Validating electromagnetic turbulence and transport effects for burning plasmas

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FESAC Strategic Planning Panel, July 8-10, 2014

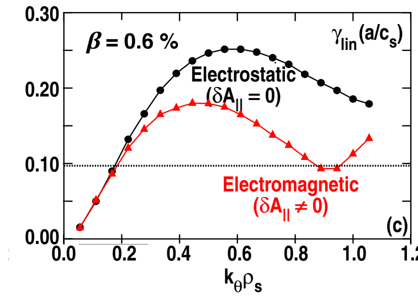
Understanding electromagnetic (EM) effects on transport is crucial for ITER/FNSF/next generation devices

- low β drift wave transport historically assumed electrostatic ($\delta B = 0$)

When are EM effects important?

- low β: predicted to significantly impact transport
  – favorable for ITER
- higher β: fundamentally new EM mechanisms predicted
  – μtearing (core), kinetic ballooning modes (pedestal) **in STs, tokamaks, RFPs & stellarators**
  – fast ion driven Global/Compressional Alfvén eigenmodes appear to enhance thermal transport in NSTX

Local GYRO linear growth rates (r/a = 0.6) for DIII-D discharges



C. Holland, NF 2012

- *Time is ripe for validation of models with EM effects*
  – *dramatic advances last decade* in code/computation capability for EM effects
  – comparison of predicted and measured δB is fundamental — internal δB diagnostics show promise for validation with focused development

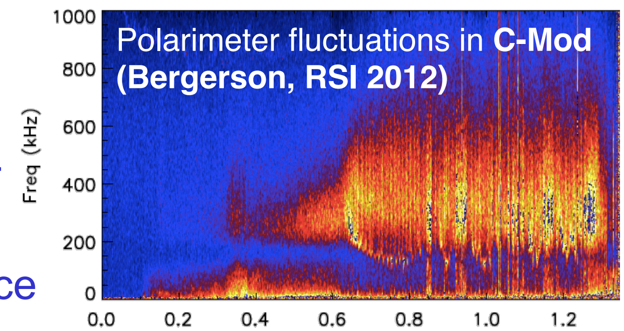
Initiative: enhance & employ internal δB diagnostics to validate models with EM effects

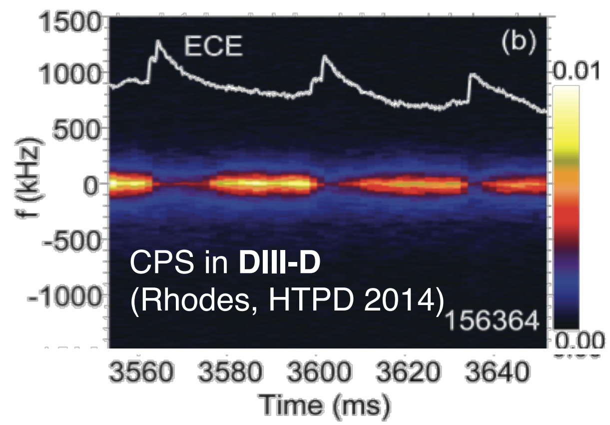
Proposed initiative addresses FES strategic goals

- Gap identified in Greenwald-Panel report (2007):
  - **G1: Sufficient understanding of underlying plasma physics to predict the performance and optimize design and operation of future devices (e.g. FNSF, ITER, DEMO)**

- Report recommended major initiative to address gap, "I-1. Initiative toward predictive modeling and validation":
  - **Combine advances in simulations with vigorous effort to validate with experiments…**
  - **"A critical element would be development and deployment of new measurement techniques"**

Internal magnetic fluctuation diagnostics show promise — validation possible with increased support for development



