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

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PPPL

For the NSTX National Team

DOE Review of
NSTX Five-Year Research Program Proposal
June 30 – July 2, 2003

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The scientific potential of NSTX fusion energy research is enormous

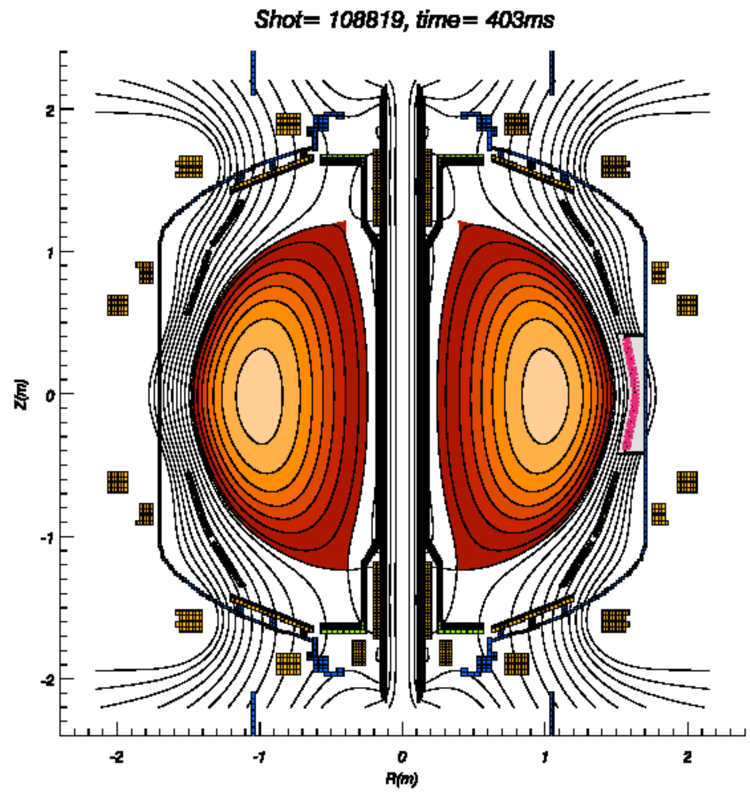
- Recent results has generated excitement about what this program can accomplish
- Science and energy missions are intimately intertwined - they are not separable
- High performance with long pulse is part of an exciting plan that is grounded in recent results, emerging theory/experiment comparisons, & plans for flexible tool development.
- NSTX is part of a larger scientific endeavor that stretches theory and strengthens understanding of fusion experiments and high beta plasmas

The NSTX Team research plan is 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

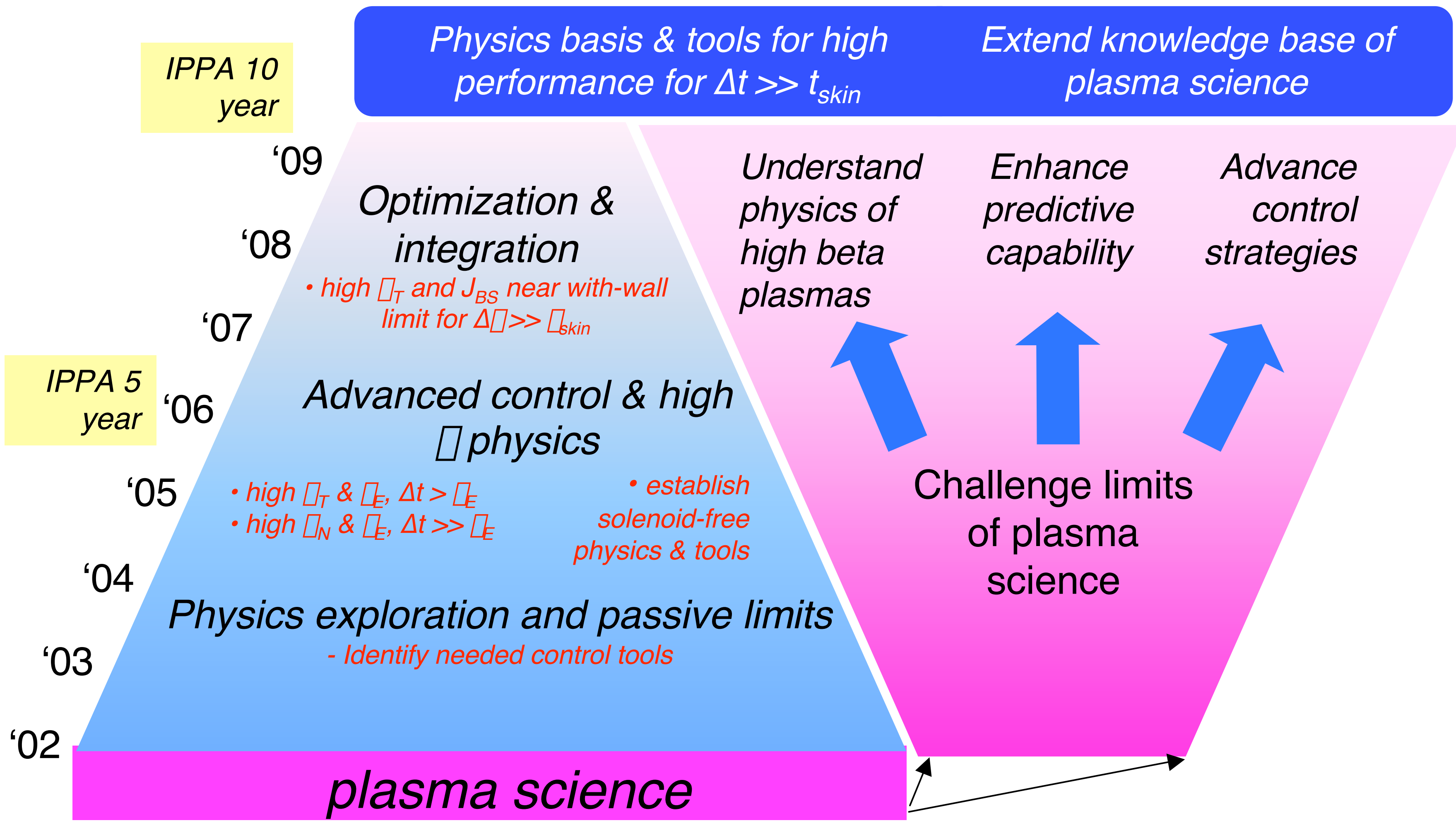
- Using ST plasma characteristics to *further a deeper understanding of critical toroidal physics issues*

- Both pursuits are guided by the IPPA implementation approach



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

NSTX is poised to assess the attractiveness of the ST as a fusion energy concept



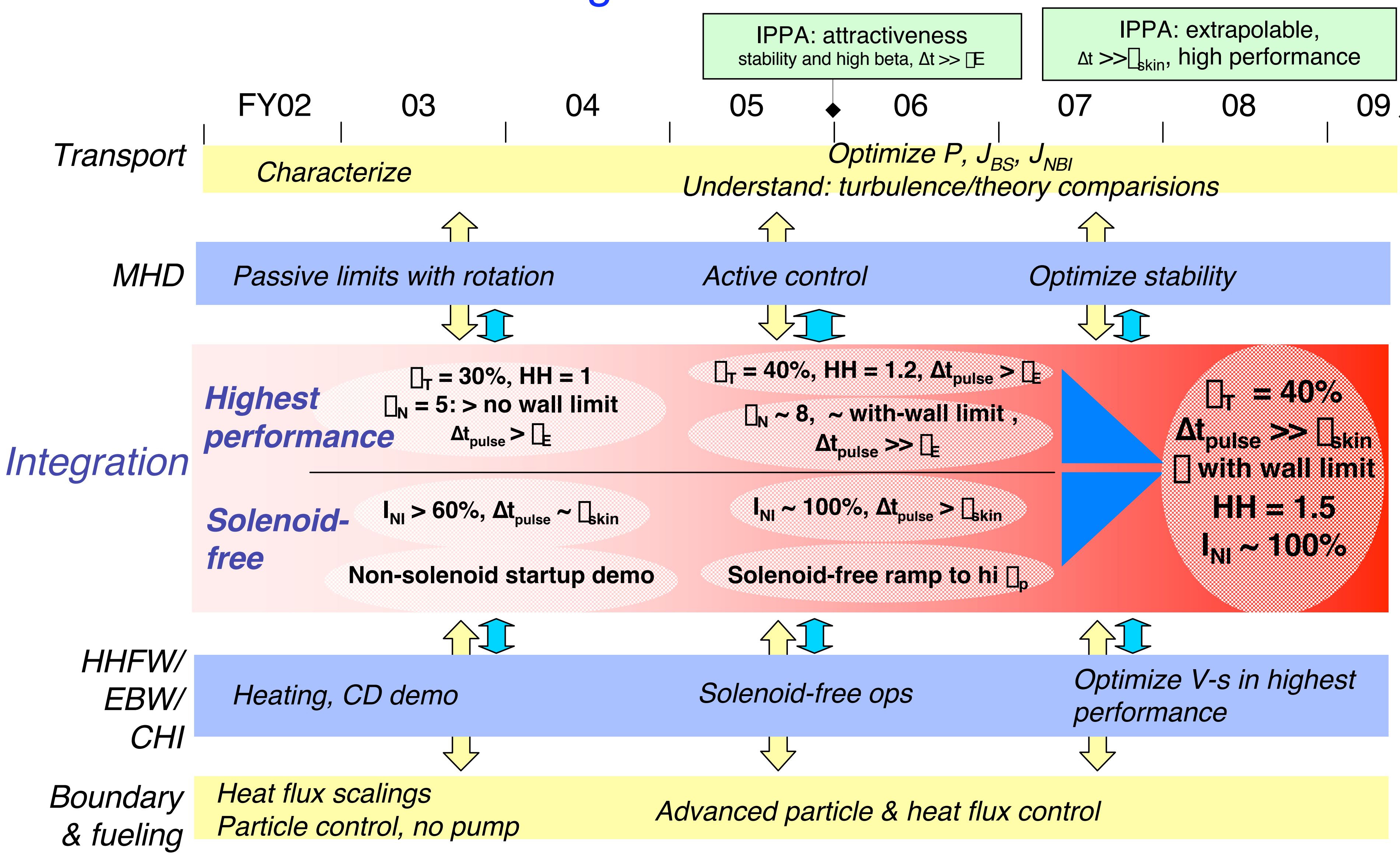
The NSTX Program can meet the FESAC objectives in a timely manner

- 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 $\tau_{pulse} \gg \tau_E$
    - Non-inductive startup & sustainment should show progress

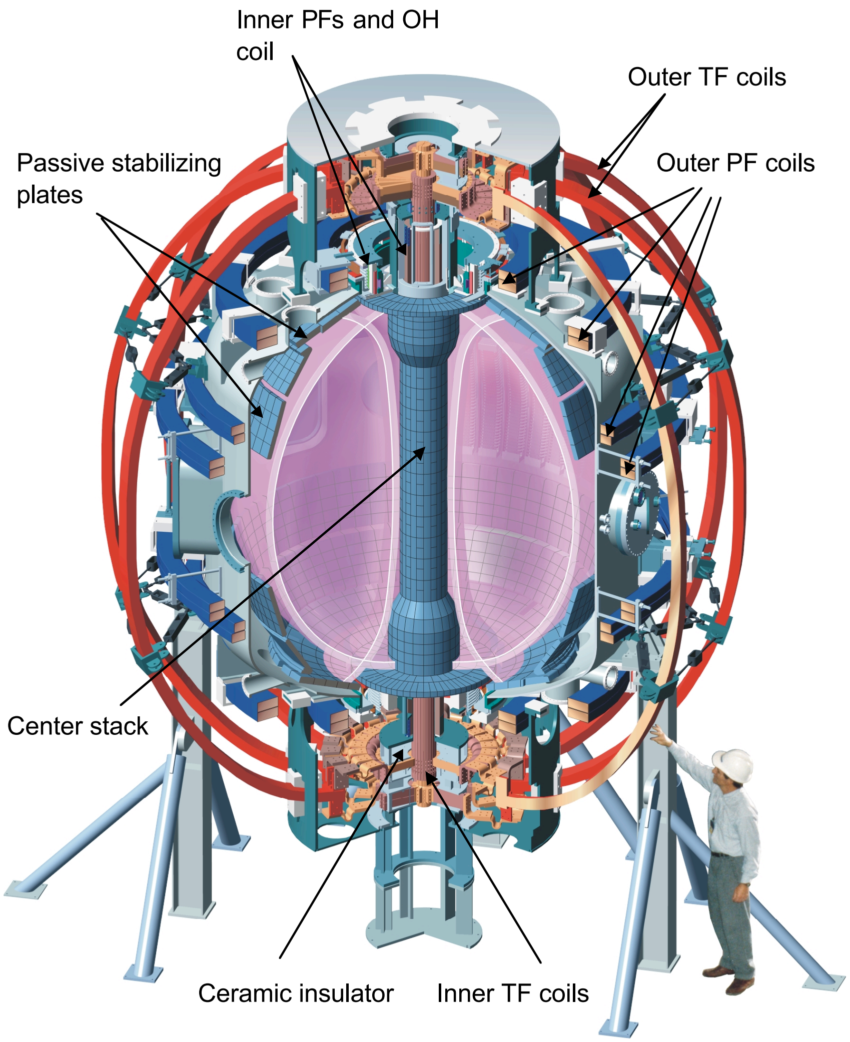
- 2009+: 10 year IPPA Goal 2:
  - Assess the attractiveness of extrapolable, long-pulse operation of the ST for $\tau_{pulse} \gg \tau_{skin}$
  - Develop fully integrated capability for predicting the performance of externally-controlled systems including turbulent transport, macroscopic stability, wave-particle physics, and multi-phase interfaces

