ST Issues and Opportunities for Performance Extension (PE) and Burning Plasma (BP) Physics Testing

1. Tentative 10-MA concept
2. Data required from PoP
3. Scientific opportunities of PE
4. Cost scale, technology, savings

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Magnetic Fusion Concepts WG
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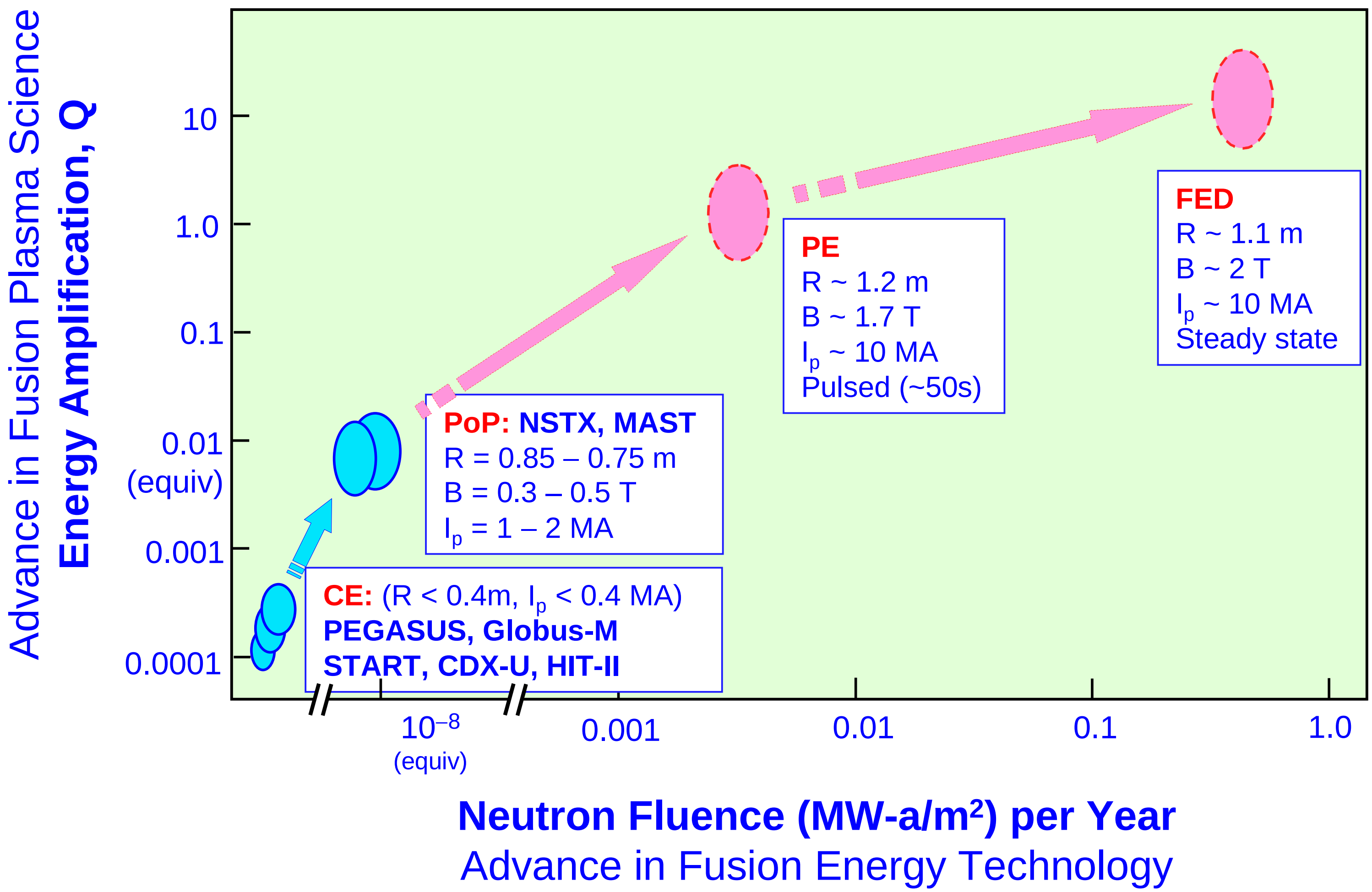
Small-Size ST Devices Have Been Envisioned for PE and FED Stages



