Supported by

NSTX Research Plans for 2005 - 2007

E.J. Synakowski
PPPL

on behalf of the NSTX National Team

For the NSTX Program Advisory Committee

September 9, 2004

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

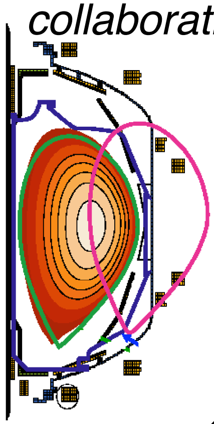
- **This science forms the basis for extending the ST itself.** This scientific understanding defines the control tool requirements that will enable long pulse, high beta operations in NSTX and in future STs.

- **The science reaches beyond the ST and towards burning plasmas.** Targeted theory tests are planned with NSTX high beta plasmas, advanced diagnostics, new control tools, & inter-device experiments.

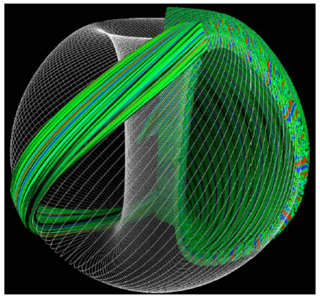
Unique NSTX plasma properties provide scientific leverage in all major areas of toroidal confinement research

Strengthen the scientific basis for fusion energy

Experimental collaboration



Theory-experiment coupling



Core transport & turbulence

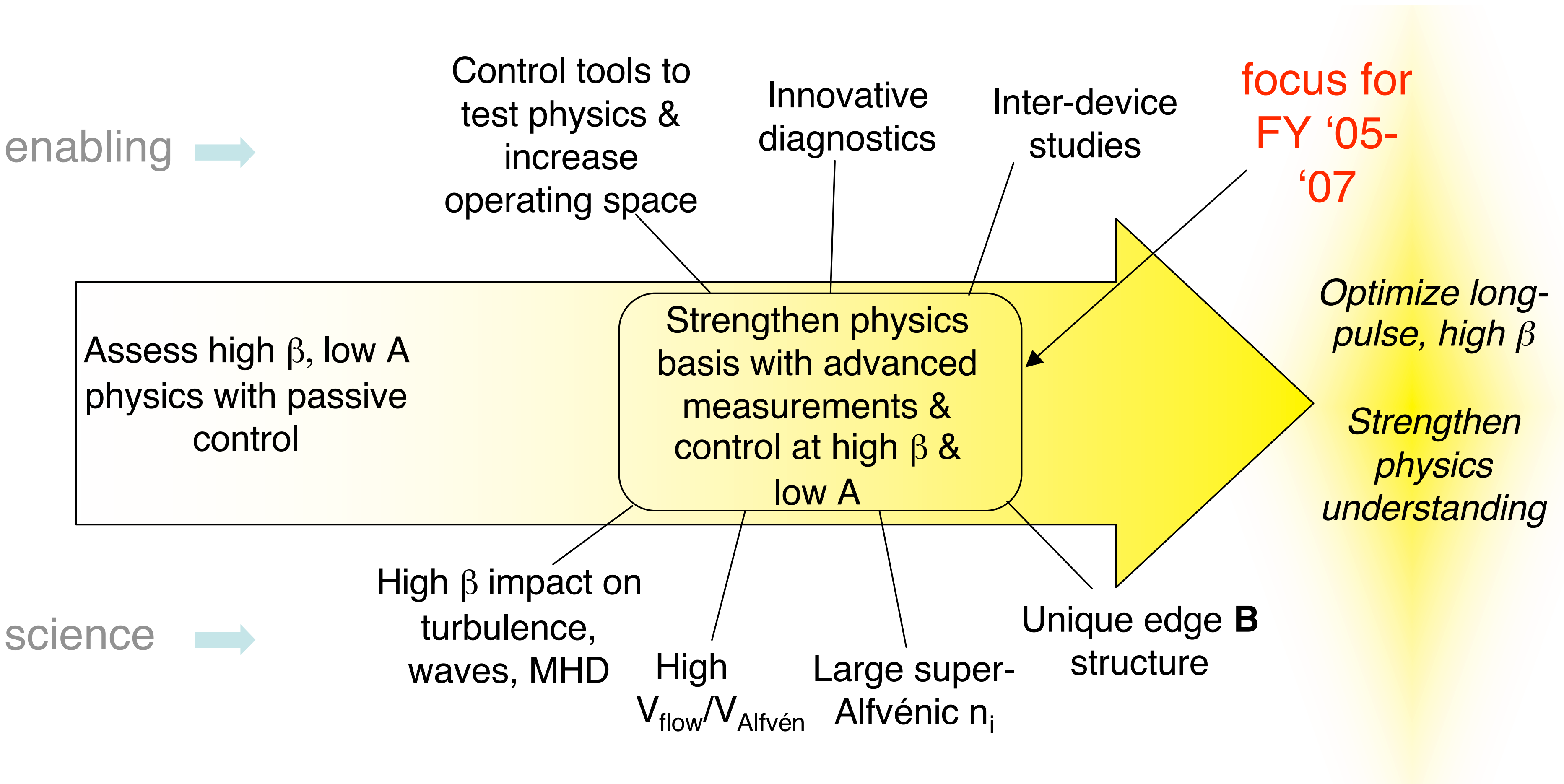
Edge transport & stability

MHD: stability & helicity injection

Wave/particle interactions

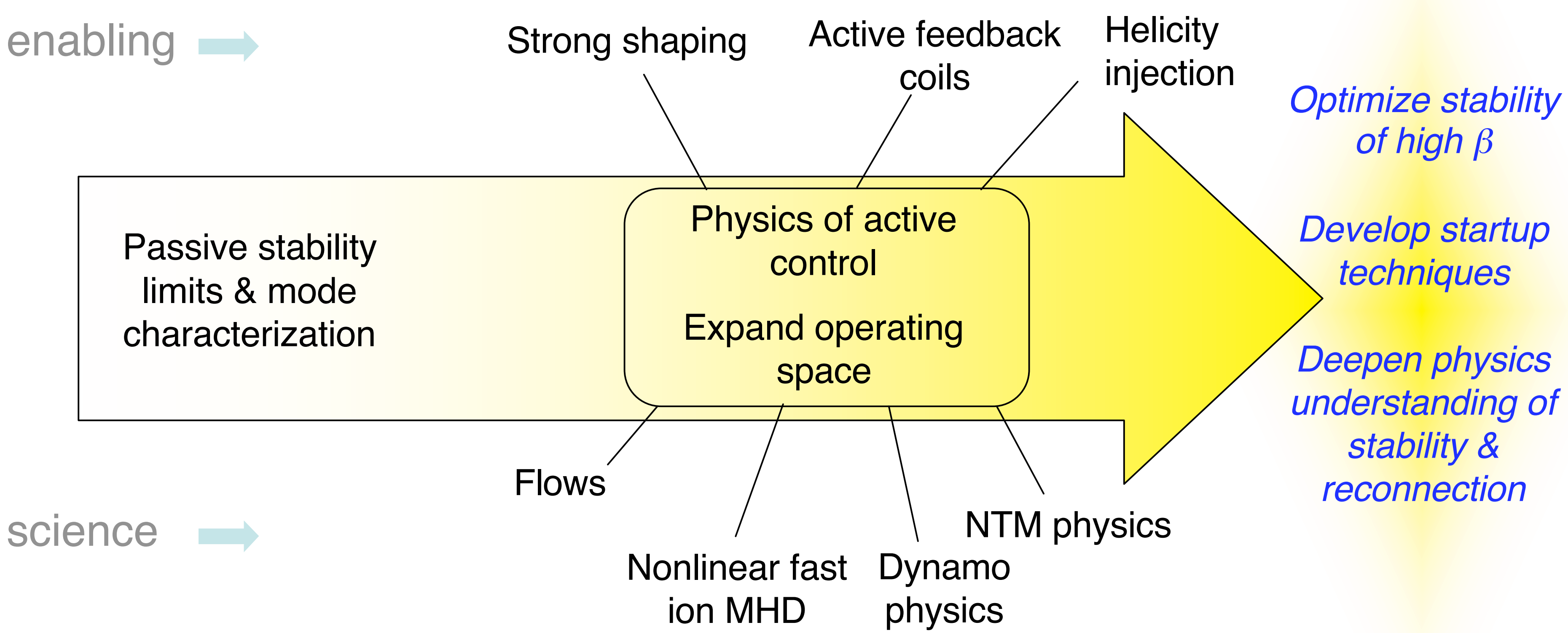
Test theory by isolating important physics and challenging models at their extremes of applicability

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*

MHD & macroscopic plasma behavior

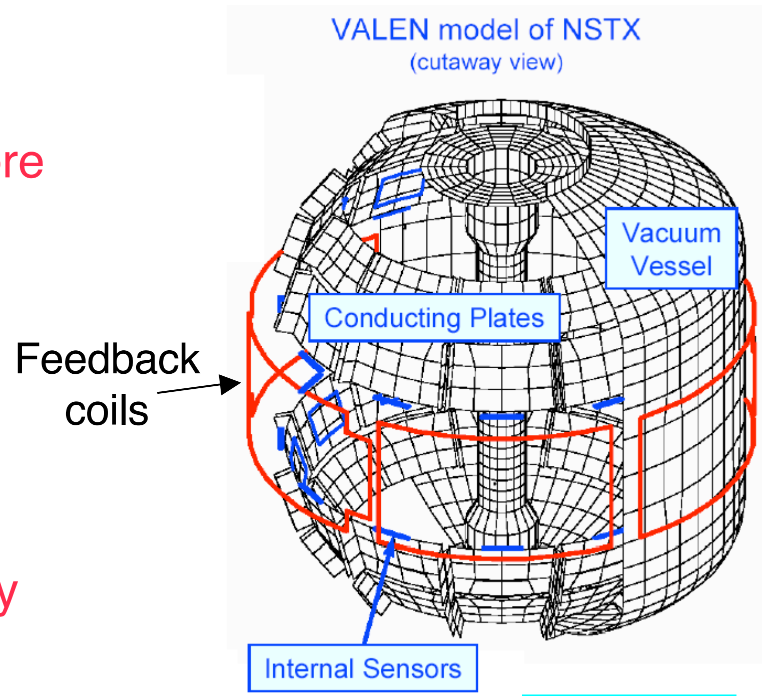


MHD physics opportunities

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

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 $\Delta t >> \tau_E$

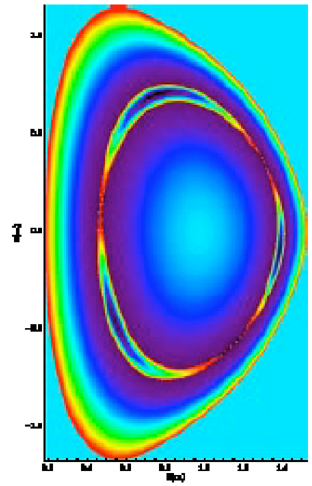


Columbia U.

