Towards assessing the ST: the NSTX Research Program For FY ‘04 - ‘08

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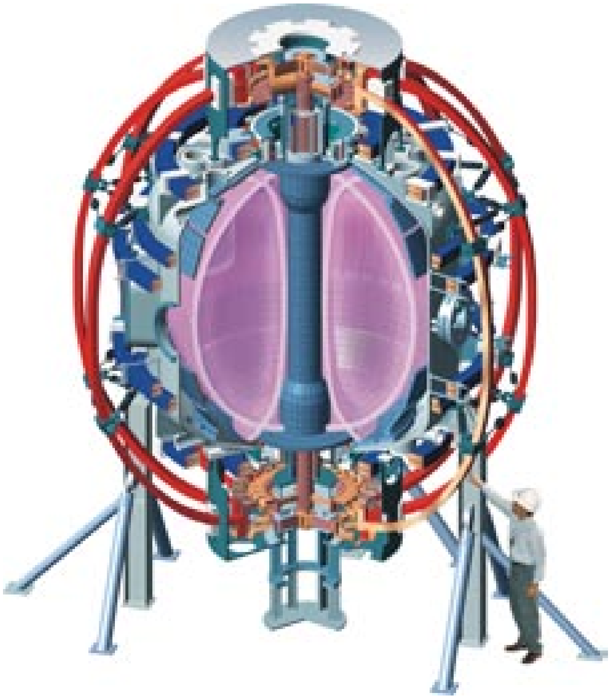


Presentation for the Program Advisory Committee Meeting

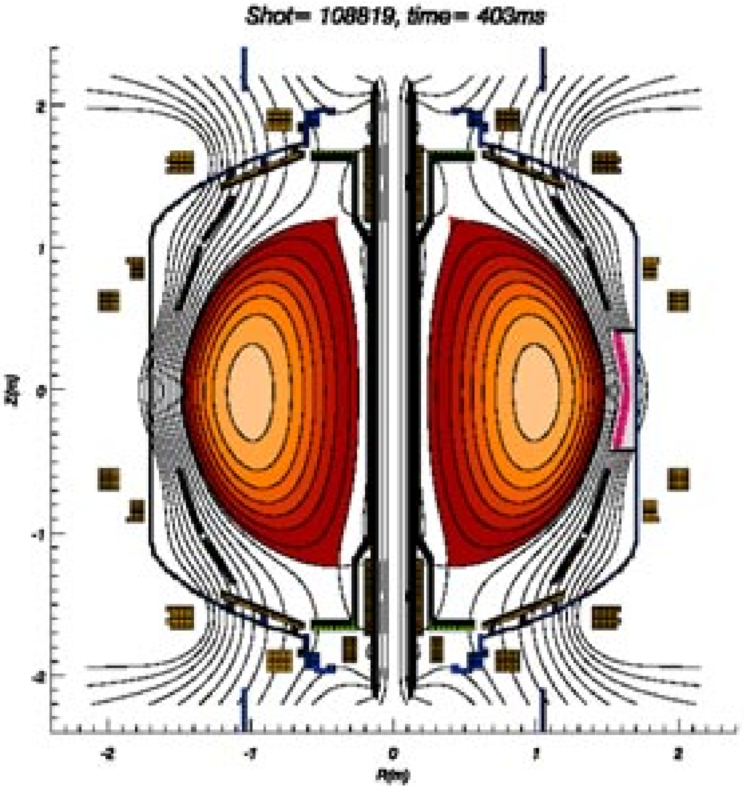
October 1, 2002

The NSTX Team is developing a research plan aimed at meeting two broad goals

- *Assessing the attractiveness of the ST as a fusion energy concept in its own right*
  - Grounded in integration of topical science

- Using ST plasma characteristics to *further a deeper understanding of critical toroidal physics issues*

- Both pursuits are guided by the IPPA implementation approach

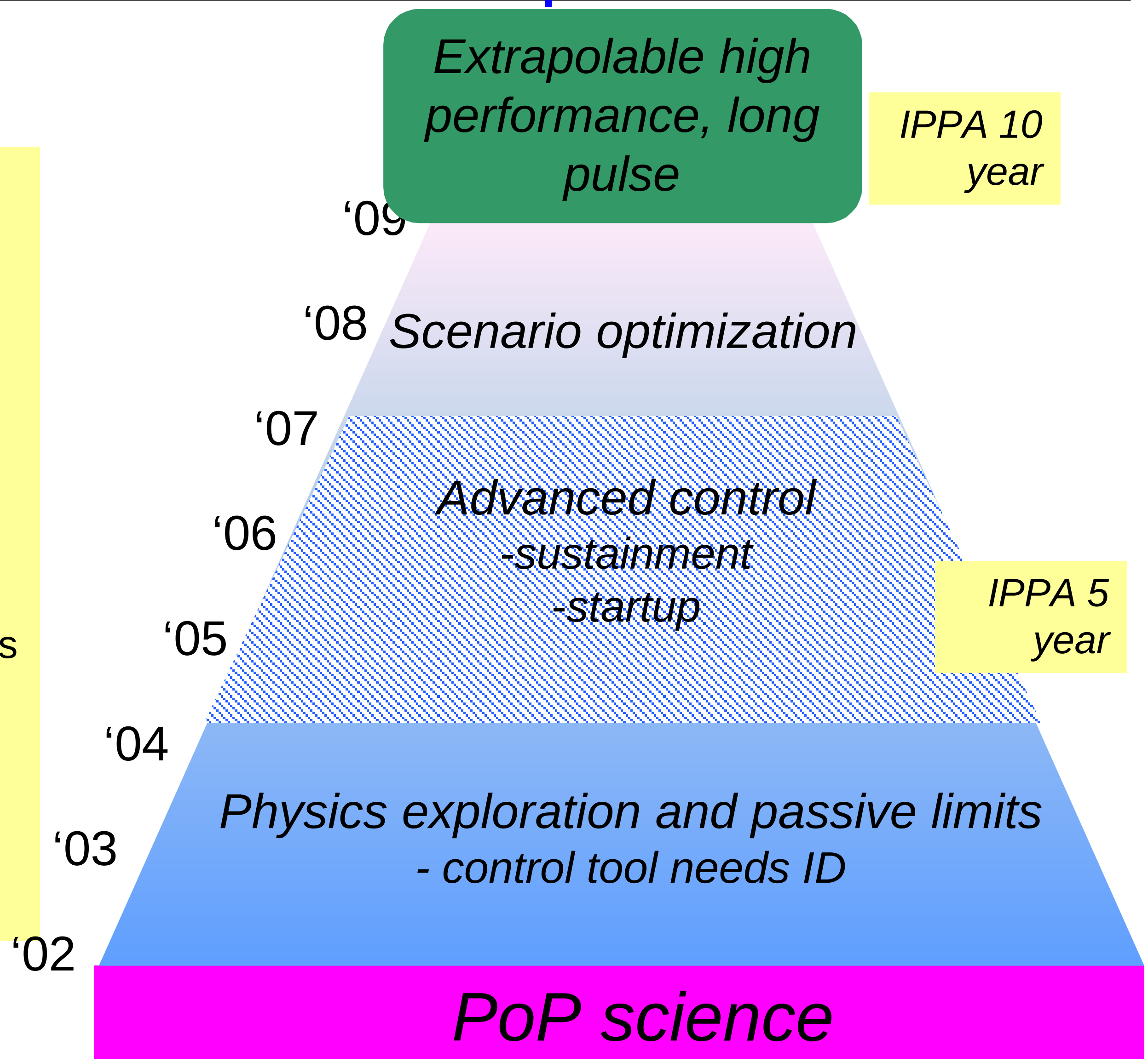


Key elements to achieving both include

- *–Developing advanced control tools to maximize device flexibility*
- *–Developing & deploying advanced diagnostics*
- *–Promoting strong theory/experiment coupling*

Integration of topical science is at the foundation of the NSTX Proof-of-Principle mission

- PoP ⇒ establishing an *extrapolable basis* for advancing the ST that is grounded in plasma science
- Integration with advanced control tools and diagnostics central to the performance and scientific missions
- Strong coupling with theory is at the heart of establishing this basis
- High beta, low aspect ratio enable stringent tests of toroidal plasma physics



The NSTX Program can meet the FESAC objectives in a timely manner

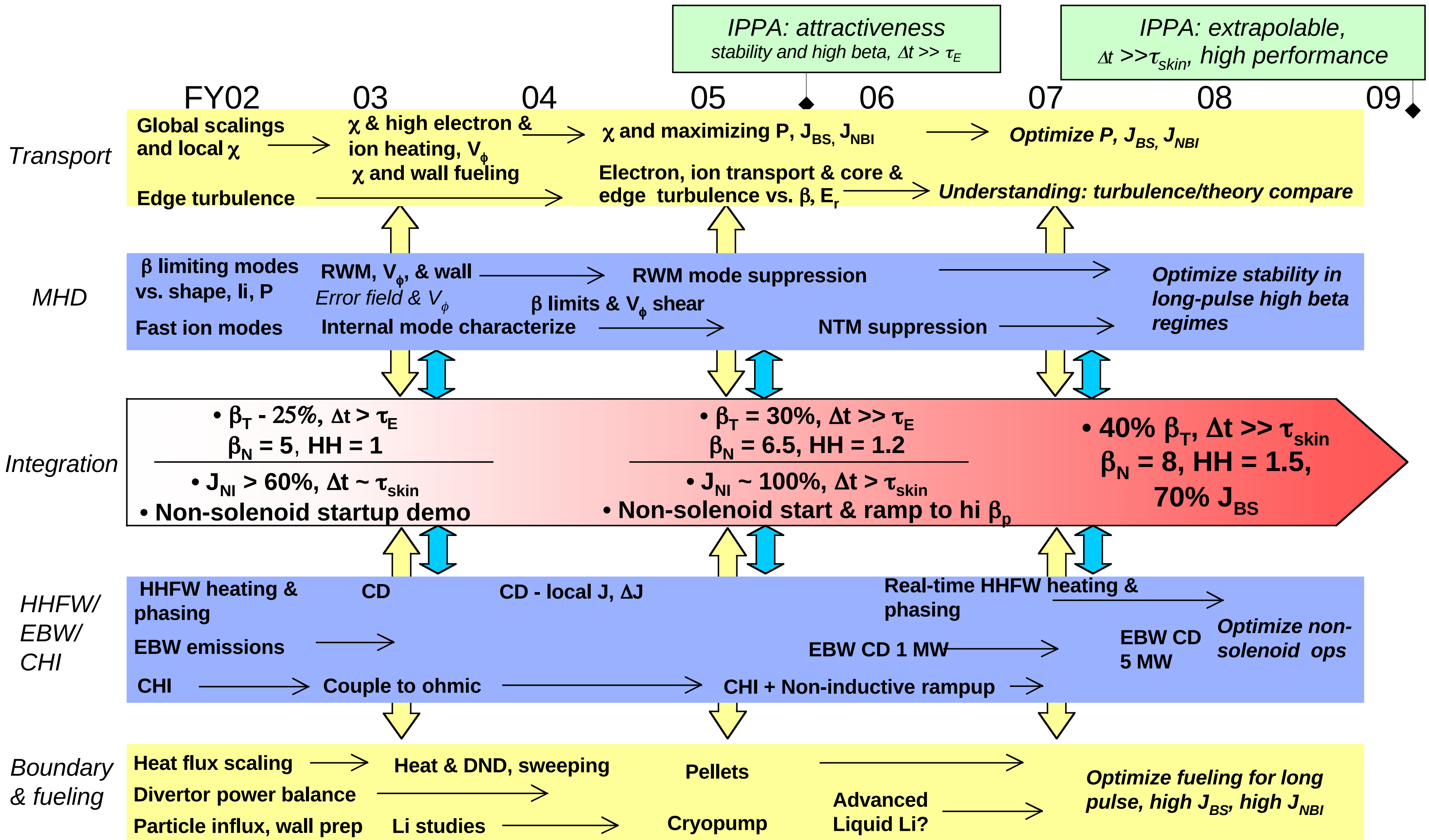
- Assessing the ST as an attractive fusion concept
  - End of 2005: 5 year IPPA goal 2.1: *Make a preliminary assessment of the attractiveness of the ST by assessing high β stability, confinement, self-consistent high-bootstrap operation, and acceptable heat fluxes, for $\tau_{pulse} >> \tau_E$*
    - Non-inductive startup & sustainment should show progress
  - 2009+: 10 year IPPA goal: *Assess the attractiveness of extrapolable, long-pulse operation of the ST for $\tau_{pulse} >> \tau_{skin}$*

