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NSTX Integrated Scenario Research Plans for 2009-2013

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Jonathan Menard

For the NSTX Research Team

National Tokamak Planning Workshop
MIT, Cambridge, Massachusetts

September 17-19, 2007

- *Culham Sci Ctr*
- *U St. Andrews*
- *York U*
- *Chubu U*
- *Fukui U*
- *Hiroshima U*
- *Hyogo U*
- *Kyoto U*
- *Kyushu U*
- *Kyushu Tokai U*
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- *JAERI*
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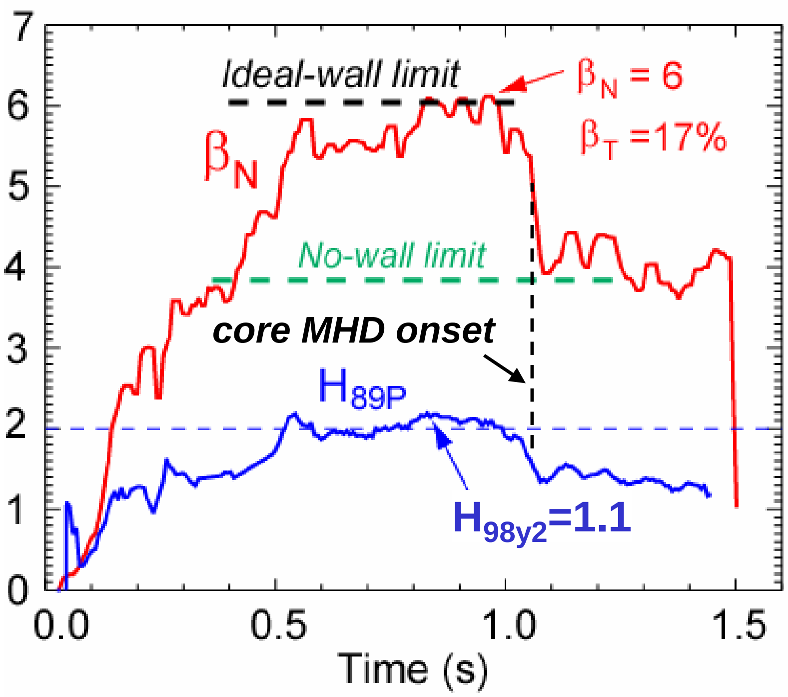
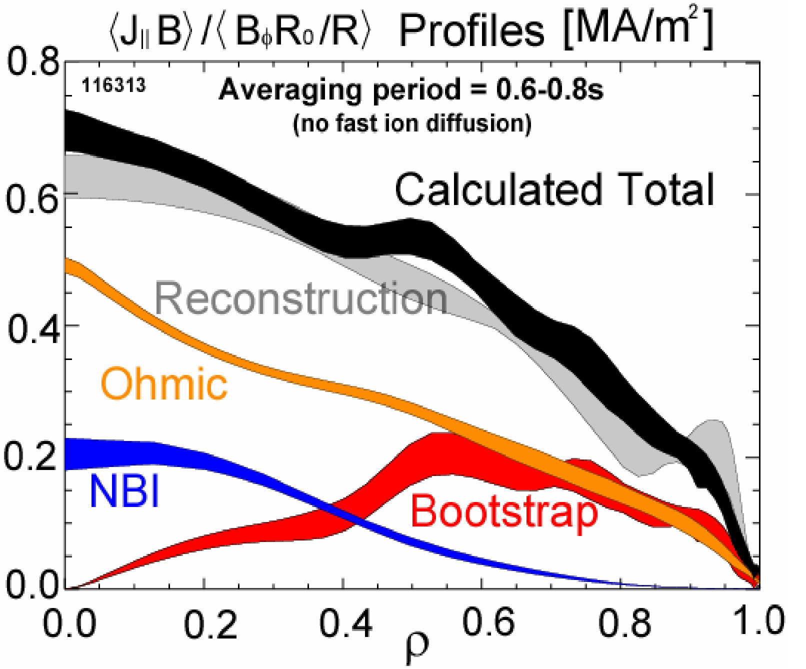
- *Ioffe Inst*
- *RRC Kurchatov Inst*
- *TRINITI*
- *KBSI*
- *KAIST*
- *ENEA, Frascati*
- *CEA, Cadarache*
- *IPP, Jülich*
- *IPP, Garching*
- *ASCR, Czech Rep*
- *U Quebec*

NSTX has made substantial progress in developing and understanding high performance plasmas w/ high non-inductive current fraction





- Routine operation near ideal-wall stability limit $\beta_N \leq 6$
  - Plasma quiescent until q evolves toward $q_{MIN} \leq 1.2$ → core MHD
- H-mode with $H_{98y2} > 1$ at high β_N

- Utilized novel low-B_T MSE diagnostic to validate current drive sources
  - Core MHD can redistribute fast ions
- Non-inductive CD fraction up to 65%
  - f_{BS}=55%, f_{NBICD} = 10% with β_N near 6

NSTX 5 year integration goal is to meet or exceed key dimensionless performance parameters of NHTX and ST-CTF

	NSTX full-NI target	NHTX	ST-CTF
A	1.5	1.8	1.5
H_{98y2}	1.1-1.4	1.3	1.3
κ	2.6	2.8	3.0
q*	5.3	3.8-4.5	3.3-4.2
β_T	14%	12-16%	16-25%
β_N [%-mT/MA]	6.2	4.5-5	4-5
f_{BS}	0.7-0.8	0.65-0.75	0.45-0.55
f_{GW}	0.7-1.0	0.4-0.5	0.3-0.5
Dimensional parameters:			
I_P [MA]	0.75	3-3.5	8-10
B_T [T]	0.55	2.0	2.5
R_0 [m]	0.86	1.0	1.2
a [m]	0.58	0.55	0.8
I_P / aB_{T0} [MA/mT]	2.3	2.7-3.2	4-5

