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# OH-Solenoid free plasma startup program plans on NSTX for the Fy 04 to 08 period

**Roger Raman**
University of Washington, Seattle

**For the NSTX National Team**

**DOE Review of**
**NSTX Five-Year Research Program Proposal**
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# NSTX has an important focus on solenoid-free plasma startup research

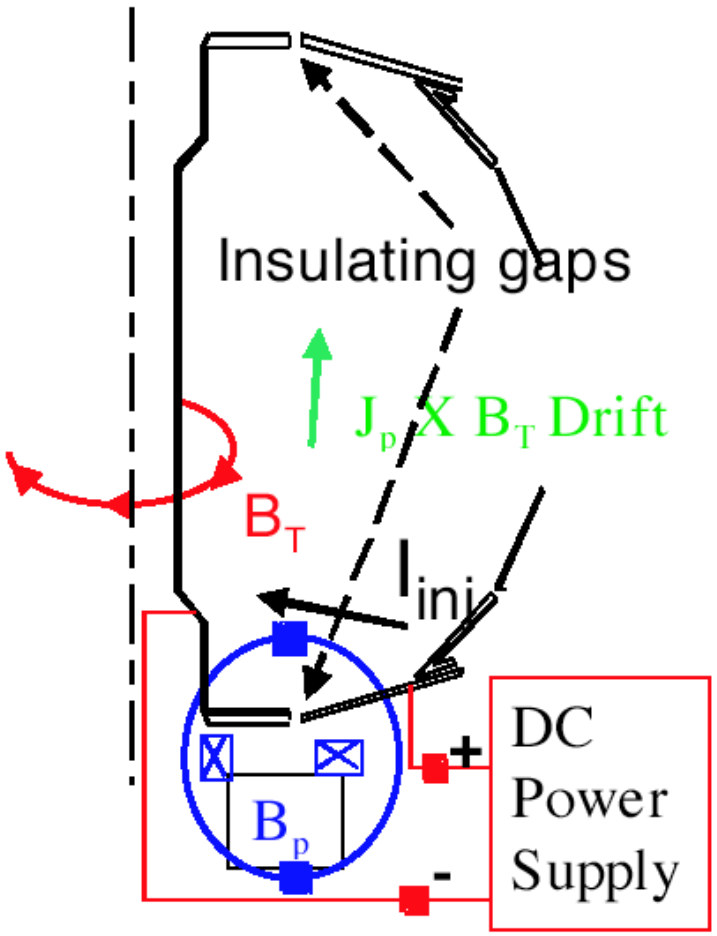
- The development of methods for solenoid-free current initiation will improve the prospects of the ST as a fusion reactor
- Advanced tokamak designs (ARIES-AT and RS) assume no central solenoid
- NSTX is focused on solenoid-free plasma startup research
- NSTX program addresses IPPA goal 3.2.1.4 for the ST which states: *"Characterize the integration of noninductive plasma startup via magnetic reconnection such as using Coaxial Helicity Injection (CHI) with other noninductive and inductive current drive techniques. Investigate a number of noninductive techniques to start and to increase the plasma current in ST plasmas while at the same time minimizing magnetic flux and helicity injection."*

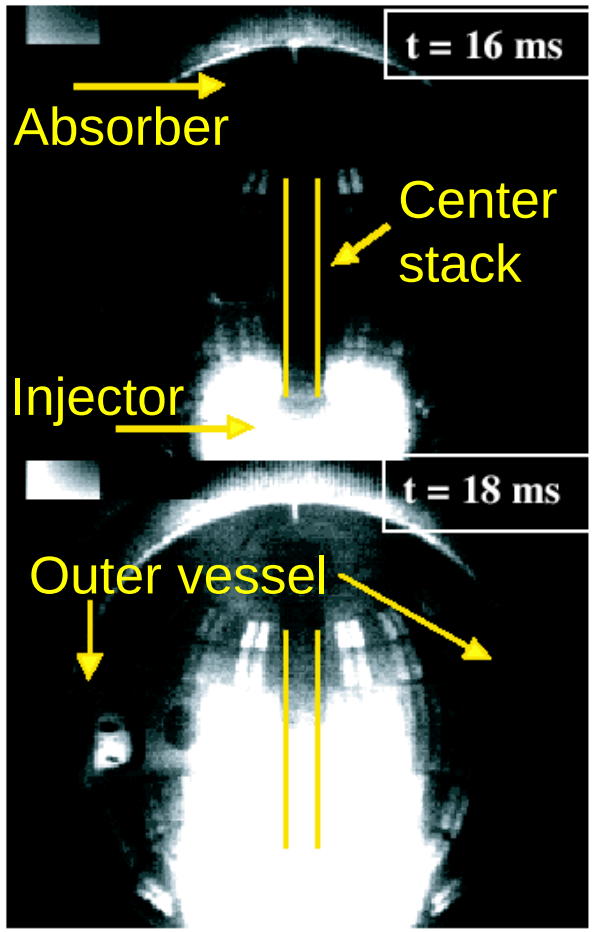
# Goal is to demonstrate in 5yrs solenoid-free plasma startup method(s)

- Dedicated experiments
- Development of theory to analyze the results and extrapolate techniques to future device
- Upgrades to facility capabilities to explore new techniques and to optimize the most promising concepts
- NSTX is pursuing several solenoid-free plasma start-up concepts
  - Coaxial Helicity Injection research (CHI)
  - Outside PF coil induction
  - EBW/HHFW research (described separately)