- 2009+: 10 year IPPA Goal 1 :
  - Advance the forefront of non-fusion plasma science and technology across a broad frontier…

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



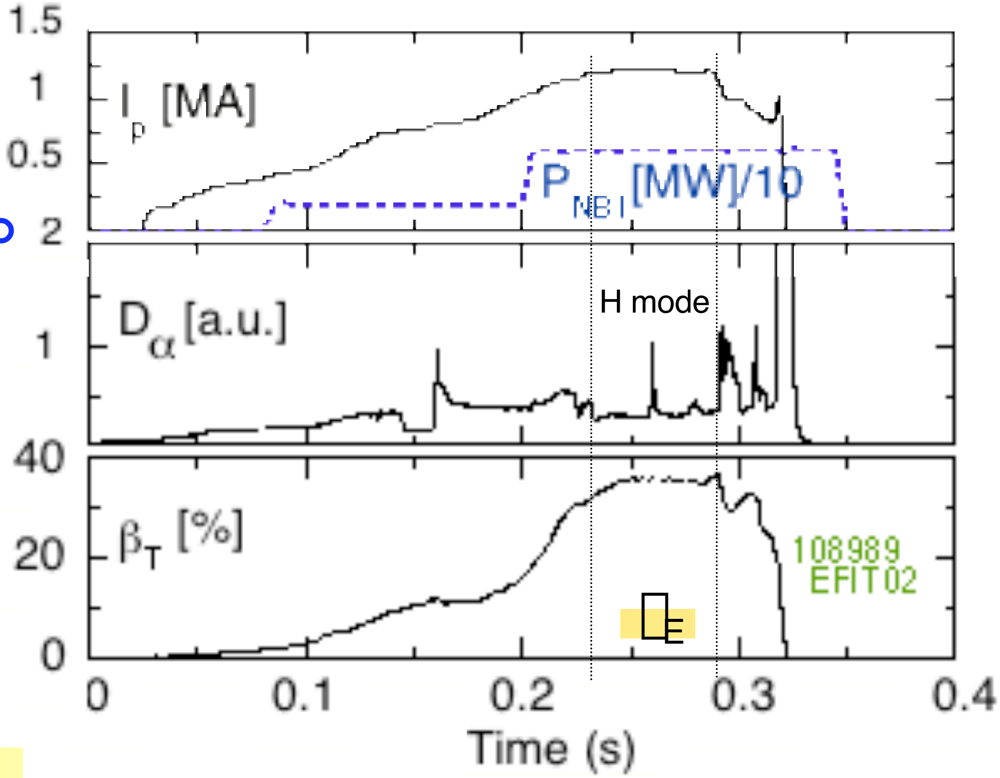
Facility capabilities have enabled the research program to advance in the last two years

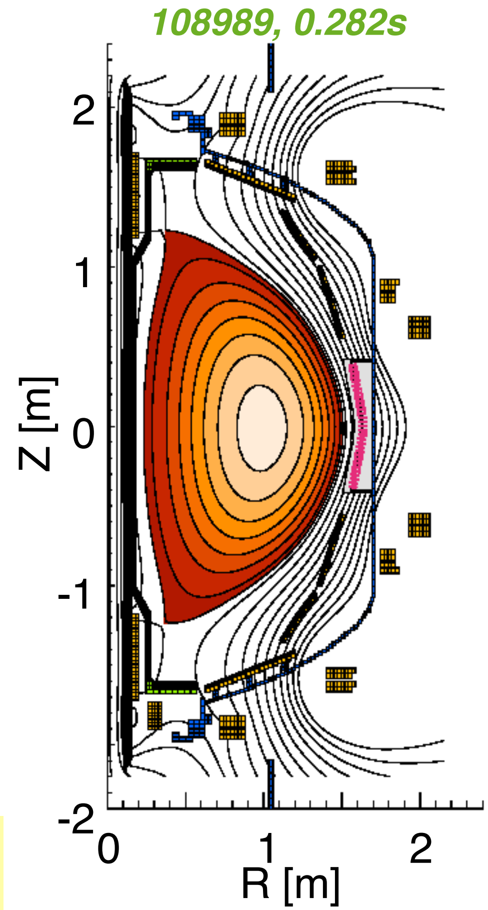


Bakeout	350°C
Gas fueling	LFS + HFS
Aspect ratio	1.27
Elongation	2.2
Triangularity	0.8
Plasma Current	1.5 MA
Toroidal Field	0.6T
Heating and Current Drive	
Induction	0.7Vs
NBI	7MW
HHFW (30MHz)	6MW
CHI	0.4MA
Pulse Length	1s achieved, 5 s with 3 kG possible

Recent results are encouraging for high beta

$\beta_T = 35\%$





$$\beta_T \equiv \frac{\langle p \rangle}{B_{T0}^2/2\mu_0}$$

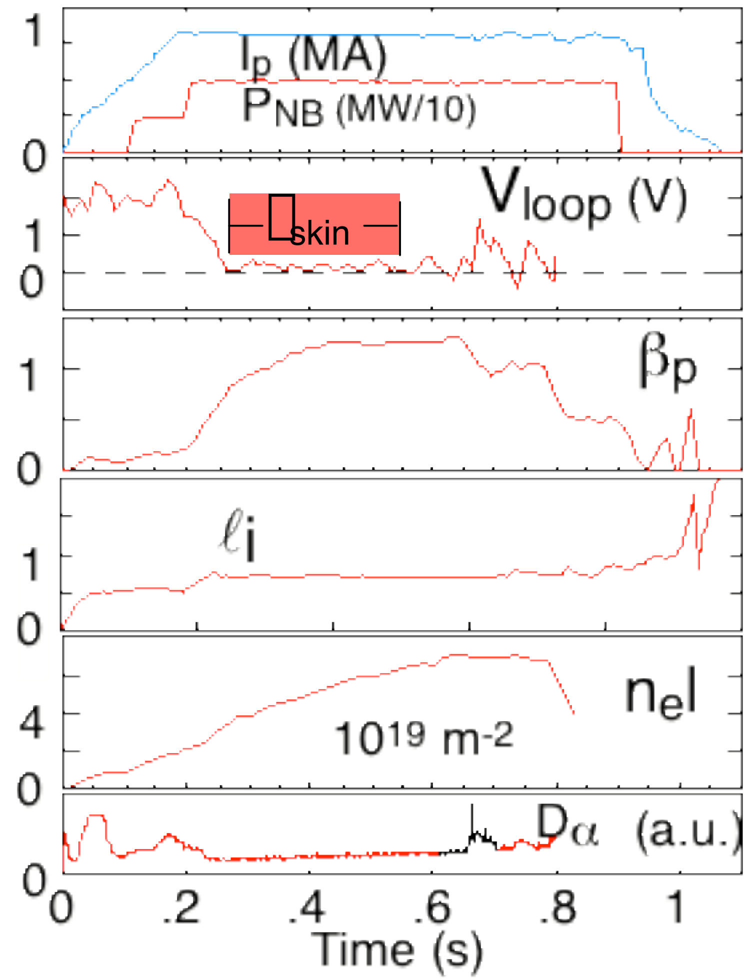
- H-mode: routine access
  - broadens pressure profile
- Enabled by maturing shape & position control system
- $\beta_N = 5.5$, $l_i = 0.6$

$B_T = 0.3T$, $A = 1.4$
$\kappa = 2.0$, $\delta = 0.8$
$q(0) = 1.4$ (EFIT)

Recent results are encouraging for long pulse

- J_{NI} = 60%
- β_N = 5.8 > no-wall stability limit
- Many parameters that are relevant to a CTF

	NSTX Long pulse	CTF base case	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



These two plasmas highlight many areas where tools and flexibility will be critical

- In long pulse, 40 - 50% of current still from solenoid

 need to develop current drive tools

- Late MHD degrades performance

 current drive and pressure profile control required

- Density increases throughout the pulse

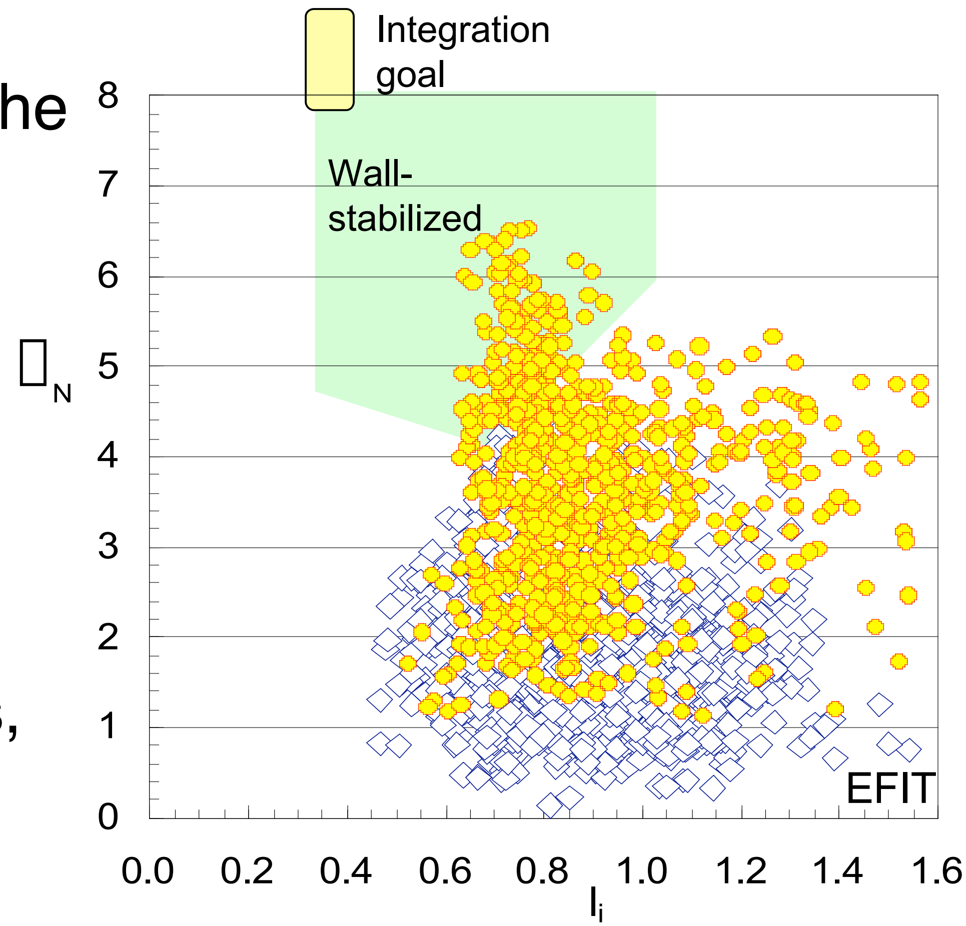
 particle control needed

- Ramp-up is from solenoid

 broad solenoid-free startup strategy needed

A long-range goal is operation near the with-wall limit at low internal inductance

- Routine operation above the no-wall limit observed
  - Broad H mode, rotation & passive stabilization key elements
- Progress in 2002 enabled by routine H mode access, error field reduction, and wall preparations



