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

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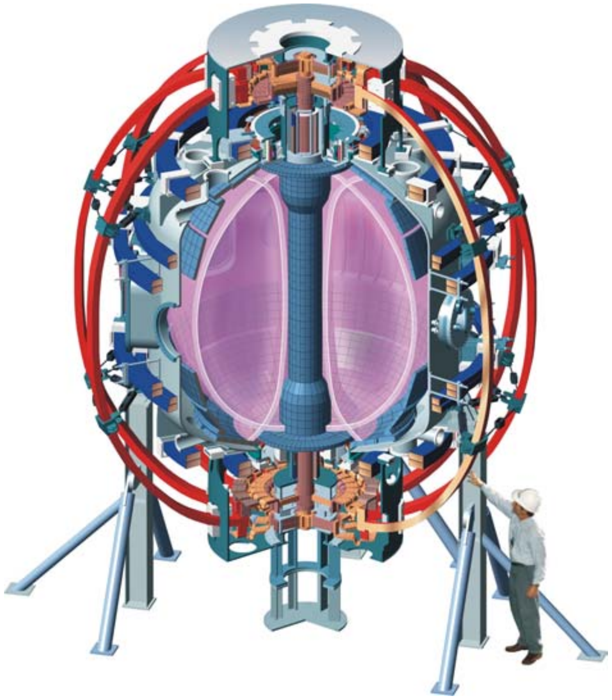
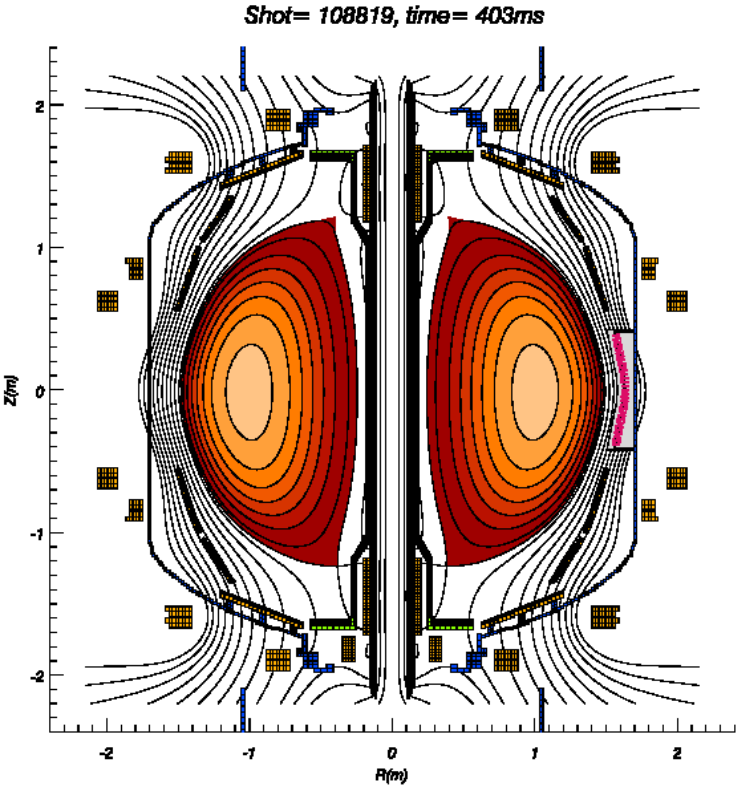


Presentation for the International ST Workshop
November 20, 2002

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*
  - 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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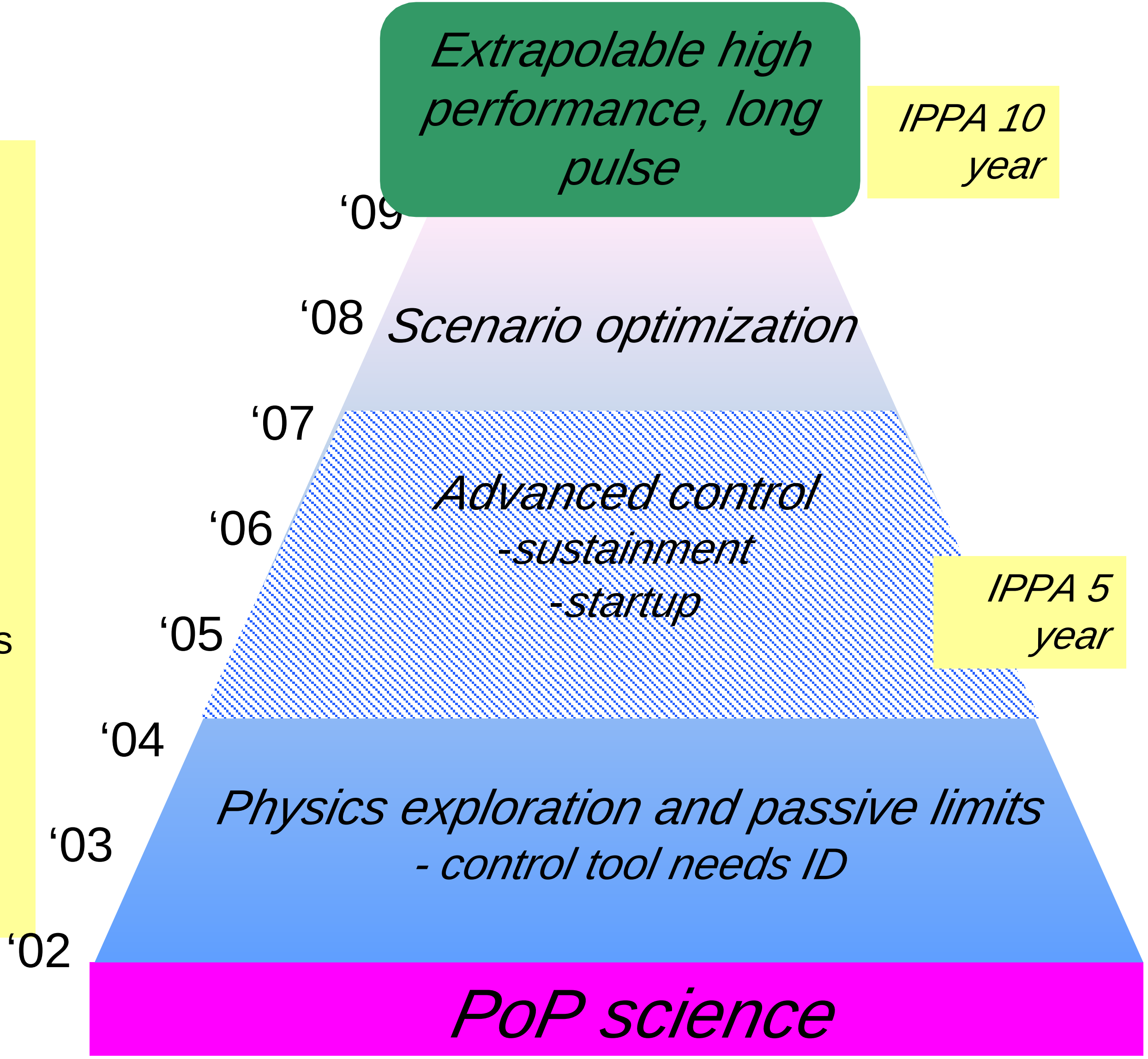
Key elements to achieving both include

- *–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



Extrapolable high performance, long pulse

IPPA 10 year

‘09

‘08 *Scenario optimization*

‘07

Advanced control
-sustainment
-startup

‘06

IPPA 5 year

‘05

‘04

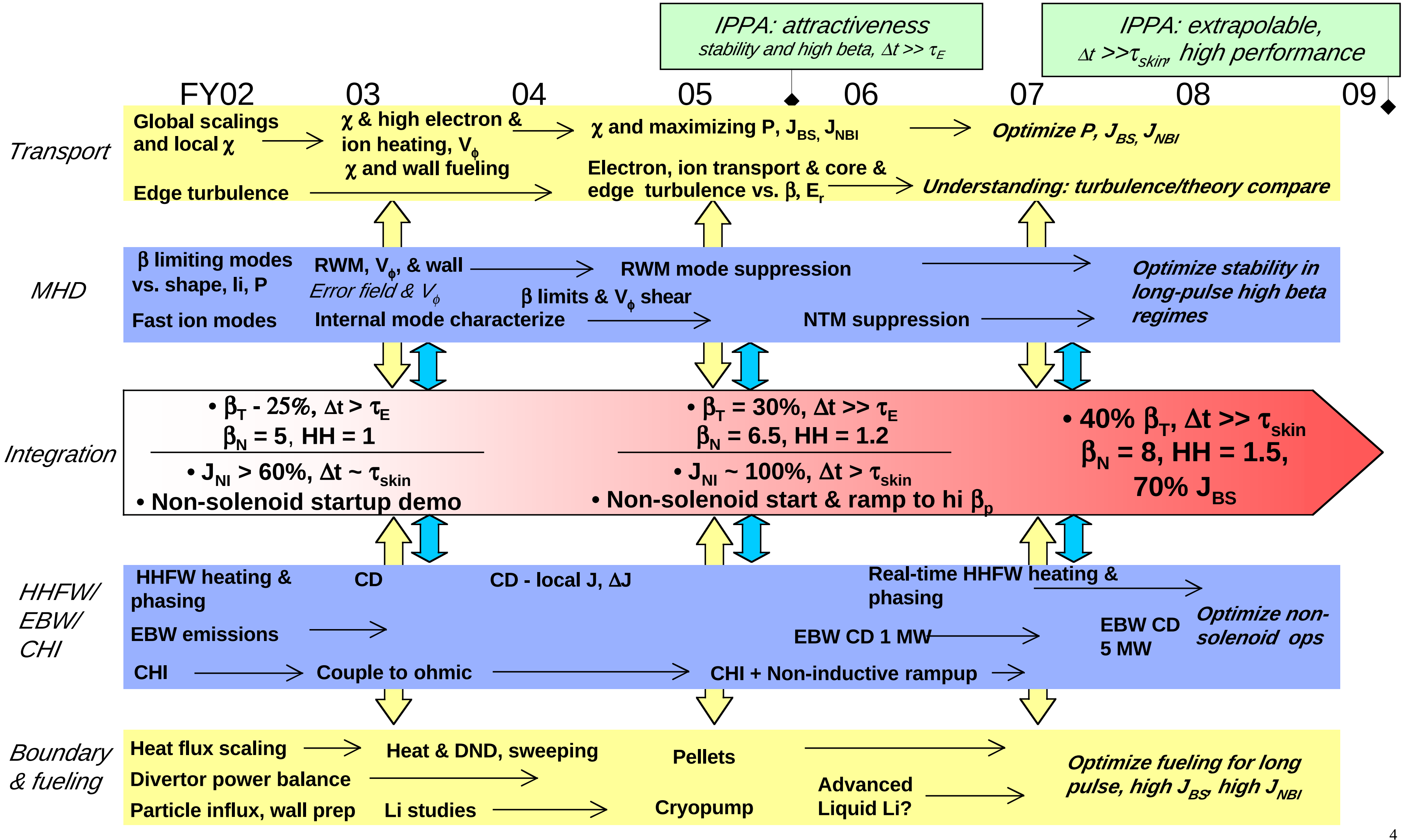
Physics exploration and passive limits
- control tool needs ID

