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NSTX Program Logic and Plan

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NSTX PAC-10 Meeting

Princeton Plasma Physics Laboratory

February 8-9, 2001

Princeton, New Jersey, USA

NSTX Program is Ready to Make Major Contributions to Fusion Energy Sciences Program

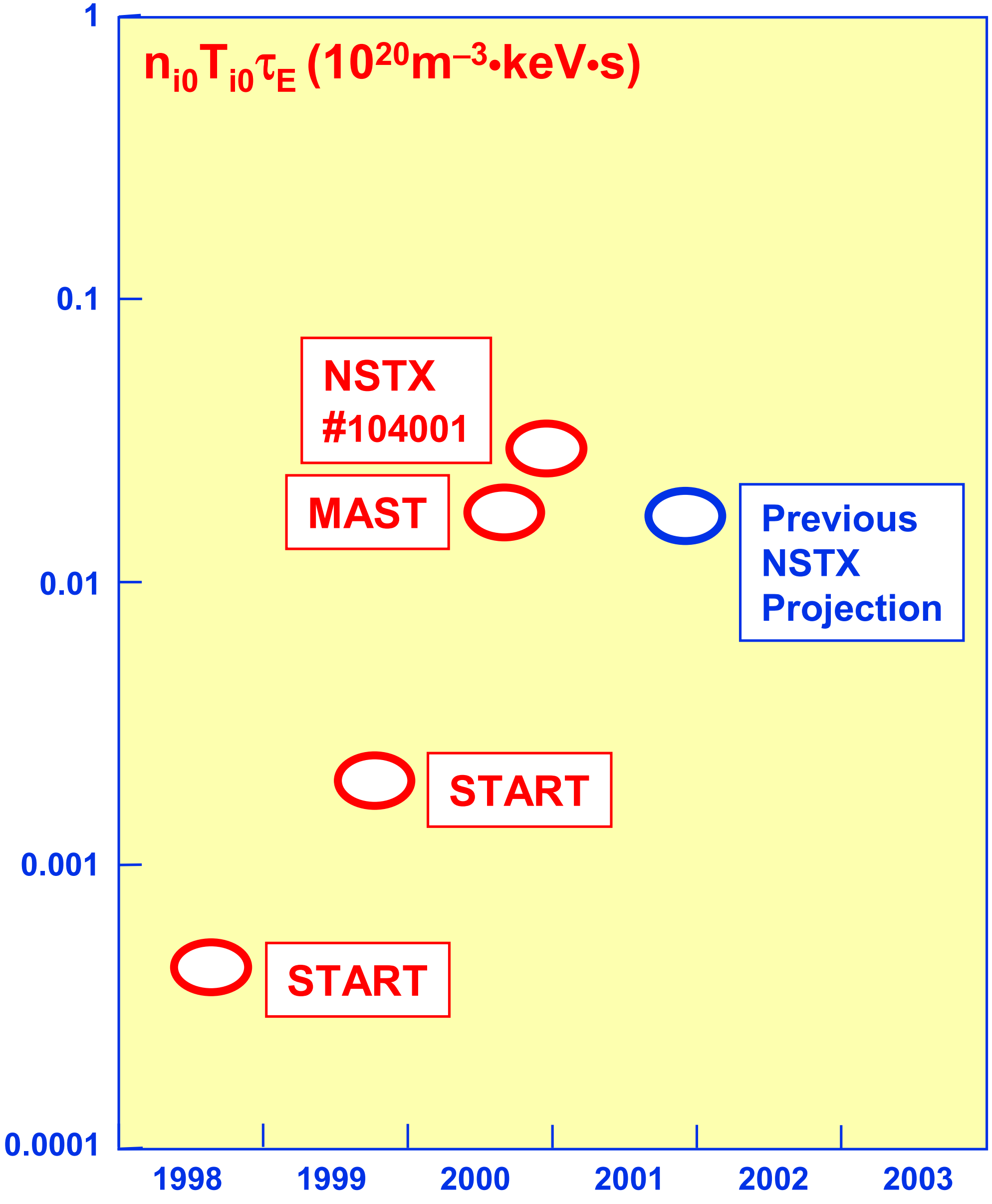
- Initial NSTX Results Have Been Very Exciting, and Opened up New Scientific Opportunities
- FESAC, IPPA, & NRC FuSAC Reports Provide a Framework for Our Research Plans
- NSTX Baseline Program Addresses Both Science and Energy Objectives
- Requested Budgetary Increments Would Deepen the Science from NSTX, Broaden Participation, and Accelerate Program in Very Important Ways

NSTX Has Provided Earlier Than Expected Opportunities for Exciting Scientific Investigations

- **Delivered**
  - NBI up to 4.5 MW
  - HHFW up to 4 MW
  - Full range of shaping
  - MPTS, CHERS
- **Ohmic Results**
  - W_p ~ 60 kJ (EFIT)
  - β_T ~ 9%
  - τ_E ~ 45 ms
  - H_{89} ~ 1.3, H_{98} ~ 1
- **NBI Results (best data)**
  - W_p ~ 160 kJ (EFIT)
  - β_T ~ 22% (β_N ~ 4.2)
  - τ_E ~ 100 ms
  - H-mode behaviors
  - ITB behaviors
- **HHFW:** $T_e(0)$ > 1 keV
- **CHI**: $I_{toroidal}$ ~ 260 kA

Early Confinement Results Have Been Encouraging!