ST PE Device Has Potential for Testing Long-Pulse D-D, and Pulsed Q~1 and Q~10

Near-Term ST Devices	NSTX/MAST		DTST			VNS	PP-like
Development Stage	Proof of Principle		Performance Extension			Fusion Energy Development	
Mode of operation	No-Wall	Wall-Stabilized	D-D H~1	Q~1 H~1	Q~10 H~3	Q~1 Driven	Q>10 Sustained
Major radius (m)	0.85		~1.2			~1.1	
Aspect ratio	≥1.25		1.4			1.4	
Toroidal field (T) at major radius	0.3–0.6		0.9	1.7	1.7	2.1	
Plasma current (MA)	1–2		~5	~10	~10	~10	
Edge safety factor	10–5		~10			~10	
Plasma cross section elongation	2–2.5		3			3	
Normal beta β_N (% Tm/MA)	5	8	3.5	3.5	5	4	8
Average toroidal beta β_T (%)	25	40	23	23	34	27	50
Average density (10^{20} m^{-3})	0.5	0.5	0.5	1	0.7	1.1	1.2
Average temperature (keV)	1	1.6	3	7	15	9	16
∇p-driven current fraction (%)	40	70	50	50	90	50	90
Plasma drive power (MW)	6–11		25	35	4	40	25
NBI energy (keV)	70–80			110		400	400
Fusion power (MW)	–		–	36	40	66	260
H (ITERH98H) [Kardaun, 1998]	1–2		1	1.2	3	1	3
Plasma flattop (burn) time (s)	1–5		~100	~10	~10	~1000	
Neutron wall load (MW/m^2)	–		0.6			1.0	4.0
Neutron fluence/year (MW/m^2)	–		~0.003			~0.3	~1.2

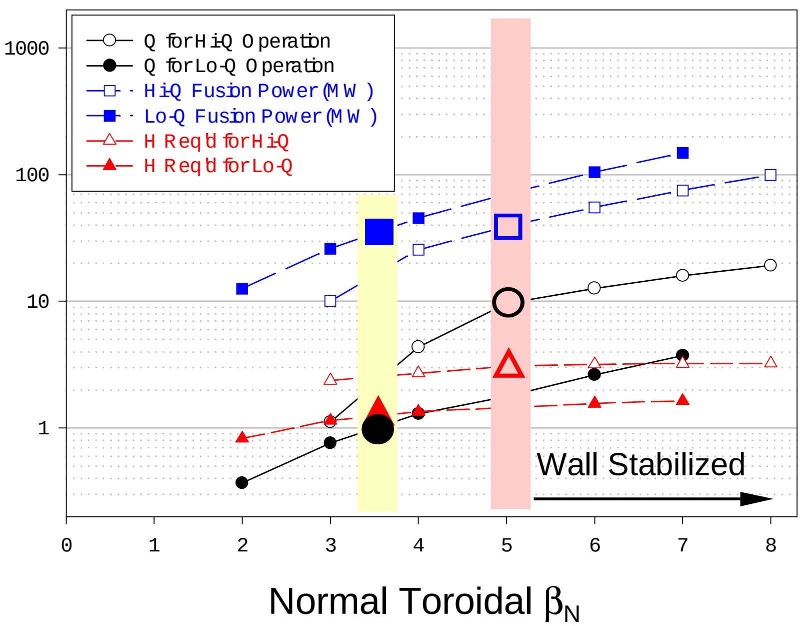
Q~1 and Q~10 Modes Are Possible for 10-MA PE Device Within "No-Wall" Regime

