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Progress and plans in NSTX Theory and Modeling Research

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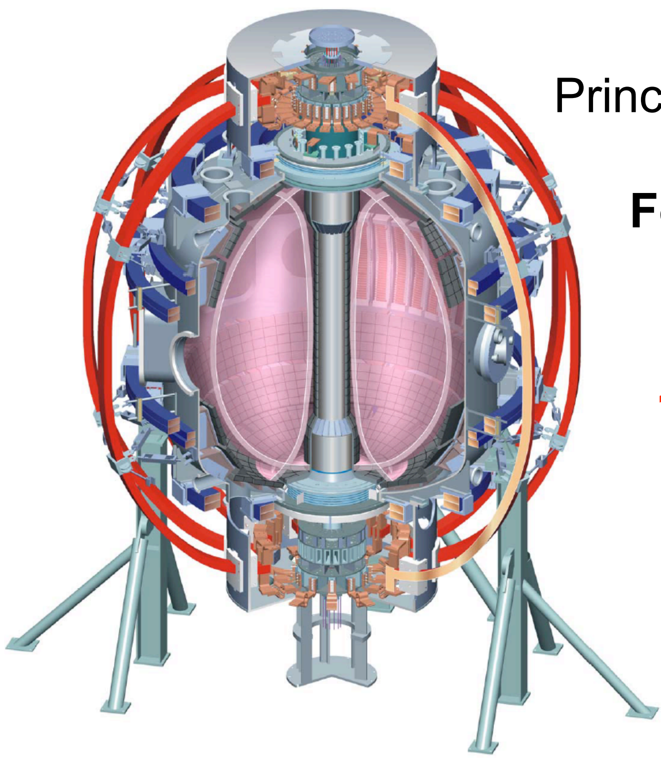
For the NSTX National Team



17th NSTX PAC Meeting
January 20 – 21, 2005

Columbia U
Comp-X
General Atomics
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There has been significant progress in ST relevant theory

- Rotation effects: Equilibrium => Stability
- μ-turbulence: Linear => Non-linear
- Treatment of kinetic effects
- Code benchmarking => applications
- Model equilibria => discharge analysis
- Experiment and theory comparisons

- Selected accomplishments and Plans

NSTX benefits from a large group of theory contributors

> 20 institutions > 50 researchers

Batchelor – ORNL	Gorelenkov - PPPL	Mau - UCSD	Schaeffer - GA
Berry – ORNL	Guazzoto - Rochester	McCune – PPPL	Sontag - Columbia
Bers - MIT	Harvey – CompX	Menard - PPPL	Soukhanovskii - LLNL
Belova - PPPL	Hinton - GA	Mikkelsen - PPPL	Sovinec – Wisconsin
Betti - Rochester	Hogan - ORNL	Myra - Lodestar	Stotler - PPPL
Bonoli – MIT	Houlberg - ORNL	Nishimura - Irvine	Strauss - NYU
Brambilla – IPP	Hu – Rochester	Park-PPPL	Tang - LANL
Carter - ORNL	Jaeger – ORNL	Phillips-PPPL	Taylor – PPPL
Cary - Wisconsin	Jardin – PPPL	Pigarov - UCSD	Umansky - LLNL
D'Ippolito - Lodestar	Kaye - PPPL	Ram - MIT	Wang - PPPL
Dorland - Maryland	Lewandowski - PPPL	Raman – Wash.	White - PPPL
Fu - PPPL	Lin – Irvine	Redi - PPPL	Wilson – PPPL
Glasser - LANL	Liu - Chalmers	Rewoldt – PPPL	Wright - MIT
	Manickam - PPPL	Sabbagh - Columbia	Zhu - Columbia

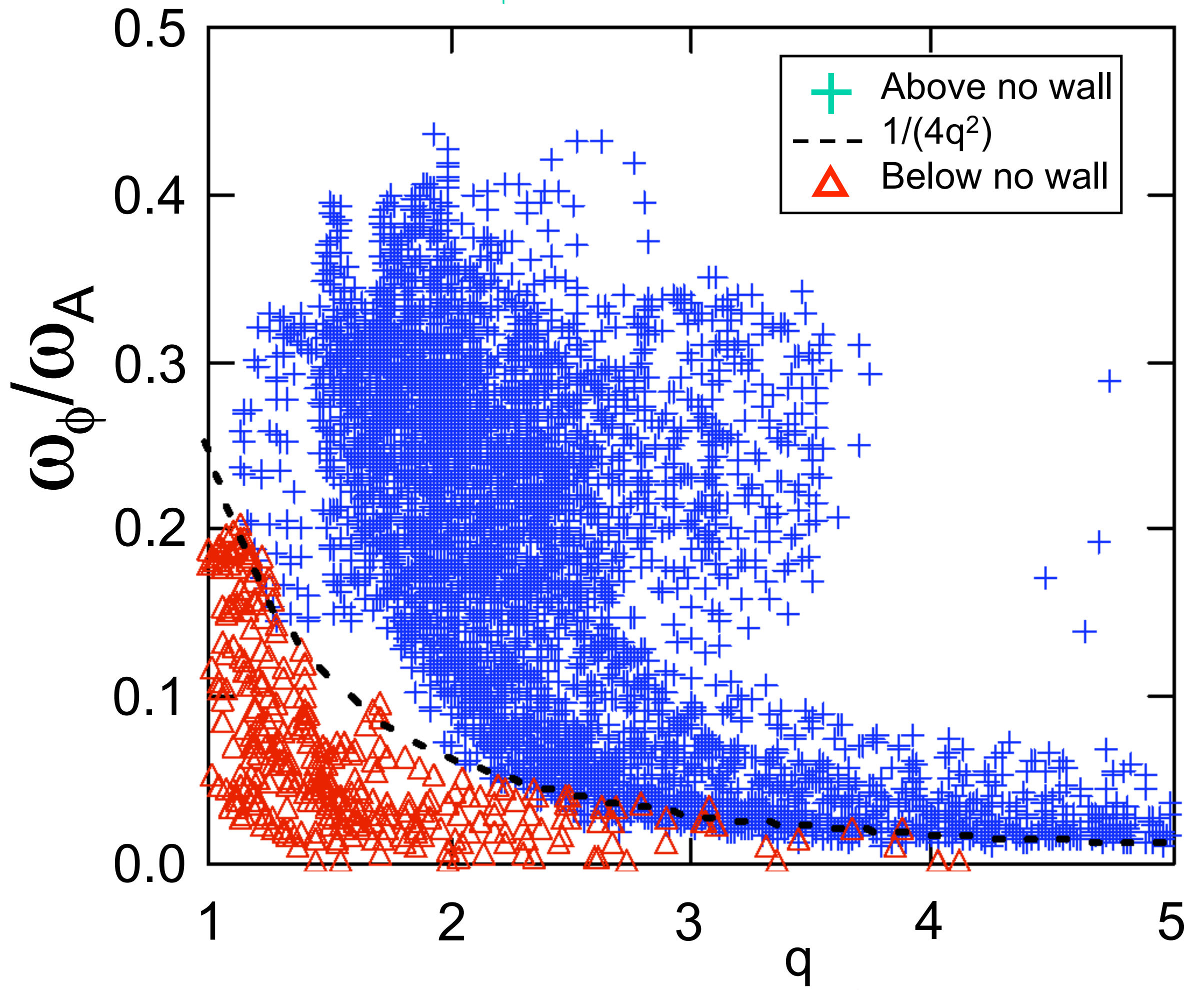
Theory issues for macroscopic stability

Focus on modes that limit high-β performance:

