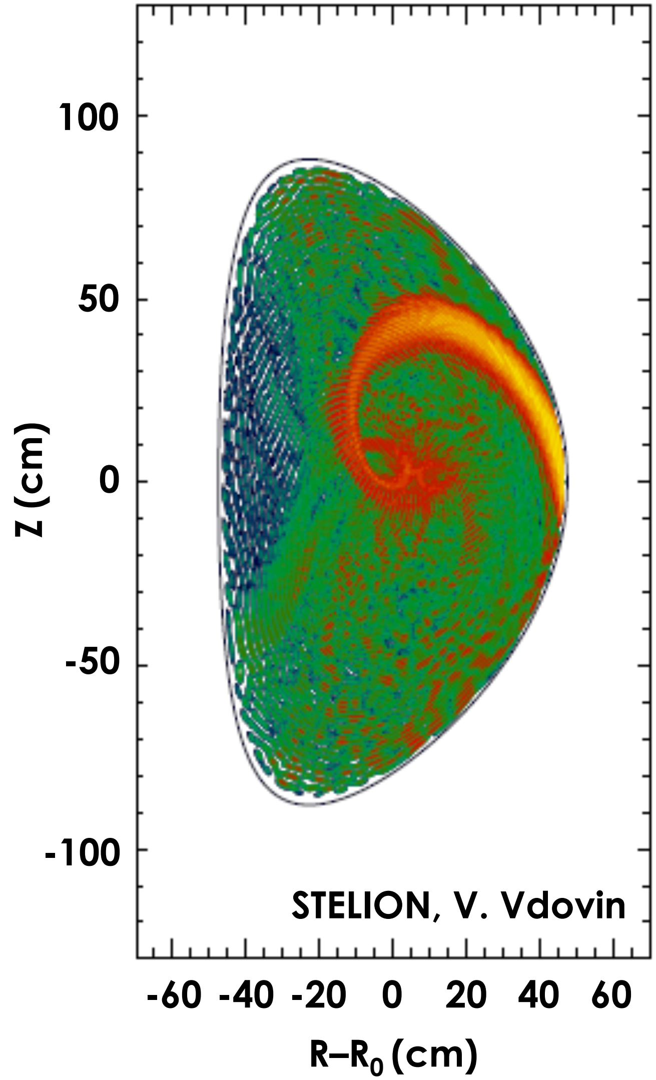
Whistlers, Helicons, Lower Hybrid Waves: the Physics of RF Wave Absorption for Current Drive Without Cyclotron Resonances

R.I. Pinsker
General Atomics



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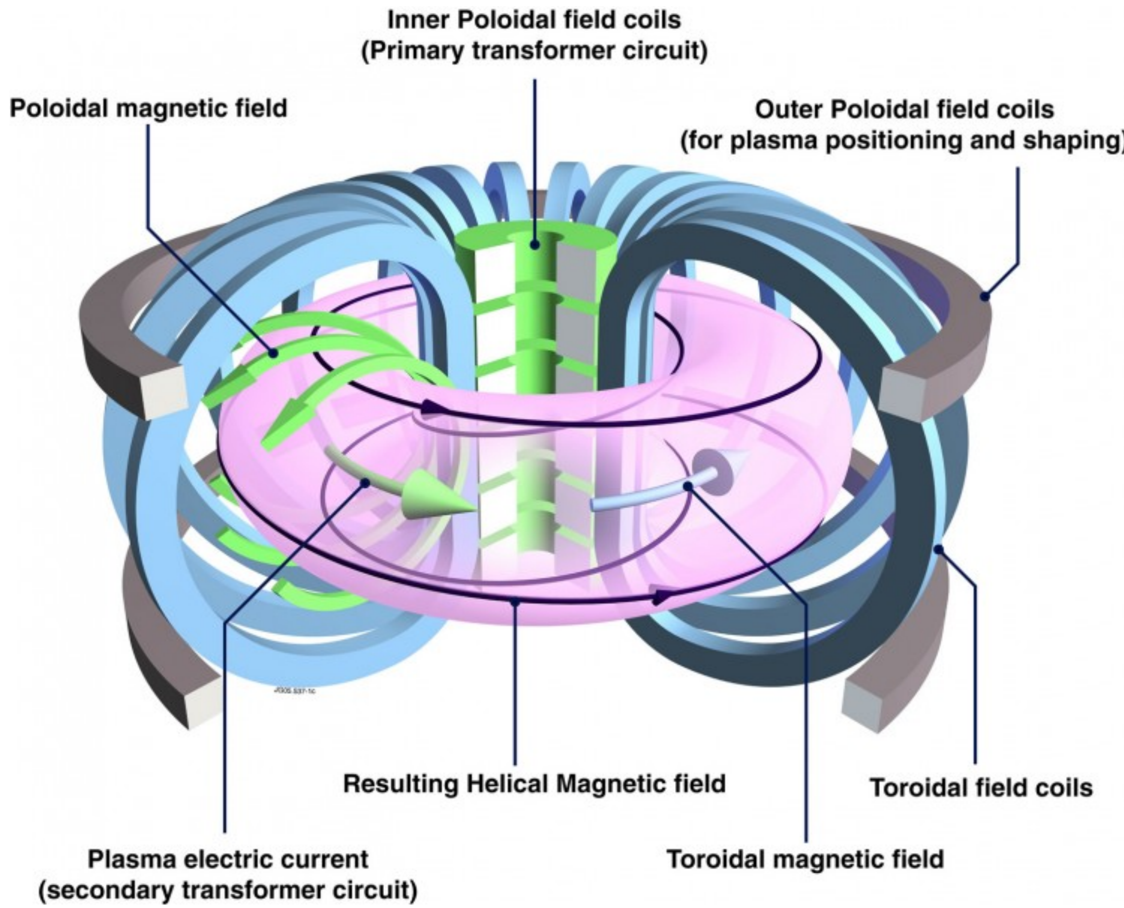
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

GENERAL ATOMICS

Tokamaks – the need for non-inductive current drive

- **Tokamaks – confinement = current**
- **Most of the current in a steady-state tokamak fusion reactor is 'bootstrap'**
- **Still need ~MA of current driven by other means**
- **Reactor studies typically show that the current must be driven at <u>mid-radius</u>**
- **Wave current drive proven successful, but challenges remain**

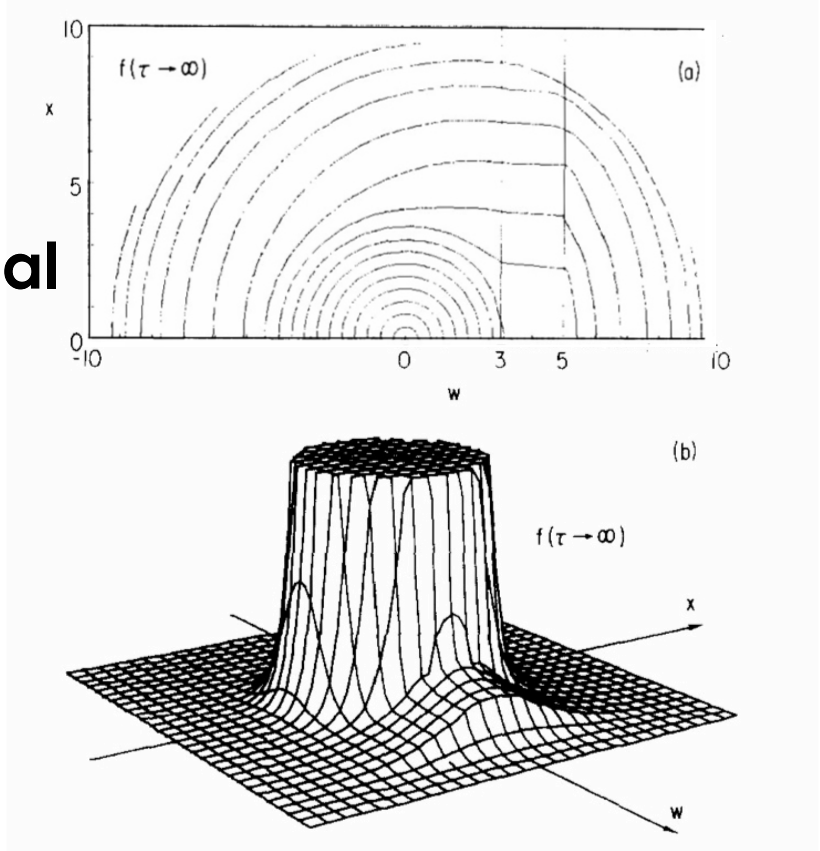


The generic tokamak

Motivation – wave current drive with collisionless damping mechanisms

- **Idea – transfer energy to electrons in toroidally directional way in velocity space**

- **Since in a reactor collisions are infrequent, must use damping mechanisms that dominate in low collisionality limit**



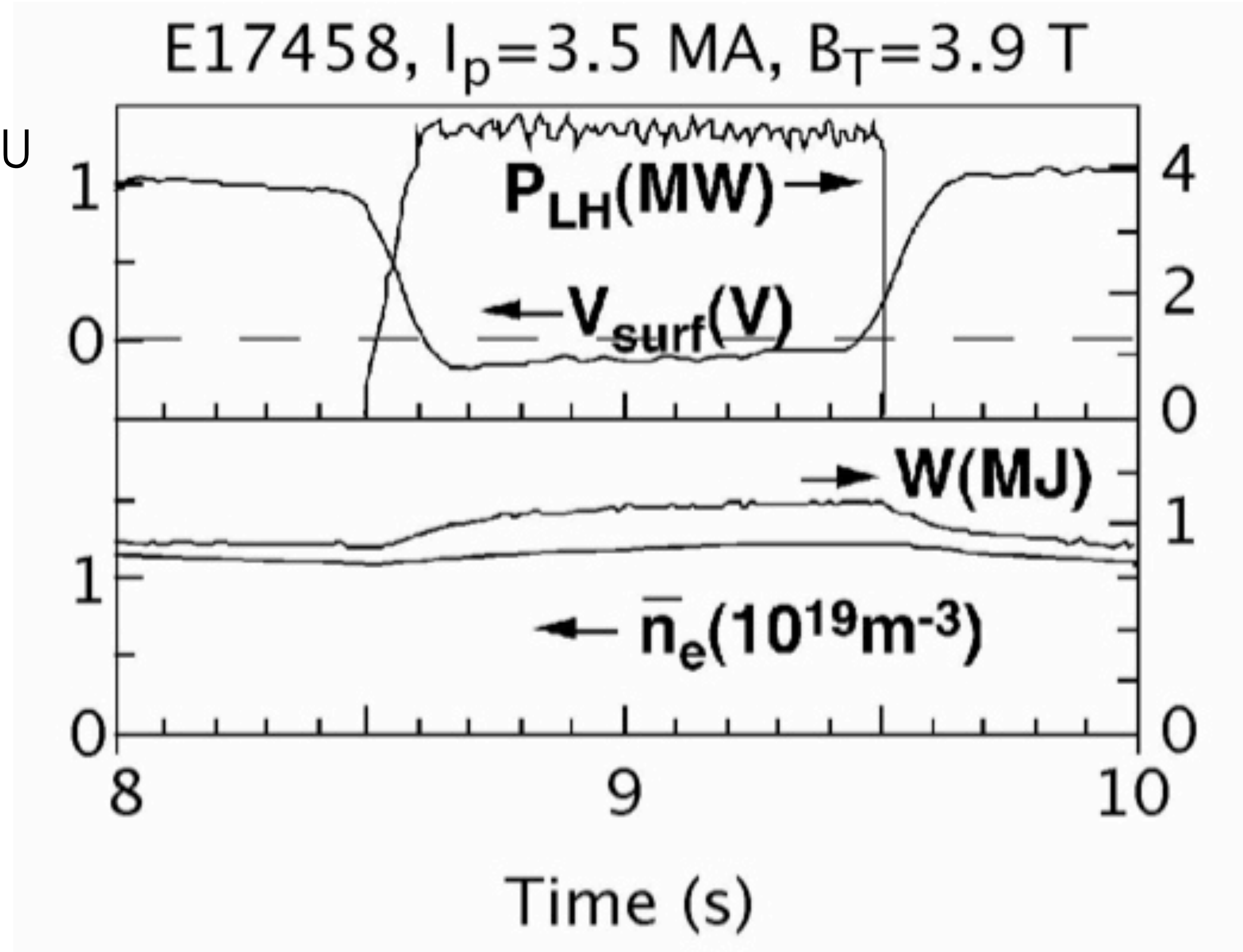
Karney and Fisch, 1979

Why you should care about this topic

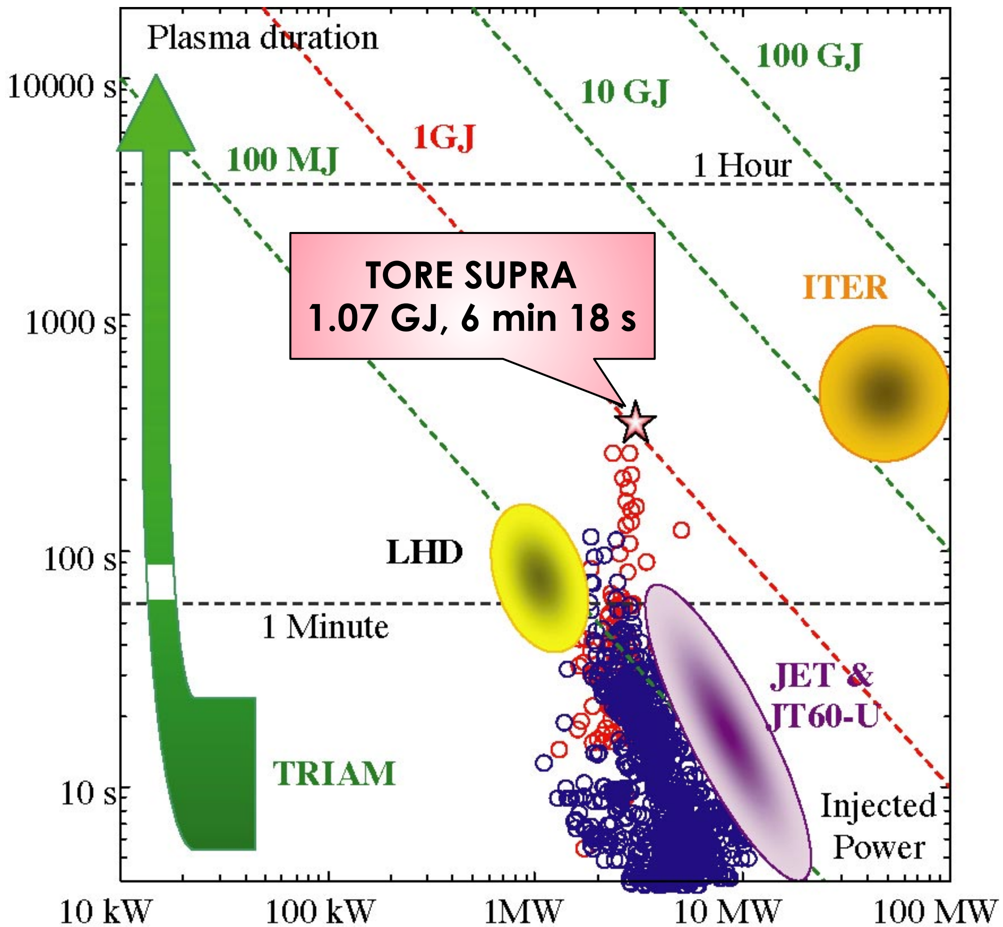
- RF current drive works spectacularly well! Let me remind you in the next few slides about lower hybrid current drive – 10 to 20 years old
- Linkages between this topic, space science, and to rf plasma source physics are intrinsically interesting
- A twist on current drive that has never been tested in a situation where it should work is about to be tried experimentally – it is required for most reactor designs based on the Advanced Tokamak

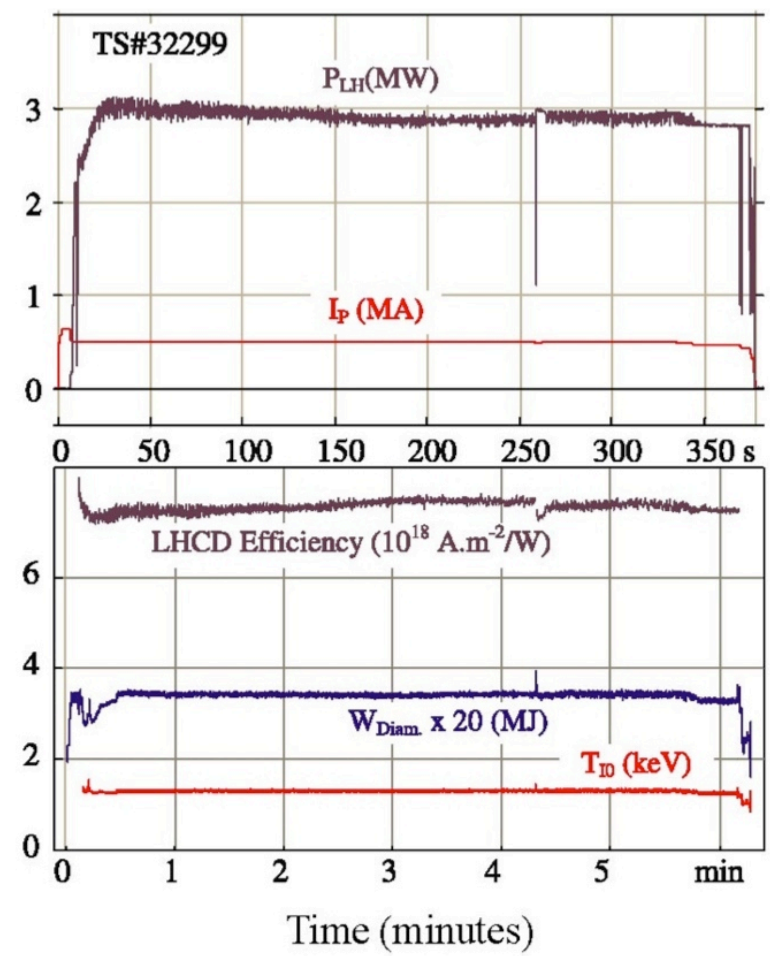
3.5 MA driven with 4.8 MW of 2 GHz LH in JT-60U at low density (~1.2 x 10^{19} m^{-3}), similar 3 MA LHCD on JET

JT-60U



TRIAM 1-M ran for over 2 hours (!), Tore Supra for 6 minutes with over 1 GJ injected and extracted – both with LHCD





- **Courtesy of Tore Supra**

Outline of presentation

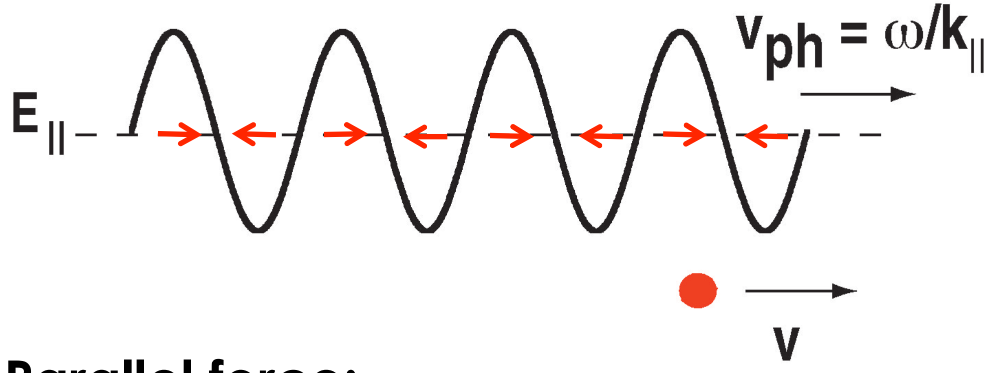
- **Electron damping mechanisms available for current drive**
  - Parallel and perpendicular damping mechanisms
  - Properties of the damping mechanisms set requirements on wave, frequency, wavelength choices
- **What waves are available?**
  - Jargon in different fields (fusion, plasma sources, space science)
  - Why the interest in the "lower hybrid range of frequencies"?
  - Wave propagation in that range
  - Fast waves: transition from Alfven-wave-like to whistler-like behavior
- **Key point: properties of Landau damping, wave 'accessibility' impose limits on wavelength that imply coupling is not easy from vacuum, for either wave branch in the LHRF**
- **DIII-D experiment on helicon/whistler**

