Towards Assessing the ST: the NSTX Research Program for FY ‘04 - ‘08

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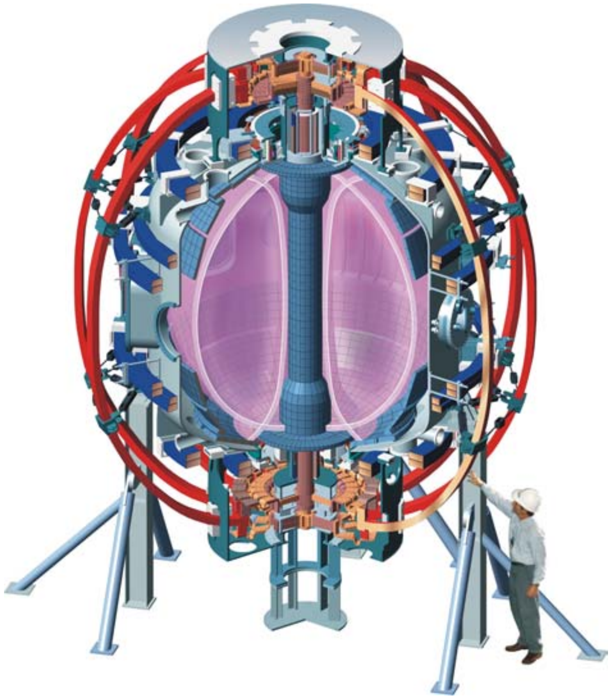

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Presentation for the NSTX Five Year Feedback Forum

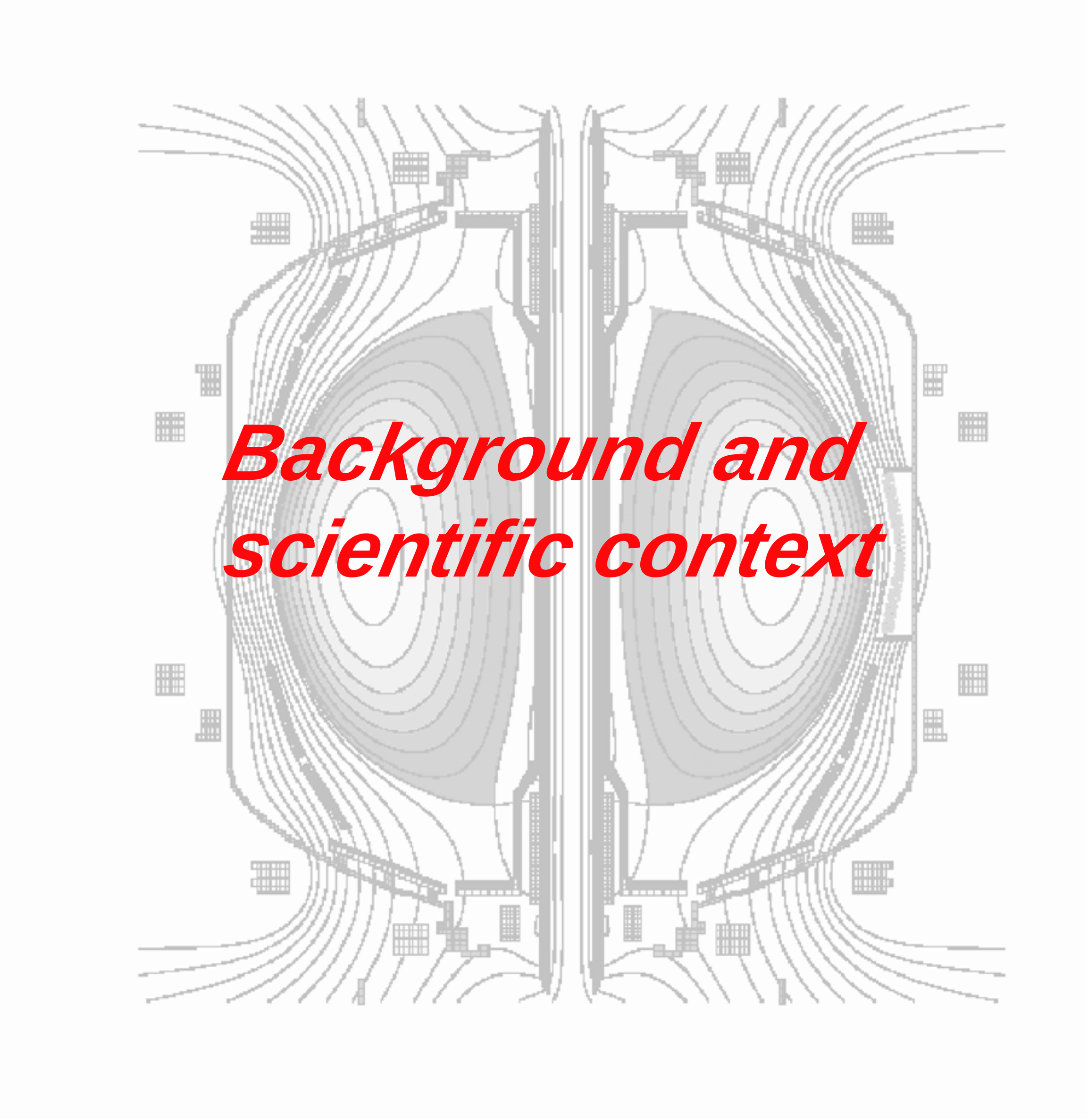
December 12, 2002

The Future of Energy on Earth is the Energy of the Stars Fusion Energy

United States Department of Energy

NSTX research is both a U.S. and international enterprise

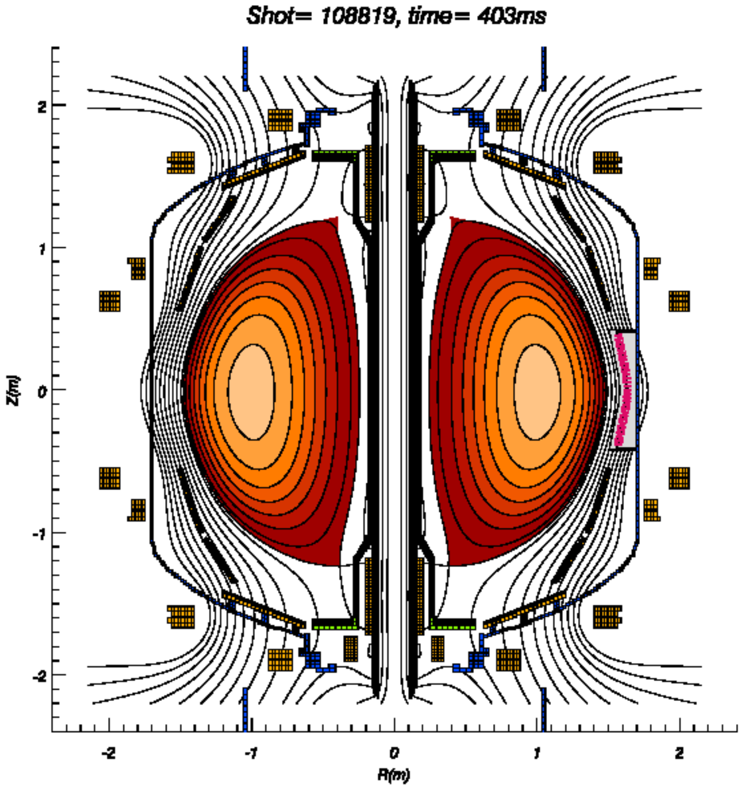
- CEA Cadarache, France
- Columbia University, New York, N.Y., U.S.A.
- CompX, Del Mar, California, U.S.A.
- ENEA, Frascati, Italy
- Euratom-UKAEA Fusion Association, Abingdon, Oxfordshire, UK
- General Atomics, San Diego, California, U.S.A.
- Kyushu Tokai University, Kumamoto, Japan
- Himeji Institute of Technology, Okayama, Japan
- Hiroshima University, Hiroshima, Japan
- Johns Hopkins University, Baltimore, Maryland, U.S.A.
- Korea Basic Science Institute, Taejon, Republic of Korea
- Lawrence Livermore National Laboratory, Livermore, California, U.S.A.
- Los Alamos National Laboratory, Los Alamos, New Mexico, U.S.A.
- Massachusetts Institute of Technology, Cambridge, Massachusetts, U.S.A.
- Nova Photonics, Princeton, New Jersey, U.S.A
- Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A.
- Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ
- Princeton Scientific Instruments, Princeton, New Jersey, U.S.A.
- Sandia National Laboratories, Albuquerque, New Mexico, U.S.A.
- Tokyo University, Tokyo, Japan
- University of California, Davis, California, U.S.A.
- University of California, Irvine, California, U.S.A.
- University of California, Los Angeles, California, U.S.A.
- University of California, San Diego, California, U.S.A.
- University of Washington, Seattle, Washington, U.S.A.
- University of Wisconsin, Madison, Wisconsin, U.S.A.



Background and scientific context

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

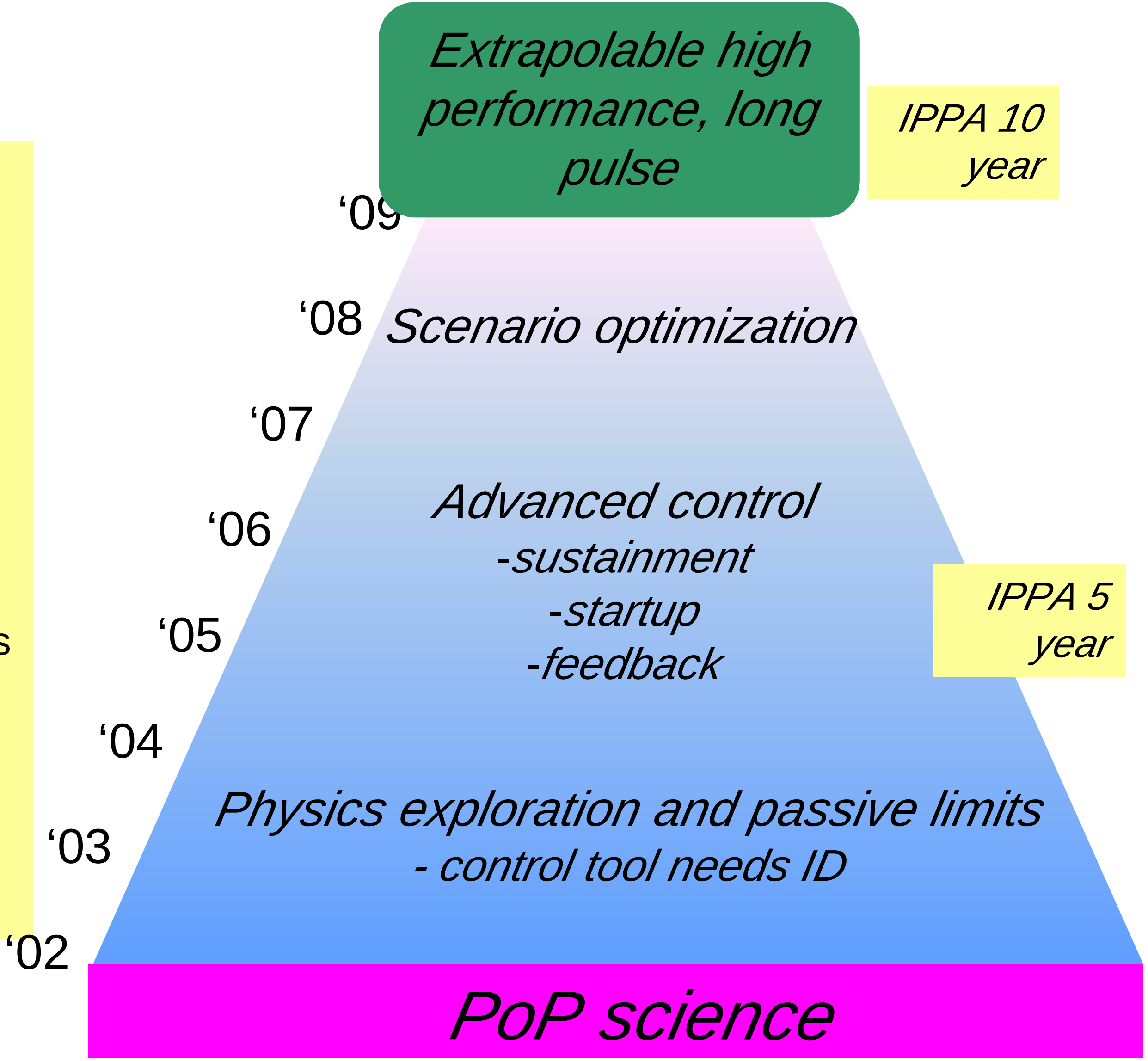
- *Assessing the attractiveness of the ST as a fusion energy concept*
  - *CTF and Demo*
  - Grounded in integration of topical science
- Using ST plasma characteristics to *further a deeper understanding of critical toroidal physics issues*
- Both pursuits are guided by the IPPA implementation approach



Challenges: <u>Understand</u> the new physics of high beta and low aspect ratio, and <u>integrate</u> it to expand the limits of the ST operating space.

