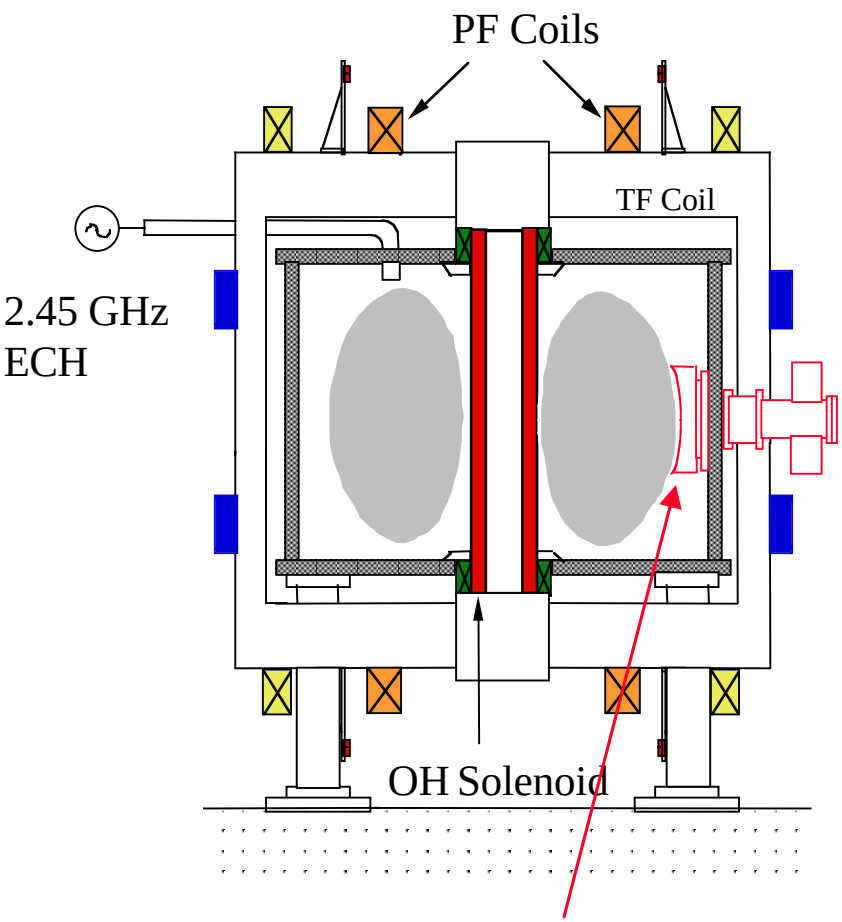
RF technology (mostly) results from CDX-U and Phaedrus-T

Summarized by Dick Majeski

Introduction and disclaimer

- This presentation is intended to summarize contributions to RF technology from one small and one middling experiment.
- CDX-U functioned as a proving ground for NSTX.
  - Most of the CDX work has been greatly extended on the larger machine.
  - Would the NSTX antenna look very different had the CDX-U experiments not been done? Unclear.
- Phaedrus-T had no such mandate.
  - Experiments were less conservative.
  - In the opinion of the management (of this presentation), the contributions of Phaedrus-T to RF technology were significant, and unique.
  - The program was cancelled.
- Lessons learned?

CDX-U experiments were designed to test high harmonic fast wave heating in an ST



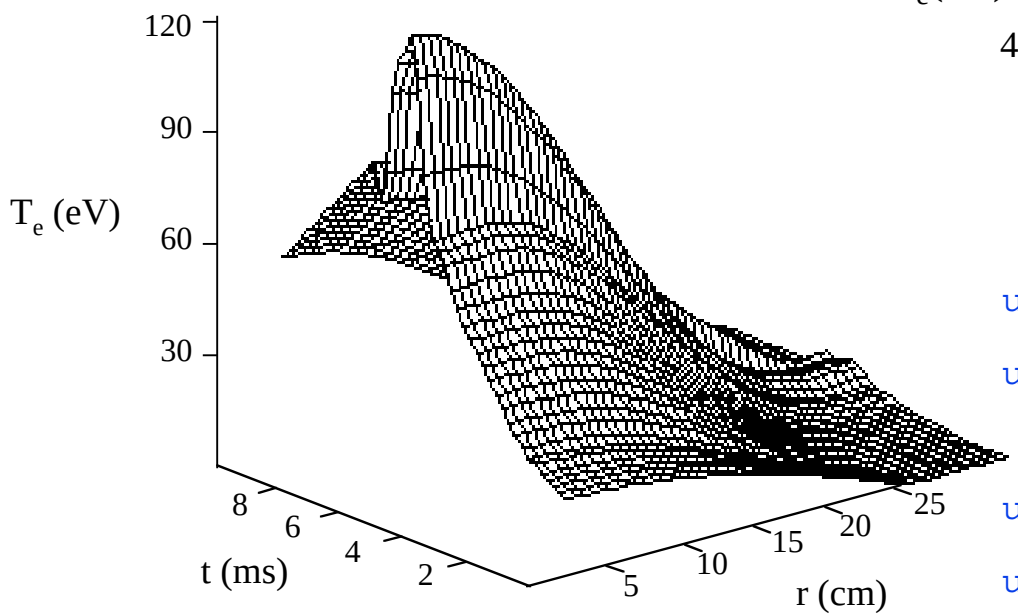
Two-strap, rotatable HHFW antenna with boron nitride limiters
Still the world's only rotating antenna