Important for AT, ITER, ST

Tearing mode physics will increase in emphasis over the next three years

- Use low aspect ratio to push the physics of the NTM onset to different extremes than at moderate A, for which average curvature and ρ^* are expected to be important

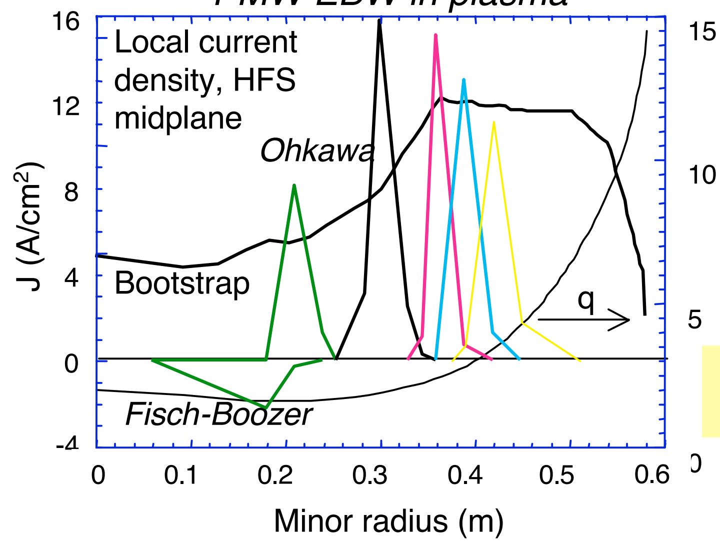


Simulation of island structures (PEST-III)

- Do we need to stabilize the NTM? Clarify NTM importance in $\beta > 30\%$ plasmas, in concert with EBW current drive studies

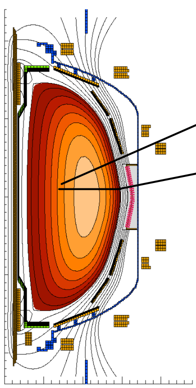
- Physics understanding of high value to burning plasmas

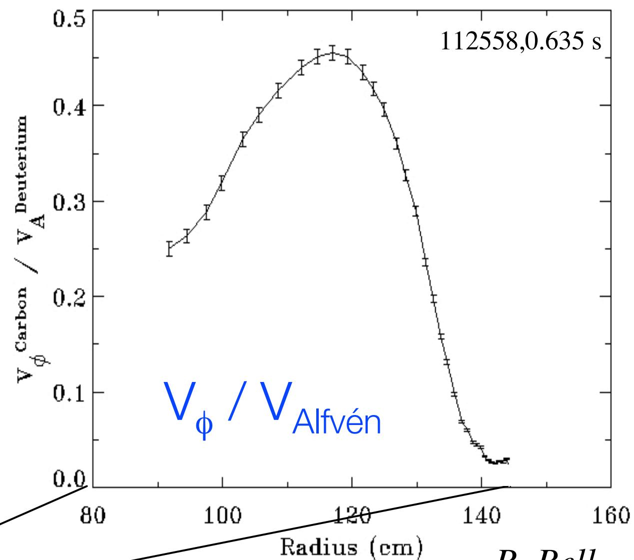
28% β_T
100% I_{NI}
scenario



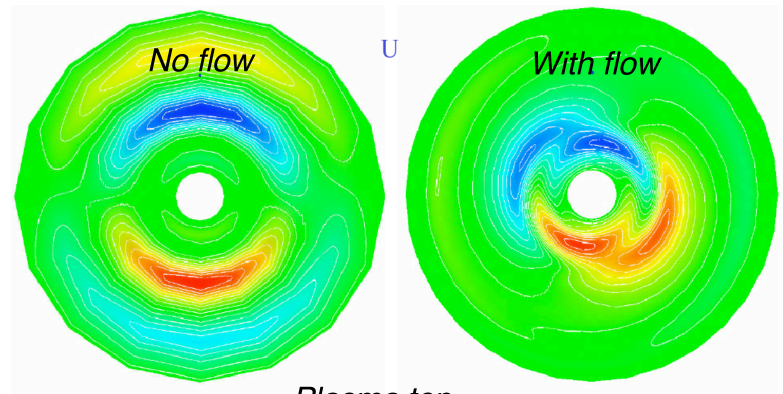
Harvey, CompX

Understanding physics of high $V_\phi/V_{Alfvén}$ on MHD stabilization is central to advancing high beta physics





R. Bell



Plasma top view

Park, M3D code

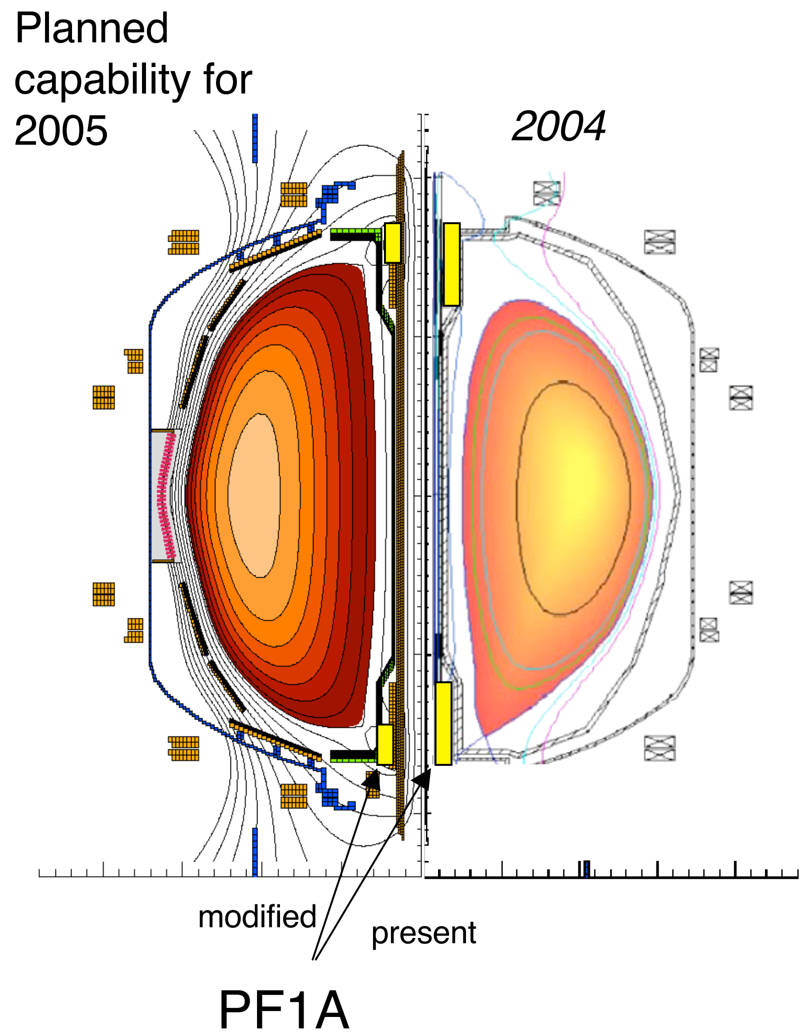
- A new regime to test MHD theory: with $V_\phi \sim V_{Alfvén}$, flow can shear apart MHD modes

- Target for ‘07: develop fully nonlinear treatment with self-consistent momentum transport ==> can codes reproduce observed saturation of internal modes?

Stronger shaping will enable access to higher β_T regimes and will be a high priority

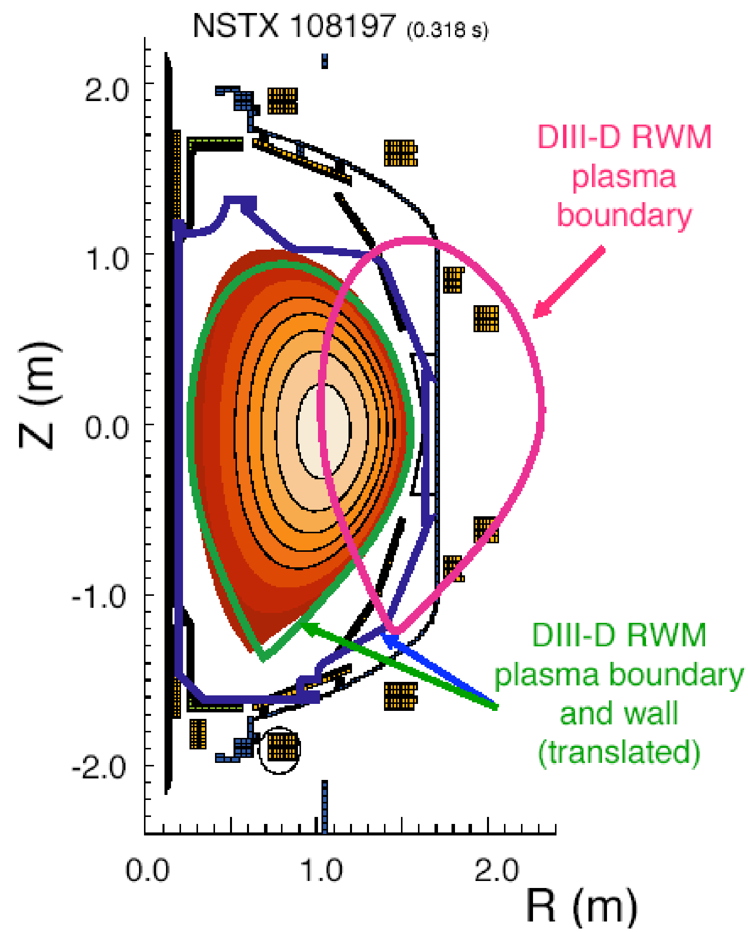
- Modification of PF 1A should enable higher simultaneous κ (= 2.7) and δ (=0.9). This work has been accelerated and will occur this outage.

