NSTX-U Candidate Baseline Year-1 Lithium Plan

- for Noteworthy Results Early in the Campaign

- Install ATJ Graphite tiles on *Lower* Inner and Outer Divertor
- Install subset of existing tile diagnostics on *Lower Outer Divertor*
- Mount the 2011 Molybdenum tiles on *Upper Inner Divertor*
- Mount the 2011 LITERs on Upper Divertor
- Mount suitable Lithium Technology for coating Upper Divertor
- Take 6 shots without lithium
- Start lithium deposition, and obtain research grade shots within 10 discharges (H.Kugel, PSI 2010, Fig.7), or do 3 TMBs and take 6 weeks (M.Bell, Startup Calendars, 2006-2010)
- Proceed to integrate, & qualify the Upgrade, & initiate characterization of NBI current drive

NSTX-U Near Term Lithium Options

- Year-1 Startup Options for Lithium Coating Lower and Upper Divertors

  1. Coat Lower Divertor using:
     2 Upper 2011-LITERs (this provides 2 spares)
  2. Coat Lower Divertor and Upper Divertor using:
     2 Upper 2011-LITERs for Lower Divertor
     and 2 Lower 2011-LITERs for Upper Divertor (provides no spares)
  3. Coat Upper Divertor using new technologies:
     2 Upper 2011-LITERs for Lower Divertor
     and new technologies for Upper Divertor
     a. LITER-Fast (200mg flash evap, w/fast cool-down, midplane & rotatable for aiming –H. Schneider) or
        LITER-Morning (5-30g each morning – e.g., EAST)
     b. Electrostatic Injection (UIUC)

- NSTX-U research progress beyond present lithium coatings and passive liquid lithium surfaces requires laboratory R&D on
  - maintaining a chemically-active, moving, liquid lithium divertor surface
  - demonstrating capability to be solidified and re-liquefied for recirculation many times
  - developing diagnostic capability to measure surface quality and flow between discharges

Backup

Laboratory Experiments 2012-2014 Will Provide Guidance for Design of NSTX-U Flowing Liquid Divertor

- Analysis of 5 proposed flowing liquid concepts indicates common questions that impact the selection, fabrication, installation, and operation of a reliable flowing liquid divertor system for NSTX-U.

- How does D retention in CPS mesh behave in presence of high power densities?

- How does the selected liquid lithium substrate wet, accumulate impurities, effect D retention versus vacuum impurities, discharge impurities, and operating temperature.

- Will continuous impurity buildup impede restart after cooling? What is the required maximum system temperature for restart? Is it is best to drain system before cooling?

- What is the range of Li flow rates as determined by D retention, impurity accumulation, and long term reliability.

- What is the optimum heating fluid and technique for the NSTX-U environment?

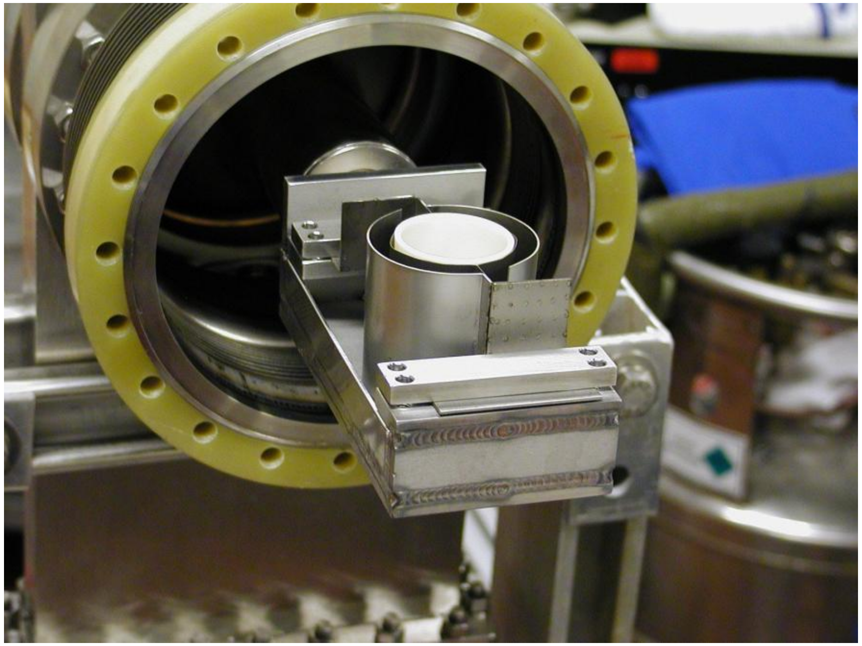
- How to provide diagnostics for real-time Li surface quality indication, internal Li flow measuring, external flow metering, ….

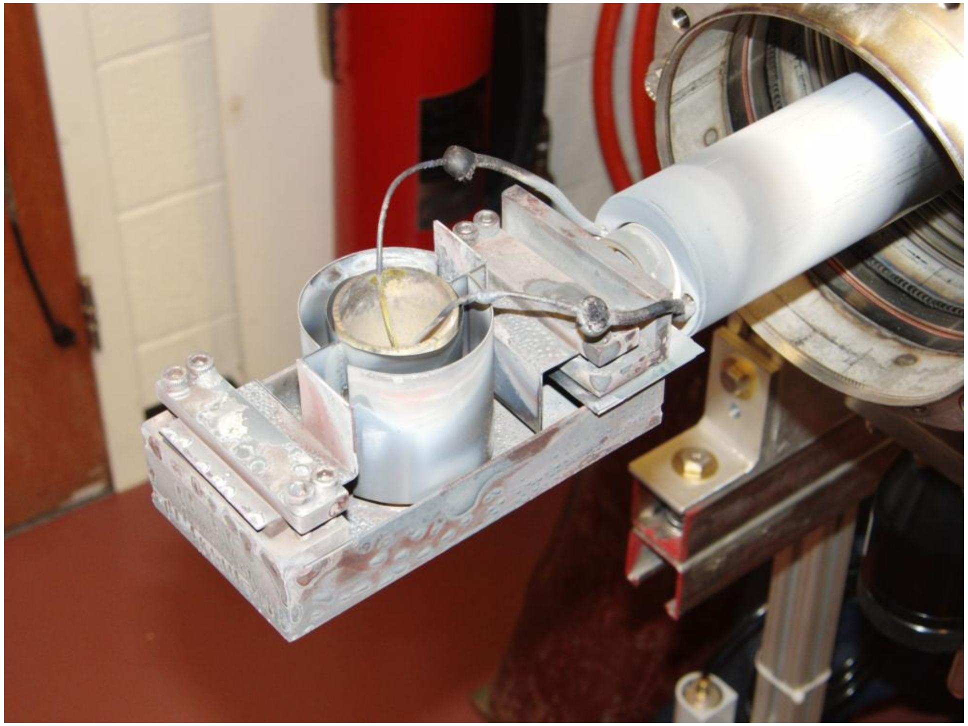
Pathway for Development of a Clean, Continuously Moving, Liquid Lithium Divertor Surface for NSTX-U

- The R&D pathway to develop this capability could proceed as follows:
  1. Test simple-as-possible Single-Pass and Cyclical Flow concepts
  2. Characterize simple-as-possible operation in tokamak-like vacuum
  3. Characterize behavior in vacuum of candidate NSTX PFC prototypes
  4. Move portable candidate PFC to high power density source & characterize
  5. Characterize PFC in applied magnetic fields with high power densities

- The Proposed R&D
  - The goal would be to assemble a simple facility to accomplish R&D Steps 1, 2, and 3
  - The developed system should be portable enough to enable the performance of Steps 4 and 5 on a suitable Test Stand

LTX – style lithium evaporators for NSTX



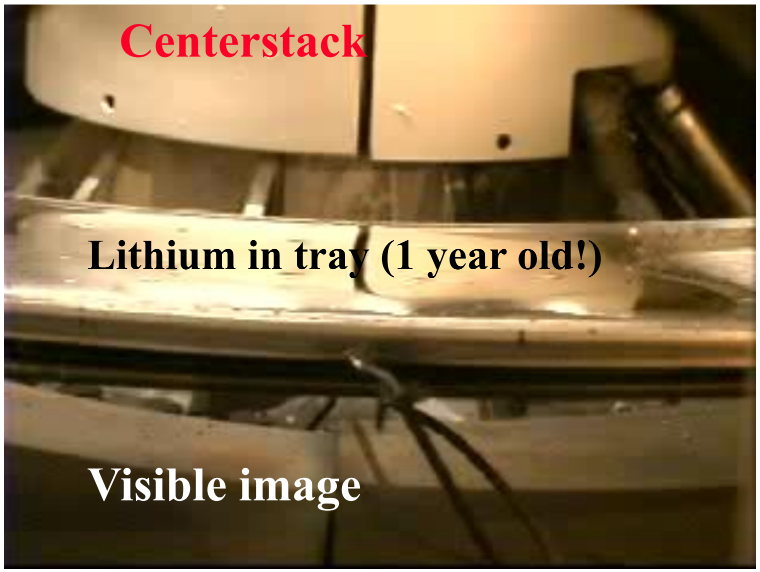


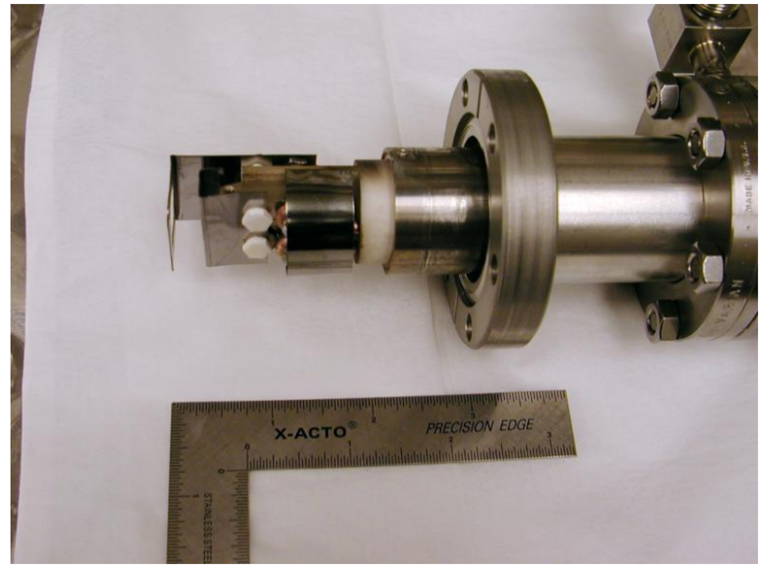
Y_2O_3 crucible, Ta heater

- Two evaporators with motion stages installed on LTX
- Capacity 8-10 of lithium
- Low mass crucible + heater for fast cooldown
  - Could add radiating fins for quicker cooldown
- Crucible can be prefilled & popped in very quickly

Stirred liquid lithium divertor target

- Only system to successfully produce visibly clean, liquid lithium PFC
  - 300g of lithium lasted for a year, was still going strong
- CDX used (LTX will use) a modest-power magnetically steered ebeam to stir the lithium; other approaches possible

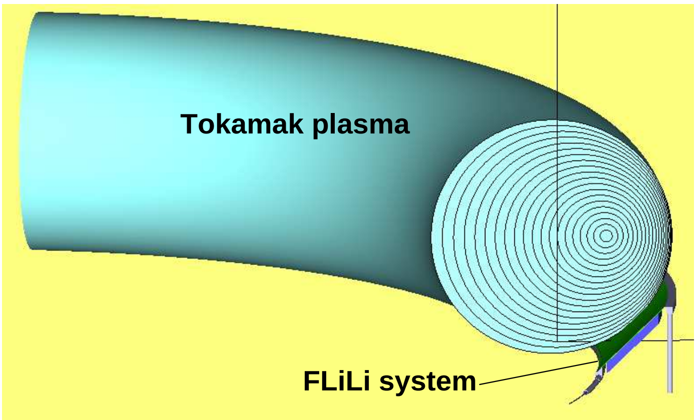




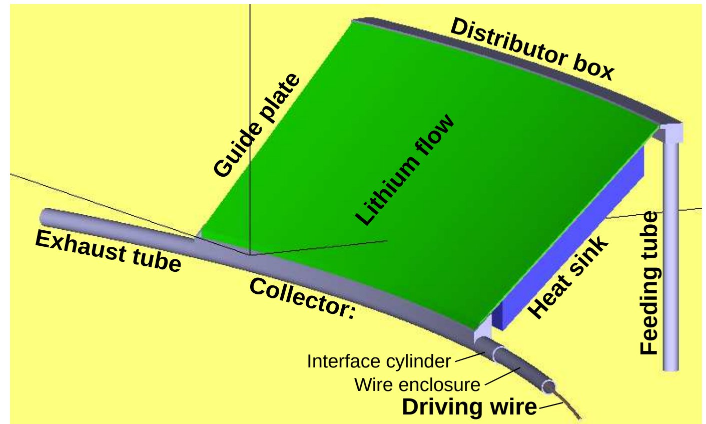
- Lithium surface did not distort during flow (no surface ripples)
- LTX will further explore this concept with a fill of the lower shell
- Convective effects in liquid lithium can be estimated with 2-3 kG fields in LTX
  - Simple conduction not sufficient to keep lithium from overheating
- Radial motion of the lithium allowable in LTX (bathtub approach)
  - Discharge-induced toroidal motion never observed
- LTX uses a lithium-wet molybdenum limiter system to protect the shell lips

Flowing Liquid Lithium (FLILI) System

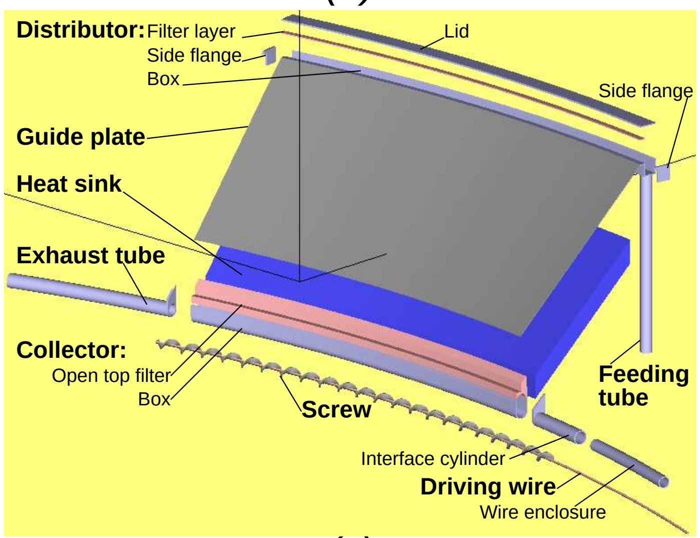
Leonid E. Zakharov, Charles Gentile, Richard Majeski, Henry Kugel, Dennis Mansfield



(a)



(b)



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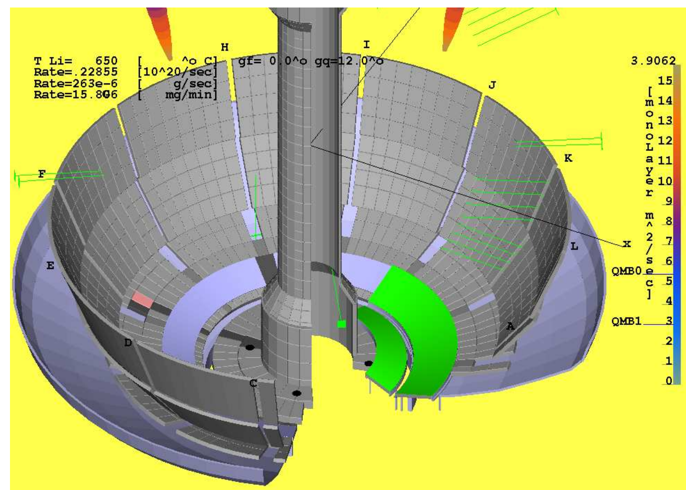


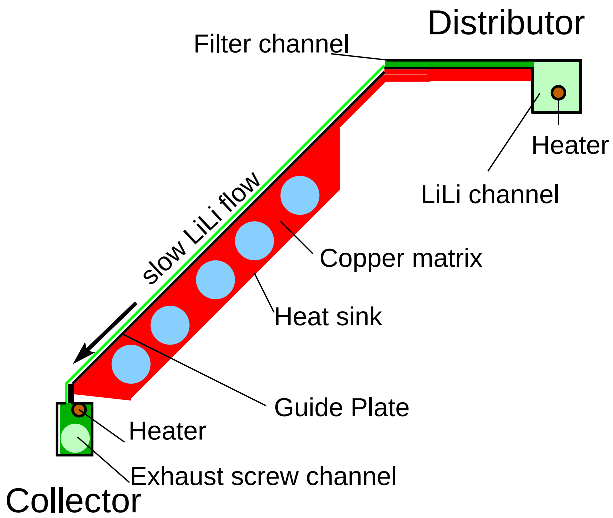
(d)

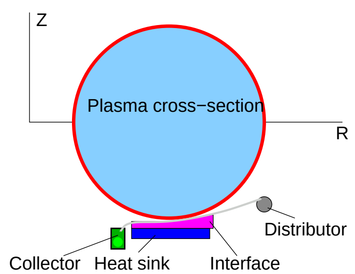
Conceptual design of the FLiLi system. (a) Example of FLiLi system as a limiter for a tokamak with a circular cross section (e.g., HT-7). (b) Assembly of distributor, feeding pipe, guide plate with LiLi flow (green), heat sink, collector and exhaust mechanism. (c) Separate parts of FLiLi system. (d) Two FLiLi systems for NSTX-U

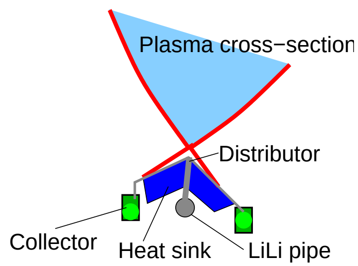
Flow parameters and key properties

$$V_{cm/s} = 0.2 - 1, \quad Q_{cm^3/s} = 1 - 2, \quad H^{filt}_{mm} = 1, \quad L^{filt}_{cm} = 2 - 10$$

$$\Delta p^{filt}_{Pa} = 1.6 \cdot 10^2 V^{filt}_{cm/s} L_{cm} B_T^2, \quad \Delta p^{dist}_{Pa} = 1.6 \cdot 10^2 V^{dist}_{cm/s} L_{cm} \frac{d}{w} B_\perp^2$$







Design requirement $\Delta p^{filt}_{Pa} > \Delta p^{dist}_{Pa}$

Good properties are countless:

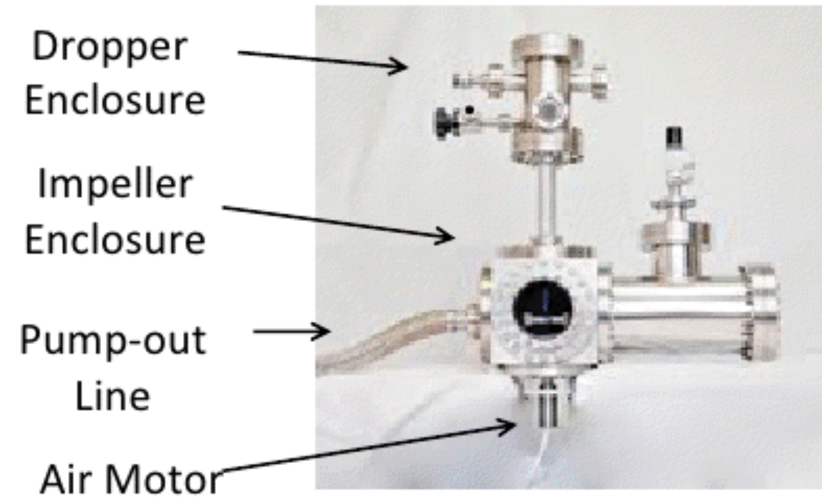
1. *FLiLi solves the problem of the Li surface contamination: open loop during machine operation, close loop overnight*
2. *Flow rate is under external control by pressure in the feeding pipes.*
3. *The system is scalable in both poloidal and toroidal direction, and from a laboratory test chamber to a real tokamak device.*
4. *Minimal in-vessel inventory of LiLi. LiLi is supplied from outside and is exhausted to outside the VV.*
5. *The bulk of LiLi is protected from plasma disruptions by the filter layer.*
6. *No side walls for LiLi flow, no leading edges.*
7. *Simple for maintenance, at the end of the campaign can be flushed out by argon and then by vinegar.*
8. *Is insensitive to yet unknown* $\mathbf{j} \times \mathbf{B}$ *forces.*
9. *Filter channel geometry and orientation is flexible.*

FLiLi is compatible with any tokamak, including NSTX-U. The plasma regime, it can provide, is beyond the dreams.

