Non-Inductive Current Buildup in a Spherical Tokamak

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Outline

- Introduction and Motivation
- Basic Equations and Physical Effects
- Inductive vs Non-Inductive Current Buildup
- 2D Simulation Results of 90% Bootstrap Current Buildup in an ST
- 1D Model and results
- Timescales and Comparison to Experiments
- Conclusions

Introduction

- Non-inductive current drive is essential for high-performance STs because of
  - lack of room for large OH solenoid
  - desire to operate long-pulse or steady state
- Options for current buildup include
  - RF current drive
  - Bootstrap current
  - NB current drive
- What are the time-scales associated with these, and are they acceptable?

Basic Equations and Essential Physics

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E}$$
$$\vec{E} + \vec{V} \times \vec{B} = \eta(\vec{J} - \vec{J}_{CD})$$
$$\mu_0 \vec{J} = \nabla \times \vec{B}$$

TSC

$$\frac{\partial \iota}{\partial t} = \frac{\partial V_L}{\partial \Phi}$$

$$\iota(\Phi,t) \equiv \frac{1}{q(\Phi,t)} = \frac{\partial \Psi}{\partial \Phi}$$

$$V_L = \frac{2\pi\eta(\Phi,t)\left\langle \vec{B} \bullet (\vec{J} - \vec{J}_{CD}) \right\rangle}{\left\langle \vec{B} \bullet \nabla\phi \right\rangle}$$

$$\Psi = \frac{1}{2\pi} \iiint_{vol<\Psi} \vec{B} \bullet \nabla\theta \, d\tau$$

$$\Phi = \frac{1}{2\pi} \iiint_{vol<\Phi} \vec{B} \bullet \nabla\phi \, d\tau$$

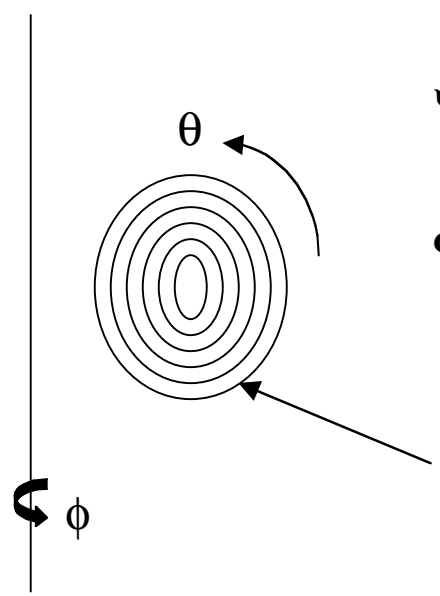
$$\vec{B} \bullet \nabla\Psi = \vec{B} \bullet \nabla\Phi = 0$$