- External modes → RWM
  - Comparison with drift kinetic theory
  - Comparisons with MARS, M3D
  - Understanding role of resistivity and dissipation
- Internal kink modes
  - Understanding saturation at high β and rotation
  - Impact of non-linear effects on fast ion and thermal rotation
  - Does this core mode reduce its own instability drive?
- Flow damping from MHD modes
  - Neoclassical toroidal viscosity (NTV) largely consistent with data

NSTX critical rotation data aids understanding of rotation/dissipation stabilization of RWM

$\omega_\phi/\omega_A(q,t)$ profiles



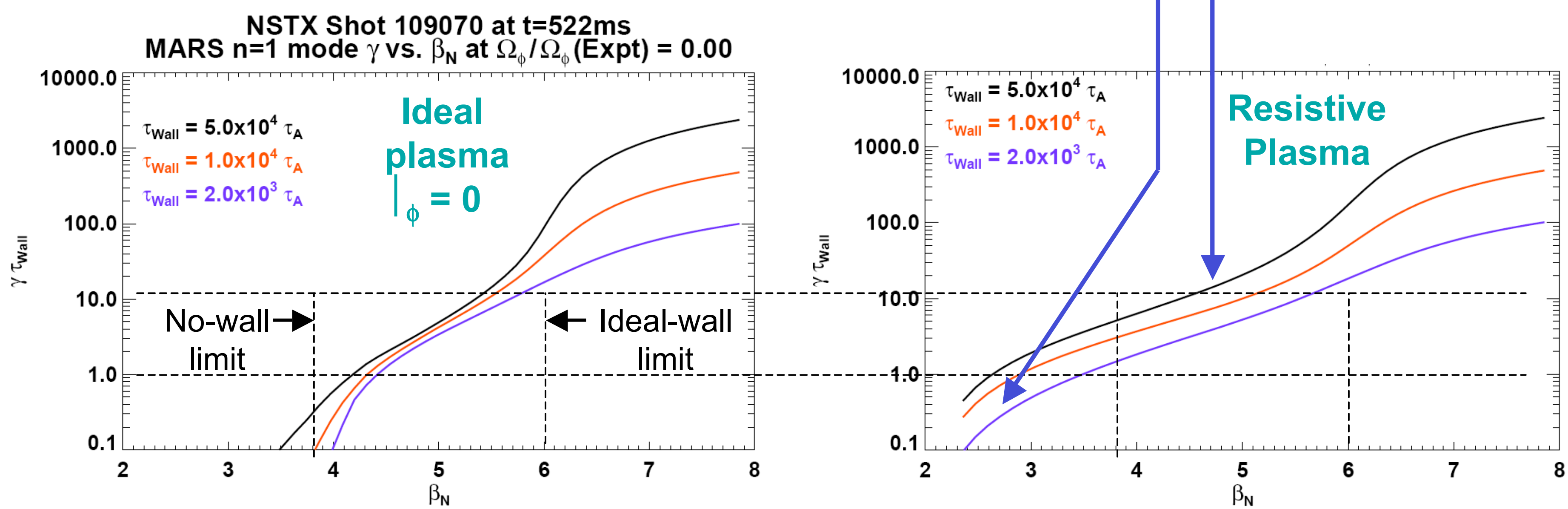
- Experimental $/_{crit}$
  - Stable vs. unstable regions separated by $\omega_\phi = \omega_A/(4q^2)$
- Drift Kinetic Theory
  - Trapped-particle effects significantly weaken ion Landau damping
  - Toroidal inertia enhancement modifies eigenfunction when $\omega > \omega_A/4q^2$

ITPA NSTX- DIII-D similarity experiment planned

Columbia,LANL

Studies of NSTX RWM physics with MARS code

- Example: impact of resistivity
  - $\eta > 0$ increases $\gamma\tau_{WALL}$ for large τ_{WALL}
  - Also apparent lowering of no-wall limit



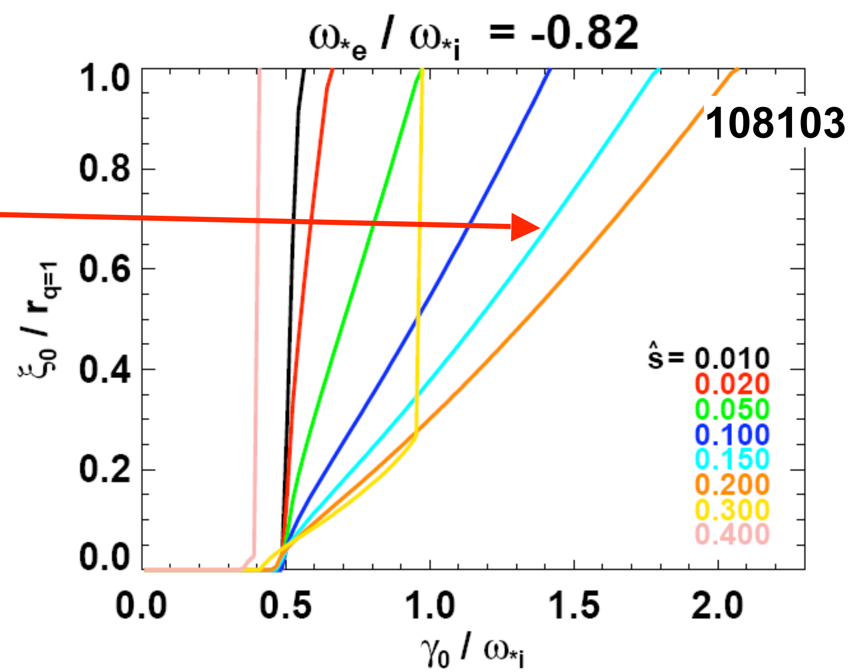
- $\eta > 0$ required for benchmarking/comparison to M3D
  - Studying interplay between resistivity and dissipation
- Will test Bondeson/Chu kinetic damping model in MARS for NSTX

Chalmers, GA,PPPL

Diamagnetic effects may contribute to saturation of the 1/1 mode at high β

NSTX

- High $\beta \Rightarrow$ increased $\omega_{*i} / \omega_A \propto \beta_i A \delta_i / a$ ⟵ $A = R_0/a$ = aspect ratio, δ_i = ion skin depth, a = minor radius
- Displacement of core by 1/1 island can enhance local pressure gradient and magnetic shear in reconnection region
  - Significant non-linear stabilization possible in ST
  - Both ω_{*i} and ω_{*e} important
- Shear parameter $s \approx 0.15$ allows $\xi_0 / r_{q=1} \approx 0.5$, similar to observed displacement
- MSE will allow shear measurement this year



Understanding of Rotation Damping from MHD Modes is Being Tested Quantitatively in NSTX

