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Spherical Torus

ST Development Path

The ST is a cost effective element of the fusion energy development path to an attractive Demo

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General Atomics, Jan. 13-14, 2003

ST has attractive features for fusion energy

A cost effective path to an attractive Demo

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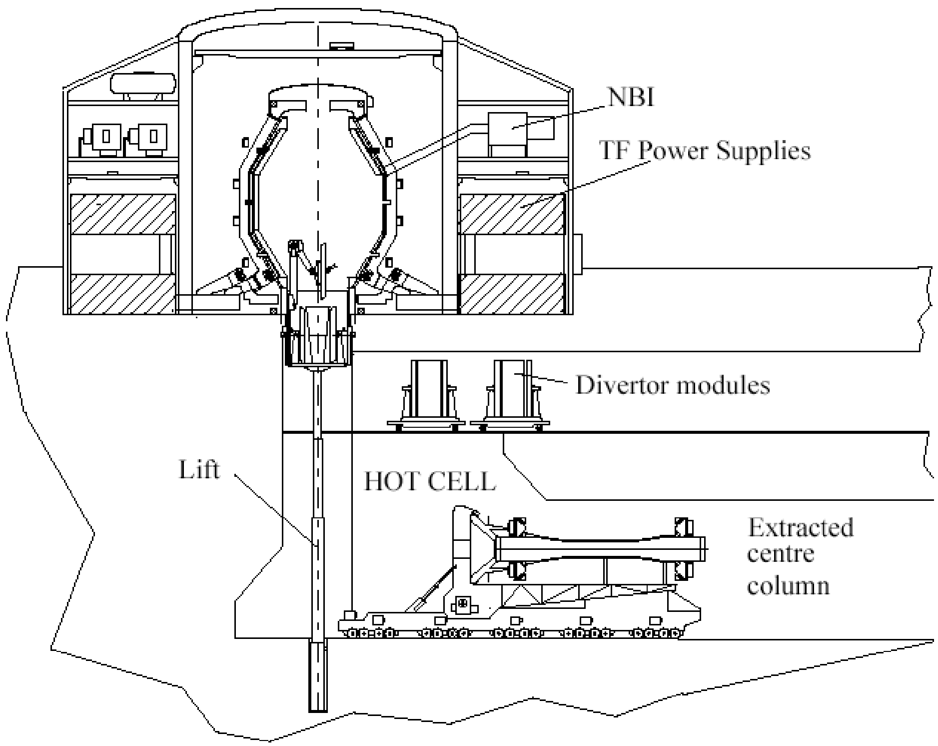
- Potential physics advantages:
  - Full bootstrap without reversed shear
  - Reduced NTM drive
  - Reduced halo current disruption forces
- Simplified configuration for maintenance
  - Once center column removed – similar to IFE
- Low technology TF magnet
- Natural application to CTF mission.

