Phased Array Operation with HHFW

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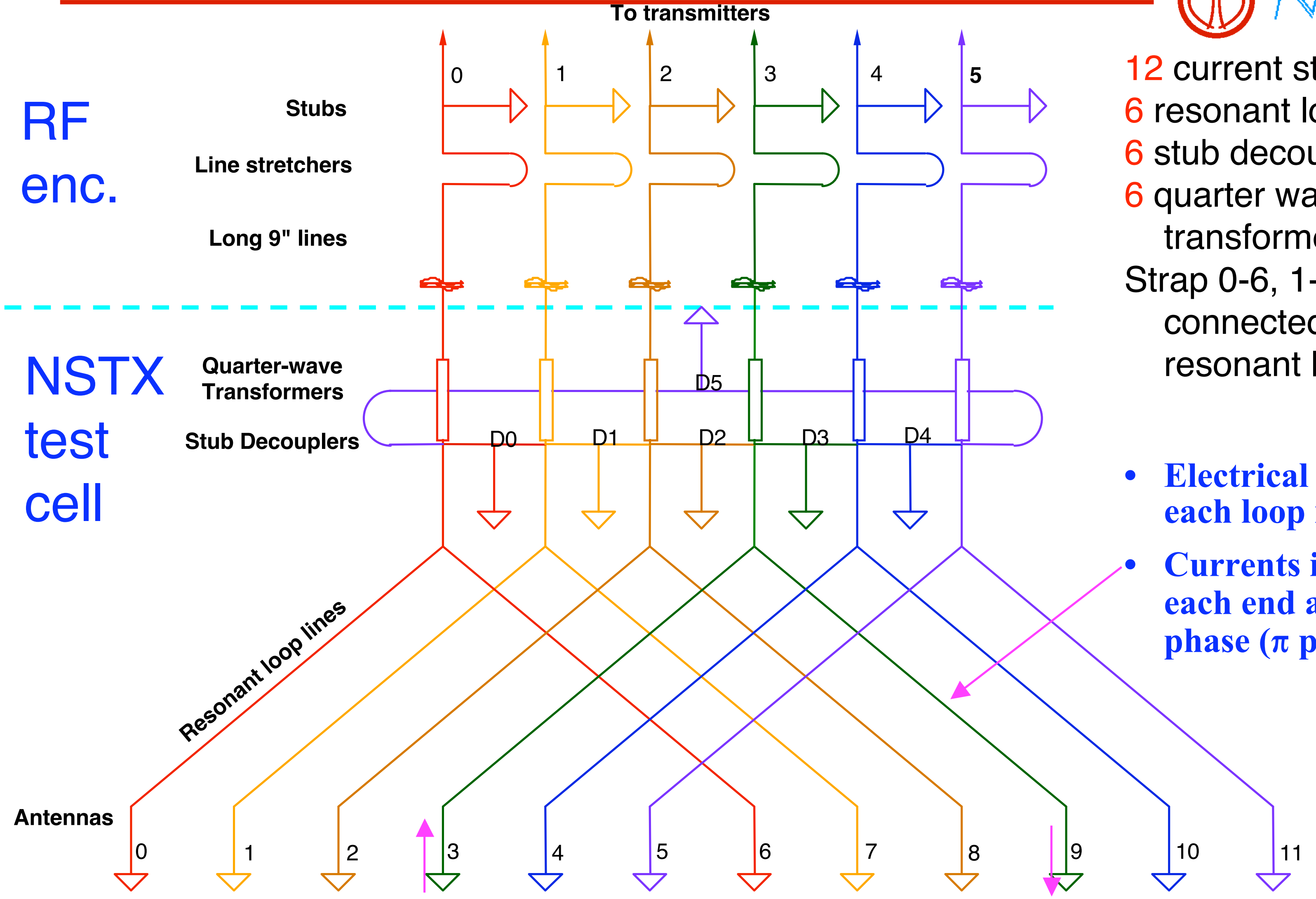
NSTX Results Review
PPPL
September 10, 2002

Phased Array Operation with HHFW

- **Improved phase control**
- **Heating vs. array phasing ($k_{||}$ = 8 m^{-1})**
- **Plasma loading vs. array phasing**
- **Wave spectra**
- **Evidence for current drive**

6 transmitters: Fixed frequency, 30 MHz, drive resonant loops



12 current straps
6 resonant loops
6 stub decouplers
6 quarter wave transformers
Strap 0-6, 1-7,... connected in resonant loops

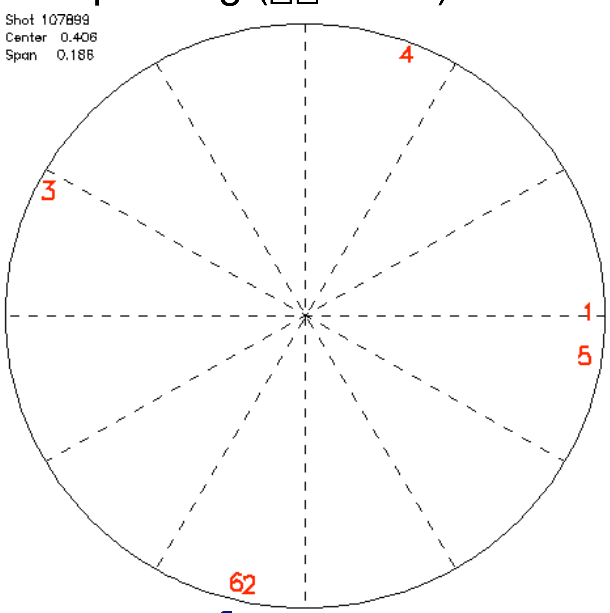
- **Electrical length of each loop is 2 λ**
- **Currents in straps at each end are out of phase (π phasing)**

Improved phase control system- dynamic phase change now possible

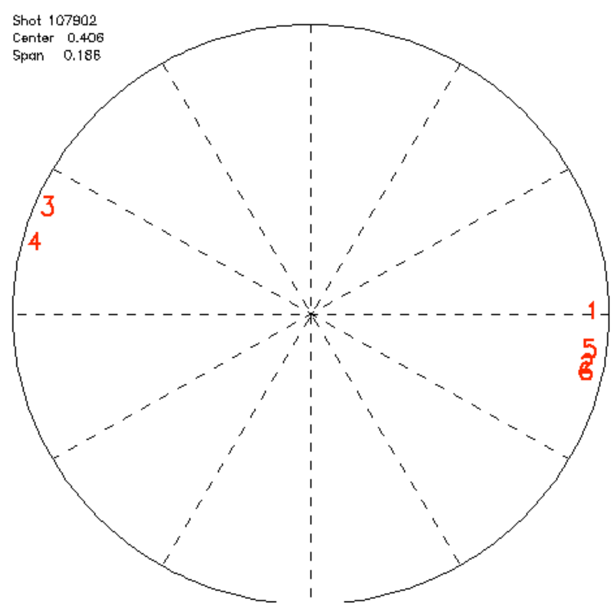
- **Inter-source phase control**
  - Set electronically via a computerized waveform generator
  - Feedback control of source phases to fix the phases of antenna currents
- **Can set for any inter-source phasing, and can vary with time during a shot**
  - Pre-programmed phase(t)
  - Operated with constant □□, and changed □□ by 45° during a shot (e.g, 90° to 45°)

We have operated with some “Standard” phase settings….