- Will allow extension of tests of stability theory in addition to anticipated β increase



Joint experiments are part of the plan for assessing RWM, tearing mode, and fast ion MHD physics

- Comparing aspect ratio yields high leverage for physics understanding
  - RWM: Similar V_{sound}, different $V_{Alfvén}$ ==> discern RWM dissipation mechanisms
  - Tearing mode: poloidal mode coupling challenges theory
  - Fast ion MHD: predicted *AE mode structure depends on aspect ratio. First studies already done (IAEA talk)



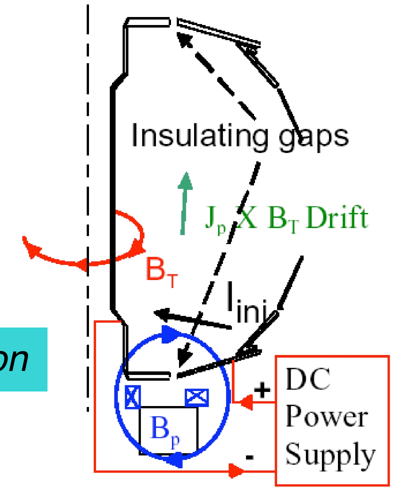
Developing the physics basis of coaxial helicity injection brings the NSTX program into the arena of dynamo physics

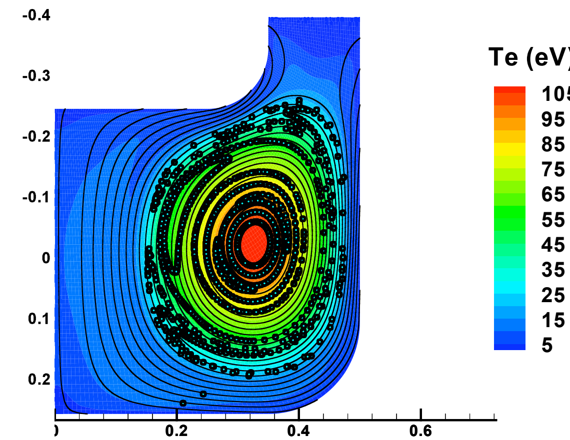
- Reconnection theory & dynamo formation: laboratory and astrophysical relevance
  - With long-pulse CHI, resultant toroidal plasma current is driven by dynamo voltage associated with MHD & reconnection

- 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)

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

U. of Washington





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

Success in this arena will benefit the AT as well

NSTX MHD research makes strong contributions to high priority fusion physics issues

FESAC Priorites Panel Topic

T1: How does magnetic field structure affect plasma confinement?

T2: What limits the maximum pressure that can be achieved in laboratory plasma?

T3: How much external control vs. self-organization will a fusion plasma require?

T6: How do magnetic fields in plasmas rearrange and dissipate their energy?

NSTX Program Elements

Stability dependence on shaping and current profile effects

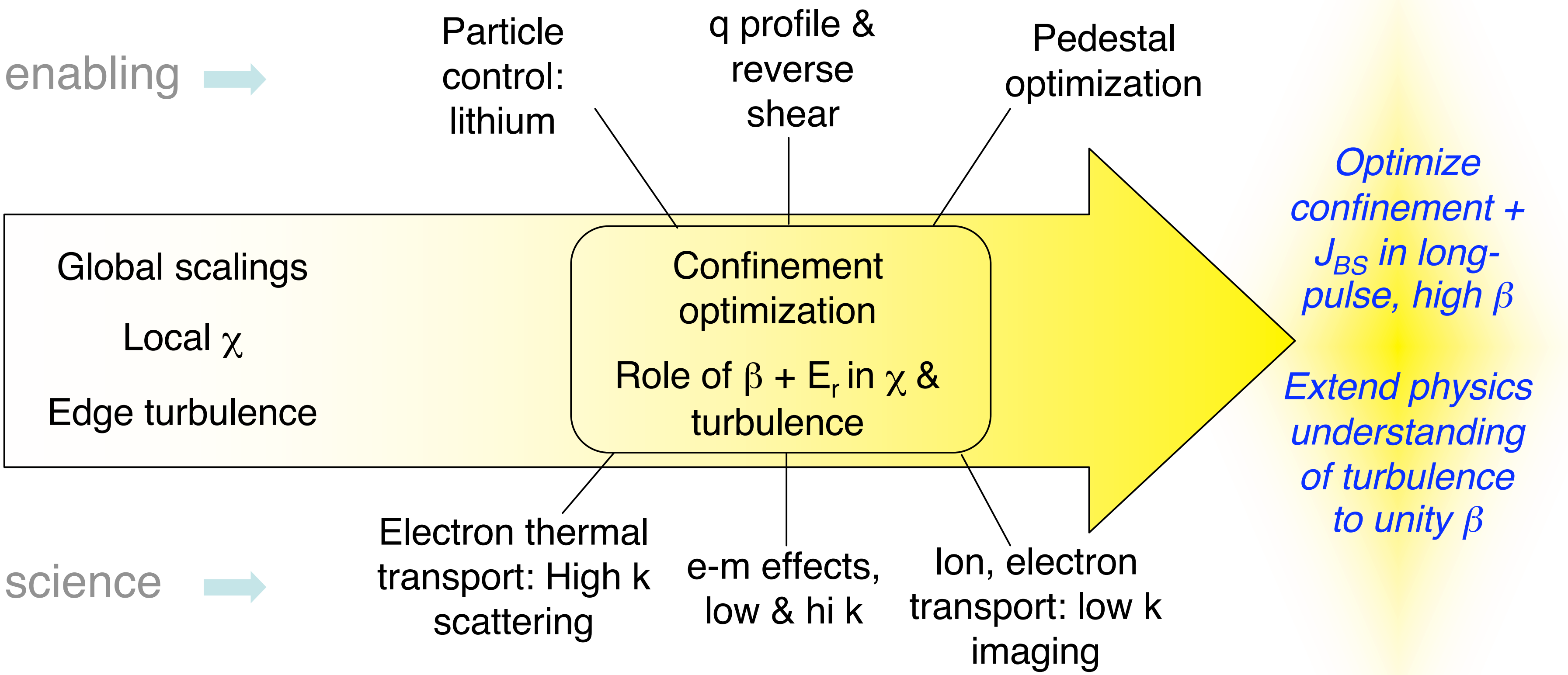
Stability at high beta. Flows and internal & external modes. NTMs. Aspect ratio & ELMs.

Active control vs. passive control research

Regimes with high J_{BS}

CHI: reconnection & dynamo physics

Transport & turbulence



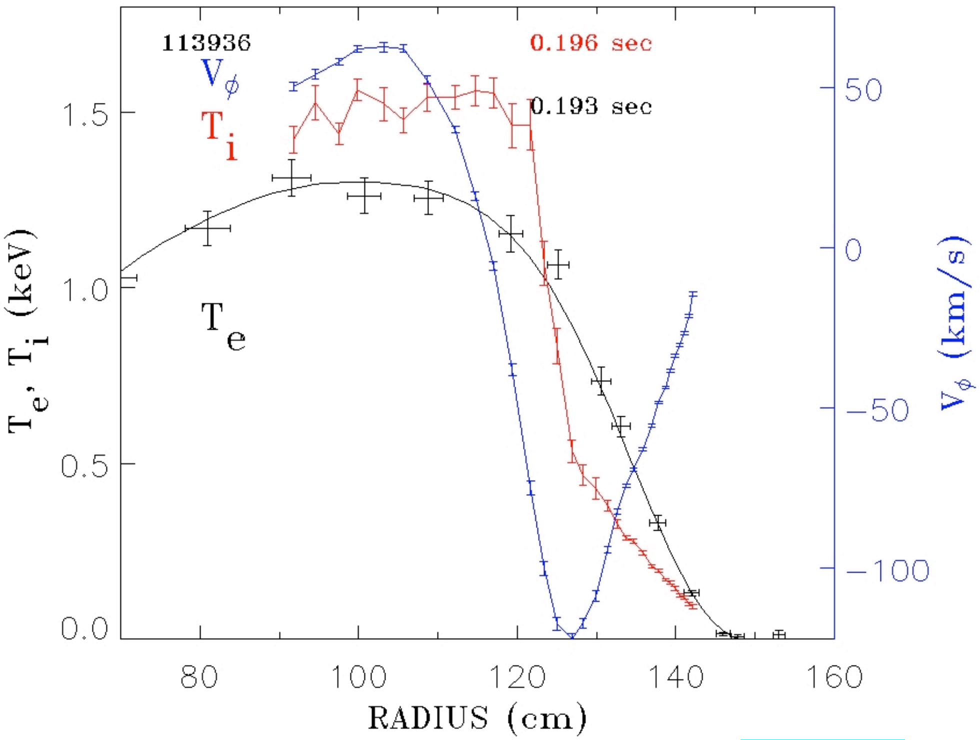
Transport & turbulence physics opportunities

- *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

Plasma flows will be a focal point of research through ‘07

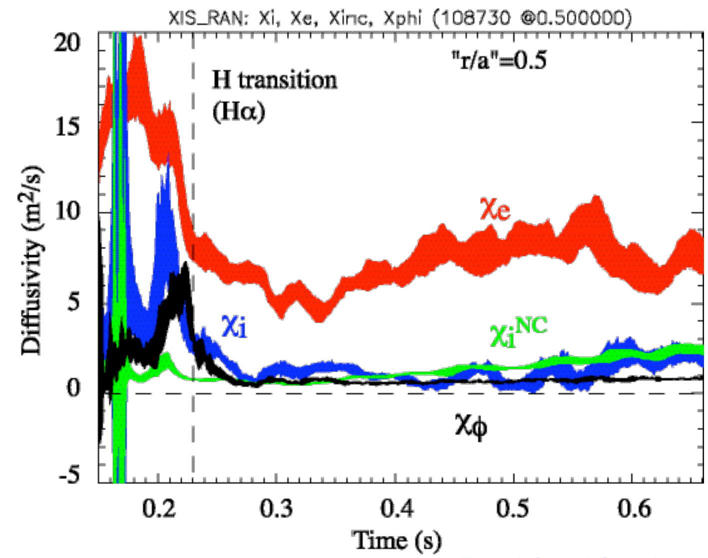
- Understanding momentum transport a national transport priority
- Motivated by observations
  - Counter-directed flow with co-injection
  - V_θ, V_ϕ with HHFW & prior to ohmic H modes
- Needed to reconstruct E_r & profile
- V_θ measurements deeper in the core will be developed for ‘06



