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NSTX Contributions in the USDOE FESAC Fusion Energy Development Plan

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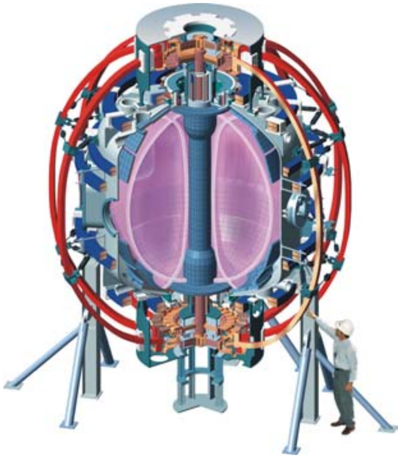


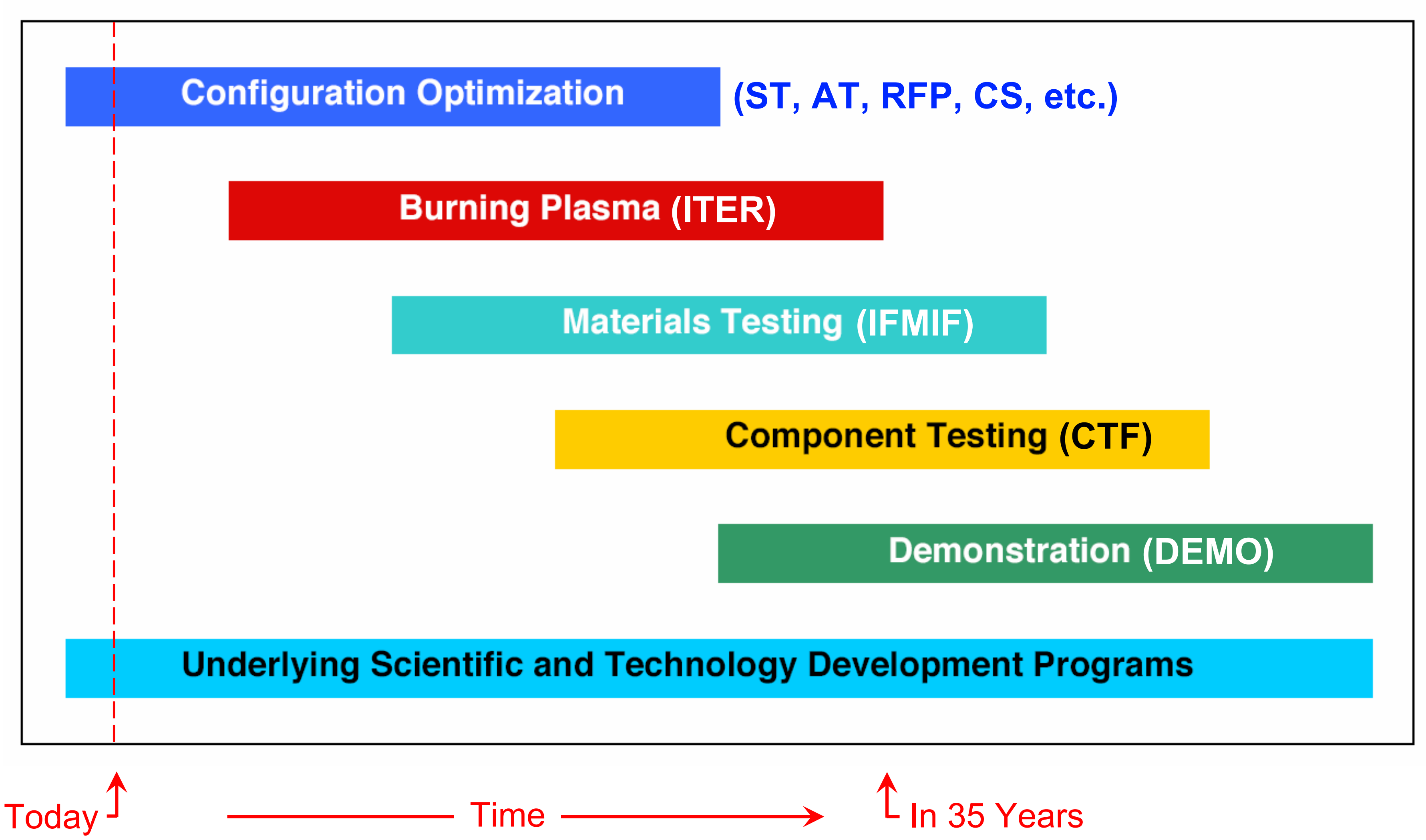
The Spherical Tokamak Workshop 2003
Culham Science Center, Abingdon, U.K.
September 15 – 17, 2003