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

‘06

Advanced control

-sustainment

-startup

-feedback

IPPA 5 year

‘05

‘04

Physics exploration and passive limits

- control tool needs ID

‘03

‘02

PoP science

NSTX science is emerging at a time of rapid change in our field

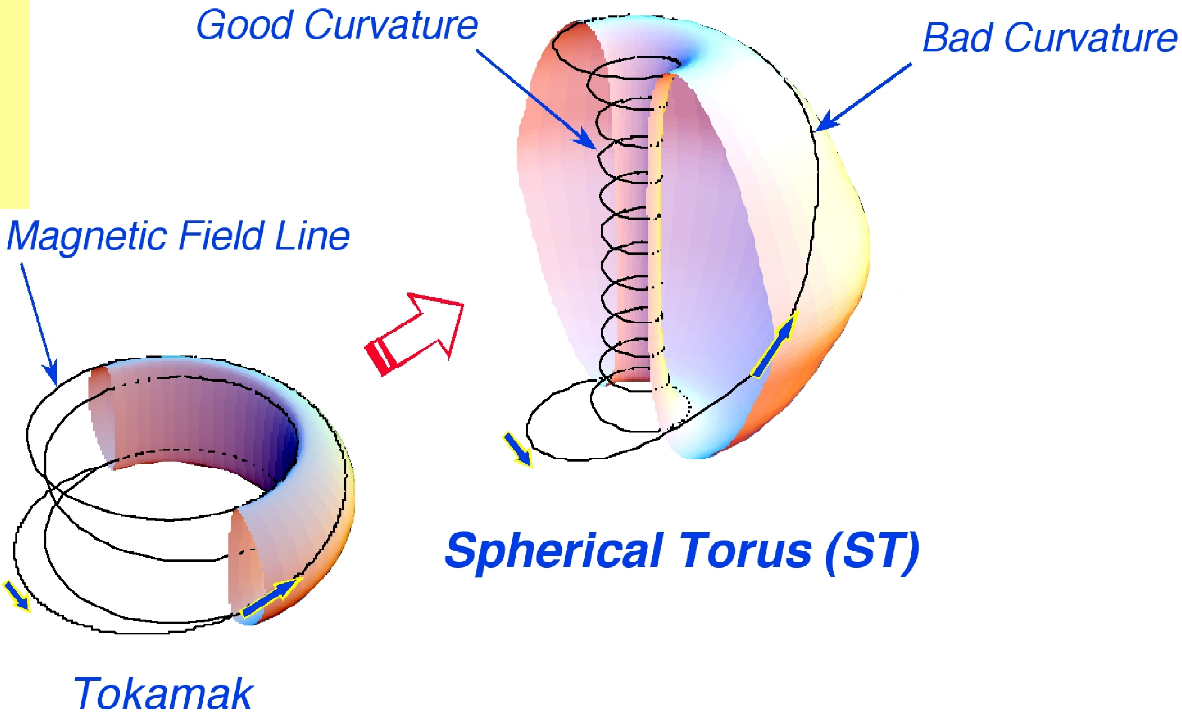
- This is recognized by our sponsors:

"From my own reviews of recent research on magnetically confined plasmas, I believe this field has benefited, as many other fields have, from the revolutionary improvements in *computing power* and *instrumentation*. The ability to predict plasma parameters in realistic simulations and then test them in detail in actual devices *has changed the character of the entire field* substantially...." (italics added)

Jack Marburger
Director
Office of Science and Technology Policy
Testimony for the NRC panel

The differences in field line geometry between devices can be viewed as the basis of a scientific experiment

Change the aspect ratio, increase beta: what physics changes?



A strong NSTX science program enables physics tests in areas of high concern to any next-step device

Moderate A, lower β	Lower A $\beta(0) \Rightarrow 1$		Testable toroidal physics
Strong flow shear: possible Electrostatic turbulence	Strong flow shear: typical? Strong electromagnetic turbulence?	$\Rightarrow$	Global scalings Barrier dynamics Electron thermal transport
$V_{Alfven} > V_{beam} > V_{th}$	$V_{beam} > V_{Alfven} \sim V_{th}$	$\Rightarrow$	Equilibrium theory Rotational shear effects on MHD MHD wall coupling theories Fast ion & wave coupling
Smaller Larmor radius Poorer average curvature Less poloidal damping	Larger Larmor radius Better average curvature Stronger poloidal damping	$\Rightarrow$	Pedestal models H mode theories
Lower flux expansion in divertor	Higher flux expansion in divertor	$\Rightarrow$	SOL transport and divertor 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

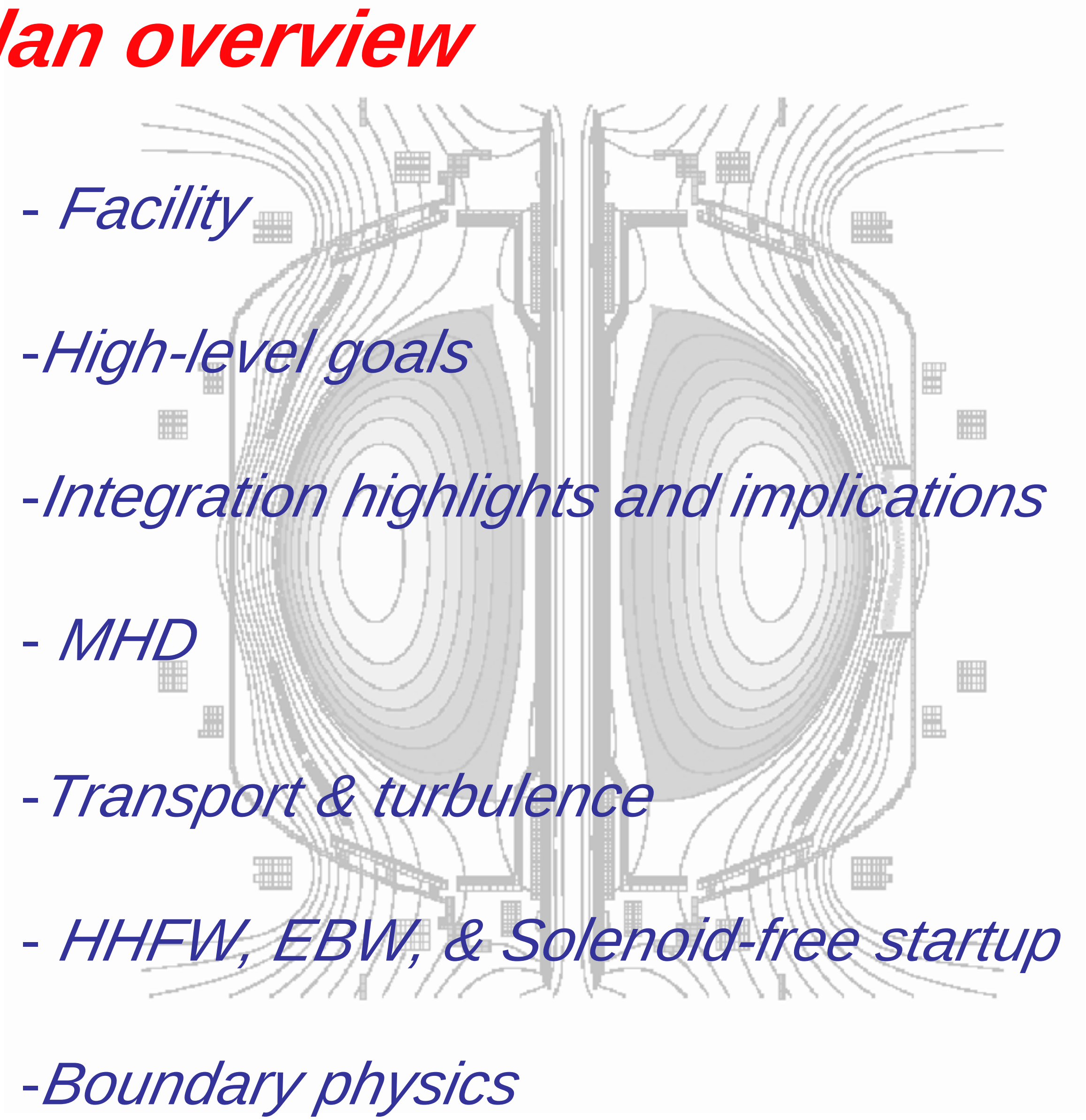
  - 2009+: 10 year IPPA goal: *Assess the attractiveness of extrapolable, long-pulse operation of the ST for* $\tau_{pulse} >> \tau_{skin}$

- Developing ST contributions to toroidal physics
  - IPPA science goals are guiding principles

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

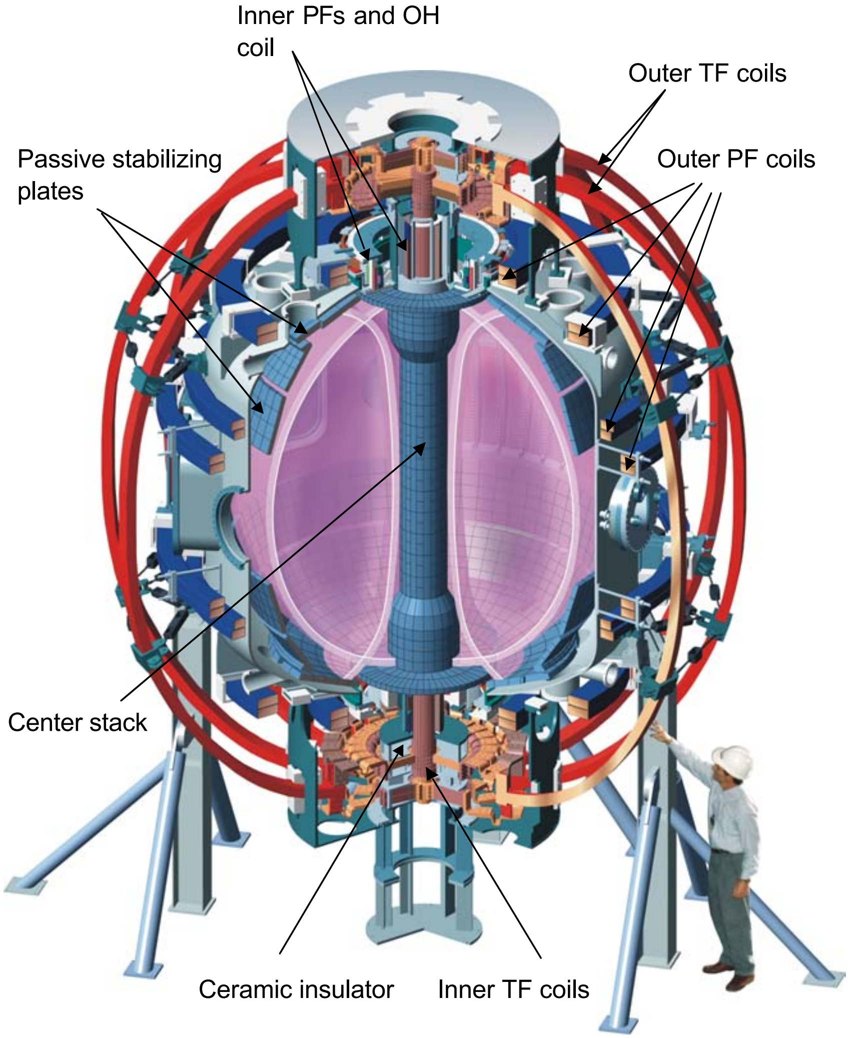
- We were informed last spring that we would be joining C-Mod and DIII-D in a five year review this spring.
- First step: input obtained in Five Year Plan Workshop, 6/24 - 6/26
  - Topical discussion groups (science topics & integration)
  - Tasks put to the participants included
    - Identify elements 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
- This fall: NSTX PAC got first look at plan ideas
- This step: Five Year Plan Feedback Forum, 12/12 - 12/13
- January ‘03 PAC: Updated plan and programmatic feedback
- Review in June

Plan overview



- Facility
- High-level goals
- Integration highlights and implications
- MHD
- Transport & turbulence
- HHFW, EBW, & Solenoid-free startup
- Boundary physics

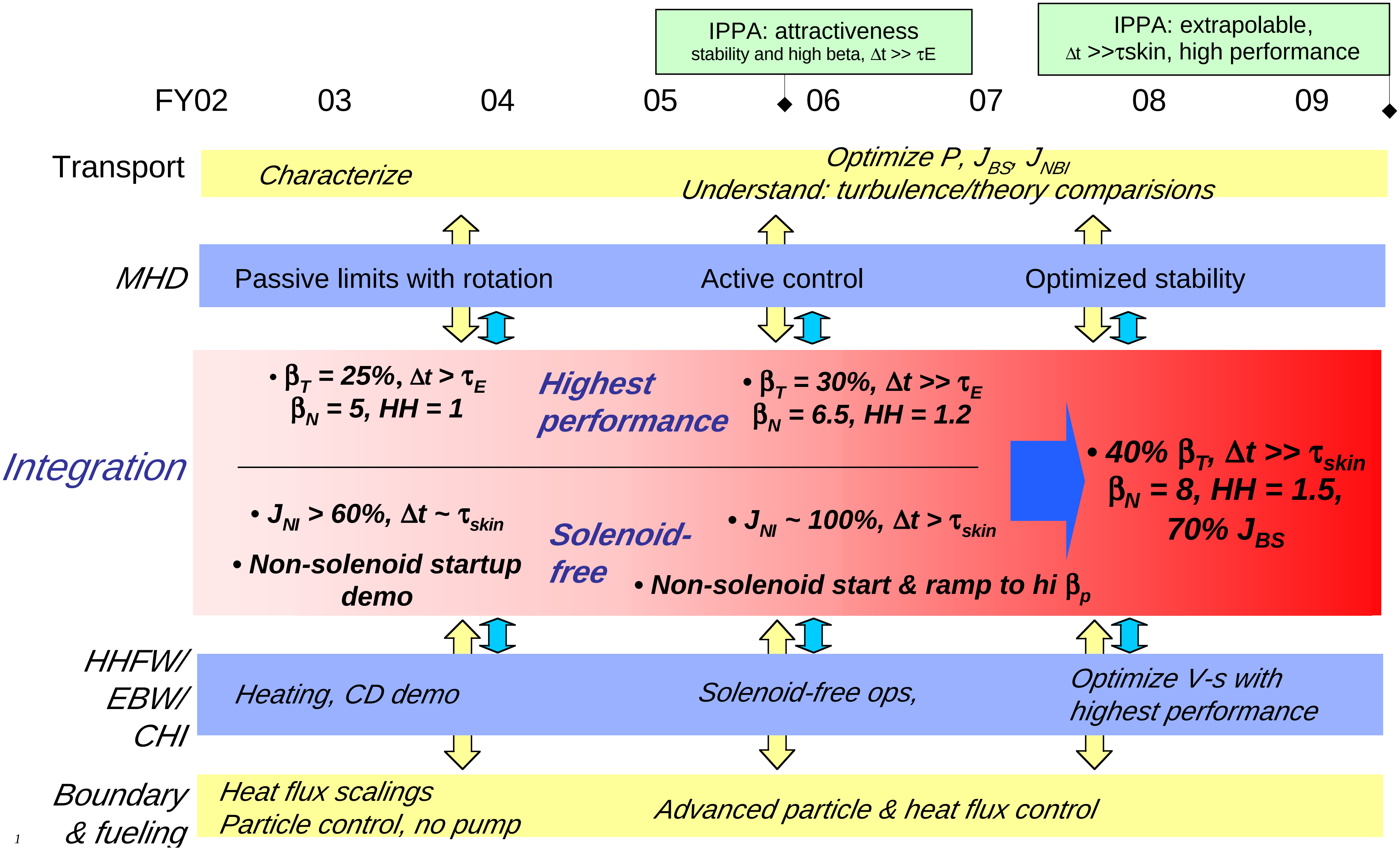
Facility capabilities have enabled the research program to advance in the last two years



Bakeout	350°C
Gas fueling	LFS + HFS
Aspect ratio	1.27
Elongation	2.2
Triangularity	0.8
Plasma Current	1.5 MA
Toroidal Field	0.6T
Heating and Current Drive	
Induction	0.7Vs
NBI	7MW
HHFW (30MHz)	6MW
CHI	0.4MA
Pulse Length	1s achieved, 5 s with 3 kG possible

Bell will discuss control & integration plans

Integrating topical science & control tools 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
Characterize
Optimize P, J_{BS}, J_{NBI}
Understand: turbulence/theory comparisions

