NSTX-U

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NSTX-U FY2013 Year-end Report:
Notable outcomes, research milestones

J. Menard (PPPL)

FES Room G258
PPPL Room B205
October 22, 2013

Coll of Wm & Mary
Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
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MIT
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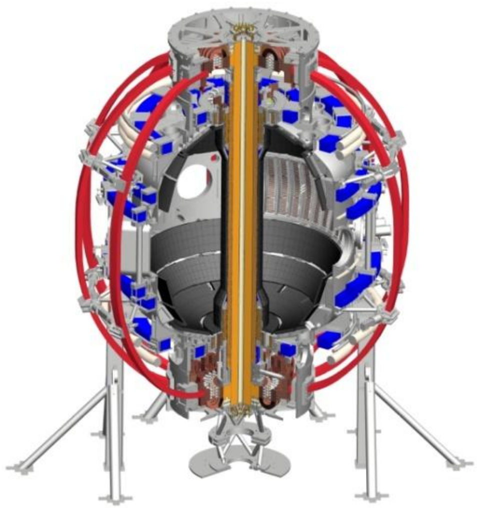

Culham Sci Ctr
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
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JAEA
Inst for Nucl Res, Kiev
Ioffe Inst
TRINITI
Chonbuk Natl U
NFRI
KAIST
POSTECH
Seoul Natl U
ASIPP
CIEMAT
FOM Inst DIFFER
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

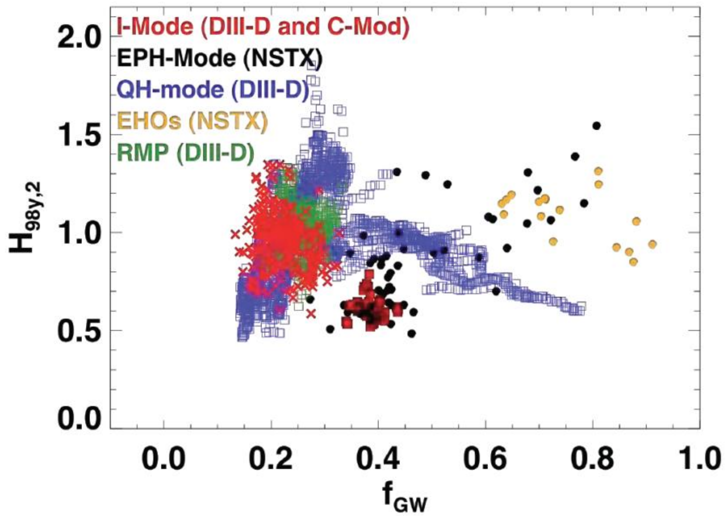
FES FY2013 Notable Outcomes for NSTX-U

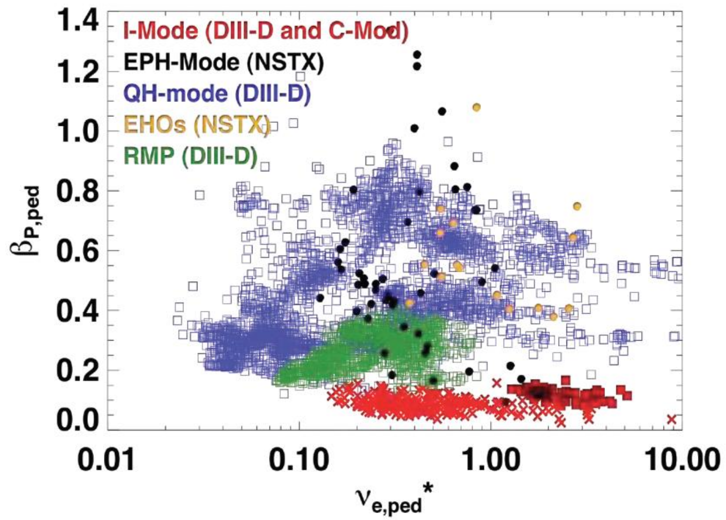
- Outcome 1.1a “Support the FES joint research target to explore enhanced confinement regimes without large edge instabilities, but with acceptable edge particle transport and a strong thermal transport barrier and to extrapolate these regimes to ITER.”
- Outcome 1.2a “Carry out high impact research relevant to NSTX-U through domestic and international collaborations”
- Outcome 3.1b – “Develop a prioritized research plan for NSTX-U to provide an assessment, within five years, of the viability of the ST concept as an attractive Fusion Nuclear Science Facility”

Outcome 1.1a "Support the FES joint research target (1)

to explore enhanced confinement regimes without large edge instabilities, but with acceptable edge particle transport and a strong thermal transport barrier and to extrapolate these regimes to ITER."

- Stefan Gerhardt (PPPL) was JRT leader and coordinated group telecons and discussions/meetings between the participating researchers
- NSTX team contributed data from Enhanced Pedestal H-mode (EP H-mode) – an attractive regime of nearly stationary high confinement + high β

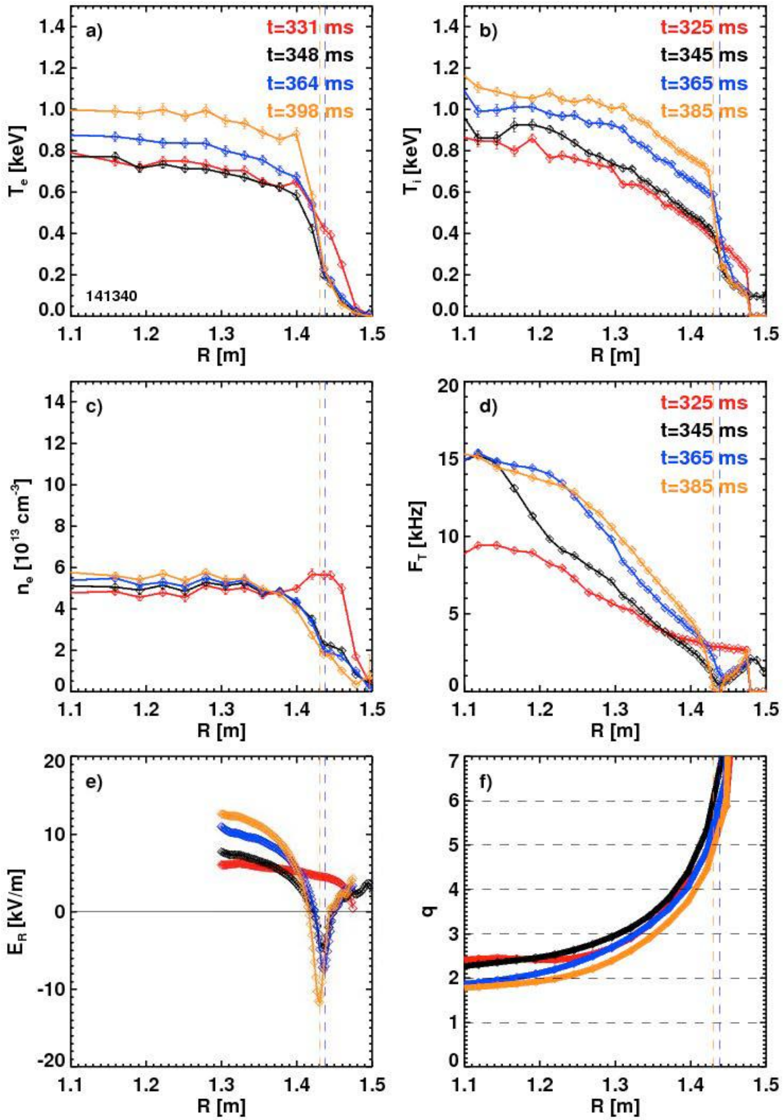




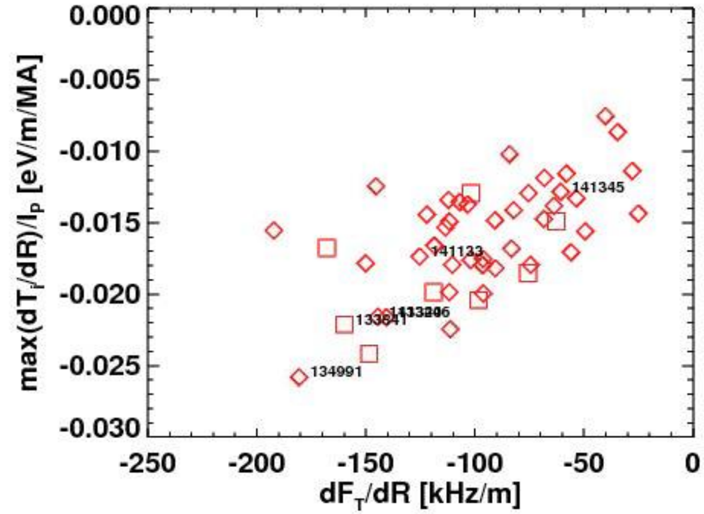
- NSTX research into EP H-mode developed:
  - Better understanding of the range of ion temperature profile shapes in EPH
  - Improved correlations between T_i pedestal parameters and the edge rotation shear
  - An assessment of turbulence as inferred from the edge reflectometer (UCLA), and examined those results with XGC0 and GS2 modeling

Outcome 1.1a "Support the FES joint research target (2)

to explore enhanced confinement regimes without large edge instabilities, but with acceptable edge particle transport and a strong thermal transport barrier and to extrapolate these regimes to ITER."