ST Research Offers Broad Opportunities to Expand Plasma Science & Provide Attractive Next Steps

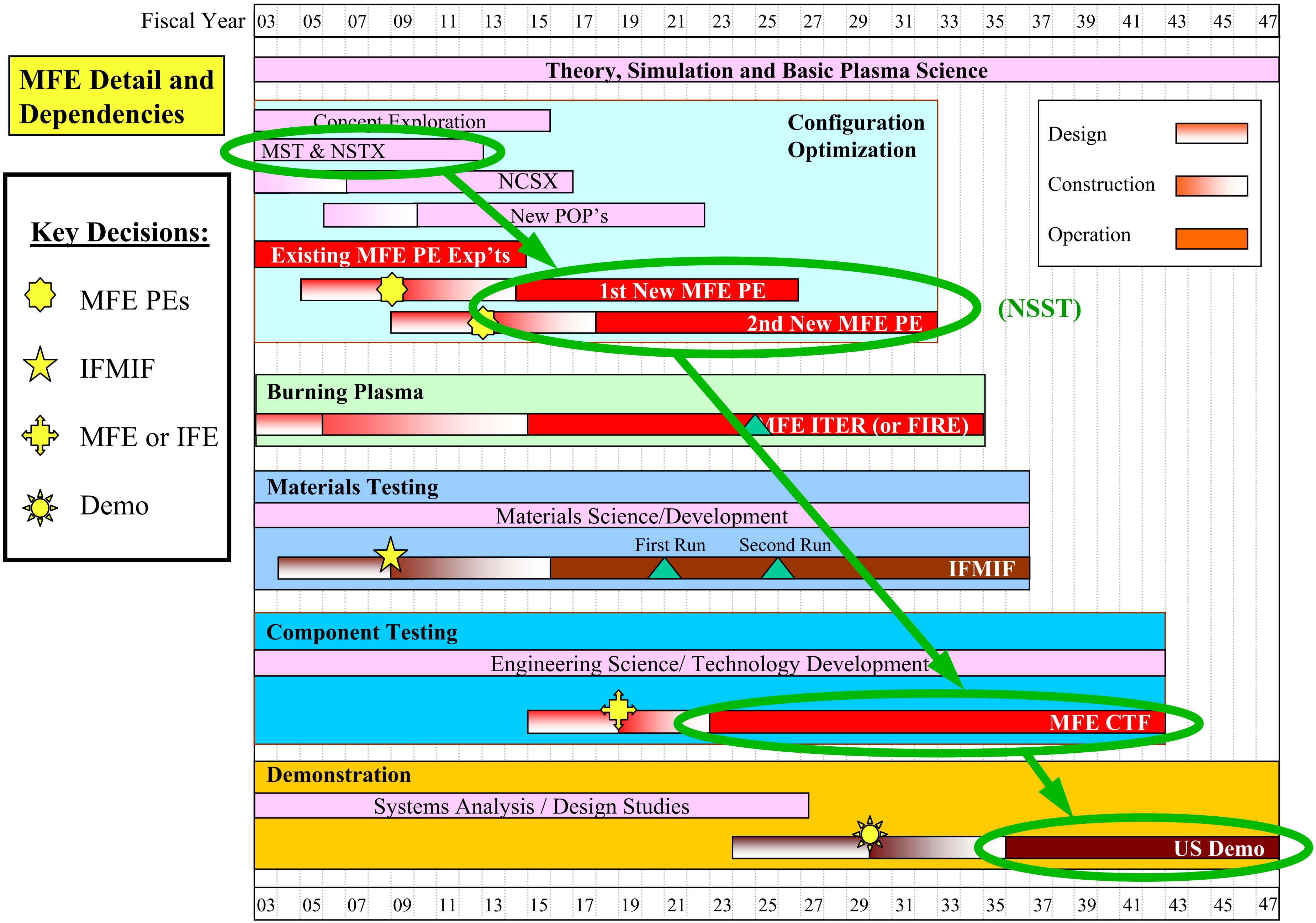
- FESAC outlined Fusion Development Plan
- ST research in plasma science for energy development in this plan
- Physics contributions from present experiments, already close to goal in some key topics.
- Additional contributions needed at the 5 – 10 MA level
- NSTX 5-year plan to carry out this exciting research