$$\psi(\vec{x},t) = \iint G(\vec{x},\vec{x}')J_\phi(\vec{x}',t)d^2\vec{x}'$$

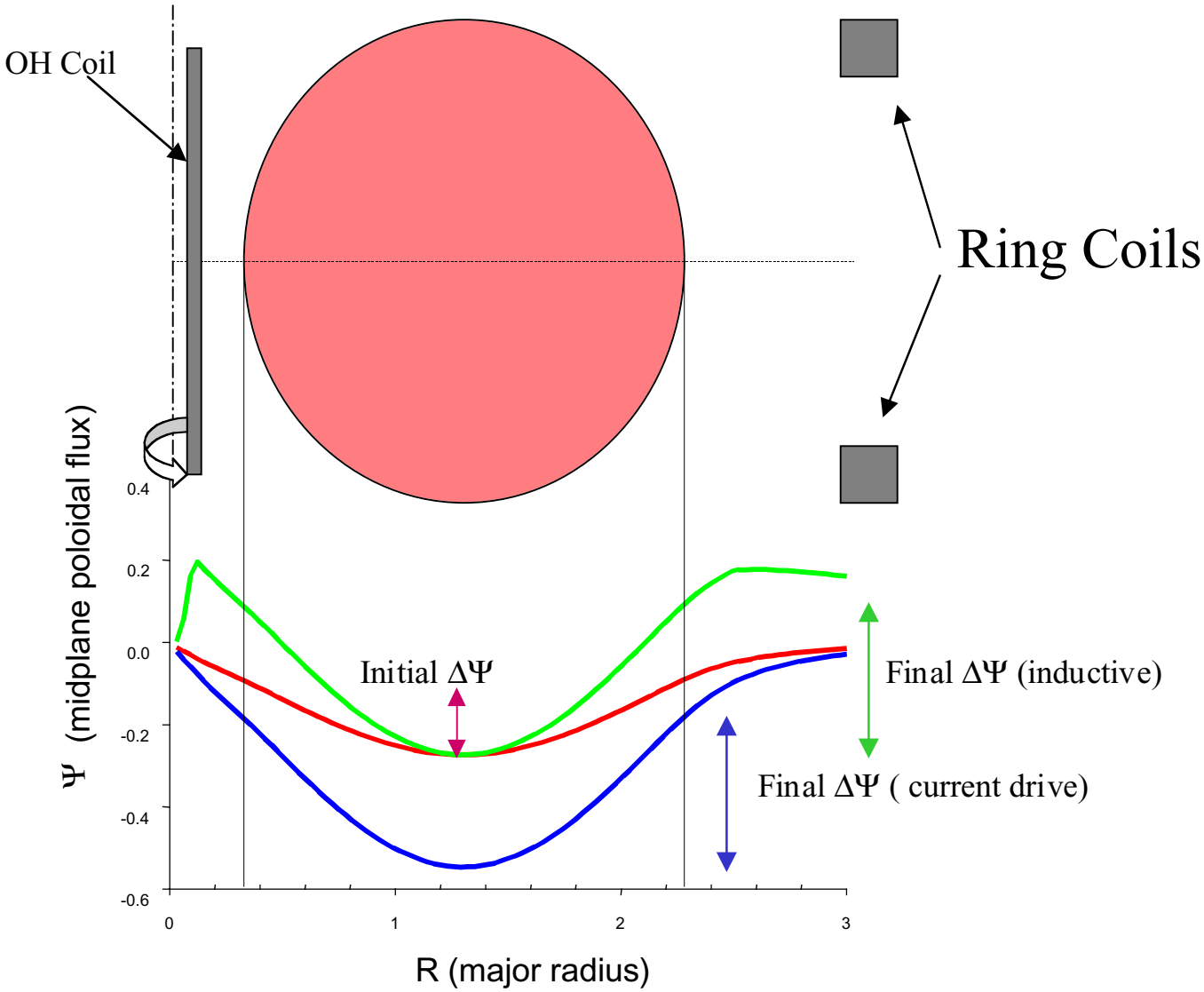
$$J_{CD} = J_{BS} + J_{RF} + J_{NB}$$

Transport Model

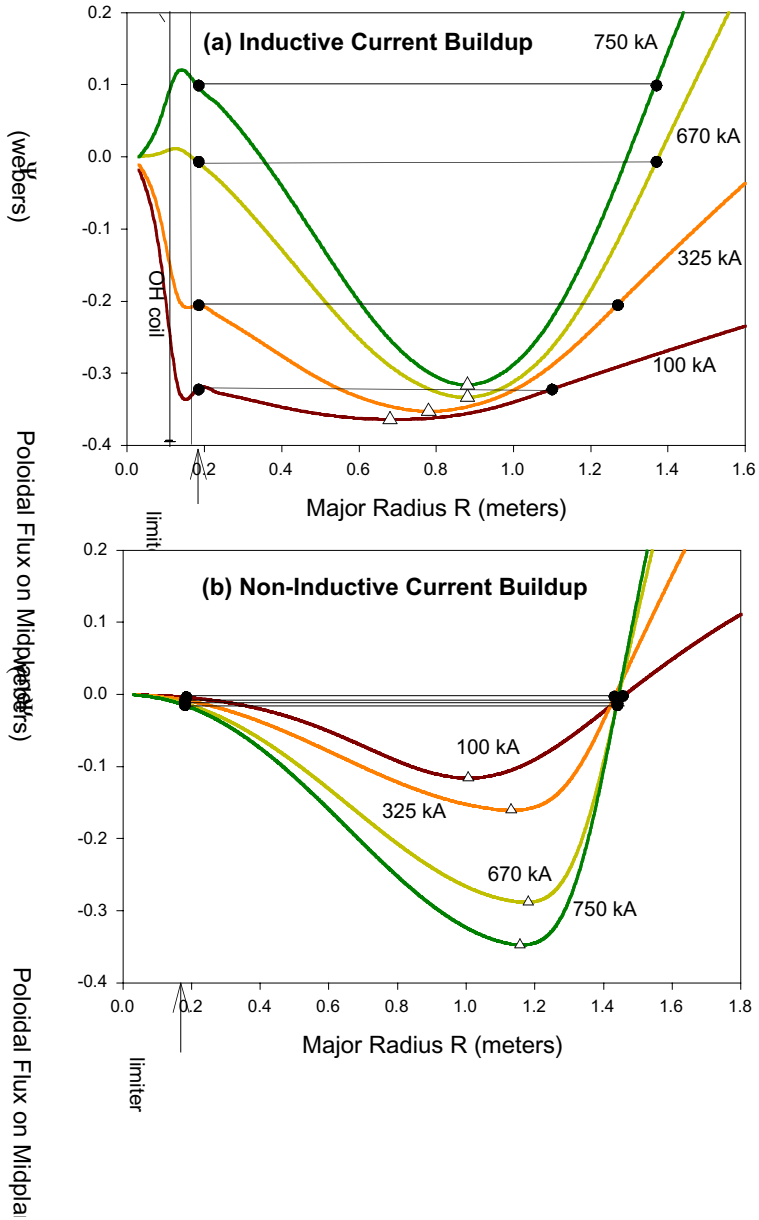
$\chi(r,t)$, $D(r,t)$



Poloidal Flux Change for Inductive and CD Current Increase