Initiate solenoid-free plasma currents, couple to non-inductive CD methods and ramp-up to high beta, high bootstrap current fraction discharges

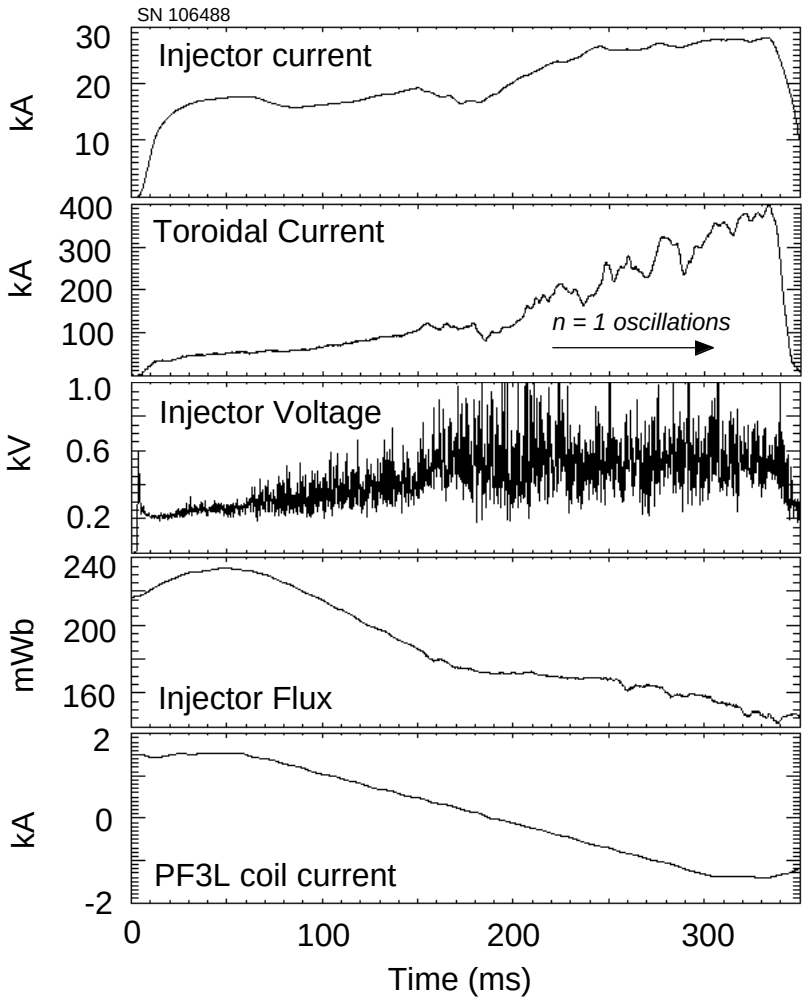
# Simple description of CHI start-up




Expect reconnection processes to redistribute edge current to the interior, forming closed flux surfaces

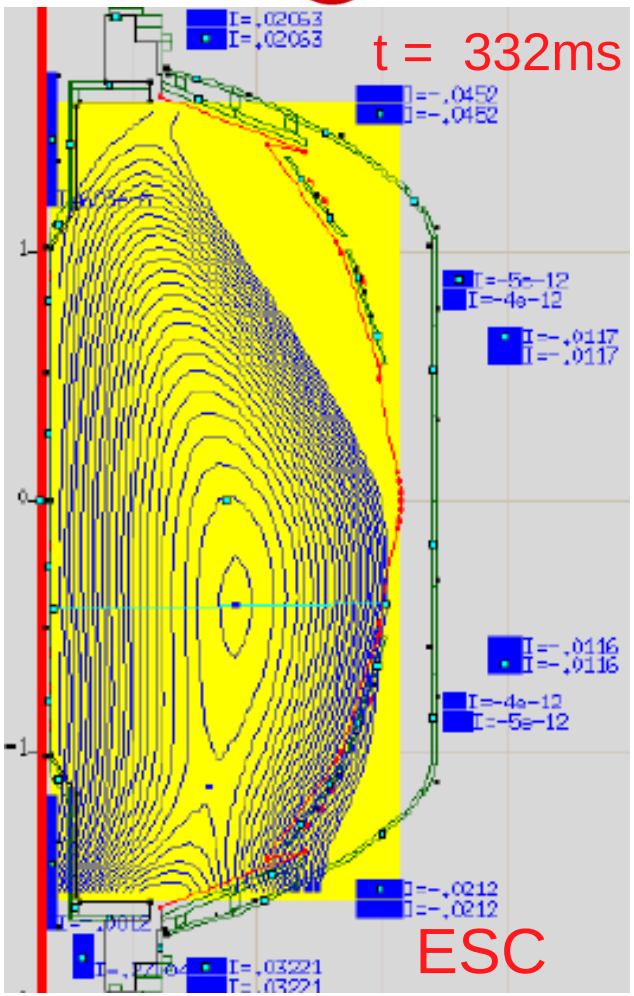
# Obtained 390kA with current multiplication of 14 in 330ms long discharges (steady-state CHI)




- Evidence for good *n=1* oscillations deemed necessary for flux closure
- ESC and EFIT reconstructions consistent with but not conclusive of flux closure