NSTX



- **Laser Thomson Scattering (MPTS)**
  - $n_{e0} \sim 0.4\times10^{20}m^{-3}$
  - Varied $n_e(R)$ profiles, sensitive to MHD
- **Magnetic Reconstruction (EFIT)**
  - $W_p \sim 125$ kJ
  - $\tau_E \sim 0.07$ s
  - H_H(98pby2) ~ 1.4
- **Impurity Spectroscopy**
  - Zeff ~ 2

    $\Rightarrow n_{i0} \sim 0.3\text{x}10^{20}m^{-3}$
- **First Charge Exchange Spectroscopy (CHERS)**
  - $T_{i0} \sim 2$ keV
  - Broad T_i profile

$n_{i0}T_{i0}\tau_E \sim$ $0.04\times10^{20}m^{-3}$•keV•s

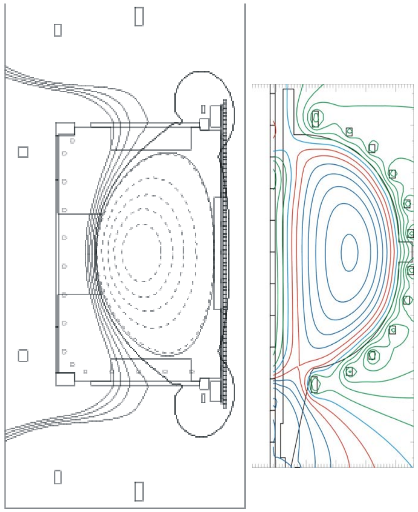
FESAC Sets Challenging Goals and Exciting Opportunities for ST with 5 & 10-year Objectives

- **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.**
  - ***5-year objective:*** Make preliminary determination of the attractiveness of the Spherical Torus, by assessing high-beta stability, confinement, self-consistent high-bootstrap operation, and acceptable divertor heat flux, for pulse lengths >> energy confinement times.
  - ***10-year objective:*** Assess the attractiveness of extrapolable, long-pulse operation of the Spherical Torus for pulse lengths >> current penetration times. ***(This requires NSTX center stack upgrade.)***
- **The Panel also recommends funding increases, among four areas, to:**
  - Focus Advanced Tokamak program, including international collaboration, and to a lesser degree the spherical torus program, towards a 5-year assessment point; and prepare for participation in a burning plasma experiment.

IPPA Articulated Near-Term Metric, Key Issues, and Implementing Approaches for the 5-Year Objective

- **Metric** – Degree of understanding of the (*physics*) processes and techniques that extend plasma pressure, improve plasma confinement, and allow sustained plasmas in a spherical torus concerning candidate devices for studying burning plasma physics and/or testing fusion-nuclear technologies.
- **Key Issues**
  - Stability & good confinement at high β ($\Downarrow$ development cost)
  - High performance in modest-size for $\tau_{pulse} \gg \tau_E$ ($\Rightarrow \tau_{pulse} \gg \tau_{skin}$)
  - Very high β and low A $\Rightarrow$ new research opportunities
  - Noninductive startup & sustainment $\Rightarrow$ future steady state fusion devices
- **Implementing approaches**
  - **Achieve Efficient Heat & Particle Confinement**
  - **Verify Stability of Large Scale MHD Perturbations**
  - **Heat High-beta Over-dense Plasmas**
  - **Test Plasma Startup with Noninductive Techniques**
  - **Disperse Edge Heat Flux at Acceptable Levels**
  - **Integrate High Confinement & High Beta**
  - **Explore Spherical Torus Issues in Directed Laboratory Experiments: (Pegasus, HIT-II, CDX-U)**