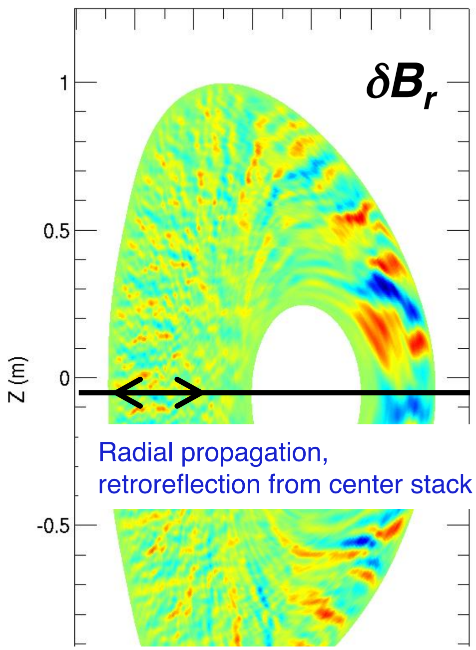


- Polarimetry – measurement shows sensitive to turbulent δB,
  - broadband fluctuations observable – C-Mod, DIII-D, MST
  - line-integrated – multi-chord desirable, costs $
  - tearing mode particle flux in MST ⇒ develop for turbulence
- Cross polarization scattering (CPS) – localized δB measurement ($k_\theta \rho_s$ ~ 0.25 – 10)
  - only localized, k_θ-resolved δB ⇒ *ideal for validation*
  - *under development* at DIII-D with DOE diagnostic grant
  - increased support ⇒ accelerated development/ implementation (STs & tokamaks)
  - recent measurements also in MAST (UCLA-CCFE)
- Many other potential techniques may advance initiative ⇒ support for development/implementation
  - HIBP, Li-beam, MSE + long history of other methods in literature
  - In many cases non-turbulence δB already achieved ⇒ development required for turbulence
- Initiative facilitated by broad β range in complementary devices
- Importance of validation⇒*targeted* support for development/implementation

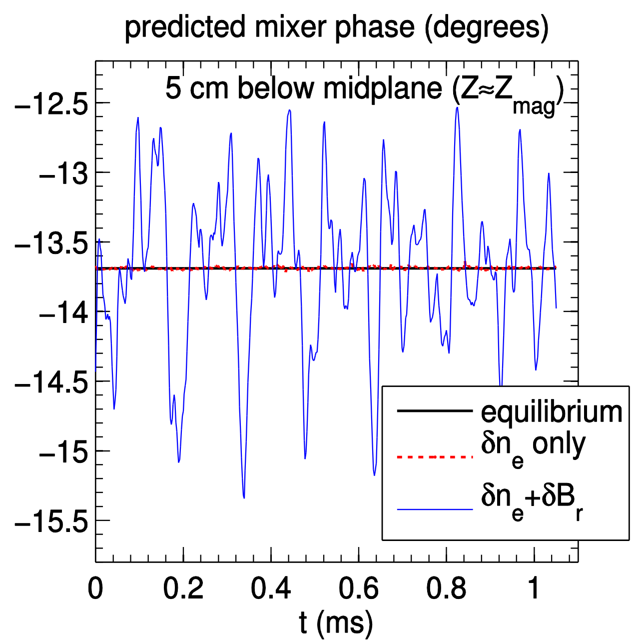
Dedicated support for synthetic diagnostic/simulation integration offers multiple benefits

- Synthetic diagnostic models measurement given simulation data
- Synthetic diagnostics necessary for comparison of experiment with measurement (e.g. synthetic diagnostics integral part of DIII-D experiments to validate GYRO code physics model)
- Facilitate planning of validation experiments — (e.g. NSTX-U, see below)
- Potentially optimize & prioritize diagnostic development through scoping studies

GYRO NSTX μtearing simulation



Predicted polarizer measurement



Importance of EM effects motivates increased support for simulation

- Existing codes (e.g., GYRO, GEM, GENE) show importance of EM effects – inclusion of EM effects challenging
  - Often require increased resolution, resources
  - Substantial effort to test resolution, global effects
  - Often encounter numerical challenges
- Routine use for validation experiments would benefit from improvements
  - e.g. more robust numerical algorithms
- Importance of EM motivating development of upgraded global-EM codes (e.g. GTS, XGC1, GTC, Gkeyll)
  - Verification important, requires dedicated effort

5-10 year goal: establish new/dramatically enhanced internal magnetic fluctuations measurements, validate EM physics

Joint theory/experiment effort:

- Coordinate theorists &experimentalists to routinely develop and interface synthetic diagnostics with simulations
  - Promote routine use for design of experiments – *experiment time costs $*
  - Target development of diagnostic capabilities for validation with support for diagnostic scoping *prior to* prototyping/implementation
    - Optimize diagnostic design to support successful validation
    - FES could prioritize support for diagnostic development/implementation
- Expand ongoing experimental validation of simulations with data
  - Requires support for increased effort running full EM simulations

