NSTX

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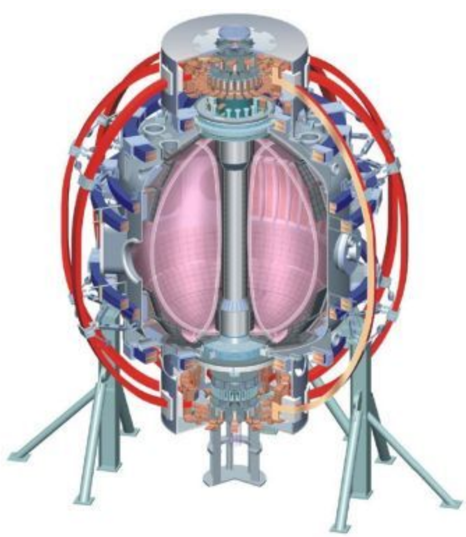
NSTX Program and Project Directors

for the NSTX Research Team

Fall 2009



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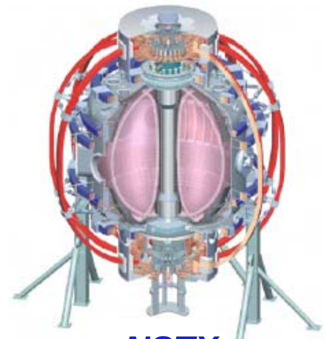
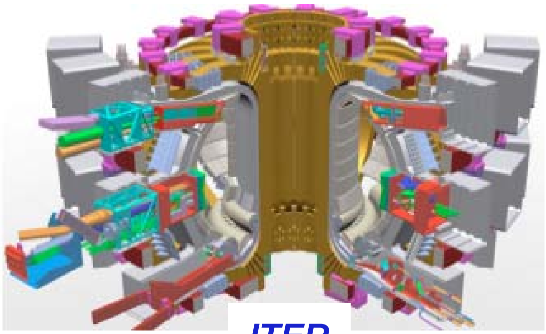
NSTX Mission Elements

- **Understand unique physics properties of ST**
  - Assess impact of low A, high β, high v_{fast} / v_A on toroidal plasma science



NSTX

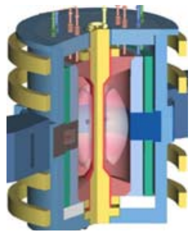
- **Complement tokamak physics, support ITER**
  - Exploit unique ST features to improve tokamak understanding
  - Benefit from tokamak R&D



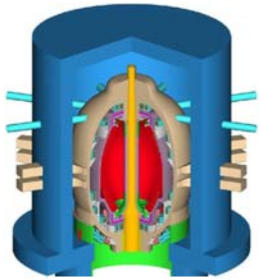
ITER

- **Establish attractive ST operating conditions**
  - Understand and utilize ST for addressing key gaps between ITER and DEMO
  - Advance ST as fusion energy source

NHTX



ST-FNSF/CTF



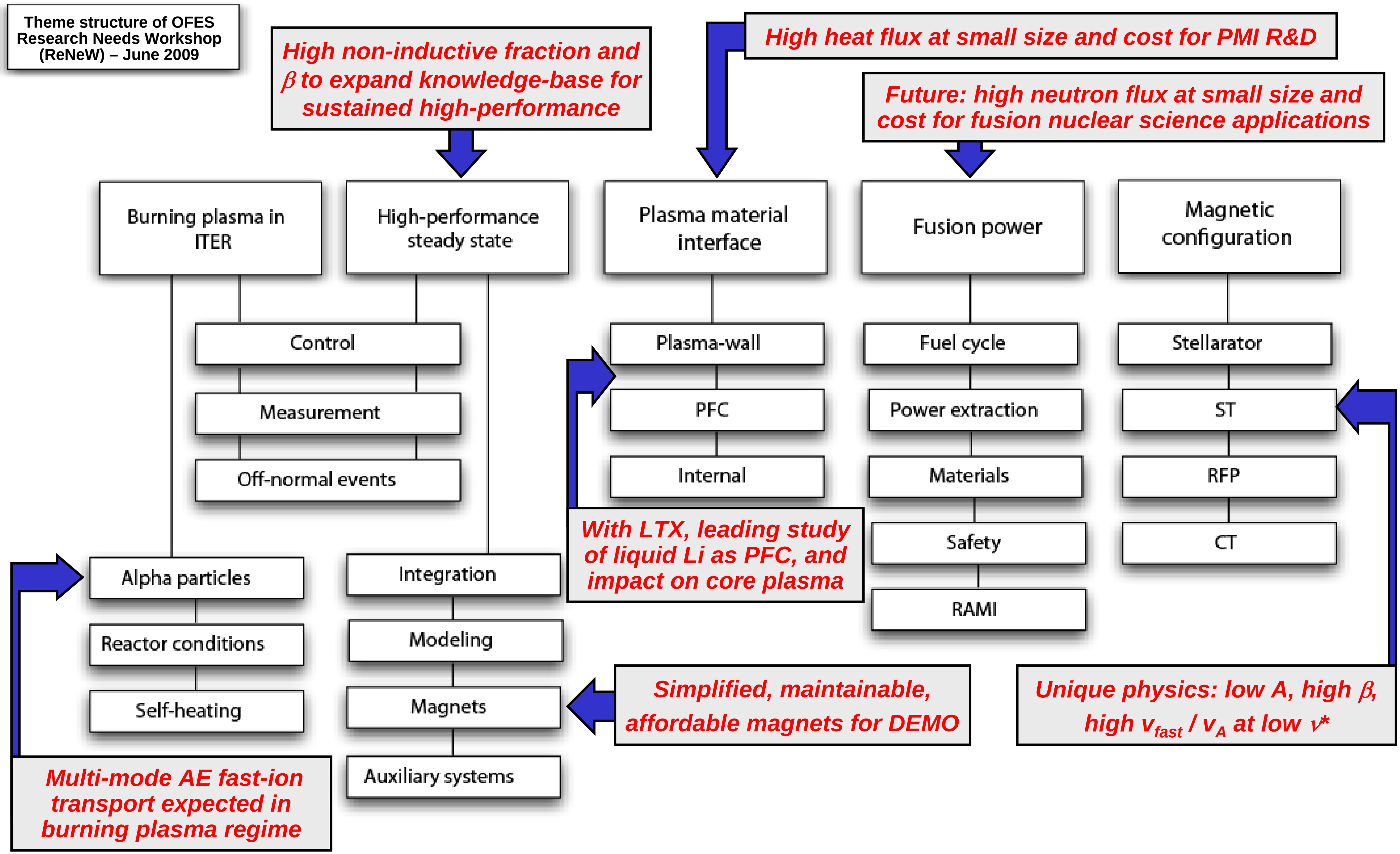
ARIES-ST

Pre-conceptual designs

NSTX Research Priorities:

- Full non-inductive current sustainment (i.e. without central solenoid)
  - ST/tokamak requires full non-inductive current drive for steady-state
  - Neutral beam current drive may be strongly influenced by Alfvénic instabilities in ST
- Electron and ion transport in high-confinement regimes
  - Need predictive capability to confidently extrapolate to next-steps
  - Electron energy transport increases in operating regimes of ST (i.e. high β, ρ^*, ν^*)
- Non-inductive start-up and ramp-up
  - Essential for ST applications without solenoid: CTF, DEMO
- "Taming the plasma-material interface (PMI)"
  - Solutions for very high particle/heat/neutron flux needed for CTF and DEMO
- High β, MHD control near stability limits, disruption physics
  - Higher β would accelerate component testing in CTF, essential for DEMO

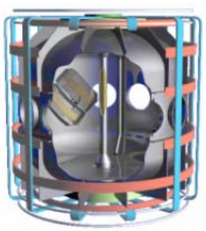
NSTX is providing unique contributions to all magnetic fusion research needs – for the ITER era and beyond



The ST offers attractive near-term applications for fusion development complementary to ITER

ST characteristics:

- High normalized pressure
- Compact geometry
- Simplified magnets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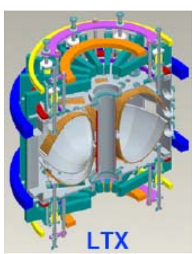
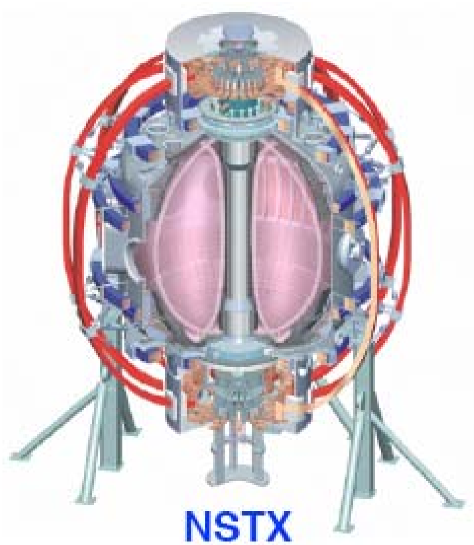


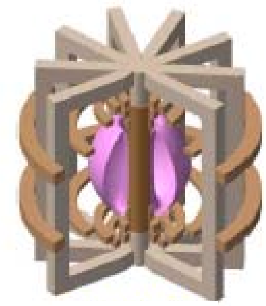


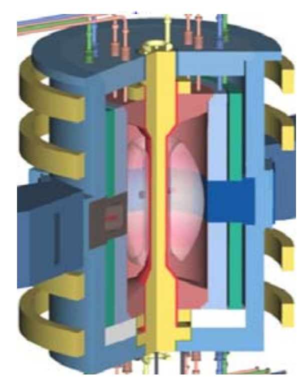
Implications:

- High heat flux at small size and reduced cost
- Simplified construction, access, and maintenance
- High neutron flux at small size and reduced cost, reduced tritium consumption

Near-term ST Applications:

Plasma-Material Interface R&D + Advanced Physics





Fusion Nuclear Component Testing

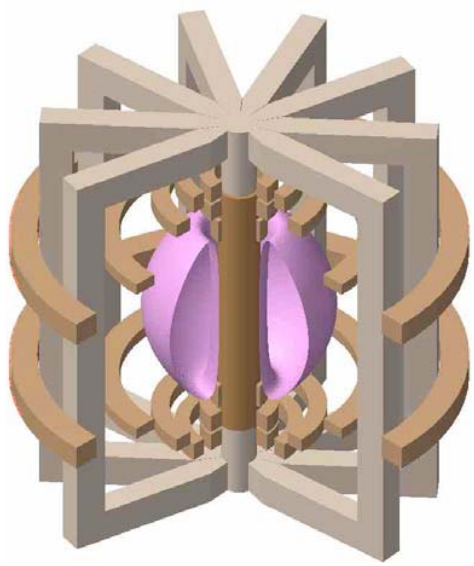
Longer term: ST Power Plant offers simplest magnets, easiest maintenance

ST is attractive configuration for "Taming the plasma-material interface"

- FESAC-PP identified PMI issue as highest priority: "…solutions needed for DEMO not in hand, …require major extrapolation and substantial development"

Scientific mission of National High-power advanced Torus eXperiment (NHTX):
"Integration of a fusion-relevant plasma-material interface with stable sustained high-performance plasma operation"

- **PMI research and integration goals:**
  - Create/study DEMO-relevant heat-fluxes
  - Perform rapid testing of new PMI concepts
    - Liquid metals, X-divertor, Super-X divertor
  - PMI research at DEMO-relevant $T_{wall} \sim 600°C$
  - Plasma-wall equilibration: τ_{pulse} = 200-1000s
  - Develop methods to avoid T retention
  - Demonstrate compatibility of PMI solutions with high plasma performance:
    - High confinement without ELMs
    - High beta without disruptions
    - Steady-state, fully non-inductive
  - Study high β_N, f_{BS} for ST-DEMO and ST-CTF
  - Test start-up/ramp-up for ST-CTF and ST-DEMO



National High-power advanced Torus eXperiment (**NHTX**)

Baseline operating scenario:

P_{heat}	50MW
R_0	1m
A	1.8-2
κ	≤ 3
B_T	2T
I_P	3-3.5MA
β_N	4.5
β_T	14%
n_e/n_{GW}	0.4-0.5
f_{BS}	$\approx$ 70%
f_{NICD}	100%
$H_{98Y,2}$	≤ 1.3
E_{NB}	110keV
P/R	50MW/m
Solenoid	½ swing to full I_P

ST-based Component Test Facility (ST-CTF) is attractive concept for "Harnessing Fusion Power"