- Developing ST contributions to toroidal physics
  - IPPA science goals are guiding principles
  - High β NSTX operations provides many challenges to theories:
    - High beta
    - Low aspect ratio and different field line structure, especially at the edge
    - High V_{beam}/V_{alfven}, V_{ϕ}/V_{alfven}
    - High Mach number

This is part of a process to inform our thinking about how to best meet the FESAC goals

- Last time we met, C-Mod and DIII-D were planning to be reviewed this spring. We were informed last spring that we would be joining them.
- First step: input obtained in Five Year Plan Workshop, 6/24 - 6/26
  - Topical discussion groups (science topics & integration)
  - Tasks put to the participants included
    - Identify elements you think necessary to reach IPPA goals
    - Discuss possible major facility upgrades
    - Identify opportunities and role for advanced diagnostics, control tools
    - Identify theory and modeling requirements
  - Several from the general community participated (C-Mod, DIII-D, MAST, Pegasus) and provided insight on their planning status and thinking
- Now: feedback and perspectives from you on key elements
- Next Step: Five Year Plan Workshop, 12/12 - 12/13
- February PAC: more detailed plan and your feedback
- FESAC review in June

Integrating control tools & topical science is central to advancing the NSTX mission

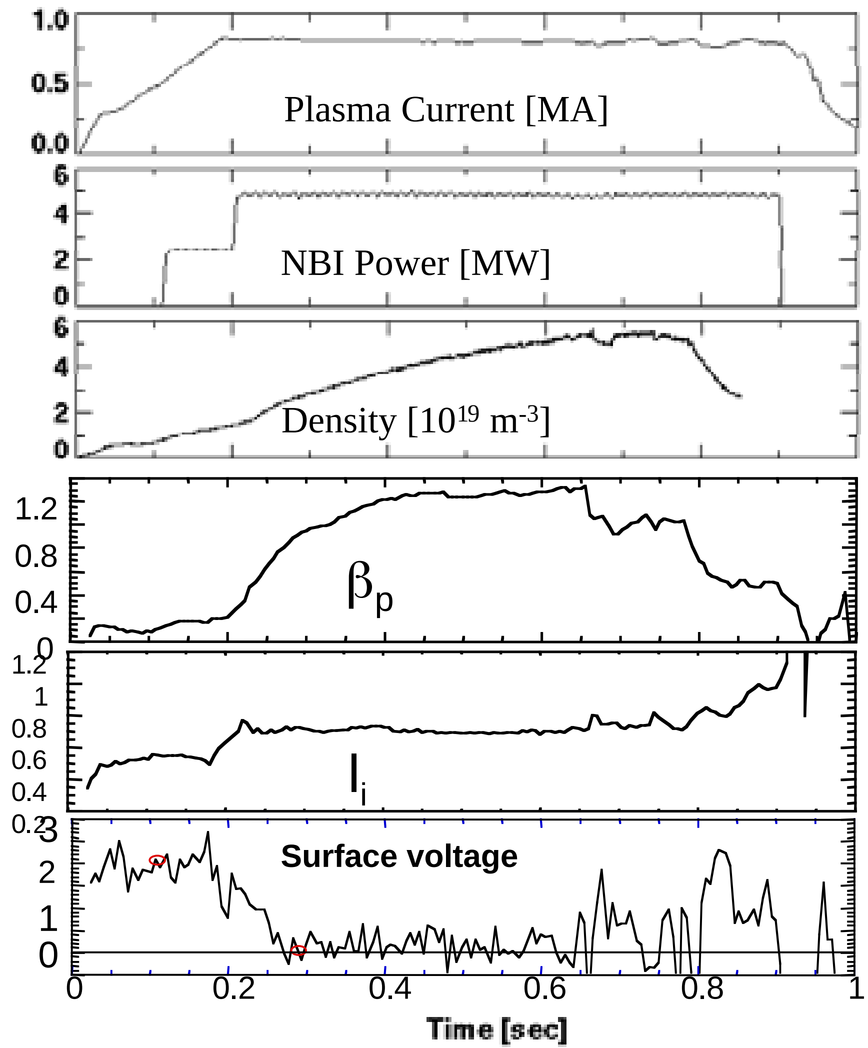


Recent results are very encouraging for both long pulse and high beta

- Integrating these is the challenge
  - High points include: 34% β_T transiently, 15 - 17% β_T sustained for of order a skin time (τ_{skin} ~ 230 ms)

- Long pulse discharge has many parameters that may be relevant to a CTF

	NSTX Long pulse	CTF	ARIES-ST
β_T	15%	20%	50%+
β_N	5	5	8
β_p	1.2	1	1.4
q_{cyl}	3.2	3	3



To meet long range goals, several long-range challenges have to be met

Again, consider the long-pulse discharges

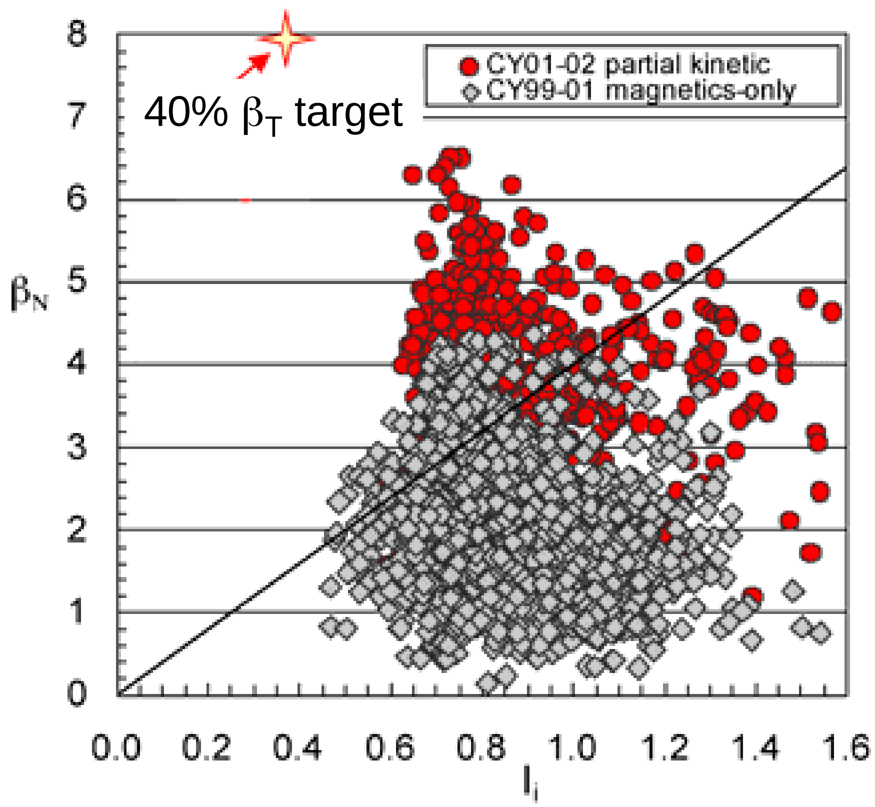
- Performance degrades with what may be q(r,t)-related MHD
  - *Combined HHFW + NBI critical? Particle control for J(r) modification?*
- Confinement favorable compared to scalings
  - *Power degradation of χ_i, χ_e: Extrapolation and implications?*
- NTMs not significant limitng factor
  - *More deleterious at higher power, lower q?*
- Density rises throughout the pulse
  - *Density control/ELM optimization required?*
- Startup is inductive
  - *Will CHI or some other strategy work?*
- About 50 % inductive current
  - *Will HHFW, NBI, bootstrap be made to fill the gap?*

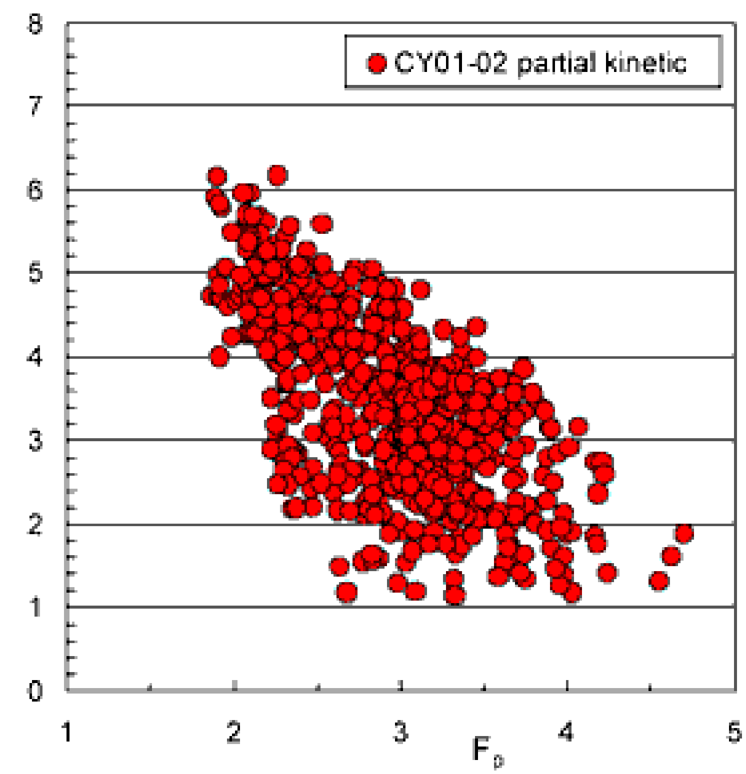
 ⇒ *The 5 year plan takes aim at these and other critical issues*

fi *More on integration later in the talk…*

Progress has been made towards achieving target of 40% β_T

IPPA Goal 1.2: Develop detailed predictive capability for macroscopic stability, including resistive and kinetic effects