Experiment effort:

- Implement/develop proven/novel diagnostic(s) at appropriate facility(ies)

Theory effort:

- Expand testing/improving existing codes & developing new codes with EM effects

10 year goal: establish new/dramatically enhanced internal magnetic fluctuations measurements, validate EM physics

Deliverables

- Significant advances in internal δB measurement capability
- Significantly advance understanding of EM effects in transport
  - EM effects on "electrostatic" turbulence at finite β
  - Effects of fundamentally EM phenomena – μtearing, Alfvén eigenmodes, …
- Sufficient understanding of EM effects on transport to optimize performance of finite β future device (FNSF, ITER, DEMO, …)
- World leadership in diagnosing, simulating and validating EM physics in turbulence & transport for burning plasma research

Budget estimate

Activity	Yearly Cost
Diagnostic Development/Implementation	2 M $
Validation experiments & Running EM GK simulations	1 M $
Integration of synthetic diagnostics with simulation	½ M $
EM simulation + model development	1 M $
Total	**4½ M $**

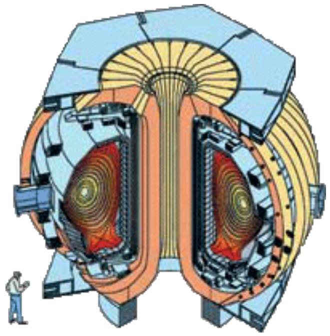
Total cost of increased effort (i.e. beyond existing effort):
4½ M $/year

Summary

- Initiative promotes US World leadership in diagnosing, simulating and validating EM physics in turbulence & transport for burning plasma research — ITER, FNSF, DEMO…
- Understanding of EM effects on transport will *improve predictive capability*, helping optimize β for future devices (FNSF, ITER, DEMO …)
- Improved magnetic diagnostics offer benefits in other areas:
  - e.g. MHD physics, disruption precursor detection

Backup Slides

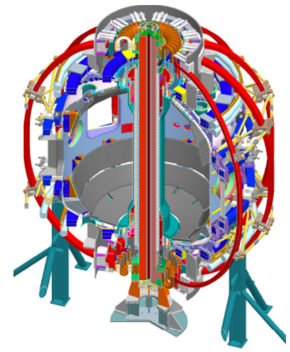
Understanding electromagnetic (EM) effects on transport is crucial for ITER/FNSF/next generation devices



Optimal FNSF performance
A=? β=?

A~3
Lower β

A~1.5
Higher β



- At lower beta (larger aspect ratio), increasing beta can be favorable for core performance
  - Finite β provides stabilizing effect to traditional electrostatic drift waves, **favorable for ITER predictions** (Kinsey, NF 2011)
  - Stabilizing effect is stronger in presence of fast ions (Holland, NF 2012; Citrin, PRL 2013) → **important for burning plasmas**
- At higher beta (lower aspect ratio), limits of further increasing beta are unclear
  - **New classes of EM drift waves** predicted (Applegate, PoP 2004; Wong, PRL 2007)
  - **Global/Compressional Alfven eigenmodes** appear to enhance electron thermal transport in NSTX (Stutman, PRL 2009; Gorelenkov, NF 2010)
  - Discrepancies in multi-machine confinement scaling with beta, collisionality (Petty, PoP 2007) → **influences extrapolations for CTF/FNSF (Valovic, NF 2010; Menard, NF 2012)**

Electromagnetic effects are emerging as increasingly important for many toroidal devices, from core to pedestal

- "Microtearing" drift waves (fundamentallly EM, unique from electrostatic mechanisms) predicted both in core and near pedestal top of:
  - **Spherical tokamaks**: **NSTX** (Wong, 2007; Guttenfelder 2011/12), **MAST** (Applegate, 2007; Dickinson, 2012)
  - **Tokamaks**: **AUG** (Vermare, 2007), **DIII-D** (Petty, IAEA 2012), **JET** (Sareelma IAEA 2012; Moradi, NF 2013), **ITER** (Wong, APS 2010)
  - **Stellarators**: **LHD** (Ishizawa PoP 2014)
  - **RFPs**: **MST** (Carmody, PoP 2013); **RFX** (Predebon, PRL 201)
- EM mechanisms (peeling-ballooning + KBM drift wave) appear to set constraint for H-mode pedestal (Snyder, NF 200)
- EM effects likely important for ELM dynamics (Wilson/Cowley? Xu)