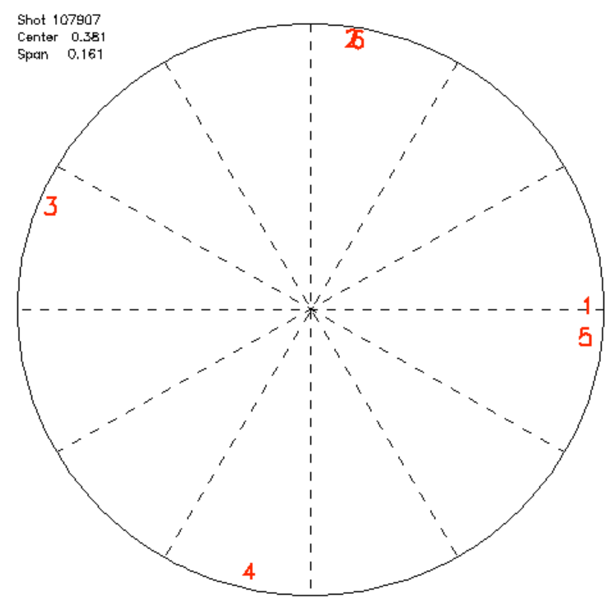
CD phasing (□□ ≈ -π/2)



Fast symmetric phasing (00ππ00)



counter-CD phasing (□□ ≈ π/2)



ANTENNA ARRAY PHASING EXPERIMENTS
Heating, loading, current drive, etc.

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We have done a series of experiments with different phasings to study the effects of phasing changes and to look for current drive.

- Heating efficiency *fairly* insensitive to phasing, as measured by stored energy
  - *Possible* improvement in stored energy with counter-CD (□□ = $+\pi/2$) rel. to co-CD (□□ = $-\pi/2$)
  - Limited data at other phasings (±60°, ±45°, ±30°)
  - Counter-CD phasing gives higher central electron temperatures.
- Substantial difference in loading of the antennas for co- vs. counter current drive phasing
  - Agrees with theory when large pitch angle of the magnetic field is taken into account
- Current drive experiments encouraging but not conclusive, because we have no diagnostic yet for measuring central current density.

Heating: confinement follows usual scaling

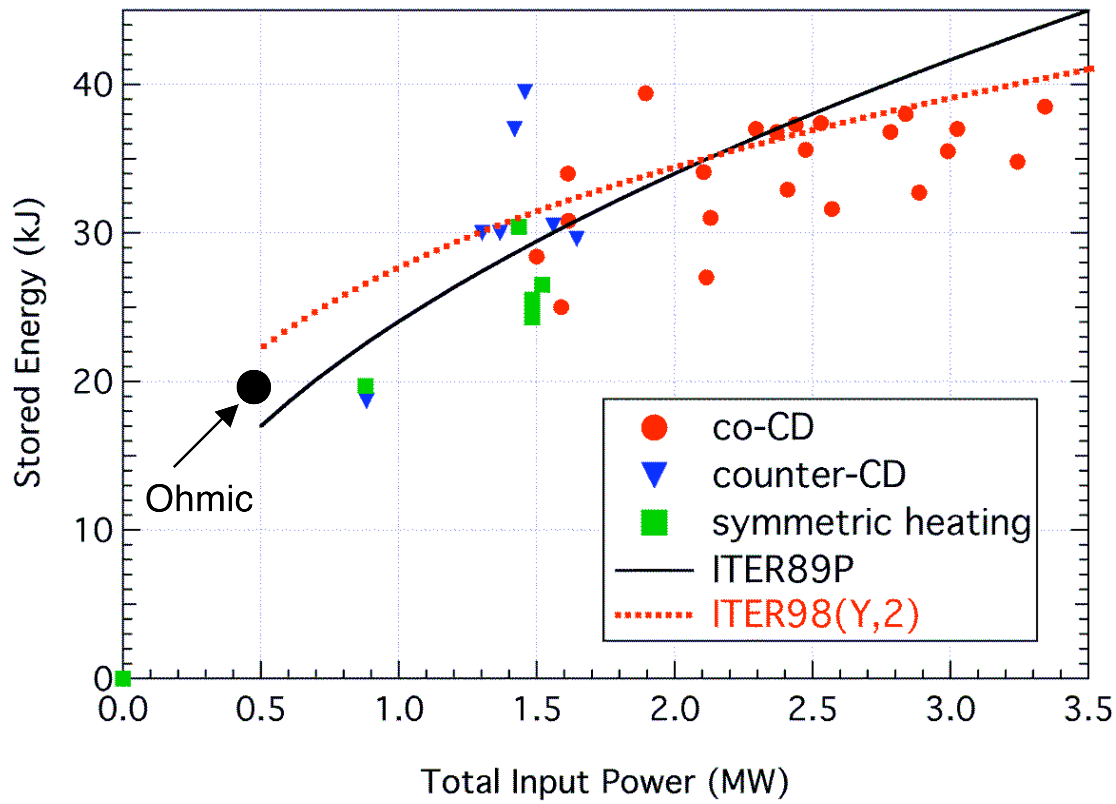
- **Heating efficiency (as measured by total stored energy in plasma from EFIT) is *fairly insensitive* to phasing (slightly better for counter-CD?)**

- **Confinement comparable to calculated values using**
  - ITER89P scaling (black curve)
  - ITER98(y,2) scaling (red curve)

Scaling calc. parameters:

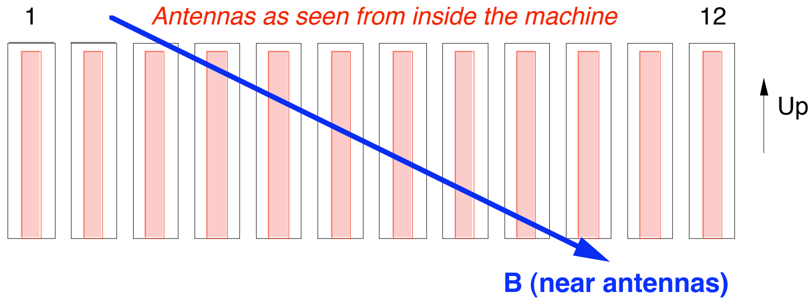
- Ip = 500 kA
- B0 = 0.45 T
- $<n_{20}>$ = 0.1
- M = 2
- R_0 = 0.85 m
- a = 0.65 m
- [] = 1.7
- H = 1