- Maximum normalized Ti gradient proportional to rotation shear



- BES, FIR: no reduction in fluctuation amplitudes evident during EPH
- XGC0: ion thermal profiles most consistent w/ kinetic neoclassical
- GS2: plasma is 2nd stable (KBM not observed), increasing ∇T_i stabilizing, most dominant mode TEM/KBM hybrid

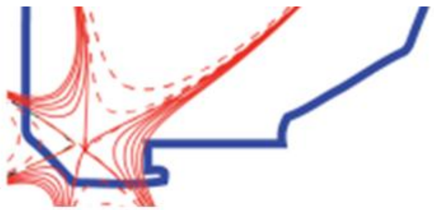
Outcome 1.2a "Carry out high impact research relevant to NSTX-U through domestic and international collaborations"

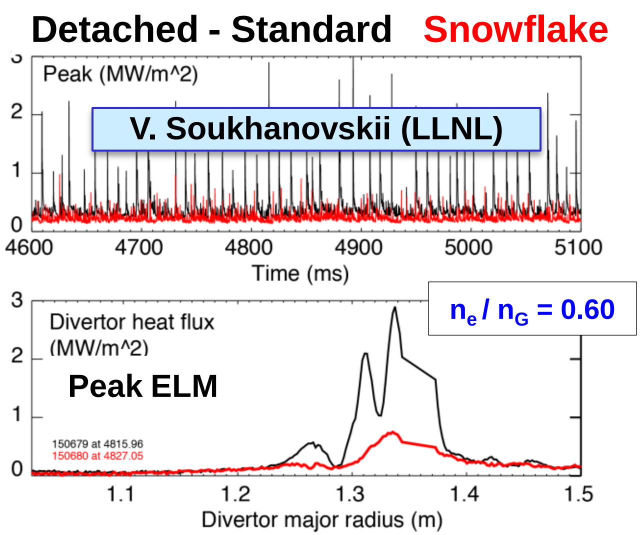
A few examples:

- Heat-flux mitigation development on DIII-D
- CHI start-up system design for QUEST at Kyushu, Japan
- EBW start-up, fast-ion, and transport research on MAST
- MHD stability and NTV research on KSTAR

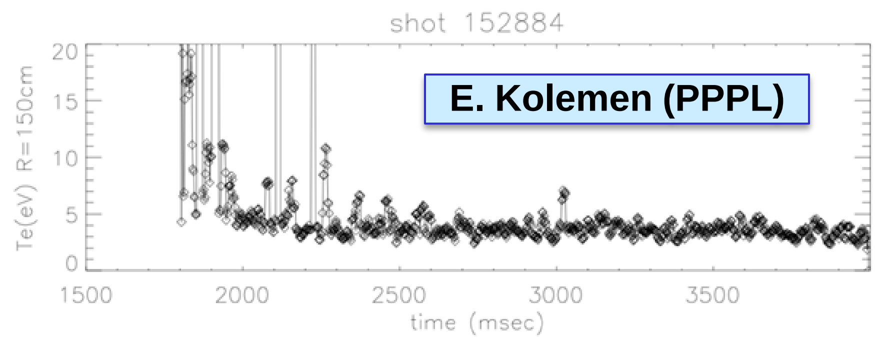
Developed snowflake and radiative detachment control on DIII-D in preparation for usage on NSTX-U

- Significant heat flux reduction between and during ELMs in DIII-D snowflake
- Developed SF magnetic control





- Real-time divertor radiation / detachment control developed, sustained detachment achieved



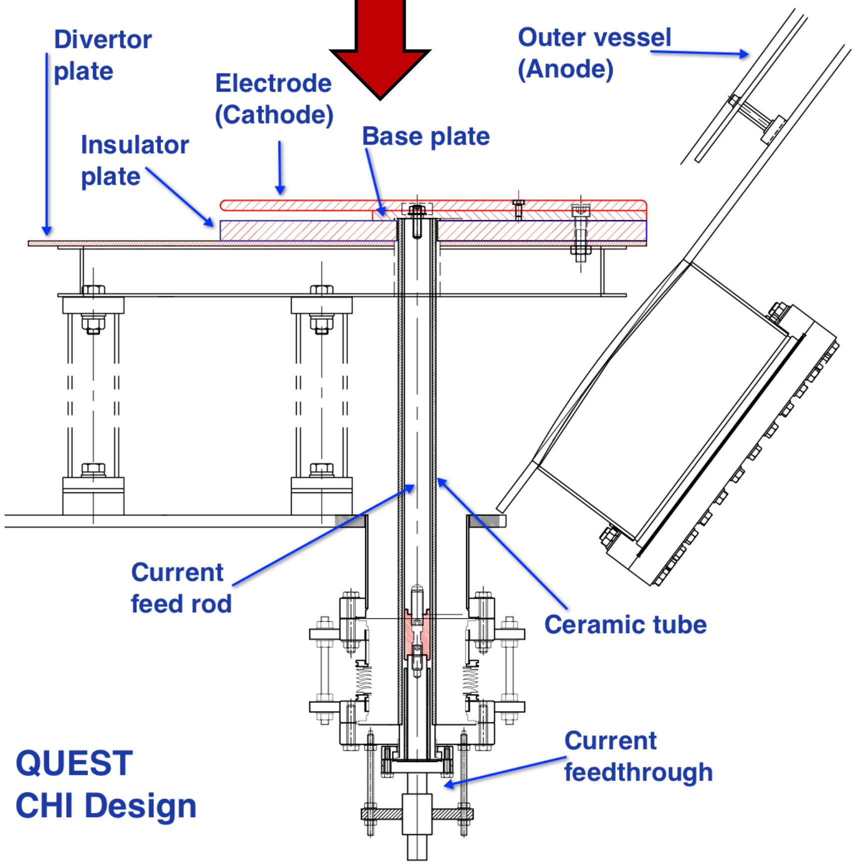
- Real-time diagnostics: bolometry, D_β, interferometry, Thomson (divertor, core, tangential)
- Actuators: D_2 and Ne gas puffing to obtain desired level of detachment and/or radiation.

V. Soukhanovskii was co-leader of snowflake-divertor portion of heat-flux mitigation experiments in recently completed DIII-D "National Campaign"

CHI Design for QUEST Supports NSTX-U and FNSF Research

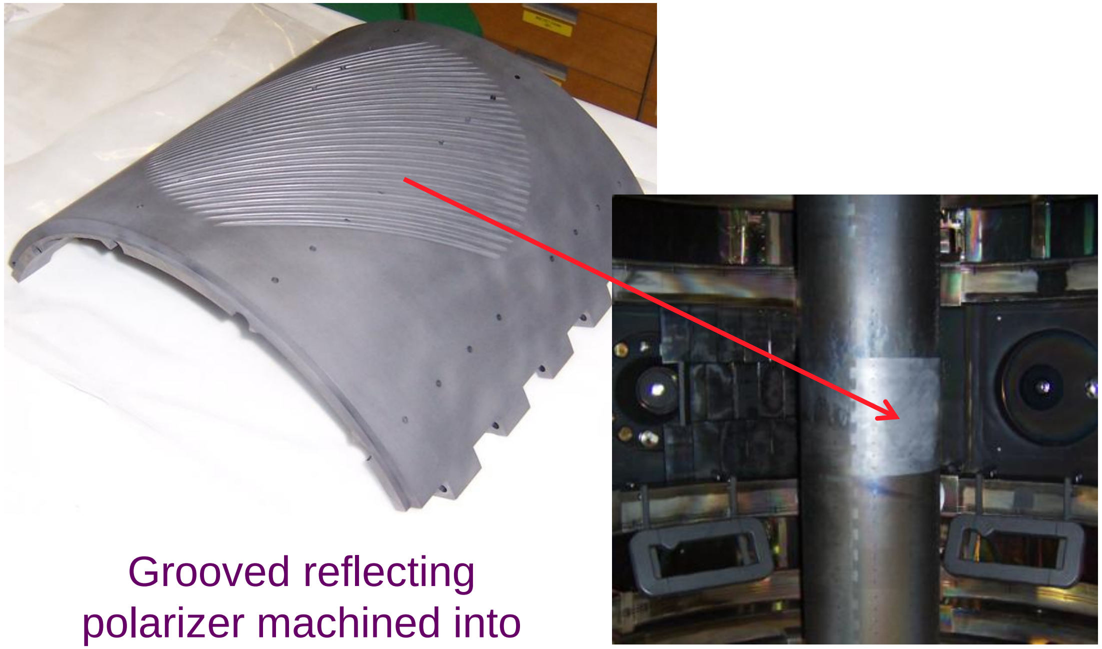
R. Raman (Univ. Washington) collaboration with Kyushu University (Japan)

Electrodes mounted on top of existing divertor plate

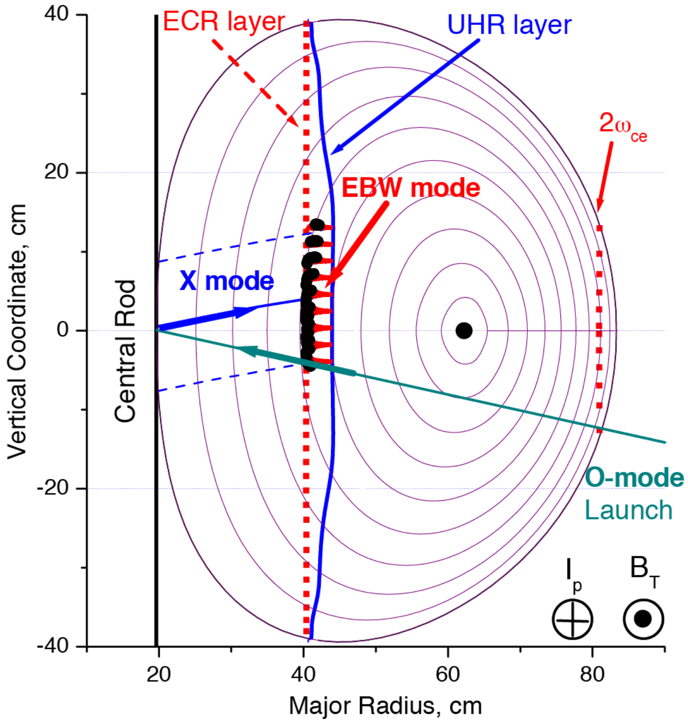


- QUEST ST aims to develop technologies for SS operation
  - Use CHI in biasing mode to vary edge density gradient for EBW experiments
  - High CHI current provides new target for SS CD studies on QUEST
  - Interested in potential of steady-state CHI for edge current drive (aided by all metal nature of QUEST + ECH)
- Benefits to NSTX-U & QUEST
  - Test metal electrodes to reduce low-Z impurities
  - Test ECH heating of CHI target at 0.5MW level
  - Test new electrode configuration to enhance compatibility with FNSF