UKEA ST Power Plant Maintenance Concept

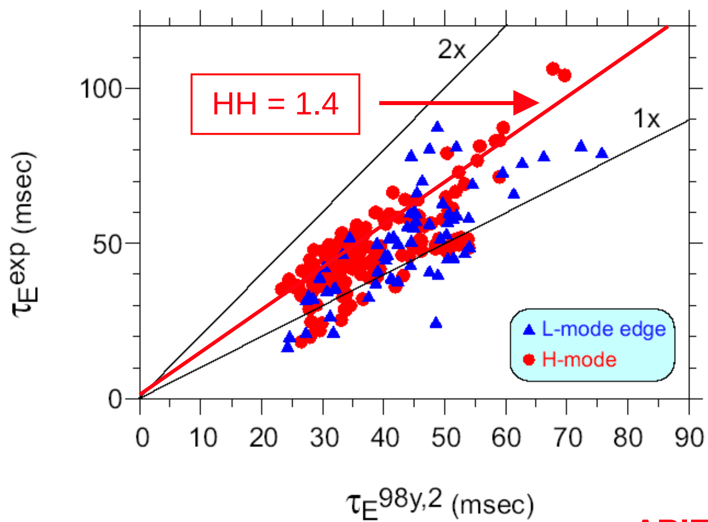


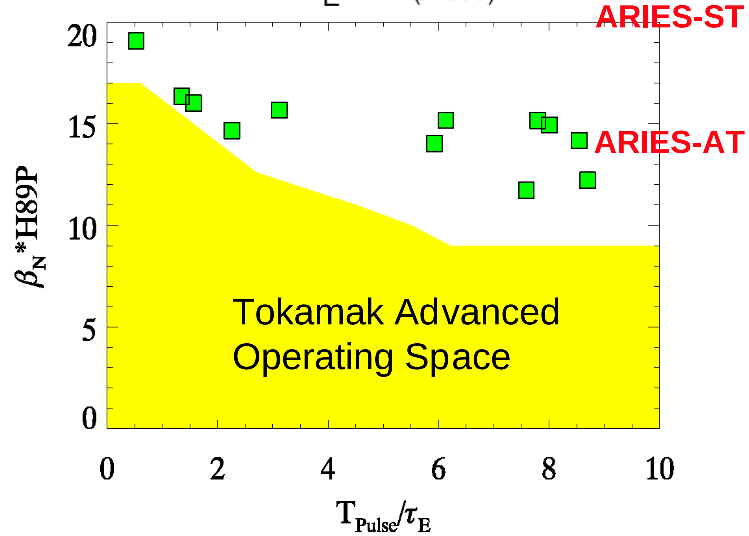
Research goal: Reduction of recirculating power

Rapid Progress Achieved In Spherical Torus Physics

Spherical Torus

- **High beta**
  - $<\beta_T> \approx 35\%$ at 1. 2MA
  - $\beta_N \leq 6.5$
  - 30% over no-wall limits
- **Good heating and confinement**
  - H (98pby2) ≡ HH ≤ 1.7
  - H (89P) ≡ $H_{89P} \leq 2.5$
- **Progress on integrated scenarios**
  - $\varepsilon\beta_p \sim 1$ at 800 kA, $f_{NI} \sim 60\%$
  - $<\beta_T> \approx 16\%$, $\beta_N \approx 6$, $H_{89P} \approx 2.5$
  - τ-pulse > τ-skin or 8 τ_ ($V_{loop} \sim 0.1V$)
- **Boundary Physics**
  - Good H-mode access ($P_{thesh} < 1$ MW)





ST Success Built Upon Tokamak Foundation

ST Development Path
Contributing toward attractive Demo

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I. PoP/CE facilities to develop ST innovations for attractive Demo

- Ultra-Low-Aspect Ratio ST (ST-Spheromak-boundary) - PEGASUS
- Practical non-OH plasma start-up method(s) - NSTX, HIT-II
- High performance PFCs (Liquid Lithium) - CDX-U
- Establishing ST physics principles at <T> ~ 1 keV range - NSTX, MAST

II. A PE facility NSST (Next Step ST) to provide physics basis for Demo and CTF at fusion plasma parameters

- Explore high beta physics for attractive Demo (ST or tokamak)
- Provide physics basis needed for CTF construction

  e.g., ~ 5 MA non-ohmic start up and non-inductive sustainment

III. A Compact CTF facility to provide technology basis for Demo

- Adequate neutron fluence and divertor heat load to develop attractive blanket and divertor modules.
- Low tritium consumption and longer term self-sufficiency (P_{fusion} ~ 70 - 250 MW)
- Minimize cost and optimize reliability through compactness and design simplicity
- Broadens BP operational database to widen parameter range

Three Representative ST Facilities

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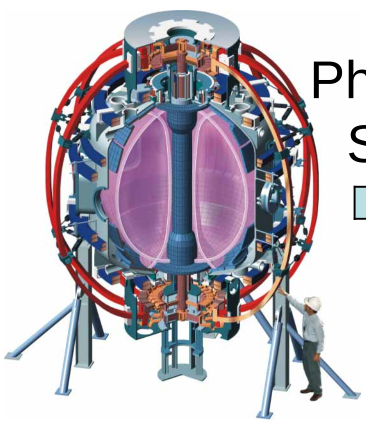
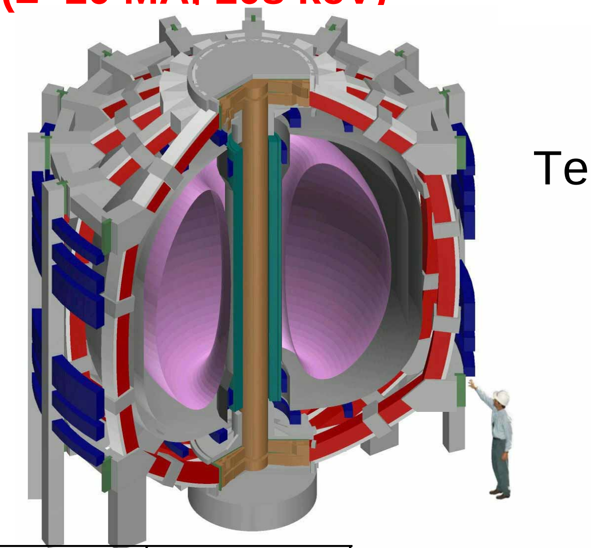
NSTX and MAST
(≈ 1 MA, keV)



