Application of Helicons to Off-Axis Current Drive in DIII-D and FNSF

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General Atomics

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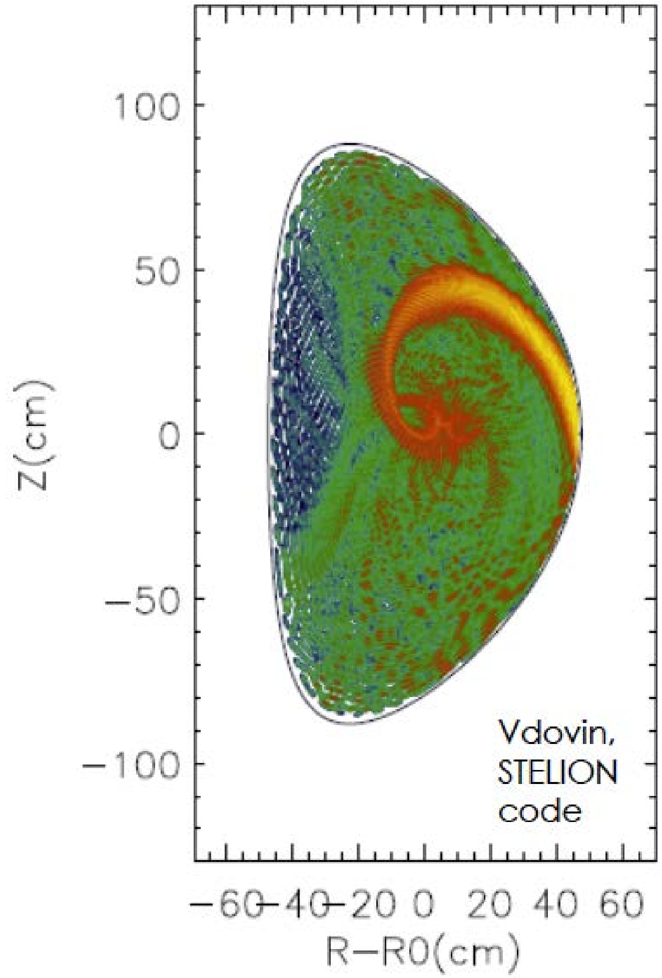

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What are ‘helicons’ (or ‘whistlers’)?

- **Fast waves in the frequency range 500 to 1500 MHz**
  - well above the ion cyclotron frequency (of order 30th harmonic) but well below the lower hybrid frequency
- **These waves tend to propagate in a spiral around the magnetic axis**
  - the spiral is what leads to off-axis current drive
- **Their absorption rate is sufficient that they may be damped in a single pass in plasmas with high electron beta**
- **They drive current by Landau damping (same way as lower hybrid waves, but no tail on the distribution function is generated)**

The wave physics is very well understood

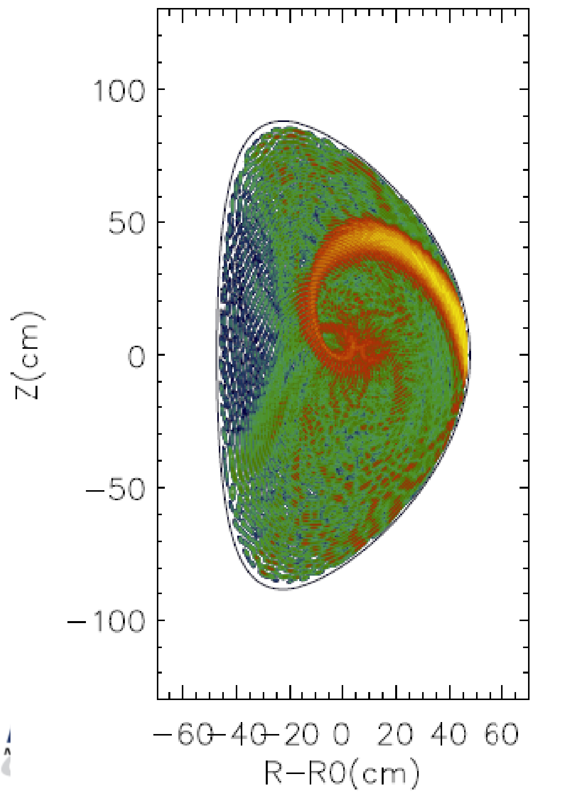
- **The wave physics presented here is fully described in Stix' book**
- **Experiments were performed on current drive in this frequency range starting in the 1980s**
- **What's new here:**
  - the specialization to plasmas with high electron beta, which gives full single-pass damping
  - the proposed use of a traveling wave antenna, which can launch this wave effectively
- **Result: off-axis current drive with efficiency 2 to 4 times higher than that from neutral beam injection or electron cyclotron waves**

