results
- Conceptual Design Review for GPI planned for this summer

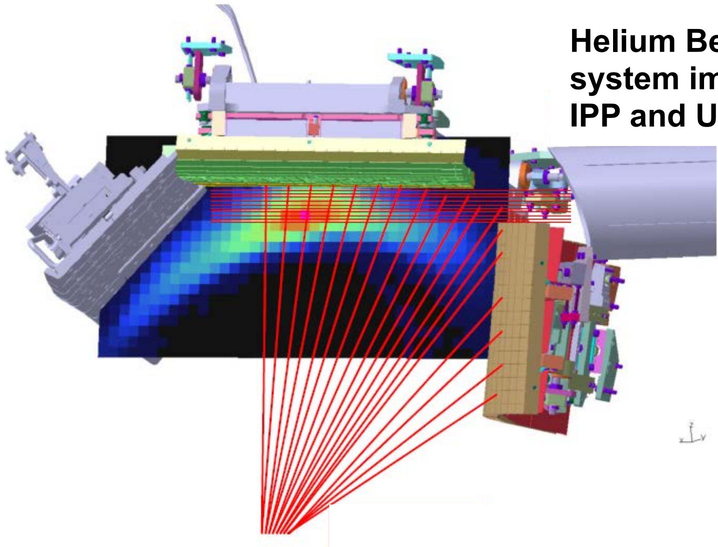


Budget: 2019-2021 funding just approved at $741k ($247k per year funds 1 grad student & 1 FTE junior scientist)

- Enough to continue operation of fast camera thru OP 1.2b & to proceed through Final Design Review of GPI for OP 2
- However, this is a significant shortfall from the $1.45M requested for procuring (~$100k), testing, installing, and operating GPI. Supplemental funding of an additional $200k per year is needed for **timely hardware procurement** and **on-site placement of a post-doc for GPI installation & operation**, both of which we consider to be essential for the fruition of this project

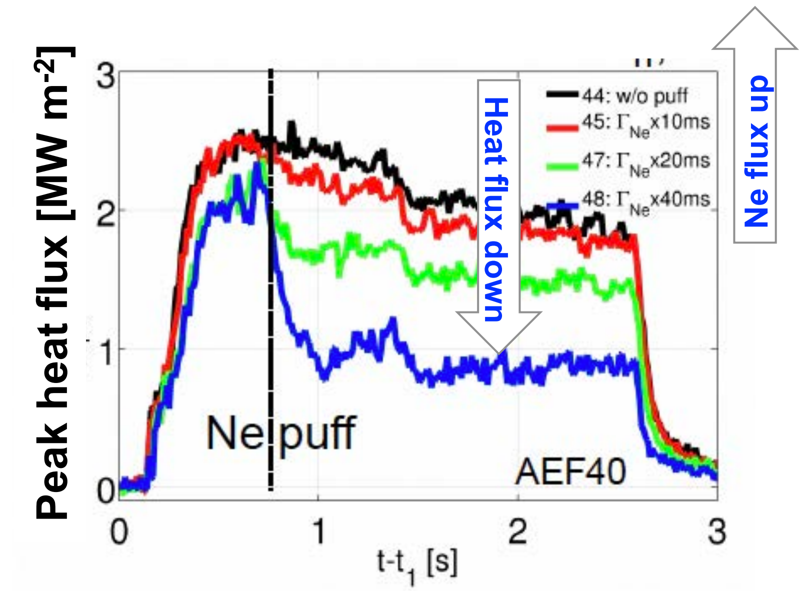
Successful first demonstration and characterization of radiative edge cooling including the intrinsic C source was accomplished

Key diagnostic: divertor thermal helium beam was made available as standard diagnostic

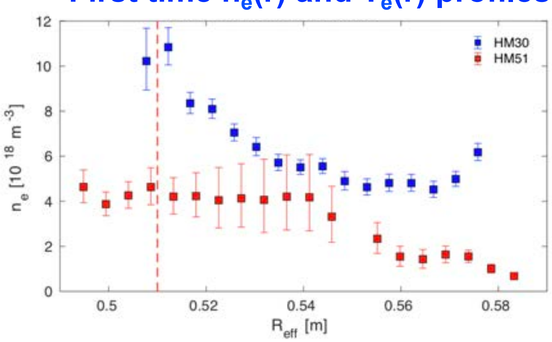


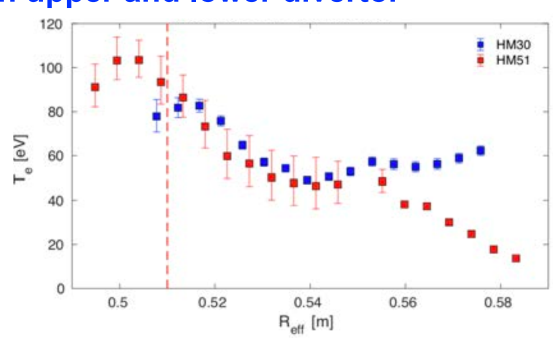
Helium Beam observation system implemented by IPP and UW Madison

Divertor heat flux control by impurity seeding was accomplished



First time $n_e(r)$ and $T_e(r)$ profiles in upper and lower divertor





Promising progress to demonstrate and thoroughly characterize an optimization scheme for the island divertor

THE UNIVERSITY of WISCONSIN MADISON

Procurement: three Wisconsin in-situ Penning (WISP) gauges have been implemented, four new spectrometers are in use now at helium beam

Targeted opportunities to boost demonstration and understanding of divertor protection by radiative edge cooling