FLiLi is simply amazing.

Real-time resupply of Li into NSTX

•Long-pulse discharges require method to resupply the Li during a discharge.
•The Li dropper has released up to 120 mg/sec of Li powder per injector into NSTX
•We have tested 0.6 mm diameter pellets using the new Li injector and have injected up to 100mg/sec in the lab.
•Pellet size (up to 1mm diameter) and velocity (up to 100 m/s) can be varied to optimize injection parameters.
•Injector may be capable of inducing ELMs, reducing the heat flux in the divertor, controlling MHD.
•All dropper control hardware/software exists. Minimum effort required to control air pressure to injector motor.



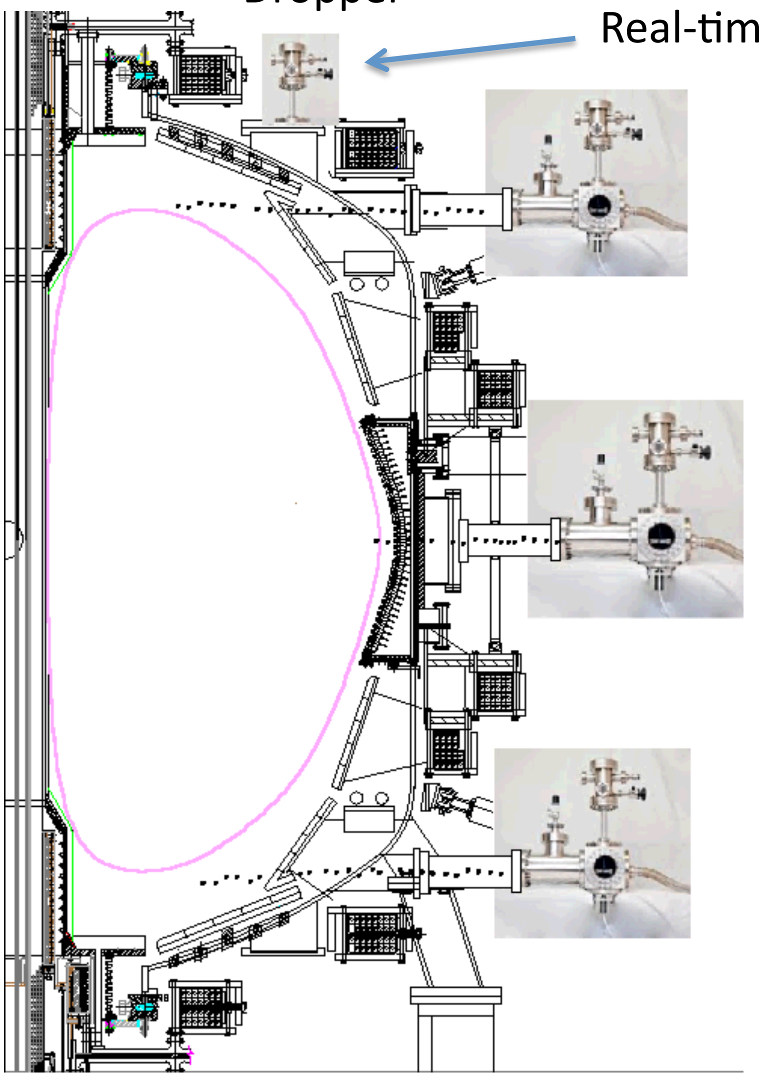
Injectors are presently being sent to RFX, EAST, DIII-D???.

NSTX should have 1or 2.

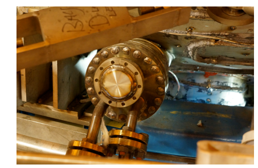
Li Injector locations on NSTX

Dropper

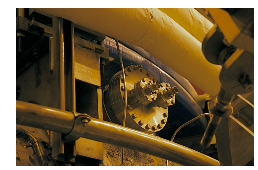
Real-time resupply of Li



Real-time resupply of Li
in the upper divertor



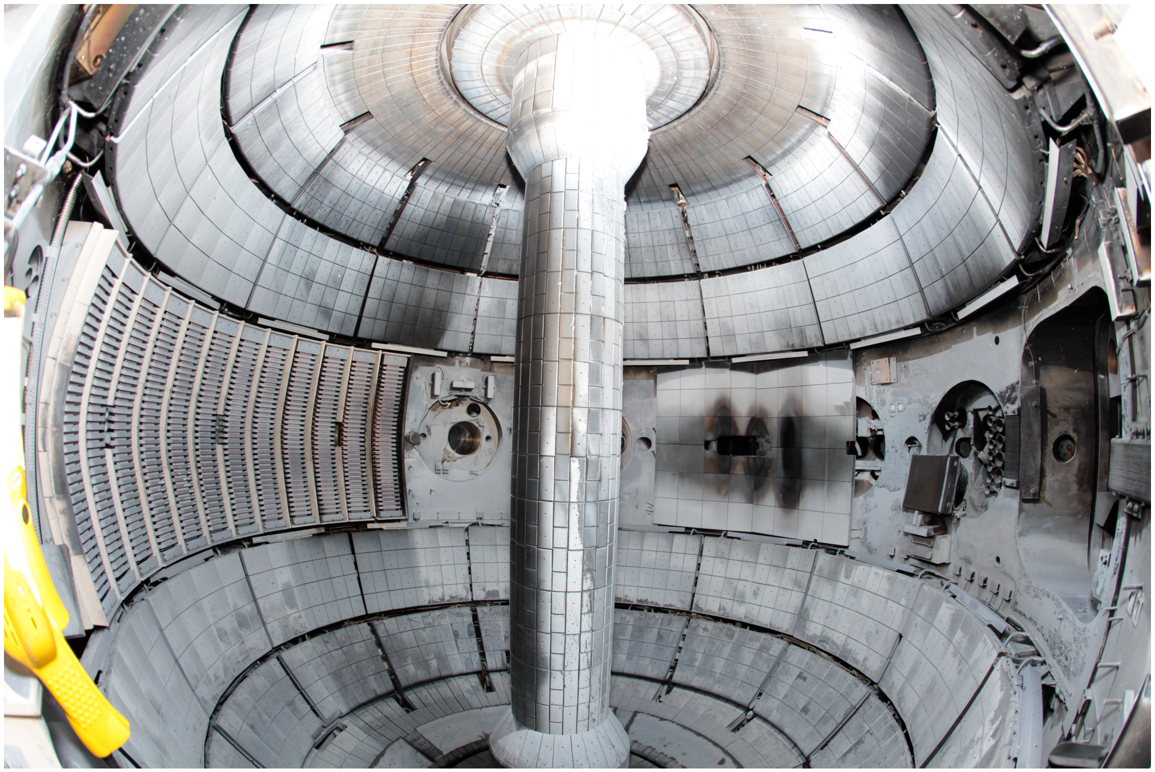
Induce ELMs/Resupply of Li



Real-time resupply of Li
In the lower divertor

Provide divertor
views at B/F top

Masking LITERs to control Li deposition



•Li is deposited in ~ 180 spread

•Midplane region with diagnostic windows/ RF antenna is thickly coated

•Masking LITER output would concentrate deposition in lower/ upper divertor region.

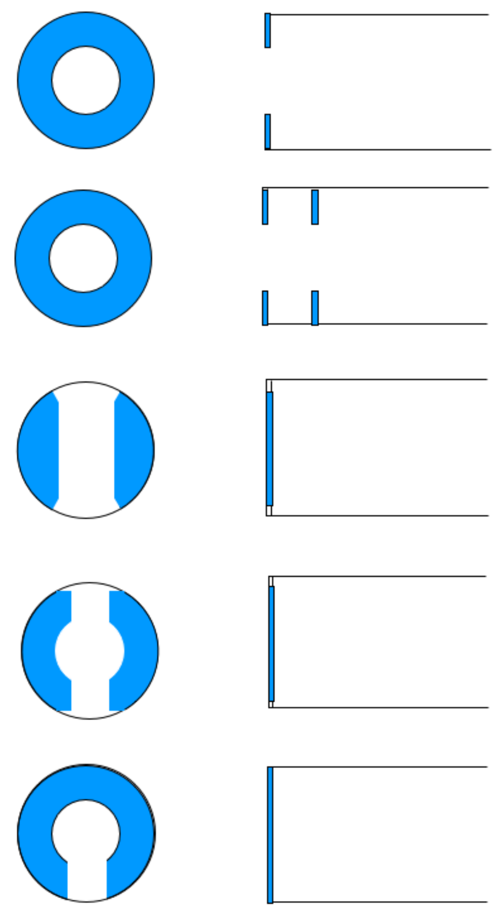
Masking LITERs to control Li deposition

- Present LITERs deposit Li in a ~180 arc

•Applying Li only on the divertor region to separate the effects of Li in the divertor as compared to the passive plates leading to better understanding of the role of Li.

•Global spewing of Li affects diagnostic windows, causes shorts across insulators, and places an overly-thick coating on the RF antennas which limits the peak injected power.

•By "surgically" applying Li only where it is needed, the number of costly refills will be reduced and post-run cleanup will be easier and health risks will be reduced.



Possible mask concepts

Dual-band IR thermography for NSTX-U

(J-W. Ahn, R. Maingi, T.K. Gray)

- NSTX-U will operate in very high heat flux environment ($I_p \leq$ 2MA and $P_{NBI} \leq$ 12MW) virtually everywhere, with lithium

- Lithium poses emissivity problem for T_{surf} measurement
  - Needs dual band IR measurement

- Asymmetric heat deposition often occurs (ELM, 3-D fields application, disruption, etc, possibly in snowflake configuration too?). Increasing evidence that the asymmetric heat deposition is more common in other conventionally normal situations caused by error fields, MHD modes, etc
  - Need to cover as much PFC area as possible

- Transient heat deposition has to be properly measured
  - Fast framing rate (≥ kHz) is necessary

- Two wide angle fast IR cameras for lower div. with dual-band adaptor each
- Fast IR camera for upper div. with dual-band adaptor
- Center stack and RF antenna coverage with dual-band adaptor

- Synergy in combination with other proposed div. heat flux diagnostics (Fast TC, real time surface emissivity measurement, etc)

NSTX-U Oak Ridge National Laboratory Supported by U.S. DEPARTMENT OF ENERGY Office of Science

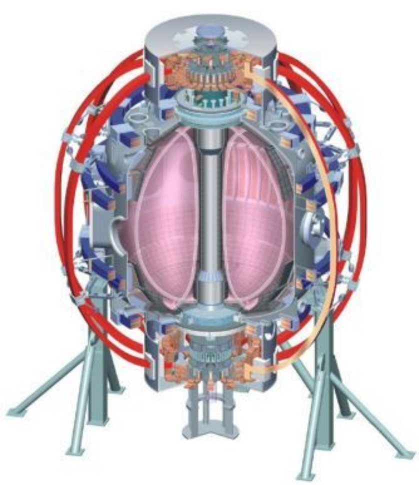
Pellet injector for ELM pacing and core fueling

Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
ORNL
PPPL
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Washington
U Wisconsin

T.K. Gray, L.R. Baylor, S.K. Combs, R. Maingi, and D.A. Rasmussen
Oak Ridge National Laboratory

NSTX-U Facility Enhancement Brainstorming Meeting

Feb 7-8, 2012



Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
NFRI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

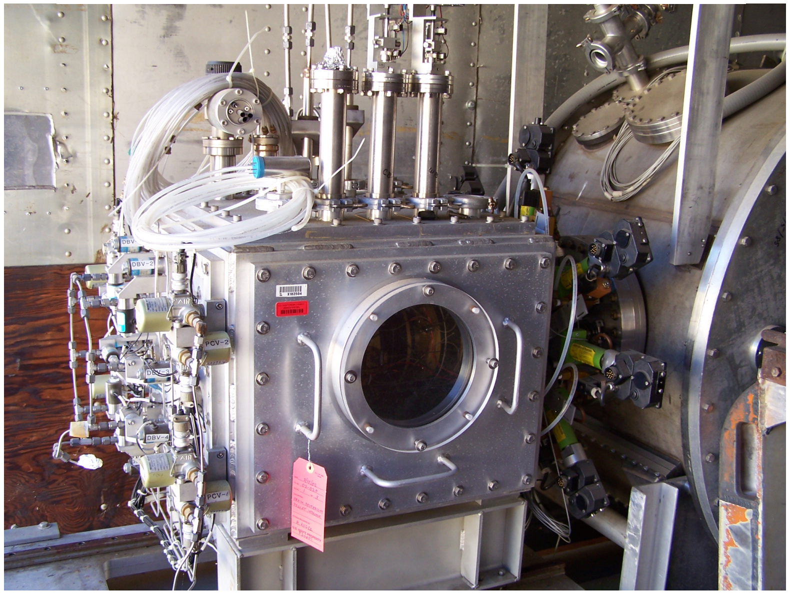
Increased Core Fueling Moves NSTX-U away from High Edge Fueling Scenarios when Lithium is used

- PBX pellet injector can be resurrected for low-cost
  - Simple gas gun design
  - 8 - barrels, 1.0 - 2.7 mm diameter
  - 5×10^{19} – 9×10^{20} atoms
  - 200-1500 m/s pellet speed
  - Can upgrade to an internal cryo-cooler for simple operation

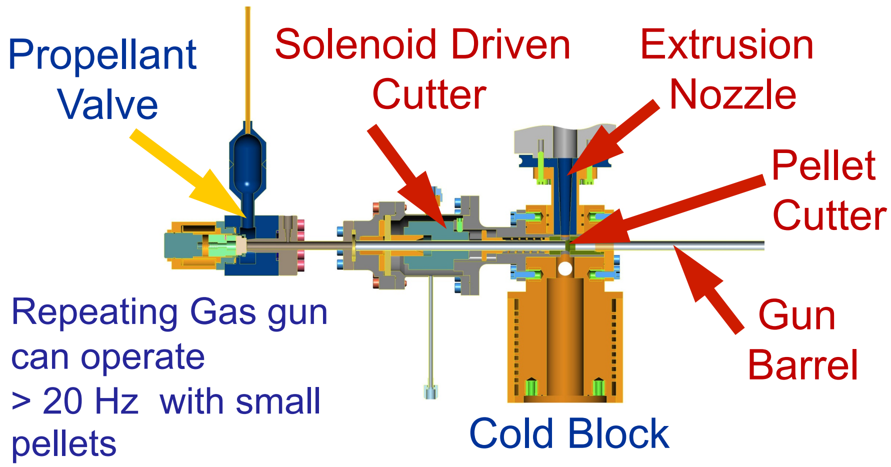
- Optimized new fueling system for NSTX is one that provides:
  - Central fueling
  - Minimized recycling – HFS vertical injection
  - Repetitive - 10 Hz with ~10% perturbations
  - Reliable operation

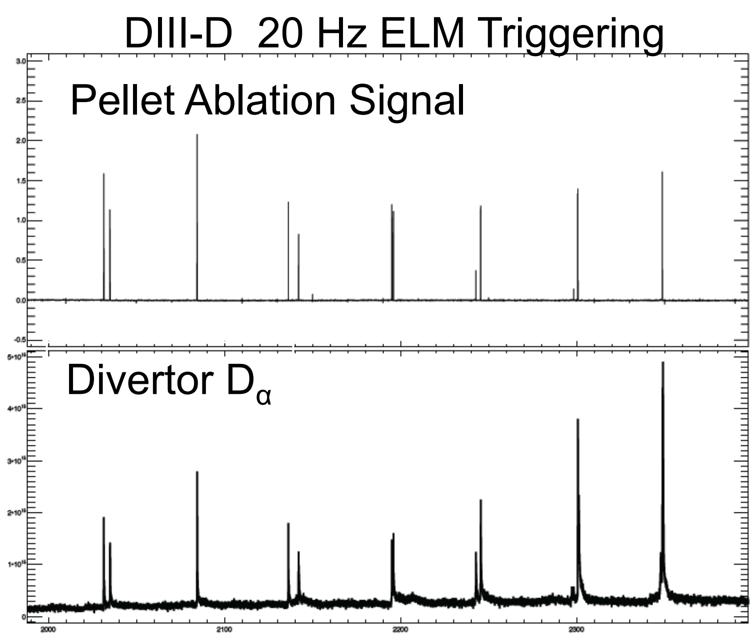
PBX Pellet Injector

(currently on site @ PPPL)



Demonstration of Impurity Control in NSTX-U is a Top Priority – Pellet ELM Pacing a Possible Technique





- ELM pacing is also a top ITER priority
- Best results on NSTX so far have come with lithium + triggered ELMs
- Pellet pacing on DIII-D has been shown to trigger rapid small ELMs
  - Pellets 1.3mm injected on LFS midplane and near divertor
  - **Impurity accumulation strongly reduced**
- High rep rate, small pellets are needed to trigger small ELMs
  - Not perturb the core density
  - Create smaller ELMs than natural ELMs or triggered ELMs
  - Flush impurities to the divertor

Fast liquid Lithium “shower” injector

G. A. Wurden
Los Alamos

NSTX Brainstorming Meeting
Feb 7-8, 2012

Purpose: to mitigate disruptions

How can ~100 grams of material be injected quickly into a tokamak to both prevent runaway electron formation & radiate away the thermal quench energy?