Examples of TSC calculations of current buildup in an ST



For inductive current buildup, poloidal flux at magnetic axis increases

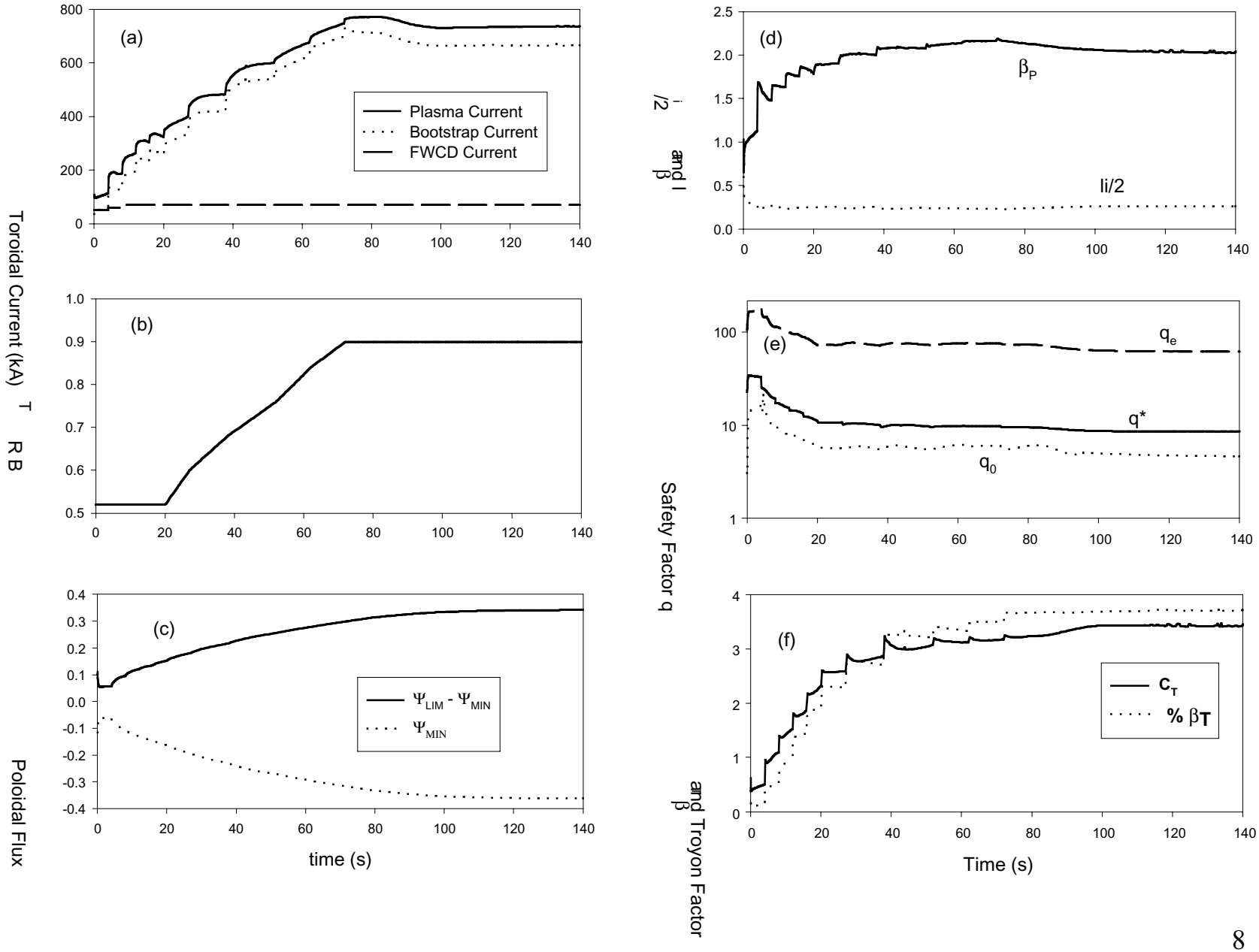
For non-inductive current buildup poloidal flux at magnetic axis decreases

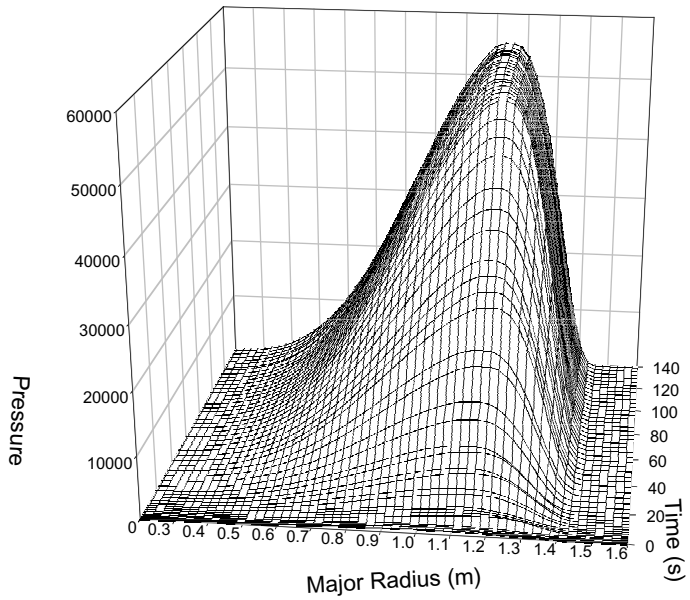
Note: OH coil is absolutely necessary for inductive current buildup

