Extending 3D Magnetic Diagnostics in NSTX-U

by
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Presented to
NSTX-U MS TSG

At **PPPL**

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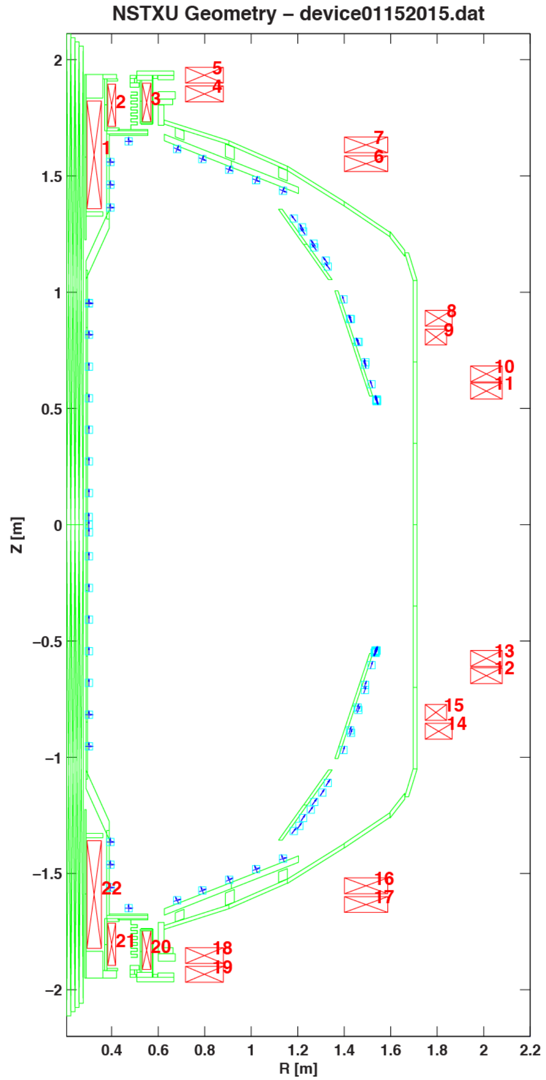


GENERAL ATOMICS

A new focus of PPPL-GA collaboration is on the extension of 3D magnetic diagnostic for NSTX-U

- **Project is part of long-term PPPL-GA collaboration (since 1999)**
  - Recent Title: Collaborative research on configuration optimization of advanced operating scenarios and control including macroscopy stability
  - PI: Rob La Haye (DOE FOA: DE-FG02-99ER54522)

- **Approach/Objectives**
  - Leverage lessons learned from 3D magnetics upgrade on DIII-D to enhance detection of 3D fields in NSTX-U
    - Source expertise from multiple institutions
  - Enable new physics results
    - Model validation: Ideal, resistive, extended MHD, kinetic models
    - Improved error field compensation and rotation control
    - Multi-mode control
    - Disruption physics
  - Provide input to future devices and upgrades

Physics objectives drive the requirements for non-axisymmetric field measurements (from DIII-D)

Objectives	Requirements
• **Plasma response (PR) to applied 3D fields** – PR to error fields and RMPs – Direct measurement of EM torque	$n \leq 3, m \leq 15$ $\delta B_p, \delta B_r$
• **Equilibrium reconstruction** – Improve axisymmetric equilibrium reconstruction – Full and perturbed 3D equilibrium reconstruction	$n = 1, m \leq 5$ $\delta B_p, \delta B_r$
• **Unstable plasma modes: low n, low frequency** – Poloidal structure of non-rotating modes n>1 – Poloidal structure of rotating modes	$n \leq 3, m \leq 15$ $\delta B_p, \delta B_r$
• **Unstable plasma modes: high n, high frequency** – Detection of ELM precursors – Energetic particle instabilities	$high\ m, n$ $high\ f \rightarrow \dot{B}_p$
• **Disruption physics** – Runaway electrons & their instabilities	$n = 1, m \leq 5$ $\delta B_p, \delta B_r$

Physics objectives drive the requirements for non-axisymmetric field measurements (from DIII-D)

Objectives

- **Plasma response (PR) to applied 3D fields**
  - PR to error fields and RMPs
  - Direct measurement of EM torque
- **Equilibrium reconstruction**
  - Improve axisymmetric equilibrium reconstruction
  - Full and perturbed 3D equilibrium reconstruction
- **Unstable plasma modes: low n, low frequency**
  - Poloidal structure of non-rotating modes n>1
  - Poloidal structure of rotating modes
- **Unstable plasma modes: high n, high frequency**
  - Detection of ELM precursors
  - Energetic particle instabilities
- **Disruption physics**
  - Runaway electrons & their instabilities

Are these objectives/ requirements valid also for NSTX-U?