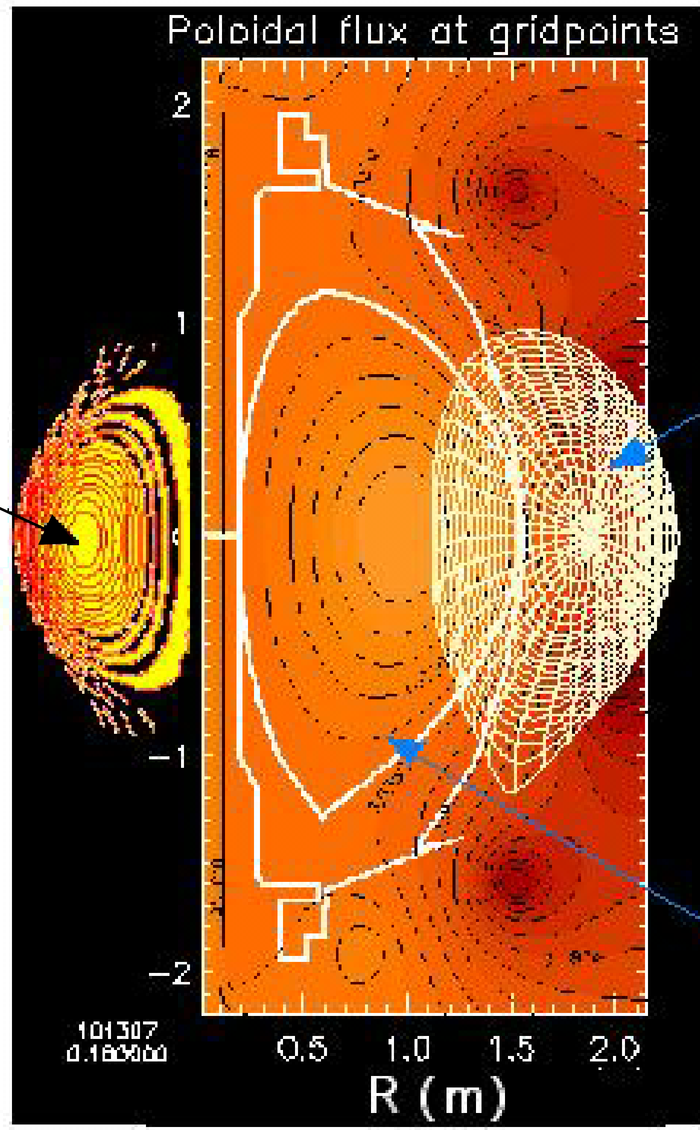
Pegasus, HIT-II, CDX-U Explore Innovative ST Limits



CDX-U
PPPL

HIT-II
U. Wash

Pegasus
U. Wisc



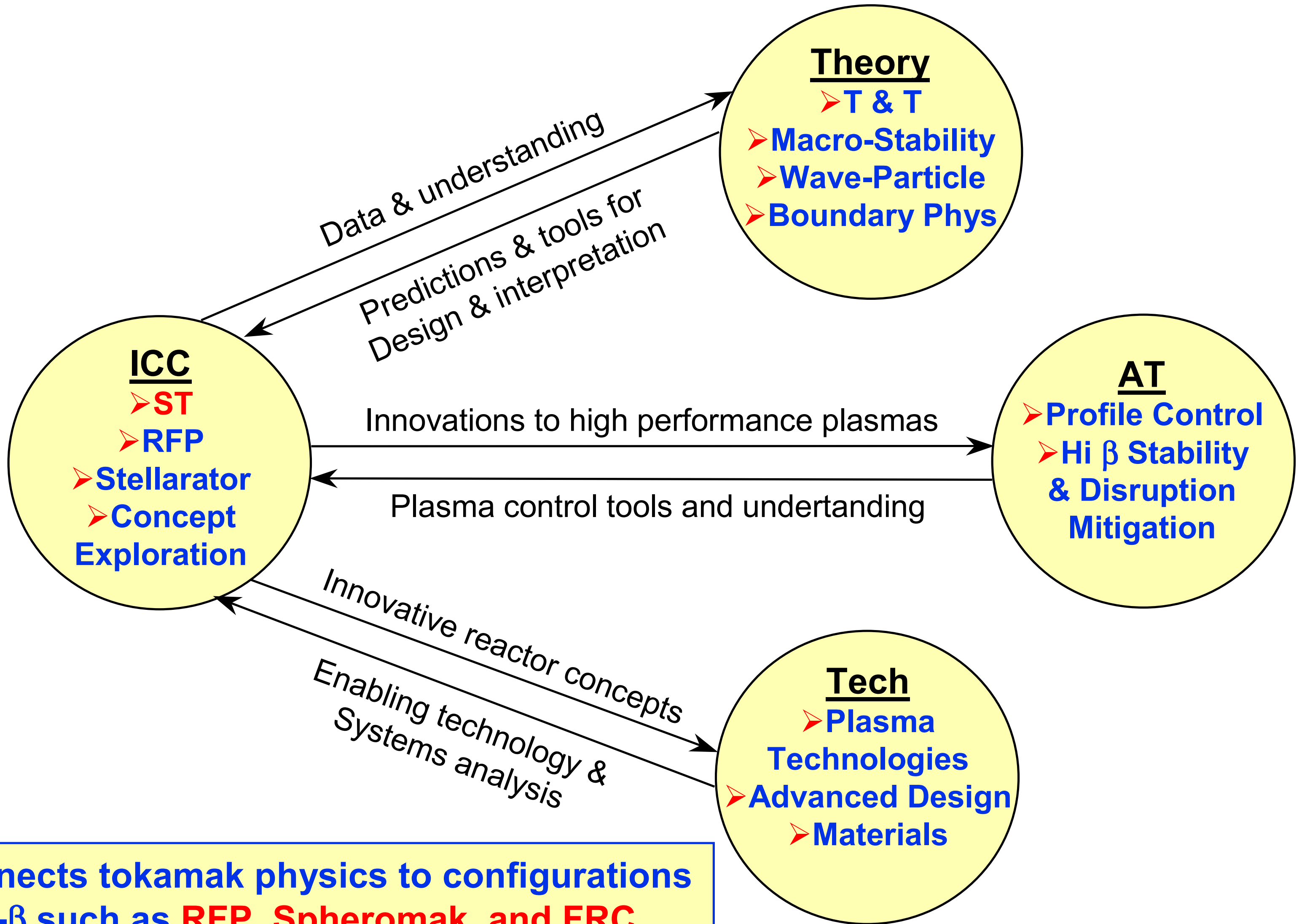
DIII-D
GA

NSTX
PPPL

Paoletti, Sabbagh (Columbia)