MHD
Passive limits with rotation
Active control
Optimized stability

Integration

Highest performance
- ***$\beta_T = 25\%$, $\Delta t > \tau_E$***
  $\beta_N = 5$, HH = 1
- ***$\beta_T = 30\%$, $\Delta t >> \tau_E$***
  $\beta_N = 6.5$, HH = 1.2

Solenoid-free
- ***$J_{NI} > 60\%$, $\Delta t \sim \tau_{skin}$***
- ***Non-solenoid startup demo***
- ***$J_{NI} \sim 100\%$, $\Delta t > \tau_{skin}$***
- ***Non-solenoid start & ramp to hi β_p***

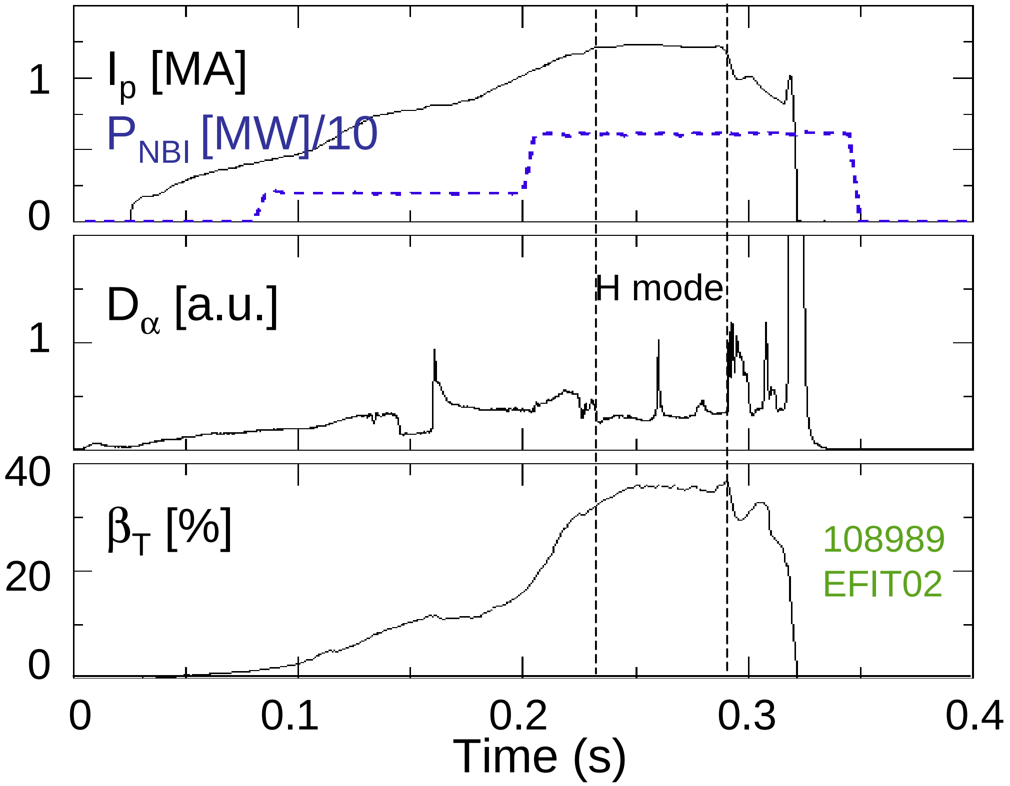
- ***40% β_T, $\Delta t >> \tau_{skin}$***
  $\beta_N = 8$, HH = 1.5,
  70% J_{BS}

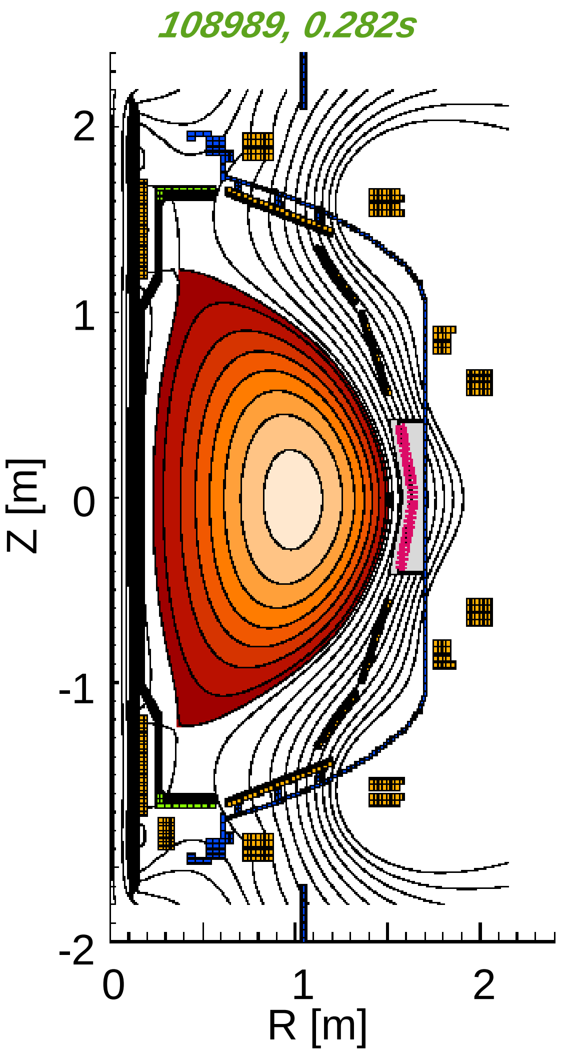
HHFW/ EBW/ CHI
Heating, CD demo
Solenoid-free ops,
Optimize V-s with highest performance

Boundary & fueling
Heat flux scalings
Particle control, no pump
Advanced particle & heat flux control

Achieved toroidal beta $\beta_T = 35\%$

$$\beta_T \equiv \frac{\langle p\rangle}{B_{T\,0}{}^2/2\mu_0}$$



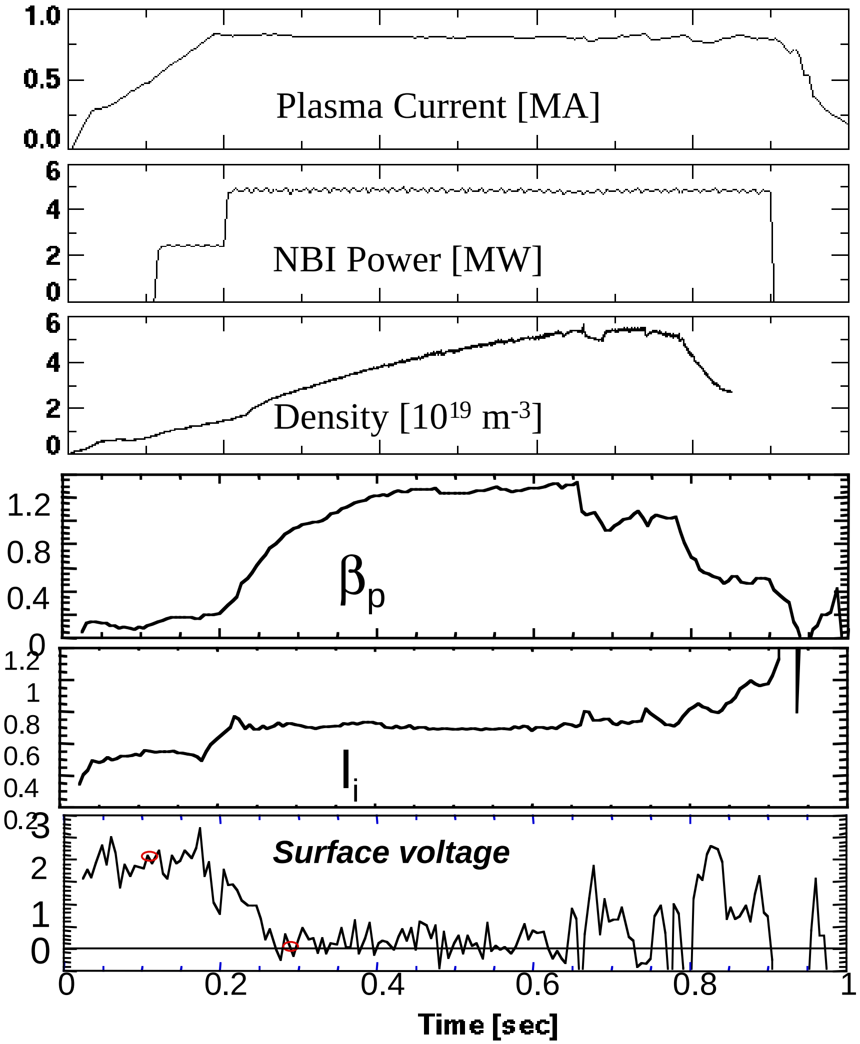


- β_T from EFIT including ϕ_{dia} and p_e profile
- $B_T = 0.3$T, $A = 1.4$, $\kappa = 2.0$, $\delta = 0.8$
- $l_i = 0.6$, $q_0 \approx 1.4$
- H-mode broadens pressure profile
- 1/1 mode saturates beta

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

- Integrating these is the challenge
  - High points include: 35% 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

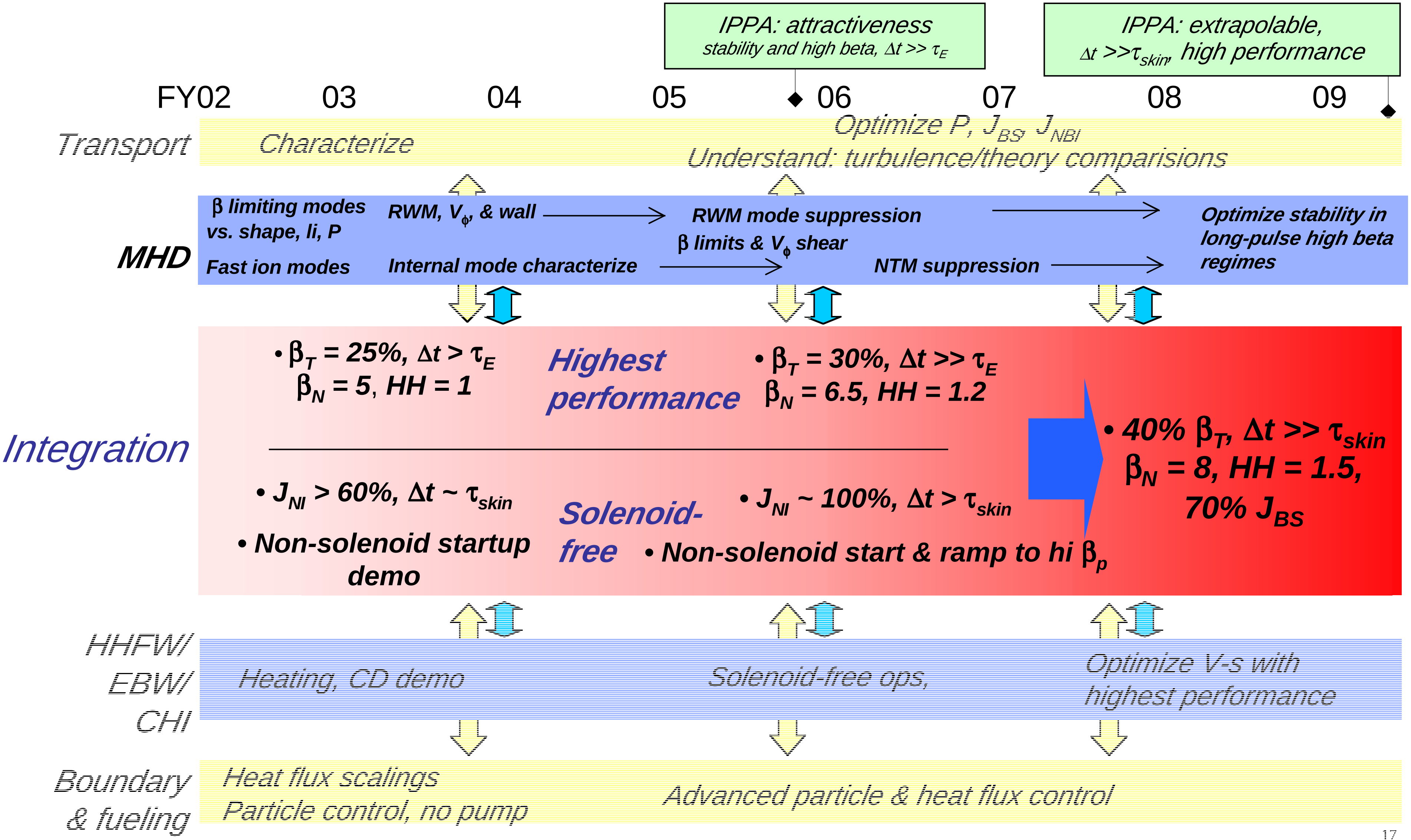
To meet long range goals, several long-range challenges have to be met

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 limiting 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?*

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

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



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

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

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Transport
- Characterize
- Optimize P, J_{BS}, J_{NBI}
- Understand: turbulence/theory comparisions

MHD
- β limiting modes vs. shape, li, P
- Fast ion modes
- RWM, V_ϕ, & wall →
- Internal mode characterize →
- RWM mode suppression →
- β limits & V_ϕ shear
- NTM suppression →
- Optimize stability in long-pulse high beta regimes

Integration

Highest performance
- $\beta_T = 25\%$, $\Delta t > \tau_E$
  $\beta_N = 5$, HH = 1
- $\beta_T = 30\%$, $\Delta t >> \tau_E$
  $\beta_N = 6.5$, HH = 1.2