FESAC Panel Articulates Key Components Needed for Developing Net Fusion Electricity in 35 Years

(“A Plan for the Development of Fusion Energy,” final report to FESAC, March 5, 2003)

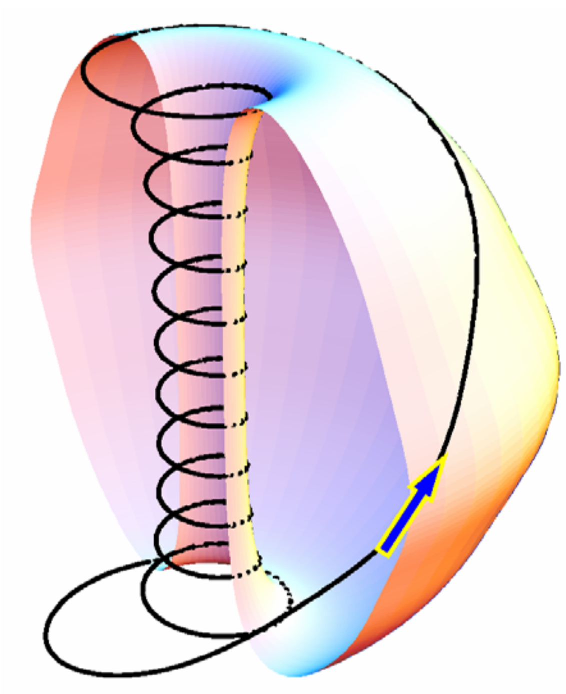


Spherical Torus Is an Integral Part of the Development Plan



Spherical Torus Offers Extended Physics Parameter Space for Studying Plasma Science

Spherical Torus Magnetic Configuration



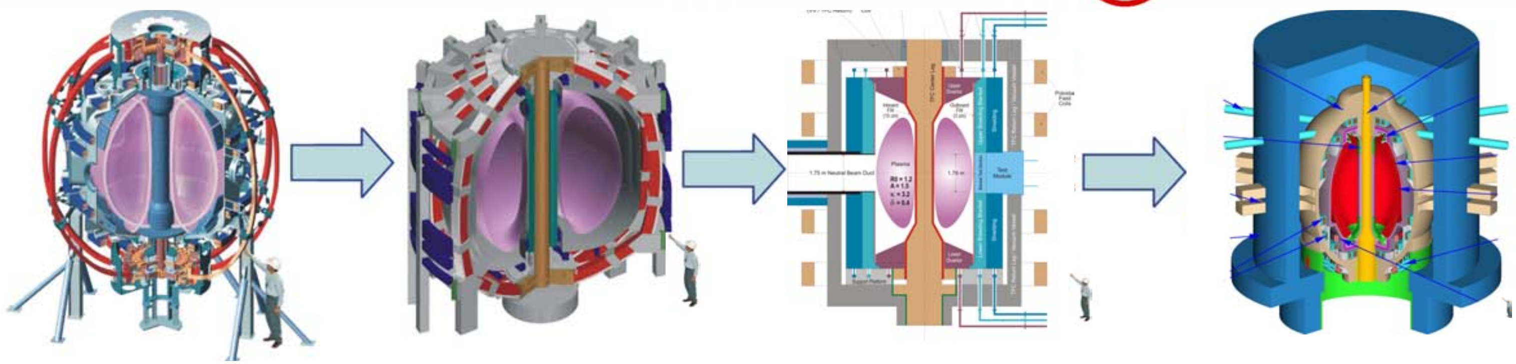
Extended Physics parameter space:

- High β_T ($\leq$ 40%) & central β_0 (~100%)
- Strong plasma shaping & self fields ($A \geq 1.27$, $\kappa \leq 2.5$, $B_p/B_t \sim 1$, $q_{edge} \sim 10$)
- Small plasma size relative to gyro-radius ($a/\rho_i \sim 30–50$)
- Large mirror in core & edge B field ($f_T \rightarrow 1$)
- Large plasma flow ($M_A = V_{rotation}/V_A \leq 0.3$)
- Large flow shearing rate ($\gamma_{ExB} \leq 10^6$/s)
- Supra-Alfvénic fast ions ($V_{fast}/V_A \sim 4–5$)
- High dielectric constant ($\varepsilon = \omega_{pe}^2/\omega_{ce}^2 \sim 50$)

ST Research Helps Establish Expanded Physics Basis, yielding Optimized Future Steps

Plasma Science of Expanded Parameter Space	$\Rightarrow$	Optimized Toroidal Fusion Steps
1) Solenoid-free Startup	$\Rightarrow$	Simplified design, reduced operating cost
2) Reduced turbulence	$\Rightarrow$	Smaller unit size for sustained fusion burn
3) Stable high β_T & β_0	$\Rightarrow$	Lowered magnetic field and device costs
4) Effective wave-energetic particle-plasma interaction	$\Rightarrow$	Efficient fusion α particle, neutral beam, & RF heating
5) Dispersed plasma fluxes	$\Rightarrow$	Survivable plasma facing components
6) Attractive sustained burning plasma properties	$\Rightarrow$	Steady state fusion power source

Nearer-Term ST Steps Must Make Major Advances in I_p, B_T, Steady State, W_L, Solenoid-Free Ops, and Duty Factor



Device	NSTX		NSST		CTF		DEMO
Mission	Proof of Principle		Performance Extension		Energy Development, Component Testing		Practicality of Fusion Electricity
R (m)	0.85		~1.5		~1.2		~3
a (m)	0.65		~0.9		~0.8		~2
κ, δ	2.5, 0.8		~2.7, ~0.7		~3, ~0.5		~3.2, ~0.5
I_p (MA)	**1.5**	**1**	**~5**	**~10**	~10	~12	~25
B_T (T)	**0.6**	**0.3**	**~1.1**	**~2.6**	~1.7	~2.1	~1.8
Pulse (s)	**1**	**5**	**~50**	**~5**	**Steady state**		Steady state
P_{fusion} (MW)	–		**~10**	**~50**	**~77**	**~300**	~3100
W_L (MW/m^2)	–		–		**~1**	**~4**	~4
Duty factor (%)	~0.05		~0.05		**~15**	**30**	60
TFC; Solenoid	Multi-turn; Solenoid		Multi-turn; Solenoid		Single-turn; No-solen.		Single-turn; No-solen.

Physics Basis for ℓ_i, n_G, β's, & High Rational q Can be Developed Today at Relevant Levels

NSTX

	NSTX	*NSST*	*CTF*	*DEMO*
Solenoid-free startup				
Internal inductance, ℓ_i	**0.5**	0.25 – 0.5	~0.25	~0.13
Internal poloidal flux $\propto \ell_i R_0 I_p$ (m-MA)	**0.43**	**1.9 – 7.5**	~3.6	~10
Poloidal field energy $\propto \ell_i R_0 I_p^2$ (m-MA^2)	**0.43**	**9.4 – 75**	~43	~150
Stable high β's				
Nominal Greenwald density, n_G	**~0.5**	~0.5	~0.5	~0.6
Beta normal, β_N	**≤ 8**	8 – 4	4 – 8	~8
Average toroidal beta, β_T	**0.2 – 0.4**	0.4 – 0.2	0.2 – 0.4	~0.5
Beta gradient, β_T' (/m)	**0.25 – 0.5**	0.26 – 0.13	0.13 – 0.26	~0.06
Aligned bootstrap current fraction, f_{BS}	**0.7**	**0.8 – 0.2**	0.5 – 0.8	~0.9
Resonant field errors / B_T (%)	**~ 0.1**	**~ 0.03**	**~ 0.01**	< 0.01
High q values in plasma	**≥ 1 – 3**	≥ 1 – 3	> 2 – 3	> 3

But, Physics Basis for Non-inductive Poloidal Flux & Energy, I_{BS}, & Minimum Error Fields Requires Larger Test.

