Fusion Energy Development Applications **Utilizing the Spherical Tokamak** and Associated Research Needs and Tools

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Collaborative and international effort including 23 co-authors

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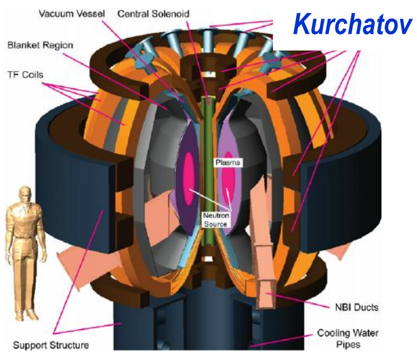
Abstract / Overview

The fusion community is assessing the suitability of the ST for applications to advance fusion energy including the development of:

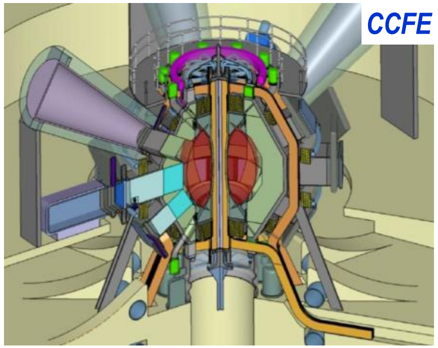
1. Solutions for the plasma-material-interface (PMI) challenge
2. Fusion neutron source / Fusion-fission hybrid systems
3. Fusion components capable of withstanding high fusion neutron flux/fluence including breeding blankets (Component Test / Fusion Nuclear Science Facility)
4. Demonstrating electricity break-even from a pure fusion system (Pilot Plant)
5. Electricity production at industrial levels in modular fusion power plants
6. Electricity production at industrial levels in larger-scale fusion power plants

This range of fusion energy development applications utilizing the ST is described, common application-driven research needs discussed, upcoming and recently achieved ST facility capabilities and relevant highlights described, and near-term prioritized ST research directions supporting longer-term fusion energy development applications presented.

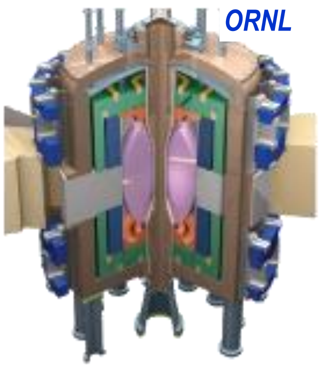
Possible next-step ST facilities

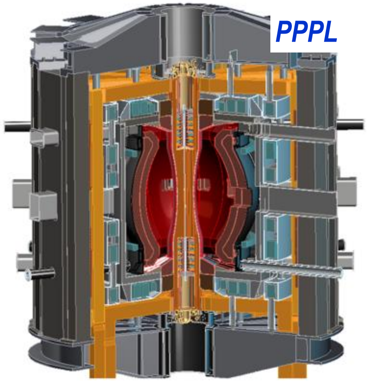


Fusion neutron source (FNS-ST)

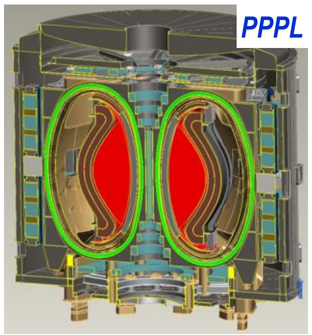


Component Test Facility (ST-CTF)



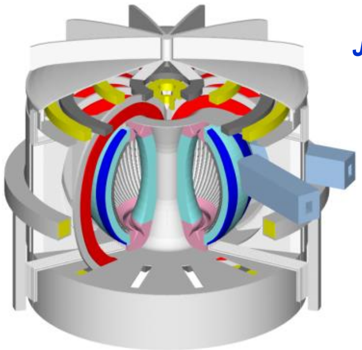


Fusion Nuclear Science Facility (ST-FNSF)

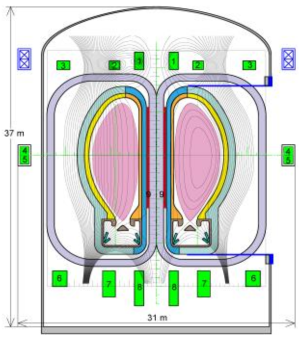


Low-A (A=2) HTS Pilot Plant

Japan



A=2.3 VECTOR

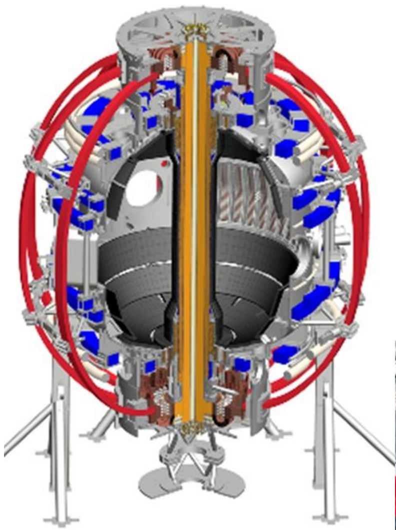


A=1.8 JUST

SC low-A reactors

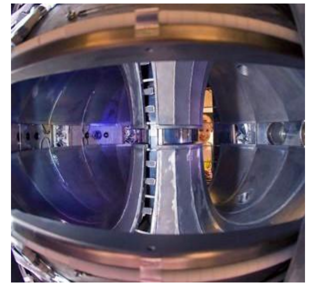
17 existing/near-term international ST facilities