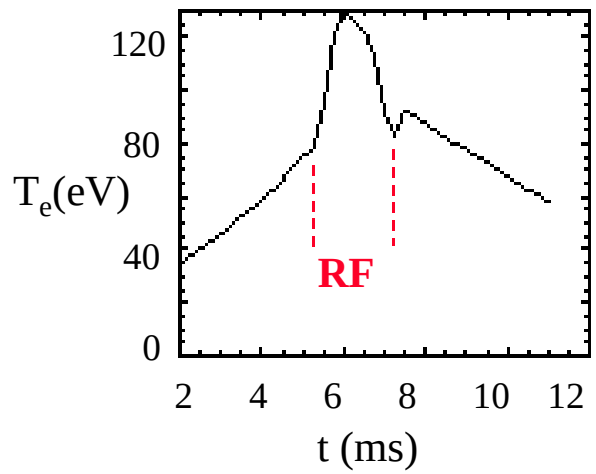
- R_0 = 34 cm
- a = 22 cm
- $A \equiv R_0/a > 1.5$
- $\kappa \leq 1.6$
- $\delta \leq 0.3$
- $B_t \leq 0.13$ Tesla
- $n_e(0) = 0.5 - 1.5 \times 10^{13}$ cm^{-3}
- $T_e(0)$ = 80-150 eV
- Central $\beta \leq 4\%$
- I_p = 50 - 80 kA
- Total pulse length = 15 - 20 msec
- 100 kW of rf power at 12 MHz
  $\Omega_{rf} \sim 12 - 15\ \Omega_i$

HHFW heating of a spherical torus plasma was demonstrated on CDX-U

Johns Hopkins University

D. Stutman et al., Plasma Phys. Control. Fusion 41, 867 (1999)





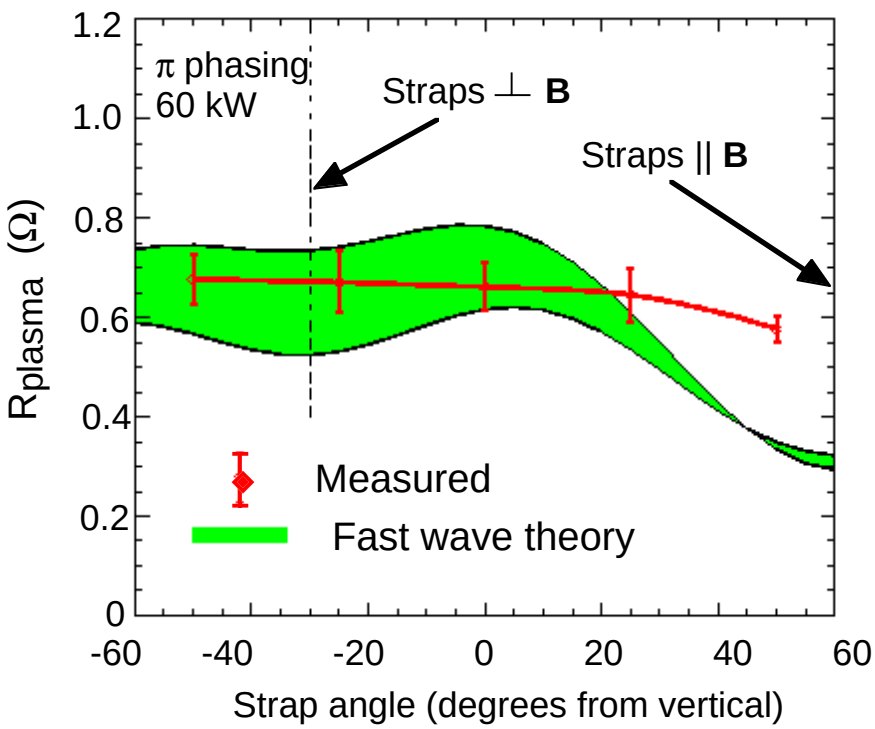
Central temperature

- 100 kW, 12 MHz, π phasing (n_ϕ =8).
- B_0 = 1.2 kG, I_p = 75 kA. $\omega_{rf} \sim 13\Omega_i(0)$
- $n_e(0) \sim 1 \times 10^{13}$ cm^{-3}.
- Temperature inferred from spectroscopic line ratios, checked with Thomson scattering

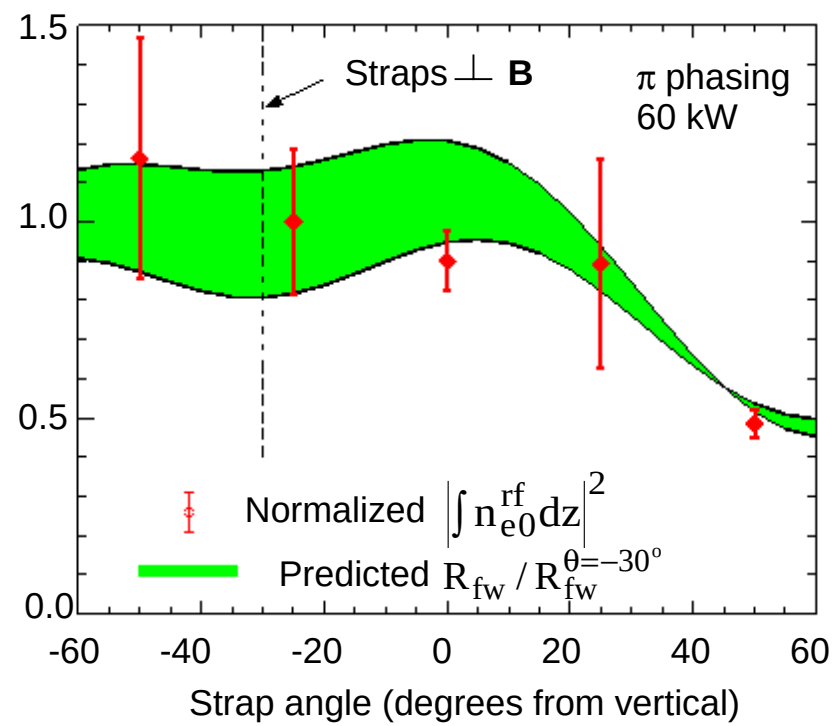
⇒Heating was inconsistent. Later experiments at *higher* power did not show evidence of heating. It's still hard to apply RF heating to small machines.