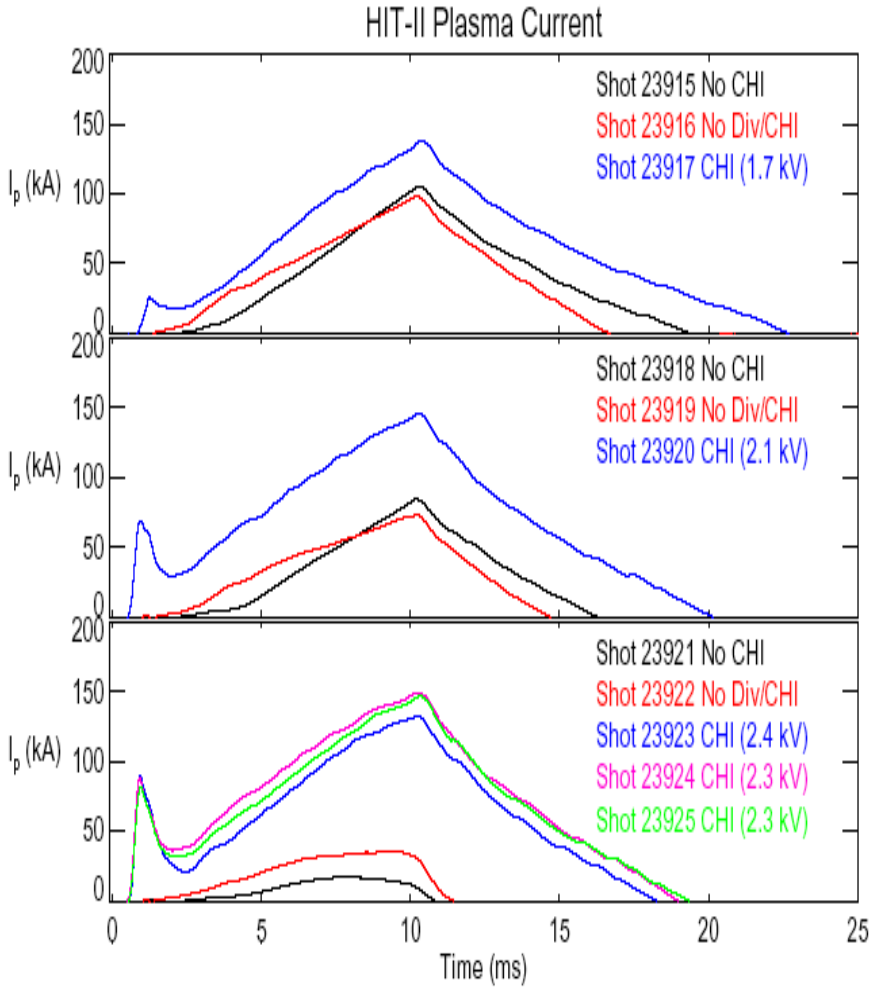
# Theory status

- MFIT code used in control room
  - (M. Schaffer, GA)
- ESC adapted for CHI discharge reconstructions
  - (L. Zakharov, PPPL)
- EFIT also adapted for CHI
  - (M. Schaffer, L. Lao, GA)
- Work in progress to use TSC
  - (S.C. Jardin, PPPL)
- Work initiated on using CHIP (3DMHD) to understand CHI physics
  - (X. Tang, LANL)



# Joint effort with HIT-II resulted in development of a new CHI startup method (transient CHI)

- CHI started discharges coupled to and improved the performance of inductive discharges
- Saved volt-seconds
- CHI started discharges much more robust and less sensitive to wall conditions
- CHI started discharges produced record plasma currents on HIT-II (265kA)



# New revised thinking for CHI research on NSTX

- Decouple plasma startup and steady-state current sustainment objectives
  - Use ***transient CHI*** for plasma startup
  - Use ***steady-state CHI*** for edge current drive

    CHI capability enables edge biasing studies
    - Edge current profile modification
    - Favorably modify edge SOL flows
    - Induce edge rotation

# Fy 04-06 CHI Research Plan

FY04: Transfer transient CHI plasma to the PF system

- Commission new absorber (field nulling requirements)

FY05: Transfer transient CHI plasma to non-inductive CD system

- Increase current levels produced by transient CHI

Reestablish 300kA steady-state discharge

FY06: Establish transfer of CHI to non-inductive CD system and establish edge current drive

- Investigate SOL effects
- Establish preferred method for startup

# Fy 07-08 CHI Research Plan


## FY07: Flux closure studies in steady-state CHI

- Profile measurements using MSE and dynamo probe
- Mechanisms leading to flux closure

## FY08: Use methods developed for volt-seconds savings to help high performance discharges

- Use CHI in conjunction with other CD methods
- Improve performance of fully non-inductive discharges via CD and SOL modifications

# Plasma Start-up Using Outer Poloidal Field Coils

**Outer PFs have been used to start-up the plasma:**

- MAST (START) - poloidal field coils + radial compression
- JT-60U - Aggressive application of rf heating and current drive

**Three exciting new approaches for outer PF start-up are explored:**

# I. Outer PF ramp from near zero flux and current. Use variety of non-inductive current drive for ramp-up assist (HHFW, NBI, BS, etc. )