NSTX-U, USA

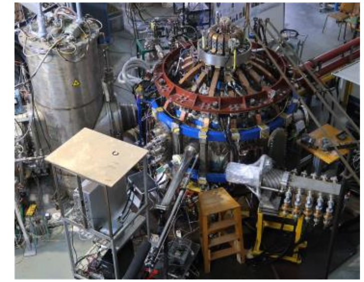


PEGASUS, USA

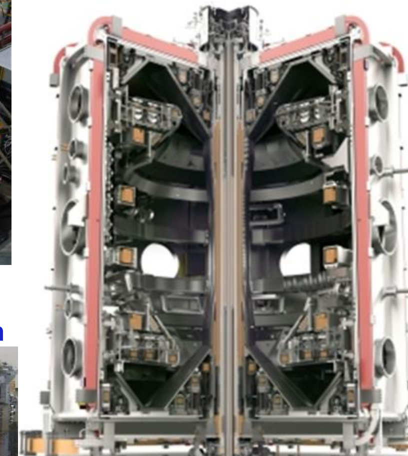
LTX-β / CDX-U, USA



GLOBUS-M2, Russia

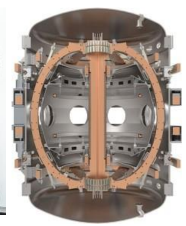


MAST-U, UK



PI3, Canada

ST40, UK

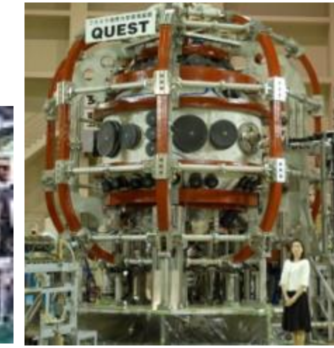


Proto Sphera, Italy

SUNIST, China

KTM, Kazakhstan

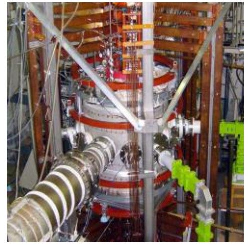
QUEST/CPD, Japan



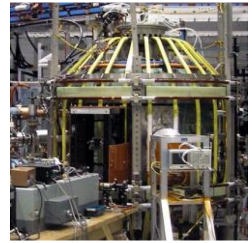
VEST, Korea

HIST, Japan

LATE, Japan



TST-2, Japan

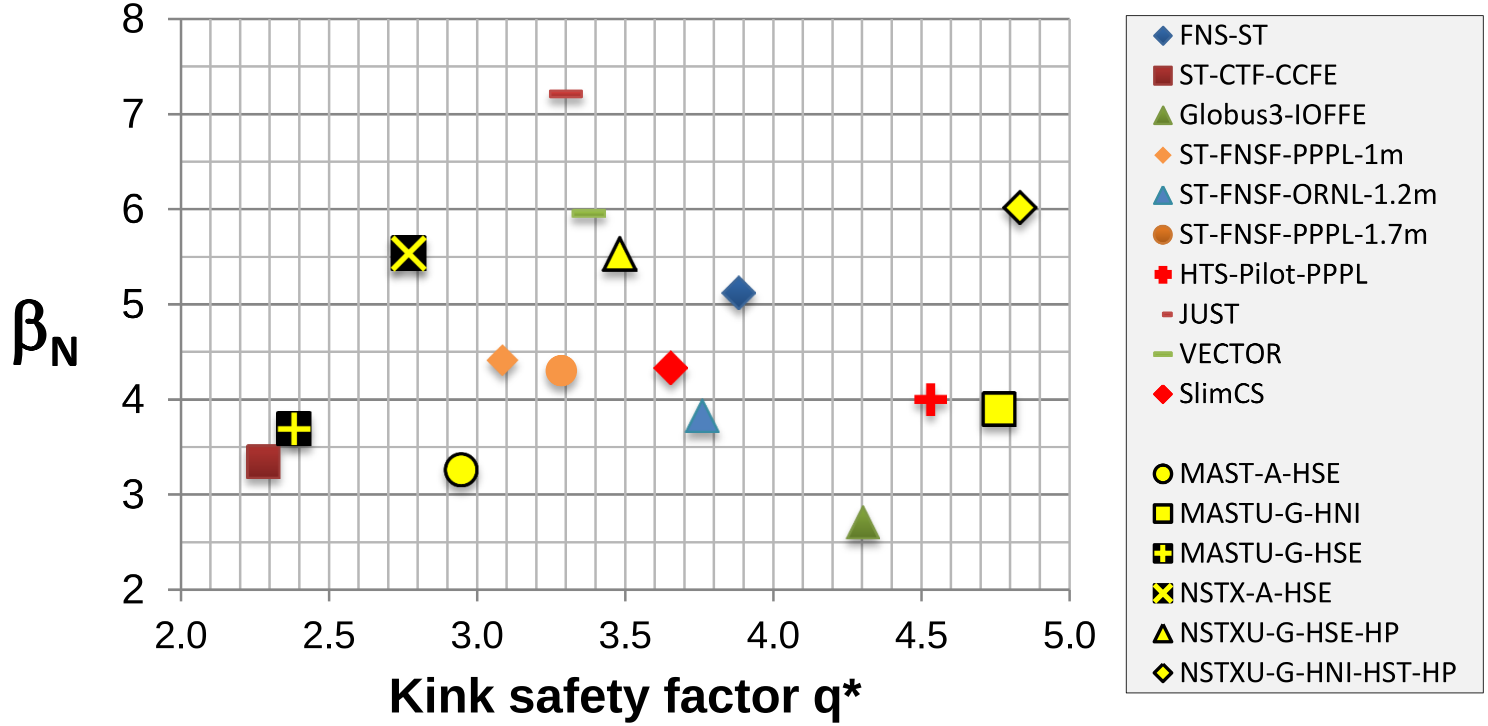


UTST, Japan

TS3/4, Japan