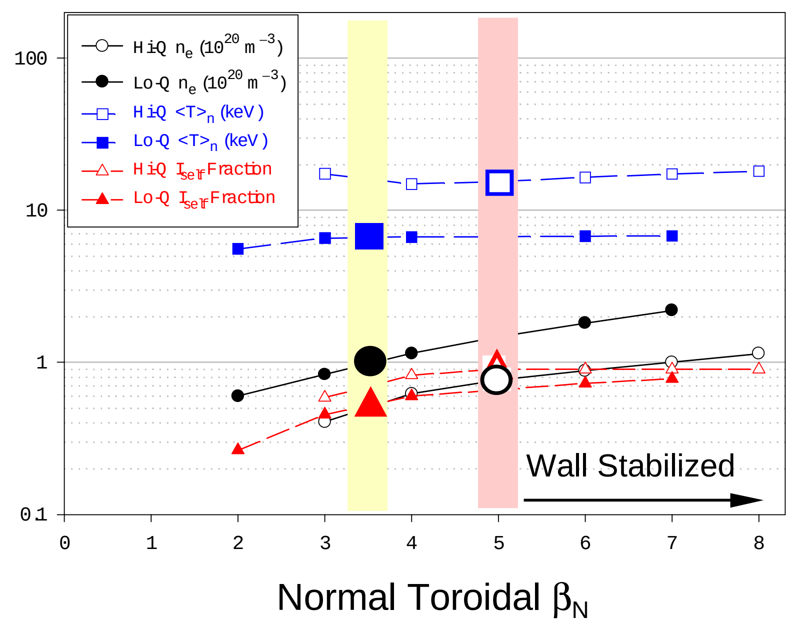
VNS Mode

- < "no-wall" β_T limit
- β_N ~3.5, $f_{\nabla p}$ ~ 0.5, Q~1

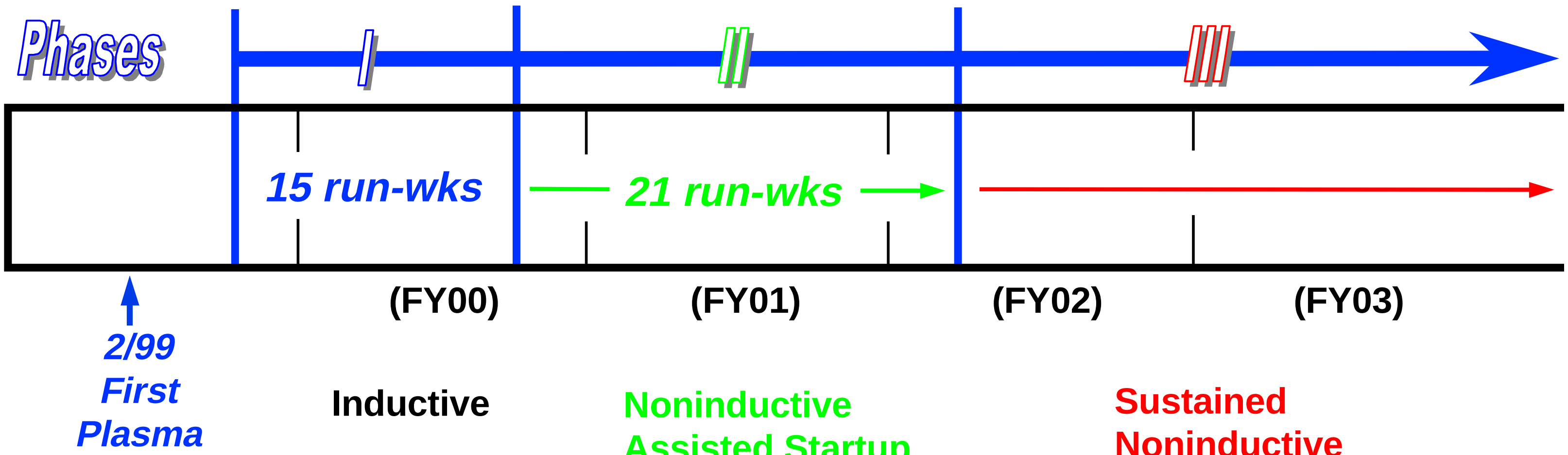
High-Q Mode

- ~"no-wall" β_T limit
- β_N ~5, $f_{\nabla p}$ ~ 0.9, Q~10





NSTX Research Plans Capabilities to Investigate Key ST Physics Issues in the Next 4-5 Years



	Inductive	Noninductive Assisted Startup	Sustained Noninductive Operation
Toroidal Beta, β_T		→ 25% (no-wall limit)	→ 40% (wall stabilized)
Bootstrap Current		→ 40% (no-wall limit)	→ 70% (wall stabilized)
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
CHI Startup	→ 0.2 MA	→ 0.5 MA	~ 0.5 MA
Measure	$T_e(r)$, $n_e(r)$	j(r), $T_i(r)$, flow	**turbulence**