Physics Basis for Low ν^*, High Ion τ_E, $M_{Alfvén}$ & Flow Shear Can be Developed Today at Relevant Levels

NSTX

	NSTX	*NSST*	*CTF*	*DEMO*
Reduced turbulence & improved confinement				
Average temperature (keV)	**~1**	**4 – 8**	~10	~20
Average collisionality, ν^*	**0.05 – 0.2**	0.03	~0.02	~0.02
Thermal ion minor radius, a/ρ_i	**40**	**80 – 120**	~100	~150
Ion confinement neoclassical factor, H_{Neoc}	**~1**	~1	~1	~1
Electron confinement H-mode factor, H_{98e}	**~0.7**	**~1**	~1	~1
Alfvén Mach number, $M_A = V_{Plasma}/V_{Alfvén}$	**0.3**	~0.3	~0.3	~0.1
Flow shearing rate (10^5/s)	**1 – 10**	1 – 10	1 – 10	0.3 – 3

But, Physics Basis for High Temperature, ρ^* & Electron τ_E Requires Larger Test.

- Reactor Relevant ρ^*, T, and H_{98e} can be met in NSST.

Physics Basis for High $\omega_{pe}^2/\omega_{ce}^2$, ρ^*_{fast}, & Velocity Can be Tested Today at Relevant Levels

NSTX

	NSTX	*NSST*	*CTF*	*DEMO*
Effective heating and sustainment				
$\omega_{pe}^2/\omega_{ce}^2$	**50**	50 – 20	~ 20	~ 25
Beam ion minor radius, a/ρ_{Beam}	**5**	15 – 22	~ 22	~ 34
Fusion α minor radius, a/ρ_α	–	N/A – **6**	~ 6	~ 14
$V_{Beam}/V_{Alfvén}$	**4**	1	~ 1	~ 1
$V_\alpha/V_{Alfvén}$	–	N/A – **4**	~ 4.5	~ 5
Dispersed plasma fluxes				
$P/R\Delta_H$ (MW/m), $f_{rad} = 0.5$	**8**	**13 – 20**	**20 – 40**	**87**
Integrated attractive operations				
τ_{pulse}/τ_{skin}	**~ 3**	**~ 10 – 0.5**	**→ ∞**	→ ∞