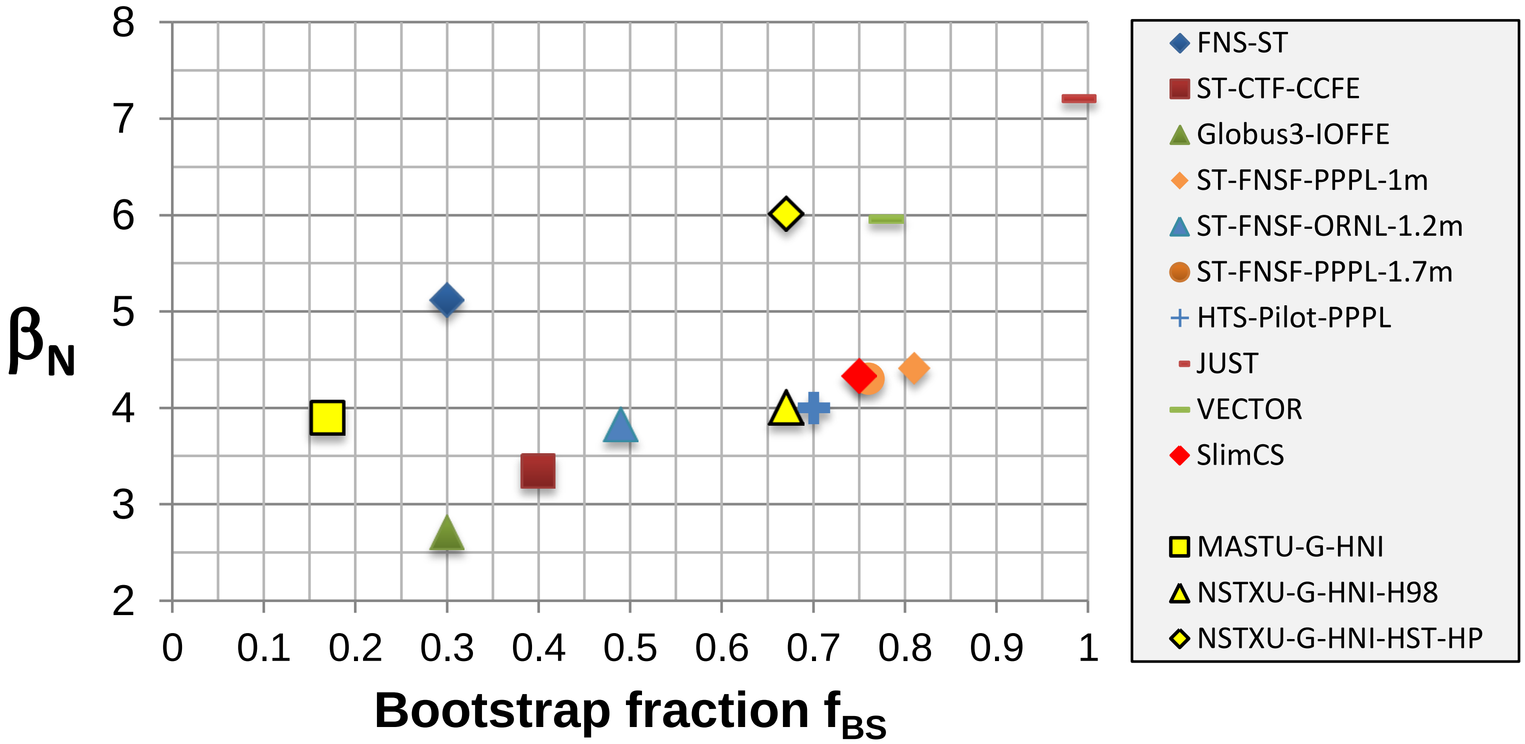
Near-term STTs support wide MHD stability space spanning nearly all proposed next-step ST configurations

- Exception: β_N = 7 of JUST exceeds expected near-term capabilities
  - Additional studies needed to assess MHD stability of JUST scenarios



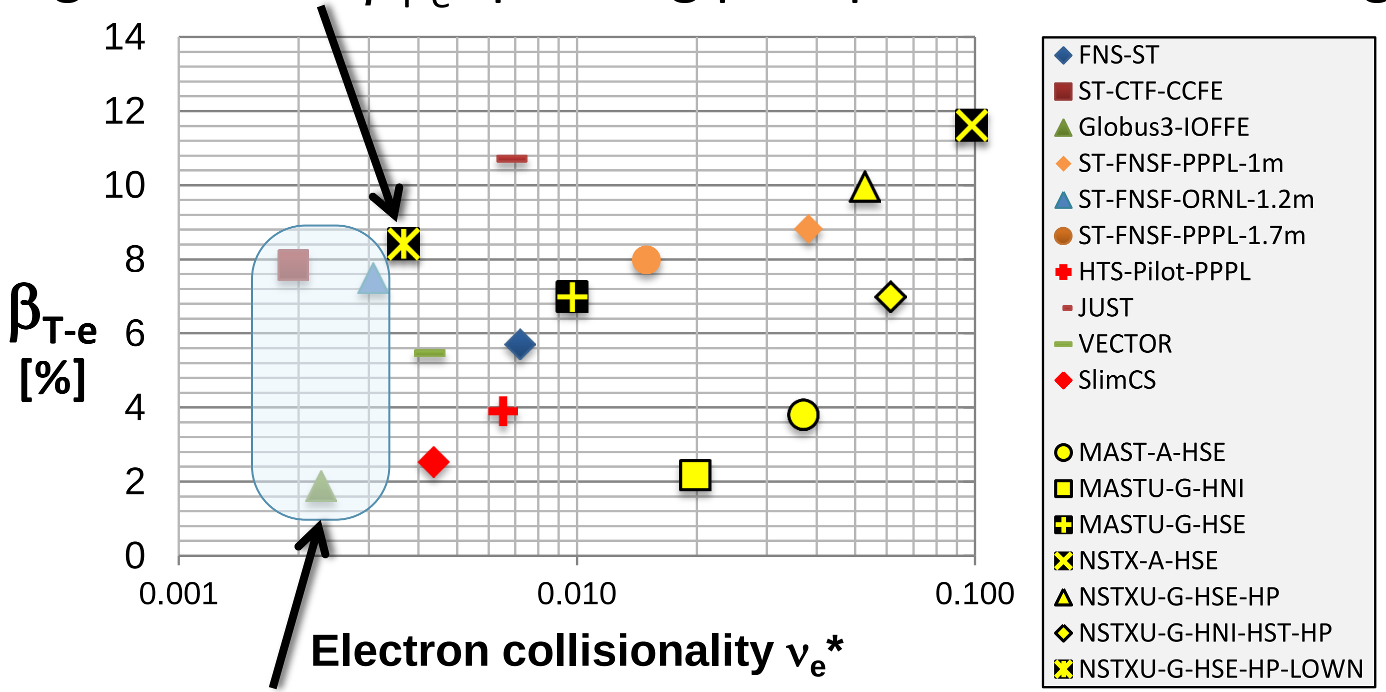
Near-term STs will need to access higher f_{BS} to study scenarios anticipated for steady-state ST reactors

- MAST-U / NSTX-U baseline non-inductive scenarios: $f_{BS} \approx$ 15-70%
- PPPL FNSF/Pilot and Japanese reactors: f_{BS} = 70-95% → research gap