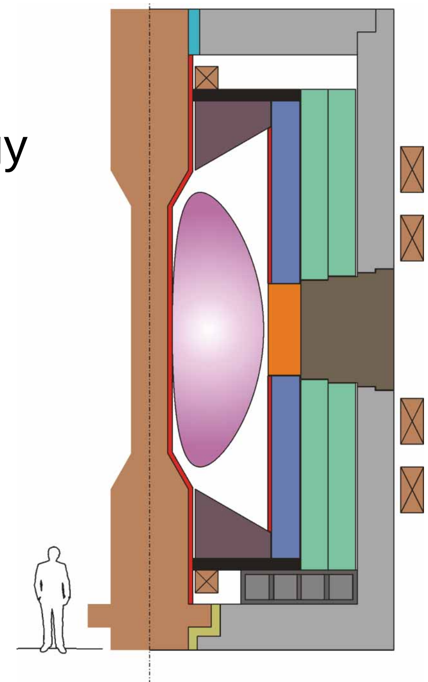
Physics Step

Next-Step ST (NSST)
(≤ 10 MA, 10s keV)



Technology Step

Component Test Facility (CTF)
(Steady-State; Nuclear Facility)



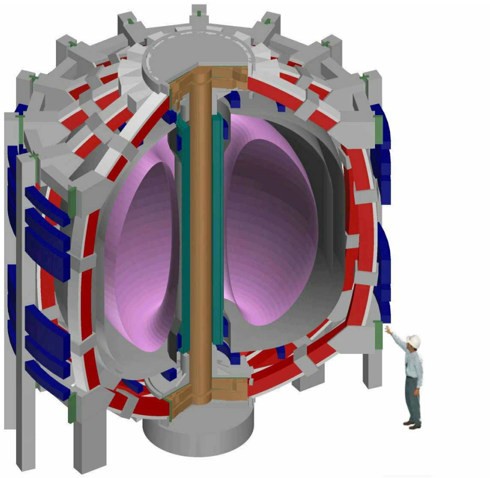
	NSTX (achieved)	NSST (base)	CTF (base-adv.)
R(m)	0.85	1.5	1.2
a(m)	≤ 0.65	≤ 0.94	0.8
κ, δ	2, 0.8	2.7, 0.6	3, 0.4
Ip (MA)	≤ 1.5	5 - 10	~ 12
B_T(T)	0.3 - 0.6	1.1 - 2.6	~ 2.4
β_N H_{89P}	~ 15	15 - 10	10 - 22
P/R (MW/m)	≤ 12	≤ 30	37 - 67
T-pulse (sec)	~ 1	50 - 5	Steady-state
TF	Multi-turn	Multi-turn Cryogenic	Single-turn

- Simple Design
- Very limited diagnostic access

NSST Mission Elements

NSST

- ST Physics at Fusion Parameters
  - Non-Ohmic Start-up and Non-inductive Sustainment
  - Plasma Confinement and Stability
  - Power and particle handling
  - Alpha physics
  - Advanced ST Physics



- Develop Adv. ST Physics scenarios for Attractive Demo
- Provide physics basis for an ST-based compact CTF
- Contribute to General plasma / astrophysics/ fusion science
  - high β waves/turbulences, energetic particles, magnetic reconnections