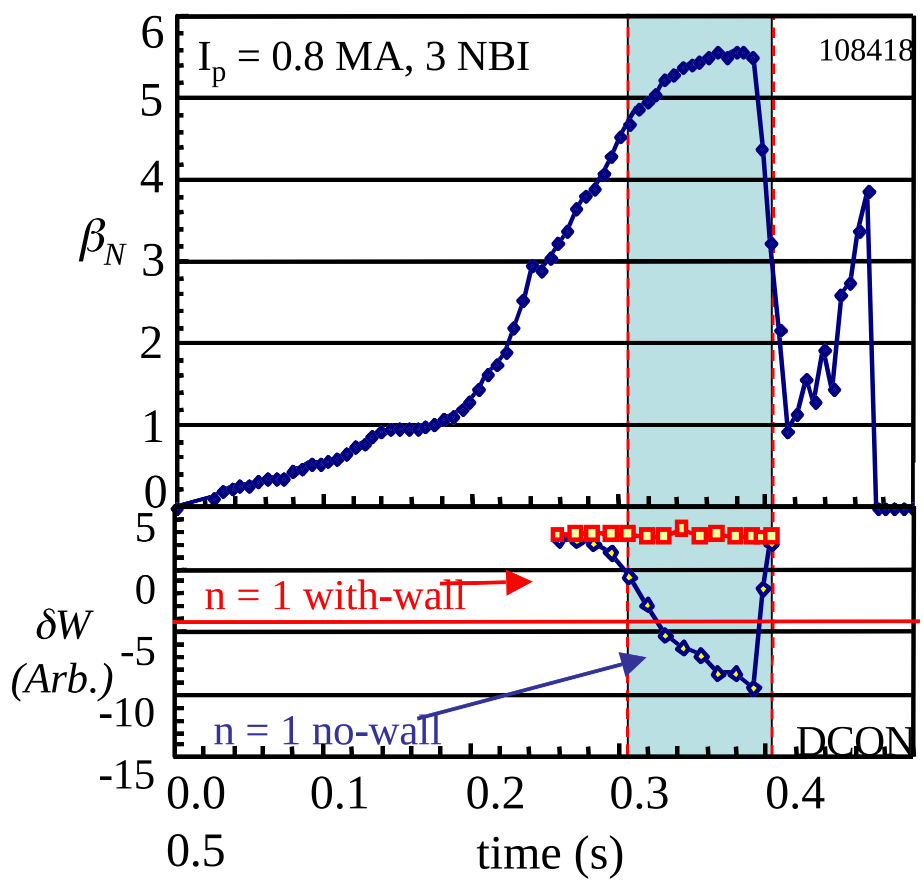




- $\beta_N = 6.5$, $\beta_N / l_i > 9.5$. $\beta_N > 30\%$ over $\beta_{N\ \text{no-wall}}$
- Maximum β_T of 34% obtained
- Takes advantage of broad P(r) in H mode

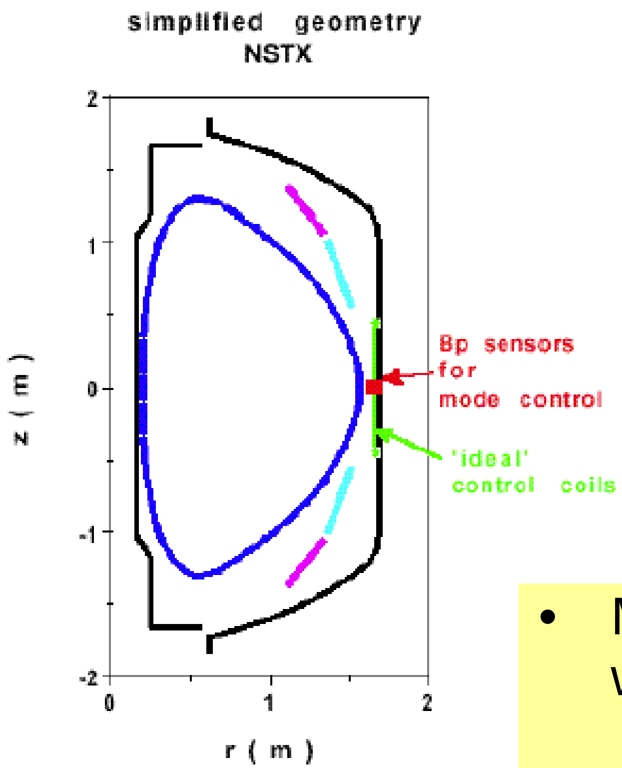
No-wall limit exceeded for many wall times

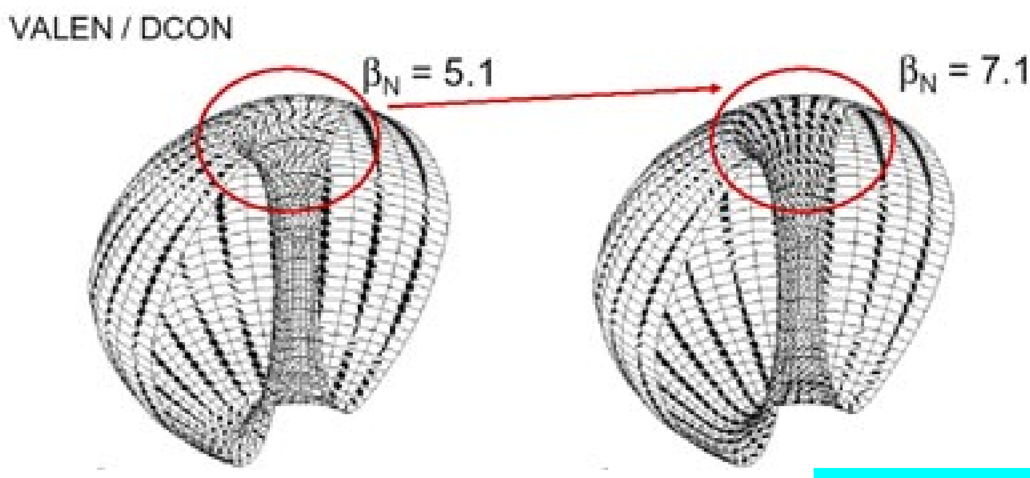
- High β_N portion calculated to be no-wall unstable for 90 ms
- Wall stabilization likely enabled by broad pressure coupling of mode to wall at higher β_N and high V_ϕ
  - Studies of V_ϕ/wall interactions will be key for establshing physics basis
- Rotational shear effects may also be important



Sabbagh, Columbia; Glasser, LANL

A goal of the next 5 years is to optimize the passive plates and feedback system configuration



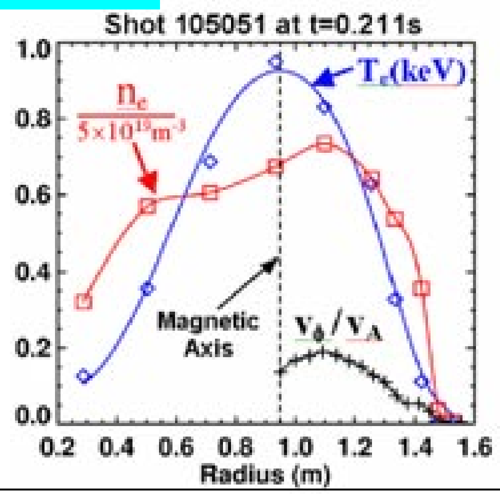


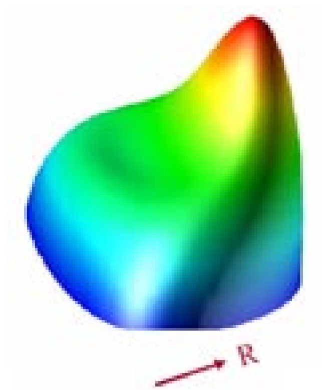
VALEN: Bialek (Columbia)

- Midplane coils may increase β limit to near ideal wall values for some modes
  - external coils do 75% of the job of an ideal wall
- At highest β_N, mode structure moves towards center stack
  - passive plate modification required. Simultaneous mods for cryopumping

Rotational effects on MHD may significantly alter equilibrium & kink stability characteristics

R. Bell, LeBlanc

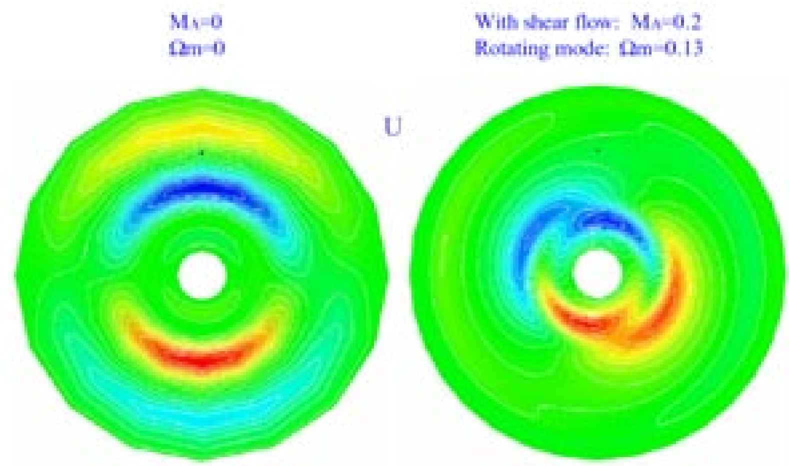




- Experiment: Density shows in-out asymmetry
- MHD theory benchmarked: captures asymmetry when flow effects and hot particle pressure is included (M3D)
- Effect of high Mach number of driven flow

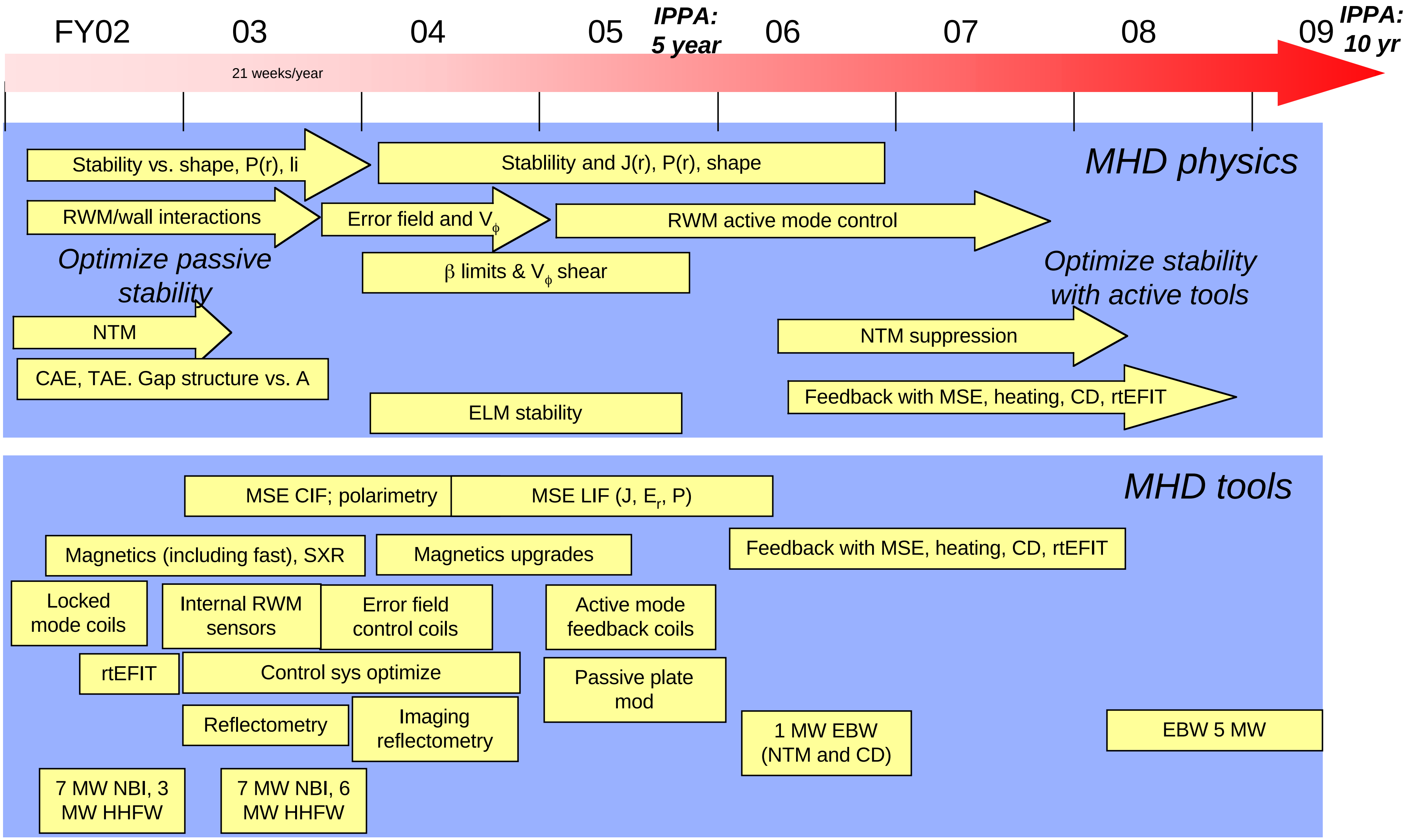
M3D: Park

- Experiment: kinks saturate (Stutman, JHU)
- Theory: reduction of linear growth rates. Saturation due to rotational shear can occur
  - effect of mode on the shear itself is important
- For physics basis: Need to understand how rotational shear stablization scales to larger devices



