Volt-second Consumption During Initial Operation of NSTX

J. Menard, PPPL

with *many* contributions from the NSTX team

APS-DPP Meeting
Seattle, WA
November 17th, 1999

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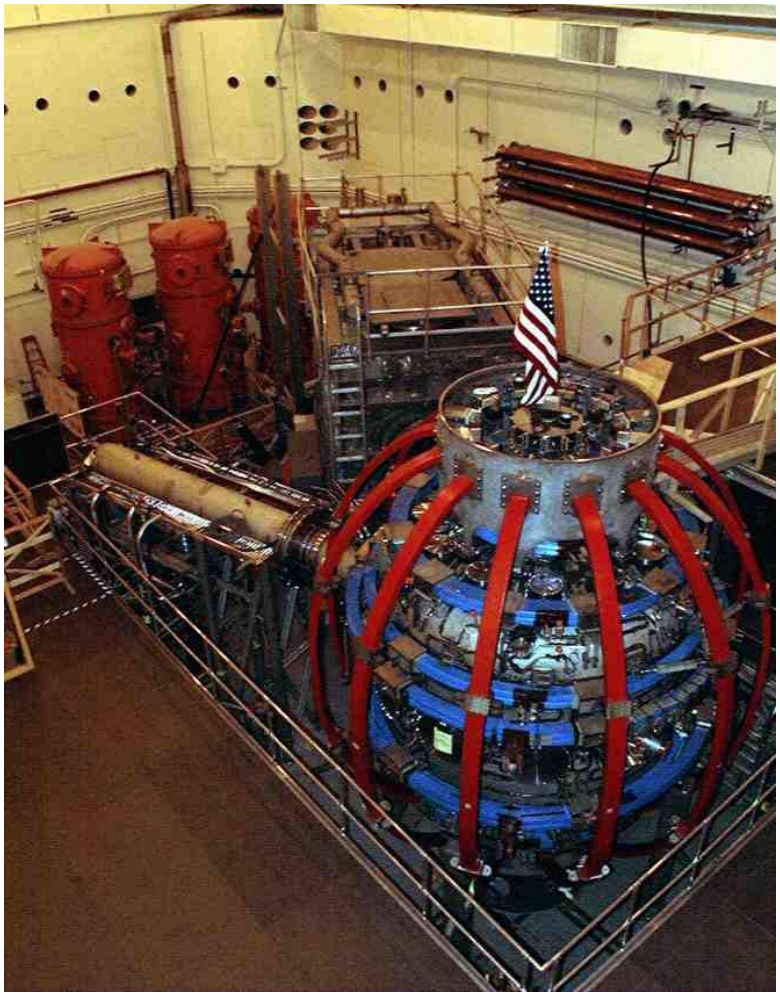

The NSTX Team:

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Lawrence Livermore National Laboratory
Massachusetts Institute of Technology
Oak Ridge National Laboratory
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University of California at Los Angeles
University of California at San Diego
University of Washington

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Motivation

- Spherical tori (ST) have small ohmic heating (OH) transformers
  - NSTX has a double-swing solenoid flux of only 0.7Wb ⇒
  - flux consumption optimization is more important than in a conventional tokamak.

- Well-optimized Ohmic plasma is needed as a starting point for studies of:
  - Confinement scaling
  - Stability limits
  - Density limits
  - Boundary and divertor physics
  - HHFW coupling, heating, and CD
  - CHI current drive with OH target
- OH plasma will be used as target plasma for high power NBI and HHFW

- Goals:
  - Maximize I_P with available OH flux
  - Characterize OH efficiency ⇒ power balance and Ejima analysis
  - Understand why optimal configuration is optimal

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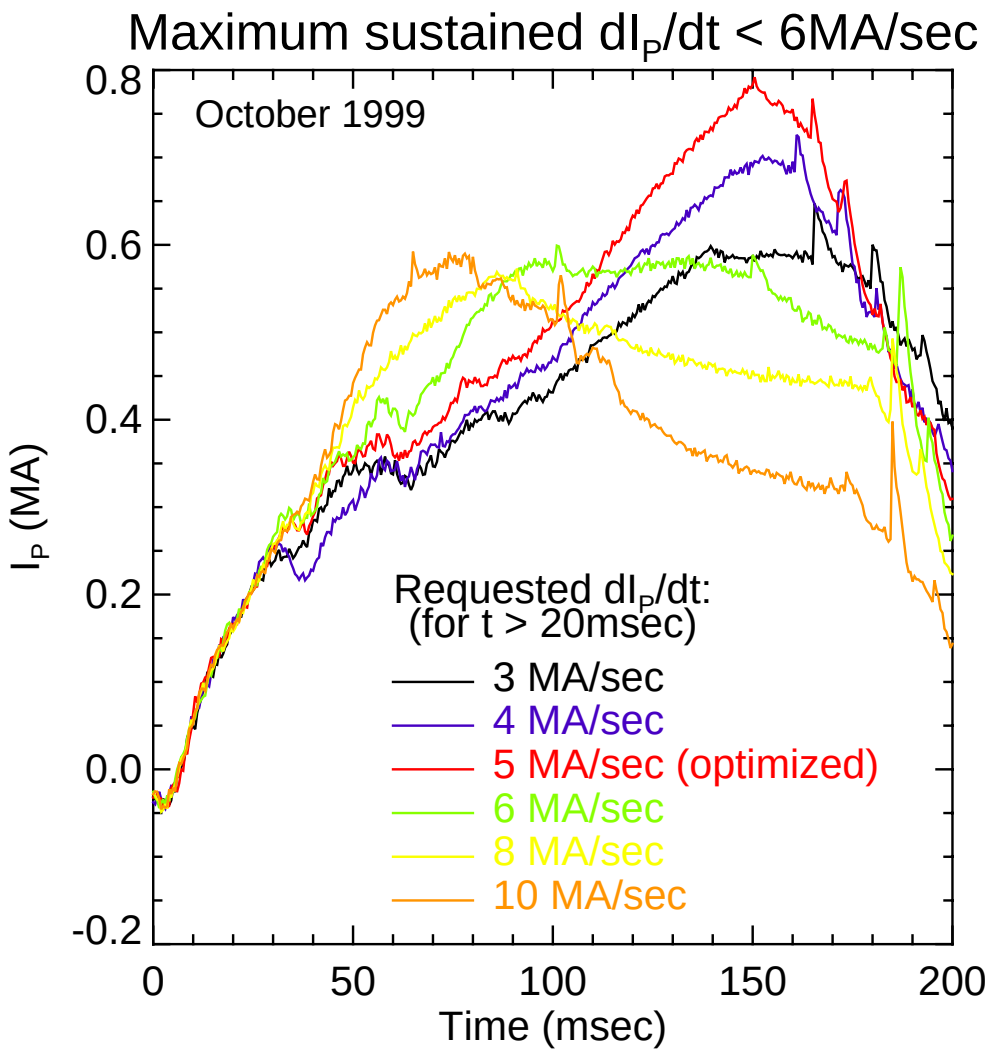
NSTX can ramp to I_P > 700kA in 150msec