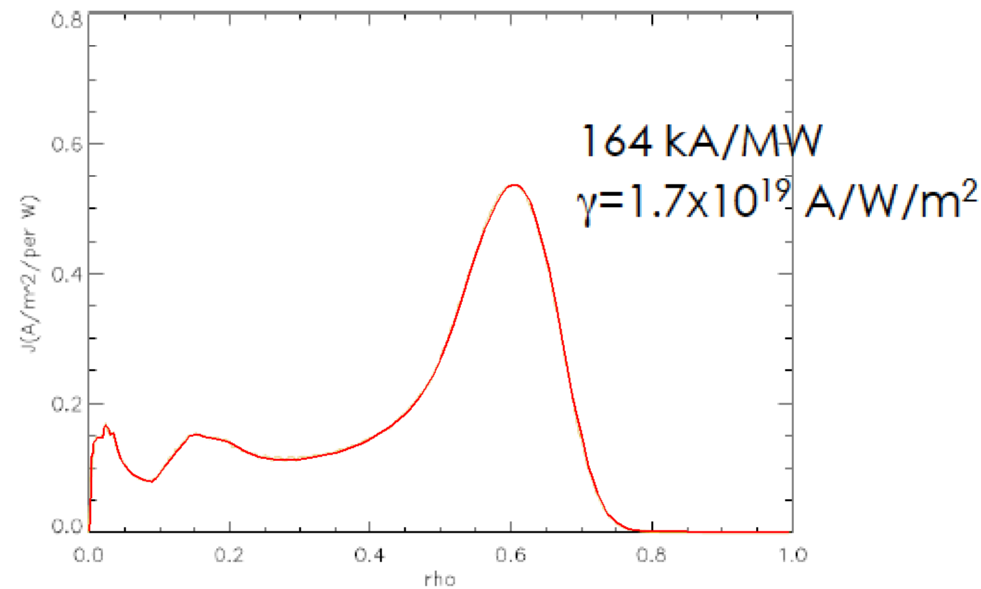
High frequency and high β_e improve damping of the fast wave

- **Steady-state tokamak scenarios require off-axis current drive**
- **The stronger the damping the more likely to deposit power off-axis**
  - Low harmonic fast waves in DIII-D are weakly damped and always deposit power and current centrally
  - High harmonic fast waves are more strongly damped
- **What helps: high frequency, high β_e, high density**

