Reference: IAEA Fusion Physics, 2012, Chapter 6,

M. Porkolab et al

RF Waves in Magnetically Confined Plasmas: a Historical Perspective of EU-US Collaboration for 50 years*

Miklos Porkolab

Special thanks for direct or indirect contributions from :

P. Bonoli, E. Melby, R. Parker, A. Ram, R.Temkin, N. Tsujii, G. Wallace, S. Wukitch, J. Wright, MIT PSFC

V. Chan, C. Petty, R. Pinsker, R. Prater, General Atomics; F. Jaeger, L. Berry, ORNL; R. Harvey, Comp-X;

S. Bernabei, N. Fisch, J. Hosea, M. Ono, R. Wilson, PPPL; J. H. Belo, P. Bibet, T. Hoang, Tore Supra; S. Coda, CRPP;

M. Brambilla, F. Leuterer, J. Noterdaeme, IPP; F. Durodie, C. Gormezano, M. Henderson, J. Jacquinot,

M.P.S. Nightingale, EFDA, JET, ITER

Meeting of the European Physical Society, Plasma Physics Division,

Espoo, Finaland, July 1-5, , 2013

Porkolab_EPS2013_Alfven-Prize

* Work supported by the US Department of Energy

RF Heating and Current Drive Physics in Fusion Plasmas Has Progressed Rapidly as a Result of Strong Collaboration Between EU and US Scientists: Varenna, Italy, 1977

EU-US RF Conferences and Workshops active since 1972 (Varenna, Grenoble, Rome, Ghent, Sorrento, and alternating with US sites since 1982)

Continued Collaboration Between EU and US Scientists :
-RF Power in Fusion Plasmas Conference: Rome, 1984

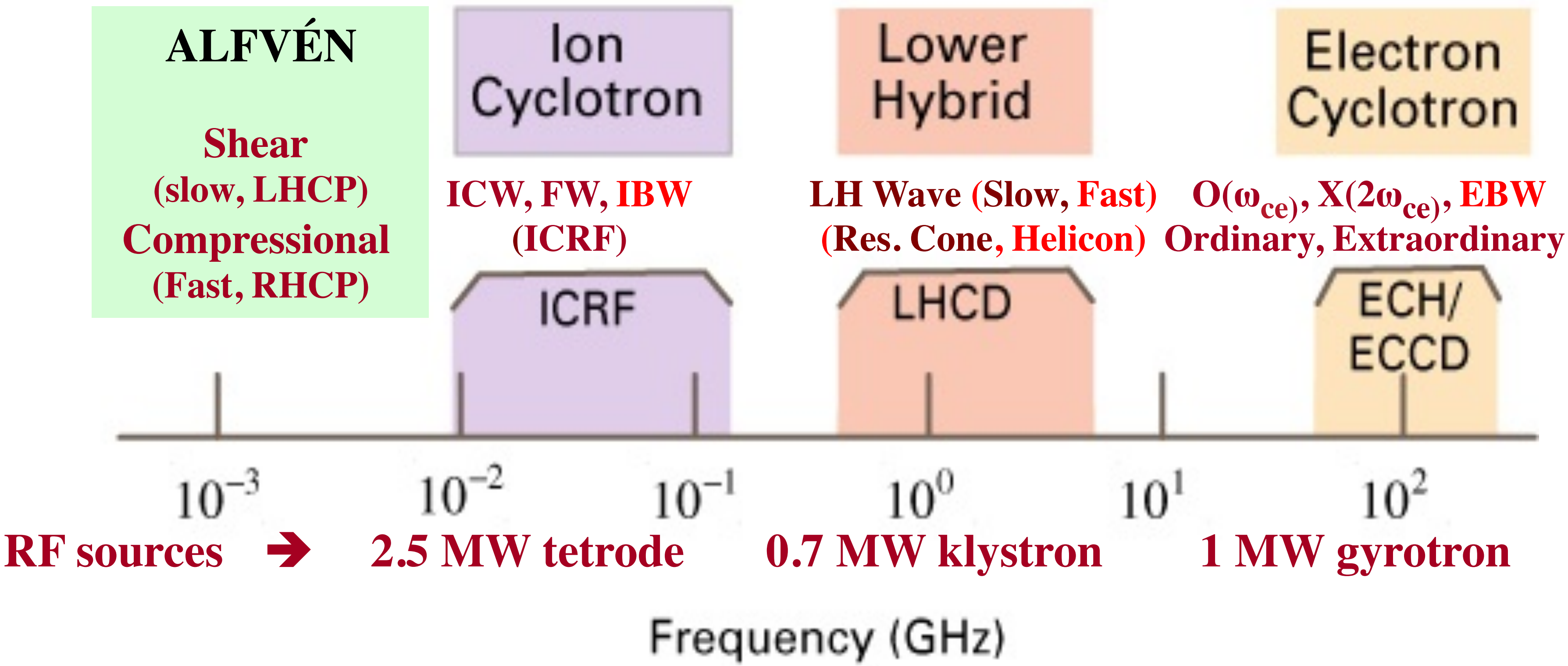
EU-USA RF CONFERENCE 40 YEARS LATER STILL ACTIVE