‘03

‘02

PoP science

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



IPPA: attractiveness
stability and high beta, $\Delta t >> \tau_E$

IPPA: extrapolable,
$\Delta t >> \tau_{skin}$, high performance

FY02 03 04 05 06 07 08 09

Transport

Global scalings and local χ → **χ & high electron & ion heating, V_ϕ** → **χ and maximizing P, J_{BS}, J_{NBI}** → ***Optimize P, J_{BS}, J_{NBI}***

χ and wall fueling

Edge turbulence → **Electron, ion transport & core & edge turbulence vs. β, E_r** → ***Understanding: turbulence/theory compare***

MHD

β limiting modes vs. shape, li, P

RWM, V_ϕ, & wall → **RWM mode suppression** → ***Optimize stability in long-pulse high beta regimes***

Error field & V_ϕ

β limits & V_ϕ shear

Fast ion modes

Internal mode characterize → **NTM suppression** →

Integration

- β_T - 25%, $\Delta t > \tau_E$
  $\beta_N = 5$, HH = 1
- $J_{NI} > 60\%$, $\Delta t \sim \tau_{skin}$
- Non-solenoid startup demo

- $\beta_T = 30\%$, $\Delta t >> \tau_E$
  $\beta_N = 6.5$, HH = 1.2
- $J_{NI} \sim 100\%$, $\Delta t > \tau_{skin}$
- Non-solenoid start & ramp to hi β_p

- 40% β_T, $\Delta t >> \tau_{skin}$
  $\beta_N = 8$, HH = 1.5,
  70% J_{BS}

HHFW/ EBW/ CHI

HHFW heating & phasing **CD** **CD - local J, ΔJ** **Real-time HHFW heating & phasing** →

EBW emissions → **EBW CD 1 MW** → **EBW CD 5 MW** ***Optimize non-solenoid ops***

CHI → **Couple to ohmic** → **CHI + Non-inductive rampup** →

Boundary & fueling

Heat flux scaling → **Heat & DND, sweeping** **Pellets** →

Divertor power balance →

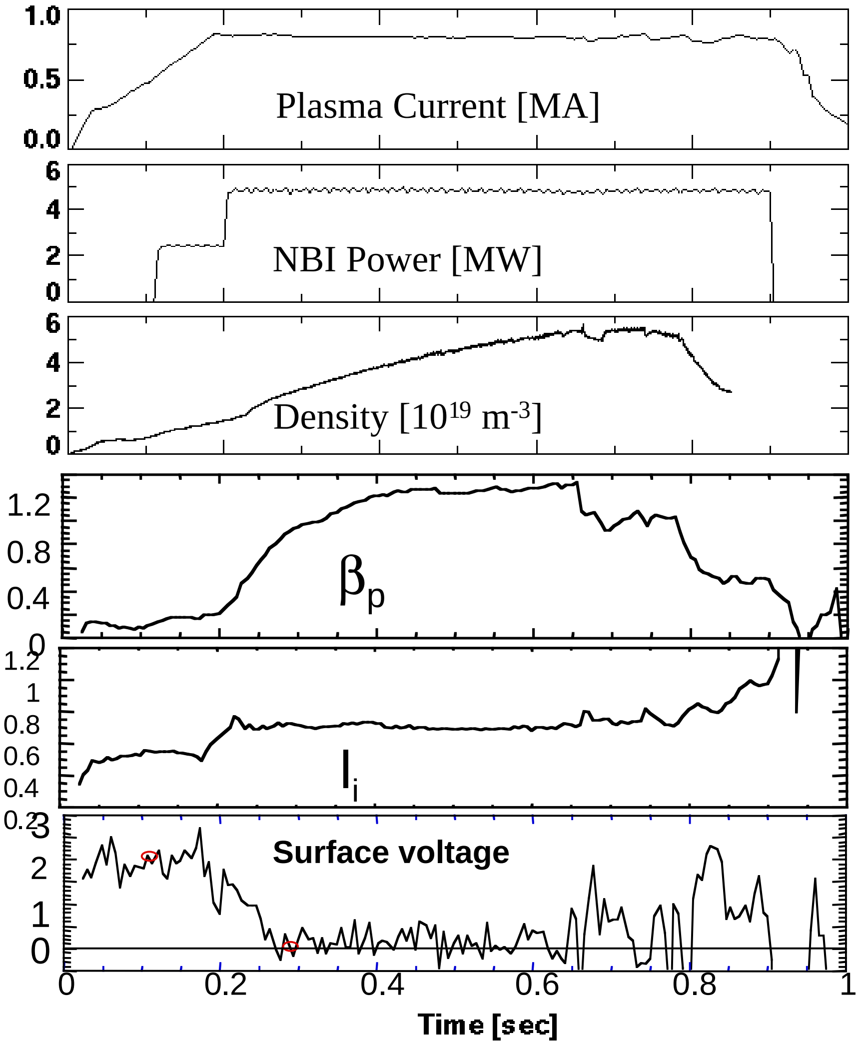
Particle influx, wall prep **Li studies** → **Cryopump** **Advanced Liquid Li?** → ***Optimize fueling for long pulse, high J_{BS}, high J_{NBI}***

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)

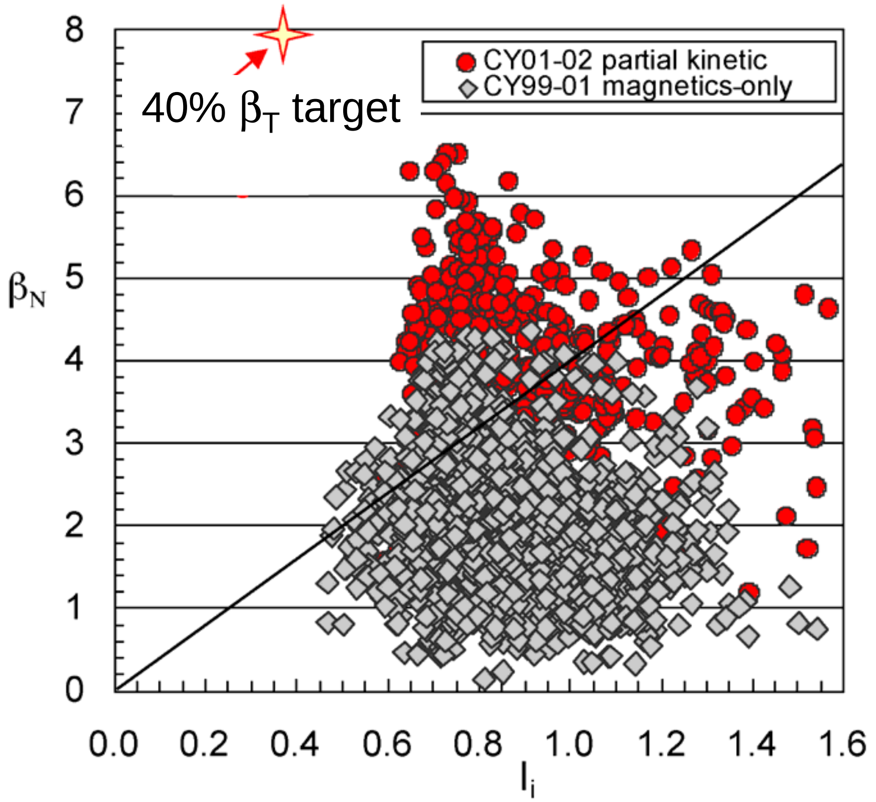
- Long pulse discharge has many parameters that may be relevant to a CTF

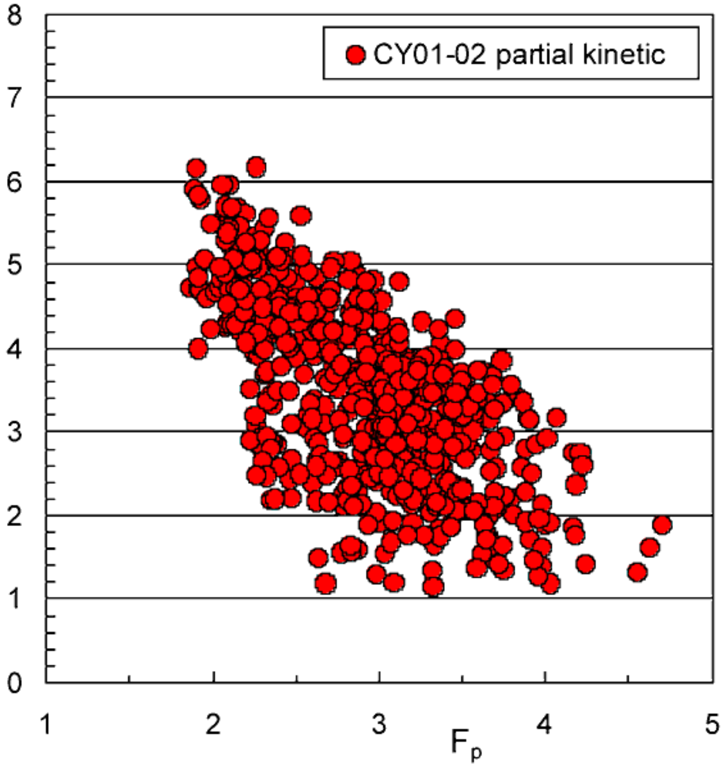
	NSTX Long pulse	CTF	ARIES-ST
β_T	15%	20%	50%+
β_N	5	5	8
β_p	1.2	1	1.4
q_{cyl}	3.2	3	3



Progress has been made towards achieving target of 40% β_T

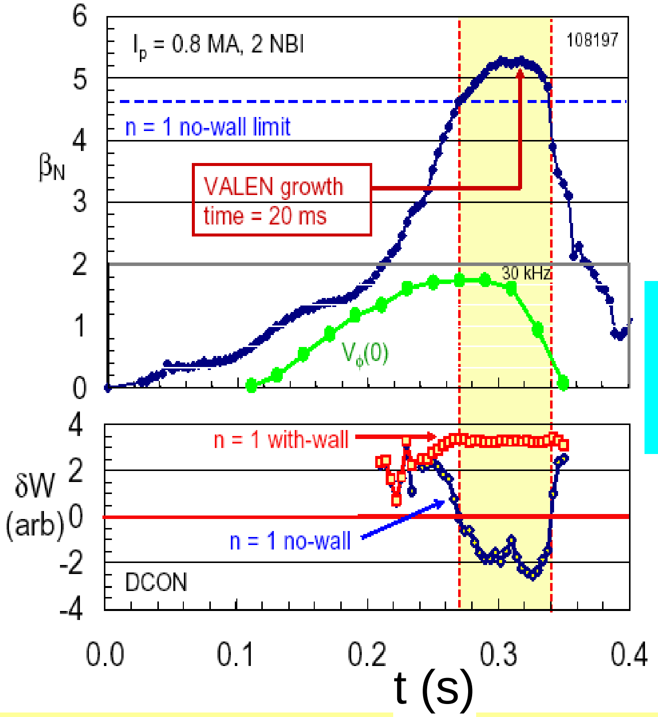
IPPA Goal 1.2: Develop detailed predictive capability for macroscopic stability, including resistive and kinetic effects