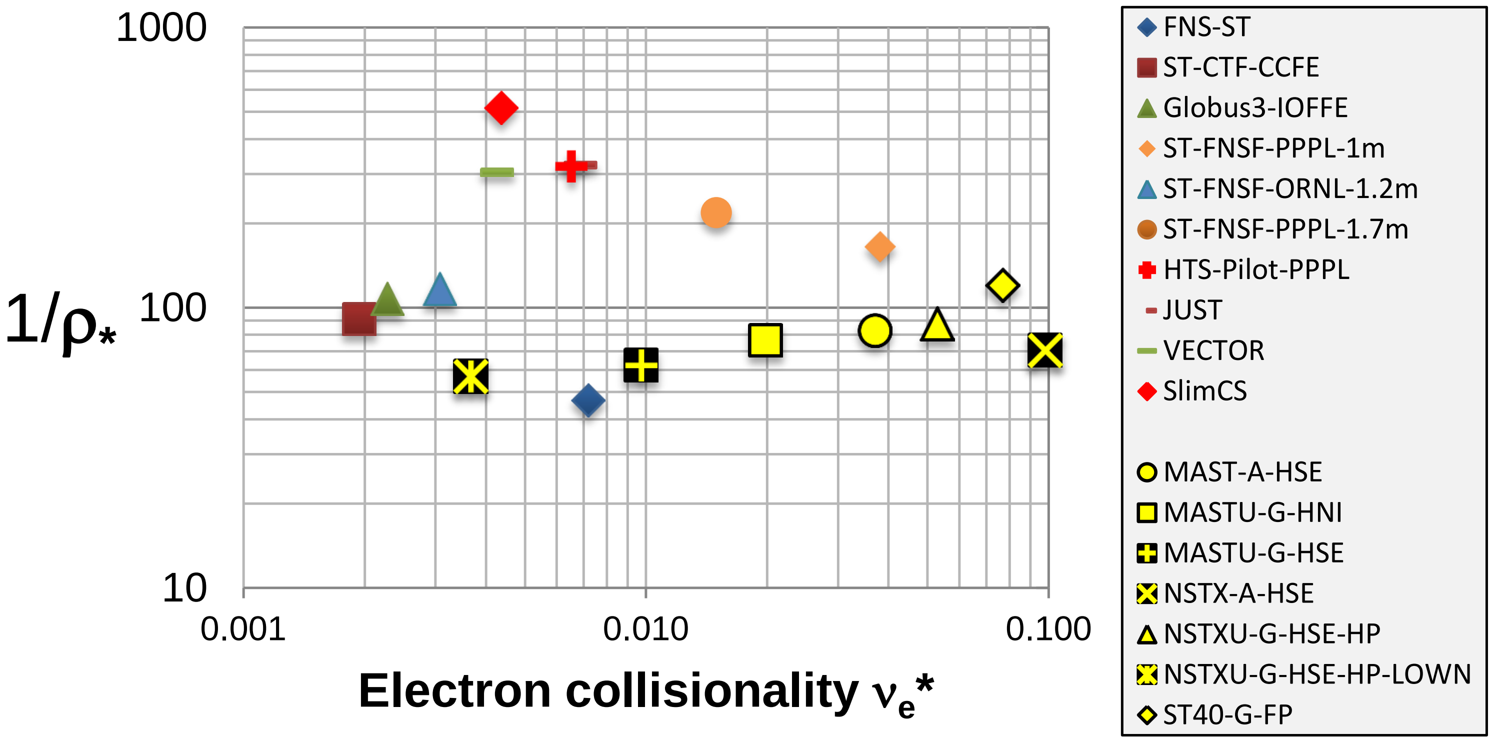
Near-term STs greatly expand access to high β at low ν*

- NSTX-U at full field, power and low density (f_{GW}=0.25) accesses low ν_e^* at high electron $\beta_{T\text{-}e}$ spanning pilot plant and reactor regimes



- Low f_{GW}=0.25 CTF/FNSF projected to access ~2x lower ν_e^*

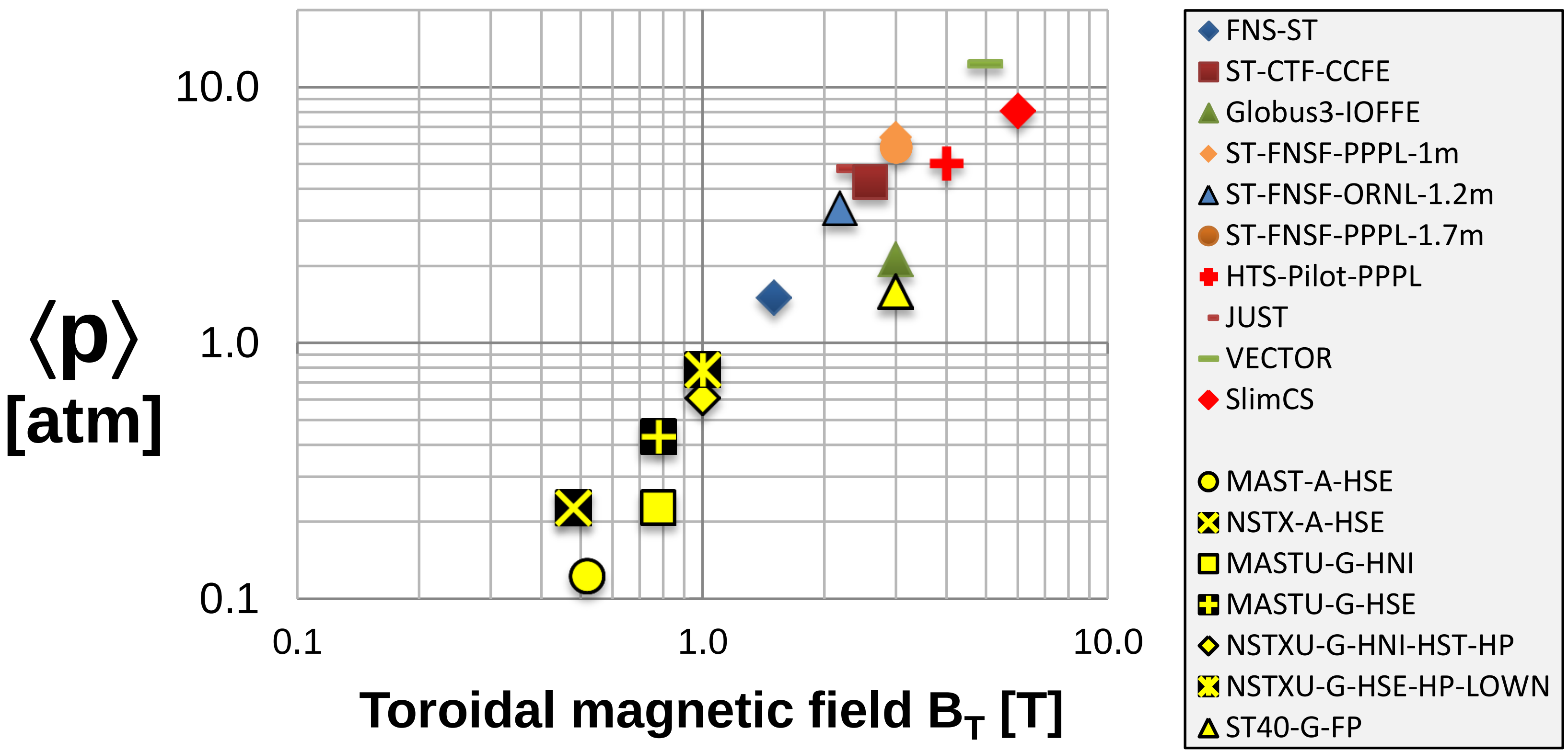
Near-term STTs cannot access low ρ_* of larger next-steps