MAST: 28 GHz EBW start-up campaign in 2013 used new low-loss transmission line to achieve record plasma current



Grooved reflecting polarizer machined into center column in MAST

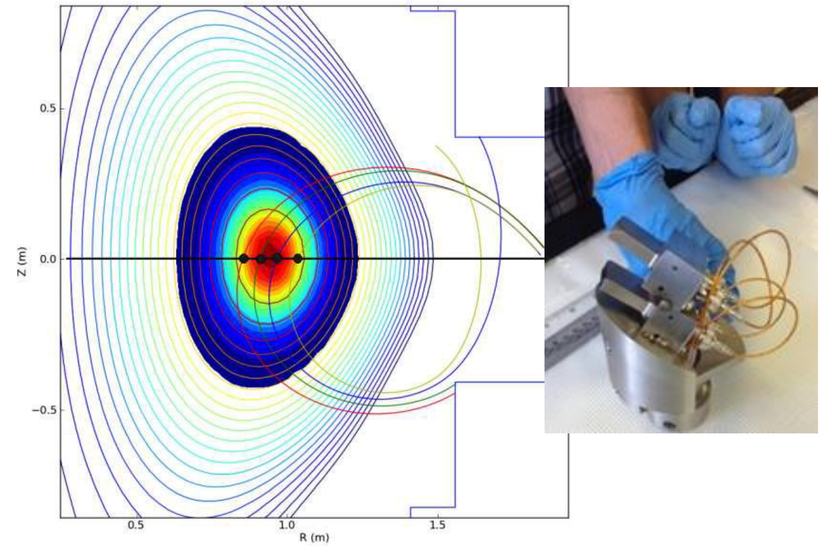


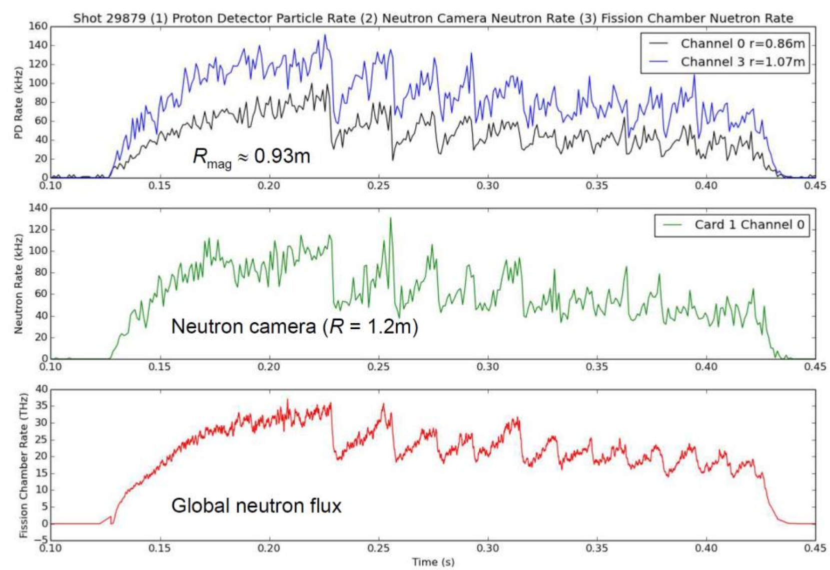
- 28 GHz O-mode weakly absorbed (< 2%) below $n_e \sim 1 \times 10^{19}$ m^{-3} cut off
- Polarizer on center column converts to X-Mode that then 100% converts to EBWs
- Previously achieved I_p~33 kA but arcs in waveguide limited RF power [Sept 2009]
- **During two one-week EBW start-up campaigns in 2013 coupled 70-100 kW for 300-400 ms achieving I_p = 50-75 kA**

G. Taylor (PPPL), with ORNL

Fast ion diagnostic collaboration with MAST

- D. Darrow (NSTX-U/PPPL) visited MAST August 2013 to contribute to tests of Florida International University (FIU) MeV proton detector on MAST
- Detector measures radial profile of DD fusion reactivity through detection of the 3 MeV protons and 1 MeV tritons produced in DD reactions
  - Testing conducted in conjunction with Prof. W. Boeglin and R. Perez (FIU), and the MAST team.
- Data on the radial profiles obtained under range of conditions:
  - Quiescent plasmas, sawtoothing discharges, and during fishbone modes
- Comparisons with profiles obtained from MAST neutron camera are underway
- Results encouraging for development of a higher channel count system for NSTX-U





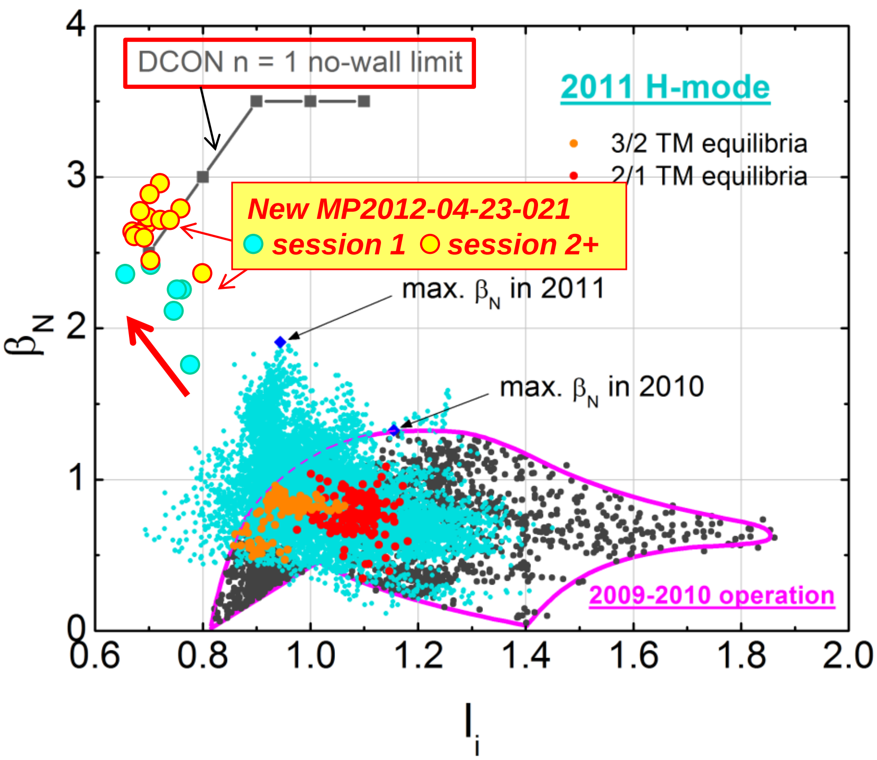
Additional fast-ion and transport collaborations with MAST during M9

- Studied fast ion redistribution caused by TAE avalanches, extending previous studies on NSTX (Podesta, Fredrickson)
  - D-alpha emission found to be sensitive to fast-ion losses
- Measured momentum transport in MAST L-modes using 3D field perturbations for rotation braking (W. Guttenfelder)
  - Also initiated particle transport exts (gas puffs, high time-res Thomson)
- DBS diagnostic implemented on MAST – collaboration with UCLA and NSTX-U (A. Diallo, M. Podesta)
  - Observed transitions from a negative- to a positive-frequency-peaked spectrum related to change in core intrinsic rotation
  - Fluctuations with f~100–150 kHz from TAEs, possibly due to a fluctuating ExB flow associated with the TAE electric field perturbation
  - Diagnostic will be installed on NSTX-U after MAST M9 is complete

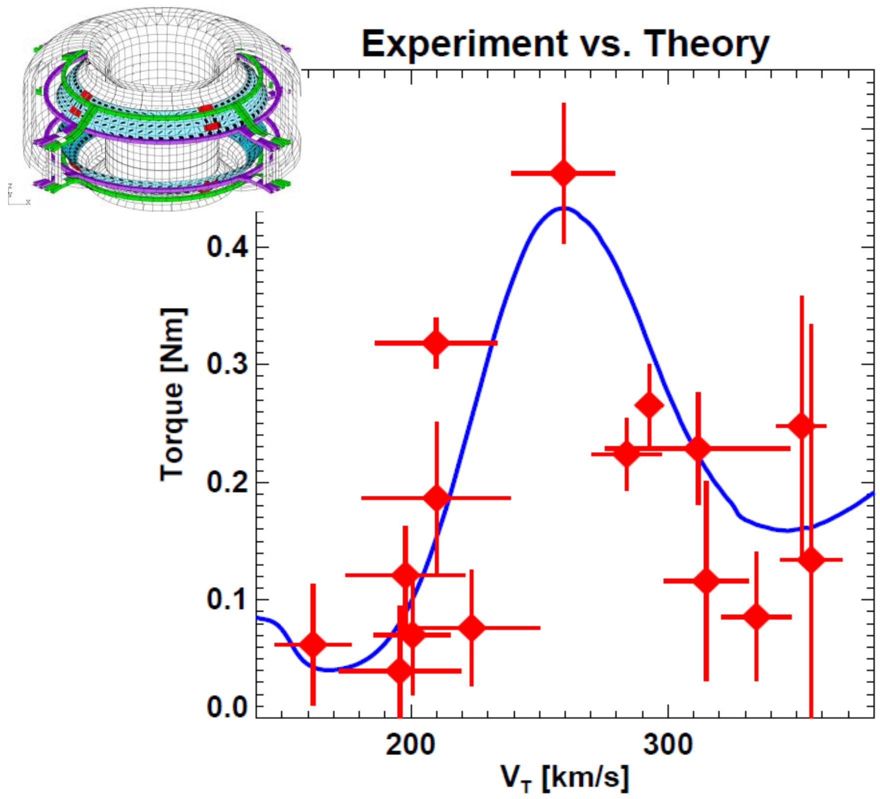
NSTX experience in scenario development, high-beta, and 3D physics is having significant impact on KSTAR research