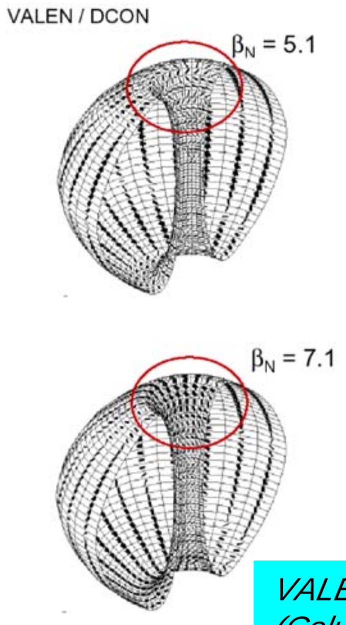


- $\beta_N = 6.5$, $\beta_N / l_i > 9.5$. $\beta_N > 30\%$ over $\beta_{N\text{ no-wall}}$
- Maximum β_T of 34% obtained
- Takes advantage of broad P(r) in H mode

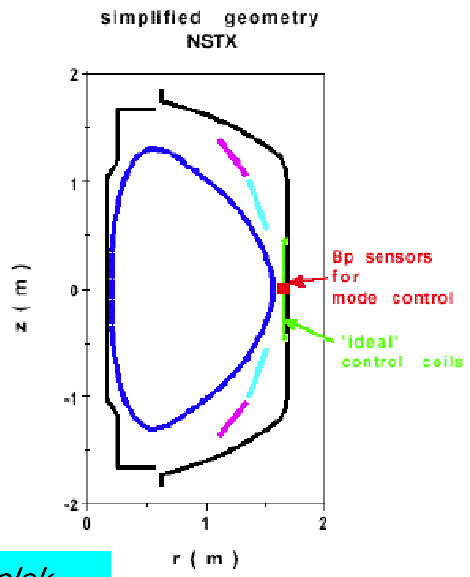
With evidence for wall stablization, a goal of the plan is to optimize the passive plates and feedback system configuration



Sabbagh, Columbia; Glasser, LANL



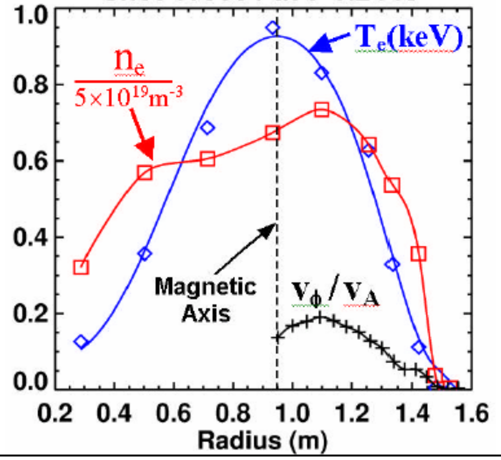
VALEN: Bialek (Columbia)

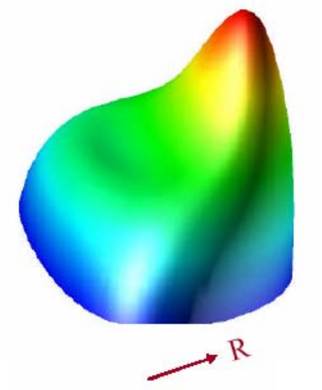


- Midplane coils may increase β limit to near ideal wall values for some modes
  - external coils do 75% of the job of an ideal wall
- At highest β_N, mode grows in amplitude near center stack
  - passive plate modification required. Simultaneous mods for cryopumping

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

R. Bell, LeBlanc

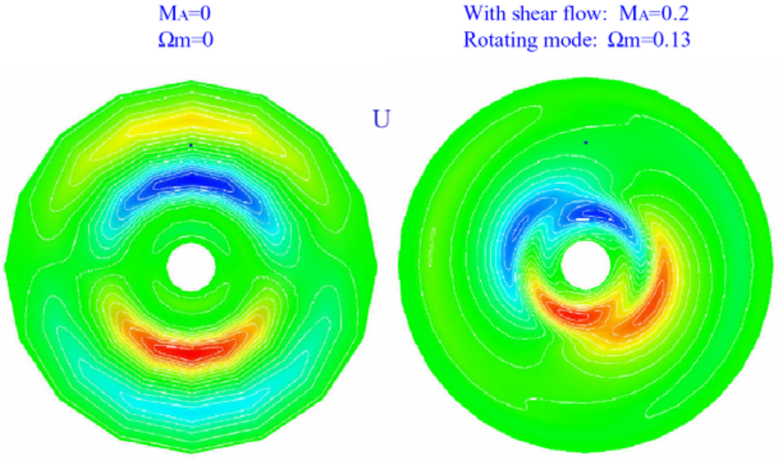




- Experiment: Density shows in-out asymmetry
- MHD theory benchmarked: captures asymmetry when flow effects and hot particle pressure is included (M3D)
- Effect of high Mach number of driven flow

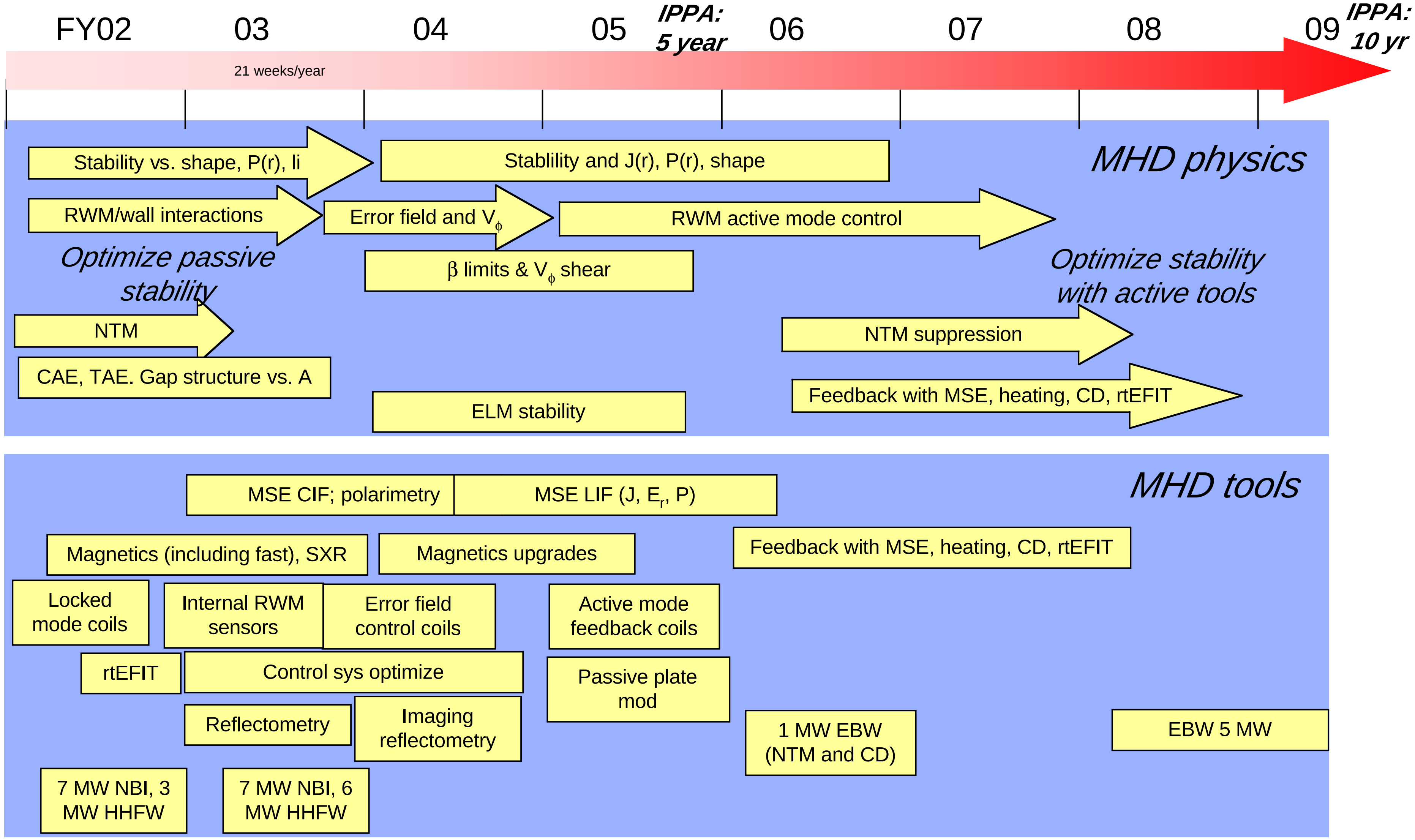
M3D: Park

- 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



FY02 03 04 05 *IPPA: 5 year* 06 07 08 09 *IPPA: 10 yr*

21 weeks/year

MHD physics

Stability vs. shape, P(r), li

Stablility and J(r), P(r), shape

RWM/wall interactions

Error field and V_ϕ

RWM active mode control

Optimize passive stability

β limits & V_ϕ shear

Optimize stability with active tools

NTM

NTM suppression

CAE, TAE. Gap structure vs. A

ELM stability

Feedback with MSE, heating, CD, rtEFIT

MHD tools

MSE CIF; polarimetry

MSE LIF (J, E_r, P)

Magnetics (including fast), SXR

Magnetics upgrades

Feedback with MSE, heating, CD, rtEFIT

Locked mode coils

Internal RWM sensors

Error field control coils

Active mode feedback coils

rtEFIT

Control sys optimize

Passive plate mod

Reflectometry

Imaging reflectometry

1 MW EBW (NTM and CD)

EBW 5 MW

7 MW NBI, 3 MW HHFW

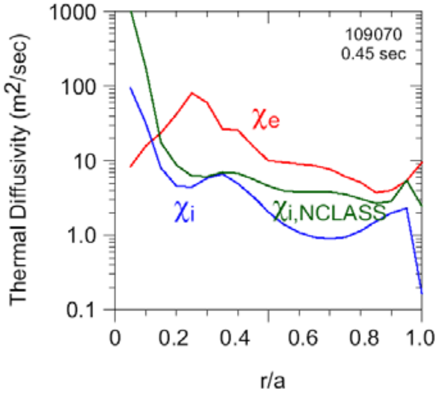
7 MW NBI, 6 MW HHFW

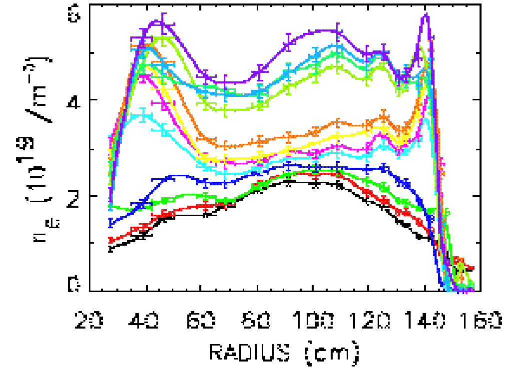
Understanding confinement trends has important practical implications, high physics leverage

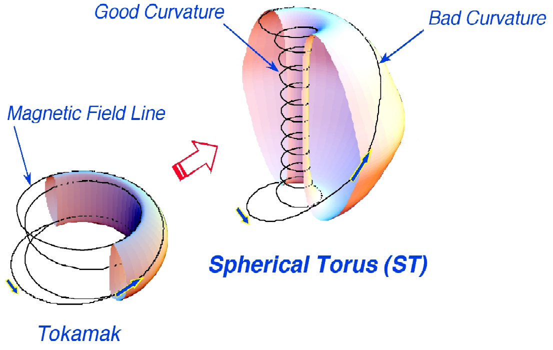
- For extrapolable physics basis: need to understand how electron and ion χ's scale with engineering and physics parameters

- 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.