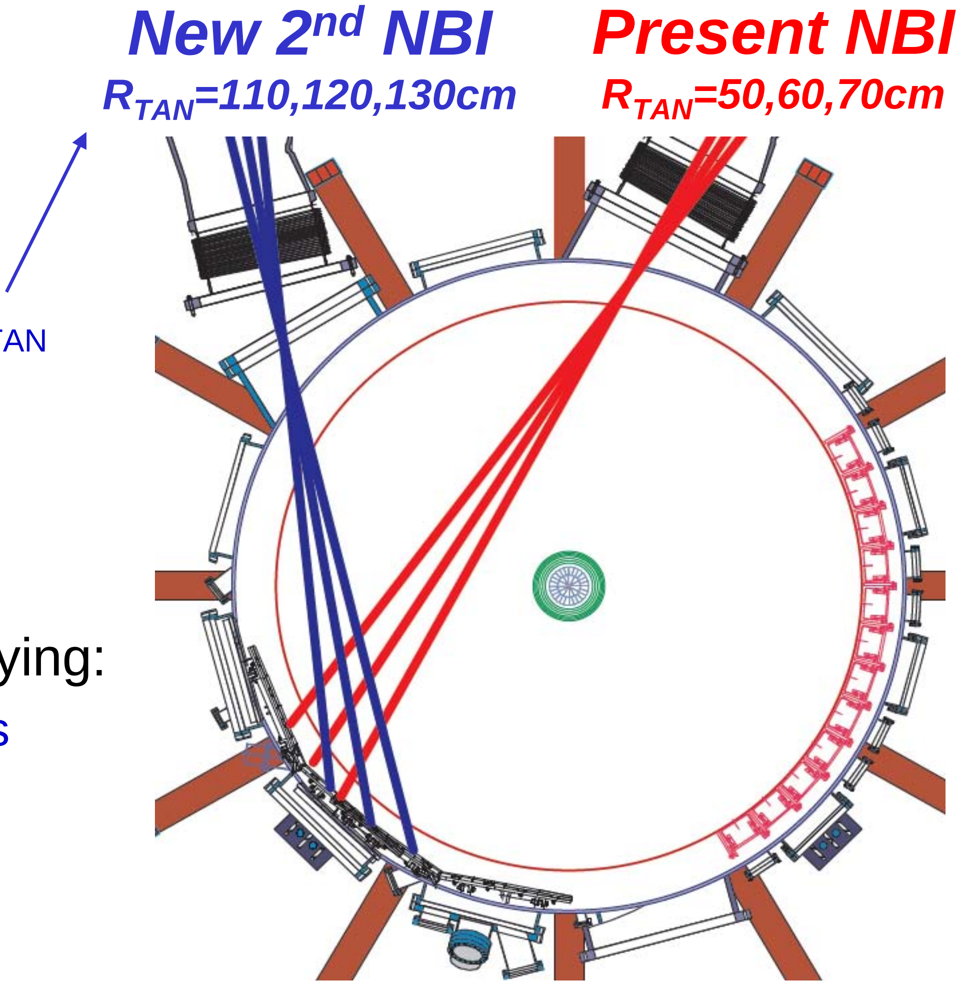
5 year goal: Achieve full NICD at high β and confinement while advancing startup/ramp-up research for NHTX/ST-CTF/DEMO

- Full non-inductive current drive strategy and method:
  1. Increase BS current ↔ higher $\beta_{P\text{-th}}$ thru higher P_{HEAT} and/or H-factor
  2. Increase NBICD and P_{HEAT}, achieve J profile control ↔ 2nd NBI source
  3. Control and improve confinement and stability ↔ J profile control
  4. $f_{GW} < 1$ & $\beta_N \sim 6$, n_e & J equilibration ↔ high B_T=5.5kG w/ longer flat-top
  5. Control n_e, increase confinement ↔ liquid lithium divertor (LLD)
  6. Sustain τ_E, β_N by suppressing ELM, RWM, EF ↔ off-midplane 3D coils

- Plasma formation and ramp-up strategy and method:
  1. Increase Coaxial Helicity Injection (CHI) I_P ↔ higher pre-ionization, V_{CHI}
  2. Optimize non-CHI start-up ↔ PF-only w/ PI and heating, plasma guns
  3. Increase early pre-ionization/heating power ↔ 350kW ECH/EBW system
  4. Extend long-pulse plasmas ↔ use CHI/PF/Gun for ohmic flux savings
  5. Ramp-up I_P to full-NI target ↔ high-I_P start-up for FW & NBI heating/CD

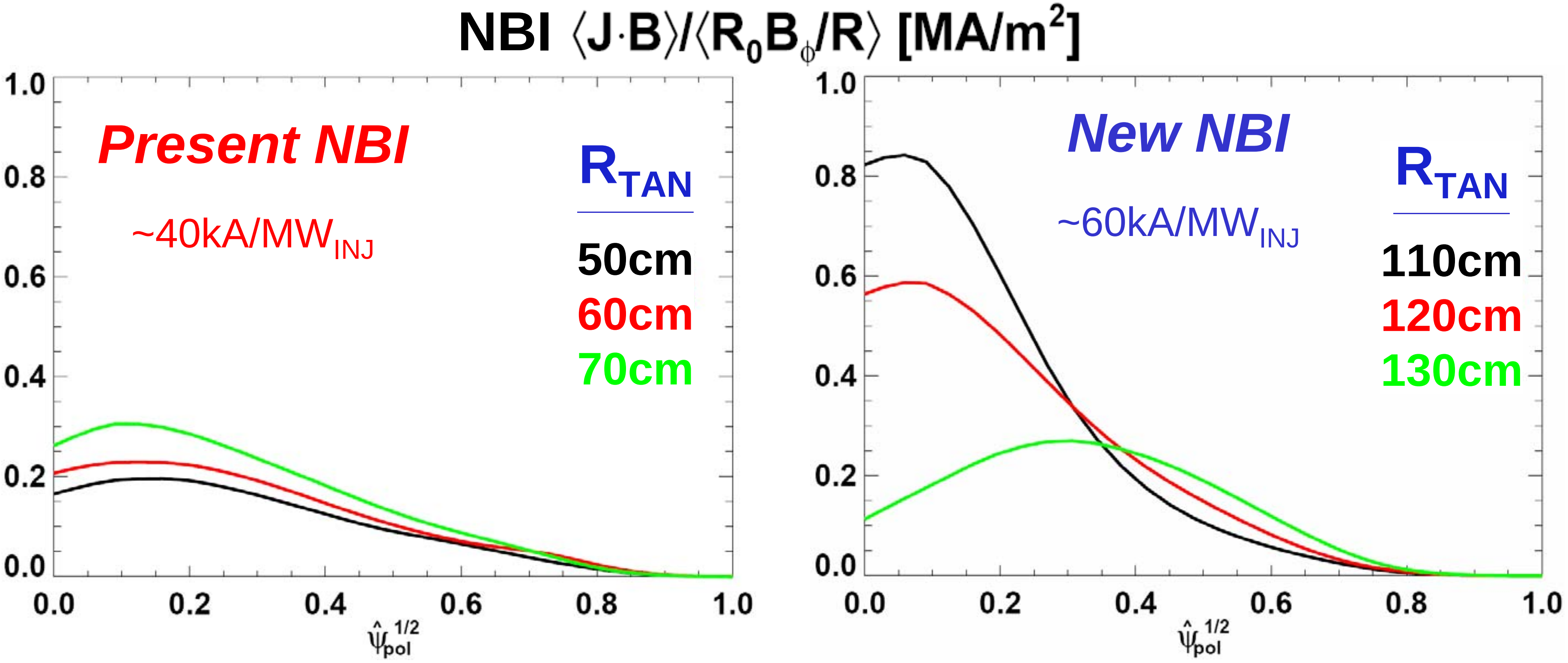
Addition of 2nd NBI source with increased tangency radius of injection offers several potential advantages