- Improved shape control, improved access to low l_i + high κ: D. Mueller, D. Battaglia, E. Kolemen (PPPL)

- Studying MHD stability near no-wall beta limit: S. Sabbagh (CU)



- Bounce-harmonic resonance in NTV observed in KSTAR for the first time in tokamak, and compared to theory/IPEC: J-K Park (PPPL – 2010 ECRP)
  → **Published in PRL**



Outcome 3.1b – "Develop a prioritized research plan

for NSTX-U to provide an assessment, within five years, of the viability of the ST concept as an attractive Fusion Nuclear Science Facility"

Highest priority research goals for 5 year plan:

1. Demonstrate 100% non-inductive sustainment at performance that extrapolates to ≥ $1 MW/m^2$ neutron wall loading in FNSF
2. Access reduced ν^* and high-β combined with ability to vary q and rotation to dramatically extend ST physics understanding
3. Develop and understand non-inductive start-up and ramp-up (overdrive) to project to ST-FNSF with small/no solenoid
4. Develop and utilize high-flux-expansion "snowflake" divertor and radiative detachment for mitigating very high heat fluxes
5. Begin to assess high-Z PFCs + liquid lithium to develop high-duty-factor integrated PMI solutions for next-steps

Longer-term (5-10 year) goal:

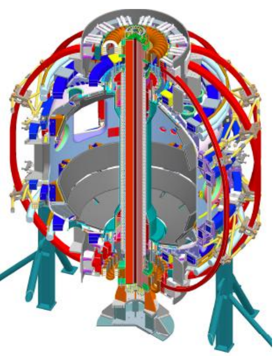
Integrate 100% non-inductive + high β and τ_E + divertor solution + metal walls

NSTX-U goal staging: first establish ST physics + scenarios, transition to long-pulse + PMI integration (5YP incremental)

2014	2015	2016	2017	2018	2019	2020	2021	2022	2023

Upgrade Outage (2014) | **Establish ST physics, scenarios** (2015–2018) | **Integrate long-pulse + PMI solutions** (2019–2023)

New center-stack



Start-up and Ramp-up
- Increase CHI closed-flux current → Achieve NI start-up/ramp-up
- Assess plasma gun start-up at increased device size → Increase/extend ramp-up heating and off-axis current-drive for advanced scenarios
- Develop/understand ECH/EBW H&CD for ST

Boundary Physics
- Establish main-ion density and ν^* control → Understand snowflake divertor performance → Understand high-Z first-wall erosion, migration, particle sources & sinks

Materials and PFCs
- Assess baseline graphite PFC performance → Assess high-Z tile/divertor impact and performance → Assess high-Z divertor and/or first-wall → Assess impact of high-temperature first-wall

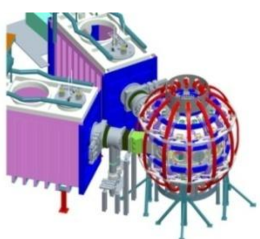
Liquid metals / lithium
- Establish low impurities / Z_{eff}, assess increased Li coverage, replenishment → Test flowing liquid metal for heat-flux mitigation, surface replenishment → Assess flowing LM PFC with full toroidal coverage

MHD
- Understand kinetic MHD, extend mode and disruption detection, develop mitigation → Enhance non-axisymmetric field spectrum and capabilities with off-midplane coils for control of: RWM, EF, RMP, rotation, NTM, EP

Transport & Turbulence
- Understand ES and EM turbulence at high β, low ν^*, emphasizing e-transport → Extend wave-number coverage of turbulence measurements

Waves and Energetic Particles
- Characterize AE stability, fast-ion transport, NBI-CD, support plasma start-up, assess effectiveness of fast-wave in NBI H-modes → Prototype driving edge-harmonic oscillations (EHOs) and/or *AE

Scenarios and Control
- Demonstrate full non-inductive, high I_P & P_{AUX} operation; Control: boundary, β, divertor heat flux, Ω & q profiles → Assess integrated control of long-pulse / high-performance



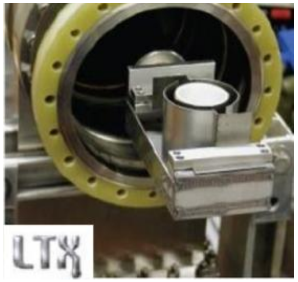
2nd NBI

Inform choice of FNSF: **aspect ratio, divertor, and PFCs**

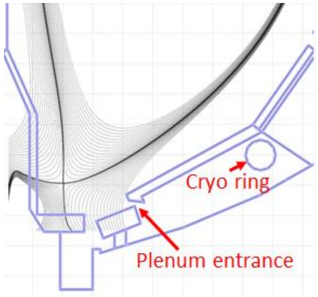
5 year plan includes longer-term facility enhancements to fully utilize Upgrade capabilities, support ITER and FNSF

- **Improved particle control tools**
  - Control deuterium inventory and trigger rapid ELMs to expel impurities
  - Access low ν^*, understand role of Li

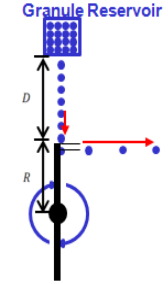
Upward Li evaporator



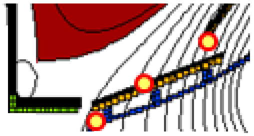
Divertor cryo-pump



Li granule injector (LGI)

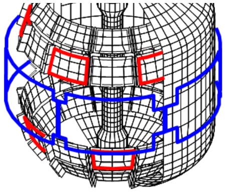


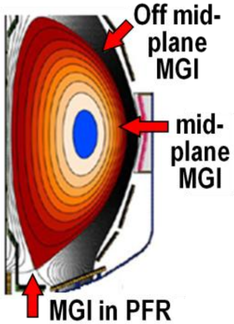
- **Disruption avoidance, mitigation**
  - 3D sensors & coils, massive gas injection



Extended low-f MHD sensor set

Midplane + off-midplane non-axisymmetric control coils (NCC)





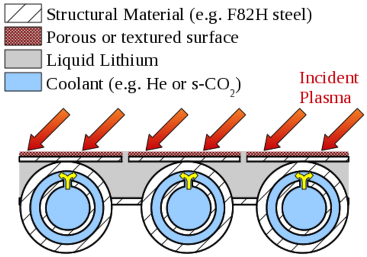
- **ECH to raise start-up plasma T_e to enable FW+NBI+BS I_P ramp-up**
  - Also EBW-CD start-up, sustainment

1-2MW 28 GHz gyrotron

- **Begin transition to high-Z PFCs, assess flowing liquid metals**
  - Plus divertor Thomson, spectroscopy

High-Z tiles

Actively-supplied, capillary-restrained, gas-cooled LM-PFC



The NSTX-U 5 Year Plan review comments were largely favorable

- **Programmatic comments (from debrief report):**
  - “The quality of the proposed research is excellent, employing state-of-the-art diagnostics to obtain data that will be compared to theory using a wide variety of numerical models.”
  - “The proposed research addresses fundamental problems in magnetic fusion and will advance the state of knowledge in a number of areas.”
  - “The proposed research is essential for advancing the ST to a nuclear science mission.”
- **Facility enhancement comments (from written report):**
  - “The addition of a divertor cryo-pump will be an excellent addition to their program.”
  - “NCC will greatly enhance physics studies and control”
  - “Given the essential need for non-inductive startup for FNSF-ST, acquisition of a 28 GHz gyrotron to provide capability for heating CHI plasmas to allow better absorption of HHFW, is important to the long-term program”
  - “The proposed additions of the flowing liquid Lithium divertor and divertor Thomson scattering diagnostic are desirable.
    - Reassessment of the importance of the flowing Lithium divertor relative to other items covered under base funding is recommended.”

NSTX-U FY2013 Research Milestones

- R(13-1): Perform integrated physics and optical design of new high-k_θ FIR system

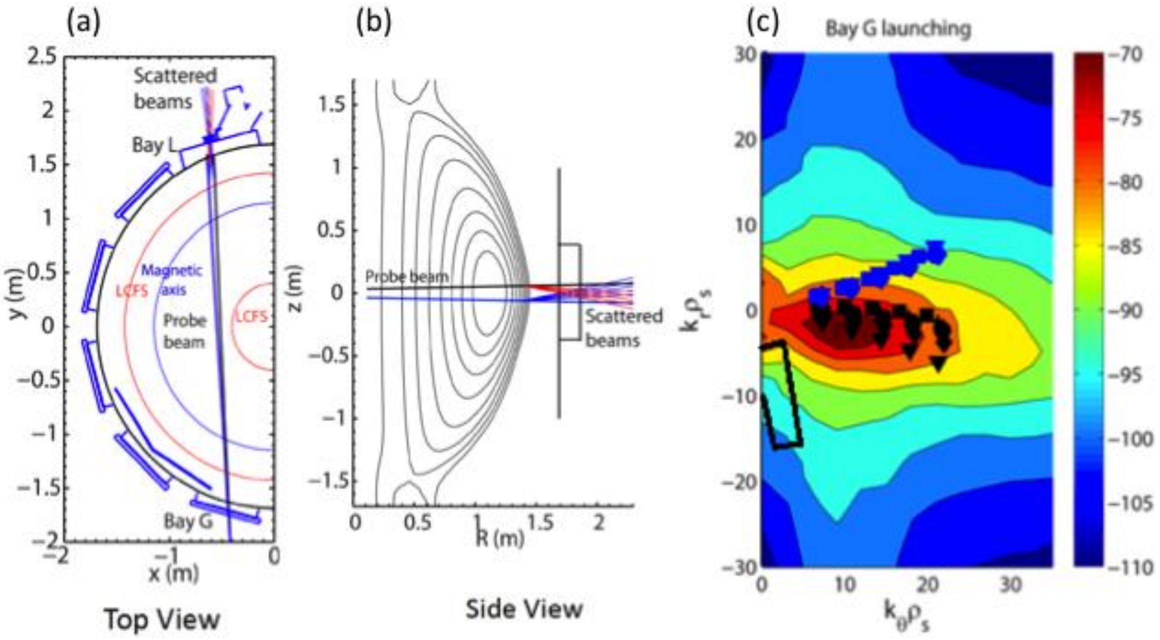
- R(13-2): Investigate the relationship between lithium-conditioned surface composition and plasma behavior
  - See results slide in Masa's presentation