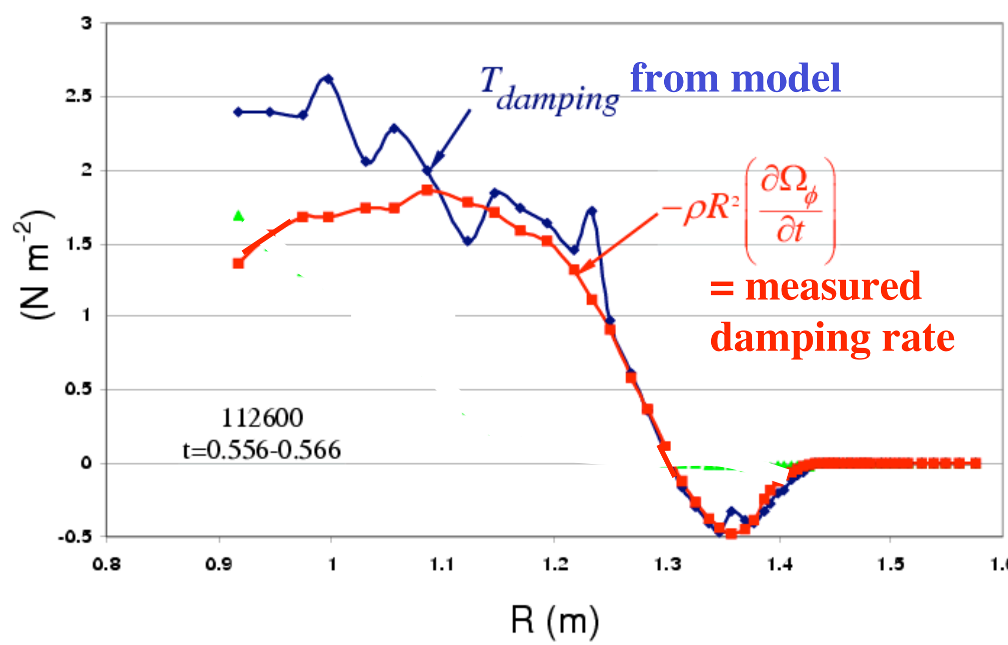
- Example: Coupled 1/1 and 2/1 modes in high-β collapse involve:
  - Neoclassical Toroidal Viscous (NTV) differential torque from 1/1 mode
  - Entrainment of plasma mass inside phase-locked 2/1 island (T_{EM} is small)
  - Fluid viscosity outside islands

Torque balance ⇒ $$\rho R^2 \frac{\partial \Omega_\phi}{\partial t} \underbrace{- R^2 \frac{1}{r}\frac{\partial}{\partial r}\left[\rho \mu_\perp r \frac{\partial \Omega_\phi}{\partial r}\right] + T_{NTV}}_{\textstyle\rightarrow \boldsymbol{T_{damping}}} + T_{EM}\,\text{(on island only)} = S_\phi$$

$$T_{\mathrm{NTV}} \sim (T_{\mathrm{i}})^{\frac{1}{2}} \sum_{m,n} \left(\Omega_\phi - \Omega_{\mathrm{mode}}^{m,n}\right) \left(\frac{b_r^{m,n}}{B}\right)^2$$

Use SXR to reconstruct amplitude of perturbed helical flux $\delta\Psi_h \Rightarrow b_r^{m,n}$

RWM & other modes show similar good agreement



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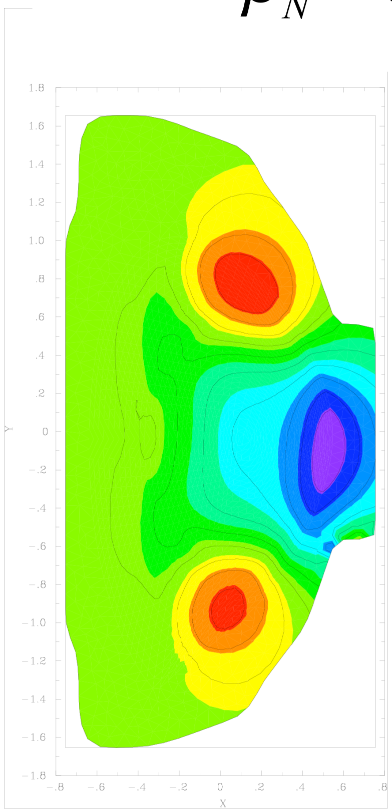
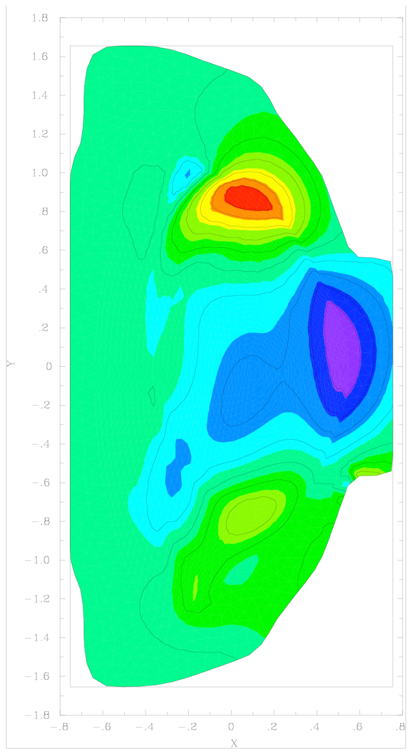
Initial linear RWM studies using M3D

NSTX

$\beta_N = 5, q_0 = 1.7$



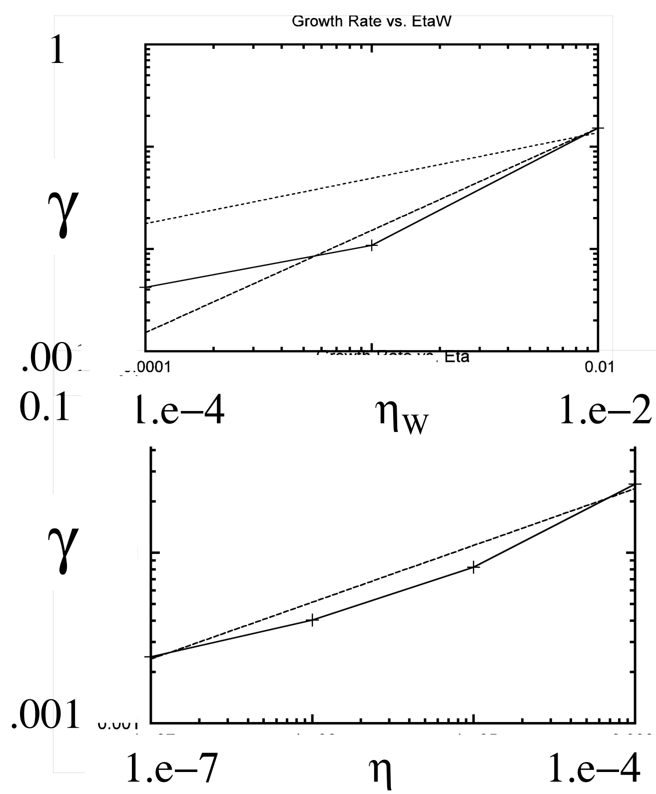
Perturbed Poloidal flux at $\Omega = 0$



Saturated at $\Omega = 0.05 \frac{v_A}{R}$ w/ collisional viscosity

PPPL,NYU

Resistive plasma / resistive wall mode growth rate scaling:



Find scaling

$\gamma \sim \eta^{1/3} \eta_w^{4/9}$

Similar to analytic result, will compare to MARS

Transport and turbulence issues

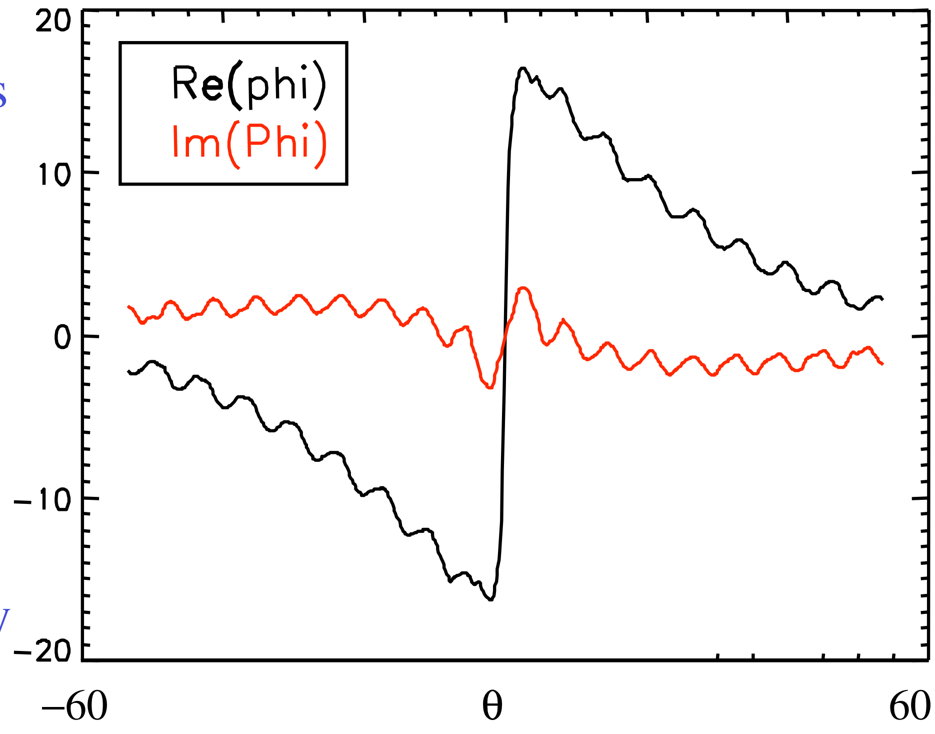
NSTX

- Ion transport
  - Microturbulence studies - linear and non-linear
  - Neoclassical Theory – NCLASS, GTC-NEO
- Electron transport
  - ETG, μ-tearing
  - High-k turbulence measurement
- Fast ion confinement
  - Energetic particle modes
- Thermal confinement properties
  - with B_T, dimensionless parameters (β, ρ^*, ν^*)
- Internal transport barriers

GS2 - Gyrokinetic Calculations for NSTX

Progress:

- Linear GS2 simulations: low and high density L-mode, H-mode, high β plasmas
- ITG, TEM, ETG, μ–tearing parity drift modes
- Initial correlations with χ_e, χ_I



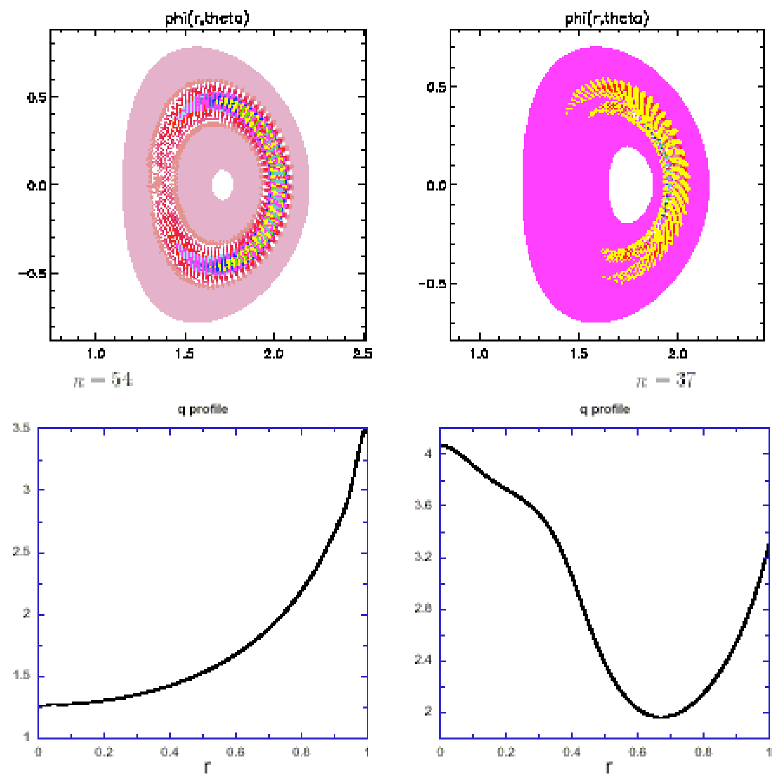
Plans:

- Continue nonlinear GS2 simulations
- Microtearing nonlinear simulations may require 10-100x computational time needed for ITG, ETG
- GYRO profile code comparisons, including ExB shear

GA,Maryland,PPPL

New neo-classical code: GTC-NEO is being applied to equilibria based on experiment

- GTC-Neo global simulation allows for large and non-standard orbits & shaped tokamak geometry (calculates particle, momentum, energy transport, j_b, E_r, …)
- Scaling of q_i and E_r with B, and also convergence with radial resolution of MHD equilibrium, have now been checked
- However, no impurity or beam species yet in GTC-Neo
- GTC-Neo Code is now being applied to experimental cases

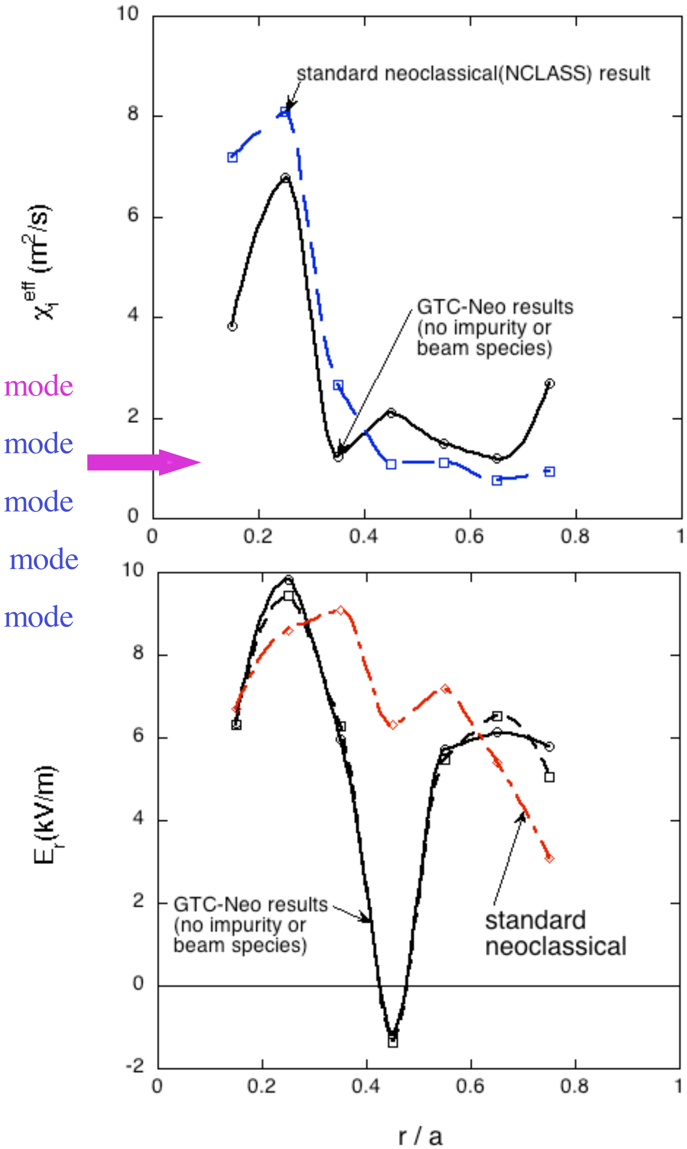


A shaped geometry application
Comparing monotonic and RS profiles

Initial results from GTC-Neo for NSTX

- Initial results here for NSTX shot 112989
    - (low-density shear-reversal L-mode with electron and ion ITBs)
    - no carbon or beam species in GTC-Neo
- For this case, GTC-Neo $\chi_i^{eff}(r)$ similar to standard neoclassical, but other GTC-Neo cases can show strong nonlocality !
- For this case, GTC-Neo $E_r(r)$ gives a much deeper well, near the middle of ITBs, compared to standard neoclassical, different $V_{pol}(r)$!
- E_r to be input to GYRO