- Higher P_{HEAT} for higher β_P, f_{BS} at presently sustainable $H_{98y2} \leq 1.2$
- Increased NBICD from higher P_{NBI}
  - And higher CD efficiency of large R_{TAN}
- Increased control of *q* profile
  - Optimize $q(\rho)$ for high τ_E, β, f_{NI}
- Increased research flexibility by varying:
  - *q*-shear for transport & MHD physics
  - Heating, torque, rotation profiles
  - β at higher I_P and B_T
  - Fast-ion distribution and instabilities
  - Divertor P/R and pulse-length



NBI upgrade operational mid-FY10

Increased R_{TAN} NBI provides 50% higher CD efficiency and much more control over NBICD $J_{||}$ profile than present NBI



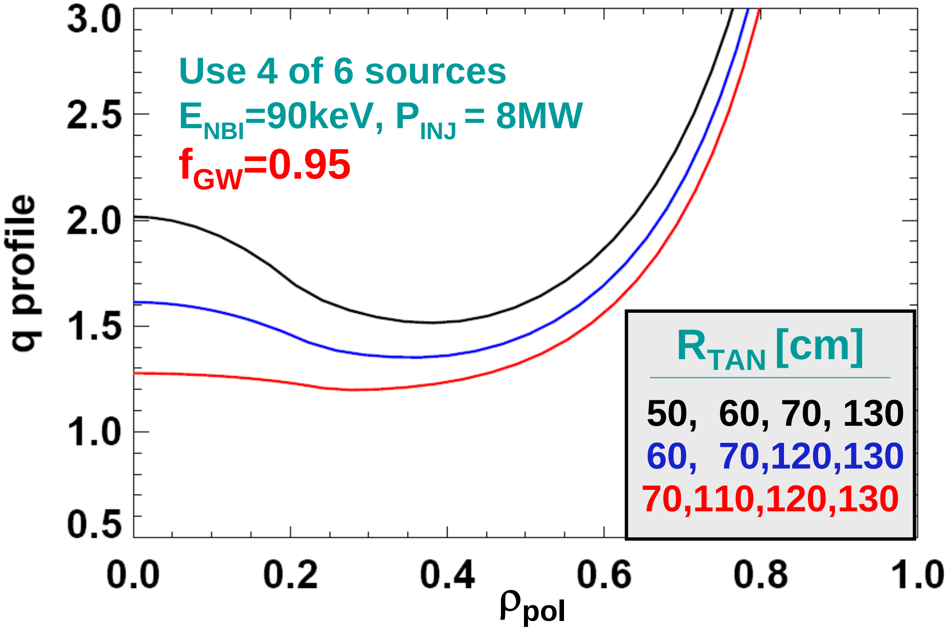
NBI $\langle J \cdot B \rangle / \langle R_0 B_\phi / R \rangle$ [MA/m^2]

P_{NBI}=2MW E_{NBI}=90keV, I_P=0.82MA, f_{GW}=0.58 $\overline{n_e} = 4.4 \times 10^{19} m^{-3}$, $\overline{T_e}$ = 1.2keV

- **Small R_{TAN} NBI provides little variation in NBI $J_{||}$ profile shape**
- **Large R_{TAN} can vary NBI $J_{||}(0)$ by a factor of 8 → peaked to hollow $J_{||}$**

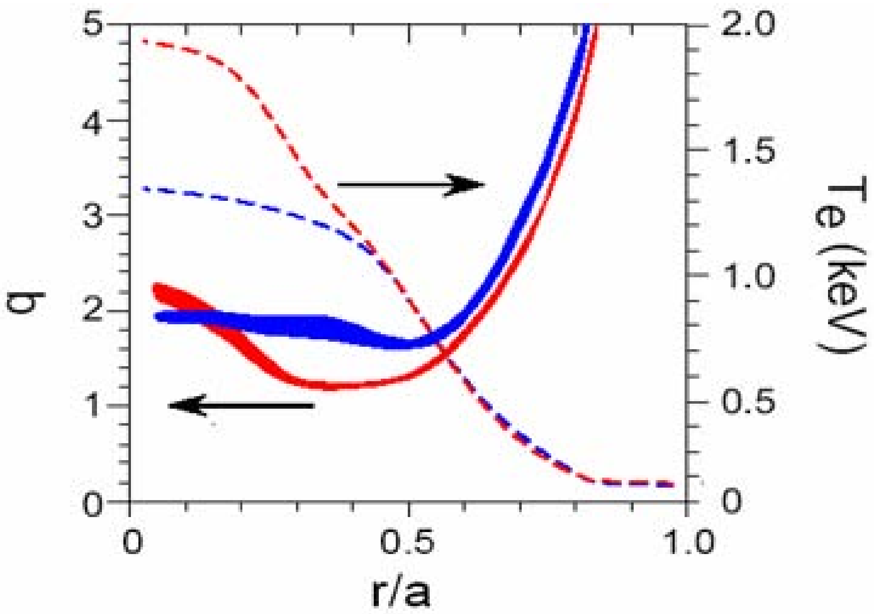
2nd NBI would enable control of core q and χ profiles in fully non-inductively-driven scenarios using only NBI + bootstrap

- Combination of available sources can control q_{MIN} and core q-shear
  - At H_{98y2}=1.2, J control with $q_{MIN} > 1.2$ requires operation with $f_{GW} > 0.9$



I_P = 725kA, B_T=0.55T, β_N = 6.2, β_T = 14%
H_{98y2} = 1.2, f_{NICD} = 100%, $f_{\nabla p}$ = 73%