- R(13-3): Perform physics design of ECH and EBW system for plasma start-up and current drive in advanced scenarios

- R(13-4): Identify disruption precursors and disruption mitigation and avoidance techniques for NSTX-U and ITER

R(13-1): Perform integrated physics and optical design of new high-k_θ FIR system

- **System will provide measurement of k_θ-spectrum of both ETG and ITG modes**
  - NSTX 280 GHz high-k tangential system of NSTX will be replaced by a 604 GHz (CO_2-pumped FIR laser) poloidal scattering system being developed by UC Davis
  - The reduced wavelength in the poloidal system will result in less refraction and extend the poloidal wavenumber coverage from the current 7 cm^{-1} up to > 40 cm^{-1}
- **Anisotropy in 2D k-spectrum of ETG turbulence (i.e. ETG streamers), can be determined by comparing k-spectrum measured by different schemes:**
  - Total of 4 scattering schemes possible w/ different combinations of toroidal, poloidal tilt angles



a) Schematic of the toroidal cross section of the high-k scattering beam geometry

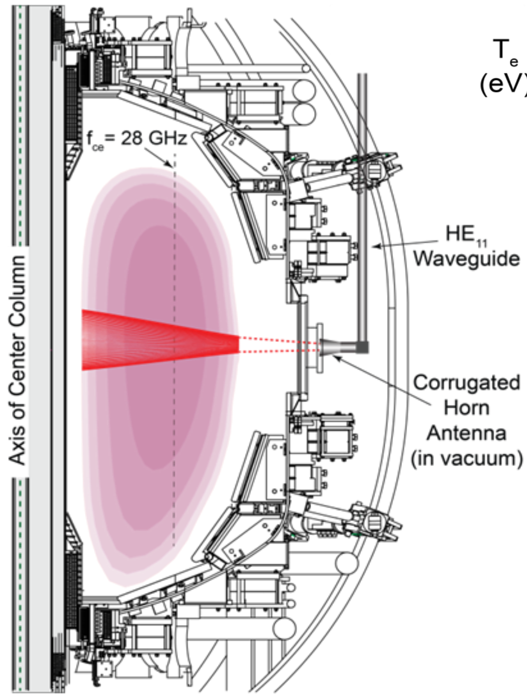
b) Poloidal cross sectional view of the beam geometry

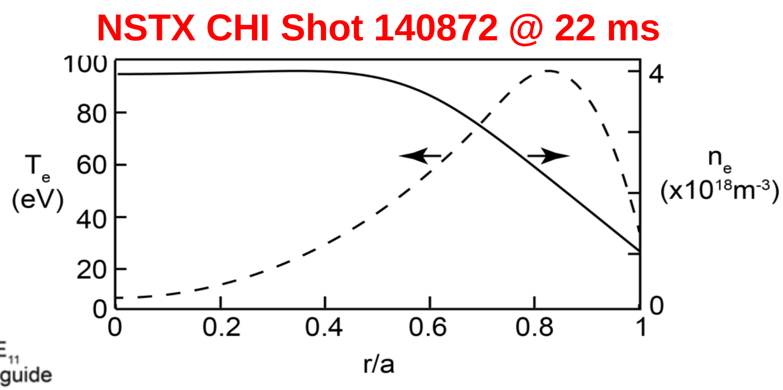
c) Regions in 2D k_r and k_θ space covered by two scattering schemes

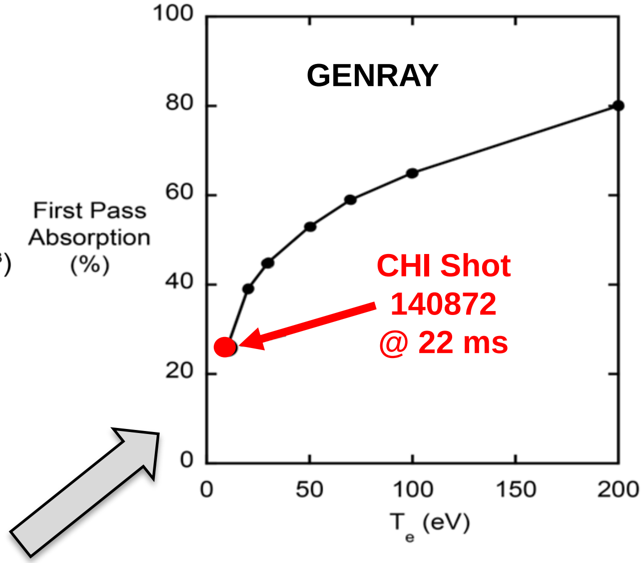
Y. Ren (PPPL), with UC Davis

R(13-3): Perform physics design of ECH and EBW system for plasma start-up and current drive in advanced scenarios (1)

- **Low n_e = 3-4 x 10^{18} m^{-3} CHI discharges amenable to 28GHz EC heating:**

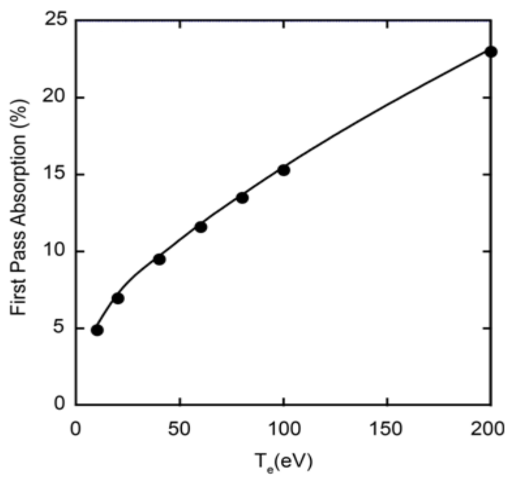






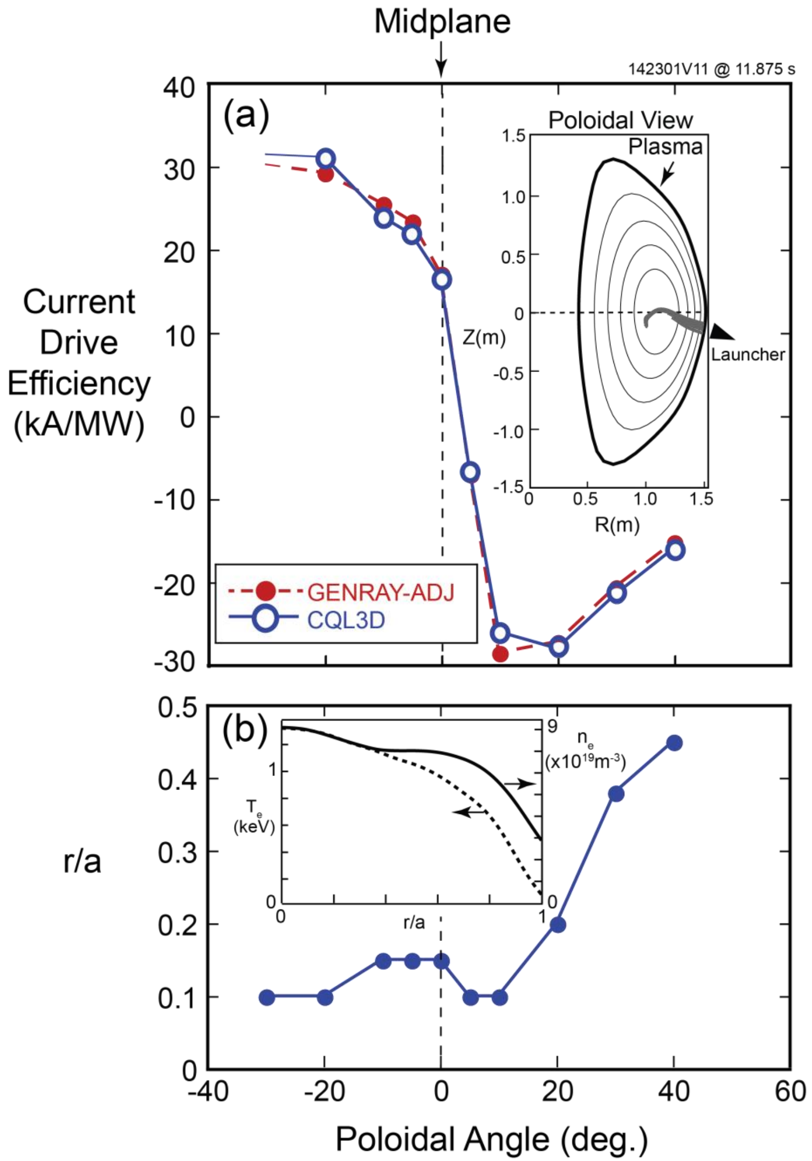
- At $B_T(0)$ = 0.55T, first pass EC absorption ~25% → expect rapid heating to ~200 eV

- At $B_T(0)$ = 1T, first pass EC absorption (at fundamental) is reduced by factor of ~4