20th Topical Conference on RF Power in Plasmas

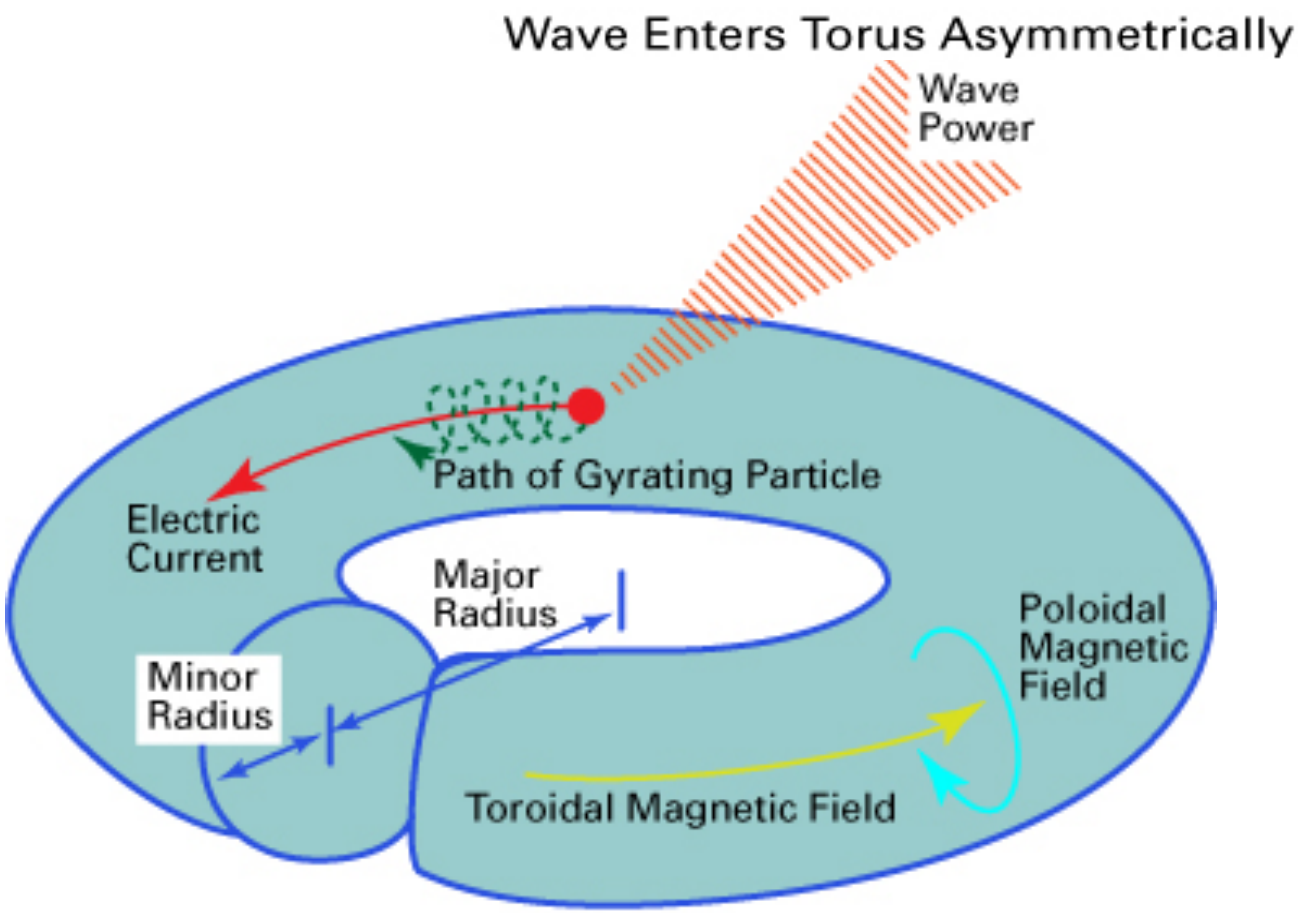
June 24-29, 2013, Sorrento, Italy

Radio Frequency Waves of Interest for Heating