The spiral nature of helicon ray trajectories favor off-axis CD

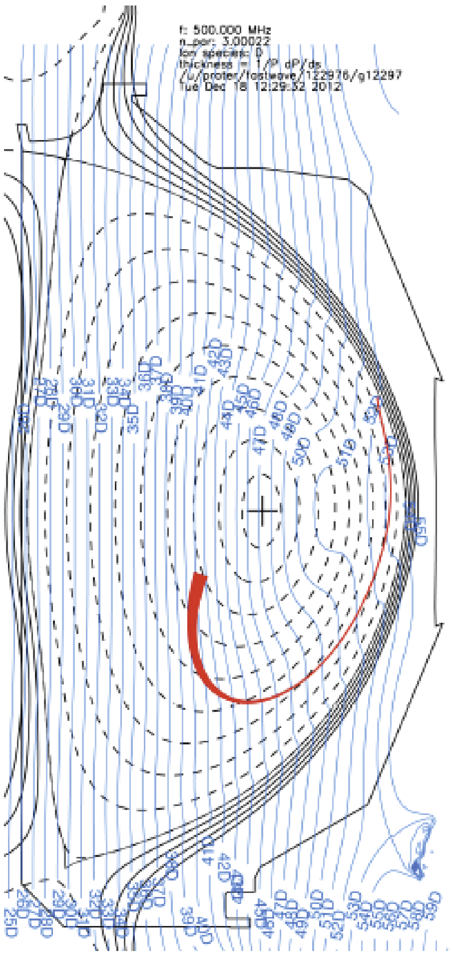
- **Vdovin showed calculations from his STELION full wave code that show wave power spiraling about the center, with most power absorbed off-axis**



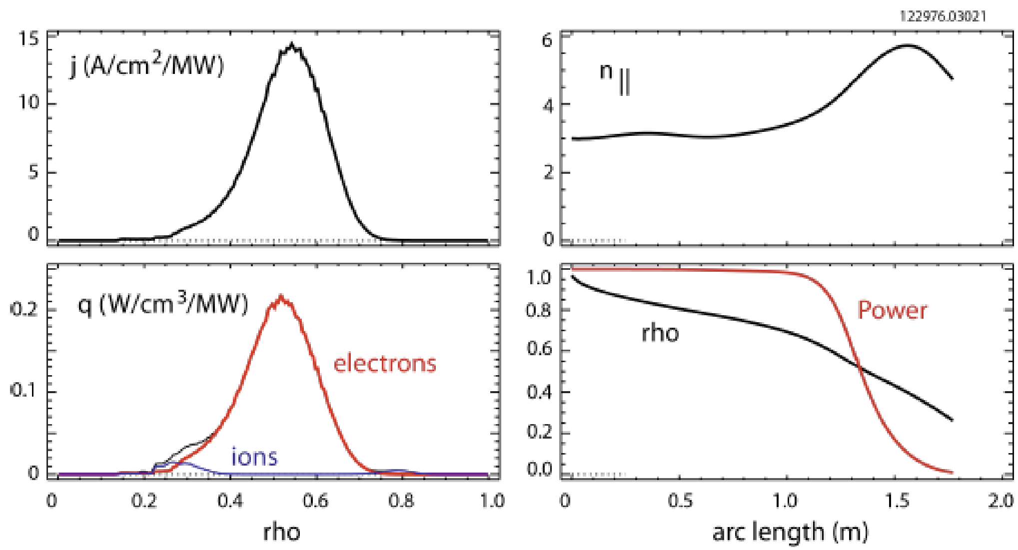


Magnitude of |E| on a logarithmic color scale

GENRAY shows rays with power flow similar to STELION full wave code

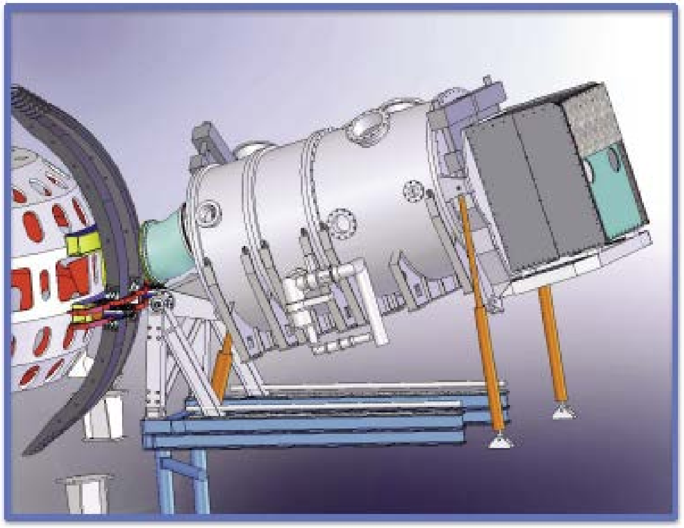


$n_{||}(a) = 3.0$, f=500 MHz
$n_e(0) = 10.3$, $T_e(0) = 3.4$, $T_i(0) = 7.2$, Zeff ~ 2.2
$\beta_e(\rho=0.5) = 3.2\%$