Two classes of collisionless absorption: parallel and perpendicular (to static B field) interactions

- **What are the damping mechanisms?**

- **Charged particle motion along static B-field unaffected by B_0, so interactions divide into parallel and perpendicular**

- **Familiar resonance condition is $v_{||}=v_{ph}$ or $\omega - k_{||}v_{||} = 0$ →**
  Landau damping

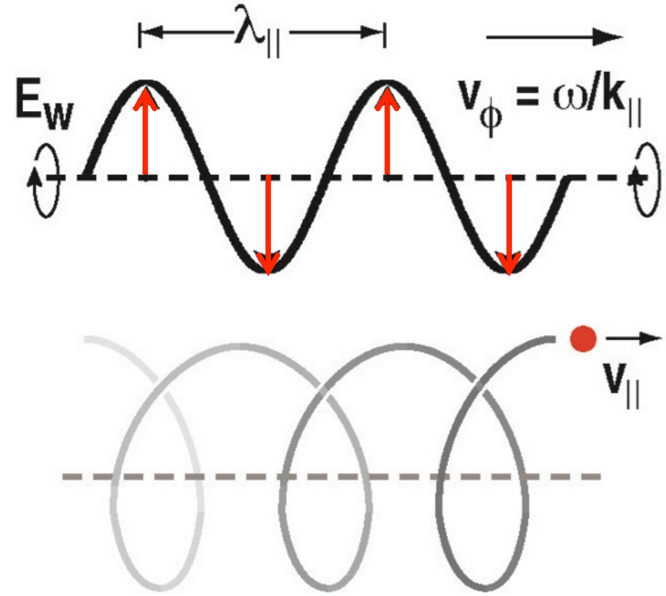


- **Parallel force:**
  - Electric: wave $\tilde{E}_{||}$ pushes on charge via $F_{||}=qE_{||}$
  - Cares about sign of $k_{||}$, so by launching waves with only one sign of $k_{||}$ (directional spectrum), can interact with electrons moving in one direction: *current drive*

Other collisionless absorption process: cyclotron damping ('perpendicular')

- **Charged particle interacts with circularly polarized wave electric field component $\perp B_0$**
- **Resonance condition: particle sees steady E-field in its rest frame**
- **Particle feels wave fields at Doppler-shifted frequency $\omega - k_{||}v_{||}$, and resonance requires**
  - $\omega - k_{||}v_{||} = \Omega_q$ and
  - Handedness of rotation same as that of the charged particle's orbit
- **If wave fields vary across orbit ($k_{\perp}\rho \sim 1$), interaction exists at harmonics, so general resonance condition:**

  $\omega - k_{||}v_{||} = \ell\Omega_q$ **(ℓ an integer)**

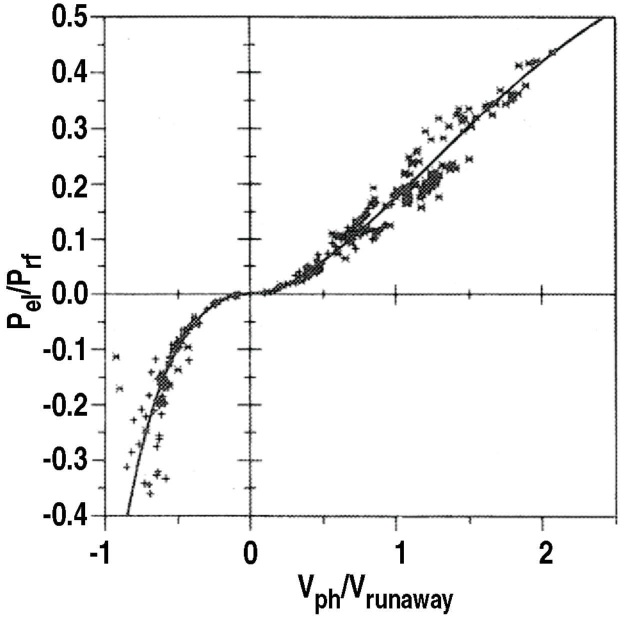


Different parts of the wave electric fields are involved in the two classes of collisionless damping

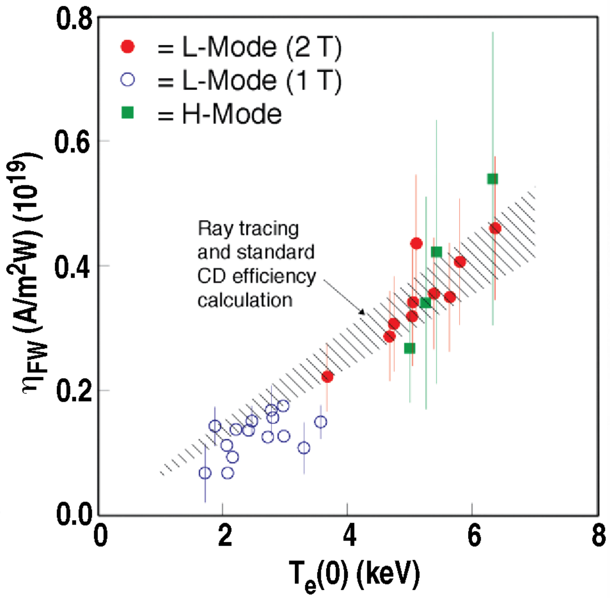
- **$|\ell|>0$: Cyclotron damping**
  - Involved E-field is perpendicular to B_0, and parity of circularly polarized component of wave field matters a lot
  - Frequency close to cyclotron frequency or harmonics if perpendicular wavenumber is nonzero
- **We are interested in electron current drive, done by asymmetrically interacting with electrons with $+v_{||}$ and $-v_{||}$**
- **Can be done with $\ell=1$ or $\ell=2$ electron cyclotron interaction, which is another story (ECCD)**
- **At frequencies below $\ell=1$ ECR, only available collisionless electron damping is via parallel interactions ($\ell=0$), where the involved E-field is parallel to B_0**

Even in complicated regimes, damping and current drive efficiency are well understood

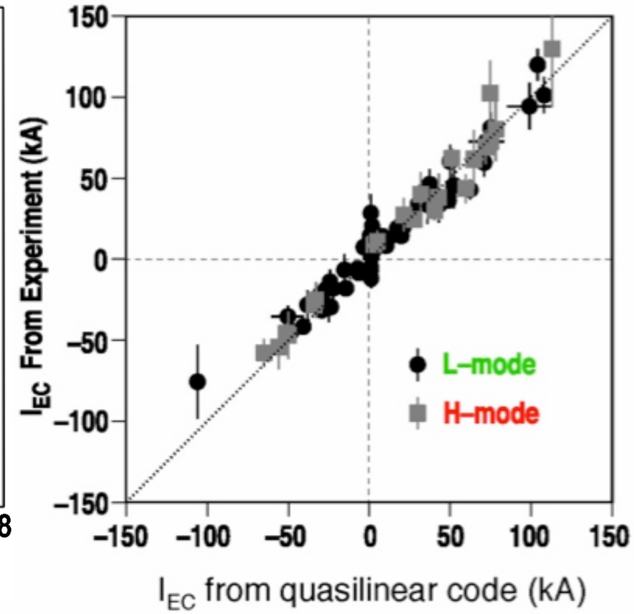
LHCD on PLT



FWCD on DIII-D



ECCD on DIII-D



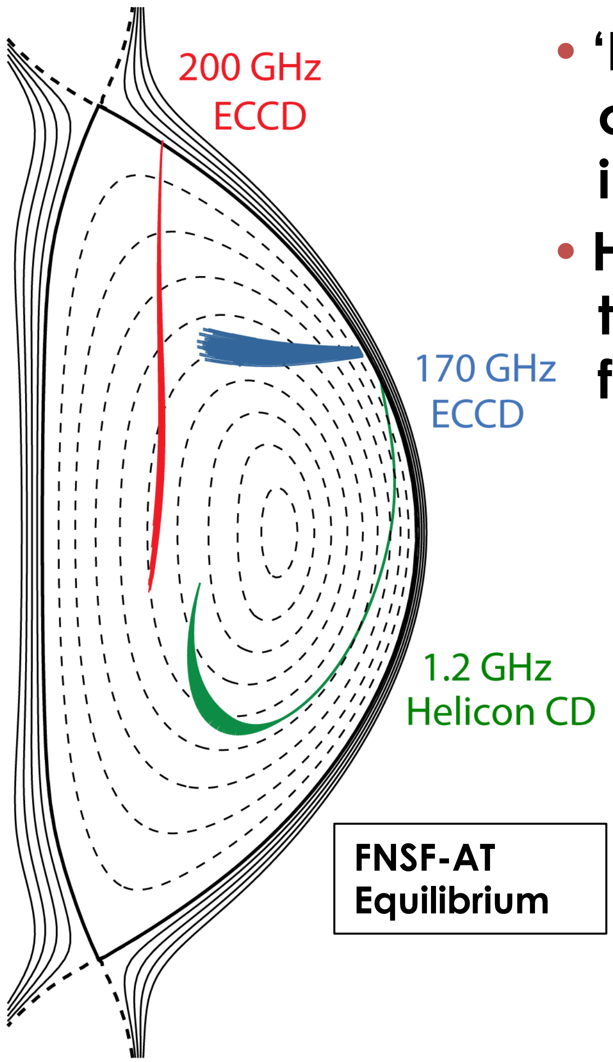
- To advance towards more challenging task of <u>mid-radius</u> current drive, need to apply understanding of wave propagation and current drive efficiency to find the best wave parameters – the ones that are 'just right'

What are the advantages of using ℓ=0 absorption processes for off-axis current drive?

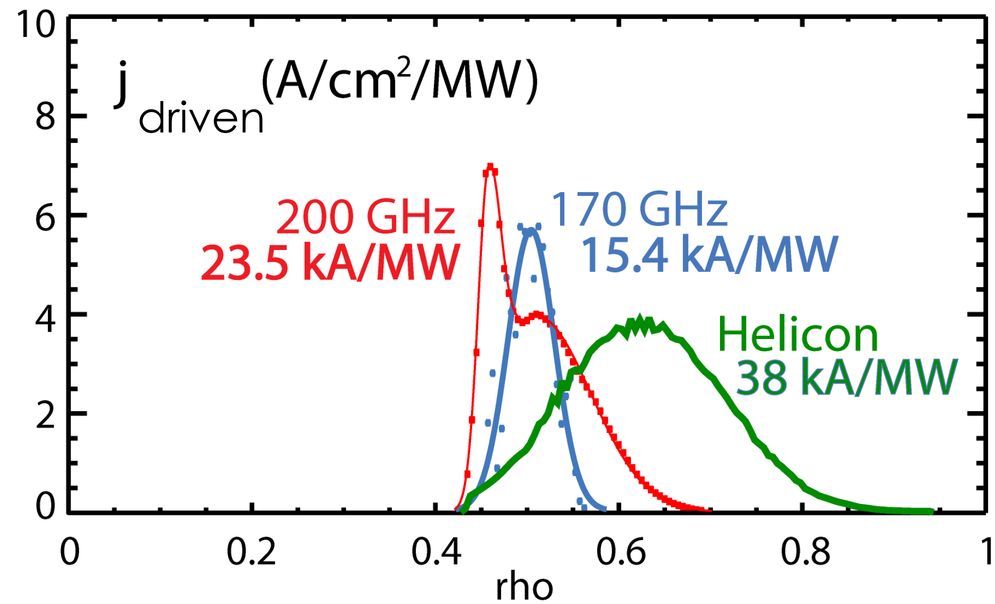
Efficiency and accessibility:

- **Greater efficiency is possible (and demonstrated for slow wave LHCD) – efficiency of current drive scales as $v_{\parallel}^2$**
  - Trapping can be a small effect for absorption by parallel interactions with fast electrons (interacting with electrons far from trapped-passing boundary in velocity space)
- **Ray paths in ECRF refract away from high density, so penetration at high (reactor-like) densities can be an issue (example of wave accessibility)**
- **Key point: often conflict between the most efficient waves and their accessibility to the desired location in the plasma**
- **Leads to existence of optimal choices**

Example of advantage of || interactions: 'helicons' in FNSF-AT

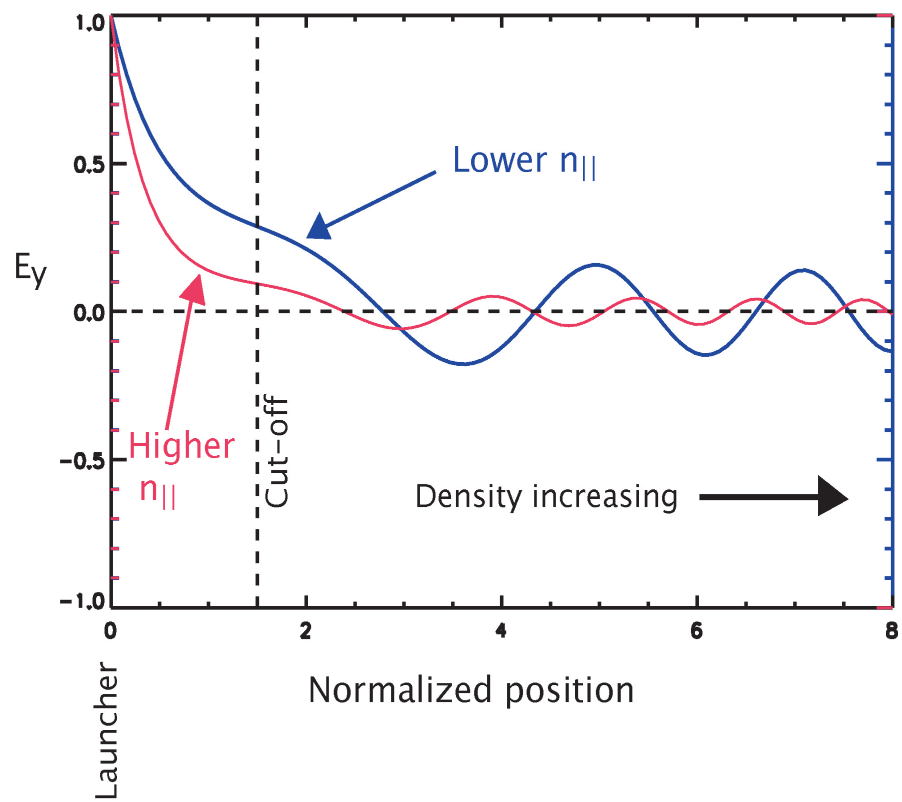


- 'Helicons' predicted to drive off-axis current 1.5-2.5x more efficiently than ECCD in FNSF-AT design
- Higher CD efficiency in the right place in the plasma is why helicons were chosen for ARIES-AT [Jardin, et al., 1997]



Waves that Landau damp must be evanescent in vacuum → coupling challenge

- **No electrons have $v_{||} > c$, so for Landau damping waves must have $v_{ph||} < c$**
- **Waves with $n_{||}=c/v_{ph||} > 1$ decay radially in vacuum region, near antenna**
- **Rapidity of decay increases with $n_{||}$ at fixed frequency, or with frequency at fixed $n_{||}$**
- **More rapid decay ⟹ higher electric fields needed in antenna to couple power**



The search for the appropriate wave(s) for mid-radius CD

- **To do electron current drive, we need to be able to**
  I) Excite the wave from an antenna in the vacuum region, without excessive wall interaction
  II) Wave must propagate from the antenna to the desired location of damping/current drive, without excessive damping along the way
  III) Damp on electrons in a radial zone that is well-defined

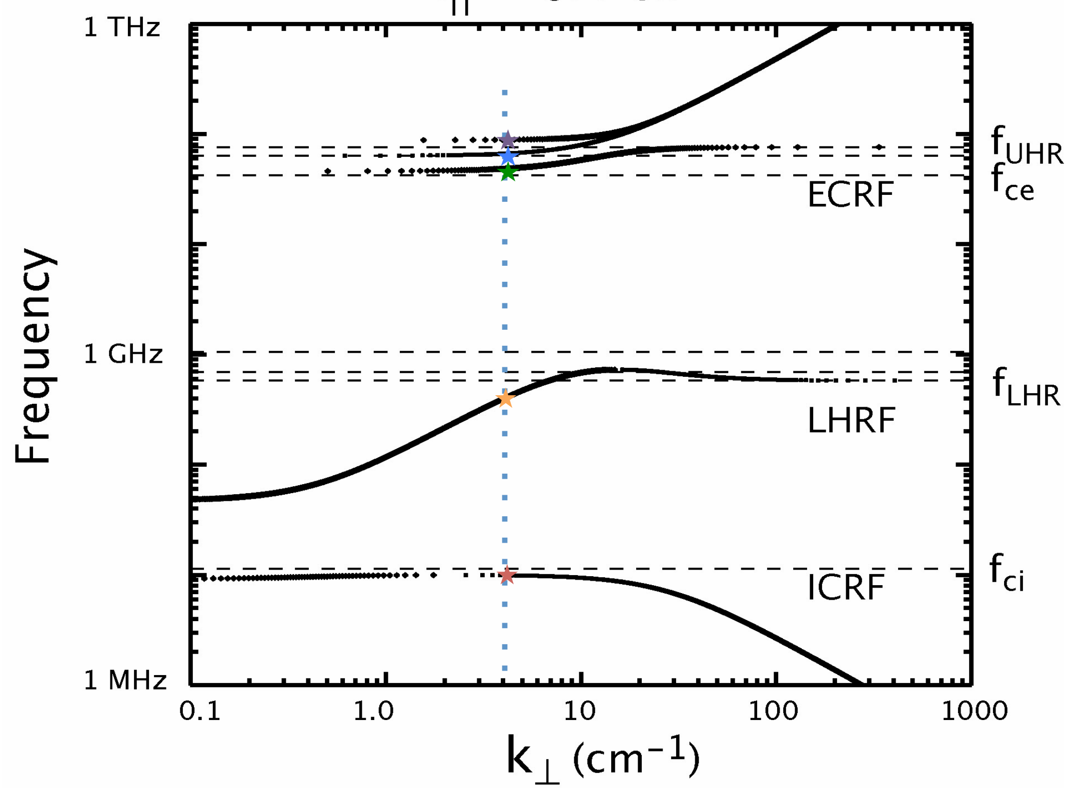
- **Hence we examine what waves are available with $n_{||}>1$ for tokamak parameters**

Cold plasma waves at fixed $k_{||}$ - the BIG picture

- **How many cold plasma waves there are depends on what's held constant**

- **At fixed $k_\perp$ and $k_{||}$, there are up to five different frequencies satisfying the dispersion relation**