and Current Drive Cover a Wide Range of Frequencies

Radio Frequency Spectrum



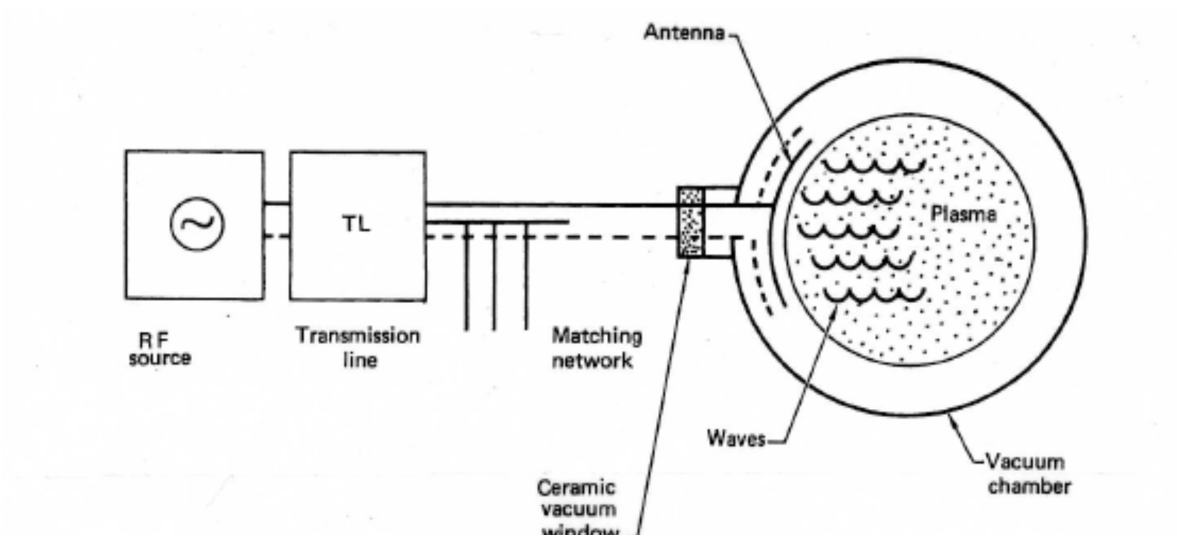
Theorist's view of RF heating and current drive