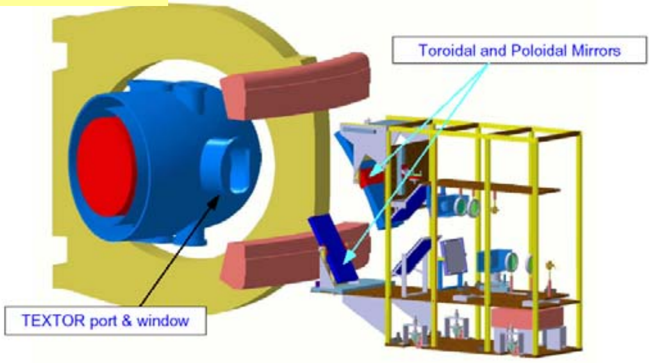




Turbulence diagnostics can enable unique NSTX contributions to universally important transport issues

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

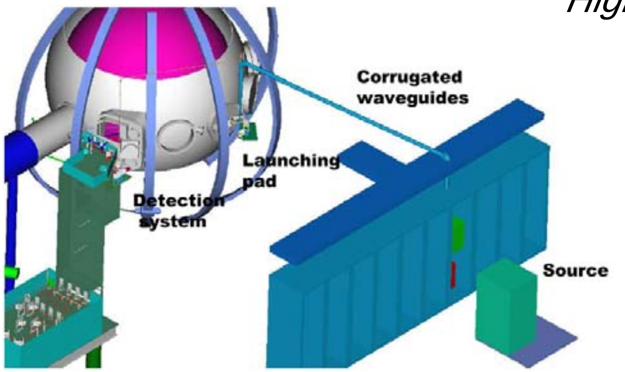
- Long wavelengths: naturally suppressed?
  - Reflectometry imaging being developed on TEXTOR.
  - Possible NSTX deployment in ‘05



Low k Imaging

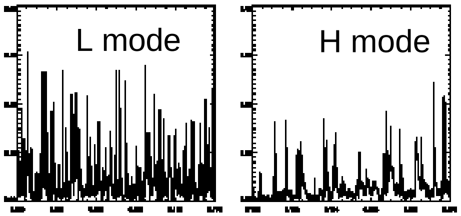
- Short wavelengths: key to ubiquitous electron transport problem? Large $\rho_e \Rightarrow$ big modes, ideal scattering geometry on NSTX
  - prototype implemented in FY ‘03/’04
  - k_r = 6, 20, and 30 cm^{-1}

High k scattering



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

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

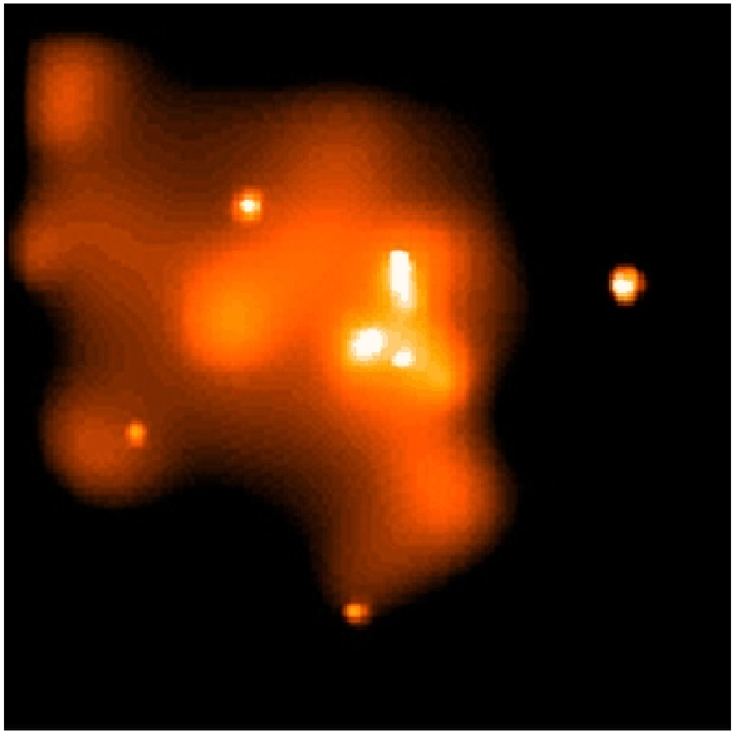


Boedo (UCSD)

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

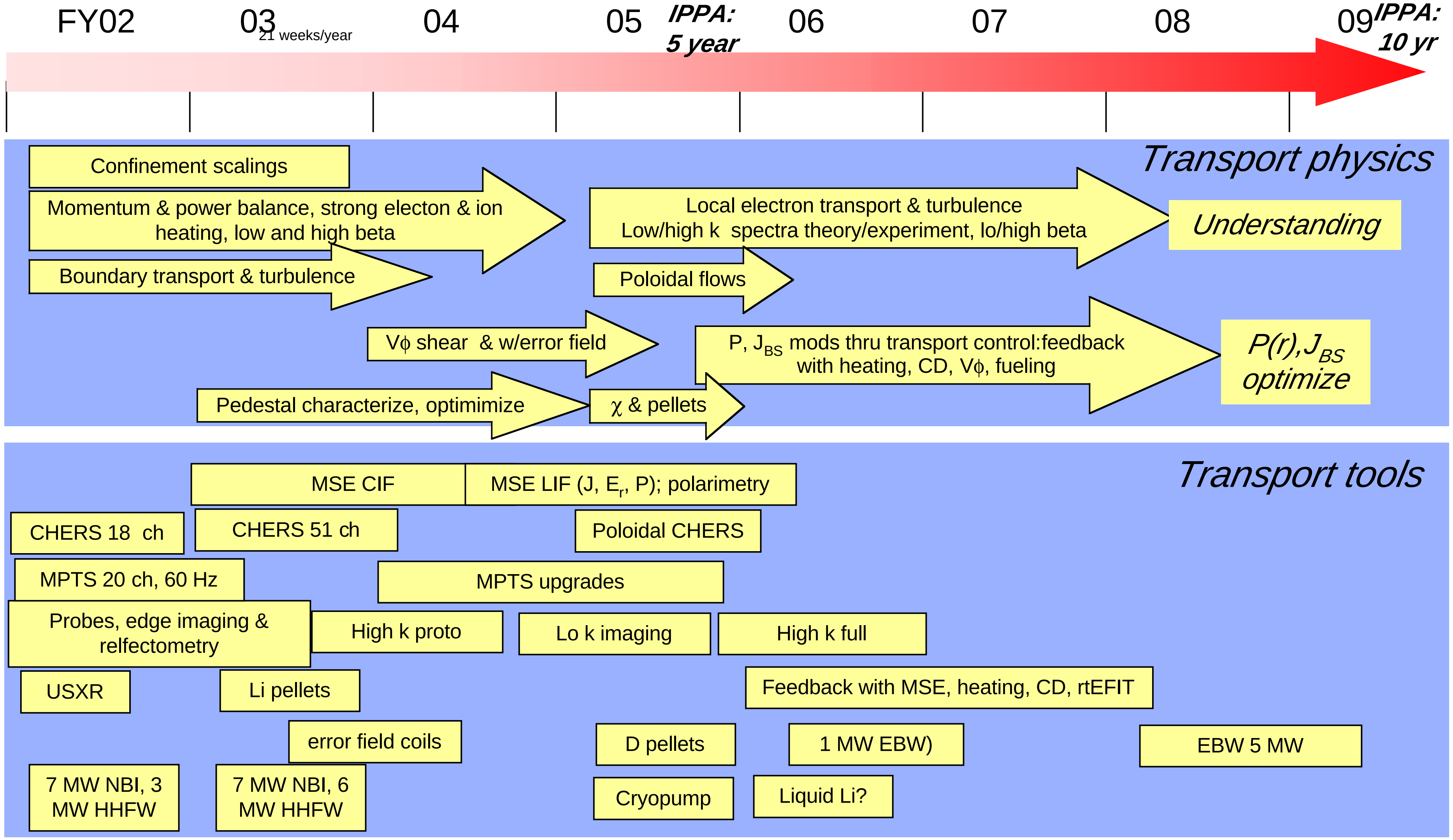
⇒ Their community wants to benchmark gk codes with diagnosis of β ~ 1 laboratory turbulence



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



FY02
03
21 weeks/year
04
05
IPPA: 5 year
06
07
08
09
IPPA: 10 yr

Transport physics

Confinement scalings

Momentum & power balance, strong electon & ion heating, low and high beta

Boundary transport & turbulence

Local electron transport & turbulence
Low/high k spectra theory/experiment, lo/high beta

Understanding

Poloidal flows

Vϕ shear & w/error field

P, J_{BS} mods thru transport control:feedback with heating, CD, Vϕ, fueling

P(r),J_{BS} optimize

Pedestal characterize, optimimize

χ & pellets

Transport tools

MSE CIF

MSE LIF (J, E_r, P); polarimetry

CHERS 18 ch

CHERS 51 ch

Poloidal CHERS

MPTS 20 ch, 60 Hz

MPTS upgrades

Probes, edge imaging & relfectometry

High k proto

Lo k imaging

High k full

USXR

Li pellets

Feedback with MSE, heating, CD, rtEFIT

error field coils

D pellets

1 MW EBW)

EBW 5 MW

7 MW NBI, 3 MW HHFW

7 MW NBI, 6 MW HHFW

Cryopump

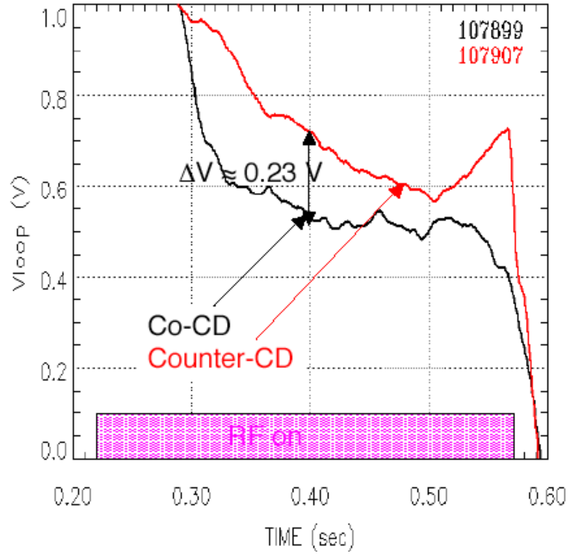
Liquid Li?