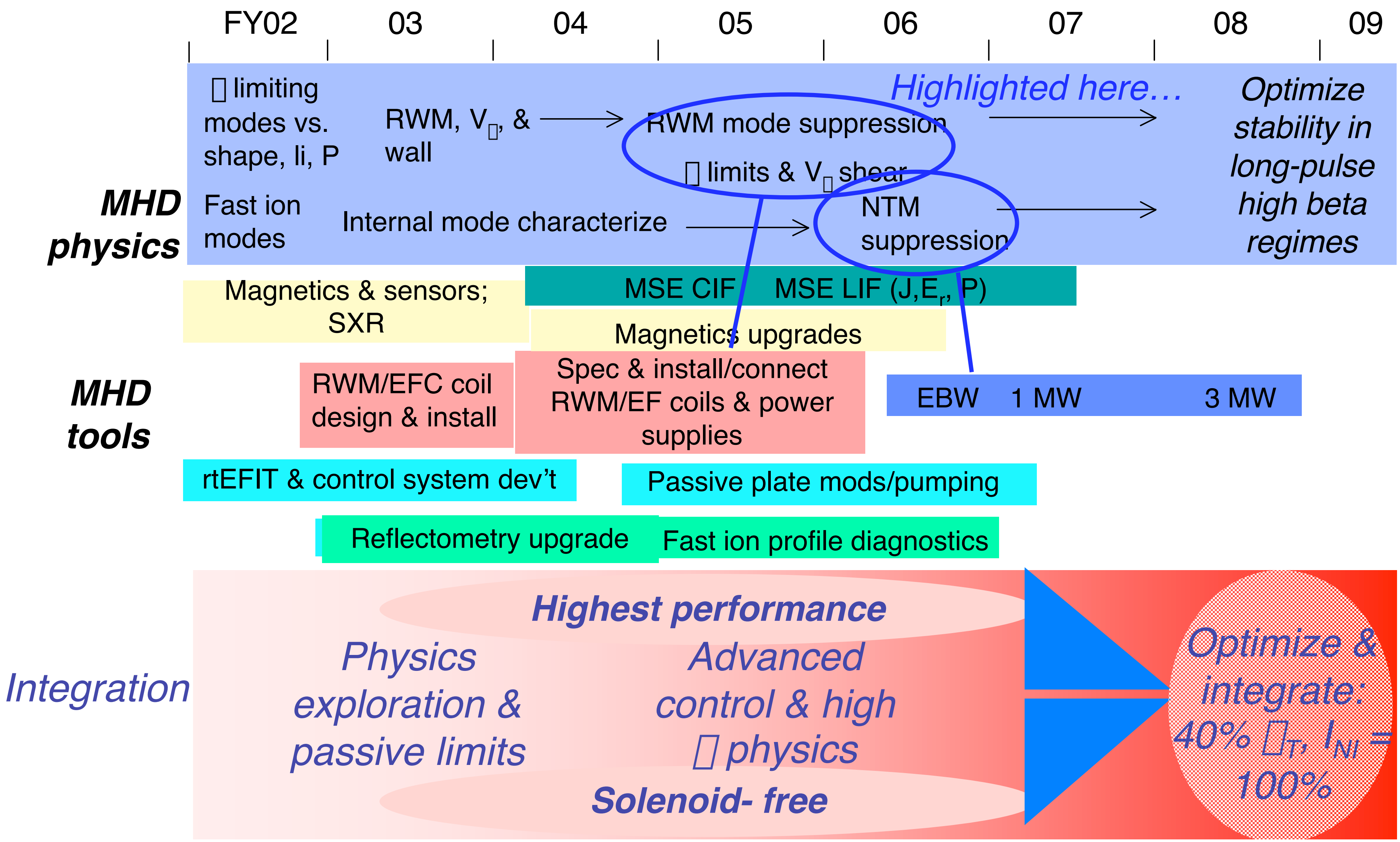
Control tools are central elements to developing robust path to high performance, long pulse targets

NSTX plasmas enter new physics regimes and enable development of new solutions

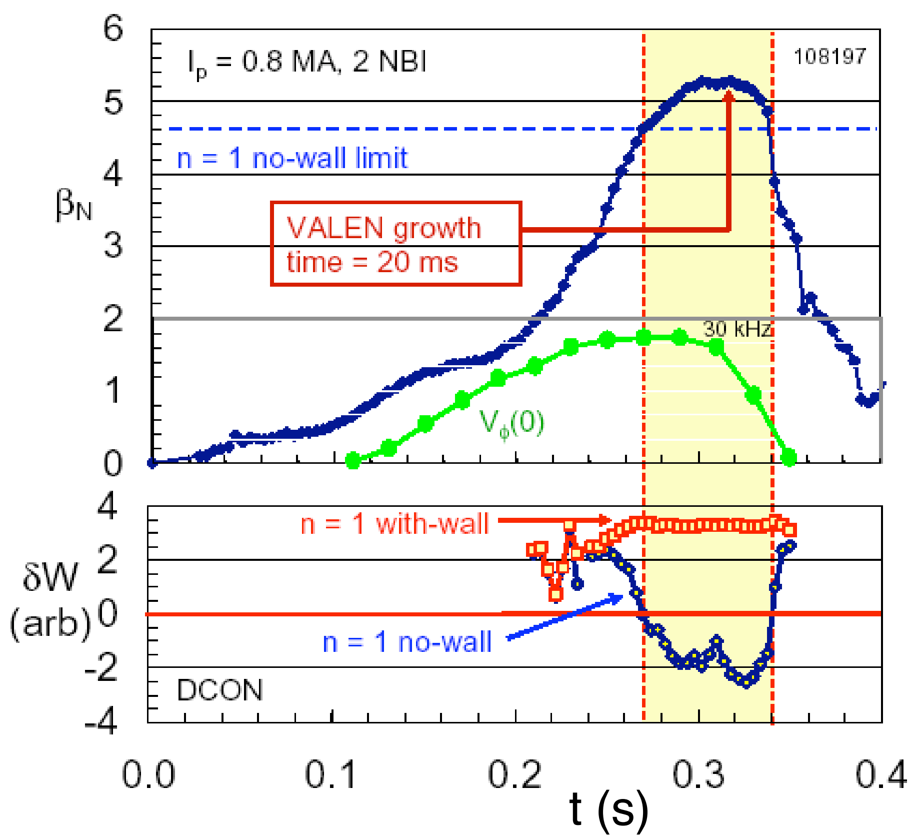
- MHD
- Transport & turbulence
- Wave-particle & startup
- Boundary physics
- Integration of the science

- *Distinguish V_A, C_s effects for rotation damping*
- $V_{\square}/V_A \sim 1 \Rightarrow V_{\square}' \sim \square^{n}_{MHD}$

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



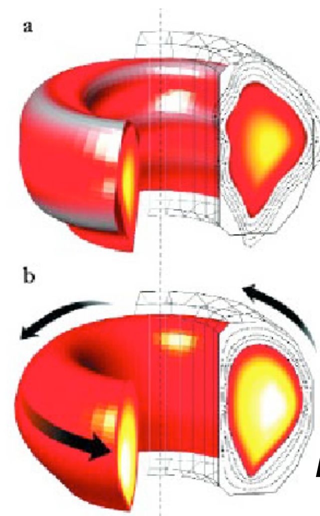
Interplay between stability, wall, error fields, and rotation is a key element of the program



- 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 other plasmas

- V_ϕ/C_s comparable to tokamaks, but V_ϕ/V_A an order of magnitude larger on NSTX

Plan includes using these differences between NSTX & DIII-D to assess physics of rotation damping

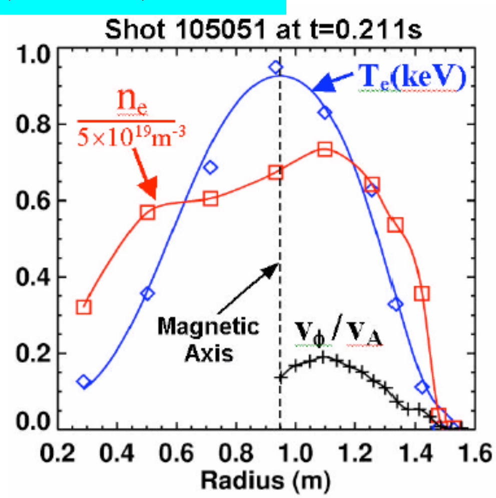


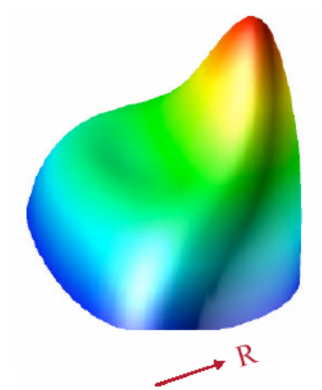
DIII-D

IPPA Goal 3.1.2: Develop detailed predictive capability for macroscopic stability, including resistive and kinetic effects

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

R. Bell, LeBlanc, Menard

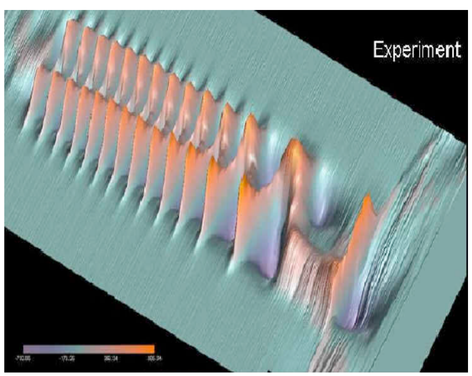




- Experiment: Density shows in-out asymmetry
- Effect of high Mach number of driven flow

Plan includes treating the physics of MHD & rotation self-consistently & comparing to mode dynamics

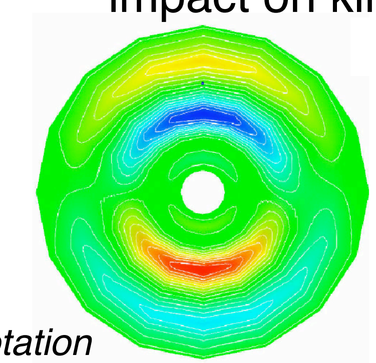
- Experiment: kinks saturate



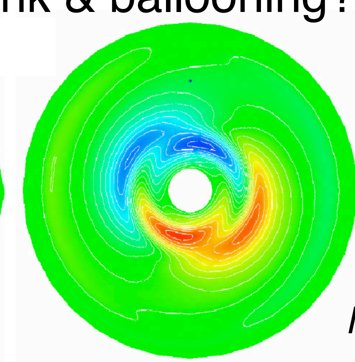
Stutman (JHU)

M3D: Park

- Theory: $V_\phi' \sim \gamma^{in}_{MHD}$ => growth affected by high flow shear: impact on kink & ballooning?



No rotation

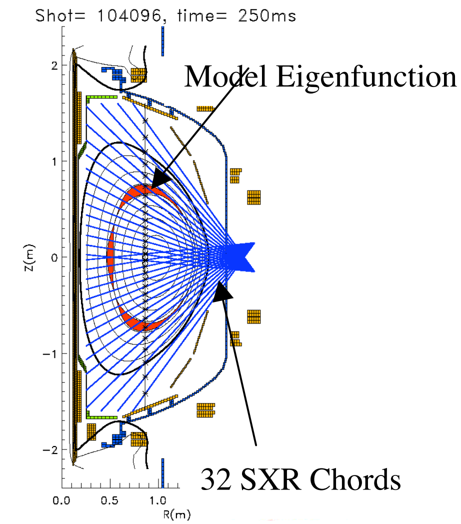


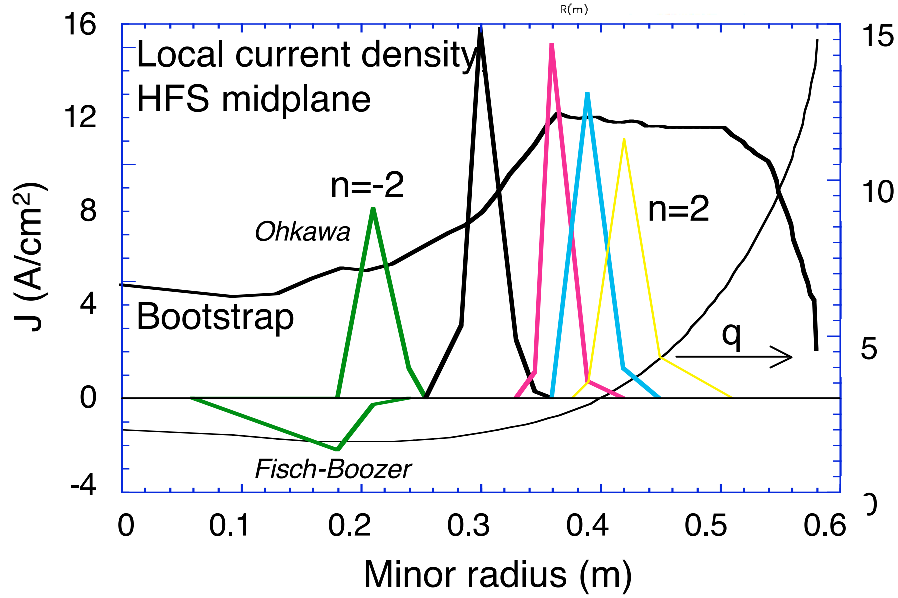
$M_A = 0.2$

Menard & Sabbagh will discuss MHD plans

Electron Bernstein Waves hold promise for NTM control

- NTMs can degrade NSTX performance with $q_{min} < 2$
- 1 MW EBW can deliver current densities comparable to bootstrap, as required for NTM suppression
- Build on ASDEX-U, DIII-D successes with ECCD
- Collaborative EBW research with MAST