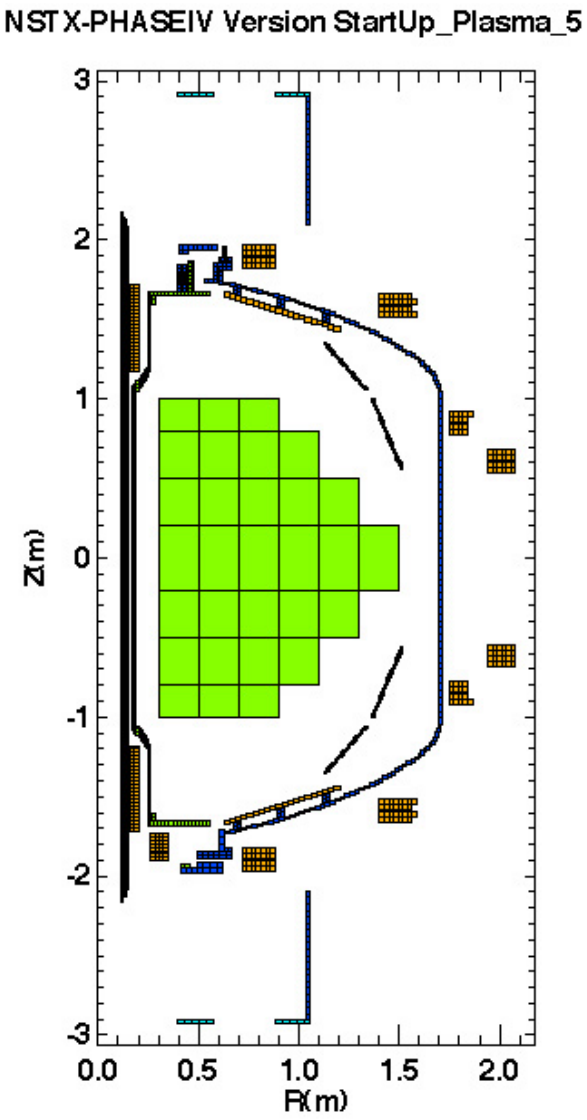
# 2. Approach based on the JT-60U experience. Strong heating & CD for initiation and ramp-up could relax the Lloyd condition.

# 3. Error field minimization to satisfy the "Lloyd condition" for plasma start up with strong preionization, $E_T \cdot B_T / B_P \geq 0.12$ kV/m achieved while retaining as much flux as possible for subsequent current ramp .

# PF-only scenario development for NSTX

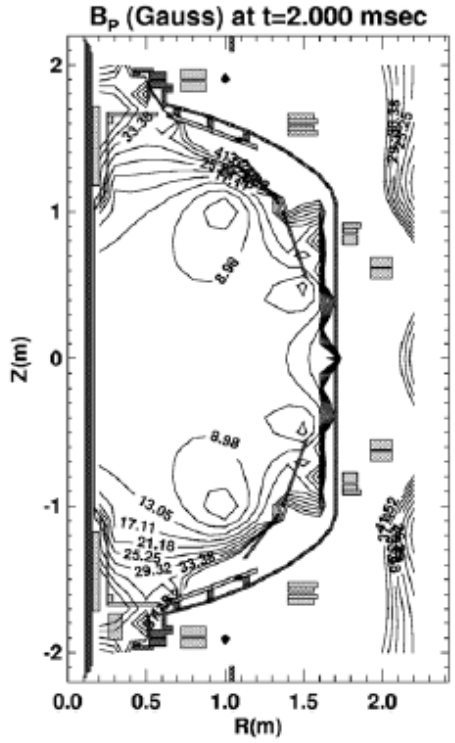
## Analysis by Menard's LRDIAG

- Circuit equation solver
  - Coils and conducting structures
  - Eddy currents accounted
  - No plasma equilibrium
- Plasma modeled by passive coils
  - Distribution of "plasma" coils
  - Variable resistivity profile in space but constant in time
  - Model selected to reproduce 1MA NSTX plasma (~70eV equivalent Te)