(1) Complete funding for on-site assistant scientist (RO of Helium beam)

Dr. Tullio Barbui is headquartered on-site and is the local RO for the Helium Beam system, only fractional funding was included in renewal proposal Funding need: 120kUSD, needed for only one year

(2) Complete DoE funded edge spectroscopy setup for HeBeam

Add high spectral resolution spectrometer to edge spectroscopy system used for HeBeam observation, leverages IPP investment into expensive cameras

Funding need: 55kUSD

(3) Implement *upstream* helium beam for $n_e(r)$ and $T_e(r)$ measurements

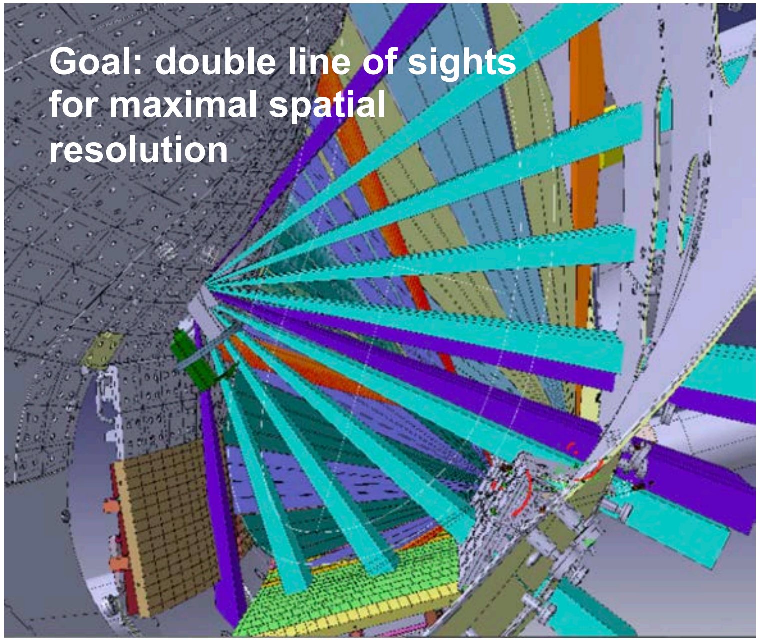
Joint project with IPP, enables consistent link between divertor plasma and LCFS for the first time, essential + first time measurement for divertor characterization

Funding need: 95kUSD

(4) Enhance edge bolometer to improve radiative edge measurements

Joint project with IPP, increases poloidal resolution of edge bolometer to measure high-resolution edge radiation structures

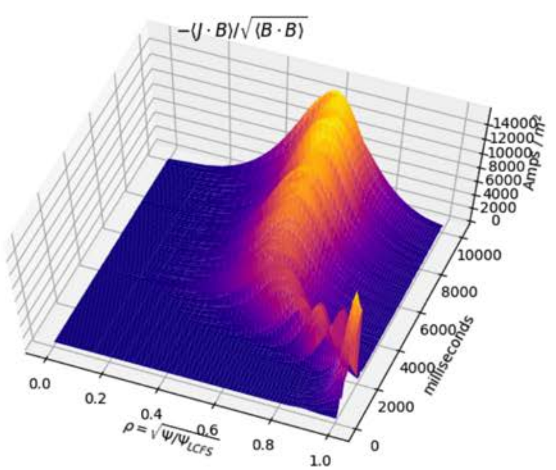
Funding need: 120kUSD



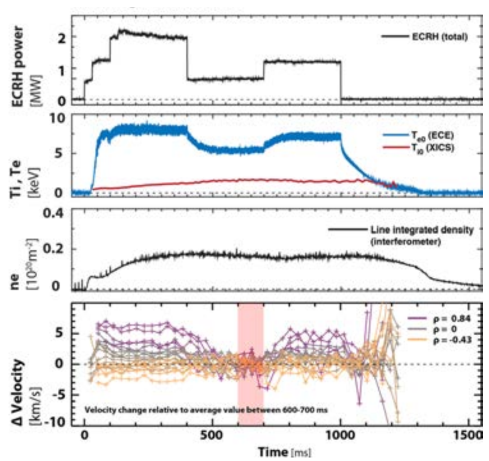
Successful implementation of CIS diagnostic on W7-X and new AU opportunities

• **AU activities span broad range: Equilibrium reconstruction and bootstrap current evolution; XICS and ion transport, edge flow measurements with CIS**

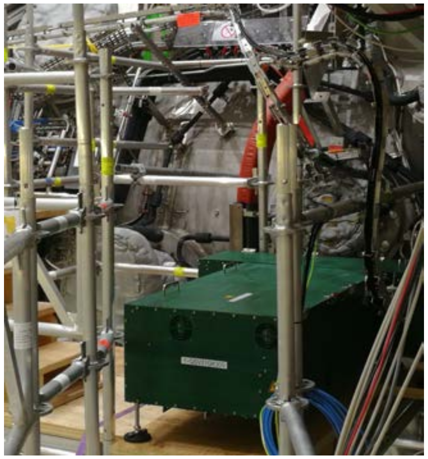
New collaboration established between Auburn University and IPP to construct and optimize two coherence imaging instruments. Successfully developed for OP1.2a,b.



