HIGH HARMONIC FAST WAVE OPERATION ON NSTX*

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ABSTRACT

A high harmonic fast wave (HHFW) antenna array, designed to provide up to 6 MW of power at 30 MHz for heating and current drive applications, has been operated on the NSTX experiment at Princeton Plasma Physics Laboratory. Initial rf operation used eight straps to form four resonant loops, which were driven by two transmitters. Two adjacent loops were connected with a half-wavelength coax section and hence were driven out of phase by a single transmitter. The decoupler network was not used at this time. Up to 2 MW of power was delivered during this stage of operation; inter-loop phasings of $0-\pi-\pi-0$ and $0-\pi-0-\pi$ were investigated. Models of the power distribution system indicate the nominal plasma loading was about 5 Ω/m, close to the design value of 6 Ω/m. The HHFW system has since been re-configured for full 12-strap, 6-transmitter operation and will use the decoupler network to isolate adjacent loops. The goal is to increase the power delivered to the plasma to the 6 MW level.

INTRODUCTION

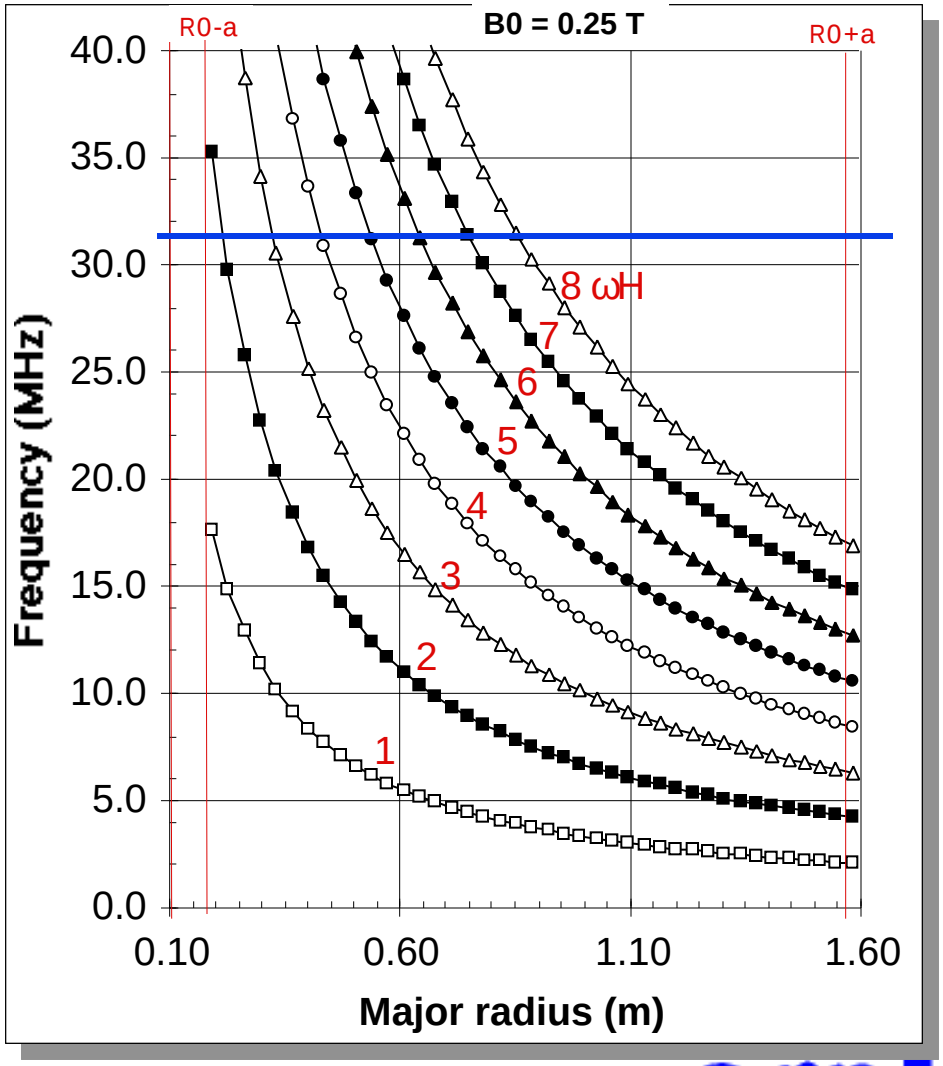
The NSTX spherical tokamak at PPPL has a high harmonic fast wave (HHFW) designed to provide up to 6 MW at 30 MHz for plasma heating and current drive. Initial operation was with two transmitters using 8 current straps. The system is now configured for 12-strap, 6-transmitter operation and plasma experiments began in September.

- RF system description and design
- Results from initial 8-strap HHFW experiments without decouplers
- Commissioning/operation of the 12-strap, 6 transmitter system with decouplers
- Results from recent 12-strap HHFW experiments

NSTX provides unique challenges to ion cyclotron heating and current drive

- Low field, leads to HHFW (high harmonic fast wave) heating and current drive.
- Magnetic field at antenna changes from nearly toroidal at startup to ~45° angle at 1 MA plasma current
- Up to 40% β causes large change in equilibrium and plasma gradients
- Physics questions that had to be examined:
  - Should antenna straps be tilted?
  - Are BN insulators needed?
  - Can the achievable spectrum work for a variety of plasmas?
  - How cold a plasma can be heated?

NSTX vacuum toroidal field



HHFW System Design: Objectives and Constraints

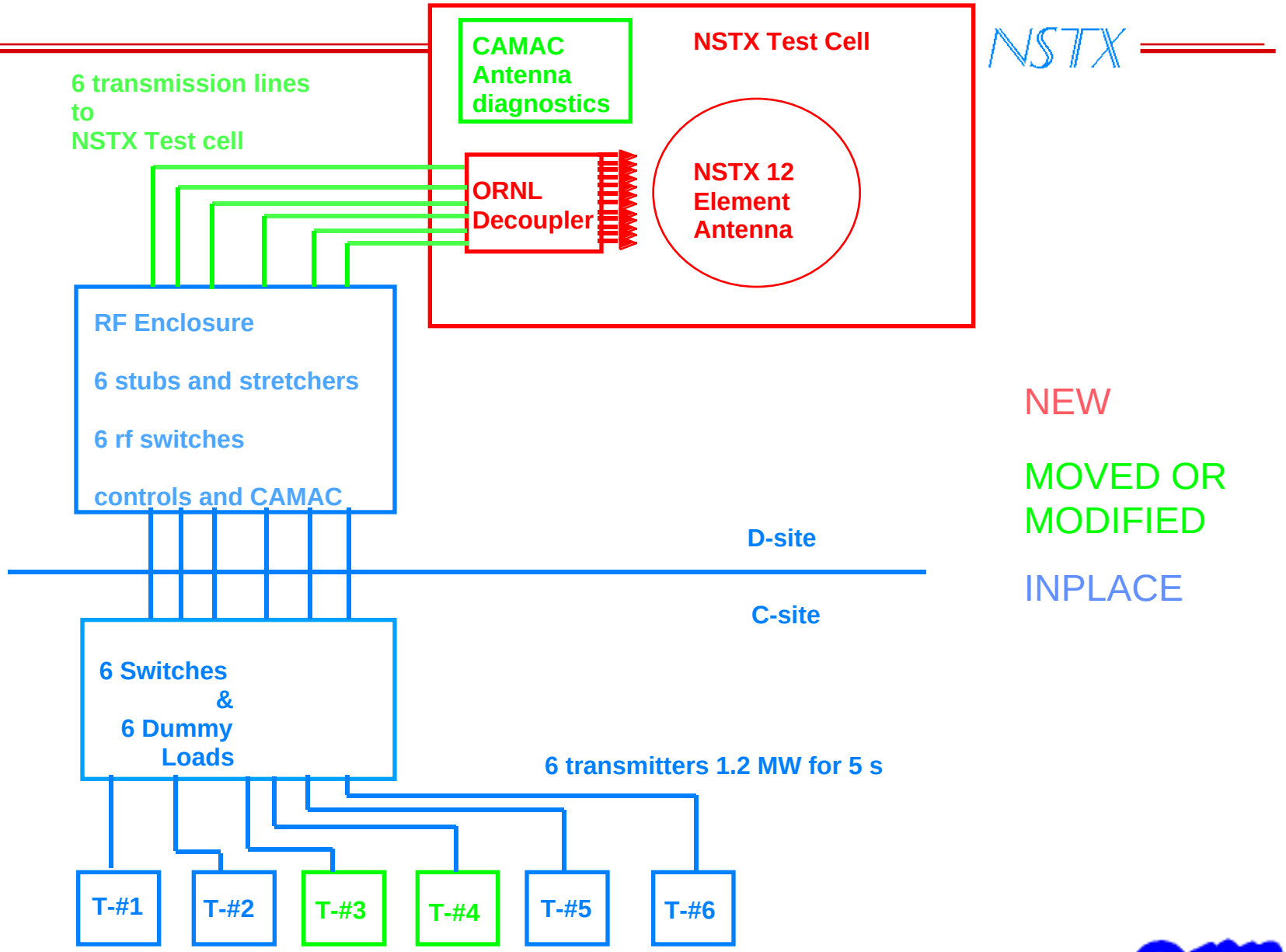
Objectives

- 12-strap array for current drive efficiency (directional spectrum)
- Variable inter-element phasing (30°– 150°) during a shot
- 30 MHz operation
- 6 MW delivered to plasma (5% to 40% β)
- Operation should be possible with fewer than six transmitters.