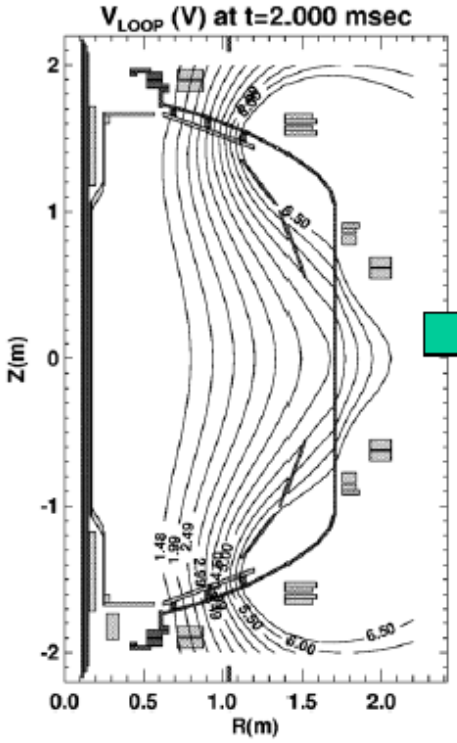


# #1. Outer-PF ramp from near zero current/flux

Good null

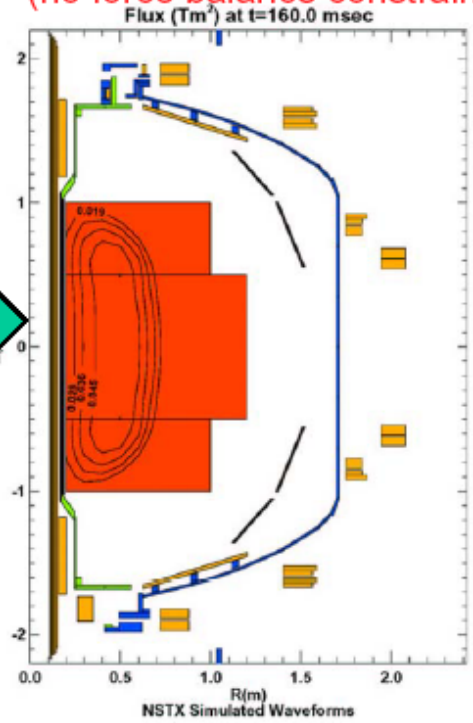



Significant $V_{Loop}$




Can form closed flux

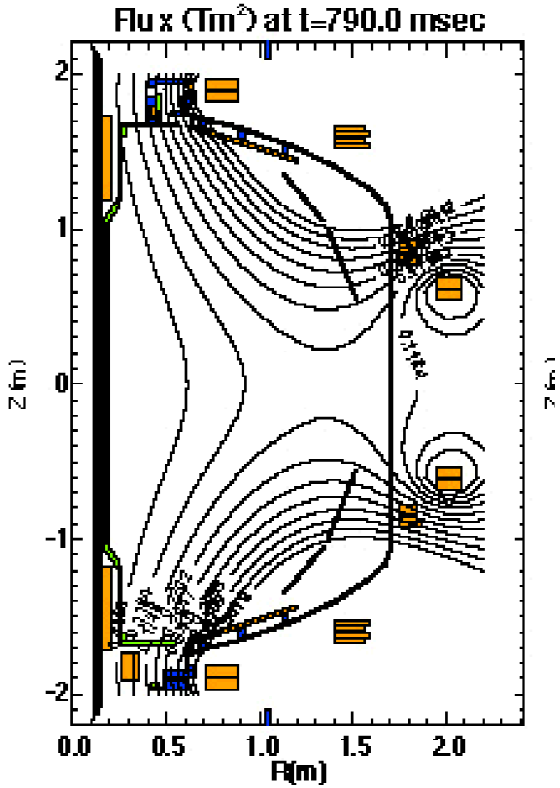
(no force balance constraint)




- Higher $I_P$ possible with additional current drive: RF, NBI, BS?
- Initial simulations show core back-EMF – current hole?