- Measurements & theory/computation tools are insufficient to broadly measure, predict & validate these effects, lags understanding of electrostatic transport
  1. Challenging to measure microscopic internal magnetic fluctuations (localization; smaller amplitude), although promising base of work already exists (next slides)
  2. Numerical simulations challenged by resolution, global effects, typically requires more resources
- With investment, US could become world leader in validating EM transport effects, for STs and tokamaks

Internal δB Diagnostics
Soltwisch, Diagnostics Workshop, Madrid, 1992

Deflection of Heavy Ion Beams	ST (1975)
Fast-Ion Orbits created by Tangential Neutral Beam Injection	ATC (1978) PDX (1985)
Polarization Spectroscopy of Intrinsic Impurity Lines	TEXT (1988)
Neutral Lithium Beam Spectroscopy	PULSATOR (1977) ASDEX (1986), TEXT (1987)
Observation of injected H- and Li-pellets	TFR (1986), JET (1989) TFTR (1990)
Motional Stark Effect on Neutral Hydrogen Beams	JET (1989), PBX-M (1989) DIII-D (1991)
Harmonic Generation by Microwave Beams	ST (1975)
Incoherent Thomson Scattering	DITE (1978), TORTUR (1989)
Faraday-Effect on Far-Infrared Laser Beams	TEXTOR (1984), JET (1989)
Excitation of Alfvén-Waves	TCA (1989), TEXTOR (1990)

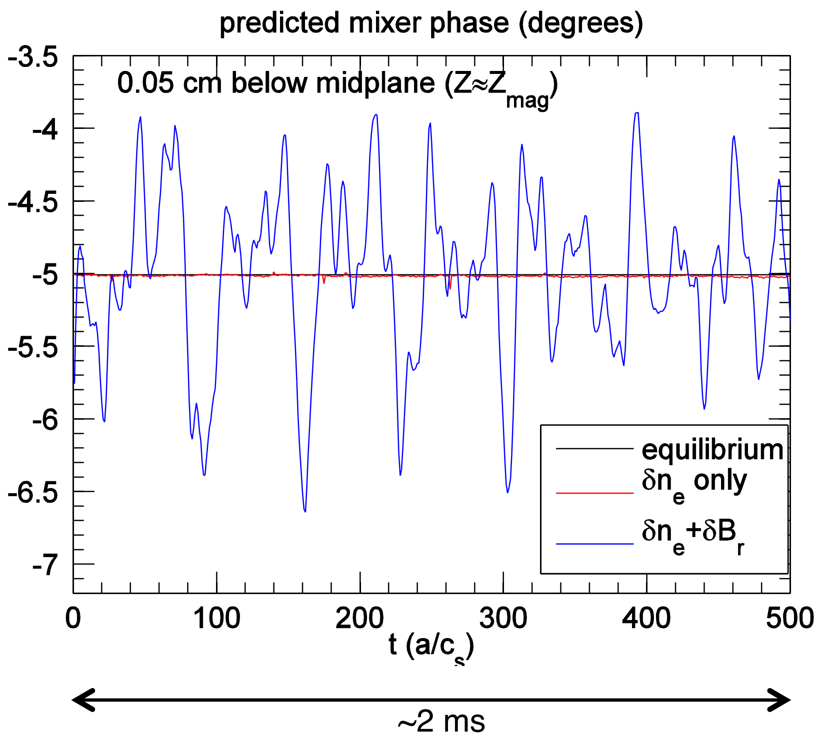
Tab. 1: List of methods for internal magnetic field measurements and corresponding tokamaks.