B_0=1.5 T, n_e=5x10^{19} m^{-3}, deuterium
$k_{||}$ = 0.4 cm^{-1}

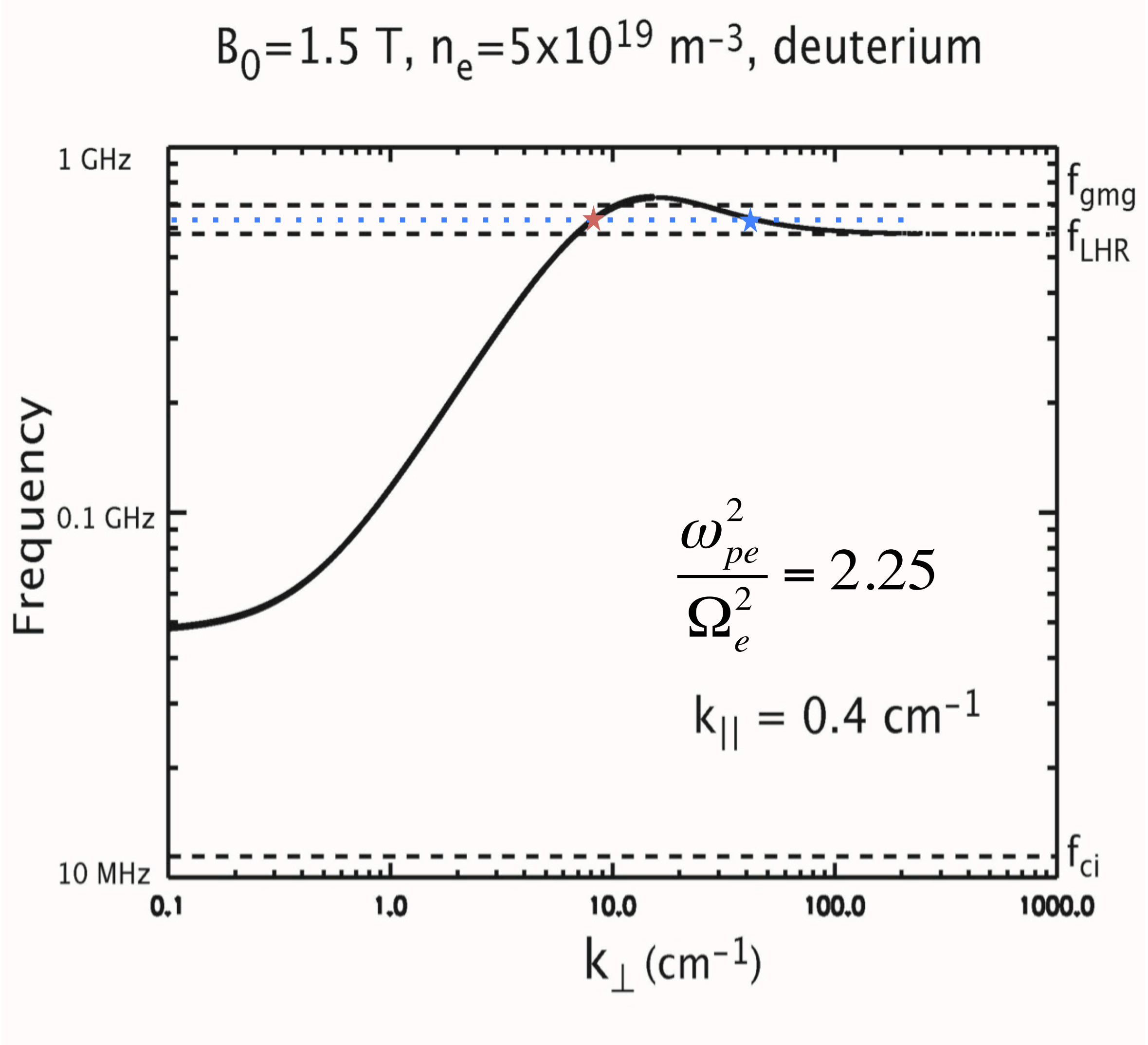


f_{ci} = 11 MHz; f_{ce} = 42 GHz; f_{gmg} = 0.69 GHz
f_{pi} = 1.05 GHz; f_{pe} = 63 GHz

f_{LHR} = 0.58 GHz, f_{UHR} = 76 GHz

Cold plasma waves at fixed $k_{||}$ - zoom in on LHRF

- At <u>fixed</u> frequency and $k_{||}$ there are 0, 1, or 2 different values of $k_\perp$ that satisfy the dispersion relation
- If 2, the bigger $k_\perp$ root is called (radially) "<u>slow</u>" and the other "<u>fast</u>"



Why is the range of frequencies between the ion and electron cyclotron frequencies called the LHRF?

- In very high IC harmonic range, $\Omega_i << \omega << \Omega_e$, call this range Lower Hybrid Range of Frequencies (LHRF), because wave frequency is near lower hybrid resonance frequency

- At lower hybrid resonance, wavelength across field of SW goes to zero, perpendicular group velocity goes to zero – wave can never reach LHR (wave resonance)

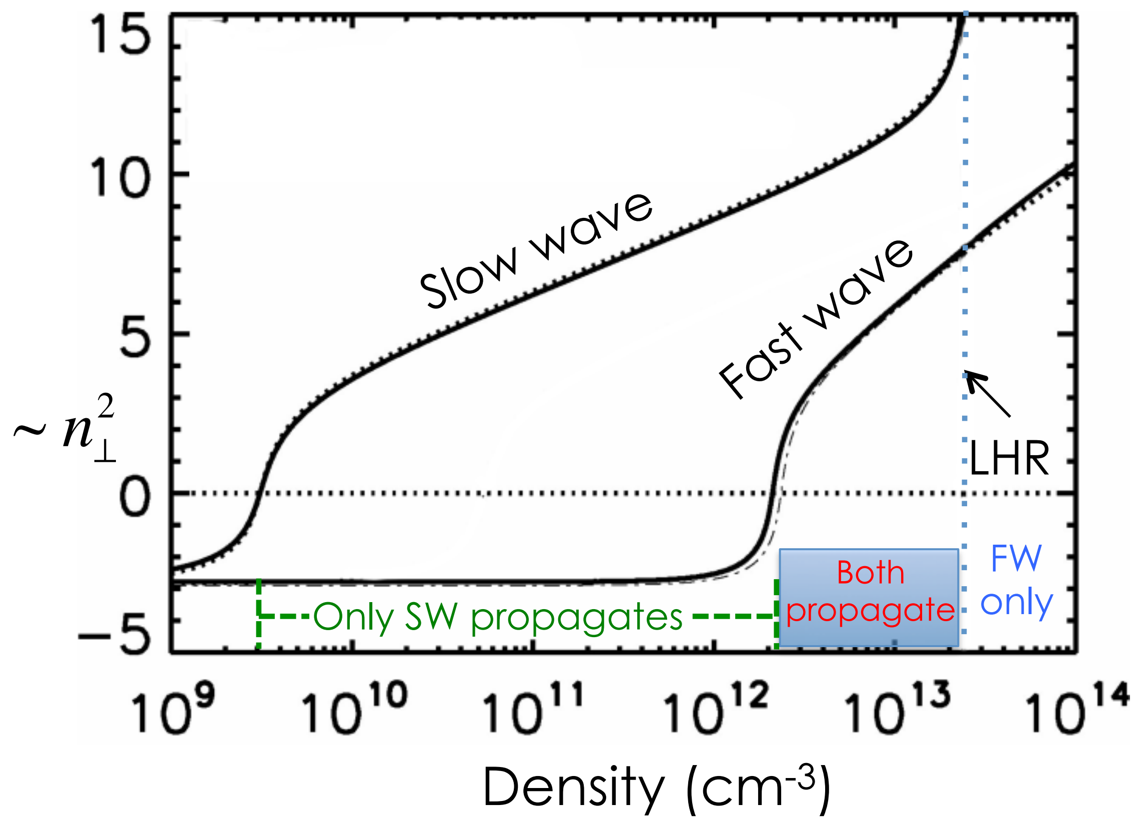
- If $\omega_{pe}^2 << \Omega_e^2, \quad \omega_{LH} \approx \omega_{pi}$ (low density, high field)

- If $\omega_{pe}^2 >> \Omega_e^2, \quad \omega_{LH} \approx \sqrt{\Omega_i \Omega_e} \equiv \Omega_{gmg}$ (high density, low field), which defines the geometric mean gyrofrequency Ω_{gmg}

How does the lower hybrid resonance affect the propagation of slow and fast waves?

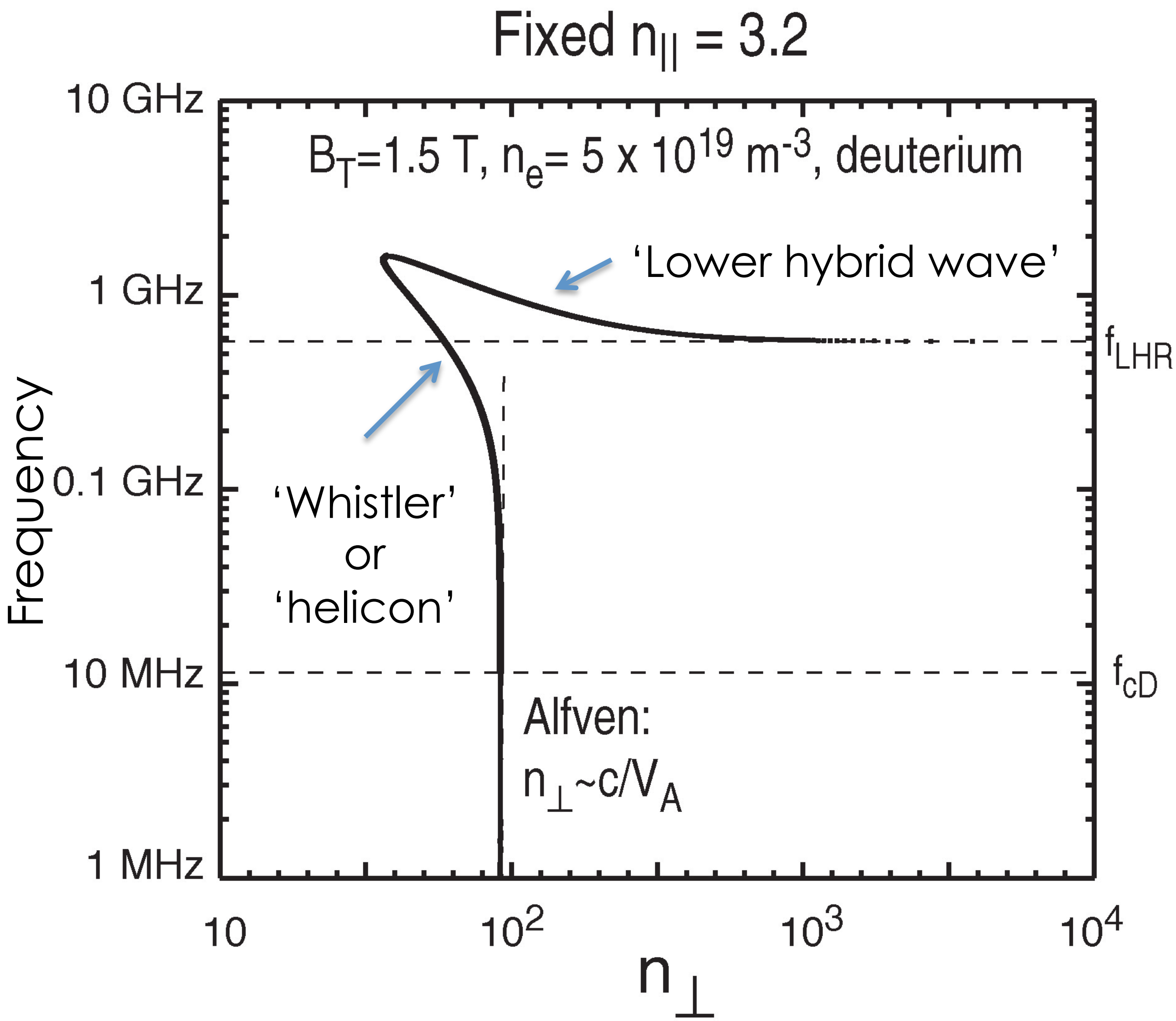
- In LHRF, both fast and slow waves propagate in significant volume of the plasma at the same $n_{||}$
- Fast wave does not 'see' the lower hybrid resonance, slow wave is stopped by it
- How can that happen? Answer: different polarizations for the two branches at different $k_\perp$

- 500 MHz waves at $n_{||}=3$



Available waves for electron absorption by parallel processes, from low to high frequency

- At $n_{||} > 1$, no propagating cold plasma waves at higher frequencies
- Origin of the terms 'whistler' or 'helicon'?



Helicons and whistlers I am NOT talking about

- Mt. Helicon (Greece)

- In British Columbia

- E-flat Helicon (related to the tuba)

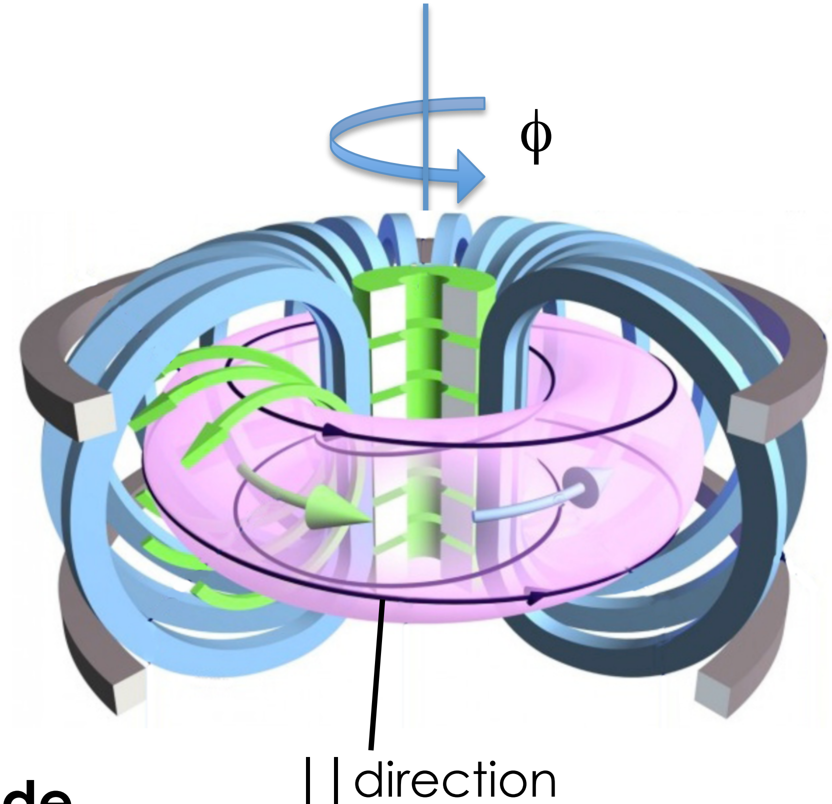
- In Musée d'Orsay

Jargon in different applications of the cold plasma mode(s) in the LHRF

	Fusion/ tokamaks	Plasma sources (bounded geometry)	Magnetosphere physics
Mainly electromagnetic wave (radially forward wave)	Fast wave in the lower hybrid range of frequencies	Helicon	Whistler
Mainly electrostatic wave (radially backwards)	Lower hybrid wave (or ‘slow wave’)	Trivelpiece-Gould mode	Sometimes considered just part of whistler
Main linear damping mechanisms	Landau damping in core plasma, maybe collisional, sheath losses in edge	Collisional damping of TG modes at high densities, maybe some LD on non-thermal electrons at low density	In ionosphere, collisional In magnetosphere, Landau damping on non-thermal population

Different situations regarding wave excitation in tokamaks, space science, and plasma sources

- **Why refer to a fixed $k_{||}$, or $n_{||}$ at fixed frequency?**
- **In <u>tokamak</u>, launch waves at a specific frequency and toroidal wavelength**
- **Static magnetic field (defines || direction) is mainly toroidal**
- **Axisymmetry implies toroidal mode number is conserved**
- **Hence $n_{||}=k_{||}c/\omega = c/v_{ph||}$ is approximately conserved**

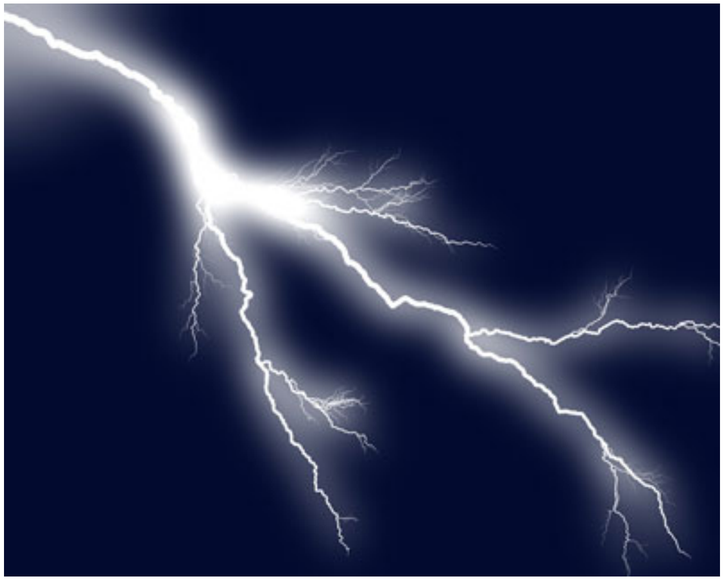


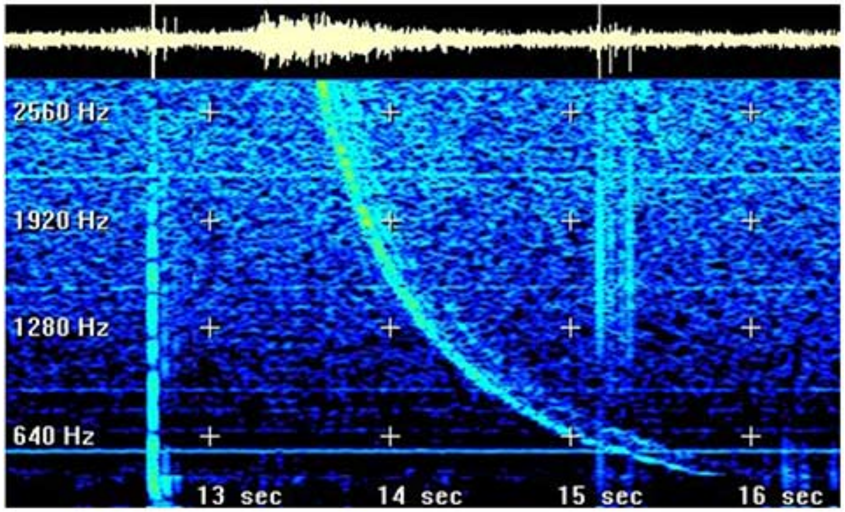
ϕ direction ignorable, almost same as || direction

Different situations regarding wave excitation in tokamaks, space science, and plasma sources

- In space science, waves at audio frequencies are excited by an impulse in time and localized in space – lightning!

