NSTX

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Diagnostic Upgrades Supporting Macroscopic Stability High Priority Research Goals

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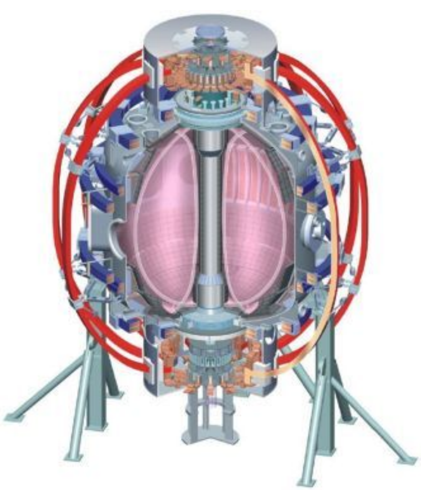
Jack Berkery and Jong-Kyu Park

for the NSTX Team

Macroscopic Stability Group Meeting
Princeton Plasma Physics Laboratory
September 7, 2011



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Draft list of key diagnostics

- Real time MSE (Global, Tearing)
- Internal magnetic fluctuation profile measurement (Tearing)
- MSE-LIF (Global, Tearing)
- Edge imaging of pitch angle, Lithium beam Zeeman polarimetry (Global)
- rtMPTS, Edge TS (Global, Tearing)
- New diamagnetic loop, Magnetic refurbishment (Global, Disruption)
- ERD (Global, Tearing)
- Interferometer rotation measurement (Global, Tearing)
- Toroidally displaced ME-SXR (Global, Tearing, Disruption)
- SOLC with magnetic probes, electrodes, sensors (Tearing, Disruption)
- Error field measurements with external coils (Tearing, Disruption)
- Fast thermography, thermocouples (Disruption)
- Visible bremsstrahlung imaging (Tearing)
- Improved reflectometer system (Tearing)
- Radiation tomography (Disruption)

Diagnostics

- Support improved equilibrium reconstruction
  - MSE-LIF (J. Foley)
  - Coherent imaging of pitch angle in the edge (A. Diallo)
  - Edge Thomson scattering (A. Diallo)
  - New diamagnetic loop (H. Takahashi)
  - Magnetics refurbishment (S. Gerhardt) *(magnetics upgrade? (H. Takahashi))
- Support rtEFIT for real time stability
  - Real time MSE (H. Yuh)
  - rtMPTS (B.P. LeBlanc)
- Low m,n islands and kinks
  - Visible bremsstrahlung imaging (D. Darrow)
  - Improved reflectometer system (N. Crocker)
- Measure edge current density / SOLC
  - Lithium beam Zeeman polarimetry (A. Diallo)
  - SOLC tracing with electrodes (H. Takahashi)

Diagnostics

- Identify magnetic island locations, disruption precursors
  - Internal magnetic fluctuation profile measurement (J. Foley)
- Support improved rotation profile measurement
  - Upgrade of edge rotation diagnostic (M. Podesta, R. Bell)
  - Interferometer rotation measurement (G. Kramer)
- Supports disruption studies
  - Fast thermography, thermocouples (A. McLean)
  - Radiation tomography (V. Soukhanovskii)
  - SOLC with magnetic probes and tile current sensors (H. Takahashi)
- Non-mag. mode ID, MHD precursors, distruption thermal quench
  - Toroidally displaced ME-SXR (K. Tritz)
- Error field measurement
  - Error field measurement with external sensing coils (H. Takahashi)

Real-Time MSE (rtMSE)

- Hardware/software upgrade to MSE-CIF system to provide magnetic field pitch angles in real time.

- Spatial(1-3 cm) and time(5 ms) resolution the same as the present MSE-CIF system.

- Combined with real time equilibrium reconstruction to provide q-profiles for current profile control using NBI.