Theory/experiment coupling critical for PoP basis

Integrating MHD science with control strategies is key to establishing physics basis

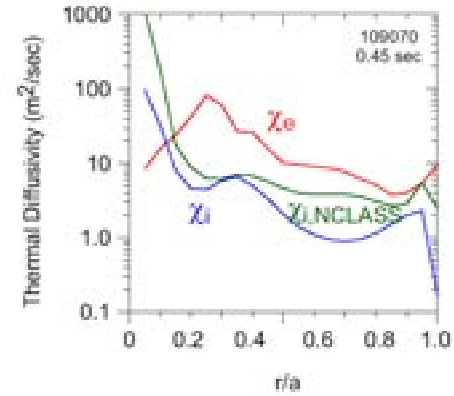


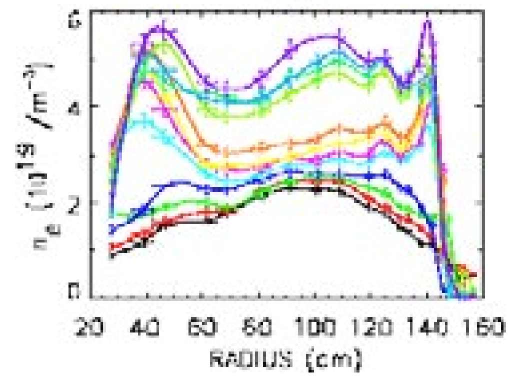
Understanding confinement trends has important practical implications, high physics leverage

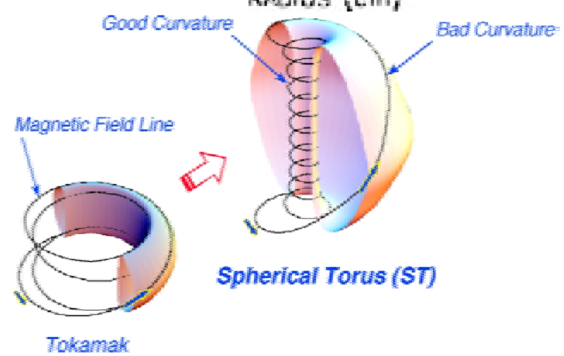
- For extrapolable physics basis: need to understand how electron and ion χ's scale with engineering and physics parameters

- χ control $\Rightarrow$ enormous leverage on P(r,t), J_{BS}
  - One of the community's toughest problems, but potentially enormous payoff
  - Heating and fueling flexiblity, J control are our best tools

- NSTX can teach us about broadly important issues
  - Important opportunities in low & high k turbulence
  - Electron transport
  - H mode: ST/tokamak comparisons must tell us something about role of field lines.





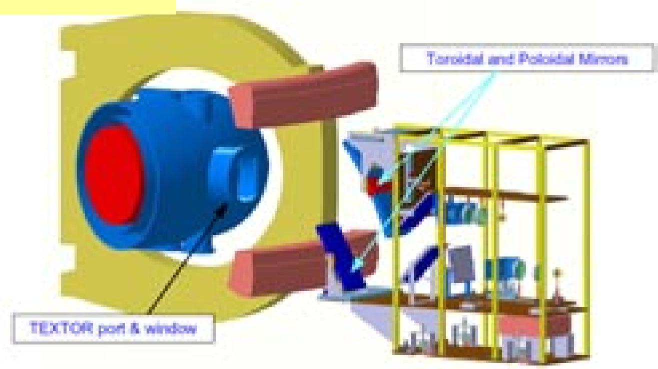


Turbulence diagnostics can enable unique NSTX contributions to universally important transport issues

IPPA Goal 1.1: Advance transport physics based on understanding of turbulence & turbulence dynamics

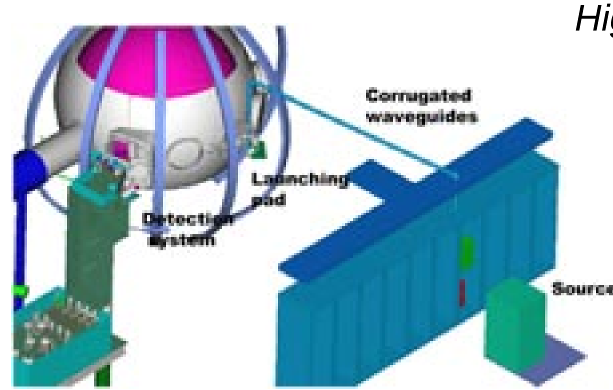
- Long wavelengths: naturally suppressed?
  - Reflectometry imaging being developed on TEXTOR.
  - Possible NSTX deployment in ‘05

Low k Imaging



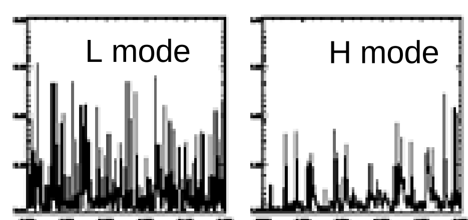
- Short wavelengths: key to ubiquitous electron transport problem? Large $\rho_e \Rightarrow$ big modes, ideal scattering geometry on NSTX
  - prototype implemented in FY ‘03/’04
  - k_r = 6, 20, and 30 cm^{-1}

High k scattering



Mazzucato, Munsat, Park; Lee, Luhman (UC Davis)

- SOL: high intermittency seen in imaging (LANL), probes (UCSD). Determinant in heat fluxes?

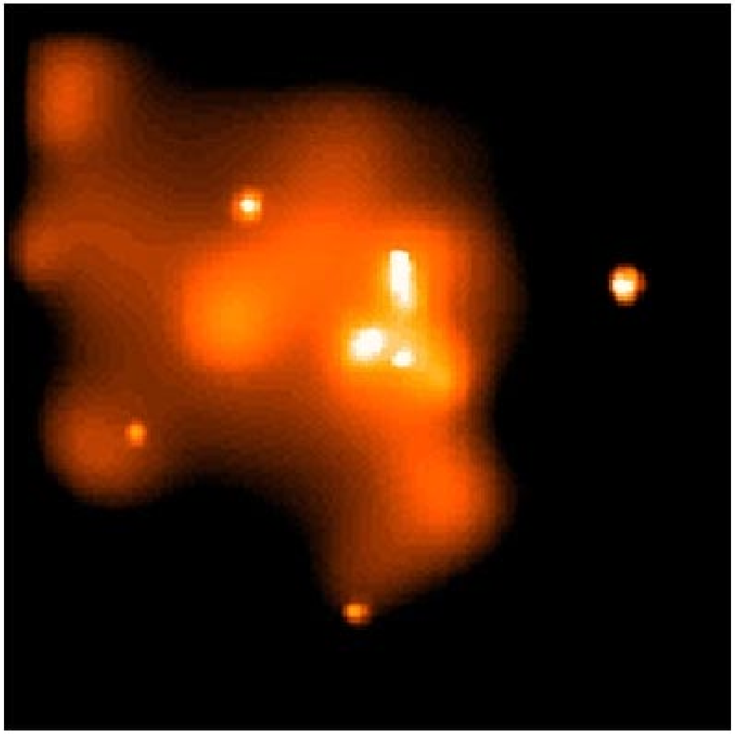


Boedo (UCSD)

Detailed diagnosis and gyrokinetic comparisons of β ~unity turbulence challenges us and is of keen interest to astrophysics community

- Turbulence dynamics: cascading of MHD turbulence to ion scales is of fundamental importance
- NSTX can provide tests electron thermal transport theory, important for tokamaks, at a high β extreme
- Gyrokinetic formalism applicable to high beta astrophysical turbulence problems

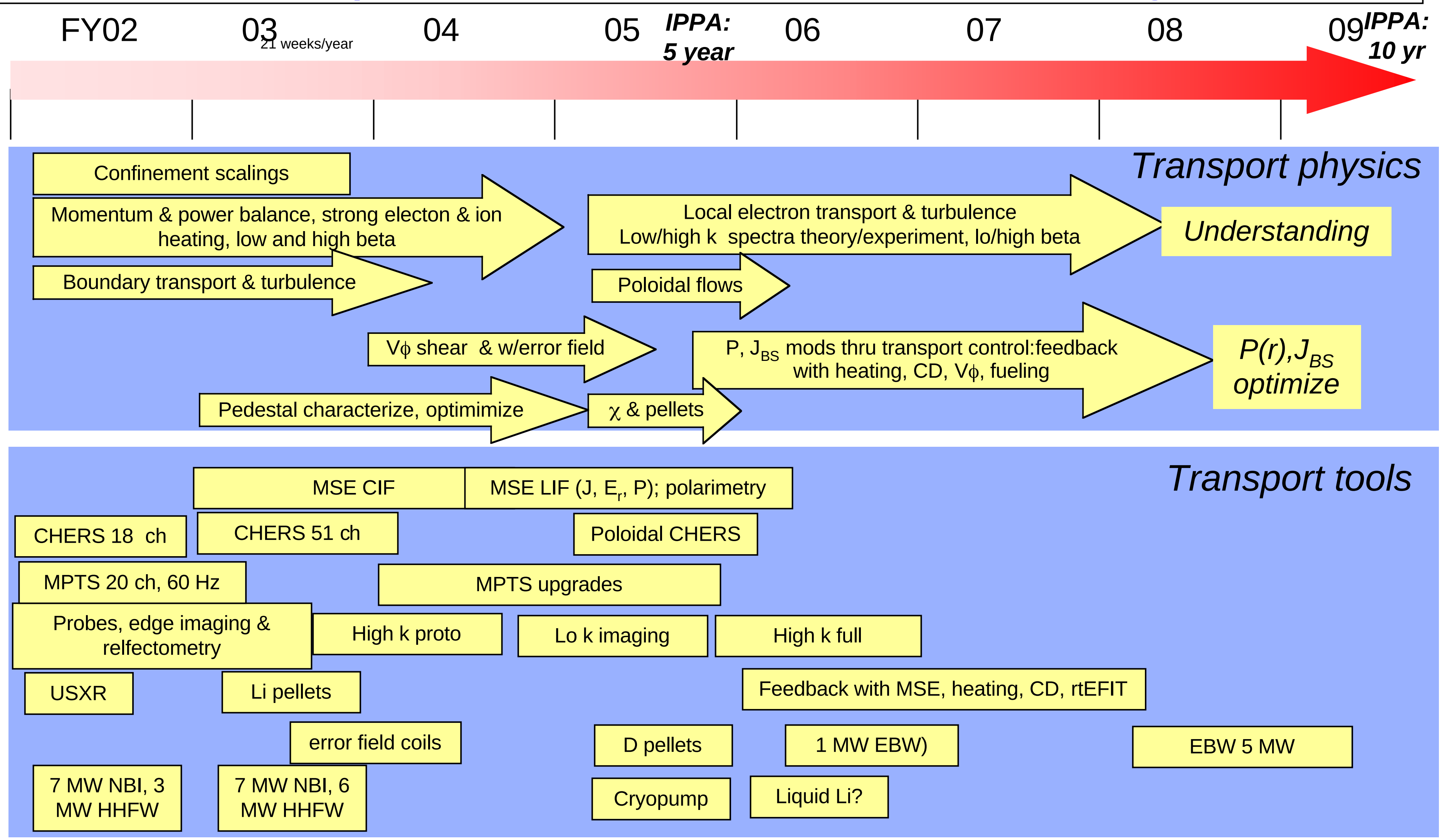
⇒ Their community wants to benchmark gk codes with diagnosis of β ~ 1 laboratory turbulence



