Solenoidless Start-up on NSTX

Y. Takase, D. Gates, J. Menard, O. Mitarai, Y. Ono,
J.R. Wilson, M. Yamada

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Overview of the Experiment

TST-2 @K

- Goal
  - Demonstrate plasma current start-up without using the center solenoid
  - Evaluate
    - role of noninductive plasma production (ECH and/or HHFW)
    - requirements for magnetic configuration (scenarios 2A, 2B and 3)
  - Constraints: no new coils or power supplies

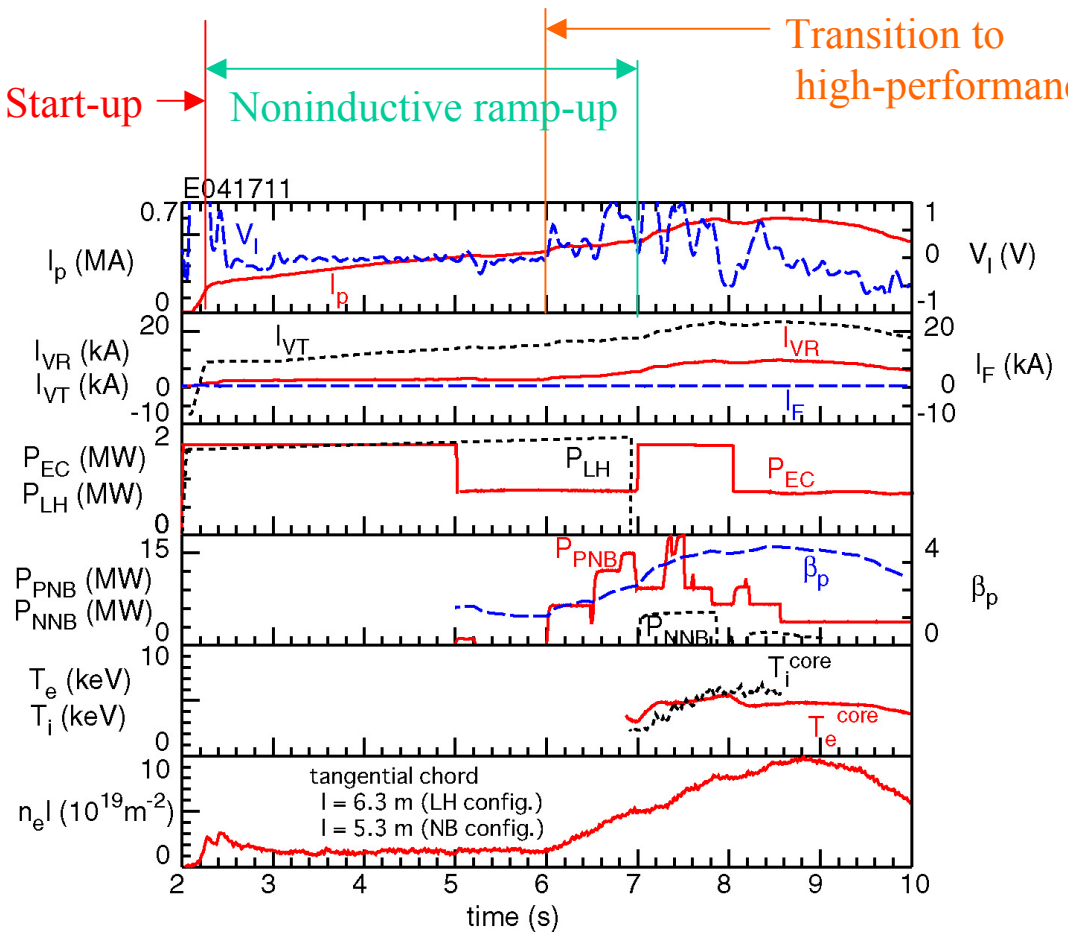
- PF induction + RF (EC/HHFW) -- scenarios 2A and 2B
  - B_v swing from + to – (JT-60 scenario)
    - Is field null required? $\rightarrow$ scenarios with (2A) / without (2B) field null
    - Initially no force balance
    - Requires strong plasma source

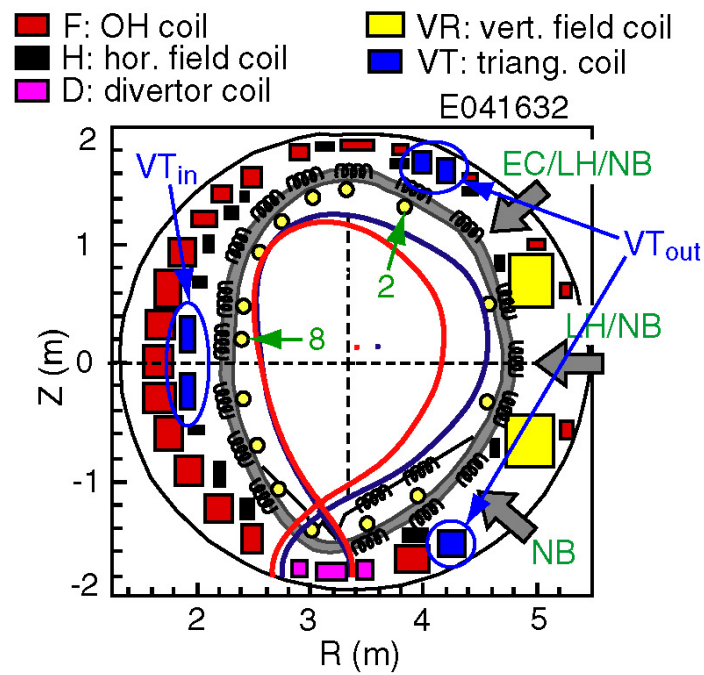
- Merging/compression (MAST/TS-3 scenario) -- scenario 3
  - Demonstration of merging/compression start-up by external coils

CS-less formation of advanced tokamak plasma demonstrated in JT-60U

TST-2 @K

$\beta_p = 3.6$
$\beta_N = 1.6$
$H_H = 1.6$
$f_{BS} > 90\%$





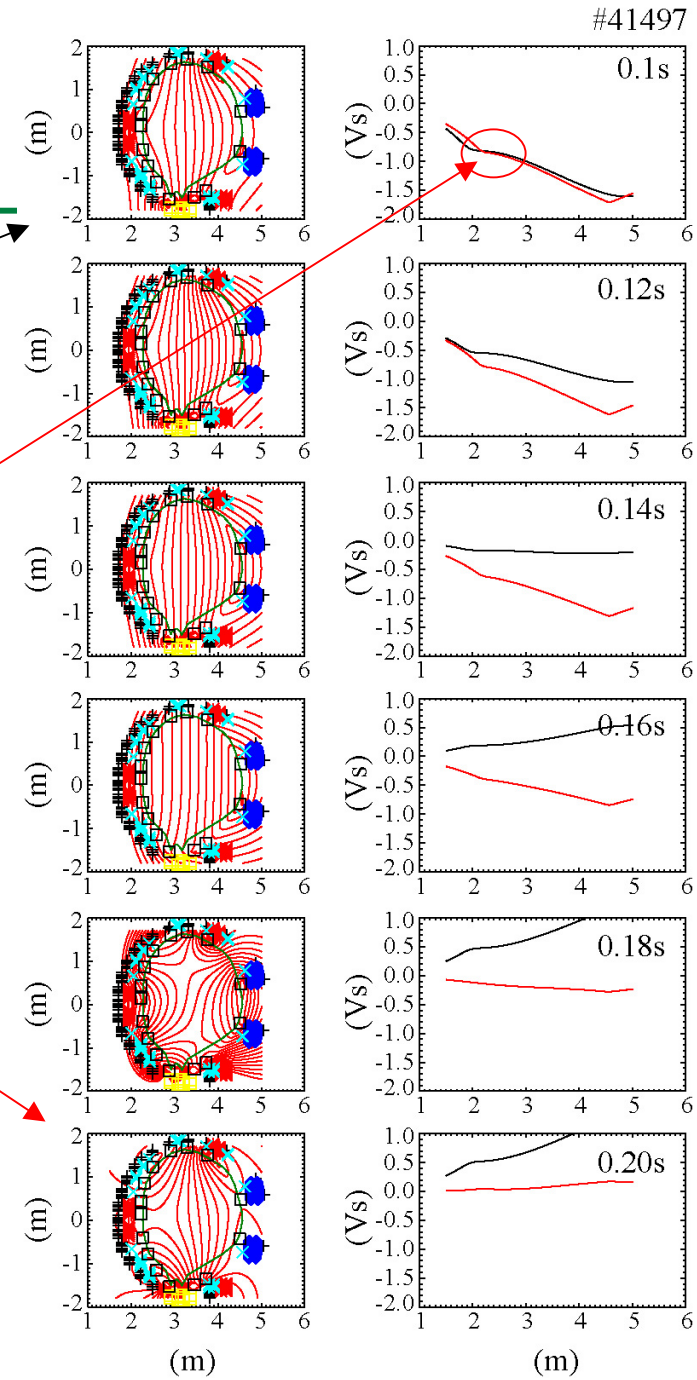
Additional degree of freedom provided by: VT flux swing, LHCD

Vacuum Field Evolution

41497: no I_p start-up (no gas)

41495: I_p start-up at 0.105 s

- A small "field null" exists on the inboard midplane before VT and VR coil ramp
- Initially B_v is in the wrong direction
- B_v does not reverse sign until 0.19 s (0.09s after start of VT and VR ramp)
- Poloidal equilibrium, but no toroidal equilibrium?