Motional Stark Effect with Laser-Induced Fluorescence (MSE-LIF)

- Installation for first operation in upcoming run.
- Diagnostic neutral beam and laser.
- Measurements of magnetic field magnitude and pitch angle.
- Can operate during startup and for RF studies.
- |B| can be used to reconstruct the total plasma pressure, use for MHD studies, and for fast ion pressure.
- With MSE-CIF system, determine radial electric fields of interest for transport.
- Time resolution ~5 ms, spatial resolution 1–3 cm, 38 channels planned (fibers for 10 channels presently installed)

NOVA PHOTONICS

Internal Magnetic Fluctuation Profile Measurement

- Utilizes MSE-CIF system. Coherent magnetic pitch angle fluctuation measurement has 5–10 ms time interval with ~100 kHz frequency bandwidth, same 18 spatial channels as MSE.
- Capability presently installed - completed filter upgrade in 2010 - initial analysis underway.
- Simultaneously measure density fluctuation profile, and phase angle between density and magnetic field fluctuations.
- Can identify magnetic island locations, provide information for stability control.
- MHD studies, including seeking internal magnetic field fluctuation precursors to disruptions.

NOVA PHOTONICS

Lithium Beam Zeeman Polarimetry on NSTX

A. Diallo

- Knowledge of the edge current density is crucial for the understanding of the local MHD and pedestal physics.
- Lithium beam polarimetry in combination with EFIT could provide such measurement. Characterization of the Zeeman triplet components of Lithium emission at 670 nm.
- Inline with the assessment of pedestal at up to 2.0 MA.
- Suited for industry/university.

Coherent Imaging of the Magnetic Pitch Angle in the Edge Region

A. Diallo

- Knowledge of the edge current during the inter-ELM phase in the pedestal region is important for local MHD stability and pedestal physics.
- Measurement of the pitch from polarization characteristics of D_α components of Stark splitting in the edge region.
- Target an imaging polarization interferometer approach for greater spatial resolution and throughput. The temporal resolution can be 5 ms.
- 2D imaging scheme will supplement the magnetic equilibrium solver, EFIT, for equilibrium reconstructions in the pedestal region.
- Will provide 2D snapshot of the pitch angle, which could be synchronized with ELM events for enhanced temporal resolution in the pedestal.
- Suited for industry/university.

rtMPTS

B.P. LeBlanc after discussion with S.P. Gerhardt and S.A. Sabbagh

- rtEFIT does not have internal constraints at present
  - Only magnetics…magnetic flux and fields, loop voltages
- rtMPTS can provide internal constrains
  - p_e isobaric (à la EFIT02) or T_e isotherm (à la LRDFIT04, EFITXX)
  - Constrain magnetic axis location
  - Can help constrain outer gap
  - Useful to estimate resistivity for current profile control
- Resolution:
  - 2 Nd:YAG lasers → 16.7msec; 11ms with a 3rd laser
  - 10 to 20 radial channels distributed on both sides of magnetic axis
- Scheme and latency
  - Use existing buffered outputs, do initial-guess T_e and n_e calculations
    - Iterative fit steps might be possible
  - 0.4ms intrinsic latency, plus computation time → 1ms after laser pulse

•***Innocent bystanders: A. Diallo. J. Dong, and H. Schneider***

Edge Thomson Scattering System

A. Diallo

- Dedicated edge system at the region of near optimal flux expansion (20 cm below midplane)
- Increasing spatial resolution in the pedestal region (sub-mm). Further constraining the EFIT equilibrium reconstruction.
- Support the pedestal physics studies and turbulence codes.
- Suited for industry/university.

NSTX-U diagnostic proposal: upgrade of ERD (M. Podestà, R. E. Bell)

- Goal: upgrade Edge Rotation Diagnostic to improve spatial and temporal resolution
  - Complement CHERS/pCHERS with passive measurements
    - Measured lines: C III and He II
  - Keep basic configuration: toroidal + poloidal views
- Modify existing fiber holders; add 210μm fibers
  - Spatial resolution: ~20 radial channels, ≤1 cm resolution
  - Measurements in the range 135 cm < R < 155 cm
  - Time resolution: ~1 kHz (x10 with respect to present system)
  - Need new CCD camera
- Supports NSTX-U research on
  - Routine measurement of edge features, electric field
  - RF ion heating at the edge
- Project is more suitable for PPPL
  - Fiber holders for CHERS/pCHERS/RTV/FIDA must be re-designed
  - Analysis software already exists