Large poloidal field, extreme edge field line angle does not inhibit fast wave excitation in CDX-U

- Loading measurements indicate fast wave loading dominates unless straps are nearly || B.



- Measurements of the fast wave-induced density fluctuations at the plasma axis confirm that the fast wave can be launched over a wide range of antenna angle.

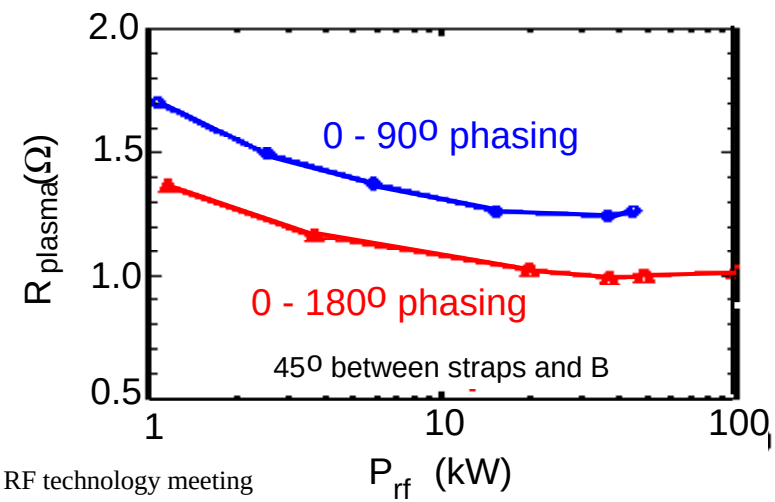


J. Menard, R. Majeski, et al., Phys. Plasmas 6, 2002 (1999)

HHFW loading measurements indicate that rf-edge effects are not significant at power levels relevant to heating

Results from CDX-U with insulating antenna limiters

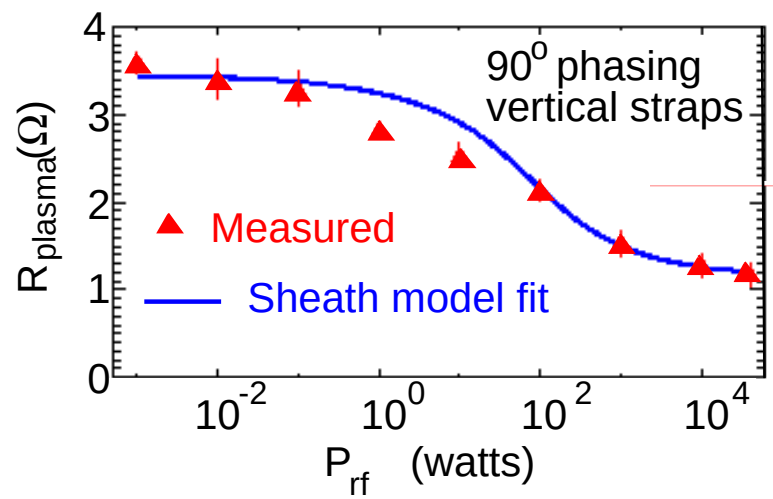
- Loading is independent of power above 10 kW.
- Loading for π phasing is lower than for 90°.
  - Self-bias effects in the plasma edge are strongest for small phase angles.
- NSTX antenna straps will subtend a similar angle to the magnetic field line.



- Detailed measurements of the antenna loading at low power (<10 kW) agree with rf sheath model.

(D'Ippolito and Myra, Phys. Plasmas **3** (1996) 420.

- Similar results for all phasings, antenna strap angles.



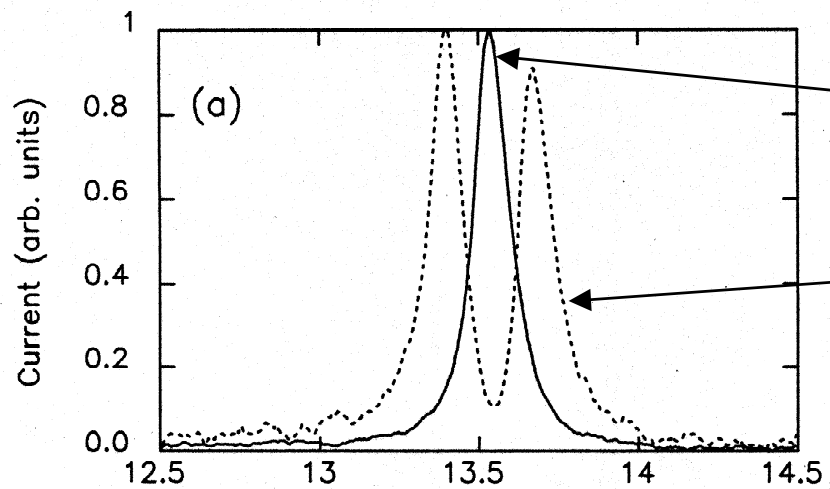
⇒No direct comparison with conducting limiters

Contributions from the Phaedrus-T program

Phaedrus-T was not funded to explore RF technology.
Nevertheless the program made several contributions to RF technology