- Has to be fast… < 5 milliseconds from trigger to delivery across the central axis
- Has to be reusable, and easy to reload
- Has to be armed and ready to fire any time
- Should minimize side effects….such as holes in armor on opposite wall, or unwanted propellant gas load, or residual contamination

Issues

- Gas guns are borderline too slow, especially for high Z delivery. Conductance limitations are problematic if valves are far away.
- A 100-gram bullet is out of the question (at 1 km/sec, it carries 50 kJ of energy).
- An equivalent of a shotgun blast (thousands of small pieces) might do the trick.
- But gas loads, and acceleration times have to be minimized, as well as any sabot debris.

Consider an electromagnetic "flyer plate" launcher

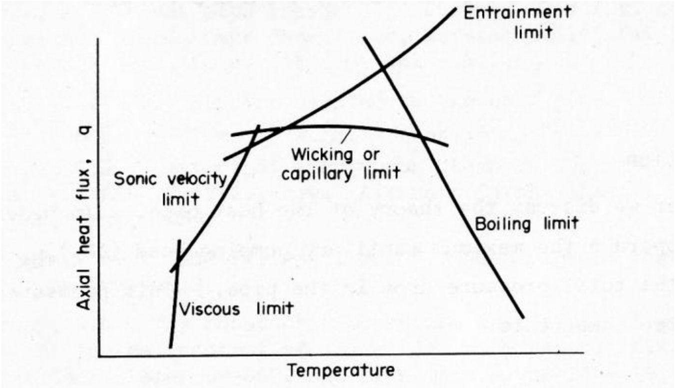
- A sufficiently strong, rapidly pulsed magnetic field under a conducting plate, will cause it to fly away.
- Speeds of 1 km/sec are readily achievable.
- Consider a dish with a thin layer of molten lithium (0.5 g/cc, implies ~10-15 cm diameter)
- A liquid conductor pancake will break-up in flight, into many small droplets.
- The tray can be reloaded from below with a fill tube, with more liquid, for the next shot.
- The injector should be located somewhere in the bottom of the vessel armor or divertor, to have gravity help keep the liquid in the tray, while it waits for a launch command.

A launcher prototype system needs some design work.

- How fast do the fields have to rise? How much current is needed in the coil launcher? Launcher needs to be at ~ 200 degrees Centigrade, for liquid lithium. Would solid lithium break up as well?
- How efficient is the injector? 50 kJ in the overall payload may mean a large amount of stored energy in the launcher.
- Lithium obviously has conditioning effects. What about hydrogen pumping while you wait? What about hydrogen (tritium) trapping later? What about lithium buildup? What about lithium dust?
- How do the injected droplets interact with the main or post-disruption plasma?
- How fast does the toroidal current decay as a result of this injection? Too fast is also not good, as resulting electromagnetic disruption forces may be too large for ITER to handle.
- Can we design and build a prototype system on NSTX, given that NSTX already uses lithium, and it may have secondary uses as a lithiumization tool?

PPPL Proposed to Develop Actively Cooled and Wetted Li Capillary Porous System for Divertor Targets

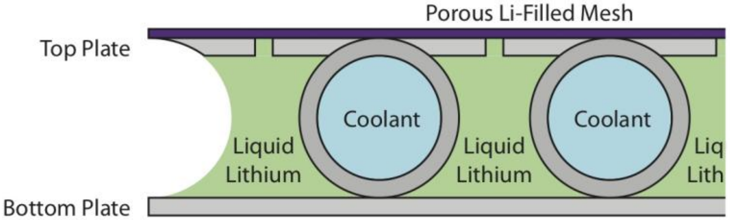
- **Three major areas of materials science research are necessary to design, construct and operate confidently liquid metal CPS PFCs on high-power, potentially long-pulse or steady state, front-line tokamak experiments:**
  - **Active wetting**
    Validate large-area active wetting strategies.
  - **Contamination and decontamination**
    Demonstrate ability to produce and recover clean large-area capillary wetted surfaces.
  - **High-power plasma-material interactions**
    Determine distribution between radiated power, evaporative cooling and power delivered to CPS surface, in high power plasma



- **Facilities were identified to perform these studies**
  - **High vacuum chamber now in C-128** to be upgraded to allow studies of wetting "sorptivity": $v_w = S^2/(2x_w)$, test decontamination strategies in NSTX-like vacuum.
  - **Bruce Koel's lab** to measure surface and bulk contamination.
  - **Collaboration with Magnum-PSI** for high-power plasma testing.
- **Proposed schedule is October 2012 – October 2015**

NSTX-U Should Test Large-Area CPS Divertor in 2016

- **Pre-tokamak R&D essential to accelerate & reduce risk of advanced PFCs**
- **If DOE Proposal is funded, NSTX-U should begin design of large-area CPS divertor to be installed in 2016.**
  - Information on wetting and contamination /decontamination of lithium CPS is scheduled to be available by January 2014.
  - Could begin design to be confirmed by Magnum-PSI in 2014 (wetting) and 2015 (wetting + cooling).



- **If DOE Proposal is not funded…**
  - Could do wetting and contamination/decontamination studies with PPPL facilities, collaboration with Koel nominally "cost-free".
  - Magnum-PSI has separate funding, so perhaps some activity could proceed with NSTX support for PPPL activities.
- **Replaceable Divertor Module would provide valuable tests in either case.**
  - If no DOE funding, and no Magnum-PSI, RDM could play the role of Magnum PSI in 2014 – 2015, before we install large-area divertor in 2016.
  - If DOE funding, RDM would provide valuable additional tests in 2014 – 2015, before installing large-area divertor in 2016.

Proposals for
Monitoring and Actively Driving SOLC on NSTX-U for Machine Protection and Performance Extension

1. Monitor SOLC for machine protection

2. Compensate for SOLC-generated error field in machine control and equilibrium reconstruction

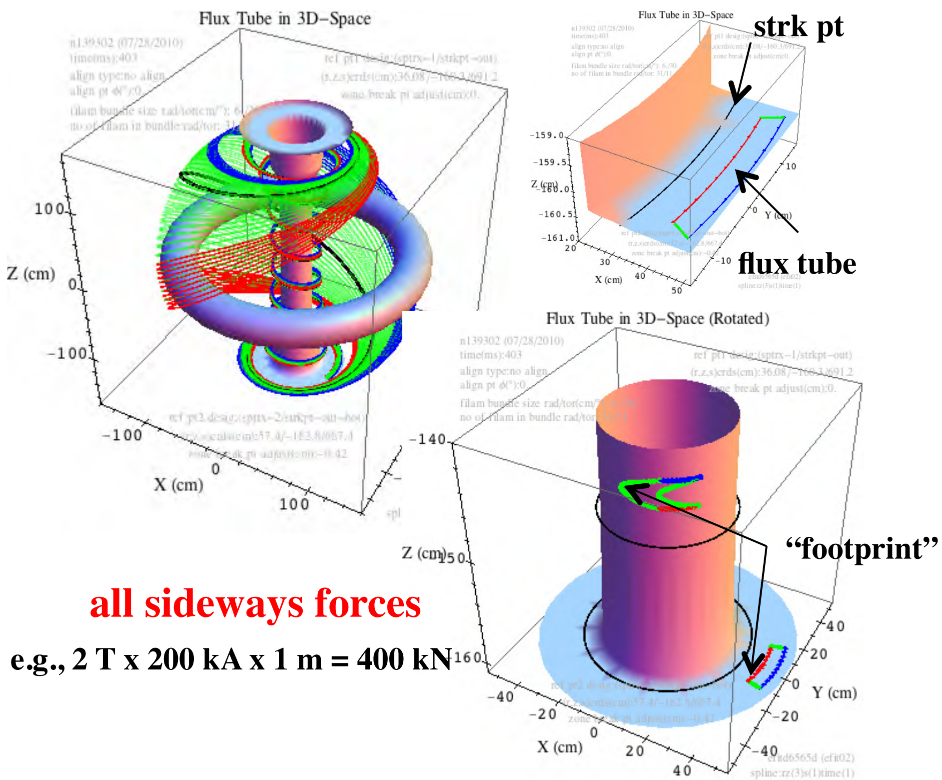
3. Drive SOLC externally for machine performance extension

Hiro Takahashi
Princeton Fusion Research LLC
Presented at
NSTX-U Facility Enhancement Brainstorming
February 7-8, 2012

Field-line Structure Affects Sideways Forces on Center Stack

low-shear

retains asymmetry

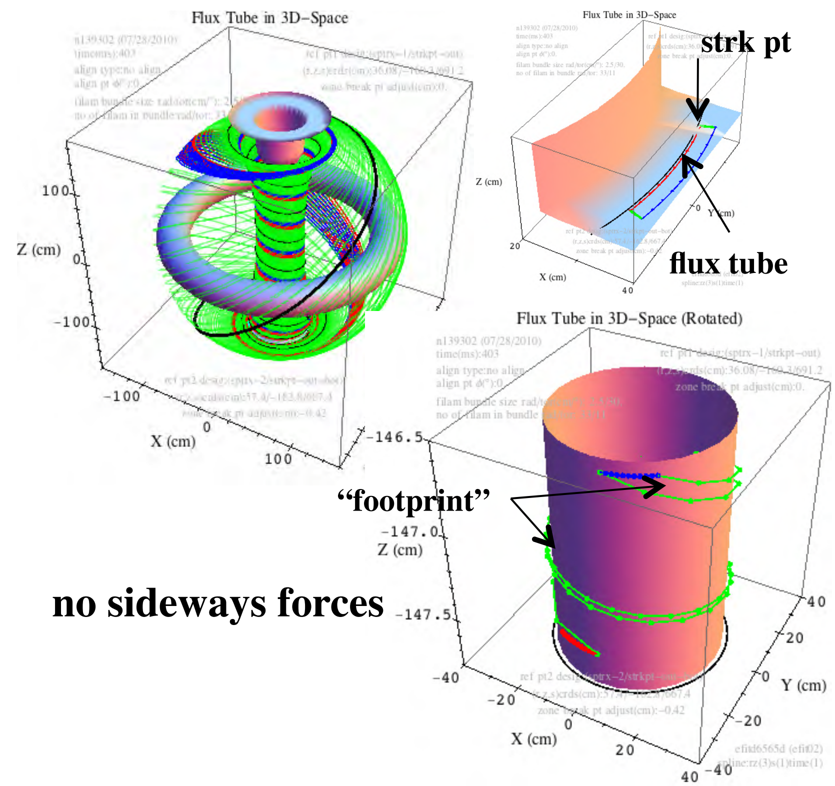


all sideways forces

e.g., 2 T x 200 kA x 1 m = 400 kN

high-shear

destroys asymmetry



no sideways forces

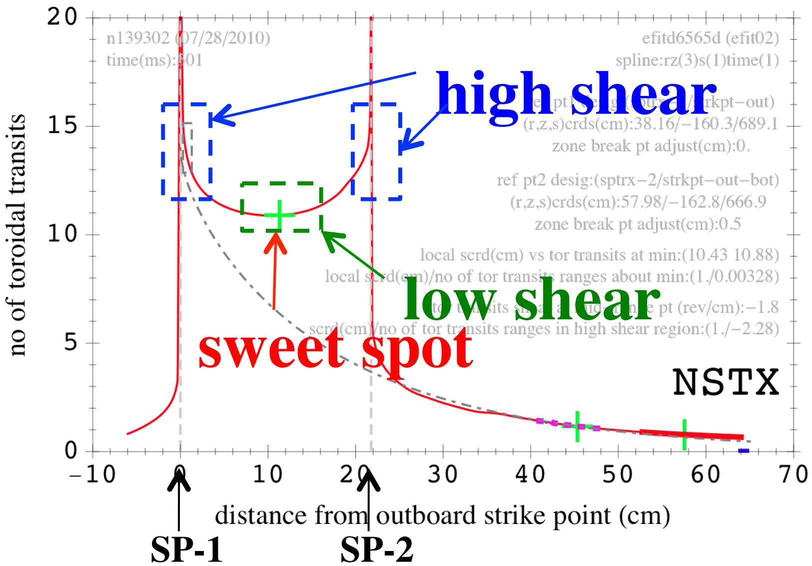
Narrow (~ 30 deg) rotating peaks have been observed; stationary narrow peaks could elude detection by a sparse sensor array.

Important to monitor where SOLC flows.

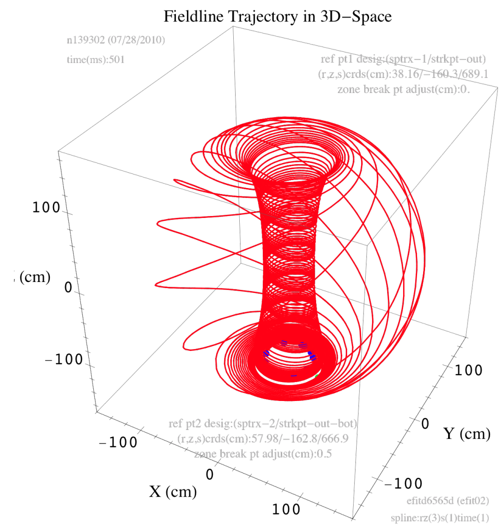
PPPL PRINCETON PLASMA PHYSICS LABORATORY

Drive SOLC for Performance Extension

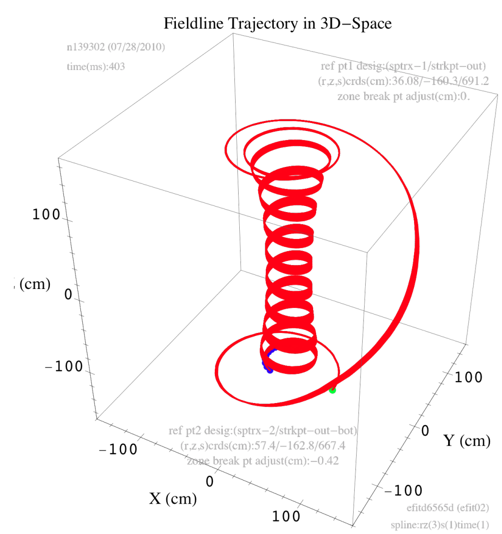
Toroidal Transits Executed by a Field Line



Wide Band



Narrow Band



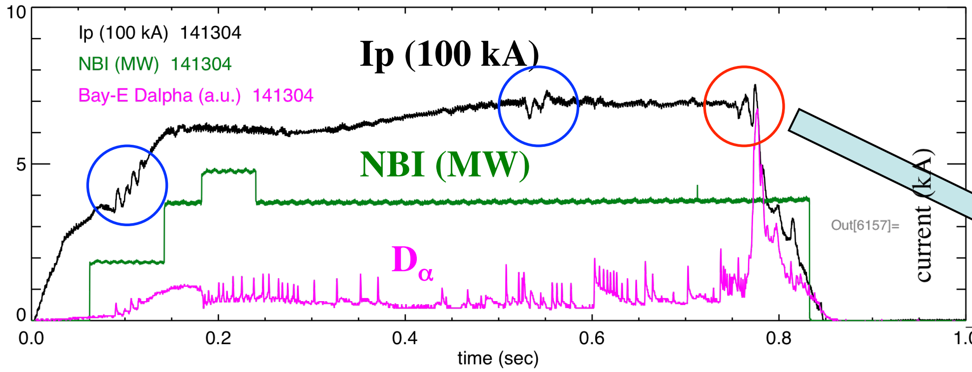
- **Create stochastic field via 3D field caused by narrow-band SOLC driven at sweet spot for:**
  - **On-demand ELM Trigger to expel impurity from long steady-state (density) discharges.**
  - **Possible extension to runaway mitigation method.**
- **Improve vertical stability (n-index) at high aspect ratio via 2D field generated by SOLC driven in high-shear regions.**

From APS '11

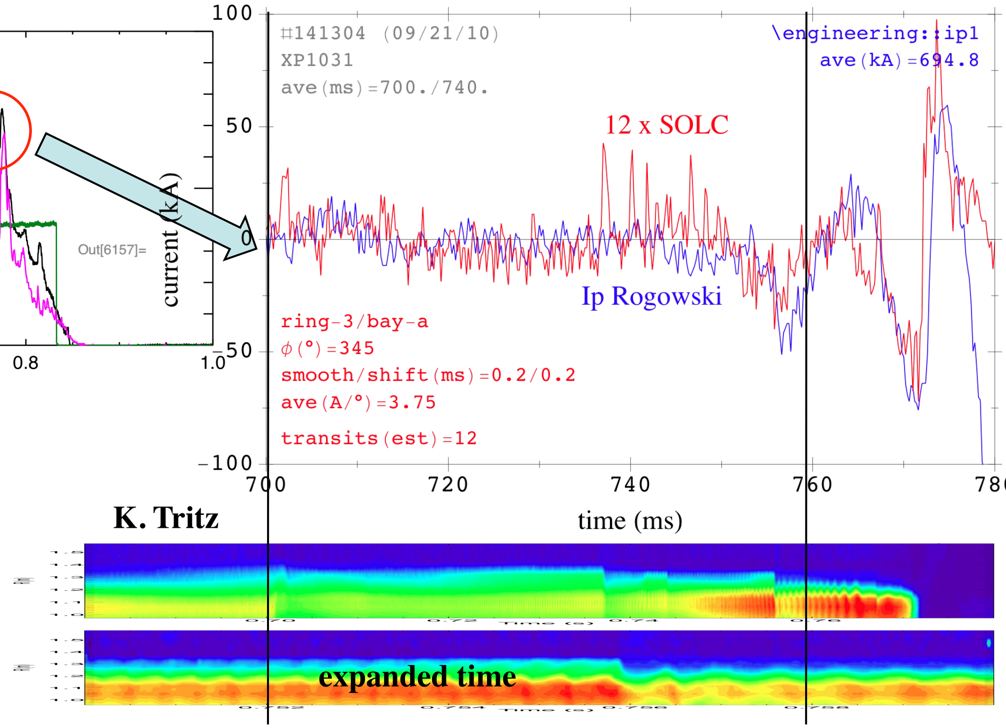
PPPL PRINCETON PLASMA PHYSICS LABORATORY

Compensating Magnetics for SOLC May Help Performance

Discharge Overview



Toroidal Current (Deviation from Mean) vs Time



A commonly observed I_p *signal* behavior just before disruption may be traced to SOLC, not to *true* plasma current.

SOLC may account for up to ~ 10 % of I_p *signal* in this discharge.

Did this discharge die an unnecessary death because feedback control tried to save the discharge when it needed no saving???

High-performance (parameter-pushing) discharges may be sensitive to control/ equilibrium errors.