Stored energy vs. input power for co, counter, and symmetric phasing at 8 m^{-1}



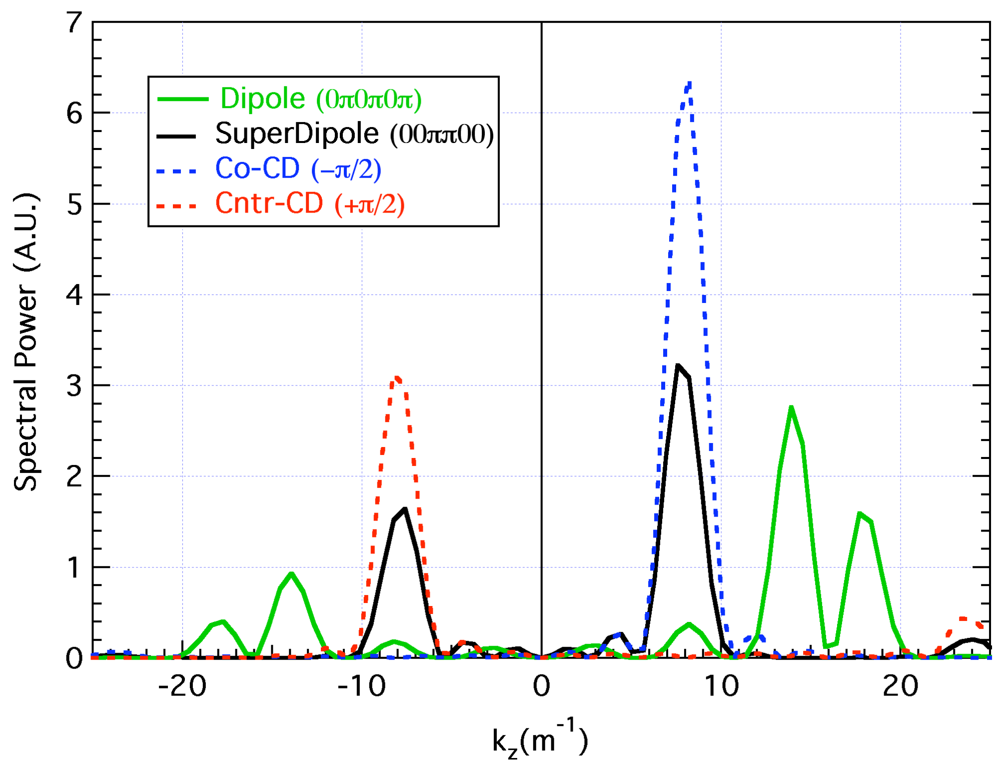
Asymmetric plasma response to the wave direction results from large pitch angle of magnetic field

Pitch angle of the magnetic field at the antennas can be as large as 45º



- **Asymmetries between co-CD and counter-CD directions are more pronounced at higher wavenumbers.**
- **Asymmetric plasma response means even symmetric phasings can give rise to directional wave spectra.**
- **CD and "super-dipole" phasings give wave velocities resonant with 1.2 keV electrons.**
- **Dipole phasing gives rise to waves resonant with 250 and 400 eV electrons**

k_z power spectrum from GLOSI/RANT3D calculations



We understand the loading asymmetry between co-CD and counter-CD phasing and can calculate the full 12x12 strap impedance matrix

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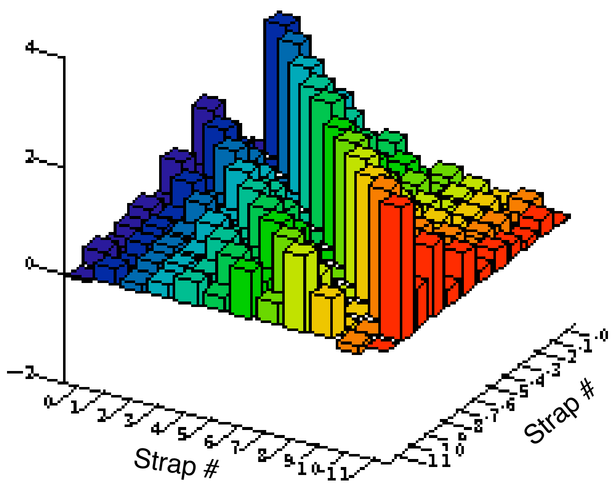
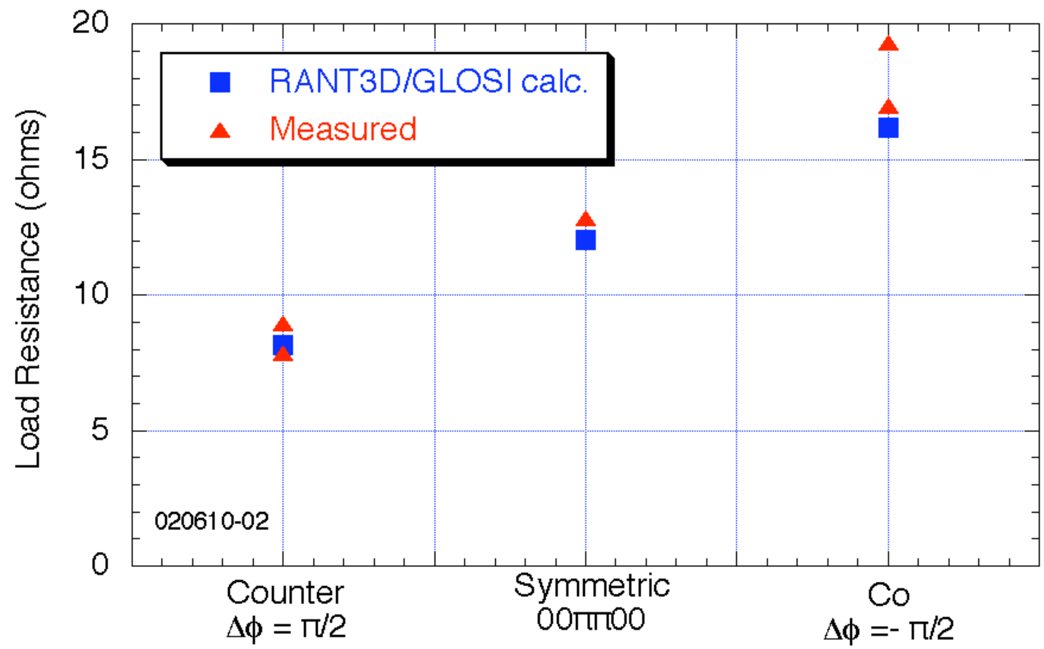
- **Loading of antennas with □□ = -π/2 phasing is ≈ twice the loading with +π/2**
- **Asymmetry caused by pitch angle of magnetic field in front of antenna.**
  - RANT3D/GLOSI used to calculate 12x12 impedance matrix of antennas
  - 12-strap, 6-loop circuit model used to calculate load resistance R_{load}
  - Calculations in good agreement with measured loading

12x12 impedance matrix from RANT3D (Im part, diag. term suppressed) shows asymmetry

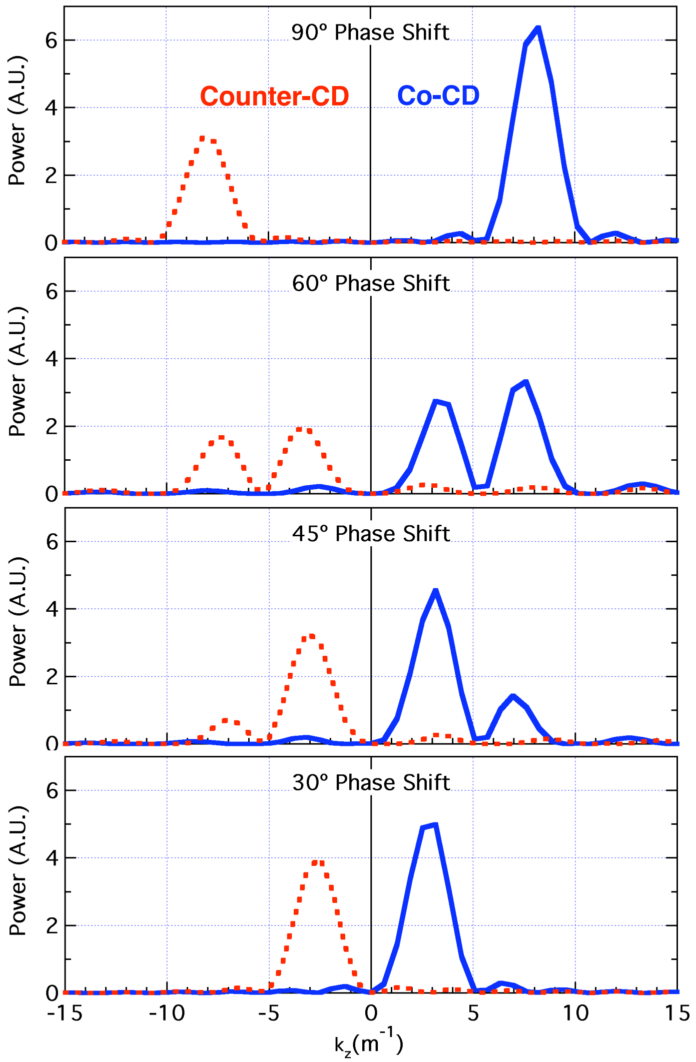


Measured load resistance R_{load}* for co-, counter-, and 00ππ00 phasing agrees with calculations



