Supported by

NSTX Research Results and Implications for Plans for 2005 - 2007

E.J. Synakowski
PPPL

on behalf of the NSTX National Team

APS-DPP 2004

Savannah, Georgia

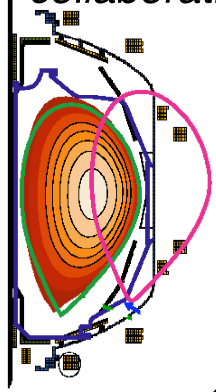
Columbia U
Comp-X
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
NYU
ORNL
PPPL
PSI
SNL
UC Davis
UC Irvine
UCLA
UCSD
U Maryland
U New Mexico
U Rochester
U Washington
U Wisconsin
Culham Sci Ctr
Hiroshima U
HIST
Kyushu Tokai U
Niigata U
Tsukuba U
U Tokyo
Ioffe Inst
TRINITI
KBSI
KAIST
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
U Quebec

- Presented here are some highlights from 2004's research effort, with a discussion of implications for the plan and goals for 2005 - 2007. The 2004 run period saw increases in operating space that enabled extensions of studies of high beta plasma science. In establishing the physics basis for long pulse, high beta ST operations, advantage was taken of this with an expanded set of diagnostic, analysis, and control tools. Research in 2004 focused on critical elements of transport, including turbulence measurements and the studies of electron thermal transport. MHD studies include the first application of active field perturbation coils. Solenoid-free startup and sustainment research focus on exploration of new startup techniques, as well as EBW research aimed at assessing the viability of EBW current drive. Boundary physics studies focus on edge transport characteristics as well as the nature of the mechanisms driving the fluxes. Examples of progress and issues, and elements of the plans regarding each of these topics will be outlined.

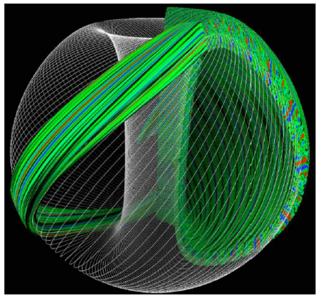
Unique NSTX plasma properties provide scientific leverage in all major areas of toroidal confinement research

Strengthen the scientific basis for fusion energy

Experimental collaboration



Theory-experiment coupling



Core transport & turbulence

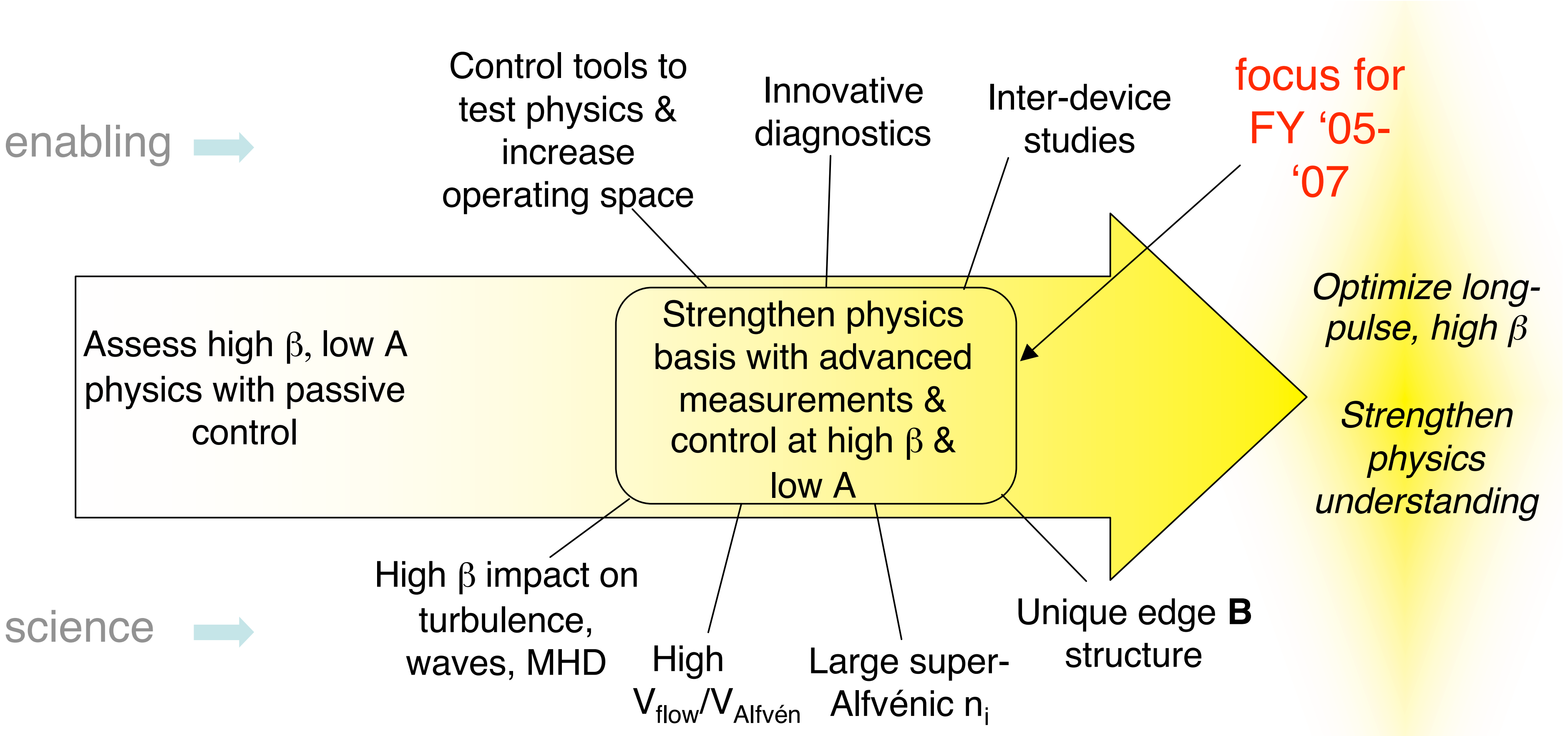
Edge transport & stability

MHD: stability & helicity injection

Wave/particle interactions

Test theory by isolating important physics and challenging models at their extremes of applicability

NSTX research is entering a phase of advanced diagnostic implementation and advanced control

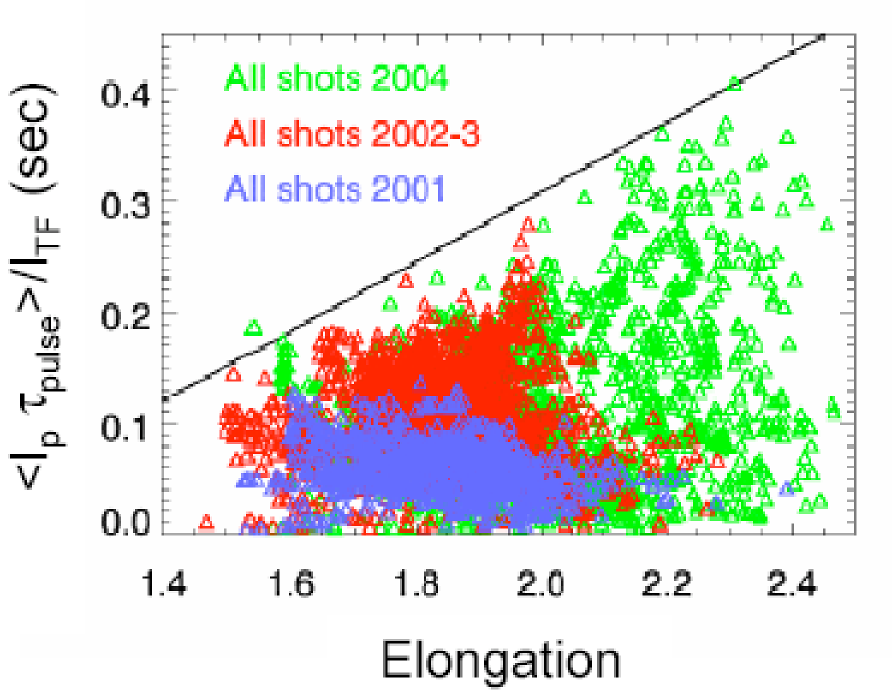


- *Take maximal scientific advantage of ST plasma characteristics through novel diagnostics and new control tools, and targeted inter-device studies*

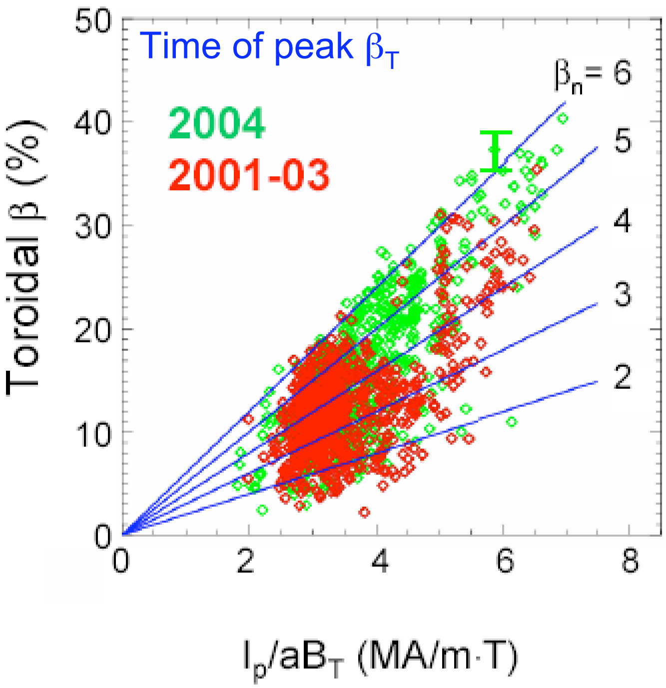
NSTX research led to an expansion of operating space in 2004

Reduced latency improved vertical control at high-κ, high-β_T

More routine high κ, δ
Longer current flattop duration
$\tau_{pulse} = \tau(>0.85\ I_{p,max})$

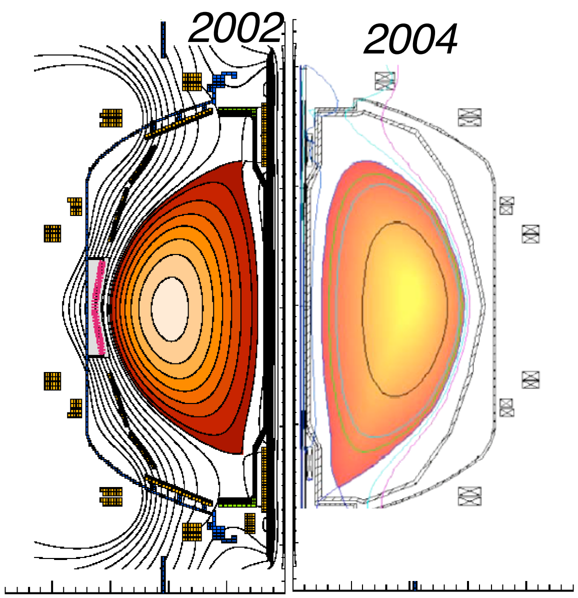


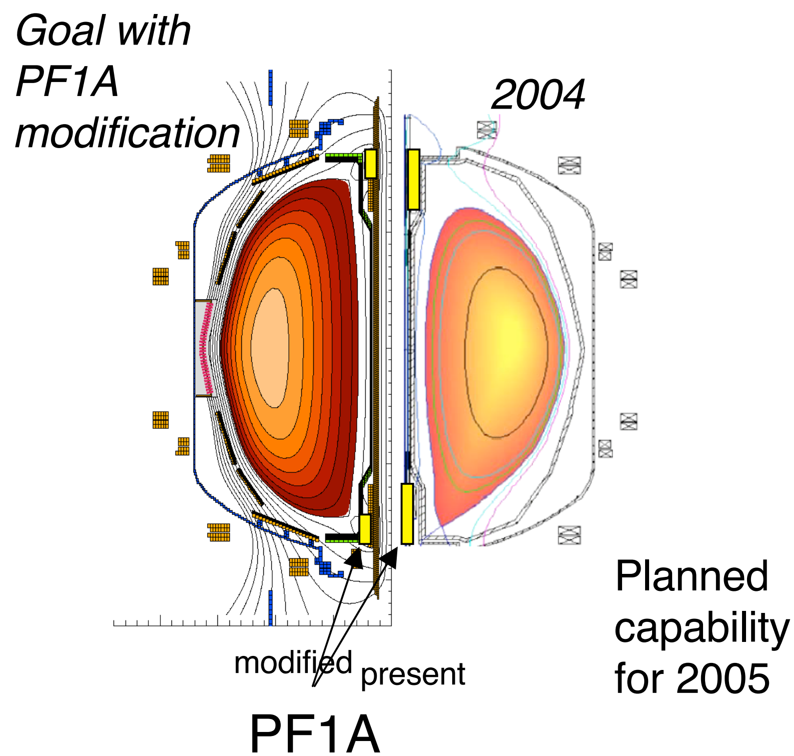
Capability for higher κ, δ
allowed higher I_P/aB_T
Significantly more high-β_T
(β_N=6.8 %·m·T/MA achieved)