From NSTX Results Review - MHD, '11

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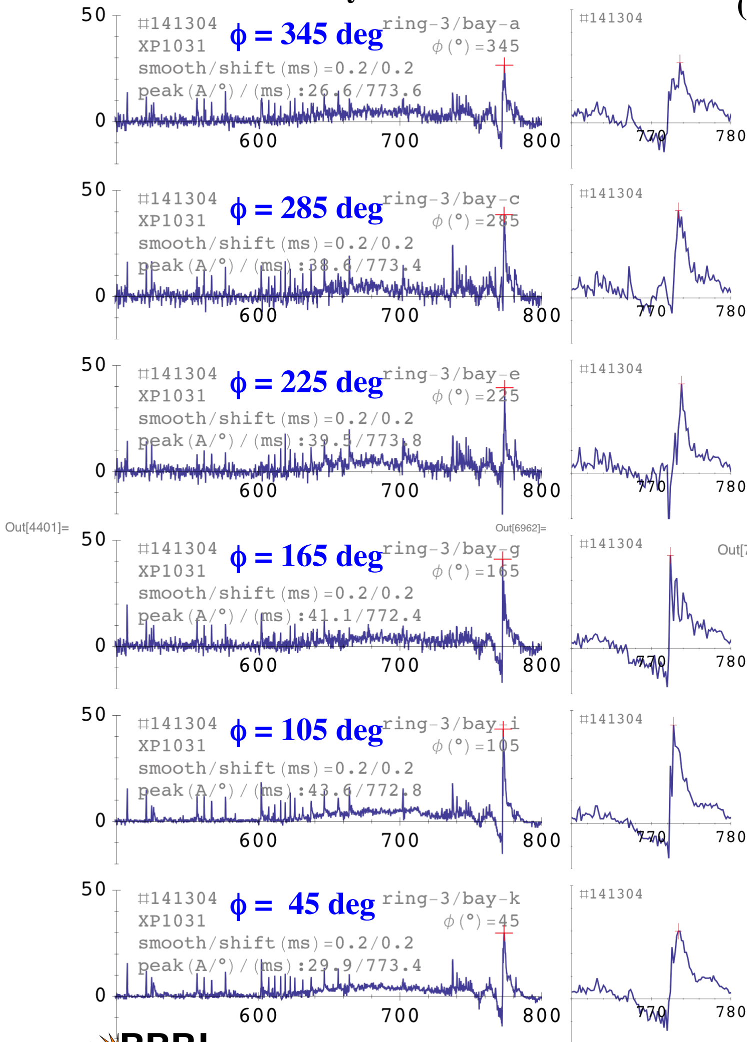
Axisymmetric and/or non-axisymmetric parts of SOLC may affect machine performance:

- **Report false plasma current and position**
- **Sound false alarm for growing MHD modes**
- **Report false MHD mode phase (*positive* feedback)**
- **Change vertical stability (n-index)**
- **Destabilize MHD modes**
- **SOLC field significant fraction of equilibrium field at measurement points (DIII-D)**

Large Current Flows in Near SOLC Zones

Toroidal Spatial Variations

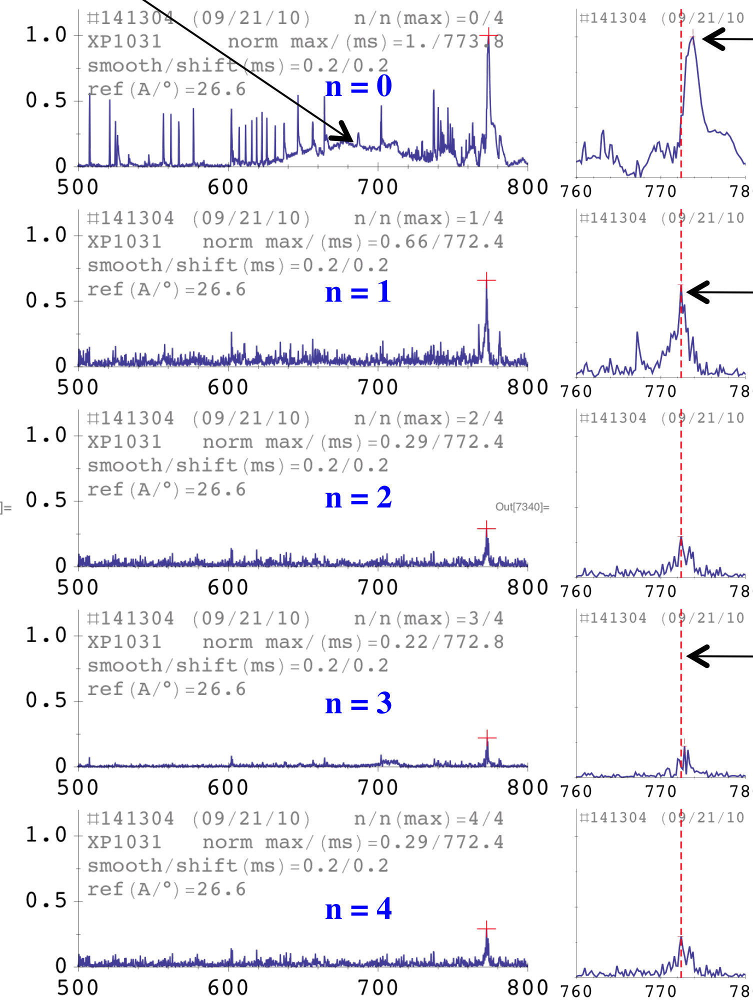
SOLC Density Vs Time **End Period**



n = 0
~ 1.9 kA (pol)
~ 23 kA (tor)
(~ 3 %)

Toroidal Harmonic (SVD) Analysis

SOLC *Normalized* Harm Amp **End Period**



n = 0
~ 10 kA (pol)
~ 120 kA (tor)
(~ 17 %)

n = 1 (RMS)
~ 4.5 kA (pol)
~ 54 kA (tor)
(~ 8 %)
MHD?
thermal instability?

n > 0 leads n = 0
causality?

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Summary

• **Monitor SOLC signals for delineating safe operating space.**

• **Use SOLC for magnetic compensation in machine control and real-time/ off-line equilibrium reconstruction for improved performance:**

  • **Tile-current sensor arrays**
  • **Magnetic sensor arrays**

• **Create stochastic field via 3D field caused by narrow-band SOLC driven at sweet spot for:**

  • **On-demand ELM Trigger to expel impurity from long steady-state (density) discharges.**
  • **Possible extension to a runaway mitigation method.**

• **Improve vertical stability (n-index) at high aspect ratio via 2D field generated by SOLC driven in high-shear regions.**

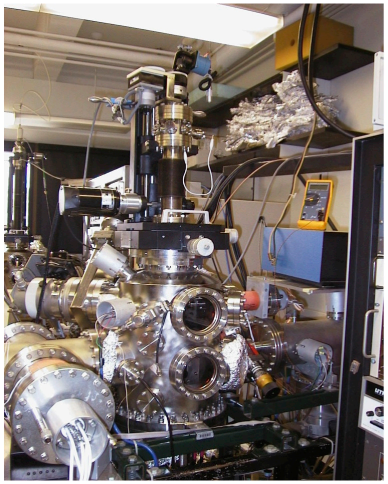
Surface studies to support particle control

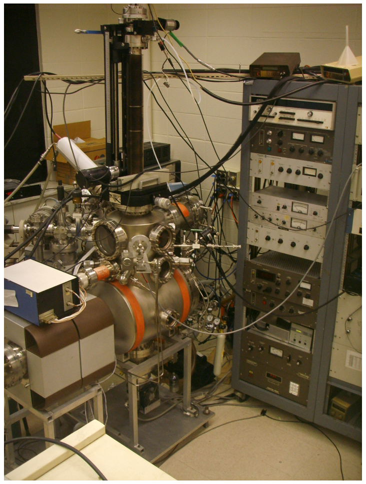
- Lithium conditioning will be important tool for density control for optimizing and controlling high non-inductive current-drive fraction scenarios in NSTX-U.
- Fundamental 'engineering' data for designing effective Li-PFCs is sorely needed:
  - D uptake vs. D fluence (saturation) on solid / liquid Li surfaces.
  - D uptake vs. surface temperature
  - D uptake vs. surface contamination
  - Chemical state of Li on carbon and Mo surfaces vs. all of the above.
- Modest incremental support in recommissioning surface analysis equipment at PPPL and installation of additional components to allow sample transfer and higher D fluxes, would accelerate the above studies
- Facility will also be invaluable for surface analysis of samples from NSTX-U.

Bottom line:

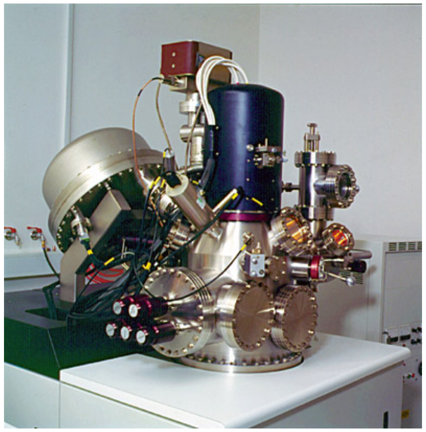
- *Surface data key to achieving NSTX-U mission*
- *It will accelerate innovation and reduce the risk for Li-PFCs in NSTX-U.*
- *Minimizing innovative Li-PFC risk is also critical for NSTX-U's missions in Advanced Scenarios, Boundary Physics, Macroscopic stability, Turbulence, Startup, Waves…*

Surface analysis

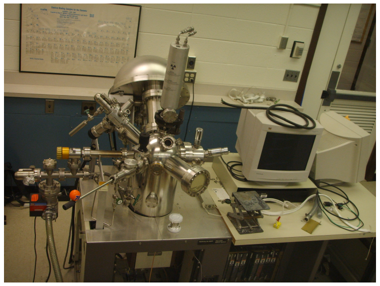




- We have access on-site to custom surface analysis equipment operated by Prof. Bruce Koel that is already contributing relevant information on surface chemistry (LRTSG talk *'Initial results for reactivity of lithium films on a molybdenum substrate'* 26 Jan 2012).



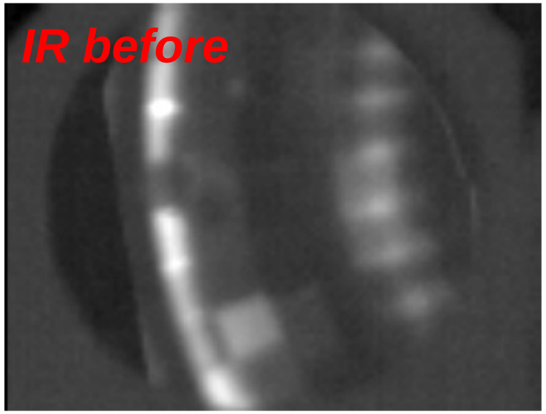
- Information on Li-PFC materials is needed to inform NSTX-U PFC material decisions in late 2011.
- Some PPPL support but progress limited by manpower.
- Technical help in commissioning instruments would help get data in time (contrast JET-ILW data late for ITER PFC decisions).
- Details to be negotiated.

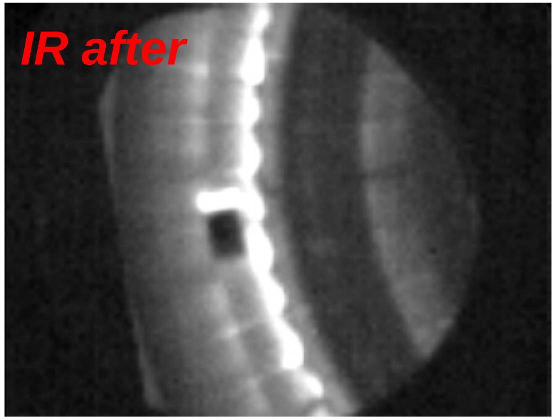


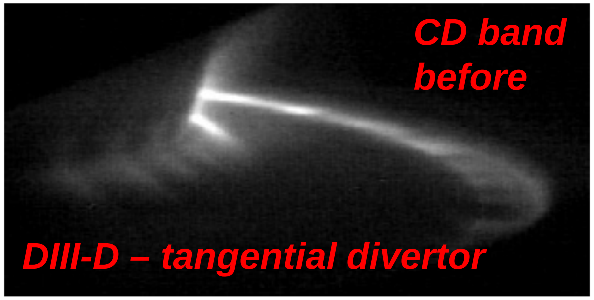
Improving tile alignment in the divertor might help reduce carbon sources

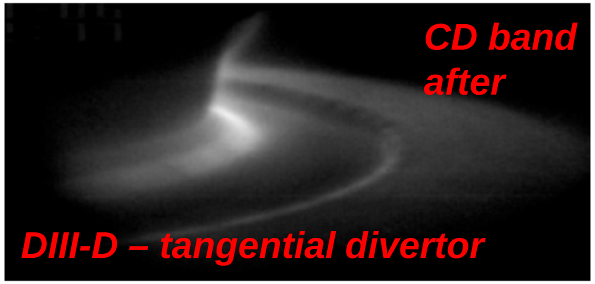
- Reducing carbon accumulation is critical for NSTX ELM-free regimes
- Improving tile height alignment and reducing gaps could help reduce C source (and reduce chance of melting Moly)
- In DIII-D, better tile-to-tile alignment in upper (2000) and lower divertor (2006)
- Tile gap reduced (2.4 $\rightarrow$ 0.4 mm), top surface alignment improved (1.0$\rightarrow$0.1mm)
- More uniform C sources and more even tile heating
- Reduction of core C content observed in DIII-D (not clear if only due to this though)

DIII-D – IR divertor top-down view







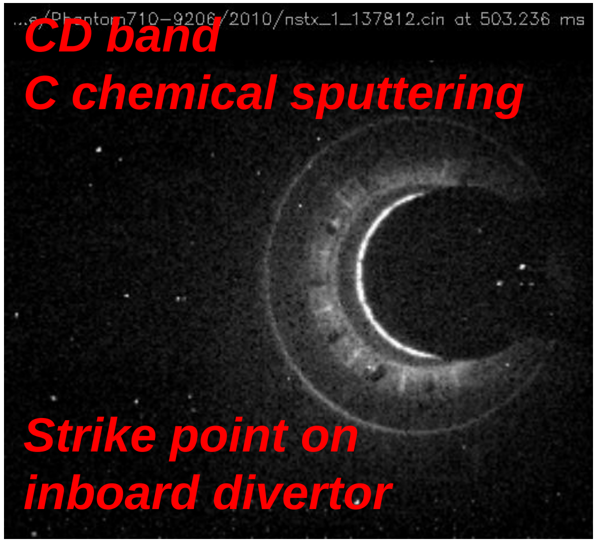


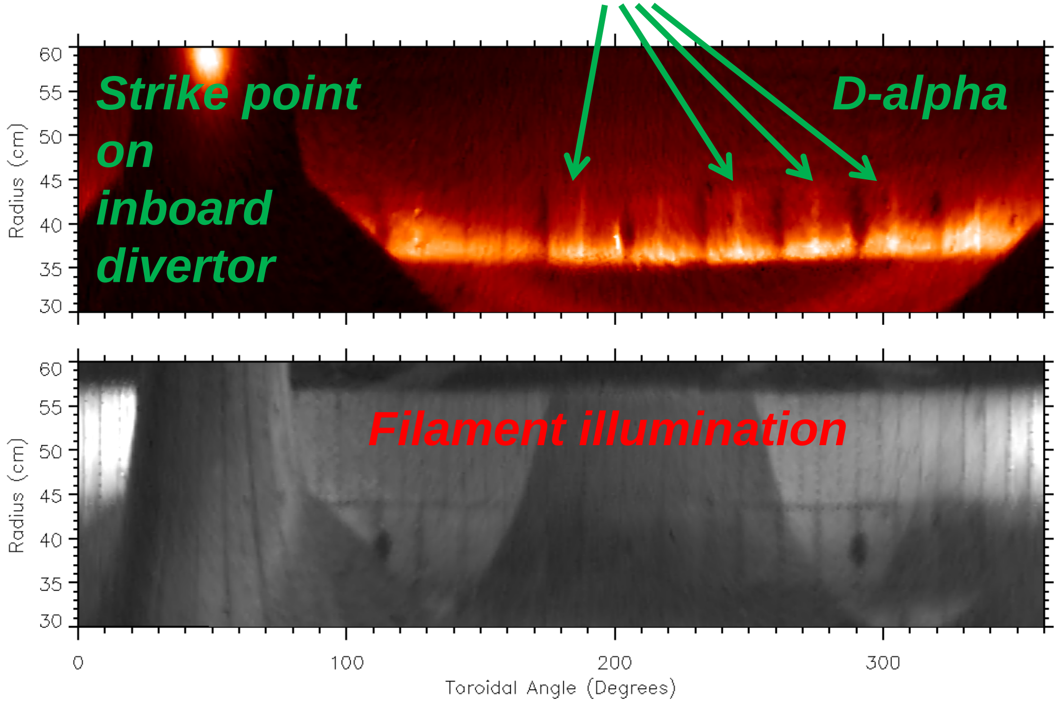
C. J. Murphy, et al. Fusion Science and Technology 52 (539), 2007.
M. A. Mahdavi et al, Journal Nucl. Mater. 290-293(2001) 905-909.

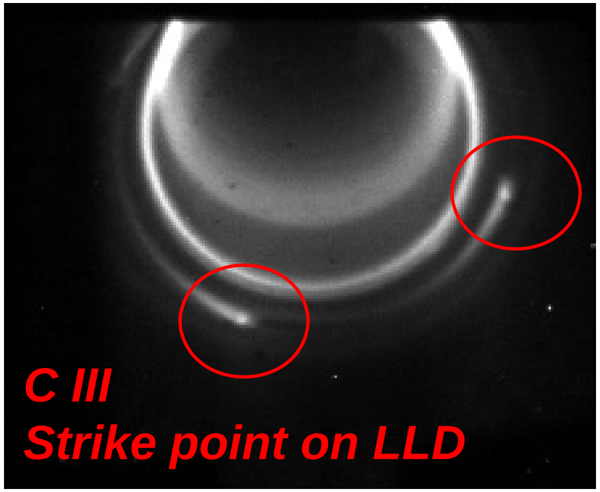
Height non uniformity and leading edges seen in the lower divertor graphite tiles

- Height variations and leading edges of graphite tiles are visible on vis. cameras on both inboard and outboard divertor (bull-nose and diagnostic tiles).