Constraints

- Use six existing transmitters
- Limit voltage to ≤ 25 kV on straps, ≤ 35 kV on transmission lines
- Loading may vary by factor of two during a shot

High Harmonic Fast Wave (HHFW) System Overview



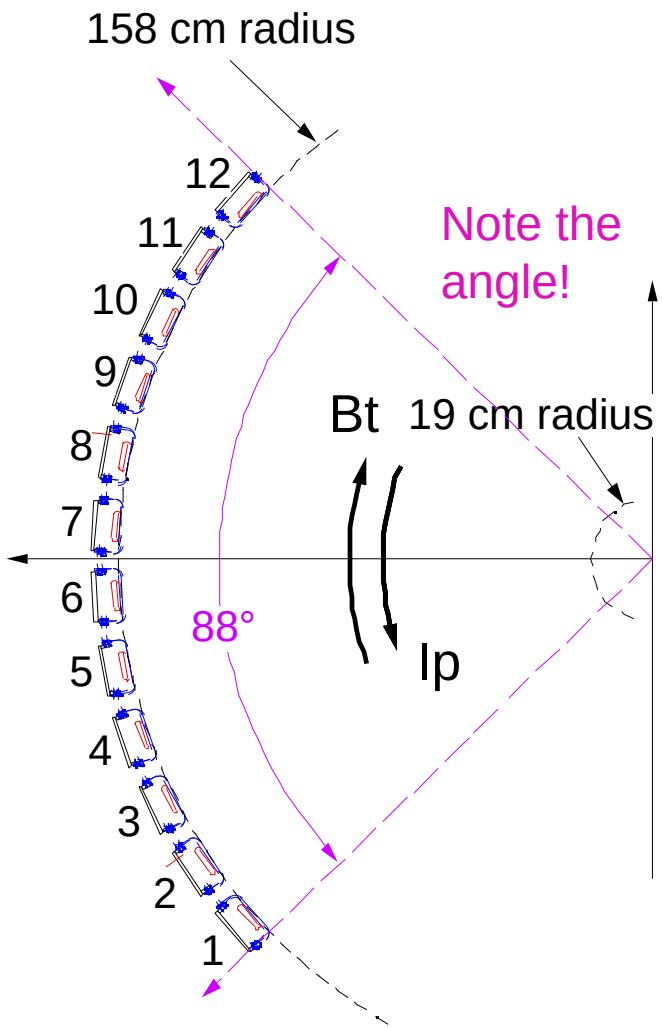
NEW

MOVED OR MODIFIED

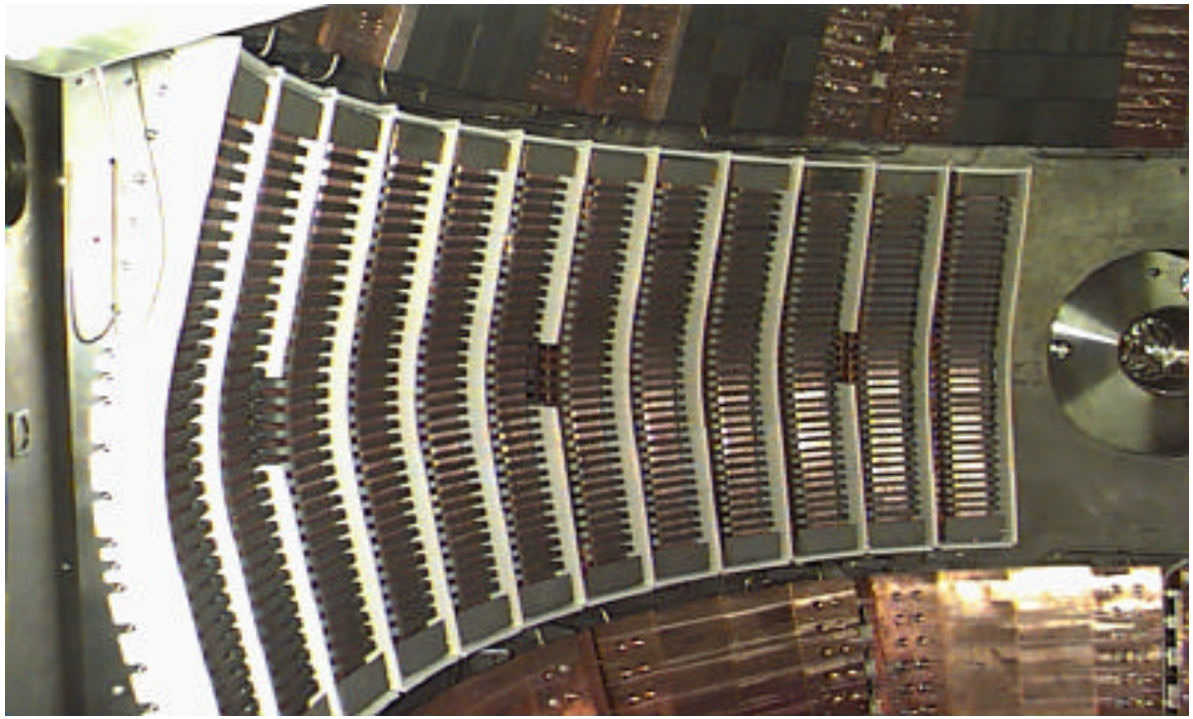
INPLACE

12-strap antenna array takes up almost 90° toroidally

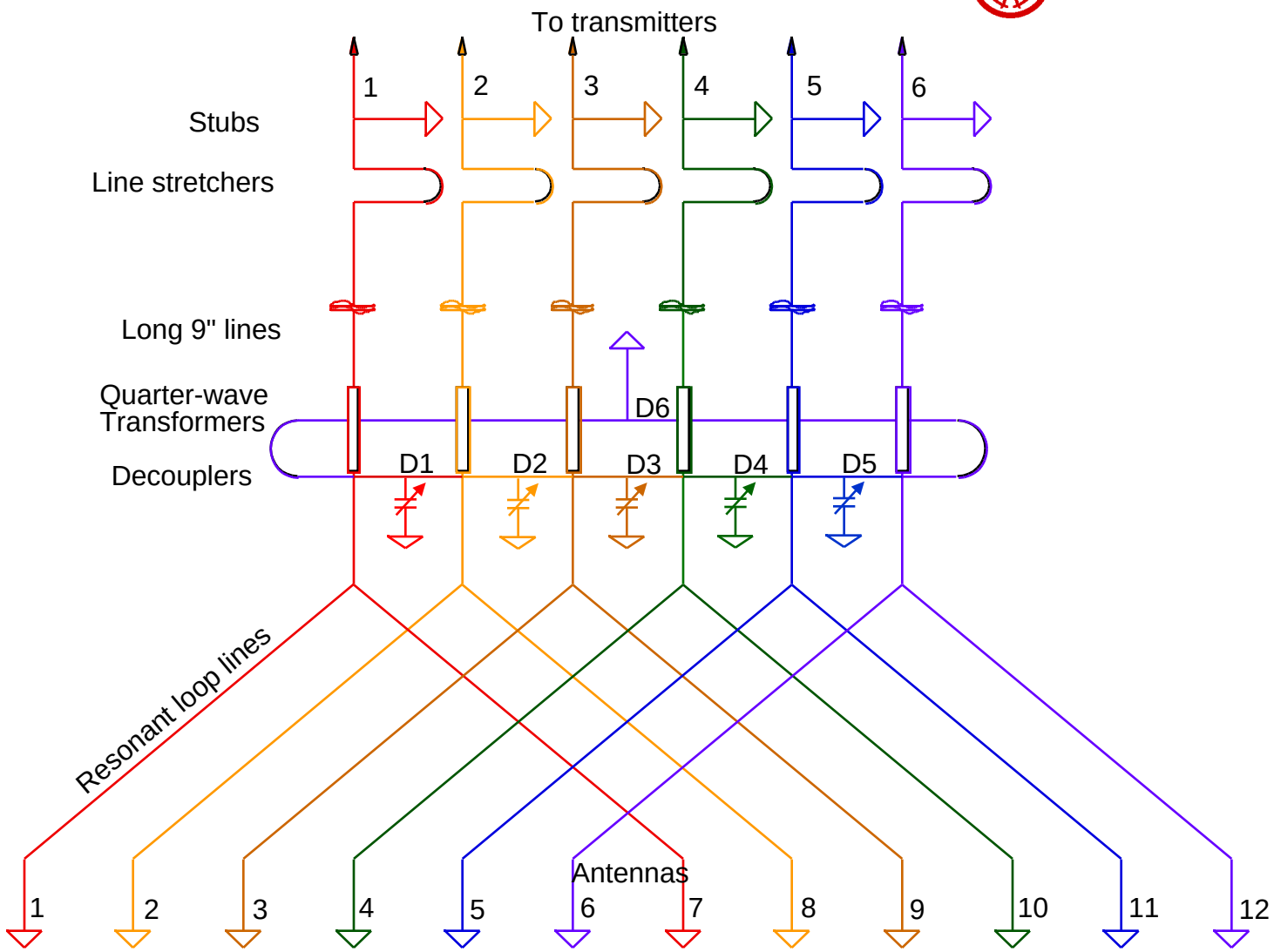
Cut through antenna midplanes, viewed from above