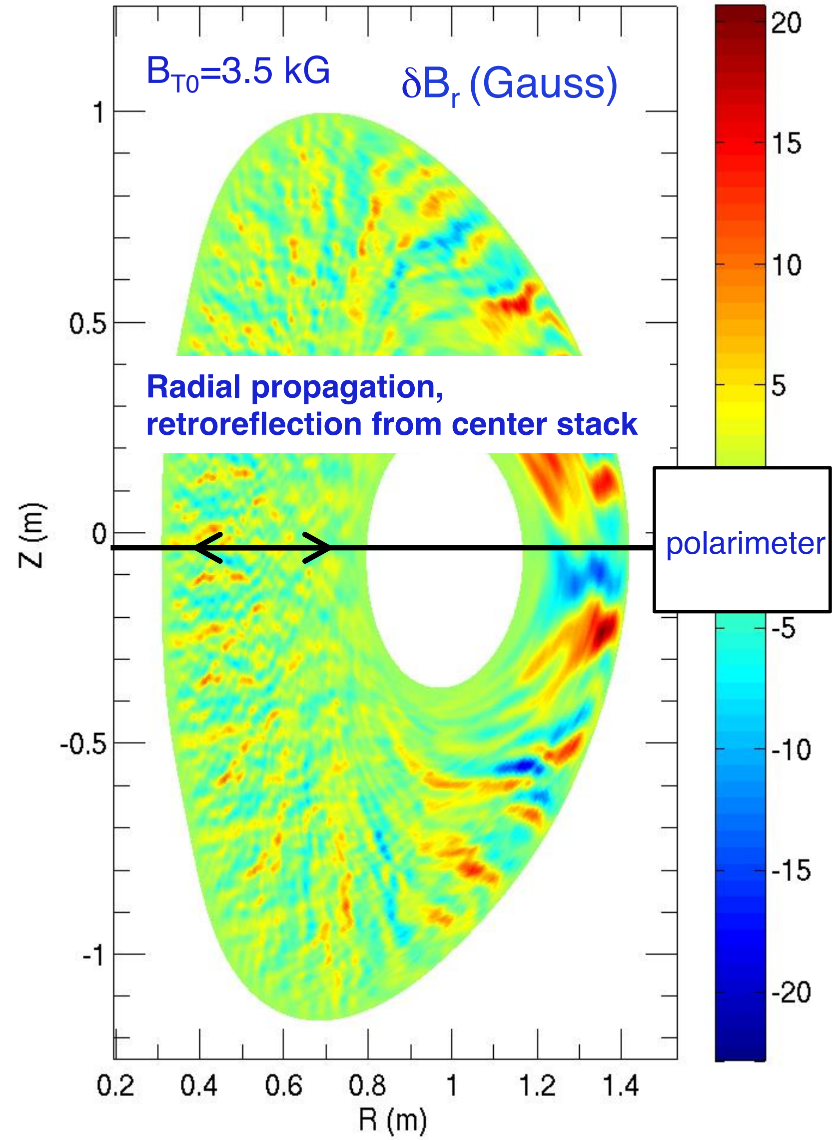
Fine-scale Gaps

- 4.b.3 – Predictive modeling
  - Gap: Verification
  - Gap: Validation
  - Gap: Turbulence & transport
  - Gap: Plasma edge turbulence
  - Mission elements:
    - Improved diagnostics for validation of theory/simulation
    - Enhancements to basic theory for models
    - Improvements in numerical models and algorithms
    - Computing facilities (ASCR

Polarimetry for magnetic field fluctuations

- New UCLA polarimetry system (J. Zhang, PP9.71)
- Simulations suggest $(\delta B/B)_{internal} \leq 0.1\%$ may be detectable (1-2^0 or ~0.3^0 rms mixer phase)