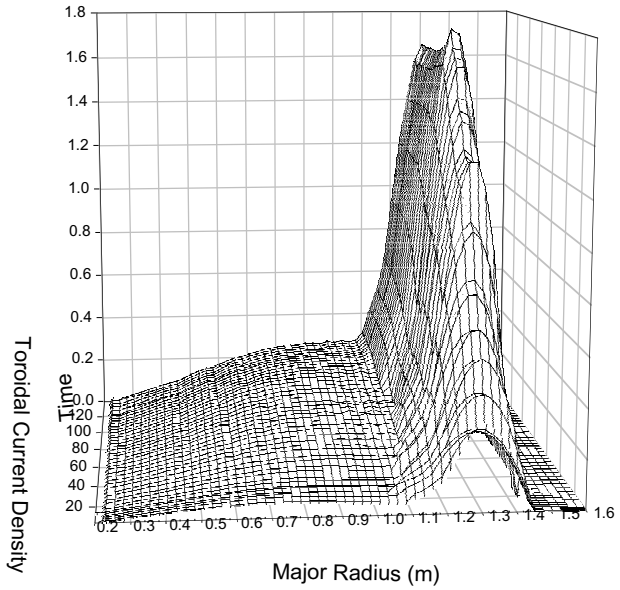
Outer PF coils by themselves can never provide flux to ramp up plasma current in a high beta ST.

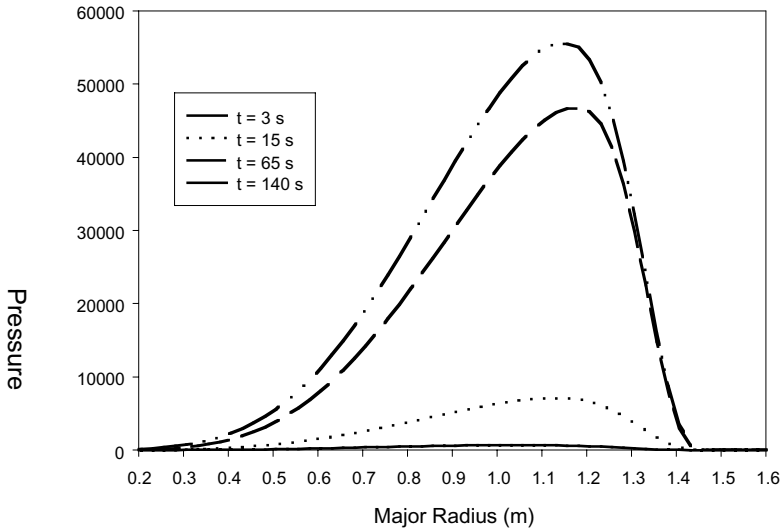
2D Results…application to NSTX-U

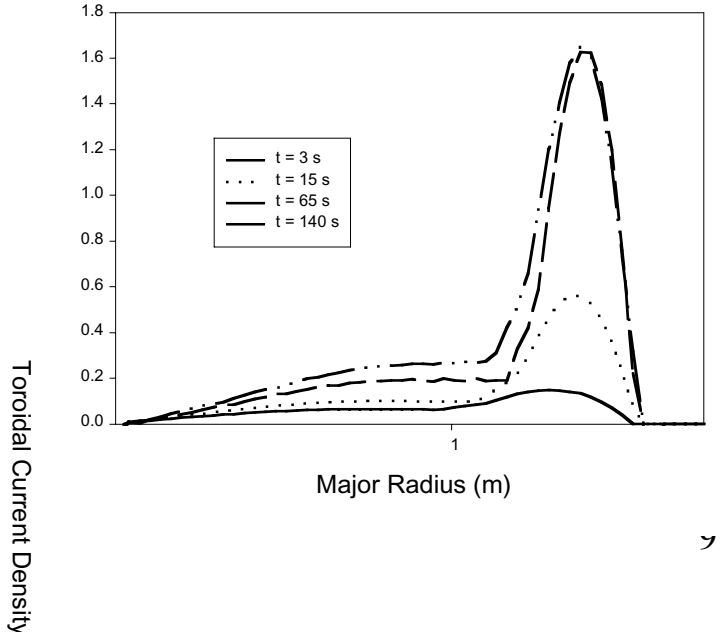
- Simulation of non-inductive rampup using RF + Bootstrap
- Complete transport calculation (4.3 keV peak)
- Start with 100 kA, ramp to 750 kA 10% RF + 90% bootstrap
- $\beta_P \cong 2$ for bootstrap overdrive
- $I_P \propto a\, B_T\, C_T / \beta_P$
- For a and C_T fixed, $I_P \propto B_T$
- Time-scales are very long, 75 + 45 seconds for steady state
- Compare with $t_0 = a^2 \mu_0 \eta(0) = 85\ s$


(a)
Plasma Current
Bootstrap Current
FWCD Current
Toroidal Current (kA)
(b)
$R_T B$
(c)
$\Psi_{LIM} - \Psi_{MIN}$
Ψ_{MIN}
Poloidal Flux
time (s)
(d)
β_P
li/2
β and li/2
(e)
q_e
q^*
q_0
Safety Factor q
(f)
C_T
% β_T
β and Troyon Factor
Time (s)