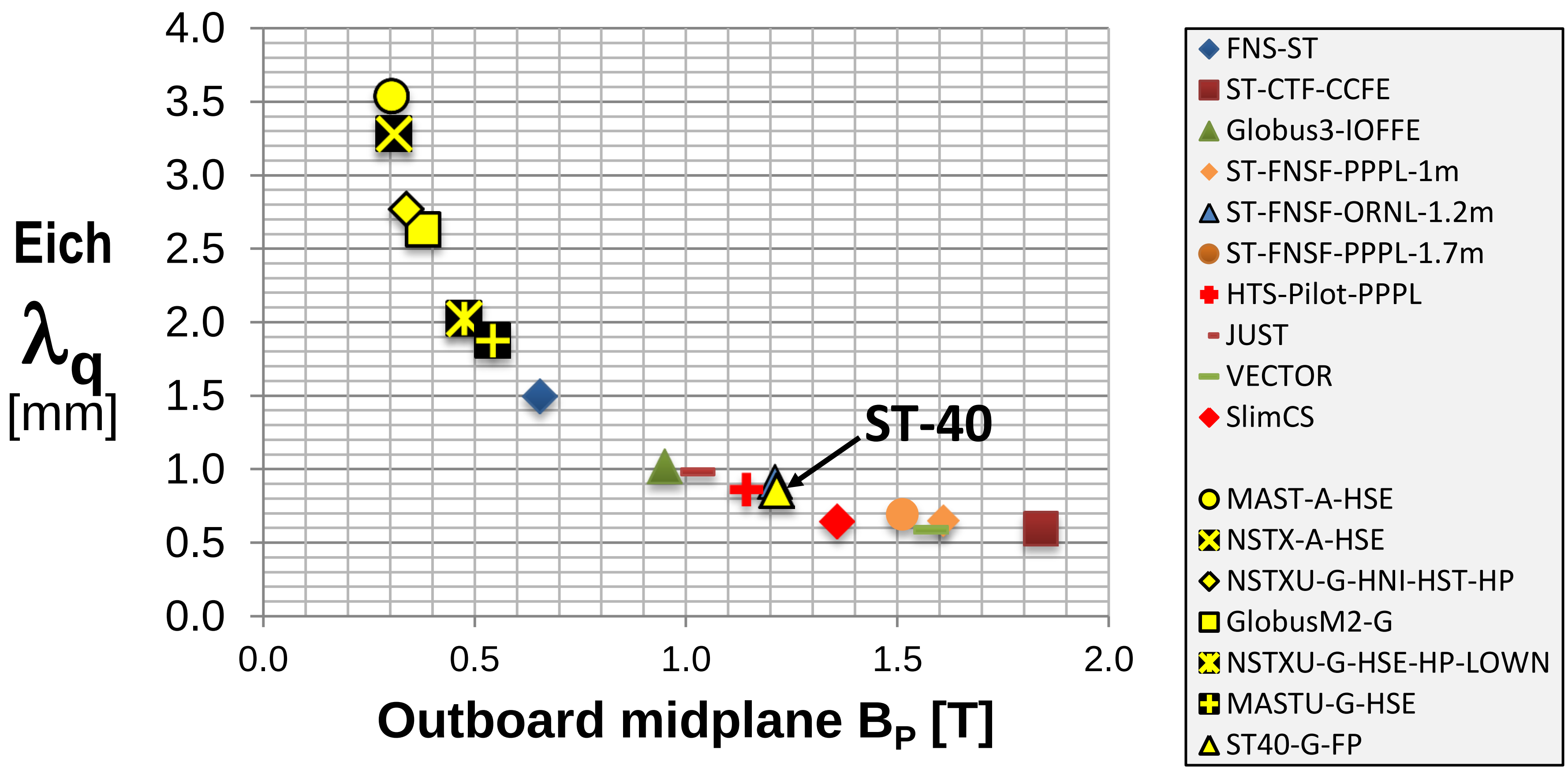
- Larger and/or higher field needed for more reactor-relevant ρ_*, ν^*