Chandra X-ray Observatory
Central 10 years of our galactic center
10^5 times "too dim"
High beta ion-scale turbulence problem

Quataert (Berkeley), Dorland (MD)

Transport studies will emphasize P(r) optimization and transport & turbulence understanding

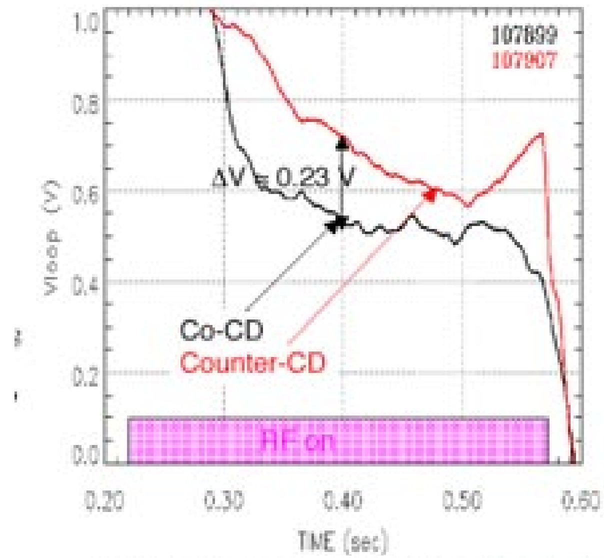


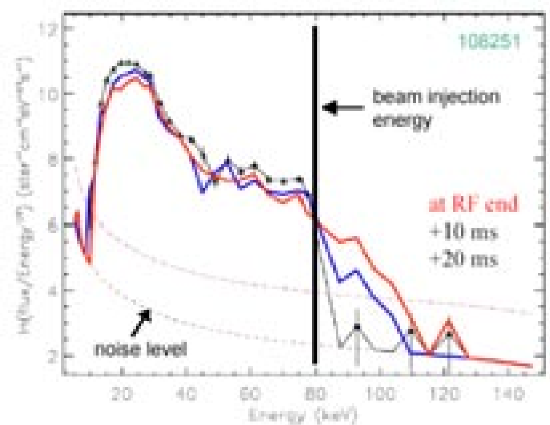
RF research in several areas will grow in importance in FY '04 - '08

IPPA Goal 1.3: Develop predictive capability for plasma heating, flow, and current drive, as well as energetic particle driven instabilities…

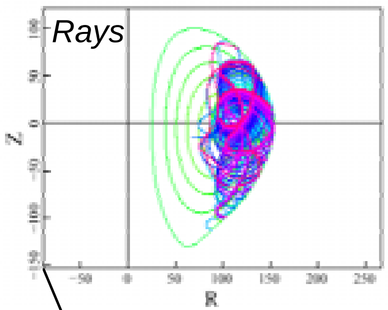
Ryan, Swain (ORNL); Hosea, Wilson

- HHFW heats effectively; CD indicated by surface voltage
  - Next step - local ΔJ measurements
- HHFW interactions with fast ions found (Rosenberg (Ph.D. Thesis), Medley)
  - Important for assessing CD efficiency
- EBW emissions being studied to identify requirements for possible new system.
  - Development path for EBW as a NTM and CD tool outlined

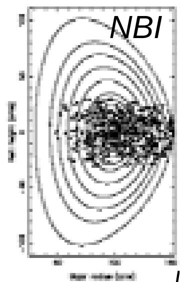




Benchmarking of fast models uses advanced theory developed by SCIDAC as well as NSTX data



GENRAY



CQL3D

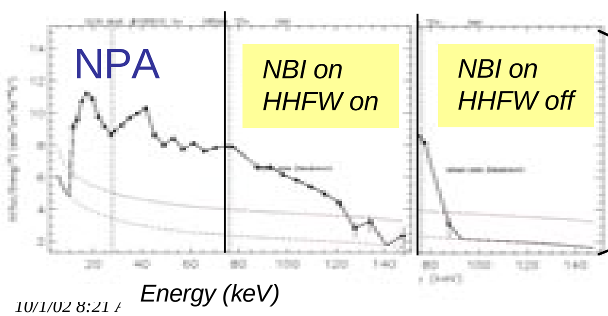
Approach: *benchmark and test* faster models against most sophisticated theory and measurements

Benchmark with complete wave theory
AORSA-2D (Batchelor, Jaeger, ORNL) (SciDAC)

Faster model: Ray tracing
GENRAY (Harvey, CompX)
CURRAY (Mau, UCSD);
HPRT (Rosenberg, P.U., Menard)

Analysis of transport, current drive
TRANSP

Faster model: Full wave
TORIC (Bonoli, MIT);
METS (Phillips; SciDAC)



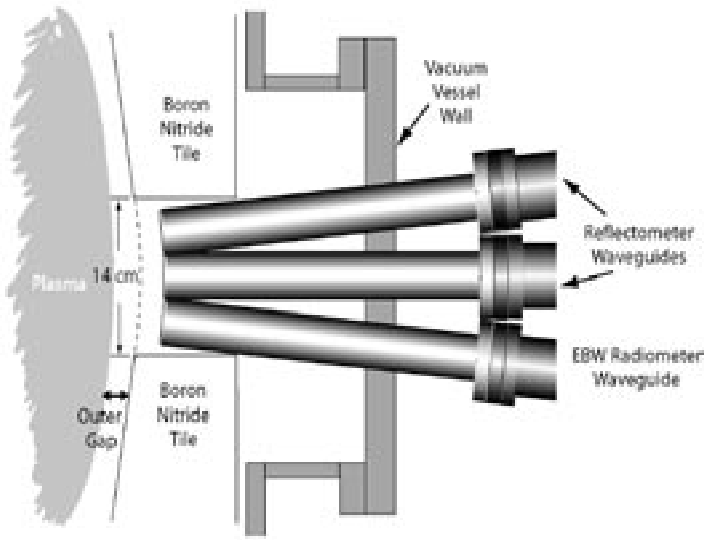
Benchmarking with NSTX Data
Wave-particle interactions
Source measurements

HHFW current drive goal is feedback control based on local measurements

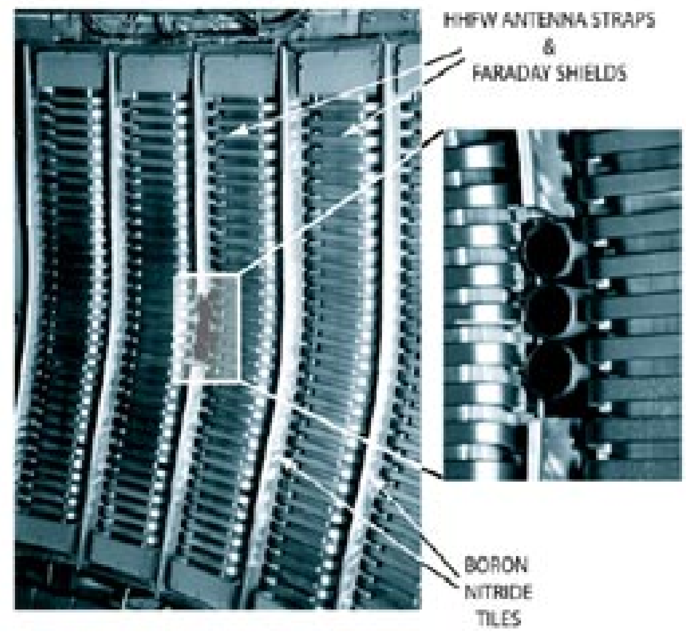
- Near-term focus is on making system more reliable, higher power
- FY ‘03 will permit the first measurements of pitch angle changes driven by HHFW
  - CIF MSE deployed at start of FY '03
  - Measurement resolution target: ΔI_p ~ 1.5 kA within half-radius, assuming no E_r complication
- LIF MSE: first photons late FY’04, fully utilized in FY '05
  - E_r, J(r) effects on MSE signal will be separated. Will enable direct measure of pressure profile as well
- Possible improvements to antenna will be assessed
- Goal in FY ‘04 - 08: using phased array, control system (rtEFIT), P(r,t), J(r,t)

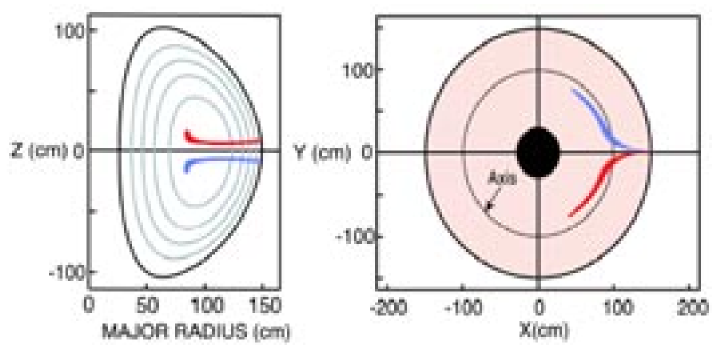
$\Rightarrow$ feedback control on HHFW CD current and heating

EBW studies aim to assess requirements for startup, CD, possible NTM control



- Measure L_n with ORNL X-Mode Reflectometer

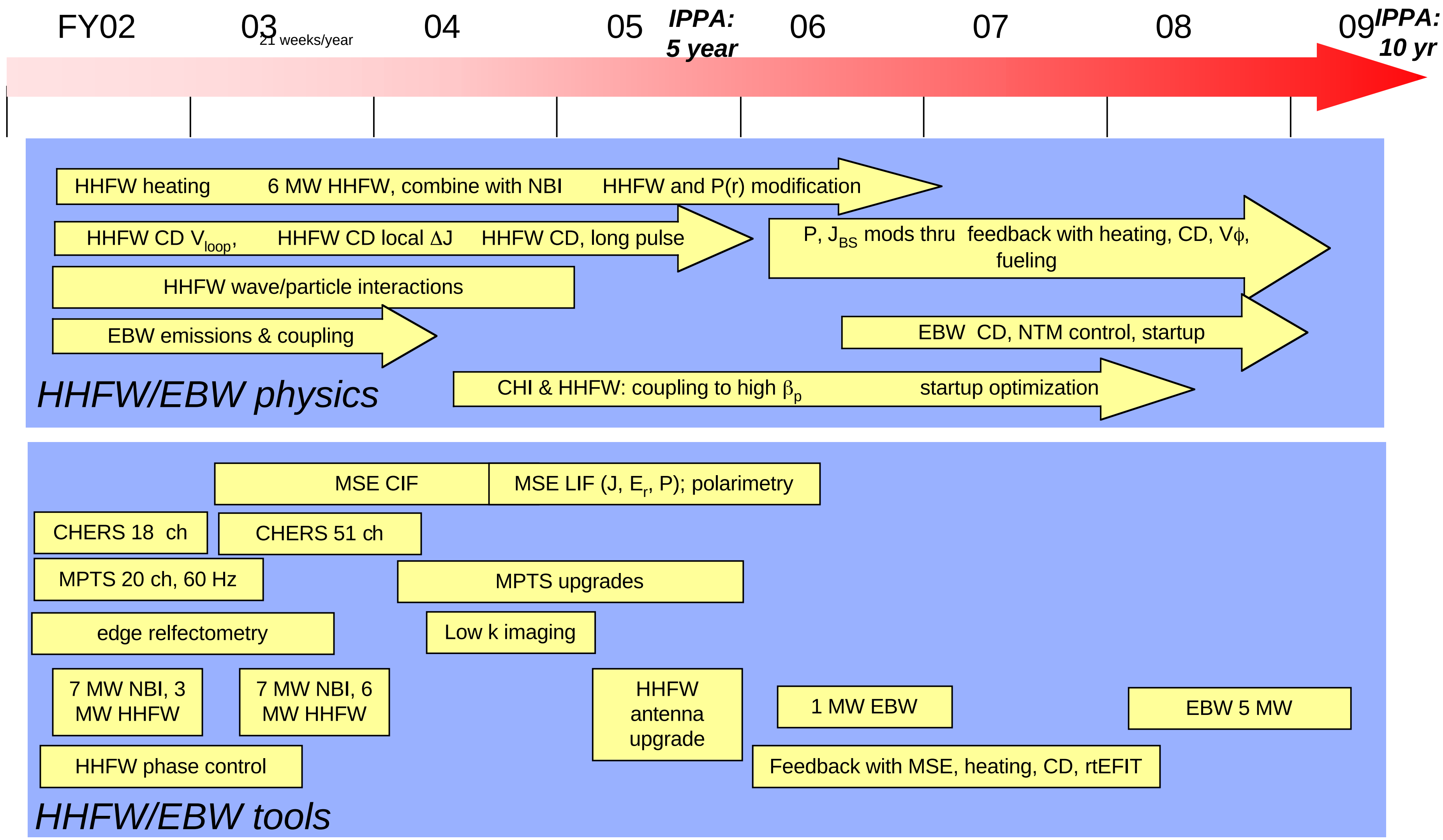




- Experiments show expected L_n dependence on conversion efficiency (Taylor; Wilgen (ORNL))
- Modeling indicates EBW efficiency comparable to ECH at β ~ 10 - 20%
- Coupling experiments encouraging; controlled EBW limiter deployed for FY ‘03