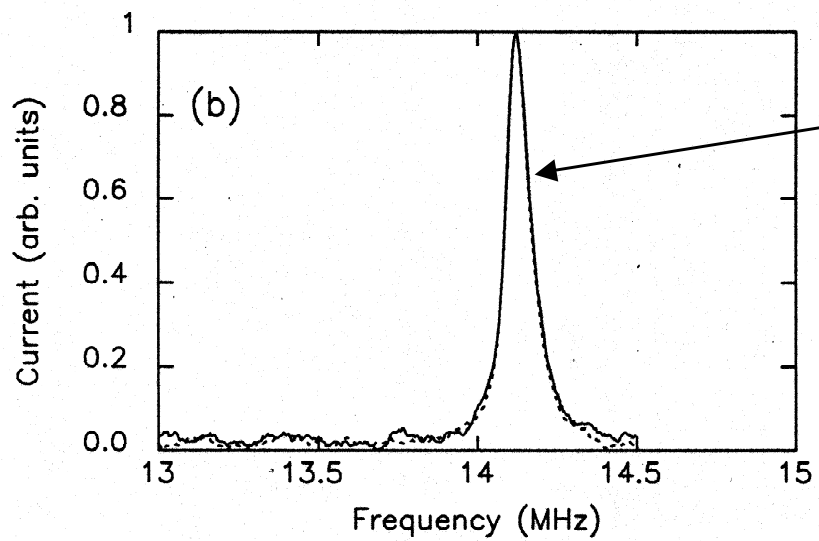
- The first implementation of a decoupler to allow arbitrary strap phasing.
  - Subsequent implementations of decouplers were much more sophisticated, culminating with the NSTX system.
  - But a similar system was used on CDX-U.
- The first demonstration of insulating guard limiters.
- Simultaneous with Textor, successful operation of an unshielded antenna.
- Demonstration of low phase velocity heating and current drive.
  - Lower phase velocities would have been nice.
  - Yes, this bears on RF technology.

The Phaedrus-T decoupler



Single strap excitation (short the other)

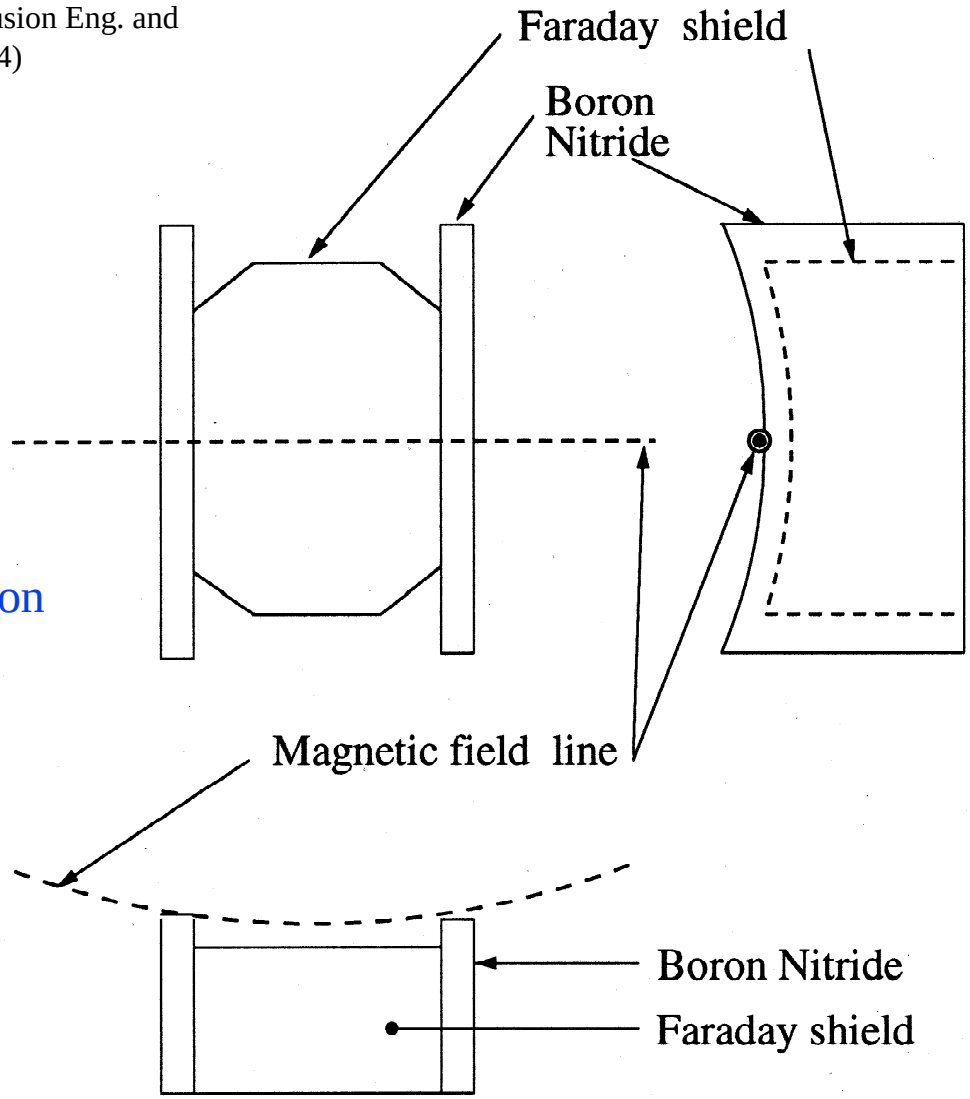
Response curve when decoupler is not adjusted