Equilibrium modeling



Core spectroscopy



Edge spectroscopy

Successful implementation of CIS diagnostic on W7-X and new AU opportunities

- **Coherence imaging system to measure T_i**

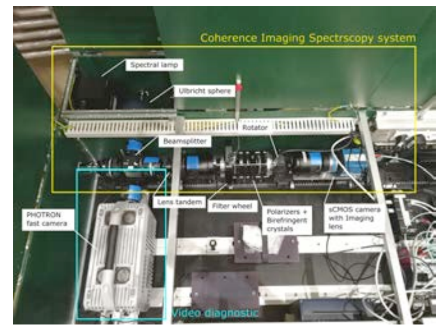
  -- List components 65k$

  --Recondition high resolution McPherson 209 spectrometer 45k$

  -- High resolution fiber optic bundle 75k$

Use CTH as test bed for similar edge plasma parameters

To have diagnostic fully functional for OP 2

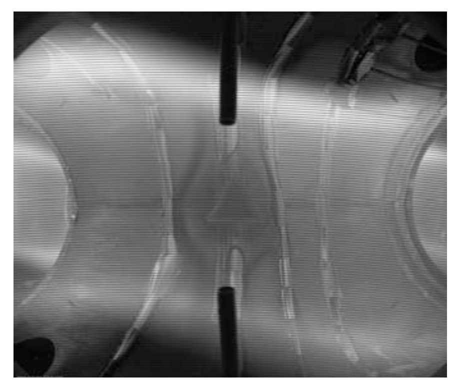


- **Additional non-hardware**

  -- Fully fund J. Schmitt 12k$/year

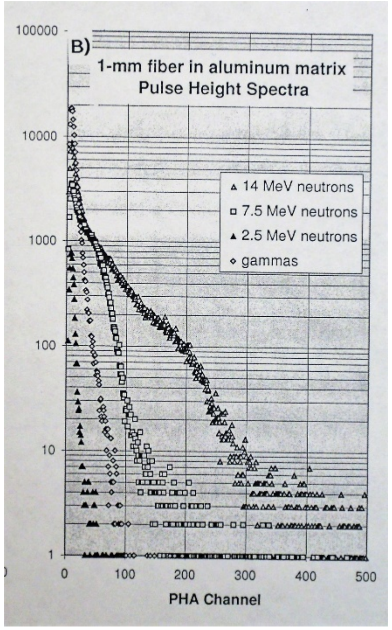
  -- Travel funds 20k$

  -- Full 12 months for 2 students 28k$/student-year



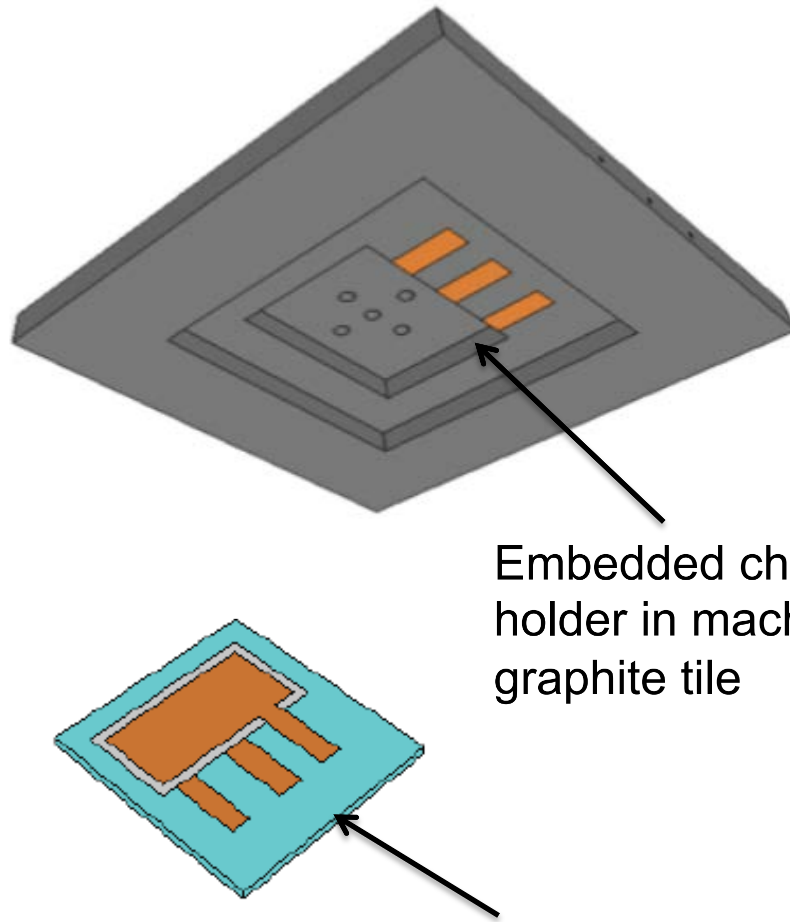
W7-X: Focus on fast particles 2019-2021

- Wurden’s present Change-of-Station assignment ends Nov. 2018. Level funding of only $300k/year (since 2011) will force him to cut-back to ½ time status on W7-X.
  - New Scraper Element observation system is installed, and will be operational for OP1.2b. Data analysis will extend into 2019
  - Analysis work in multiple arenas: Identification of low-frequency breathing mode, reference shots for detecting coatings on divertor structures.
- For OP2, a $400k/year plus-up would enable 1 FTE work on new approaches to detecting both confined and lost fast particles on W7-X, associated with NBI and deuterium operation
  - Scintillating Fiber 14 MeV neutron detectors (LANL SciFi gear from Japan) will be improved for lower count rates on W7-X, and tested at ASDEX-U. New collaboration with E3 (with Robert Wolf) and LHD, while mentoring a German graduate student. Used for measuring triton burnup during DD operation.
  - Water-cooled modifications for scraper endoscope to enable use in OP2.0 for detecting localized hot spots caused by NBI trapped ion losses on the wall baffle plates and armor.
  - Providing assistance in building primary machine protection viewing systems: testing, and calibrating them before OP2.0 begins (with Joris Fellinger).