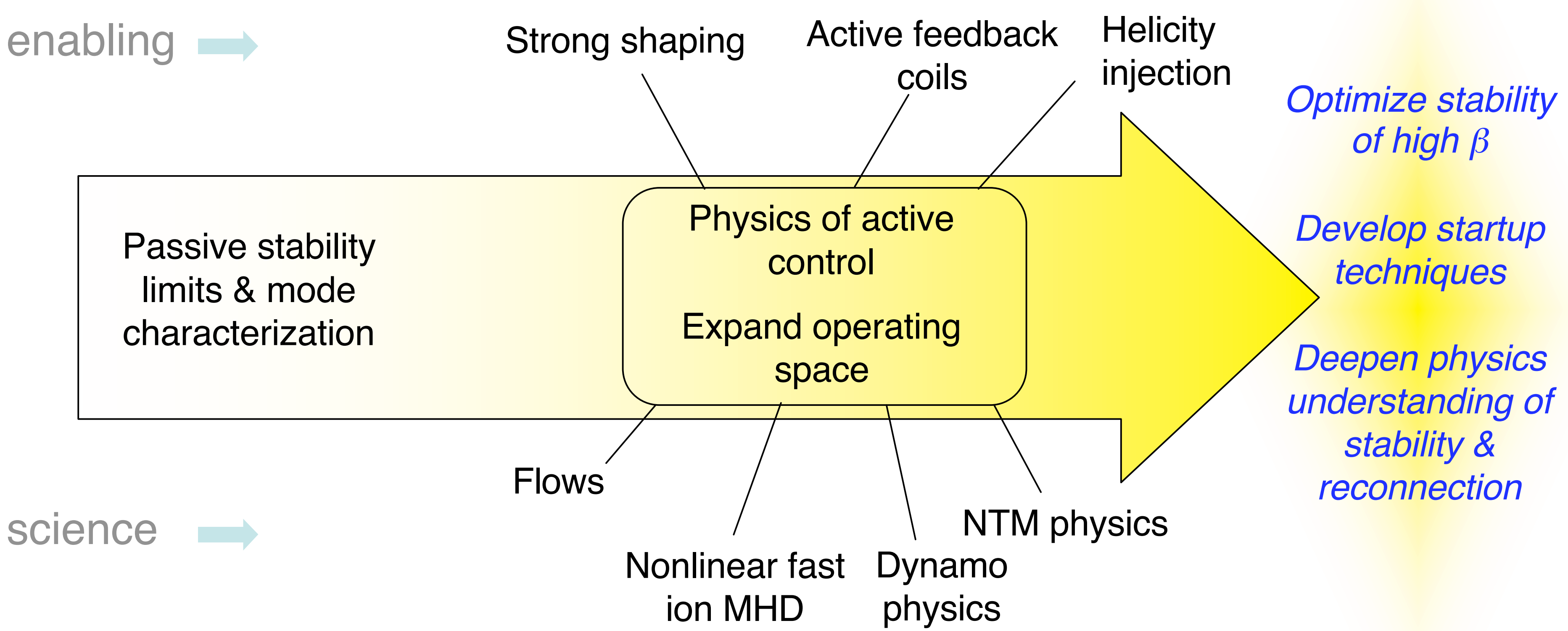
Stronger shaping enables access to higher β_T regimes and continues to be a high priority

- Modification of PF 1A should enable higher simultaneous κ (= 2.7) and δ (=0.9). This work has been accelerated and will occur this outage.
- Will allow extension of tests of stability theory in addition to anticipated β increase





MHD & macroscopic plasma behavior



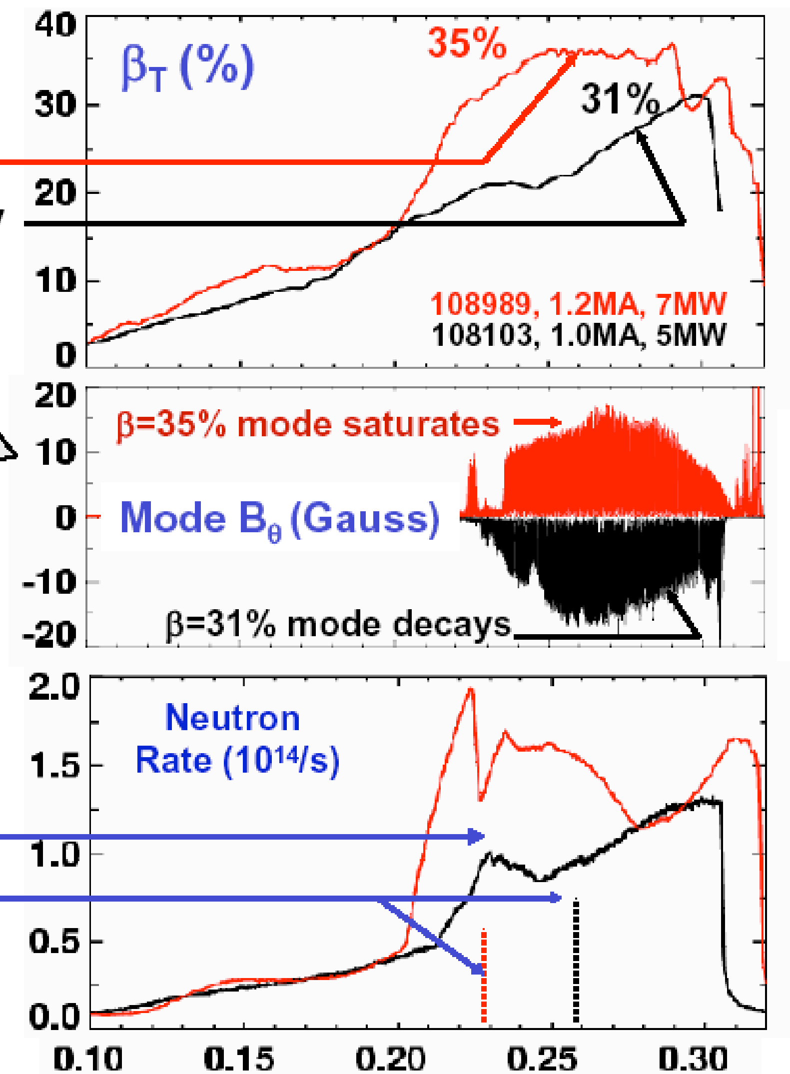
MHD physics opportunities

- *Distinguish V_A, C_s effects for RWM dissipation physics*
- $V_{flow}/V_A \rightarrow 1$ => $V_{flow} \sim \gamma^{lin}_{MHD}$
- *Test NTM stabilization theories at low A*
- *Dynamos and helicity generation*

High β obtained despite large 1/1 modes

- Sawtooth activity rare at high β
  - Rotating 1/1, usually ⇒ β roll-over
- In highest β shots, β saturates or actually rises during 1/1 activity
- 1/1 saturates or decays at high β
- $\beta \rightarrow 1.2\text{-}1.4 \times$ onset β
  - Onset β_N = 4.2 - 4.5 ≈ n=1 ideal limit
  - These shots reach β_N = 5.5 – 6
- Synergistic effects may aid high β
  - 1/1 mode flattens core *p* and *J*
    - Large fast ion diffusion or loss
  - **H-mode** onset broadens *p* and *J*
  - **Broad *p*, *J* + rotation stabilizing**

How do the modes saturate?

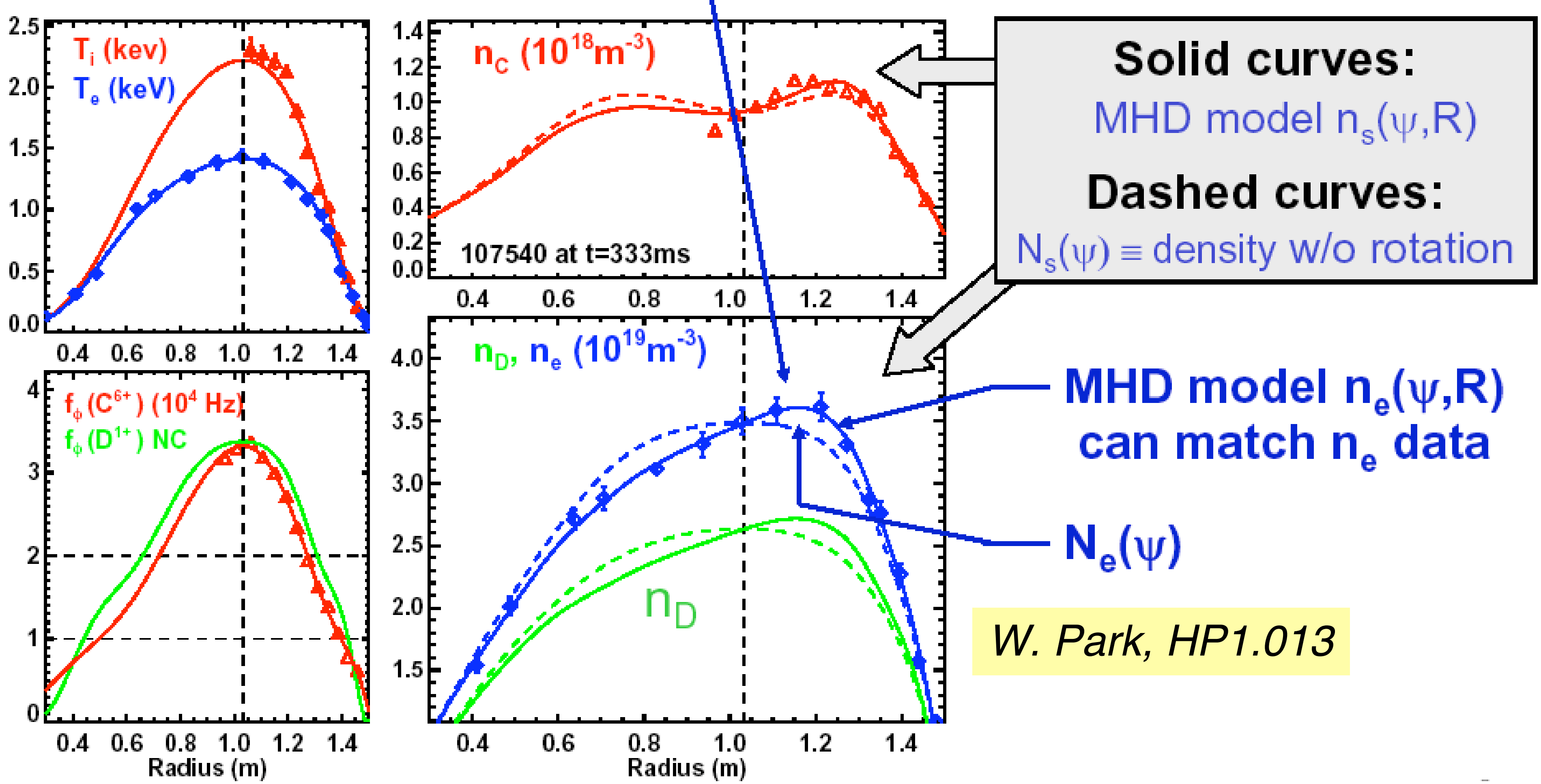


Menard, IAEA 2004

Rotation effects are strong in NSTX plasmas

$M_S = v_\phi / v_{sound} = 0.4\text{-}0.8$, $M_A = v_\phi / v_A = 0.2\text{-}0.4$