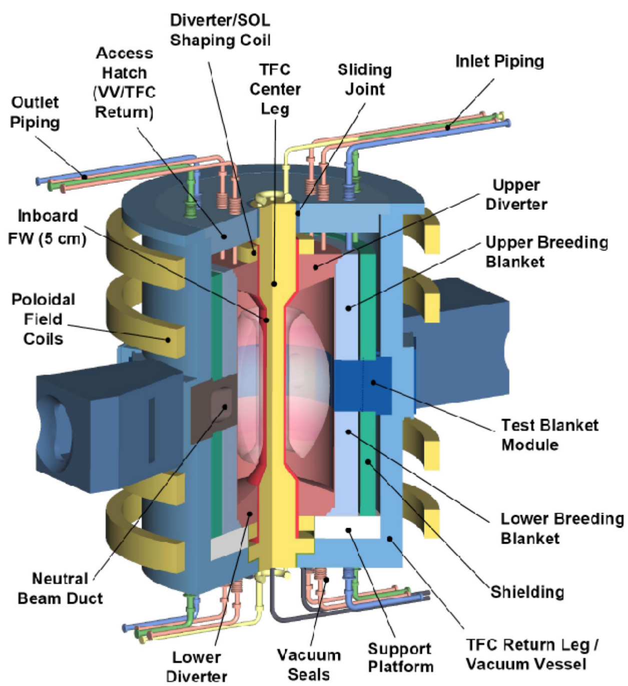
- **ST-CTF Required Conditions:**

From M. Peng APS-2007, based on NCT presentation to FESAC 8/7/2007

Performance metrics	ITER	Required Conditions	Demo Goals
Continuous operation	~hour	weeks	~months
14-MeV neutron flux on module (MW/m^2)	~0.8	1.0-2.0	~3
Total neutron fluence goal ($MW\text{-}yr/m^2$)	~0.3	6	~6-15
Duty factor goal	~1%	30%	~80%
Tritium self-sufficiency goal (%)	~0	~100	≥100

W_L [MW/m^2]	0.1	1.0	2.0
R0 [m]		1.20	
A		1.50	
kappa		3.07	
qcyl	4.6	3.7	3.0
Bt [T]	1.13	2.18	
Ip [MA]	3.4	8.2	10.1
Beta_N	3.8		5.9
Beta_T	0.14	0.18	0.28
n_e [$10^{20}/m^3$]	0.43	1.05	1.28
f_{BS}	0.58	0.49	0.50
T_{avgi} [keV]	5.4	10.3	13.3
T_{avge} [keV]	3.1	6.8	8.1
HH98		1.5	
Q	0.50	2.5	3.5
$P_{aux\text{-}CD}$ [MW]	15	31	43
E_{NB} [keV]	100	239	294
P_{Fusion} [MW]	7.5	75	150
T M height [m]		1.64	
T M area [m^2]		14	
Blanket A [m^2]		66	
$F_{n\text{-}capture}$		0.76	
P/R [MW/m]	**14**	**38**	**61**
Solenoid		Iron core or MIC solenoid for startup	

- **ST advantages for CTF:**
  - Compact device, high β
    - Reduced device cost
    - Reduced operating cost ($P_{electric}$)
    - Reduced T consumption
  - Simplified vessel and magnets
    - Fully modularized core components
    - Fully remote assembly/disassembly



ST-based Component Test Facility (ST-CTF)

FESAC Toroidal Alternates Panel (TAP) recently prioritized issues and gaps for the Spherical Torus (ST) for the ITER era

ST ITER-era goal: ***"Establish the ST knowledge base to be ready to construct a low aspect-ratio fusion component testing facility …. to inform the design of a demonstration fusion power plant"***

"Tier 1" issues and key questions from TAP, and NSTX goals:

1. **Startup and Ramp-Up:** Is it possible to start-up and ramp-up the plasma current to multi-MA levels using non-inductive current drive w/ minimal or no central solenoid?
   – NSTX goal: demonstrate non-inductive ramp-up and sustainment

2. **First-Wall Heat Flux:** What strategies can be employed for handling normal and off normal heat flux consistent with core and scrape-off-layer operating conditions?
   – NSTX goal: assess high flux expansion, detached divertors, liquid metals

3. **Electron Transport:** What governs electron transport at low-A & low collisionality?
   – NSTX goal: determine modes responsible for electron turbulent transport and assess the importance of electromagnetic (high β) and collisional effects

4. **Magnets:** Can we develop reliable center-post magnets and current feeds to operate reliably under substantial fluence of fusion neutrons?
   – NSTX goal: develop and utilize higher performance toroidal field magnet

Performance gaps between present and next-step STs motivate near-term research prioritization and upgrades

Gaps to next-step STs:

For NHTX, ST-CTF: reduce: n_e & ν^*_e, increase: NBI-CD, confinement, start-up/ramp-up
For ARIES-ST: increase: elongation, β_N, f_{BS}, confinement, start-up/ramp-up

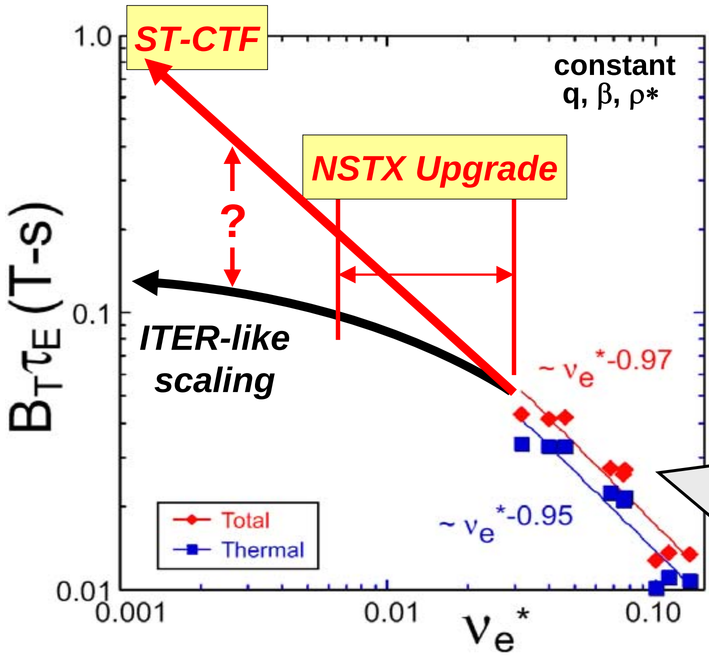
Near-term highest priority is to assess NHTX → ST-CTF scenarios

Present high β_N and f_{NICD}	NSTX	Upgraded NSTX	NHTX	ST-CTF	ARIES-ST
A	1.53	1.65	1.8	1.5	1.6
κ	2.6-2.7	2.6-2.8	2.8	3.1	3.7
β_T [%]	14	10-16	12-16	18-28	50
β_N [%-mT/MA]	5.7	5.1-6.2	4.5-5	4-6	7.5
$l_i(1)$	0.5-0.65	0.55-0.75	0.5-0.7	0.25-0.5	0.24
f_{NICD}	0.65	1.0	1.0	1.0	1.0
$f_{BS+PS+Diam}$	0.54	0.6-0.8	0.65-0.75	0.45-0.5	0.99
f_{NBI-CD}	0.11	0.2-0.4	0.25-0.35	0.5-0.55	0.01
$f_{Greenwald}$	0.8-1.0	0.6-0.8	0.4-0.5	0.25-0.3	0.8
ν^*_e	0.15	0.04	0.01	0.002	0.007
H_{98y2}	1.1	1.15-1.25	1.3	1.5	1.3