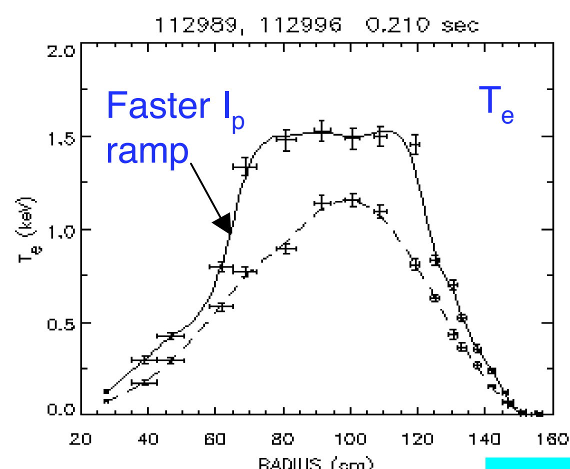
R. Bell

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

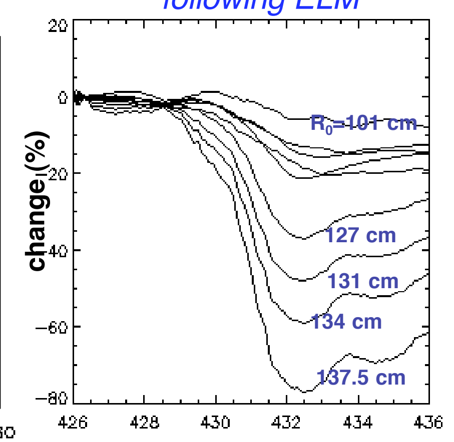
- The dominant energy loss channel & a topic of broad importance to fusion & burning plasmas, including ITER.
- Potentially important for RF & CD
- While χ_e transport is rapid, it can be modified
  - Can it be improved to enable larger J_{BS}, more efficient electron heating?
- Collaborative core transport similarity experiments through ITPA (MAST, DIII-D)



LeBlanc, R. Bell, Kaye



Rapid cold pulse propagation following ELM

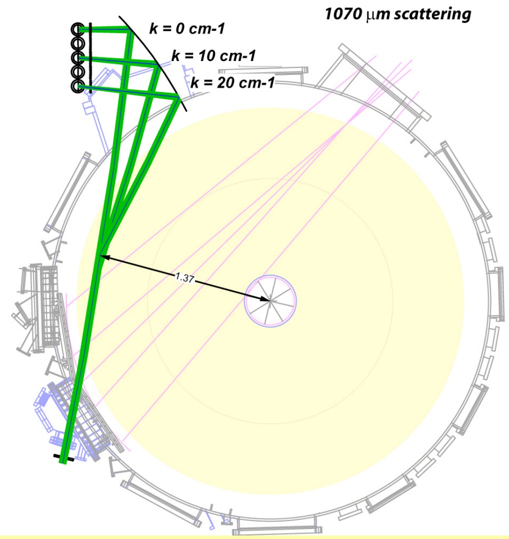


Stutman, JHU

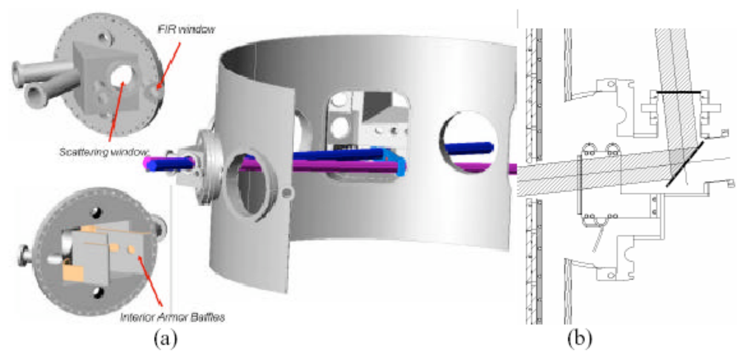
High k scattering measurements will be developed in FY' 05

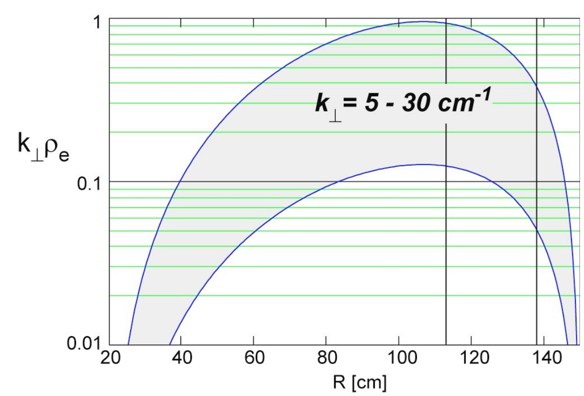
- Initial system will allow range of k measurements in select locations (2 - 20 cm^{-1}) with good spatial resolution & $\Delta n/n < 0.1\%$
- Major installation this opening.

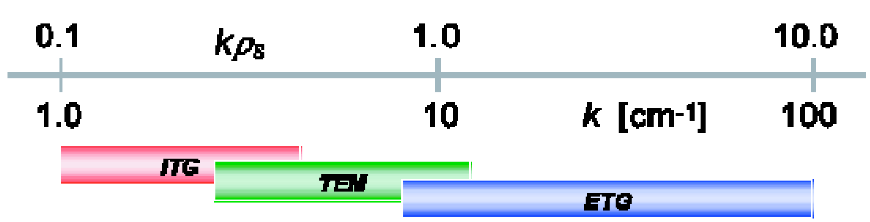
High k scattering



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

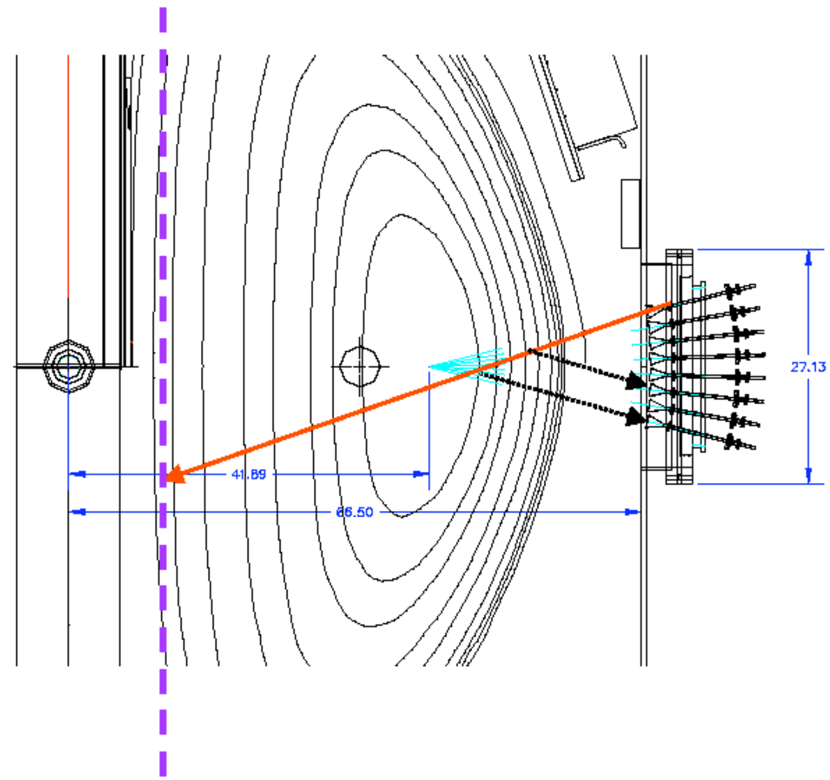






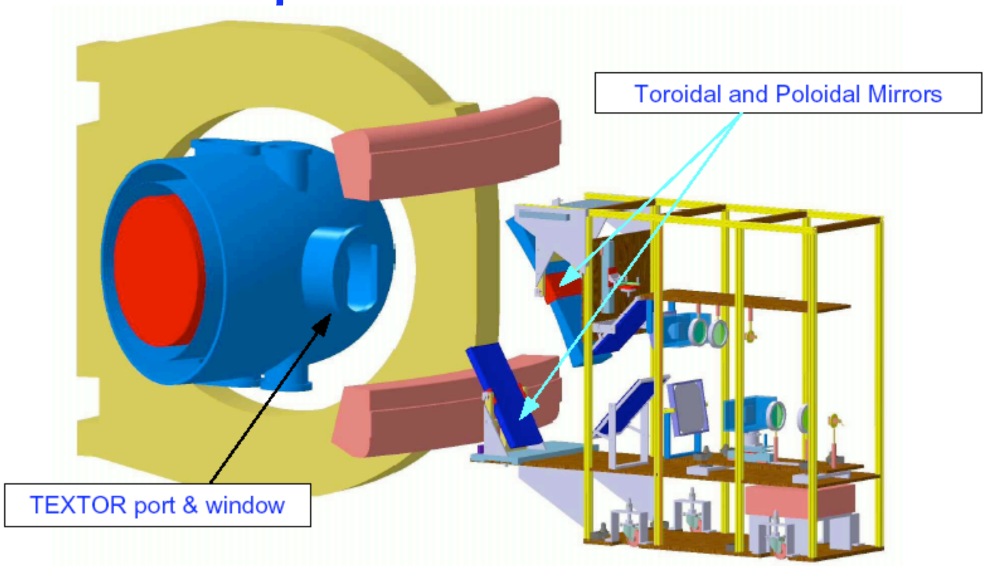
Large angle back-scattering will allow probing of high radial wavenumbers

- Launch 100 GHz with waveguide/antenna/lens combination
- Wavenumbers from 35 - 40 cm^{-1} can be studied
- Refraction will not signficantly change scattering angle --> should be good contrast between low and high k