- Can result in heating of tile edges and increased C influxes
- Possibly worse in NSTX-U due to higher heat fluxes







NSTX

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Long pulse divertor biasing on NSTX-U

Devon Battaglia

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General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
ORNL
PPPL
Princeton U
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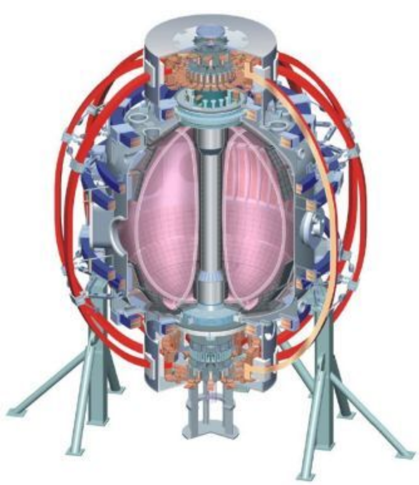
NSTX-U Facility Enhancement Brainstorming
PPPL
February 7 and 8, 2012



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NFRI
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ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

NSTX-U has unique opportunity to test long pulse divertor biasing as a tool for addressing ST physics/concerns

- Hard part is done: inner/outer VV is electrically isolated
  - Need new or repurposed long pulse power supply
  - 100s of volts, 10s of amps, ~0.5s (~ kJ stored energy)
- Follows rich history of experiments on large-A tokamaks
  - Positive effects, but not game changing
  - But ST has unique physics/challenges
- Various biasing schemes possible
  - LSN, low-δ: differential SOL bias
  - LSN, high-δ: unipolar bias of plasma
  - DN, low-δ: differential in-out SOL bias

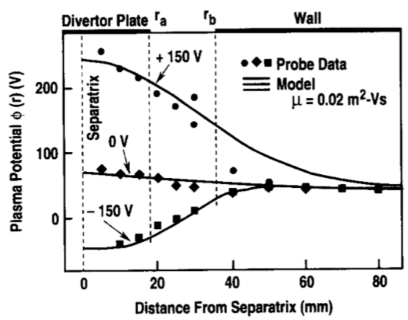
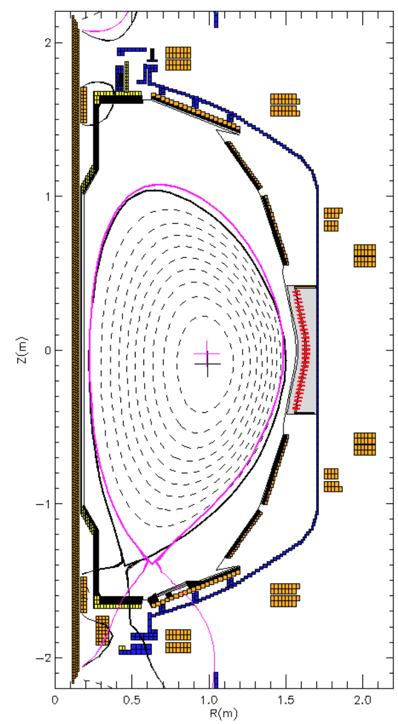


Fig. 11. Plasma potential measured at the outboard midplane by Langmuir probes on TdeV showing profiles obtained when the outboard divertor target plates are biased for three voltages, +150, 0, −150. From Ref. [9].

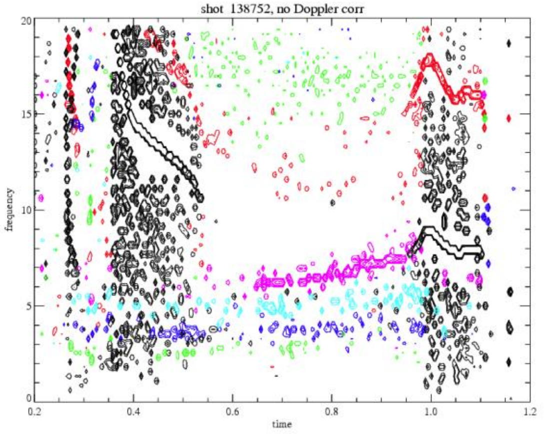
J.L. Lachambre et al. CFPP 1993 v.2, p.639



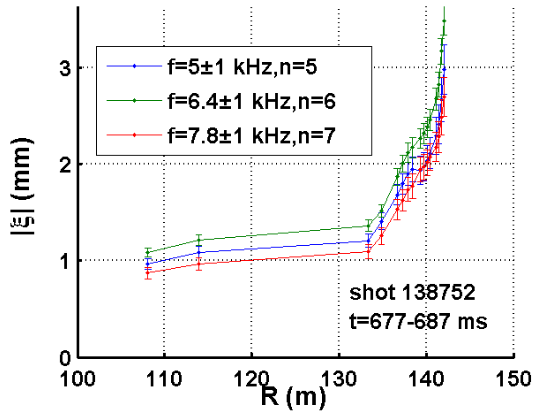
Potential applications of a biased divertor

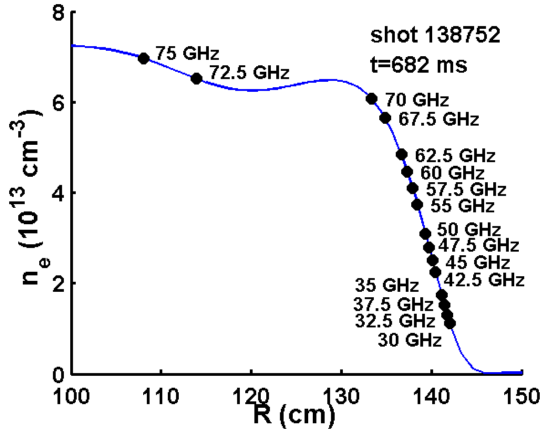
- Increase divertor pressure independent of core fueling
  - Divertor detachment control
  - Impurity mitigation
- Heat and particle flux profile control
- Contribute to SOL physics
  - In/out asymmetries – especially interesting in ST
  - SOL current and sheath properties (I-V characteristic)
- Modify edge E_r
  - Edge rotation control
  - L-H transition: either help or hinder (for I-mode access)
  - ELM control: mitigate or trigger
- Helicity injection
  - Non-inductive current drive

We see EHOs Reproducibly in Lithiated NSTX Discharges with I_p ~ 800 kA, B_T ~ 4.5 kG, P_b ~ 4 MW

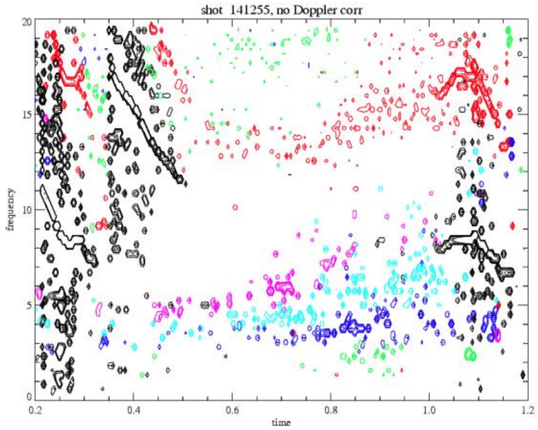


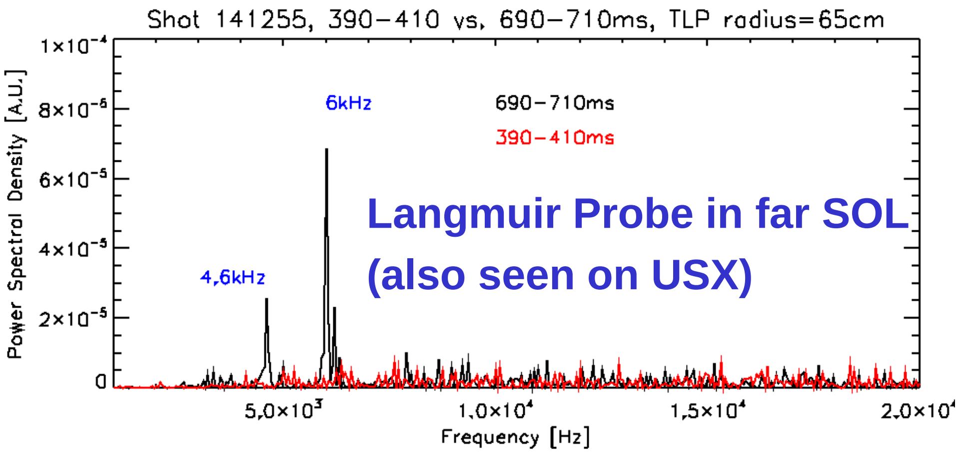
Mirnov Coils





Reflectometer

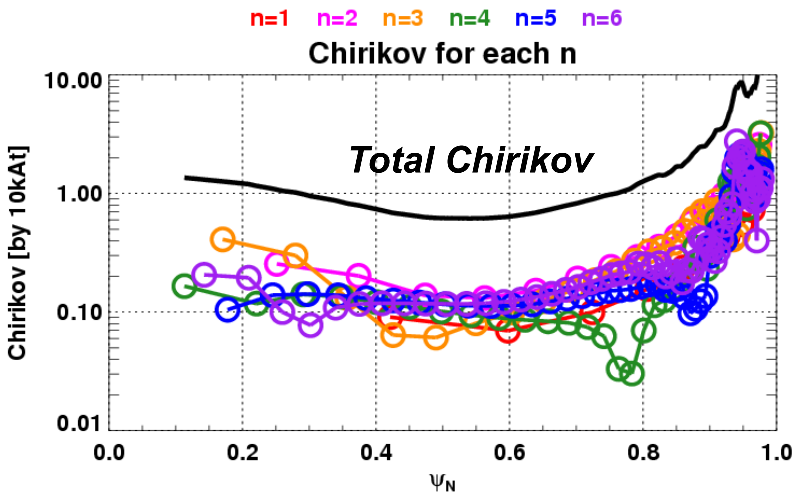


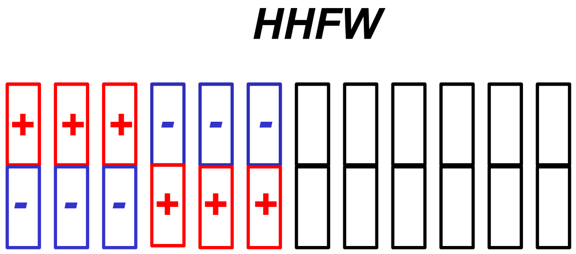


Langmuir Probe in far SOL (also seen on USX)

No evidence of density or impurity control.
But Mirnov amplitude ~ tenths of Gauss vs. ~ 3 Gauss for EHOs on DIII-D.

We Can Drive EHOs with Audio Currents in HHFW Antenna



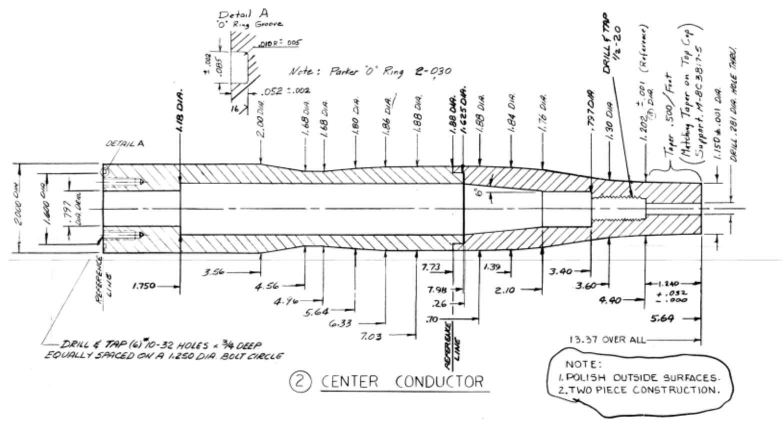


Use ½ of the HHFW Antenna

Fewer straps ⇒ higher currents.

Audio-amp system we built for DIII-D.

Feedthrus are robust.



External, adjustable control of edge density and pressure gradient would be extremely valuable for NSTX-U, ITER and Demo.

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Comment on Distant RMP Coils

SPG

Columbia U
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INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
ORNL
PPPL
Princeton U
Purdue U
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Think Tank, Inc.
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UC Irvine
UCLA
UCSD
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U Washington
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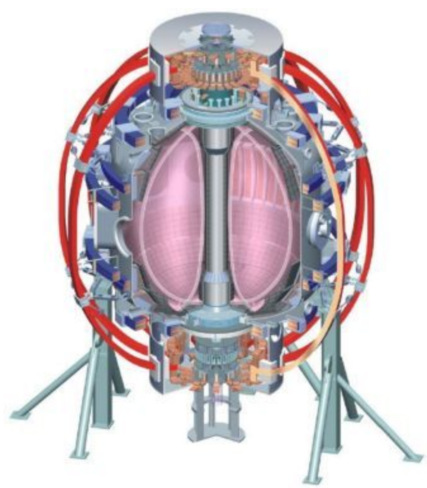

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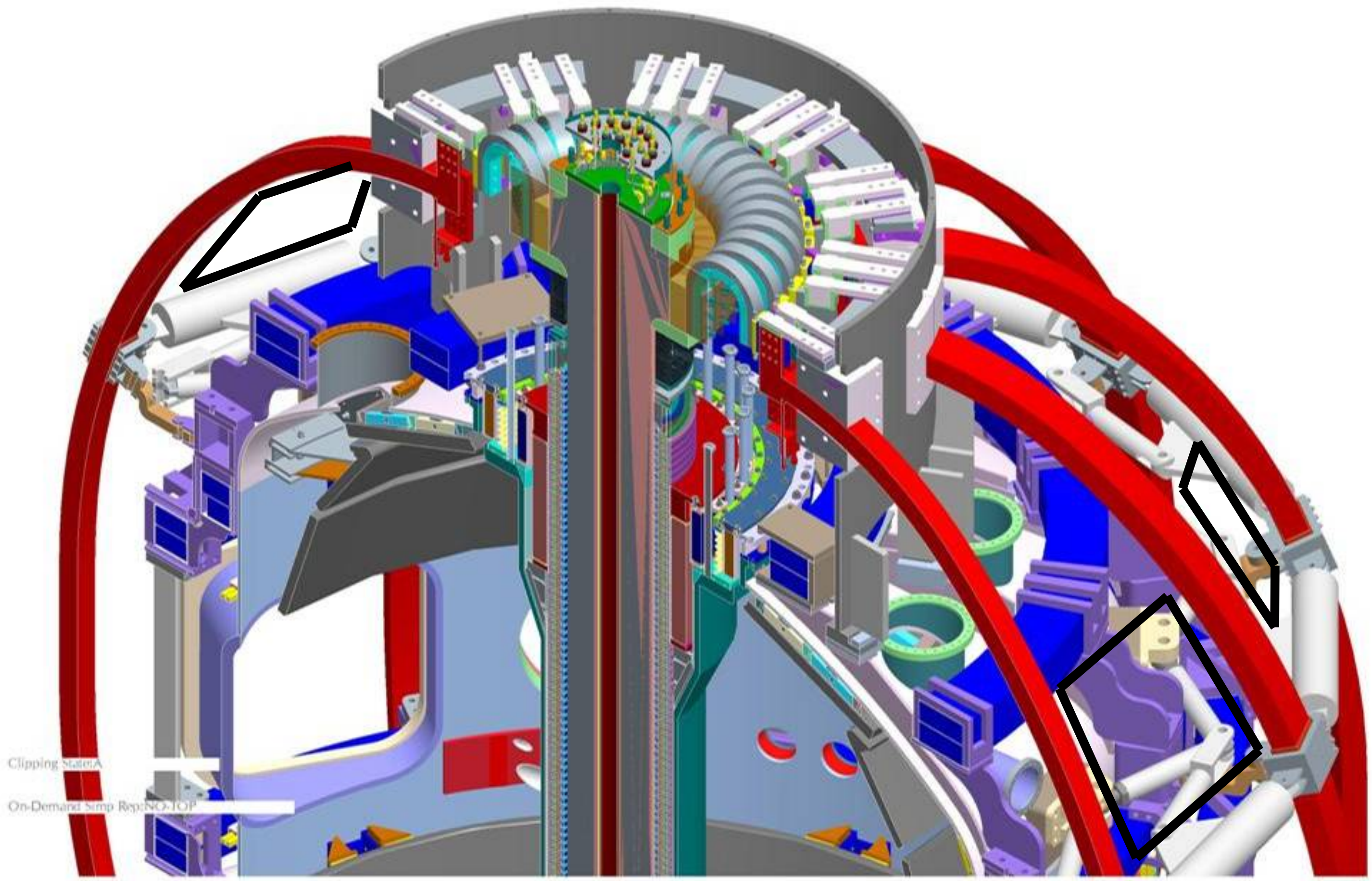
NSTX Could Explore a Unique Niche With Higher-n "Distant" RMP/RWM/EFC Coils

- Earliest you can imagine RMP coil upgrade is ~2016.
  - Two years after first plasma.
- D-IIID, MAST, ASDEX-Upgrade will have many years of experience with close fitting, off-midplane coils.
- Those coils are VERY difficult to implement in a DEMO like environment.

- Define "Distant" to mean a distance, normalized to R_0 or a, that a DEMO or CTF could use.
- Off midplane, distant coils are uncommon.
  - JET has n=2 coils outside the vessel.
  - D-IIID has midplane C-coil.
- State-Space RWM controller has shown promise for RWM control with more distant coils.
  - Oksana's thesis work.
- Research with these coils might be more directly transferable to to next-step devices.

- Easier to implement than internal coils: No high-current feedthroughs, easier maintenance, no impact on vacuum, react forces against other coils and their supports.
- Harder to implement than internal coils: More random interferences with diagnostics, surely require higher current levels, forces transferred to other coils and their supports.

Pre-Conceptual Idea For Locating Them



SPG Suggestion: As the internal coil physics designs are developed, also consider in tandem a distant coil design for comparison.

NSTX

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Non-axisymmetric Control Coil Upgrade and related ideas

S.A. Sabbagh[1], J.W. Berkery[1] J.M. Bialek[1], T.E. Evans[2], S.P. Gerhardt[3], Y.S. Park[1], K. Tritz[4]

[1]Department of Applied Physics, Columbia University, NY, NY
[2]General Atomics, San Diego, CA
[3]Plasma Physics Laboratory, Princeton University, Princeton, NJ

NSTX-U Facility Enhancement Brainstorming Meeting
February 8th, 2012
PPPL

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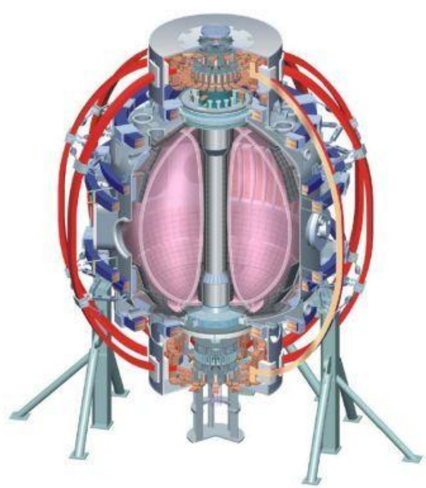

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V1.0

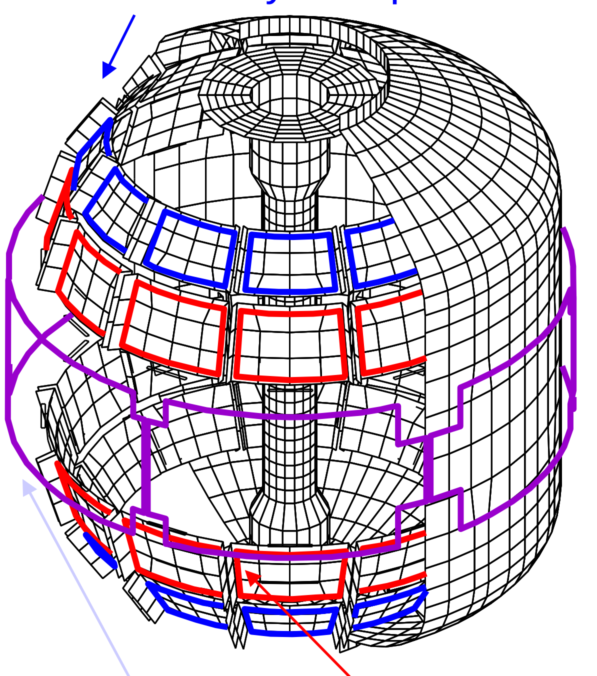
Proposal and Motivation for Non-axisymmetric Control Coil (NCC) goes back many years – research still needed

- Capabilities √
  - 2nd NBI √
    - q profile variation
    - momentum source variation
  - Non-axisymmetric control coil (NCC) – at least four applications
    - RWM stabilization (n > 1, higher β_N)
    - DEFC with greater field correction capability
    - ELM mitigation (n = 6)
    - V_ϕ control increase; n > 1 propagation)
  - Non-magnetic RWM sensors; advanced RWM active feedback control algorithms (ITER, etc.)
  - Possible alteration of stabilizing plate materials / electrical connections

Proposed Internal Non-axisymmetric Control Coil (NCC)

(12 coils toroidally)

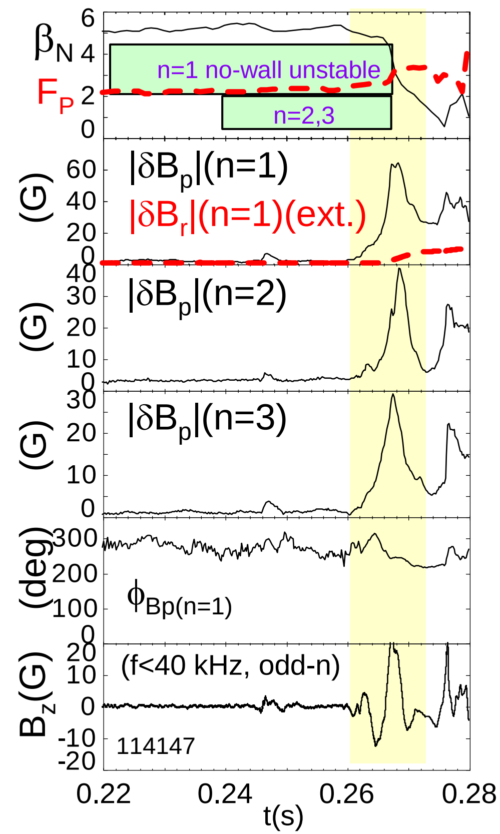
Secondary PP option



Existing coils

Primary PP option

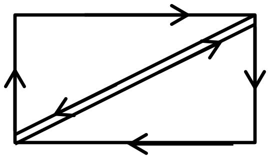
RWM with n > 1 RWM observed



(Sabbagh, et al., Nucl. Fusion 46, 635 (2006).)