Right: Flux profile on the midplane

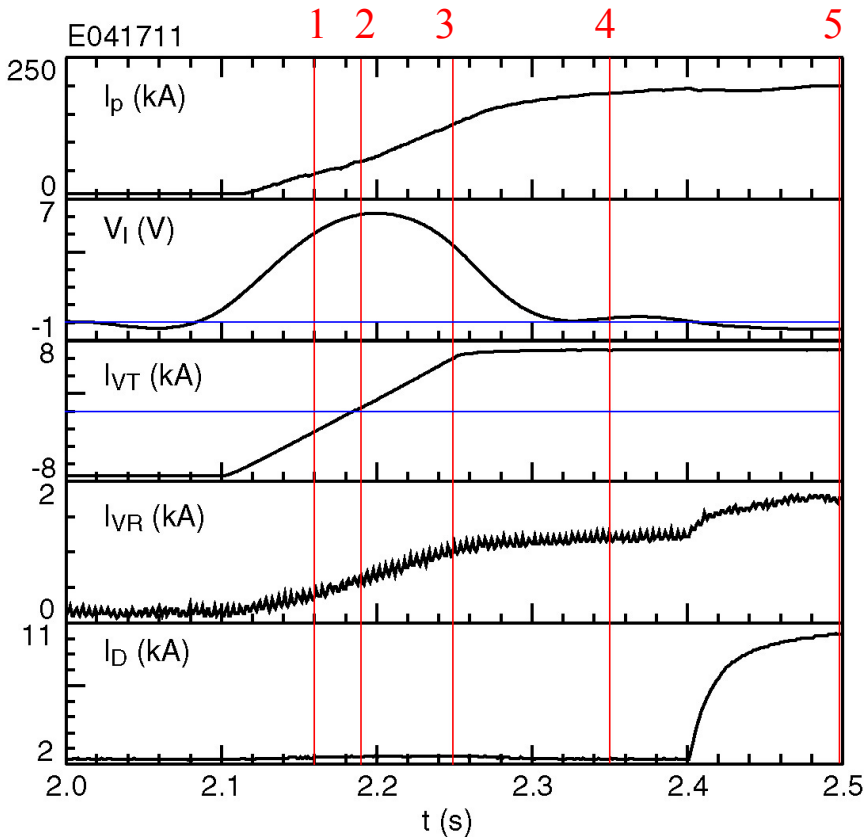
Black: coil currents only

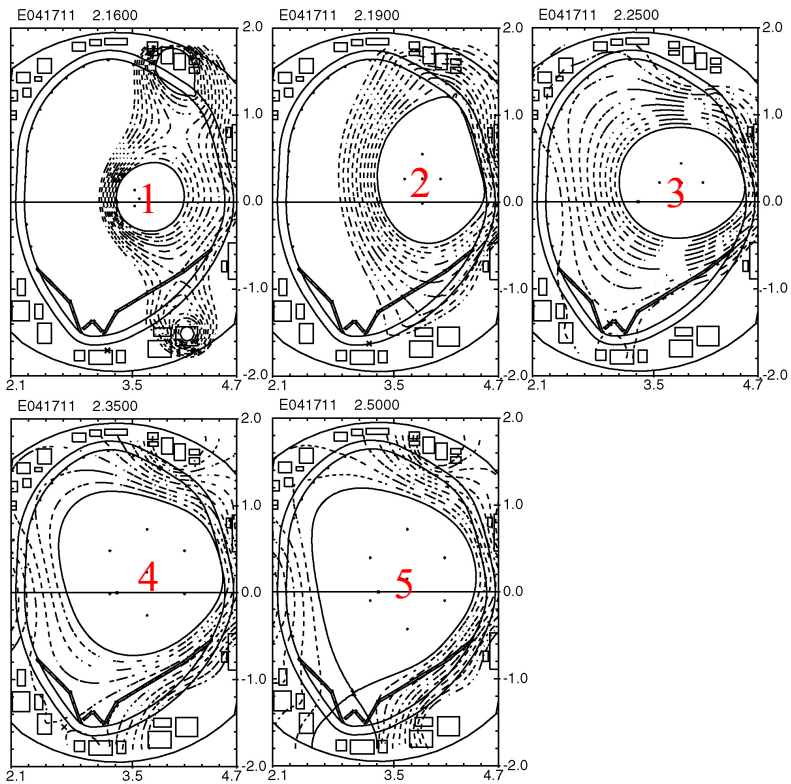
Red: coil currents and eddy currents

Left: flux contours (with eddy currents)

Configuration Evolution During CS-less I_p Start-up

- I_p ramp-up accomplished by EC/LH preionization and VT/VR coil ramps
- Transition to divertor configuration (5) and further I_p ramp-up by LHCD





Scenario development for NSTX

TST-2 @K

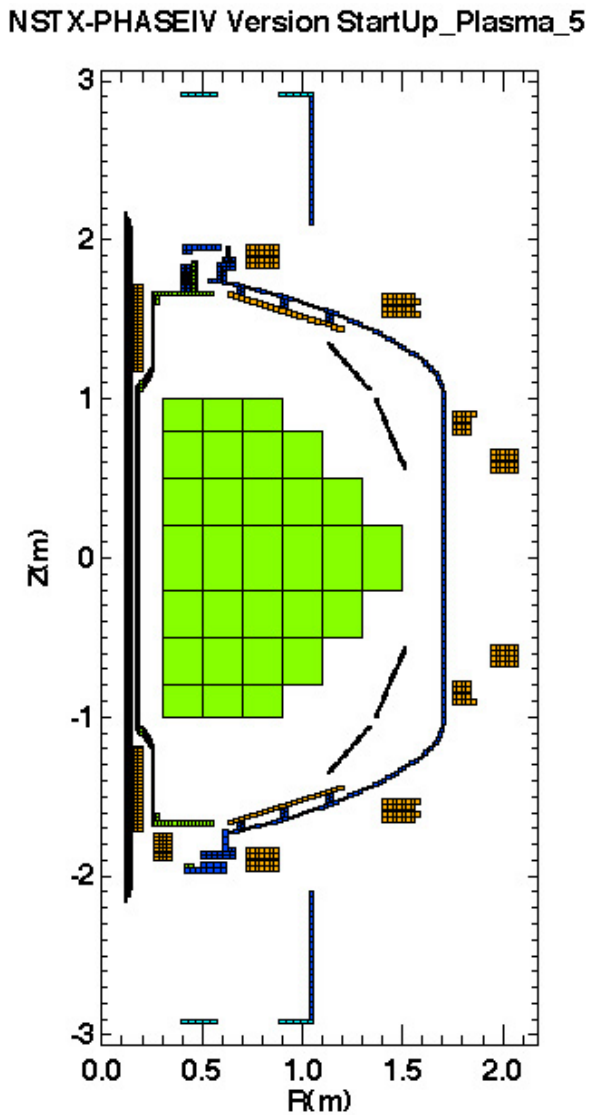
Analysis by Menard's LRDIAG

- Circuit equation solver
  - NSTX coils and conducting structures
  - Eddy currents taken into account
  - Very well benchmarked