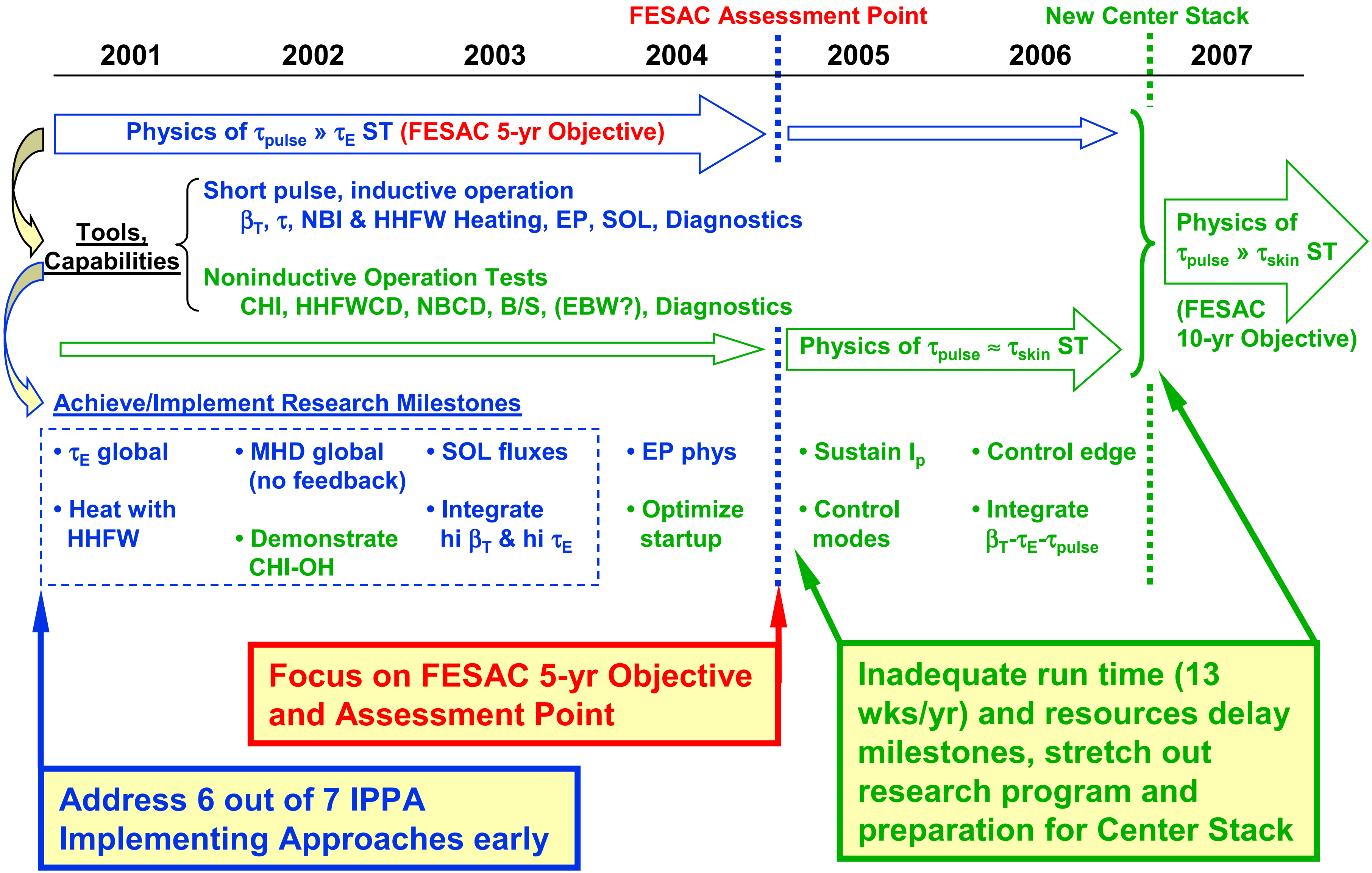
- Pegasus
  - Extreme low A (→1.1)
  - Connections to high-β CTs
  - $\omega_{pe}^2/\omega_{ce}^2$ >>> 1 RF heating
- HIT-II (HIT-SI)
  - Innovations in CHI
- CDX-U
  - Plasma-wall interaction control via liquid surface

The ST Activities Provide Tools and Capabilities to Enable, and Benefit from Other Activities



ST connects tokamak physics to configurations of high-β such as RFP, Spheromak, and FRC.