Dimensional/Device Parameters:

	NSTX	Upgraded NSTX	NHTX	ST-CTF	ARIES-ST
Solenoid Capability	Ramp+flat-top	Ramp+flat-top	Ramp to full I_P	No/partial	No
I_P [MA]	0.72	1.0	3-3.5	8-10	28
B_T [T]	0.52	0.75-1.0	2.0	2.5	2.1
R_0 [m]	0.86	0.92	1.0	1.2	3.2
a [m]	0.56	0.56	0.55	0.8	2.0
I_P / aB_{T0} [MA/mT]	2.5	1.8-2.4	2.7-3.2	4-5	6.7

Access to reduced collisionality is needed to understand underlying causes of ST transport, scaling to next-steps



Normalized electron collisionality $\nu_e^* \propto n_e / T_e^2$

- Future ST's are projected to operate at 10-100× lower normalized collisionality ν*
- Conventional tokamaks observe weak inverse dependence of confinement on ν*

ITER $B\tau_E$ (e-static g-Bohm) $\propto \rho_*^{-3} \beta^0$ $\nu_*^{-0.14}$ $q^{-1.7}$

Petty et al., PoP, Vol. 11 (2004)

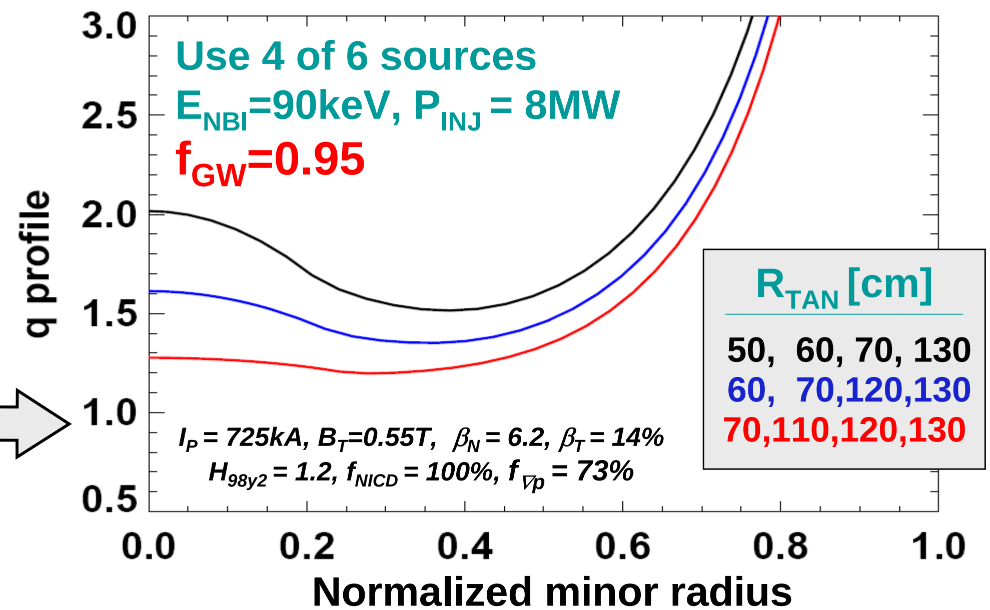
- NSTX observes much stronger scaling vs. ν*
  - Does favorable scaling extend to lower ν* ?
  - What modes dominate e-transport in ST ?
    - Electrostatic or electromagnetic?

- Higher toroidal field & plasma current enable access to higher temperature
- Higher temperature reduces collisionality, but increases equilibration time
- Proposed upgrade: Double field and current + 3-5× increase in pulse duration to substantially narrow capability gap

Increased auxiliary heating and current drive are needed to fully exploit increased field, current, and pulse duration

- Higher heating power to access high temperature and β at low collisionality
  - Need additional 4-10MW, depending on confinement scaling
- Increased external current drive to access and study 100% non-inductive
  - Need 0.25-0.5MA compatible with conditions of ramp-up and sustained plasmas
- Proposed upgrade: double neutral beam power + more tangential injection
  - More tangential injection → up to 2 times higher efficiency, current profile control
  - ITER-level high-heat-flux plasma boundary physics capabilities & challenges

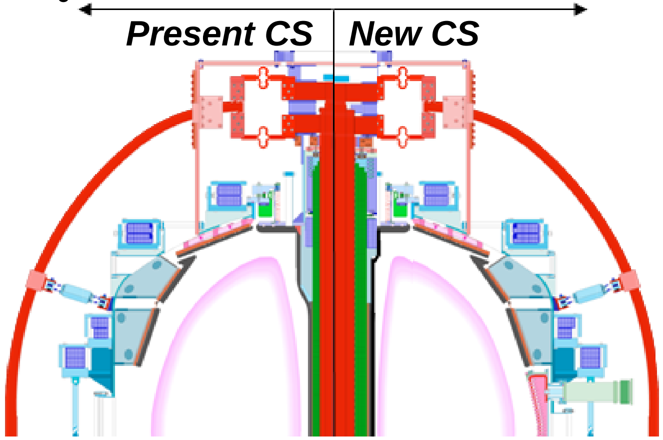
- q(r) profile very important for global stability, electron transport, Alfvénic instability behavior
  - Variation of mix of NBI tangency radii would enable core q control

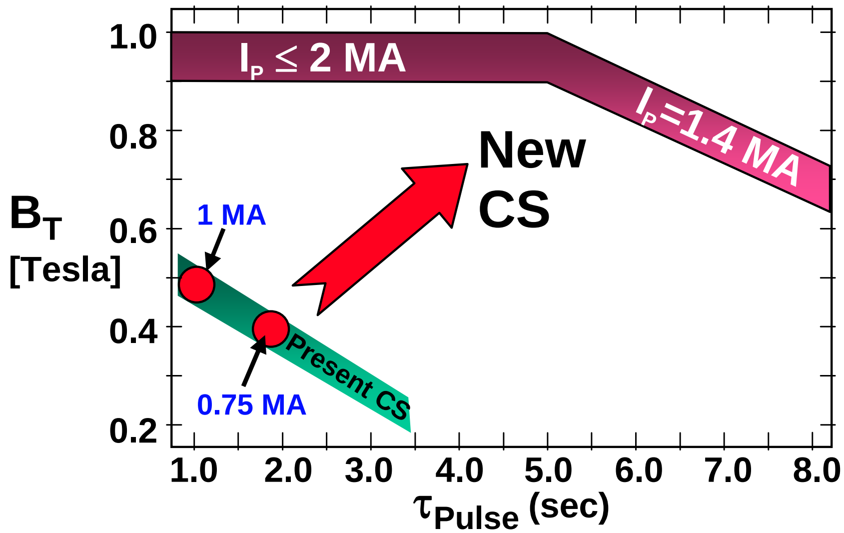


Major facility upgrades are proposed to bridge performance and understanding gaps between present and next-step STs