  but does not calculate plasma equilibrium

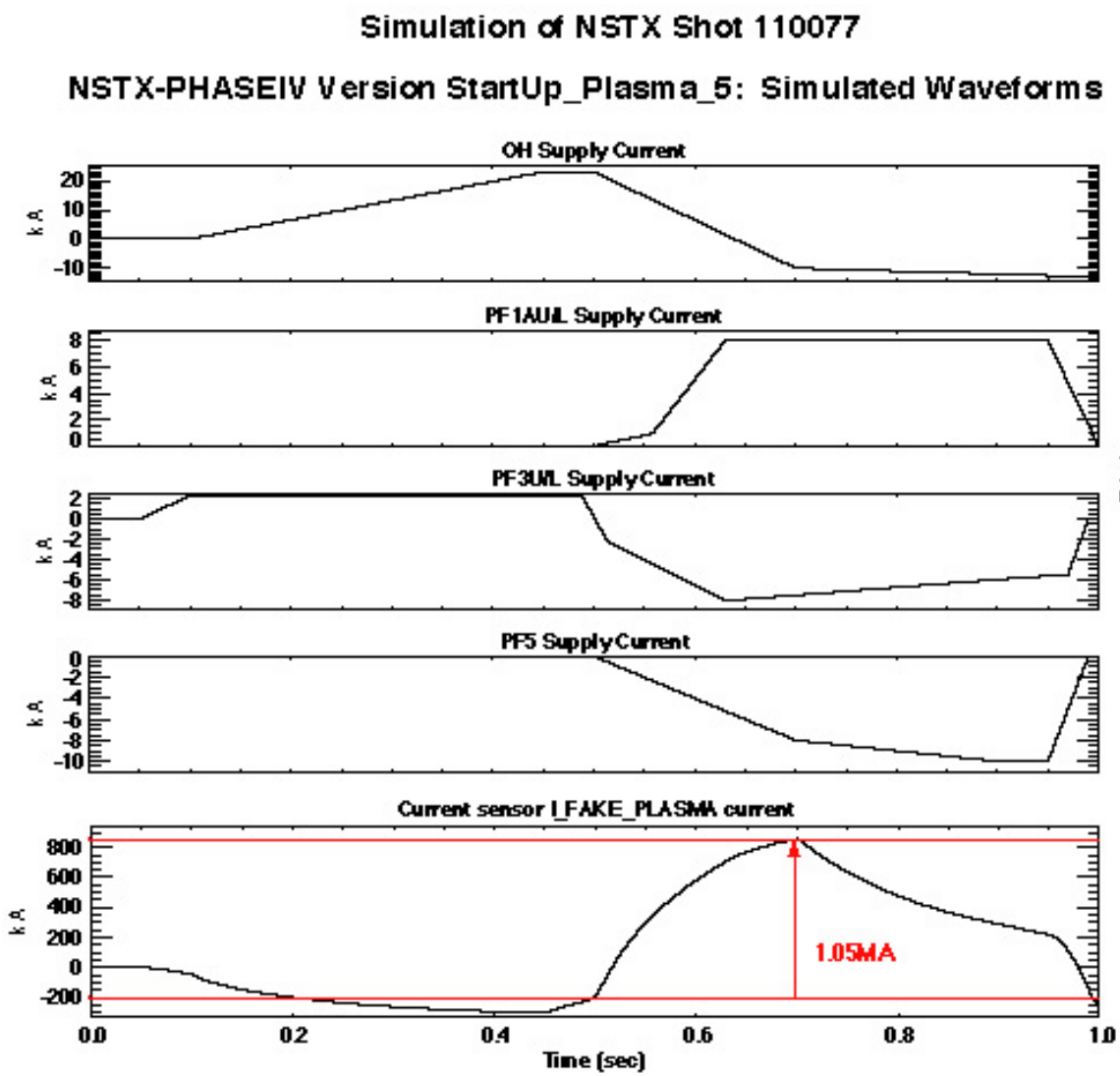
- Plasma modelled by passive coils
  - Various distribution of "plasma" coils
  - Each coil can have different resistivity

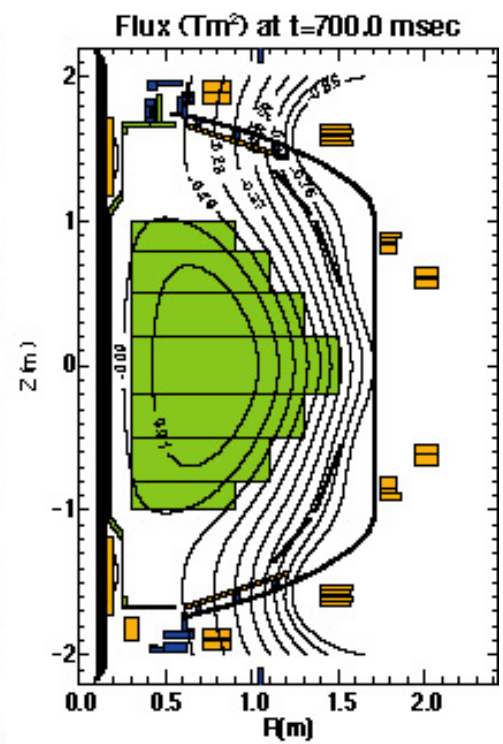
  but constant in time



Plasma model selected to reproduce I_p ramp-up of a 1MA NSTX plasma

Resistivity of Inconel 625
(equiv. to 70 eV plasma)

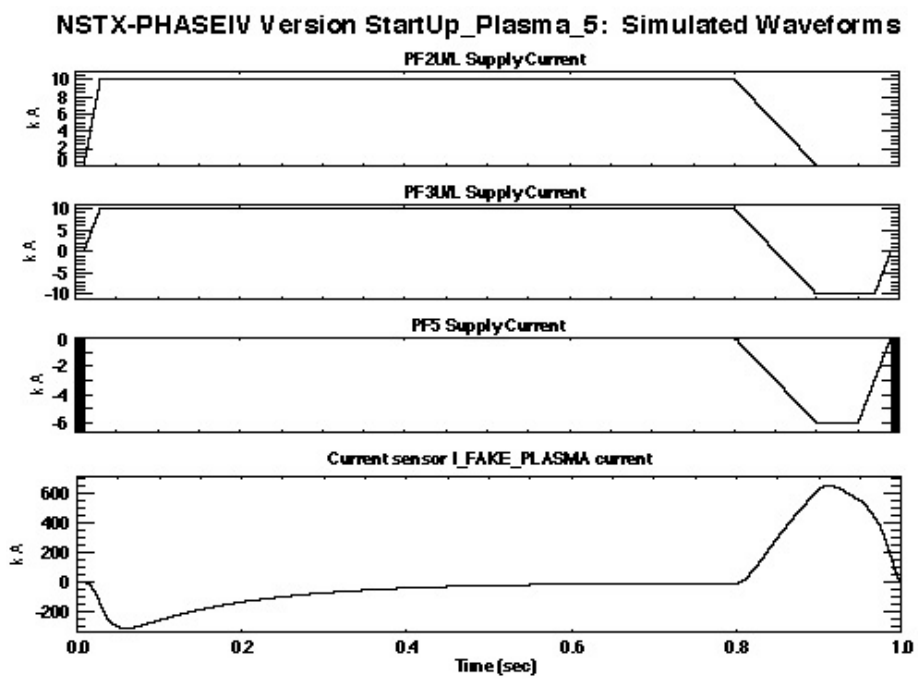


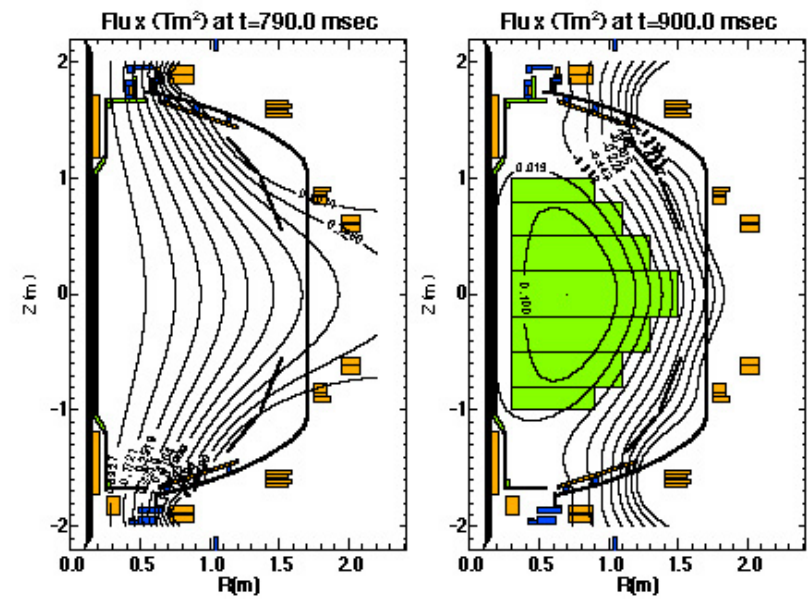


This model reproduces inductively driven (OH start-up) 1MA NSTX discharge

Scenario (2B) JT-60U scenario
B_v ramp from + to – (no field null)