- Magnetic shear control could be important tool for controlling core confinement and MHD stability
  - Core transport reduced in RS L-mode



Real-time MSE, CHERS available mid-FY10

Parameter scans confirm higher P_{NBI} & B_T aid achievement of full non-inductive current drive using only NBI + bootstrap

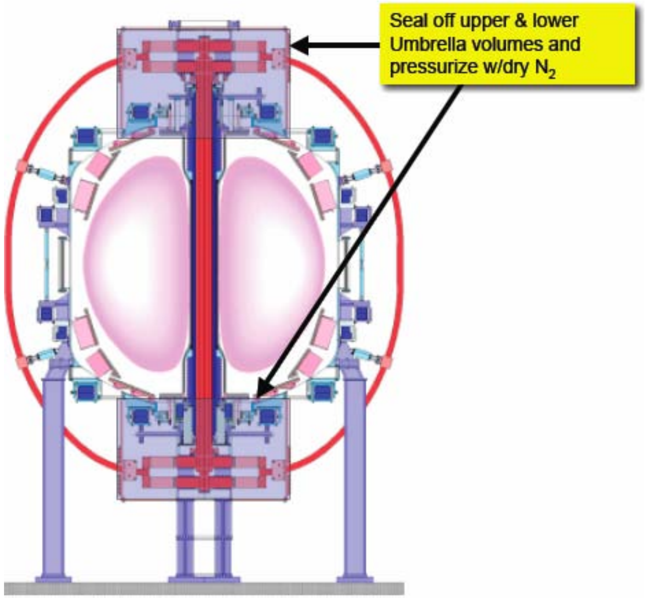
- P_{NBI}=8-10MW needed for full NICD if H_{98y2}=1.1-1.2 and $q_{MIN} \geq 1.2$

	High β_P expt. at 0.52T	H_{98y2} scan at 0.55T			B_T=0.45T
P_{INJ} [MW]	5.8	6.0	8.0	10.0	8.0
f_{NICD}	0.65	1.0	1.0	1.0	1.0
H_{98y2}	1.2	1.4	1.2	1.1	1.1
q_{MIN}	1.3	1.5	1.35	1.25	1.2
β_N	5.7	6.1	6.2	6.3	6.6
f_{GW}	1.0	0.84	0.96	0.94	1.07
I_P [kA]	720	720	725	740	585
β_T	13.4	14.2	14.0	14.7	15.0
β_P	1.7	2.3	2.3	2.3	2.6
f_{BS}	0.54	0.77	0.73	0.69	0.74
f_{NBICD}	0.11	0.23	0.27	0.31	0.26

- High B_T=0.55T operation is favorable for:
  - Lower β_N → closer to β_N=6 achieved experimentally
  - Reduced f_{GW} → below 1
  - Higher I_P (prompt loss increases rapidly for I_P < 600kA)

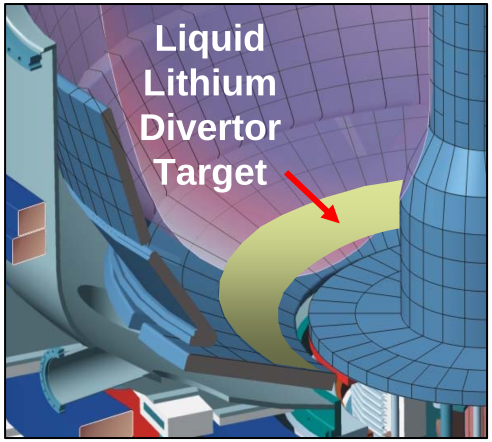
Long-pulse integrated scenarios benefit from extended TF and OH coil operation at full B_T, and require *sustained* density control

- Sub-cooled OH and TF (-50°C-100°C) provide 2.5s flat-top at B_T=0.55T
  - Longer flat-top needed to reach density equilibration & J relaxation at higher T_e
  - B_T = 0.52-0.55T aids 700-750kA full-NI
  - Long-pulse OH → I_P=1MA for 2.5s
    - Use increased NBICD of 2nd NBI source



Sub-cooling operational mid-FY10

- Liquid Lithium Divertor for D pumping
  - Designed to reduce density 25-50% depending on triangularity
  - Consistent with f_{GW} > 0.8 needed for fully-NI target scenarios
- Long-pulse pumping and core fueling required for sustained density control



Initial LLD operational FY09

Pumping upgrade in FY10

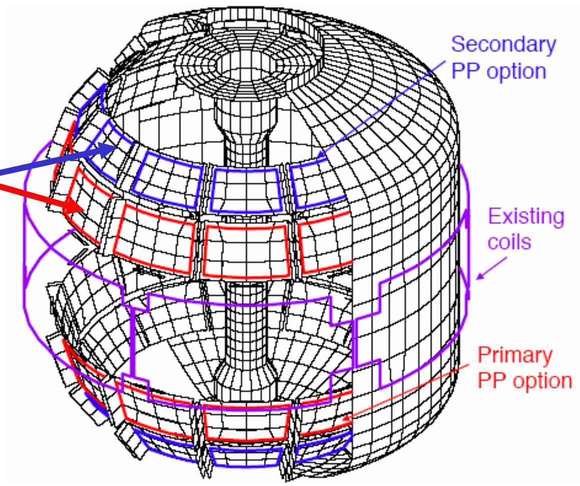
Implement core fueling FY10-12

NSTX could provide unique contributions to ELM suppression physics understanding for future ST and AT NCT and reactors

- **For ST - interplay between ELM control and $\beta_N > \beta_{N\text{-no-wall}}$** (islands, flow damping)
- **For ST/AT - 12 coils toroidally → high-n (n=6), mixed intermediate-n (n=3+n=4)**