G. Taylor (PPPL), with CompX

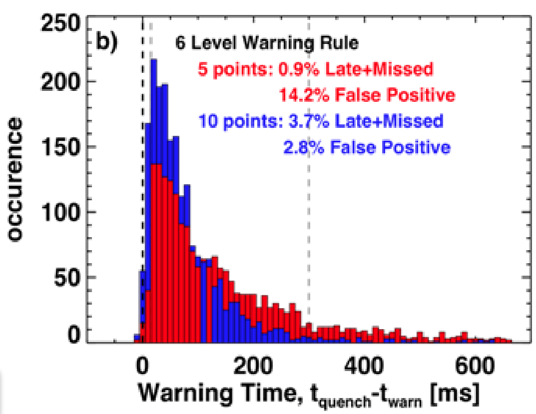
R(13-3): Perform physics design of ECH and EBW system for plasma start-up and current drive in advanced scenarios (2)

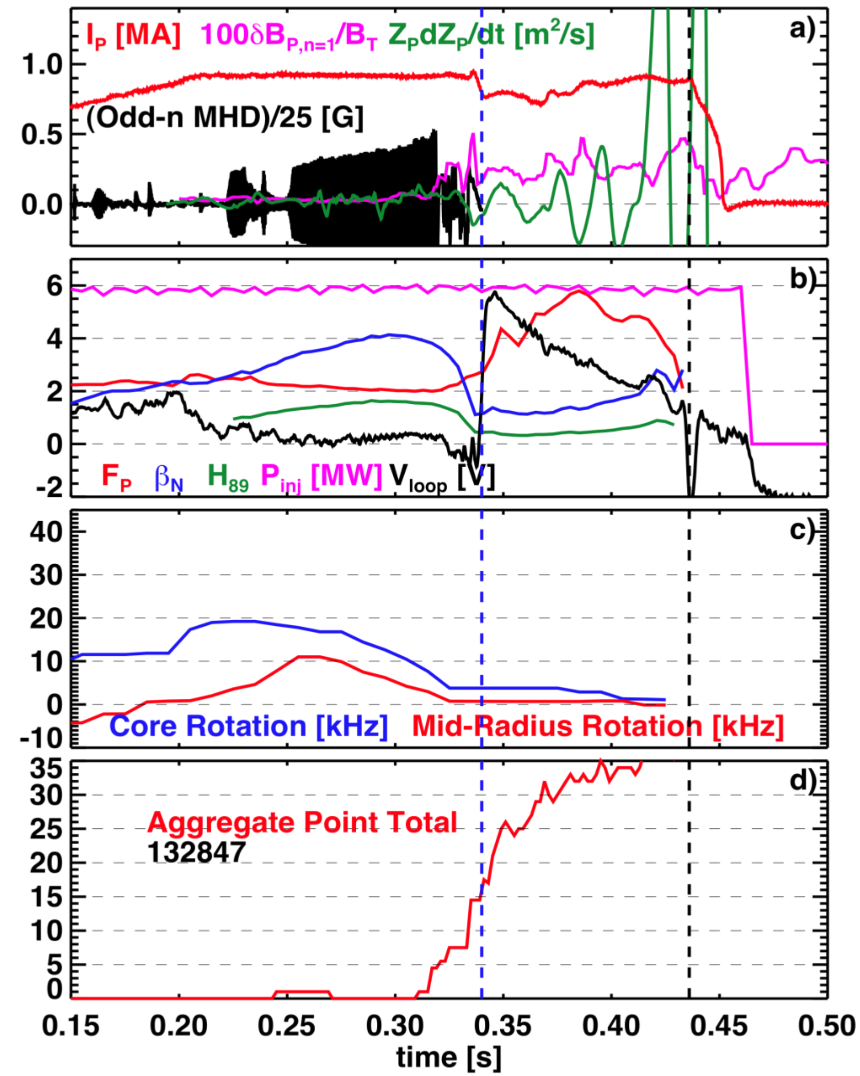


- I_P =1.1 MA, $B_T(0)$ = 1T, H-mode
- EBWH, CD modeling tools:
  - GENRAY ray tracing + ADJ quasi-linear package
  - CQL3D Fokker-Planck
- Max. O-X-B mode conversion efficiency: $n_{||} = \pm 0.7$ at launch
- Poloidal launch angle scanned from -30˚ to 40˚
  - Max CD efficiency: ~±30kA/MW
  - **Normalized efficiency comparable to NBICD**
- Deposition minor radius variable between 0.1 to 0.5
- Adjusting B_T or f_{RF} → can position peak J_{EBWCD} at r/a ≥ 0.8

R(13-4): Identify disruption precursors and disruption mitigation and avoidance techniques for NSTX-U and ITER (1)

- Most critical measurements, analysis:
  - I_P vs request, δB, Z^*dZ/dt, F_P, β_N, H_{89}, V_{LOOP}, rotation frequency, neutron rate…
- Disruption warning methodology:
  - Each threshold test is executed, # of points for each test is evaluated
  - Points from individual tests are totaled to form "aggregate" total
  - Disruption warning declared if total exceeds a pre-defined threshold
- Late or missed disruptions can be traded against false-positives





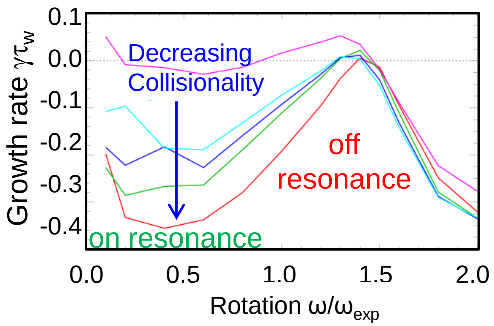
S. Gerhardt (PPPL)

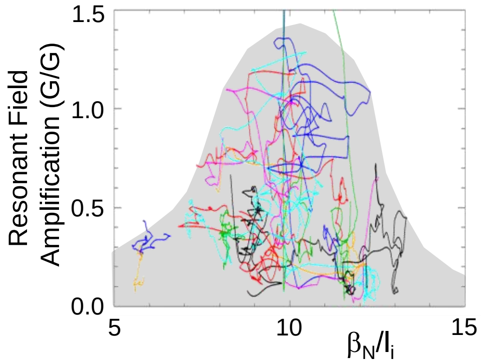
R(13-4): Identify disruption precursors and disruption mitigation and avoidance techniques for NSTX-U and ITER (2)

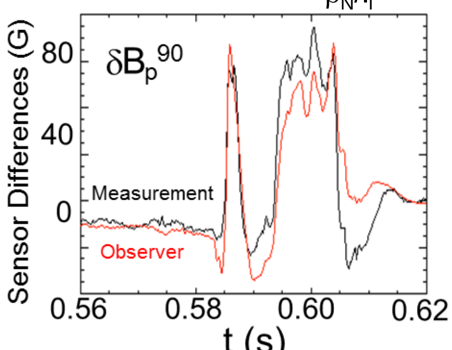
Predictors → ***Disruption Warning System*** → ***Mitigation***

Predictors → ***Control Algorithms*** → ***Disruption Warning System***

Control Algorithms → ***Avoidance Actuators***







Kinetic Physics

- Evaluate simple physics criteria for global mode marginal stability in real-time

MHD Spectroscopy

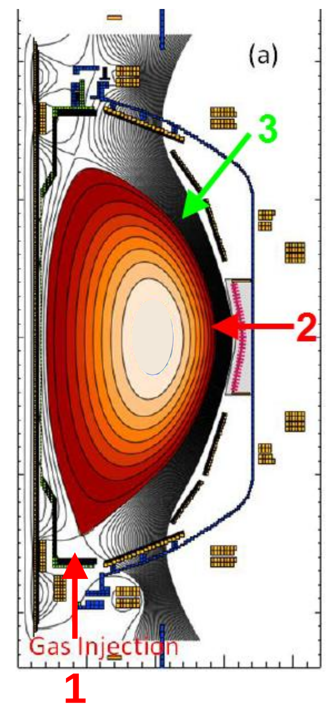
- Use real-time MHD spectroscopy while varying rotation, q_{min}, and β_N to predict disruptions

→ ***q, v_ϕ, β_N control***

RWMSC observer

- Compare mismatch between the RWMSC observer and sensor measurements, and disruption occurence

→ ***3D fields, feedback***

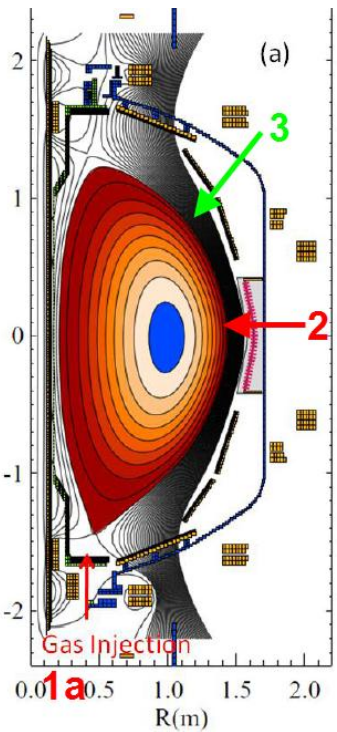


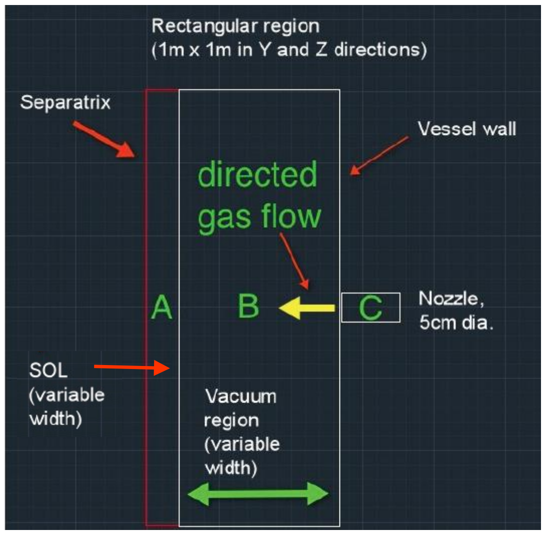
ITER gas-loading :

Injection into private flux region with higher assimilation efficiency?