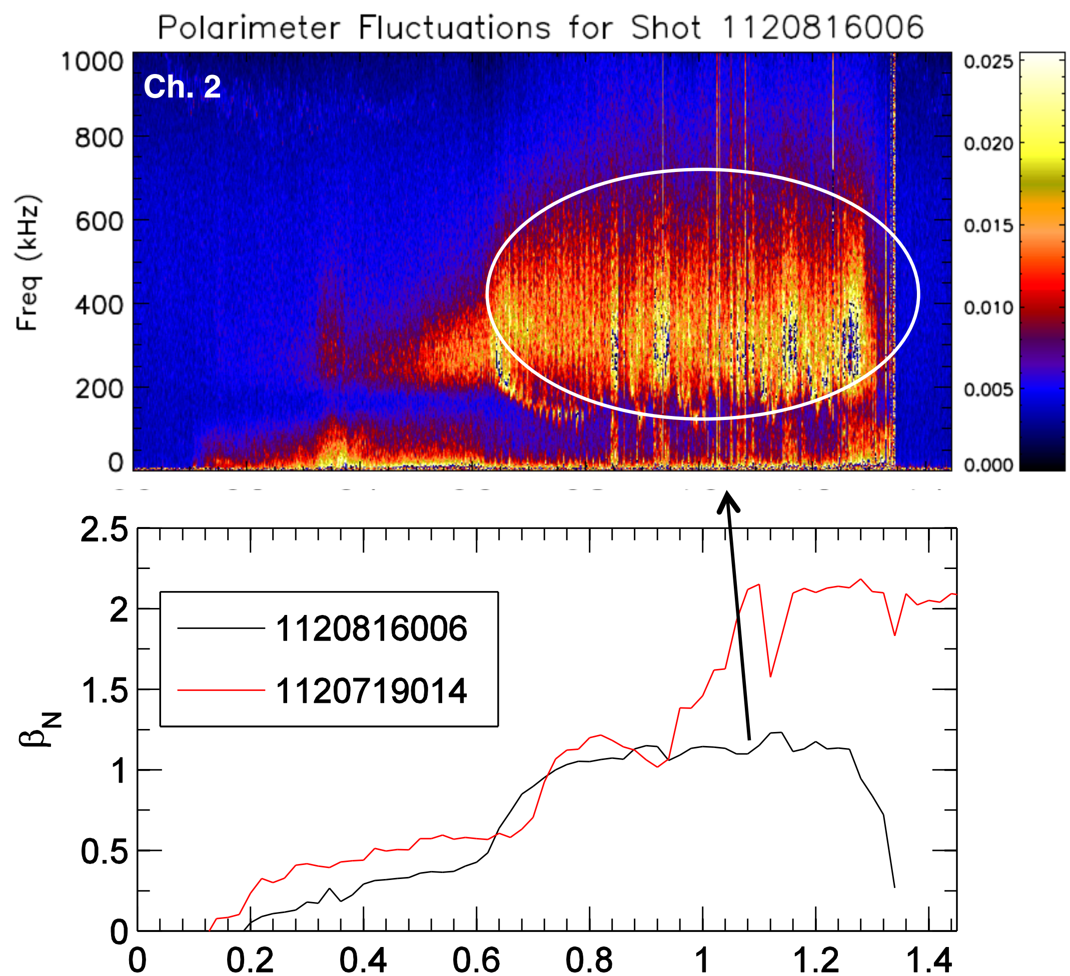




Collaborating with C-Mod to investigate electromagnetic effects & diagnostics related to NSTX-U

- Broadband fluctuations observed in C-Mod line-integrated polarimeter ($\sim n_e \cdot B$), not seen in PCI ($\sim n_e$ only) (Bergerson, RSI 2012)

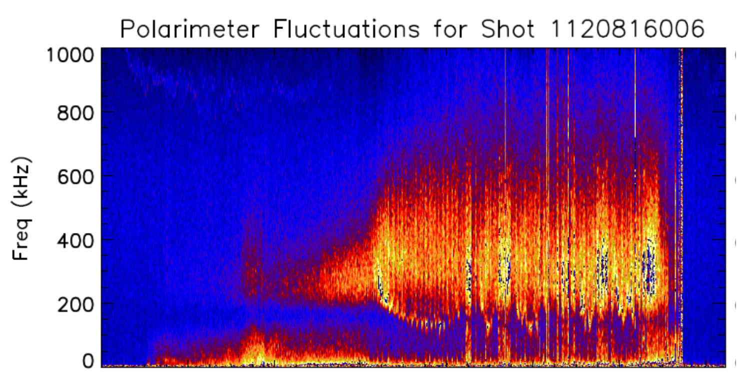
- Collaborating on gyrokinetic analysis and measurement interpretation in anticipation of related NSTX-U research
  - Experimental run time allocated for FY14 to investigate $\beta_N \sim 2$ ITER-like scenarios, hopefully with new polarimeter data