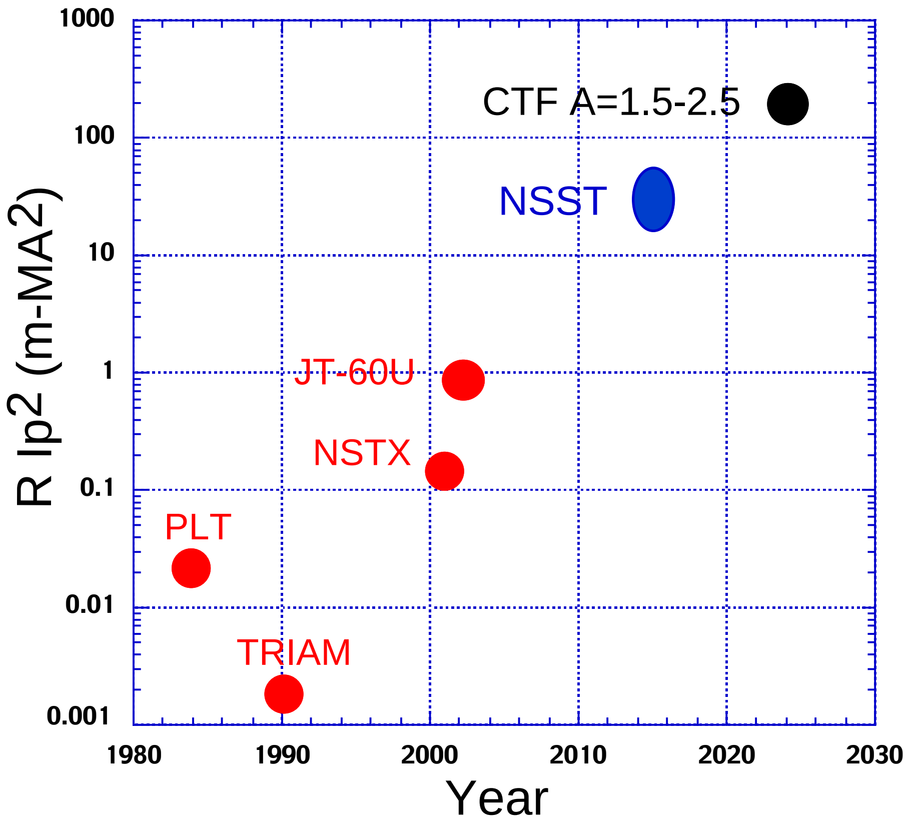
Non-Ohmic Plasma Start-Up
Key Early Research Topic on NSST

NSST

- Attractive fusion CTF and PP design requires OH elimination
  - Compact CTF requires elimination of OH regardless of A
  - ARIES-AT and ARIES-ST design assumes no OH.

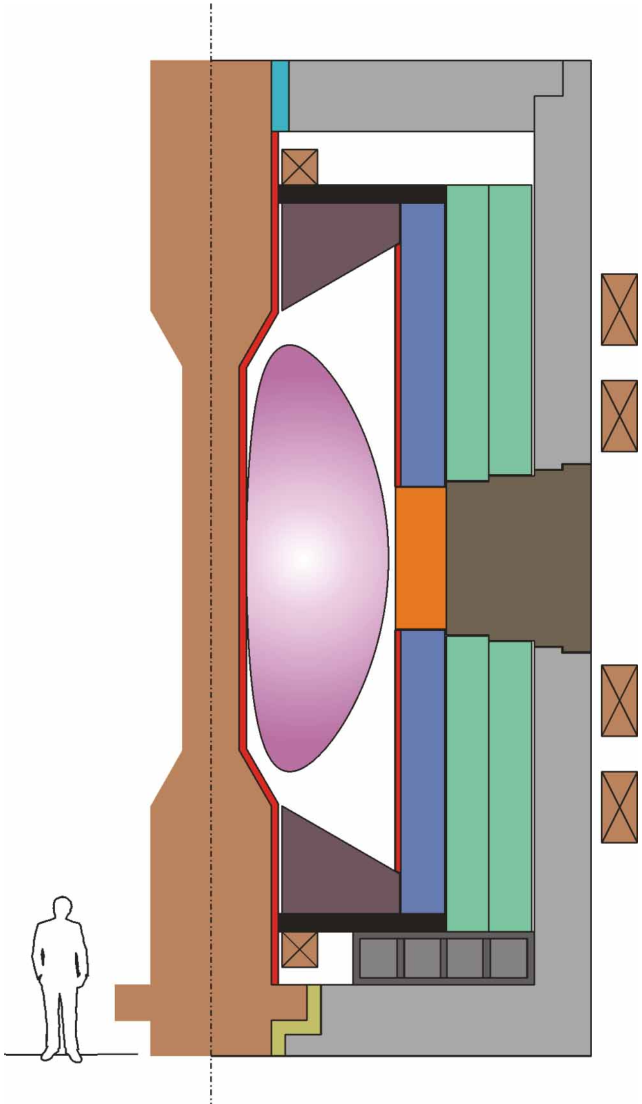
- Several methods demonstrated at sub MA level and high q(a) ≥ 15:
  - JT-60U (small "OH", ECH, LHCD, poloidal field, bootstrap, NBI, negative NBI ~ 600 kA)
  - PLT (LHCD ~ 130 kA), WT, JIPPT-IIU, TRIAM
  - NSTX (CHI ~ 400 kA), HIT, DIII-D, CDX-U