Near-term ST facilities targeting ⟨p⟩ ≈ 1 atm

- NSTX-U ≤ 0.8 atm, ST-40 ≤ 1.6 atm, next-steps: 1.5 to 12 atm

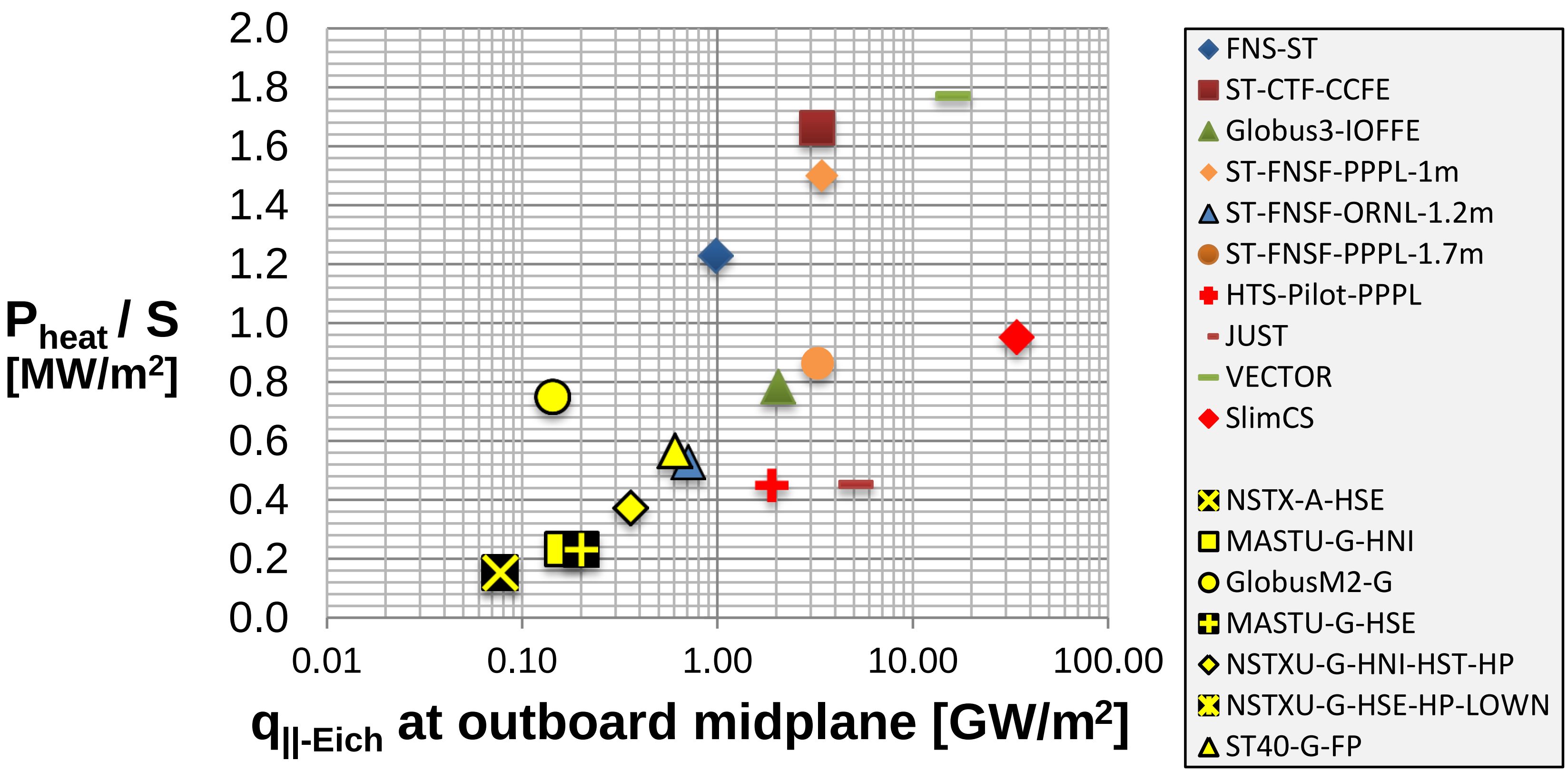


ST-40 could provide important tests of SOL-width scaling



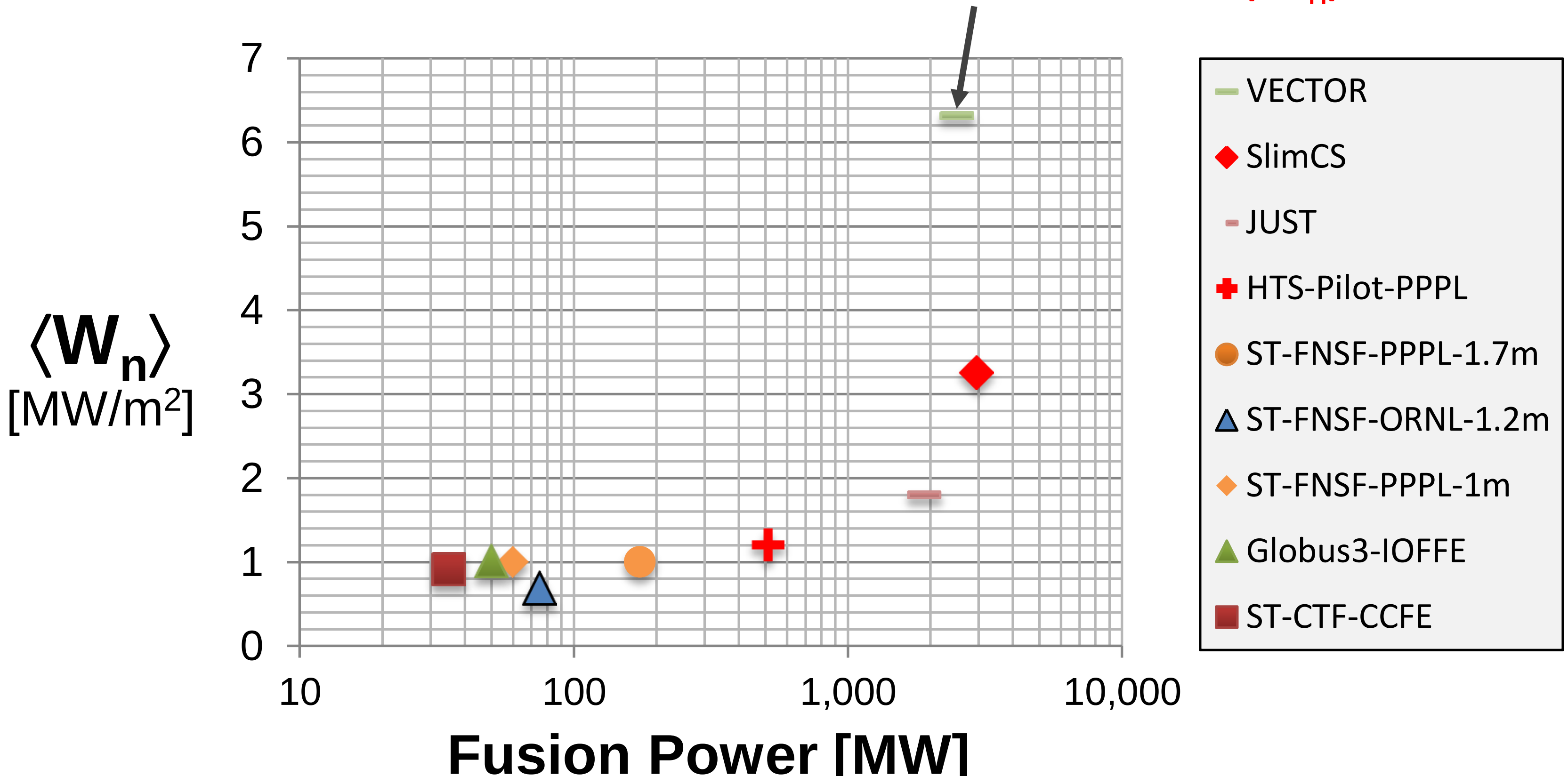
Next-steps extrapolate to higher P/S, very high $q_{||}$

- Advanced/new divertor concepts needed to mitigate $q_{||}$ = 1-30GW/m^2



Most next-steps have neutron wall loading ≈ 1-3 MW/m²

- **Exception**: (very) compact ST reactor VECTOR with $\langle W_n \rangle \approx 6$ MW/m²



Summary of research needs to support next-steps

- MHD stability, access to low ν^* covered by near-term STs
- NSTX-U plans access to high f_{BS} and full non-inductive
  - Need to extend to 70-95% bootstrap fraction for reactor-relevant scenarios
- Near-term STs limited to $1/\rho_{i*} \leq \approx 50\text{-}120$
  - Need to extend to 200-300 with new facility (?) and/or leverage tokamak results
- Full performance ST-40 could test ST λ_q scaling to high B_P
- Very high $q_{||}$ in next-steps requires divertor innovation
  - MAST-U Super-X capability and/or liquid metals (LTX-β, long-term NSTX-U)
- Very compact ST reactors (R=3-4m) generate high neutron wall loading and require innovations in blankets and first-wall