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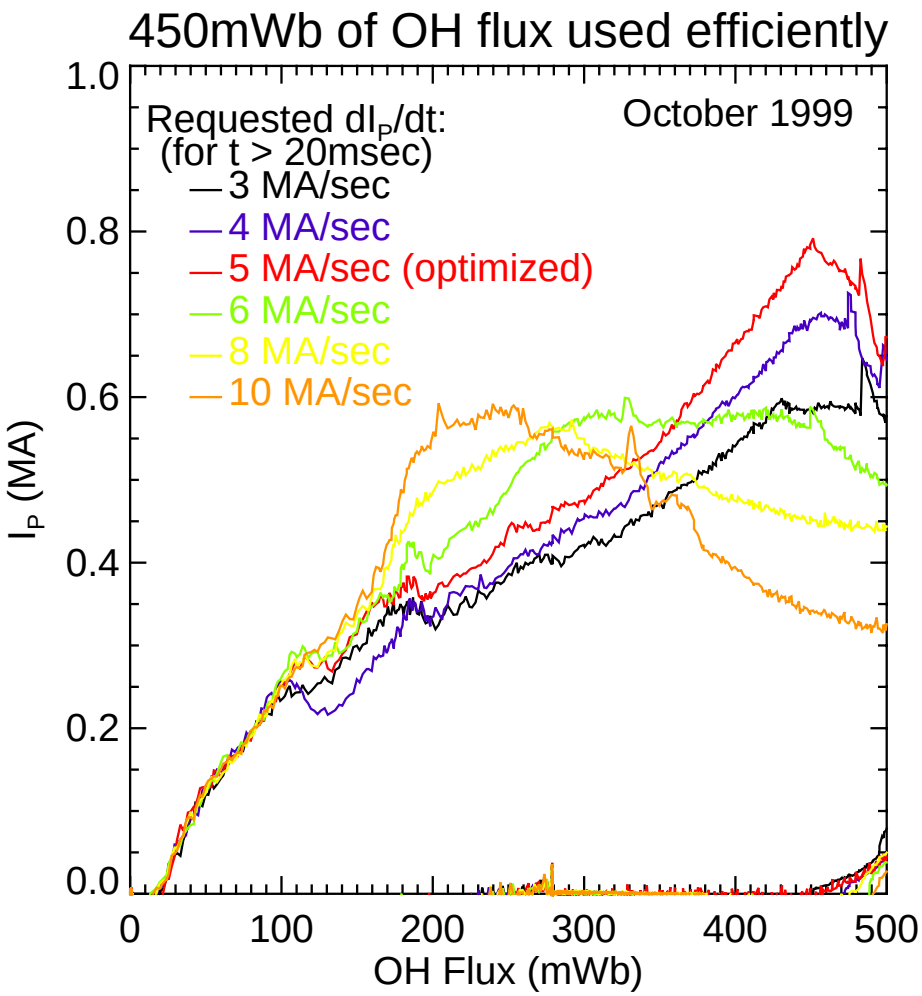
NSTX achieves I_P > 700kA using 65% of OH flux

⇒ can reach 1MA with <u>short</u> flat-top (as designed)



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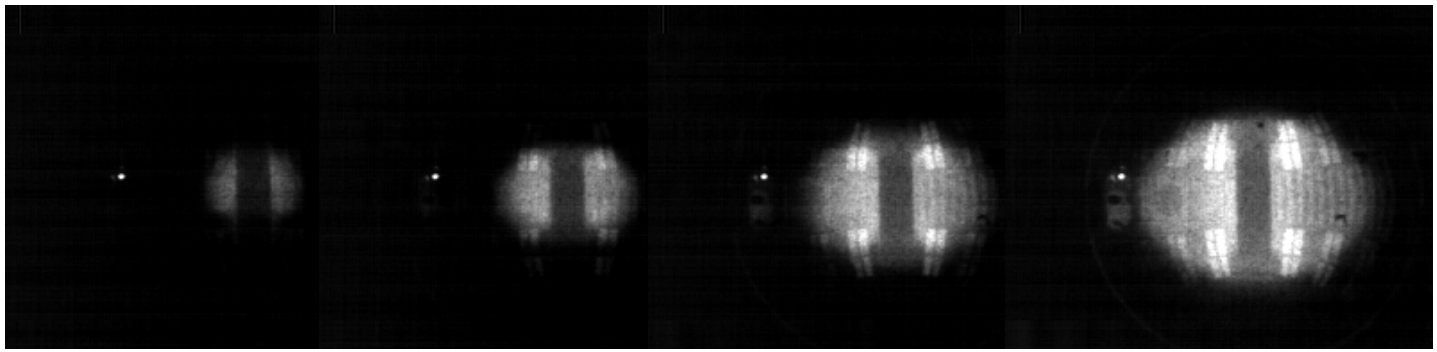
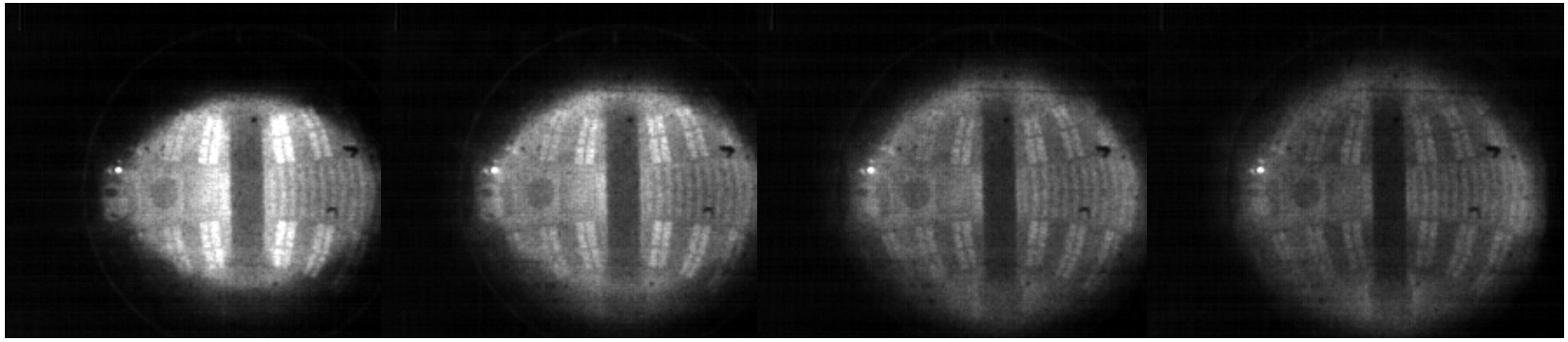
Rapid initiation consumes little OH flux