- Hence frequencies and wavelengths that propagate can be detected 'downstream' – plasma in magnetosphere acts as a frequency and wavelength filter or delay line

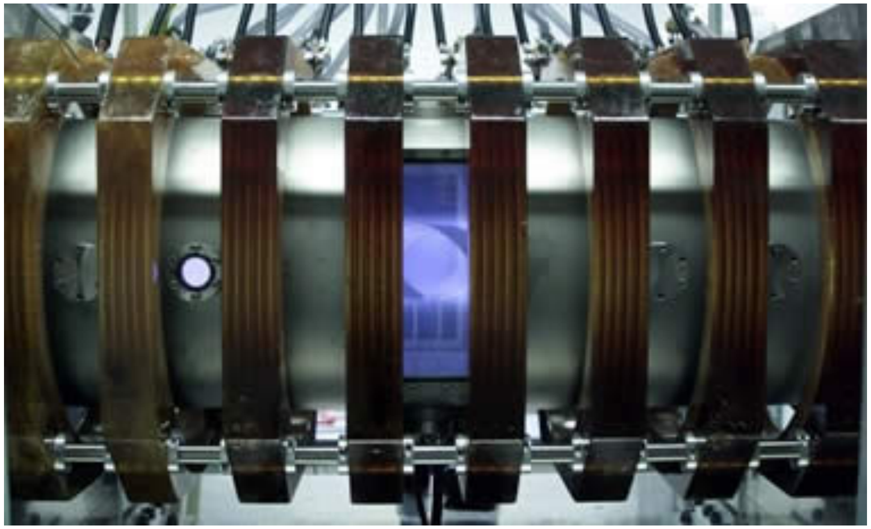




Different situations regarding wave excitation in tokamaks, space science, and plasma sources

- In rf plasma sources, waves are excited with a specific frequency, typically 13.56 MHz, by antennas that are not strongly k-specific

- The waves that will fit into the bounded geometry at the particular density and field – eigenmodes – are what propagates



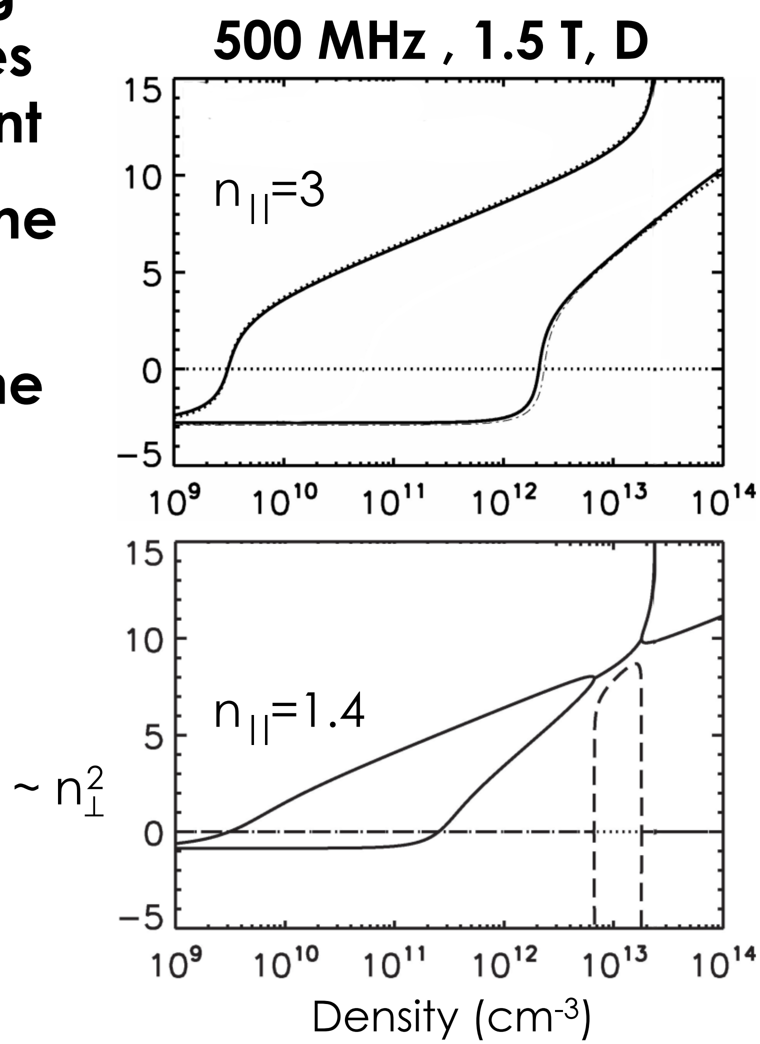
VINETA, IPP-Garching

Wave parameters in the three fields ~ same dimensionless range, which is the Lower Hybrid Range of Frequencies (LHRF)

	Tokamaks (core)	Plasma sources	Space science (magnetosphere)
Electron density (m^{-3})	10^{19} - 10^{20}	10^{18} - 10^{19}	10^{8} - 10^{10}
Magnetic field (G)	10^{4} - 10^{5}	10^{2} - 10^{3}	10^{-2} – 10^{-1}
Ion mass (amu)	2 (D)	40 (argon)	1-16 (H-O) [mostly 1]
Geometric mean gyrofrequency	(0.5 - 5) GHz	(1 – 10) MHz	(0.2 – 7) kHz
Typical wave freq.	(0.1 -1) GHz	10 MHz	(1 -10) kHz
ω_{pe}/Ω_e	0.1 - 3	3 -100	0.3 - 300
ω/Ω_i	1 - 100	250 - 2500	7 – 1 x10^{4}
Ω_e/ω	30 - 3000	30 - 300	3 - 300

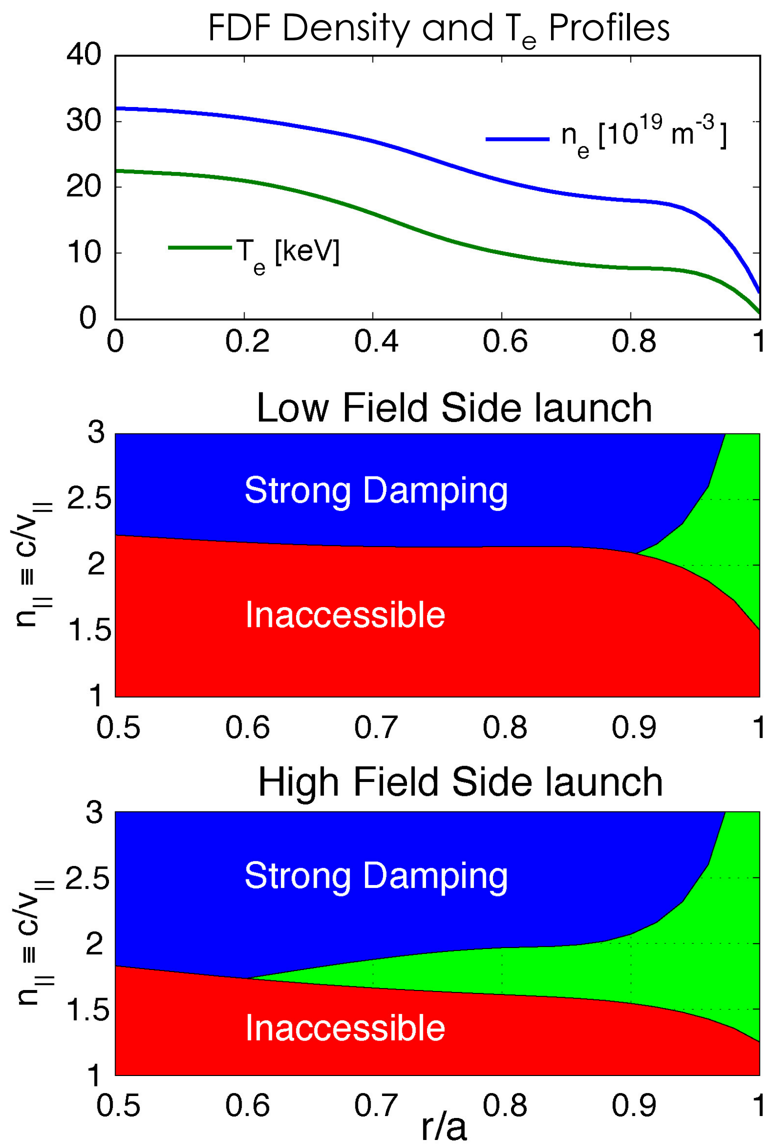
More on accessibility in the LHRF

- At a fixed frequency and $k_{||}$, in varying density or magnetic field, two branches can have the same $k_\perp$ at a certain point
- There, the branches coalesce – have the same polarization, are not distinct
- Wave energy in one mode flows into the other ('mode conversion')
- Incoming energy on one root reflects, propagates out on the other branch
- Prevents energy on either branch from reaching higher density
- We say higher densities are 'inaccessible'



Improved accessibility for slow waves from high field side may permit application for mid-radius CD in some reactor designs

- **Above LHR frequency, accessibility limit on $n_{||}$ is the same for slow and fast waves**
- **FWs continue at lower frequencies, where they are accessible at lower $n_{||}$ values**
- **Best accessibility at a given frequency from high field side, due to strong dependence on B_T**
- **To obtain slow wave accessibility to mid-radius at typical lower hybrid frequencies (~5 GHz), inside launch may be used**
- **See P. Bonoli's talk on Friday, YI1.001, 9:30 am**



Now turn our attention to the helicon branch in lower part of LHRF for the remainder of this talk

- Electron Landau damping of helicon weaker than that of the lower hybrid wave, due to smaller wave $E_{||}$

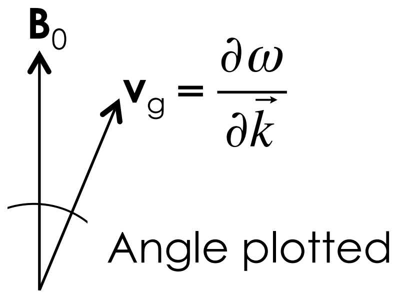
- This allows penetration to higher T_e region at a given $n_{||}$ for this wave

- FW frequency and $n_{||}$ must be optimized to give mid-radius deposition – higher frequency yields stronger damping at a given $n_{||}$

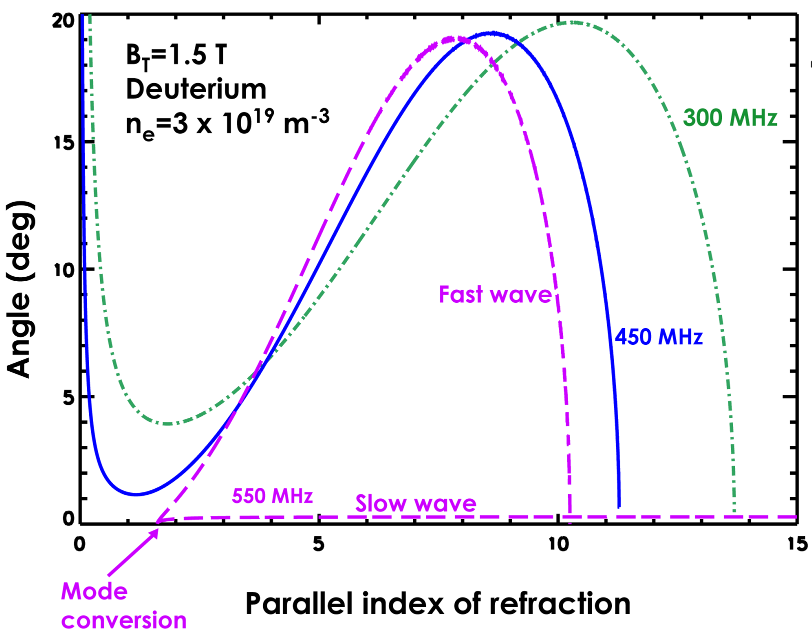
What is the difference between Alfven-wave-like and whistler-like propagation?

- Examine changes in FW propagation as frequency is raised from ICRF into the LHRF
- For uniform plasma calculate the angle between the ray direction (group velocity vector) and B_0, as function of $n_{||}$, frequency as parameter
- We will find a big difference between frequencies just above the ion cyclotron fundamental (ICRF) and the LHRF, especially at values of $n_{||}$ in the practical range from 1 to 5 or 10

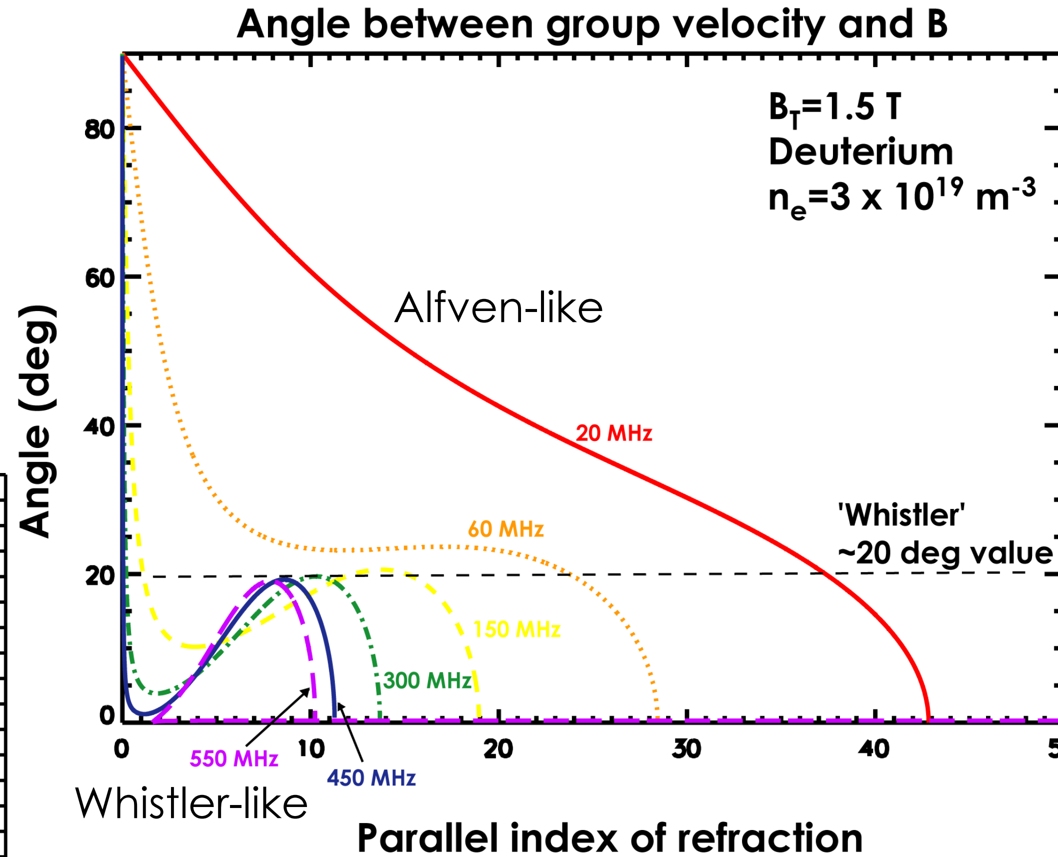
Ray angle transitions from Alfven wave to whistler/helicon behavior as frequency increases



Zoom in



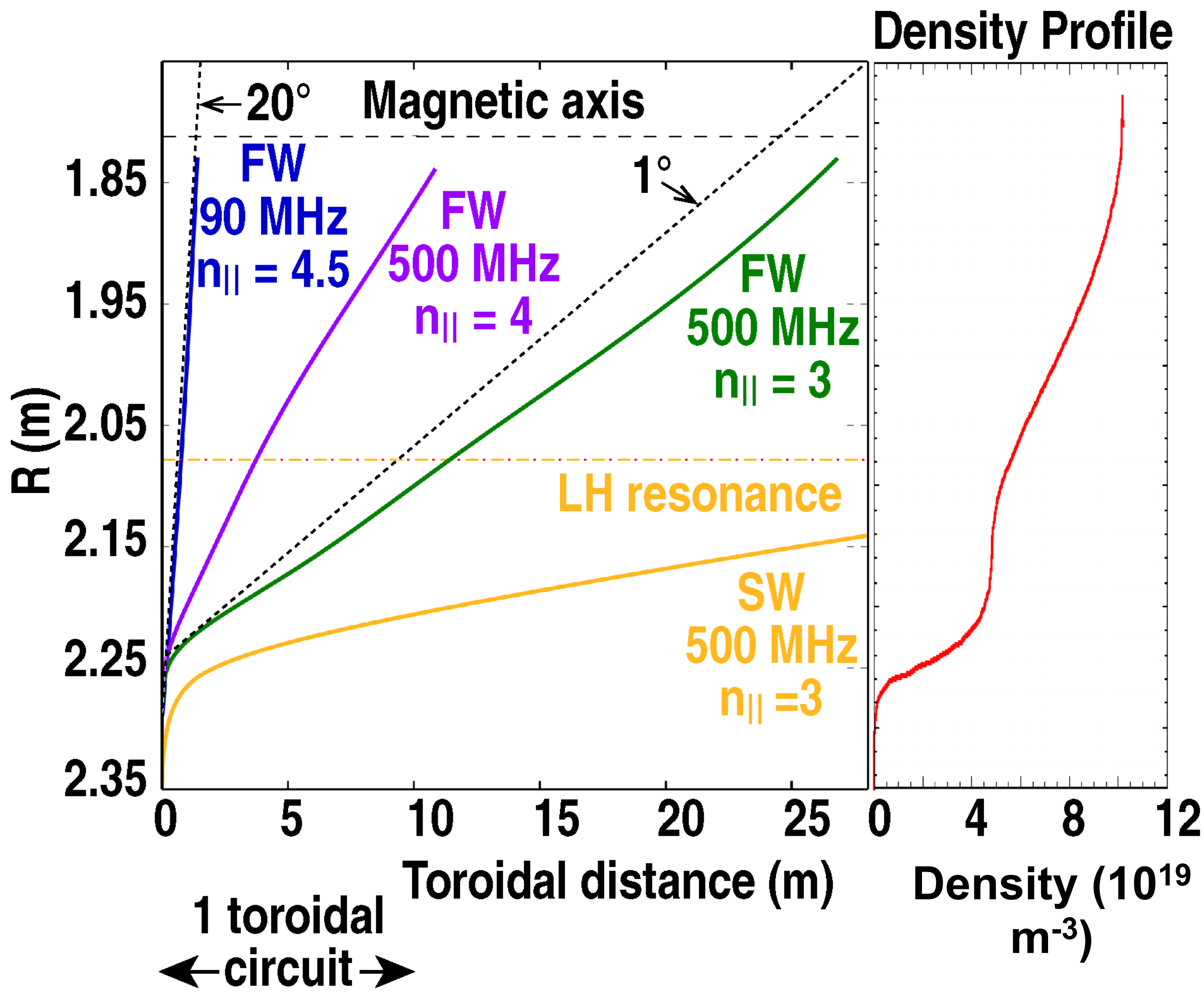
f_{LHR} = 527 MHz



- **Key difference between Alfven and whistler/helicon: latter has angle <u>increasing</u> with $|n_{||}|$ at values near accessibility limit**