112989 – L- mode
112996 – L- mode
108213 – L- mode
112596 – H- mode
112600 – L- mode



GA,ORNL,PPPL

Nonlinear GYRO Simulation Studies have begun

NSTX

1. Non-adiabatic electron effects greatly increase long-wavelength transport. This is not ETG activity, it is only TEM /ITG synergy.
2. As expected, ExB shear derived from the measured v_{tor} strongly reduces the low-k turbulence, but the predicted transport fluxes are comparable to or larger than the actual heating power.
3. The predicted ion heat flux is higher than the electron heat flux, but the experimental transport analysis reverses that ordering.
4. Need to evaluate the turbulent ion-electron heat transfer power.
5. Future topics:
   - Further convergence studies.
   - Compare with GS2.
   - Determine influence of uncertain inputs on predictions.
   - Evaluate electromagnetic effects.
   - Compare with reflectometer measurements.

GA,Maryland,PPPL

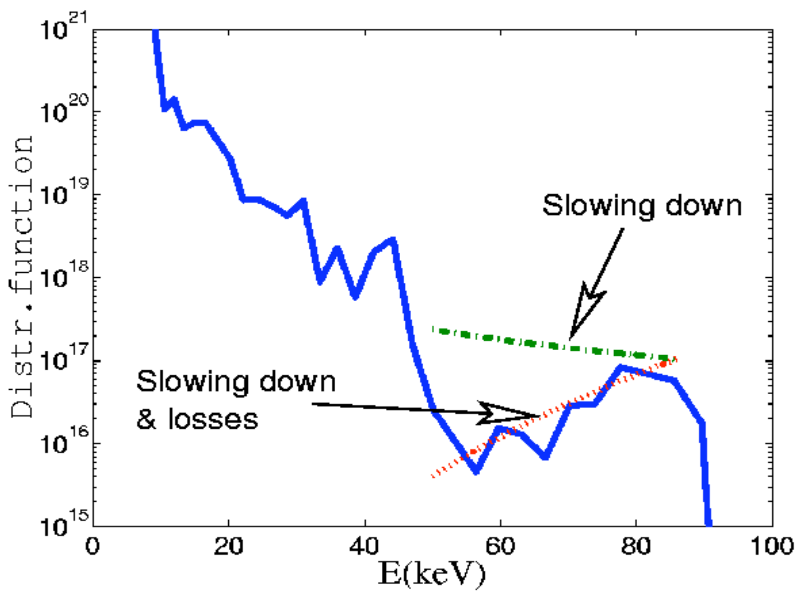
Energetic particle driven issues

NSTX

- MHD induced fast particle loss
- CAE, GAE simulations
- Non-linear hybrid simulation of TAE
- Comparison with experiment

MHD induced redistribution of beam ions in NSTX

Analytical theory has been applied to calculate the loss time in NSTX shot #108730 at t~400msec: τ_{loss} = 1msec.



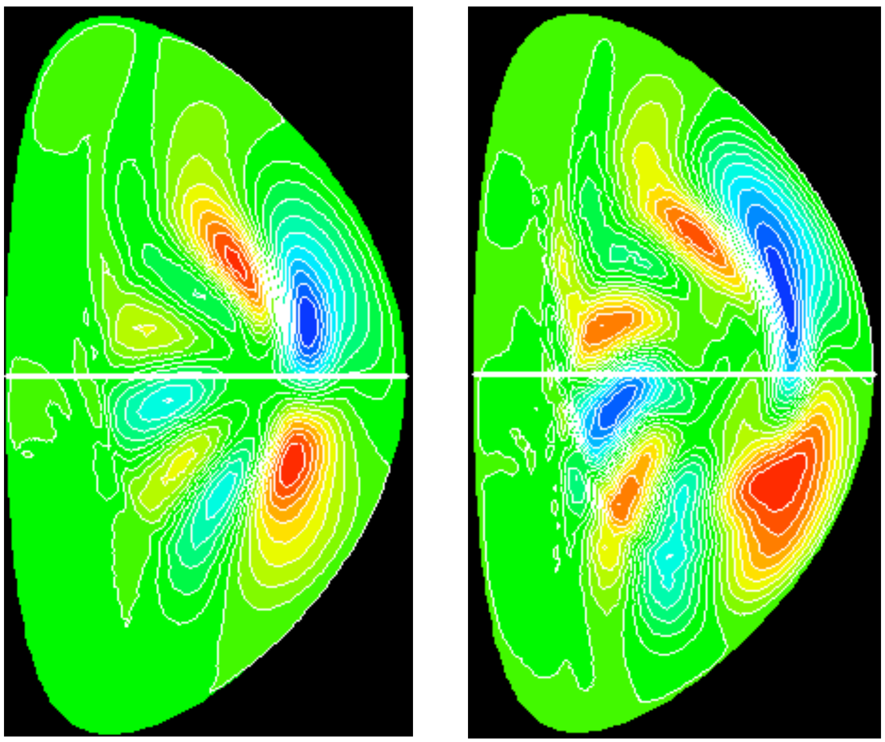
- Application of the ORBIT code gave results consistent with observations.
- Losses are selective in energies through resonant interaction with MHD activity.
- Predicted strong sensitivity to the q-profile needs to be confirmed.

1. **Spectrum obtained by NPA (S.S. Medley)**
2. **Fast ions with energies 50<E(keV)<80 are affected**