Measurement of bulk plasma flows with an interferometric technique

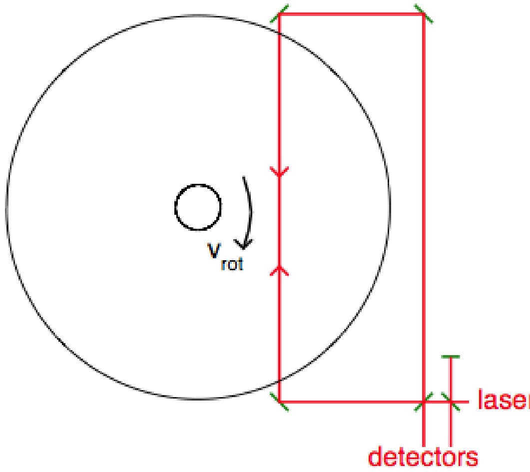
Gerrit J. Kramer

- The speed of light in a medium depends on the velocity of the medium:

$$v_{light} = 1/R\ (c +/- v_{medium}\ (R^2-1)\ /\ R) \qquad \text{(R: index of refraction)}$$

experimentally verified by: H. Fitzeau, Ann. de Chim. et de Phys. 57 (1859) p. 885
P. Zeeman KNAW, Proceedings, 17 I, 1914, Amsterdam, (1914) p. 445

- We can use this effect to measure the plasma rotation in NSTX
- Let light (or microwaves) pass through the plasma at the same line of sight in both co– and counter to the rotation and measure the phase difference between the signals
- This will give a measure of the line–integrated plasma velocity projected on the sight line but it is weighted to the tangency radius



- The (line integrated) density should also be measured to get index of refraction
- With this technique rotation measurements can be made that are independent from (diagnostic) NBI injection
- This project is suitable for university collaboration

Edge Reflectometer at the HHFW Antenna

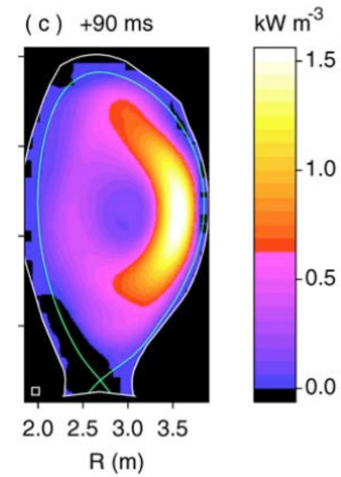
- The present reflectometer measures the plasma density profile and localized density fluctuations in the edge region around the HHFW array.
- Needed for RF/plasma coupling studies, power losses to PDI, and antenna modification assessments.
- Reflectometer system ~13 years old and in need of refurbishing
- New |B| requires change in frequency sweep
  - Presently sweeping 5.7–26.8 GHz
    - First cutoff for 0.28 T is ~5.7 GHz
    - At 1 T, first cutoff will be at ~19 GHz
  - Will need 10–40 GHz to cover 0.5–1 T plasmas
- Existing instrument can be upgraded to cover 10–40 GHz
  - Need new phase detector, amplifiers and local oscillator
  - Maintain capability for edge-density profiles, PDI, and density fluctuations
- Existing waveguide horns do not perform well above 30 GHz
  - Existing launchers were optimized for the 6-26 GHz frequency range
  - Need to reduce diameter of launchers from 1.5” to 0.75” OD
  - Coaxial feed cables are rated to 40 GHz

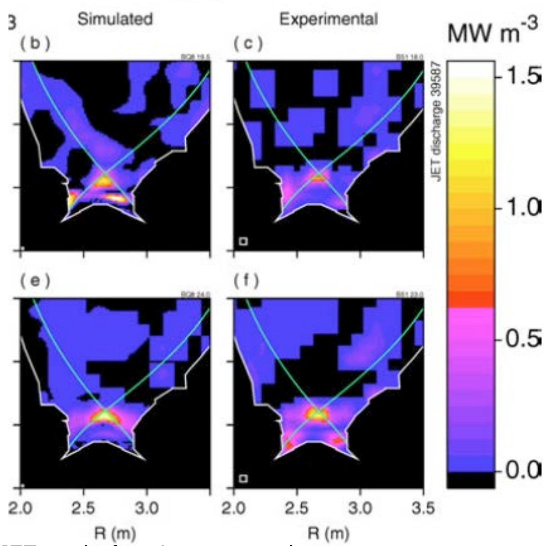
Visible bremsstrahlung imaging of Alfvén eigenmode spatial structure (Darrow, Fredrickson, …)