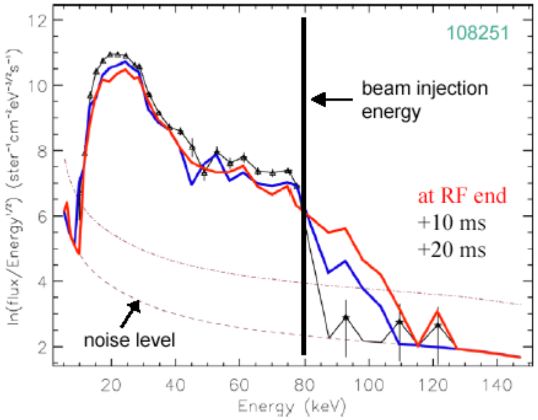
RF research in several areas will grow in importance in FY ‘04 - ‘08

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

- 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

Ryan, Swain (ORNL); Hosea, Wilson



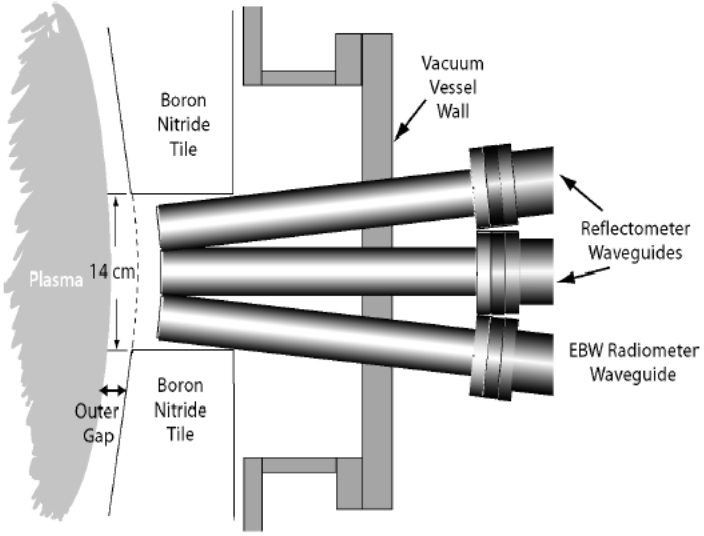


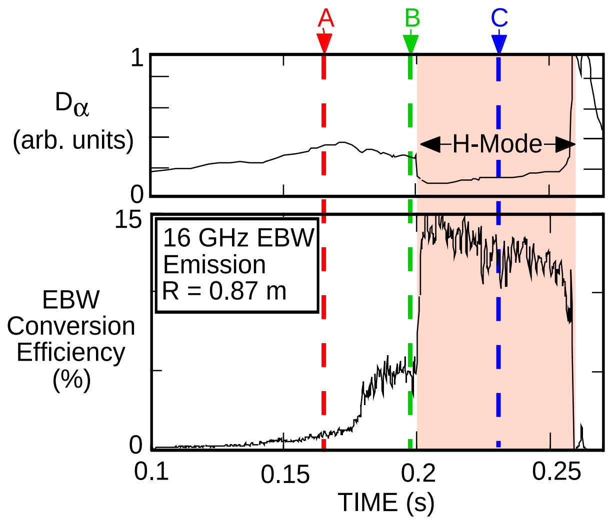
HHFW current drive goal is feedback control based on local measurements

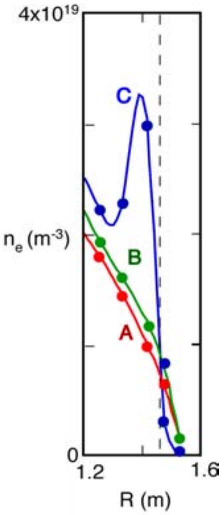
- Near-term focus is on making system more reliable, higher power
- FY ‘03 will permit the first measurements of pitch angle changes driven by HHFW
  - CIF MSE deployed at start of FY '03
  - Measurement resolution target: ΔI_p ~ 1.5 kA within half-radius, assuming no E_r complication
- LIF MSE: first 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)

⇒ feedback control on HHFW CD current and heating

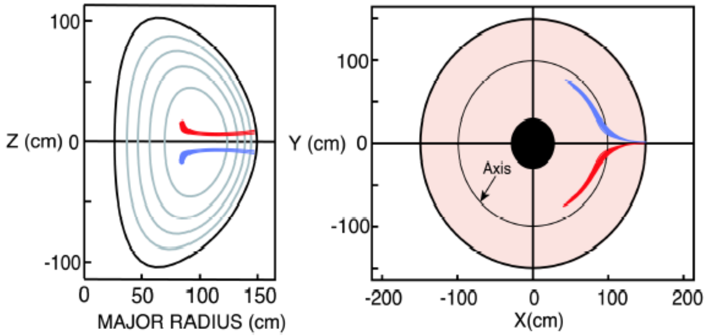
EBW studies aim to assess requirements for startup, CD, possible NTM control







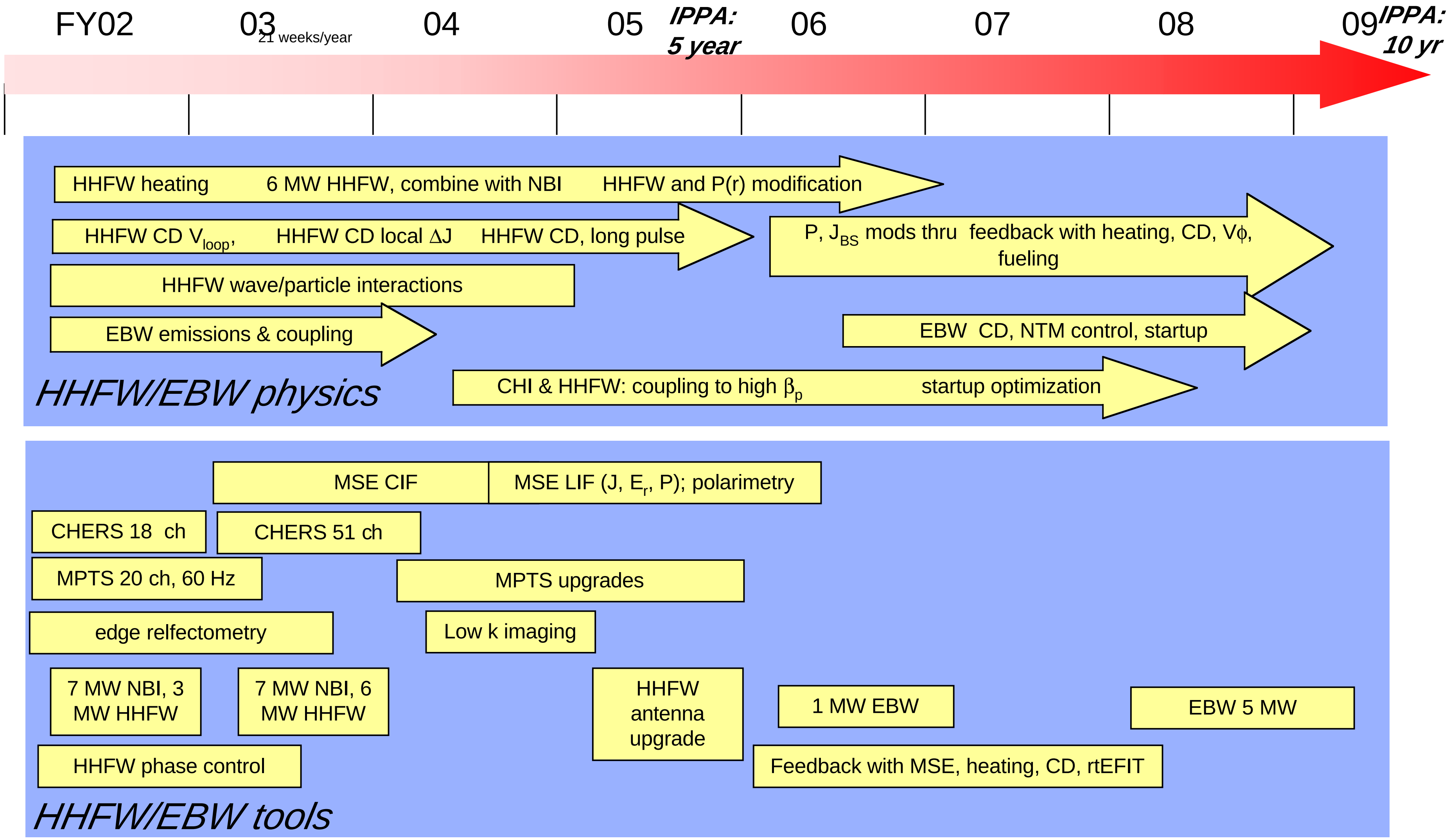
- Measure L_n with ORNL X-Mode Reflectometer



Harvey, CompX

- 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

Assessing HHFW, EBW science part of development strategies



FY02 03 04 05 06 07 08 09

21 weeks/year

IPPA: 5 year

IPPA: 10 yr

HHFW heating 6 MW HHFW, combine with NBI HHFW and P(r) modification

HHFW CD V_{loop}, HHFW CD local ΔJ HHFW CD, long pulse

P, J_{BS} mods thru feedback with heating, CD, $V\phi$, fueling

HHFW wave/particle interactions

EBW emissions & coupling

EBW CD, NTM control, startup

CHI & HHFW: coupling to high β_p startup optimization

HHFW/EBW physics

MSE CIF

MSE LIF (J, E_r, P); polarimetry

CHERS 18 ch

CHERS 51 ch

MPTS 20 ch, 60 Hz

MPTS upgrades

edge relfectometry

Low k imaging

7 MW NBI, 3 MW HHFW

7 MW NBI, 6 MW HHFW

HHFW antenna upgrade

1 MW EBW

EBW 5 MW

HHFW phase control

Feedback with MSE, heating, CD, rtEFIT

HHFW/EBW tools

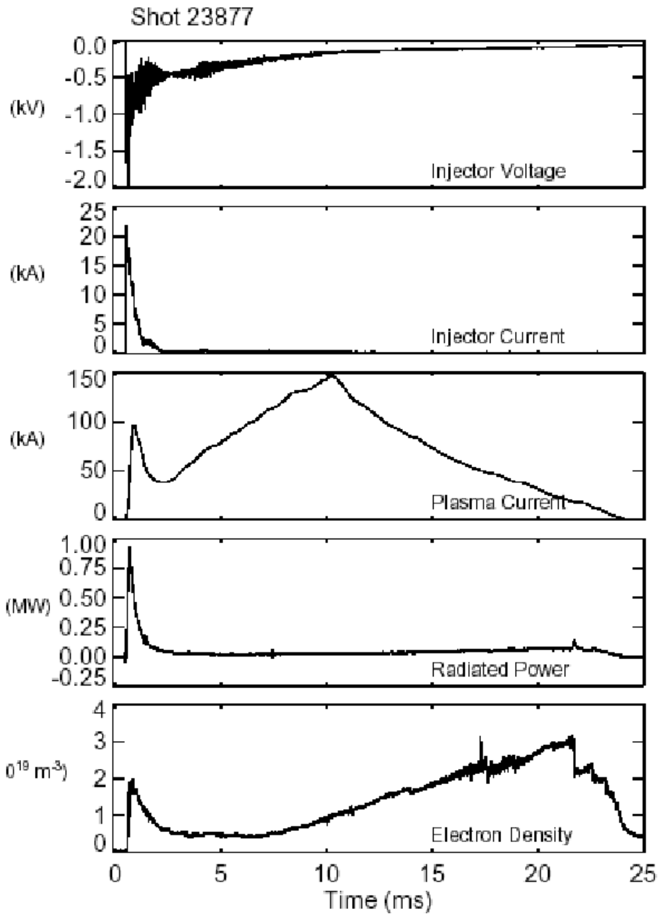
Non-inductive startup research can be divided into different tasks