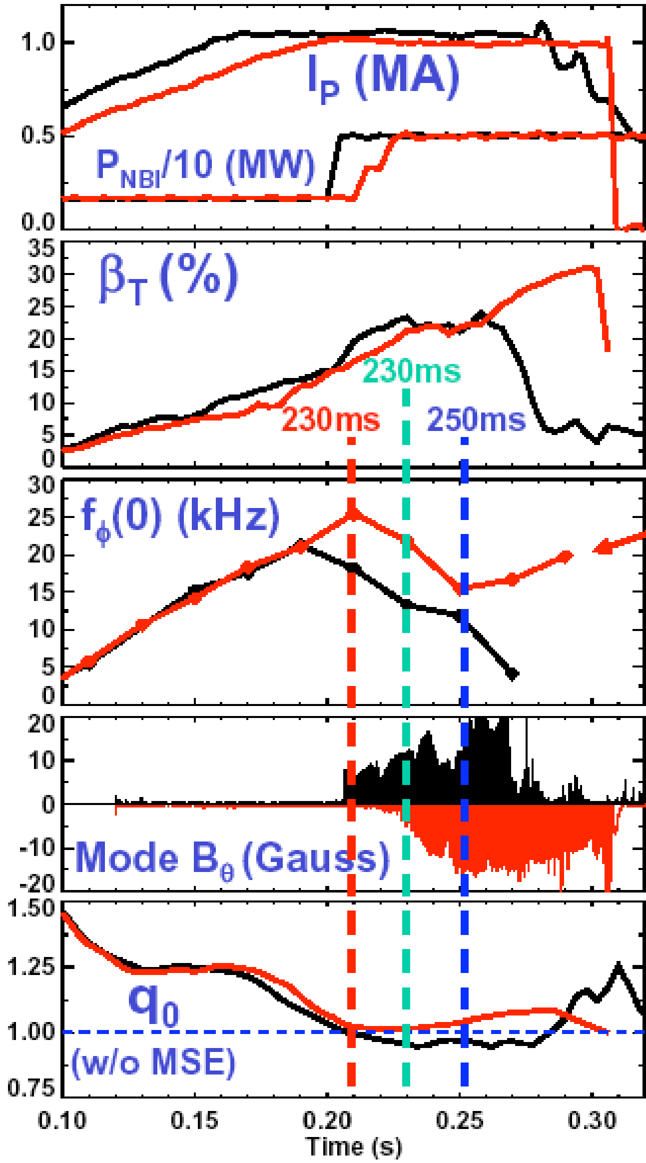
Centrifugal effects evident in $n_e(R)$ profiles:



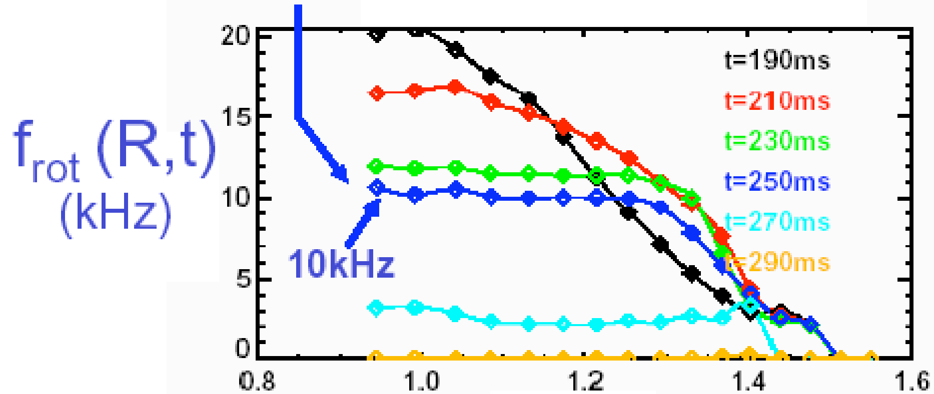
Rotation data => sheared flow correlates with saturation

NOTE: Carbon f_ϕ data is 20ms average >> τ_{growth}, $1/f_\phi$

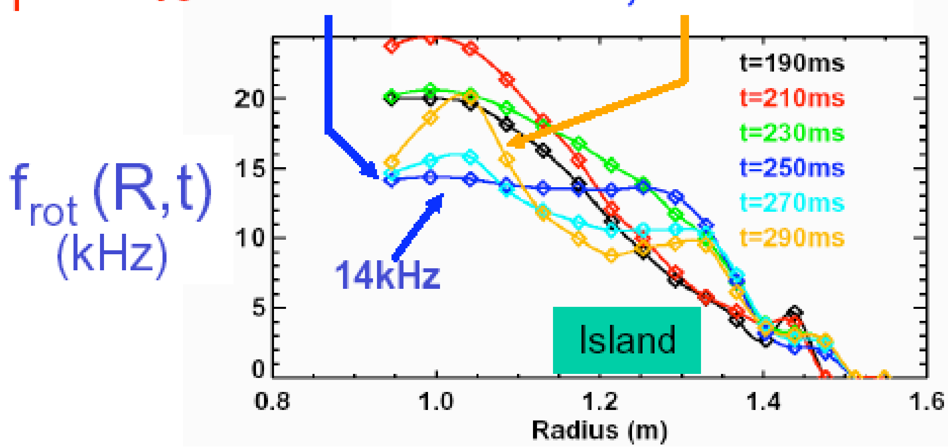
$\beta_T \leq 23\%$ $\beta_T \leq 31\%$



β_T=23% - Rotation flattens, broadens, collapses

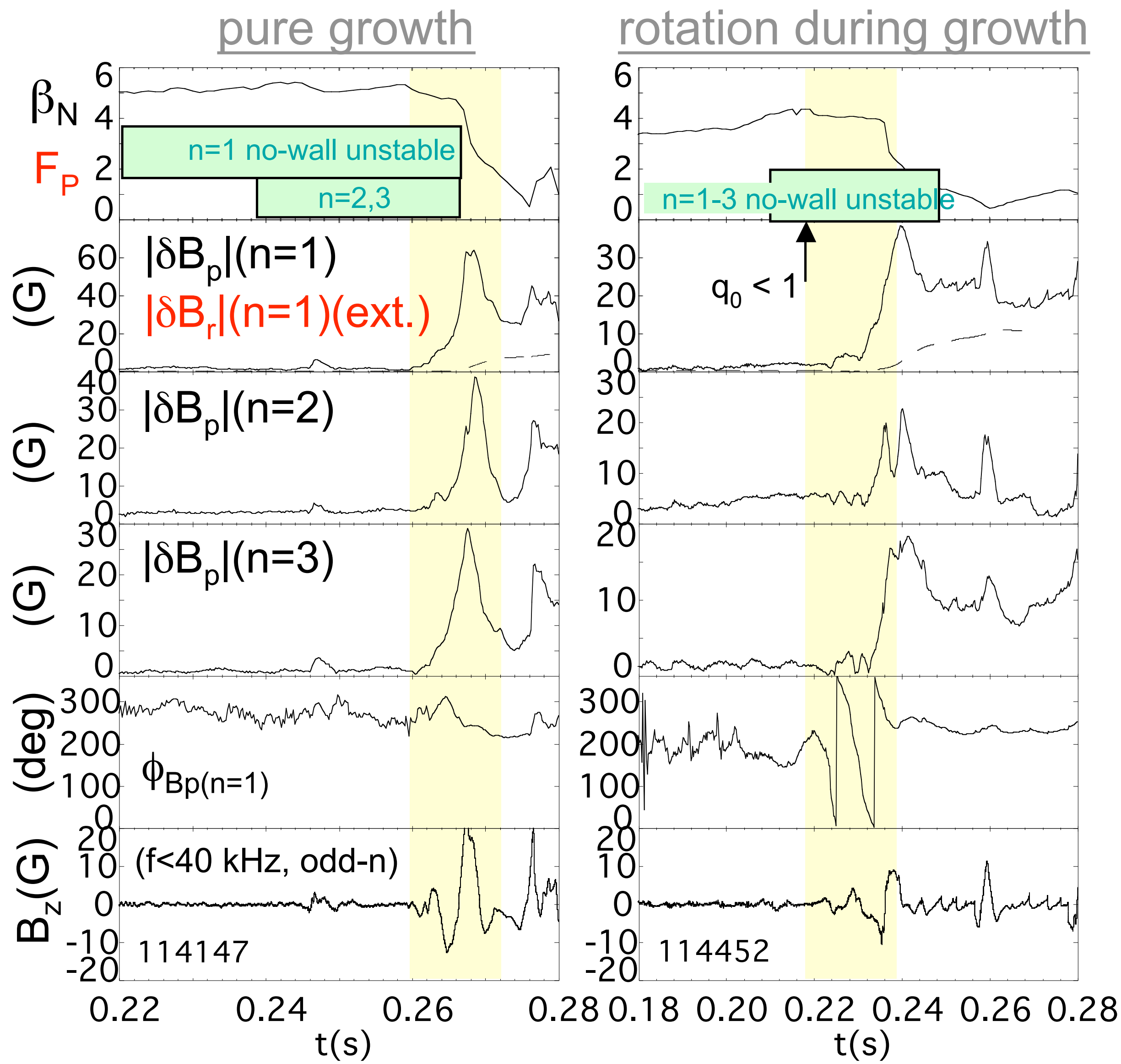


β_T = 31% - Rotation flattens, then core recovers



Favorable q or Ω_ϕ profile slows mode growth?
Enough rotation retained for later saturation?

Unstable RWM dynamics follow theory



- F-A theory / XP show
  - mode rotation can occur during growth
  - RWM phase velocity follows plasma flow
  - growth rate, rotation frequency ~ $1/\tau_{wall}$
- Unstable n=1-3 modes observed
  - ideal no-wall unstable (DCON) at high β_N
  - n > 1 expected by theory at low A
- Low frequency tearing modes absent

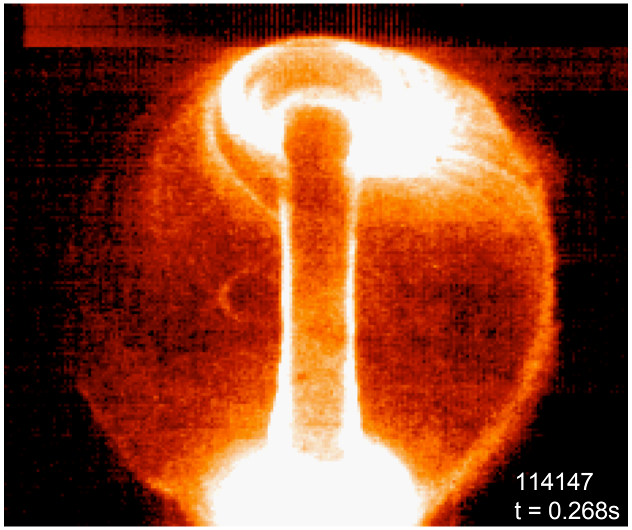
Sontag, BI1.003

Sabbagh, JP1.008

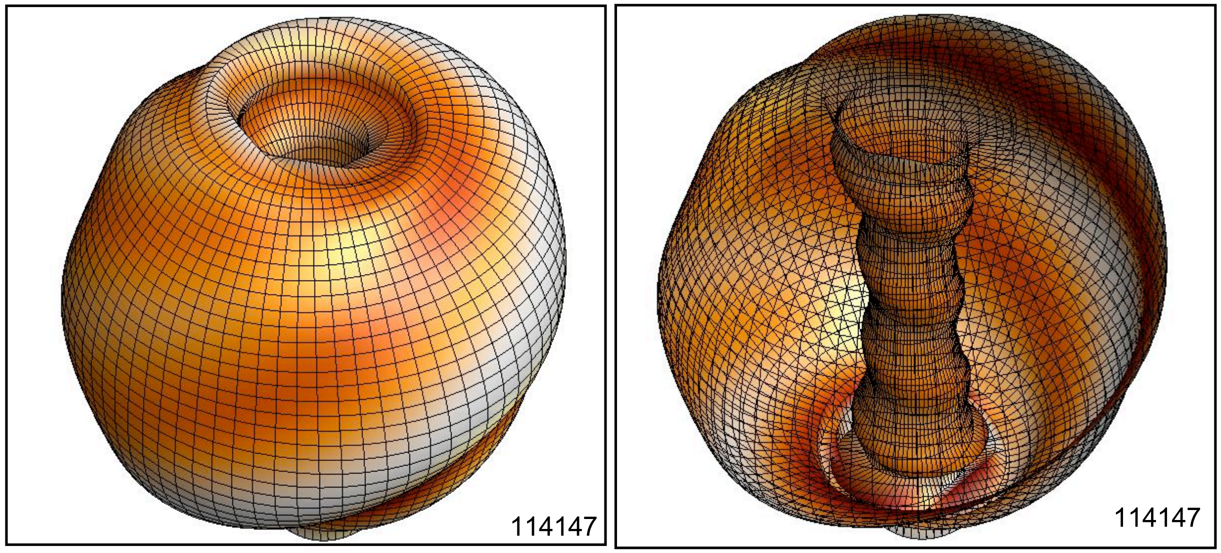
Zhu, CO3.008

Fast camera shows scale/asymmetry of RWM

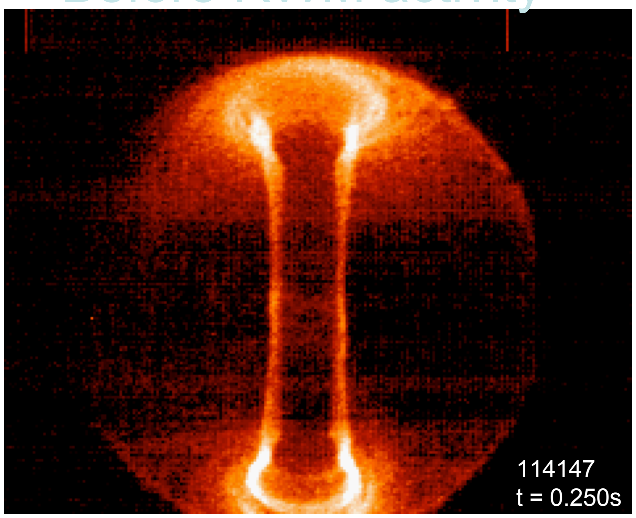
RWM with ΔB_p = 92 G



Theoretical ΔB_r (x10) with n=1-3 (DCON)