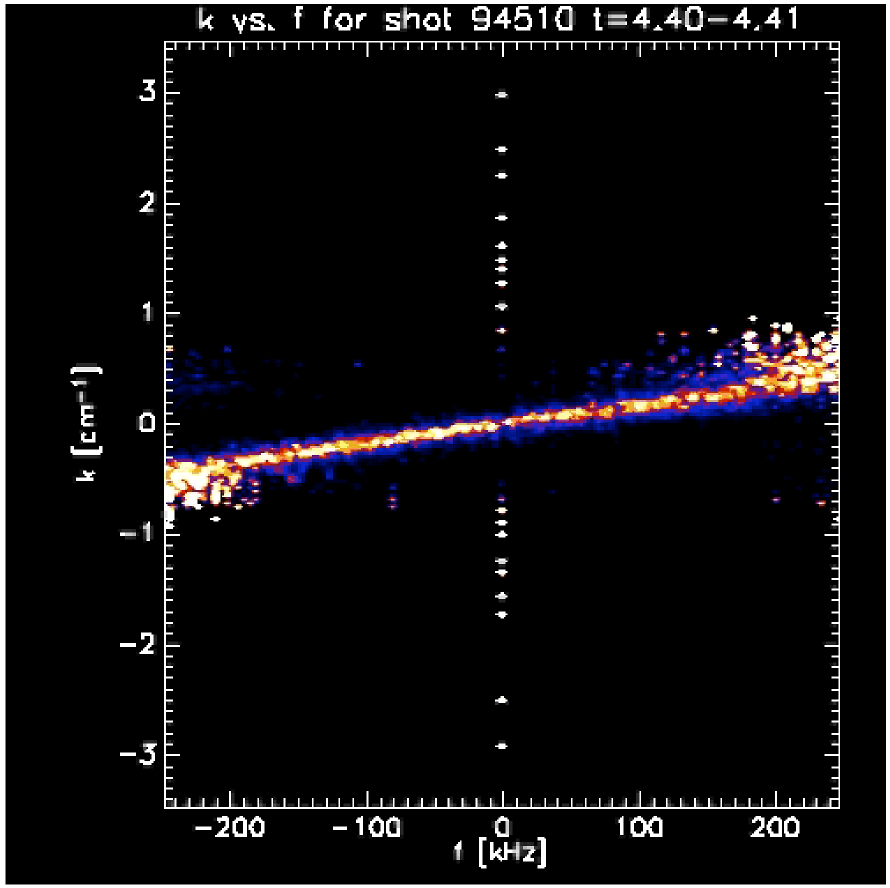


Peebles, Kubota, UCLA

Low k turbulence imaging development represents a major advance in core transport measurements



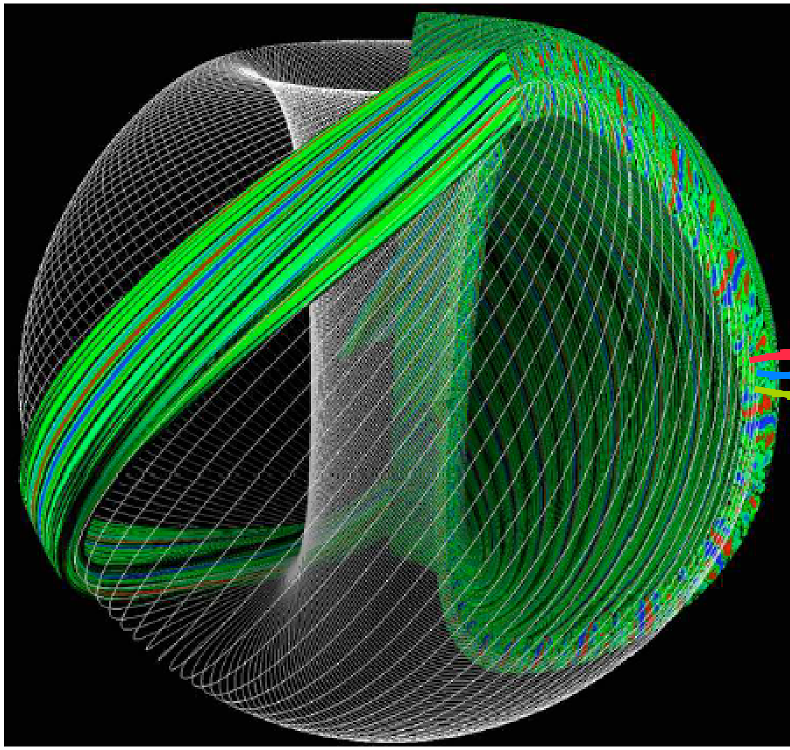
TEXTOR low k imaging data



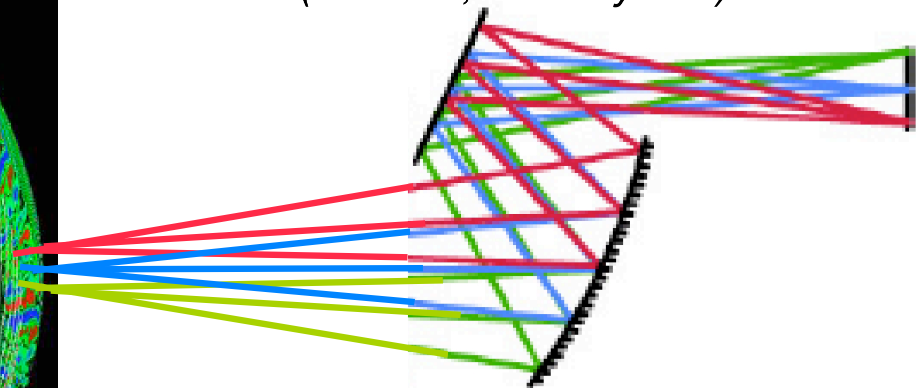
- System being developed for NSTX will enable k_r and k_θ resolution
- Build on DOE investment in development on TEXTOR. To be deployed on NSTX in FY '07
- Complementary with high k scattering. Both will enable a broad range of **k** to be diagnosed in detail

Munsat (U. Colorado), Mazzucato (PPPL), Park (PPPL); Luhman (UC Davis)ˆ

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)

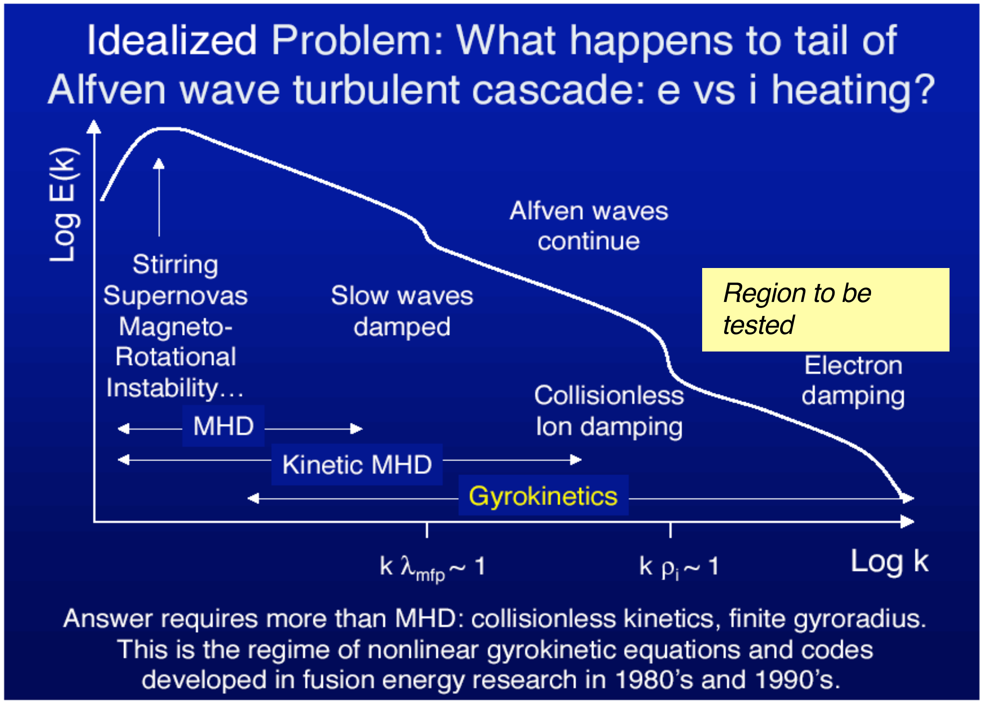


Low-k imaging (Mazzucato, Park; Munsat (Colorado), Luhmann (UC Davis))

- 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

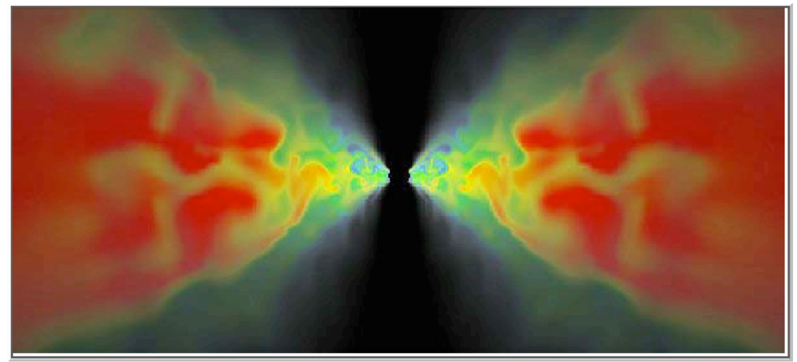
Need & opportunity: strong theory community coupling

Detailed diagnosis and gyrokinetic theory of β ~ unity turbulence is of broad scientific importance



NSTX/gyrokinetic opportunity: show that $k_{perp}\rho_i \geq 1$ can be understood at $\beta \sim 1$

Armitage (U. Colorado)