Prototype W7-X Fast Ion Loss Detector Development Underway

- Prototype sensor specified
- Reynard and Acree both identified as vendors
- Prototype graphite tile to be machined in-house
- Testing facility identified (Texas A&M Ion Beam Lab)
- Diagnostic testing to begin in early Fall 2018
- **Incremental: $400k in FY19 to implement detector array on W7-X for OP2.0**



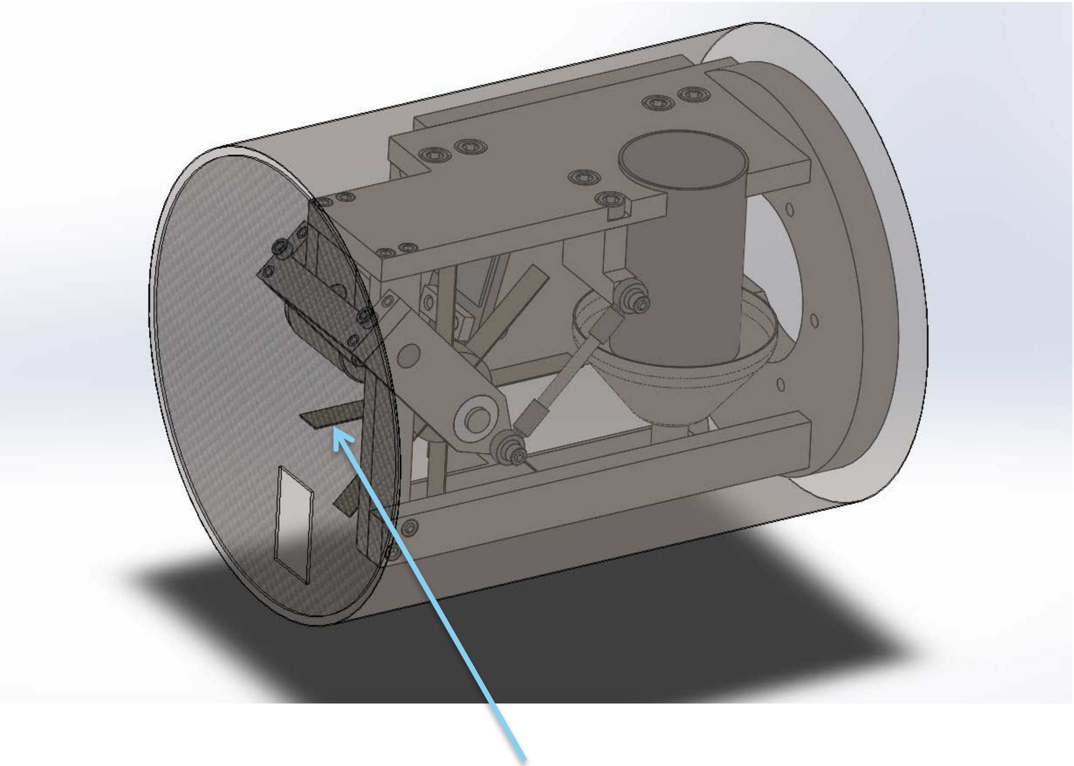
Embedded chip holder in machined graphite tile

Al conductor on Al2O3
Vacuum vapor deposited

Boron powder dispenser being developed for W7-X (OP1.2b)

- Boron powder injector enables steady state wall conditioning – crucial for long pulse operation
- Test injector to be probe mounted (multi-purpose manipulator
- If test is successful, permanent system will use gravity feed from machine top
- Will need 5 injectors for permanent system
- **Incremental: $350k in FY18 or 19 for construction and installation of permanent system. 200k/yr for edge physics post-doc**

Probe-Mounted Powder Injector (PMPI)



Spinning paddle wheel injects boron

Numerous opportunities for LHD collaboration have been identified for the W7-X break

- Install powder dropper (new post-doc)
- Edge Thomson measurements (Diallo, NSTX-U loan)
- Real-time Thomson electronics (Kolemen, NSTX-U Loan)
- Reinstall LHD XICS diagnostic (Pablant and LHD scientist)
- Comparative transport experiments with W7-X (both thermal and impurity) – organized by the CWGM (stellarator ITPA)
- Optimization collaborations (Gates, Suzuki)

- **Incremental: ~$200k/yr**

HSX Program Going Forward

Program Role: Conducts innovative research to advance stellarator optimization, collaborates with long-pulse stellarators, and addresses critical issues as defined in the STELLCON report

Directions:

- Vary 3D shaping to influence turbulence saturation and heat flux; GENE comparisons
- Implementing turbulence diagnostics (previously funded); CECE, μ-wave scattering
- Using a neutral beam to examine energetic ion confinement with magnetic structure
- Time evolution of E_r and flows; dependency on magnetic topology
- Measure impurity diffusion/convection using laser blow-off techniques
- Increased emphasis on He plasmas to reduce ion charge-exchange losses

International collaborations key element of the HSX program:

- Working with Olaf Grulke to set up comparative turbulence measurements between W7-X and HSX; GENE collaborations to understand possible turbulence reductions (IPP and PPPL)
- Gavin Weir on reflectometry measurements on W7-X; HSX student participating
- Edi Sanchez (CIEMAT) on EUTERPE/GENE comparisons; zonal flow oscillations and decay with/without symmetry; determine appropriate conditions to conduct experiment
- S. Oshima to measure zonal flows in HSX
- N. Tamura (LHD/STRAHL code), B. Geiger (IPP) impurity blow-off and transport modeling