t=6 msec 7 msec 8 msec 9 msec



$\Delta\Phi_{OH} = 40$mWb

10 msec 11 msec 12 msec 13msec I_P=100kA



Shot 100925

Fast camera images from R. Maqueda

Los Alamos National Laboratory

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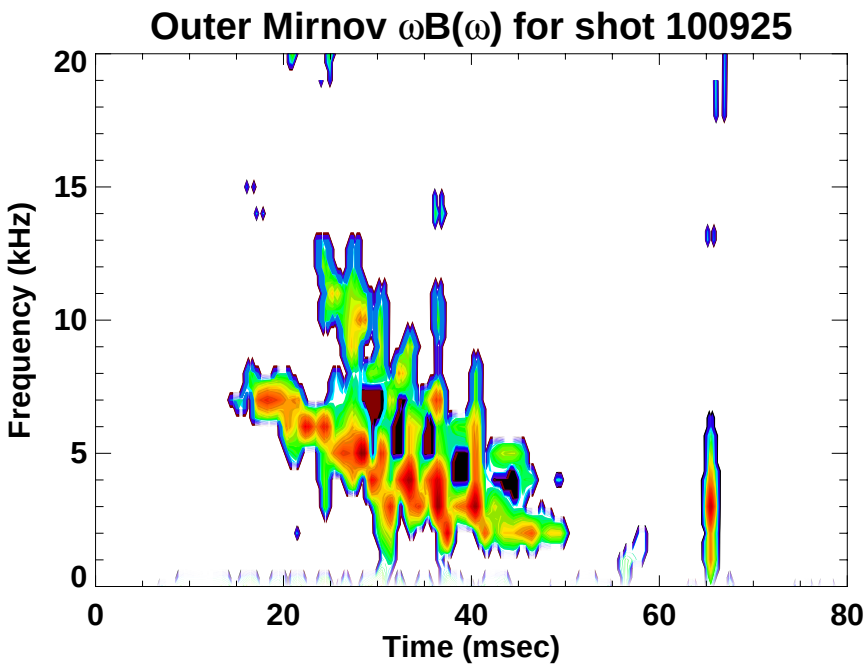
But, rapid plasma formation also triggers tearing activity with decreasing mode frequency



- Also persistently observe a rapid MHD burst at 60-70msec.
- Mode(s) may dissipate significant OH power early in discharge.
- Interestingly, mode does <u>not</u> appear to inhibit dI_P/dt later in discharge.
- Future experiments will decrease initial ramp-rate to investigate reduced early MHD activity.

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Power Balance Calculations

Start with Poynting's Theorem:

$$-\int \mathbf{E}\times\mathbf{B}\bullet d\mathbf{S} / \mu_0 = \int dV\ \partial/\partial t\ [B^2/2\mu_0 + \varepsilon_0 E^2/2] + \int dV\ \mathbf{J}\bullet\mathbf{E}$$

$$P_{Input} = I_P\ V_{Surface} + I_{TF}\ \partial\Phi_{TF}/\partial t = \partial W_{field}/\partial t + \partial W_{loss}/\partial t$$

$$\text{Total Energy Input} \equiv \int P_{input}\ dt'$$

But, $I_{TF}\ \partial\Phi_{TF}/\partial t \approx \int dV\ \partial/\partial t\ B_\phi^2/2\mu_0 \Rightarrow$

$$I_P V_{surface} = \int dV\ \partial/\partial t\ B_P^2/2\mu_0 + \partial W_{loss}/\partial t$$

Net Power into plasma — **Poloidal field ∂W / ∂t** — **Resistive Heating + Radiation**

Use time-series of EFITs (S. Sabbagh - Columbia Univ.)