Due to the fixed 180º phase between straps 1-7, 2-8, … the wave spectra are not continuously variable

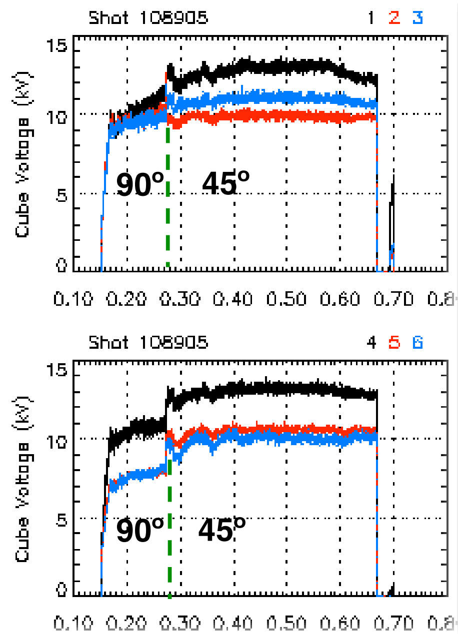
Calculated Spectra From RANT3D



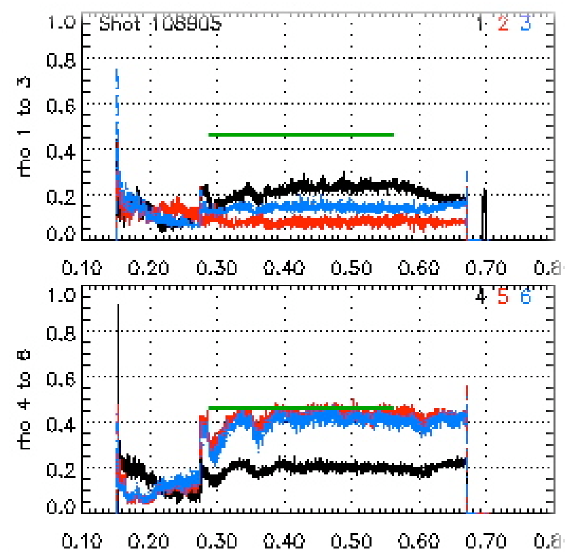
- 30º and 90º relative phasing give single-peaked spectra at m = 5, 13 ($k_{||}$ = 3, 8 m^{-1}).
- 45º and 60º give double-peaked spectra at the same wave numbers.

Phase has been changed from 90° to 45° during shot at 1.9 MW

Voltage jumps up as loading drops



Reflection coefficient increases as match changes



HHFW CD: measurements and analysis

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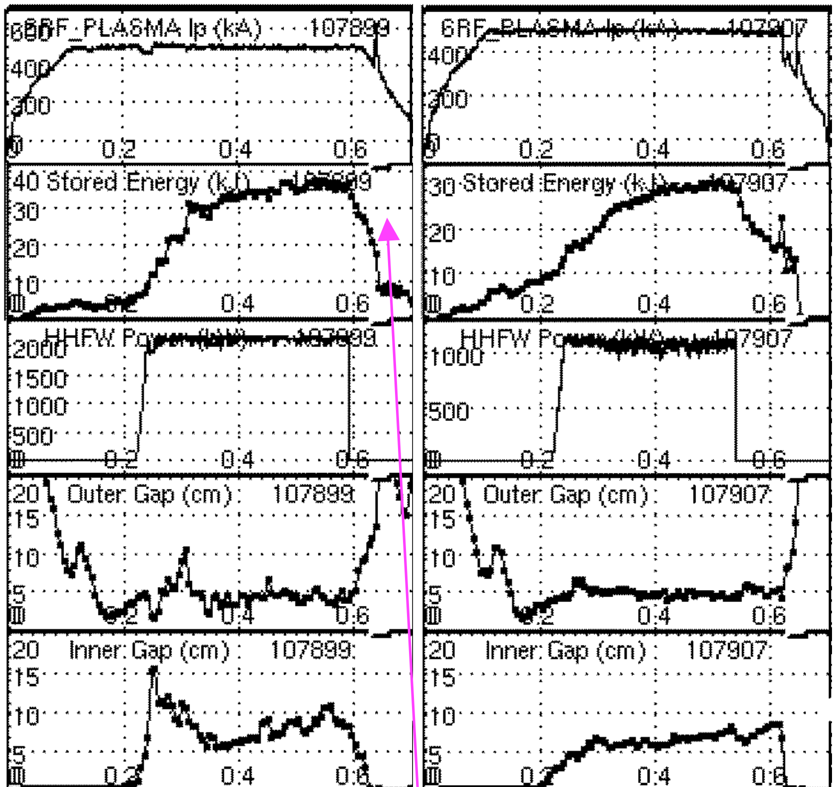
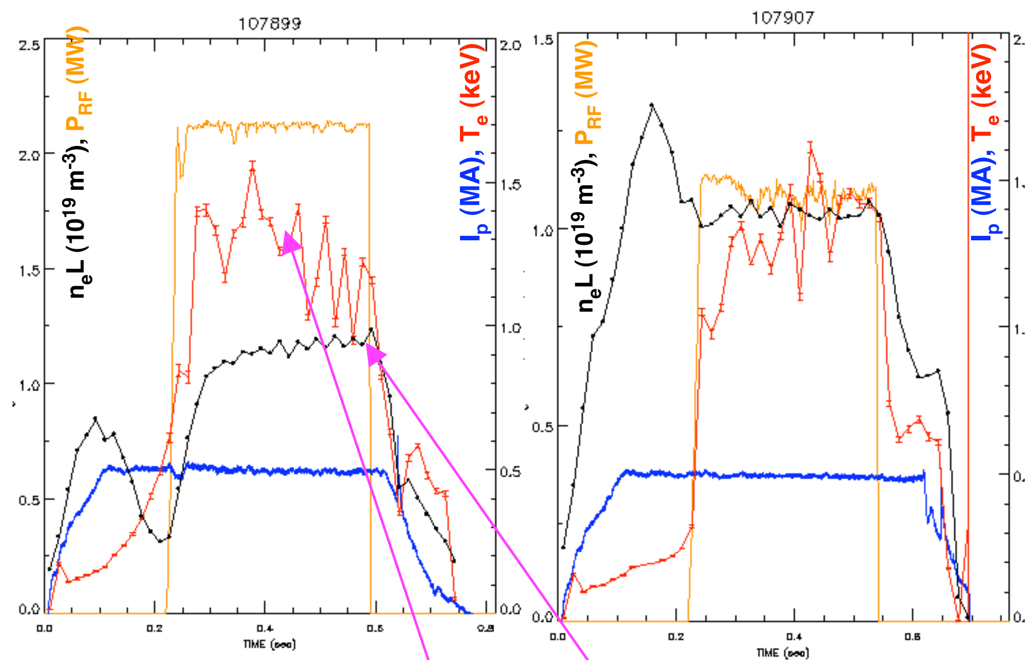
107899: Co-CD, P_{HHFW} = 2.1MW
108907: Counter-CD, P_{HHFW} = 1.2 MW