Initial B_v is opposite to that required for radial force balance



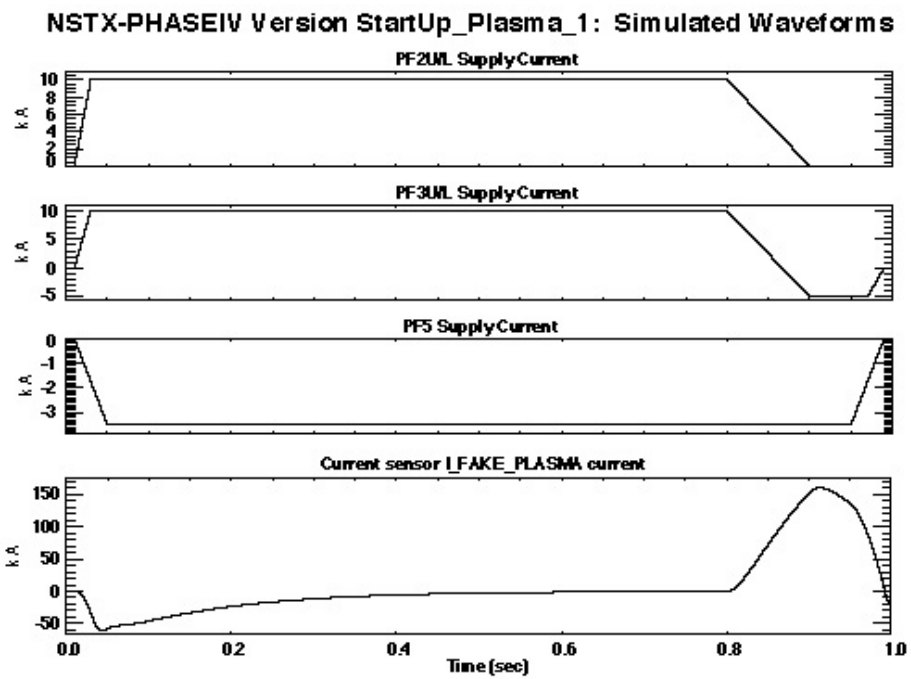


- Requires a strong plasma source (HHFW/ECH)
- Ramp up to I_p = 650 kA may be possible

Fig. 1

Scenario (2A)
JT-60U scenario (with outboard X-point)

For B_T = 0.6 T (at R = 0.85 m)
EC resonance is at R = 0.95 m



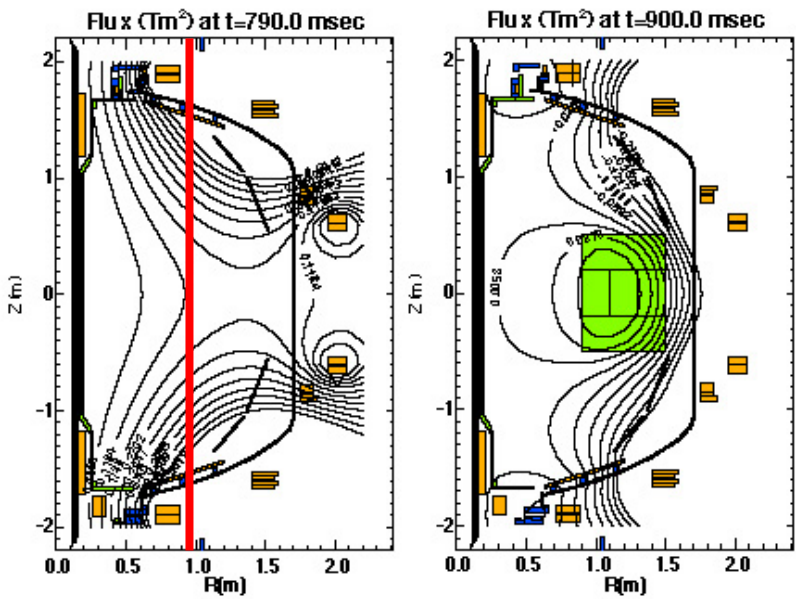
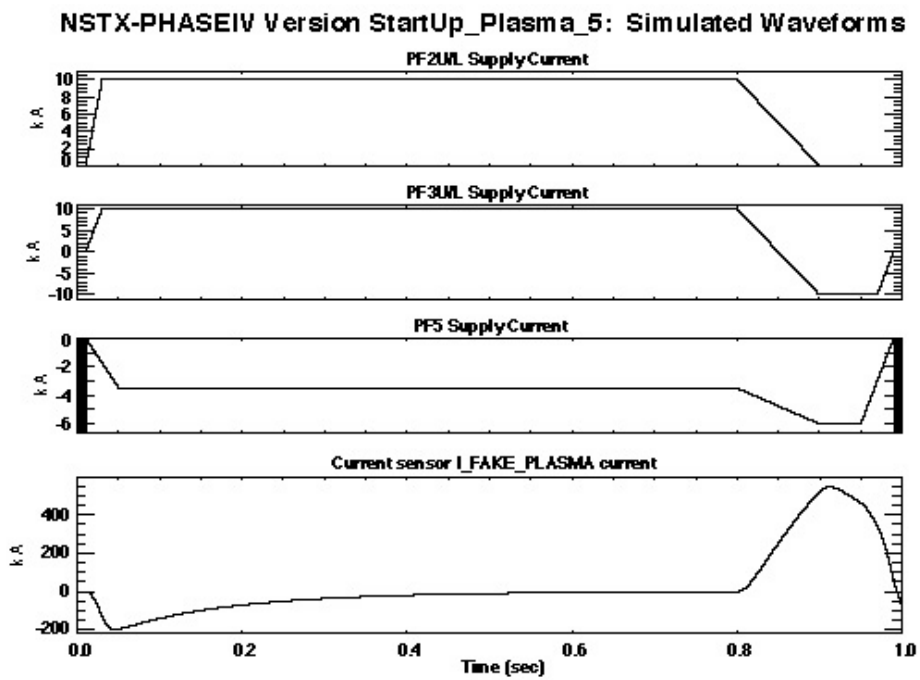


Fig. 3

Assume ramp-up at large R → limited to I_p = 160 kA
(but could be amplified by compression)