NSTX antennas installed in the vacuum vessel
B_4C limiters surround each antenna

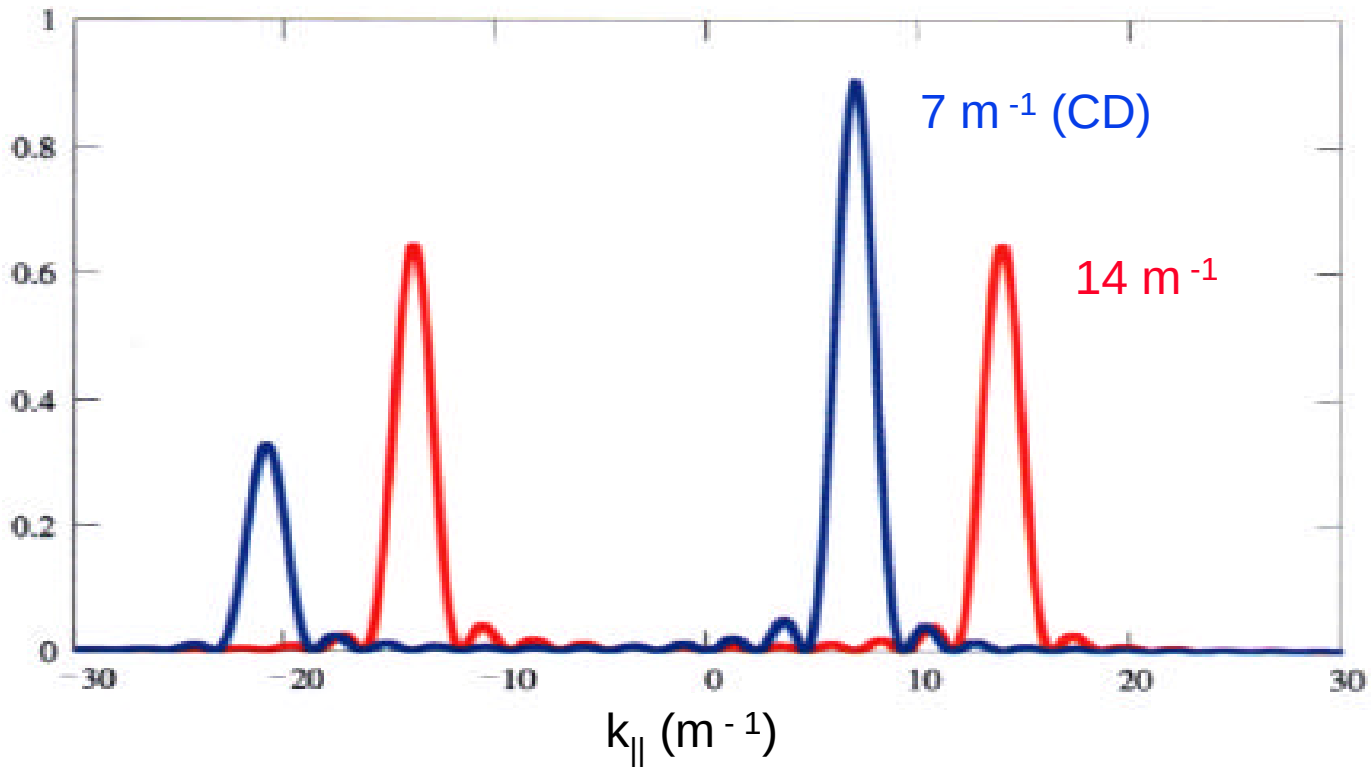


HHFW System Design:
12 straps, 6 transmitters, 6 decouplers



POWER SPECTRUM OF ANTENNA IS PROGRAMMABLE OVER A WIDE RANGE OF $k_{||}$

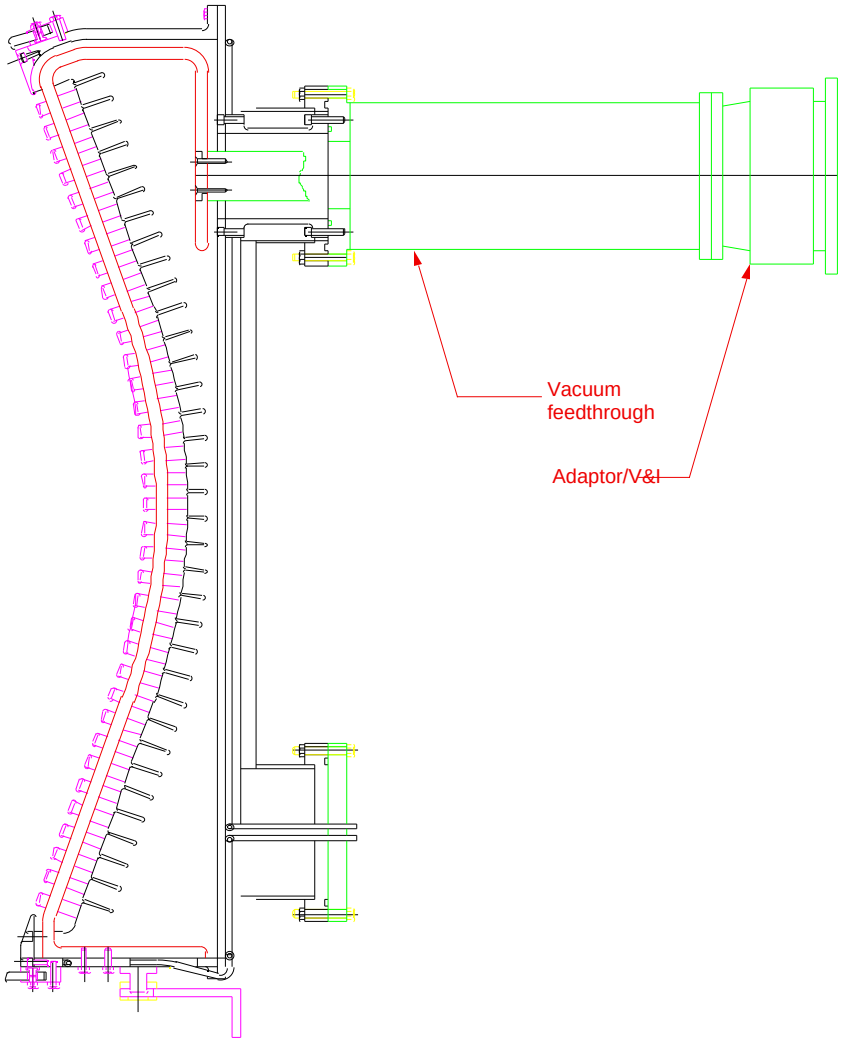
Antenna Power Spectrum



- Programming $k_{||}$ facilitates heating to higher T_e and change to CD phasing
- Decoupling between adjacent straps provided with decoupling loops
  - minimizes mutual effects in vacuum
  - mutual to plasma has small effect on decoupling
- Experiments which follow were conducted with $k_{||} \sim 14\ m^{-1}$

Straps Modeled as Coupled Transmission Lines

Electrical Parameters from 2D Analysis



Z_0 = 27.5 Ω, L = 20 cm

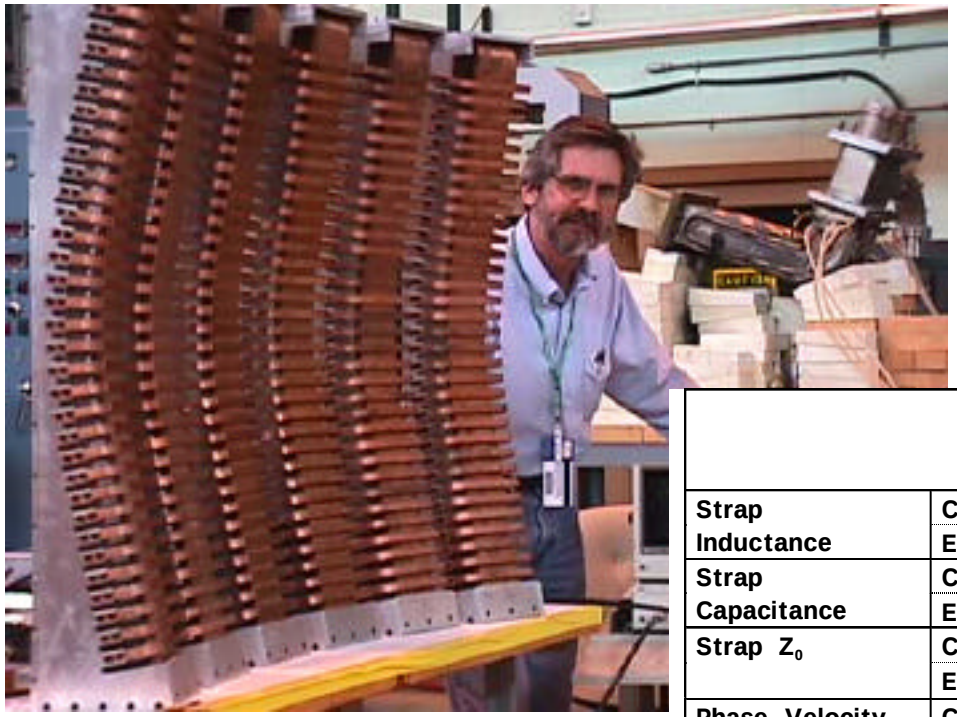
Z_0 = 53 Ω
v_p = 0.52 c
k = 14%
L = 30 cm

Z_0 = 48 Ω
v_p = 0.57 c
k = 9%
L = 30 cm

Z_0 = 53 Ω
v_p = 0.52 c
k = 14%
L = 30 cm

Characteristic impedance (Z_0), phase velocity (v_p), and coupling coefficient (k) for each section of antenna strap