NCC upgrade can investigate several key physics issues, some new ideas based on new capabilities/understanding

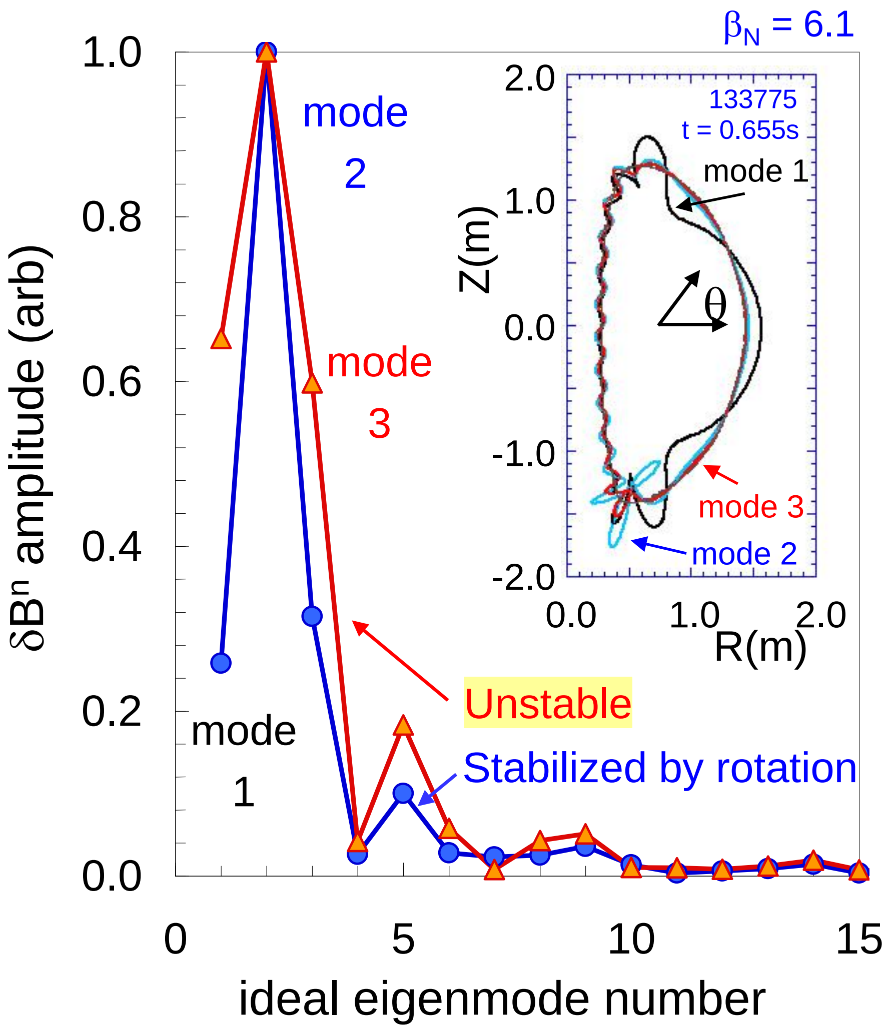
- NCC physics
  - Performance analysis performed for both RWM stability (Columbia) and ELM mitigation (GA - Evans) – now need to redo for NSTX-U (including recent physics understanding)
  - Several configurations considered:
    - Coils internal to vessel, coils external to vessel (i.e. "distant" coils)
    - Coils in front of primary/secondary passive plates, or among plates with altered plate material for some of the plates (e.g. SS)
  - Possible inclusion of diagonal elements for "stellarator" field



- NCC in light of present day ideas / capabilities
  - Internal "hairpin" coils (similar to KSTAR IVCC design) may ease implementation, give greater flexibility for physics studies
  - New RWM state-space controller allows far greater flexibility of global mode stabilization physics studies with these coils, with a relatively simple control software upgrade
  - New option of coils closer to divertor for control of "divertor" mode (multi-mode physics)
  - New consideration: field spectrum to produce favorable V_ϕ profile by NTV and NBI for kinetic global mode stability (MISK physics)
  - Examine best NCC field spectrum to potentially change edge fast ion profile for RWM and edge mode stability alteration (MISK physics)
  - Addition of "delta coils": strategically located dipole fields to enhance field spectrum for ELM mitigation, and possibly for time-dependent pulsed fields for ELM studies (T. Evans)

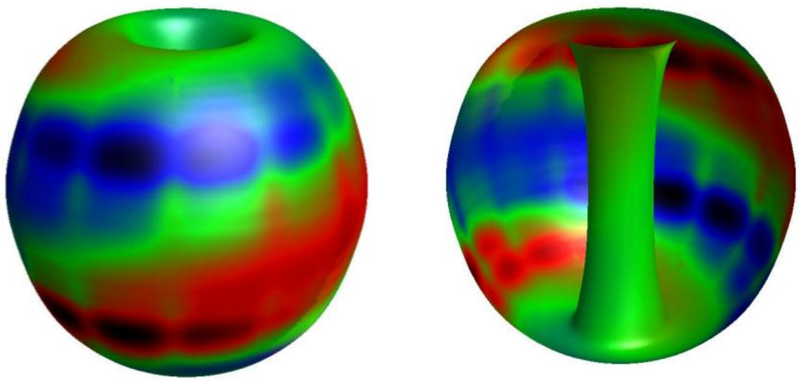
Multi-mode RWM computation shows 2nd eigenmode component has dominant amplitude at high β_N in NSTX stabilizing structure

δB^n RWM multi-mode composition



mmVALEN code

δB^n from wall, multi-mode response



- NSTX RWM not stabilized by ω_ϕ
  - Computed growth time consistent with experiment
  - 2nd eigenmode ("divertor") has larger amplitude than ballooning eigenmode
- NSTX RWM stabilized by ω_ϕ
  - Ballooning eigenmode amplitude decreases relative to "divertor" mode
  - Computed RWM rotation ~ 41 Hz, close to experimental value ~ 30 Hz
- ITER scenario IV multi-mode spectrum
  - Significant spectrum for n = 1 and 2

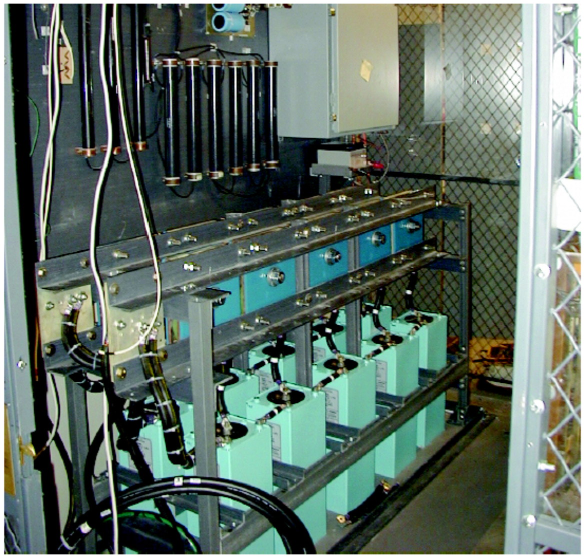
BP9.00059 J. Bialek, et al.; see poster for detail

Some new diagnostics would significantly enhance proposed MHD stability studies

- Magnetic
  - Low frequency MHD sensors over a wider poloidal range
    - Midplane: for global mode/RWM diagnosis – are our eigenfunction expectations from MHD correct, especially during mode growth? WIll internal sensors show key difference compared to external LMD?
    - Closer to divertor: diagnose, and perhaps feed back upon the "divertor" mode with the NCC
    - Direct use in RWM state space controller: for both physics studies of the observer model, and improved control – defined needs for ITER, etc.
- Kinetic
  - SXR sensors for global mode feedback
    - Magnetic sensors problematic in future high neutron environments
    - Typically aimed at RWM – still a major application. Proposed before for NSTX (JHU), but not funded
    - Also use in real-time to detect internal (global) kinks - using NBI, plasma rotation as actuators to alter mode stability in feedback; disruption detection

Capacitor Bank & MOV Upgrade for CHI in NSTX-U

NSTX- CHI capacitor bank



- 50mF, 2.0 kV capacitor bank (5mF x 10): 100kJ

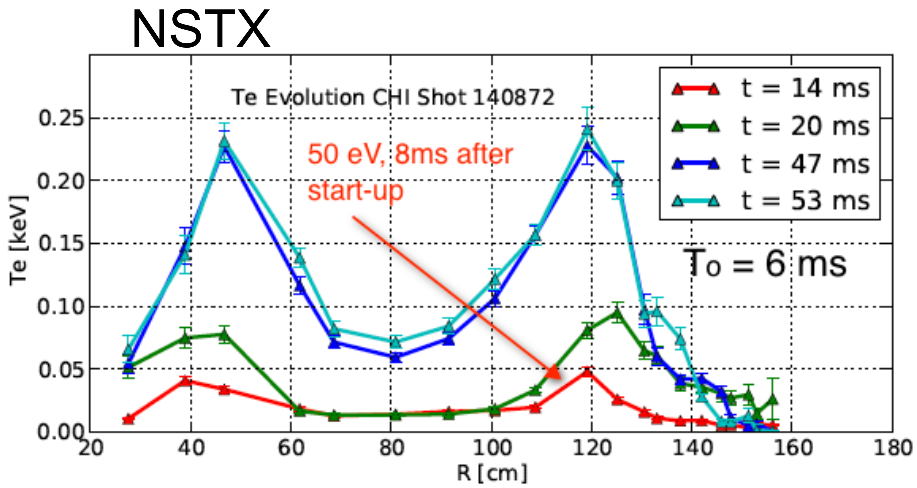
  45mF , 1.75 kV used in experiments

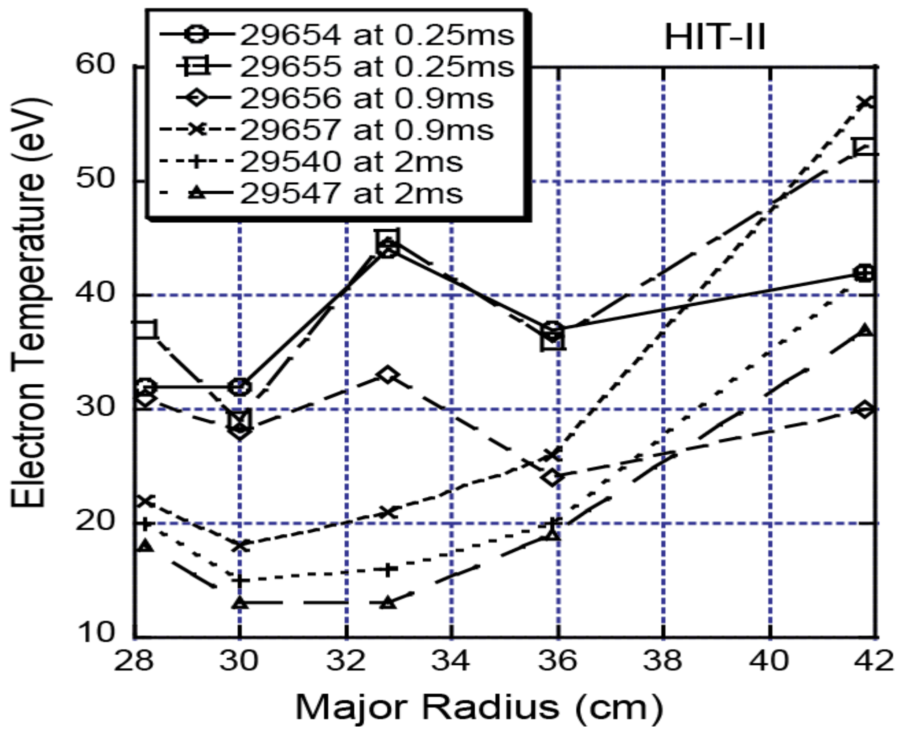
- Fast crowbar system to interrupt injector current
- Three modules
- MOVs limit voltage to 1.7kV

NSTX-U CHI capacitor bank requirements

- Cap bank should eventually support 1MA start-up
- 1MA plasma has 100kJ inductive stored energy: cap bank ~250-300kJ
- Configuration: 10 capacitors x 6 mF: 60 mF
- Capacitor voltage: 3kV (replace with bigger, higher energy density capacitors to minimize hardware reconfiguration)
- Cap bank energy: 270kJ (Peak currents >30kA)
- Consider increasing to 4-5 modules
- Retain and if necessary increase energy capability of crowbar system and energy dissipation resistors in cap bank
- MOVs need to allow 3kV cap bank operation (snub voltages above 3.6kV) – Needed for Day-1 Ops.
  - These are now being used to support standard inductive operations – need extra back-up MOV assemblies
- Assess if snubber capacitor/assembly needs improvements & if a second snubber system should be added
- Next 5-yr plan will consider IGBT switched power system (technology still developing)

1MW ECH & Upper Divertor Li for CHI in NSTX-U





R. Raman, T.R. Jarboe, et al. – CHI for NSTX-U -02072012

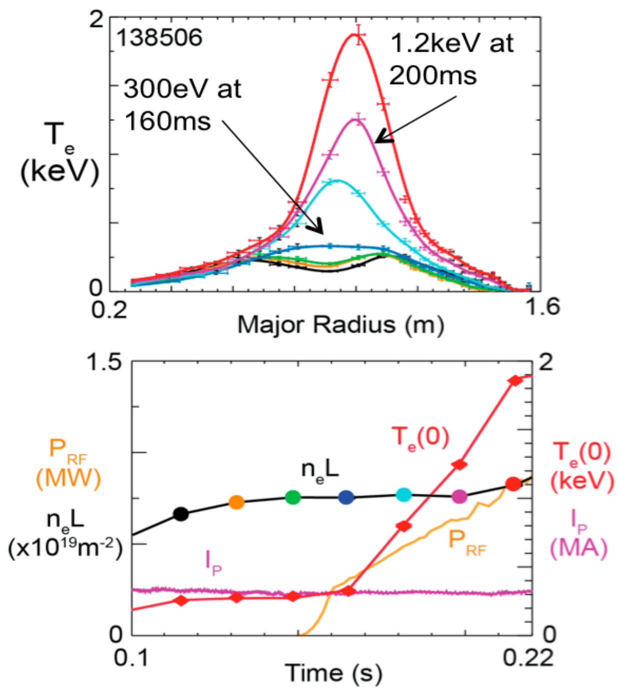
- Both NSTX and HIT-II have attained 50eV during the CHI phase
- At higher levels of start-up current, with improved electrode surfaces further increases in Te are likely
- During Inductive ramp-up, Te ramps-up fast (from 50 to 100eV in 6ms)
- These results and on-going simulations suggest that 0.5MW of coupled ECH power could increase Te by an additional 200eV during the current decay phase

Upward directed Li evaporator

- HHFW can increase Te of a 300kA plasma from 300eV to 750eV in 20ms & to 1.25keV by 40ms

- In a 500kA CHI target, 1MW ECH + HHFW should allow for direct coupling of CHI started currents to NBI-CD in NSTX-U

- This is a high-priority NSTX-U goal



- Reducing electron density in the absorber should make it more difficult for an absorber arc to initiate

- We had in the past considered the possibility of a cryo-pump in the absorber for this purpose

- FY11 CHI plans called for coating the upper divertor with Li using the Li dropper

- Recent experiments on NSTX have shown that DC rectifier sustained divertor cleaning discharges could not be sustained after extensive Li deposition on the lower divertor plates

- Rapid pumping by Li is hypothesized to be the cause

- An upward directed Li evaporator would help with absorber arc reduction and reduce the influx of impurities during an absorber arc

Upper CHI Injector Capability & Upper Mo Divertor Plates

- NSTX-U is up/down symmetric

-This allows for the possibility of initiating CHI from the upper divertor region

    - The gas injection system and a possible upper divertor ring bus for CHI current feed should be considered and implemented to allow this operational capability

- In the event that a cryo pump is installed in the lower divertor, CHI could be initiated from the upper divertor and the cryo pump would help reduce the incidence of absorber arcs (an appropriate design need to be worked out)

- Converting the upper divertor plates from carbon to Mo and coating it with Li should further reduce the amount of oxygen injected into a CHI discharge during an absorber arc

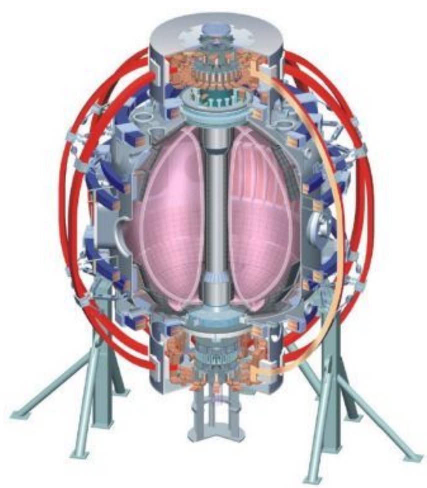
NSTX Supported by U.S. DEPARTMENT OF ENERGY Office of Science