Scenario (2A)
Assume full cross section plasma



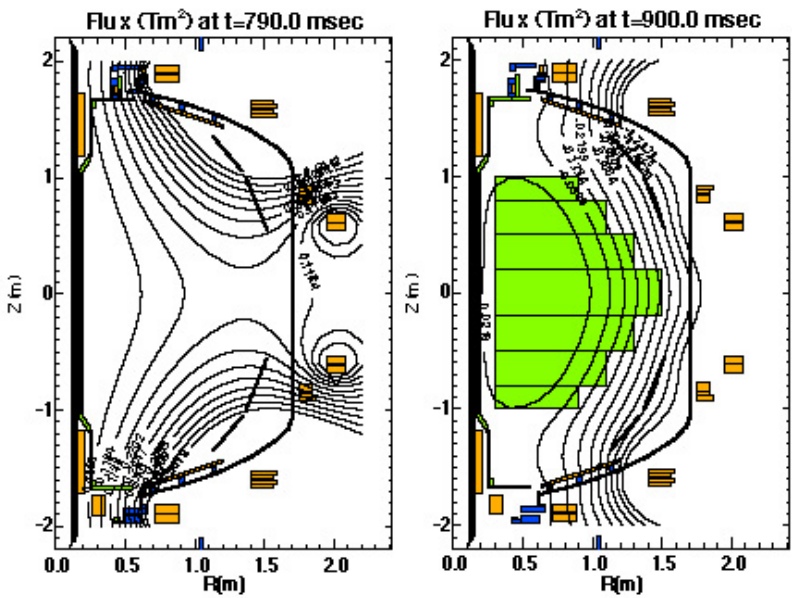
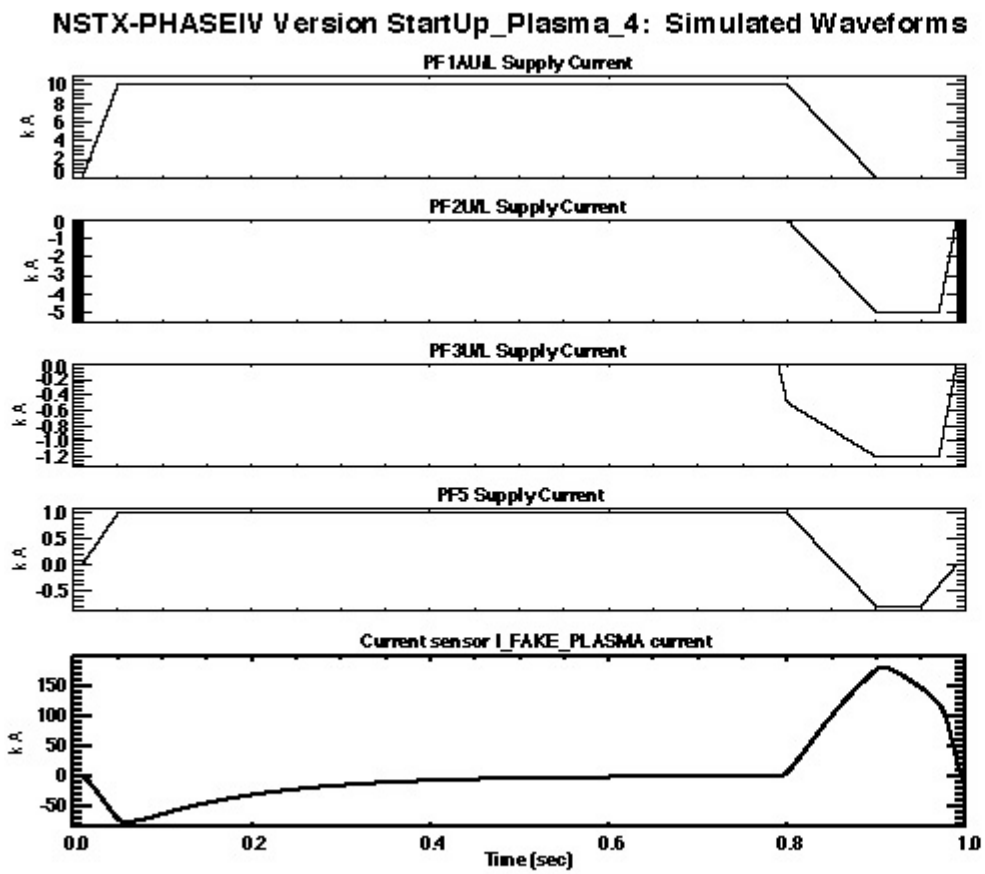
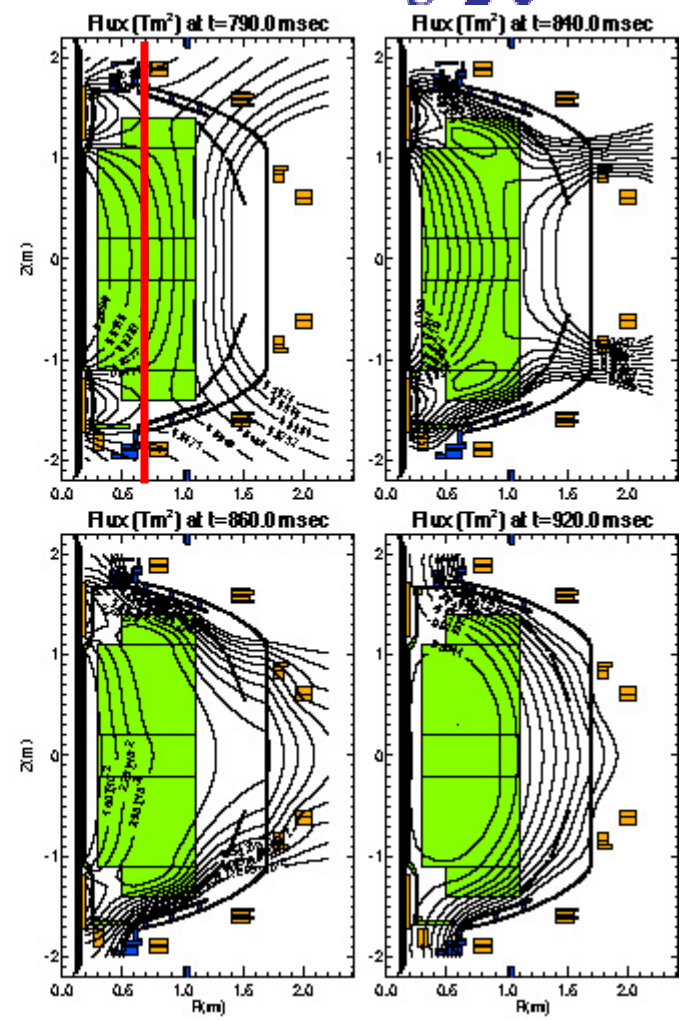


Fig. 2

Ramp up to I_p = 550 kA may be possible

Scenario (3)
Merging/compression (MAST/TS-3 scenario)





Start-up from PF1A-PF5 nulls

Ramp up to I_p = 180 kA predicted

B_T = 0.44 T (at R = 0.85 m) locates EC resonance at R = 0.7 m

Fig. 4

Proposed Shot Sequence - 1

TST-2 @K

Three types of start-up scenarios will be tried in the order (2A), (2B), (3).

- Preionization ECH will be used in all scenarios.
- In addition, HHFW will be used for preionization at a few hundred kW level.
- Scenario (2B)
  - Radial force balance is not satisfied during the initial start-up phase.
    - requires a strong source of plasma
  - If plasma current does not ramp up, raise the HHFW power to over 1 MW. Initial experiments will use preprogrammed coil currents.
  - If successful start-up to 100 kA is achieved, vertical position control will be implemented.

- Scenario (2A)
  - This scenario has a field null on the outboard midplane.
  - A loop voltage of ~10 V can be induced at the field null by PF coil ramps.
  - The toroidal field should be as high as possible (at least 0.45 T, preferably 0.6 T). Start the experiment with prefill pressure in the lower range of normal OH start-up, and find the optimum pressure for most efficient ramp-up.
  - The ramp rate is varied to optimize start-up.
  - Apply HHFW (~1 MW) in the electron heating mode to increase T_e

Proposed Shot Sequence - 2

TST-2 @K

- Try the merging-compression scenario (3) using external coils only
  - toroidal field of 0.45 T.
  - Start with coil currents as shown in Fig. 4
  - Find the optimum condition for current rise
  - Varying initial field null configuration and subsequent poloidal field evolution for merging and compression.

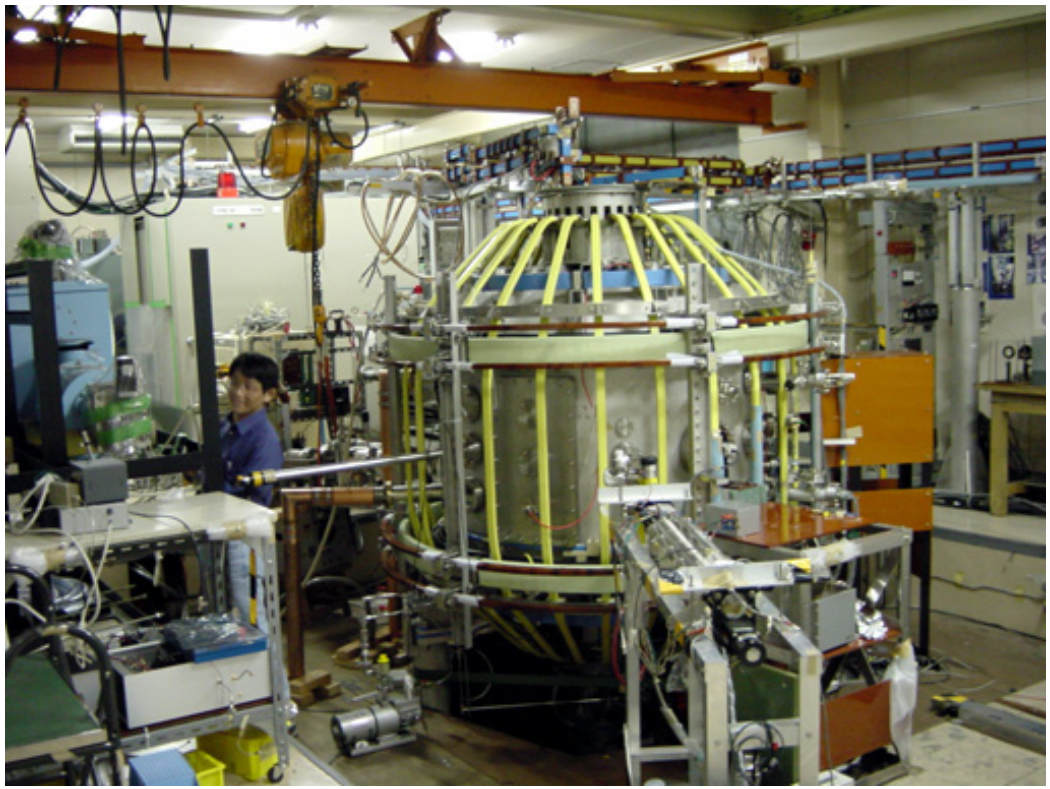
- Choose scenario from (2A), (2B), and (3) that appears most promising.
  - Final coil currents are varied to optimize start-up and the produced plasma.
  - Pre-bias coil currents may also be adjusted if it is judged necessary for better balance between the flux swing and the resultant vertical field.