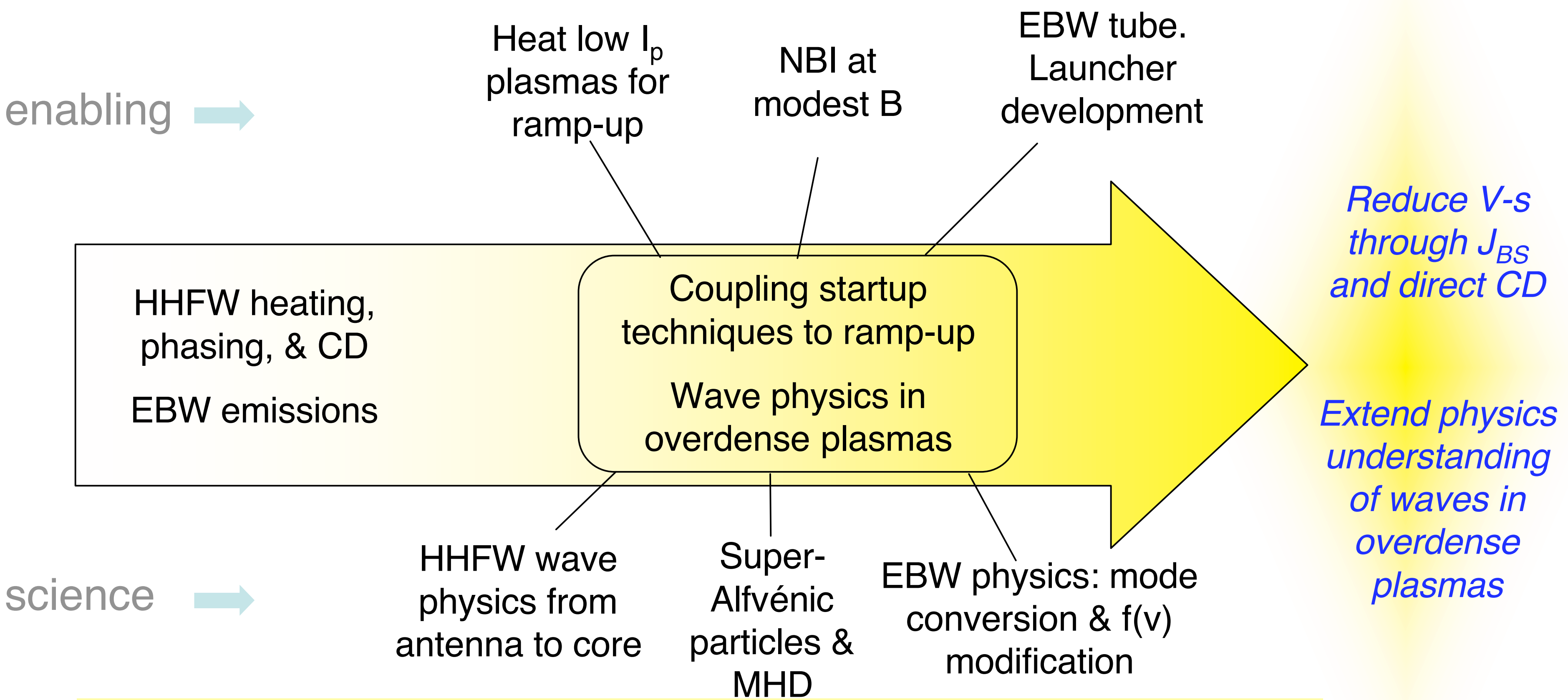
Turbulence in accretion disk of supermassive black hole at galactic center: gyrokinetics & damping of turbulence on ions vs. electrons

- Astrophysics and turbulence dynamics: cascading of MHD turbulence to ion scales is of fundamental importance at beta ≥ 1
- Fusion's gyrokinetic formalism is applicable to high beta astrophysical turbulence problems, e.g. shocks, solar wind, accretion disks

NSTX transport & turbulence research makes strong contributions to high priority fusion physics issues

FESAC Priorities Panel Topic	*NSTX Program Elements*
T1: How does magnetic field structure affect plasma confinement?	Unity β low and high k turbulence diagnosis with high spatial and k resolution, with q profile variations
T4: How does turbulence cause heat, particles, and momentum to escape from plasmas?	Transport with intrinsically high ExB shear Rotation variation with controlled application of error fields
T5: How are large-scale electromagnetic fields and mass flows generated in plasmas?	Flow measurements, including poloidal rotation (with the effects of RF) and direct E_r capability being developed (LIF MSE)

Waves & energetic particles

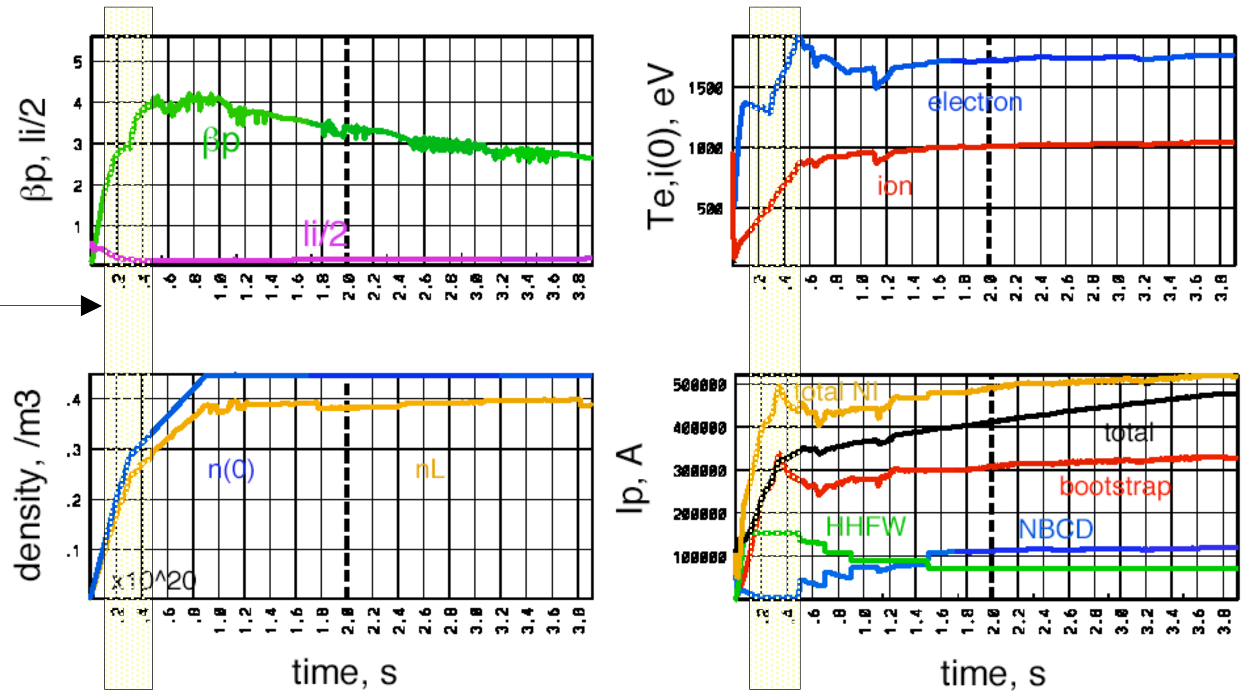


Wave-particle physics opportunities

- *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

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?

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

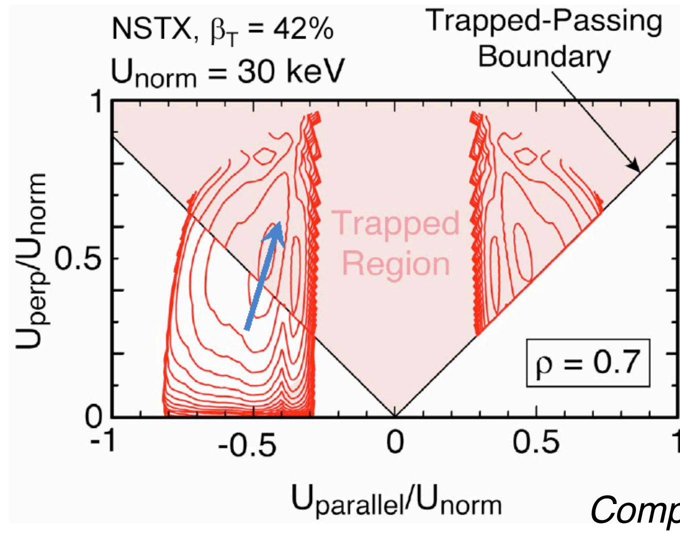
- Sheath physics
  - This opening: extend BN tiles at antenna, install Rogowski's at passive plates, RF probe on reciprocating probe head, Reverse B_T experiments. Modify antenna feed to reduce near-antenna $E_{//}$ (next opening)
- Parametric absorption
  - spectroscopy, reflectometry
- Core wave penetration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

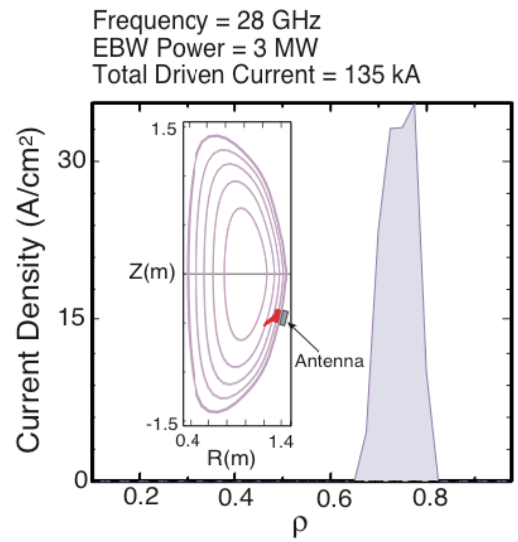
ST properties and recent experiments make EBW attractive & high priority

- 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
- MAST effort includes EB startup at 28 GHz (< 200 kW) & sustainment studies at 60 GHz (1 MW)