- Goal: Obtain 2D images of AE structures to constrain fits of measured mode numbers and amplitudes to NOVA eigenmode calculations
- Method: Capture a tangential view of plasma, preferably at midplane, with widest possible rectangle in R & Z; view at VB wavelength with high speed 12-16 bit video camera
  - AE identification & modeling presently use Mirnovs for freq & n number, plus microwave reflectometer array for absolute ñ to match NOVA eigenmodes
  - Camera data would aid in selection between nearly degenerate modes
- Resolution: ~1 cm & ~20 μs
- Supports NSTX-U research on:
  - Redistribution of NB-driven current
  - Fast ion redistribution & loss by Alfvén modes
- Suitable for university collaboration

Radiation tomography system for full cross-section radiation profile

- In NSTX-U experiments, increased emphasis on power balance in core and divertor
  - Radiative divertor and Radiative mantle
  - Disruption and Disruption mitigation studies
  - Double-null divertor studies
  - Core/Edge poloidal asymmetry studies
  - 3D physics, ELM studies
- 5-10 AXUV diode arrays needed for full coverage
- Ample NSTX experience (e.g. JHU arrays, LADA / RADA)
- Complementary to existing divertor bolometers
- Possibility for SXR filtering





Figures of JET results from Ingesson et al.
TOMOGRAPHY DIAGNOSTICS: BOLOMETRY AND SOFT X-RAY, FUSION SCIENCE AND TECHNOLOGY VOL. 53 FEB. 2008

Fast thermography and thermocouples for feedback

A. McLean, R. Maingi, J-W. Ahn, T.K. Gray

- Potential for transition to very high q operation in NSTX-U
  - Destructive to PFCs, detrimental impact on plasma performance
- Processing of dual-band IR camera data too intensive for use in real-time operations response
- 10-16 additional 'eroding' thermocouples for high speed (~1 ms response time) $T_{surface}$, q measurements in NSTX-U
  - Coverage throughout lower divertor, higher radial spatial resolution at targets (5-10 cm)
  - Customizable to ATJ, Mo, W PFCs
  - Added to existing DAC system with analog output for feedback in PCS (~1 ms latency)
    - Would be first-of-it's kind in a Tokamak
- 1-D IR diodes for high speed band-integrated measurements
  - 10-15 chord array, commercial MWIR PbS/PbSe diodes, 10 kHz operation

- Additional application of dual-band IR imaging in NSTX-U
  - Tangential wide-angle system for observation of the center stack and wall
- Enhancement of dual-band technique to simultaneous multi-band
  - Improved accuracy, immunity to Li window coatings and other losses

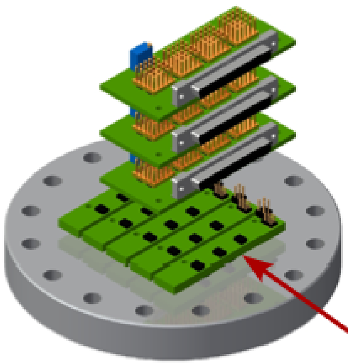
BES: Expansion and Increased Resolution

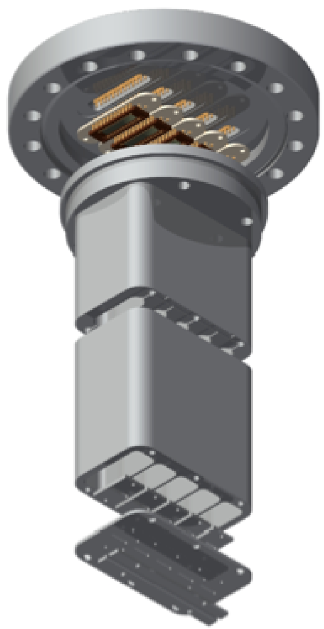
D. Smith, R. Fonck, G. McKee, I. Uzun-Kaymak, *University of Wisconsin*