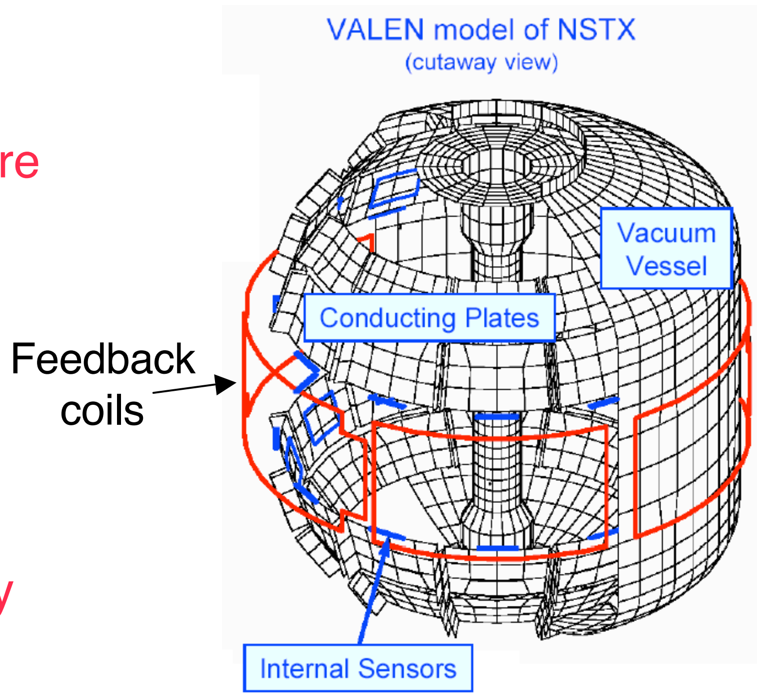
Before RWM activity



- Visible light emission toroidally asymmetric during RWM
- DCON theory computation displays mode
  - uses experimental equilibrium reconstruction
  - includes $n = 1 - 3$ mode spectrum
  - uses relative amplitude / phase of n spectrum measured by RWM sensors

Active feedback will enable mode damping theory tests, leading to a tool for operations near the with-wall limit

- Compared to tokamak,
  - Similar sound speed, smaller $V_{Alfvén}$, larger $V_{flow}/V_{Alfvén}$ --> distinguish mode damping theories thru complementary research (ITPA)
  - At lower A, higher n modes expected to be more important --> benchmark RWM theories
- First stage: controlled variations to assess damping physics & enable initial active feedback studies
  - Use improved magnetics diagnostics to identify elements needed in feedback loop
- By end of '07: enable high beta plasmas near the with-wall limit for $\Delta t >> \tau_E$



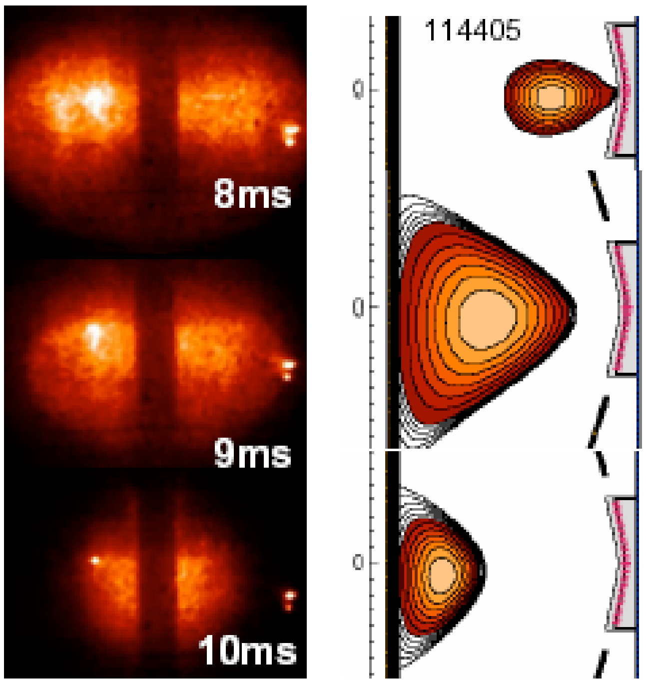
Columbia U.

Important for AT, ITER, ST

Non-inductive Current Generation Explored by Various Techniques

1) PF-only startup

- 20 kA generated



Need to maintain plasma on outside where V_{loop} is high

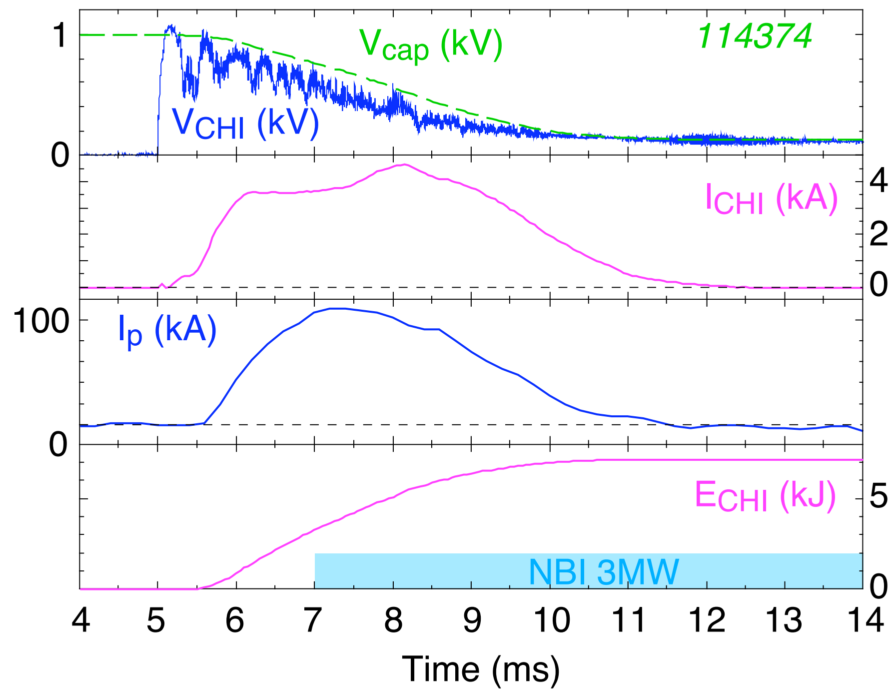
W. Choe, PP1.003

Menard

KAIST

2) Transient Co-Axial Helicity Injection

- I_p up to 140 kA, $I_p/I_{injector}$ up to 40



Need to extend I_p beyond duration of $I_{injector}$

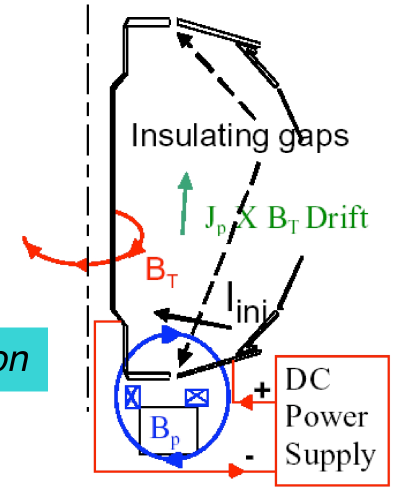
Raman, CO3.006

U. Washington

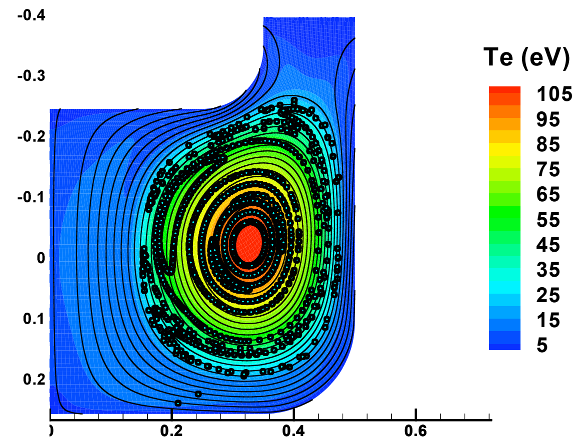
Developing the physics basis of coaxial helicity injection brings the NSTX program into the arena of dynamo physics

- Reconnection theory & dynamo formation: laboratory and astrophysical relevance
  - With long-pulse CHI, resultant toroidal plasma current is driven by dynamo voltage associated with MHD & reconnection

U. of Washington



- NSTX internal measurements will enable benchmarking of comprehensive MHD simulations
  - NIMROD, fully 3-D with strong coupling to transport physics, is applied to SSPX and will be brought to bear on HIT-II & NSTX (Sovinec (Wisc); SCIDAC)
  - Also X. Tang (LANL)

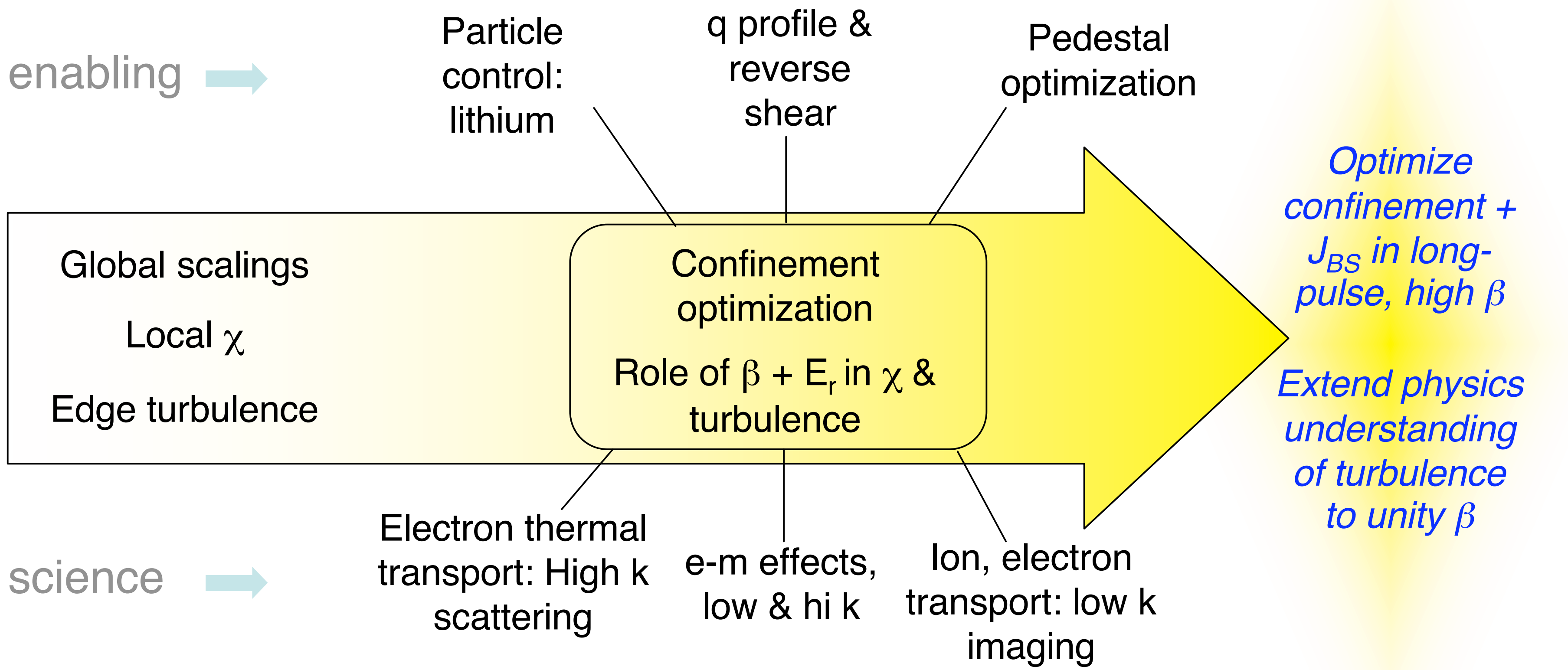


NIMROD results for SSPX on poloidal flux (solid lines), magnetic topology (punctures), and temperature profiles (color) during partial drive.