Calculated Values For Antenna Array Were Adjusted to Match Mockup Measurements

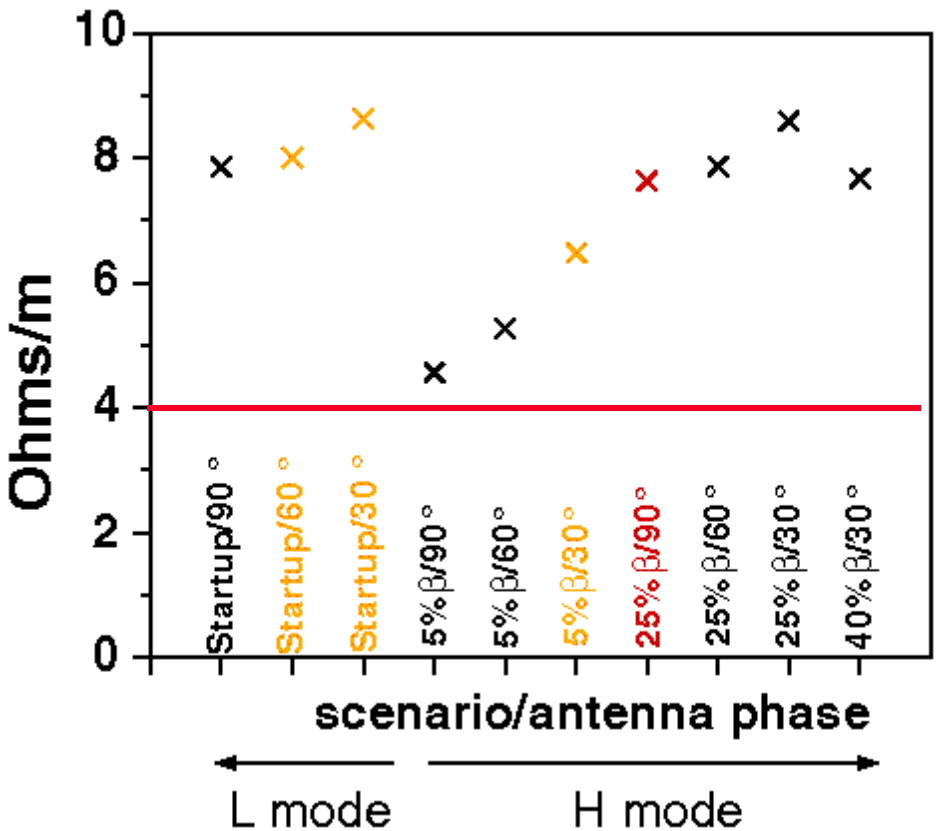


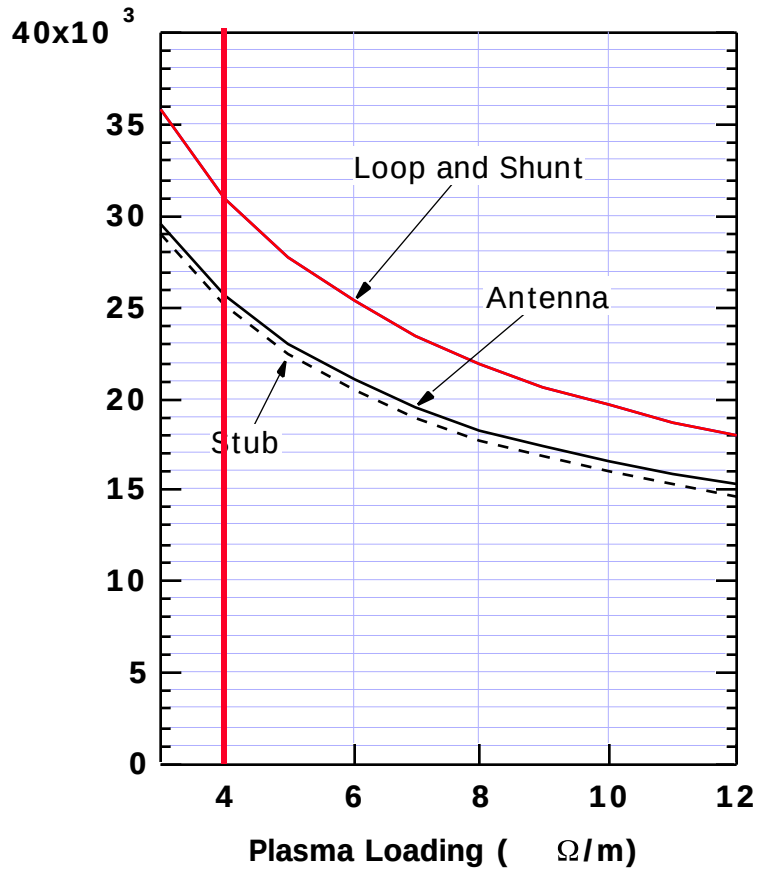
Full-scale, 6-element mockup array was fabricated and tested at ORNL

		Calculated Design Values	Values To Match Mockup Measurements
Strap Inductance	Center	2.81e-7 H/m	2.94e-7 H/m
	Ends	3.39e-7 H/m	3.57e-7 H/m
Strap Capacitance	Center	1.21e-10 H/m	1.12e-10 F/m
	Ends	1.21e-10 H/m	1.08e-10 F/m
Strap Z_0	Center	48 Ω	52 Ω
	Ends	53 Ω	58 Ω
Phase Velocity	Center	0.57 c	0.58 c
	Ends	0.52 c	0.54 c
Inductive Coupling, k_{12}	Center	0.09	0.08
	Ends	0.14	0.10
Inductive Coupling, k_{13}	Center	*	0.02
	Ends	*	0.02
Strap Length	Center	0.30 m	0.285 m
	Ends	0.30 m	0.285 m
Feed Length		0.20 m	0.35 m
Feed Z_0		27.5 Ω	26 Ω

Conservative System Design: Voltages in system < 35 kV

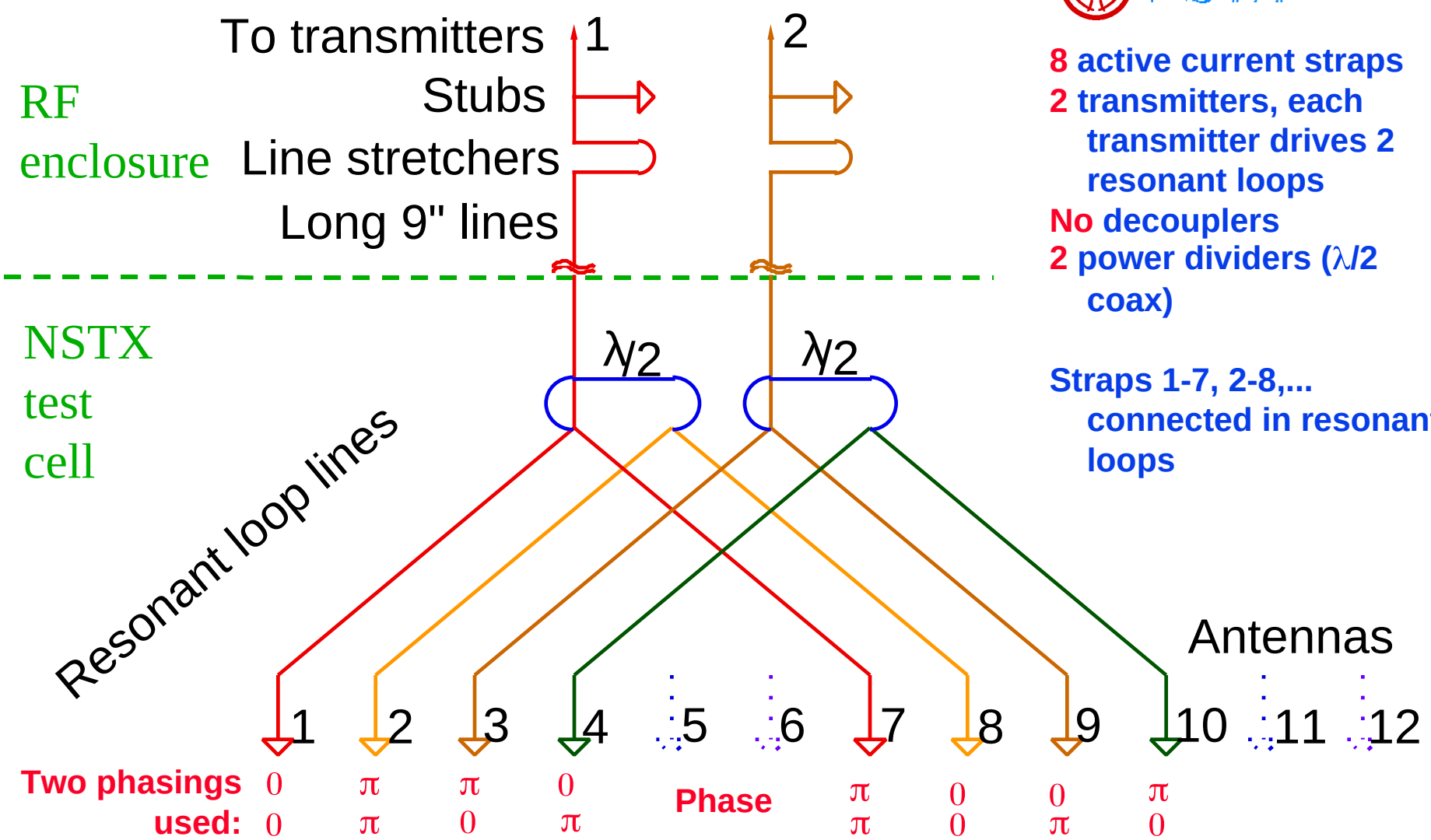
- Load resistance > 4 ohms/m for expected operating conditions
- Antenna voltage ≤ 25 kV





Initial Plasma Operation:

used two transmitters to drive eight antennas



- 8 active current straps
- 2 transmitters, each transmitter drives 2 resonant loops
- No decouplers
- 2 power dividers (λ/2 coax)