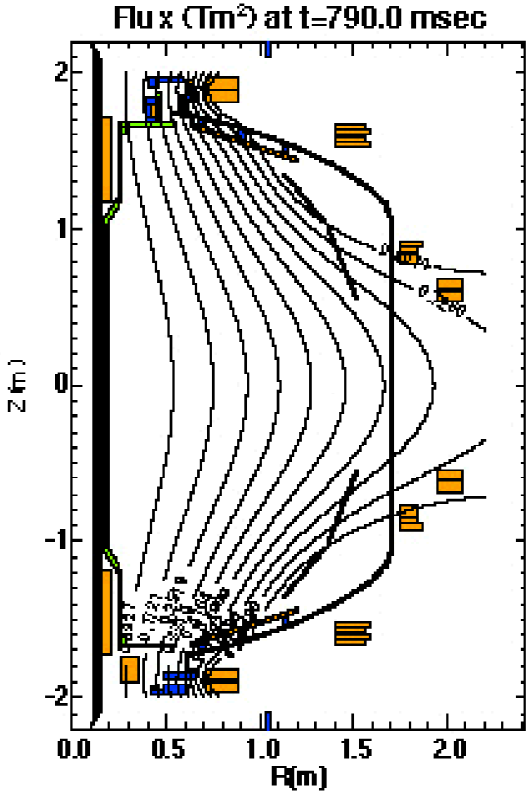
# # 2. Different scenarios modeled

## Outboard X-point



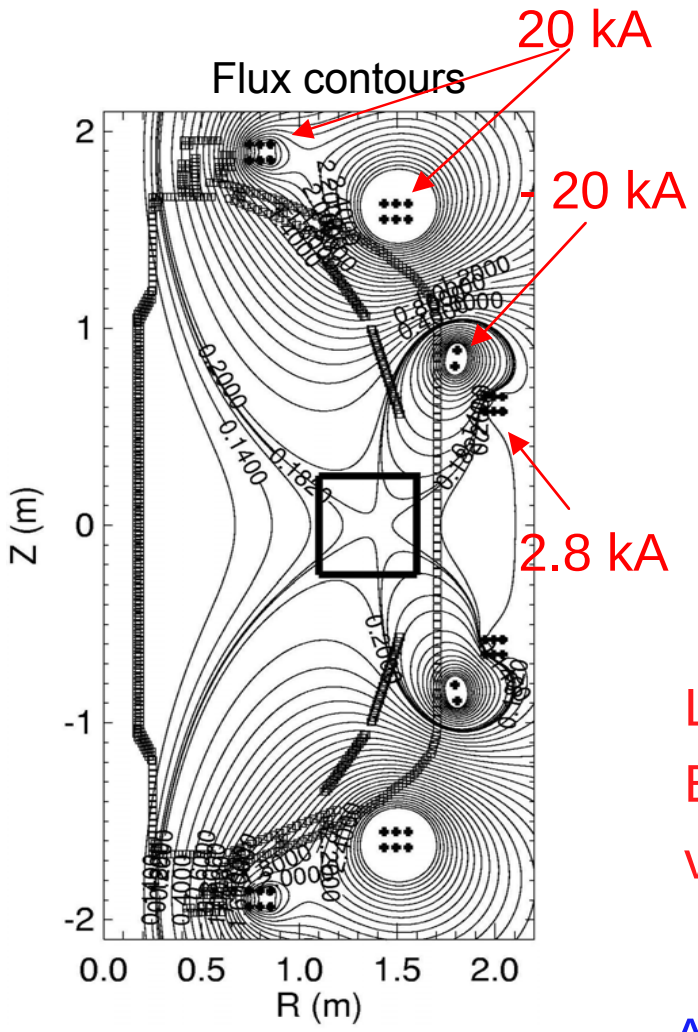

- $I_p$ = 550 kA may be possible

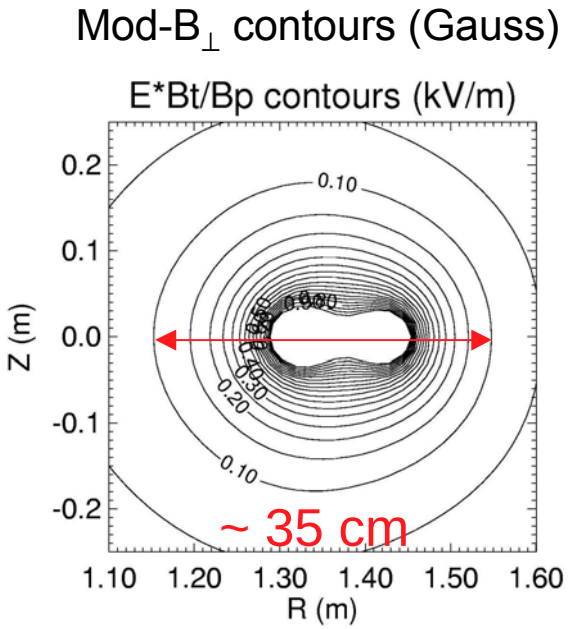
## Scenario 2 (JT-60U-like)




- Requires strong plasma source (HHFW/ECH)
- $I_p$ ~ 650 kA may be possible

# #3. Creation of high quality field null possible by energizing the presently unused PF 4

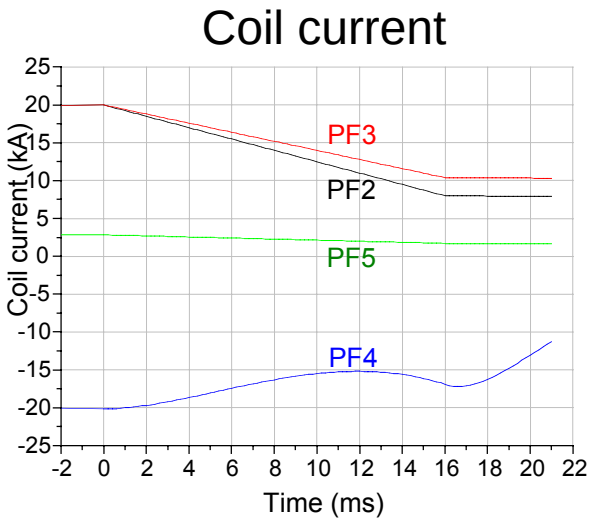


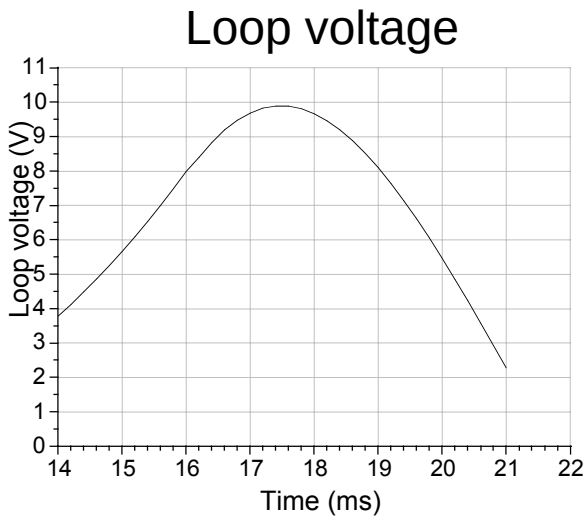



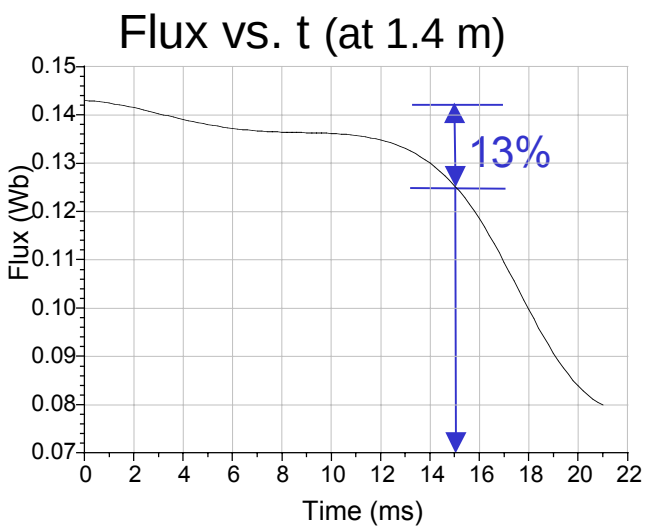

Lloyd's condition, with strong pre-ionization, $E_T \cdot B_T / B_P \geq 0.12$ kV/m satisfied in a significant volume