- PF induction joins CHI as the major approaches to solenoid-free plasma startup for FY '05 - '07 (w/ U. Tokyo)

Success in this arena will benefit the AT as well

Transport & turbulence



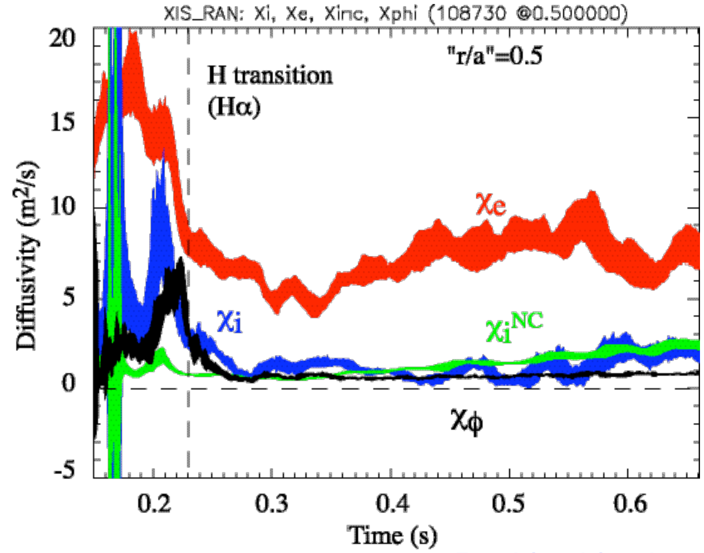
Transport & turbulence physics opportunities

- *Role of β: onset of electromagnetic effects broadens theory/experiment comparisons*
- *Electron transport: Broad range of k for theory tests*

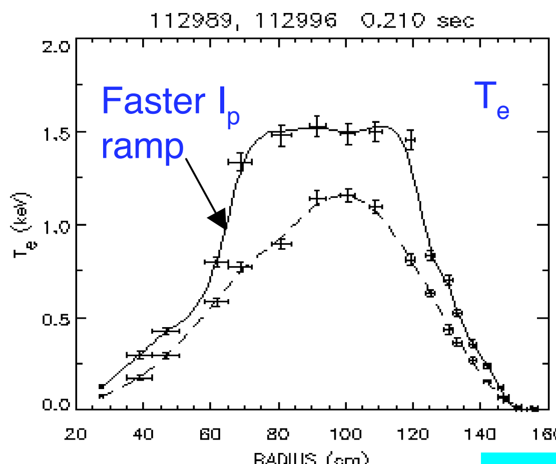
Edge/pedestal-related transport issues to be discussed in boundary section

Understanding electron thermal transport will be a focus for '05 - '07

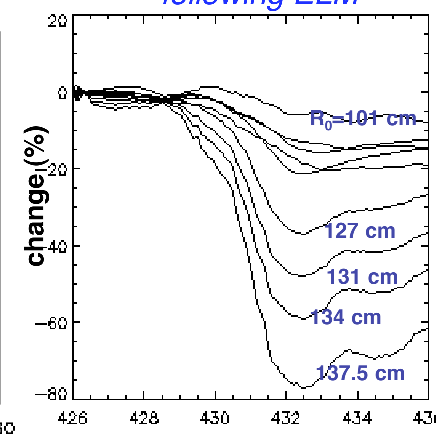
- The dominant energy loss channel & a topic of broad importance to fusion & burning plasmas, including ITER.
- Potentially important for RF & CD
- While χ_e transport is rapid, it can be modified
  - Why the flat center?
- Collaborative core transport similarity experiments through ITPA (MAST, DIII-D)



LeBlanc, R. Bell, Kaye



Rapid cold pulse propagation following ELM

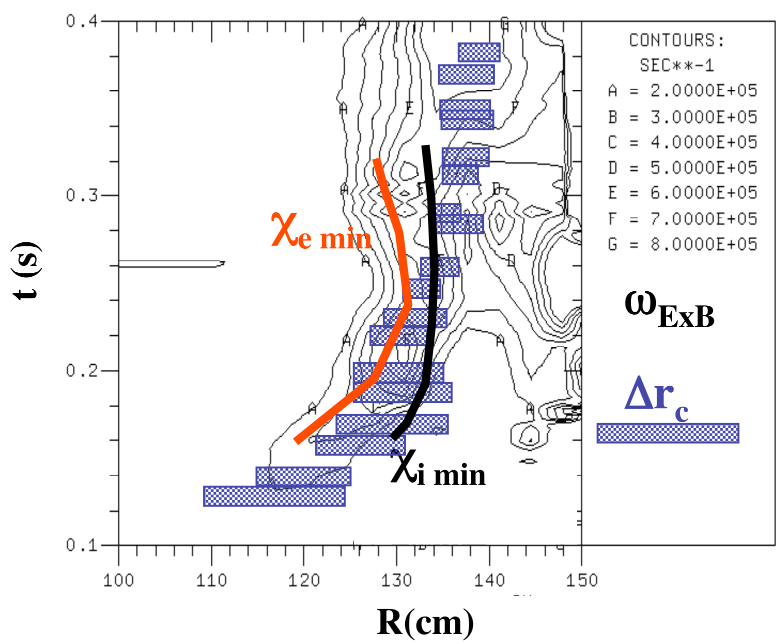


Stutman, JHU

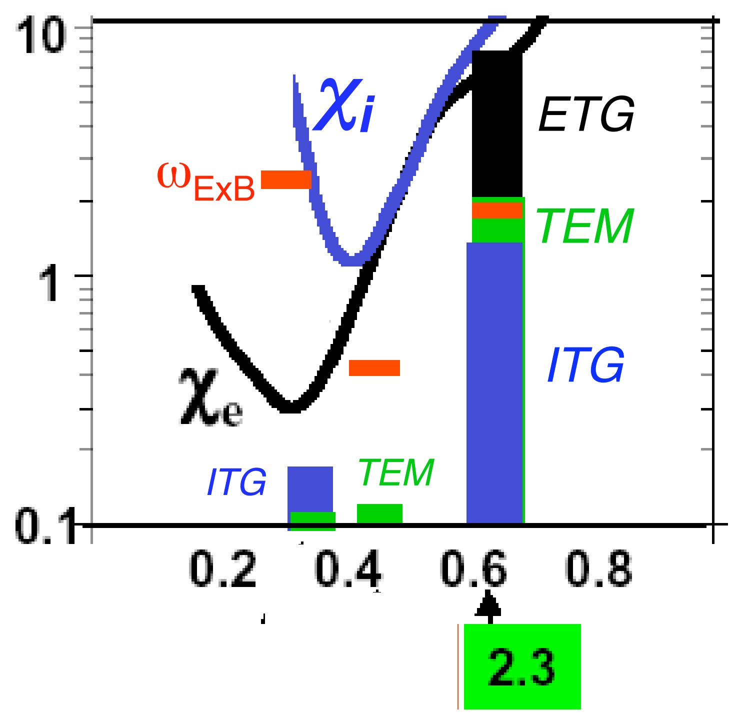
t (ms)

Core turbulence characteristics being explored with measurement and theory

Fast ramp 112989



Fast ramp 112989



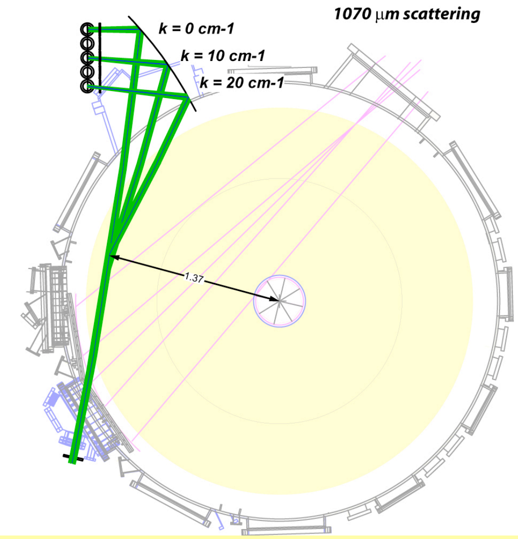
- What are the modes near the transport barrier with such large correlation lengths?
- GS2 analysis points to possible roles of ETG modes in electron thermal transport
  - μtearing suggested in higher n_e H modes

High k scattering measurements will be developed in FY' 05

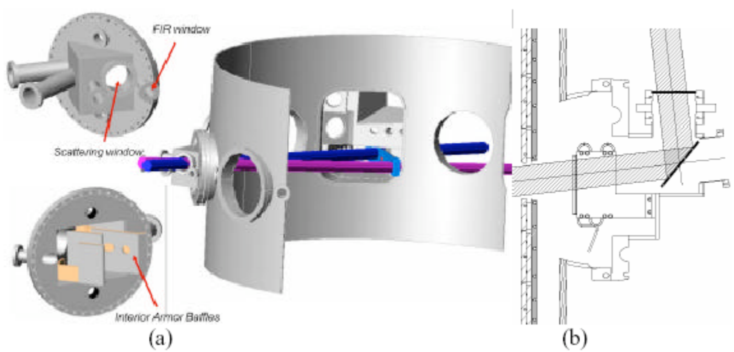
- Initial system will allow range of k measurements in select locations (2 - 20 cm^{-1}) with good spatial resolution & $\Delta n/n < 0.1\%$

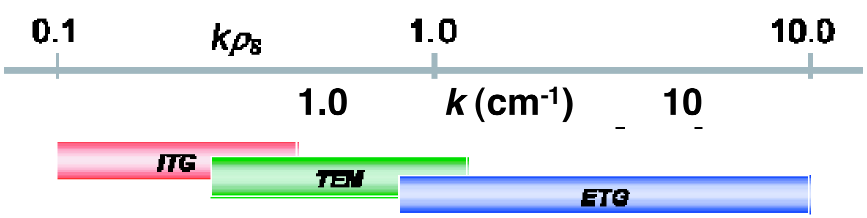
- Major installation this opening.

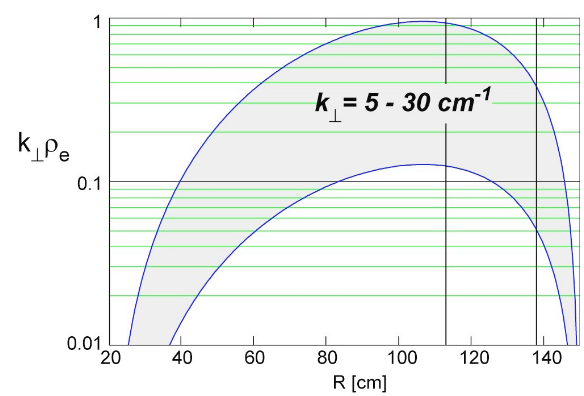
High k scattering



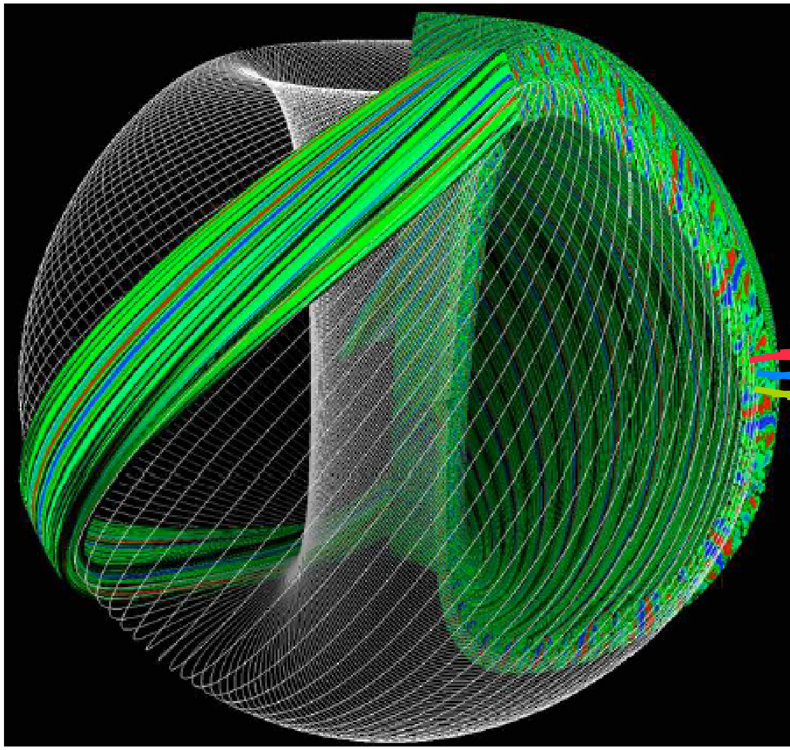
Luhmann (UC Davis), Munsat (U. Colorado)
Mazzucato, Park, Smith (Princeton U.)