Potential Upgrades to the NBI System for NSTX-Upgrade

SPG, TS

Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
ORNL
PPPL
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Washington
U Wisconsin

- Beam dumps
- Power supplies
- Injection Angle



Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
NFRI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

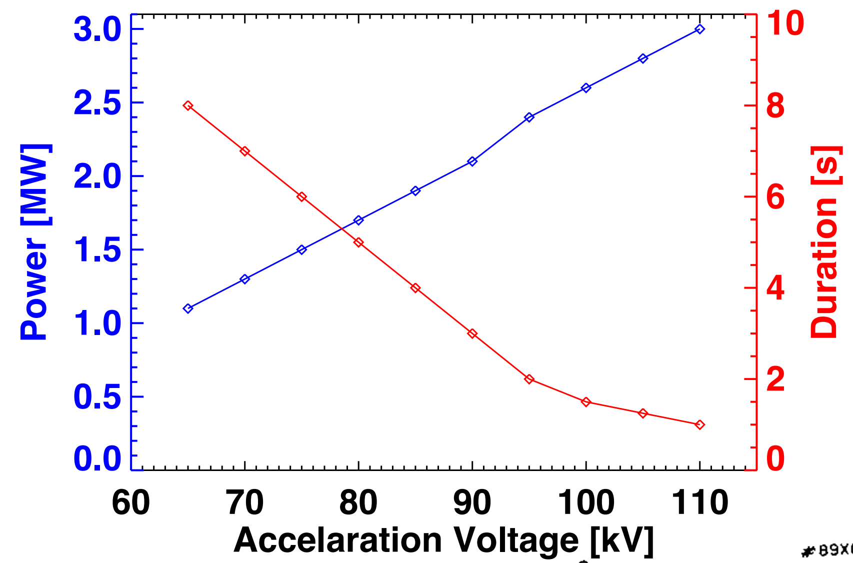
Ion Dumps Limit Pulse Length for a Given Voltage

Example Performance Impact

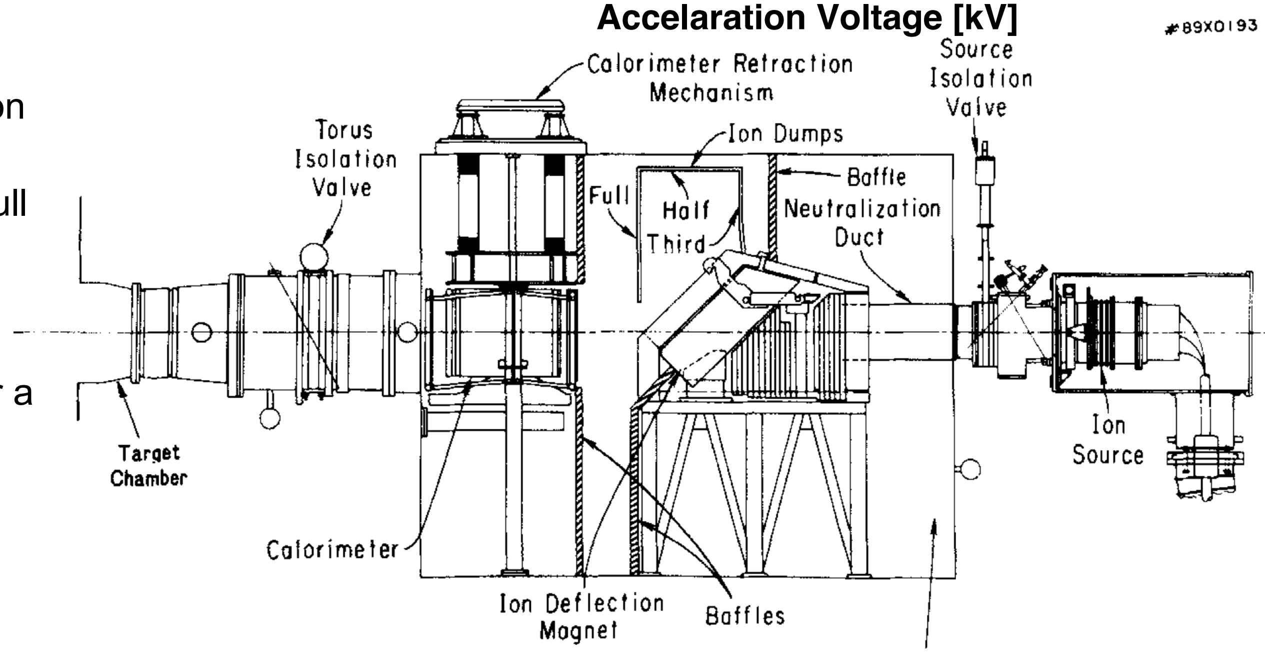
100% non-inductive scenario at B_T=1 T, 6 sources, $H_{98y,2}$=1

V [kV]	I_P [MA]	W_{tot} [kJ]	Duration [s]
80	800	425	5
100	1050	650	1.5

Also:
Beam diagnostics will have significant issues at 80 kV due to small beam penetration.
Will be an issue even if the higher power is not desired.

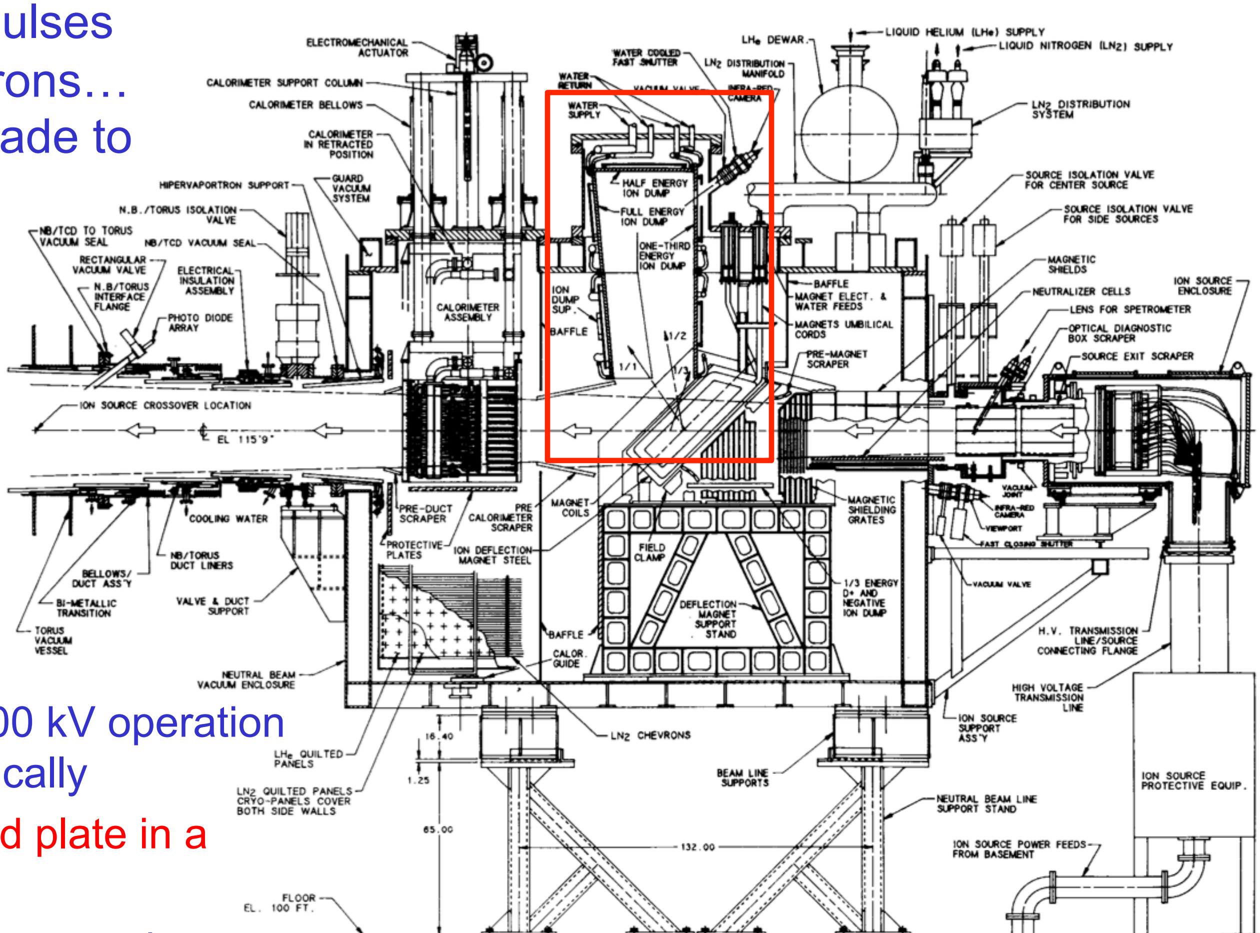


- Pulse duration limit is due to low-cycle fatigue & surface cracking on the primary energy ion dump.
- Done on an "every 2.5 minutes, full pulse duration, 10 hour day, 3 months a year" basis.
  - May be very conservative
- TFTR ran 95 kV for 4 seconds for a few shots, with no observed damage.
- Can maybe extend limits after engineering revisits assumptions, but if not…



Designs from Late TFTR Period Could Increase the Dump Power Handling

- TPX design for 1000 s pulses used many hypervaportrons… mandate extensive upgrade to the water system.



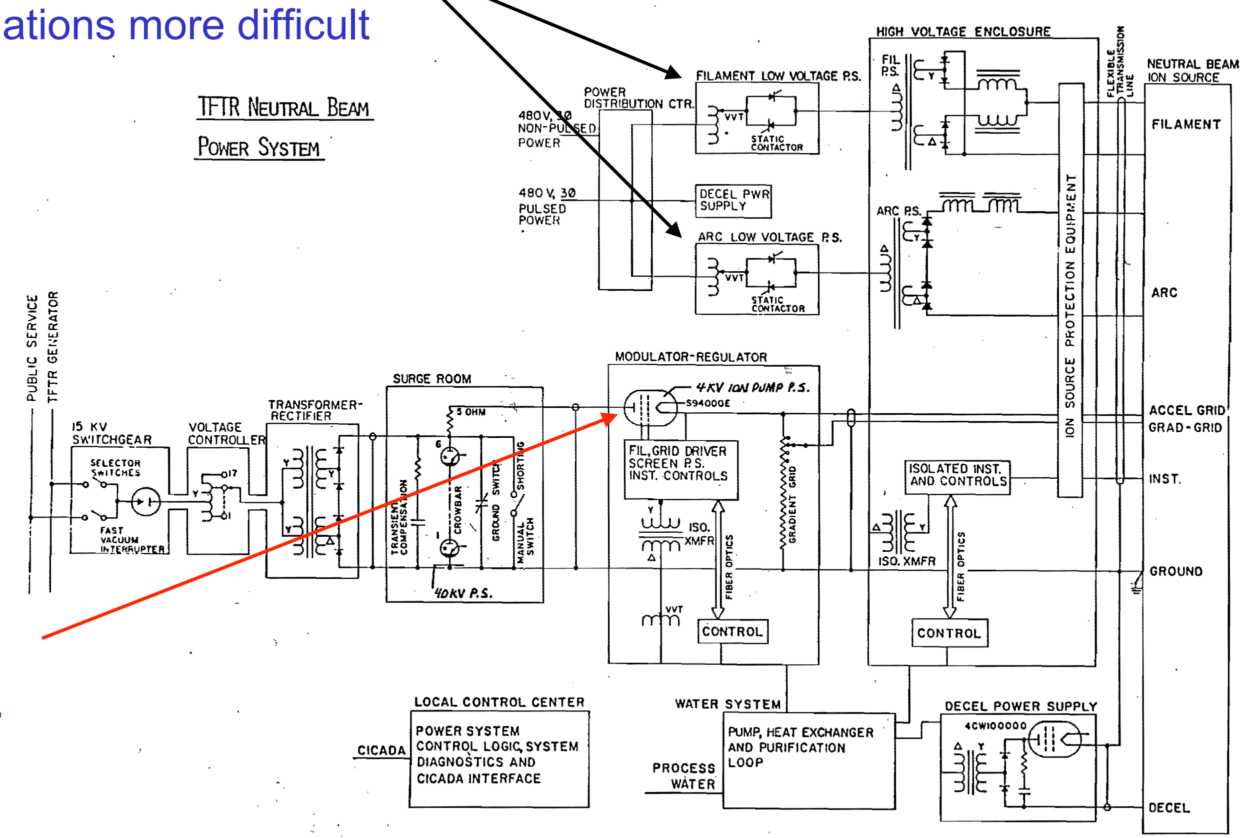
L.R. Grisham et al. / Fusion Engineering and Design 26 (1995) 425–430

Fig. 1. Elevation view of the conceptual design of a TPX neutral beamline.

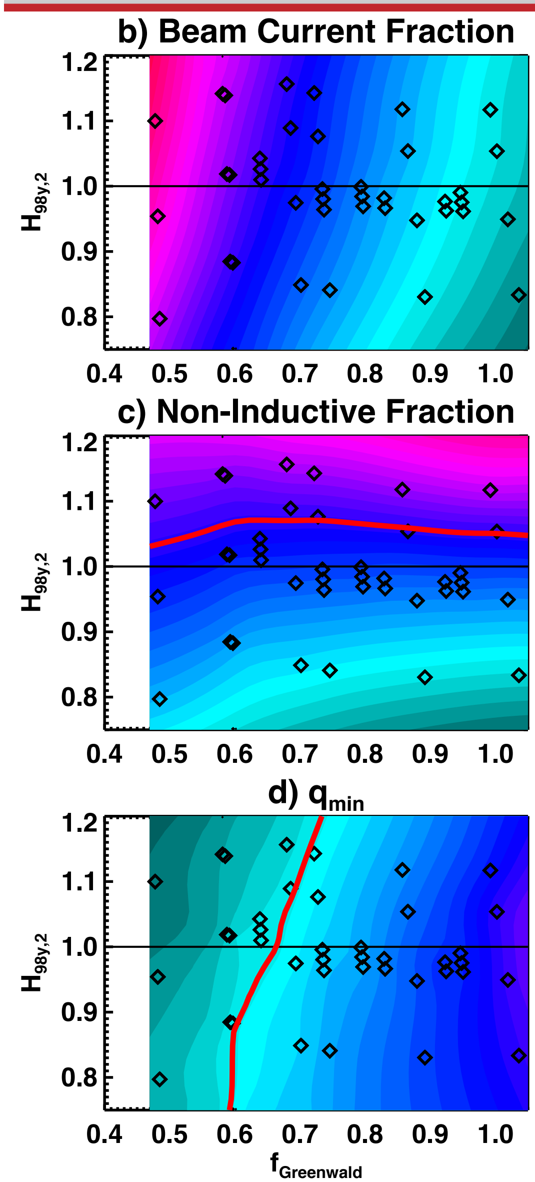
- Simpler upgrade for 5 sec, 100 kV operation extends the beam dump vertically
  - Adds a second, water cooled plate in a “clapboard” configuration.
- Need analysis of 2nd and 3rd energy dumps, other components.
- Note: Longer-pulse operation at high power would increase wear on the sources

Power Supply Side Considerations

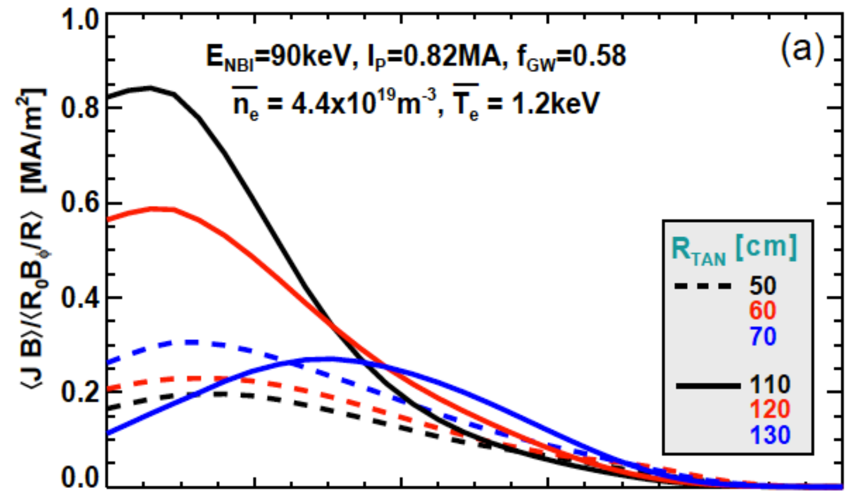
- Much of the NSTX-Upgrade physics program assumes that beams can be arbitrarily modulated.
  - Concerns about the grid power handling were somewhat alleviated by successful 15 ms on/off modulation in 2011
- Arc and filament supplies are unregulated.
  - Can make beam modulations more difficult
- Could upgrade them to IGBT supplies.
  - Propose to see how things work, then consider upgrades here as necessary.
- Limited supply of high-voltage modulator tubes.
  - Increased pulse length at high power will tax the tubes more heavily.



Elevated q_{min} Operating Space Might Be Extended By Tilting 2nd Beamline



1 T, 1 MA, 6 source, 90 kV scenarios



- Sources 2B & 2C (R_{tan}=110 & 120) tend to have strong central current drive.
  - Outer gaps of 15 or more cm help alleviate the problem for the 2C source.
- Results in q_{min} being driven under 1.0 for many lower-density scenarios.
  - 2C source at R_{tan}=110 cm may not be that useful for long-pulse.
- Tilting the beamline would move this peak off-axis, potentially widening stable the operating space.
  - Need to do TRANSP simulations as part of the 5-year plan lead-in.