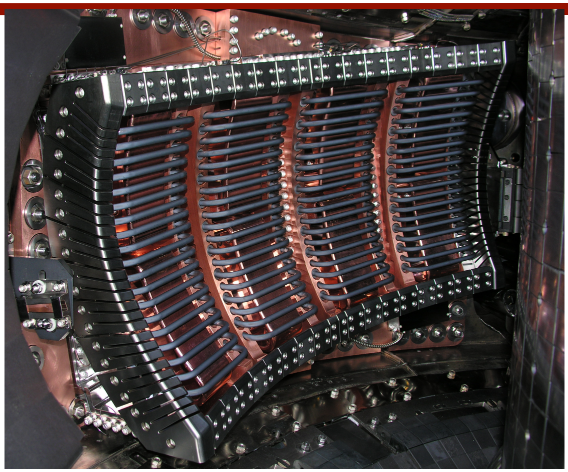


After Nat Fisch, 1980s

Physics and Technology issues in RF heating are complex

RF heating system layout, after M. Porkolab, in FUSION, Ed. by E. Teller, 1981





Alcator C-Mod field aligned antenna (Wukitch, 2012)

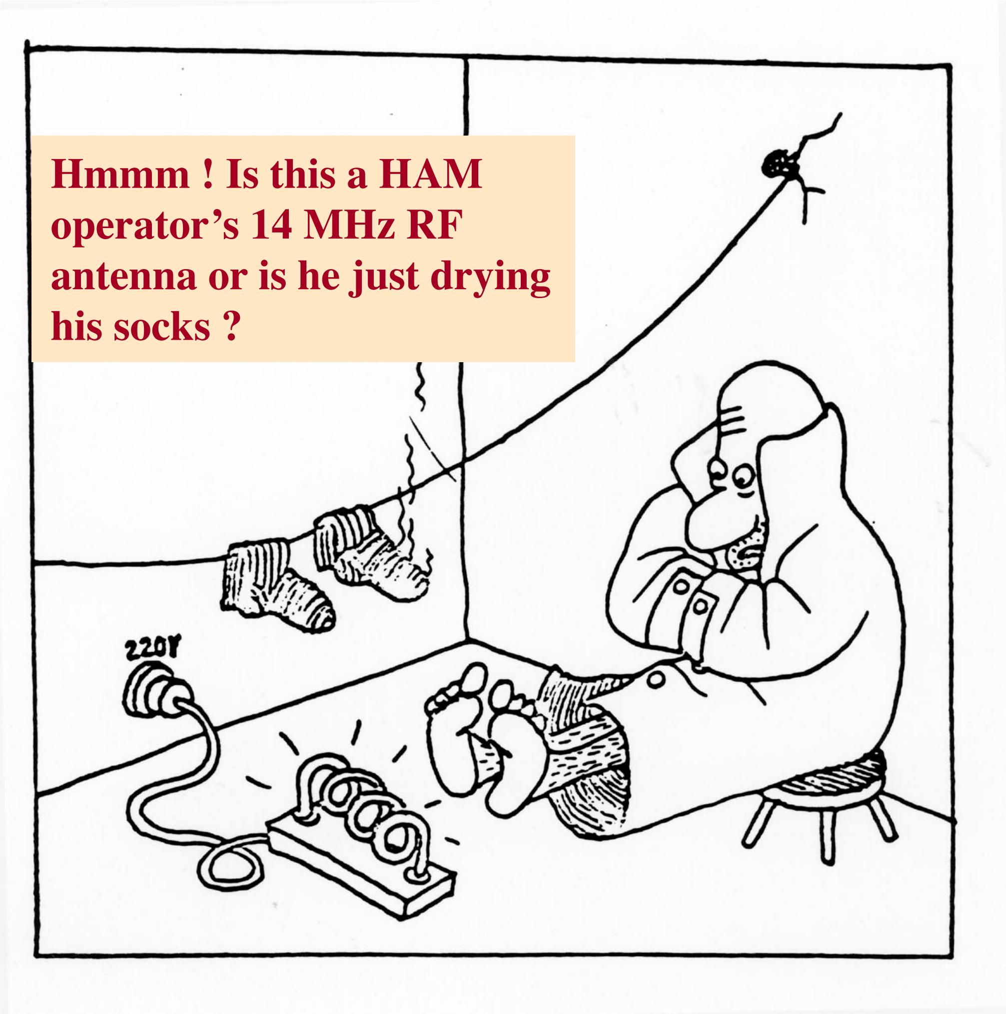
"Accessibility" - is the wave free to propagate to the absorption layer, or is it reflected back or converted to another wave part way in