NSTX Baseline Program Responds to Near-Term Objectives by FESAC & IPPA



NRC FuSAC Emphasizes Scientific Understanding

- **Broaden institutional base and reach into the wider scientific community**
  - **Broaden research participation in fusion program**
  - **Enrich pool of ideas**
- **Predictive Capability**
  - **Measure success in scientific understanding as well as progress toward fusion energy**
  - **Advance understanding of key science issues in concerted efforts**
    - Identify and implement diagnostic tools required to compare with theory in sufficient detail
    - Allocate sufficient experimental resources to address key scientific issues
- **Plasma Confinement Configurations - Investigate and contribute to scientific questions that cut across configurations (~FESAC Goal 1)**

Advances in science stimulate and accelerate progress in energy research, and vice versa!

NSTX National Collaboration/Cooperation

Supported by

Columbia U	MHD & eddy current modeling, mode control, stellar flare spectroscopy
GA	CHI modeling, HHFW phys, real-time plasma control
J-H U	USXR & SXR tomography
LANL	Fast visible & infrared imaging, MHD modeling & simulation
LLNL	Edge-SOL and turbulence modeling, stellar flare spectroscopy
Lodestar	Boundary stability and turbulence modeling
MIT	ECH/EBW & HHFW modeling, edge measurements
NASA GRC	Coaxial helicity ejection propulsion phys
Nova Photonics	MSE (CIF and LIF)
NYU	RF and transport modeling
ORNL	HHFW & ECH/EBW tech & phys, plasma-wall int., CLR Metrol.
PPPL	Phys analysis, run coordination, joint research, fac. & exp. ops
PSI	Fast tangential X-ray imaging
SNL	Plasma facing materials and material surface analysis
UCDavis	Far infrared tangential interferometer polarimeter
UCLA	Core reflectometry
UCSD	HHFW modeling, fast probes
U of Wash	CHI phys, joint research with HIT-II

NSTX Baseline Program Logic Addresses Science and Energy Goals

NSTX

FESAC Assessment Point (between 2004 and 2005) | New Center Stack (between 2006 and 2007)

2001	2002	2003	2004	2005	2006	2007

Identify/Enable Unique ST Scientific Opportunities (Diagnostics, Theory, Simulation)

- 2001:
  - Hi shear in V_ϕ, ∇p-flow?
  - Hi-trapping fraction transport?
  - RF in $\omega_{pe}^2/\omega_{ce}^2$ » 1 plasma?
- 2002:
  - Hi V_s/V_A & V_ϕ/V_A effects?
  - Hi resonance-gap TAE/BAE?
  - Hi-T_e fast reconnection?
- 2003:
  - Hi M_B & SOL expansion?
  - Hi ρ_i^*, ρ_{fi}^* & in-out asymmetry on p(r) & MHD dynamics?
  - Li migration
- 2004:
  - Low Alfven turbulence?
  - Int+ext mag flux source effects?
  - Hi β_T e-m turbulence?
- 2005:
  - H, CD, χ synergy?
  - NTM, RWM control & avoidance?
  - Hi trapping fraction turbulence dynamics?
- 2006:
  - J(r), p(r), E×B shear, & edge fluxes synergy?
  - L surface

Physics of τ_{pulse} » τ_{skin} ST

(FESAC 10-yr Objective)

Achieve/Implement Research Milestones

- 2001:
  - τ_E global
  - Heat with HHFW
- 2002:
  - MHD global (no feedback)
  - Demonstrate CHI-OH
- 2003:
  - SOL fluxes
  - Integrate hi β_T & hi τ_E
- 2004:
  - EP phys
  - Optimize startup
- 2005:
  - Sustain I_p
  - Control modes
- 2006:
  - Control edge
  - Integrate β_T-τ_E-τ_{pulse}

- Baseline program strives to
  - National and international participation
  - Install diagnostics to measure and compare with theory & simulation
  - Optimize run time and capabilities to achieve research milestones
  - Milestones ⇒ new scientific opportunities ⇒ new tools ⇒ new milestone
- Fiscal constraints limit depth of scientific understanding

Strong Synergy Exists Between Science and Energy Goals

NSTX

Example in Transport & Turbulence

- **Observations from "τ_E Global" Experiments:**
  - H-mode and ITB-like behavior
  - Good confinement in high β_T plasmas
  - Broader T_i profile (than T_e) in NBI plasmas
  - Very high C toroidal flow ($V_C/V_A \sim 0.2$)
- **Scientific Questions:**
  - Does large momentum & ∇p-driven flow shear affect turbulence & transport?
  - Does high β_T alter nature of turbulence?
- **Measurement Needs:**
  - New fluctuation and flow measurements
- **Understanding can improve future high performance discharges and research milestones**

NSTX Baseline Program Logic – All Together

NSTX

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- Integrate hi β_T & hi τ_E

2004
- EP phys
- Optimize startup

2005
- Sustain I_p
- Control modes

2006
- Control edge
- Integrate β_T-τ_E-τ_{pulse}

Physics of τ_{pulse} » τ_E ST (FESAC 5-yr Objective)

Tools, Capabilities

- Short pulse, inductive operation
  - β_T, τ, NBI & HHFW Heating, EP, SOL, Diagnostics
- Noninductive Operation Tests
  - CHI, HHFWCD, NBCD, B/S, (EBW?), Diagnostics

Physics of $\tau_{pulse} \approx \tau_{skin}$ ST

Physics of τ_{pulse} » τ_{skin} ST (FESAC 10-yr Objective)

Major Increments Are Needed for NSTX to Achieve Deeper Scientific Understanding and Meet Assessment Point

NSTX

Present baseline (13 run-wks/yr)

- Emphasizes **FESAC 5-yr objective & assessment point** –attractiveness for short-pulses (τ_{pulse} » τ_E).
- Identify and pursue unique opportunities for **new scientific understanding**, and fast progress in **research milestones**.
- Delay **longer-pulse tests** ($\tau_{pulse} \approx \tau_{skin}$) to FY05-06.
- **Upgrade center stack** in FY07 to enable tests for FESAC "10-yr" objective – attractiveness for long-pulses (τ_{pulse} » τ_{skin}).