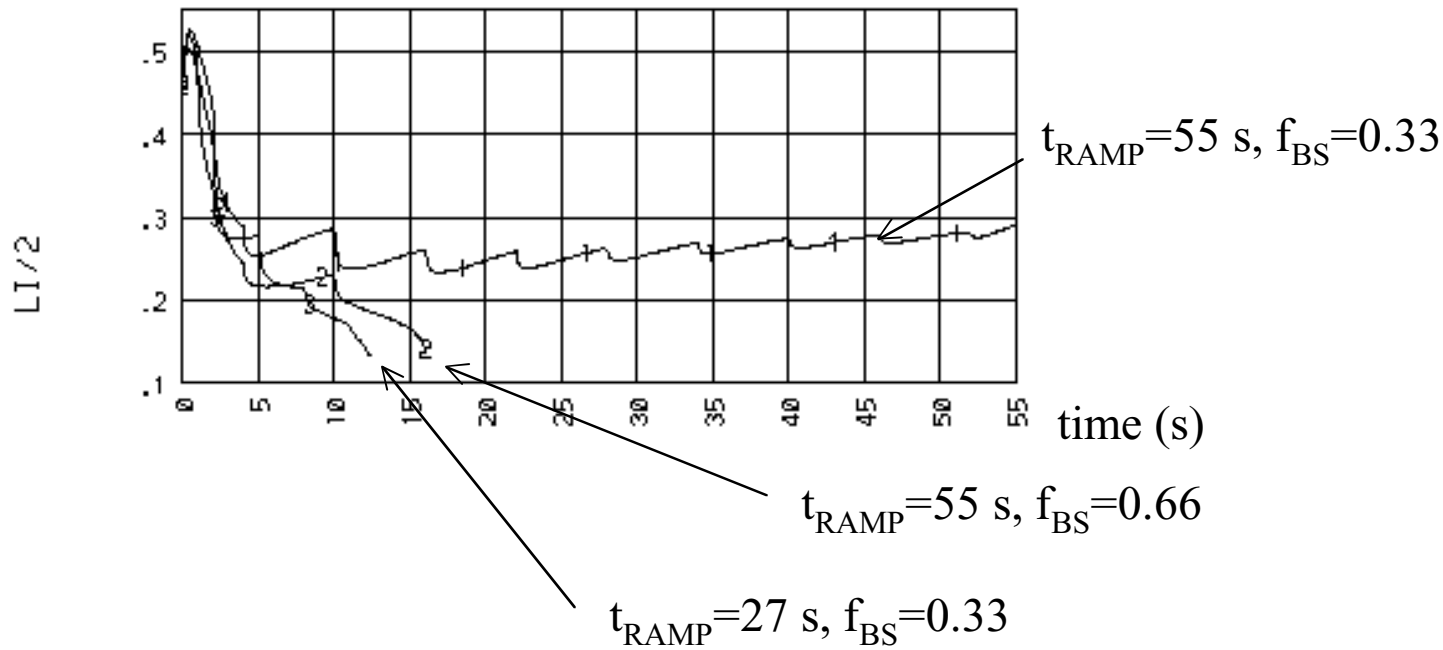

Pressure
Major Radius (m)
Time (s)


Toroidal Current Density
Major Radius (m)
Time

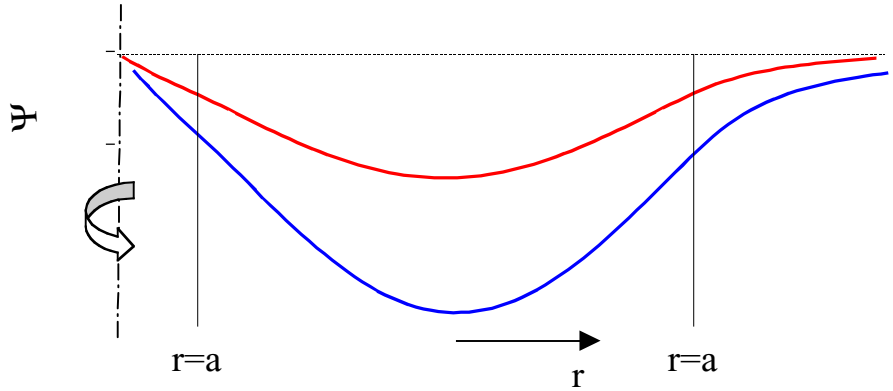

Pressure
Major Radius (m)
t = 3 s
t = 15 s
t = 65 s
t = 140 s


Toroidal Current Density
Major Radius (m)
t = 3 s
t = 15 s
t = 65 s
t = 140 s

Another series of calculations with slightly lower central temperature (3.5 keV) shows that calculation will fail because l_i becomes too small for ramp time too fast.
Also, higher bootstrap fractions require longer times.