- **Physics uncertainty makes $R\ I_p^2 > 10$ m-MA^2 (~PF energy) demonstration at relevant q(a) essential for the compact CTF without OH.**



NSST with 50 sec pulse length and $R\ I_p^2 \leq 50$ m-MA^2 is designed to be a good test bed for such demonstration.

Single Turn TF Leads to an Attractive ST CTF



R = 1.2m, a = 0.8m

Wall Loading at Test Modules (MW/m^2)	1.0	3.0
HH (ITER98pby2)	1.4	1.8
Applied toroidal field (T)	2.4	2.2
Plasma current (MA)	12.6	11.4
Normalized beta (β_N)	4.1	7.0
Toroidal beta (β_T, %)	26.8	45.1
n/n_{GW} (%)	17	52
Q (using NBI H&CD)	2.4	5.8
Fusion power (MW)	72	214
Number of radial access ports	7	7
Radial access test area (m^2)	12.8	12.8
P_{Heat}/R (MW/m)	37	67
Tritium burn rate (kg/full-power-year)	4	12
Total facility electrical power (MW)	286	272
Fraction of neutron capture (%)	81.6	81.6
Local T.B.R. for self-sufficiency	1.23	1.23
Toroidal field coil current (MA)	14.6	13.2
Center post weight (ton)	89	89
Capital cost ($B) with 40% contingency	1.47	

Key Physics Issues are Handled in a Step Wise Fashion

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- α–physics in high β is needed for design of Demo.
- Non-dim. parameters are similar for major ST steps.

	NSTX	NSST	CTF	ARIES-ST
ν^*	0.2	0.04	0.02	0.015
a/ρ_i	35	130	108	140
β_T	≤ 40%	≤ 40%	22 - 37%	> 50%
β_α / β_T		~ 4 %	18 % - 7%	9.6%
V_{NBI}/V_{Alfven}	3	0.7		
V_α/V_{Alfven}		4.4	5.8	5

- $I_p \geq 5$ MA in NSST enables confined α-particles orbit.
- Q ~ 5 - 10 possible at HH = 1.7 in 10 MA NSST