- 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

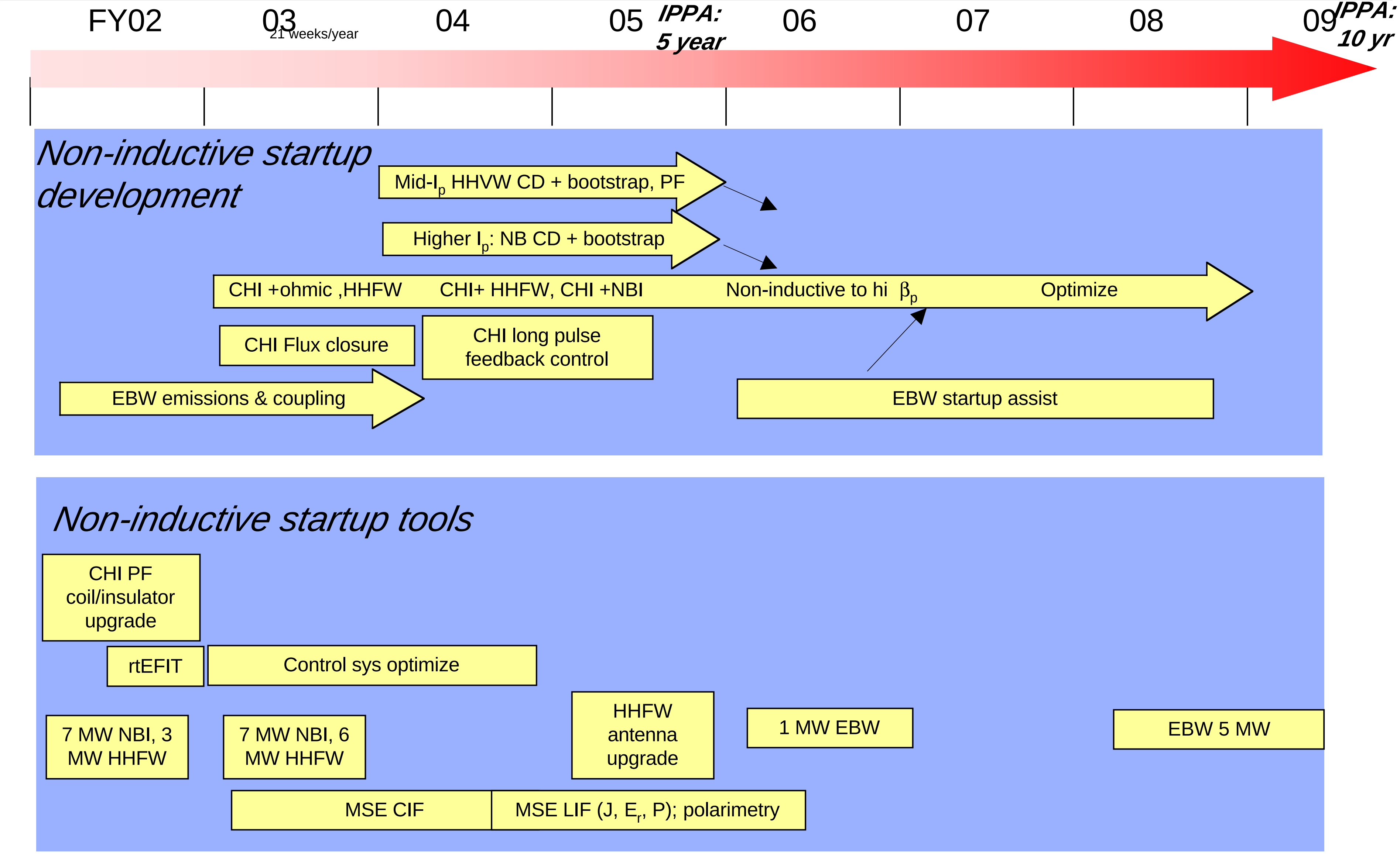
Recent work on HIT-II demonstrates that CHI and induction can be coupled

- 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

Several techniques for non-inductive startup are being pursued



FY02 03 04 05 06 07 08 09

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Non-inductive startup development

Mid-I_p HHVW CD + bootstrap, PF

Higher I_p: NB CD + bootstrap

CHI +ohmic ,HHFW CHI+ HHFW, CHI +NBI Non-inductive to hi β_p Optimize

CHI Flux closure

CHI long pulse feedback control

EBW emissions & coupling

EBW startup assist

Non-inductive startup tools

CHI PF coil/insulator upgrade

rtEFIT

Control sys optimize

7 MW NBI, 3 MW HHFW

7 MW NBI, 6 MW HHFW

HHFW antenna upgrade

1 MW EBW

EBW 5 MW

MSE CIF

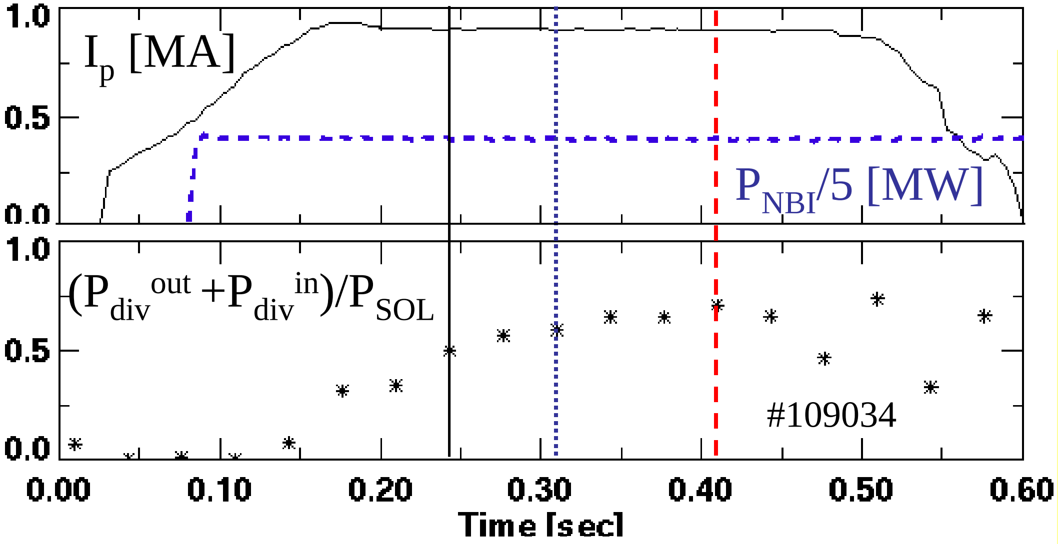
MSE LIF (J, E_r, P); polarimetry

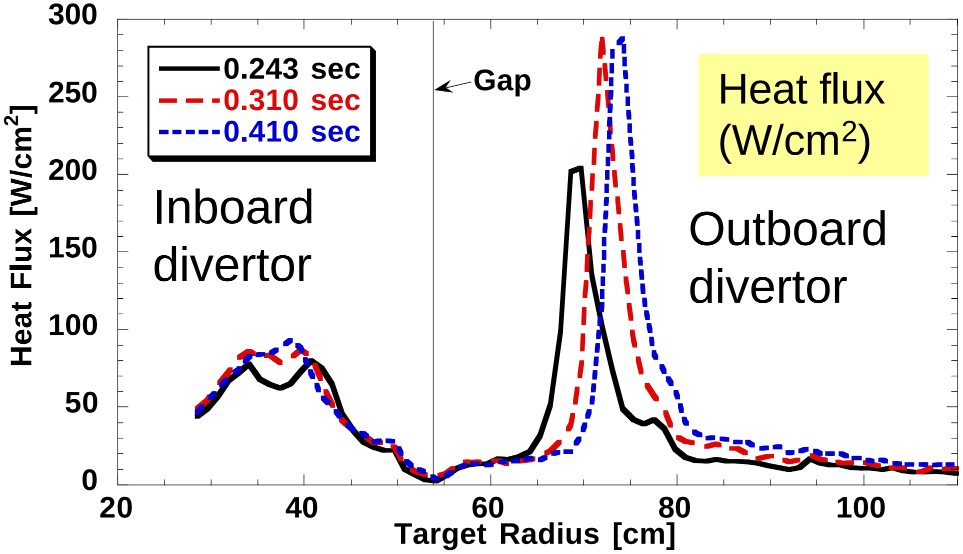
Boundary physics assessment speaks to developing future edge divertor solutions

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
- 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

About 70% of available power is deposited in the divertor in quiescent H modes



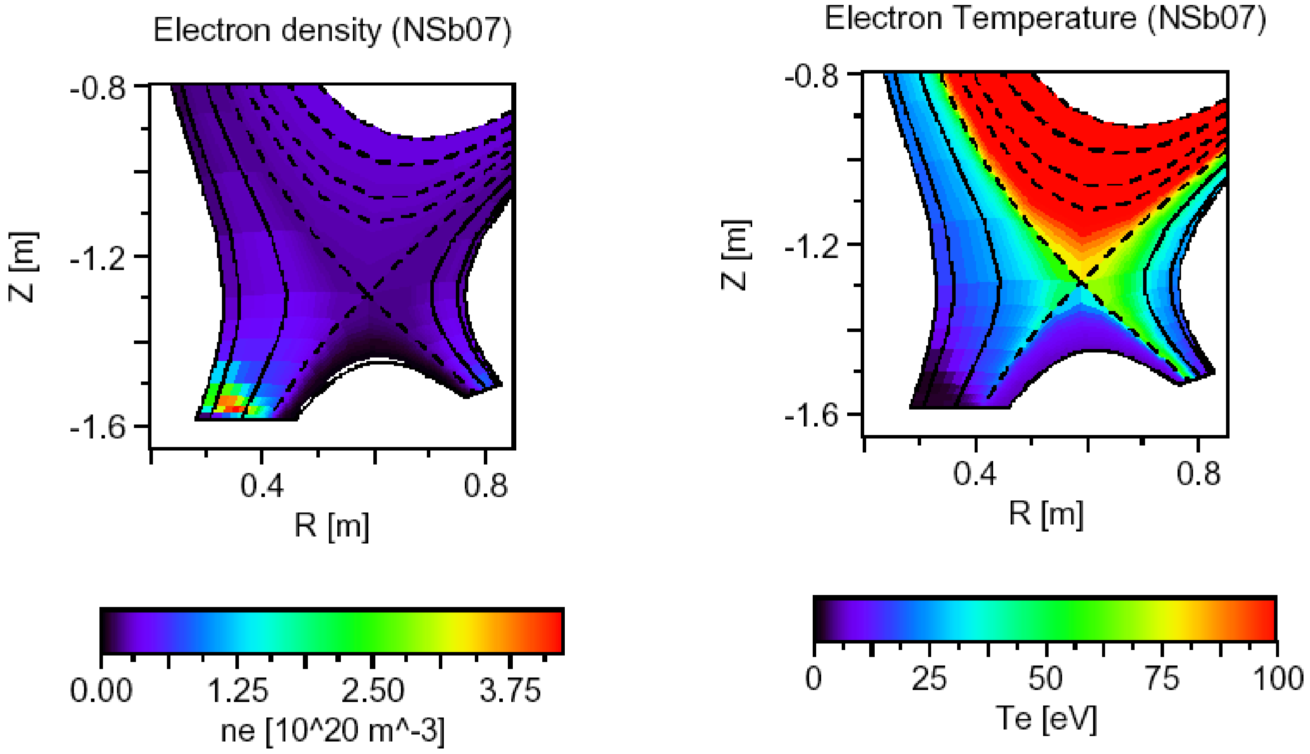


- Both inner and outer side profiles come to equilibrium in about 100 ms
- Power flow to outer side is three times inboard side
- Heat flux width being compared to model predictions