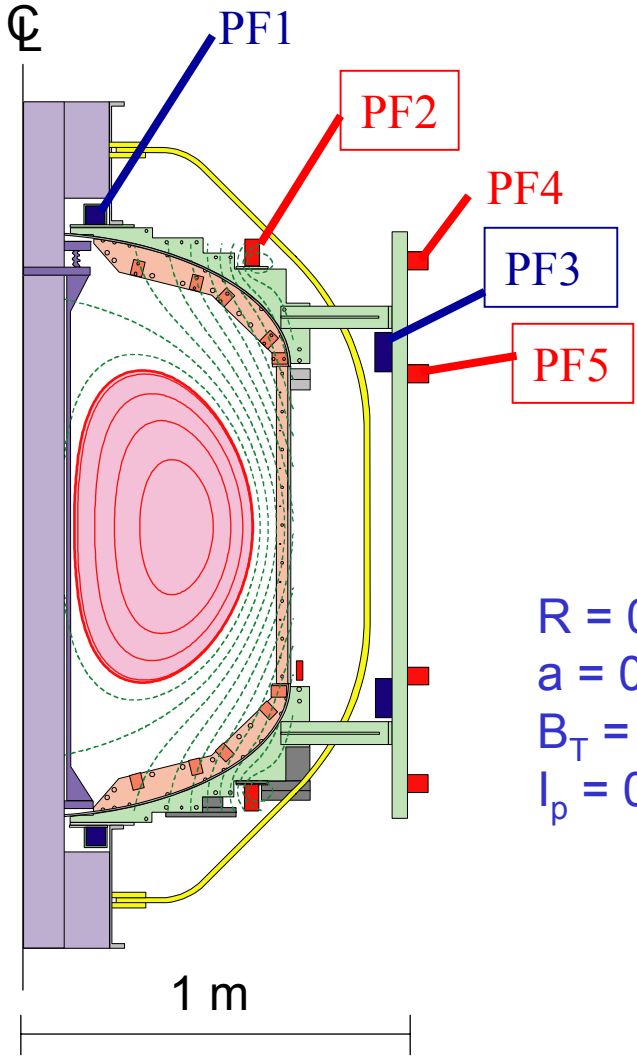
- The total number of shots required for this experiment is estimated to be about 30 shots *(yeah right!)*.
  - Adjustments to optimization steps will be made depending on the outcome of the experiment.

Shot Sequence Summary

Scenario	PF1A (kA)	PF2 (kA)	PF3 (kA)	PF5 (kA)	ramp time (ms)	RF (MW)	NB (MW)	comments	shots
2A	0	10→0	10→–10	–3.5→–6	50	1	0	scan prefill	5
2A	0	10→0	10→–10	–3.5→–6	30, 70,100	1	0	scan ramp time	3
2B	0	10→0	10→–10	0→–6	100	>=1	0	vary RF power	3
2B	0	10→0	10→–10	0→–6	<=100	1	0	vary ramp time	3
3	10→0	0→–5	0→–1.2	1→–0.8	100	1	0	optimize null and current rise	6
best case	optimize	optimize	optimize	optimize	optimize	3	5	optimize coil currents	~10
								total	~30