Major increments are needed

- To take advantage of **new opportunities** to achieve **deeper scientific understanding**, accelerate **milestones** and **new center stack** to FY05
  - **Increase run-time** (to 20 wks/yr)
  - **Add new diagnostics** (core fluctuations, div. TS, He spectroscopy, etc.)
  - **Advance operation capabilities** (EBW, mode control, div. cryo., etc.)
  - **Enhance & broaden research participation**
  - **Enhance cooperation** in **theory/simulation** and **enabling technology**

Requested Increments Allows Deeper Scientific Understanding, and Accelerate Research Milestones and New Center Stack

NSTX

FESAC Assessment Point | New Center Stack

2001	2002	2003	2004	2005	2006	2007

Identify/Enable Unique ST Scientific Opportunities (Diagnostics, Theory, Simulation)

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Achieve/Implement Research Milestones

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- Demonstrate CHI-OH

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- Optimize startup
- Sustain I_p
- Control modes

- Control edge
- Integrate β_T-τ_E-τ_{pulse}
- (Install center stack)

Physics of τ_{pulse} » τ_E ST (FESAC 5-yr Obj.)

Tools, Capabilities

- Short pulse, inductive operation
  - β_T, τ, NBI & HHFW Heating, EP, SOL, Diagnostics
- Noninductive Operation Tests
  - CHI, HHFWCD, NBCD, B/S, (EBW?), Diagnostics

Phys of τ_{pulse} ≈ τ_{skin} ST

Physics of τ_{pulse} » t_{skin} ST? (FESAC 10-yr Objective)

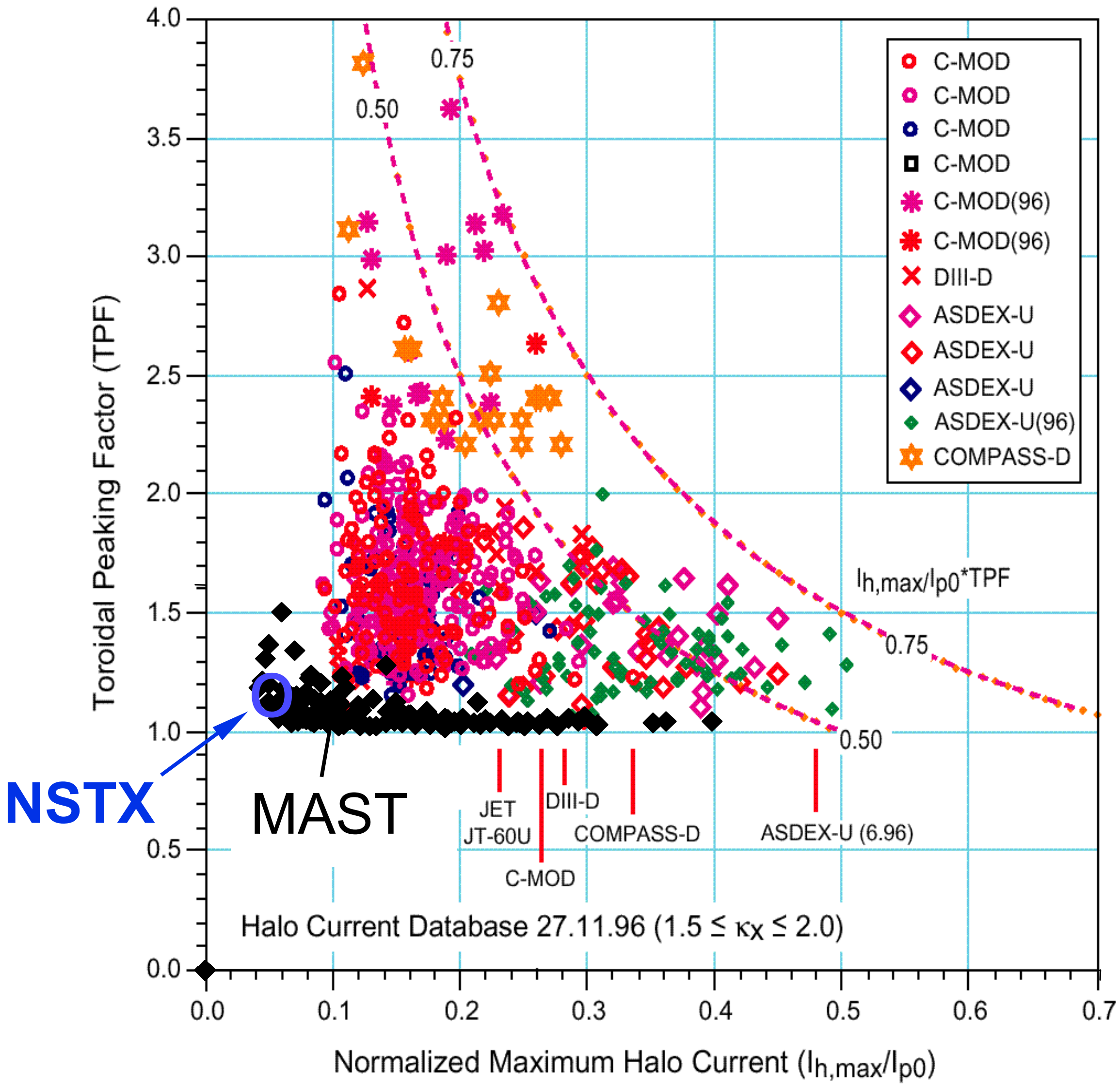
NSTX Will Make Major Critical Contributions to Fusion Energy Science