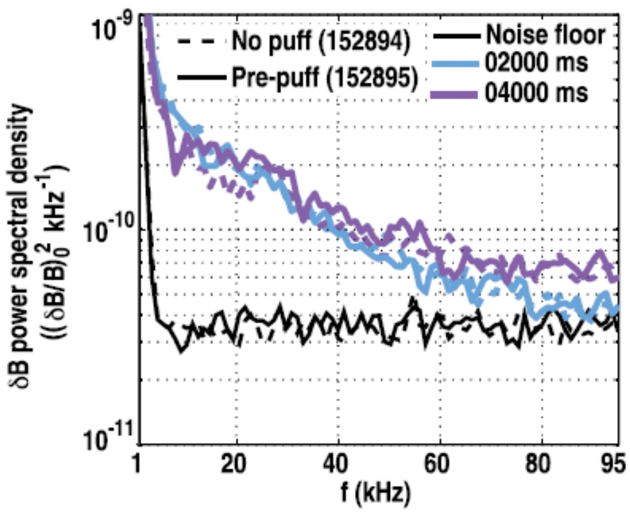
Recent internal magnetic fluctuation measurements show promise for use in EM validation studies

- Polarimetry – line-integrated but sensitive to many features
  - MST (e.g. Brower, RSI 2001; Ding PRL 2013), pioneering work in the RFP
  - Recent measurements in tokamaks indicate magnetic fluctuations observable

Broadband polarimeter fluctuations in **C-Mod**, not observed in PCI density fluctuations
Bergerson, RSI (2012)
Full capabilities not realized due to 2012 funding cuts



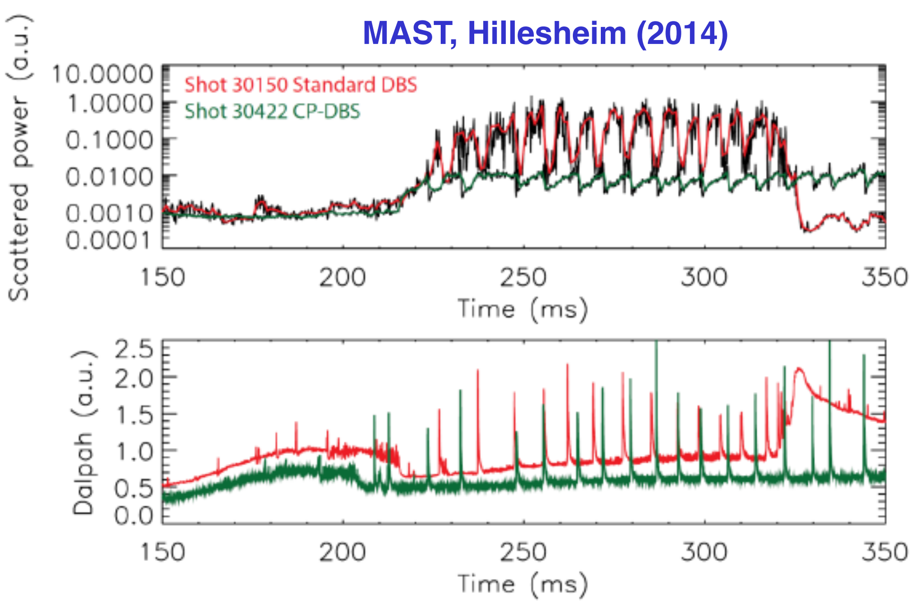
Broadband polarimeter fluctuations in **DIII-D** from runaway electrons
Zhang, RSI 2012; Paz-Soldan, PoP (2014)



Recent internal magnetic fluctuation measurements show promise for use in EM validation studies

- Polarimetry – line-integrated but sensitive to many features
  - MST (e.g. Brower, RSI 2001; Ding PRL 2013), pioneering work in the RFP
  - Recent measurements in tokamaks indicate magnetic fluctuations observable
  - Very limited progress in validation of first principles EM simulations
- Cross polarization scattering (CPS) – localized measurement
  - Following earlier work, e.g. on Tore Supra (Zou, PRL 1995)
  - Distinct behavior observed in CPS (~δB) compared to Doppler backscattering (DBS, ~δn), in both MAST and DIII-D

MAST, Hillesheim (2014)



DIII-D, Rhodes, HTPD (2014)