Solenoid-free
- $J_{NI} > 60\%$, $\Delta t \sim \tau_{skin}$
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- 40% β_T, $\Delta t >> \tau_{skin}$
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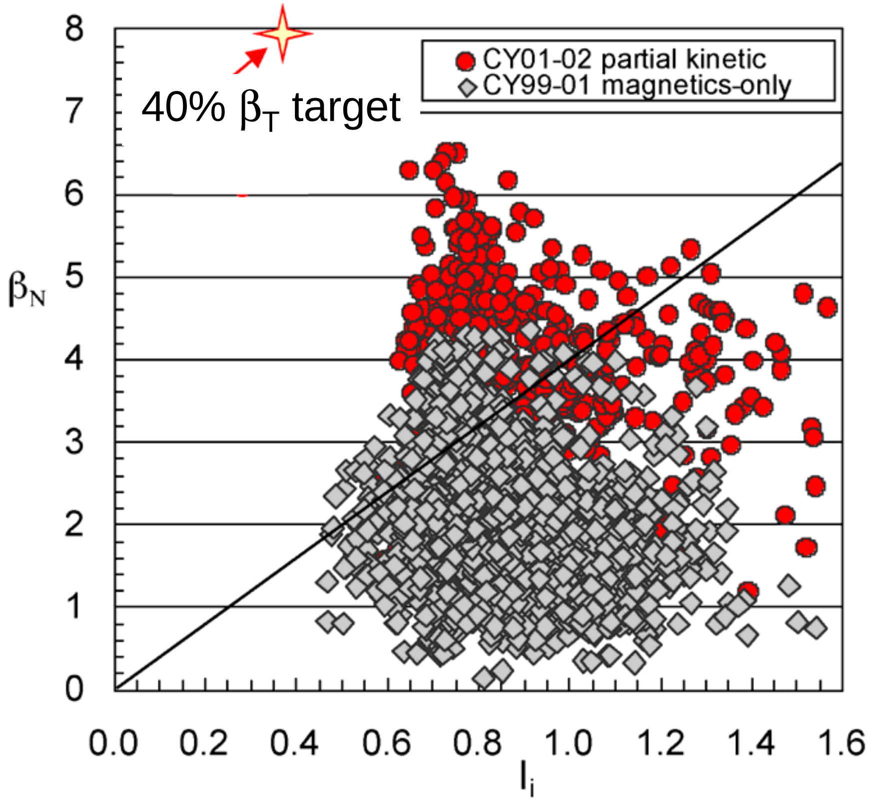
  70% J_{BS}

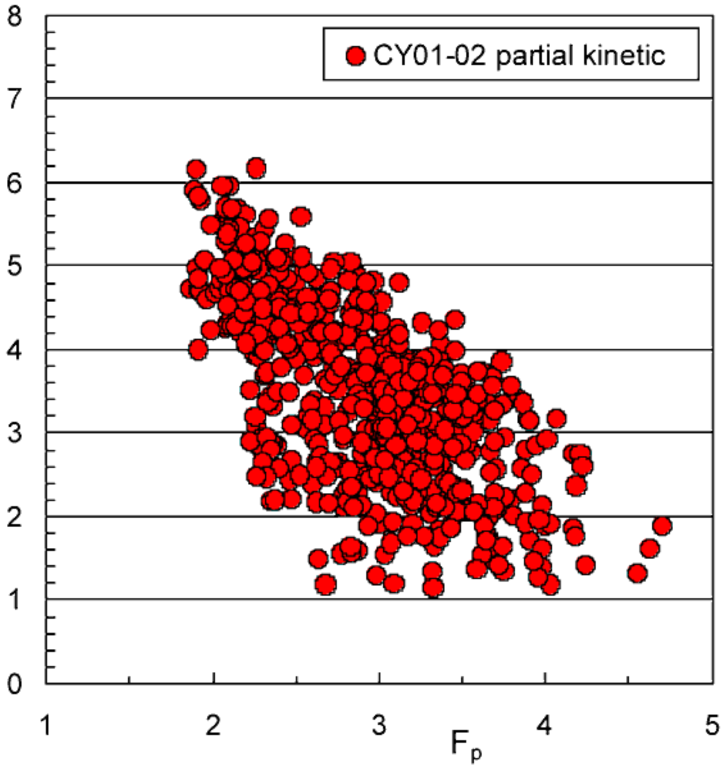
HHFW/ EBW/ CHI
- Heating, CD demo
- Solenoid-free ops,
- Optimize V-s with highest performance

Boundary & fueling
- Heat flux scalings
- Particle control, no pump
- Advanced particle & heat flux control

Progress has been made towards achieving target of 40% β_T

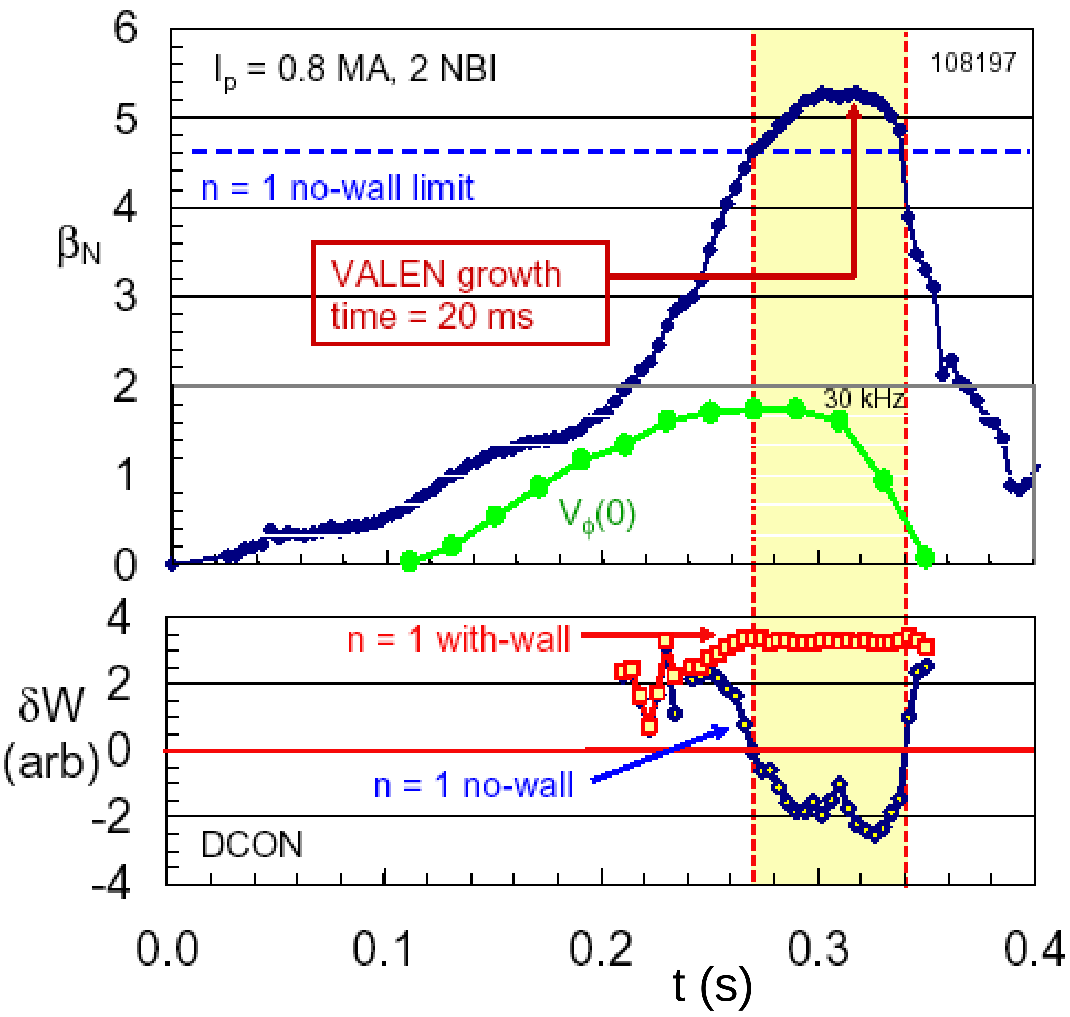
IPPA Goal 1.2: Develop detailed predictive capability for macroscopic stability, including resistive and kinetic effects



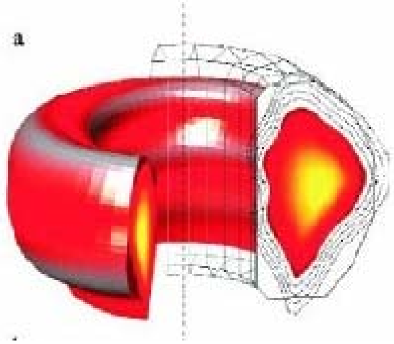


- $\beta_N = 6.5$, $\beta_N / l_i > 9.5$.
- $\beta_N > 1.3\ \beta_{N\ \text{no-wall}}$
- Takes advantage of broad P(r) in H mode

Study of interplay with stability, wall, error fields, and rotation a key element of the program

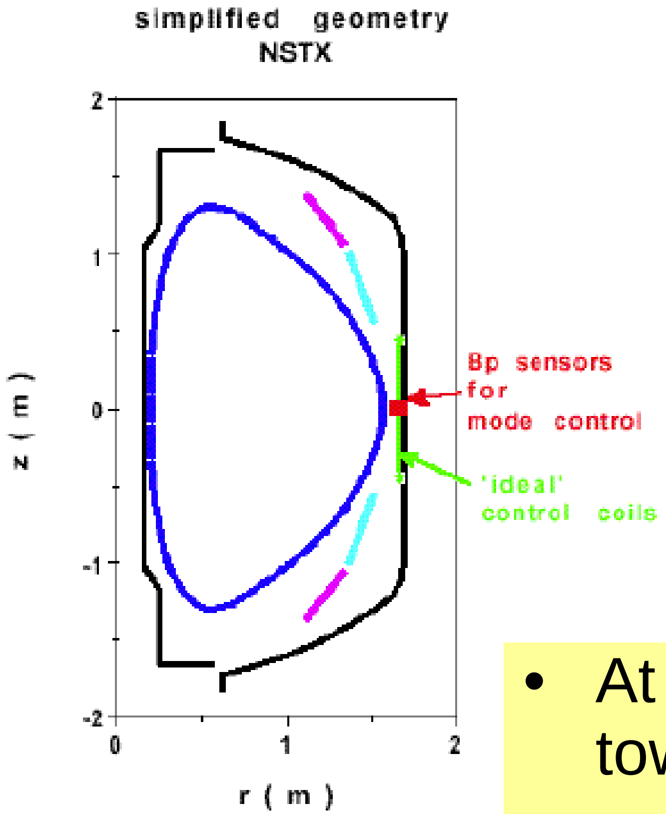


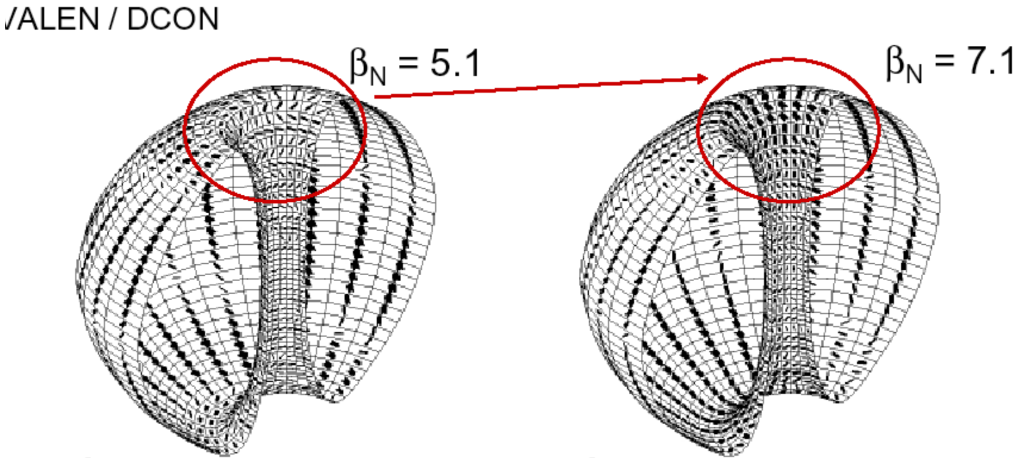
- β initially above no-wall limit, but collapses after V_ϕ falls below critical value
  - – Timescale ~ τ_{wall}
  - – Exceeded no-wall limit for up to ~20×τ_{wall} in best case
- Modeling shows effective coupling of mode to wall



With DIII-D: reveal nature of scaling of critical rotation

Strategy includes passive plate modification, controlled error field studies, and active control





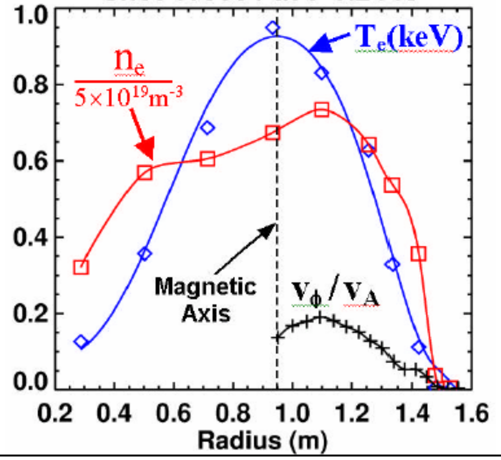
VALEN: Bialek (Columbia)

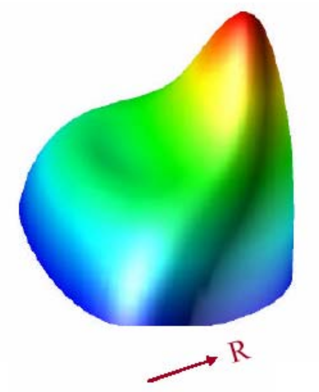
Menard, Sabbagh will discuss MHD plan, issues, and options

- At highest β_N, mode structure moves towards center stack
  - Passive plate modification may help. Simultaneous mods for cryopumping
- Internal active coils can increase β limit to near ideal wall values for some modes

Influence of high V_ϕ/V_A already seen in equilibria: relevant to stabilization?