NSST with DT capability + ITER/FIRE provides BP data to Demo

Fusion Energy Development Path Defines Key Decision Points for ST

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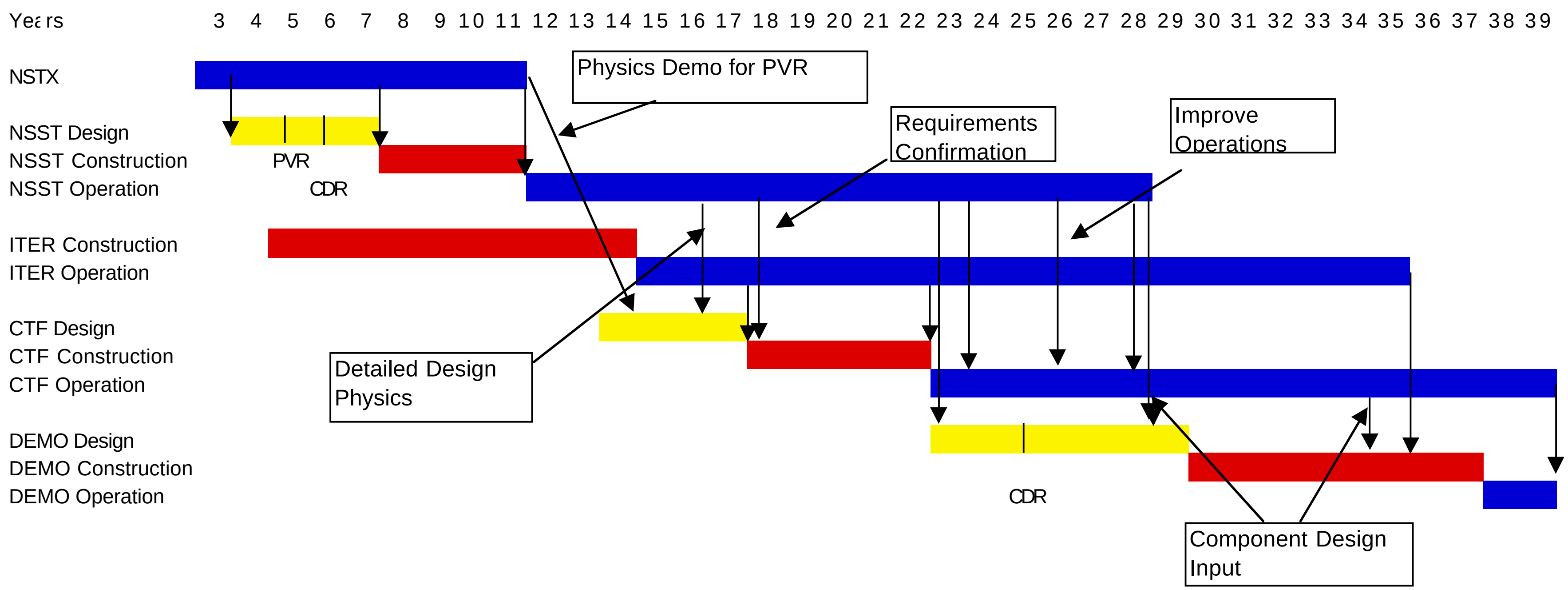

- CTF Facility to start operations around FY 23 to provide core components and high duty factor operation around FY 25 - 35 for Demo.
- NSST facility to start operations in FY12 to provide physics basis needed for the CTF construction decision expected around FY 18 and advanced ST physics scenarios for Demo design to start around FY 23.

Critical ST Decision Points and Criteria

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2006: NSTX Research Deliverables for NSST CDR

- Credible non-ohmic plasma start-up concept(s)
- Non-inductive sustainment
- Stability and Confinement basic understanding and scaling
- Basic power and particle handling understanding

2018: NSST Research Deliverables for CTF CDR

- ~ 5 MA non-OH start-up
- ~ 5 MA non-inductive sustainment
- Sufficient confinement / stability for CTF parameters
- Power and particle handling (High P/R)

2023: NSST Research Deliverables for Demo PVR

- Alpha-physics at moderate to high beta
- Advanced ST operating scenarios

2025-2035: CTF R&D Deliverables for Demo

- High duty factor feasibility
- Reliable fusion core components

ST Development Cost (FY 02 $ M)

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	FY 03	FY 04	FY05	FY06	FY 07	FY 08	FY 09	FY10	FY 11	FY12	FY 13	FY 14	FY 15	FY 16	FY17	FY18	FY 19	FY20	FY 21	FY22	FY23	FY24	FY25
NSTX	32	36	36	36	36	36	36	33	33														
Base ST	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
NSST																							
Pre-CD		1	3																				
CD				5																			
Eng. Design					20	40																	
Construction							56	63	63	59	19	10											
Operations										28	60	65	75	75	75	75	75	75	75	75	75	75	75
Total	35	40	42	44	59	79	95	99	99	90	82	78	78	78	78	78	78	78	78	78	78	78	78

NSST TPC ~ $ 330 M including 30% contingency and assumes TFTR-like site credits

	FY 03	FY 04	FY05	FY06	FY 07	FY 08	FY 09	FY10	FY 11	FY12	FY 13	FY 14	FY 15	FY 16	FY17	FY18	FY 19	FY20	FY 21	FY22	FY23	FY24	FY25
CTF																							
Pre-CD										10	20												
Design												40	70	90	100								
Const																220	240	240	240	230			
Operations																					125	125	125
Total	0	0	0	0	0	0	0	0	0	10	20	40	70	90	100	220	240	240	240	230	125	125	125

CTF TPC ~ $1.47 B, ITER-based cost algorithms, with 40 % contingency, government site.
(Test modules in technology program needed in parallel.)

Variation on the ST Development Path

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I. Tokamak BP + NSST + non-ST CTF

Tokamak CTF likely to be single copper column design.