Harvey, CompX

Assessing HHFW, EBW science part of development strategies



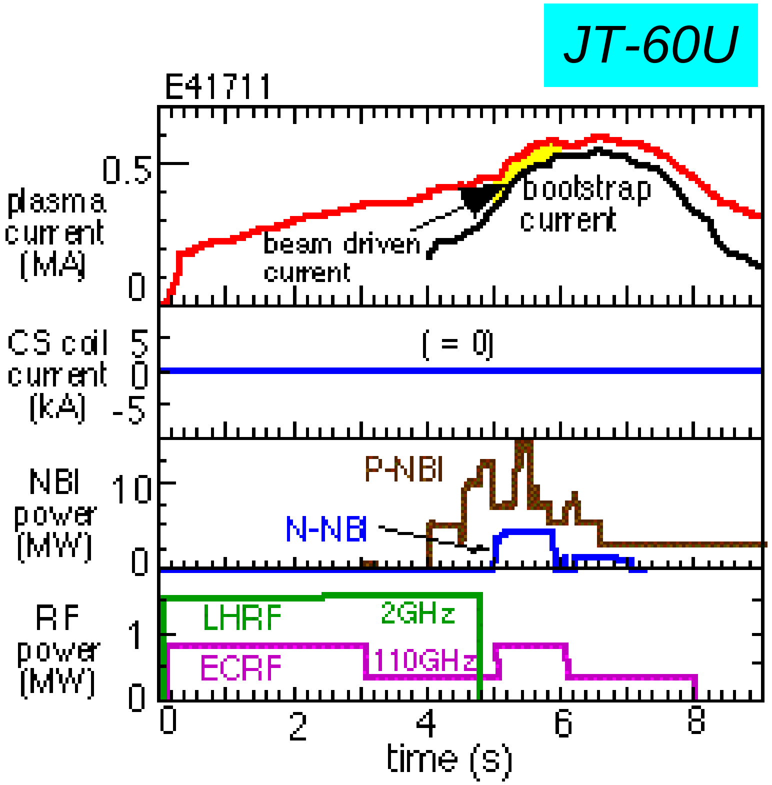
Non-inductive startup research can be divided into different tasks

- Startup: 0 - 150 kA
  - CHI the primary tool at present
  - EBW
- Initial rampup: 150 - 500 kA
  - HHFW, EBW, bootstrap
  - Research can be performed with an ohmic start
  - Developing a high I_p CHI base for handoff being investigated as well.
  - PF induction - scenarios being assessed
- Final ramp to flattop
  - 500 - 800 kA: NBI CD, bootstrap current overdrive are candidates

Each step is separable. Combining each is a control challenge

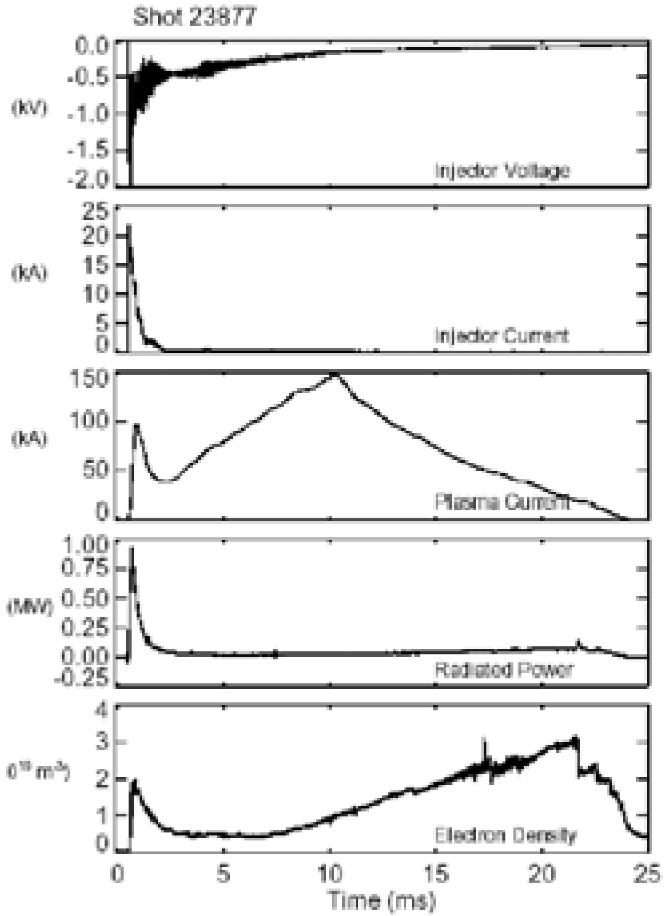
Recent results highlight promise of solenoid-free ramp-up

- Significant bootstrap fraction
- Resultant plasma was high performance (HH = 1.6)



Recent work on HIT-II demonstrates that CHI and induction can be coupled

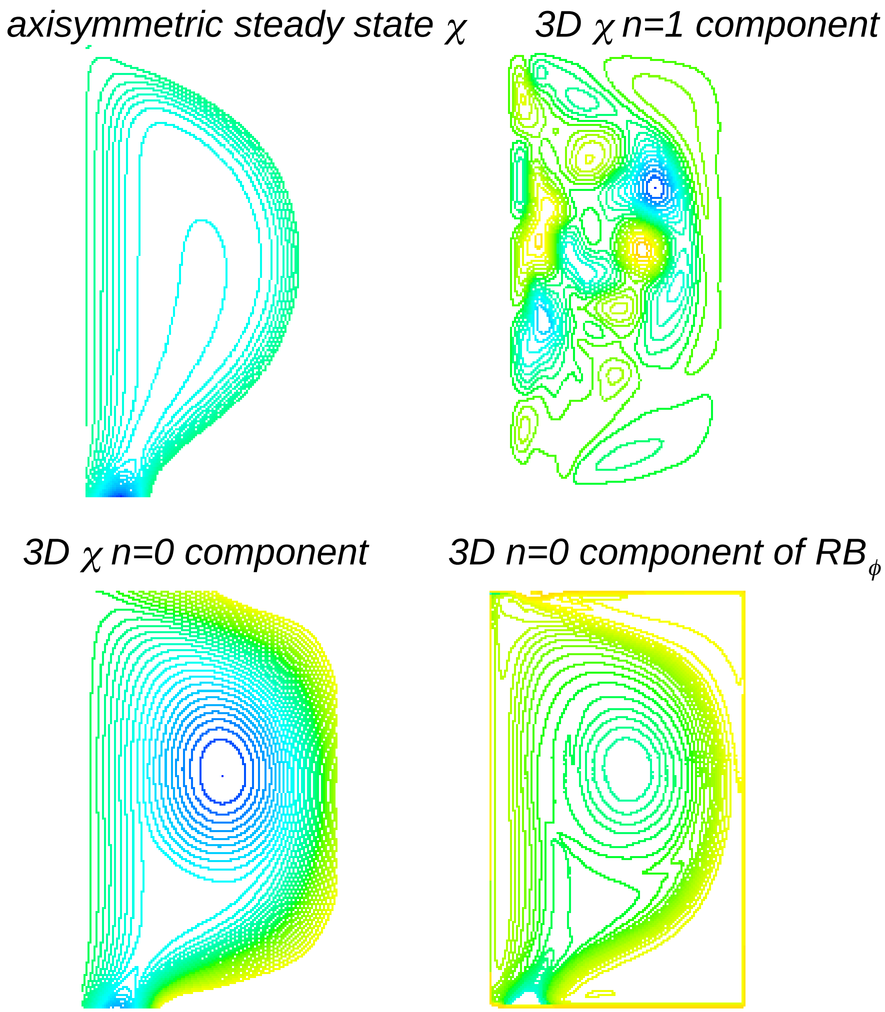
- Knowledge that a CHI solution exists emboldens our program
  - Aim for CHI+ohmic in FY '03, initial work with CHI + HHFW
- Change in CHI strategy
  - *Transient* CHI startup + hand-off: a new element
- High current CHI-to-handoff will also be developed



Raman, Jarboe, Nelson

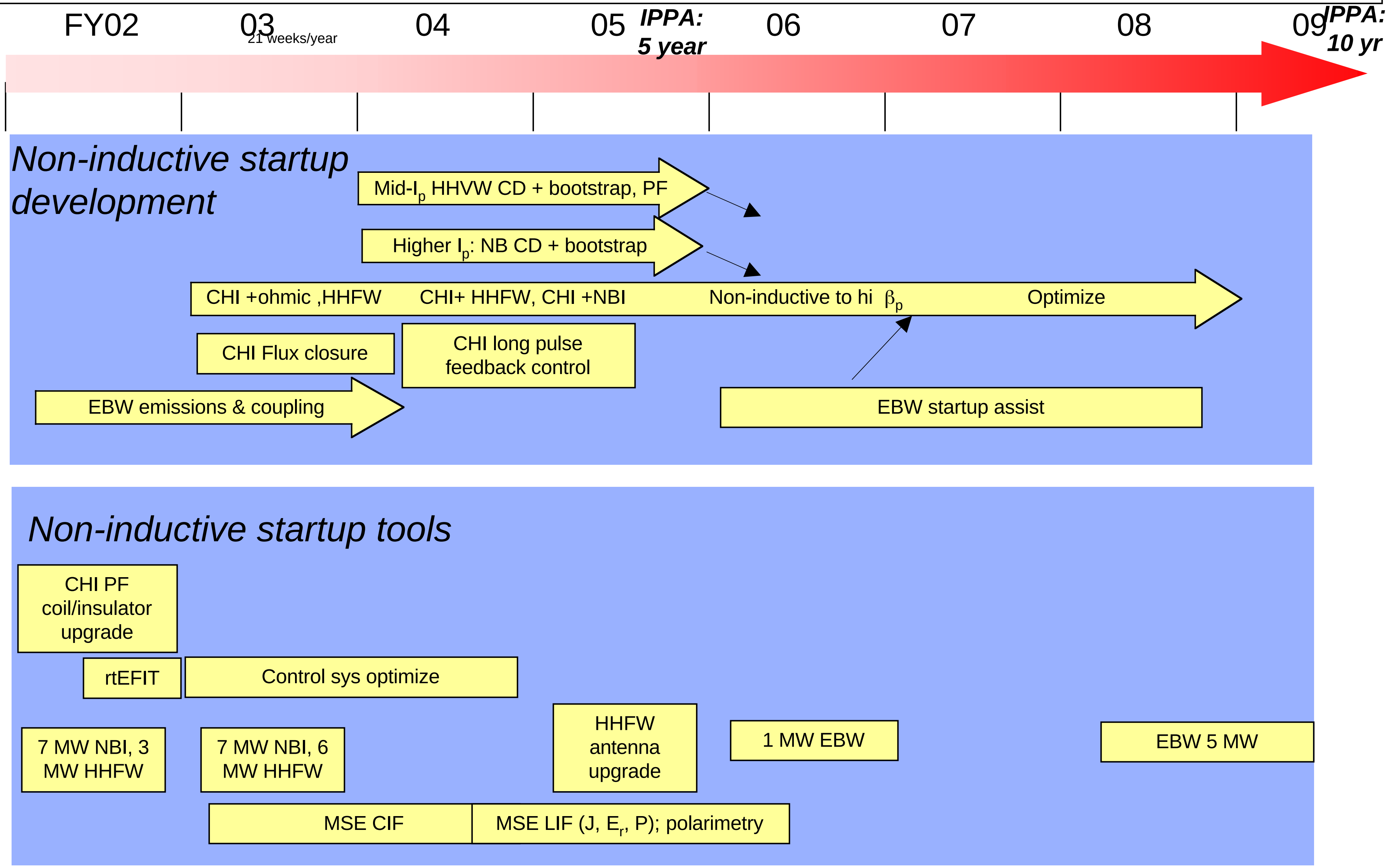
Theoretical understanding of helicity transport is growing