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Ejima Coefficient from Power Balance

$$I_P\, V_{surface} = \int dV\, \partial/\partial t\, B_P^2/2\mu_0 + \int dV\, \mathbf{J}\bullet\mathbf{E} \;+\; \text{Radiation}$$

Ejima's analysis $\Rightarrow \Phi_{Surface} \equiv \int dt'\, V_{surface} = \Phi_{Inductive} + \Phi_{Resistive}$

$$\Phi_I(t) = \int dt'/\, I_P \int dV\, \partial/\partial t'\, B_P^2/2\mu_0$$

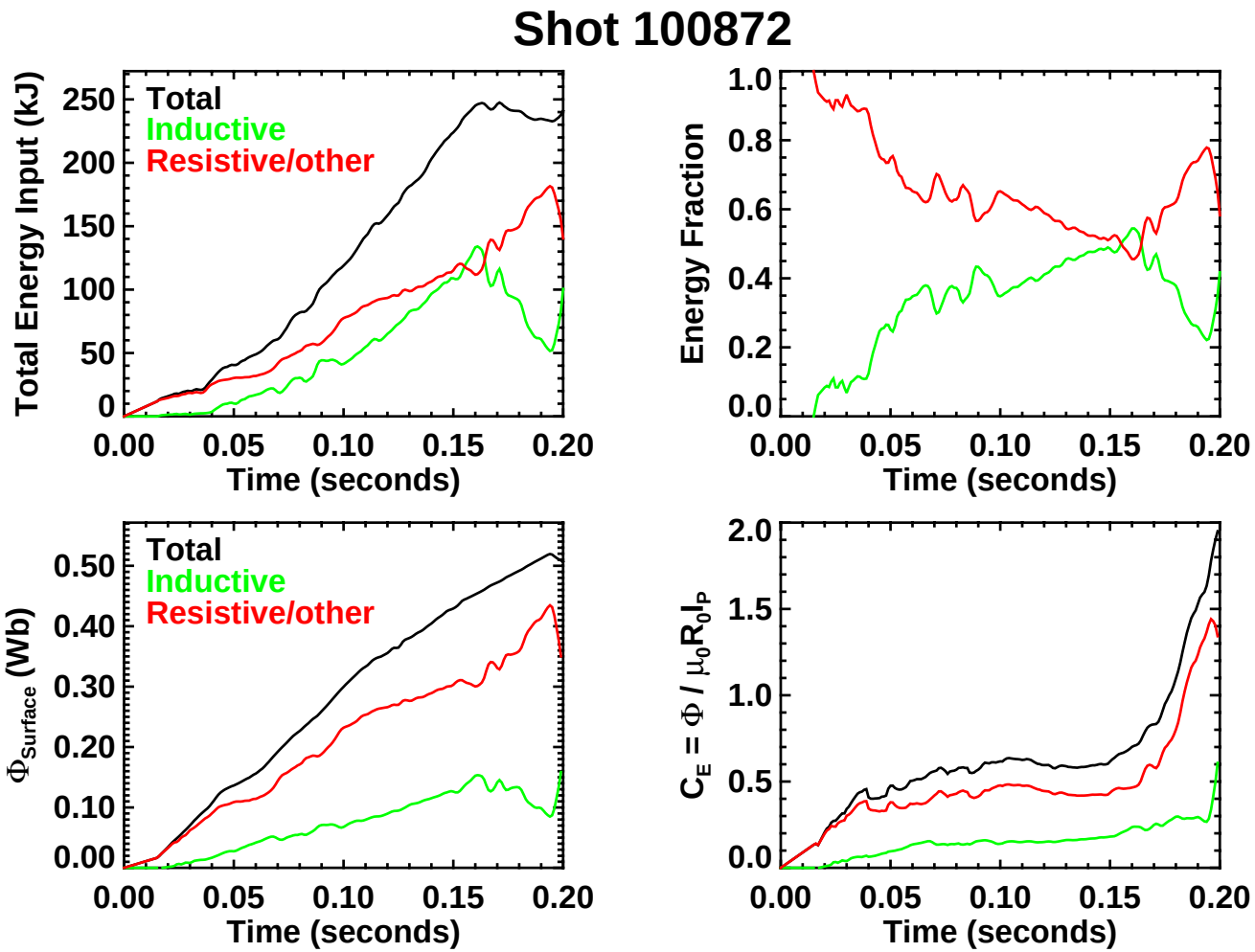
$$\Phi_R(t) = \int dt'/\, I_P \left[\int dV\, \mathbf{J}\bullet\mathbf{E} \;+\; \text{Radiation} \right]$$

$$\mathbf{C_E \equiv \Phi_S / \mu_0 R_0 I_P}$$

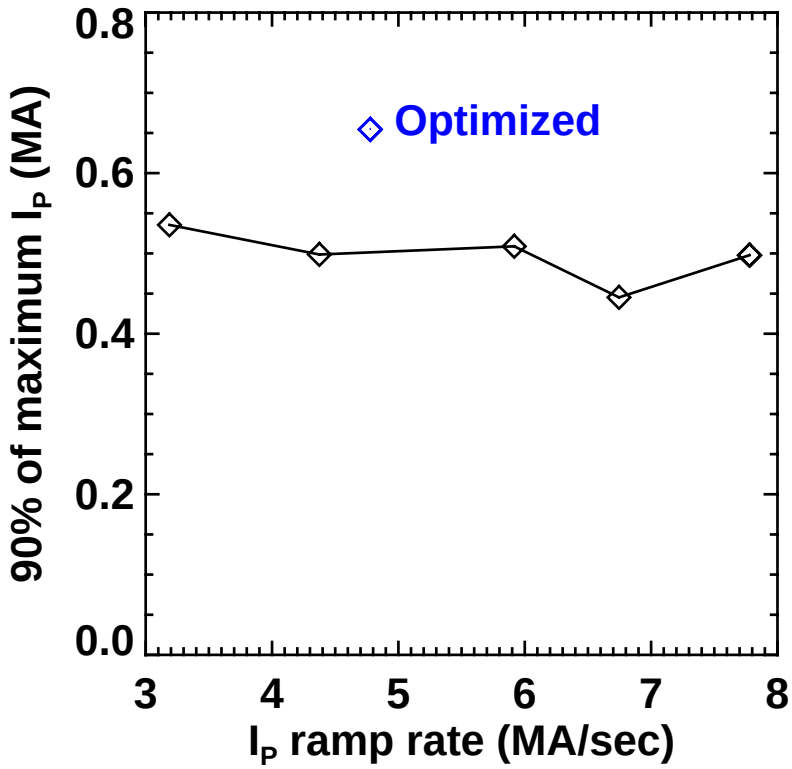
or…

$$\mathbf{C_E \equiv \Phi_R / \mu_0 R_0 I_P}$$

Typical power balance for optimized shots



Peak I_P from ramp-rate scan is nearly independent of I_P ramp-rate



- Low ramp-rate shots deplete OH flux
- Fast ramp-rate shots experience MHD events
- Optimized shots: ramp quickly during early phase to conserve flux, ramp slower at higher I_P to avoid MHD