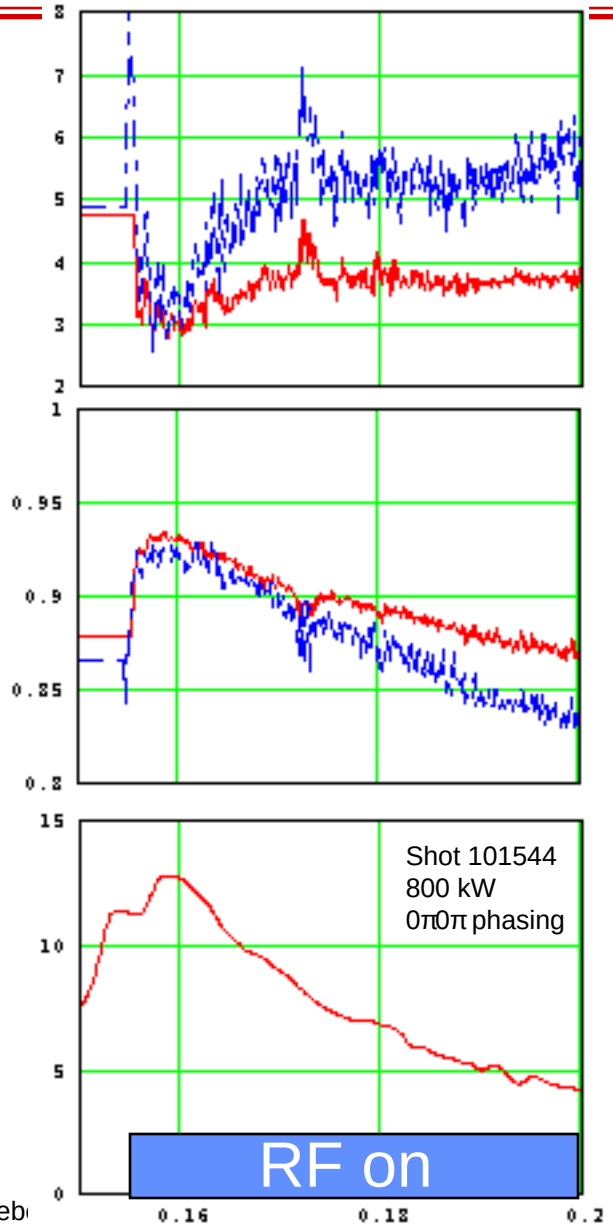
Straps 1-7, 2-8,... connected in resonant loops

R', L' calculated from forward and reflected power measurements

R'(ohms/m)
Trans. 1
Trans. 2

L'/L'$_{vac}$
Trans. 1
Trans. 2

Inner gap
Outer gap



Analysis method:

- Coupled loop analysis with eight straps
- Measure rho near transmitter, calculate rho at input to resonant loops
- Using coupled circuit model, calculate
  - R' (loading on current strap in ohms/m)
  - L'/L$_{vac}$ (inductance of current strap,normalized to vacuum value)
- Assume only R' and L' change, mutual coupling constant (*approximation*)

Points to note:

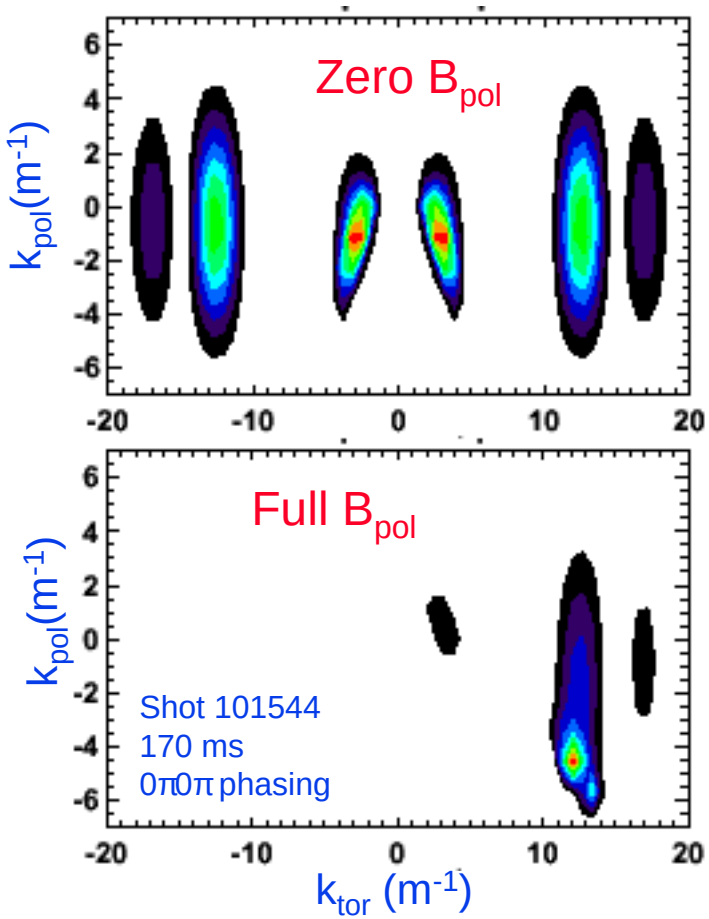
- Loading increases as gap decreases
- Significant difference in loading for the two rf sources
- Strap inductance decreases significantly as gap decreases

Large B_{pol}/B_{tor} give significant asymmetry in spectra and coupling

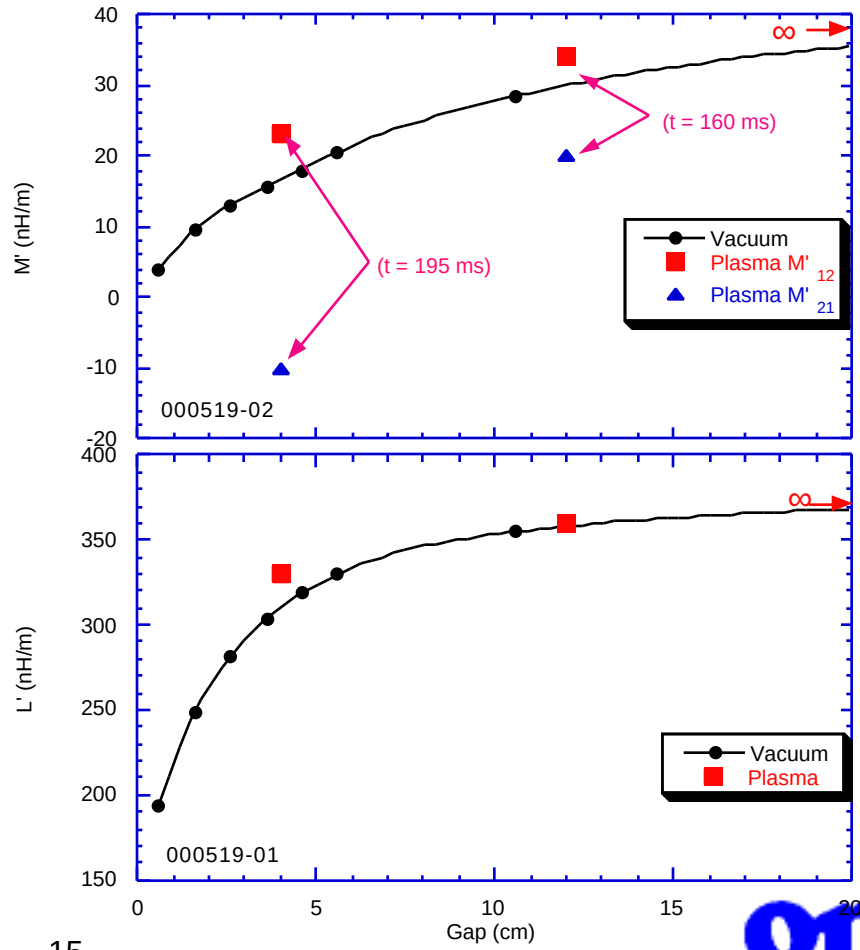
Theoretical results from FWLOAD, RANT3D

- k-spectrum is very asymmetric (large B_{pol})

Radiated power spectra



- Mutual inductance between adjacent straps very asymmetric



Heating results for 8-strap operation: magnetics indicate effective rf heating

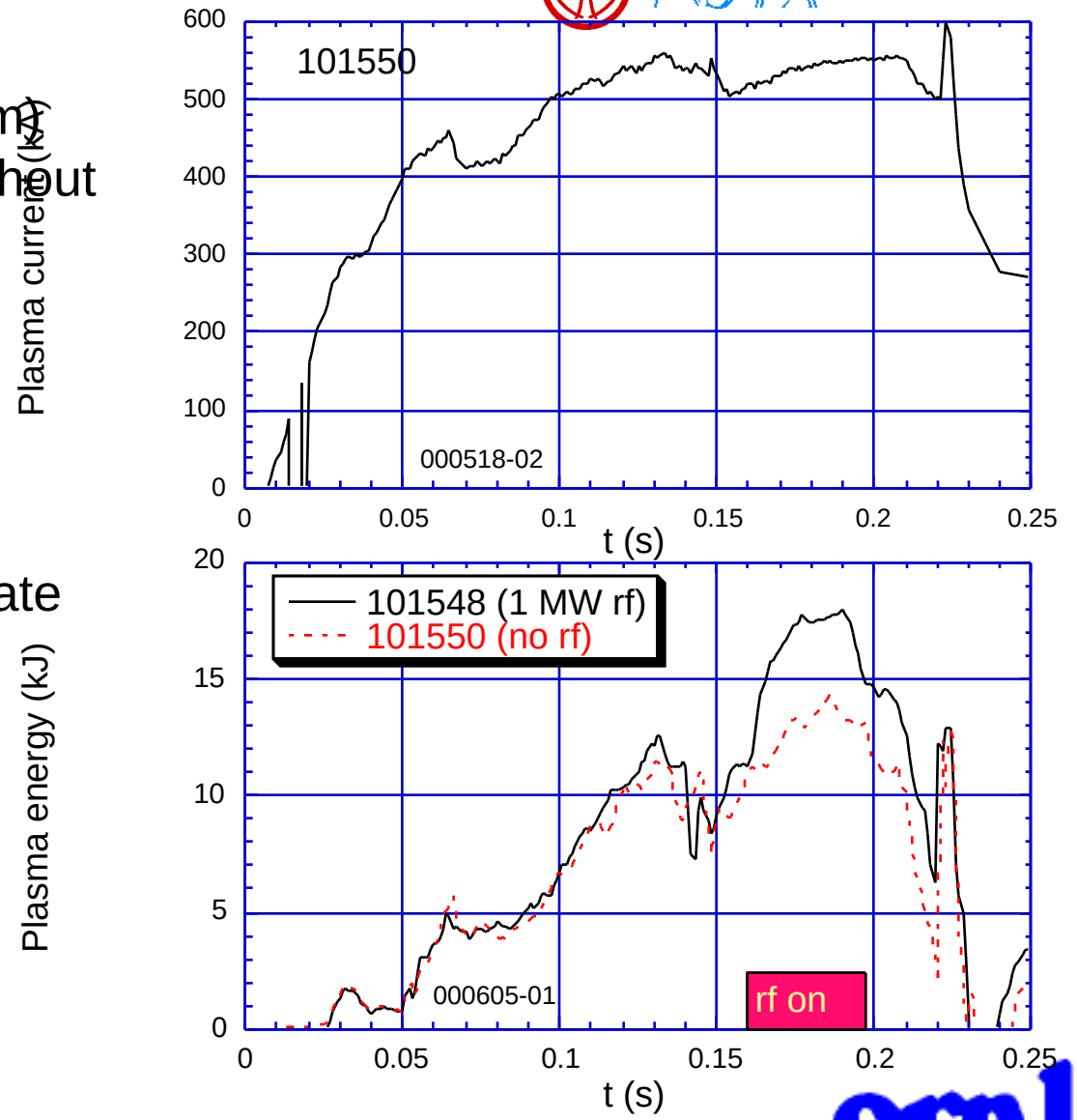
Comparison of plasma energy (from EFIT magnetic equilibrium) for two shots, one with, one without RF heating