- **Initial experimental results are extremely exciting and creates new scientific opportunities!**
- **FESAC sets challenging goals for ST**
  - IPPA Articulates Near-Term Metric, Key Issues, and Implementing Approaches
- **NRC FuSAC emphasizes scientific understanding.**
- **NSTX Program Baseline Strategy is responsive to the FESAC Goals and NRC Recommendations**
- **Requested budgetary increments would deepen the science from NSTX, broaden participation, and accelerate research in very important ways.**
  - Accelerate new center stack to FY05
- **NSTX will provide key information for the FESAC 5-year assessment.**

Backup
VUs

Halo currents in MAST & NSTX

UKAEA Fusion Working with Europe



(ITER Physics Basis, Nuclear Fusion ***39*** *(1999) 2137)*

- **Lower and more symmetric halo currents in ST than in tokamak**
- **Scientific Understanding Important**

- CALOUTSIS, A and GIMBLETT, C G, Nuclear Fusion **38** (1999) 1487.

  POMPHREY, N, BIALEK, J M & PARK, W, Nuclear Fusion **38** (1998) 449.

Incremental Research Milestones and Operation Capabilities Are Needed to Meet the Checkpoint

NSTX

Incremental Research Milestones					
	• Ohmic studies • Initial CHI • Initial HHFW	• Transport • Full HHFW • Macro-stability	• Full CHI • Plasma-wall • β-τ_E integration	• Turbulence Sup. • Active Stabil. • Edge control	• Noninductive startup • Integration >> τ_E

(FY99)	(FY00)	(FY01)	(FY02)	(FY03)	(FY04)
Run-wks:	(14)	(19)	(19)		

2/99 ↑ *1st Plasma* ↑ *12/99* **1 MA, κ ~2** *FESAC Checkpoint* ↑

Operation Capabilities	Inductive	Noninductive Assisted	Noninductive Sustained
• Toroidal Beta, β_T		• → 25%	• → 40%
• Bootstrap Current		• → 40%	• → 70%
• Current	• → 0.5 MA	• → 1 MA	• ~ 1 MA
• Pulse	• → 0.5 s	• → 1 s	• → 5 s
• HHFW Power	• → 4 MW	• ~ 6 MW	• ~ 6 MW
• NBI Power		• → 5 MW	• ~ 5 MW
• EBW Power	• ~ 30 kW	• → 0.4 MW (incremental)	• ~ 0.4 MW
• CHI Startup	• → 0.2 MA	• → 0.5 MA	• ~ 0.5 MA
• Control	• current, R, shape	• heating, density	• profiles, modes
• Measure	• $T_e(r)$, $n_e(r)$	• $j(r)$, $T_i(r)$, flow, edge	• turbulence

The Baseline Budget Leads to Delays in Research on Noninductive Sustained Plasmas

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Baseline Scientific Milestones

- Ohmic studies
- Initial CHI
- Initial HHFW

- Transport
- Full HHFW

- Macroscopic stability
- Full CHI

- Plasma-wall
- Initial β-τ_E integration

(FY99)	(FY00)	(FY01)	(FY02)	(FY03)	(FY04)
Run-wks:	(14)	(13)	(13)	(13)	