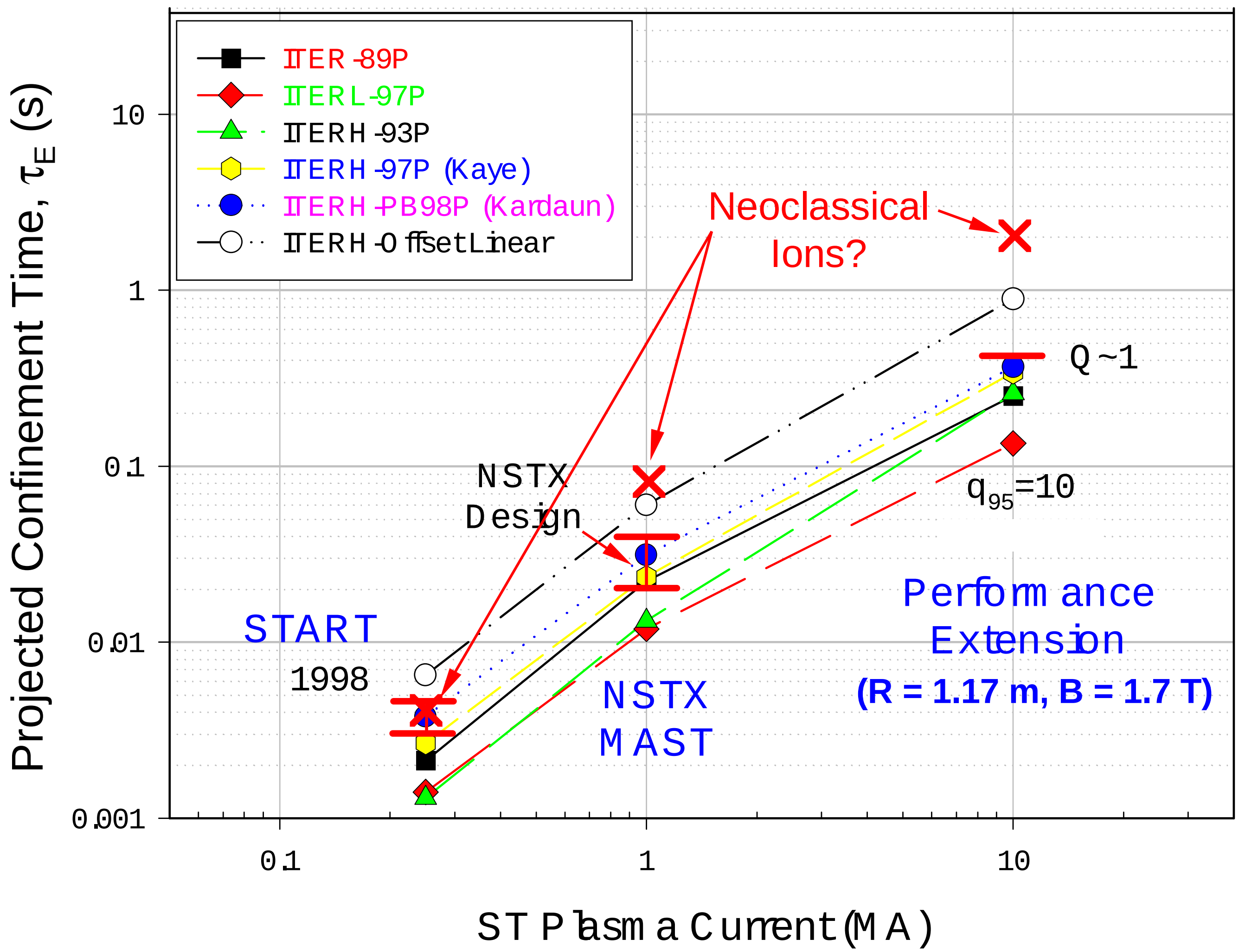
Database Needed from PoP to Support Design of PE Device (Driven VNS Mode)

- Properties of noninductive ramp-up of large current (≥0.5 MA, in ~ 5 s)
- Plasma heating up to the "no-wall" limit (β_T ~ 25%, ℓ_i ~ 0.2–0.3, q_0~2–3)
- Confinement scaling in ρ* and ν* and H(ITER98H) ~ 1, with p-profile consistent with above β_T limit
  - Factors in ρ* and ν* are ~ 0.7 and 0.1, respectively, from PoP to PE
- Maintaining p and j-profiles for several τ_E (~1 s), then for ~ τ_{skin} (~3 s), for $I_{\nabla p}/I_p$ ~ 40%, I_{CD}/I_p ~ 60%
- Conditions for NTM and large-ELMs avoidance
- NBI ion orbit confinement (HHFW included) for H&CD with minimized TAE, "fishbone" impact
  - ρ_{NB}* and Δ_{NB}/a in PoP similar to ρ_α* and Δ_α/a in PE
- Plasma boundary and divertor operation
  - Inboard limited, ND: SOL M_B~4, f_{exp}~10, L_{conn}~10 m→ heat flux ~1 MW/m^2, lower H
  - DN, SN: SOL M_B~2, f_{exp}~2, L_{conn}~4 m→ heat flux ~10 MW/m^2, higher H