- Advanced computation key to forming physics basis
- Fundamentally a nonlinear, resistive MHD problem
- Time-dependence of diagnostics can be used to decipher MHD dynamics



X. Tang, LANL

Several techniques for non-inductive startup are being pursued



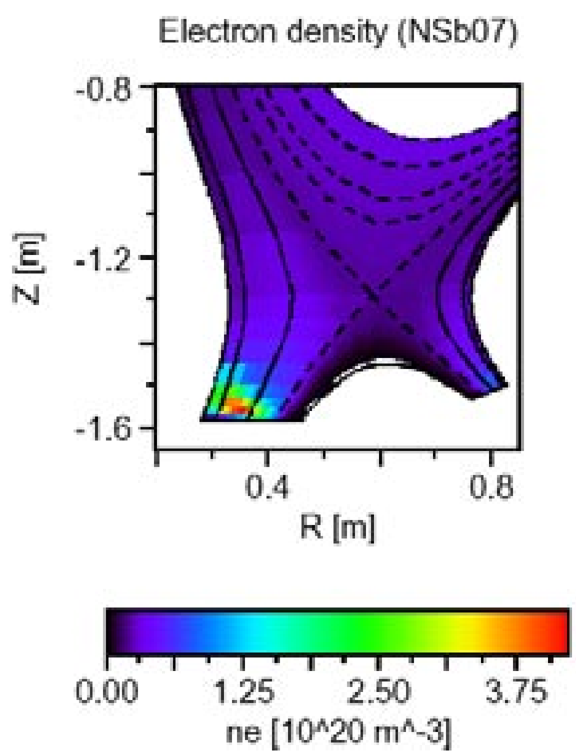
Boundary physics assessment key to developing future edge divertor solutions

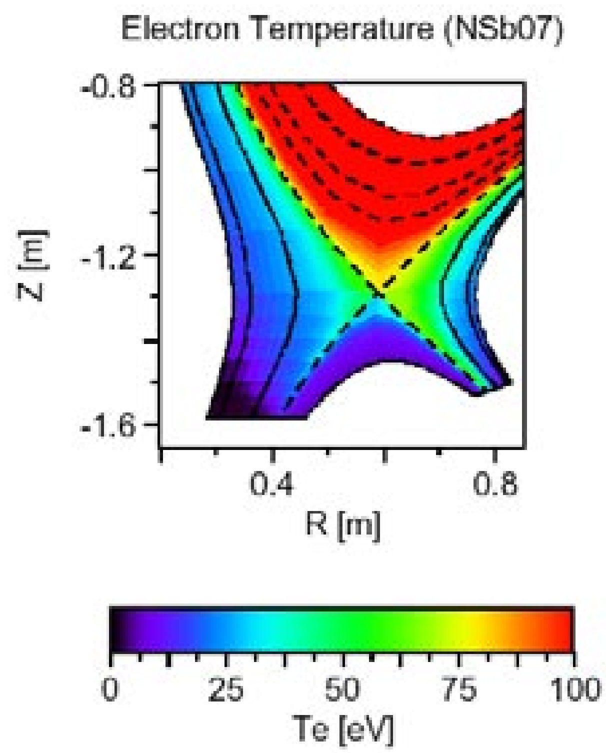
IPPA Goal 1.4: Advance the capability to predict detailed multi-phase plasma-wall inteerfaces at high power and particle fluxes

- Heat flux handling an issue for steps beyond NSTX. Early indications are that this is managable on NSTX for several τ_{skin} @ 10 MW
  - A research question that should be answered this year
- An extrapolable understanding of heat flux scaling will require
  - measurements of character (e.g. bursty?) of cross-field transport with probes (UCSD)
  - use of these data in analysis codes (UEDGE, B2.5, DEGAS)
- NSTX density control will likely be an important issue for the long term
  - Particle control tool needs: to be assessed in FY '03; possibly deploy cryopumps in '05
  - Pellet injector an important component of this in Full Utilization scenario
- Li wall research on CDX-U being followed: possible module on NSTX
  - Has to meet stringent facility requirements. Cryo top, Li mod bottom?
  - Research collaboration with VLT

Coupling of edge measurements and advanced modeling are central for establishing ST boundary science

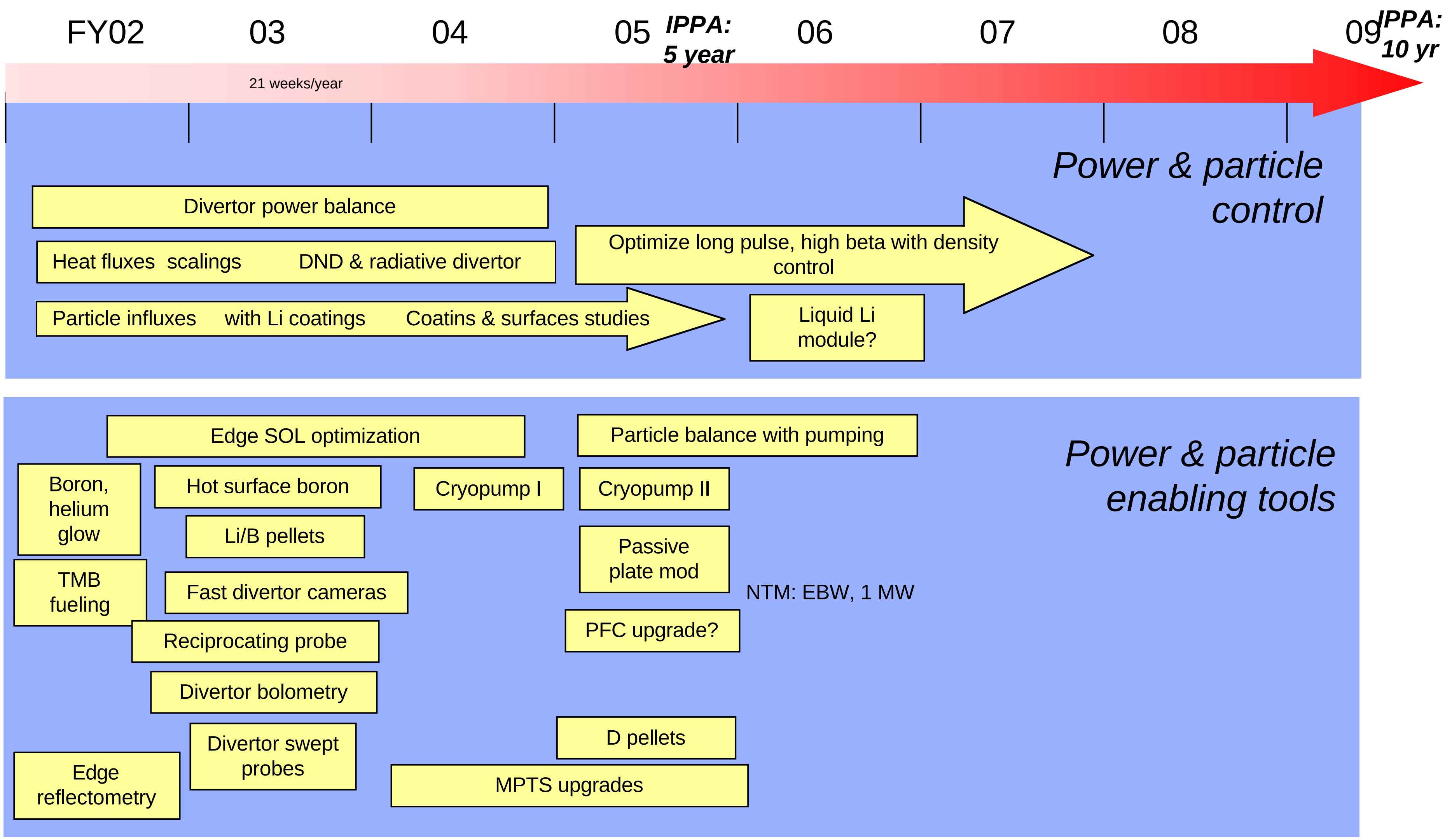
- Required to integrate atomic and plasma physics in complex, 3D problem
- Collaboration with VLT will indicate path for Li module
- Further involvement with MAST will be important





Rensink, Porter, Wolf (LLNL; Stotler

Many boundary tools are available or planned to help enable NSTX's integration goals



Analysis is underway to explore the requirements for four research scenarios

- $\tau_{pulse} >> \tau_{CR}$ by any means possible
  - Bootstrap, NBCD, induction permitted
  - What is required to extend existing 1 second discharges?
- $\tau_{pulse} >> \tau_{CR}$ fully non-inductively sustained
  - Same as above, but replace induction with HHFW
  - Can we drive current in the right place?
  - Explore density dependence, need for higher T_e to increase bootstrap fraction