Harvey, CompX

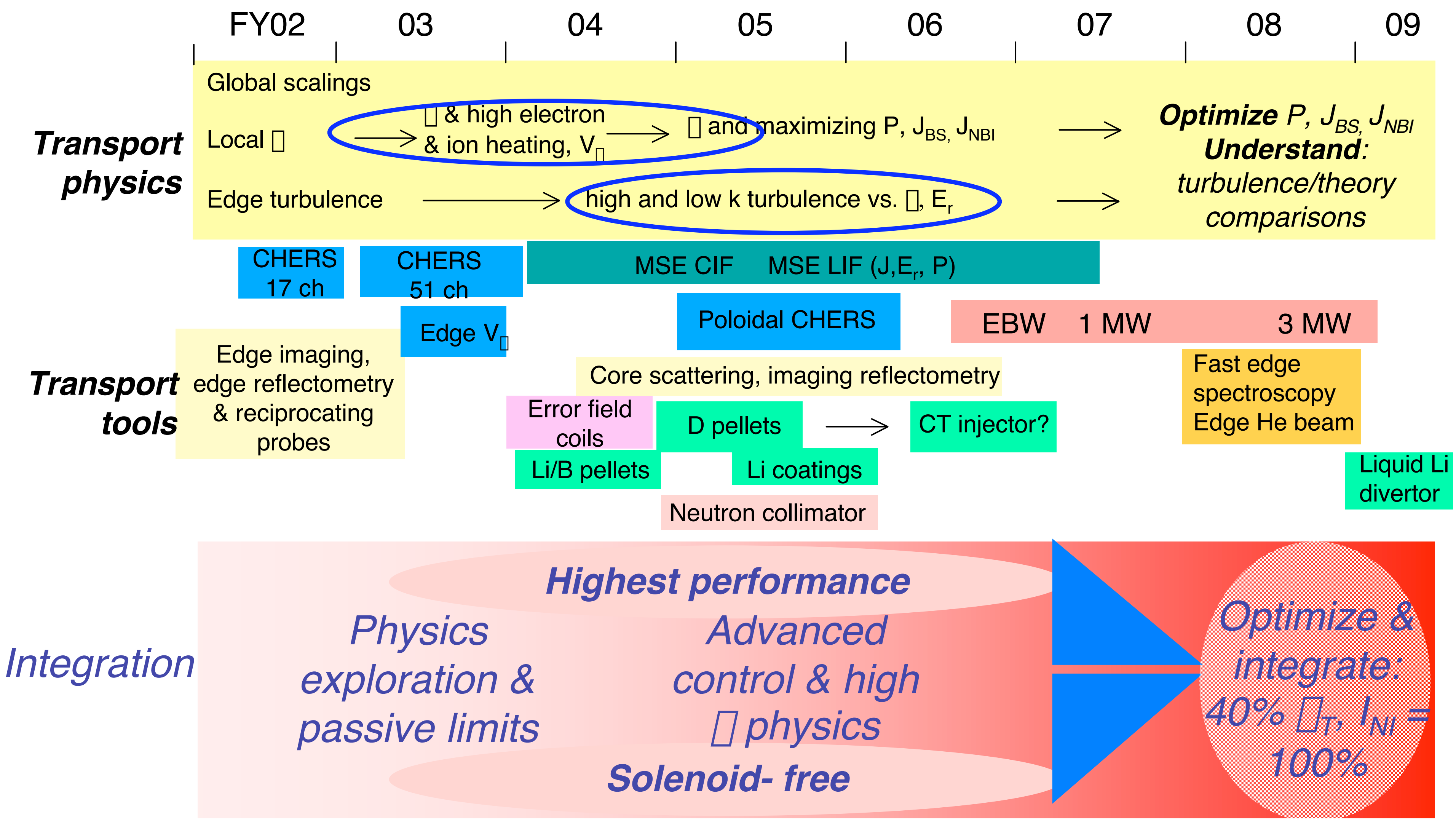
28% β_T
100% I_{NI}
scenario

1 MW EBW in plasma

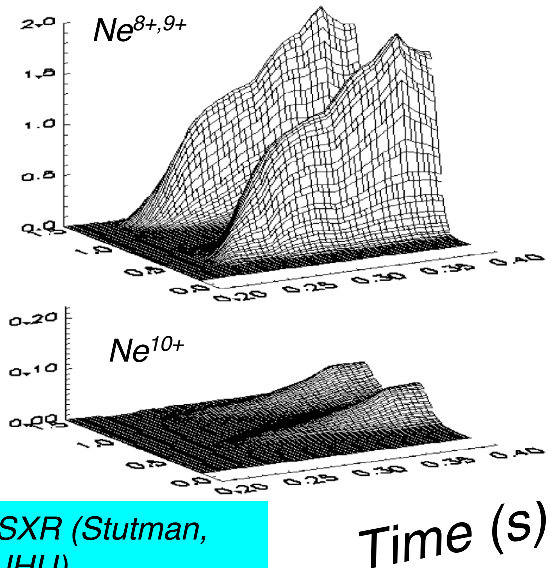
NSTX plasmas enter new physics regimes and enable development of new solutions

- MHD
  - $V_\phi/V_A \sim 1 \Rightarrow V_\phi' \sim \gamma^n{}_{MHD}$
  - *Distinguish V_A, C_s effects for rotation damping*
- Transport & turbulence
  - *Low k with NBI: intrinsically stable?*
  - *Low and high k may be controllable with NBI & HHFW.*
- Wave-particle & startup
- Boundary physics
- Integration of the science

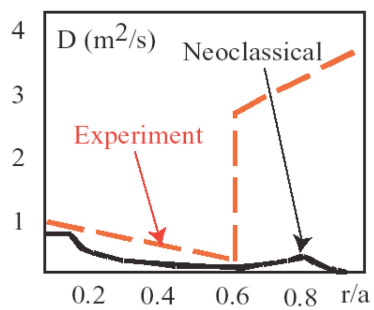
Transport studies will emphasize P(r) optimization and transport & turbulence understanding

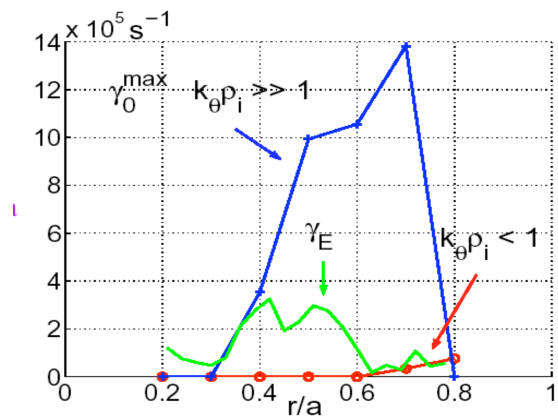


Theory & experiment suggest long wavelength turbulence may be suppressed with NBI…



SXR (Stutman, JHU)





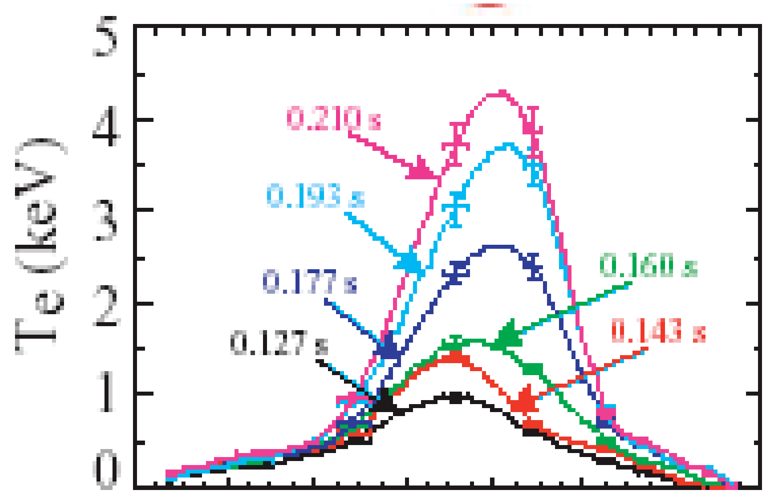
Bourdelle (Cadarache)

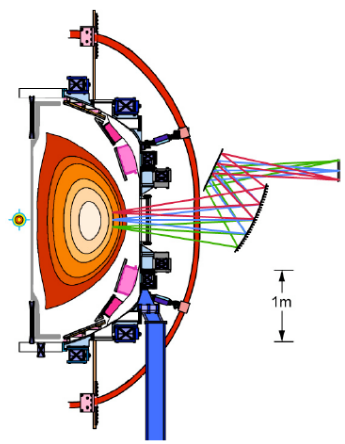
- Experiment: Impurity puffing reveals naturally occurring core barrier with an L mode edge
  - No bifurcation
- Theory, pre-NSTX: suggested low k suppression was likely (Rewoldt, Kotschenreuther)
- Theory with measured profiles: Long wavelength modes stable, or strong ExB shear should suppress them

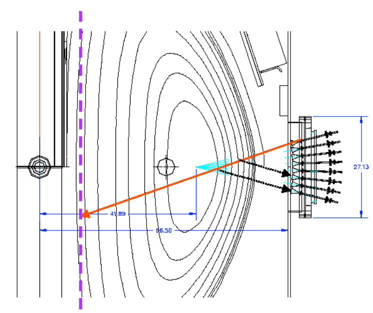
IPPA Goal 3.1.1: Advance transport physics based on understanding of turbulence & turbulence dynamics

… but relation between high & low k turbulence is predicted to be modified with addition of HHFW heating

- High T_e/T_i predicted to *stabilize* ETG on NSTX
- Electron barriers seen with HHFW, with $\chi_i > \chi_i^{neo}$
- May be possible to generate regimes with only high k or low k
- Plan: detailed high and low k turbulence measurements (scattering, reflectometry)







Kaye will discuss transport & turbulence plans

Imaging reflectometry: Mazzucato, Munsat, Park

Backscattering: Peebles, Kubota (UCLA)

NSTX plasmas enter new physics regimes and enable development of new solutions

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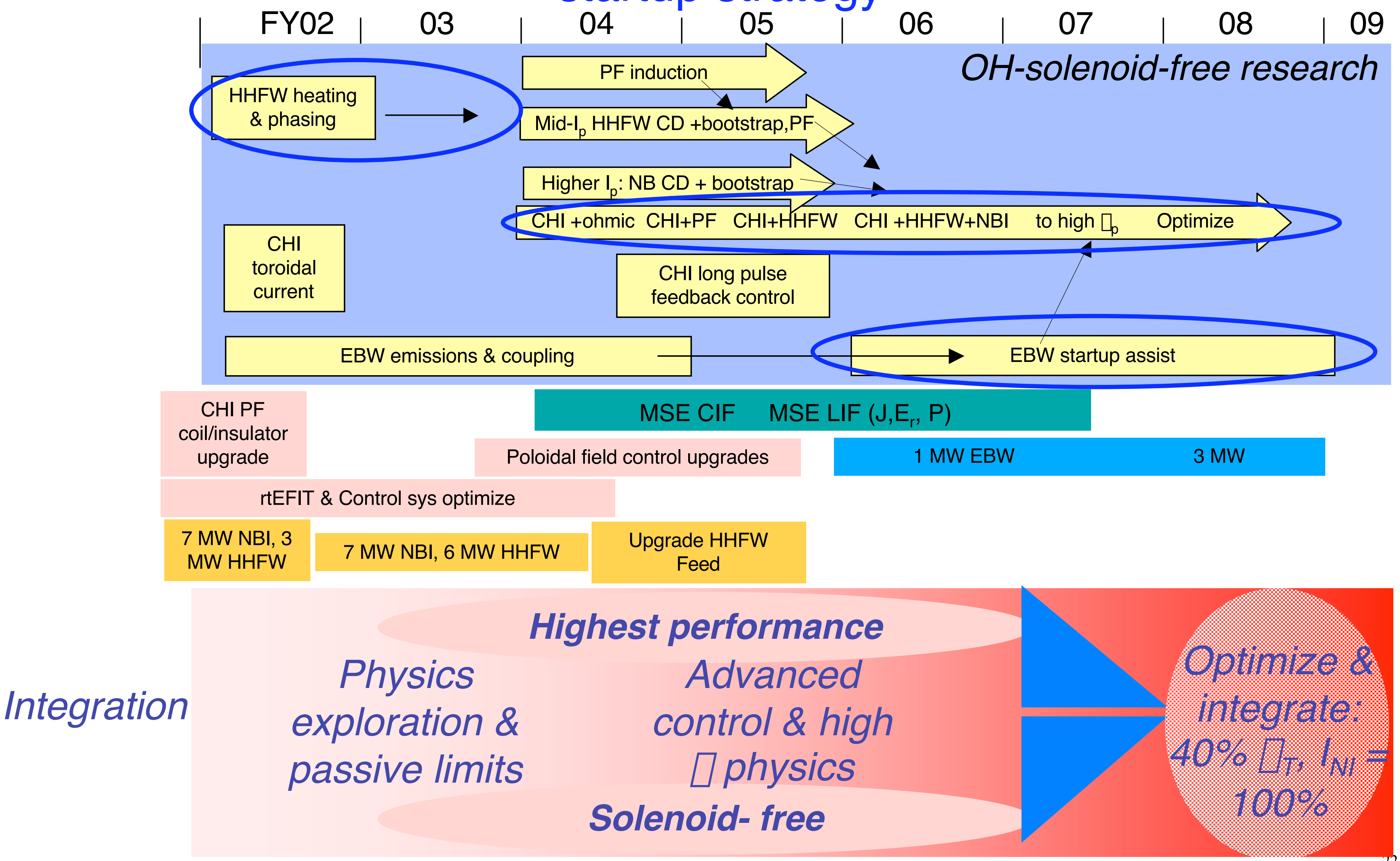
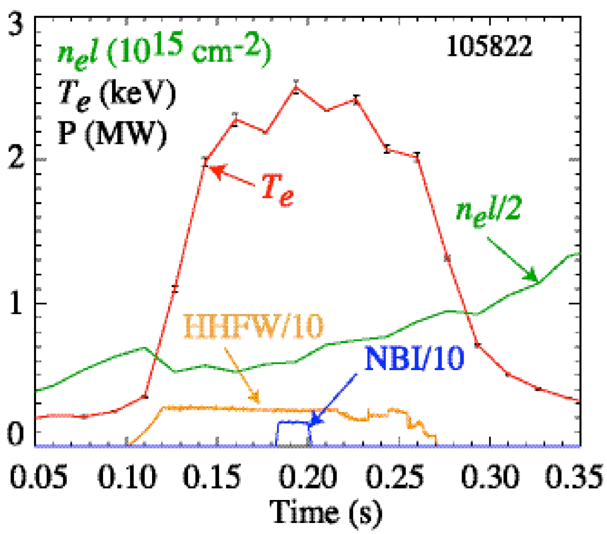
- Wave-particle & startup
  - *HHFW, EBW: new physics & tools for overdense plasmas*
  - *OH-solenoid-free plasma startup research addressing urgent issue for AT & ST.*
- Boundary physics
- Integration of the science