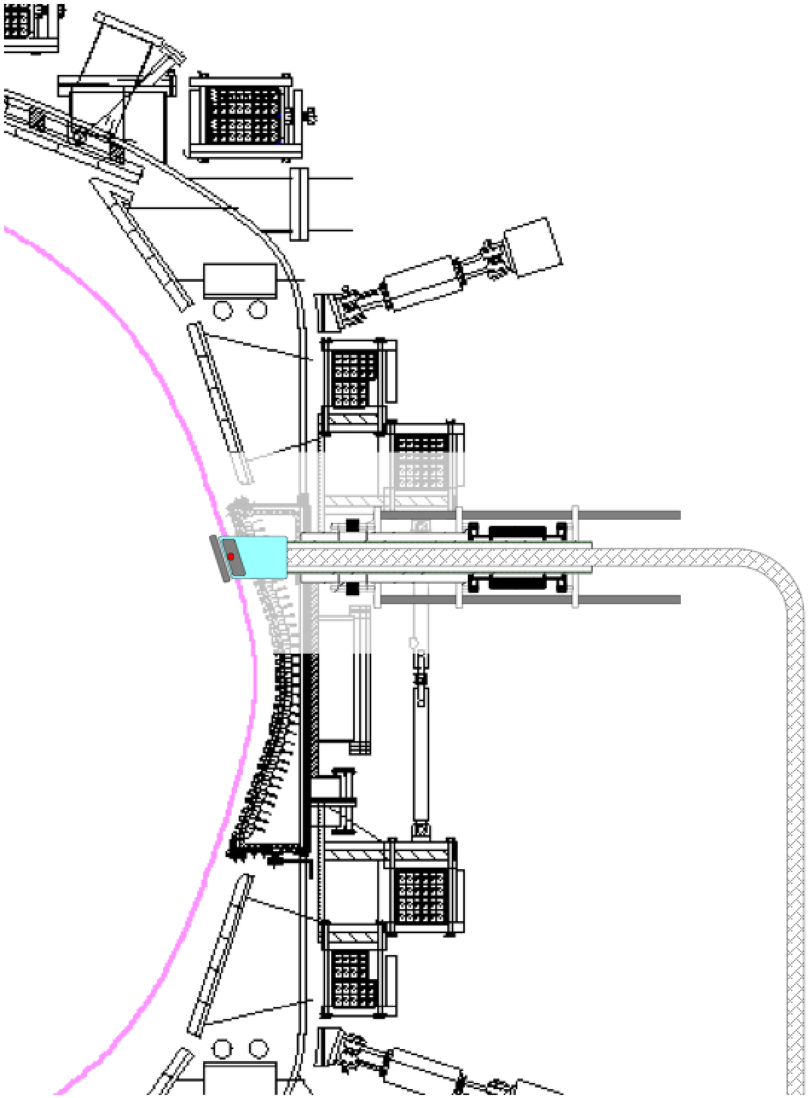
Point-Source Helicity Injection Startup

- Capabilities are being explored for NSTX-U…
  - ~1 MA startup plasma, appropriate for OH, NBI, and/or RF sustainment
  - Well-defined startup procedures and plasma development scenarios
  - Unobtrusive and retractable injection hardware

- Pegasus results are evolving the conceptual design:
  - Arc gun needed to generate the "seed" plasma
  - Formation of the poloidal field null is sensitive the geometry
  - Outer-PF induction provides finite Volt-seconds
  - Passive electrodes may be the optimum tool for providing maximum effective Volt-seconds with high Taylor limit for I_p
  - Electrodes and guns require different fuelling → active gas control
  - Local limiters mitigate impurities (Pegasus $Z_{eff} \leq 2$ during HI; ~1 in OH)

Conceptual design for the NSTX-U startup system

- Gun/electrode injector:
  - Single 8+ inch port off midplane
  - Retractable behind gate valve
  - Combines gun with large electrode
  - Piezoelectric gas control
  - Local limiter structure
- Power supplies:
  - Bias comparable to Pegasus
    (1-2 kV; 15 kA; $\Delta t \sim 1$ ms)
  - Arc plasma uses simple PFN supply
- Robust operating scenarios
  - Especially null formation and I_p buildup
  - Pegasus experiments informing and validating scenario development



NSTX-U ECH/EBWH System

Joel Hosea

Gary Taylor

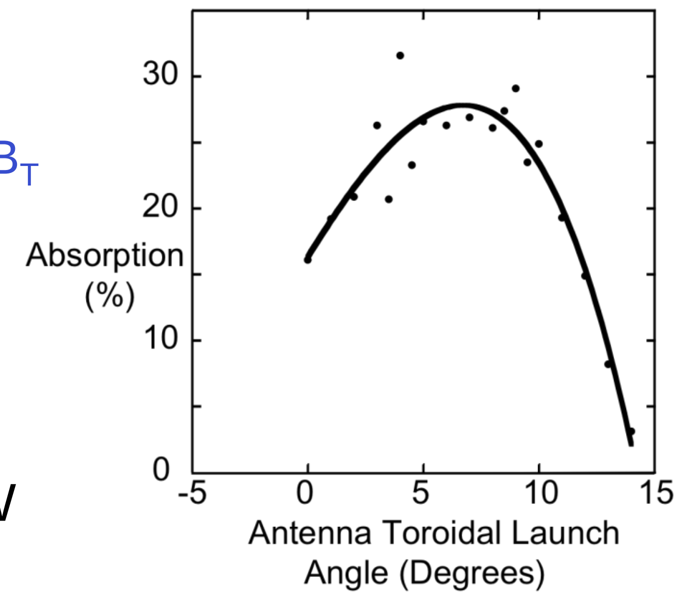
NSTX-U Facility Enhancement Brainstorming Meeting

February 8, 2012

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

28 GHz ECH System Supports Solenoid Free Start-up & Can be Upgraded as a Prototype EBWH System

- Initially provide 10-50 ms, 0.5-1 MW pulses to support discharge start-up
  - Earlier analysis for NSTX T_e~25 eV CHI start-up plasma predicted 25-30% absorption of 28 GHz second harmonic X-mode using a 7 degree toroidal launch angle
  - Need to model 28 GHz fundamental O-mode at $B_T(0)$ ~ 1 T in NSTX-U, optical depth lower in O-mode, but T_e should be higher at higher B_T

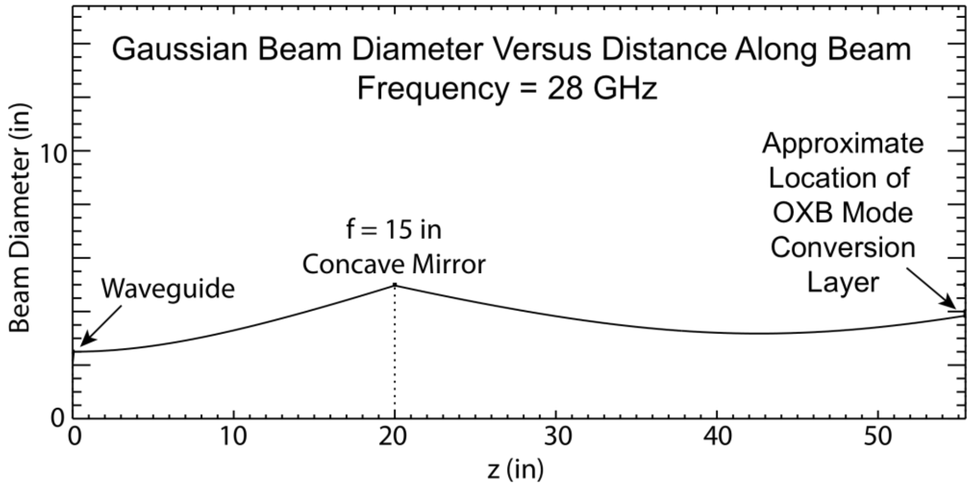


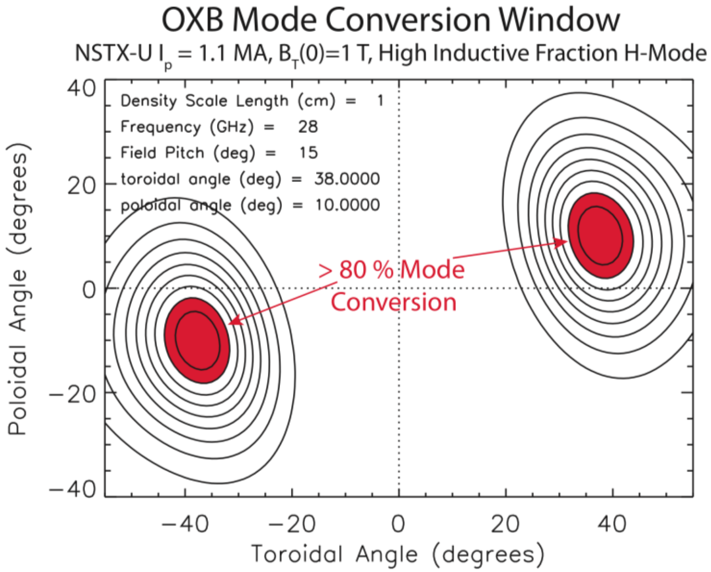
28 GHz X-mode second harmonic ECH Modeling Results for NSTX CHI Plasma

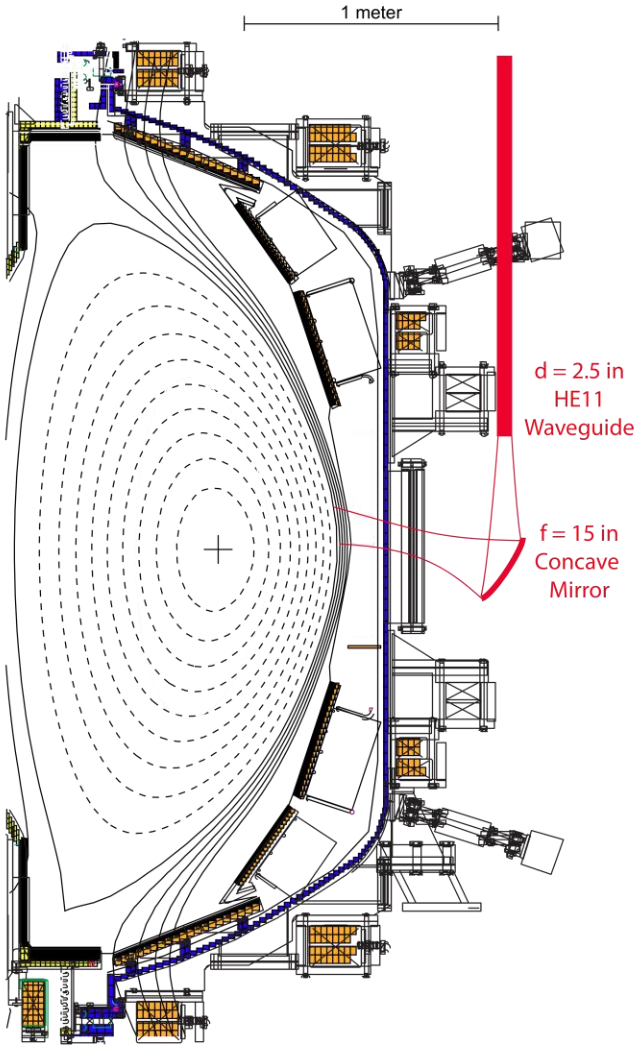
- Upgrade later to O-X-B oblique launch EBWH system with 500 ms pulses at 1-2 MW
  - Use steerable mirror launcher near midplane

Conceptual Design for NSTX-U EBW O-X-B Antenna

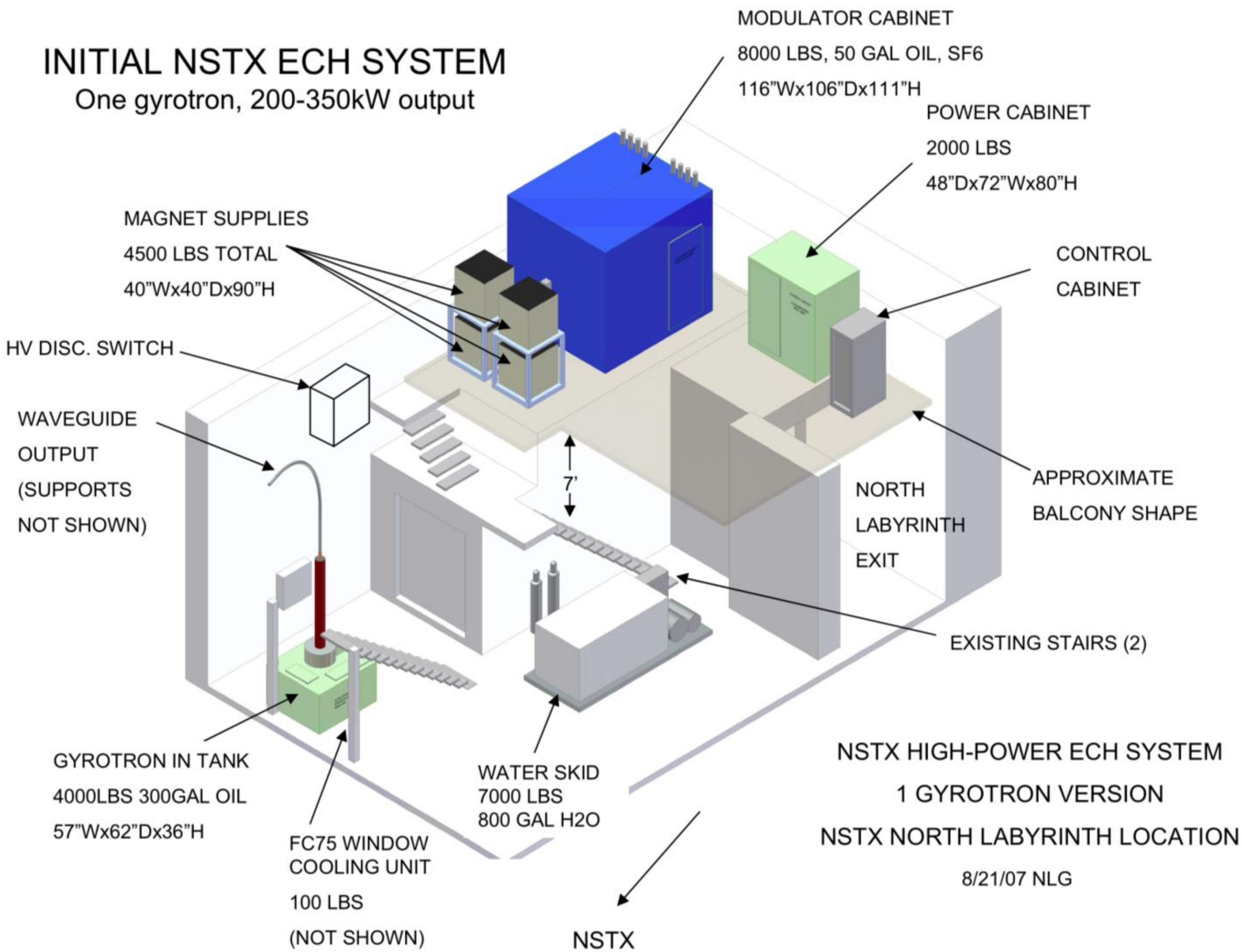
- Low-loss HE11 2.5 inch circular corrugated waveguide & metal steerable mirror designed for 1 s, 2 MW 28 GHz pulses located outside the vacuum vessel







Gyrotrons and associated equipment will need to be located in TFTR Test Cell or in the south NB bay area



- Conceptual location in 2007 in NSTX Test Cell is occupied by second beam line

MPTS Long Term Plans

B.P. LeBlanc, A. Diallo

PPPL, Princeton, NJ 08543, USA

NSTX-U facility enhancement brainstorm meeting

February 8th , 2012

* Work supported by USA DoE contract DE-AC02-09CH11466

CAMAC Replacement

- MPTS is a crucial diagnostic which is entirely CAMAC based
  - This is a liability that needs to be addressed in order to avoid interruption of MPTS coverage
- A modern data-acquisition electronics would permit to:
  - Do away with the our obsolete sample and hold electronics – very hard to replace parts
  - Permit higher time rate of acquisition – more later
  - Enable better understanding of stray laser light by using fast digitizers
  - Likely to enable dust measurements – Mie scattering and stray laser light are expected to have different time signatures

Laser Upgrade with Bursting Capability

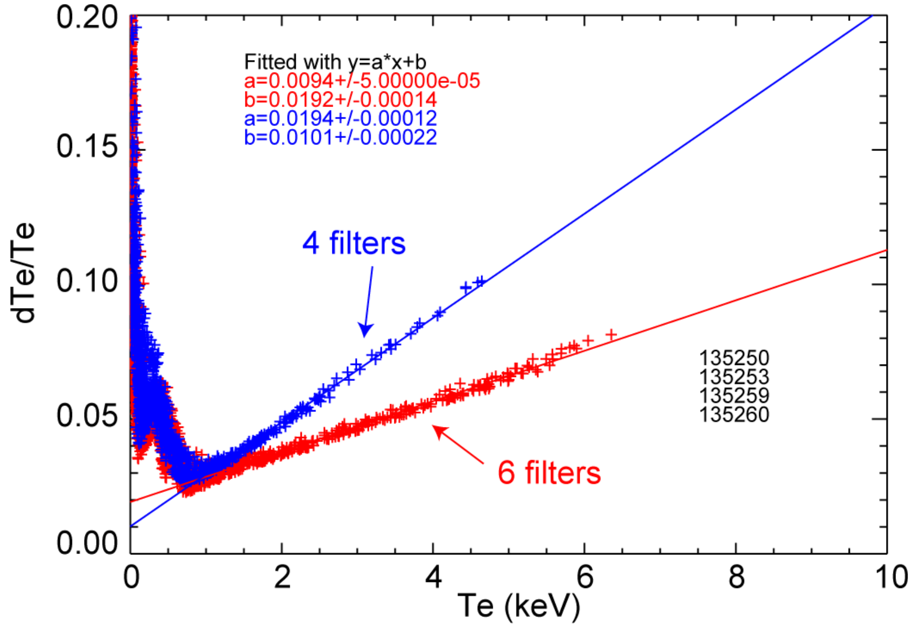
- The MPTS configuration for NSTX-U includes input and exit flight tubes capable of handling three laser beams
- Propose installing a third laser with bursting capability:
  - Operation at 30Hz until burst of 10 to 20 pulses at a repetition rate of up to 2kHz the latter limit is set by the current data acquisition – <u>could be faster with modern DAQ electronics</u>
    - Similar to work done by Den Hartog at U. of Wisconsin
  - The other two – exiting – lasers would continue to operate at their normal rate *i.e.* 2 x 30Hz

Improved Core and Edge Accuracy

- Modify the filter set of some of the core polychromators in order to obtained 5% error bar at 10keV

- Modify the filter set of polychromators seeing the SOL in order to reduce error bar

Present system expected to have poor resolution at 10keV



Improved SOL Spatial Resolution

- Install a second window and optics viewing the SOL – *e.g.* at bay G
- Radial channels interwoven with exiting channels
  - Also provide channels with large tangency radii in order to improve Z-effective measurement

Additional Laser Beam Path: Vertical

- Combined horizontal and vertical $T_e(R,t)$ and $n_e(R,T)$ profiles would provide unequaled capability in equilibrium reconstruction
  - 2D internal constrain
  - *e.g.* local elongation measurement
- Reuse existing laser beams or implement new laser(s)
- New collection optics and detection system

Monitor NB ion species mix

M. Podestà

> Knowledge of NB ion species mix (full, 1/2, 1/3 energy) crucial for
- Analysis of active charge-exchange spectroscopic data: CHERS, FIDA, …
- Predictions of NB deposition (hence NB-driven current, torque, etc.)
- Monitoring behavior of NB sources

> Values presently used (e.g. in TRANSP) obtained for TFTR sources
- Last update: 1994
- Species mix characterized for E_{inj}=80-120 keV
- Data at lower energies missing

>**Proposal**:

Install monitor for NB fractions for both NB lines on NSTX-U
- A ‘simple’ D-alpha monitor might be enough
- Some of the hardware may still be available (?)
- Vertical + radial arrays required to get information on beam divergence, footprint (perhaps a 2D camera?)