- $I_p \approx 550$ kA
- $n_e \approx 0.6 \times 10^{19}$ m^{-3}
- $P_{OH} \approx 1.4$ MW
- $P_{RF} \approx 1$ MW, 0π0π phasing

RF heating results in approximate agreement with $P^{1/2}$ scaling.

$$\frac{W_{RF+OH}}{W_{OH}} \approx \frac{18}{13.5} = 1.33$$

$$\sqrt{\frac{P_{RF+OH}}{P_{OH}}} \approx \sqrt{\frac{2.4}{1.4}} = 1.31$$



Full 12-Strap Operation Started in September

NSTX resumed operation in September with higher RF power, installation of neutral beams, and improved diagnostic set

RF system upgraded to full capability

- 6 transmitters instead of two
- 6 resonant loops will be driven independently
- Decouplers between resonant loops

Plans are to:

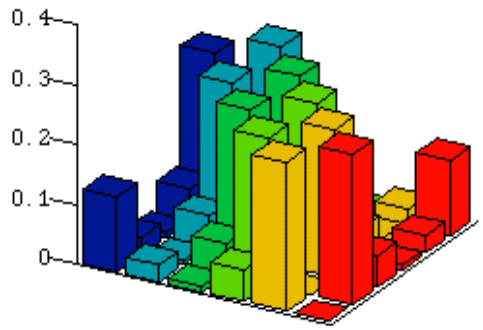
- Extend heating study
  - Broader range of plasma parameters; characterize heat and particle transport at high β and high shear, under high power
  - Deliver up to 6 MW to the plasma from the rf system
- Start active phase control during a shot, prepare for current drive

Still significant questions:

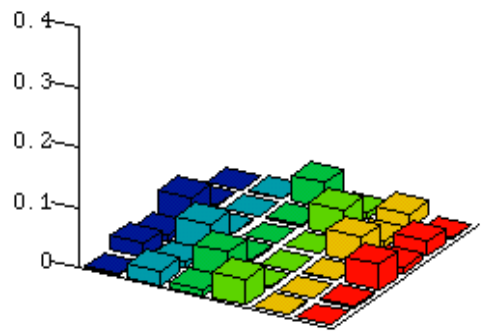
- Heating efficiency - 0ππ0 vs 0π0π?
- Why does heating sometimes disappear?
- Will predicted asymmetry in loading and coupling cause difficulty for active phase control?

12 Strap Operation With Decouplers:
Vacuum S-matrices show some residual coupling

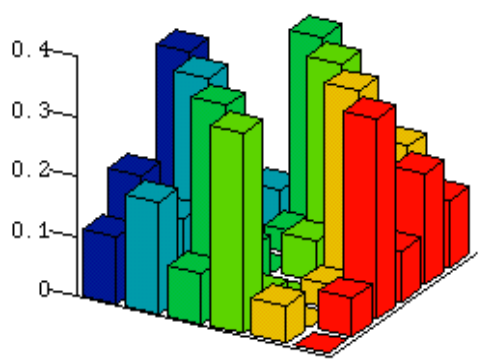
(Diagonal values suppressed)



Strong nearest neighbor coupling without decoupling loops



At feedpoints, the decoupling loops cancel nearest neighbor interactions



Load-matched transmitters see two coupled triplets (1-3-5 and 2-4-6)

PLASMA SIGNALS CONFIRM DECOUPLING

Forward Power (W) Reflected Power (W) Antenna Voltage (V)