HSX Budget Scenarios/Needs

Present Budget: $1809k [$120k to UCLA, $236k to Optimization, $1453k to HSX]
(assume flat funding based on President's FY2019 request for Long Pulse Compact Stellarator at $2500k)
HSX is up for renewal on 4/1/2019

Prioritized Increment:	FY 2018	FY 2019	FY 2020
Engineering Tech	150k	150k	150k
Collab. Costs	30k	30k	30k
Turb. Postdoc	120k	120k	120k
	$300k	$300k	$300k

Greatly increased productivity, machine availability; expanded collaborations on turbulence

20% Decrement (flat-funding for domestic)

- Reduction in unallocated International stellarator funds for FY20

If even more funds are available (beyond the requests from NSCC):
Long-term needs for DOE planning (significant upgrades): New operating regimes and access to new physics available with upgraded ECRH system (53-60 GHz, 300ms, 500 kW)

- Double electron density to 2 x 10^{13}; increased power
- Increased electron/ion coupling; warmer ions
- Longer pulse for flow evolution/bootstrap current studies

Power supply	700k	Could be staged over 3 year procurement/installation
Gyrotron	400k	
Magnet	250k	
X-mission/ctrl	200k	

HSX can continue vital contributions to the worldwide program at present levels, and even more with modest increases

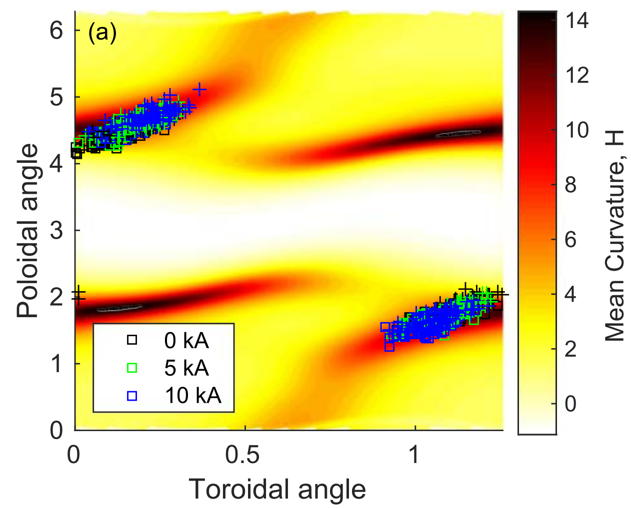
HSX

Compact Toroidal Hybrid Opportunities

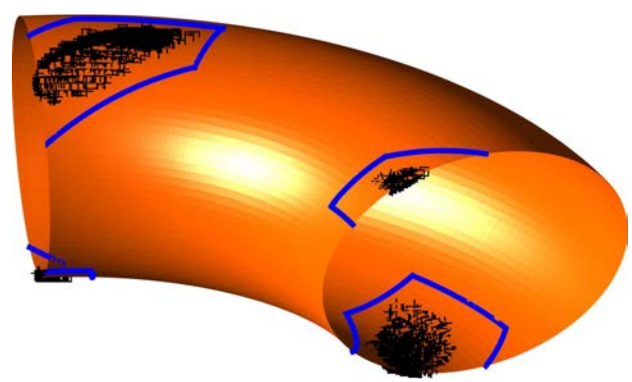
- **Fast track exploration of non-resonant divertor physics behavior with changing magnetic configuration**

-- Use flexible CTH magnet system to experimentally test positional robustness of non- resonant divertor strike points and heat/particle fluxes

-- Ohmic operation allows high density regimes not accessible in traditional stellarators



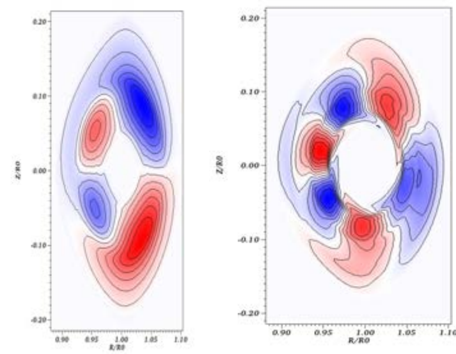
Non-resonant divertor study hardware and instrumentation 75k$
Post doc 125k$/year



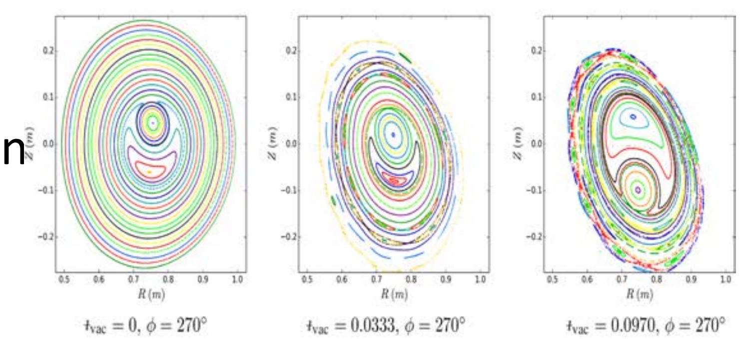
Theory/Computation plays a foundational role in advancing the stellarator