- **BES provides low-k ñ fluctuation measurements (0.1<r/a<1) for:**
  - Turbulence and transport investigations
  - Energetic particle-driven mode/GAE studies
  - Pedestal structure and instabilities
- **Increase number of channels from 32 to 64 (32 new detection channels)**
  - Simultaneously sample wide region of plasma
  - Extended poloidal capability (L_c~10 cm)
- **Implement wide-field 2D (~8x8) capability (new fiber bundles/mount)**
  - Turbulence imaging; direct shear flow measurement; nonlinear analysis
  - 2D correlation, wavenumber spectra, velocimetry
- **Increase spatial resolution (smaller viewing spots)**
  - Currently ΔX~2.5 cm; decrease to ΔX~1.5-2 cm (access higher-k)
  - Pedestal studies can especially benefit
- **Measure toroidal mode # of pedestal instab. (PB/KBM), zonal flows, xAEs**
  - Exploit new neutral beam injection system
  - Add toroidally-displaced viewing channels; also, measure background signal

Toroidally Displaced In-vessel ME-SXR arrays

K. Tritz for the JHU Plasma Spectroscopy Group





- **We propose a system of two toroidally displaced, tangential edge/core multi-energy SXR (ME-SXR) arrays**

- **Each array contains:**
  - edge sub-array ($130<R<150$) ~1cm resolution, 5 diode arrays @ 20ch. ea.
  - core sub-array ($40<R<140$) ~3cm resolution, 3 diode arrays @ 32ch ea.
  - time resolution 10-100kHz

- **In-vessel design reduces port crowding, increases placement flexibility**
  - design 1: electronics in re-entrant can @ atmosphere with air cooling
  - design 2: vacuum compatible first stage electronics on detector PCB
  - potential to incorporate A/D, (fiber?) serial output for reduced wire count

- **Projected physics capabilities for NSTX-U:**
  - impurity/electron perturbative transport measurements from the edge to the core using gas puff and repetitive laser blow-off
  - fast, high resolution edge T_e, n_e, and n_z profiles for ELM studies and code validation; edge stability analysis
  - fast, toroidally resolved edge T_e, n_e, and n_z profiles for RWM/RFA studies
  - fast, toroidally resolved core T_e, n_e, and n_z profiles for disruption studies
  - real-time T_e measurements for stability prediction and feedback control development
  - enhanced, non-magnetic MHD mode identification

- **Supports NSTX-U research priorities:**
  - I-1-4: macrostability research of RWMs, NTMs, effect of 3D fields, disruptions
  - II-3: impurity transport research (also pert. electron transport measurements)
  - III-3: measure response of edge plasma to applied 3D fields
  - VI-1,2: real-time T_e for stability feedback control, detection of instability precursors

Proposals for
Magnetic Diagnostics on NSTX-U

1. Internal Tri-axial Magnetic Probe Arrays for Determining Scrape-Off-Layer Current (SOLC) Distributions in NSTX-U (*)

2. Tile Current Sensor Arrays for Measuring SOLC Distributions in NSTX-U (*)

3. Electrode Array for Exciting ELMs and Probing SOLC Structures in NSTX-U

4. External Tri-axial Magnetic Probe Arrays for Determining Structural Error Field in NSTX-U

5. High-reliability, High-resolution, Fast, Internal Diamagnetic Loop for NSTX-U

(*) The first two viewgraphs describe the first two proposals together.

H. Takahashi
Princeton Fusion Research LLC

Presented at

NSTX-U Innovative Measurements of ST Brainstorming

Tuesday, July 21, and Thursday, July 26, 2011

PPPL PRINCETON PLASMA PHYSICS LABORATORY

Determine SOLC Distributions by Magnetic Probe Arrays and Tile (Halo) Current Sensor Arrays (with Stefan Gerhardt)

• SOLC, acting as a *transforming agent* of external error field, could be a game changer in assessment of max tolerable error field in ITER.

An *unstated assumption,* underlying a stringent symmetry requirement (5 x 10^-5) for ITER based on a device-size scaling law, is that a (small) applied error field *directly* caused observed adverse plasma response (rotation slow-down/stoppage followed by a disruption).

An external error field, intrinsic or applied, may cause SOLC to flow, which in turn generates an error field of its own that is, not only greater in magnitude but also more destructive in nature, than the external field.

A much more relaxed symmetry requirement could emerge, if adverse plasma response was a consequence of this transformed error field, provided SOLC can be controlled or eliminated.

• Study and control of SOLC, as a source of dynamically-generated error field, will broadly impact NSTX-U research, as achieving *low-collisionality regimes* through eliminating rotation slow-down/stoppage, is central in demonstrating the relevance of NSTX-U program to future STs, ITER, and beyond.