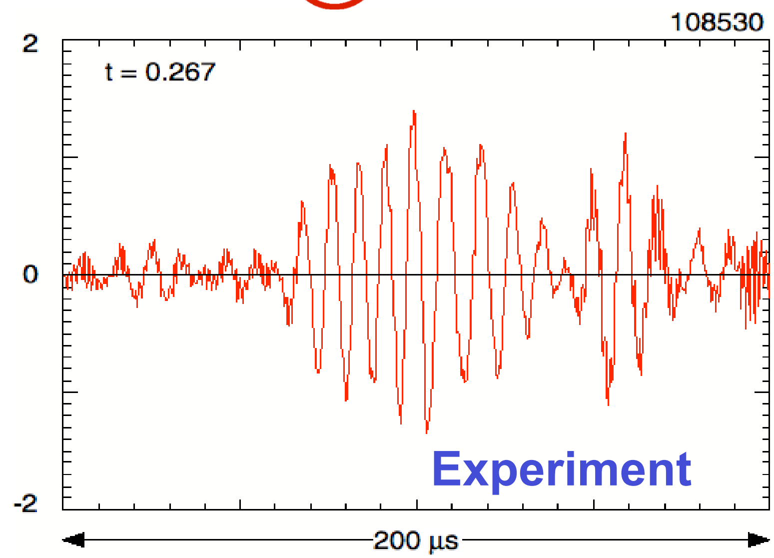
Bursting Modes in NSTX

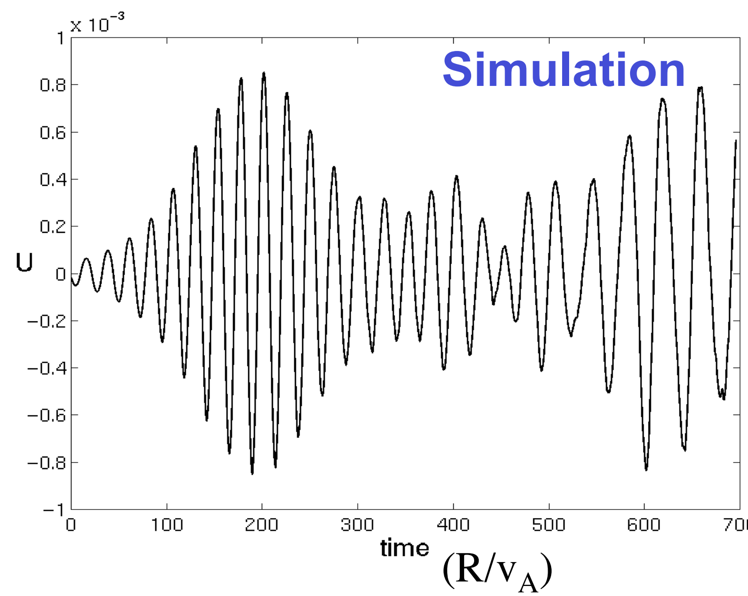
M3D Nonlinear Hybrid simulations of beam-driven modes in NSTX, shows a bursting TAE as the mode moves out radially.

t=0.0 t=336



NYU,PPPL





Significant Enhancements have been Completed on the ICRF Full-wave Solver TORIC

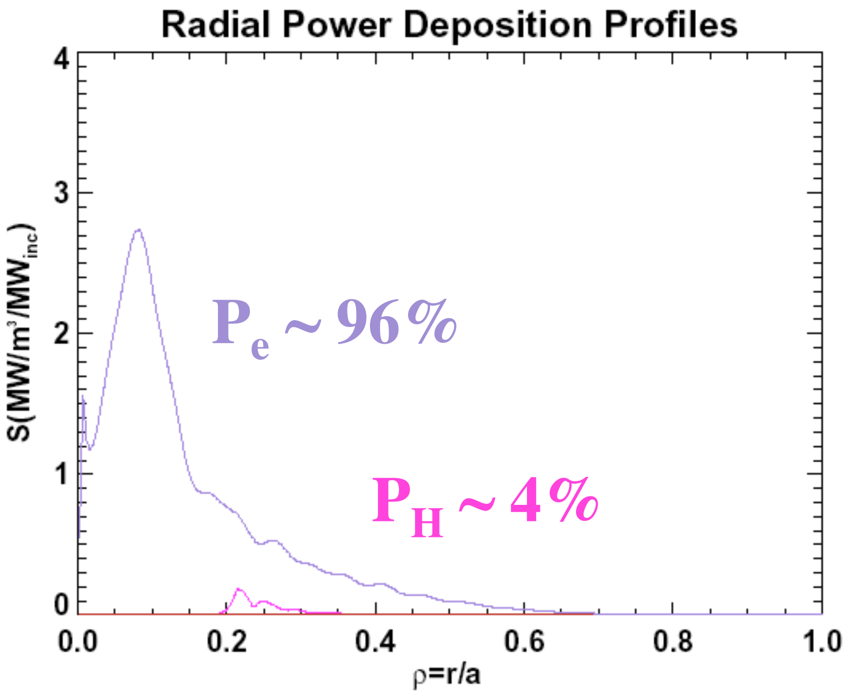
NSTX

- Has been used in standalone mode to understand the phasing dependence of HHFW heating on NSTX:
- Uses EFIT equilibria and experimental profiles
- Coupling of TORIC4 to the Fokker Planck module FPPRF is nearly complete and is being tested for release in TRANSP (D. McCune - PPPL).
- Conductivity operator is being rewritten to be valid for arbitrary particle distributions (PPPL, MIT)
  - Study HHFW – NBI interaction in NSTX
- Plasma is being extended to conducting wall with electric field boundary condition at wall:
  - Study ICRF antenna coupling in NSTX under more realistic edge plasma conditions

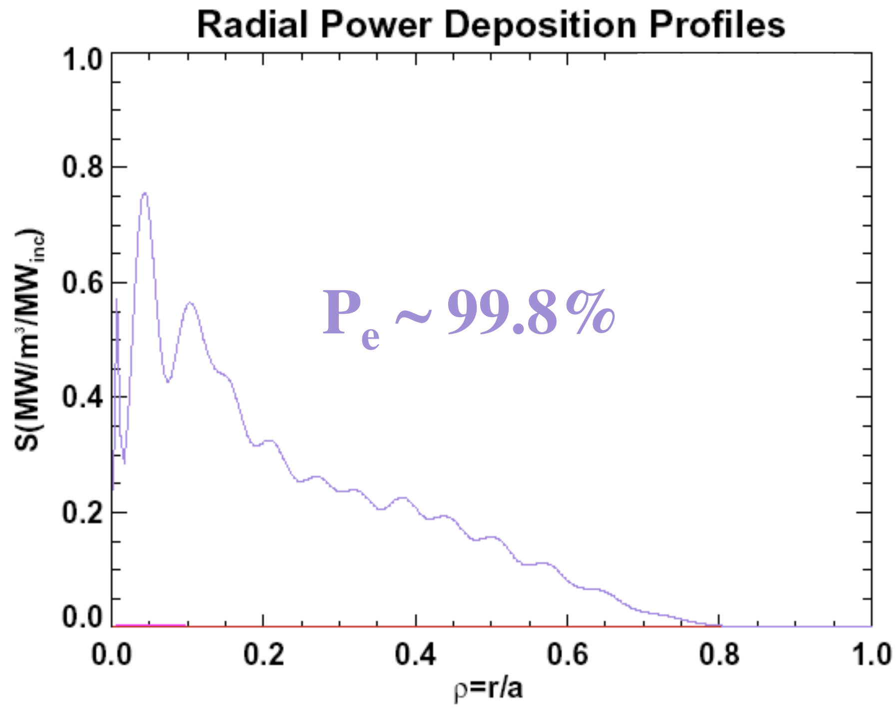
TORIC Simulations Indicate Power Deposition Dominated by Electron Absorption

NSTX

112705 :-7 m^{-1}



112699 :-14 m^{-1}



- Note that hydrogen can begin to absorb power at the lower k_{tor}
- No edge power deposition predicted with linear absorption mechanisms
- TORIC results agree qualitatively with CURRAY (ray-tracing)
- Non-linear mechanism (parametric instabilities into IBW) is needed to explain the observed edge ion heating

Numerical Studies of HHFW - NBI Interaction in NSTX Have Progressed Through SciDac

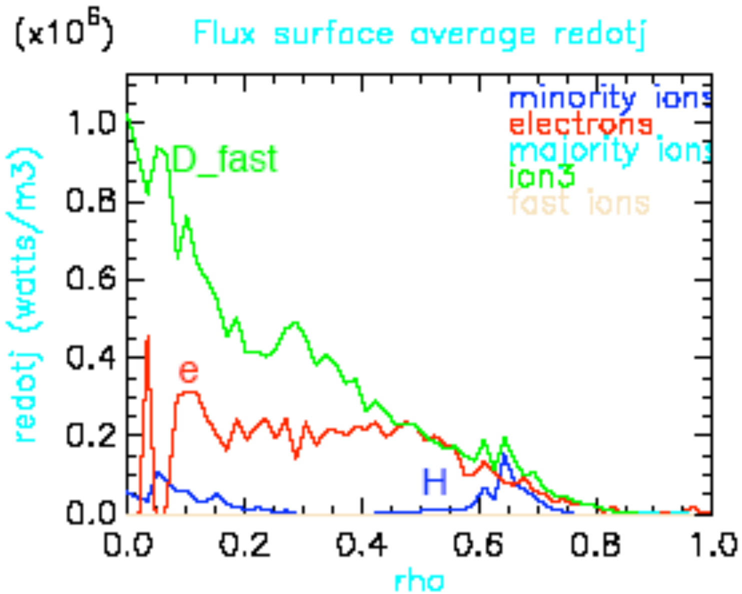
NSTX

- All Orders Spectral Solver (AORSA2D) is used to compute the HH full-wave fields.
- SIGMAD modules used to evaluate the plasma response in AORSA for non-Maxwellian particle distribution.
- Fast NB ion distribution obtained using the CQL3D Fokker Planck solver.
- Near term plans include a self-consistent iteration between all three codes.