Maingi, Paul, Soukhanovskii

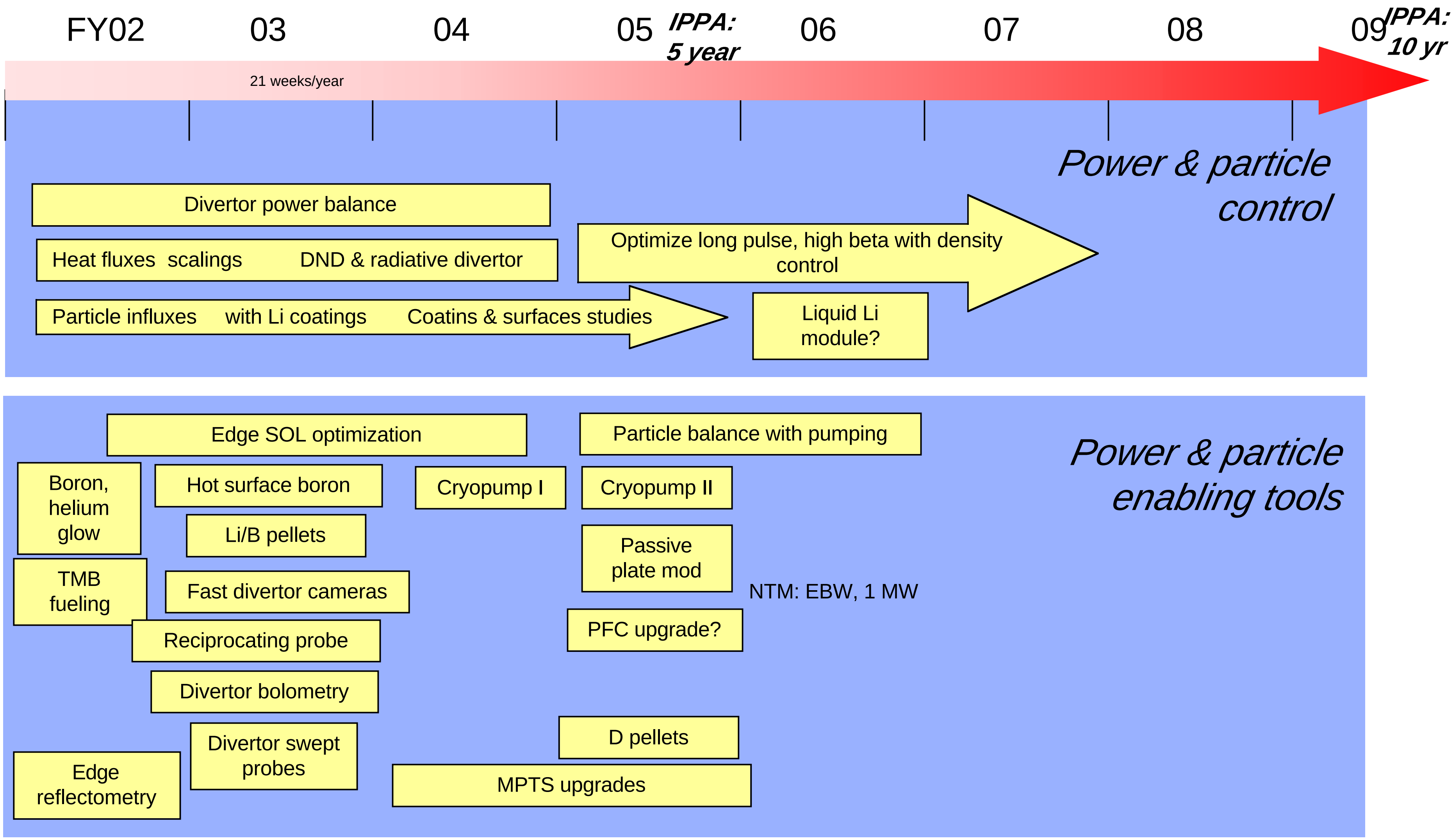
Coupling of edge measurements and advanced modeling are central for establishing ST boundary science

- 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



FY02 03 04 05 *IPPA: 5 year* 06 07 08 09 *IPPA: 10 yr*

21 weeks/year

Power & particle control

Divertor power balance

Heat fluxes scalings DND & radiative divertor

Particle influxes with Li coatings Coatins & surfaces studies

Optimize long pulse, high beta with density control

Liquid Li module?

Power & particle enabling tools

Edge SOL optimization

Particle balance with pumping

Boron, helium glow

Hot surface boron

Cryopump I

Cryopump II

Li/B pellets

Passive plate mod

TMB fueling

Fast divertor cameras

NTM: EBW, 1 MW

Reciprocating probe

PFC upgrade?

Divertor bolometry

D pellets

Divertor swept probes

Edge reflectometry

MPTS upgrades

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…

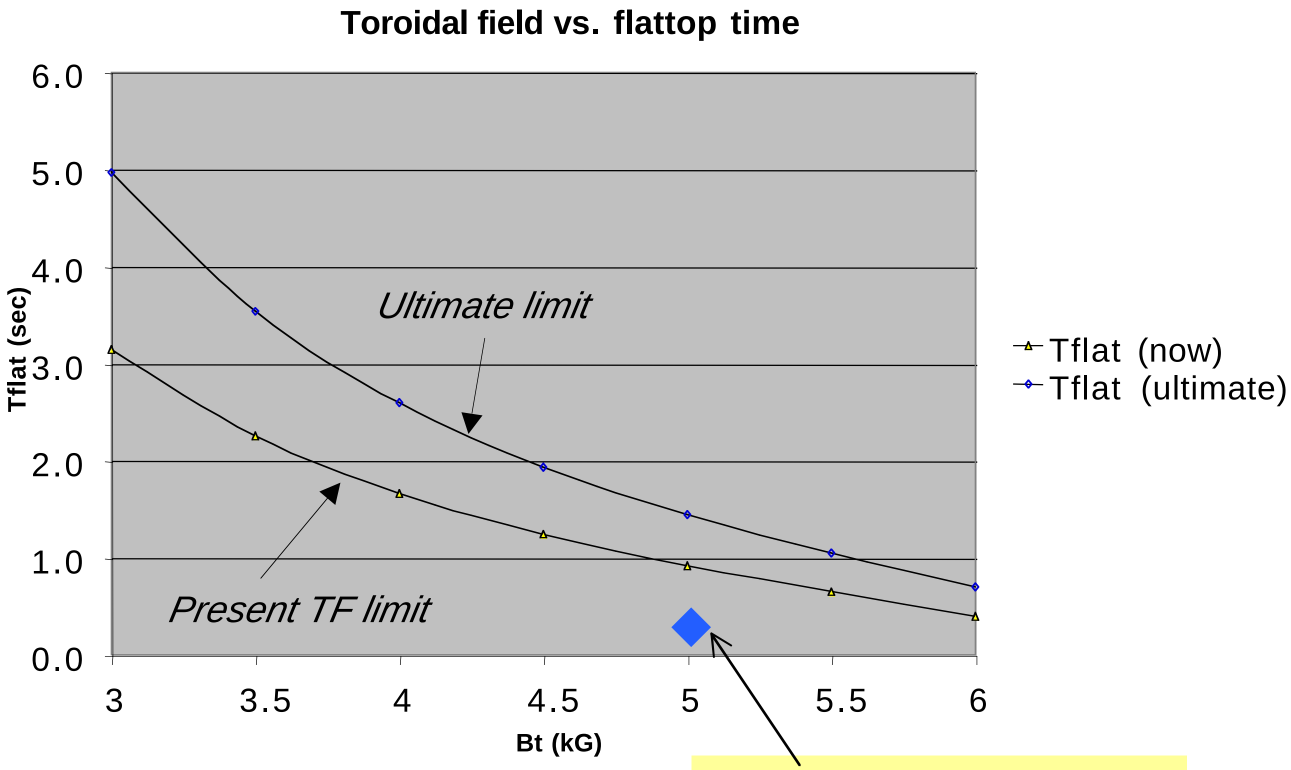
- Inductive, high performance
  - 40% β_T. Is wall stabilization sufficient?
  - Highest $\beta_T\tau_E$, highest H factor