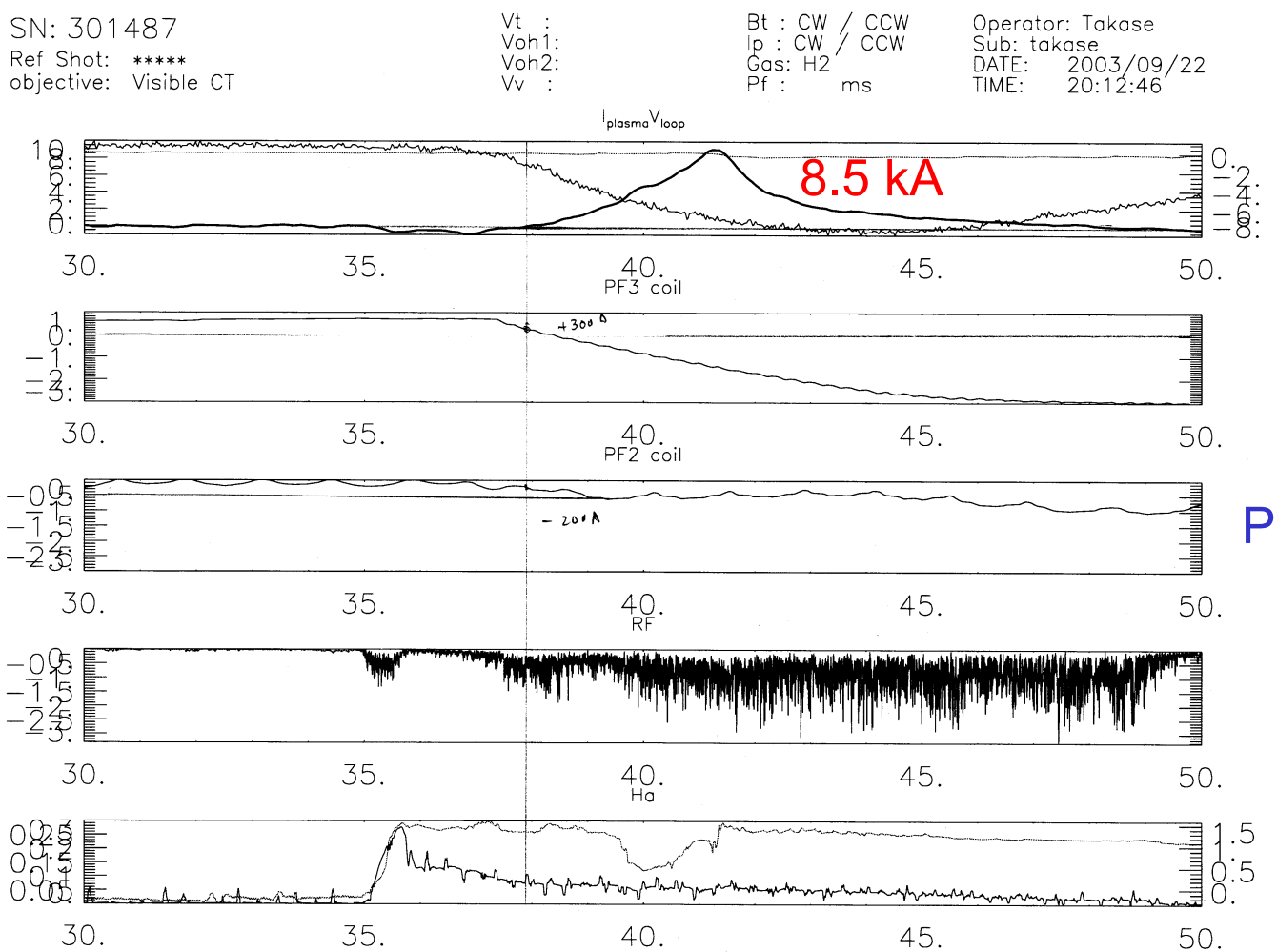
TST-2 Spherical Tokamak





R = 0.38m
a = 0.25m
B_T = 0.3T
I_p = 0.14MA

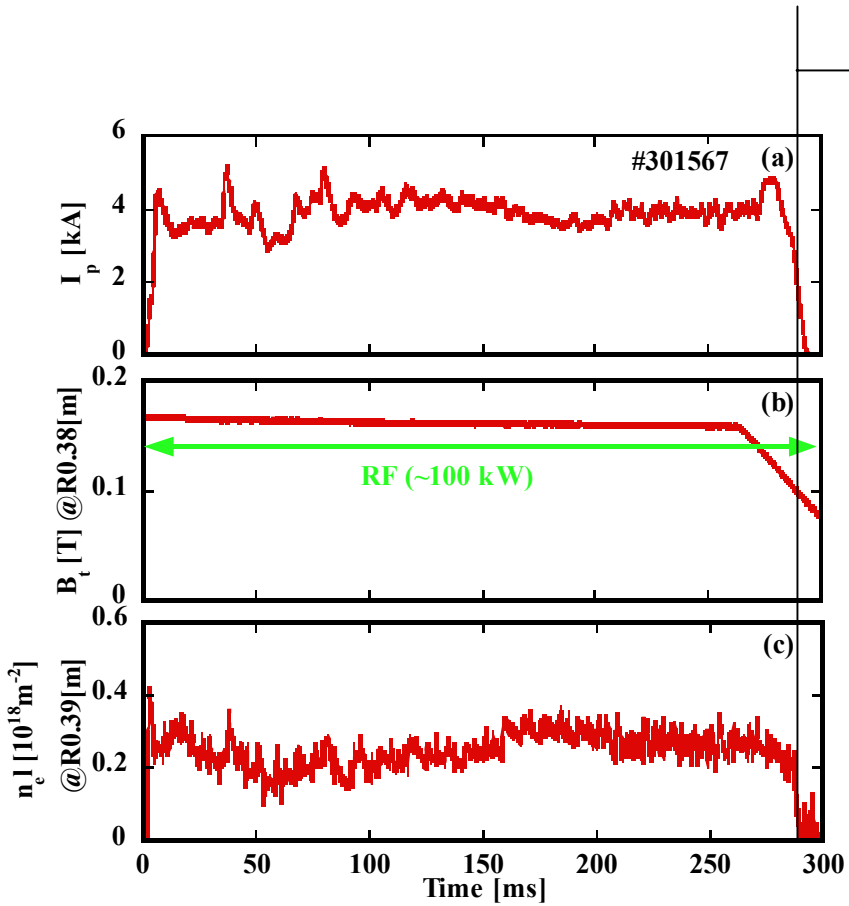
JT-60U scenario (but no inboard coil)
I_p ramp-up to 8.5 kA achieved on TST-2



PF3

PF2 + PF5

RF Start-up & Sustainment



no $\omega = \omega_{ce}$ resonance inside vac.ves.

Sustainment of steady current

~ 4 kA for > 0.27 s

with 8.2 GHz / 100 kW

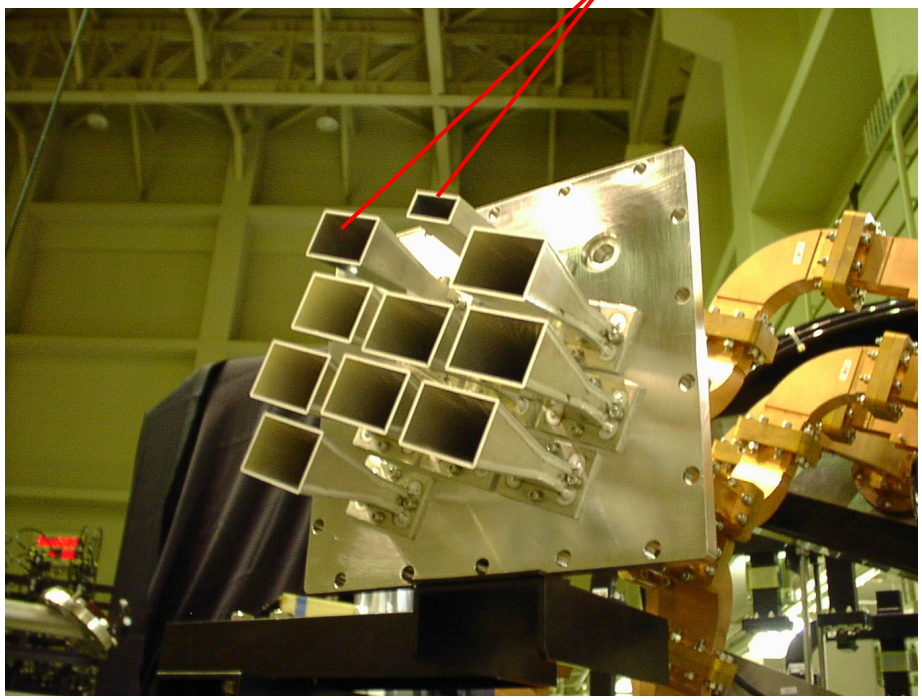
B_T = 0.16 T @ R = 0.38 m

(B_T = 0.29 T @ R = 0.21 m)

B_v ~ 2 mT

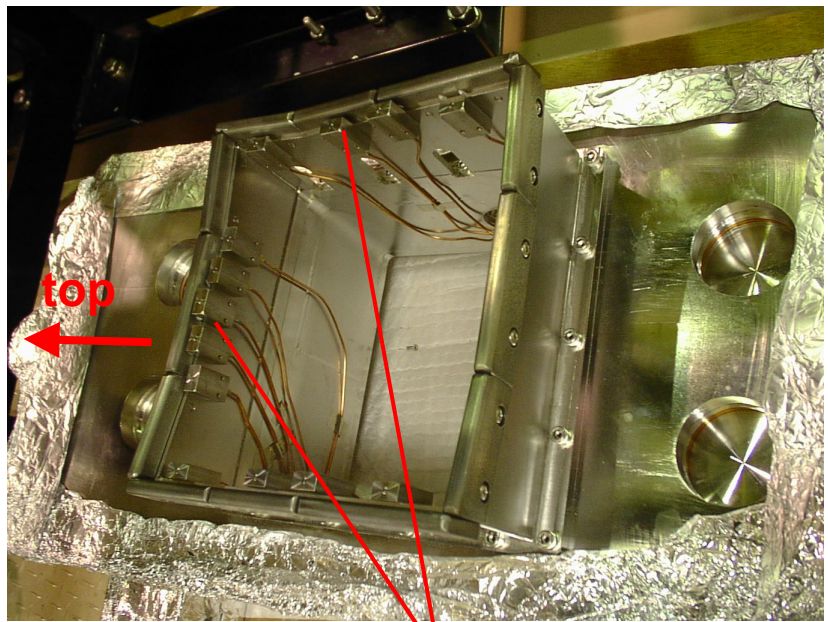
EBW antenna and local limiter

Receiving antennas



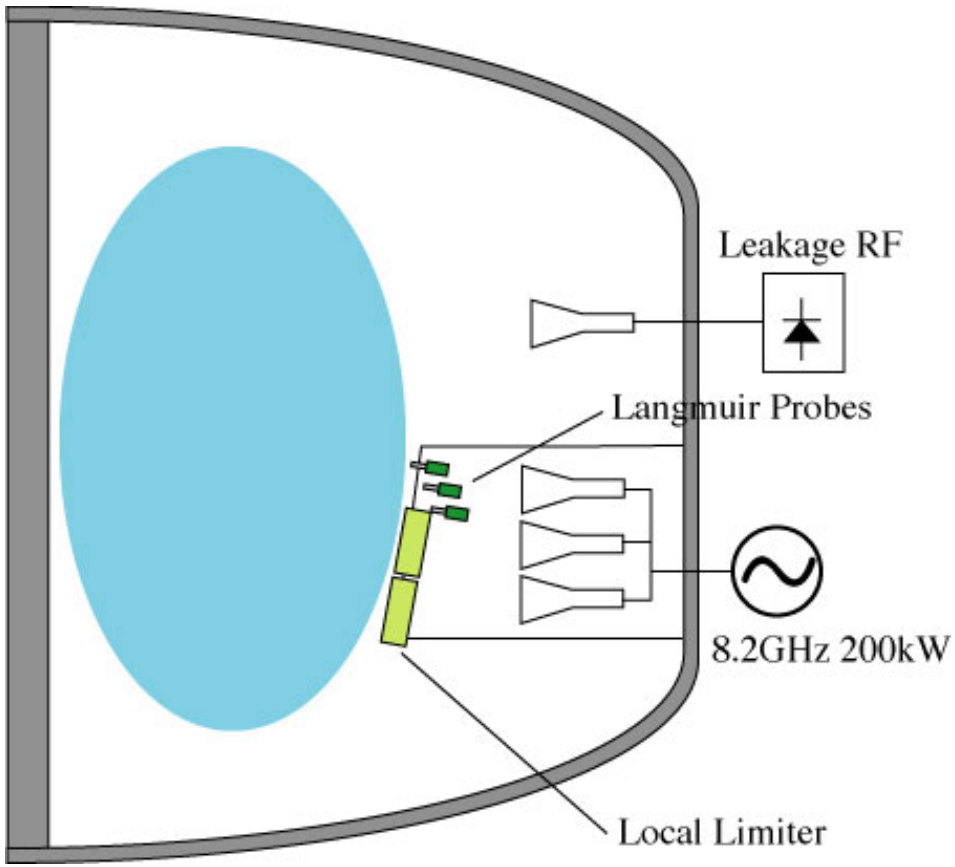
EBW Antenna
(8 horns, **E** ⊥ **B**)