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



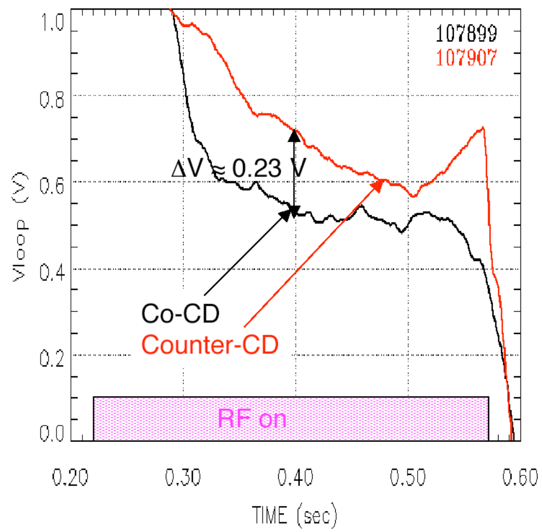
Important aspects of high harmonic fast wave explored

Electron heating demonstrated



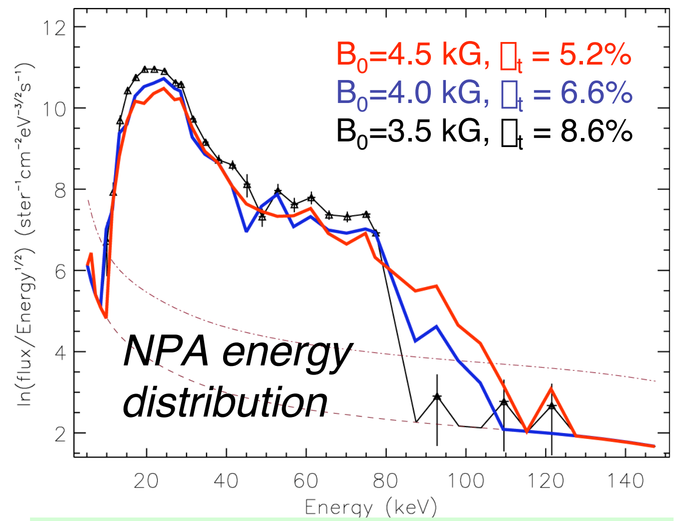
- Primary HHFW damping mechanism
- Observed over wide range in wave phase velocity

V_{loop} effects seen with current drive phasing



- Differences in V_{loop} with co and counter-directed waves consistent with theoretical modeling

Wave/Ion interactions observed

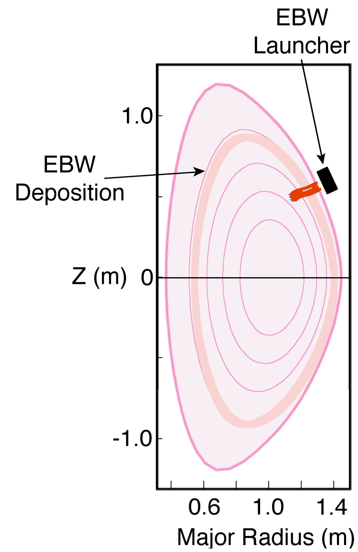


- Experiment: tail from HHFW reduced with higher beta
- Theory: much HHFW power may be damped on fast & hot ions

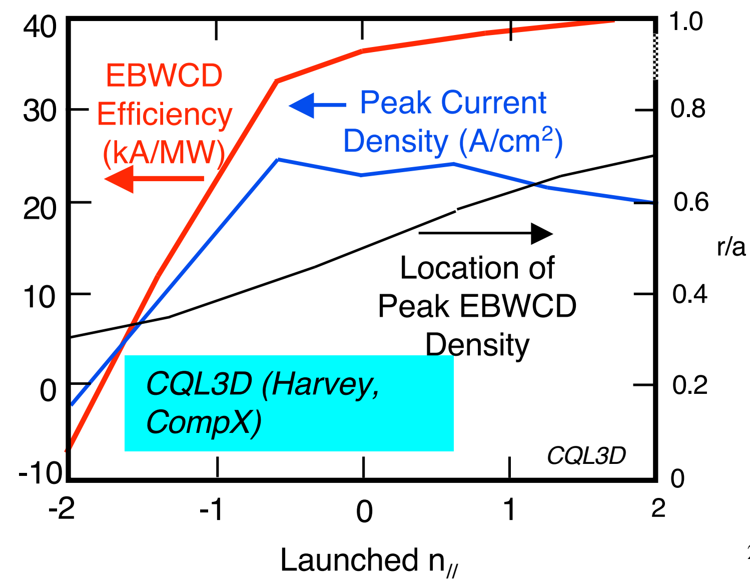
IPPA Goal 3.1.3: Develop predictive capability for plasma heating, flow, and current drive…

Developing the science of Electron Bernstein Wave heating and CD is a key element of the plan

- Ideally suited for the ST
  - *Takes advantage of* high particle trapping (Bers (MIT): Ohkawa CD)
  - Efficiency *increases* with minor radius, where it is needed most
- Off-axis CD required in advanced scenarios: elevate q & stabilize NTMs.
- Applicable to other overdense plasmas (spheromak, RFP)
- Successful coupling essential
  - CDX-U & NSTX EBW emission studies are consistent with theory.



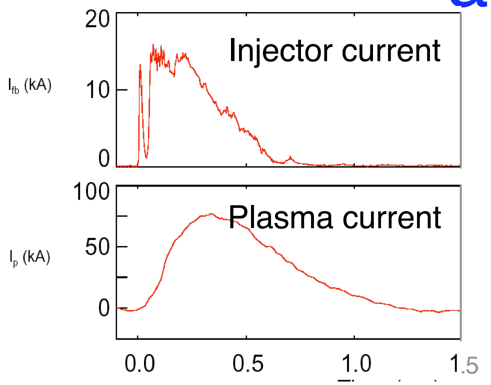
Taylor will discuss HHFW & EBW plans



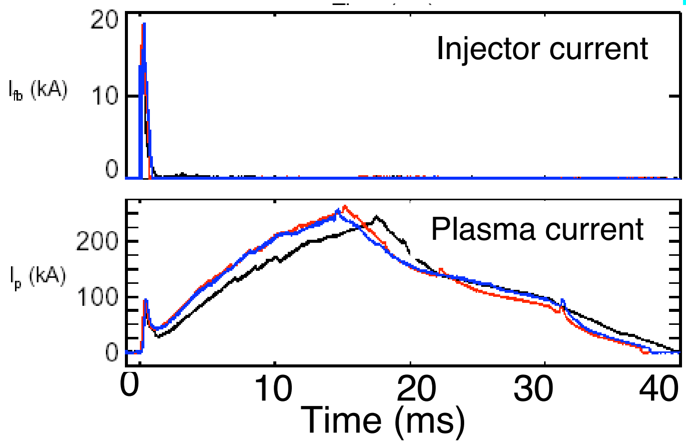
Two recent results have (re)shaped our thinking about solenoid-free startup

HIT-II

CHI only



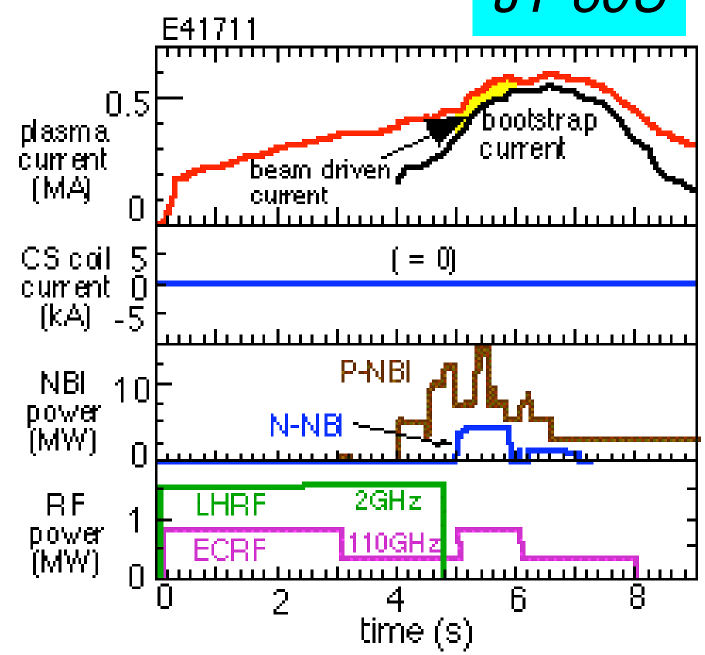
CHI + Induction



- CHI transient coupled successfully to inductive drive (Raman, U. Wash.)

- Best HIT-II plasmas generated with CHI start (highest I_p, lowest V_{loop})

JT-60U



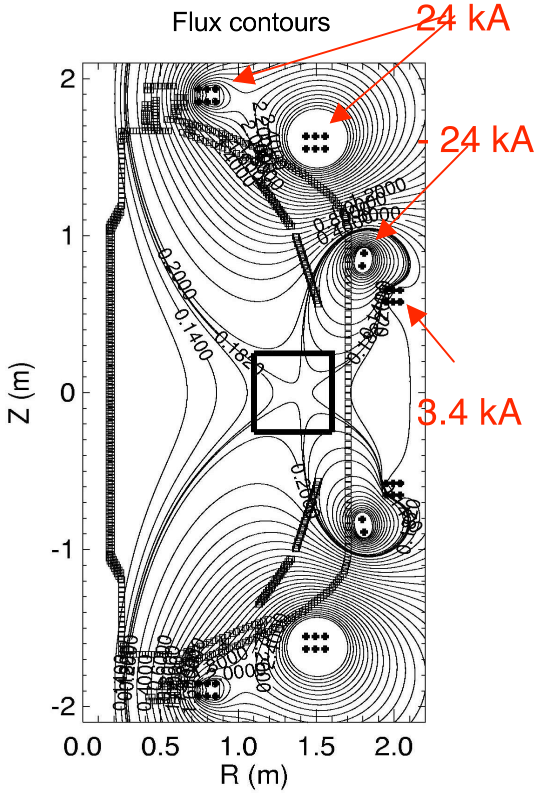
- Significant bootstrap fraction

- Resultant plasma was high performance (HH = 1.6)

- Small inboard triangularity coil contributed flux in initial period

Plan approaches solenoid-free startup research with different tasks

- Startup: 0 - 150 kA
  - CHI the primary tool at present
  - EBW may contribute as well
  - PF induction: experiments planned, new scenarios being assessed
- Initial rampup: 150 - 500 kA
  - HHFW, EBW, bootstrap
  - Can study with an ohmic start
- Final ramp to flattop
  - 500 - 800+ kA: NBI CD, bootstrap current overdrive are candidates



Each step is separable and then can be combined.