Additional Database Needed from PoP to Support Design of Limited-Pulse BP Test in PE Device

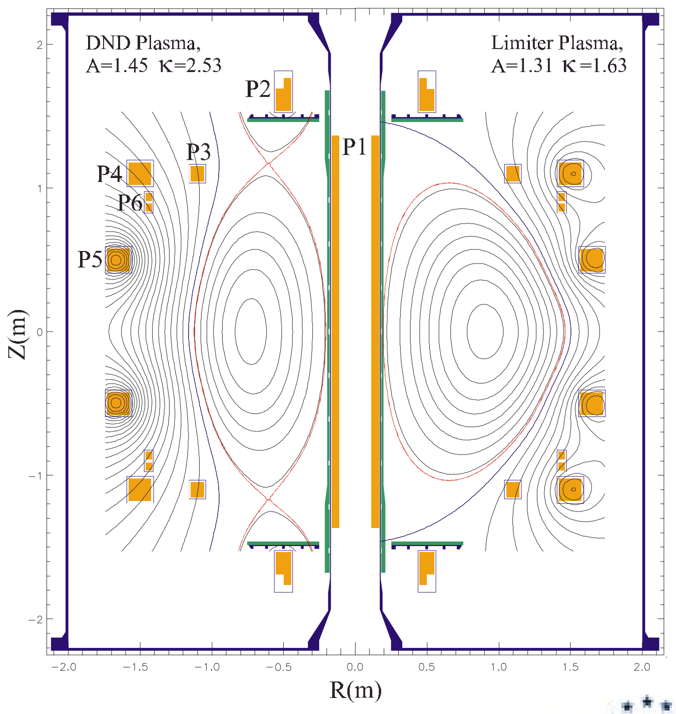
- H(ITER98H)~2 via broad μ-turbulence suppression (ITB formation)
  - Understand degree of neoclassical ion transport
- Maintaining p and j-profiles for several τ_E (~2 s) without reducing “no-wall” β limit
  - Compatibility among heating, transport, and p profiles
  - May need to adjust ρ_{NB}*, Δ_{NB}/a, and HHFW, NBI parameters
- Plasma boundary and divertor operation
  - Reduced heaitng power (to ~6 MW) reduces DN, SN divertor heat flux ~5 MW/m^2, which is consistent with higher H.