• Study roles played by SOLC in ELM physics.

• Study post-disruption halo current (Gerhardt).

Determine SOLC Distribution by Magnetic Probe Arrays and Tile (Halo) Current Sensor Arrays (with Stefan Gerhardt) – cont.

• Determine a spatio-temporal structure of SOLC, which generates both axisymmetric and non-axisymmetric fields.

Solve an *inverse problem* using an SVD method, i.e., calculating a SOLC distribution from a measured SOLC-generated field distribution. Tile current, measured only at discrete locations, will serve as constraints on the solutions.

• Develop algorithm for taking advantage of *tri-axial field measurements,* which can define a field vector at the measurement point completely, both in magnitude and direction. Three field components should exhibit correlated features that are characteristic of the nature of the field source.

• Use a toroidal magnetic sensor array on the center stack as a “pseudo-Rogowski coil” to measure post-disruption halo current (Gerhardt).

• Transfer sensors, integrators, and digitizers from the structural error field measurement project.

Electrodes for SOLC Tracing and MHD Control

Broad impact on the NSTX-U program: the capability for triggering ELMs on demand in lithiated ELM-free discharges to control radiation loss and for helping to improve the vertical stability at a high-aspect-ratio.

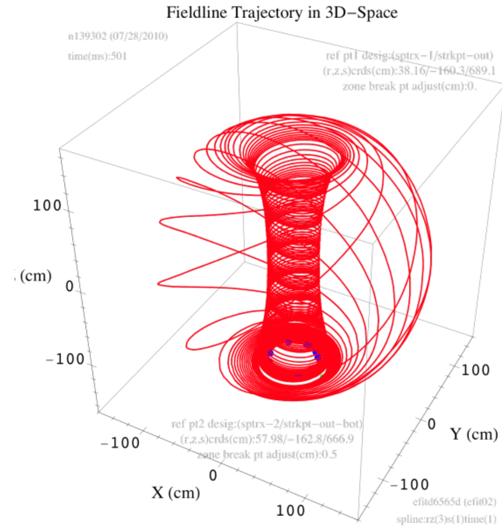
• Field lines (“wide-band”) in most part of the SOL, suffering strong toroidal angular dispersion (“phase mixing”), tend to smooth out non-axisymmetry in SOLC, with resulting axisymmetric field positively or adversely affecting the n = 0 stability.

• Field lines (“narrow-band”) around the “sweet spot,” midway between primary and secondary separatrices, tend to stay bundled together, and SOLC along these field lines generates non-axisymmetric field that may adversely affect the n > 0 stability.

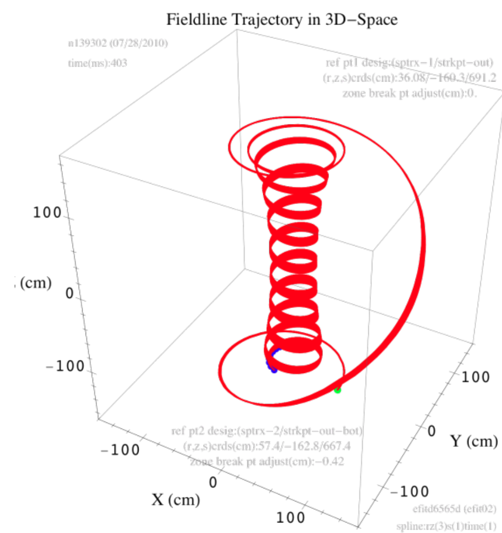
• Field lines (“interrupted”), between top and bottom divertors in far SOL well outside secondary separatrix, may play a role in triggering ELMs.

• A partial toroidal array of metal electrodes, spanning several tiles, for actively driving SOLC will give NSTX-U the capability for probing field line structures and MHD control.