- R Ip^2 ~ 50 m MA^2 non-ohmic start-up demonstration still needed for tokamak CTF which needs R Ip^2 ~ 200 m MA^2 .
- NSST 2018 deliverable is valuable for tokamak CTF construction decision.
- α-physics transferability from ITER/FIRE + NSST-DT will be able to meet 2023 Demo design input.

II. Net Electric ST-CTF Pilot Plant !?

- R = 1.5 m
- Superconducting PF coils
- ARIES-ST-class physics performance
- P_{fusion} = 750 MW
- Q_E ~ 1
- Tritium self-sufficiency

ST Research Can Contribute Cost Effectively to the Fusion Energy Development Path

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I. ST-PoP / CEs continue to provide innovations at ~ keV.

- Ultra-Low-Aspect-Ratio Regime (ST-Spheromak boundary)
- Innovative Plasma Start-Up Concepts.
- High performance PFCs - liquid lithium.

II. NSST is a logical next step as ST-PE.

- Development physics basis for attractive Demo at high beta
- Establish physics basis to construct CTF
- Explore and broaden toroidal plasma physics at reactor parameters

III. Compact CTF is essential for an attractive Demo.

- Develop high performance reliable blanket and divertor modules
- Low tritium consumption / longer term self-sufficiency
- Minimize cost of construction and operations

IV. ST-Demo is an attractive goal for fusion research.

- Potential physics advantages.
- Simplicity of technology

Back-up View Graphs

Costs of NSST with 30% Contingency in 02 M $

NSST

		Cost (M$)		Site Credit (M$)
1.0 Torus		**53.2**		
	1.1 PFCs and Passive Plates	18		
	1.2 VV	7.2	Top-down Engr Est	
	1.3 Outer TF Magnets	8.1	Bottoms-up Engr Est	
	1.4 PF Magnets	4.9	Bottoms-up Engr Est	
	1.5 Center Stack	8	Bottoms-up Engr Est	
	1.6 Cryostat/Cryogenics	2.0	Equal to FIRE	
	1.7 Torus Support Structure	5.0	Top-down Engr Est	
2.0 Aux. Systems		**57.1**		**186**
	2.1 Gas & Pellet Injection	7.6	Equal to FIRE	3
	2.2 Vacuum Pumping	10.2	Equal to FIRE	3
	2.4 RF Heating/Current Drive (10 MW -long pulse)	6.9	Scaled from NSTX Experience	30
	2.5 NBI (30 MW - long pulse)	32.4	Used TPX design and NSTX Experience	150
3.0 Diagnostics		**25**	Reflecting high physic priority	**5**
4.0 Power Systems		**36.6**	Scaled from NSTX Experience	**80**
5.0 I&C		**15.1**	0.75 of FIRE	**5**
6.0 Site		**10.0**	Engineering Judgement	**60**
7.0 Assembly		**12.5**	50 technicians @ 2 yrs	
8.0 Project Mgt		**36.4**	25 managers @ 5 yrs	
9.0 Prep for Ops		**7.9**	Two months ISTP	
Contingency	**30%**	**76.1**		**336**
TOTAL		**329.9**		

Costs of NSTX Construction in as spent dollar

(NSTX facility was constructed during 1997 - 2000 on cost and on schedule)

NSTX

		Cost (M$)	
1.0 Torus		**8.74**	
	1.1 PFCs and Passive Plates	1.90	ORNL/PPPL
	1.2 VV	1.44	
	1.3 Magnets	5.40	Outer TF, Center Stack, and PF 1 & 5. PFs 2- 4 are taken from S-1 spheromak.
2.0 Auxiliary Systems		**9.47**	
	2.1 Gas, Vacuum Pump, Cooling Water, etc.	1.87	
	2.2 RF Heating/Current Drive (6 MW - 5 sec pulse)	1.66	TFTR System, ORNL/PPPL
	2.3 NBI System (80 keV, 5 MW - 5 sec pulse, 3 ion sources)	5.94	Relocated TFTR System, New power cable, helium cryo line, and utility lines.
3.0 Diagnostics		**0.92**	Day 0 Diagnostics
4.0 Power Systems		**1.85**	Include the installation cost of the power transmission lines between the TFTR basement and NSTX.
5.0 I&C		**1.91**	
6.0 Site Prep & Assembly		**2.4**	
7.0 Project Mgt		**1.46**	
8.0 Physics Design and Conceptual Deisgn		**2.66**	
TOTAL		**29.41**	