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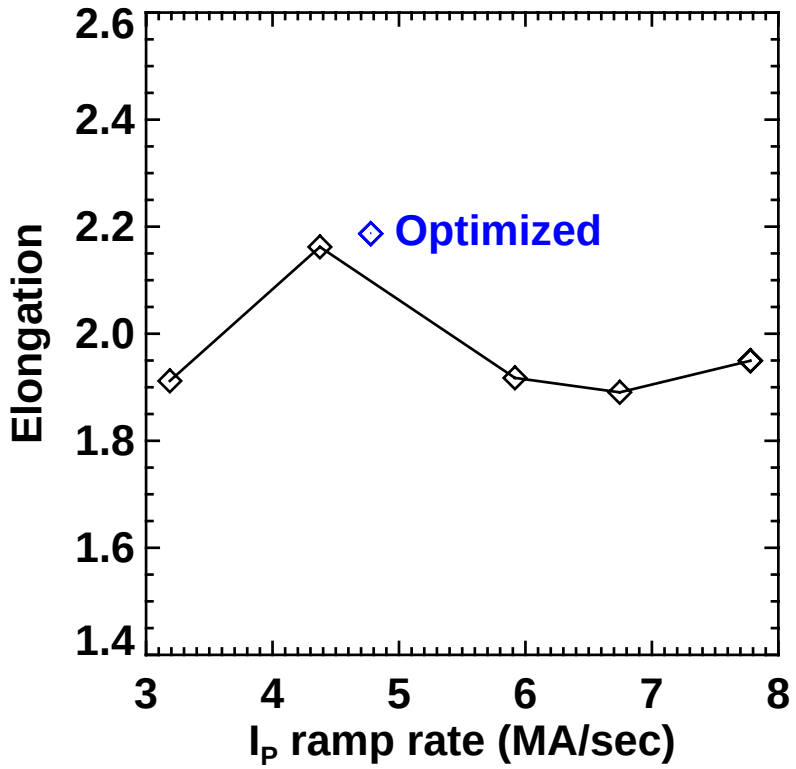
Elongation at peak I_P nearly independent of I_P ramp-rate



- PF programming adjusted during scan to keep κ nearly fixed
- Optimized case: Maintaining high κ critical to maximizing I_P
- High κ at peak current becomes increasingly difficult to control

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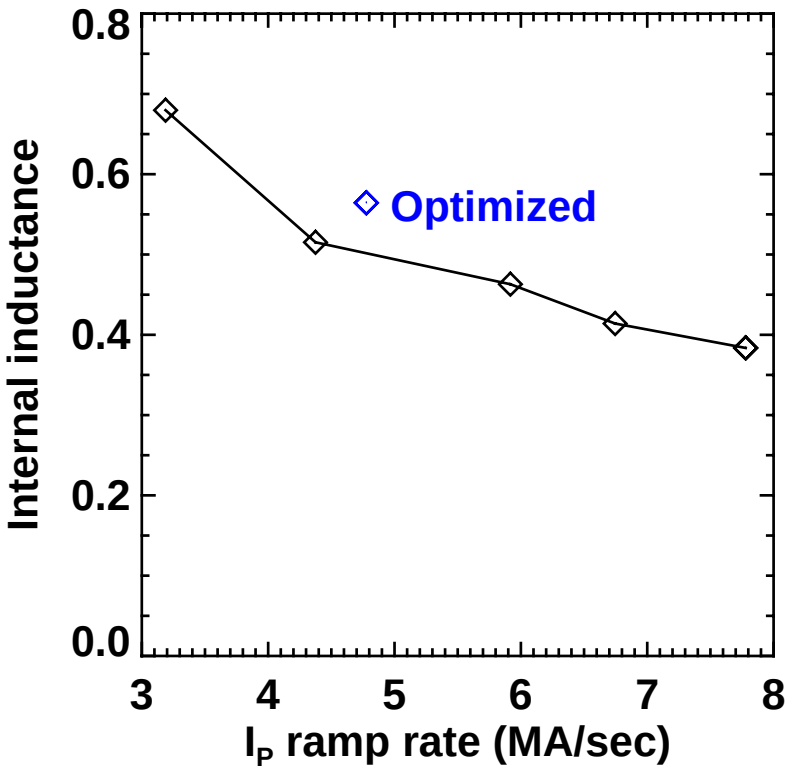
Higher ramp-rates have lower l_i at peak I_P (as expected)



- **Optimal l_i higher than observed during dI_P/dt scan - why?**
  - Optimized case has longer than normal pulse-length
  - Toroidal current profile has more time to relax.