Wide Band



Narrow Band



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Error Field Measurement by External Sensing Coils

- Immediate and broad impact on NSTX-U (attain *low-collisionality* by reducing rotation slow-down/stoppage)

- Develop a novel error field detection method for ITER (free from intractable *sensor motion* issues)

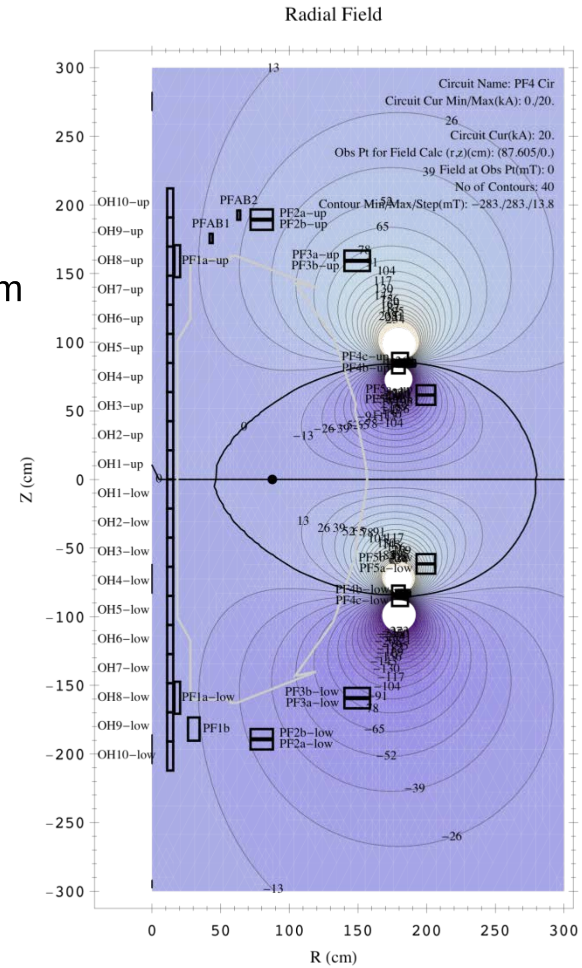
- Magnetic sensors move, if mounted on vacuum vessel under atmospheric and electromagnetic stress, but have no sensor motion issues, if mounted on (temporary) external structures independent from vessel.

- No need to accurately *install* sensors, but need only to accurately *measure* sensor locations using *cascading levels of reference points.*
  - Primary reference points on wall/ceiling/floor (laser tracker)
  - Secondary reference points on sensor frames (photogrammetry)
  - Sensor locations referred to secondary references (measuring arm)
  - Assess cumulative errors

- Develop algorithm to take advantage of *tri-axial field measurements,* which exhibit deviations from ideal response that are correlated and characteristic of the type of deviations present.

- Upon completion of external field measurement, transfer sensors, integrators, and digitizers to the internal field measurement project.

PF4 Circuit



PPPL PRINCETON PLASMA PHYSICS LABORATORY

High-Reliability/Resolution, Fast, Internal Diamagnetic Loop

- A fast-response (< 10 μs) energy diagnostic will be a unique addition to the NSTX-U diagnostic suite.

  - Establishing a causality relationship based on onset times of two phenomena – e.g., an abrupt rise of SOLC and edge thermal collapse.

  - Measuring energy change due to fast ion losses.

- Equilibrium Reconstruction

  - Diamagnetic flux provide a powerful constraint on equilibrium reconstruction process.

  With a correct diamagnetic flux, reconstruction rapidly converge to a correct equilibrium. With an incorrect diamagnetic flux, reconstruction rapidly converge to a very wrong equilibrium.

  - Tracking equilibrium changes on a fast time scale.

- Build a diamagnetic loop based on the same "philosophy" as the PBX loop.

LFS Magnetics Refurbishments

- Many flux loops and Mirnovs on the outer vessel have been damaged, but not (fully) repaired, over the years.
  - Largely masked to the research team by redundancy in that system.
  - For instance, all the lower passive plate flux loops should probably be reinstalled with guide tubes (as in the upper passive plates).
- Outage period will likely require many sensors to be displaced, and will probably break some that stay put.
  - The cutting of new ports will displace many of the vessel-mounted flux loops, high frequency Mirnov arrays.
  - Plate upgrades (?) will impact all the S/P PP flux loops and the plate-back & gap Mirnov sensors.
- Need to start the upgrade with a complete set of sensors.
  - Good enough to simply mimic the physical distribution of the present sensors.
  - Need to incorporate these needs in the outage scope.
- Also need better digitizers for the magnetics (LFS and HFS).
  - Cannot digitize the longer pulses at 5 kHz, and anything slower is getting kinda silly.
  - Efforts to test DTAQ solutions in the magnetics rack environment during the present run are in question.

•SPG