A simple 1D equation can be derived that contains all of the essential physics



$$\frac{\partial \psi}{\partial t} = \eta(r)\left[\frac{1}{\mu_0 r}\frac{\partial}{\partial r} r \frac{\partial \psi}{\partial r} - j_{CD}(r,t)\right]$$

From the definition of the plasma inductance →

$$at\ r = a:$$

$$\psi + \frac{a}{R\mu_0} L^*_{ext} \frac{\partial \psi}{\partial r} = 0$$

$$where \quad L^*_{ext} \cong \frac{3}{4}\mu_0 R\left[\ln\frac{8R}{a} - 2\right]$$

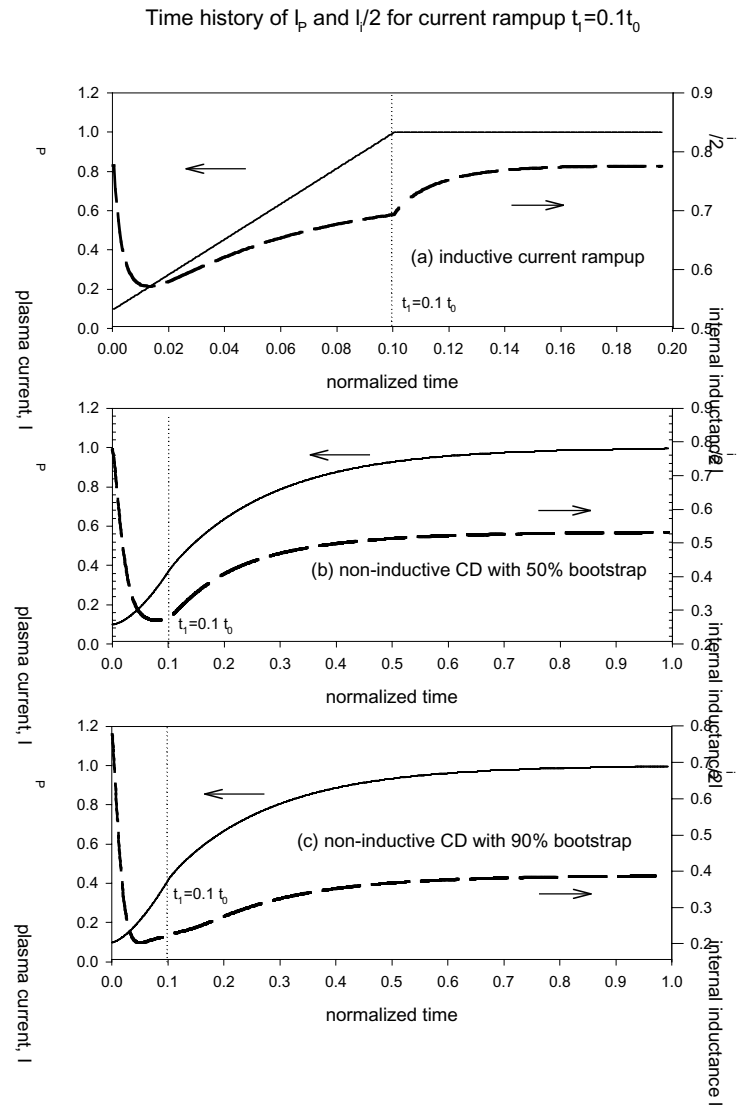
In the 1D runs, the resistivity function is taken to have the following form: $\eta(r)=\eta_0(1-r^2/a^2)^{-m}$ with m=4.

The current drive is of the form:

$$j_{CD}(r,t) = j_0(t)\left[(1-\frac{r^2}{a^2})^n + f_{BS}(\frac{r}{a})^{1/2}(1-\frac{r^2}{a^2})\right]$$

In these runs, the plasma starts in resistive equilibrium at t=0 with a current 0.1 I_0. The current source is then ramped up linearly from 0.1 I_0 to I_0 in a time 0.1 t_0.

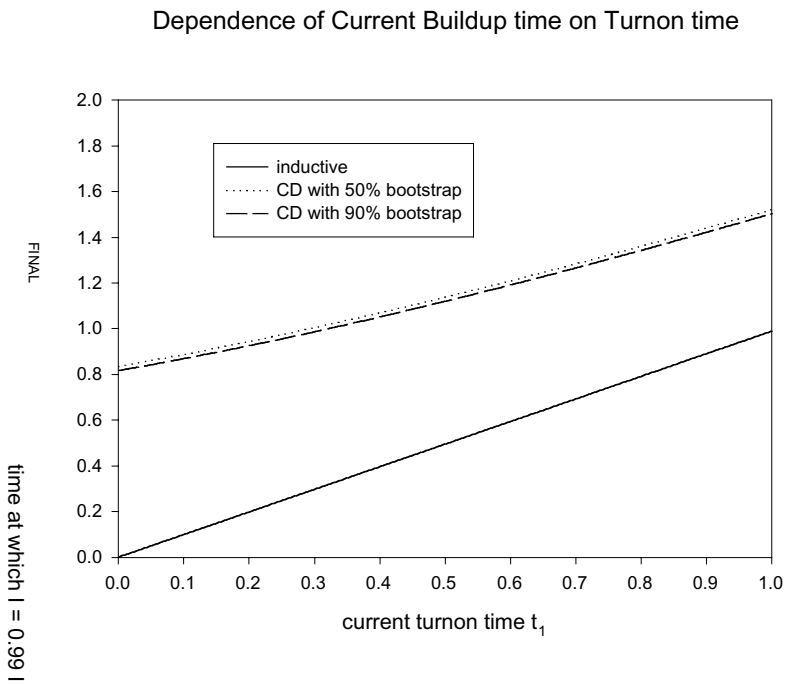
Note: $t_0 = a^2\mu_0/\eta(0)$



Note that the time at which it takes the plasma current to reach 99% of it's final value depends on the curent turnon time t_1.

For the inductive case (a) on previous slide, this time is the same as the turnon time.