Analysis by W. Choe: NULLB code

# Time-dependent calculation with vacuum vessel eddy currents included




- Significant V-S is available for current ramp-up.
- Plasma equilibrium and stability at the time of breakdown needs to be checked carefully.
- Full ramp-up scenario will require bi-polar PF 5. But initial breakdown experiment to ~100 kA should be possible with the existing power supplies.

# FY 03-08 plans for plasma startup by PF induction


## FY 03: Preparatory work scopes

- Continue start-up calculations including wall eddy currents
- Analyze electro-mechanical forces and assess bracing needs if any
- Assess basic power supply reconfigurations

## FY 04: Initial plasma initiation experiments

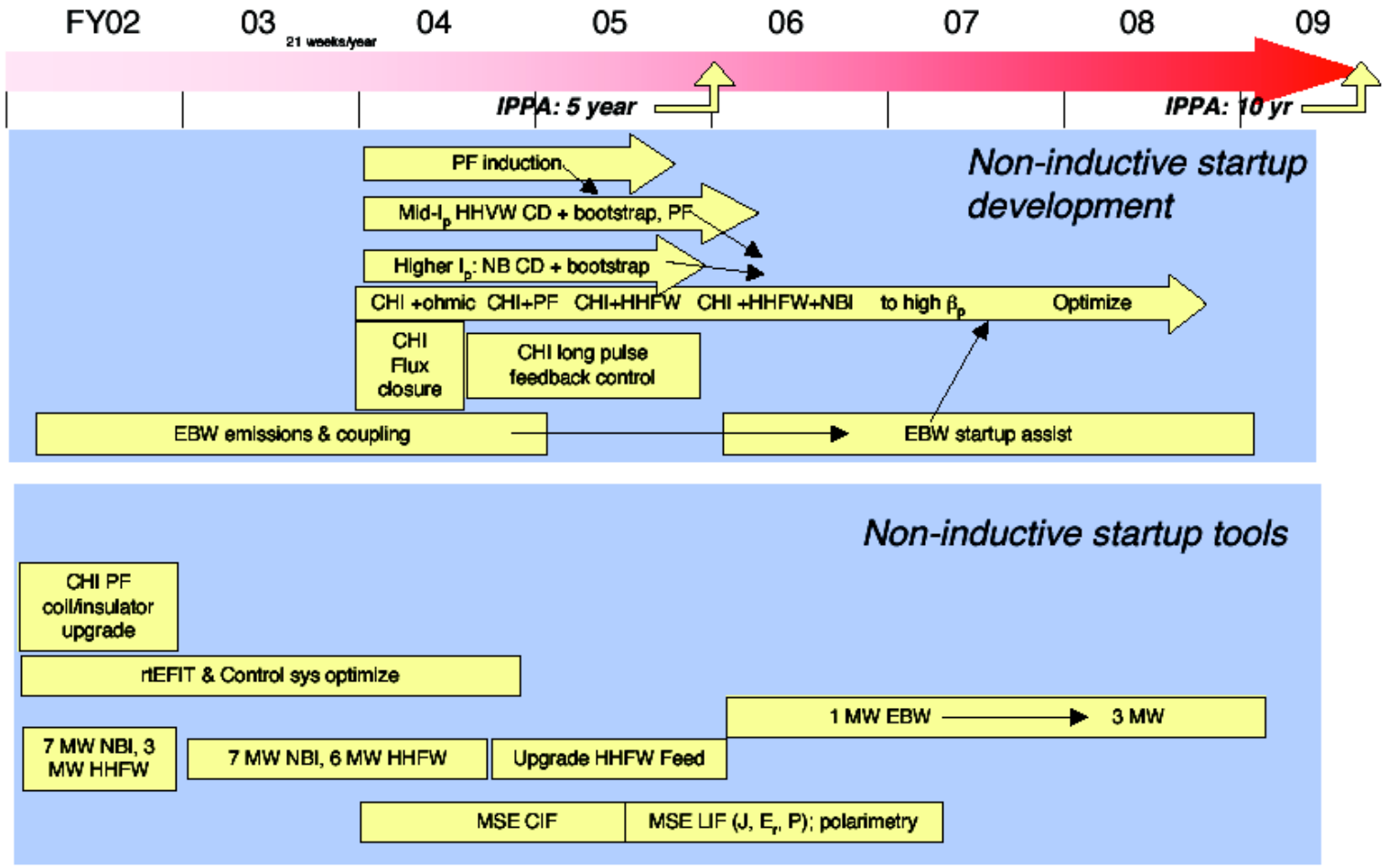
- Develop effective pre-ionization capability with ECH and HHFW
- Conduct initial breakdown experiment at ~ 100 kA with existing supplies
- After confirming breakdown, implement needed PF supply upgrades of Fy03
- Develop optimized current ramp-up scenarios using TSC with full PF
- Develop required magnetic sensors and control algorithms