Response curve with decoupler adjusted

Implementation of insulating side limiters

R. Majeski, et al., Fusion Eng. and Design 24, 159 (1994)



Similar implementation on CDX-U

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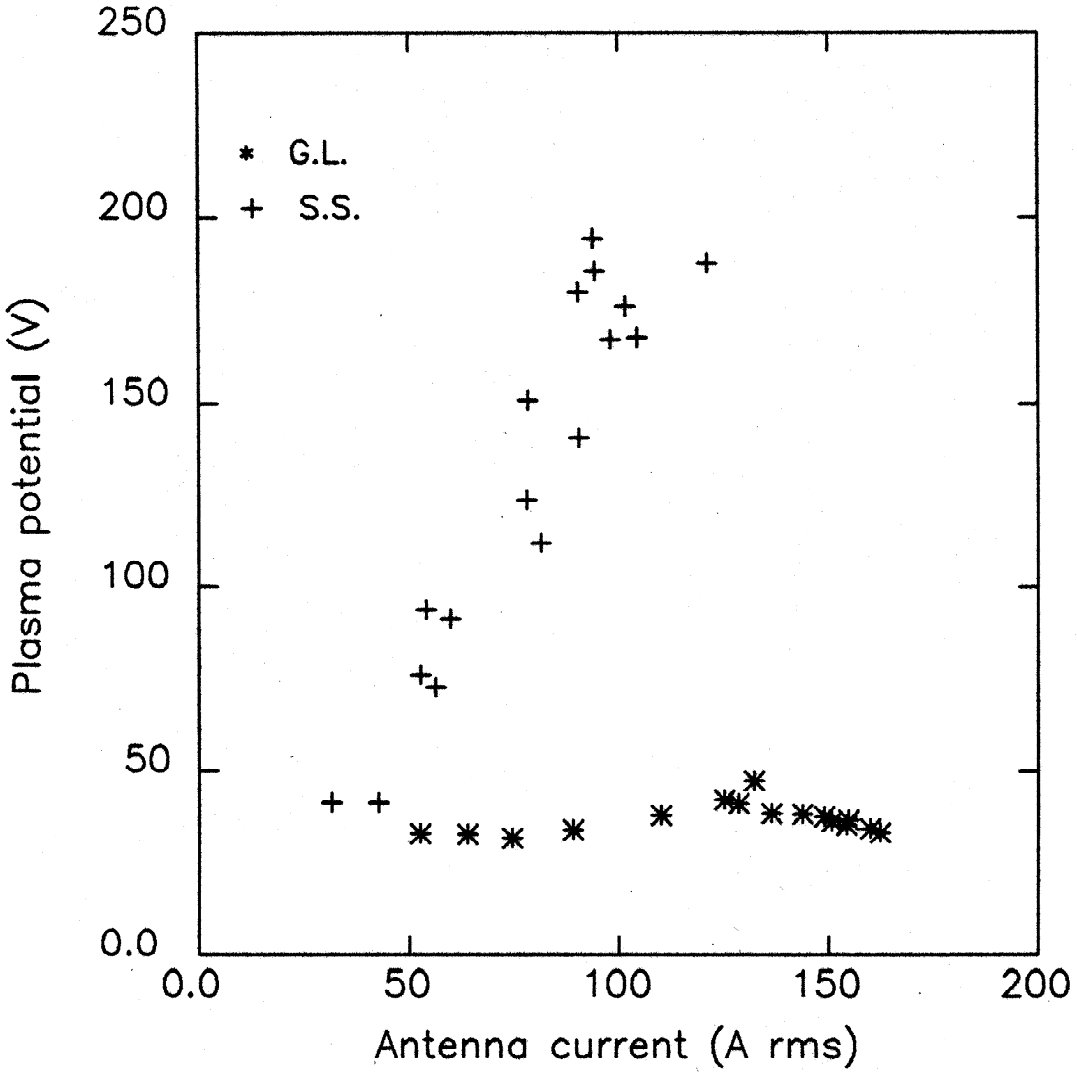
Reduction of RF-induced edge potential with insulating limiters