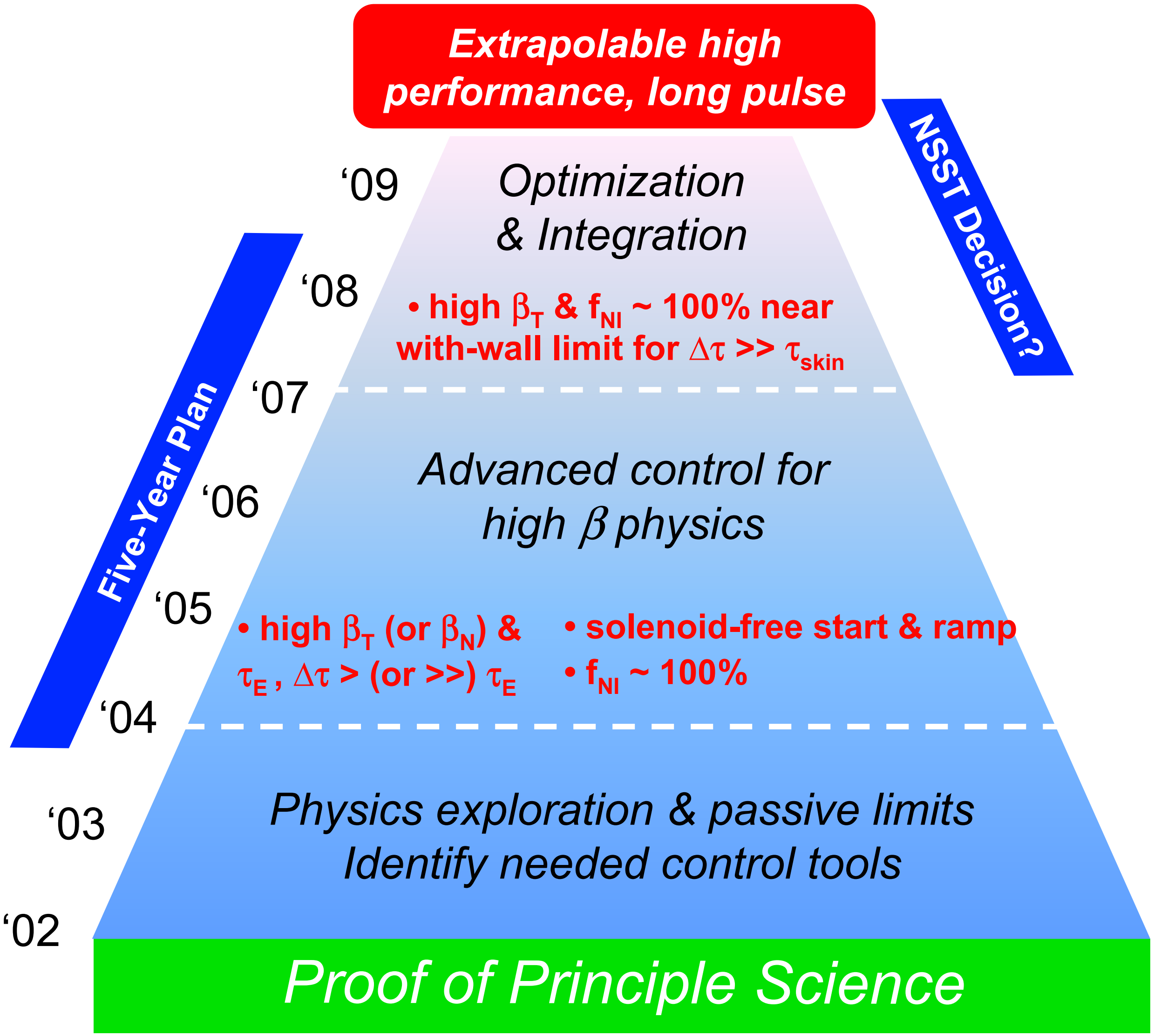
But: Physics Basis for High Heat Flux & Integrated Steady State Operations Requires Larger Tests.

- Innovative high heat flux surfaces, such as lithium, must be tested

Proposed 5-Year Research Aims to Demonstrate Long Pulse, High Performance Plasma Operations