New center stack for 1T, 2MA, 5s to access reduced ν*, 100% non-inductive ST plasmas

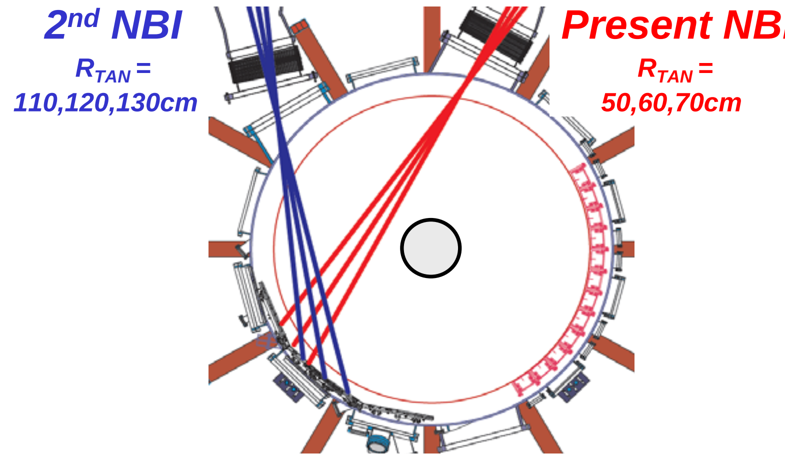
R_0/a = 1.25-1.3 → 1.5-1.6



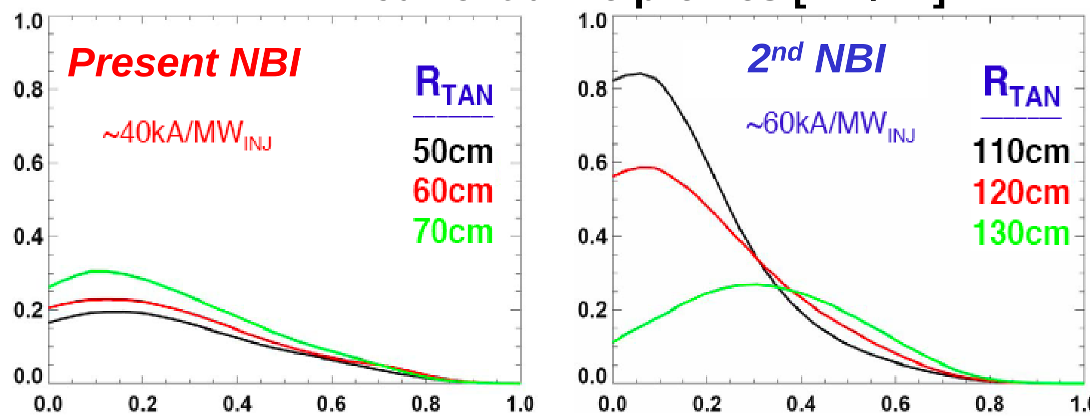


Magnet operation at ~1T (vs. 0.55T) → within a factor of 2 of next-step STs

2nd NBI with larger $R_{tangency}$ for sustained and controllable 100% NICD + high β at low ν*



NBI current drive profiles [MA/m²]



Normalized minor radius

Up to 2 times higher NBI current drive efficiency, current ramp-up with NBI, current profile control

Non-inductive ramp-up to ~0.4MA possible with RF + new CS, ramp-up to ~1MA possible with new CS + more tangential 2nd NBI

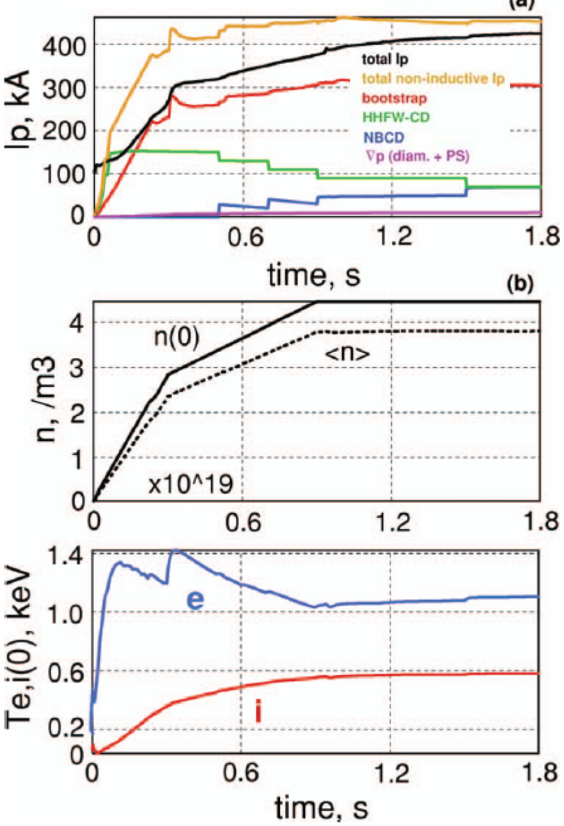
Ramp to ~0.4MA with fast wave heating:

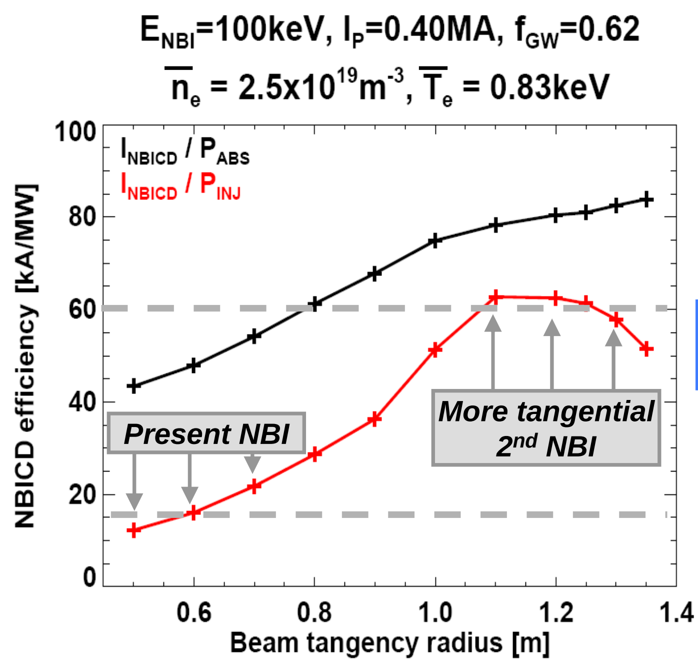
- High field ≥ 0.5T needed for efficient RF heating
- ~2s duration needed for ramp-up equilibration
- Higher field 0.5→1T projected to increase electron temperature and bootstrap current fraction

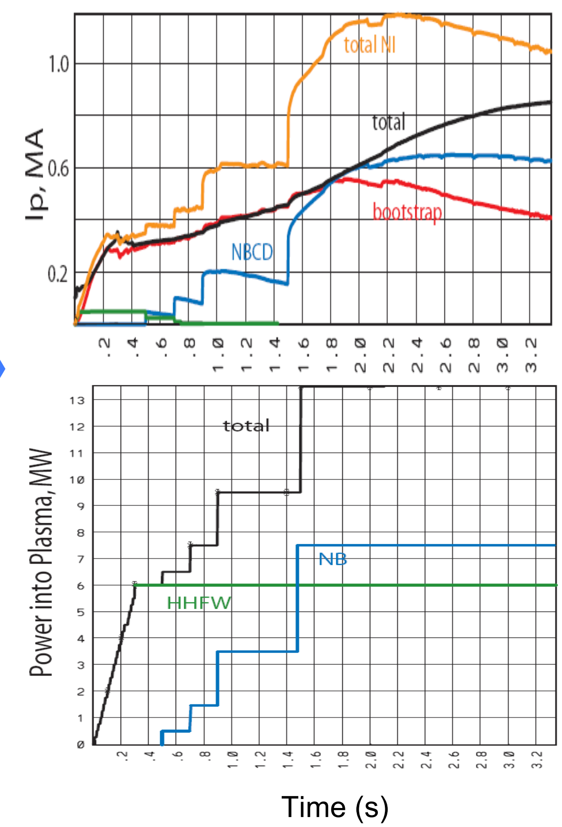
Extend ramp to 0.8-1MA with 2nd NBI:

- Benefits of more tangential injection:
  - Increased NBI absorption = 40→80% at low I_P
  - Current drive efficiency increases: ×1.5-2
- New CS needed for ~3-5s for ramp-up equilibration
  - Higher field 0.5→1T also projected to increase electron temperature and NBI-CD efficiency

TSC Simulations – C. Kessel



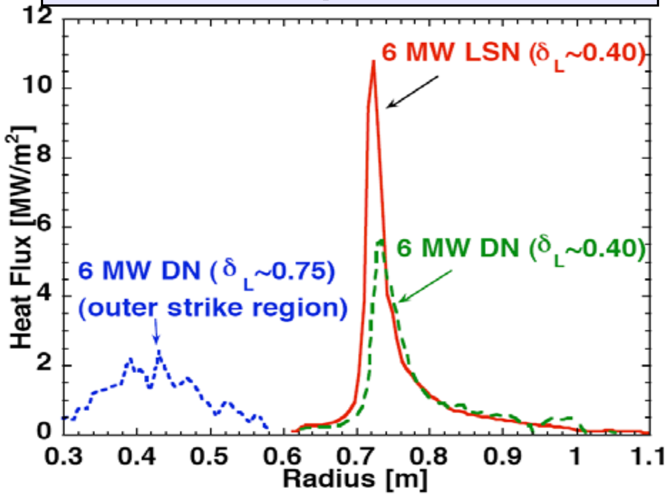




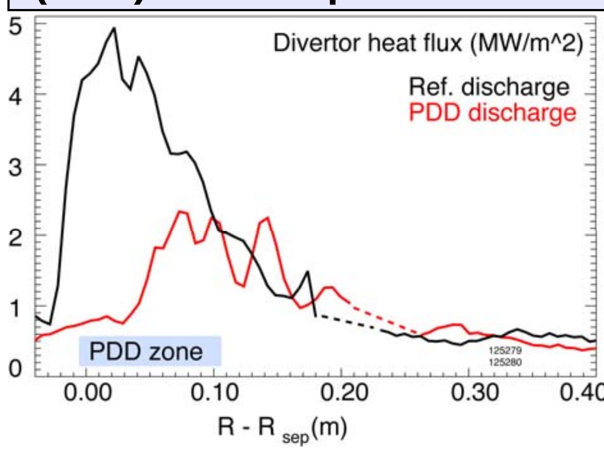
Additional PF coils of new CS would provide flexibility to control flux-expansion for heat flux control

Present NSTX:

Magnetic geometry strongly influences peak heat flux

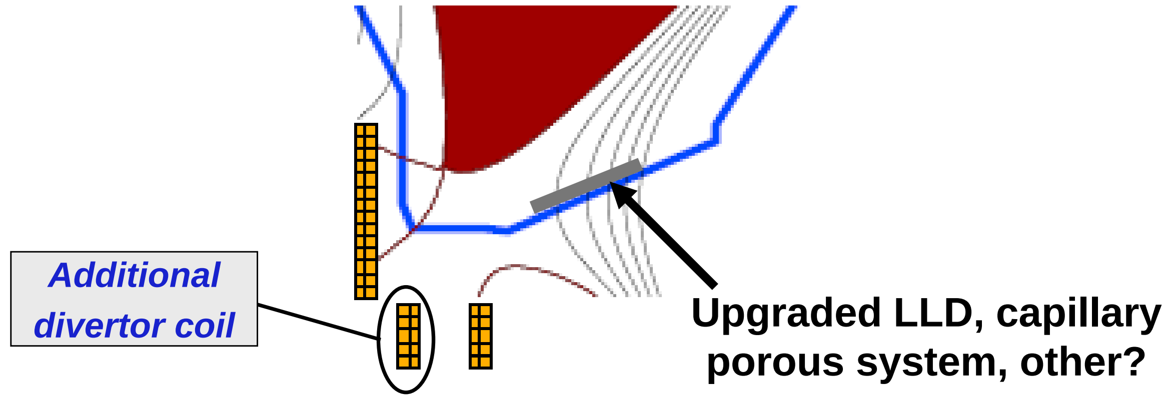


Partial divertor detachment (PDD) reduces peak heat flux

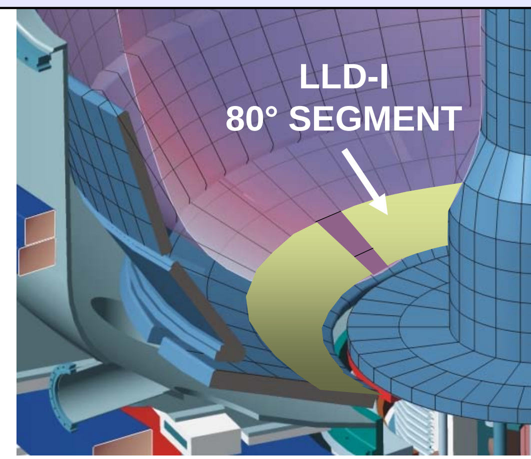


NSTX with new CS:

New divertor poloidal field coils on new CS would extend present high flux expansion ~20 to 40-60



Upgraded NSTX would test compatibility of high flux expansion, PDD, a liquid lithium divertor (LLD), and up to 5× longer pulse-length and 2-3× higher divertor heat flux

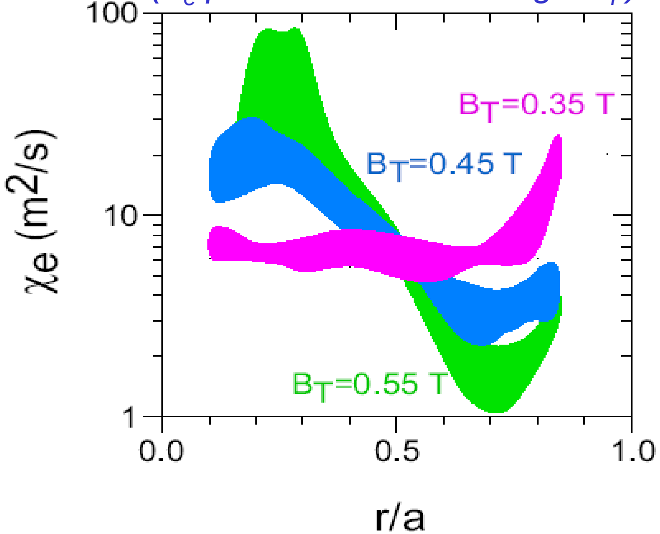


NSTX Upgrades needed to extend ST confinement scaling studies to higher field and current and lower collisionality

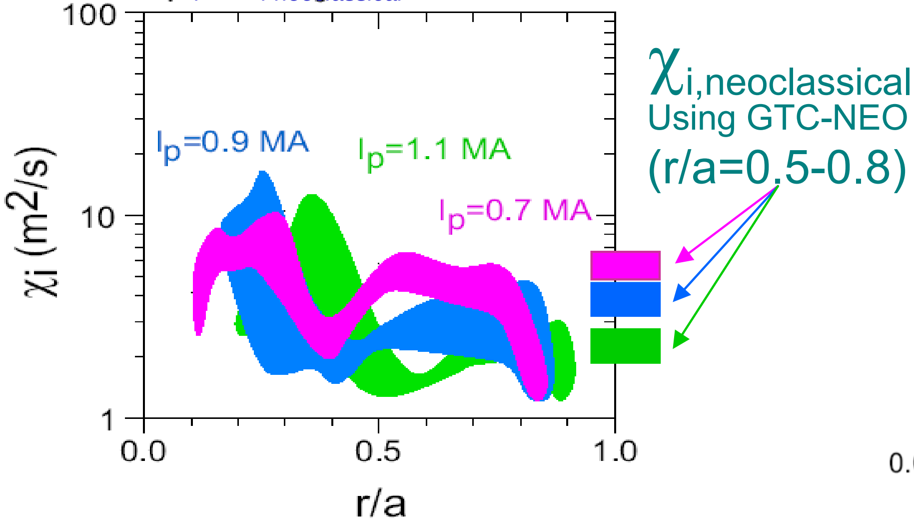
- **NSTX H-mode thermal confinement scaling differs from higher aspect ratio scaling:**

$\tau_{E,NSTX} \propto B_T^{0.9}\ I_p^{0.4}$ → strong B_T scaling $\qquad \tau_{E,98y,2} \propto B_T^{0.15}\ I_p^{0.93}$ → weak B_T scaling

Electrons largely responsible for B_T scaling of confinement
(T_e profile broadens at high B_T)

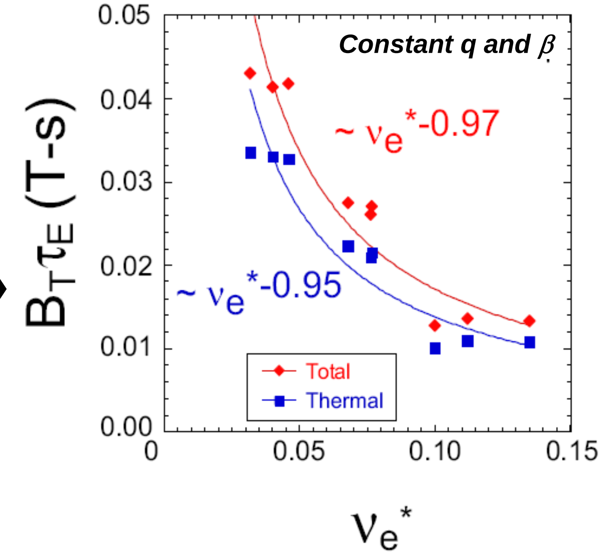


Ions largely responsible for I_P scaling of confinement
($\chi_i \approx \chi_{i\text{-neoclassical}}$ at large r/a)



New CS with 1T, 2MA operation:

- Increased range of B_T, I_P variation from 1.6 to nearly a factor of 3
- Does strong confinement dependence on ν^* extend to lower ν^*?
- Assume $\tau_E \propto B_T^{1.3}$ at fixed q, $\tau_E \propto P_{heat}^{-0.5\text{ to }-0.7}$, and $n_e/n_{gw} \propto I_P^{-0.5}$
  - Present NBI + 4MW RF, access ~ 0.75-0.9× present β, 3-4× lower ν^*
  - Present + 2nd NBI + 4MW RF: access ~0.9-1.1× present β, 4-6× lower ν^*