Strongly endorsed by 5 year plan review panel

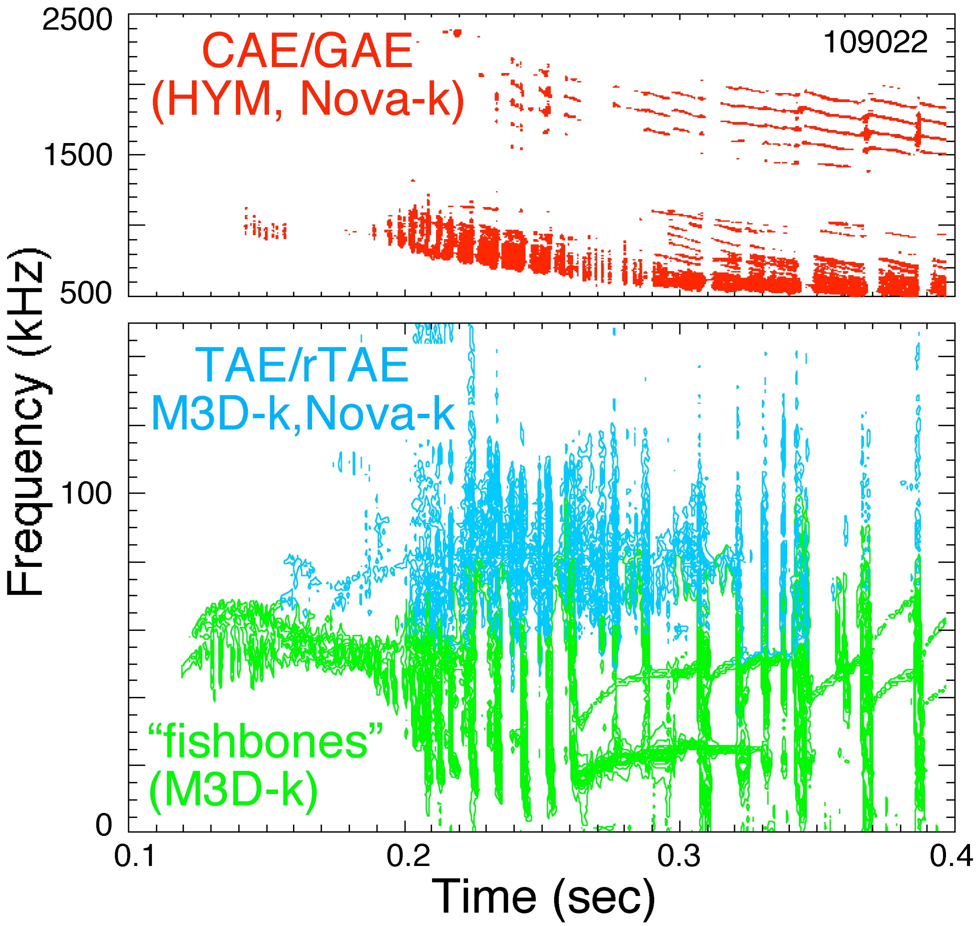


Compx Genray/ CQL3D



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

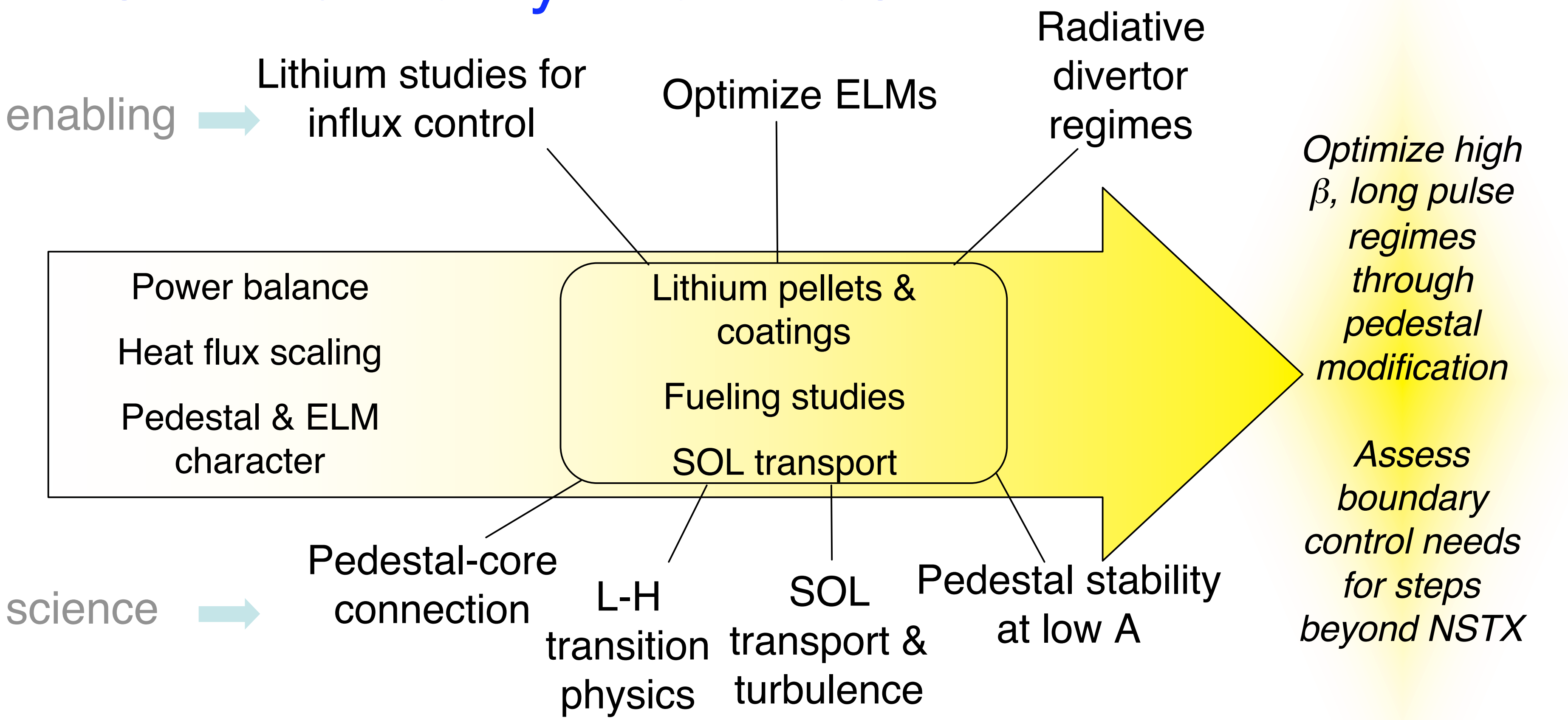
- $V_{\text{fast ion}}/V_{\text{Alfvén}} \sim 3$, similar to ITER values of ~ 2.
- Unique access to multimode Alfvénic turbulence in nearly every NBI discharge
- Fast ion population cannot be treated as a perturbation - coupling with MHD must be treated self-consistently



NSTX wave physics research makes strong contributions to high priority fusion physics issues

FESAC Priorities Panel Topic	*NSTX Program Elements*
T11: How do electromagnetic waves interact with plasma?	HHFW coupling and deposition studies for heating and current drive
T5: How are large-scale electromagnetic fields and mass flows generated in plasmas?	EBW coupling and deposition studies for heating and current drive
T12: How do high energy particles interact with plasma?	Core and edge measurements of ion heating and rotation induced by HHFW
	Nonlinear AE studies

Plasma boundary interfaces

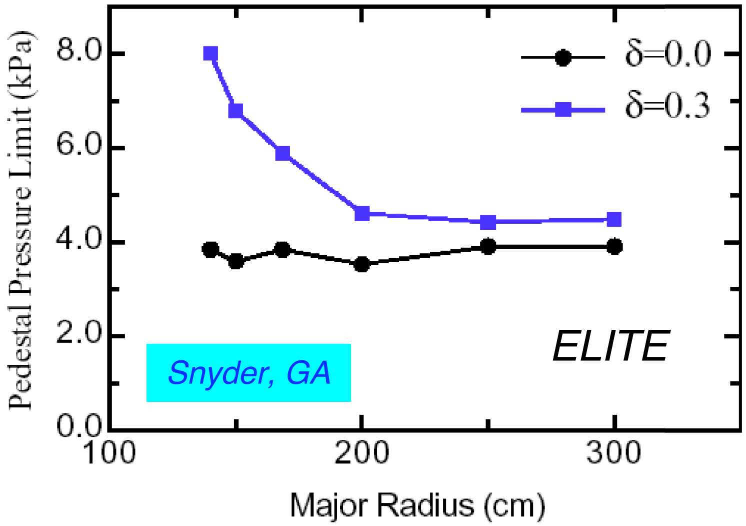


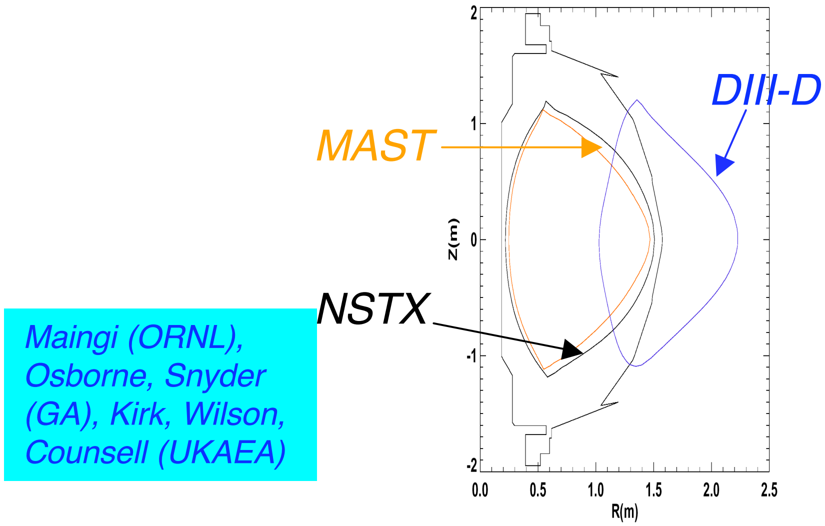
Boundary physics opportunities

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

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





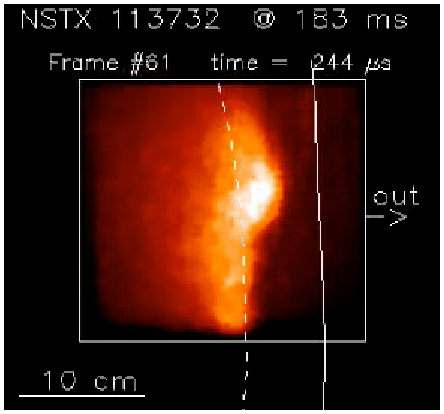
Imaging & probe measurements provide a powerful test bed for edge turbulence codes

- 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).