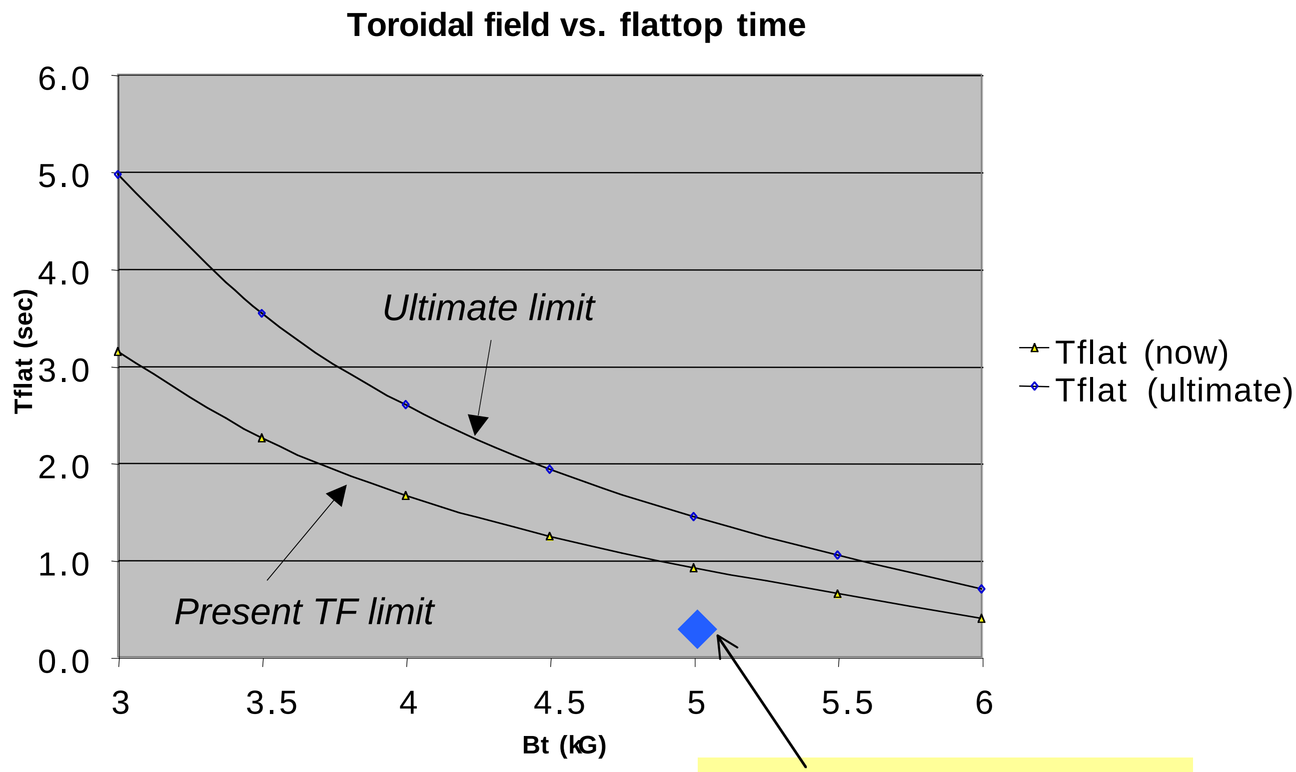
In what follows…

- Inductive, high performance
  - 40% β_T. Is wall stabilization sufficient?
  - Highest $\beta_T \tau_E$, highest H factor
- Solenoid-free ramp-up to high β_p

Kaye, Kessel, Phillips

NSTX can operate for several current relaxation times at TFs of interest

- Temperature instrumentation upgrade allows increased capability

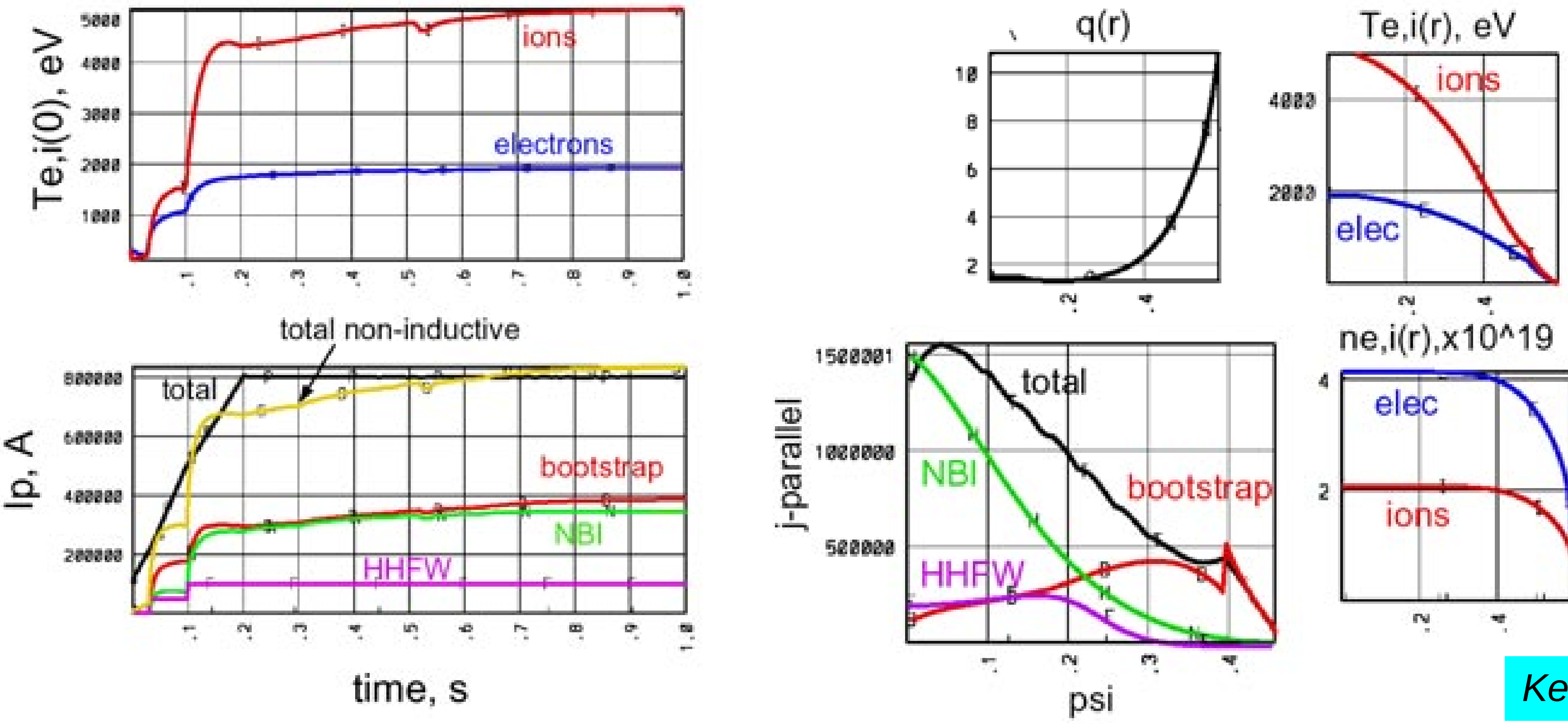


τ_{skin} = 230 ms (109070)

Long pulse discharges serve as the basis for extrapolation studies

- Start with close cousin to 109063, but with T_i documentation
- TSC free-boundary evolution from 100 kA to 800 kA
- Density profile shape prescribed to be same as 109070
- χ profiles chosen to reproduce shape of temperature profiles and T_i/T_e for 109070, then used in new scenario
- Inject 6.2 MW of NBI (only 4.2 MW absorbed), with NB CD efficiency benchmarked to 109070
- Inject 6.0 MW of HHFW, assumed deposition 50/50 electrons and ions, and assumed delivered current of 100 kA
- Improvement in non-inductive current fraction:
  - Lower n to improve NBI CD: n(0) = 0.5 ----> 0.4×10^20 /m^3
  - Increased elongation to raise q_{cyl}: κ = 2.1 ----> 2.7
  - Increased injected power: 4.2 (NBI only) ----> 10.2 MW (NBI+HHFW)
- Obtain I_p=800 kA, Bt=0.5 T fully non-inductive plasmas

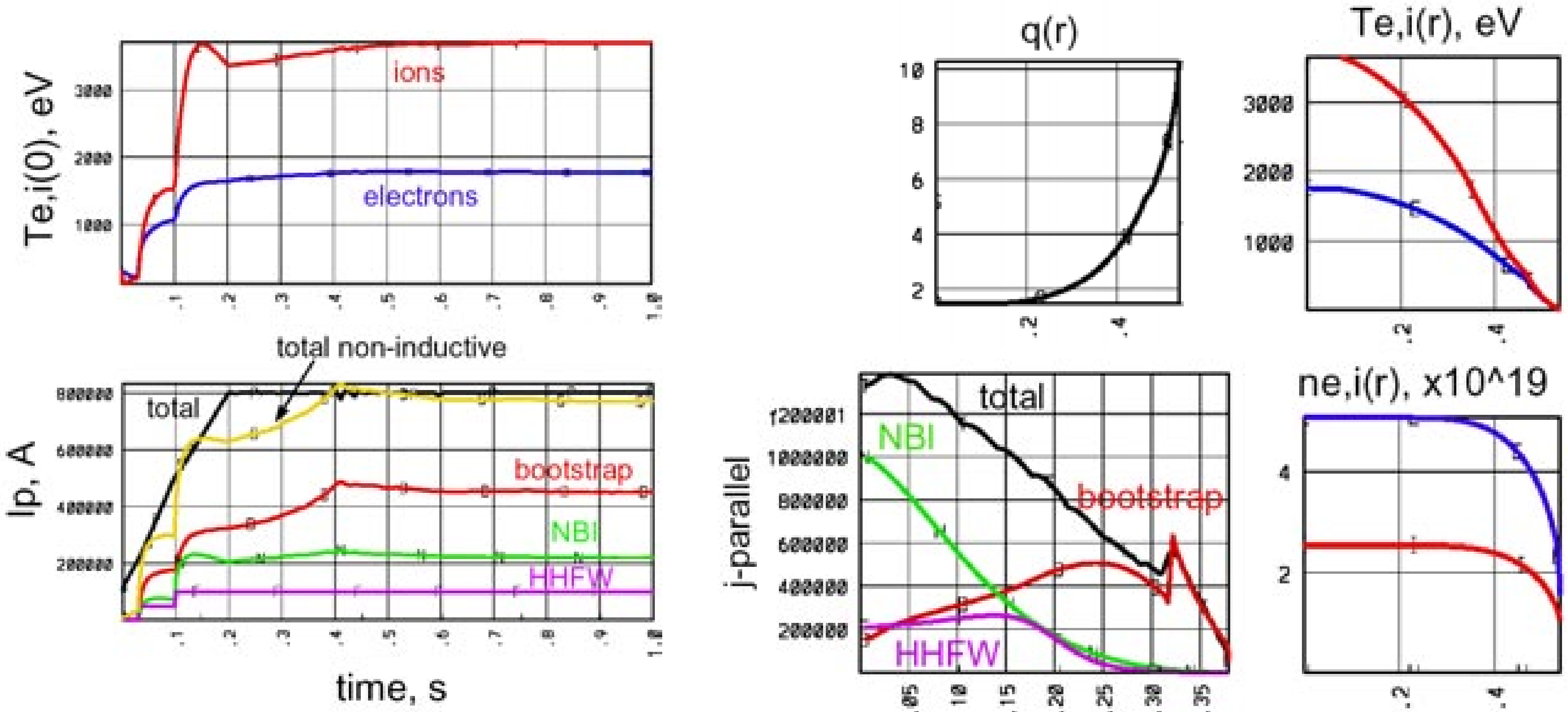
Reduced density case: 100% non-inductive achieved assuming 100 kA HHFW CD



Kessel

- n_e lower than exp't by 20%: raises NB CD, peaks J profile
- I_{BS} = 380 kA, I_{NBI} = 345 kA, I_{HHFW} = 100 kA
- q_{cyl} = 3.3, q_{95} = 10, q(0) = 1.4 @ 1 s
- $\beta_{T,\ thermal}$ = 16%, total β_T ~ 22%, β_p = 1.4, β_N(thermal) = 5.8
- Z_{eff} = 3.5, κ = 2.1, H_{98} = 1.25

Raising elongation enables a boost from the bootstrap current



- n_e at exp't value: κ raised from 2.1 to 2.7
- I_{BS} = 450 kA, I_{NBI} = 220 kA, I_{HHFW} = 100 kA
- q_{cyl} = 4, q_{95} = 8, q(0) = 1.4 @ 1 s
- $\beta_{T,thermal}$ = 15.5%, total β_T ~ 21%, β_p = 1.75, β_N(thermal) = 5
- H_{98} = 1

The NSTX program can meet the IPPA ST assessments

- The plan is constructed to meet the 5 year ST assessment by the end of '05, and major progress for 10 year goal by ‘08
- Emphasis is on expanding the operating space of high beta ST plasmas and on demonstrating and developing the basis for fully non-inductive operations
- Assessments on attractiveness (5 and 10 year) will be based on successful integration of many topical science areas
- Plan demands a strong coupling between advanced computation and experiment to form extrapolable physics basis