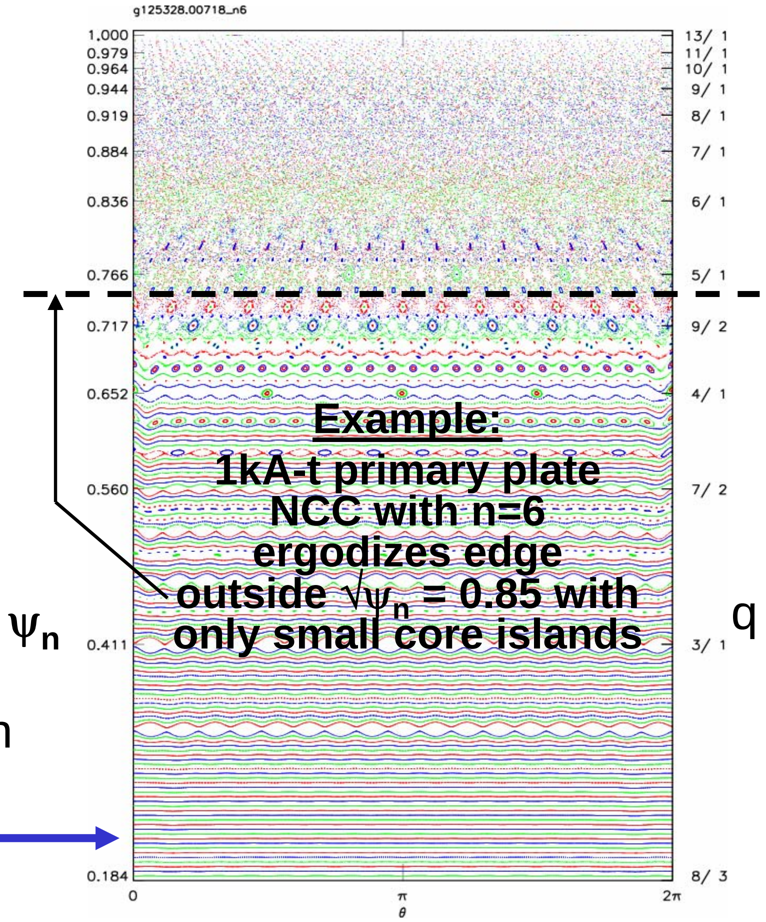
- **Investigating off-axis Non-axisymmetric Control Coils (NCC) for RMP + other MHD**

Internal NCC Option



NCC operational mid-FY12

- Internal NCC attractive for edge ergodization
  - n=3,4 using primary+secondary coils (48)
  - n=6 using primary coils (24)
  - Only few kA-turns required for each option

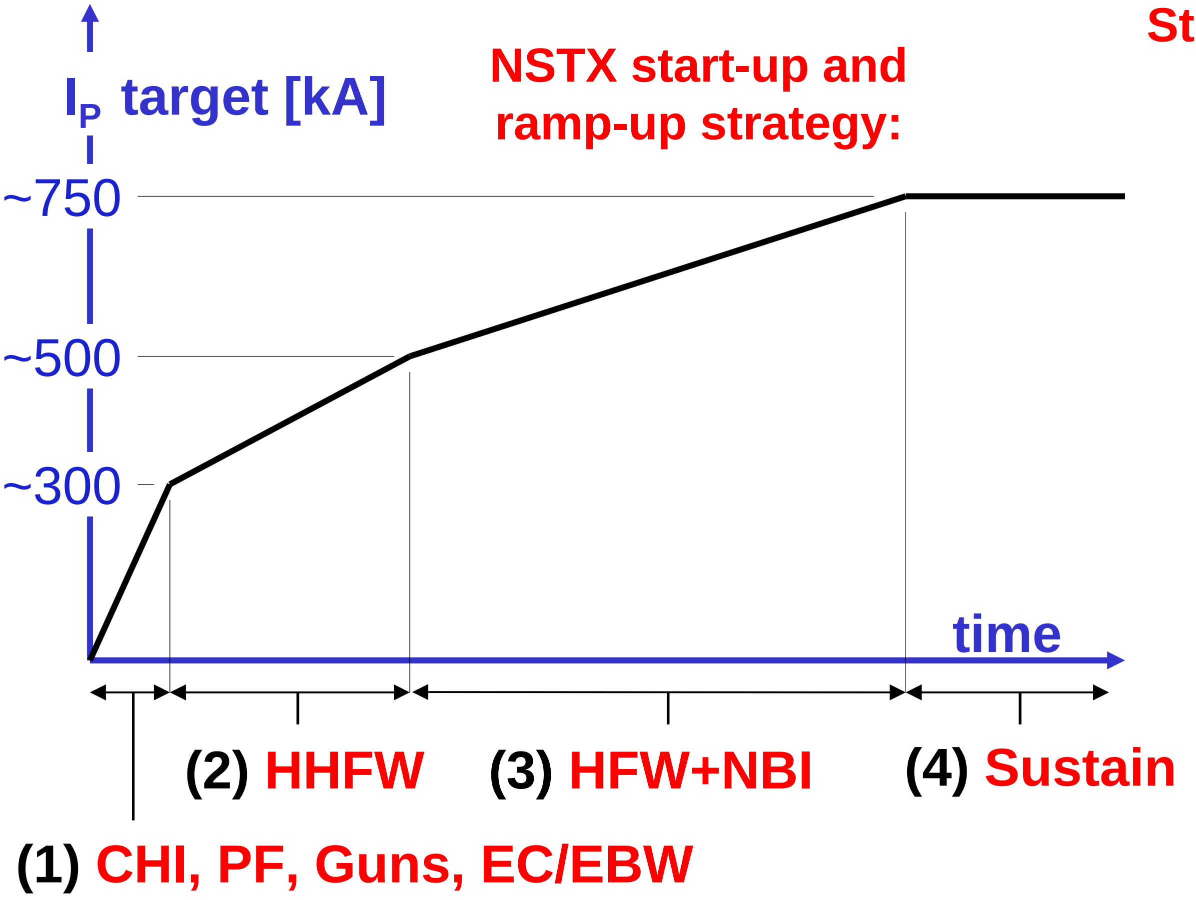


Example:

1kA-t primary plate NCC with n=6 ergodizes edge outside $\sqrt{\psi_n} = 0.85$ with only small core islands

NSTX will continue to advance the integration of plasma start-up, ramp-up, and sustainment needed for ST-CTF and reactors

NSTX start-up and ramp-up strategy:



(1) CHI, PF, Guns, EC/EBW

(2) HHFW

(3) HFW+NBI

(4) Sustain

Start-up/ramp-up requirements:

(1→2) I_P, T_e, RF coupling must be sufficiently high for HHFW to be absorbed

(2) Sufficiently high P_{RF}, τ_E must be achieved for I_P overdrive using BS and HHFW current drive

(2→3) Sufficiently high I_P needed to absorb NBI, high P_{HEAT}, τ_E, β_P needed for current overdrive