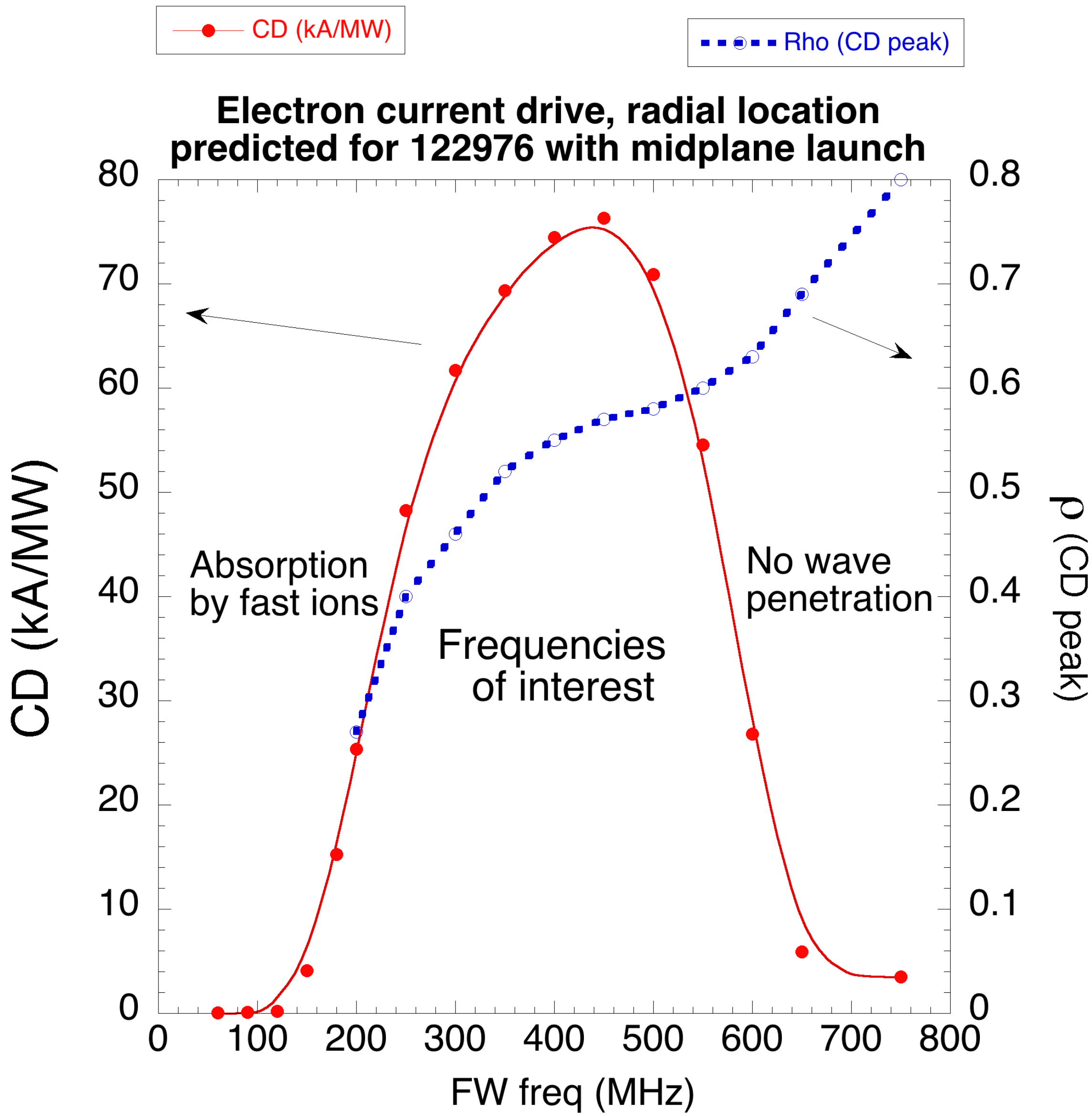
Use this angle to do 1-D ray tracing (slab geometry)

- Ray tracing in unwrapped torus slab model shows that whistler-like rays will almost follow static B-field lines, slowly penetrating
- Higher $n_{||}$ ray penetrates more rapidly

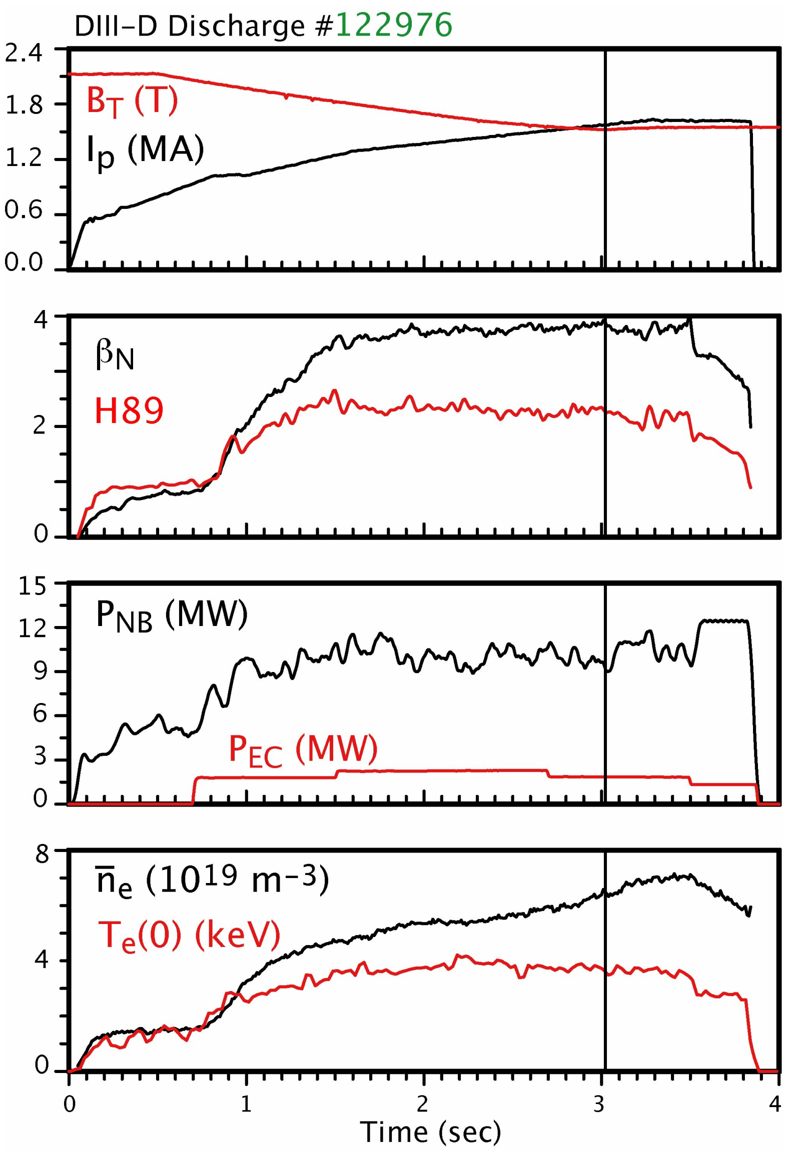


For DIII-D, optimum helicon frequency is about 0.5 GHz

- **Computations with ray-tracing model for DIII-D high-performance equilibrium**
- **Lower frequencies suffer from ion damping (we want electron current drive)**
- **Higher frequencies have problems getting into the core**
- **Also coupling problems (not shown)**

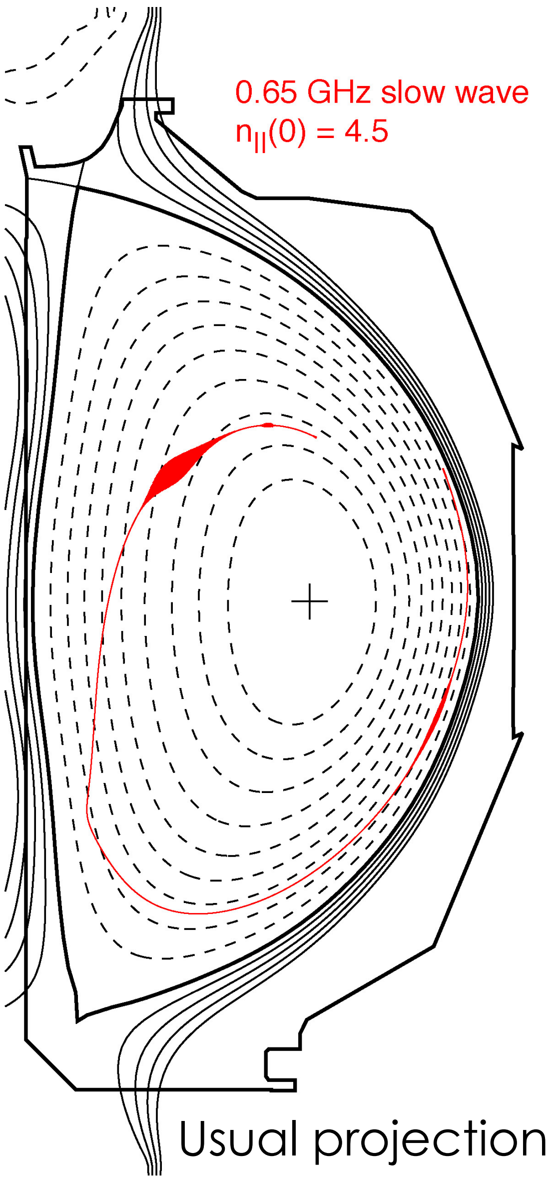


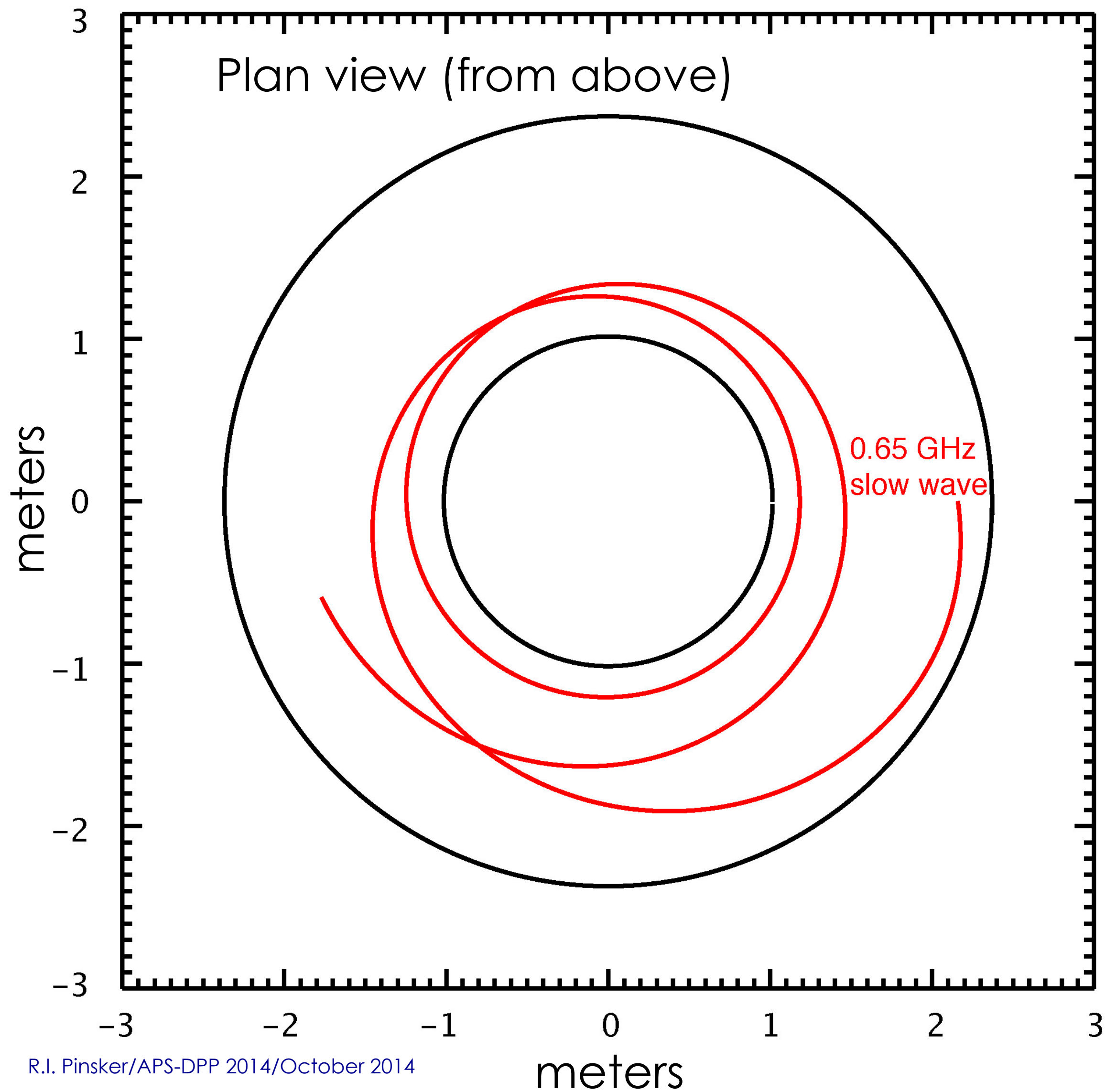
DIII-D target discharge for these studies has high density, high T_e at midradius for strong helicon absorption



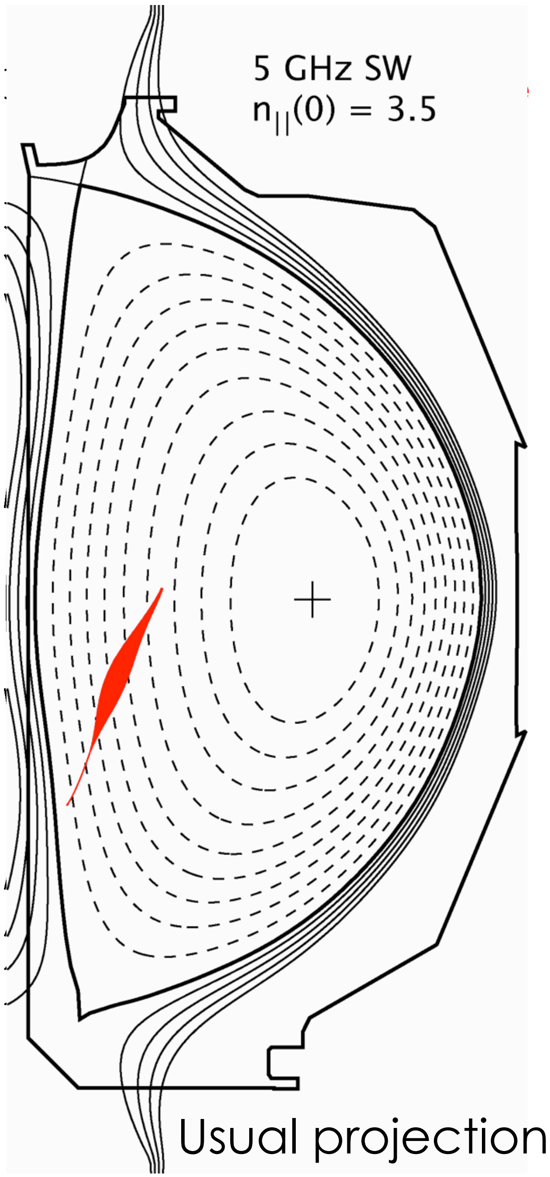
- **Discharge used simultaneous B_T and I_p ramps to create current profiles giving excellent confinement and high beta (electron damping ~β_e)**
- **Dominant neutral beam power creates fast ion population – stand-in to study absorption on alphas**
- **High density (slow radial penetration) and ~3 keV T_e at damping location**

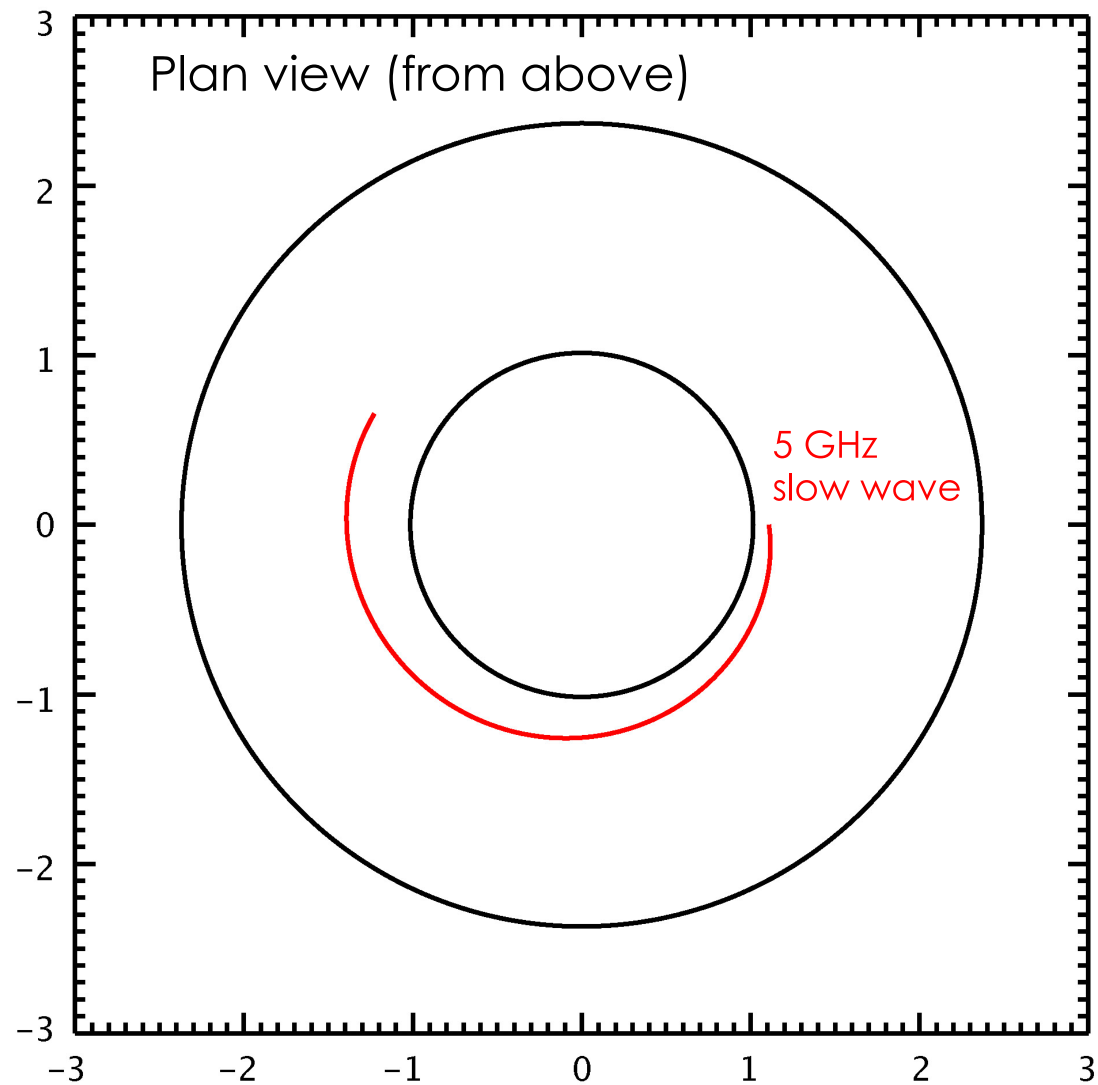
Ray tracing of 0.65 GHz slow wave at $n_{||}$=4.5 in DIII-D (above midplane launch)



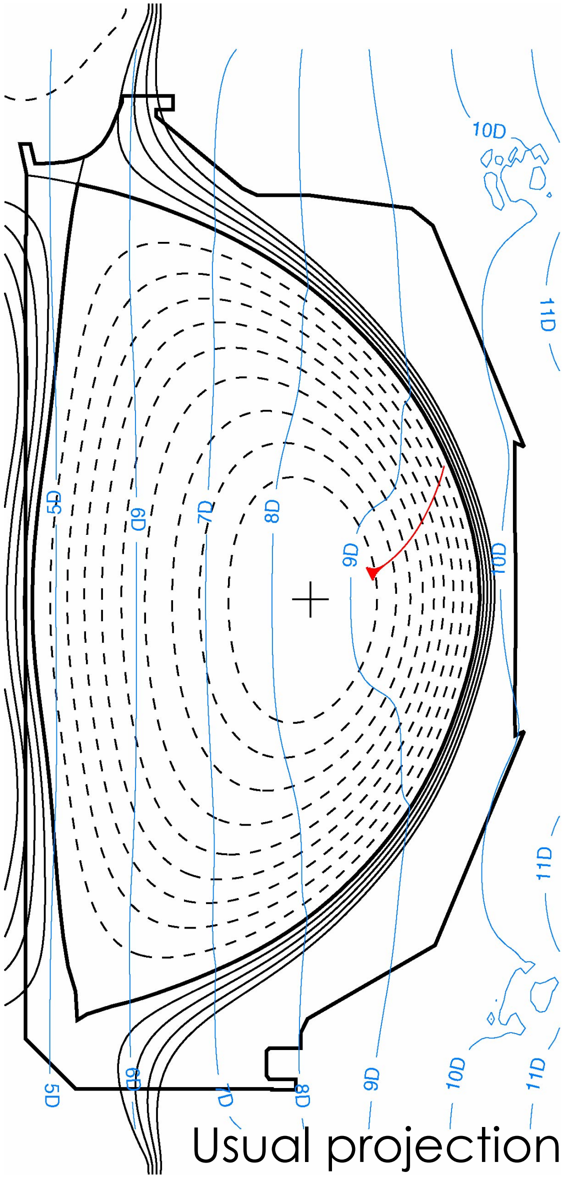


Ray tracing of 5 GHz slow wave at $n_{||}$=3.5 in DIII-D (below midplane inside launch)