- 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

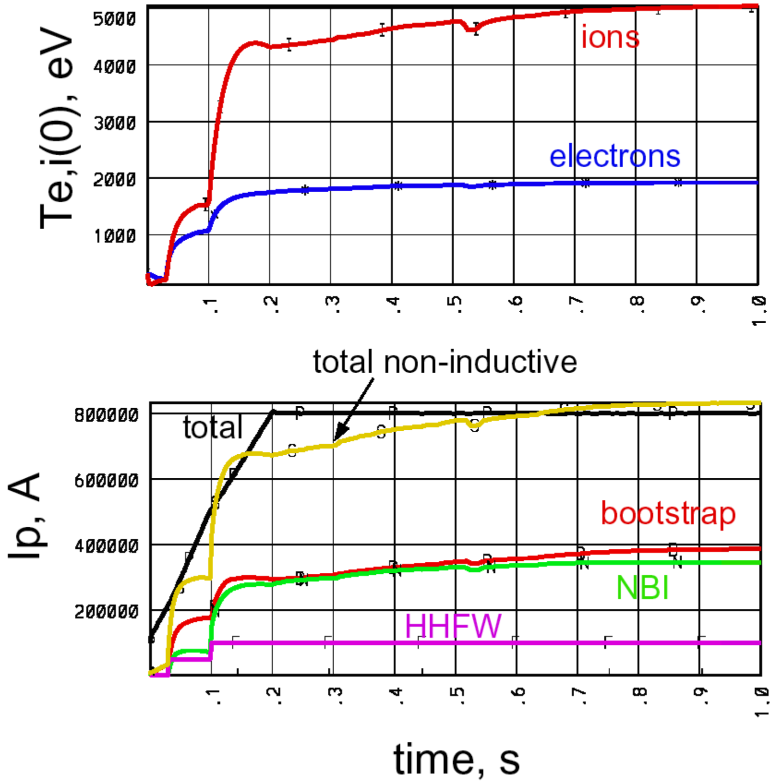

Toroidal field vs. flattop time

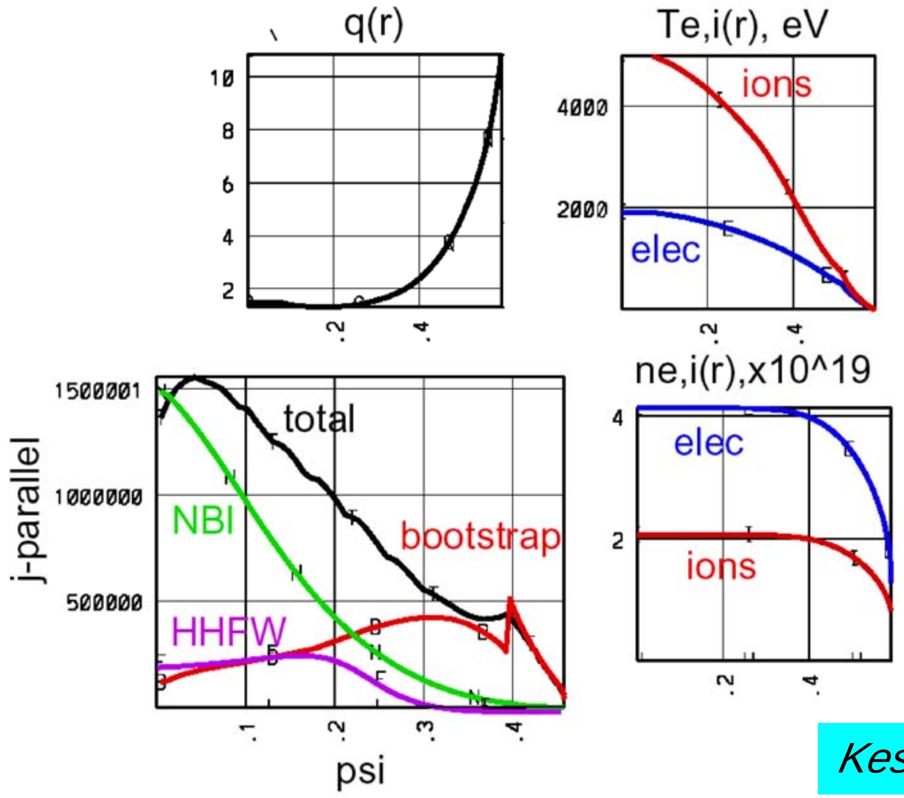
τ_{skin} = 230 ms (109070)

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

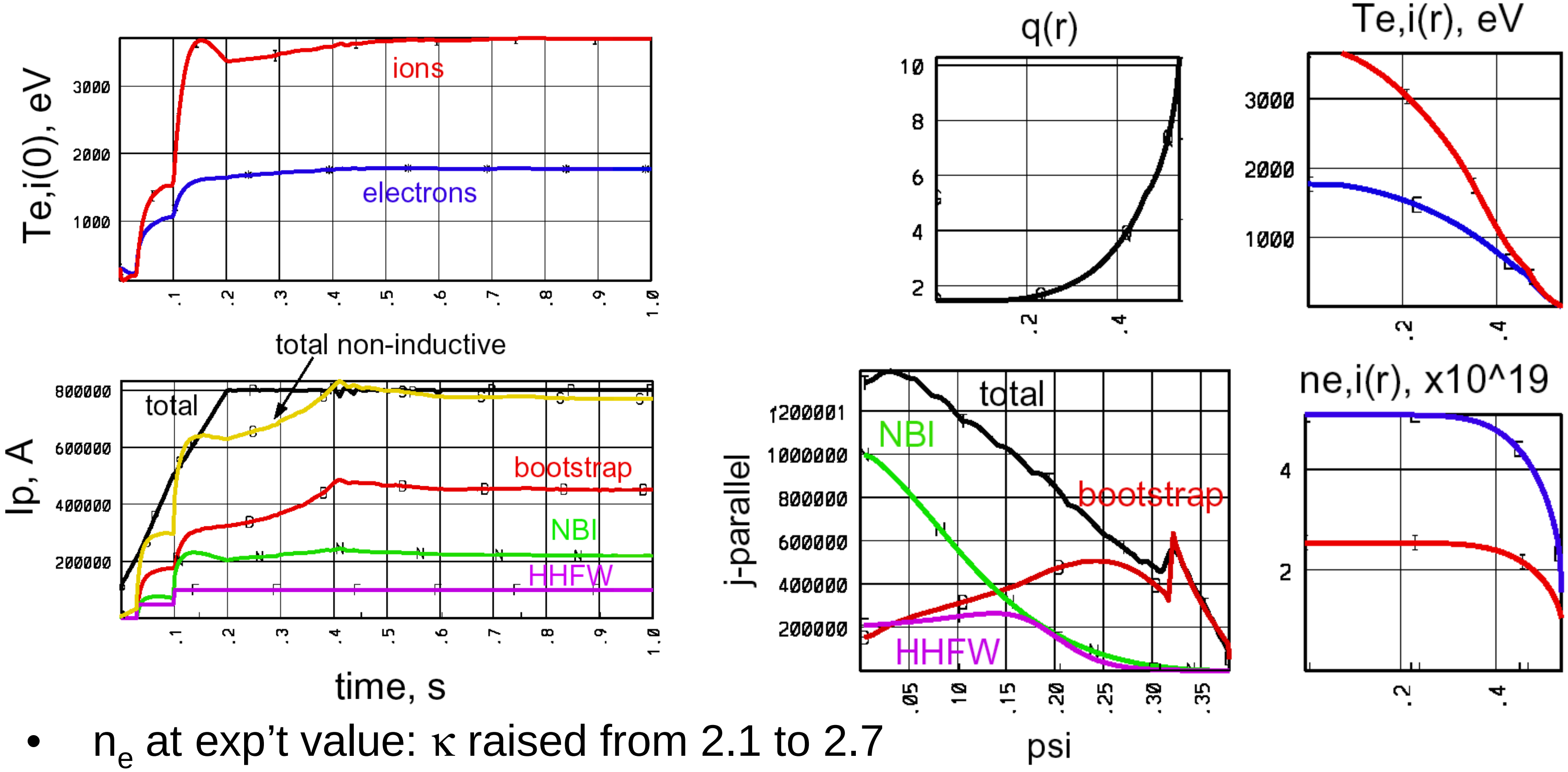




Kessel

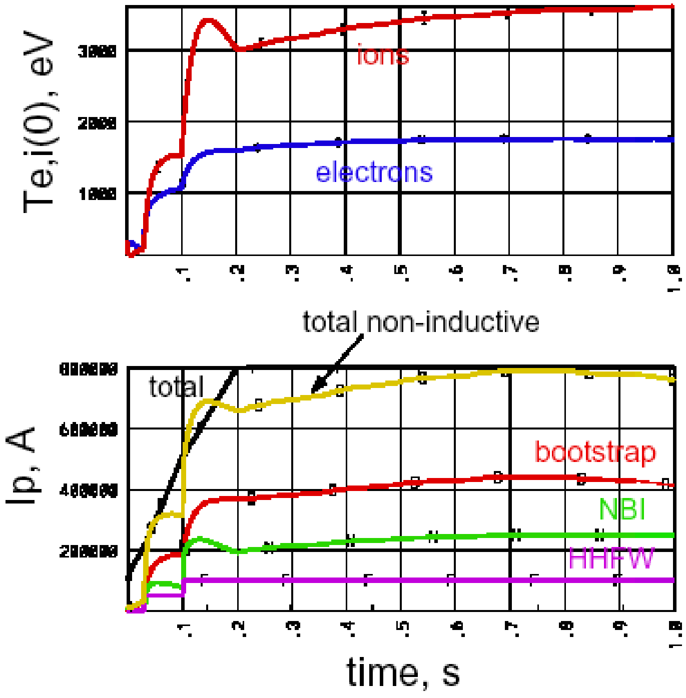
- n_e lower than exp't by 20%: raises NB CD, peaks J profile
- I_{BS} = 380 kA, I_{NBI} = 345 kA, I_{HHFW} = 100 kA
- q_{cyl} = 3.3, q_{95} = 10, q(0) = 1.4 @ 1 s
- $\beta_{T,\ thermal}$ = 16%, total β_T ~ 22%, β_p = 1.4, β_N(thermal) = 5.8
- Z_{eff} = 3.5, κ = 2.1, H_{98} = 1.25

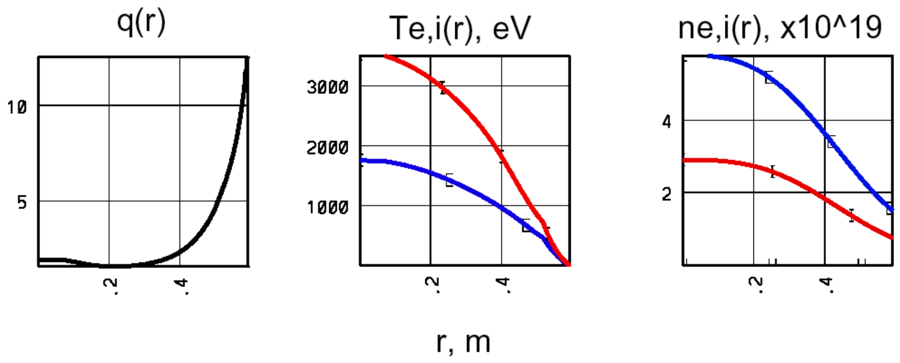
Raising elongation enables a boost from the bootstrap current

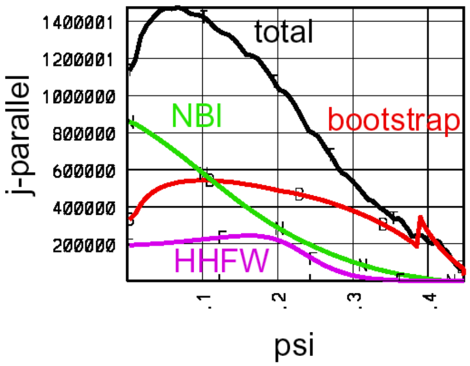


- n_e at exp't value: κ raised from 2.1 to 2.7
- I_{BS} = 450 kA, I_{NBI} = 220 kA, I_{HHFW} = 100 kA
- $q_{cyl} = 4$, $q_{95} = 8$, $q(0) = 1.4$ @ 1 s
- $\beta_{T,thermal}$ = 15.5%, total β_T ~ 21%, β_p = 1.75, β_N(thermal) = 5
- $H_{98} = 1$

Modest density peaking can enhance bootstrap, reduce NBI CD







- $n_e(0)/\langle n_e \rangle$ 1.5 (exp't=1.1)
- I_{BS} = 440 kA, I_{NBI} = 249 kA, I_{HHFW} = 100 kA
- q_{cyl} = 3.6, q_{95} = 9.9, q(0) = 1.5 @ 1 s
- $\beta_{T,thermal}$ = 14.5%, β_T = 20%, β_p = 1.4, β_N(thermal) = 5.3
- H_{98} = 1.1

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