R. Bell, LeBlanc

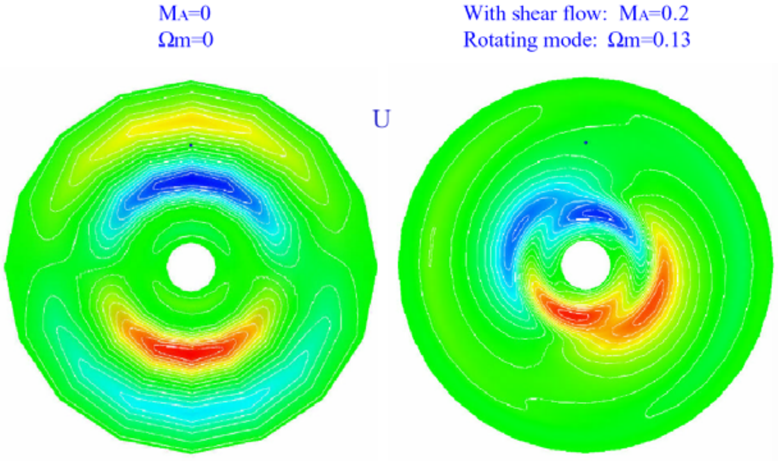




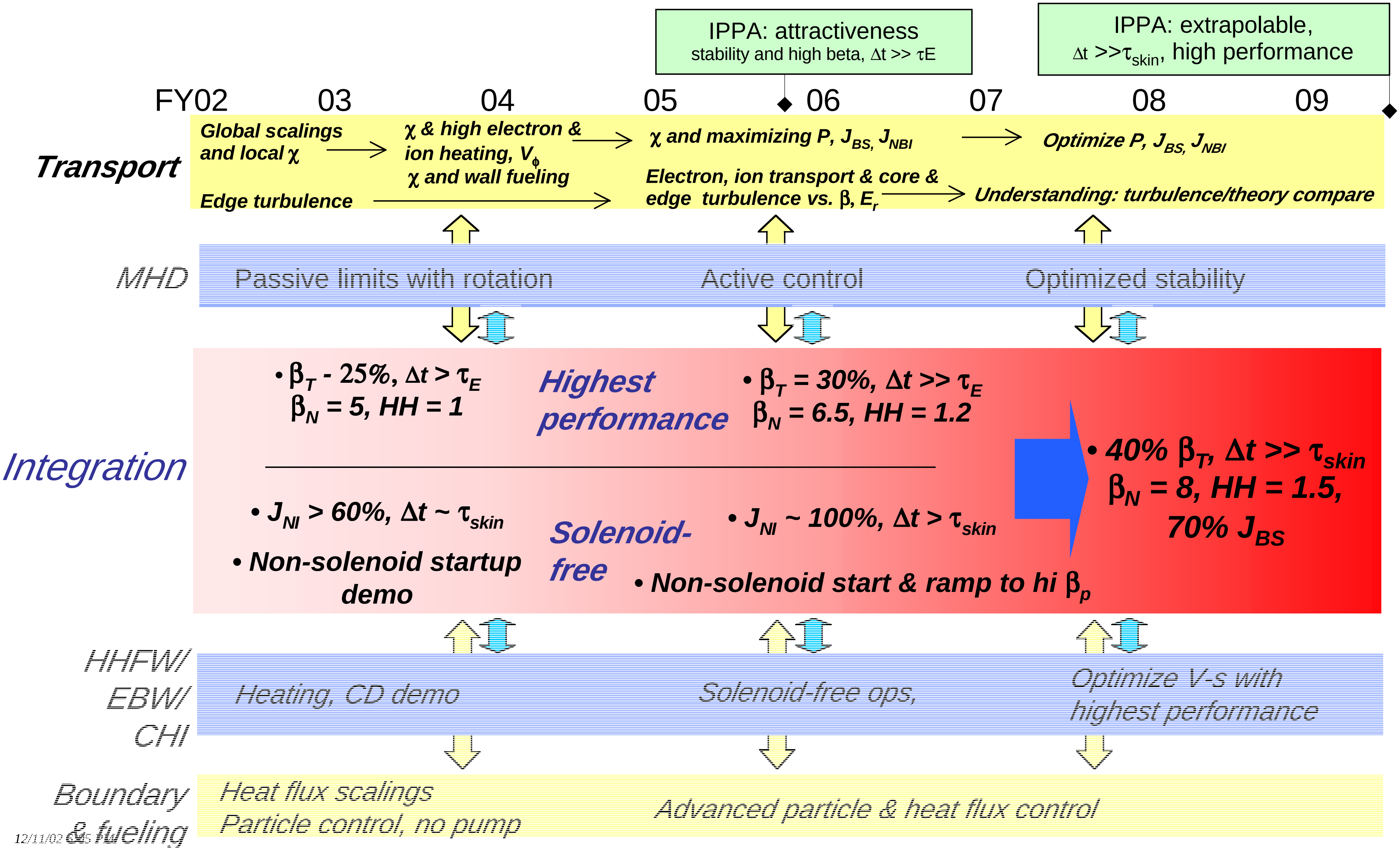
- Experiment: Density shows in-out asymmetry
- Effect of high Mach number of driven flow

M3D: Park

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



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



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Transport

Global scalings and local χ →

χ & high electron & ion heating, V_ϕ

χ and wall fueling →

χ and maximizing P, J_{BS}, J_{NBI} → *Optimize P, J_{BS}, J_{NBI}*

Edge turbulence →

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

MHD

Passive limits with rotation

Active control

Optimized stability

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- β_T - 25%, $\Delta t > \tau_E$
  β_N = 5, HH = 1

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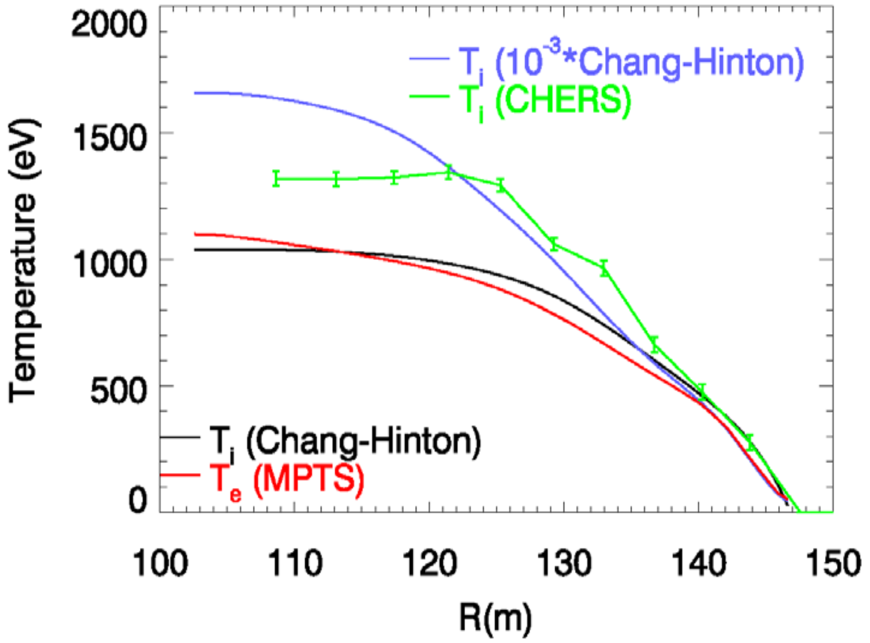
NSTX ion transport studies already reveal important surprises



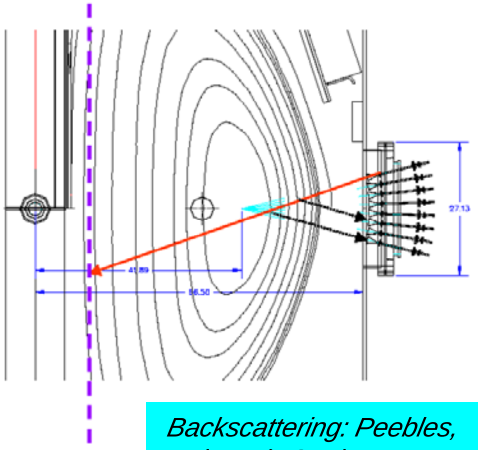
- Origin of high T_i (sub-neoclassical in some cases) is unclear
- High scientific and practical value: with a change of aspect ratio and beta, we’ve created a system we cannot yet explain

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.
- Short wavelengths: key to ubiquitous electron transport problem?
  - Large $\rho_e \Rightarrow$ big modes, ideal scattering geometry on NSTX
- SOL: high intermittency seen in imaging (LANL), probes (UCSD). Determinant in heat fluxes?

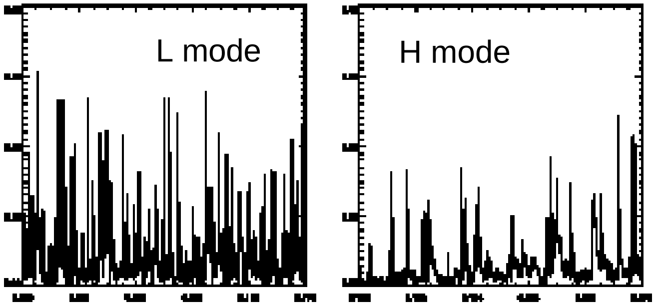
High k: scattering



ST advantage: large changes in direction of B in scattering with FIR yields high localization (Mazzucato)

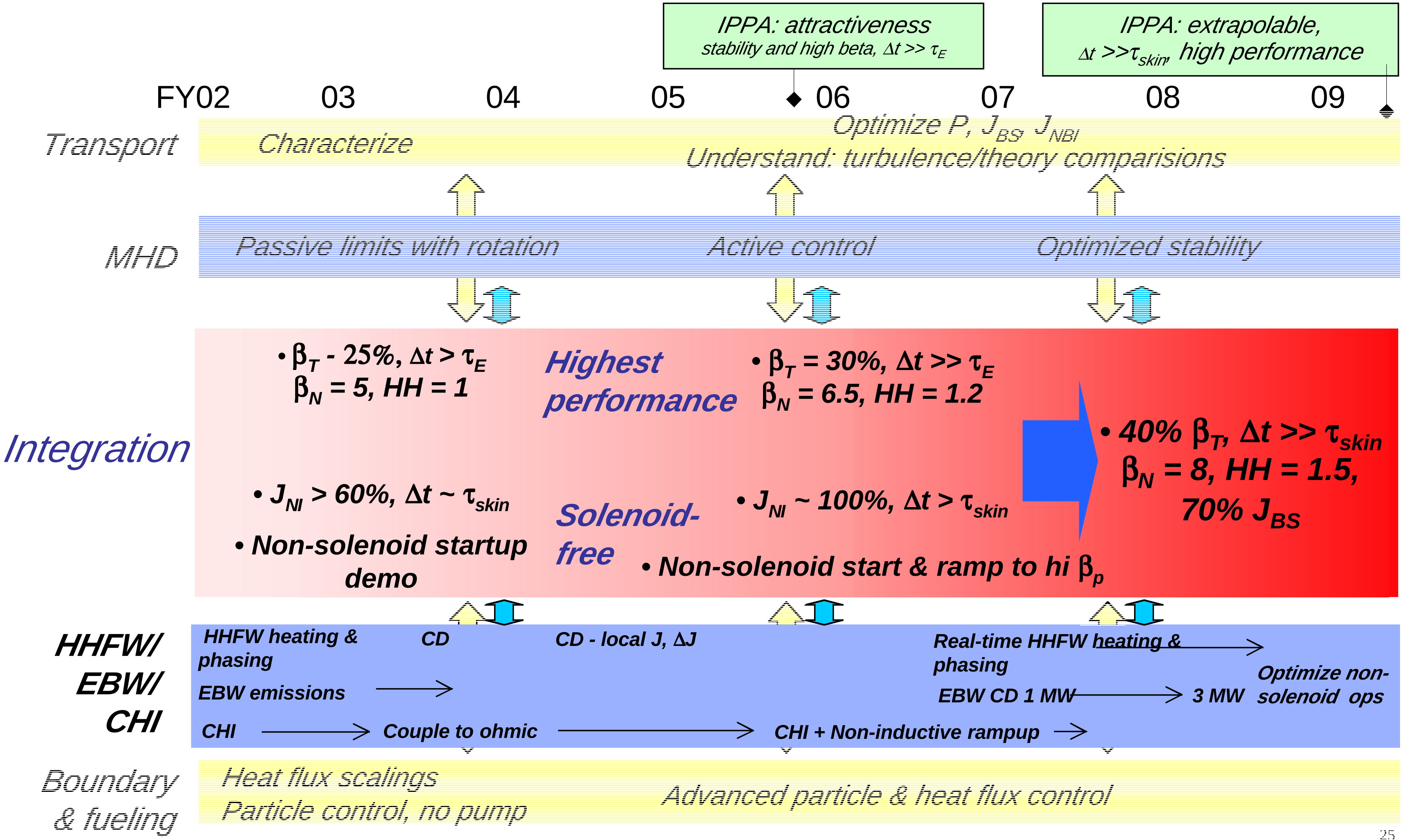
Backscattering: Peebles, Kubota (UCLA)

Kaye will discuss transport and turbulence research plan



Boedo (UCSD)

HHFW, EBW, and CHI science all part of solenoid-free startup strategy



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HHFW/ EBW/ CHI
HHFW heating & phasing
CD
CD - local J, ΔJ
Real-time HHFW heating & phasing →
EBW emissions →
EBW CD 1 MW → 3 MW
Optimize non-solenoid ops
CHI → Couple to ohmic → CHI + Non-inductive rampup →

Boundary & fueling
Heat flux scalings
Particle control, no pump
Advanced particle & heat flux control

Non-inductive startup research can be divided into different tasks

- Startup: 0 - 150 kA
  - CHI the primary tool at present

- Initial rampup: 150 - 500 kA
  - HHFW, EBW, bootstrap
  - Research can be performed with an ohmic start
  - PF induction - scenarios being assessed

- Final ramp to flattop
  - 500 - 800+ kA: NBI CD, bootstrap current overdrive are candidates

Each step is separable. Combining all three is a control challenge

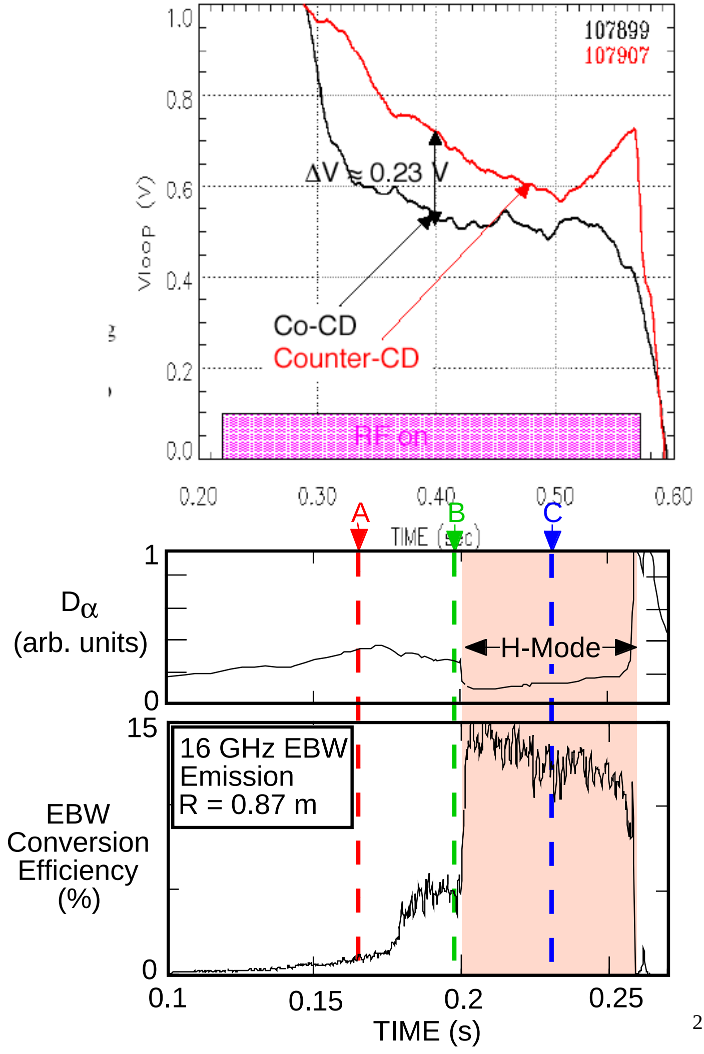
RF research in several areas will grow in importance in FY ‘04 - ‘08