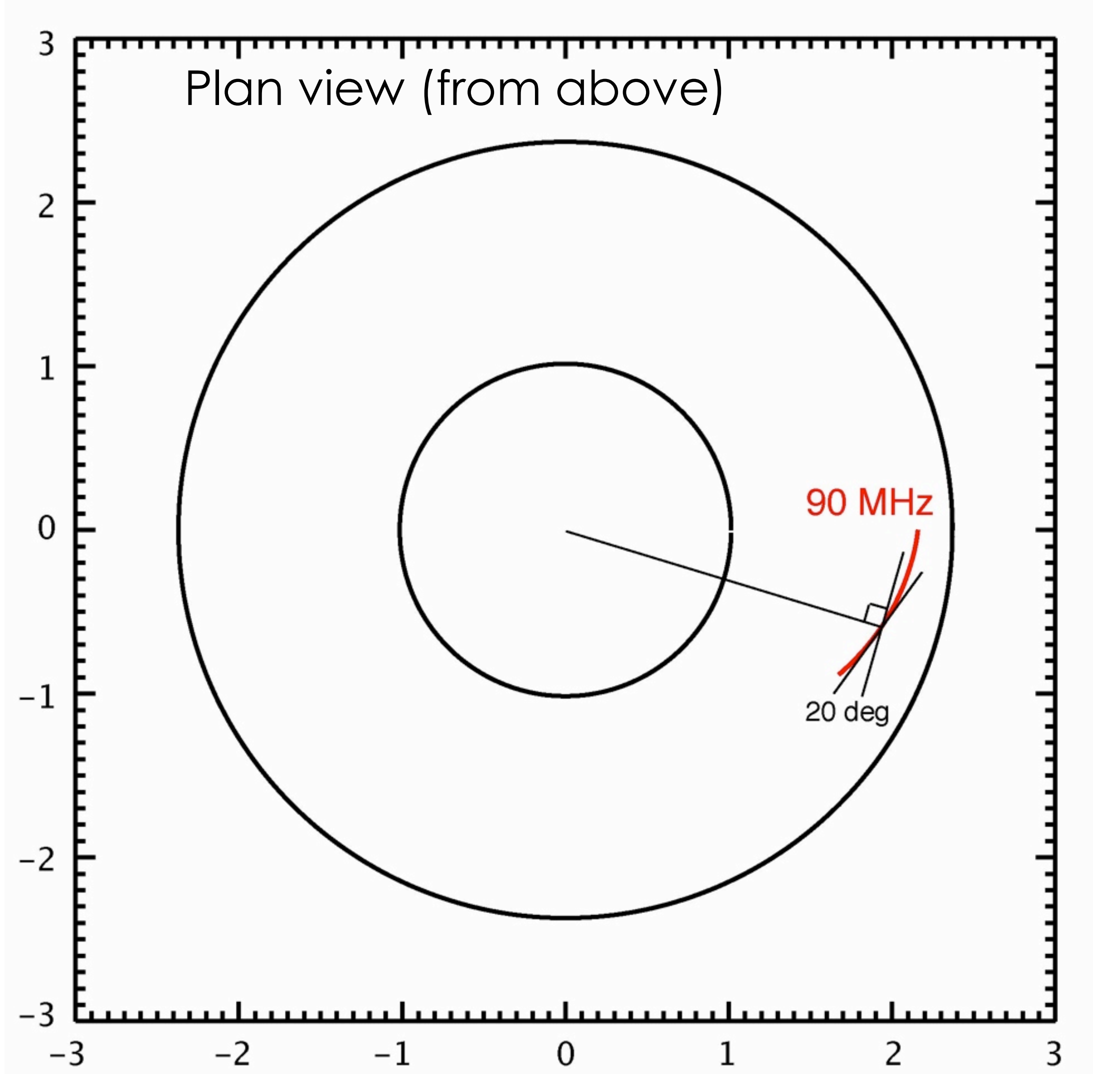




Ray tracing of 90 MHz fast wave at $n_{||}$=3 in DIII-D (above midplane launch)

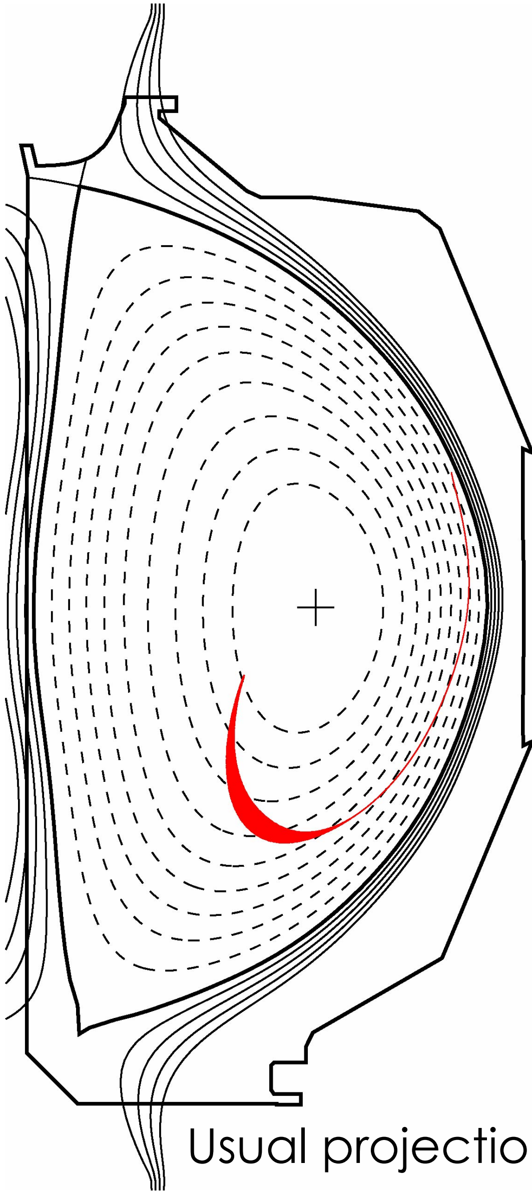


Usual projection

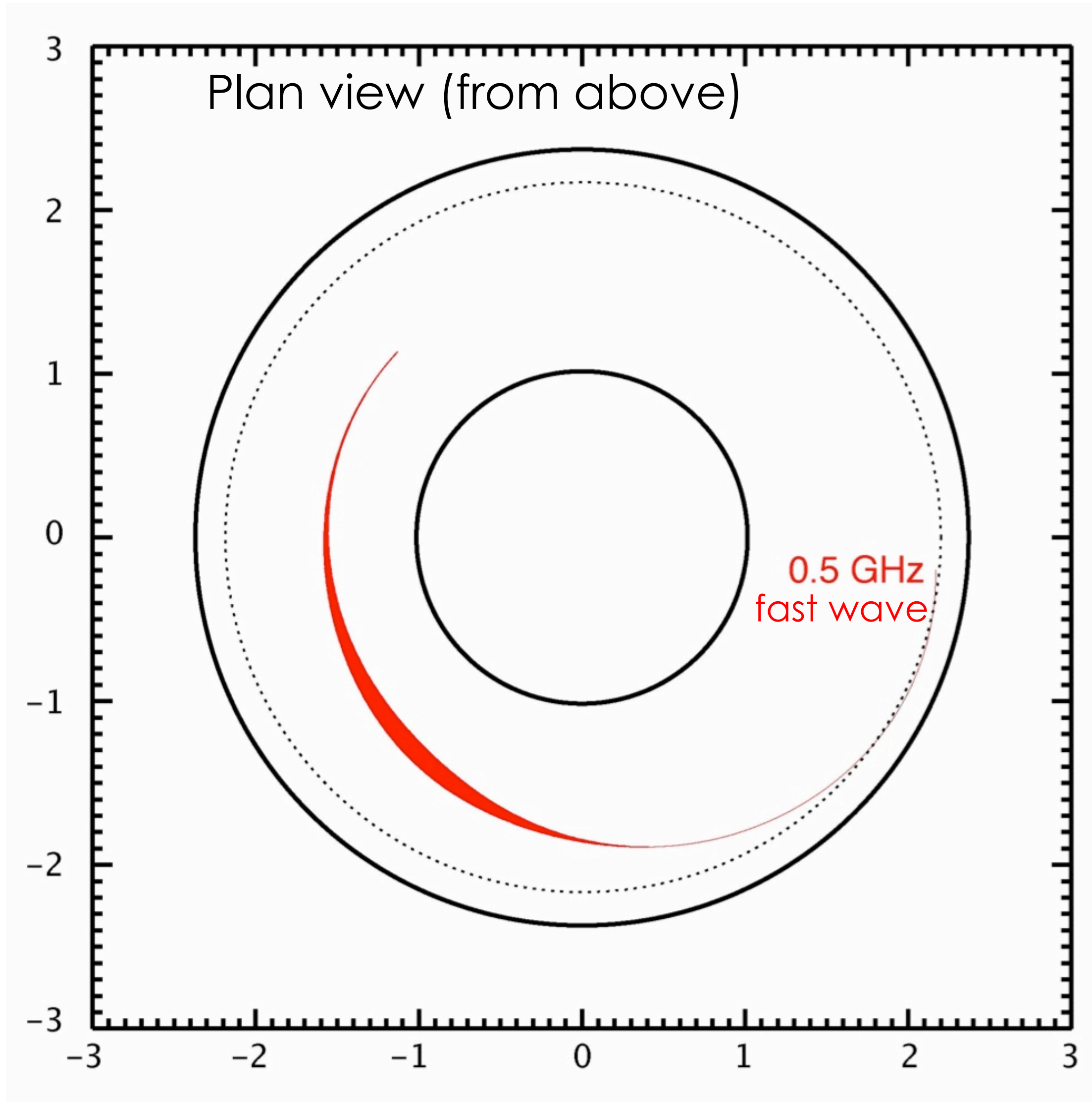


Ray ends with total ion absorption at 9th harmonic

Ray tracing of 0.5 GHz helicon at $n_{||}$=3 in DIII-D (above midplane launch)



Usual projection

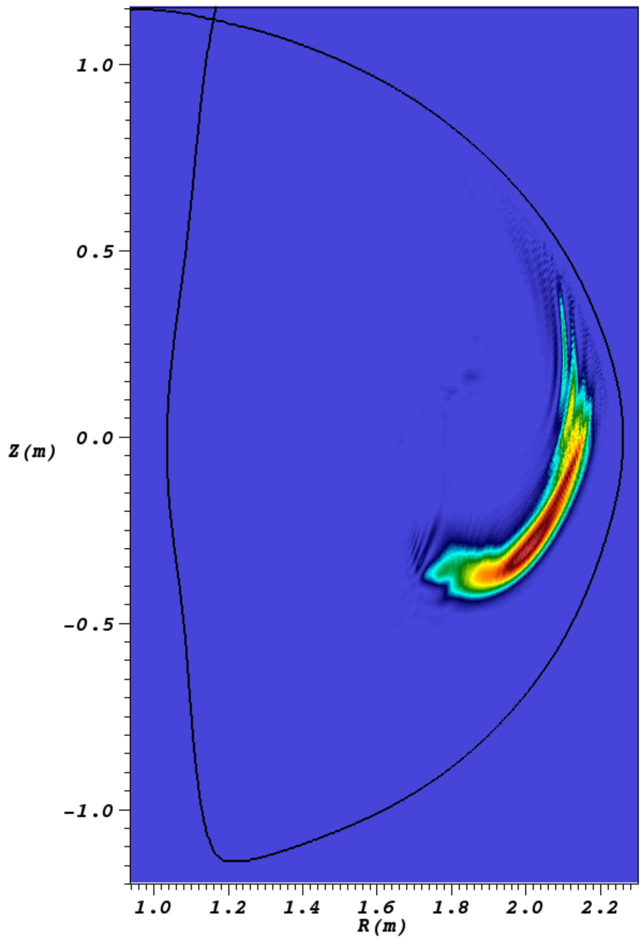


Ray ends with total electron absorption

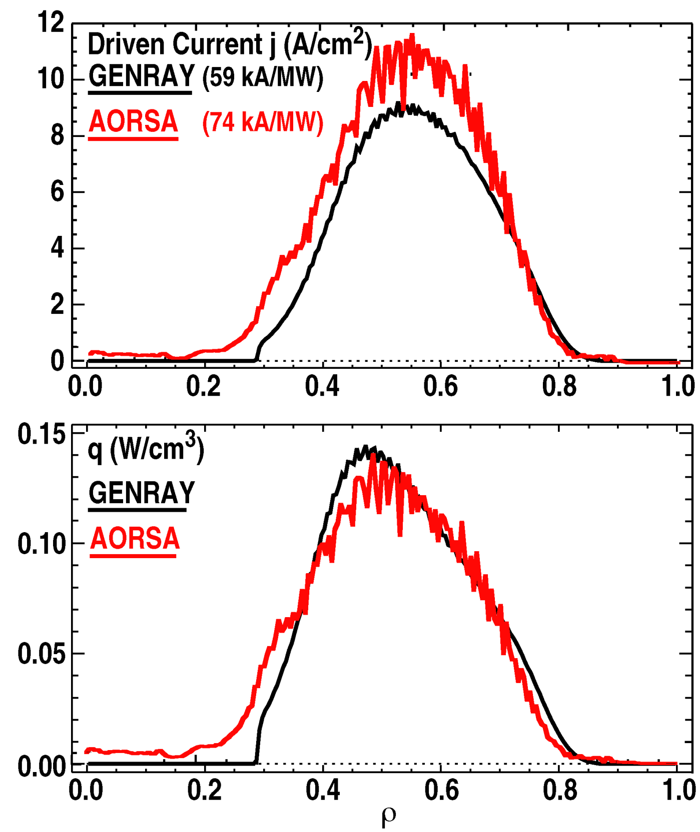
For 0.5 GHz helicon case, full-wave code AORSA shows similar results as ray-tracing, far more computationally expensive

- Electron absorption with single toroidal mode at equivalent of $n_{||} = 4$ in AORSA

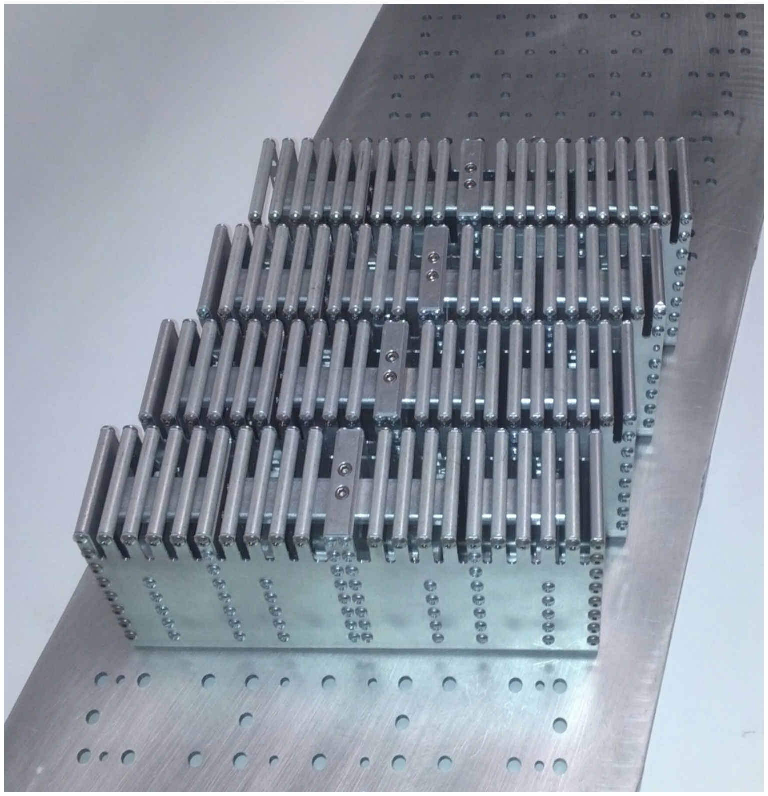
AORSA, Jaeger, et al.



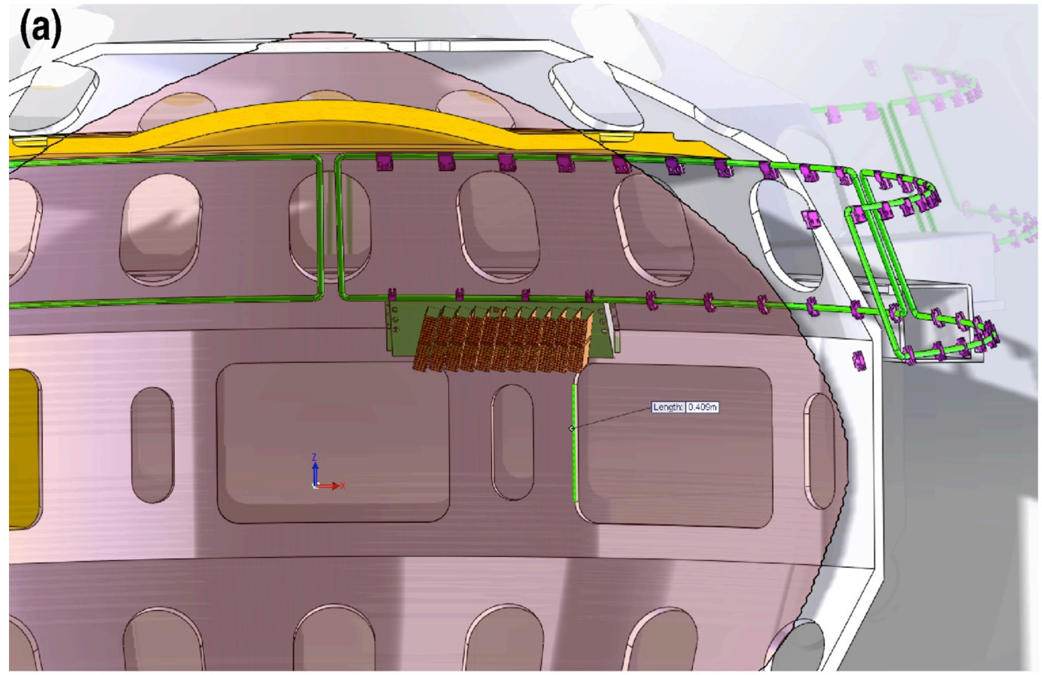
- $n_{||} = 4$



A wave-launching structure known as a 'comb-line' is being constructed for the DIII-D 0.5 GHz experiment



- Aluminum model for laboratory cold tests



- 12-element low-power prototype will be installed early 2015, 1 MW version (wider) to follow

C.P. Moeller

Questions to be answered by the DIII-D 0.5 GHz experiments starting next year

- **Main purpose of low power experiment (2015) is to investigate linear coupling**
  - Can we radiate most of the power in one pass through wave launching structure?
  - Are the SOL density profiles in the poloidal region of interest in the target consistent with good coupling?
  - Can direct excitation of the slow wave be minimized?

- **Nonlinear aspects to be addressed in the 1 MW experiment (2016) include:**
  - Does parametric decay instability, thought to become significant in the 0.1 MW- 1 MW range, cause important levels of pump depletion?
  - Is ion damping important through non-linear or even linear mechanisms?