Co-CD | **Counter-CD** | **Co-CD** | **Counter-CD**





Similar plasma stored energy

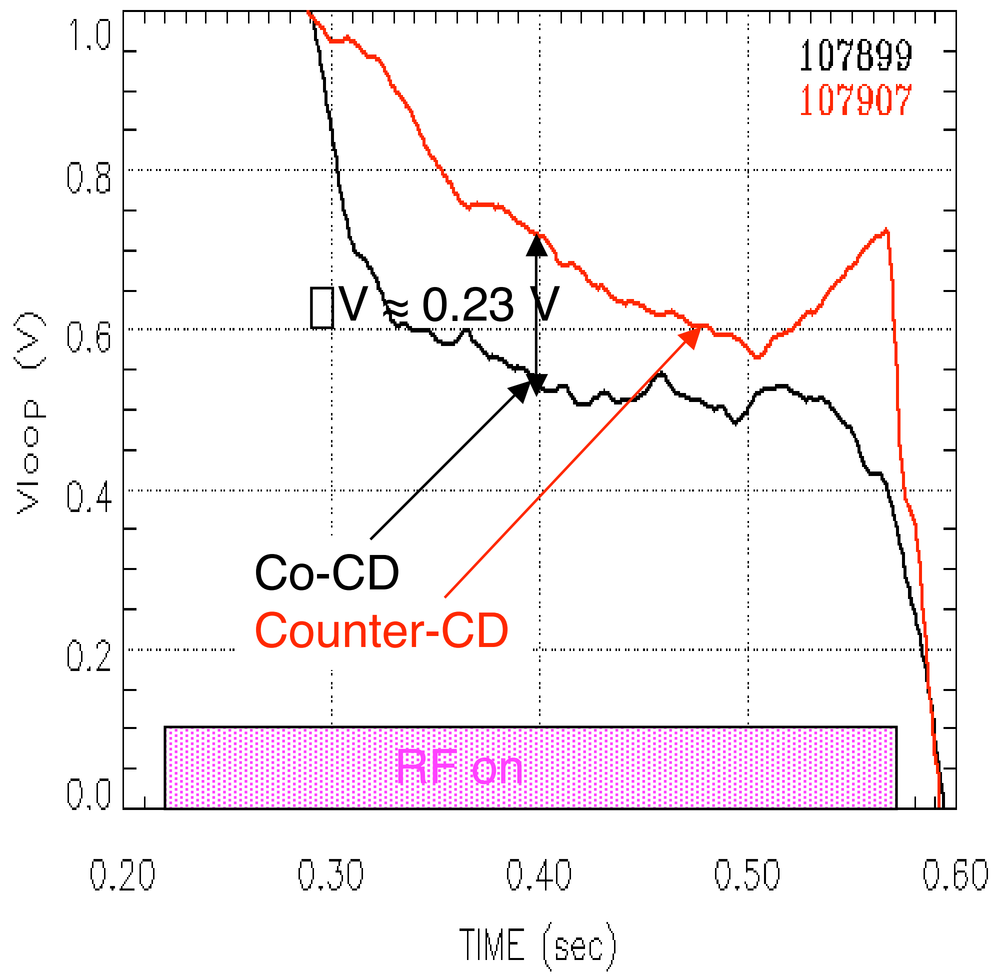
Similar Te and density

Current drive: significant difference in loop voltage seen between co- and counter-CD

No direct current-profile diagnostics yet.

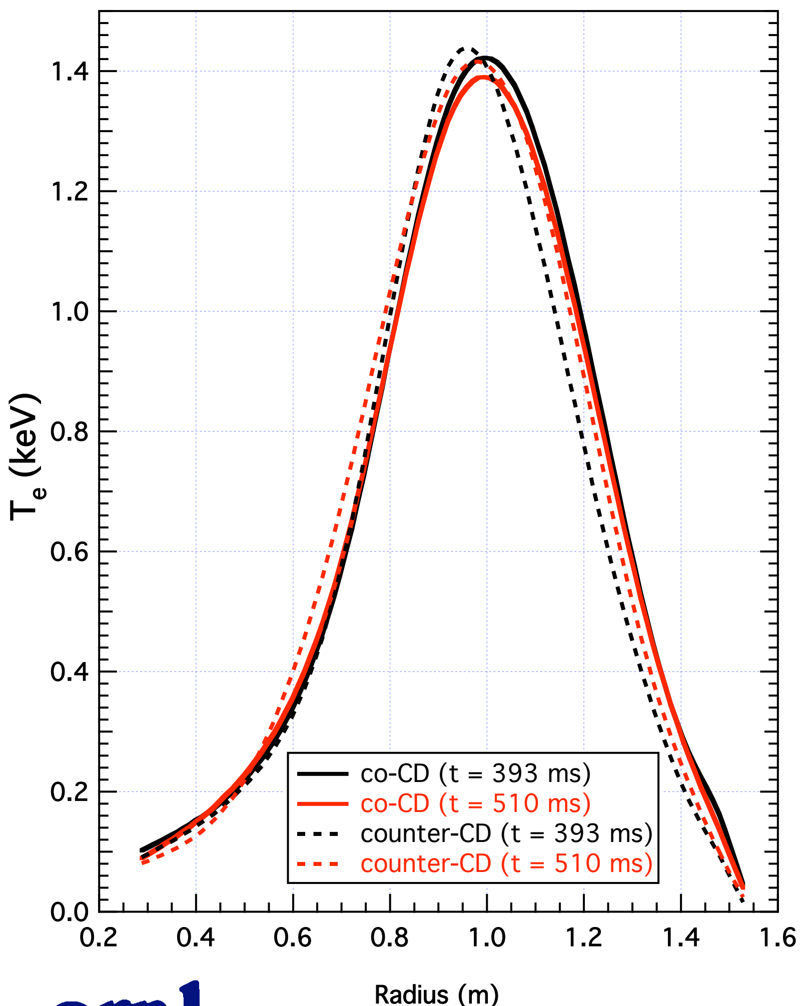
Because of lack of Motional Stark Effect diagnostic, we must look for differences in loop voltage.

- I_p is held constant on NSTX through feedback.
- It takes less loop voltage to maintain I_p for identical plasma conditions when driving current in the co-CD direction.
- Modeling predicts ~200 ms for the effect to show up on loop voltage.