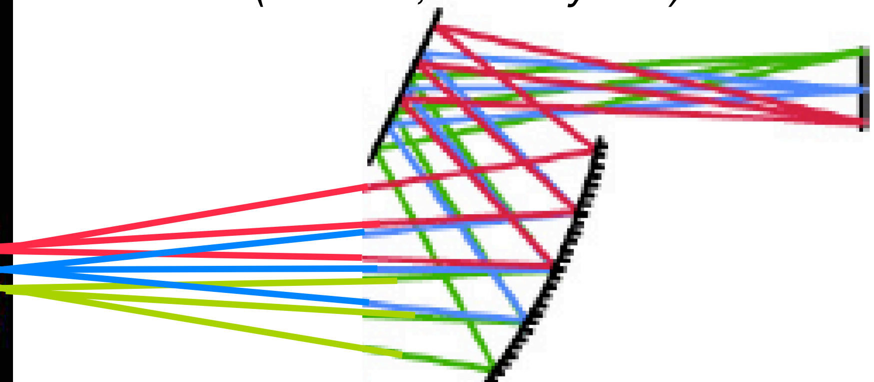




The plan aims to make NSTX a test bed for turbulence theory validation on at least three leading fronts



GS2 flux tube simulations of NSTX turbulence (Dorland, U. Maryland)



Low-k imaging (Mazzucato, Park; Munsat (Colorado), Luhmann (UC Davis))

- Critical physics (1): interactions between ion and electron scale turbulence
- Critical physics (2): electron thermal transport
- Critical physics (3) electromagnetic effects in turbulence as local β --> 1

Need & opportunity: strong theory community coupling

Waves & energetic particles

enabling →

Heat low I_p plasmas for ramp-up

NBI at modest B

EBW tube. Launcher development

HHFW heating, phasing, & CD

EBW emissions

Coupling startup techniques to ramp-up

Wave physics in overdense plasmas

Reduce V-s through J_{BS} and direct CD

Extend physics understanding of waves in overdense plasmas

science →

HHFW wave physics from antenna to core

Super-Alfvénic particles & MHD

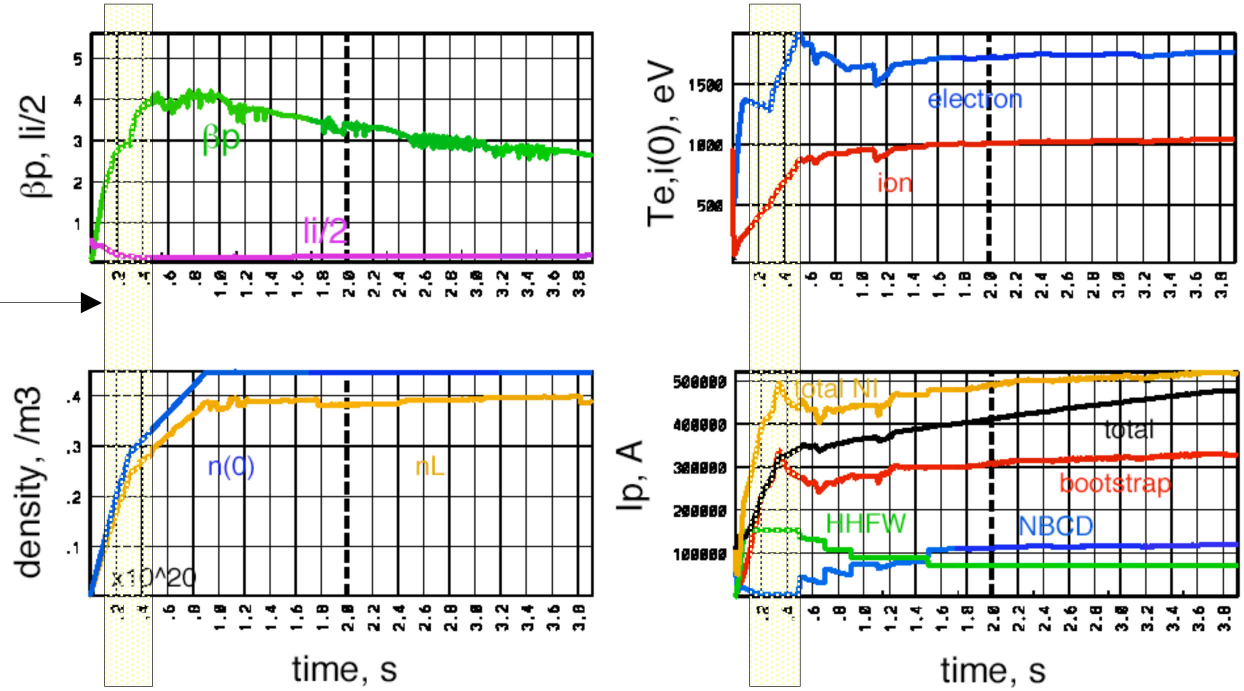
EBW physics: mode conversion & f(v) modification

Wave-particle physics opportunities

- *HHFW, EBW: wave coupling, propagation & deposition for overdense plasmas (for ST, RFP)*
- *EBW: Ohkawa current drive with high trapping fraction*
- *Non-linear fast ion MHD with large super-Alfvénic population*

A major HHFW research priority for FY ‘05 - ‘07 is using it to assisting in an I_p ramp-up without a solenoid

Solenoid-free portion of the I_p ramp, before beams. Direct CD + J_{BS}



TSC

- Scenario must elevate I_p to level where beam ions can be confined (hundreds of kA)
- Control work will target controlling antenna gap with low currents, and hand-off from seed current
- EBW can be brought to bear in ‘08 with increased budget

Kessel

More detailed look at HHFW this year reveals puzzles

- Mixed evidence thus far for significant HHFW heating in the presence of NBI heating

- Puzzling wave number dependence of heating efficiency (without beams)
  - > 80% absorption at 14 m^{-1}, 50% at -7 m^{-1}, 75% at +7 m^{-1}, ~ 0 at ±3 m^{-1}

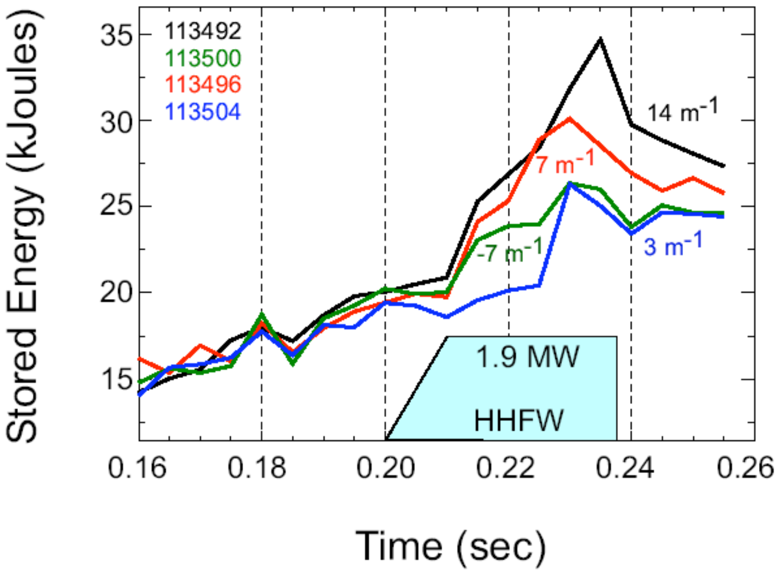
- At ± 7 m^{-1}, HHFW modulation experiments reveal τ^{E}_{inc} is *higher* in cases where heating efficiency is *lower*
  - How is phasing difference inducing an apparent change in transport?

Wilson, CO3.012

Ryan, CO3.013

HHFW Absorption Depends on Antenna Phasing

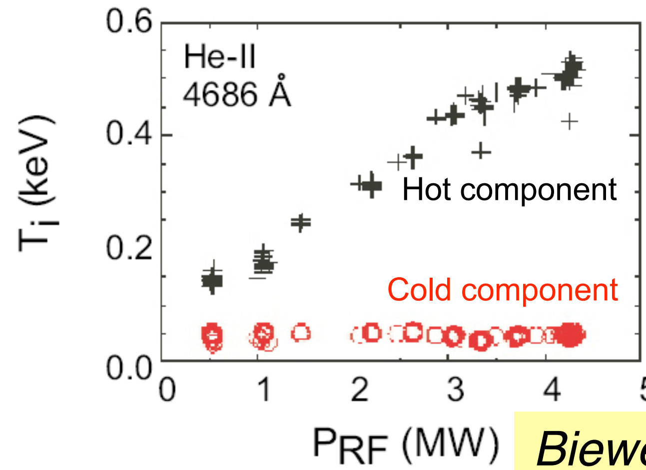
HHFW modulated to assess % absorption



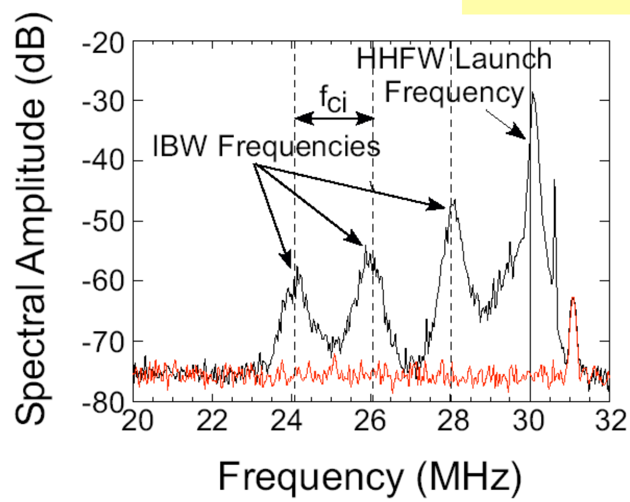
Absorption

$k_{\|\|}=14\ m^{-3}$		80%
	$7\ m^{-1}$ (ctr)	75%
	$-7\ m^{-1}$ (co)	40%
	$3\ m^{-1}$	10%

Edge ion heating _ parametric decay of HHFW



Biewer, RI1.001



Evidence for parametric absorption processes found in spectroscopy, RF probes

Plan is to clarify physics behind range of results, and make changes in operations & rf hardware where warranted

- Sheath physics
  - This opening: extend BN tiles at antenna, install Rogowski's at passive plates, RF probe on reciprocating probe head, Reverse B_T experiments. Modify antenna feed to reduce near-antenna $E_{//}$ (next opening)

- Parametric absorption
  - spectroscopy, reflectometry

- Core wave penetration
  - reflectometry, turbulence scattering

- Rapid electron thermal transport

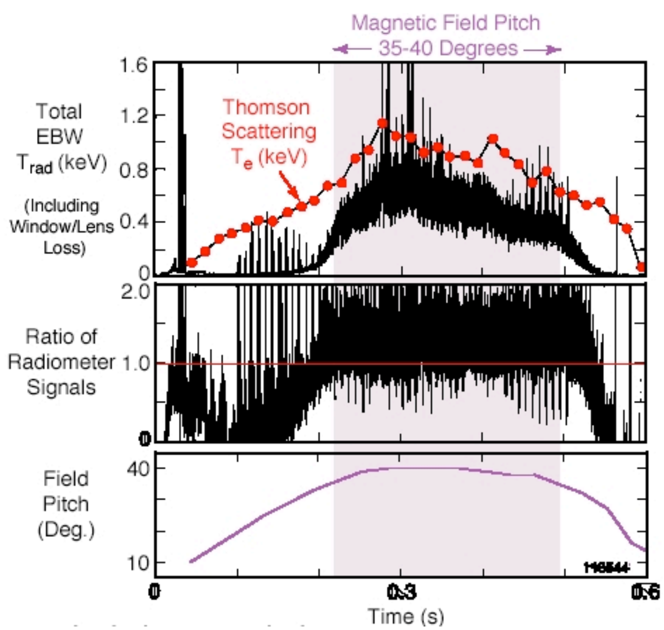
Modeling RF sheath physics with realistic conditions to estimate power dissipation and the k spectrum launched into the core would be of high value to NSTX

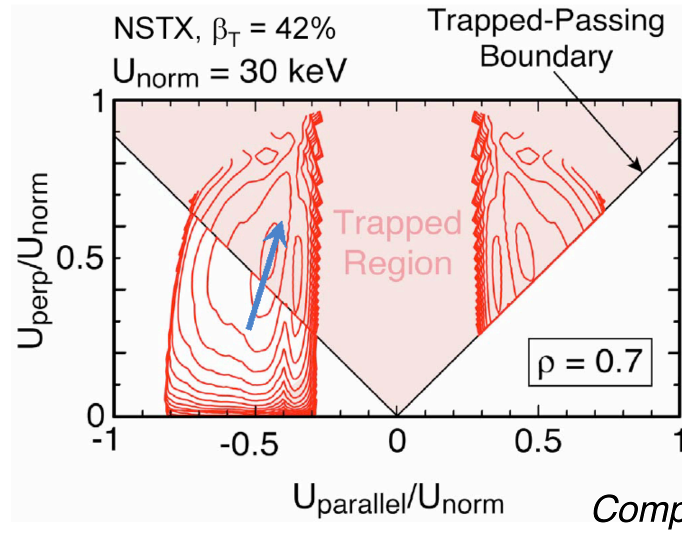
ST properties and recent experiments make EBW attractive & high priority

- EBW current drive takes advantage of high ST electron trapping fraction via Ohkawa effect. The ST is *perfect* for exploring this science.