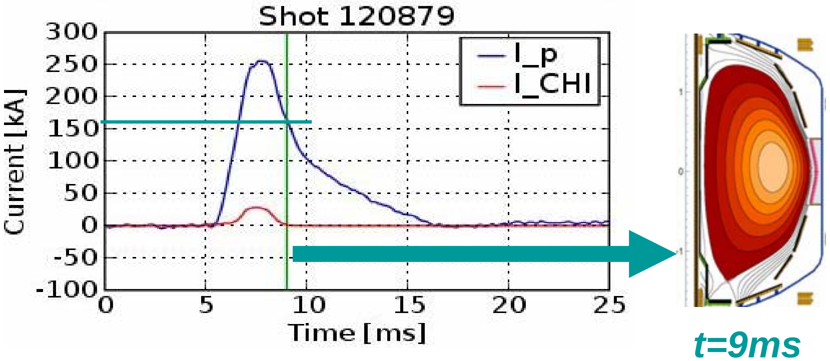
(3→4) Ramp-up plasma must be consistent with sustained high-f_{NI} scenario

In ST-CTF/DEMO, iron core could provide portion of flux needed for I_P ramp-up

NSTX FY2009-13 - Use OH to simulate iron core as needed to achieve I_P ramp-up

Coaxial Helicity Injection (CHI) is most successful non-solenoidal plasma start-up technique implemented thus far on NSTX

- **2006:** 160kA of closed-flux I_P

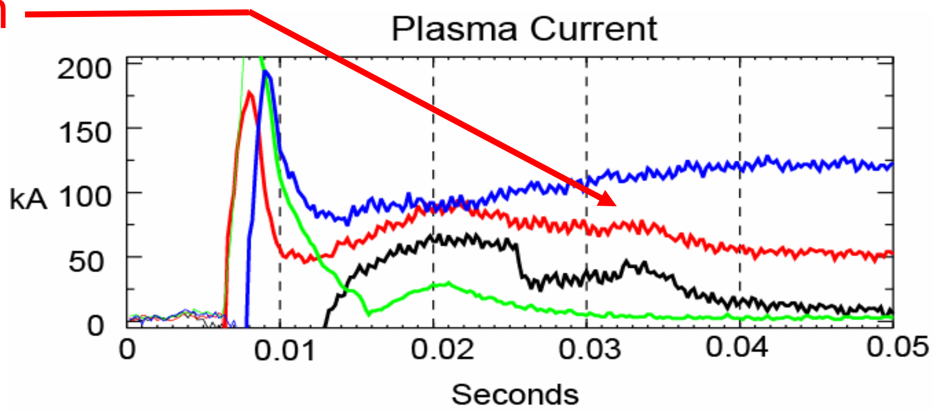


t=9ms

- **2007:** Reduced OH flux consumption

CHI only
Induction only
CHI + induction

CHI + induction: I_P = 120kA
(Boronization + improved PF programming)

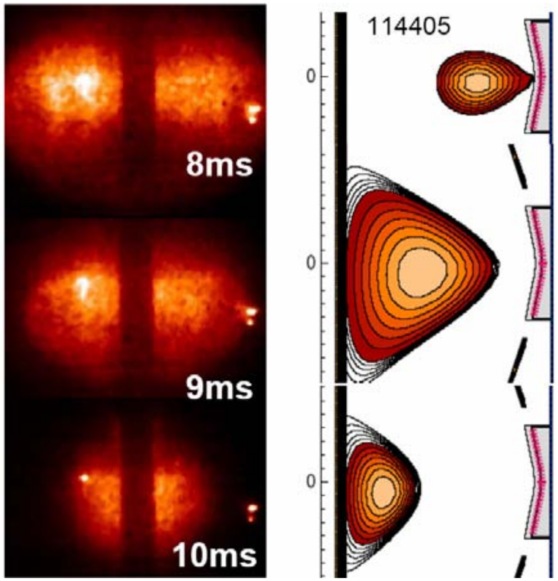


CHI Start-up Plan for 2009-13

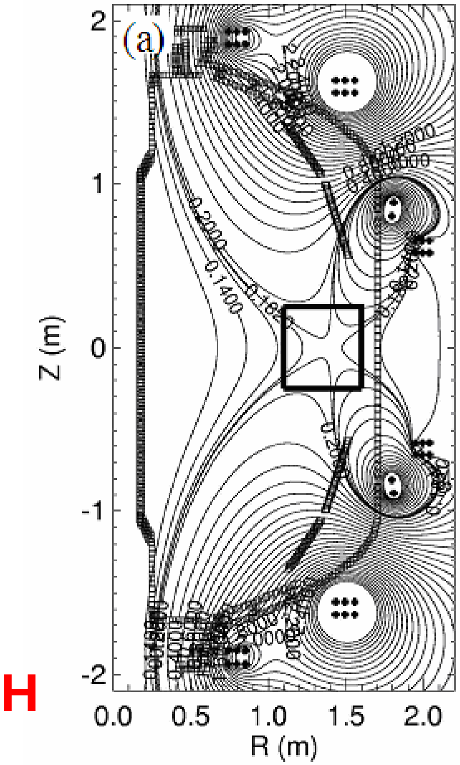
- 2008-09: Reduce OH flux consumption of long-pulse discharges
- 2009-10: Improve CHI & coupling to induction w/ 350kW ECH pre-ioniz.
- 2010-11: Increase closed flux current using higher V_{CHI} → 2kV
- 2011-12: Couple high-closed-flux I_P CHI to NBI and HHFW
- 2012-13: Use CHI + other startup/ramp-up to produce high-β discharge

PF-only startup challenge: coils providing V_{LOOP} must also provide radial force balance → must control η vs. time

- 20kA achieved w/ large-area field null
- HHFW couples until plasma moves inward
- **More heating needed for lower η → ECH/EBW**



- Scenarios with large stored flux and small area field-null tested
- No plasma-current measured
- **More pre-ionization power needed → ECH**

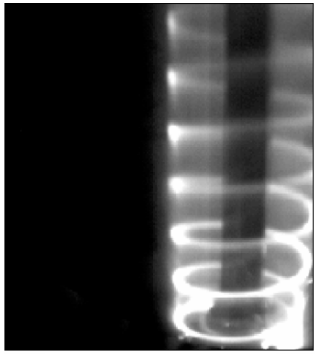


PF-only Startup Plan for 2009-13

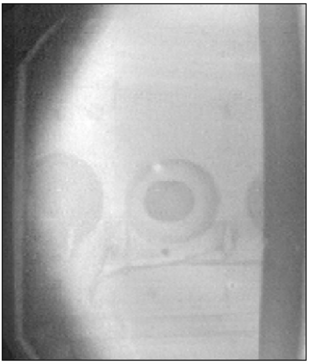
- 2009-10: Increase I_P of PF-only scenarios with w/ 350kW ECH/EBW
- 2009-11: Quantify achievable I_P vs. null quality and ECH power
- 2011-12: Couple highest I_P PF-only scenario to HHFW, NBI
- 2012-13: Use PF + other startup/ramp-up to produce high-β discharge
- 2009-13: Utilize TSC simulations to optimize ramp-up evolution