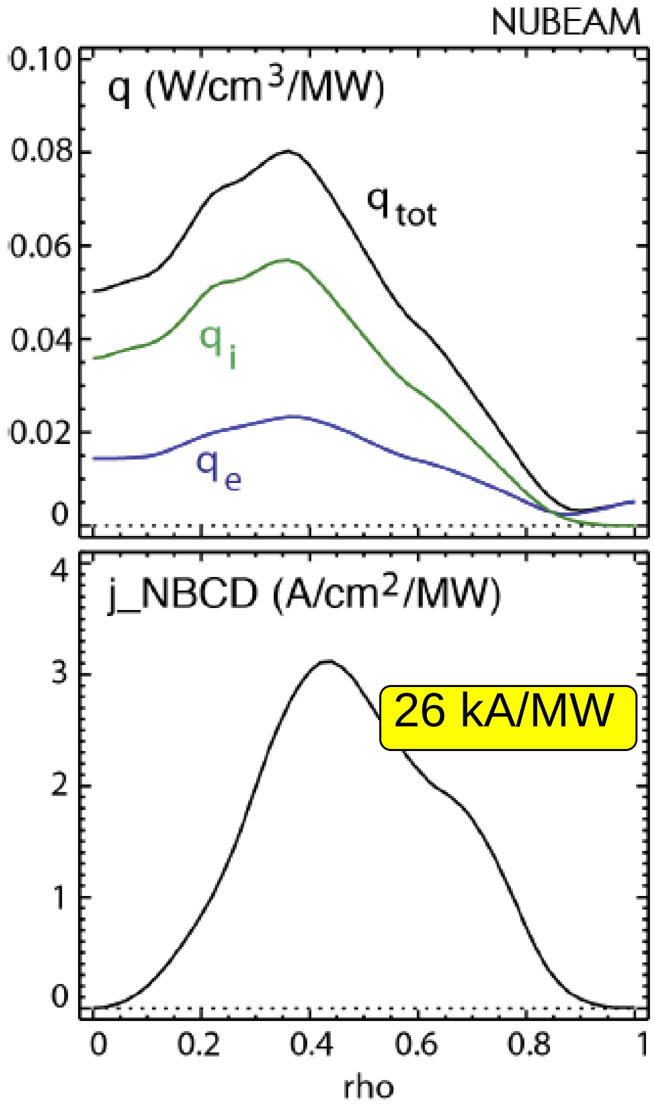


I_{CD} = 60 kA/MW
η= nIR/P = 0.5×10^{19} A/W/m^2
$\zeta = 33\ n_{20}\ I\ R\ /\ P\ T_{keV} = 0.56$