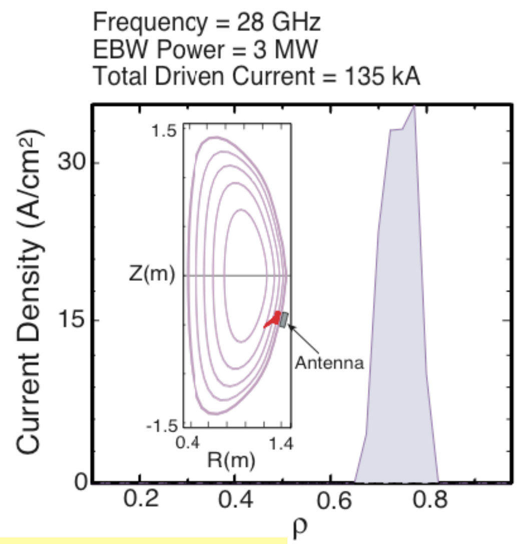
- Recent NSTX emissions evaluating EBW coupling are promising

- Modeling indicates efficient off-axis current drive





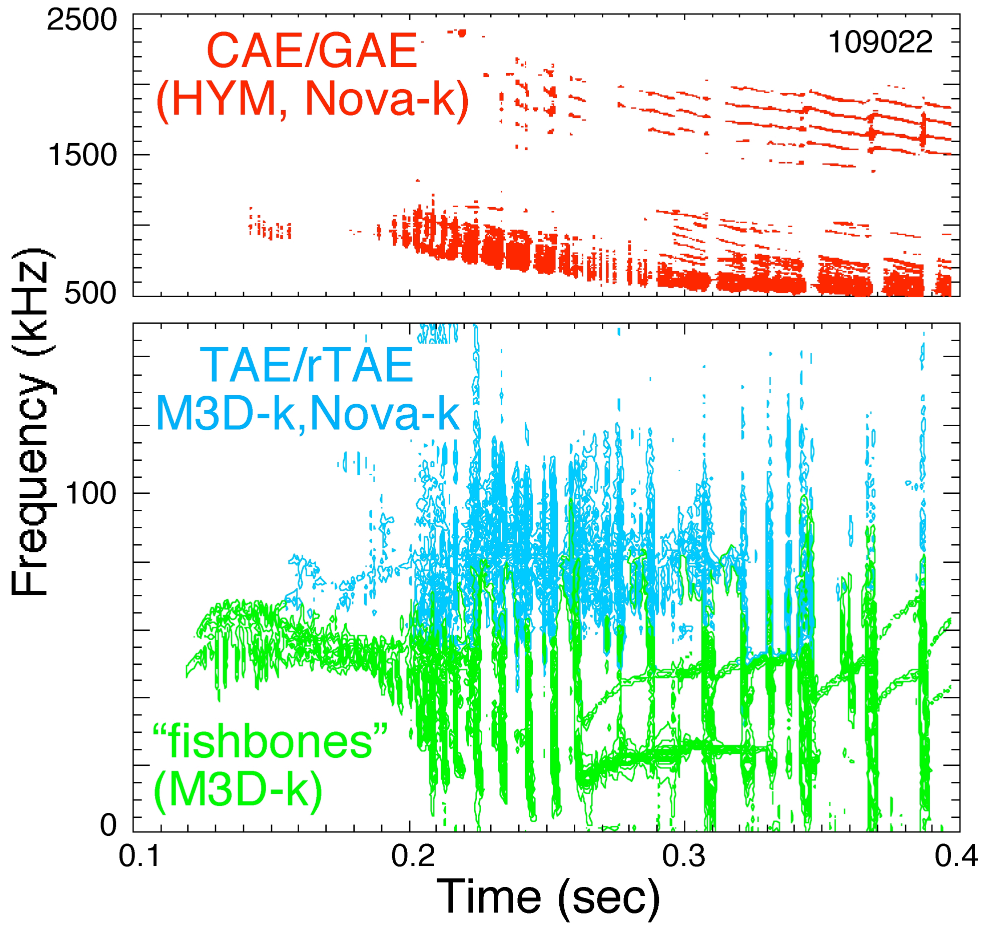
Compx Genray/ CQL3D



Taylor, CO3.014

NSTX's large population of super-Alfvénic fast particles enables an important branch of nonlinear MHD physics to be studied

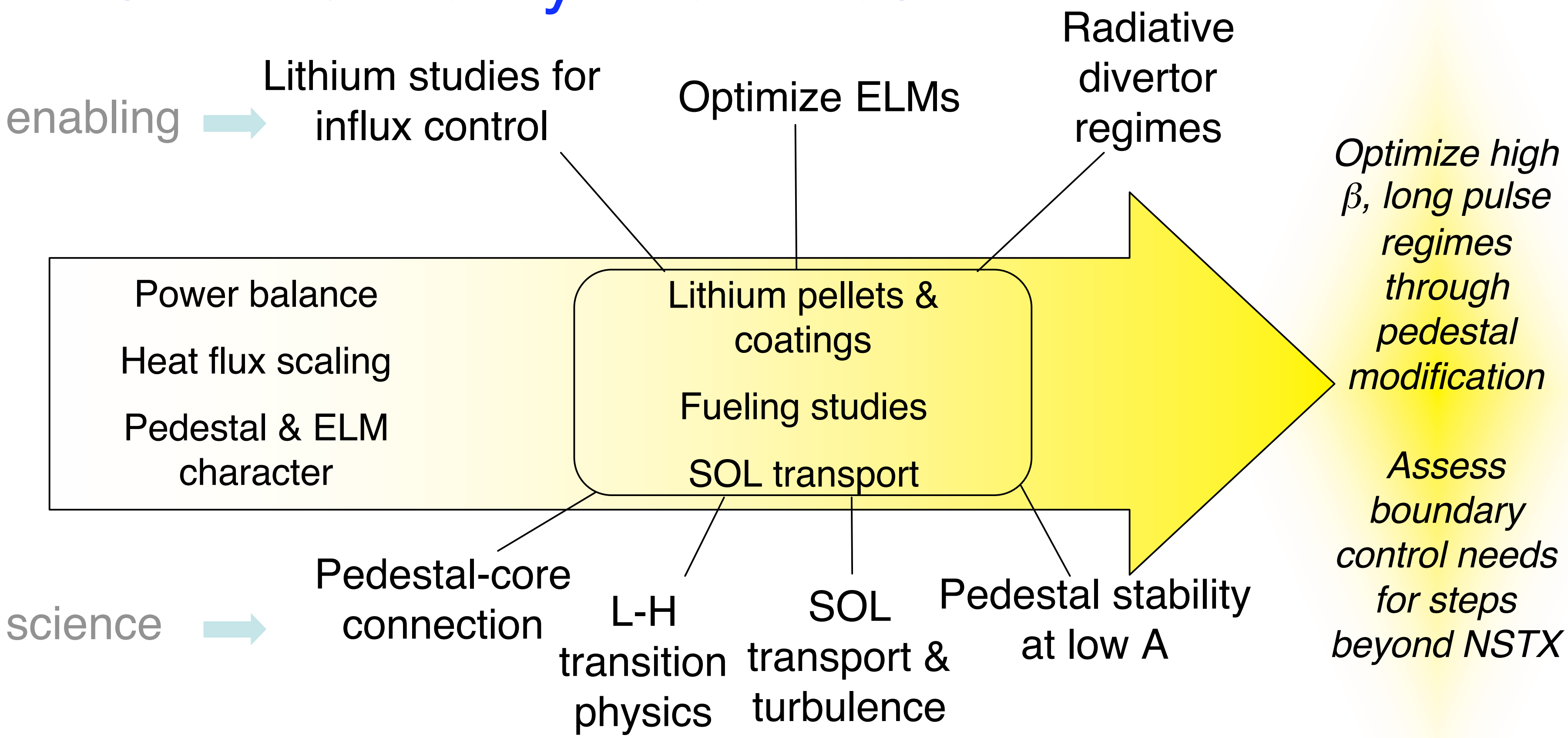
- $V_{fast\ ion}/V_{Alfvén} \sim 3$, similar to ITER values of ~ 2.
- Unique access to multimode Alfvénic turbulence in nearly every NBI discharge
- Fast ion population cannot be treated as a perturbation - coupling with MHD must be treated self-consistently



Fredrickson, IAEA 2004

Heidbrink (UC Irvine), NP1.014

Plasma boundary interfaces



Boundary physics opportunities

- *Advanced heat and particle flux management techniques relevant to all toroidal confinement concepts*
- *SOL transport: intermittency & shear Alfvénic turbulence*

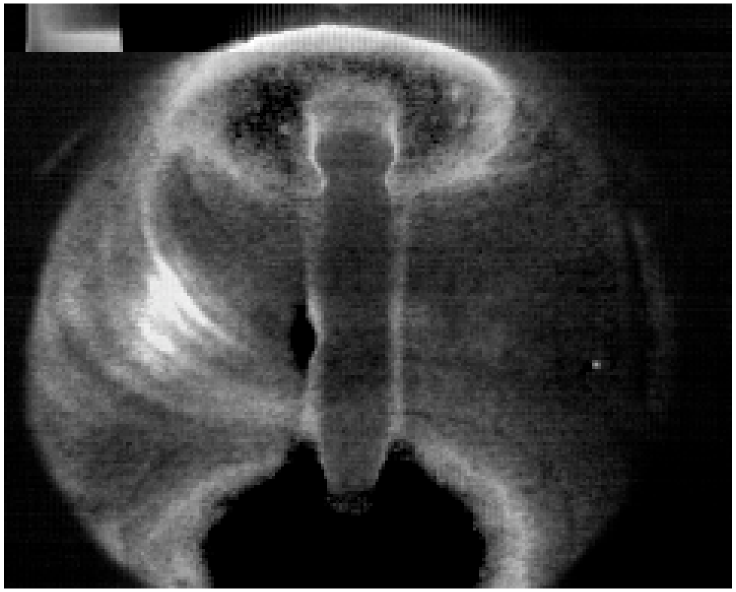
Details of ELM characteristics documented with fast camera

- Type V ELMs: small, with little change in stored energy
  - So far, found in high n_e regimes
- ELMs frequently originate near separatrix and propagate towards the midplane

Type V

Small, filamentary, perturbation

Type I

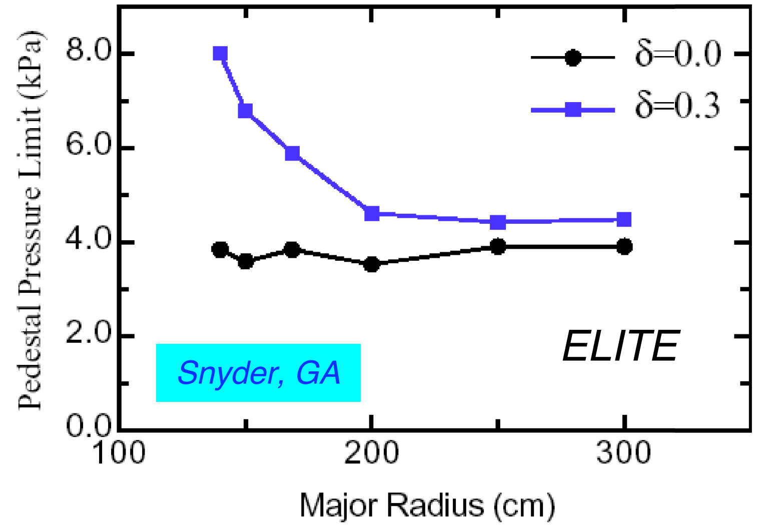


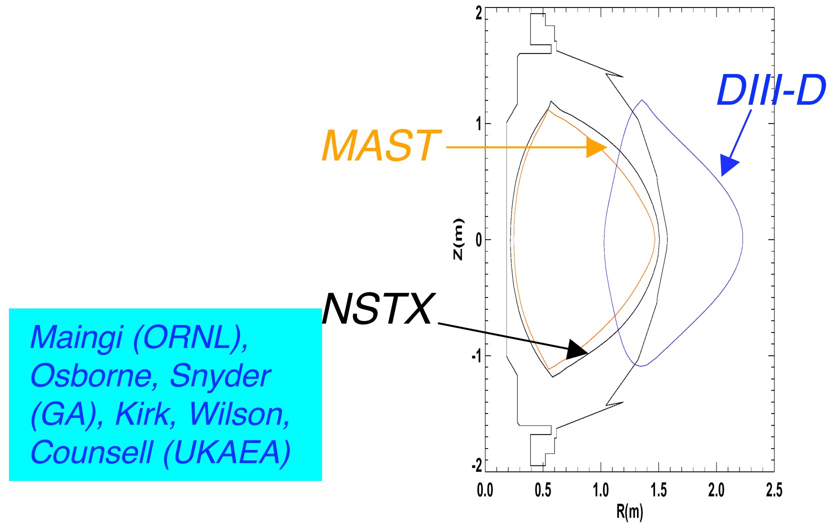
Larger low *n* perturbation

Tritz, CO3.005

Predicted edge pedestal stability differences between lower and higher A to be tested