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

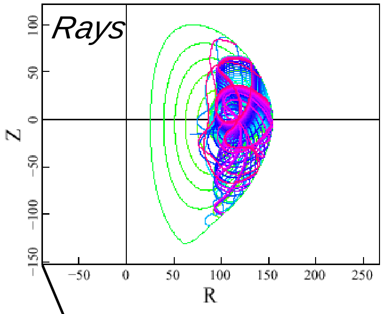
- HHFW heats effectively. CD indicated by surface voltage
- HHFW interactions with fast ions found (Rosenberg (Ph.D. Thesis), Medley)
  - Important for assessing CD efficiency
- EBW emissions being studied to identify requirements for possible new system.
  - Development path for EBW as a NTM and CD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

Taylor will discuss HHFW & EBW plans

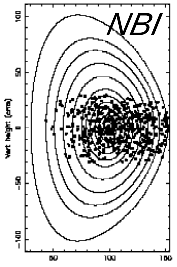
Ryan, Swain (ORNL); Hosea, Wilson



Model benchmarking approach: appeal to the most comprehensive codes (SCIDAC) as well as NSTX data



GENRAY



CQL3D

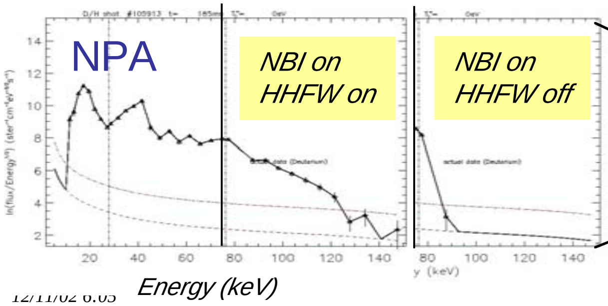
Faster model: Ray tracing
GENRAY (Harvey, CompX)
CURRAY (Mau, UCSD);
HPRT (Rosenberg, P.U., Menard)

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

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

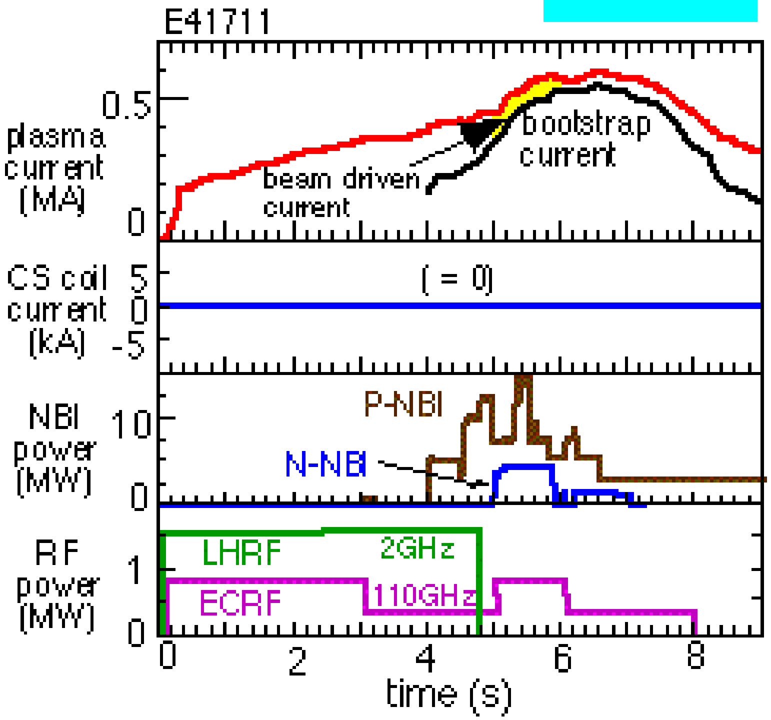


Energy (keV)

Manickam will discuss theory plans

Two recent results have (re)shaped our thinking about soleniod-free rampup: I. Recent JT-60U results

JT-60U



- Significant bootstrap fraction

- Resultant plasma was high performance (HH = 1.6)

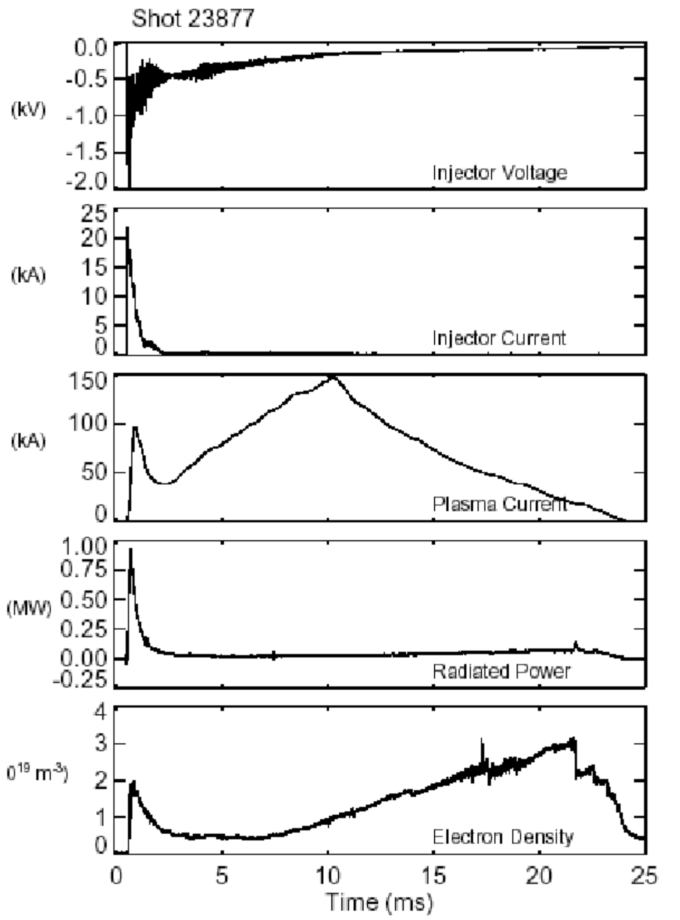
II. Recent work on HIT-II demonstrates that CHI and induction can be coupled

- HIT-II record currents now with CHI + induction

- 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



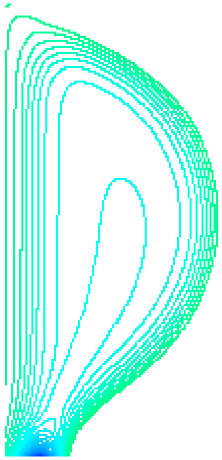
Raman, Jarboe, Nelson

Raman will discuss CHI plans

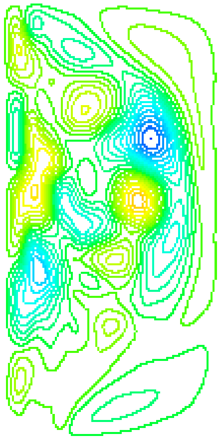
Theoretical understanding of helicity transport is growing

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

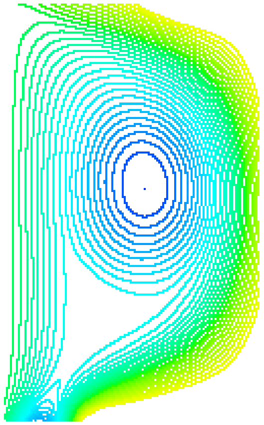
axisymmetric steady state χ



3D χ n=1 component



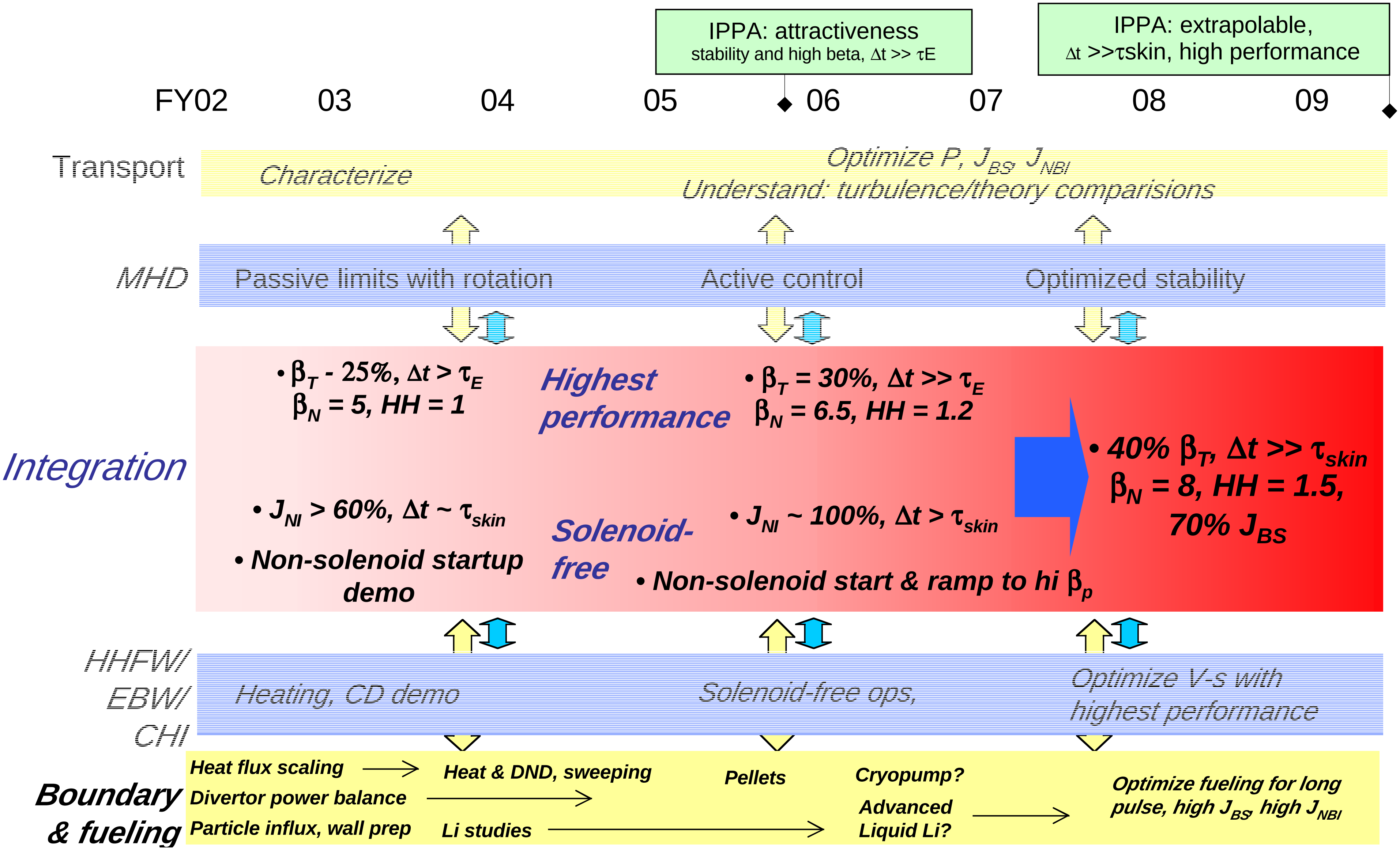
3D χ n=0 component



3D n=0 component of RB_{ϕ}

X. Tang, LANL

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



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

IPPA: extrapolable,
$\Delta t >> \tau$skin, high performance

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Transport

Characterize

Optimize P, J_{BS}, J_{NBI}
Understand: turbulence/theory comparisions

MHD

Passive limits with rotation

Active control

Optimized stability

Integration

- ***β_T - 25%, $\Delta t > \tau_E$***
β_N = 5, HH = 1

Highest performance

- ***β_T = 30%, $\Delta t >> \tau_E$***
β_N = 6.5, HH = 1.2

- ***J_{NI} > 60%, $\Delta t \sim \tau_{skin}$***
- ***Non-solenoid startup demo***

Solenoid-free

- ***J_{NI} ~ 100%, $\Delta t > \tau_{skin}$***
- ***Non-solenoid start & ramp to hi β_p***

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

HHFW/
EBW/
CHI

Heating, CD demo

Solenoid-free ops,

Optimize V-s with
highest performance

Boundary & fueling

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

Divertor power balance →

Particle influx, wall prep

Li studies →

Pellets

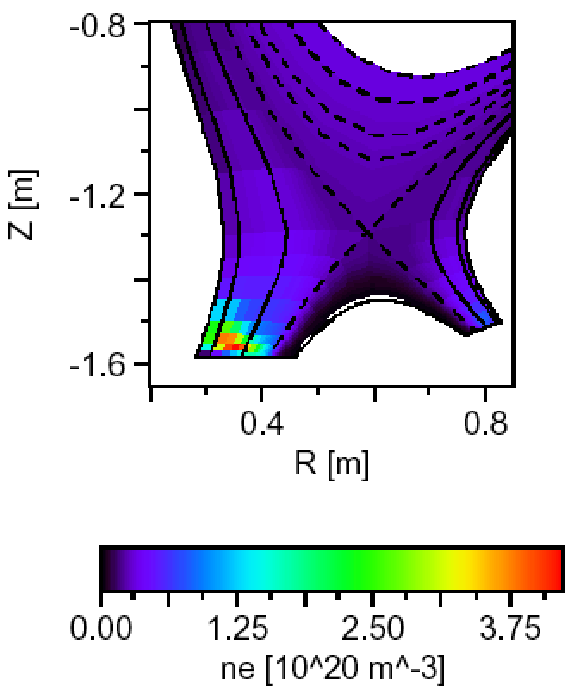
Cryopump?