2/99 1st Plasma — *12/99* 1 MA, κ ~2 — (t > τ_s) →

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• **Toroidal Beta, β_T**		• → 25%	• → 40%
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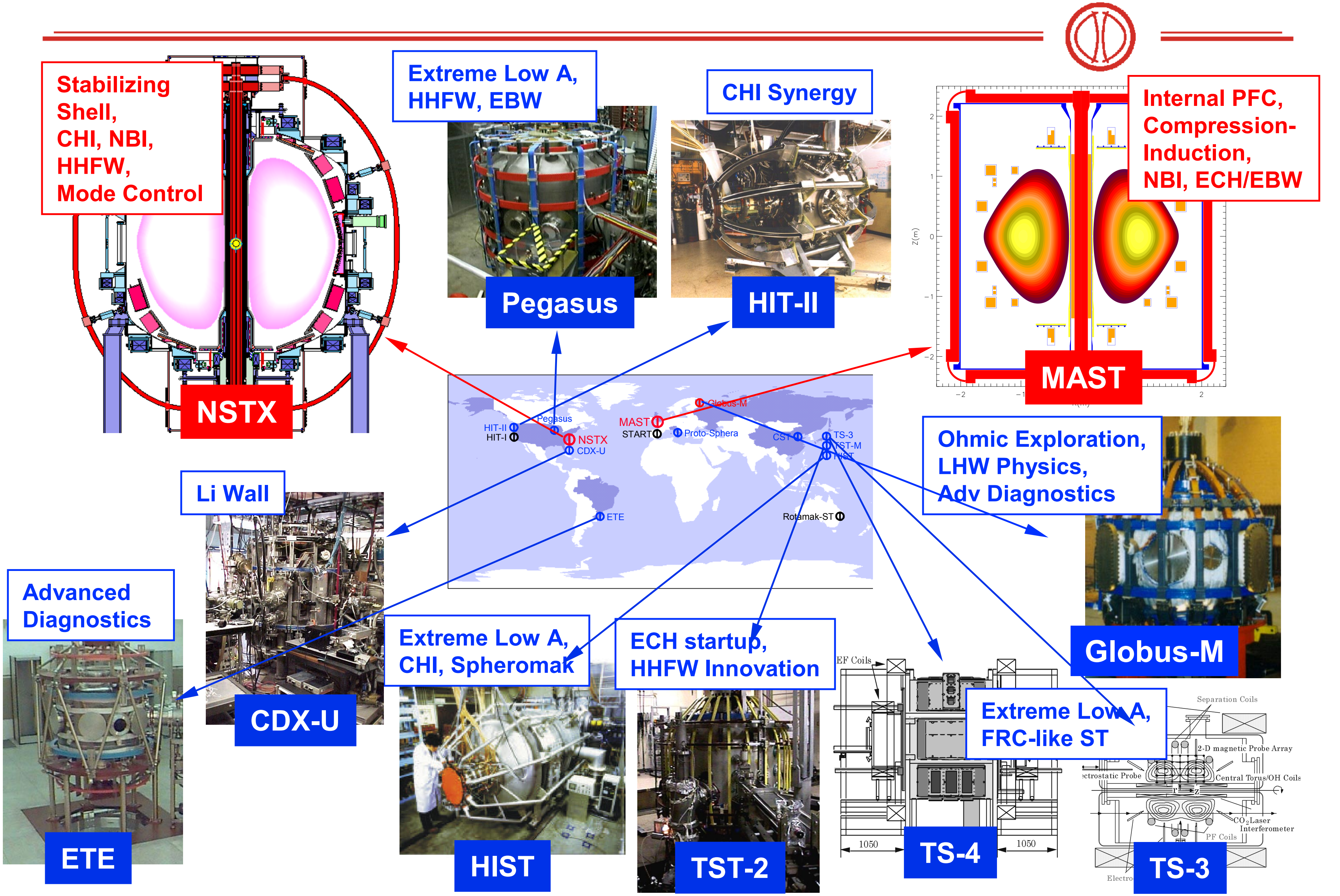
• **CHI Startup**	• → 0.2 MA	• → 0.5 MA	• ~ 0.5 MA
• **Control**	• current, R, shape	• heating, density	• profiles, modes
• **Measure**	• $T_e(r)$, $n_e(r)$	• j(r), $T_i(r)$, flow, edge	• turbulence

NSTX Is Key Part of Growing US & Worldwide ST Research

Concept Exploration (~0.3 MA) | Proof of Principle (~MA)



NSTX Research Also Benefits Greatly from Broad International Collaboration

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Brazil	INPE (ETE)	Advanced diagnostics
Japan	Hiroshima U	Divertor spectroscopy
	Himeji Inst. (HIST)	Ion Doppler spectroscopy for CHI plasmas
	Kyoto-Tokai U	Vertical field current drive
	NIFS	Confinement in presence of large magnetic well
	Niigata U	Analysis of high beta ST plasmas with large flow
	Univ. Tokyo	Ultra high beta ST, EBW emission & interpretation
	(TS-3,4, TST-2)	HHFW heating & current drive, Microwave reflectometry
R.F.	Ioffe Inst.	Conditioning, RF preionization, startup scenarios,
	(Globus-M)	Advanced diagnostics, RF heating and current drive
	TRINITI	Convective impurity transport
U.K.	UKAEA Fusion	NBI systems, NPA, energetic particles phys,
	(MAST)	Plasma heating & confinement, EBW phys,
		Fast digital signal analyzer, diagnostics
Ukraine	KINR	Energetic particle driven instabilities

Fusion Propulsion for Fast Outer Solar System Transportation

NSTX

Direct-thrust fusion propulsion concept:

- D^3He fusion reactor using ST concept
- Coaxial Helicity Ejection of plasma directly to mix with hydrogen propellant
- Confined and expanded by a magnetic nozzle to produce thrust
- NSTX provides CHE physics testbed