Plasma-gun startup techniques from PEGASUS could be tested on NSTX to complement/enhance CHI/PF-only startup research

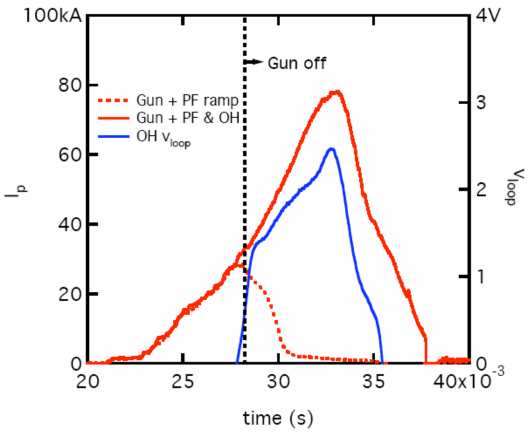
- Plasma guns in divertor produced I_P=30kA
- Successfully coupled to OH induction

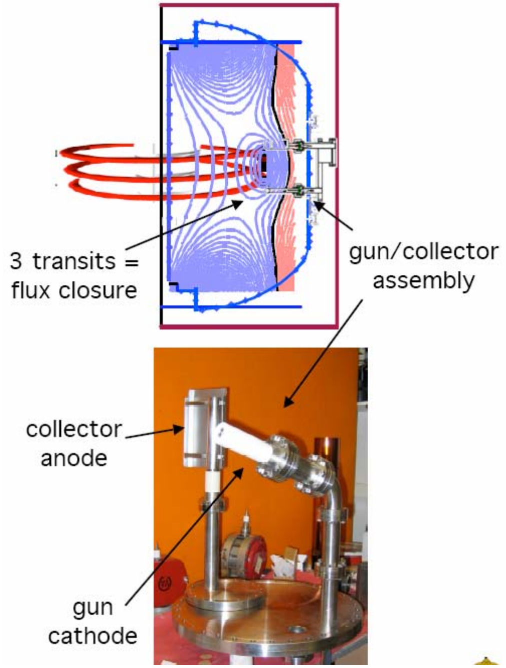


Filaments



Relaxed ST



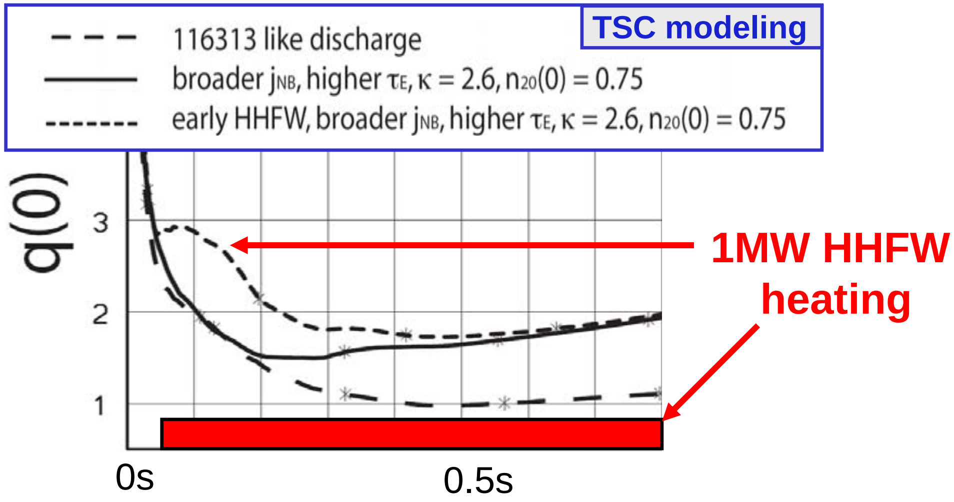


- Outboard mid-plane gun being developed

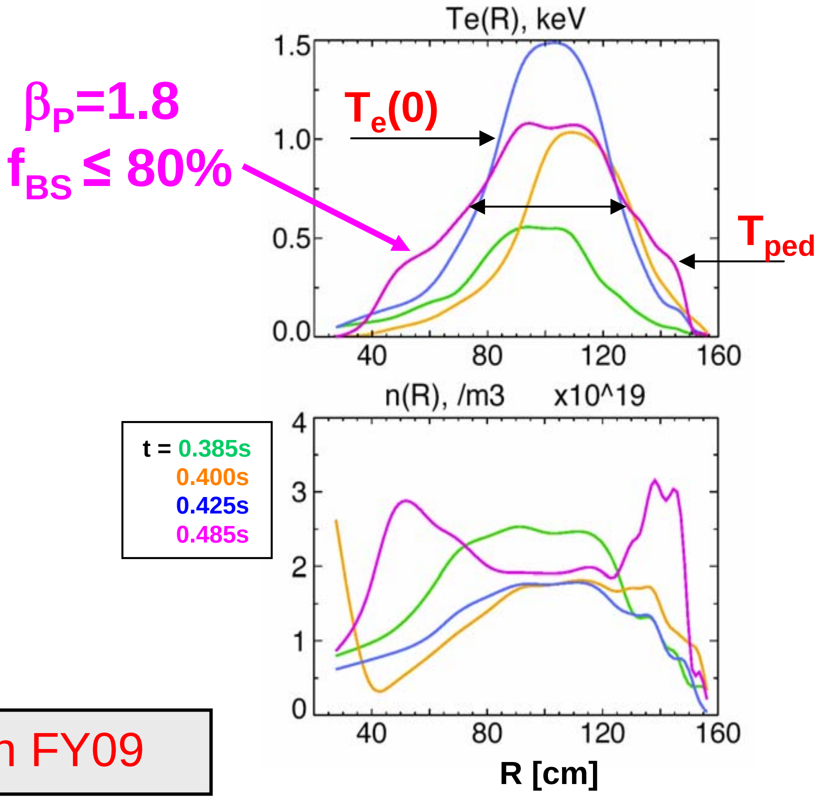
Plasma Gun Startup Plan for 2009-13	• 2008: System design for NSTX • 2009: Installation on NSTX and commissioning tests • 2009-2011: Support outer PF start-up experiments • 2010-2011: Test plasma startup using mid-plane gun • 2011-2013: Upgrade system to higher current levels as warranted