Costing for CTF (A=1.5, R=1.2m & 1.5m, W_L=1 MW/m^2) - I

SuperCode Costing Components	R=1.2m (2002M$)	R=1.5m (2002M$)	Comments (2002M$)
1. Toroidal Device	193	284	
– TF magnets	38	64	
• *TFC center post*	*(12)*	*(23)*	$U_{TFcenter}$ = 0.075/ton (single-turn cooled GlidCop)
• *TFC outer magnet (VV)*	*(26)*	*(41)*	$U_{TFouter}$ = 0.03/ton (single-turn Al, combined with VV)
– PF magnets	50	66	U_{PF} = 0.058/ton (no OH solenoid)
– Device structure	11	19	U_{MS} = 0.052/ton
– Vacuum vessel	0	0	Combined with TFC outer conductor
– Blanket modules	10	15	ITER-FEAT: 220; FIRE (reflector): 19*; CTF: basic T-breeding blankets cost 1/3 of advanced test blankets**
– Device, penetration shielding	43	59	
– Divertor, PFCs	29	46	ITER-FEAT: 109; FIRE: 42; CTF: U_{Div} = 1.61/m^2
– Fueling	12	15	ITER-FEAT: 10; FIRE: 9
2. Device Ancillary Systems	187	220	
– Machine assembly tooling	29	36	ITER-FEAT: 72; FIRE: 0; CTF only: $\propto R^{3/4}$
– Remote handling equipment	152	176	ITER-FEAT: 145, FIRE: 101; CTF only: requires high duty factor RH operation, $\propto R^{1/2}$
– External cryostat	0	0	
– Primary heat transport	6	8	U_{PHT} = \$72.3/W$^{0.7}$
– Thermal shield	0	0	
3. Tokamak Gas & Coolant Systems	88	106	
– Vacuum	19	20	ITER-FEAT: 37; FIRE: 14; CTF only: $\propto R^{1/4}$
– Tritium (and fuel) handling	41	51	ITER-FEAT: 104; FIRE: 9; CTF only: $\propto P_F^{1/2}$
– Aux heat transport	8	9	U_{AHT} = \$33.9/W$^{0.7}$
– Cryogenic plant	0	0	
– Heat rejection	8	10	
– Chemical control	12	16	

* ITER-FEAT-FIRE Cost Comparison, Fusion Study 2002, Snowmass; ** Comments by M. Abdou, B. Nelson

Costing for CTF (A=1.5, R=1.2m & 1.5m, W_L=1 MW/m^2) - II

SuperCode Costing Components	R=1.2m (2002M$)	R=1.5m (2002M$)	Comments (2002M$)
4. Power Supplies & Control	120	149	
– Magnet power supplies	63	86	
• *Resistive TFC*	*(52)*	*(72)*	U_{TFC} = 0.4/MW (4X conventional power supply)
• *Resistive PFC*	*(11)*	*(14)*	U_{PFC} = 0.13/MVA
– Heating system power supplies	0	0	Included in heating systems costs
– Site electric plant, transformers, etc.	21	23	ITER-FEAT: 38; FIRE: 18
– Device operational I&C	36	40	ITER-FEAT: 72; FIRE: 23
5. Heating, Current Drive, Diagnostics	210	238	
– Fast wave	TBD	TBD	Could replace part or all of NBI @ ~4/MW*
– ECH-EBW	40	50	8 MW & 10 MW at ~ 100 GHz (ITER-FEAT: 111)*
– NBI	125	138	30 MW & 33 MW at ~ 400 kV (ITER-FEAT: 138)
– LH	0	0	
– Plasma operational I&C	45	50	ITER-FEAT: 214; FIRE: 29
6. Site, Facilities and Equipment	252	277	
– Land, site improvement	0	0	Government site
– Buildings	180	200	ITER-FEAT: 546; FIRE: 126
– Hot cell	0	0	Included in Buildings
– Radwaste management	38	40	ITER-FEAT:12; FIRE: 11 (CTF requires FNT testing at high duty factors → increased radwaste)
– Coolant supply and disposal	18	20	ITER-FEAT: ?; FIRE: 18
– General test and qualification	16	17	(CTF requires acceptance verification of all incoming test components.)
– Magnet fabrication tools	0	0	
Total Construction Cost, no Contingency	1,050	1,274	
with 40% Contingency	1,470**	1.784	**Included in the ST development cost.

* Comments by D. Rasmussen, R. Temkin