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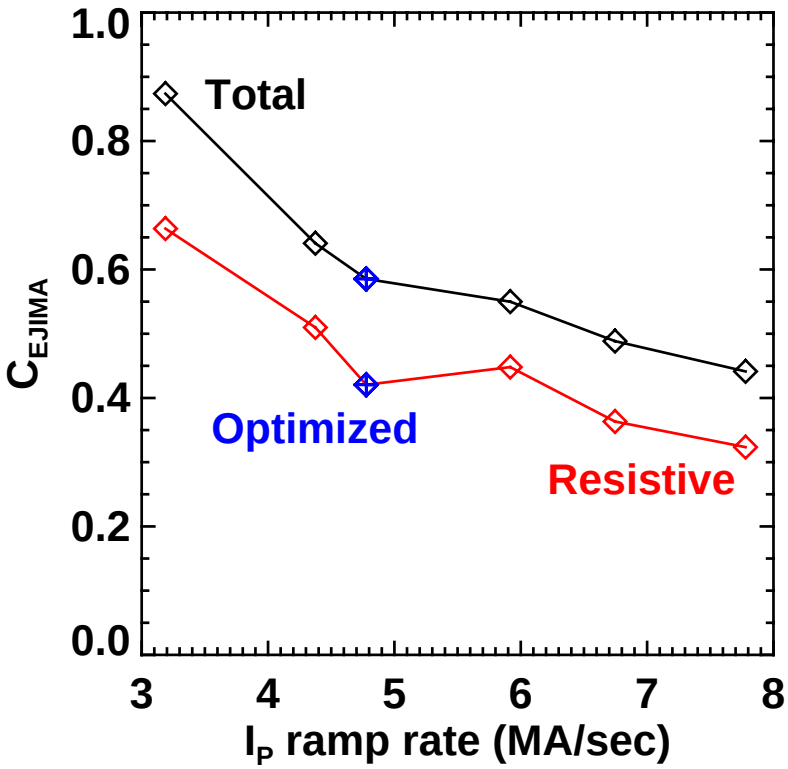
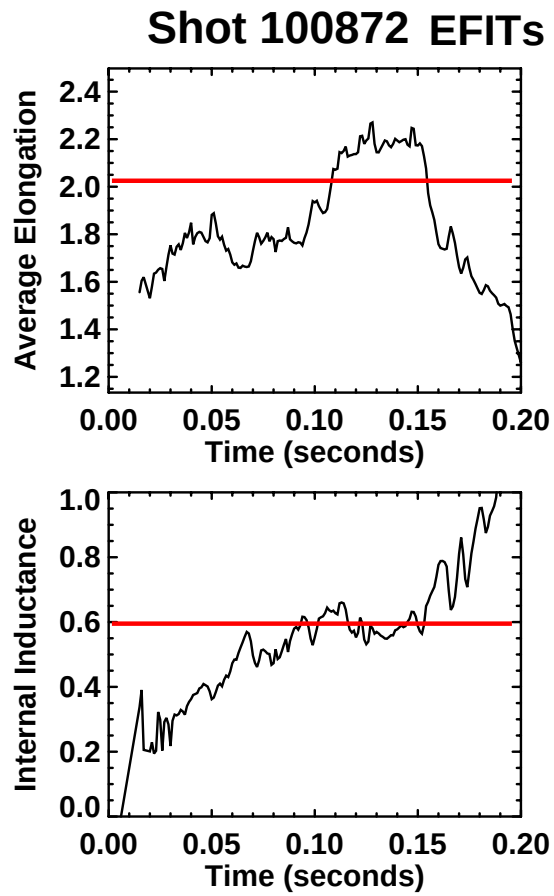
Highest I_P shots have resistive $C_E \approx 0.4$, $l_i \approx 0.6$, and are diverted with $\kappa_x > 2$





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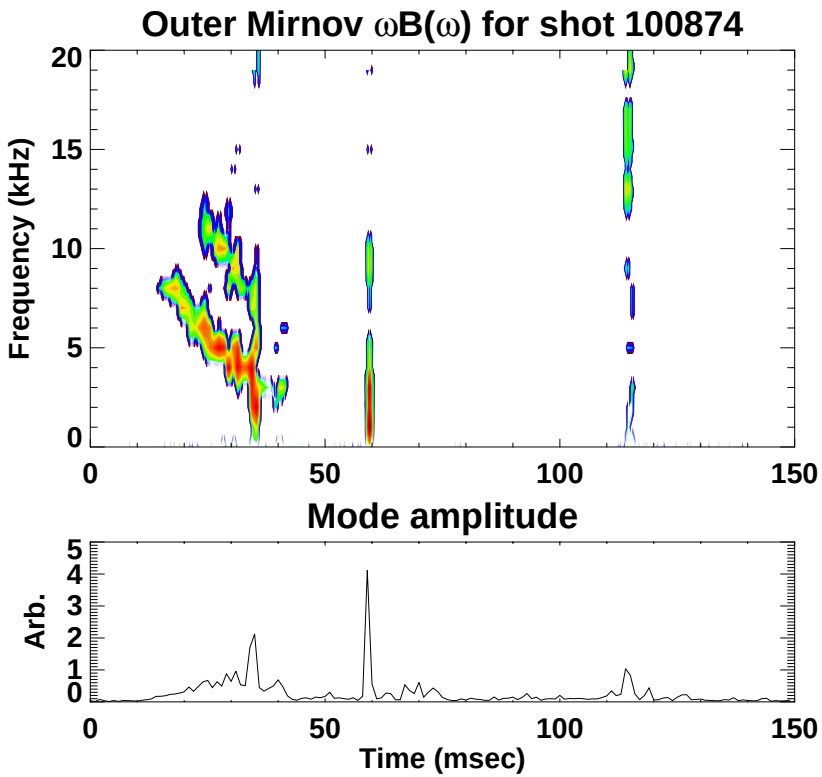
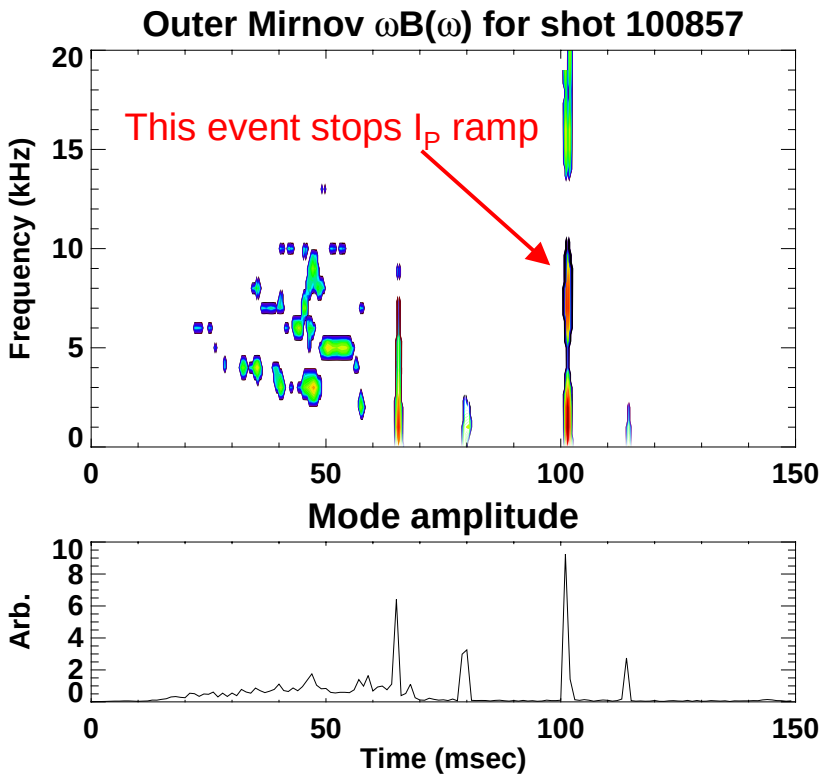
MHD events terminate faster I_P ramps