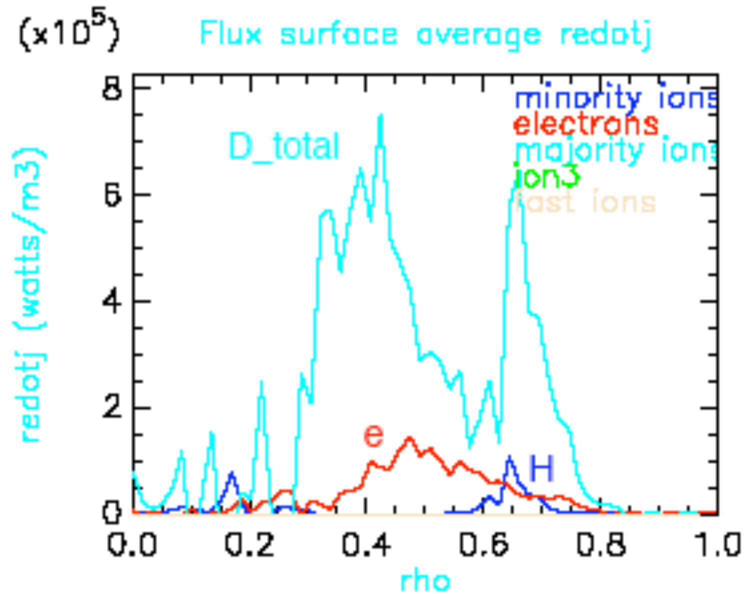
HHFW - NBI interaction study shows the importance of using proper numerical distribution functions

NSTX

Bi-Maxwellian with 17.1 keV for fast D
(analytic with *Z* functions)



CQL3D with 65X129 velocity grid



- **We see significant differences compared to two temperature Maxwellian model:**
  - Much narrower ion absorption zones around high harmonic cyclotron resonances
  - Much less deposition into electrons: 15%/41%, more power into D: 81%/52%

CompX,ORNL,PPPL

Recent EBW Modeling

- Completed GENRAY/CQL3D EBW current drive study for non-inductive β = 20-40% NSTX plasmas:
  - predict efficient off-axis Ohkawa current drive up to β = 40%
  - Ohkawa current being modeled over wide parameter range
- Measured good EBW coupling via oblique O-mode with 16-18 GHz EBW radiometry:
  - ~ 80% EBW coupling observed, consistent with Preinhaelter 3-D EBW ray tracing & coupling model prediction
- Recently started MAST collaboration to benchmark between BANDIT & GENRAY/CQL3D
- Recent results from MIT's relativistic ray tracing code, R2D2, indicate relativistic effects may affect EBW dispersion when T_e > 0.8 keV

Planned EBW Modeling

- Integrate AORSA1-D EBW coupling model with GENRAY
- Investigate impact of electron diffusion on CD localization:
  - Initial results indicate ~ 2 cm spreading for D_e ~ 10 m^2/s
- Effect of trapped electron pinch to be studied
- Integrate MIT's R2D2 fully relativistic EBW ray tracing package into GENRAY
- Benchmark MIT's drift-kinetic Fokker-Planck code, DKE, with CQL3D and BANDIT2
- MIT group to investigate edge plasma interactions of HHFW - EC - EBW
- Investigate whether parametric decay instabilities are an issue for coupling to the EBWs at high power

Edge physics theory and modeling

- Neutrals transport
  - Physics validation with experiment – done
  - Supersonic gas injector, neutrals, cryopump design studies
- Diagnostics simulation
  - GPI
- Blob theory
  - Resistive interchange – blob dynamics
  - Dust simulation – DUSTMC/UEDGE
- BOUT
  - Numerical issues – radial boundary cond., ΔT
- Impurity transport
- ELM modeling – improved resolution in data planned

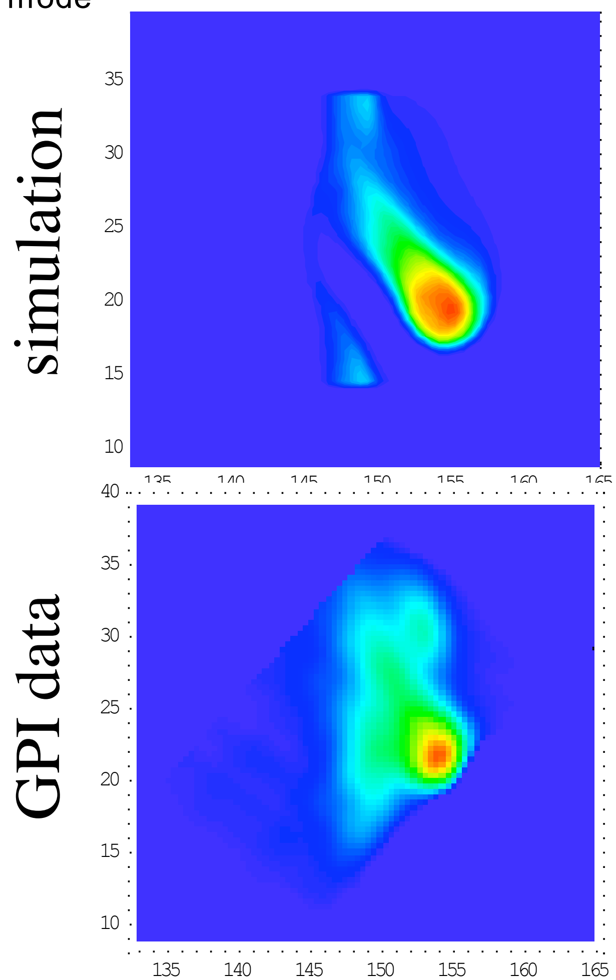
Neutral Transport Modeling with DEGAS 2

- Initial simulations of supersonic gas injector
  - Assumed fixed plasma parameters,
    - Found that higher gas flow velocity does not significantly increase penetration.
  - Planning more detailed work in support of 2005 SGI experiments & for design of future GPI injector.
- Benchmark 3-D gas flow simulations
  - Against gas conductance measurements in C-Mod,
  - And literature values for gas flow through pipes,
  - Preparing for NSTX applications,
    - Developing detailed model of in-vessel hardware.
    - Characterize poloidal variation of recycling & fueling,
    - Will lead into assessment of need for & design of cryopump.