Confinement Obtained in NSTX Aims to Enable Projections to the Next Step

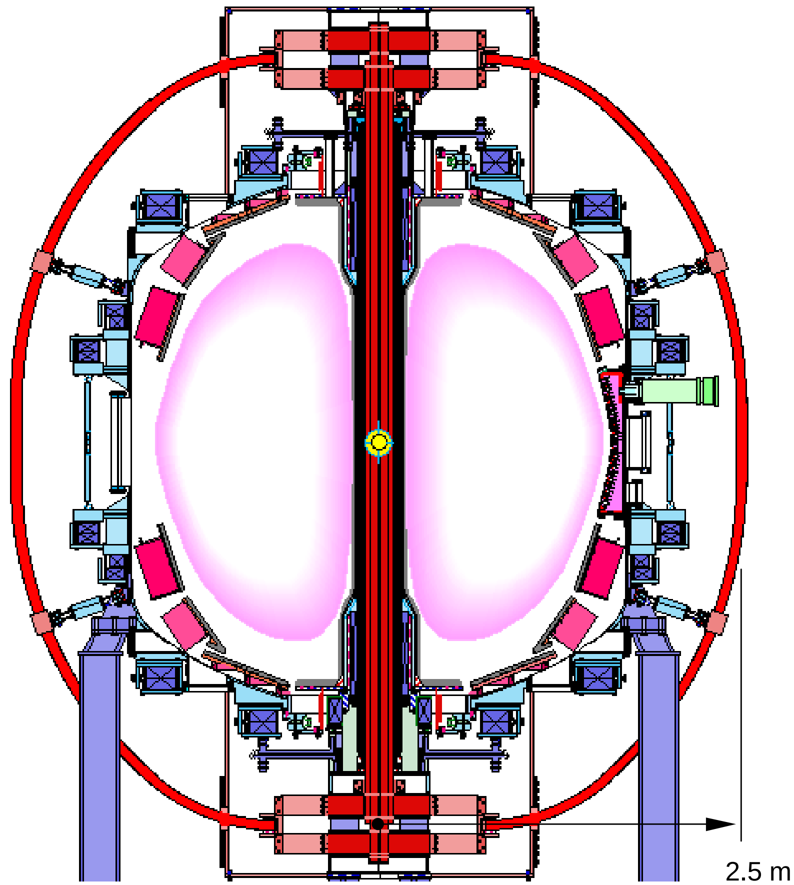


Complementing Capabilities of MAST and NSTX Strengthen World ST Fusion Research Program

MAST (U.K.)



UKAEA Fusion



• **Nearby Stabilizing Shell**	**No**	**Yes**	**(beta limits)**
• **Poloidal Field Coils**	**In-vessel**	**Ex-vessel**	**(plasma shaping flexibility)**
• **RF Heating&Current Drive**	**ECH**	**HHFW**	**(efficient sustainment)**
• **Plasma Current Startup**	**Compression**	**CHI**	**(eliminate solenoid)**

⇒ Development of comprehensive database for Performance Extension step

Projected Opportunities and Contributions by PE Device for Driven VNS of Similar Parameters

- Noninductive initiation and ramp-up of large current (~10 MA, in ~40 s)
- Plasma heated up to the "no-wall" limit (β_T ~ 25%, ℓ_i ~ 0.2–0.3, q_0~2–3)
- Confinement scaling in ρ^* and ν^* and H(ITER98H) ~ 1 with p-profile consistent with above β_T limit
- Maintaining p and j-profiles for several τ_E (~10 s) for $I_{\nabla p}/I_p$ ~ 50%, I_{CD}/I_p ~ 50%, Q~1, P_{DT}~40 MW
- Maintaining p and j-profiles at half I_p and B_T for > τ_{skin} (~100 s) in D-D
- Conditions for NTM and large-ELMs avoidance
- Fusion α confinement (HHFW included) and plasma heating with minimized TAE, "fishbone" impact
- Plasma boundary and divertor operation
  - Inboard limited, ND: SOL M_B~5, f_{exp}~20, L_{conn}~15 m$\rightarrow$ heat flux ~2 MW/m^2, lower H
  - DN, SN: SOL M_B~2, f_{exp}~2, L_{conn}~7 m$\rightarrow$ heat flux ~20 MW/m^2, higher H

Additional Opportunities and Contributions of PE Device for Limited-Pulse BP Test in PE Device

- H(ITER98H)~3 via broad μ-turbulence suppression (ITB formation)
  - Understand degree of neoclassical transport
- Maintaining p and j-profiles for several τ_E (~10 s) without violating "no-wall" β limit (β_T ~ 34%, $I_{\nabla p}/I_p$ ~ 75–90%, ℓ_i ~ 0.1–0.2, q_0~3–4)
  - Q~10, P_{DT}~40 MW, $P_{H\&CD}$ ~ 4 MW!
  - Compatibility among α-heating, transport, and p profiles
  - May need to adjust in ρ_{NB}*, Δ_{NB}/a
  - ~1 Wb solenoid provided to maintain 10-s flattop if needed
- Plasma burn dynamics
- Eases DN, SN divertor operation (~10 MW/m^2), consistent with H~3.

Note: D-T operation for > τ_{skin} to be tested in FED stage

Scale of Cost ($M) for Fully Enabled National PE Facility, Schedule, Plasma Technology, Savings

Costing Groups	NSTX	PE	Comments
Magnets + support	6	70	Scale with volume $\times B_T^2$
Vessel components	7	60	Scale with area $\times$ 3 (no Carbon)
H&CD systems	9	100	NBI-32MW ($2.5/W) HHFW-8MW ($1.5/W) EBW-4MW ($2/W)
Facility Modification	8	40	NSTX utilized ~20%
Diagnostics	2	20	Basic set at TFTR level
"Igloo" shields		20	30 for TFTR
Total Cost Scale	**32**	**310**	**D-site facility valued at ~300**

- Steady state NBI, HHFW upgrade; commercial ECH system ~70 GHz
- Conceptual design to estimate cost and schedule requires ~$30M effort; full project could begin in 5 years if approved
- Recommend *physics scoping in FY2000* to guide NSTX research