Requirements

$n \leq 3, m \leq 15$
$\delta B_p, \delta B_r$

$n = 1, m \leq 5$
$\delta B_p, \delta B_r$

$n \leq 3, m \leq 15$
$\delta B_p, \delta B_r$

$high\ m, n$
$high\ f \rightarrow \dot{B}_p$

$n = 1, m \leq 5$
$\delta B_p, \delta B_r$

Why measure both δB_p and δB_r but not δB_T ?

- **Multiple components increase confidence in measurement**
- **Sensitive to different types of modes, different physics**
- **Both components required to resolve Maxwell stress**
- **δB_T is small, doesn't provide new info; can get from δB_p,δB_r**

Source	Bp probe coupling	Br loop coupling
Equilibrium field (n=0)	✔	Small (typ. < 20% of Bp)
Nearby RMP coils	Small (minimize by design)	✔
Rotating MHD modes, ELMs	✔	negligible (at f > 1 kHz)
Non-rotating MHD modes Response to RMP	✔	✔

General considerations

- **Prudent to organize sensors into toroidal arrays**
  - Dictated by tokamaks near-axisymmetry
  - Non-axisymmetry is "small": 10^{-4} – 10^{-2} of axisymmetric field
  - Account for axisymmetric field (n=0) using sensor differences at same poloidal location (either in hardware or software)

- **For low frequency applications, need about a dozen sensors in a toroidal array to simultaneously resolve multiple toroidal modes**
  - Difficult to do more than this due to scarcity of real estate
  - Might do with fewer to get n=0 & one other n (w/ caveats)

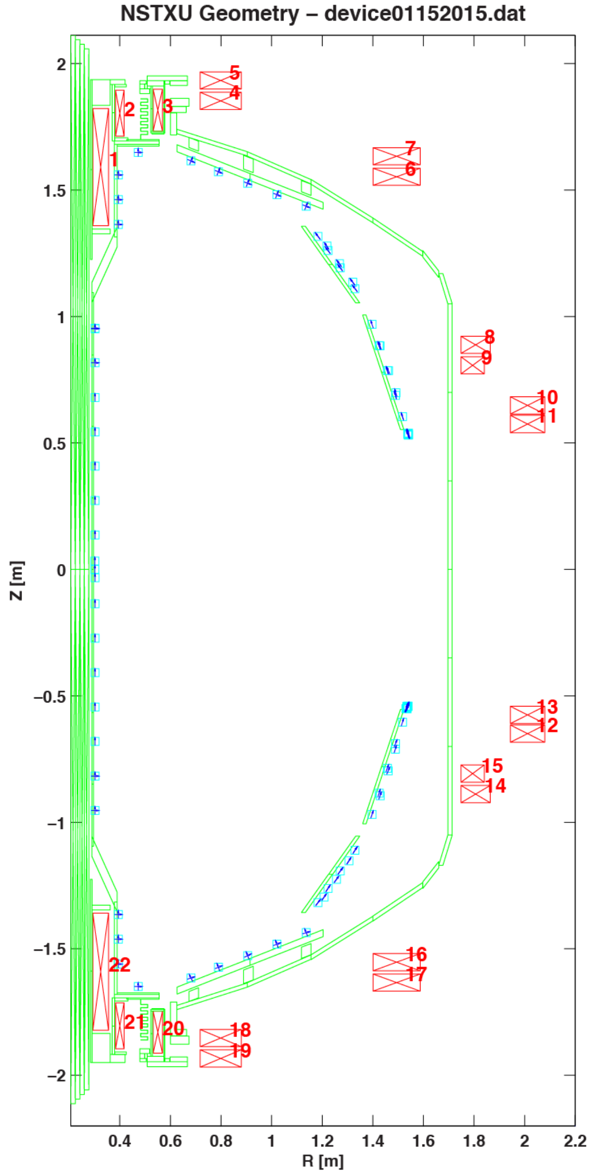
- **Location location location! -- Key questions to answer are**
  - How many new sensors are warranted?
  - How to spatially distribute the sensors?
  - What impact will compromises have on capabilities?