Theory Based Model Reproduces Blob Dynamics Seen in Gas Puff Imaging Experiments

NSTX
#108311
H mode

40 μs after blob birth

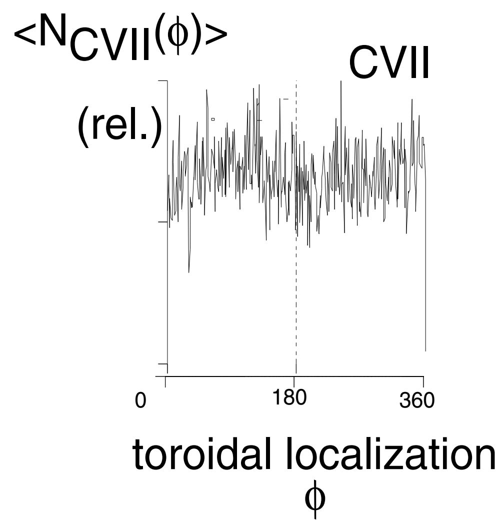


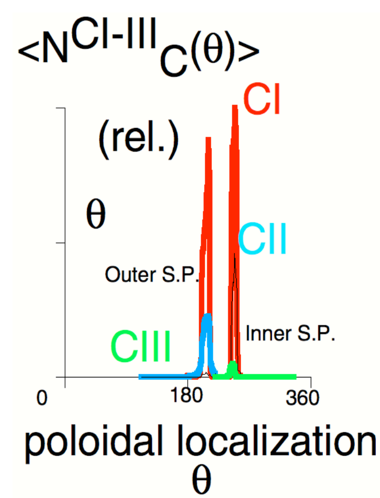
Lodestar,PPPL

- Start with DEGAS 2 neutral density, atomic physics,
- Passive convection assumption allows inverse mapping: n_e, $T_e \leftarrow I_{GPI}$
  - Gives blob initial conditions.
- Lodestar 2-D fluid code $\Rightarrow$ blob evolution,
  - Radial, poloidal motion & wake similar to experiment.
- Lodestar theory has also identified regimes for blob propagation,
  - E.g., not-too-bright GPI blobs follow predicted scaling of v_r with blob size.

Impurity transport modeling

- BBQ calculations of quiescent cross-field transport of impurities generated at the divertor strike points find little mid-plane deposition, using conventional models.
- ‘Bursty’ low-field side, far-SOL transport and/or ELMs should give higher deposition rates
- Uniform toroidally – no localization
- Poloidal localization around strike points
- The BBQ model will be compared with absolute carbon densities from CHERS under quiescent conditions in the edge / SOL.
- Also on AUG, TEXTOR, JET

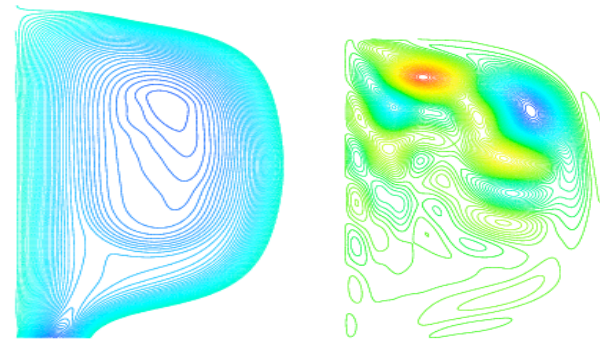


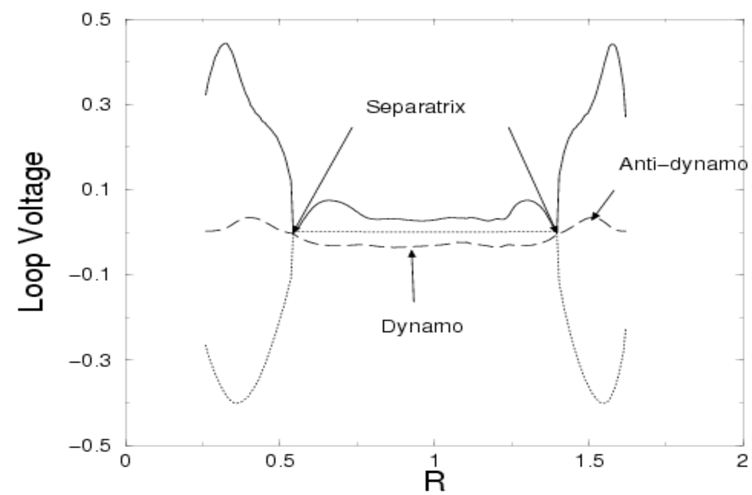


Non-inductive CD theory and modeling

- CHI
  - Formation of closed flux surfces
  - Improved understanding of the role of helical instabilities
  - Flux amplification
- Current amplification
  - Filament injection modeling for PEGASUS
  - NSTX applications

Helical instabilities cascade to relaxation





$$\frac{\partial \overline{\chi}_0(\psi,t)}{\partial t} = V_D(\psi,t) + V_\eta(\psi,t) + V_\Phi(\psi,t)$$

Columbia,LANL

Modeling Electrostatic Current Filament Injection

• Electrostatic current drive through biased probes and miniature plasma guns has been accomplished on CDX, CCT and MST.

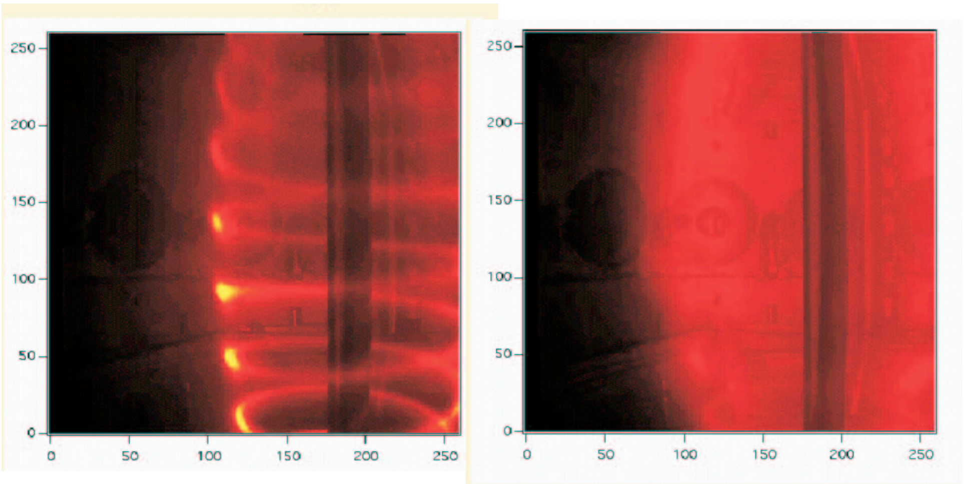
• Plasma guns also have potential as a means for non-inductive startup in spherical tori and are now being tested on the Pegasus ST at Wisconsin

• Experimentally, low power produces a distinct filament, but higher power leads to merger and current amplification greater than the vacuum magnetic winding.

• The MHD and energy transport aspects of current filament merger is being studied

•Ohmic drive with vertical-field transients has been previously simulated

•Support Pegasus studies to provide recommendations on filament injection for NSTX



Images of electrostatically driven plasmas in Pegasus at 50 V (left) and 400 V (right).

NSTX theory studies impact on Burning Plasma Physics

NSTX

- Accessing BP relevant regimes
  - Energetic particle confinement and energetic particle modes
  - RSAE induced losses
  - Non-linear coupling of RF to fast particles and neutron production
  - $V_{beam}/V_{Alfvén}$ ~ $V_{\alpha}/V_{Alfvén}$ (ITER) ~ 2 to 4
- Leverage in validating theoretical models
  - RWM modeling and rotation damping studies – high β, |
  - Kinetic transport, including electromagnetic effects – rot. Shear, ρ_i/L
  - RF modeling validation with strong mode coupling
  - High trapped particle fraction
  - Edge physics – turbulence and strong mode coupling

NSTX has an active theory and modeling program

- It is a broad based national program
- Complementary to the experimental program
- Potential for validating physics models so that they are applicable in a wide range