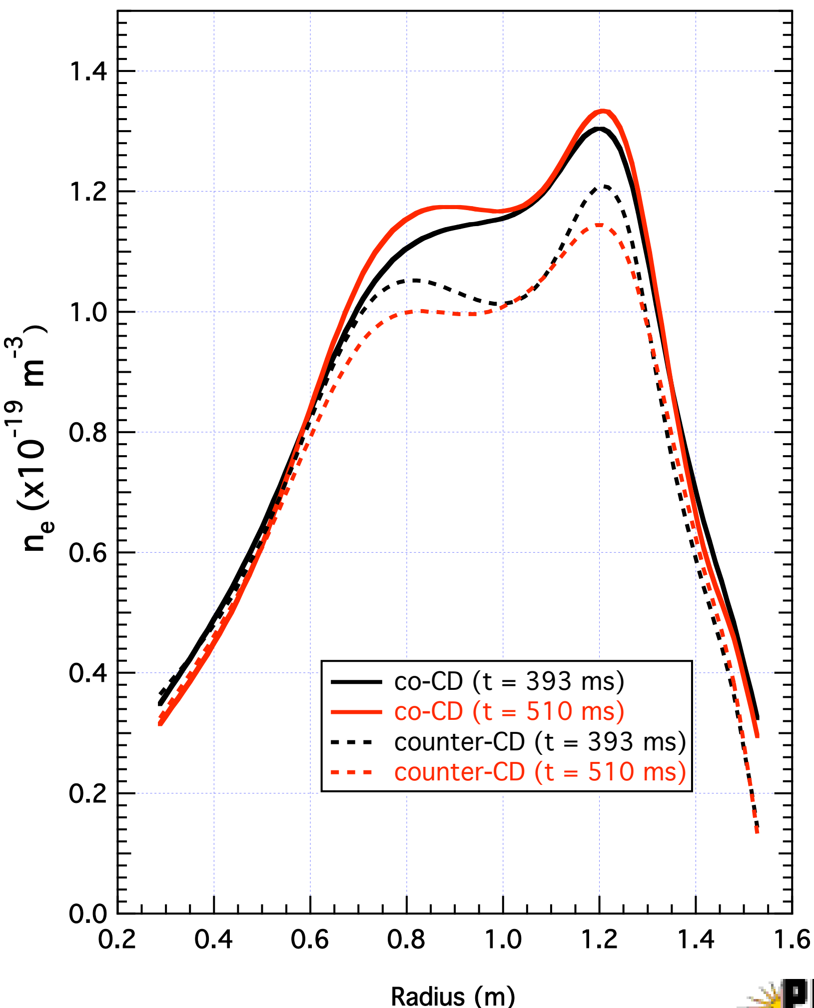


Temperature and density profiles for co- and counter-CD shots are very similar

Electron Temperature for co-, counter-CD Phasing
(107899, 107907)



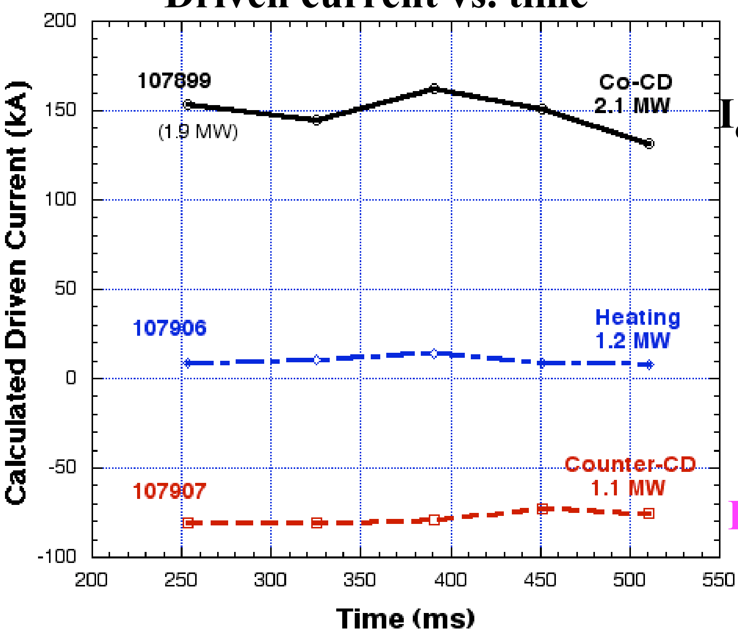
Plasma Density for co-, counter-CD Phasing
(107899, 107907)



CURRAY calculations of driven current (T. K. Mau)

- Used $k_{tor} = \pm 8\ m^{-1}$ for co-CD, $-8\ m^{-1}$ for ctr-CD, both w. $P(-8\ m^{-1})/P(+8\ m^{-1}) = 1.25$ for symmetric phasing
- Temp and dens profiles from Thomson scattering data (assumed $T_e \approx T_i$)
- $Z_{eff} \approx 3.25$
- Geometry from EFIT
- Self-adjoint calculation of I_{CD}

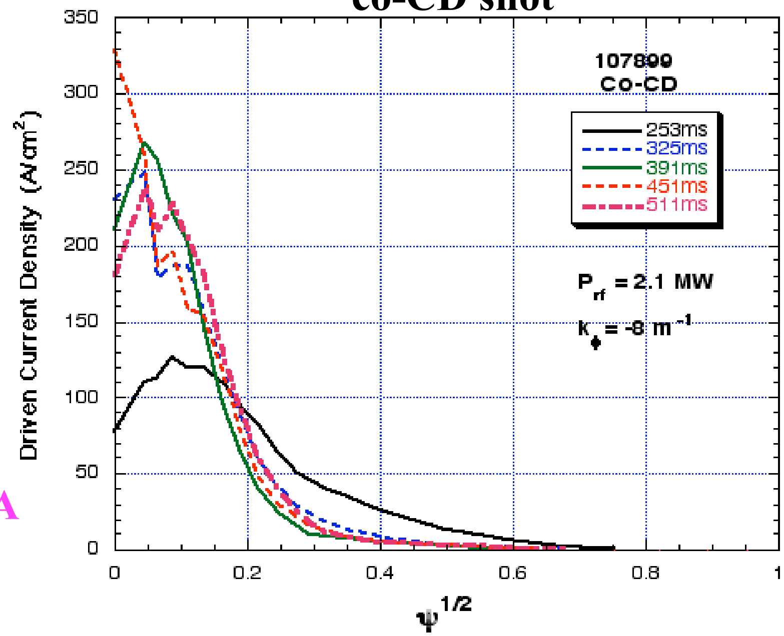
Driven current vs. time



$I_{co\text{-}CD} \approx 150$ kA

$I_{ctr\text{-}CD} \approx -80$ kA

Driven current density profiles for co-CD shot



$\Delta I_{CD} = I_{co\text{-}CD} - I_{ctr\text{-}CD} \approx 230$ kA from CURRAY

Zero-D calculation of driven current (D. Swain)

Parameters:

$I_P = 500$ kA

$P_{co} = 2.1$ MW $P_{ctr} = 1.1$ MW

$V_{co} = 0.5$ V $V_{ctr} = 0.7$ V

so $V_{co}/V_{ctr} = r_V \approx 0.7$

$I_P = I_{OH} + I_{BS} + I_{CD}$ where $I_{BS} \approx 40$ kA (bootstrap current)