Line 1

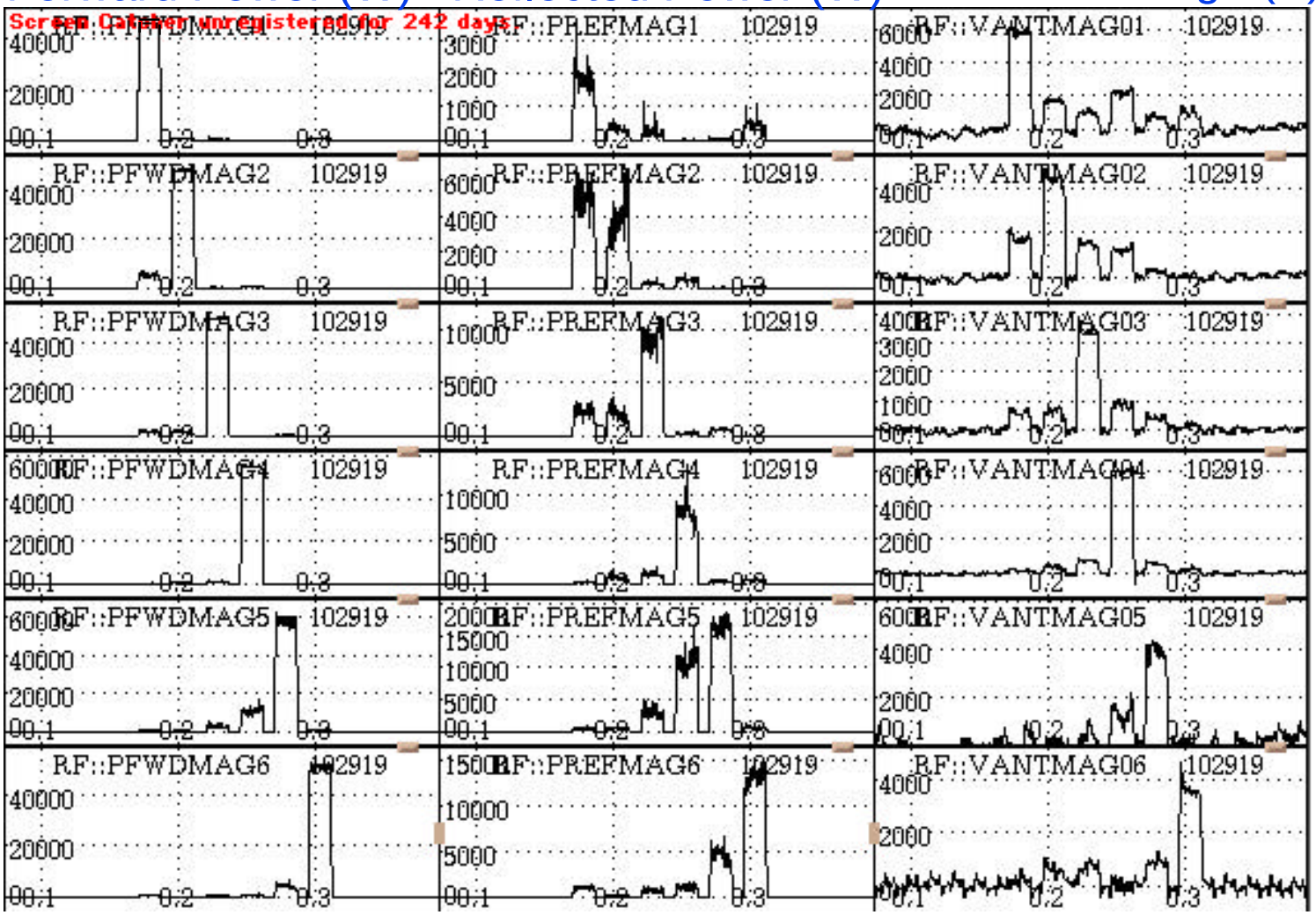
Line 2

Line 3

Line 4

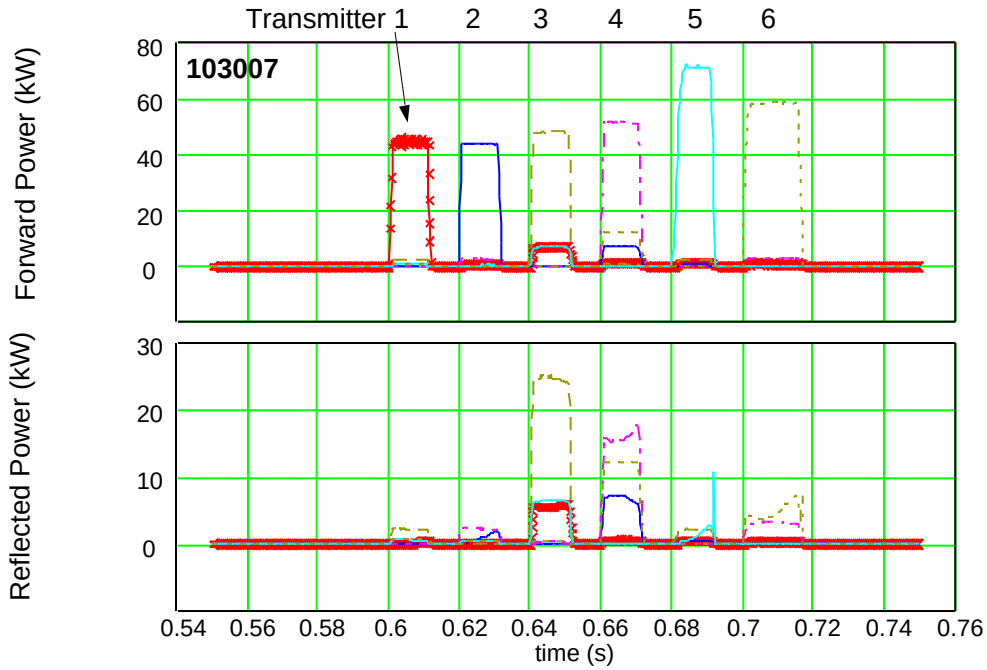
Line 5

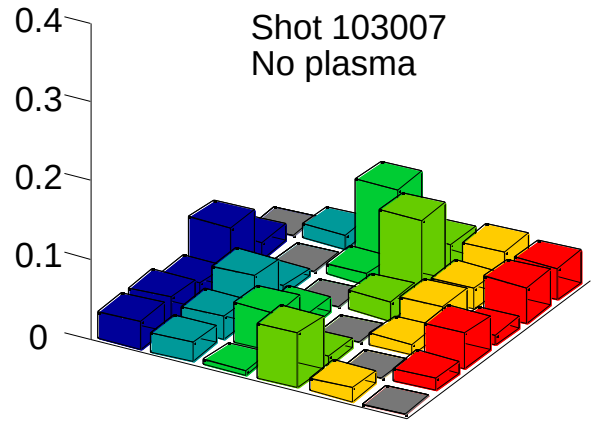
Line 6

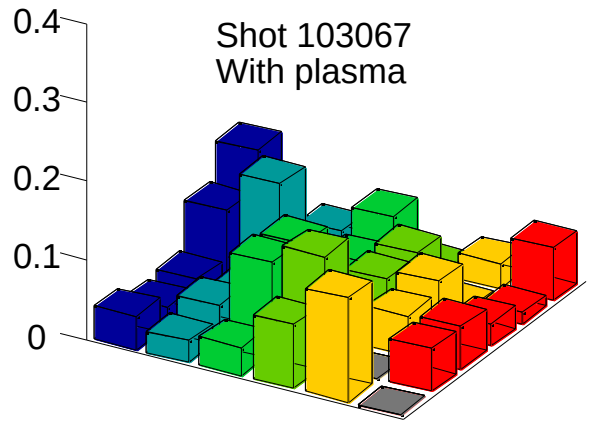


Time (s) Time (s) Time (s)

Measurements Indicate Asymmetrical Loading/Coupling With Plasma







Scattering matrices can be generated from forward/reflected power measurements at the match.

Summary of RF System Operations

NSTX

NSTX HHFW system has operated into plasma with 8 straps, no decouplers

- $P_{RF} \leq 2$ MW from two transmitters
- Heating observed in core of plasma for $0\pi0\pi$ phasing
- Substantial loading data base acquired

Full 12 strap operation with decouplers installed has begun

- All six transmitters are now operational and up to 4 MW has been delivered to the plasma.
- Decouplers effectively isolate adjacent transmitters from each other.
- Remaining coupling between next-to-nearest neighbor transmitters is not negligible but manageable. Improved matching algorithms need to be developed.
- Symmetrical phasings $0-\pi-\pi-0 \times 3$ and $0-\pi-0-\pi \times 3$ have been employed by phase-shifting transmitters 3&4 by π.

The model of the power distribution system shows good agreement with measurements.

STRONG ELECTRON HEATING HAS BEEN OBSERVED DURING HHFW

Electron temperature increases from 400 to 900 eV in Helium plasmas with 2.3 MW of rf power phased for $k_{||}$= 14 m^{-1}

No density increase

Little increase in radiated power

- Edge dominated, <10% of input power

Increase in stored energy from 43 to 58 kJ: β_T= 10% , β_N = 2.7%

Loop Voltage falls from 1.35 to 1.0 V

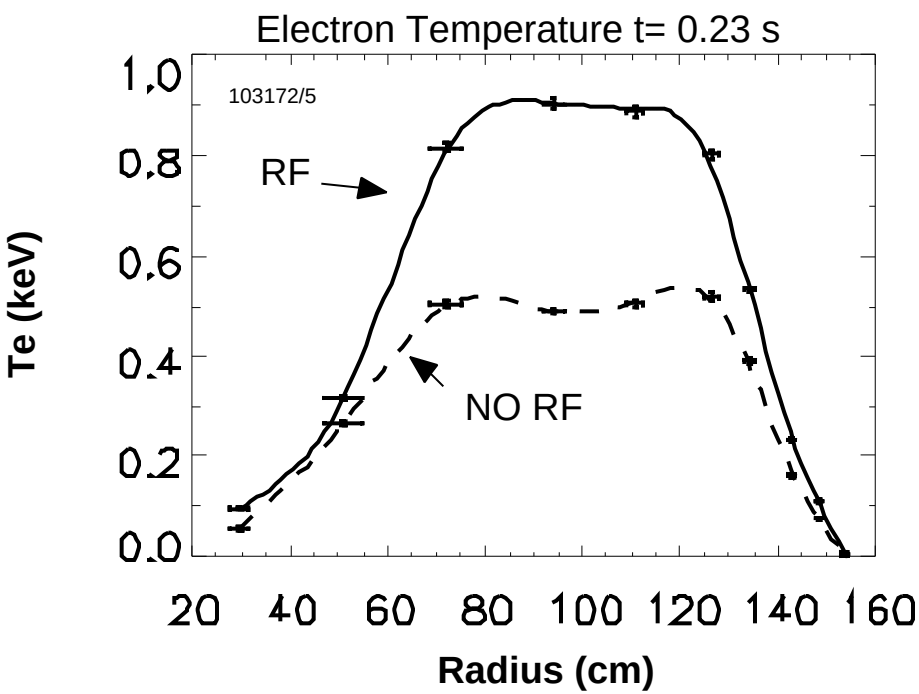
Heating is over entire profile

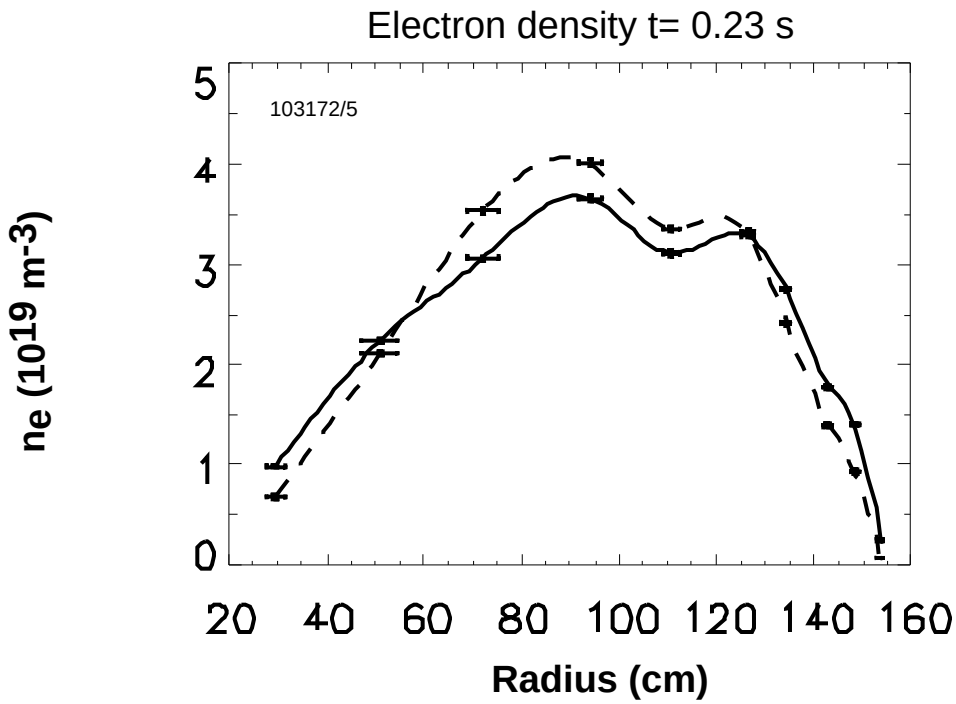
MHD stability limits duration of pulse (Sawteeth and RE)

Deuterium plasmas differ in detail

- Larger density increase
- Smaller temperature increase
- Other parameters similar