Proposed topics/steps for developing design and supporting operations, data analysis

1. Collect relevant information on NSTX-U configuration
2. Identify available and restricted wall regions
3. Assemble relevant metrics for optimizing design
4. Evaluate completeness of existing magnetic measurements
5. Collect available plasma response calculations (pursue more A/N)
6. Establish testable hypotheses (provide the strongest motivation)
7. Propose initial conceptual design
8. Address input from experts
9. Final conceptual design
10. Evaluation of measured fields, frequency response, noise spectrum
11. Document initial results with comparison to plasma response models

Collect relevant information on NSTX-U configuration

- **NSTX-U passive and active conductors in 2D ✔**
  - Sabbagh device in TokSys
- **Existing magnetic sensor locations ✔**
  - MDS spreadsheet used to build TokSys sensors
  - Vertical length of probes: Bp: 3cm and Br loops: 0.2435m ?
- **Existing 3D coil geometry ✔**
  - Simple model in TokSys
  - Will update with detailed geometry (NTVTOK)
- **Identify relevant NSTX data for 3D coils/sensors ✔**
  - Received discharge numbers from Gerhardt
  - May get more 3D field pulses today



Assemble relevant metrics for optimizing design

- **SVD Condition number of coupling matrix**
  - Given measurements at x_k and basis of linearly independent functions F_j define coupling matrix $C_{jk}=F_j(x_k)$
  - Condition number $\kappa(C)$: ratio of largest to smallest eigenvalue of SVD(C) – Indicates sensitivity of fit to errors in measurements

Equal 90° spacing:
Well conditioned array

10° spacing:
Poorly conditioned array

- **Expected poloidal wavelengths of external field and PR**

- **Capability to detect reluctance modes** (ala Logan, Boozer)

- **Bayesian approach within 3D equilibrium framework**

Collect available plasma response calculations (pursue more A/N)

- **MARS-F/K** ✔
  - Z. Wang/Park: Fluid and kinetic analysis of 2MA high beta NSTX-U model equilibria
- **IPEC/IPECOPT** (to meet with Park on Thursday)
  - Park/Lazerson/Logan: Analysis for NCC design
- **M3D-C1** ✔
  - Evans/Canal: Analysis of NSTX-U model equilibria
    - Case 6 of 9: Ip=1.45 MA, Bt=1.0 T , q95=8.7 betaN=4.0
- **VMEC/V3FIT**

Synergy with GA TokSys Control Model Development

- **Tool development for 3D magnetics proposal overlaps with control tool development in GA TokSys toolbox**

- **Examples**
  - Analysis of magnetic sensors in TokSys model supports general shape/current control model development
  - Analysis of reluctance modes could use Greens functions from TokSys model

- **GA TokSys code is now under git source control**
  - Can contact Brian Sammuli (sammuli@fusion.gat.com) for information on access to GA git server
  - Work for 3D magnetics will occur under branch "3dmags"

Summary

- **PPPL-GA collaboration focused on new 3D magnetics proposal for NSTX-U**

- **Lanctot onsite at PPPL Dec. 7-18**
  - Workplan target is to complete steps 1-5 of proposed topics
  - Deliverable: Report on Completeness of existing magnetic measurements

- **We at GA look forward to this fruitful collaboration!**

Points of Discussion

- **What are the highest priority physics objectives for NSTX-U team?**
- **What is a realistic timeline for completion of this project with respect to NSTX-U schedule?**
- **What would it take to install sensors on the centerstack?**
  - Assume HFS B-field structure essential to resolve physics
  - Will consider requirements, feasibility even though heroism needed
- **Is there a possibility to partner with MSE group to obtain internal magnetic field measurements?**
  - Direct measurement of internal magnetic fields would be transformational
  - δB likely too small to resolve given present uncertainties