- The stellarator program relies on advances from the theory and computation community
  - Strongly supported theory program required to understand, interpret and guide experimental activities
  - Theory community provides breakthroughs that can be implemented in design activities
- Investment in the theory and computation necessary to advance the stellarator concept
  - Spectrum of topics require attention (as identified in STELLCON report)
  - Advances from theory program drive re-invigorated stellarator optimization activity

n = 1, n = 2 TAE activity on LHD predicted



NIMROD simulations of CTH plasmas



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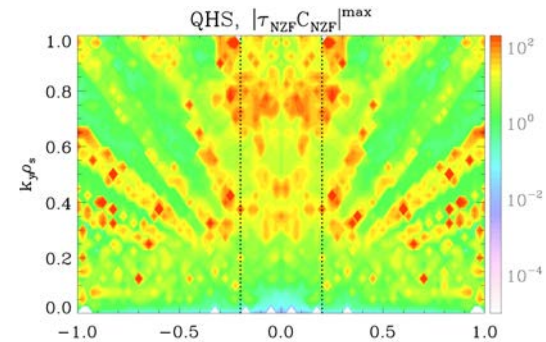
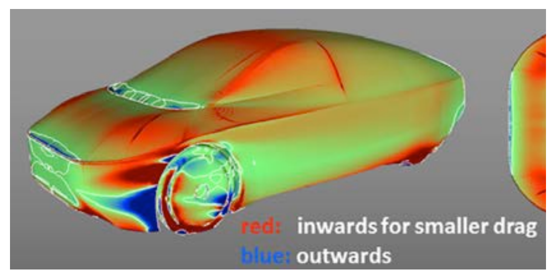
Theory and computation innovations are emerging

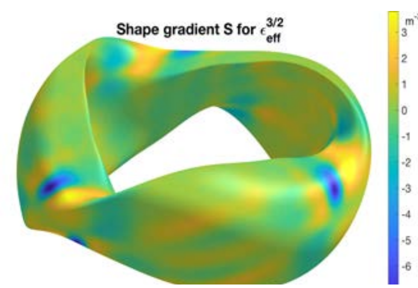
- Turbulence optimization
  - Turbulent saturation physics may be the key
- Advances in coil design
  - FOCUS, REGCOIL beginning to be exercised
- Improving optimization schemes
  - Adjoint methods for optimization
- Edge/divertor physics
  - Mathematics of **B** fields in edge region
  - New divertor concepts

Theory for ITG turbulent saturation identifies optimization metrics

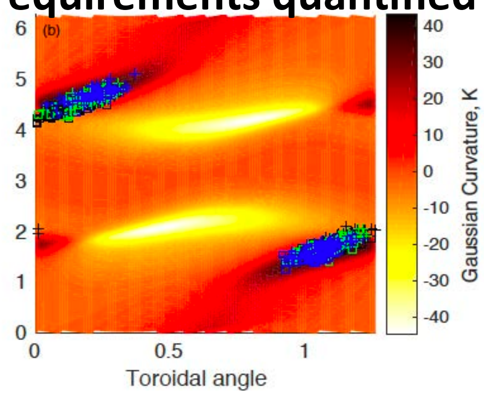


Optimization schemes from industry can be used to benefit stellarators

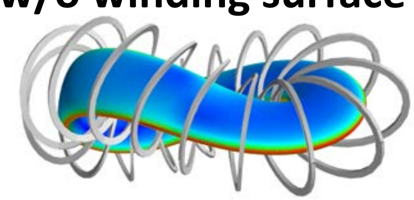


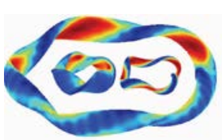


Non-resonant divertor requirements quantified



FOCUS provides coils w/o winding surface





Stellarator design benefits from new stellarator simulation tools

- New era in turbulent transport optimization in stellarators --- advances in analytic theory, gyrokinetic tools
- Numerous applications for extended MHD tools --- generation of 3D equilibrium, consequences of breaching instability boundaries, disruption avoidance
- Energetic particles --- energetic ion confinement remains an unresolved issue in stellarators, AE activity in 3D
- Impurity confinement --- can QS optimization alone be used to prevent impurity accumulation?
- 3D MHD equilibrium --- theoretical foundations of 3D equilibria, mixed topology, island healing physics
- Edge/divertor physics --- reduced models for use in optimization, development of new 3D edge physics code
- **Incremental request: $500k/year (relative prioritization is TBD)**

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Scenarios FY18 (incrementals)

- Scenario 1:
  - $2M Pellet project funded from reserves/hold back
  - $5M dollars of the FY18 increase for long pulse is allocated to stellarators
- Scenario 2:
  - Same as scenario 1
- Scenario 3:
  - $2M Pellet project funded from reserves/hold back
  - Only $3M from of the FY18 increase for long pulse is allocated to stellarators