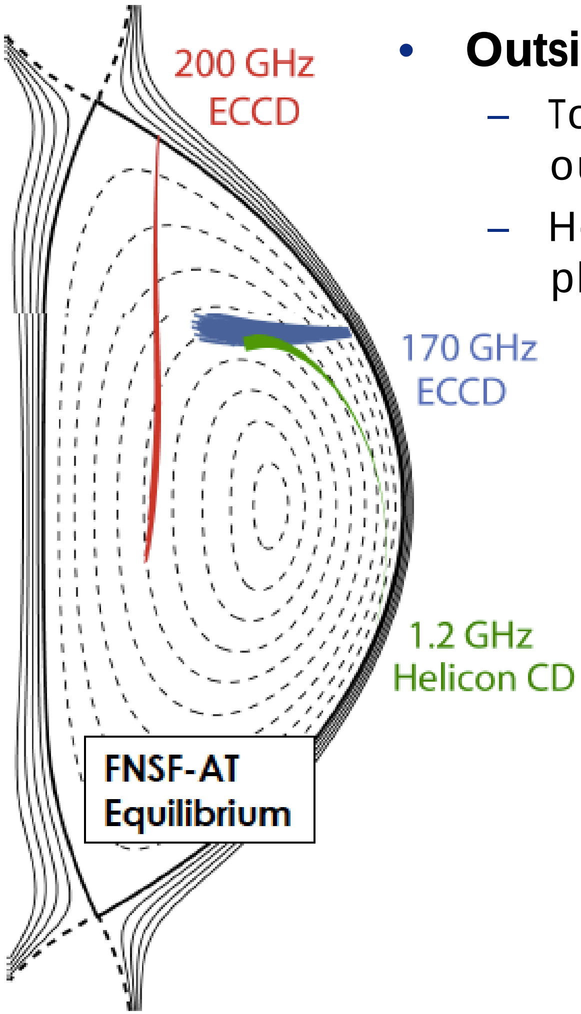
Off-axis NBCD drives about half the helicon current/MW in the same discharge



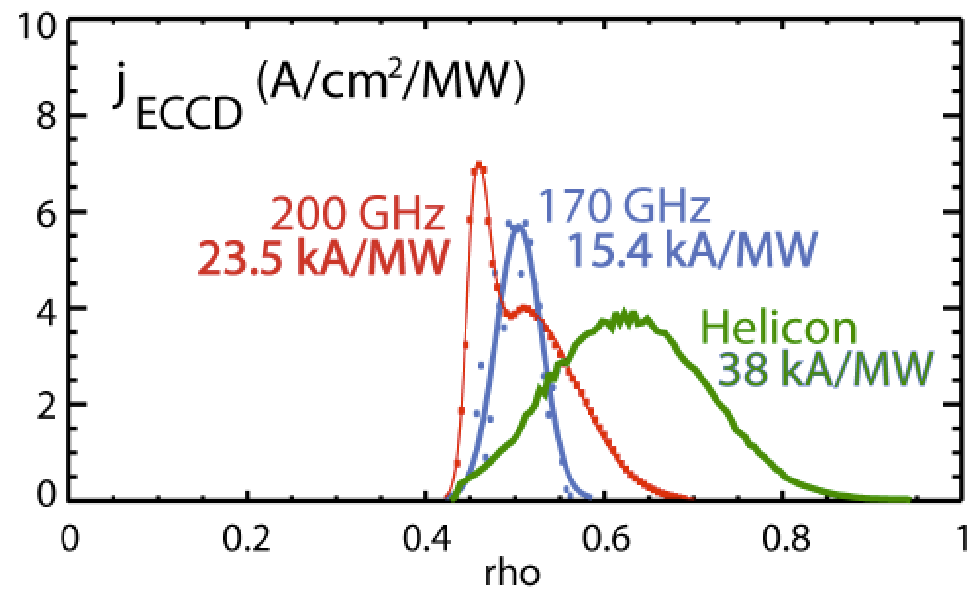
- **At maximum tilt, the DIII-D beam drives NBCD that peaks around ρ=0.45**
- **Total driven current for left source is 26 kA/MW for signs of I_p and B_t that maximize NBCD**



Helicons drive 1.5-2 times more off-axis current/MW than ECCD in FNSF-AT



- **Outside EC launch vs top EC launch vs Helicon**
  - Top launch at 200 GHz gives 50% CD increase over outside launch at 170 GHz, but reduced flexibility
  - Helicons give 150% increase over outside launch ECH, plus better CD profile