## FY 05 - 06: Start-up demonstration experiments

- Establish Ip ≤ 500 kA plasma discharges with full PF and ECH/HHFW
- Apply HHFW and/or NBI to achieve high beta poloidal discharges
- Develop comprehensive understanding and predictive capability

## FY 07 - 08: Assist the overall non-inductive research program

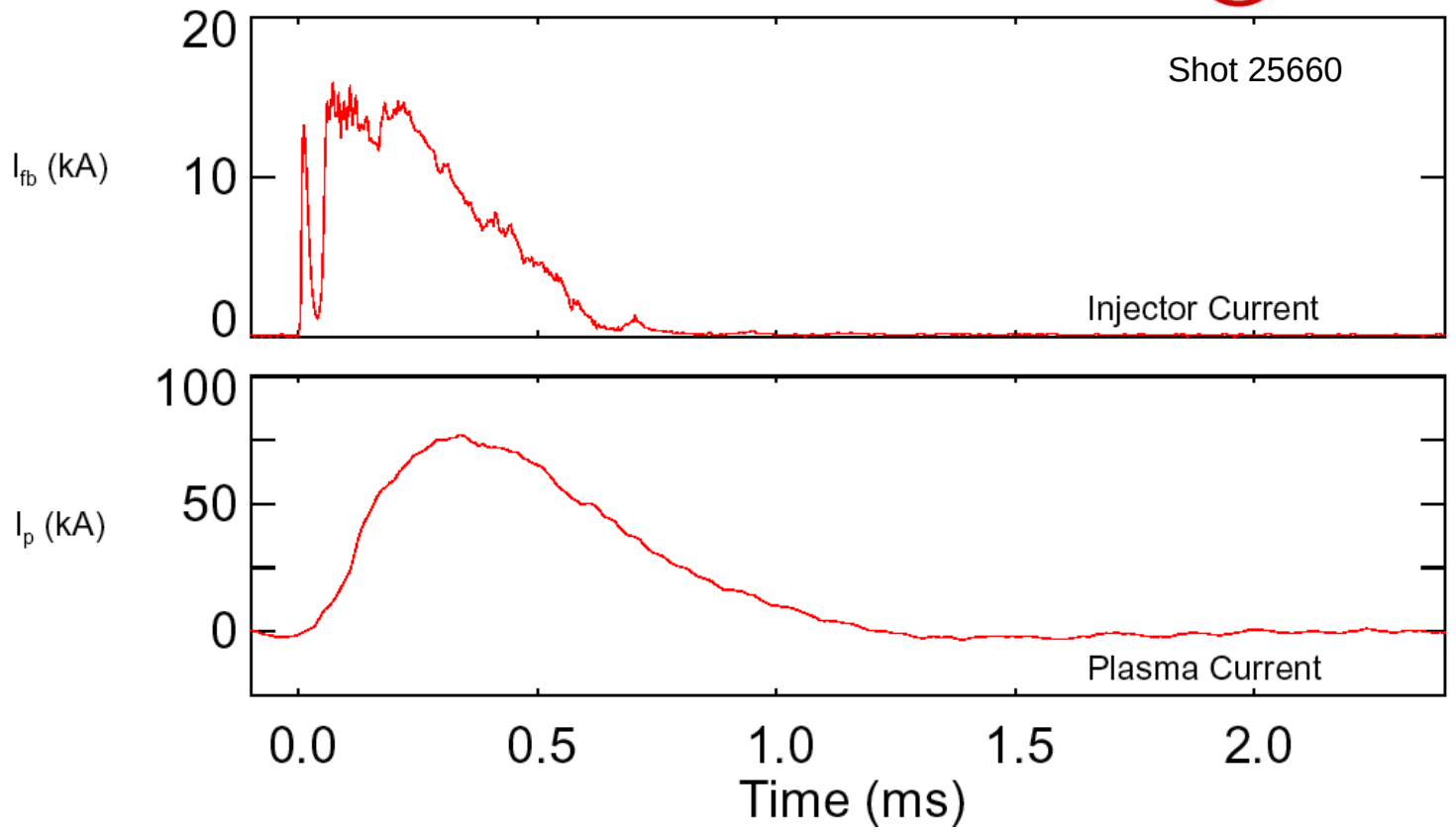
# Non-inductive plasma startup program plan



# 5yr plan allows for a demonstration of solenoid-free plasma startup on NSTX

- Transient CHI: simple method demonstrated on HIT-II
  - Advantage of non transient PF coil currents
- Steady state CHI: potential to optimize the edge region in sustained non-inductively driven discharges
- Plasma startup using outside PF induction: potential to produce MA level startup currents in large STs
  - A test of this concept is planned on NSTX

# Demonstration of flux closure in a CHI produced discharge on HIT-II




Plasma current persists after the injector current has been reduced to zero

# Highest ever plasma current on HIT-II (265kA) obtained using CHI start-up

- No transient coil currents
  - Discharges initiated & maintained in diverted configuration
- CHI is more tolerant to field errors
  - Discharges can be initiated when $-V_{Loop}$ is applied to CHI