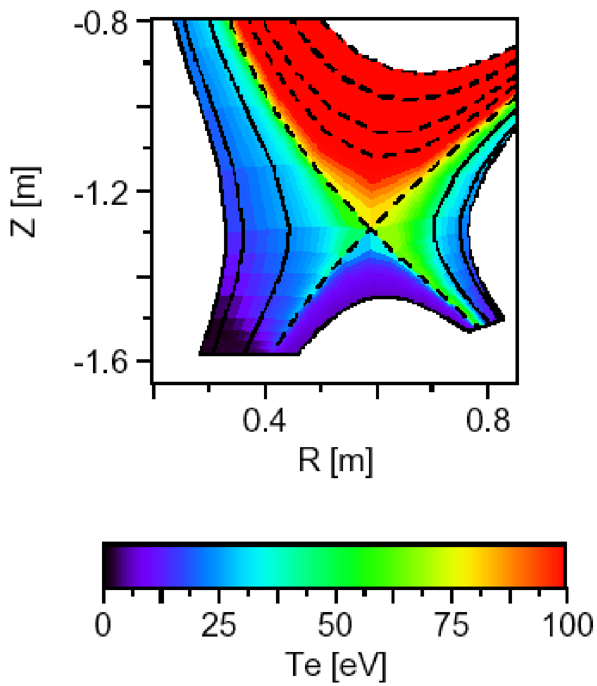
Advanced Liquid Li? →

Optimize fueling for long pulse, high J_{BS}, high J_{NBI}

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

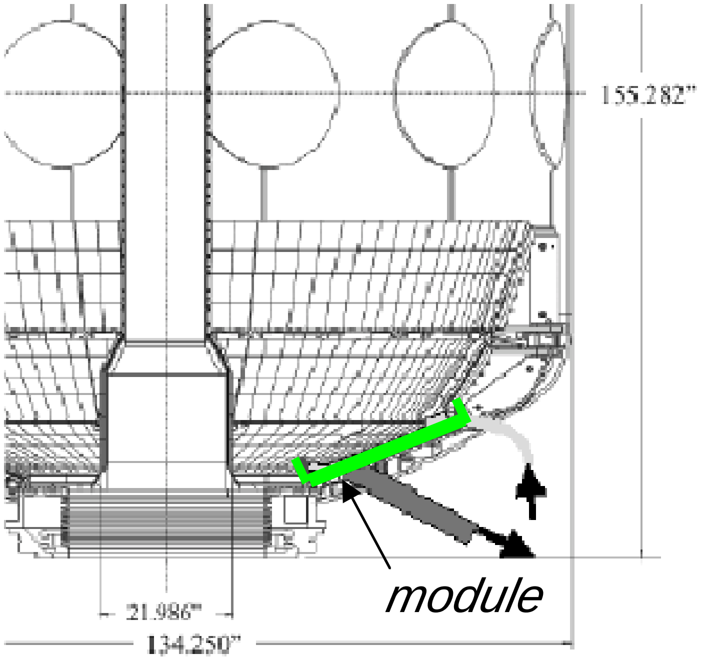

Electron density (NSb07)


Electron Temperature (NSb07)

Rensink, Porter, Wolf (LLNL; Stotler

Advanced particle and heat flux control techniques are being considered

- Liquid lithium model a possibility in the second half of the plan
- Li pellet work on NSTX part of process to determine applicability
- Assessment in conjunction with APEX, CDX-U research
- Success might have implications for entire program



ALIST liquid surface module concept

Maingi will discuss boundary physics plans

Analysis is underway to explore the requirements for our research scenarios

TSC and predictive TRANSP will be used

- Non-inductively sustained, $\tau_{pulse} >> \tau_{CR}$
  - NBCD, Bootstrap CD, HHFW CD
  - Can we drive current in the right place?
  - Need lower T_i/T_e , probably lower n_e to increase J_{BS}

Kessel will discuss

- Solenoid-free ramp-up to high β_p
- Inductive, high performance, $\tau_{pulse} >> \tau_{CR}$
  - 40% β_T; probable active MHD feedback
  - Highest $\beta_T\tau_E$, highest H factor
  - Use (1) and (2) to save V-s

Kessel, Kaye, Phillips

Integration

Highest performance

- ***β_T - 25%, $\Delta t > \tau_E$ β_N = 5, HH = 1***
- ***β_T = 30%, $\Delta t >> \tau_E$ β_N = 6.5, HH = 1.2***

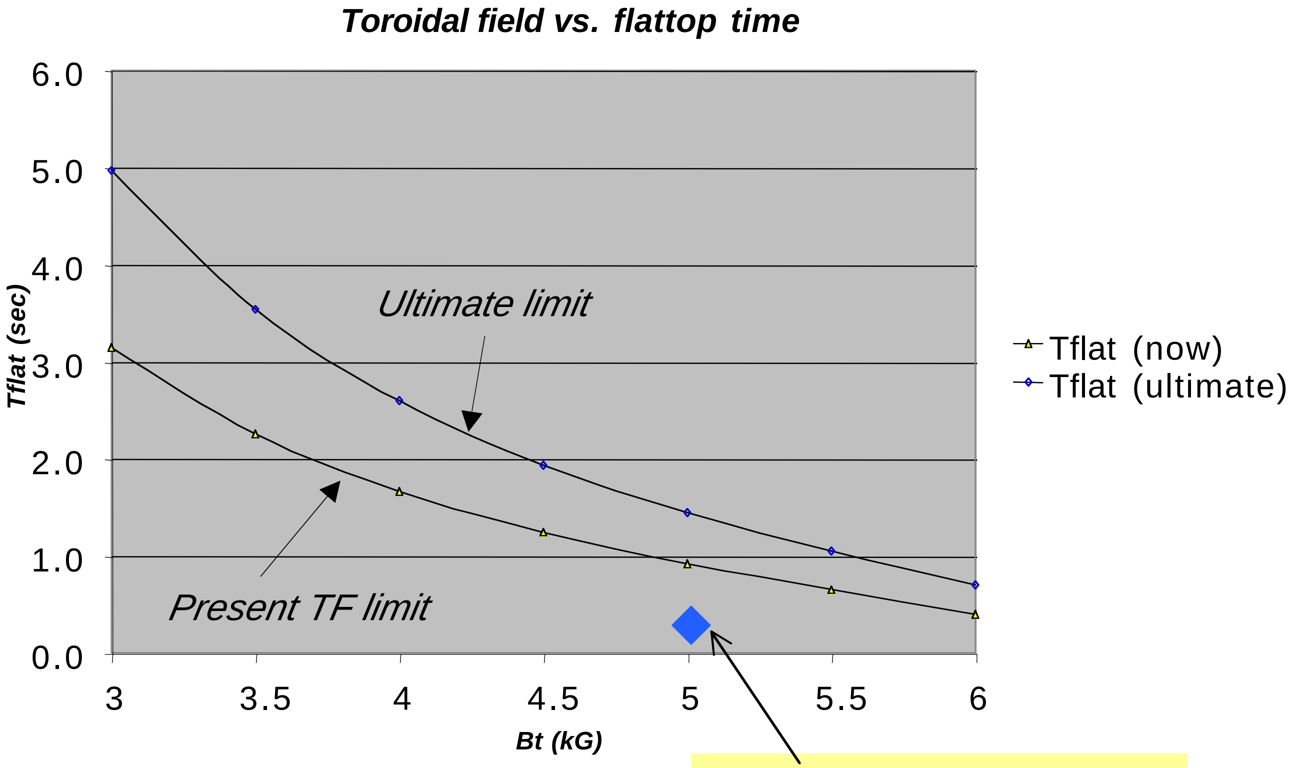
Solenoid-free

- ***J_{NI} > 60%, $\Delta t \sim \tau_{skin}$***
- ***Non-solenoid startup demo***
- ***J_{NI} ~ 100%, $\Delta t > \tau_{skin}$***
- ***Non-solenoid start & ramp to hi β_p***

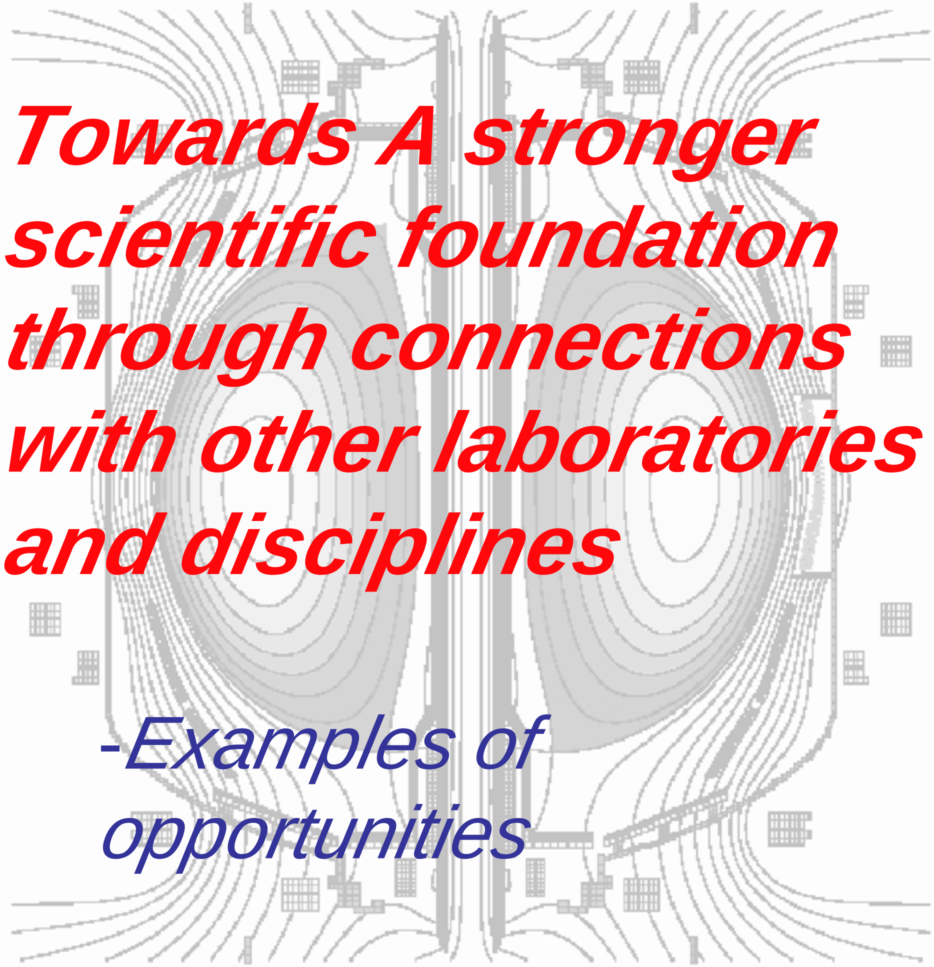
- ***40% β_T, $\Delta t >> \tau_{skin}$ β_N = 8, HH = 1.5, 70% J_{BS}***

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

- Temperature instrumentation upgrade allows increased capability



τ_{skin} = 230 ms (109070)

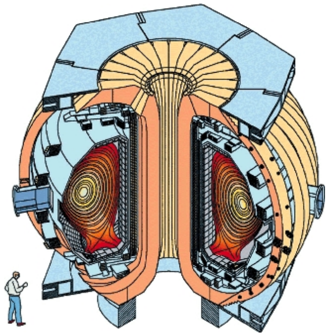


Towards A stronger scientific foundation through connections with other laboratories and disciplines

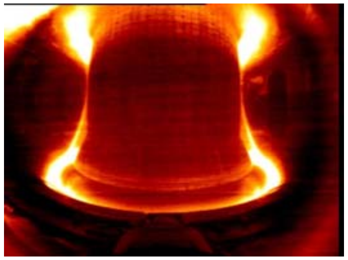
-Examples of opportunities

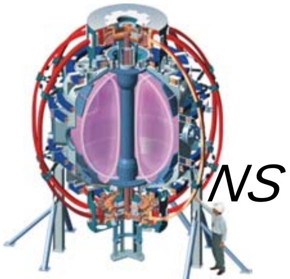
NSTX can contribute to a community-wide advance on transport & turbulence science

DIII-D



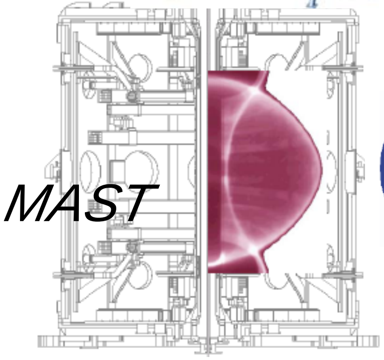
C-Mod





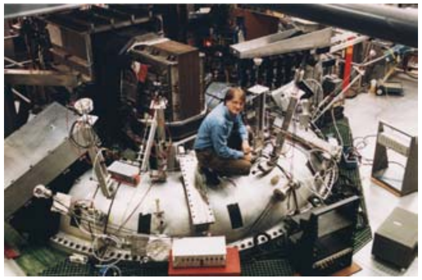
NSTX

MAST



Pegasus

MST



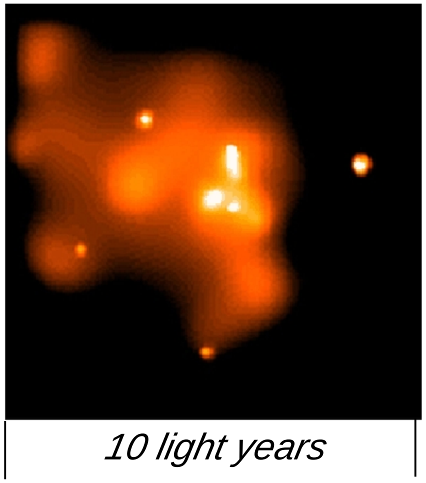
Electrostatic *E-M effects emerge* *Electromagnetic*

- Electron thermal transport: transport mystery. Burning plasma need
- TTF developing proposal for transport initiative.
- Suite of machines can develop a powerful scientific story

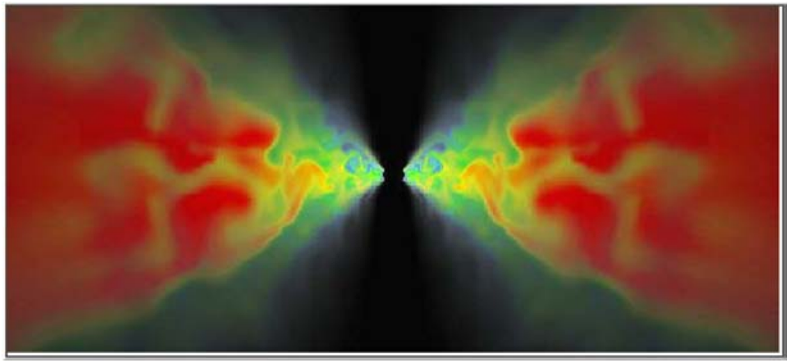
Detailed diagnosis and gyrokinetic comparisons of β ~ unity turbulence challenges us and is of keen interest to astrophysics community

- Astrophysics and turbulence dynamics: cascading of MHD turbulence to ion scales is of fundamental importance in beta unity systems
- Fusion’s gyrokinetic formalism applicable to high beta astrophysical turbulence problems
- Astrophysicists have keen interest in benchmarked codes

Subluminous black hole accretion disks



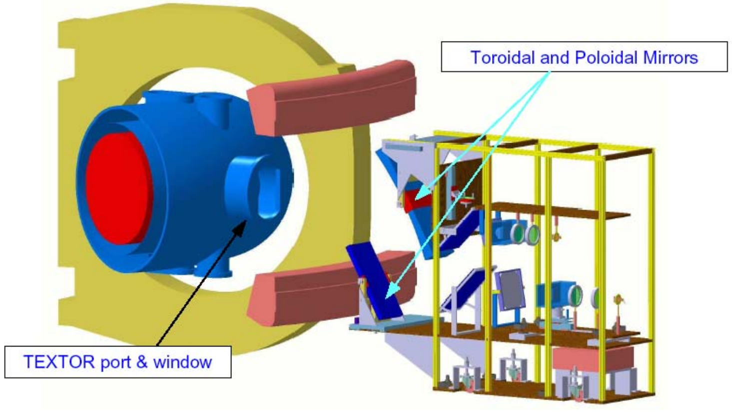
Chandra X-ray Observatory
Galactic center
10^5 times “too dim”