Summary

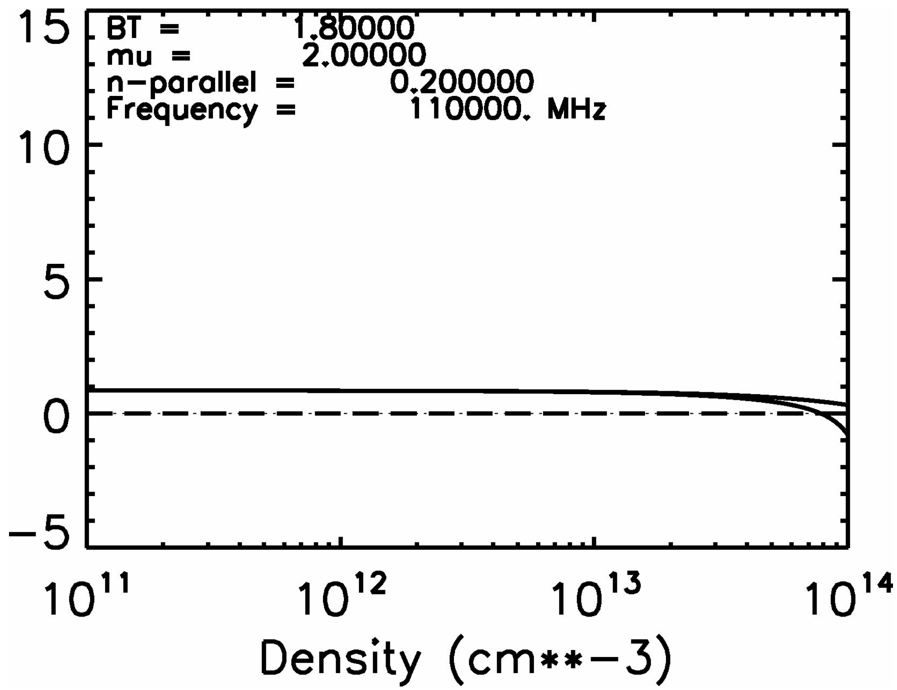
- **Electron current drive produced by electron Landau damping of asymmetric spectrum**
- **Damping is well understood**
- **To drive current at mid-radius in a reactor-scale plasma with best efficiency, need to investigate variations on already proven methods**
- **Helicons (FWs in LHRF) are one under-explored possibility, being investigated on DIII-D**
  - Need to establish that waves of the appropriate character can be launched with a reasonable structure
  - Also need to investigate non-linear processes in the outer part of the plasma
- **Other possibilities include SWs launched from the inboard side, under investigation at MIT and elsewhere**

Extras/rejects follow

What waves are available for damping by parallel processes in tokamak plasmas?

- **Since at frequencies in the ECRF radial decay of waves with $|n_{||}|> 1$ is so rapid in vacuum, must use cyclotron absorption there with waves that propagate in vacuum**
  - No coupling issue there
  - Instead of a lower density limit for propagation, there is the upper density limit due to refraction and cutoff

- **110 GHz waves at $n_{||}$=0.2**



- **What waves are available for use with $\omega<\Omega_e$?**

3 MA driven with 6 MW of 3.7 GHz LH in JET at similar density (same CD efficiency $n_e I_{cd} R/P_{rf}$ as JT-60U case)

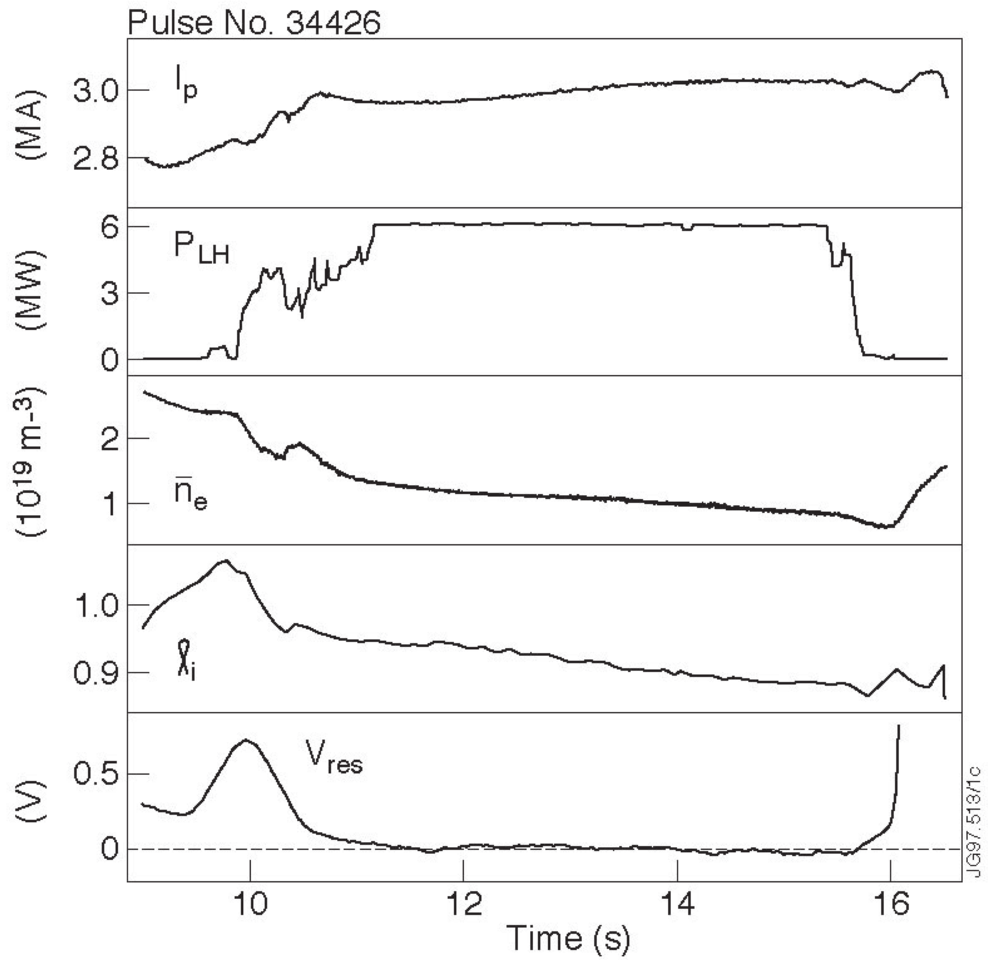


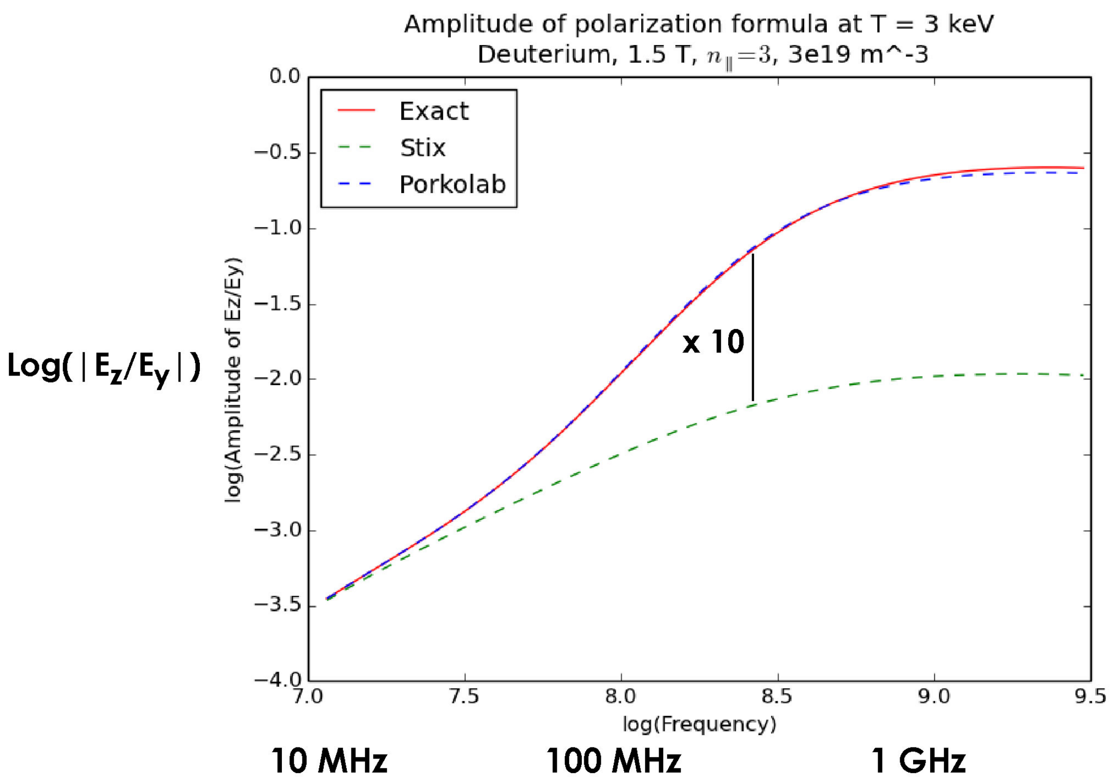
FIG. 1. Full current drive with LHCD in a 3 MA discharge. (JET)

Notes about “TTMP” force

- **Since wave $B_{||}$ is linked to the wave $E_{\perp}$ and the perpendicular wavelength and frequency by Faraday’s law, and**
- **For a given wave mode, $E_{||}$ and $E_{\perp}$ are linked by wave polarization,**
- **Electric and magnetic parallel forces are coherent and must be calculated together**
  – Leads to a well-known cancellation between TTMP and ‘cross-term’ for electron damping of fast waves at low frequencies $\omega \sim \Omega_i$
- **The cancellation also depends on the fact that $E_{||}$ being non-zero for fast wave at low frequencies is a hot plasma effect**
- **But at higher frequencies, even cold plasma fast waves have non-zero $E_{||}$ (cannot neglect electron inertia) →**
- **‘Extra’ Landau damping that totally dominates the low frequency terms**

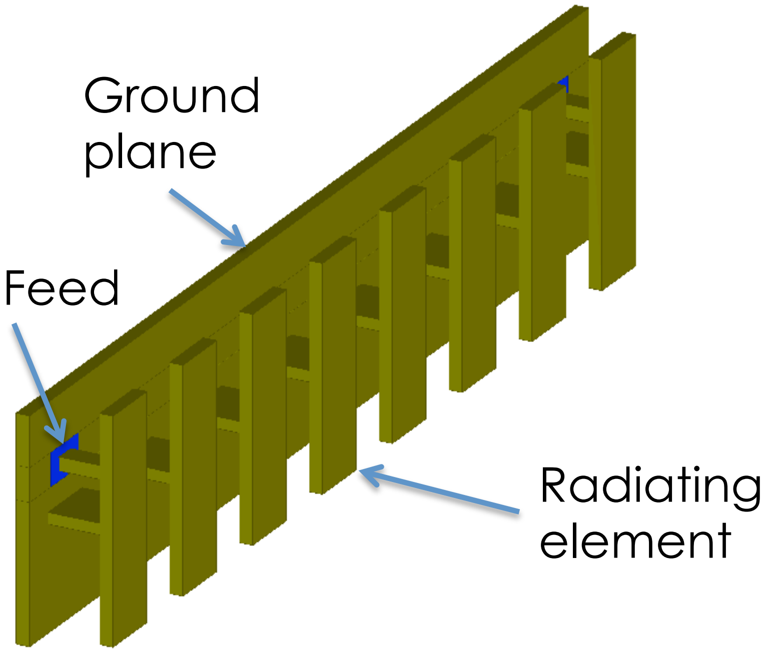
Cancellation between TTMP and 'cross term' at low frequencies for fast waves becomes irrelevant at higher frequencies

Te = 3 keV, density = 3x10^19 m^-3, BT=1.5 T, $n_{||}$=3

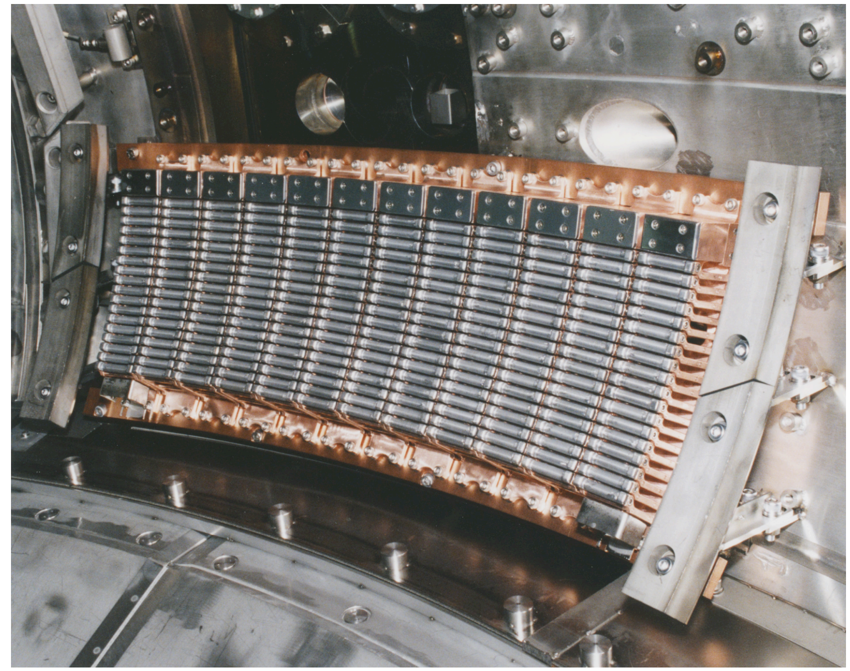


- **In fact, the 'extra' term totally dominates the Stix '75 term and TTMP can safely be ignored by comparison to LD for FWs as well as for slow waves**

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

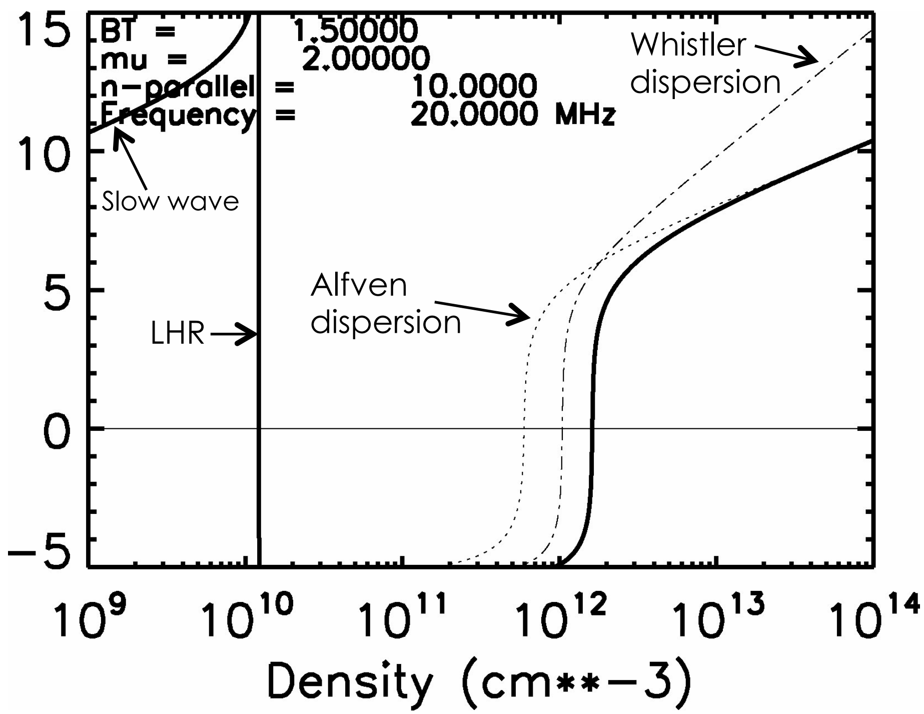


- 12 radiating straps
- Tested at voltages corresponding to 800 kW
- Experimentally successful at launching the fast wave
- Designed and built by GA

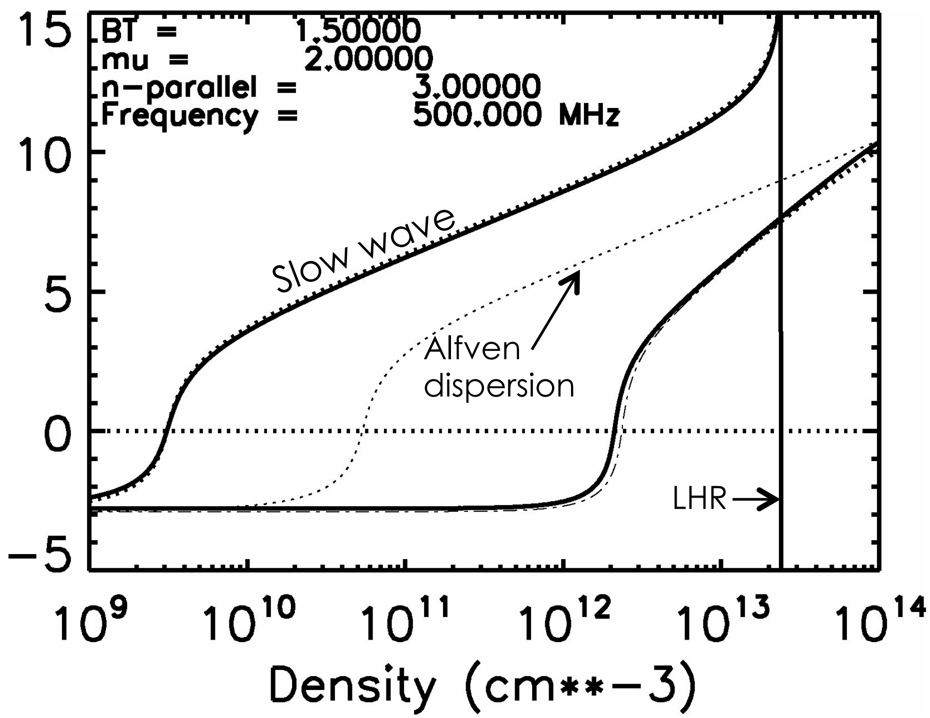
[Moeller, 1993;
Pinsker, 1996;
Ogawa, 2001]