R(13-4): Identify disruption precursors and disruption mitigation and avoidance techniques for NSTX-U and ITER (3)

MGI research will assess gas penetration efficiency by injection at different poloidal locations

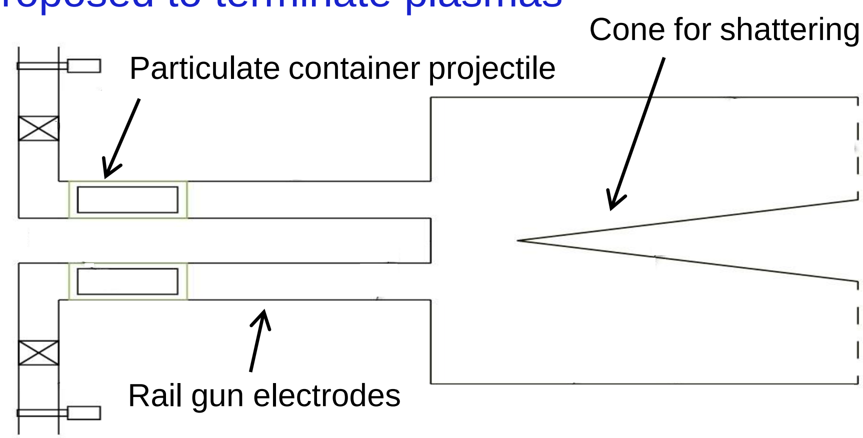




Predictive capability: Modeling using DEGAS-2 is quantifying the gas penetration past the SOL for NSTX-U

- NSTX-U can offer new insight by
  - Reducing the amount of gas
  - Injecting gas into the private flux and lower x-point regions of divertor to determine if these are more desirable locations for MGI.

Development of a novel mitigation technology – an electromagnetic particle injector (EPI) – is proposed to terminate plasmas



- The EPI is capable of delivering:
  - A large particle inventory
  - All particles at nearly the same time
  - Particles tailored to contain multiple elements in different fractions and sizes
  - Tailored particles fully ionized only in higher current discharges (to control current quench rates)
- Well suited for long stand-by periods

R. Raman (U. Washington)

Maintained strong team and publication and conference participation, development of early career researchers

	PPPL/PU	National Team (non-PPPL/PU)	International	Total
Total Researchers	79	166	61	306
Post-Docs	5	9	0	14
Students	3	26	4	33

Number of institutions	
Total	61
Domestic	32
International	29

Calendar Year	Refereed Publications	PRLs	APS Invited	IAEA Papers
2009	45	6	5	
2010	63	5	10	25
2011	58	5	8	
2012	56	1	4	30
2013	52 so far	4 (so far)	6	

- Ahmed Diallo (PPPL) received 2013 DOE Early Career Research Program (ECRP) award for: “Edge Pedestal Structure Control for Maximum Core Fusion Performance”
- NSTX snowflake divertor team featured in October 2012 FES Science Highlights, led by V. Soukhanovskii (LLNL - 2010 ECRP) – also leading DIII-D snowflake expts.

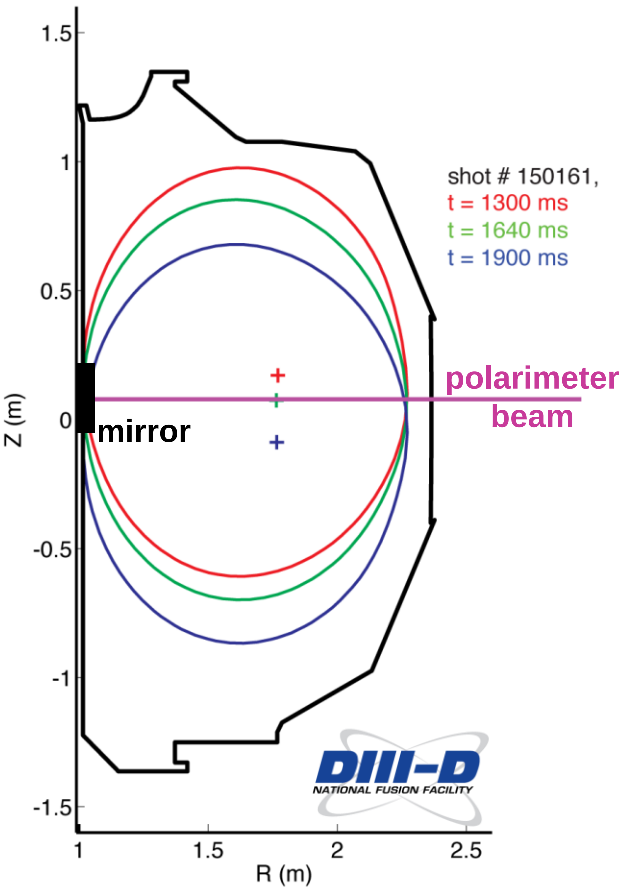
Thank you!

UCLA

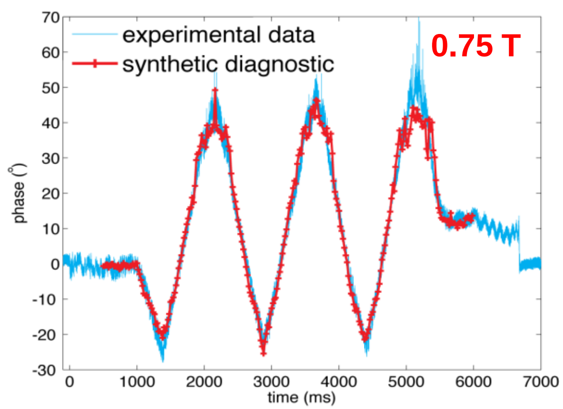
UCLA successfully tested 288 GHz polarimeter for NSTX-U on DIII-D

DIII-D NATIONAL FUSION FACILITY

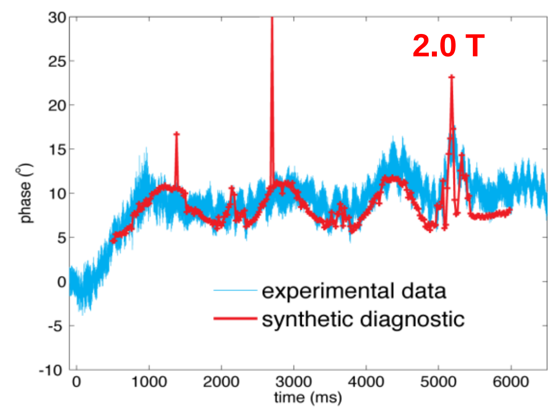
UCLA Graduate Student: J. Zhang – Thesis Project



- Dedicated DIII-D run time to test polarimeter over wide range of conditions: phase response predicted to vary strongly with vertical position and B_T.
  - Moving plasma vertically → Faraday rotation due to horizontal B ranges from weak to strong
  - Wide range of B_T → elliptization (Cotton-Mouton effect) ranges from weak to strong
- Synthetic diagnostic calculations agree with measured phase over wide range of B_T (0.75-2.0 T), plasma height