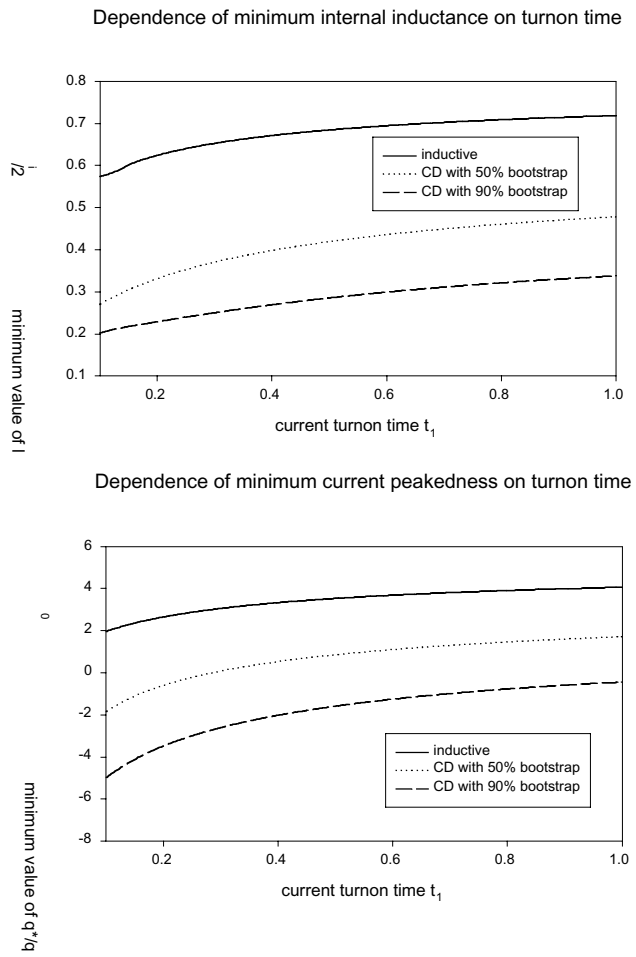
For all the non-inductive current-drive cases, it is much longer.

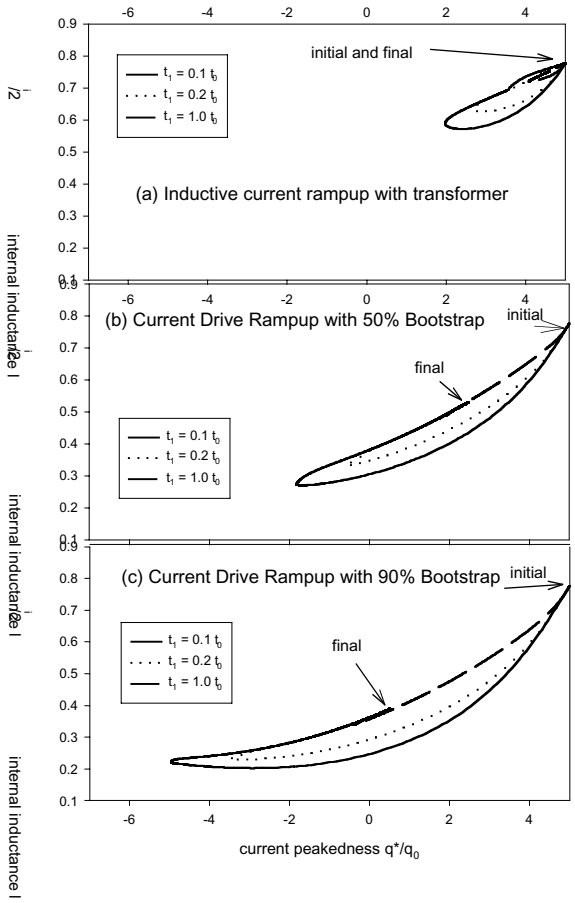


This illustrates how distorted the plasma current profile can become as it approaches steady state.

Plotted are the minimum values of the plasma internal inductance and of the plasma current peakedness as a function of the current turnon time t_1, for the inductive rampup as well as for several non-inductive rampups with differing bootstrap fractions.

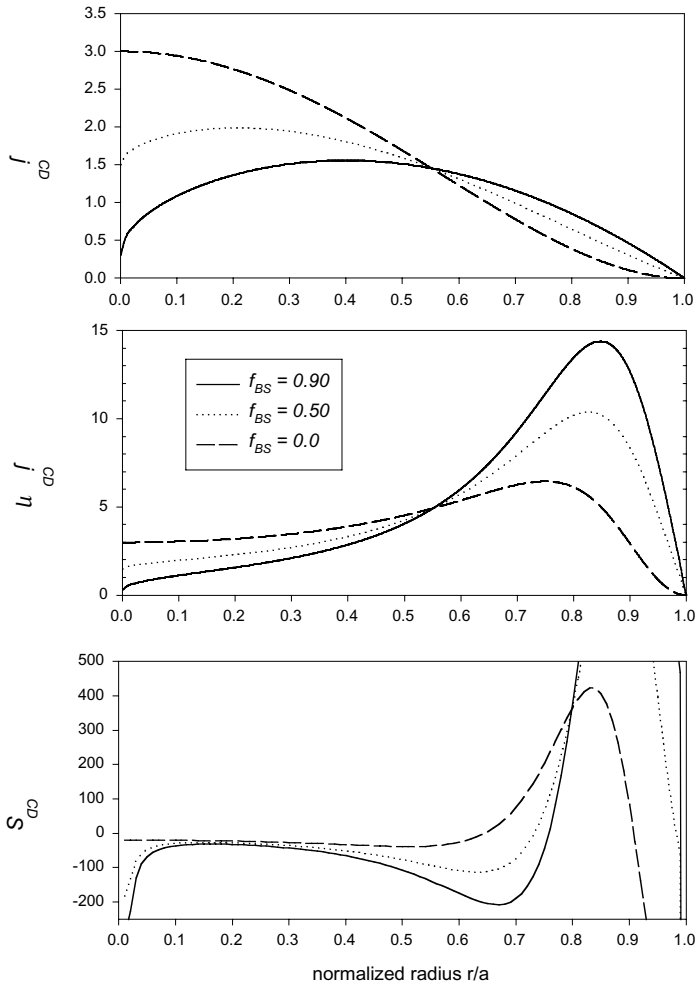
Note that a negative value of q^*/q_0 means that the central current actually went negative during the transient.