- **Higher CD efficiency is why helicons were chosen for ARIES-AT**

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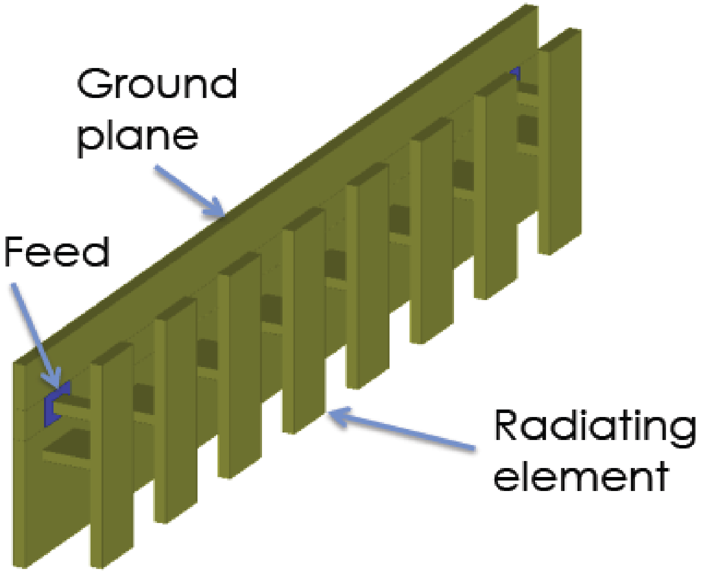
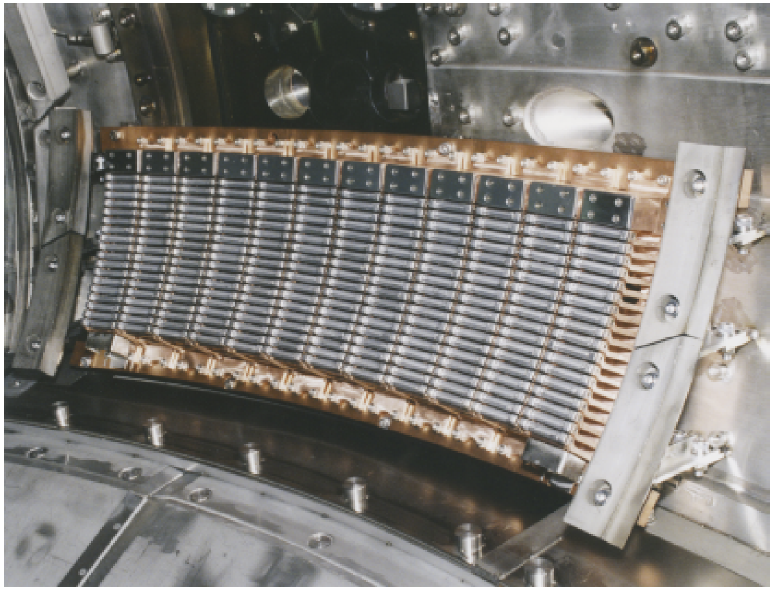
Launching the helicon wave benefits from use of a Traveling Wave Antenna (TWA)

- **TWA is a sequence of radiators coupled inductively but fed only at one end**
- **Wave amplitude decays radially exponentially near antenna, with radial 1/e length of order the parallel wavelength/2π**
  - for DIII-D, the parallel wavelength is ~20 cm
- **Traveling wave antenna works best for weak to moderate coupling per antenna element along the antenna**
  - **moderately large gap is desirable**
  - **launches narrow spectrum**

Traveling Wave Antenna was tested on JFT-2M in 1996



- 10-50 radiators
- Feedthroughs only at ends
- Matched impedance minimizes voltage
- Radiators connected inductively
- 4 or more straps per parallel wavelength



- 12 radiating straps
- Tested at voltages corresponding to 800 kW
- Experimentally successful at launching the fast wave
- Designed and built by GA

[Moeller, 1993;
Pinsker, 1996;
Ogawa, 2001]

Summary

- Helicons offer significant improvement in off-axis current drive efficiency over ECCD and NBCD, both for DIII-D and FNSF
- Coupling to the plasma is effective for gaps as large as 5 cm

- For the balanced combline with 1 MW input, the highest peak voltage is expected to be < 14 kv

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