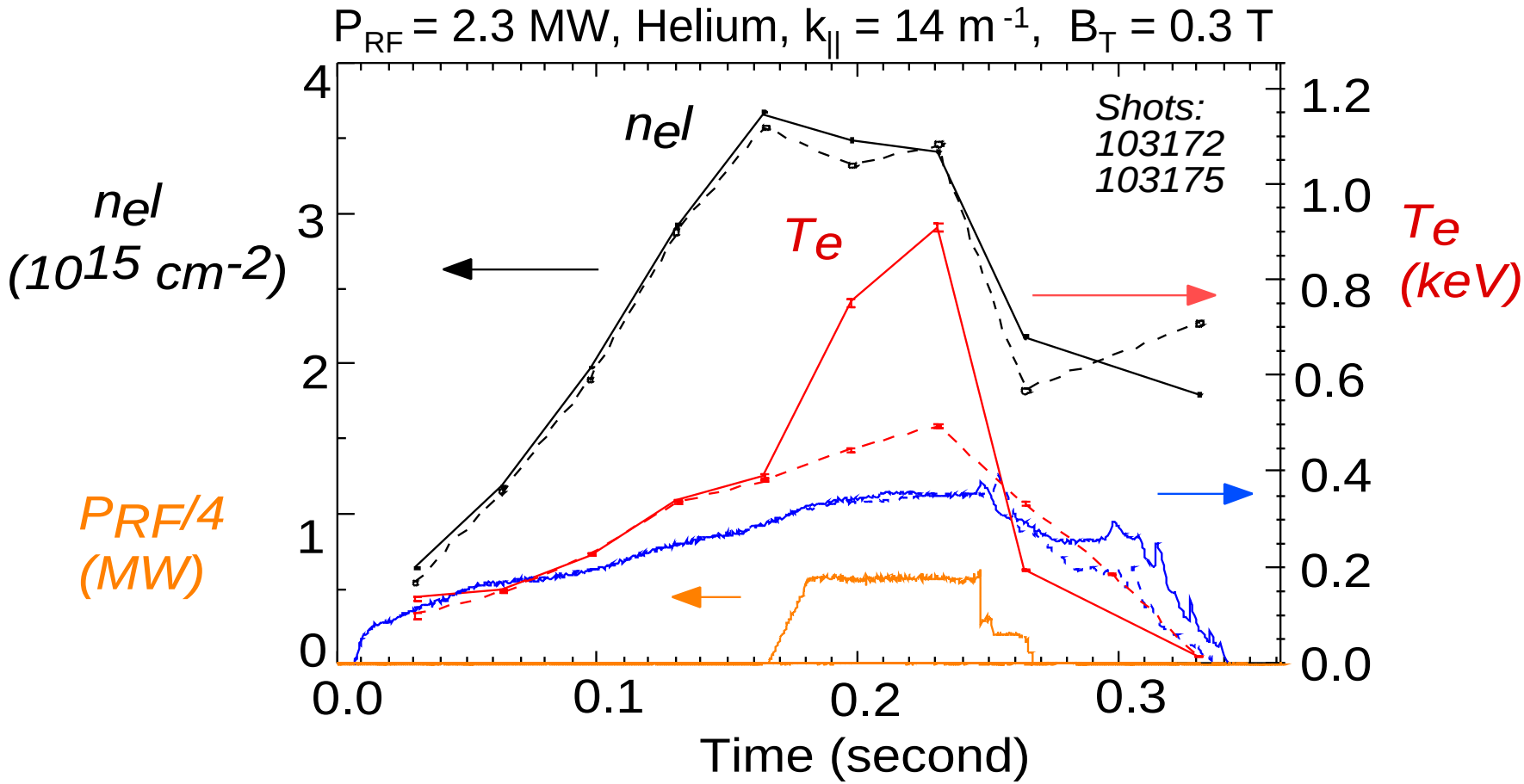
STRONG ELECTRON HEATING WITH NO DENSITY INCREASE IN HELIUM PLASMAS





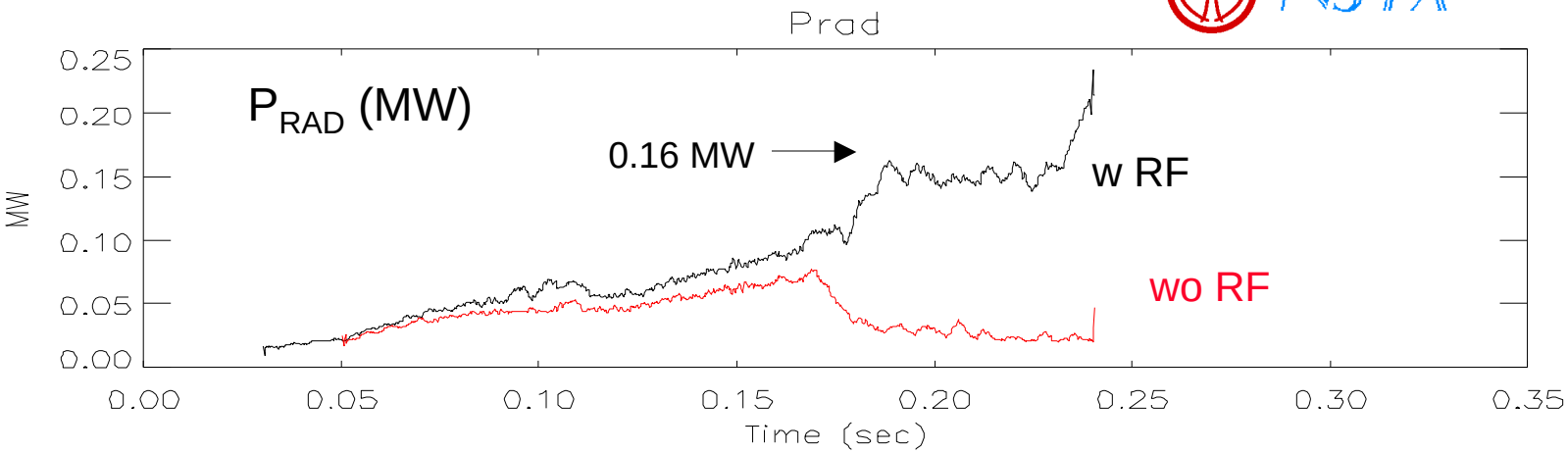
STRONG ELECTRON HEATING HAS BEEN OBSERVED IN HELIUM PLASMAS WITH THOMSON SCATTERING

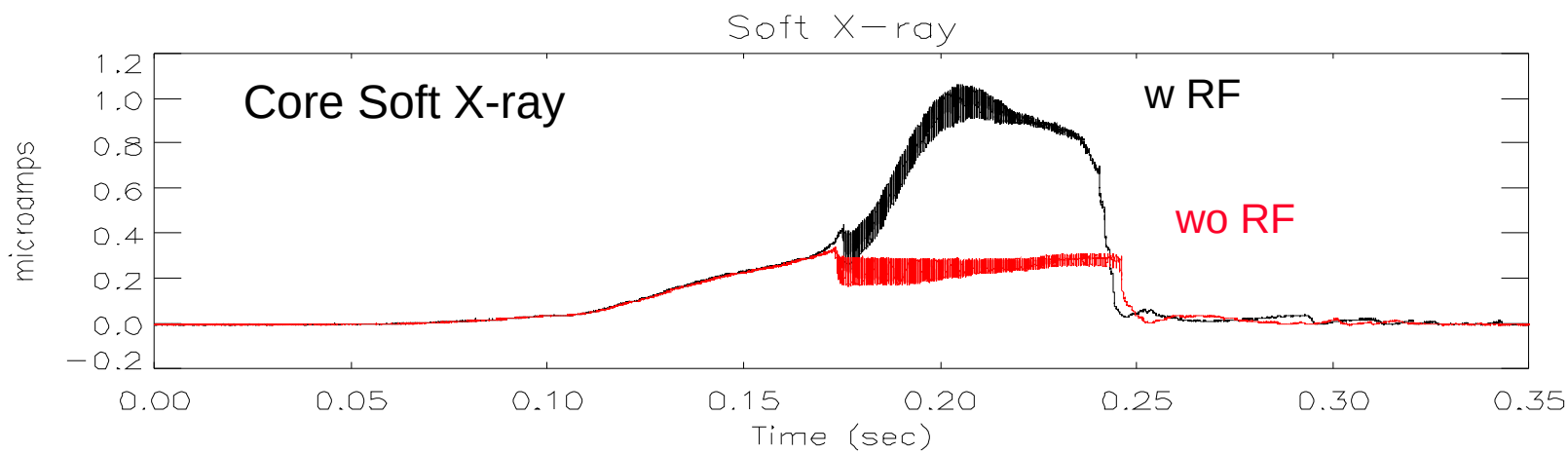
LeBlanc et al, BO1.003



- **$T_e(0)$ increases from 400 to 900 eV in helium plasma at P_{RF} = 2.3 MW**
- **No density increase with RF and V_{loop} decreases by ~ 30 %**
- **Stored Energy increases to 58 kJ: β_T = 10%, β_N = 2.7**

DISCHARGE RADIATION AND STABILITY ARE LITTLE AFFECTED BY THE RF





- Relatively small increase in P_{rad} with RF -- edge dominated, < 10 % of RF power
- RF rides through m = 1 MHD instability
- Large MHD event terminates heating and dumps energy to wall (w & wo RF)

CONCLUSIONS AND FUTURE EXPERIMENTS

HHFW heating experiments are off to a good start

- T_e of 900 eV has been obtained at $n_e \sim 4 \times 10^{19}$ m^{-3}
- Effects on stability are small at the power levels used to date
- $k_{||} \sim 14$ m^{-1} has been used to effectively heat electrons at low starting T_e as desired for start-up (also significant heating observed for $n_e \sim 4 \times 10^{18}$ m^{-3})

Effect of ion heating on power deposition is now under study

- May help explain lower electron heating observed for D plasmas thus far
- Will have a larger effect for $k_{||} \sim 7$ m^{-1} which is more suitable for higher T_e plasmas
- Also could reduce efficiency of current drive at $k_{||} \sim 7$ m^{-1}

Current drive experiments will begin shortly