These are the trajectories in ($l_i/2$, q^*/q_0) space during the current rampup.

High bootstrap fractions and short rampup times cause large excursions into the unstable regimes.



$$\frac{\partial \psi}{\partial t} = \eta(r)\left[\frac{1}{\mu_0 r}\frac{\partial}{\partial r} r \frac{\partial \psi}{\partial r} - j_{CD}(r,t)\right]$$

$$j(r,t) \equiv \left[\frac{1}{\mu_0 r}\frac{\partial}{\partial r} r \frac{\partial \psi}{\partial r}\right]$$

$$\frac{\partial j}{\partial t} = \left[\frac{1}{\mu_0 r}\frac{\partial}{\partial r} r \frac{\partial(\eta(r) j)}{\partial r} + S_{CD}(r,t)\right]$$

$$S_{CD}(r,t) = -\left[\frac{1}{\mu_0 r}\frac{\partial}{\partial r} r \frac{\partial(\eta(r) j_{CD}(r,t))}{\partial r}\right]$$

$j(r,t)$ obeys a similar equation to $\psi(r,t)$ but singular nature of S_{CD} compounds transient problems

Natural non-Inductive Current Rampup Time for an ST

$$T = \frac{a^2 \mu_0}{\eta(0)} \left(\frac{3}{16} + \frac{L^*_{ext}}{4R\mu_0} \right)$$

$$\cong 40 \left(\frac{a[m]}{.65} \right)^2 \left(\frac{T_e\,[ev]}{3000} \right)^{3/2} \text{sec}$$

- Time set by <u>central</u> resistivity
- Compounded because Current Drive systems also heat
- For sudden application in time t<T, transients will dominate
- For high bootstrap fractions especially, it may require several of these times to rampup

These estimates are consistent with non-inductive current buildup times reported in the literature for tokamaks

	WT-2[1]	T-IIU [2]	PLT[3]	PLT [4]	Alcator-C [5]
$\tau_0 = a^2\mu_0/\eta(0)$	0.2 ms	5.8 ms	0.3 s	1.65 s	0.42 s
$\Delta I / I$	4	8	3.3	0.18	0.4
T / τ_0	105	27	7.6	0.18	0.35

[1] S. Kubo, M. Nakamura, T. Cho, et al, "Toroidal Plasma Current Startup and Sustainment by rf in the WT-2 Tokamak", Phys. Rev. Lett., **50**, p. 1994 (1983)
[2] K. Toi, K. Ohkubo, K. Kawahata, et al, "Startup and Quasistationary Drive of Plasma Current by Lower Hybrid in a Tokamak", Phys. Rev. Lett.,**52**, p. 2144 (1984)
[3] F. Jobes, J. Stevens, R. Bell, S. Bernabei, A. Cavallo, et al, "Formation of a 100-kA Tokamak Discharge in the Princeton Large Torus by Lower Hybrid Waves", Phys. Rev. Lett., **52**, p. 1005 (1984)
[4] F. C. Jobes, S. Bernabei, T. K. Chu, W. M. Hooke, E. B. Meservey, R. W. Motley, J. E. Stevens, and S. von Goeler, "Current Rampup by Lower-Hybrid Waves in the PLT Tokamak", Phys. Rev. Lett., **55**, p. 1295 (1985)
[5] Y. Takese, S. Knowlton, and M. Porkolab, "Plasma current ramp-up and Ohmic-heating transformer recharging experiments using lower-hybrid waves on a tokamak", Phys. Fluids **30**, p 1169 (1987)

Summary and Conclusions

- Plasma current rampup for non-inductive current drive is fundamentally different than for inductive:
  - governed by *central resistivity* where temperature is highest
  - transients aggravated by singular source term in j evolution equ.
  - timescales are typically 4-5 times longer for same Te
- Simulation of 90% bootstrap MHD stable current buildup in an ST presented
  - Shows importance of high $\mathbf{B_T}$ for high $\mathbf{I_P}$
  - **$T \cong 70$ s for .65 m T_e=4300 ev plasma in ST**
- These estimates in apparent agreement with existing experiments
- Most of the relevant physics is 1D