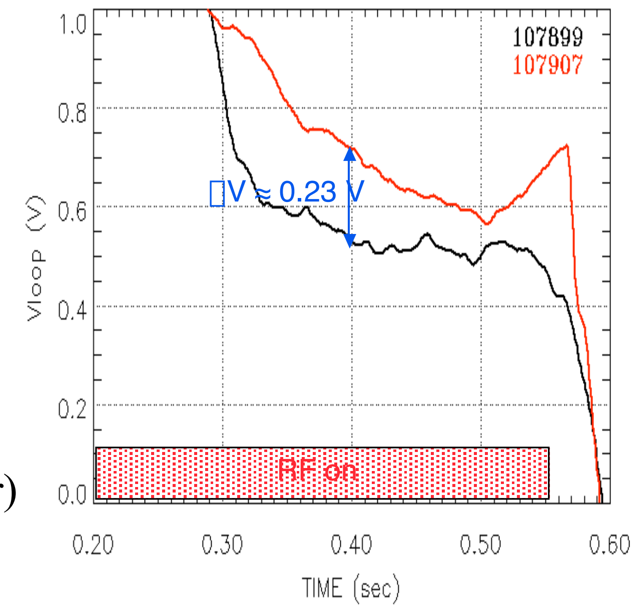
Assume

Steady-state has been achieved

$I_{OH}R_p$=V, and that

R_p is the same for both shots

– $I_{co\text{-}CD}/I_{ctr\text{-}CD} = P_{co}/P_{ctr} = r_{pwr} \approx 0.5$ (assumes I_{CD} ~ CD power)



Then

$I_{co} = (I_P - I_{BS})(1 - r_V)/(1 + r_V\, r_{pwr}) \approx 100$ kA

$I_{ctr} \approx 0.5\, I_{co} = 50$ kA

- **$\Delta I_{CD} \approx 150$ kA from 0D calculation**

$I_{CD}/P_{RF} \approx 48$ kA/MW at $n_eL = 1.7\times10^{15}$ cm^{-2}

Current drive calculation using TRANSP (S. Kaye)

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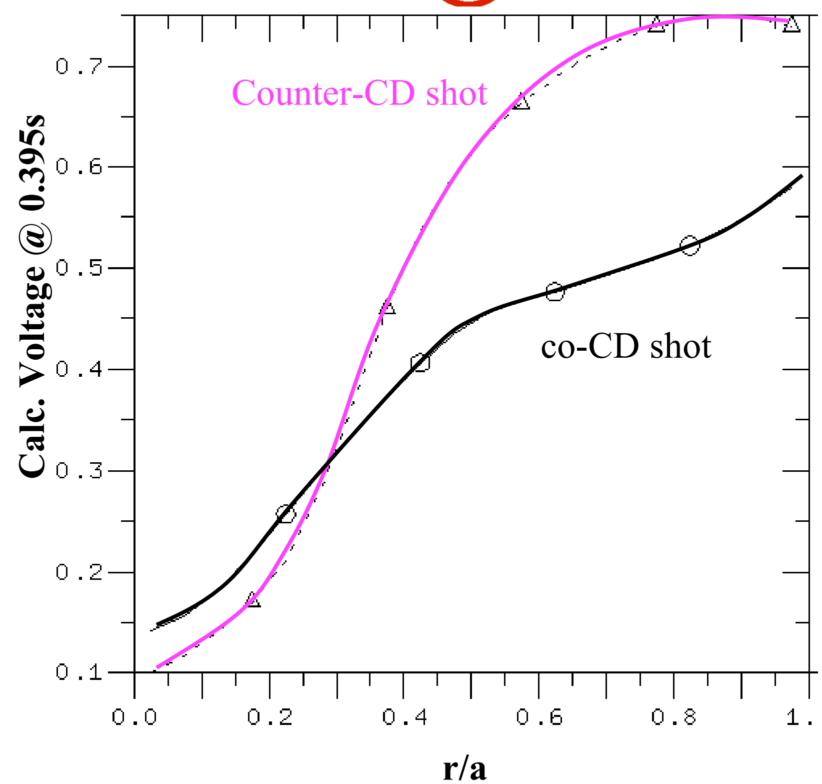
- **Use TRANSP to compute current profile evolution**
  - Use measured $V_{loop}(t)$, $T_e(r,t)$, $n_e(r,t)$, $I_p(t)$ as input
  - Compute $V(r,t)$ for co- and counter-CD shots
  - Compute $\square E(r,t) = E_{co}(r,t) - E_{ctr}(r,t)$
  - Assume neoclassical resistivity
  - Compute $\square j(r,t) = \square_{NC}(r,t)\, \square E(r,t)$
  - Integrate to get $\square I_{CD}$
- **$\square I_{CD} \approx$ 90 kA from TRANSP**