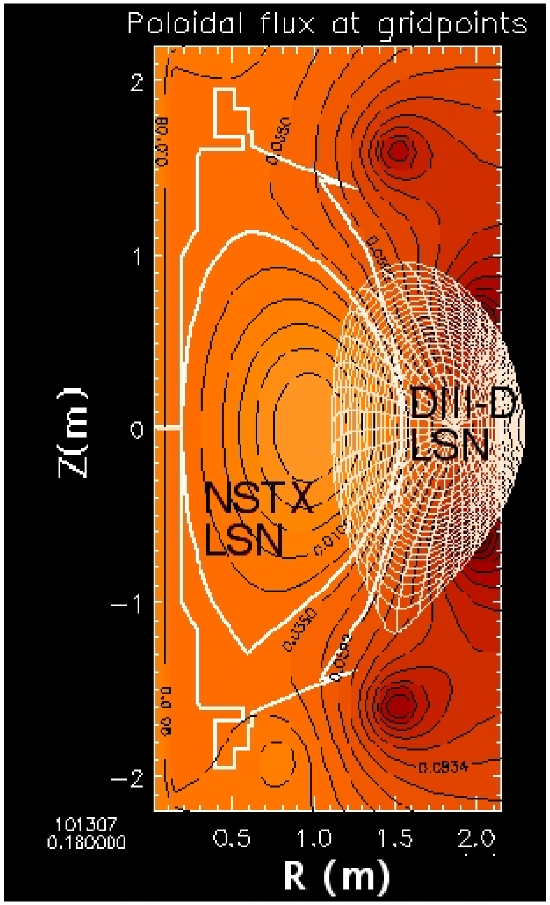
Quataert (Berkeley), Dorland (MD)

Armitage (U. Colorado)

Possible approach for low k: imaging



The NSTX program looks to help make maximal scientific advantage of intermachine comparisons

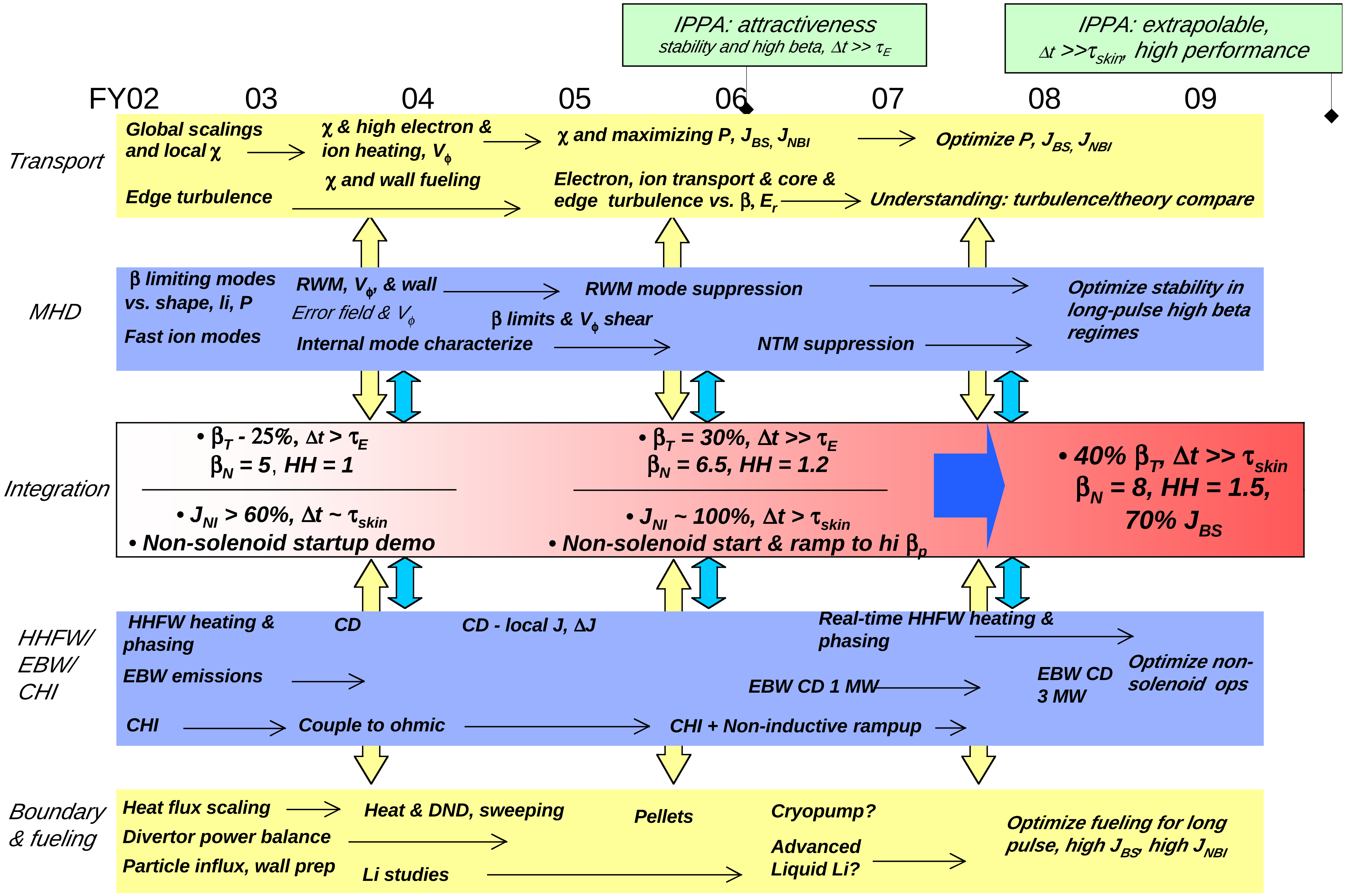


Paoletti, Sabbagh (Columbia)

- Well aligned with ITPA process
- One opportunity: beta dependence of τ_E
  - A concern for burning plasmas
  - NSTX is an ideal place to explore this
- With DIII-D: Joint experiments proposed
  - RWM
  - Fast ion MHD: CAE, TAE
  - Pedestal similarity
  - Core confinement
- MAST: wall/no-wall comparisons
  - Effects of neutrals on pedestal
  - Wall influence on ideal stability

The NSTX program is headed to meet IPPA goals as defined by the community

- The plan is constructed to meet the 5 year ST assessment by the end of '05, and major progress for the 10 year goal by ‘08
- Emphasis: expand the operating space of high beta ST plasmas and demonstrate and develop the basis for fully non-inductive operations
- NSTX research aims to couple strongly to advanced computation and other experiments, through the ITPA, to form an extrapolable physics basis
- Assessments on attractiveness (5 and 10 year) will be based on successful integration of many topical science areas



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}
- Edge turbulence → χ and wall fueling → Electron, ion transport & core & edge turbulence vs. β, E_r → Understanding: turbulence/theory compare

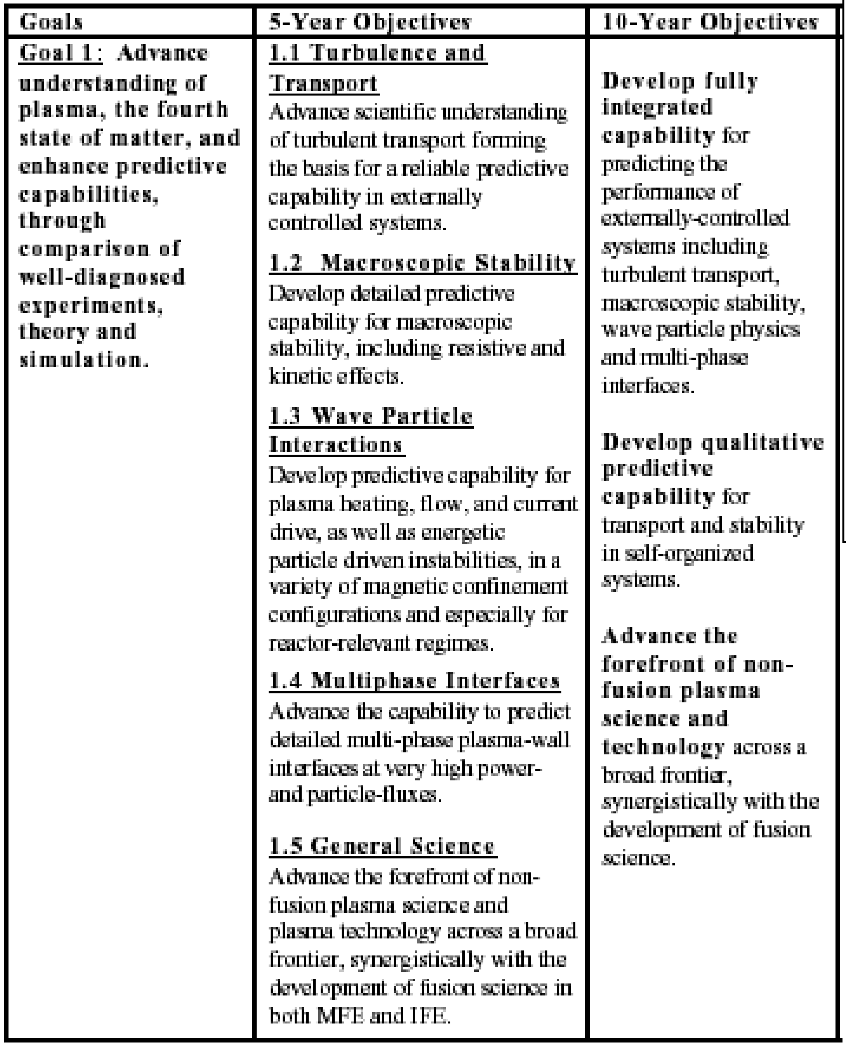
MHD
- β limiting modes vs. shape, li, P
- RWM, V_ϕ, & wall → RWM mode suppression → Optimize stability in long-pulse high beta regimes
- Error field & V_ϕ
- β limits & V_ϕ shear
- Fast ion modes
- Internal mode characterize → NTM suppression →

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}

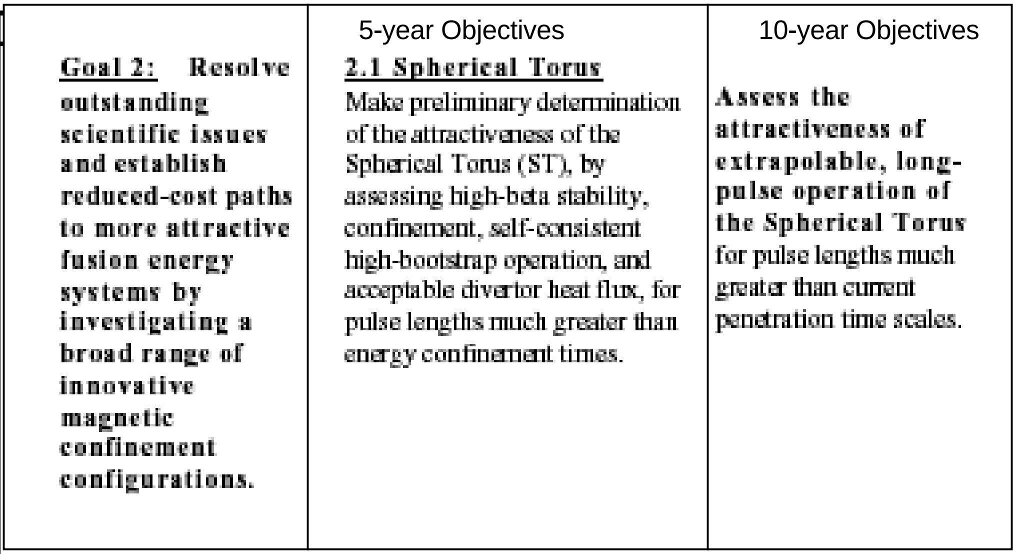
HHFW/ EBW/ CHI
- HHFW heating & phasing → CD → CD - local J, ΔJ → Real-time HHFW heating & phasing →
- EBW emissions → EBW CD 1 MW → EBW CD 3 MW
- Optimize non-solenoid ops
- CHI → Couple to ohmic → CHI + Non-inductive rampup →

Boundary & fueling
- Heat flux scaling → Heat & DND, sweeping
- Divertor power balance →
- Pellets
- Cryopump?
- Advanced Liquid Li? →
- Particle influx, wall prep → Li studies →
- Optimize fueling for long pulse, high J_{BS}, high J_{NBI}

IPPA goals and objectives



Goals	5-Year Objectives	10-Year Objectives
Goal 1: Advance understanding of plasma, the fourth state of matter, and enhance predictive capabilities, through comparison of well-diagnosed experiments, theory and simulation.	**1.1 Turbulence and Transport** Advance scientific understanding of turbulent transport forming the basis for a reliable predictive capability in externally controlled systems. **1.2 Macroscopic Stability** Develop detailed predictive capability for macroscopic stability, including resistive and kinetic effects. **1.3 Wave Particle Interactions** Develop predictive capability for plasma heating, flow, and current drive, as well as energetic particle driven instabilities, in a variety of magnetic confinement configurations and especially for reactor-relevant regimes. **1.4 Multiphase Interfaces** Advance the capability to predict detailed multi-phase plasma-wall interfaces at very high power- and particle-fluxes. **1.5 General Science** Advance the forefront of non-fusion plasma science and plasma technology across a broad frontier, synergistically with the development of fusion science in both MFE and IFE.	**Develop fully integrated capability** for predicting the performance of externally-controlled systems including turbulent transport, macroscopic stability, wave particle physics and multi-phase interfaces. **Develop qualitative predictive capability** for transport and stability in self-organized systems. **Advance the forefront of non-fusion plasma science and technology** across a broad frontier, synergistically with the development of fusion science.



	5-year Objectives	10-year Objectives
Goal 2: Resolve outstanding scientific issues and establish reduced-cost paths to more attractive fusion energy systems by investigating a broad range of innovative magnetic confinement configurations.	**2.1 Spherical Torus** Make preliminary determination of the attractiveness of the Spherical Torus (ST), by assessing high-beta stability, confinement, self-consistent high-bootstrap operation, and acceptable divertor heat flux, for pulse lengths much greater than energy confinement times.	**Assess the attractiveness of extrapolable, long-pulse operation of the Spherical Torus** for pulse lengths much greater than current penetration time scales.