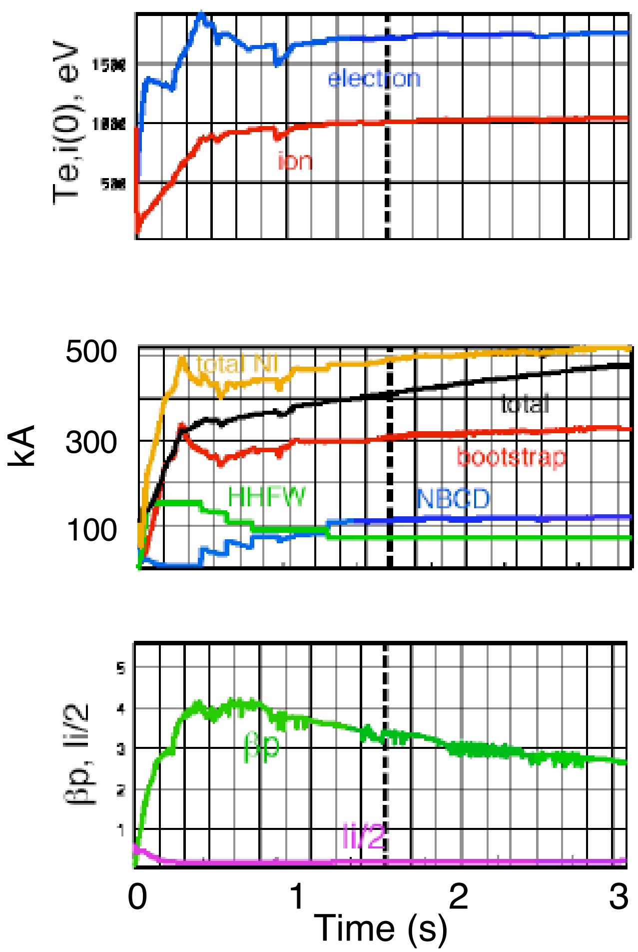
Raman will discuss startup plans

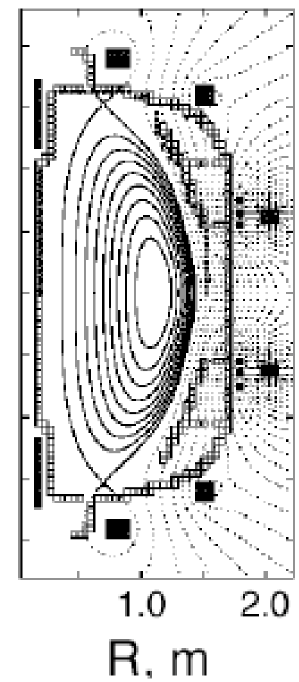
HHFW can be used following CHI or PF induction to raise the current to several hundred kA

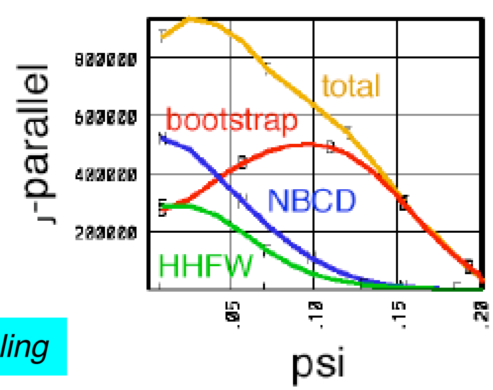
- Plan includes
  couping of CHI or PF start to HHFW/HHFW+EBW ramp

- Modeling indicates current drive and bootstrap from HHFW can ramp to 400 kA within the allowable pulse at high field

- Not fully optimized
  - No EBW assumed







Kessel will talk about Integrated Modeling

NSTX plasmas enter new physics regimes and enable development of new solutions

- MHD
  - $V_{\square}/V_A \sim 1 \Rightarrow V_{\square}' \sim \square^{n}_{MHD}$
  - *Distinguish V_A, C_s effects for rotation damping*
- Transport & turbulence
  - *Low k with NBI: intrinsically stable?*
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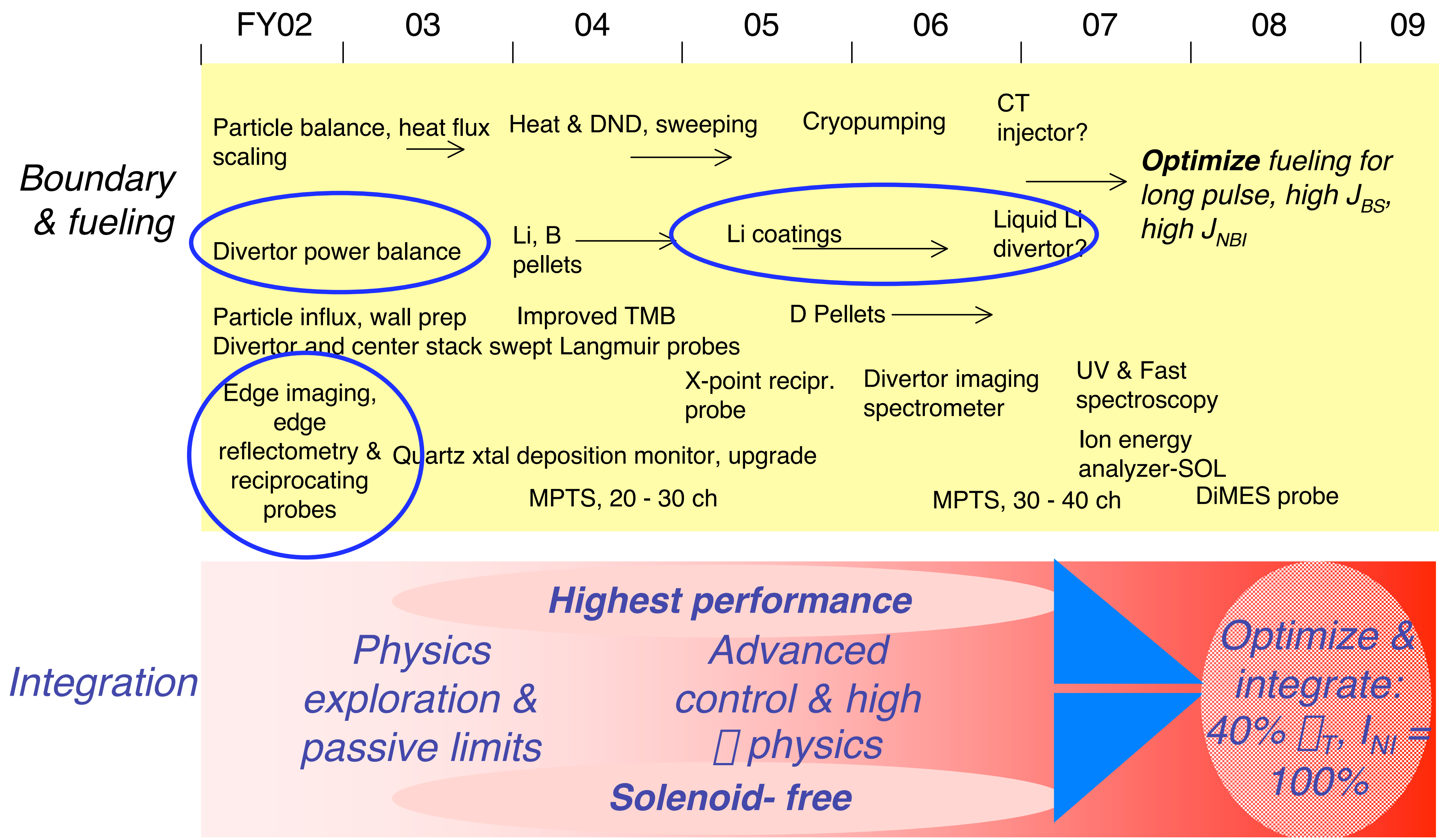
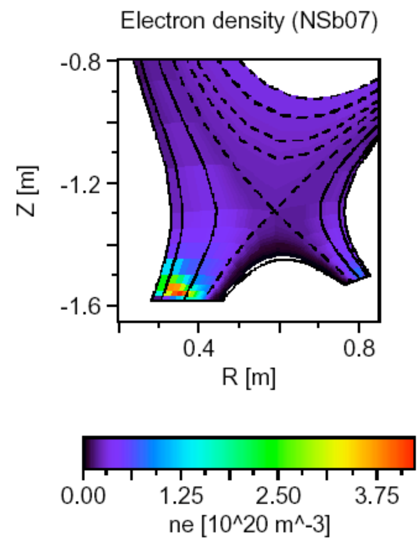
- Wave-particle & startup
  - *HHFW, EBW: new physics & tools for overdense plasmas*
  - *CHI plasma startup research addressing urgent issue for AT & ST.*
- Boundary physics
  - *Liquid lithium: develop for potentially revolutionary boundary solutions*
- Integration of the science

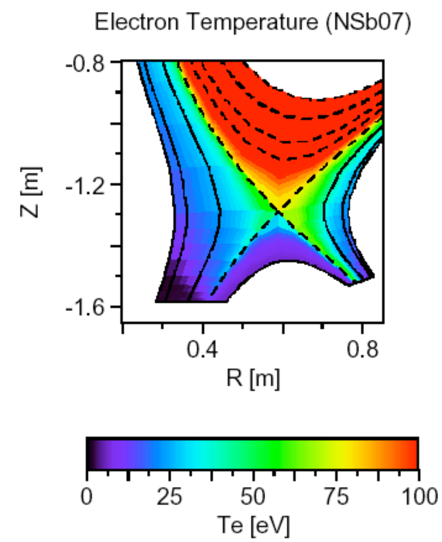
Many boundary tools are available or planned to help enable NSTX's integration goals



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

- Positions program to calculate & optimize cryopumping and liquid Li divertor designs

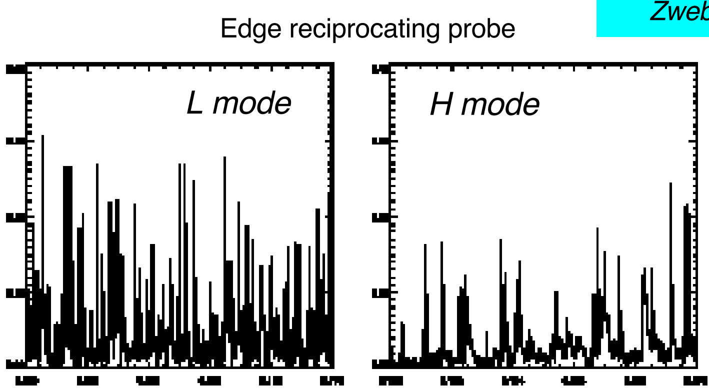




Rensink, Porter, Wolf (LLNL); Stotler

- Edge convective events: significant player in flux?
  - Testable physics: role of curvature

Maqueda (LANL), Zweben



Boedo (UCSD)

High Speed Imaging of Edge Turbulence in NSTX

with Princeton Scientific Instruments PSI-4 camera

viewing HeI(587.6 nm) light at 100,000 frames/sec

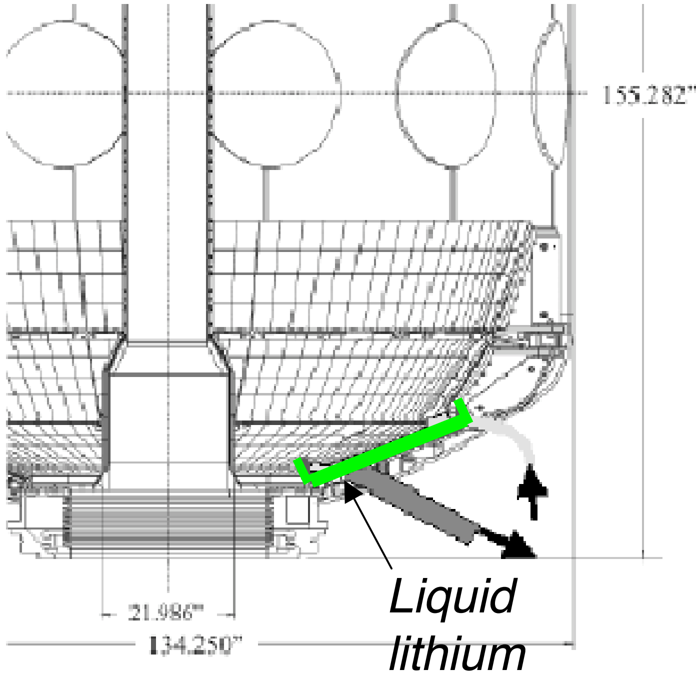
2002

IPPA 3.1.4: Advance the capability to predict detailed multi-phase plasma-wall interfaces at very high power and particle fluxes

NSTX has opportunity to develop revolutionary particle and heat flux control techniques

- Plan: lithium evaporation studies, collaboration with VLT on CDX-U to assess promise of and design liquid Li divertor

- Potential of plan: direct benefit to NSTX, solution for both particle and heat flux control: *Broad implications for fusion*



ALIST liquid surface concept

Maingi will discuss Boundary Physics plans

NSTX plasmas enter new physics regimes and enable development of new solutions

- MHD
  - *$V_{\square}/V_A \sim 1 \Rightarrow V_{\square}' \sim \square^{n}_{MHD}$*
  - *Distinguish V_A, C_s effects for rotation damping*
- Transport & turbulence
  - *Low k with NBI: intrinsically stable?*
  - *Low and high k may be controllable with NBI & HHFW*
- Wave-Particles & CHI
  - *HHFW, EBW: new physics & tools for overdense plasmas*
  - *CHI plasma startup research addressing urgent issue for AT&ST.*
- Boundary physics
  - *Liquid lithium: develop for potentially revolutionary boundary solutions*
- Integration of the science
  - *Developing flexible tools and using science learned to enable high beta & long pulse*

Major goals of value to the ST and the toroidal confinement community are integral to the plan

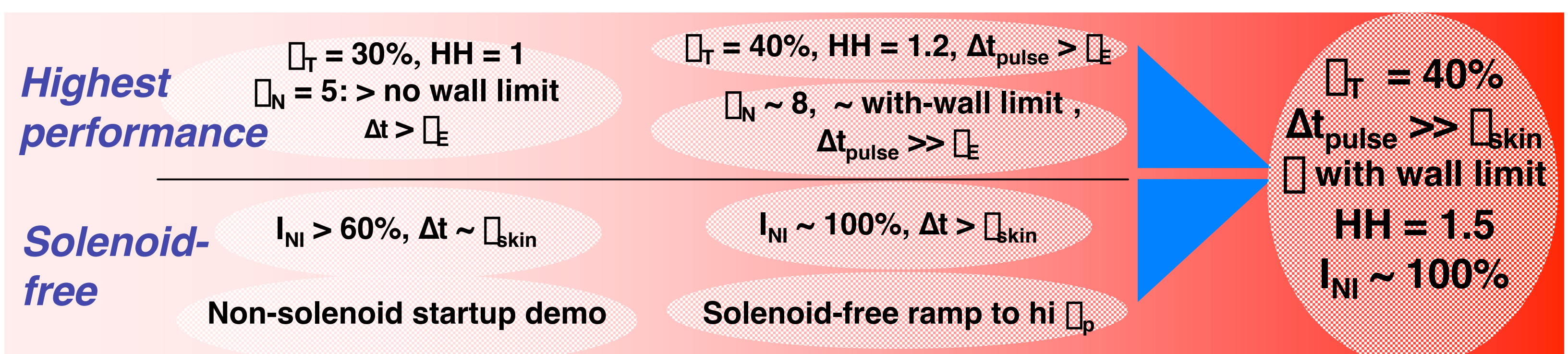
By mid-plan:

- Solenoid-free ramp to high β_p: essential to any ST- or AT-based reactor concept (discussed earlier)
- Transient high toroidal beta
- Non-inductively sustained, CTF-relevant beta, $\tau_{pulse} >> \tau_{skin}$
  - HHFW heating + NBI heating and CD, 0.5 T, 800 kA
  - HHFW + EBW, both heating and CD, 875 kA

By end of 2008:

- Integration: 40% β_T, non-inductive, $\tau_{pulse} >> \tau_{skin}$ (discussed next)

Integration

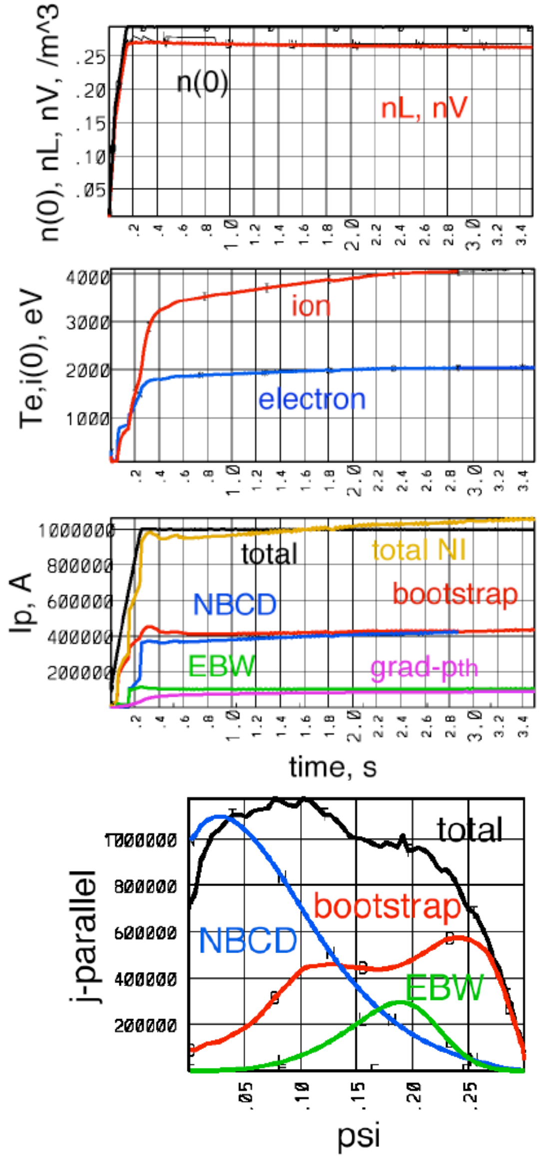


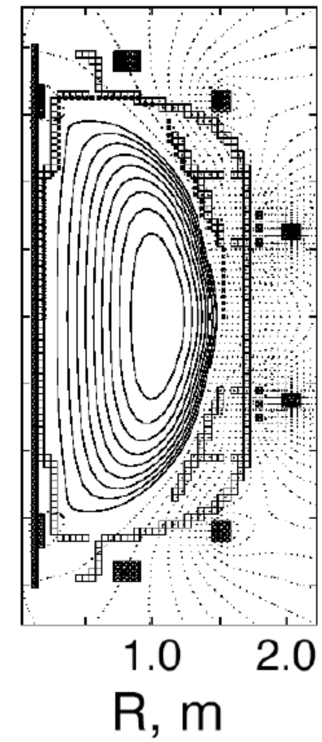
40% β_T , I_{NI} = 100%, $\tau_{pulse} >> \tau_{skin}$ within reach using the flexible tools that are planned

- *Enhanced shaping* improves ballooning stability through simultaneous high κ and δ
- Near with-wall & ballooning limits

⇒ mode control + rotation are key

- EBW provides off-axis CD to keep q > 2
- Particle control required to maintain moderate n_e for CD
- HHFW heating contributes to bootstrap, raises T_e





Kessel will discuss integrated scenario modeling

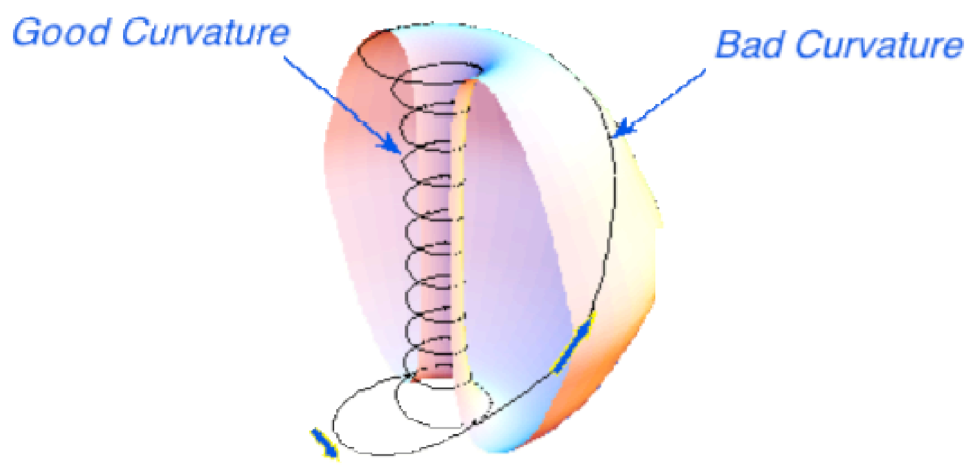
Towards a stronger scientific foundation: connections with other configurations and scientific disciplines

-Examples of opportunities

IPPA 3.1.5, General Science: Advance the forefront of non-fusion plasma science… across a broad frontier, synergistically with the development of fusion science…

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

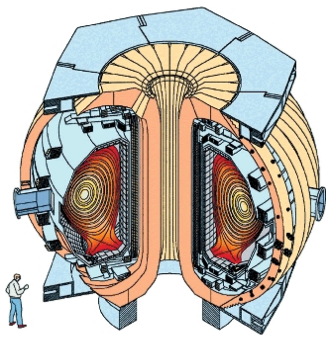
Change the aspect ratio, increase beta: what physics changes?



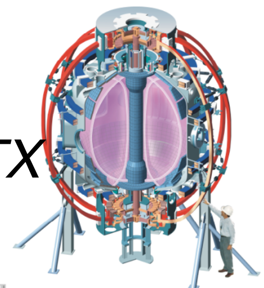
Spherical Torus (ST)

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

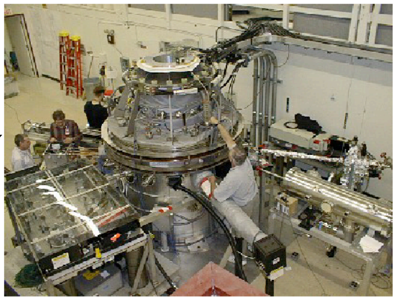
DIII-D



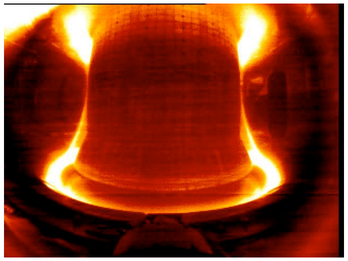
NSTX



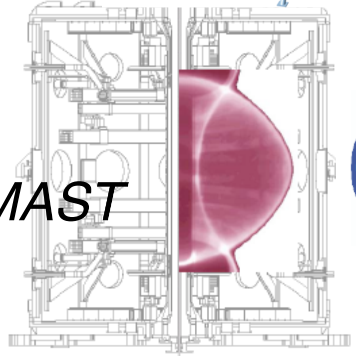
SSPX



C-Mod

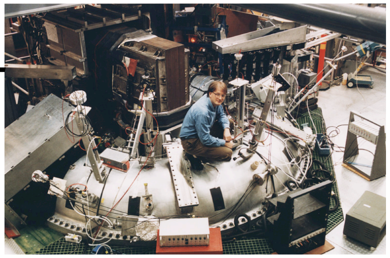


MAST



Pegasus

MST

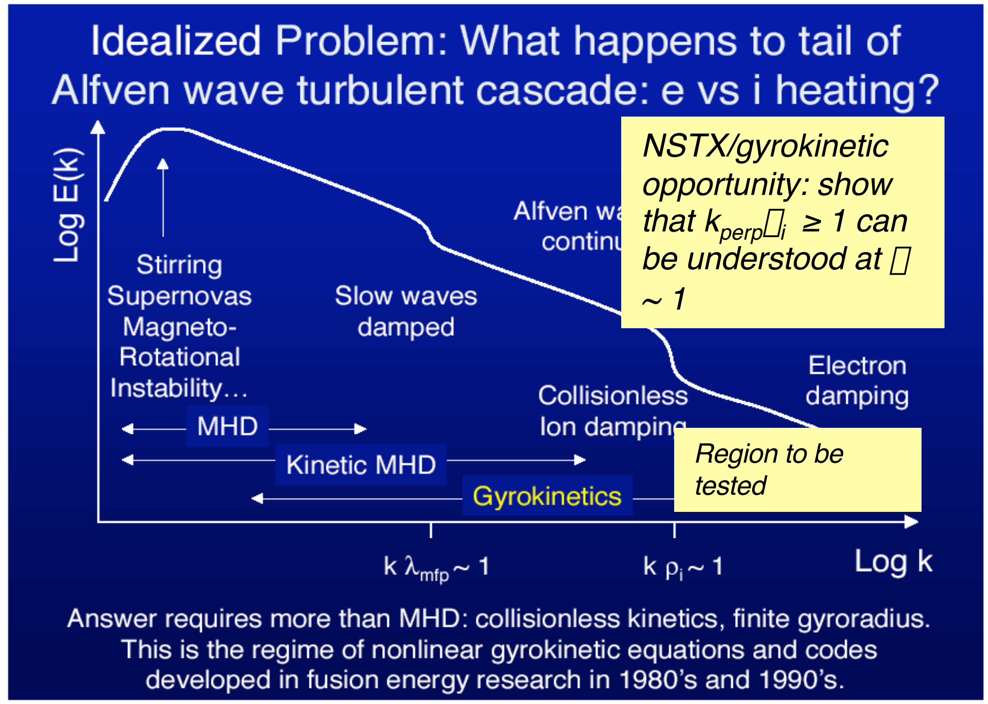


Electrostatic — *E-M effects emerge* — *Electromagnetic*

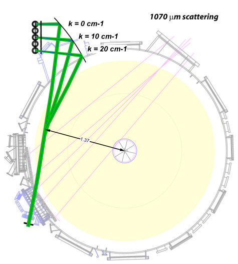
- χ_e: a deep transport mystery. Understanding is a need for burning plasmas
- TTF is developing a proposal for a renewed transport initiative.
- Suite of machine types can develop a powerful scientific story

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

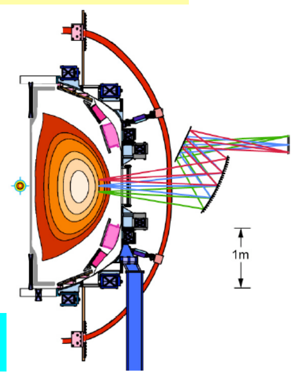
- Astrophysics and turbulence dynamics: cascading of MHD turbulence to ion scales is of fundamental importance at beta ≥ 1
- Fusion's gyrokinetic formalism applicable to high beta astrophysical turbulence problems
- Gyrokinetics applicable to astrophysical shocks, solar wind
- Astrophysicists have keen interest in benchmarked codes



High k: scattering

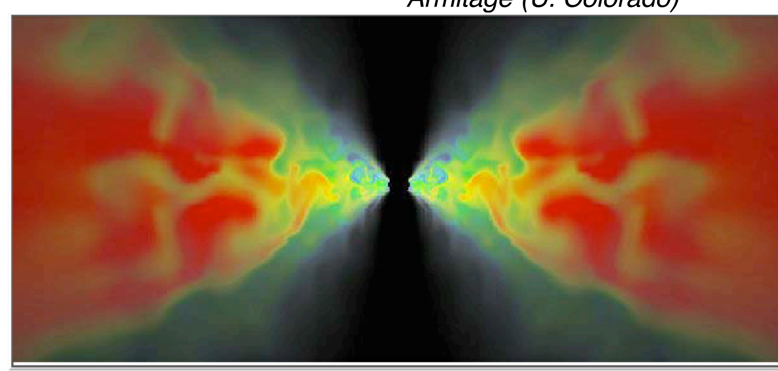


Approach for low k: imaging

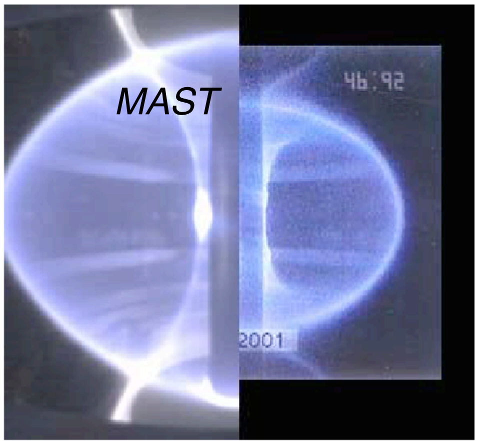


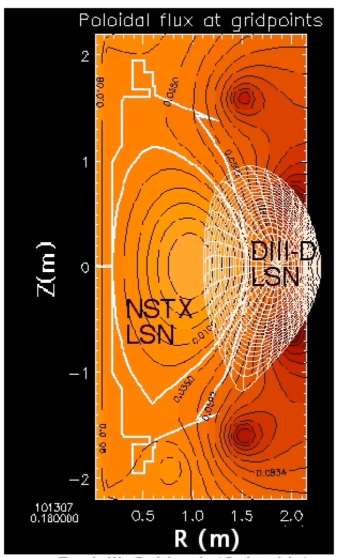
with Luhman (UC Davis)

Armitage (U. Colorado)



The NSTX program will take maximal scientific advantage of intermachine comparisons





Paoletti, Sabbagh (Columbia)

- Well-aligned with ITPA process
- MAST: EBW research underway.
- With DIII-D: Joint experiments being proposed and implemented
  - RWM
  - Fast ion MHD: CAE, TAE
  - Pedestal similarity
  - Core confinement
- C-Mod: Turbulence and flows
  - Edge turbulent structures
  - X-Ray crystal spectroscopy (T_i & $V_{\square}$)

The NSTX research program contributes directly to fusion development expands plasma science

- NSTX research extends the reach of laboratory plasma science to new realms in MHD, transport, wave-particle physics, and boundary physics.