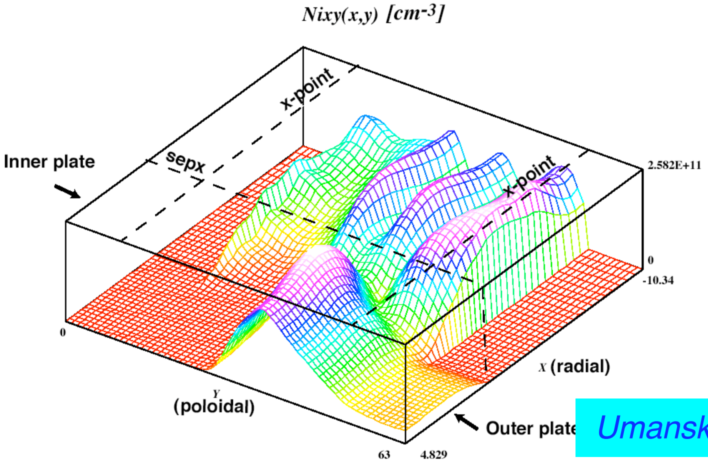
- benchmarked edge models in different conditions ==> increased confidence in models of SOL transport for ITER

- ITPA collaborative effort with C-Mod



Zweben

L mode



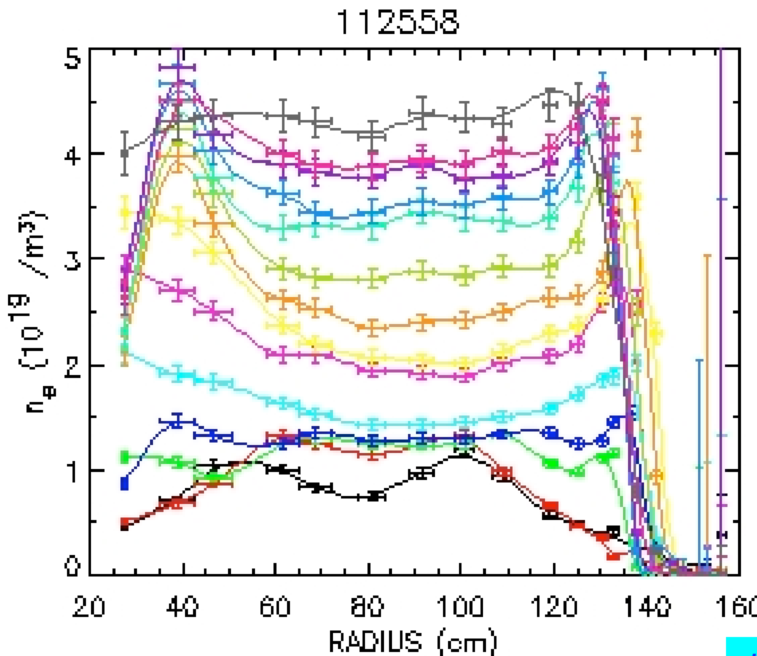
Umansky, LLNL

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

Particle control improvements will be used to seek confinement & J_{BS} increases

- Improved fueling techniques:
  - shoulder gas injector in ‘05 with improved short-pulse influx control.
  - supersonic gas injector installed and ready for the next run

- Lithium strategy being pursued for pumping. Decision on need for cryopumping or lithium module in ‘06



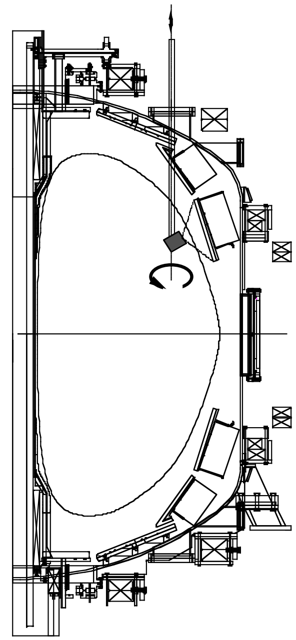
LeBlanc

Seen elsewhere: control edge influxes ==> increase edge T & thus core pressure, increase J_{BS}. A control knob for NSTX?

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

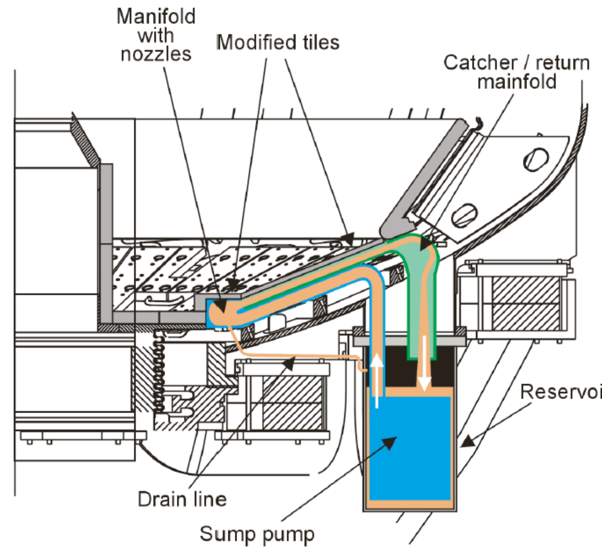
Li pellets: injector commissioned in ‘04

- Develop deposition techniques in ‘05



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

NSTX boundary physics research makes strong contributions to high priority fusion physics issues

FESAC Priorities Panel Topic

T9: How can we interface a 100 million degree burning plasma to its room temperature surroundings?

T4: How does turbulence cause heat, particles, and momentum to escape from plasmas?

NSTX Program Elements

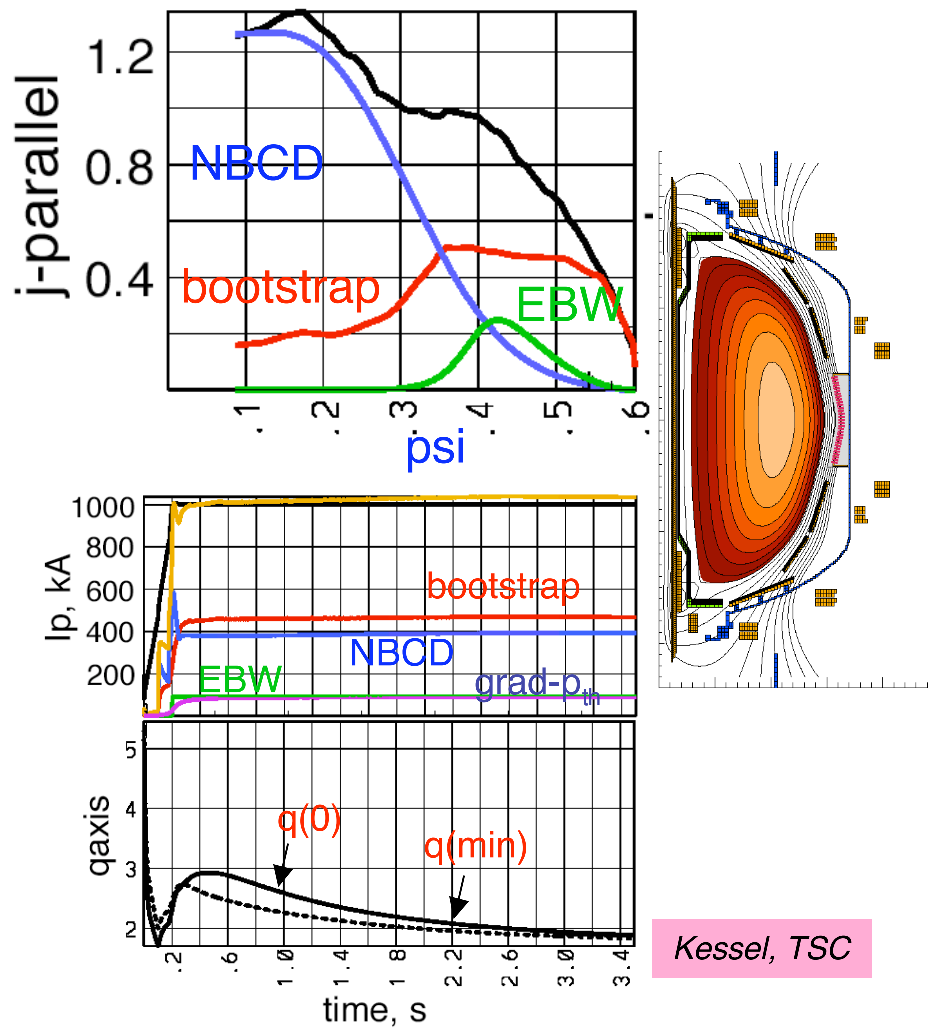
Lithium pellets & coatings studies

Pedestal/ELM stability research

Edge turbulence, including imaging and probes

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

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

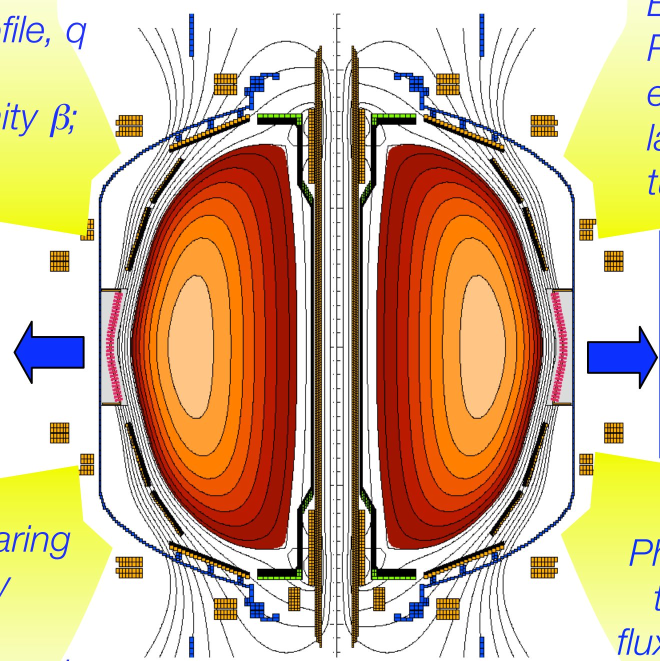
FESAC Theme: *Understand the role of magnetic structure on confinement, & plasma pressure limits*

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