Alfven-like wave near $\omega \sim \Omega_i$; whistler-like wave in LHRF

- **20 MHz waves at $n_{||}$=10**



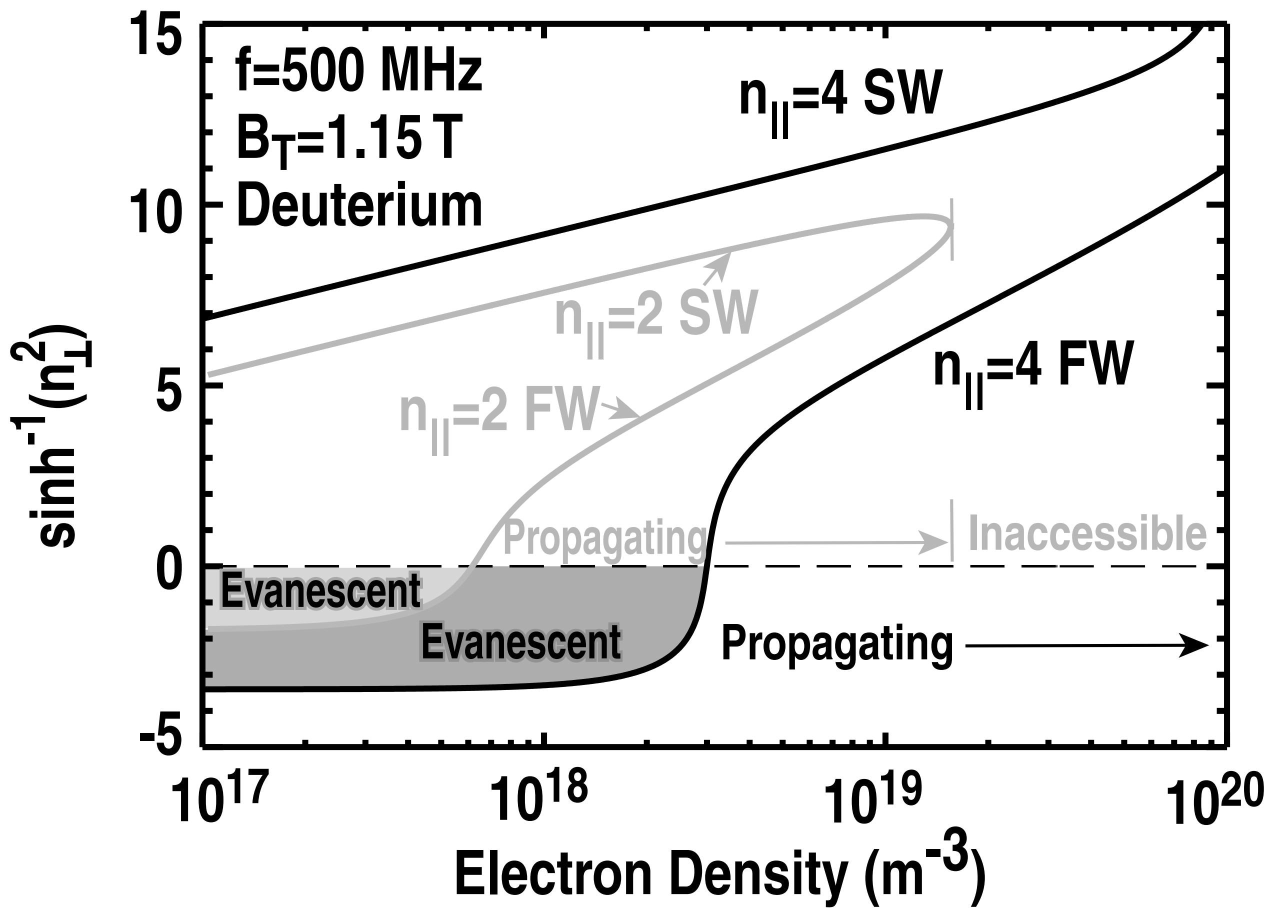
- **500 MHz waves at $n_{||}$=3**



Above LHR, fast and slow waves have an accessibility limit, preventing use of n-parallel too close to 1

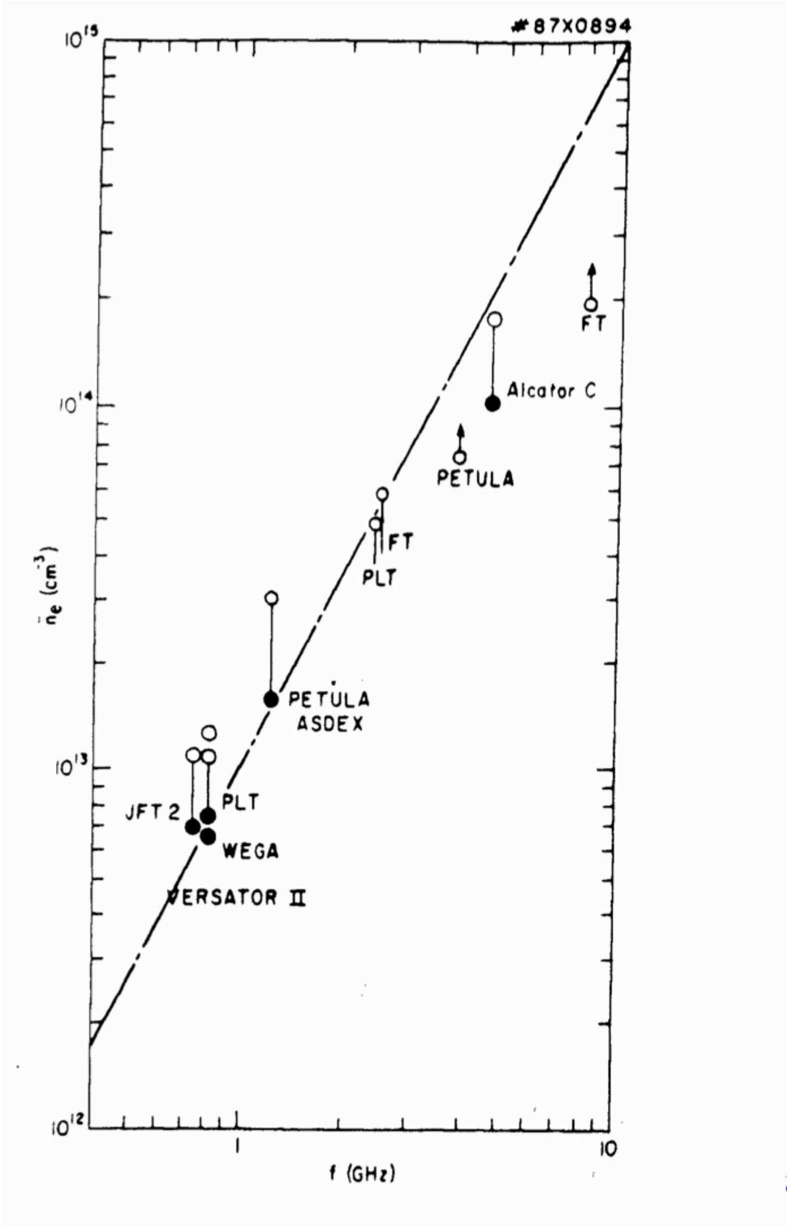
- Lower $n_{||}$ is much less strongly evanescent at low density, and the cutoff density is significantly lower

- But in this example lower $n_{||}$ cannot penetrate beyond ~2 x 10^{19}



Slow wave suffers an empirical density limit for electron interaction

- Empirical density limit for electron interaction in core for slow (lower hybrid) waves
- Limiting density scales ~f^2, as would be expected from something associated with LHR
- But it occurs even if f > f_{gmg} and there is consequently no LHR possible
- Associated with nonlinear phenomena (parametric decay instabilities)
- Recent work on C-Mod has shown that it's not quite this simple – depends on more than just frequency



Malmberg, Wharton and Drummond (GA, 1965) proved Landau damping is a real, measurable, and important phenomenon

LANDAU DAMPING OF ELECTRON PLASMA WAVES

CN-21/116

I.H. MALMBERG, C.B. WHARTON AND W.E. DRUMMOND
GENERAL ATOMIC DIVISION, GENERAL DYNAMICS CORPORATION,
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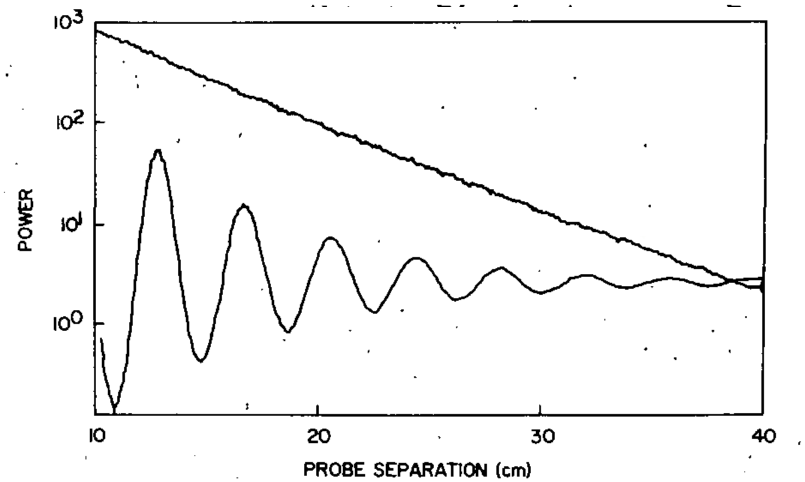


FIG. 4. Raw data. Upper curve is the logarithm of received power. Lower curve is interferometer output. Abscissa is probe separation.

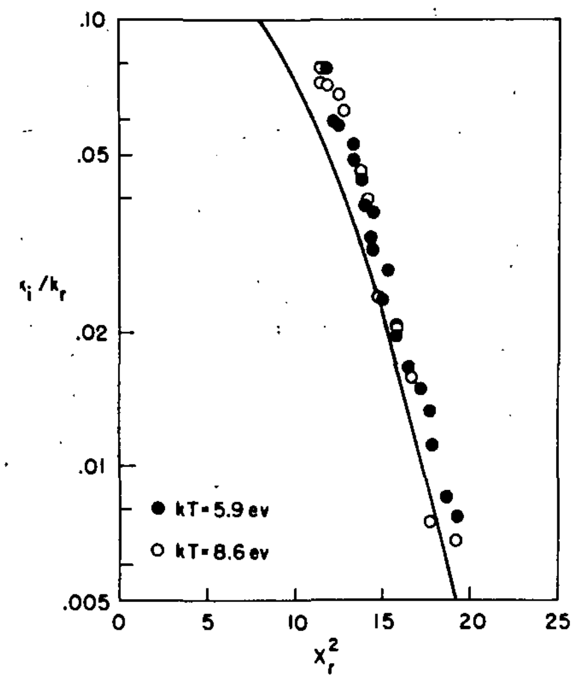
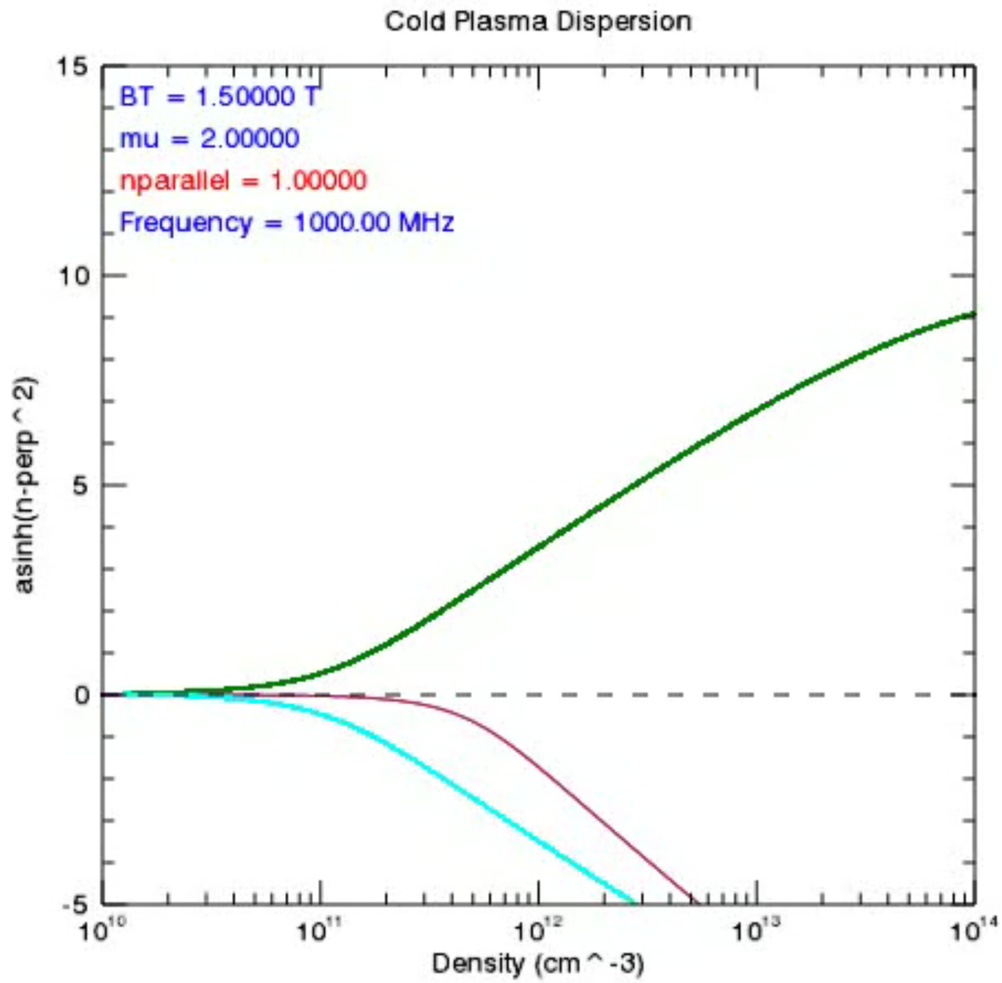


FIG. 6. k_i/k_r versus x_r^2.

- **Landau damping is not just an exercise in analytic continuation and contour integration in the complex plane, it is a real and useful phenomenon in laboratory plasmas**

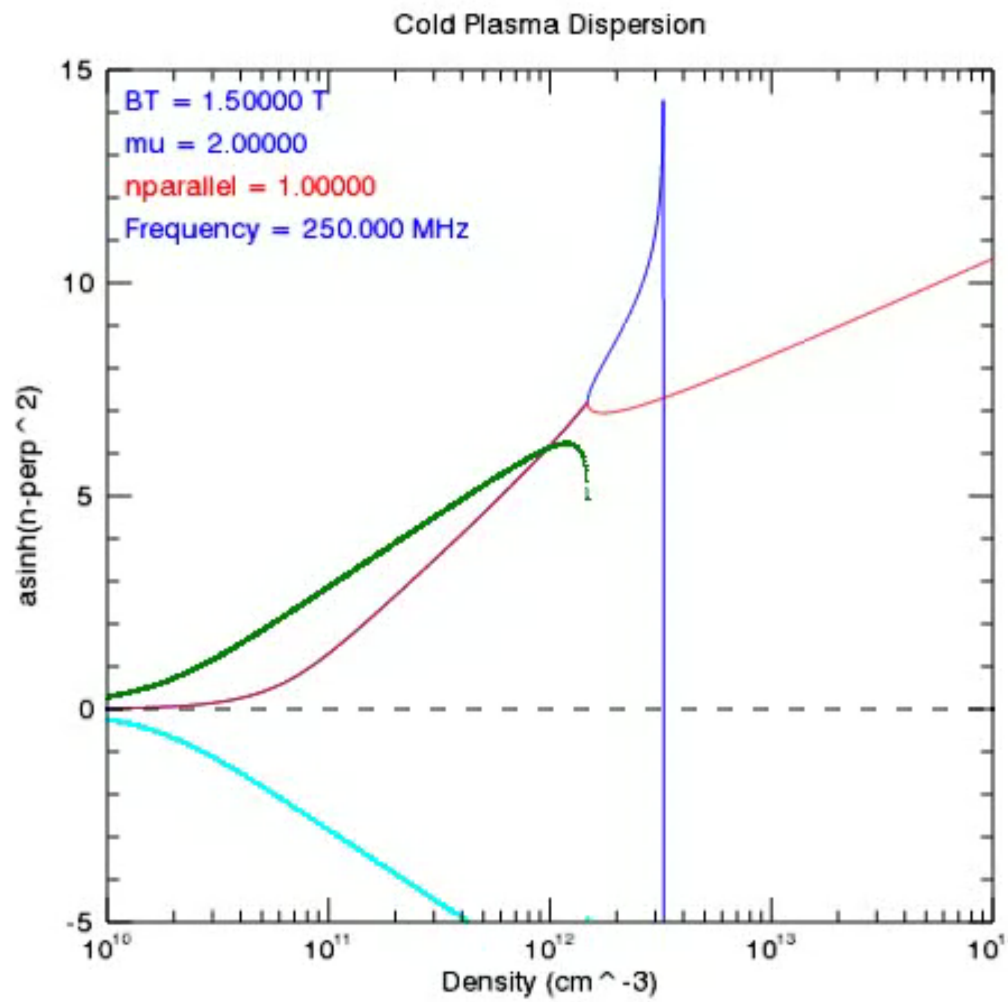
Accessibility extends to lower $n_{||}$ at lower frequency

1 GHz



Accessibility extends to lower $n_{||}$ at lower frequency

0.25 GHz

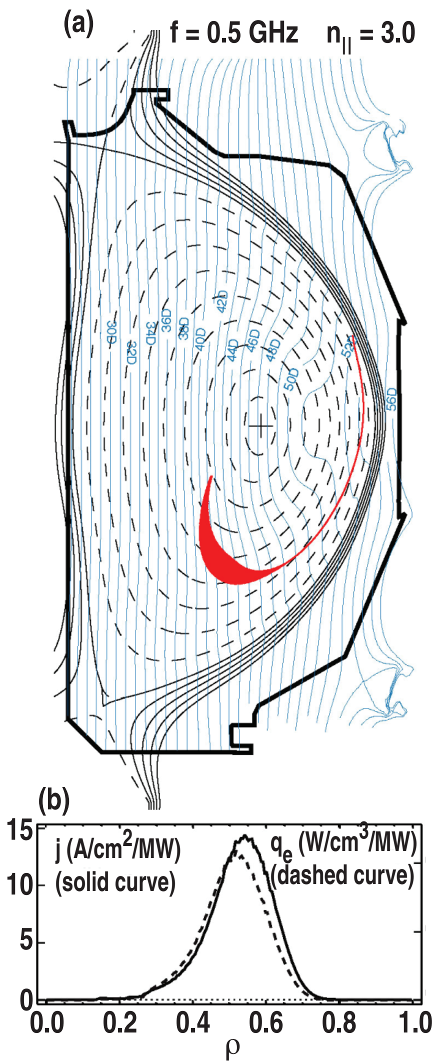


Since accessibility improves, why not use FWs in ICRF?

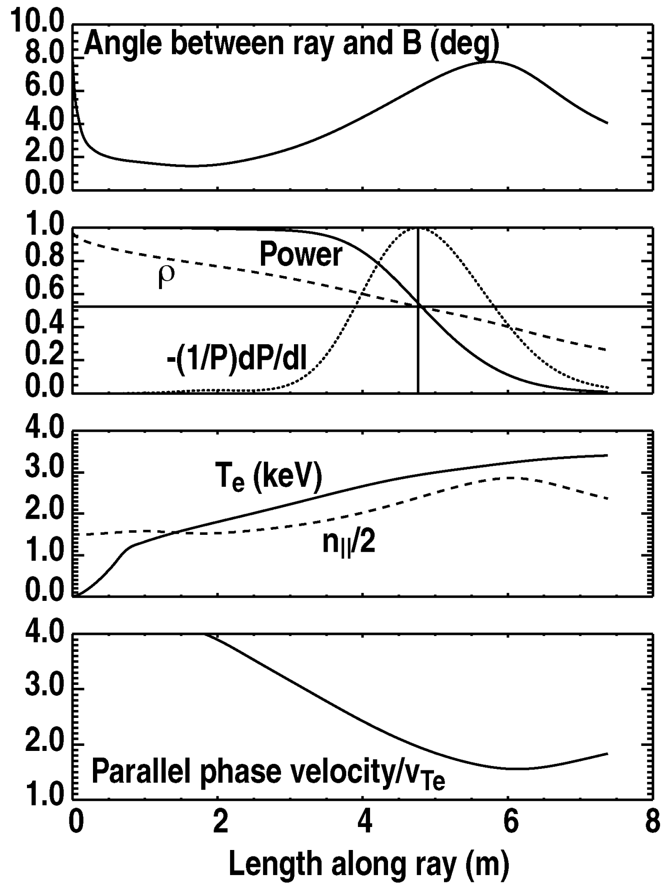
- **Two reasons:**
  - Electron Landau damping strongly increases with frequency at a fixed $n_{||}$, so difficult to get strong absorption at mid-radius at too low a frequency
  - Ion cyclotron damping siphons off the energy into ions (either fast ones (alphas, beam ions) or even thermal ions) before getting to the desired electron damping location

- **So we expect an optimum frequency for fast waves, where electron damping is strong enough, ion damping is weak enough, and accessibility is still good enough to allow a low enough $n_{||}$ to be used**

Ray tracing in full toroidal geometry shows similar properties for 500 MHz helicons



- $n_{||} = 3$



- $n_{||} = 4$