Optimized dI_P/dt = 4.5MA/sec

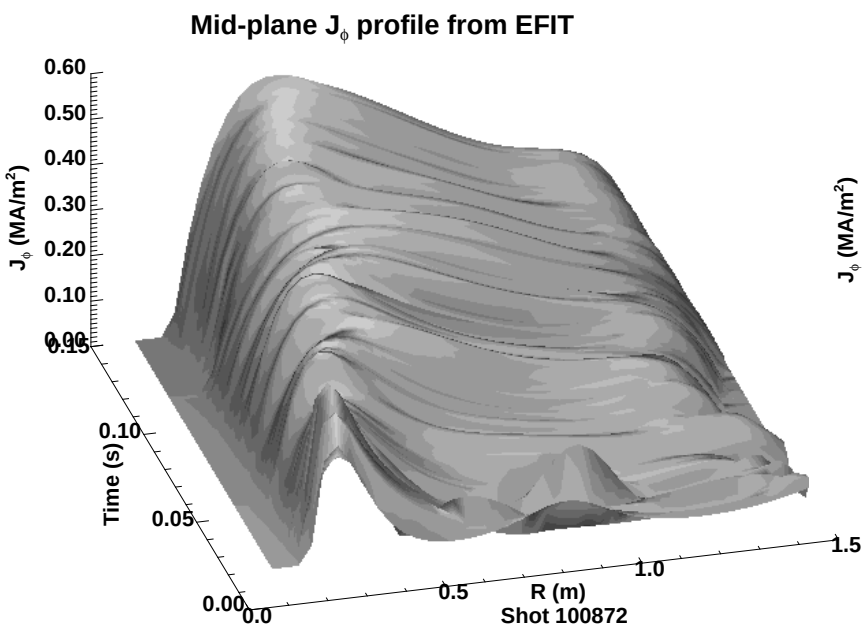
dI_P/dt = 8.0 MA/sec



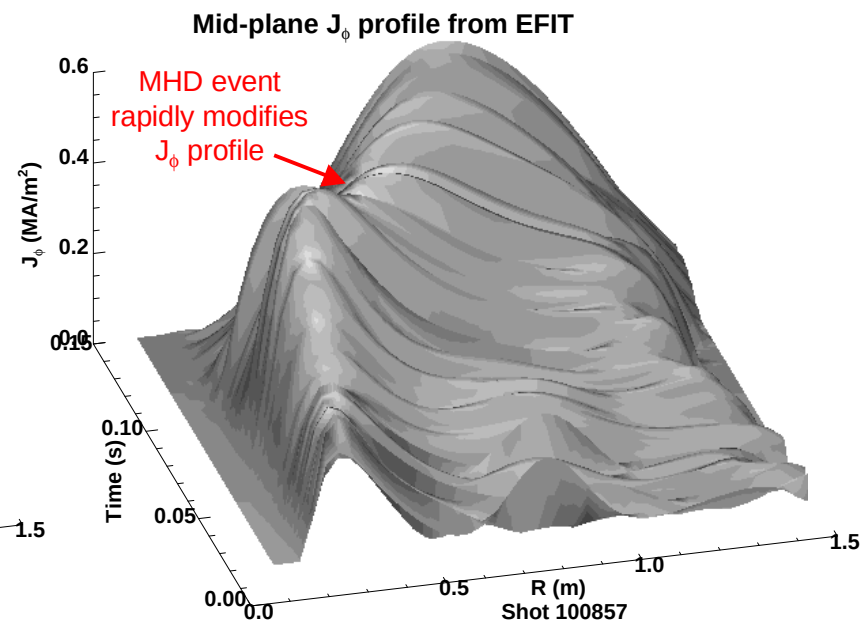


Optimized J_ϕ profile remains broad ⇒ higher natural elongation and higher stable I_P