Sign-up

Existing / Near-term ST Parameters

Existing / Near-term ST Parameters	QUEST achieved	QUEST goal	Globus-M achieved	Globus-M2 goal	ST40 goal [Programs 1-3]	ST40 goal [Future Programs]	MAST achieved [High stored energy]	MAST-U goal [High non-inductive]	MAST-U goal [High stored energy]	NSTX achieved [High stored energy]	NSTX-U goal [100% non-inductive, H_{98}=1]	NSTX-U goal [100% non-inductive, H_{ST}=1, high-power]
Device - Achieved/Goal - Scenario	QUEST-A	QUEST-G	GlobusM-A	GlobusM2-G	ST40-G-P13	ST40-G-FP	MAST-A-HSE	MASTU-G-HNI	MASTU-G-HSE	NSTX-A-HSE	NSTXU-G-HNI-H98	NSTXU-G-HNI-HST-HP
Aspect ratio A	1.7	1.7	1.5	1.5	1.7	1.7	1.3	1.56	1.56	1.45	1.78	1.73
Major radius R_0 [m]	0.68	0.68	0.34	0.34	0.4	0.4	0.85	0.82	0.82	0.89	0.94	0.94
Minor radius a [m]	0.40	0.40	0.23	0.23	0.24	0.24	0.65	0.53	0.53	0.61	0.53	0.54
Plasma elongation κ	1.2	2.5	2	2	2.5	2.5	2.1	2.5	2.5	2.5	2.78	2.76
Plasma triangularity δ	0.2	0.68	0.5	0.3	0.35	0.35	0.5	0.5	0.5	0.6	0.5	0.5
Plasma current I_P [MA]	0.01	0.3	0.25	0.5	2	2	1.2	1	2	1.33	0.87	1.4
Vacuum toroidal field B_T (at R_0 [T])	0.133	0.25	0.50	1.00	3.0	3.0	0.52	0.78	0.78	0.48	1.00	1.00
Normalized current $I_N = I_P/aB_T$	0.19	3.00	2.21	2.21	2.83	2.83	3.53	2.44	4.88	4.51	1.65	2.58
Toroidal beta β_T [%]	0.1	10	5.5	10	4.5	4.5	11.5	9.5	18	25	6.6	15.5
Normalized beta β_N	0.53	3.33	2.5	4.5	1.6	1.6	3.3	3.9	3.7	5.5	4.0	6.0
Kink safety factor q*	19.09	3.55	3.78	3.78	3.76	3.76	2.95	4.76	2.38	2.77	7.44	4.83
Internal inductance l_i	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.45	0.6	0.67
Bootstrap fraction f_{BS}	0.01	0.2	0.25	0.37	0.35	0.35	0.2	0.17		0.35	0.67	0.67
External current drive (CD) fraction							0.15	0.71		0.15	0.33	0.33
Non-inductive CD fraction f_{NICD}							0.35	0.88	0.47	0.50	1.00	1.00
Greenwald fraction f_{GW}	0.3	0.5	1.00	0.30	0.31	0.31	0.40	0.23	0.25	0.80	0.72	0.71
Fast ion fraction W_{fast} / W_{tot}	0.00	0.10	0.05	0.20	0.05	0.05	0.40	0.60	0.30	0.15	0.26	0.18
H-mode multiplier H_{98}		1.2	1.3	1.3	1.4	1.4	1	1	1	1.2	1	1.3
Ohmic heating power P_{OH} [MW]	0	0	0.65	0.6	0	0	0	0	0	0	0	0
Aux NBI heating & CD power P_{NBI} [MW]	0	2	1	2	2	2	3	7.5	7.5	6.3	10.2	15.6
Aux RF heating & CD power P_{RF} [MW]	0.05	1	0.2	1	0	2	0	0	0	0	0	0
Total heating & CD power P_{aux} [MW]	0.05	3.00	1.85	3.60	2.00	4.00	3.00	7.50	7.50	6.30	10.20	15.60
Volume [m^3]	2.37	4.09	0.55	0.55	0.83	0.83	11.8	8.5	8.5	12.6	11.6	11.9
Volume-averaged electron density [10^{20} m^{-3}]	0.01	0.26	1.36	0.82	3.14	3.14	0.31	0.23	0.51	0.79	0.63	0.94
Average T_e [keV]	0.05	0.29	0.13	1.33	1.66	1.66	0.81	1.40	2.09	0.84	1.06	1.84
Normalized electron collisionality ν_e* (Sauter)	1.4E+00	3.3E-01	3.3E+00	2.3E-02	7.7E-02	7.7E-02	3.7E-02	2.0E-02	9.7E-03	9.8E-02	1.9E-01	6.1E-02
Electron toroidal beta $\beta_{T\text{-}e}$ [%]	0.05	4.91	2.85	4.39	2.34	2.34	3.80	2.16	7.00	11.63	2.68	6.99
Thermal ion 1/ρ*	55	41	69	43	120	120	83	76	62	71	113	88
Total plasma stored energy W [MJ]	2.50E-05	0.015	0.004	0.03	0.20	0.20	0.22	0.29	0.56	0.43	0.46	1.10
Fusion power [MW]	0	0	0	0	0	0	0	0	0	0	0	0
Fusion Gain Q_{DT}	0	0	0	0	0	0	0	0	0	0	0	0
Avg. DT neutron wall load [MW/m^2]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
P_{heat} / S [MW/m^2]	0.00	0.15	0.38	0.75	0.28	0.57	0.08	0.23	0.23	0.15	0.25	0.37
Net electric output [MWe]	0	0	0	0	0	0	0	0	0	0	0	0
Number of divertors	1	2	2	2	2	2	2	2	2	2	2	2
Fraction of SOL power to outer divertor(s)	0.65	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Core radiation fraction	0.02	0.4	0.5	0.5	0.3	0.3	0.2	0.2	0.2	0.3	0.3	0.3
P_{SOL} [MW]	0.05	1.80	0.93	1.80	1.40	2.80	2.40	6.00	6.00	4.41	7.14	10.92
Estimated $B_{p\text{-}omp}$ [T]	0.01	0.11	0.19	0.38	1.21	1.21	0.30	0.27	0.54	0.31	0.21	0.34
Eich λ_q [mm]	122.1	8.21	5.04	2.63	0.87	0.85	3.54	3.55	1.88	3.28	4.19	2.77
Eich $q_{\parallel\text{-}omp}$ [MW/m^2]	0.52	23	39	144	300	608	40	161	201	77	233	360