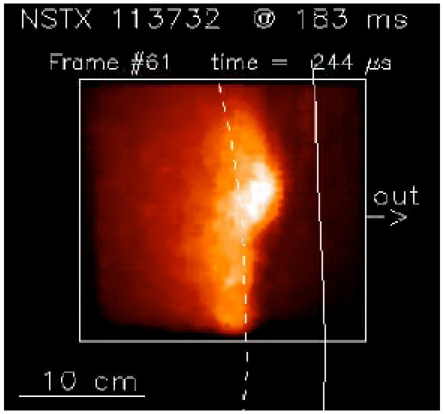
- ELITE code predicts easier access to 2nd stability at low A with moderate shaping
- Prediction is the basis of an ITPA proposed experiment with NSTX, MAST, and DIII-D
- Strong poloidal mode coupling expected at low aspect ratio presents a powerful opportunity for validation of edge stability codes (e.g. ELITE)
- Challenging pedestal models is of high importance to ITER and burning plasmas





Imaging & probe measurements provide a powerful test bed for edge turbulence codes

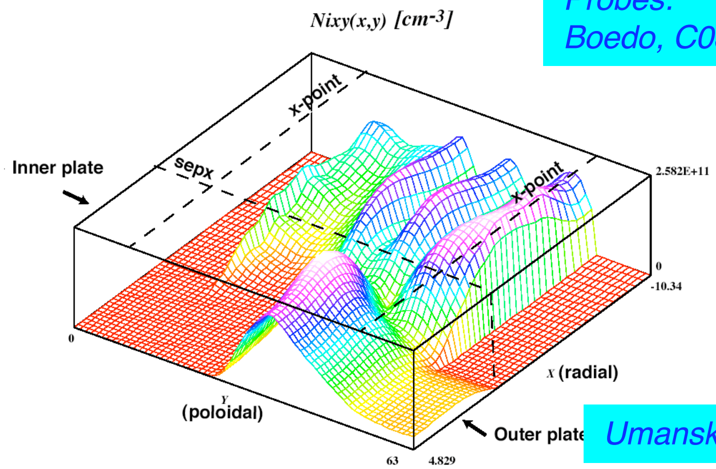
- Goal: build a physics understanding of edge turbulence based on simulation/experiment comparisons
- NSTX may be revealing new class of turblence in the edge, as BOUT simulations point to shear Alfvén eigenmodes
  - large gyroradius challenge the code at new limits (Umansky, LLNL).
- benchmarked edge models in different conditions ==> increased confidence in models of SOL transport for ITER
- ITPA collaborative effort with C-Mod



Zweben, CO3.011

L mode

Probes: Boedo, C03.010



Umansky, LLNL

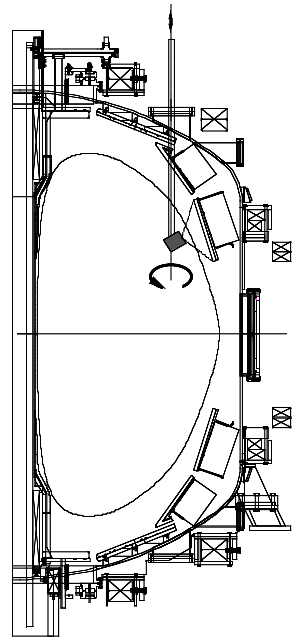
BOUT simulations underway based on measured profiles & NSTX geometry (preliminary)

Lithium edge flux control studies start with pellets, and may culminate in a powerful edge control approach

Li pellets: injector commissioned in '04

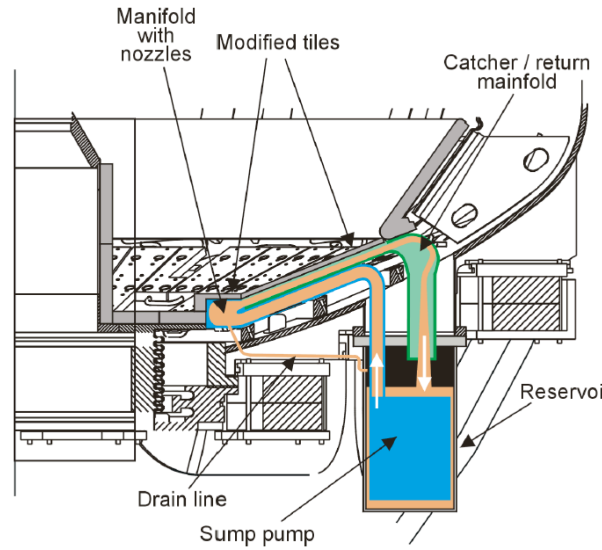
- Develop deposition techniques in '05

Kugel, JP1.007



e-beam for Li coatings in '06

- Li coatings: localized, 1000 Å *before every shot*

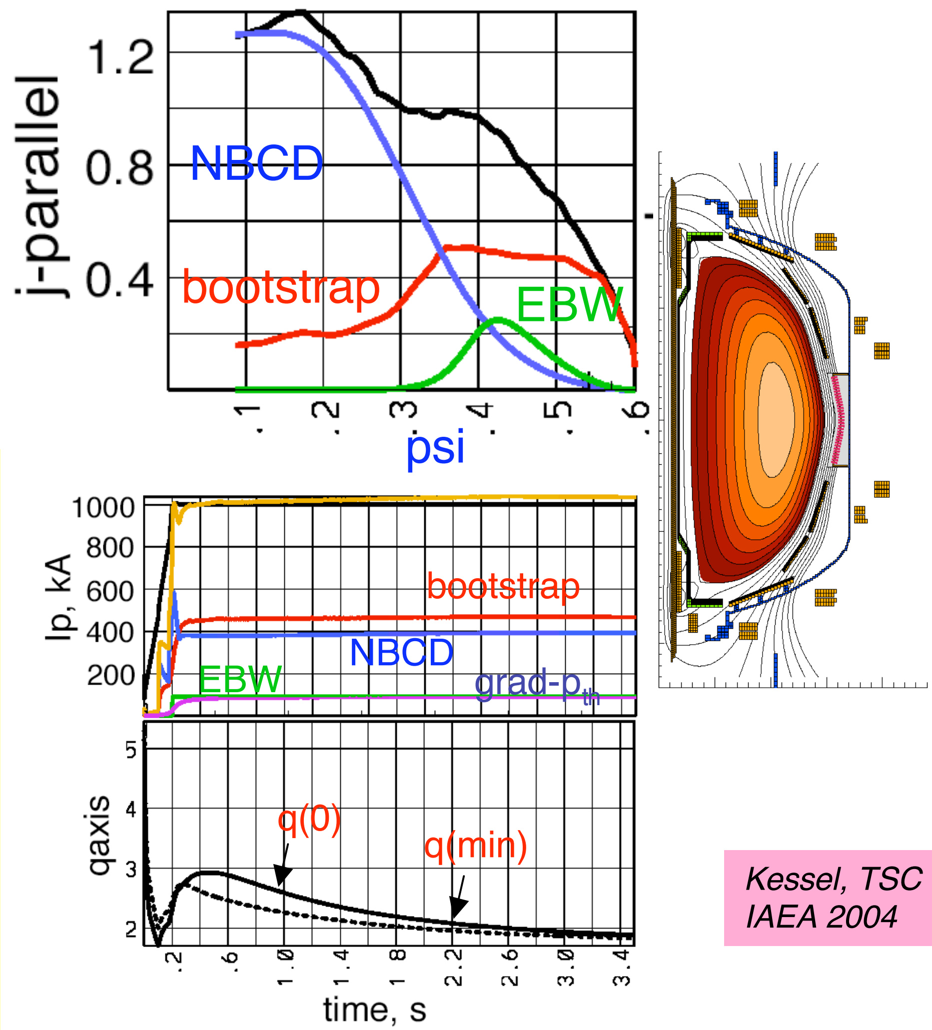


Liquid lithium module: decision following coatings studies

- Under ALIST group of VLT
- Would represent a revolutionary solution for both power and particle handling

40% β_T with ~100% I_{NI}, τ_{pulse} >> τ_{skin}, demands development of new tools and understanding their underlying physics

- NBI + EBW. NBI provides $J_{NB} + J_{BS}$ EBW drives current off-axis, less J_{BS}
- Particle control required to maintain moderate n_e for CD (4×10^{19} m^{-3})
- Near with-wall limits ⇒ mode control + rotation are key
- Enhanced shaping improves ballooning stability through simultaneous high δ and κ
- Successfully coupling HHFW to NBI would provide additional J_{BS}
- Critical issues include J_{NB} in the ST & thermal confinement improvement



Kessel, TSC IAEA 2004

NSTX research for '05 - '07 is well aligned with the fusion program's scientific priorities and supports strategic goals

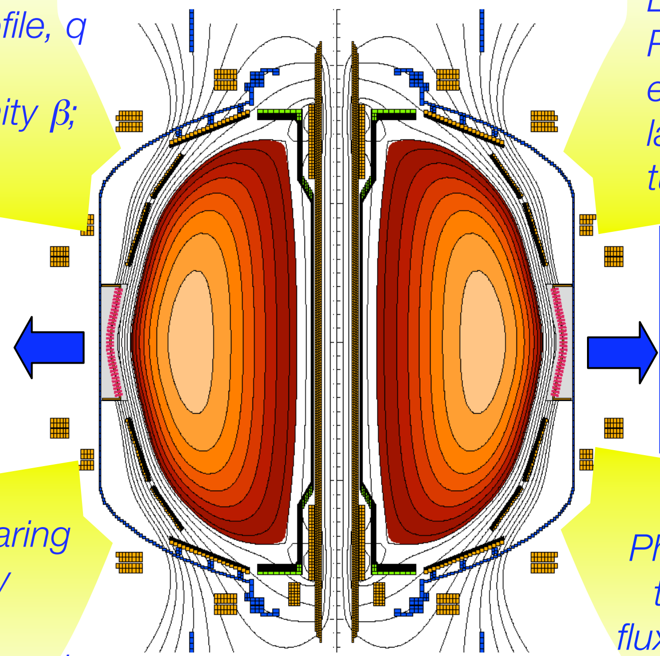
FESAC Theme: Understand the role of magnetic structure on confinement, & plasma pressure limits

Stability pressure limits & magnetic reconnection vs. A, shape, profile, q & flows, for internal & external modes with $V_{flow}/V_A \leq 0.4$ & unity β; helicity transport

FESAC Theme: Learn to use energetic particles & e-m waves to sustain and control high temperature plasmas

EM waves in overdense plasma; Phase space manipulation with high electron trapping; energetic ions with large orbits; Alfven eigenmodes and turbulence with $V_{fast}/V_A >> 1$

NSTX



Demonstrate Feasibility with Burning Plasmas

Develop Understanding and Predicitve Capability

Determine Most Promising Configurations

Develop New Materials, Components, & Technologies

Microscopic ion, electron, and tearing turbulence measurement & theory comparison over wide range in β, flows, and magnetic shear, with good average curvature and high trapping

FESAC Theme: Understand & control the processes that govern confinement of heat, momentum, and particles

Physics of ELMs, pedestal, SOL turbulence & high divertor heat flux, with large in/out asymmetry; Li coatings & liquid surface interactions with plasma.

FESAC Theme: Learn to control the interface between a 100 million degree plasma and its room temperature surroundings

NSTX research for FY ‘05 - ‘07 will extend the reach of plasma science, advancing the ST and fusion energy development

- The deepening of the science will form the basis for advancing the ST concept

- The unique properties of NSTX plasmas, combined with advanced diagnostics & collaborative experiments, will enable targeted tests of theory and simulation of value to all toroidal confinement systems

- The program addresses the overarching priorities of the fusion program
  - Understanding the plasma state
  - Creating and understanding a burning plasma
  - Making fusion power practical