NSTX

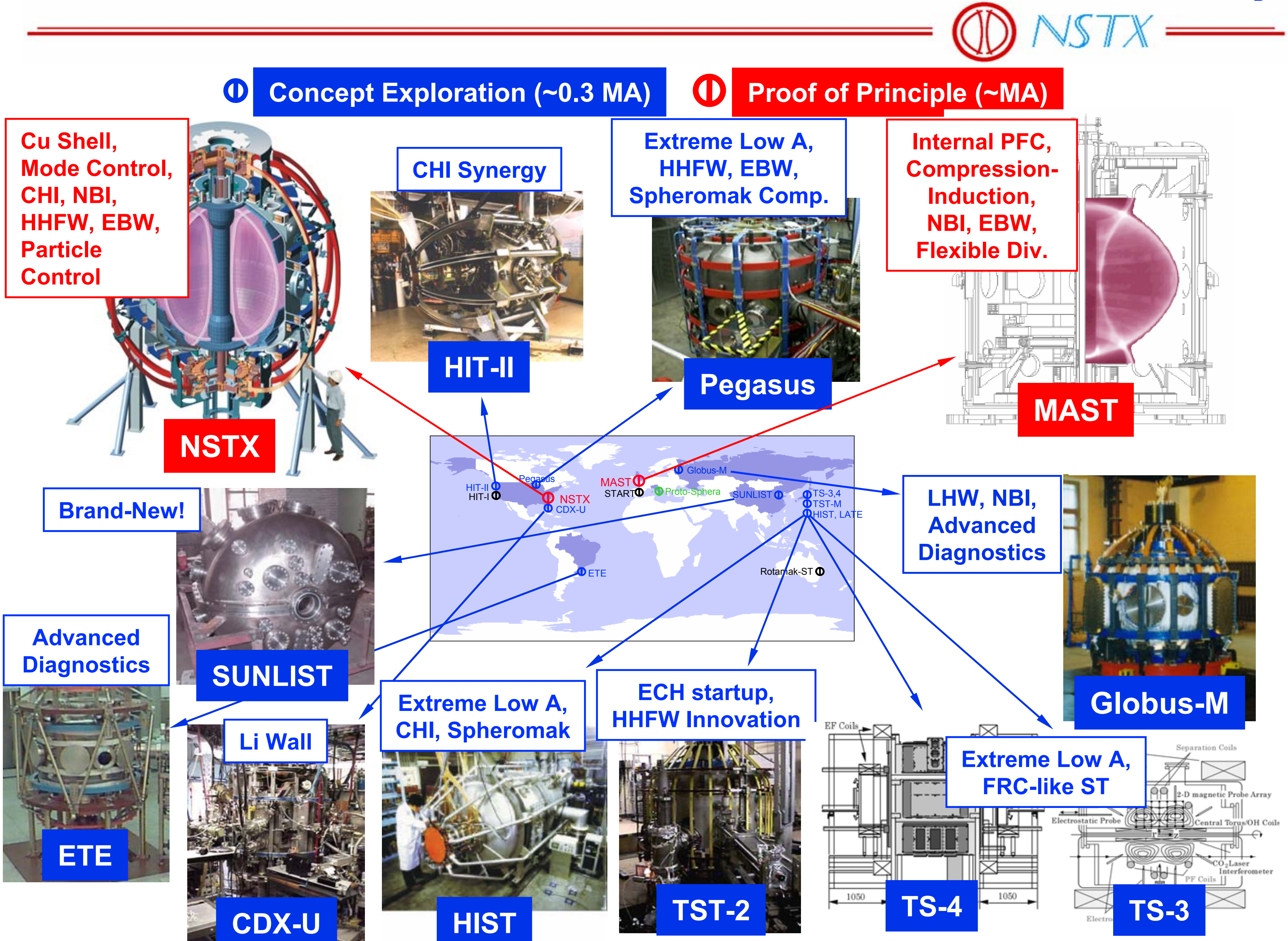
- **5-year goals**
  - Determine attractiveness
  - Establish science basis for extrapolable high performance and long pulse
  - Database for next PE step (NSST), and in turn for CTF & DEMO
- **Supporting**
  - Implement new key diagnostics
  - Advance control tools & facility upgrades
  - Carry out theory, analyses & modeling



Diagnostic and Facility Upgrades are Key Components of Research Plan

Diagnostics	Facility
MHD – EBW radiometer, fast ΔT_e – MSE/CIF, LIF polarimeter [Nova] **Transport & Turbulence** – High & low-k μ-wave scattering [UCLA, UC Davis] – μ-wave imaging reflectometer [UCD] – GPI – Planar LIF edge fluctuations [C-Mod, DIII-D, Nova, PSI, SBIR] **Edge & Divertor** – Divertor laser Thomson scattering **Astrophysics & Diagnostic Development** – X-ray imaging crystal spectrometer [LLNL, Chandra, C-Mod, KSTAR, Adv. Diagnostics Program]	**Very High β** – Ex-vessel field and mode control coils [Columbia U] – Modification of PF1A (k=2.6, δ=0.6) – Active mode control systems [CU] **CD, MHD, Integrated Scenarios** – EBW (1→4 MW source power) [VLT, MIT, ORNL] **Startup** – EBW – CHI absorber control coils – Outboard PF-only induction **Particle & Edge Plasma Control** – Cryopumps – Lithium pellets, coating, flowing surface module [VLT-PFC, CDX-U]

NSTX Is Part of the Worldwide ST Research Community



ST Research Offers Broad Opportunities to Expand Plasma Science & Provide Attractive Next Steps

- FESAC of USDOE articulated a plan to deliver net fusion electricity in 35 years, of which ST is integral part
- ST research studies an expanded physics basis to optimize future steps in this plan: e.g., NSST, CTF
- Physics basis for many key topics can be tested in present ST experiments
- Physics basis for additional key topics will require tests at the 5 – 10 MA level
- The NSTX national team is part of worldwide ST community to carry out this exciting research

NSTX National Team & Contributors

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