Upgraded HHFW will assist high performance NBI-heated H-mode scenarios and improve I_P ramp-up

- 2007: Higher B_T = 0.55kG and $k_{||}$ reduce parasitic surface waves
  - → **Significant e-heating in presence of NBI for first time in L-mode**
- Plan: extend to B_T=5.5kG H-mode
  - Example: early HHFW can elevate q



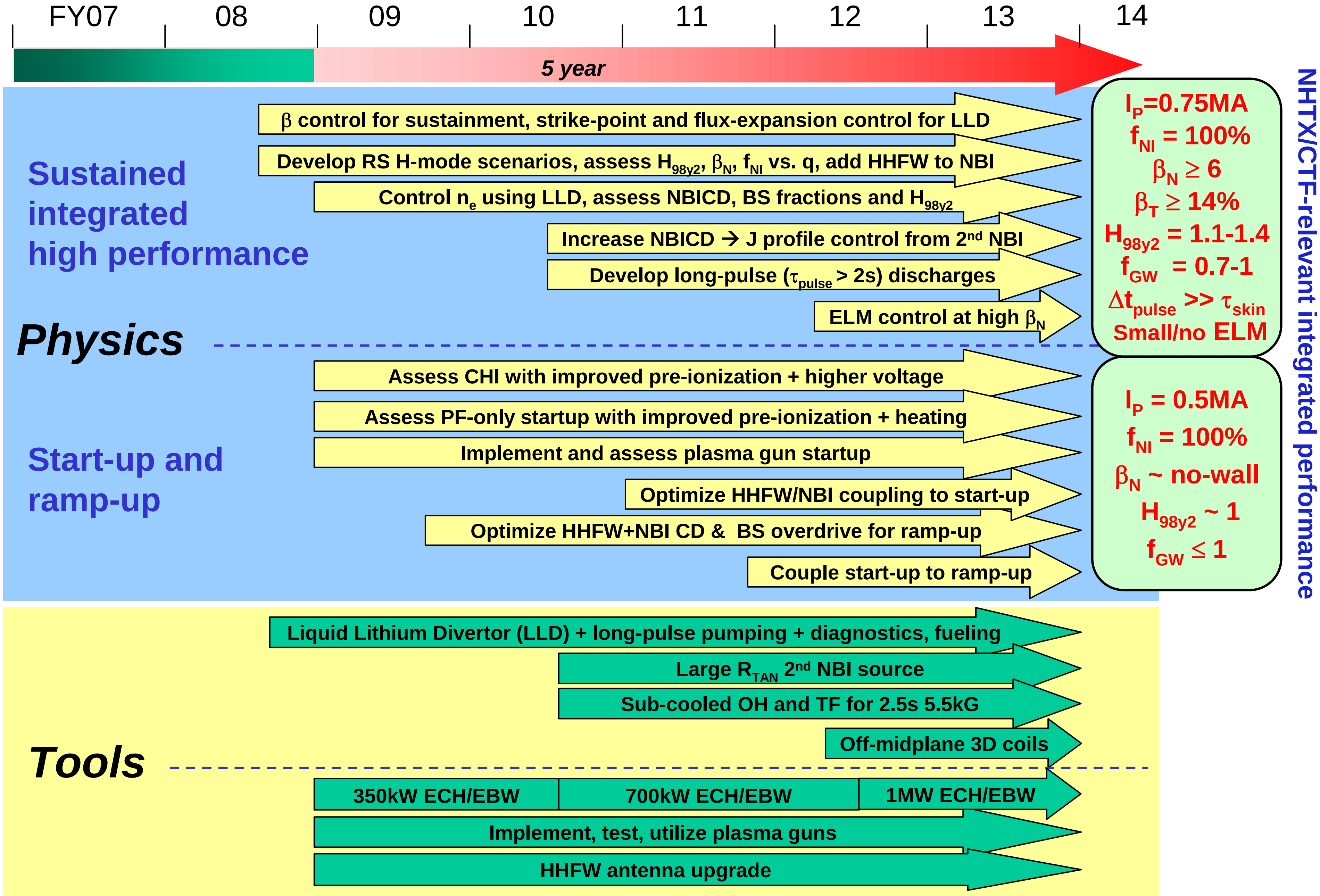
- HHFW heating at low I_P can induce high-β_P H-mode w/ V_{SURF}, V_{LOOP} → 0
  - Broad $T_e(\rho)$ best for non-OH ramp-up



Double-feed antenna for higher P_{RF}, V_{RF} in FY09

Improved matching for ELM-resilience mid-FY10

Sustainment and Start-up/Ramp-up Research Timeline



FY07 08 09 10 11 12 13 14

5 year

Physics

Sustained integrated high performance

- β control for sustainment, strike-point and flux-expansion control for LLD
- Develop RS H-mode scenarios, assess H_{98y2}, β_N, f_{NI} vs. q, add HHFW to NBI
- Control n_e using LLD, assess NBICD, BS fractions and H_{98y2}
- Increase NBICD → J profile control from 2nd NBI
- Develop long-pulse (τ_{pulse} > 2s) discharges
- ELM control at high β_N

I_P=0.75MA
f_{NI} = 100%
$\beta_N \geq 6$
$\beta_T \geq 14\%$
H_{98y2} = 1.1-1.4
f_{GW} = 0.7-1
$\Delta t_{pulse} >> \tau_{skin}$
Small/no ELM

Start-up and ramp-up

- Assess CHI with improved pre-ionization + higher voltage
- Assess PF-only startup with improved pre-ionization + heating
- Implement and assess plasma gun startup
- Optimize HHFW/NBI coupling to start-up
- Optimize HHFW+NBI CD & BS overdrive for ramp-up
- Couple start-up to ramp-up

I_P = 0.5MA
f_{NI} = 100%
β_N ~ no-wall
H_{98y2} ~ 1
$f_{GW} \leq 1$

NHTX/CTF-relevant integrated performance

Tools

- Liquid Lithium Divertor (LLD) + long-pulse pumping + diagnostics, fueling
- Large R_{TAN} 2nd NBI source
- Sub-cooled OH and TF for 2.5s 5.5kG
- Off-midplane 3D coils
- 350kW ECH/EBW → 700kW ECH/EBW → 1MW ECH/EBW
- Implement, test, utilize plasma guns
- HHFW antenna upgrade