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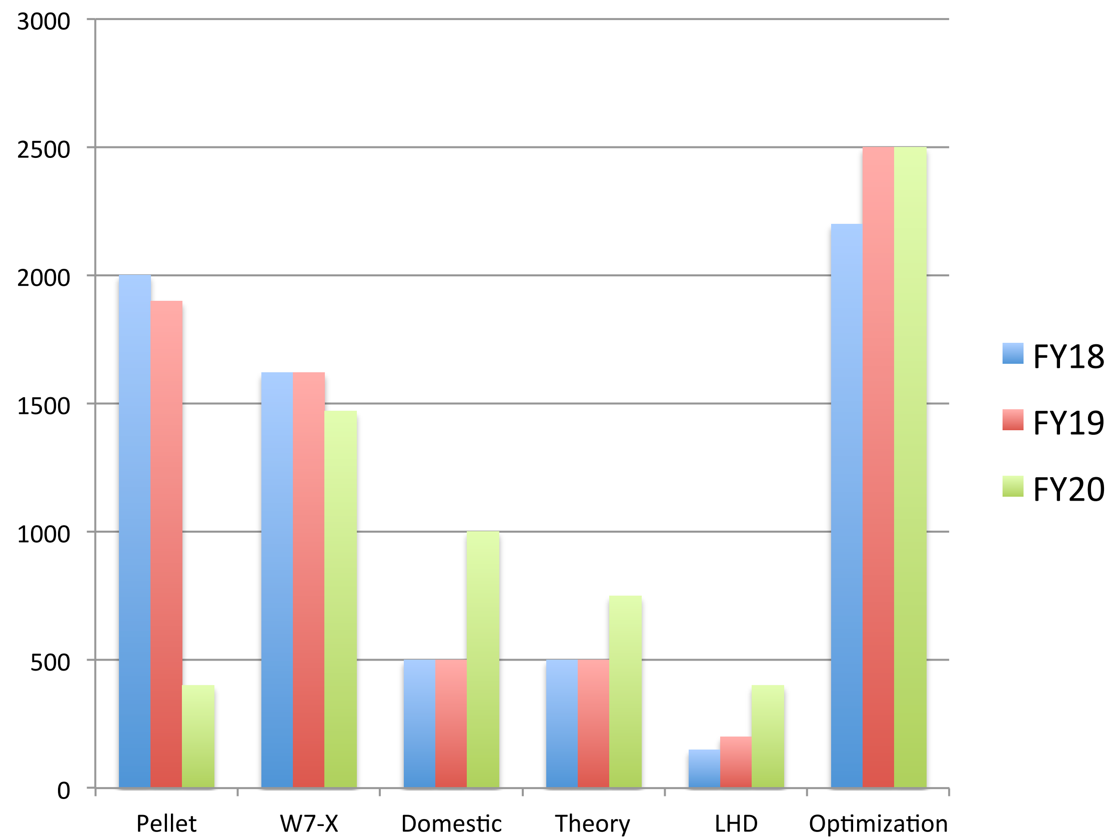
Scenarios FY19 and FY20

- Scenario 1: President's requested budget + $5M in both FY19 and FY20
- Scenario 2: President's requested budget
- Scenario 3: President's requested budget in FY19 with 20% decrement in FY20

Distribution of funds based on priorities: Scenario 1

- Goal is to fund the two highest priorities: Pellet injector and optimization initiative
- Chart based on a Scenario 1 (steady funding)
  - First scientific priority for increment is optimization study
  - Second priority is pellet project
  - W7-X enhancements is 3rd priority
  - Support domestic machines and theory at a modest level
  - Support directed collaborations on LHD



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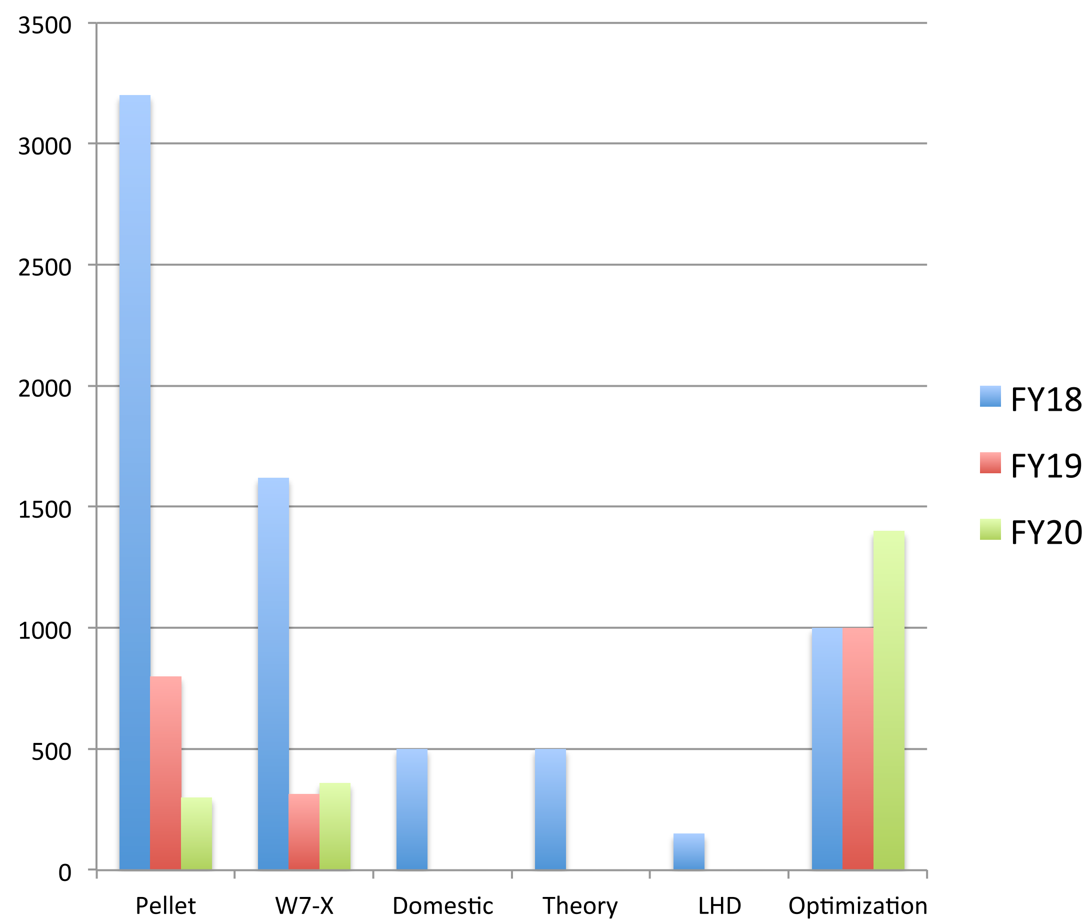
Distribution of funds based on priorities: Scenario 2