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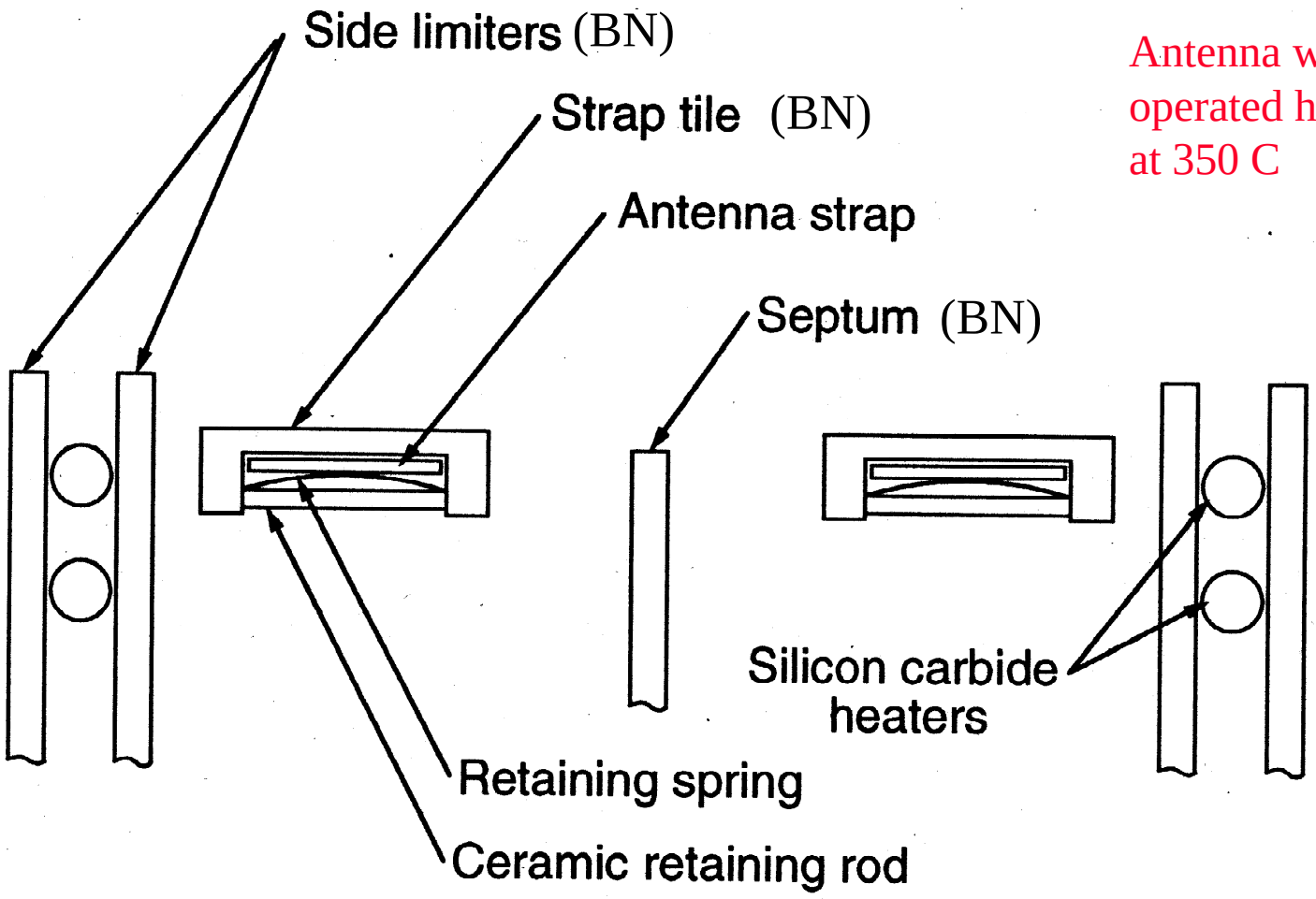
Implementation of the unshielded antenna



Antenna was operated hot, at 350 C

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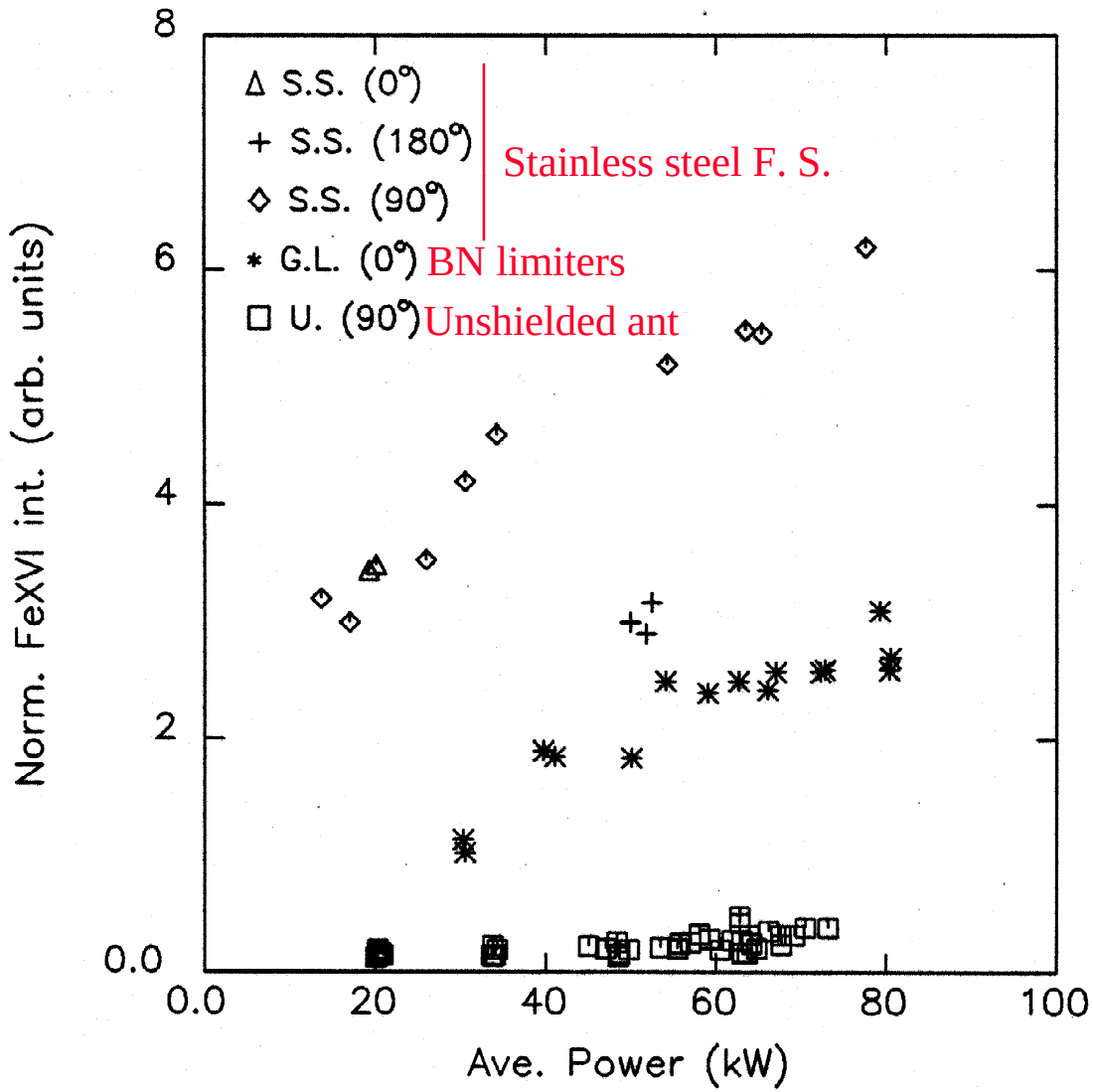
Iron influx with an unshielded, insulated antenna