Optimized dI_P/dt = 4.5MA/sec



dI_P/dt = 8.0MA/sec



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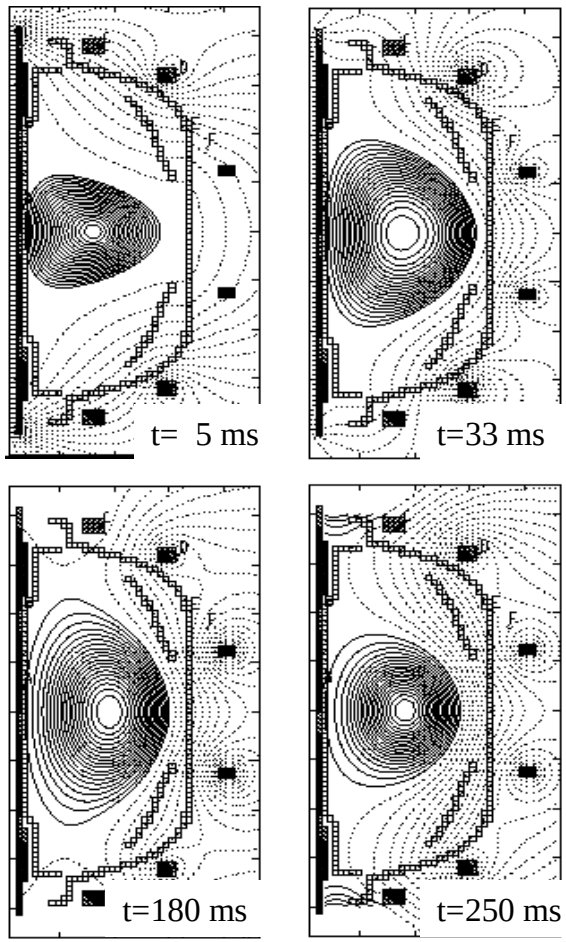
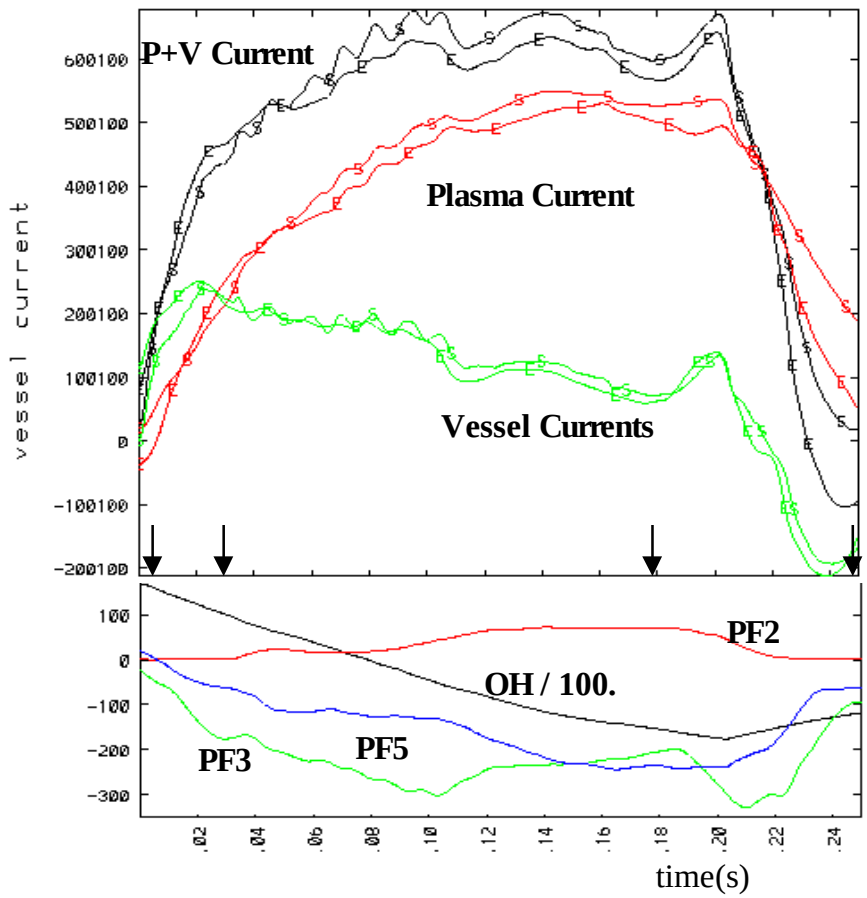
Tokamak Simulation Code (TSC) in good agreement with present experiments

(for shots without strong MHD activity)

NSTX shot 100920





(See poster by S.C. Jardin - JP1.105)

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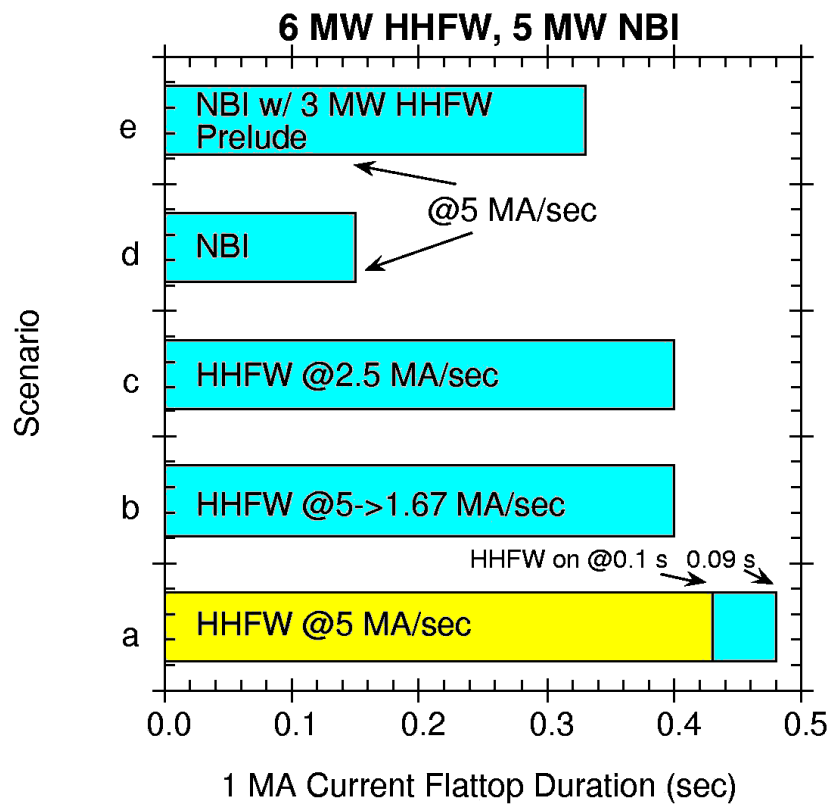
Flux consumption experiments highlight need for pre-heating and non-inductive current drive



TSC simulations show heating during I_P ramp can significantly lengthen I_P flat-top

(simulations by S. Kaye)

Summary

- Peak I_P from ramp-rate scan is nearly independent of dI_P/dt
  - Low ramp-rate shots deplete OH flux
  - Fast ramp-rate shots experience strong MHD events
  - Optimized shots ⇒ ramp quickly early, ramp slower later (relax J_ϕ profile)
- Optimized shots dissipate 50% of input energy by end of I_P ramp
  - Resistive Ejima parameter $C_E = 0.4$
  - Bake-out of passive plate graphite might reduce this significantly
- MHD activity immediately after initiation may dissipate OH power
- Present experiments extrapolate to short flat-top at 1MA
- Heating during ramp-up and HHFW and/or CHI non-inductive current drive are essential to achieving longer duration discharges

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