- Goal is to fund the two highest priorities: Pellet injector and optimization initiative (Uptick in 2018, followed by request in FY19 and FY20)
  - First scientific priority for increment is optimization study
  - Second priority is pellet project
  - W7-X enhancements are third priority
  - Support domestic machines and theory at a modest level the first year
  - LHD is funded only the first year



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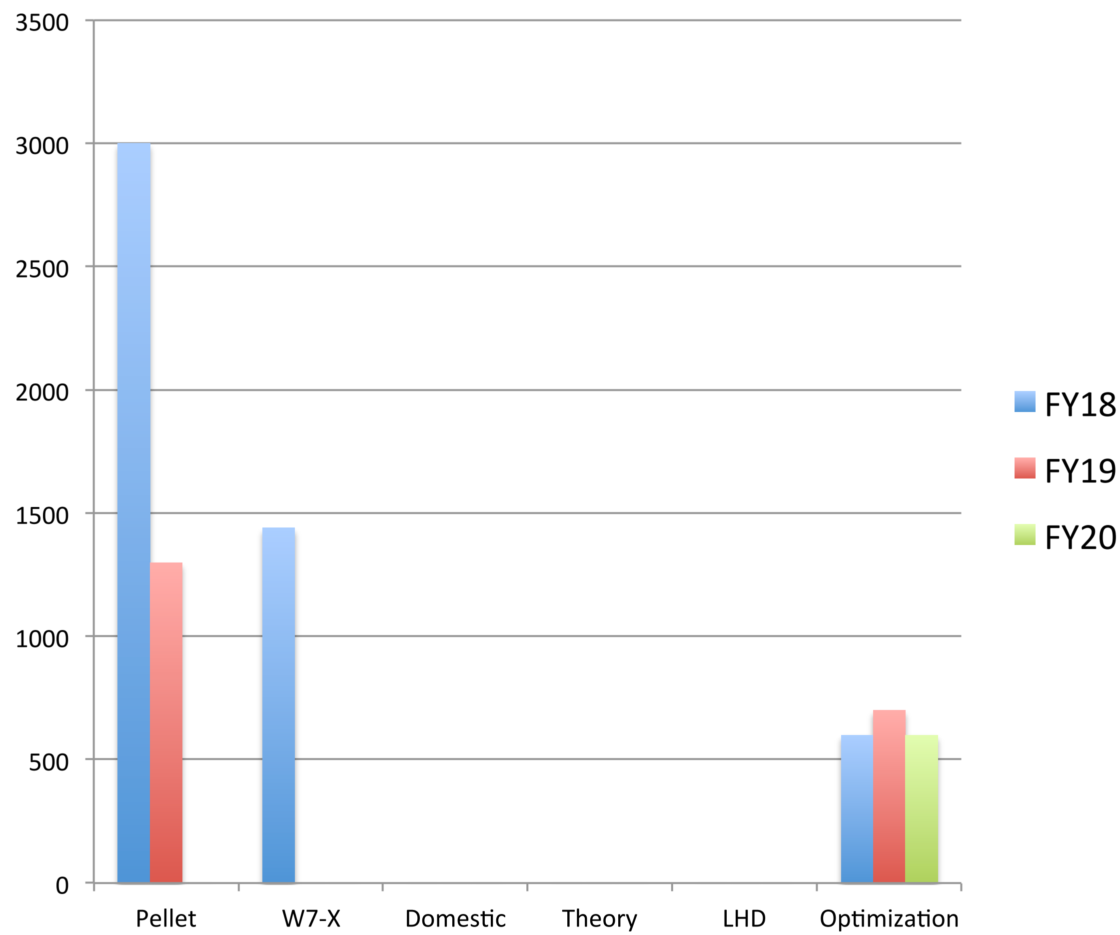
Distribution of funds based on priorities: Scenario 3

- Goal is to fund the two highest priorities: Pellet injector and optimization initiative (Uptick in 2018, followed by request in FY19 and 20% decrement in FY20)
  - First scientific priority for increment is optimization study but need flat budget so final year of funding limits project size
  - Second priority is W7-X pellet injector, but deadline drives budget
  - W7-X enhancements are funded only in the first year
  - LHD, domestic experiments and theory are not funded further



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STELLCON has Identified Proposed Program Priorities

1. **Aggressively pursue collaborations on international superconducting devices**
   - W7X - Long pulse, high β, island divertor and PMI, fueling
   - LHD – D-D campaign, high β, helical divertor
2. **Develop optimized configuration as part of a National Optimization Initiative in preparation for a next-step US facility**
   - Focus on benefits of quasi-symmetry which cannot be investigated on the existing large international facilities
   - Define the minimum scope, needs and capabilities of such a system
3. **Design an Build a mid-scale facility to test these ideas**
4. **Position US to build a world leadership-scale experiment beyond W7-X**

Utilize existing devices, as appropriate, in addressing STELLCON issues and in support of items 1 and 2. Theory and computation are a necessary component of all three elements to form an effective program

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Thanks for your attention

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