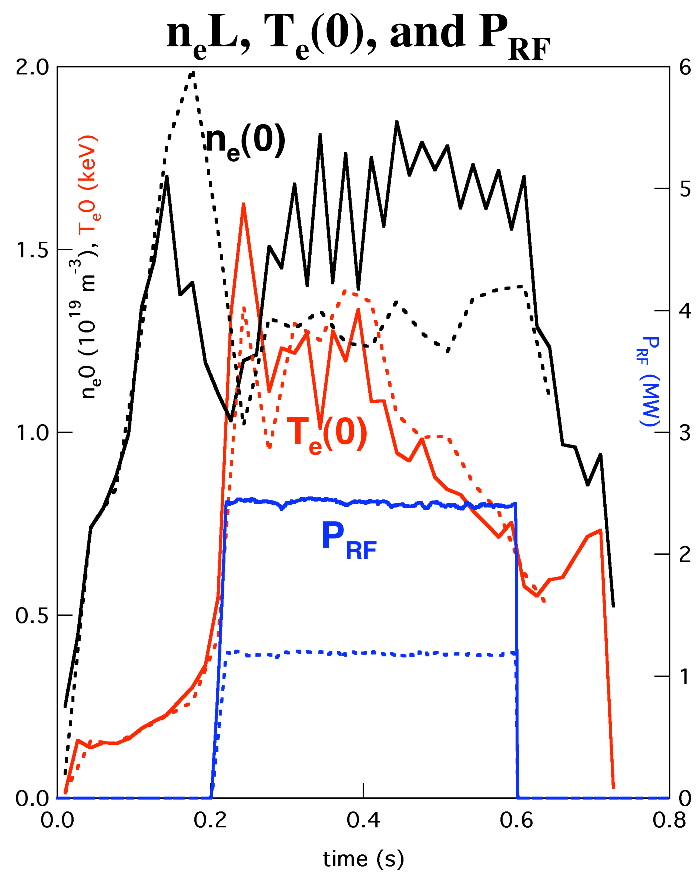


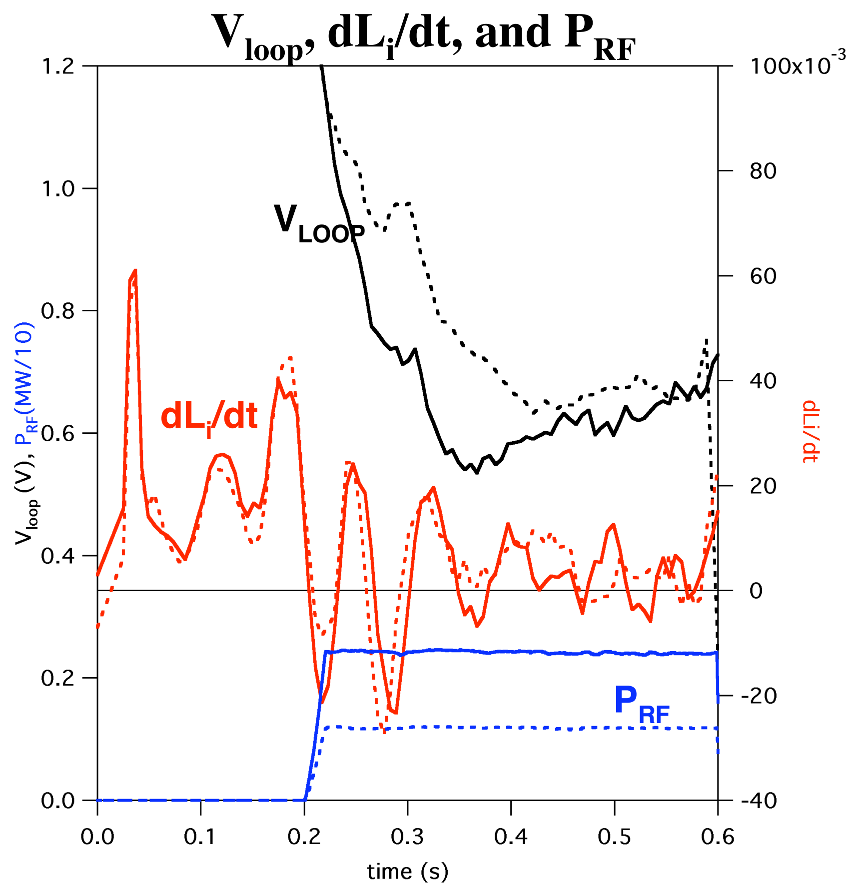
- **Summary: $\square I_{CD} \approx$**
  - 230 kA from CURRAY
  - 150 kA from zero-D
  - 90 kA from TRANSP
- **Conclusions:**
  - Current drive observed.
  - Difficult to interpret because steady-state not obtained
  - Magnitude of driven current uncertain, more work is needed.

Difference in loop voltage (30%) observed at ±π/2 phasing for comparable plasma conditions (D_2, 500 kA, 0.5 T)

Shot 108751: counter-CD (+π/2) - dotted
Shot 108748: co-CD (- π/2) - solid

I_{CD}/P_{RF} ~ 35 kA/MW for $n_eL \approx 1.6\times10^{15}$ cm^{-2} (0D estimate)





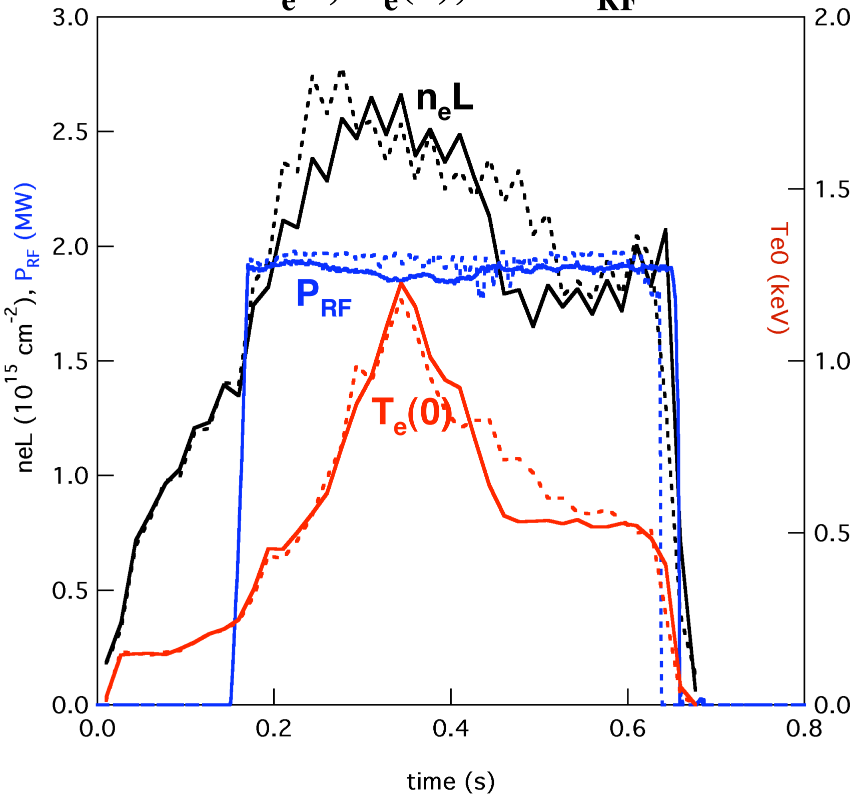
Higher phase velocity (±□/4 phasing) gives similar estimated current drive efficiency but at higher plasma density

Shot 108901: counter-CD (+ □/4) - dotted
Shot 108903: co-CD (- □/4) - solid

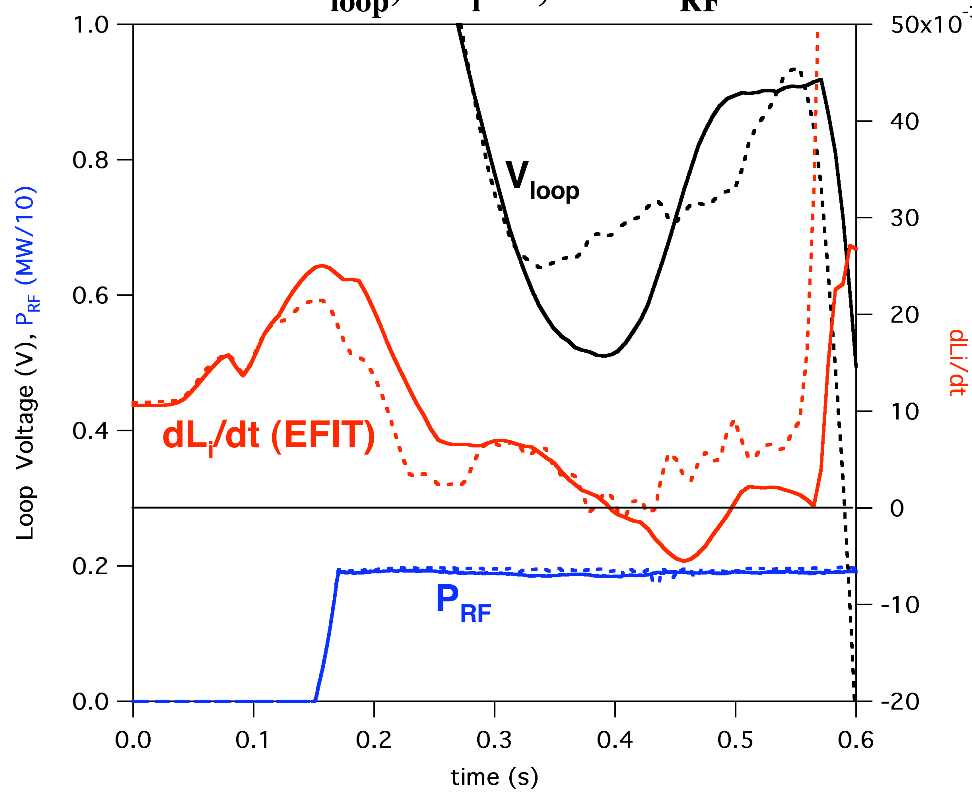
I_{CD}/P_{RF} ~ 35 kA/MW at $n_eL \approx 2.5\times10^{15}$ cm^{-2} (0D estimate)

D_2, 500 kA, 0.5 T

n_eL, $T_e(0)$, and P_{RF}



V_{loop}, dL_i/dt, and P_{RF}



Work to do

- **TRANSP and CURRAY analysis of:**

  $\pm\pi/2$ phasing (108748 and 108751)

  $\pm\pi/4$ phasing (108901 and 108903)

- **More detailed 0-D analysis of these shots.**

- **Analyze density fluctuations in the edge as a function of antenna phasing.**