Faraday rotation dominated

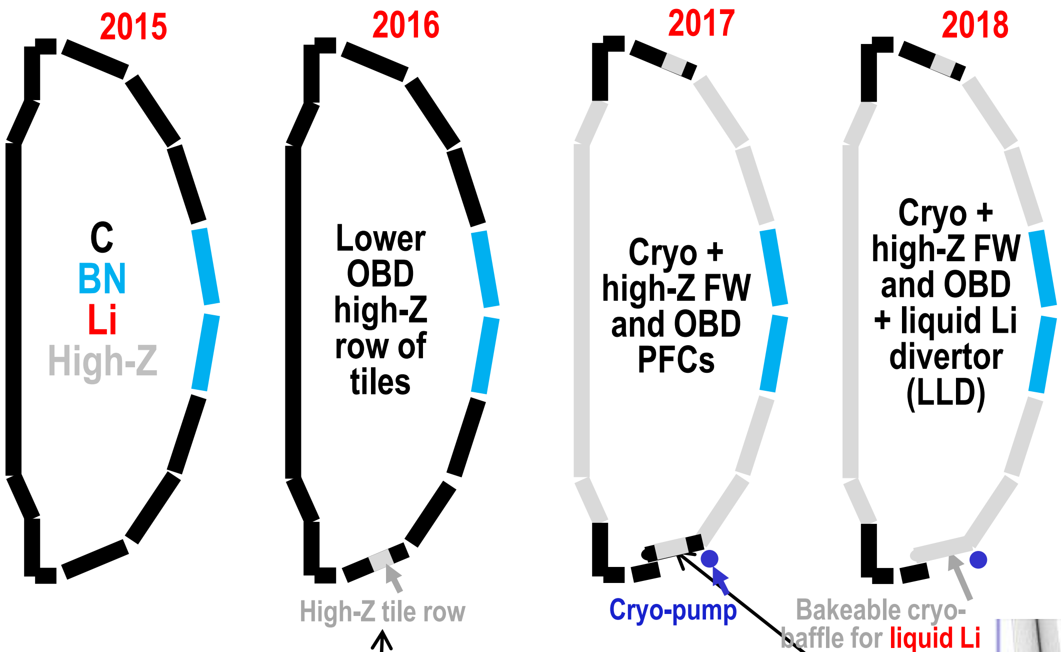


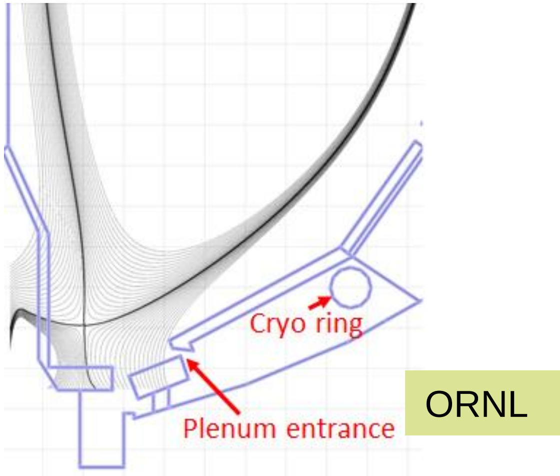
Cotton-Mouton effect dominated

- **Polarimetry planned to be used to measure μ-tearing δB in NSTX-U**

Boundary Facility Capability Evolution

NSTX-U will have very high divertor heat flux capability of ~ 40 MW/m^2



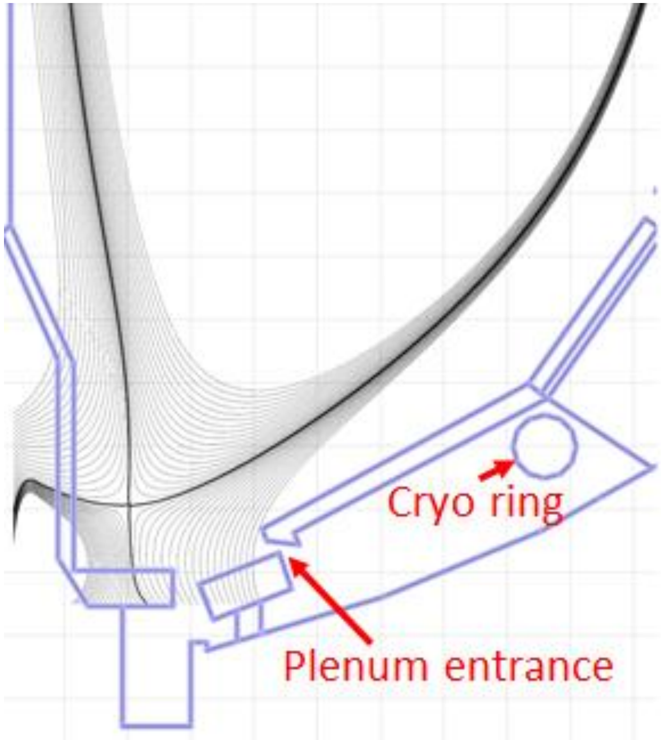


Divertor Cryo-pump for particle control

Particle pumping for broad range of divertor parameters

Basis for Divertor Cryo-Pump Budget:

- **Divertor cryo-pump is well developed. DIII-D has a long history of cryo-pump implementation.**
- **NSTX-U will adopt DIII-D cryo-pump design.**
- **Utilize DIII-D cryo-pump actual cost and adapt it to NSTX-U.**



Cost Estimate Assumptions:

- **No credit taken for smaller radius of NSTX-U**
- **SWIP cryo-pump system design achieved 14,000 hours design effort reduction. NSTX-U will take 50% of the credit.**

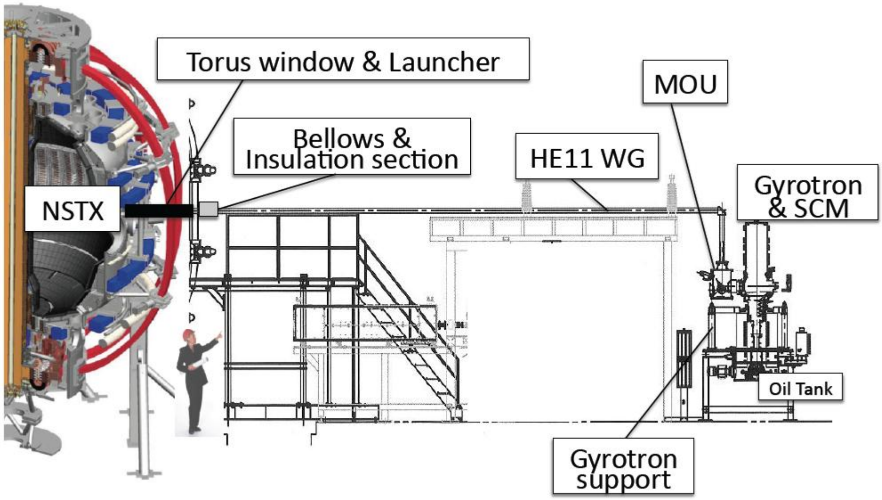
Scaling from DIII-D to NSTX-U System	$k
Inflation adjusted DIII-D actuals	$7,283
Liquid helium and nitrogen system tie in	$1,000
Credit of the design effort reduction by 7,000 hours	-$1,050
Cryo-pump tile work is covered elsewhere	-$1,000
The total estimate cost =	$6,233

1 MW 28 GHz Gyrotron System

For bridging the start-up temperature gap and EBW research

Basis for 1 MW 28 GHz Gyrotron Budget:

- **System is well defined. Similar system working in Japan (Tsukuba and QUEST).**
- **PPPL has a collaboration with DIII-D on ECH. Some internal ECH expertise.**
- **~ 50% of budget is procurement**
- **Antenna and waveguide is costed elsewhere.**
- **But with some implementation uncertainties:**
  - **- Actual location is not finalized.**
  - **- Power supply configuration not finalized. Utilize NBI power supply? Need for a polarity switch. Procure a new power supply?**



Sub tasks	Cost Estimate (k$)	Basis for cost estimate
gyrotron system procurement	$1,760	(estimate from Tsukuba University)
water system	$560	(PPPL estimate)
power supply	$3,000	(pursuing various options)
control & instrumentation	$1,500	(previous experience on similar system)
Total Cost Estimate	$6,820	

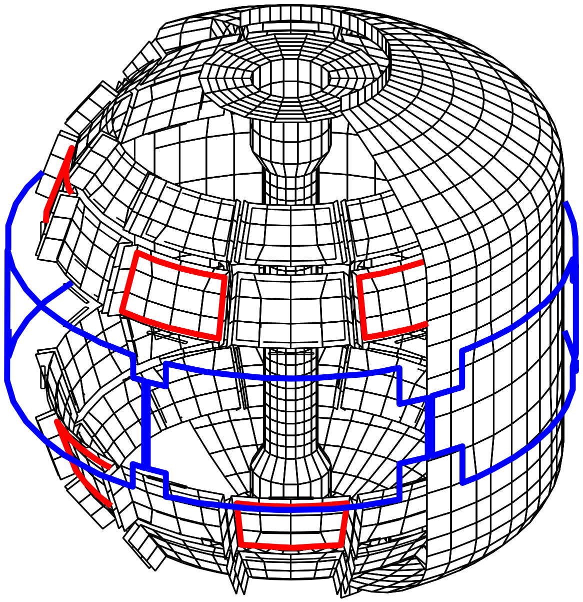
Partial NCC Coils - New MHD and Plasma Control Tools

Sustain high β_N, control rotation, modify edge transport

Basis for Partial NCC Budget:

- NCC utilized the cost actuals from the DIII-D I-Coil work.
- Actual hours spent on the I-coil tasks are the same for the NCC coils by the PPPL personnel with similar skills ($).
- M&S cost is inflation adjusted.
- DIII-D spent significant R&D and Testing of I-Coils. Assume the same level of effort for the NCC coil R&D and Testing. This may generate savings.

Partial NCC option (2 x 6 odd parity)



Cost Estimate Assumptions:

- The # of coils are the same for NCC and I-Coil systems.
- No credit taken for the NCC coil size to be half that of the I-Coil.
- NCC (RWM) diagnostics are separately funded.

Tasks	actual hours	Cost ($k)
Design	2886	$495
Fabrication	5270	$793
Installation	4102	$617
R&D Testing	8565	$1,352
M&S	inflation adj	$569
Total		$3,825

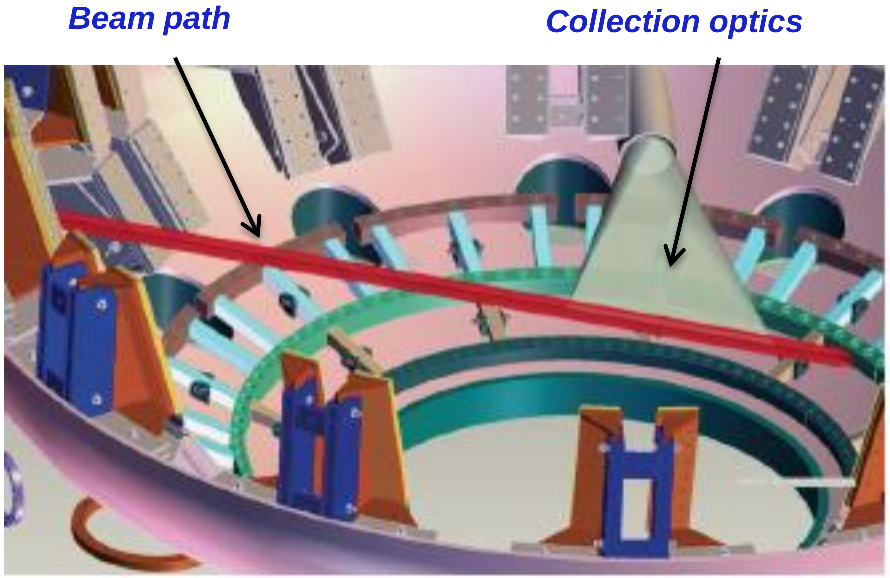
Divertor Thomson Scattering System

For divertor and SOL heat and particle transport studies

Basis for Divertor Thomson Budget:

- Relatively detailed engineering study was performed in 2008.
- A base-up cost estimate developed.
- There are two main components: Thomson scattering laser system related items and related vacuum vessel modifications and utilities.

Divertor Thomson Scattering Geometry



Cost Estimate Assumptions:

- Laser components and related items are estimated to cost ~ $950k. This includes computer, laser optics, laser safety, cooling, and 10% contingency.
- Device modification estimate is ~ $3,550k. This includes system design, laser room, AC power, interlocks, E-stop, diagnostic racks, light collection optics, laser focusing optics, vacuum vessel modification, cable tray, flight tube. We assume ~ 35% contingency due to relative complexity of the in-vessel work.
- The total cost estimate is $5.6M with overall 30% contingency.