Next-step ST Parameters	FNS-ST [Kurchatov 2011]	ST-CTF [CCFE 2008]	Compact hybrid FNS / Globus-3 [Ioffe 2018]	ST-FNSF [R=1m, PPPL 2016]	ST-FNSF [R=1.2m, ORNL 2009]	ST-FNSF [R=1.7m, PPPL 2016]	ST-E1 Modular Power Plant [Tokamak Energy 2018]	Low-A HTS Pilot Plant [PPPL 2016]	JUST [Japan 2012]	VECTOR [Japan 2002]	SlimCS [Japan 2007]
Device - Achieved/Goal - Scenario	FNS-ST	ST-CTF-CCFE	Globus3-IOFFE	ST-FNSF-PPPL-1m	ST-FNSF-ORNL-1.2m	ST-FNSF-PPPL-1.7m	ST-E1-TE	HTS-Pilot-PPPL	JUST	VECTOR	SlimCS
Aspect ratio A	1.66	1.55	1.9	1.7	1.5	1.7	1.8	2	1.8	2.3	2.6
Major radius R_0 [m]	0.5	0.81	1	1	1.2	1.7	2	3	4.5	3.2	5.5
Minor radius a [m]	0.30	0.52	0.53	0.59	0.80	1.00	1.11	1.50	2.50	1.39	2.12
Plasma elongation κ	2.75	2.4	2.5	2.75	3.1	2.75	3	2.5	2.5	2.35	2
Plasma triangularity δ	0.5	0.4	0.7	0.5	0.4	0.5	0.5	0.6	0.35	0.5	0.35
Plasma current I_P [MA]	1.5	6.5	3.5	7.2	8.2	11.5	10	12	18	14.6	16.7
Vacuum toroidal field B_T (at R_0 [T])	1.50	2.60	3.00	3.00	2.18	3.00	4.00	4.00	2.36	5.00	6.00
Normalized current $I_N = I_P/aB_T$	3.32	4.78	2.22	4.08	4.70	3.83	2.25	2.00	3.05	2.10	1.32
Toroidal beta β_T [%]	17	16	6	18	18	16.5	11	8	22	12.5	5.7
Normalized beta β_N	5.12	3.34	2.71	4.41	3.83	4.30	4.89	4.00	7.21	5.96	4.33
Kink safety factor q*	3.88	2.28	4.30	3.09	3.76	3.28	6.17	4.53	3.30	3.38	3.65
Internal inductance l_i	0.7	0.6	0.7	0.55	0.5	0.55	0.5	0.6	0.7	0.7	0.7
Bootstrap fraction f_{BS}	0.3	0.4	0.3	0.81	0.49	0.76	0.98	0.7	0.99	0.78	0.75
External current drive (CD) fraction	0.70	0.60	0.70	0.19	0.51	0.24	0.02	0.30	0.01	0.22	0.25
Non-inductive CD fraction f_{NICD}	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Greenwald fraction f_{GW}	0.2	0.24	0.15	0.8	0.3	0.8	0.9	0.8	1.5	0.83	0.98
Fast ion fraction W_{fast} / W_{tot}	0.40	0.10	0.50	0.09	0.24	0.10	0.10	0.10	0.10	0.23	0.22
H-mode multiplier H_{98}	1	1.3	1	1.25	1.5	1.25	1.5	1.8	1.8	1.44	1.3
Ohmic heating power P_{OH} [MW]	0	0	0	0	0	0	0	0	0	0	0
Aux NBI heating & CD power P_{NBI} [MW]	10	44	15	60	31	85	10	50	2	60.4	100
Aux RF heating & CD power P_{RF} [MW]	5	0	6	0	0	0	12	0	0	0	0
Total heating & CD power P_{aux} [MW]	15.00	44.00	21.00	60.00	31.00	85.00	22.00	50.00	2.00	60.40	100.00
Volume [m^3]	1.85	8.0	10.4	14.1	34.9	69.4	141	254	1057	221	768
Volume-averaged electron density [10^{20} m^{-3}]	0.93	1.60	0.53	4.66	1.08	2.58	2.04	1.20	1.21	1.75	1.02
Average T_e [keV]	3.52	8.40	8.04	4.32	8.41	7.08	10.64	13.26	12.52	19.73	22.57
Normalized electron collisionality ν_e* (Sauter)	6.9E-03	1.9E-03	2.2E-03	3.7E-02	2.9E-03	1.4E-02	1.2E-02	6.2E-03	6.6E-03	4.1E-03	4.2E-03
Electron toroidal beta $\beta_{T\text{-}e}$ [%]	5.84	8.01	1.91	9.01	7.67	8.17	5.47	3.99	10.96	5.57	2.59
Thermal ion $1/\rho$*	47	92	109	167	118	221	268	324	328	308	525
Total plasma stored energy W [MJ]	0.42	5.2	3.4	13.7	17.8	61.5	148	194	773	412	941
Fusion power [MW]	0.5	35	50	60	75	174	420	510	1900	2503	2950
Fusion Gain Q_{DT}	0.03	0.8	2.4	1.0	2.4	2.0	19	10	950	41	30
Avg. DT neutron wall load [MW/m^2]	0.03	0.91	1.01	1.00	0.69	1.00	1.71	1.21	1.80	6.31	3.25
P_{heat} / S [MW/m^2]	1.23	1.66	0.78	1.50	0.53	0.86	0.54	0.45	0.45	1.77	0.95
Net electric output [MWe]	0	0	0	0	0	0	125	100	800	1000	1000
Number of divertors	2	2	2	2	2	2	2	2	1	2	1
Fraction of SOL power to outer divertor(s)	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.65	0.8	0.65
Core radiation fraction	0.3	0.4	0.3	0.5	0.7	0.5	0.6	0.7	0.5	0.5	0.3
P_{SOL} [MW]	10.57	30.60	21.70	36.00	13.80	59.90	42.40	45.60	191.00	280.50	483.00
Estimated $B_{p\text{-}omp}$ [T]	0.65	1.84	0.95	1.61	1.21	1.51	1.09	1.14	1.03	1.58	1.36
Eich λ_q [mm]	1.49	0.59	1.02	0.65	0.91	0.70	0.93	0.86	0.98	0.58	0.65
Eich $q_{\parallel\text{-}omp}$ [MW/m^2]	980	3247	2047	3428	708	3251	2393	1896	5119	16111	34005