Local Limiter (not movable)
used to control ∇n in front of the antenna



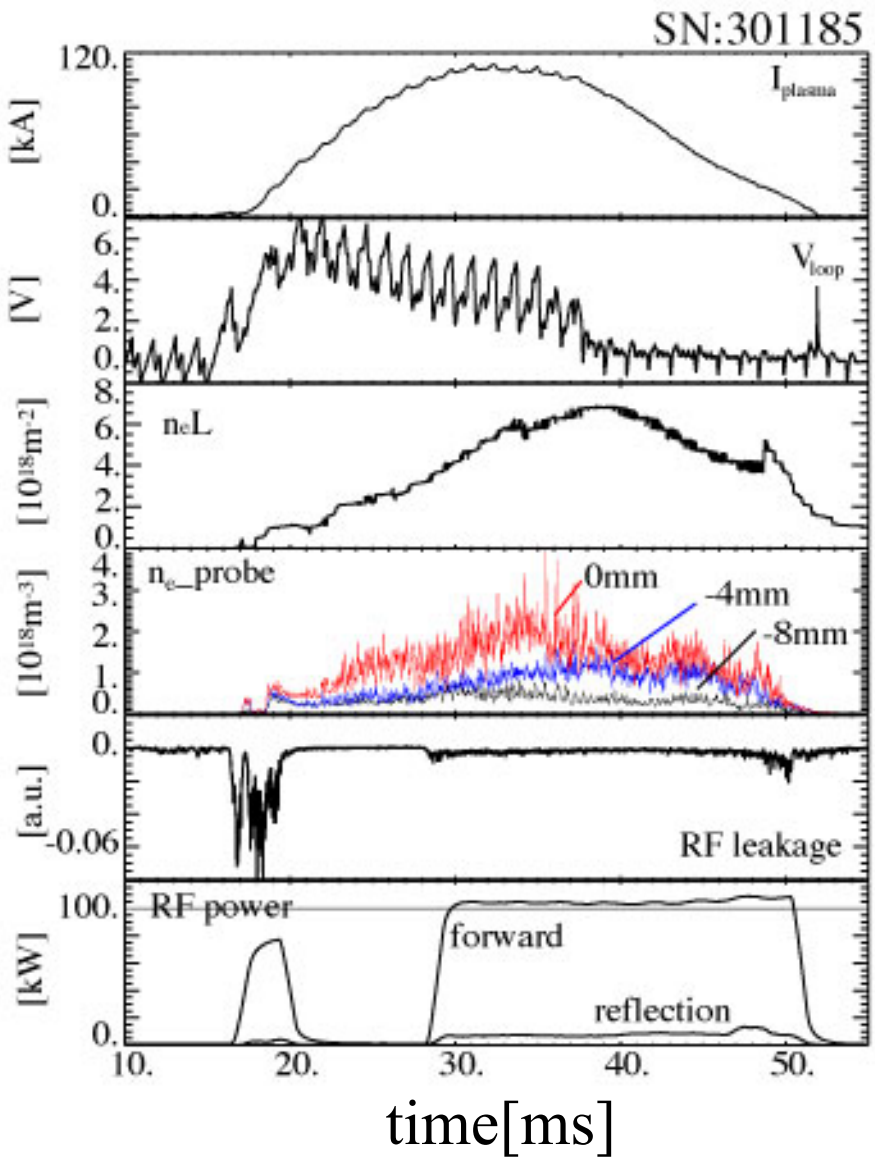
Langmuir probes
used to measure ∇n

Experimental setup (schematic)



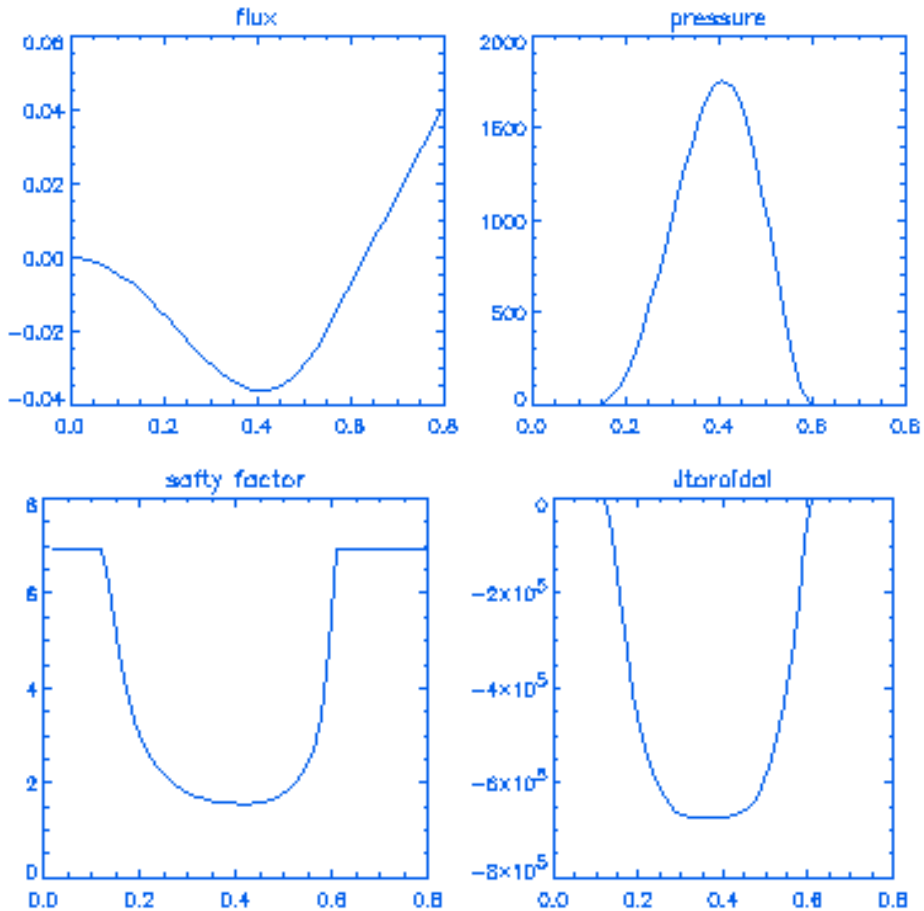
- RF source
  - 8.2GHz
  - Eight 25kW klystrons
- Local limiter
  - Controls ∇n in front of the antenna
- Langmuir probes
  - Measure ∇n
- Leakage RF
  - Detection of RF power outside the local limiter

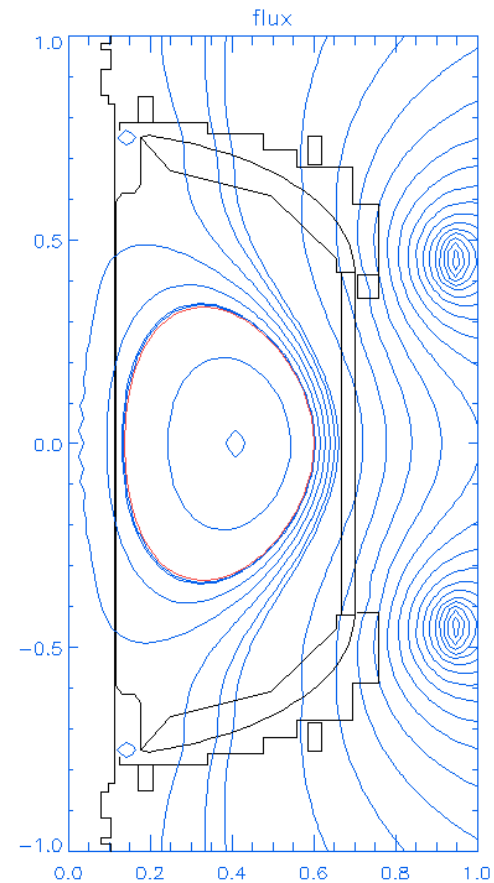
A typical discharge with RF injection (> 100 kW)



- Conditions for efficient MC seem to be satisfied:
  - Density in front of the local limiter is greater than $1 \times 10^{18} m^{-3}$ (i.e., overdense)
  - Density gradient is steep with L_n = 5.3mm @ t = 35ms
  - RF leakage is small
  - Reflection is typically 5-10%
- However, no clear evidence of heating has been observed so far

#301185 @ 37 ms





$p(0) = 1.8$ kPa $\rightarrow$ $T_e(0) + T_i(0) = 0.57$keV

$W = 0.4$ kJ $\rightarrow$ $\tau_E = 1$ ms (assuming 100% RF absorption)