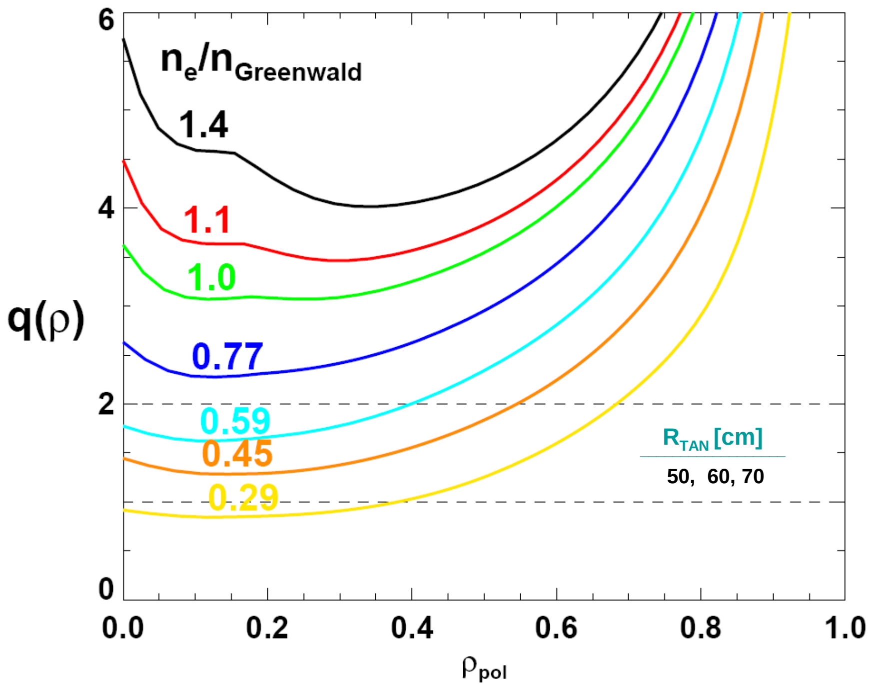


Higher field B_T=1T from new CS + 2nd NBI would enable access to wide range of 100% non-inductive scenarios

- Use present NBI-CD + fast wave heating
- Vary q_{min} with density (CD efficiency $\propto T_e/n_e$)
- State sustained for 1-1.5s (~1 τ_{CR})
  - NBI duration limited to 2s at 7.5MW

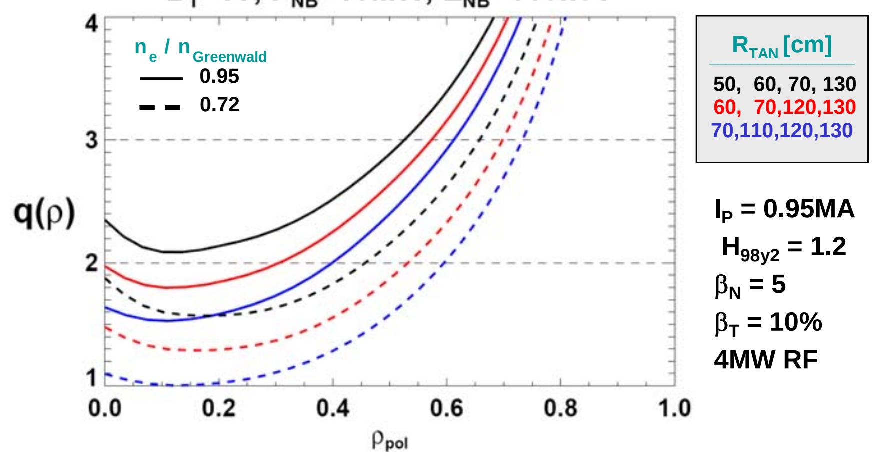
- Addition of 2nd NBI would enable:
  - Longer NBI duration → profile relaxation
    - 10MW NBI available for 5s → 3-4 τ_{CR}
  - Control q_{min} & q-shear with NBI source and B_T
  - Study long-pulse MHD stability, PMI performance

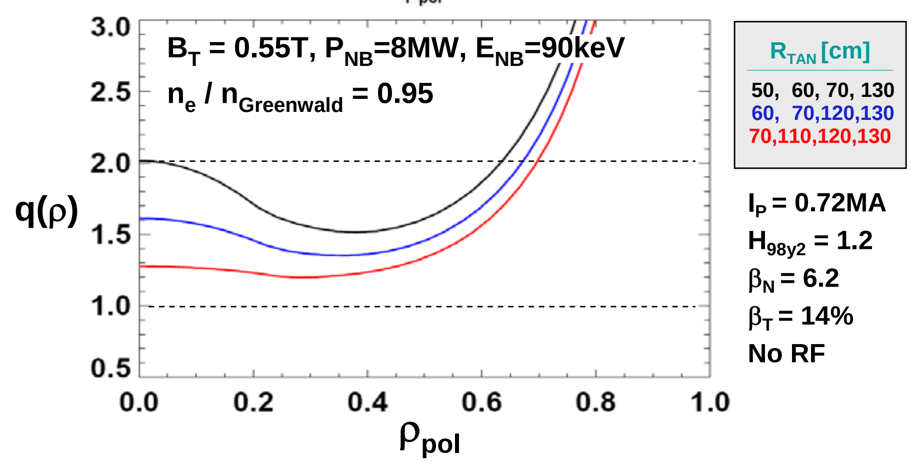
q profiles at 100% NICD fraction
B_T=1T, P_{NB}=7.5MW, E_{NB}=100keV



I_P = 0.8-1.2MA, H_{98y2} = 1.2-1.4
β_N = 4.5-5, β_T = 10-12%, 4MW RF

q profiles at 100% NICD fraction
B_T=1T, P_{NB}=10MW, E_{NB}=110keV





Summary: NSTX will lead the U.S. effort to assess the properties and potential advantages of the ST for fusion

- **NSTX will address important questions for ST and fusion science:**
  - Can high normalized pressure be sustained with high reliability?
  - What are underlying modes and scalings of anomalous transport?
  - How does large fast-ion content influence Alfvénic MHD & fast-ion loss?
  - Can steady-state & transient edge heat fluxes be understood, controlled?
    - Is liquid Li attractive for taming the plasma-material interface?
  - Are fully non-inductive high-performance scenarios achievable in the ST?
  - Can a next-step ST operate solenoid-free with high confidence?

- **Upgrades will greatly expand the scientific capabilities of NSTX:**
  - Access and understand impact of reduced collisionality on ST physics
    - Achievable through density reduction, higher B_T, I_P, power
    - Impacts all topical science areas
  - Access and understand impact of varied NBI deposition profile
    - Achievable through implementation of 2nd NBI
    - Impacts heating, rotation, current profiles, f(v) for fast-ion MHD
    - Access fully non-inductive ramp-up and sustainment

- **NSTX research will strongly address key gaps for next-step STs**