- At the foundation of assessing the ST will be the integration of this science through the development of flexible control tools, deployment of advanced diagnostics, and coupling to theory and computation.

- The development of this science and control tools will have impact beyond the scope of the ST.

- NSTX is part of a community of laboratories which together can unravel challenging problems of importance to all of toroidal confinement research.

Supporting slides

	FY02	03	04	05	06	07	08	09

Transport

- Global scalings and local □ → □ & high electron & ion heating, $V_□$ → □ and maximizing P, J_{BS}, J_{NBI} → *Optimize P, J_{BS}, J_{NBI}*
- Edge turbulence → □ and wall fueling → Electron, ion transport & core & edge turbulence vs. □, E_r →

MHD

- □ limiting modes vs. shape, li, P
- RWM, $V_□$, & wall → RWM mode suppression
- *Understanding: turbulence/theory compare* →
- *Error field & $V_□$*
- □ limits & $V_□$ shear
- Fast ion modes
- Internal mode characterize → NTM suppression →
- *Optimize stability in long-pulse high beta regimes*

Integration

Highest performance

- $□_T$ = 30%, HH = 1; $□_N$ = 5: > no wall limit; Δt > $□_E$
- $□_T$ = 40%, HH = 1.2, $Δt_{pulse}$ > $□_E$
- $□_N$ ~ 8, ~ with-wall limit, $Δt_{pulse}$ >> $□_E$

Solenoid-free

- I_{NI} > 60%, Δt ~ $□_{skin}$
- I_{NI} ~ 100%, Δt > $□_{skin}$
- Non-solenoid startup demo
- Solenoid-free ramp to hi $□_p$

$□_T$ = 40%
$Δt_{pulse}$ >> $□_{skin}$
□ with wall limit
HH = 1.5
I_{NI} ~ 100%

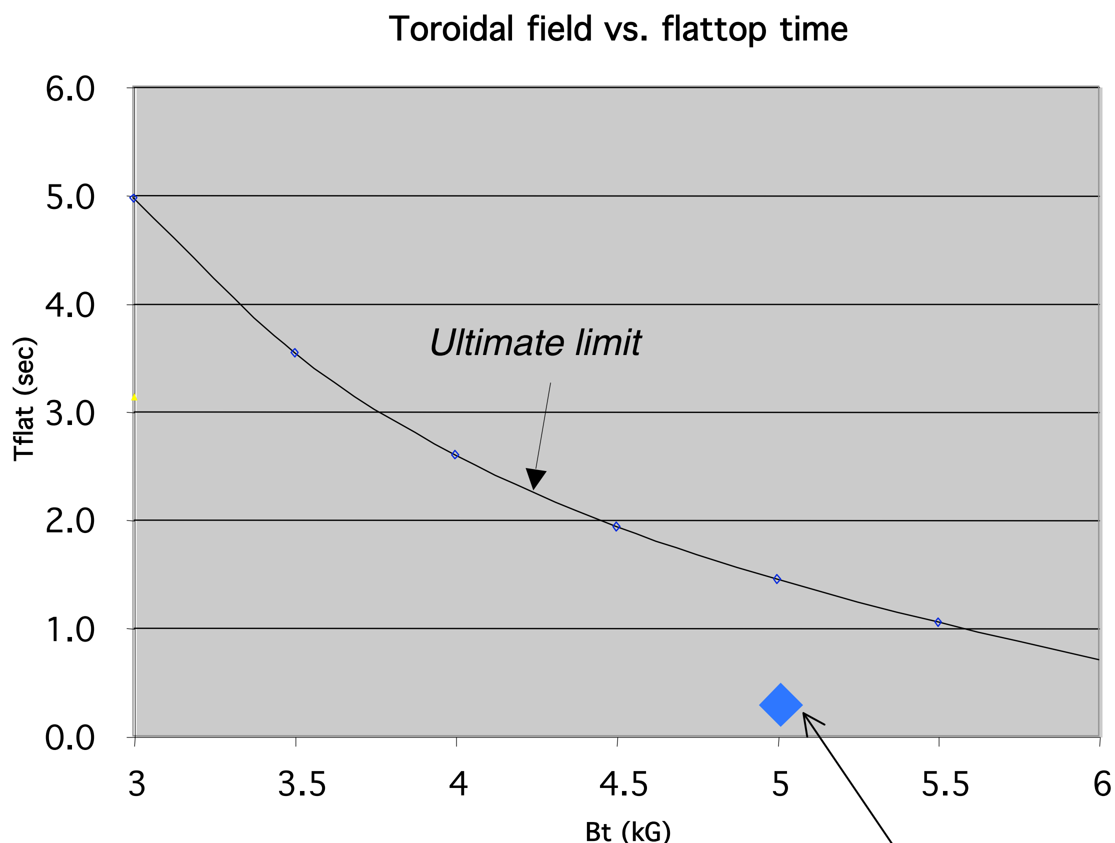
HHFW/ EBW/ CHI

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

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



τ_{skin} = 230 ms (109070)

IPPA goals and objectives

Goals	5-Year Objectives	10-Year Objectives
<u>Goal 1:</u> Advance understanding of plasma, the fourth state of matter, and enhance predictive capabilities, through comparison of well-diagnosed experiments, theory and simulation.	**<u>1.1 Turbulence and Transport</u>** Advance scientific understanding of turbulent transport forming the basis for a reliable predictive capability in externally controlled systems. **<u>1.2 Macroscopic Stability</u>** Develop detailed predictive capability for macroscopic stability, including resistive and kinetic effects. **<u>1.3 Wave Particle Interactions</u>** 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. **<u>1.4 Multiphase Interfaces</u>** Advance the capability to predict detailed multi-phase plasma-wall interfaces at very high power- and particle-fluxes. **<u>1.5 General Science</u>** 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.

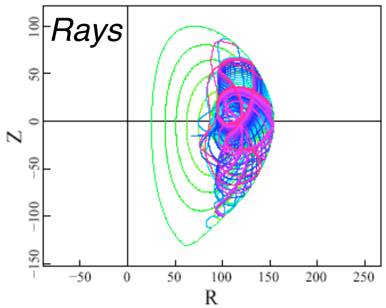
	5-year Objectives	10-year Objectives
<u>Goal 2:</u> Resolve outstanding scientific issues and establish reduced-cost paths to more attractive fusion energy systems by investigating a broad range of innovative magnetic confinement configurations.	**<u>2.1 Spherical Torus</u>** Make preliminary determination 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.

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

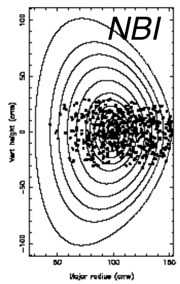
"From my own reviews of recent research on magnetically confined plasmas, I believe this field has benefited, as many other fields have, from the revolutionary improvements in *computing power* and *instrumentation*. The ability to predict plasma parameters in realistic simulations and then test them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

Forming scientific basis requires benchmarking between most comprehensive codes (SCIDAC), faster models, and data



GENRAY



CQL3D

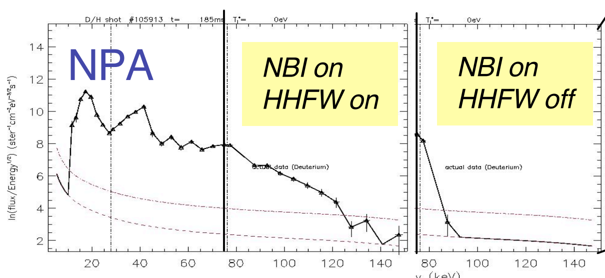
Benchmark with complete wave theory
AORSA-2D
(SciDAC)

Faster model: Ray tracing
GENRAY
CURRAY
HPRT

Analysis of transport, current drive
TRANSP

Faster model: Full wave
TORIC
METS (SciDAC)

Benchmarking with NSTX Data
Wave-particle interactions
Source measurements



Energy (keV)

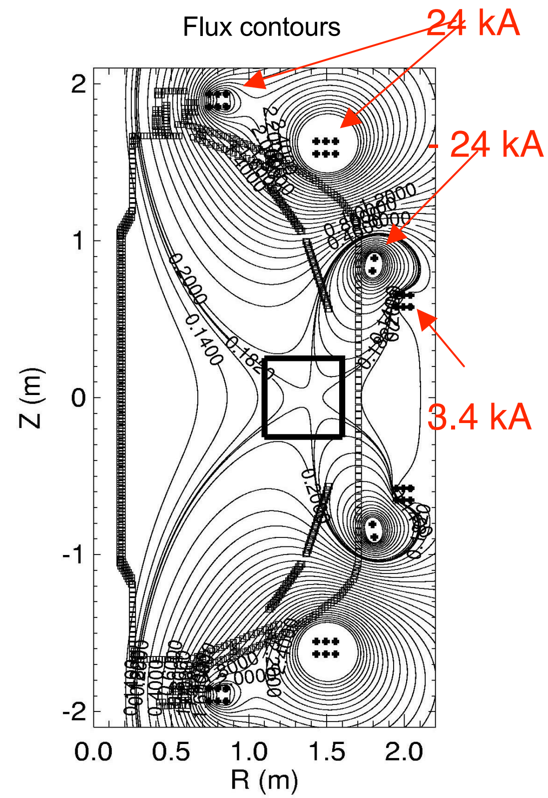
EBW can deliver required off-axis current in 40% β_T, I_{NI} = 100% case

- Current can be driven where it is needed
- Result: q > 2 everywhere, enhancing ballooning stability
- HHFW is predicted to be strongly absorbed by beam and thermal ions in this case

Picture of J profiles, Including the assumed location of EBW and reasonable deposition locations and power requirements from Harvey's on-going calculation

PF induction for breakdown and initial current ramp will be studied

- Plan includes experimental proposals to be carried out in '04 with existing coils & power supplies
- New element: energizing an existing PF coil permits a good field null to be created
  - Control requirements being assessed



Raman will discuss startup plans

Edge turbulence measurements reveal intermittent structures

- May have implications for particle handling solutions, role of main chamber recycling, divertor compression ratios.

- Tokamak/ST test: does curvature matter?
  - Some models suggest curvature drift is transporting these structures across the SOL.
  - Collaborative effort with Alcator C-Mod

- Possible MAST/NSTX test: does distance to the wall matter?
  - Most measurements made with wall a few correlation lengths away.

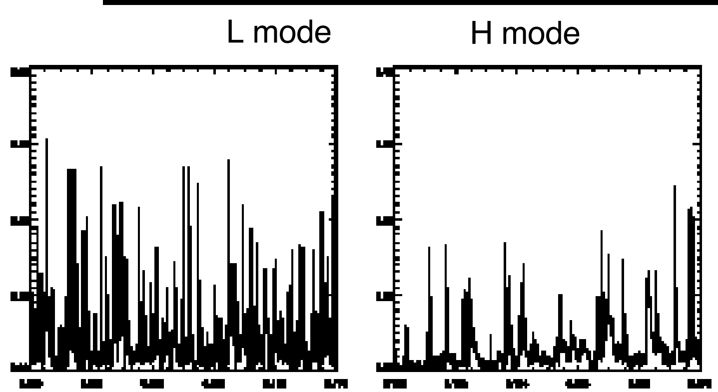
Maqueda (LANL), Zweben

High Speed Imaging of Edge Turbulence in NSTX

with Princeton Scientific Instruments PSI-4 camera

viewing HeI(587.6 nm) light at 100,000 frames/sec

2002



Boedo (UCSD)