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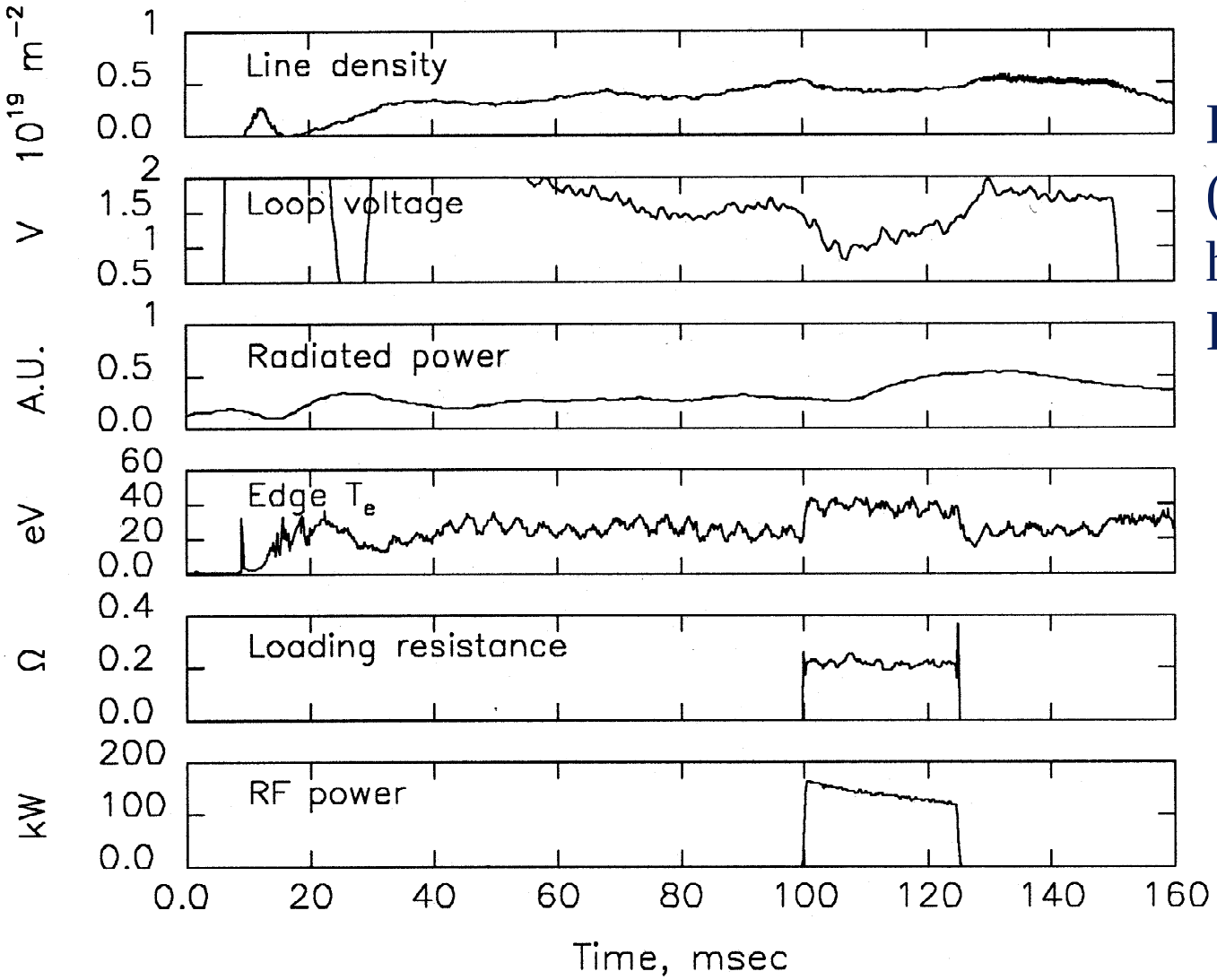

Low phase velocity (Alfven wave) heating in Phaedrus-T

R. Majeski, Physics of Fluids B 5, 2506 (1993)

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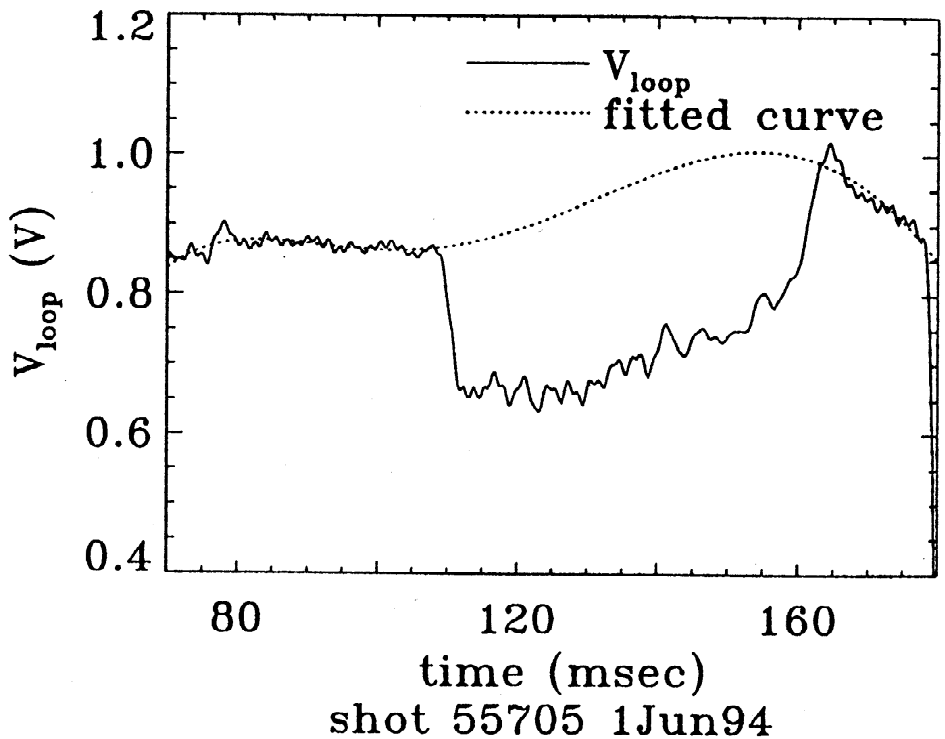
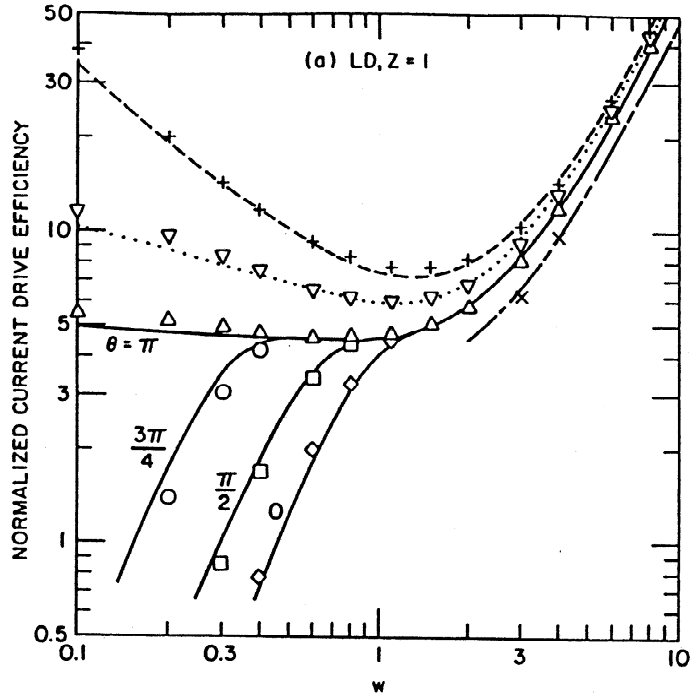
Low phase velocity current drive (v_ϕ/v_{Te}~0.6 or so)



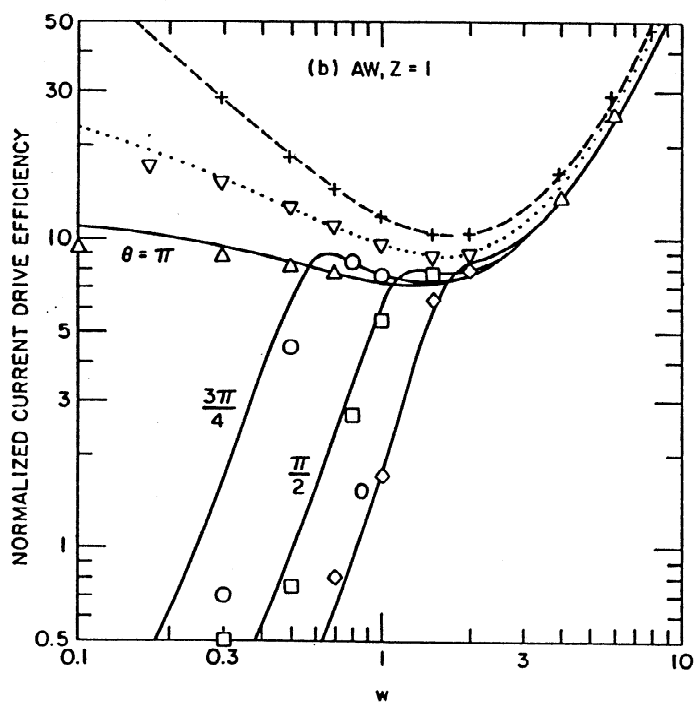
Utilized a 2 strap antenna. Coupled wavenumber is not so certain.

FIG. 5. Example shot showing a time record of loop voltage, with the curve fitted estimation of what V_{loop} would be with rising Z_{eff}, but no AWCD to depress the V_{loop}.

T. Intrator et al., Phys. Plasmas 2, 2263 (1995)



Low phase velocity current drive could approach ohmic efficiency (if momentum input to trapped electrons is recovered)



Great need for more experiments

D. Ehst and C. Karney, Nucl Fusion 31, 1933 (1991)

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Where is more work needed?

- A high power, direct comparison of conducting and insulating limiters is still needed.
  - Obvious candidate: C-mod
- Jury is *still* out on unshielded antennas
  - Like most technology tests, outcome is highly configuration dependent.
  - But Faraday shields are an Achilles heel for a reactor.
- Low phase velocity current drive has barely been studied.
  - 1 short-lived experiment!
  - Would have a major effect on the direction of RF technology development.
- Note that this experiment need not be in the Alfven regime.
  - Best venue: a device with *low Alfven speed*
  - Best candidate: ***NSTX***