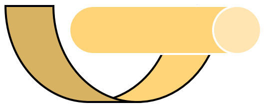
- **Absorption Processes - collisionless wave-particle interaction**

  - Landau and/or cyclotron damping, quasi-linear deformation of the particle distribution, absorption on energetic particles (beams, alphas)

- **Wave launching by the antenna , e.g., the "coupling problem"**
- **Technology– efficient RF sources, low loss transmission lines**
- **Sometimes deleterious effects at the plasma edge**

Late 1950s: the "primitive" days of RF heating





Furth's ALFVÉN wave heating scheme (1959) not successful !

But now we know: it should not have worked !

A Brief History of RF Wave Propagation and Heating
1960's: The age of "enlightenment"

➔ **1950's:**

✧ **The early "primitive" days - fusion research declassified in1958**

➔ **1960's: The age of "enlightenment"**

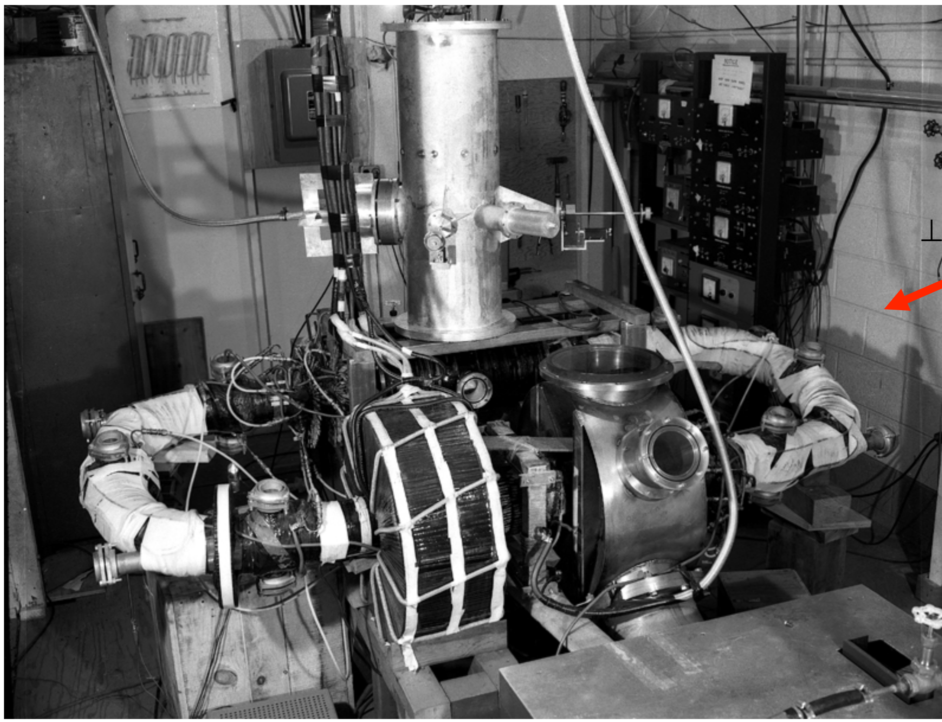
- *The Theory of Plasma Waves* - by T. H. Stix (1962)

- ✧ **Ion Cyclotron (EM) slow wave propagation and heating demonstrated (T. H. Stix, 1961, W. Hooke, 1962)**
- ✧ **Trivelpiece Gould modes characterized – akin to lower hybrid waves**
- ✧ **Laboratory experiments verify Bohm-Gross (or Langmuir) waves and Landau damping verified (Malmberg et al, 1963-1967)**
- ✧ **Electron Bernstein wave (EBW) predicted by I. Bernstein (circa 1958) and experimentally discovered by F. Crawford et al, Stanford U (1964)**

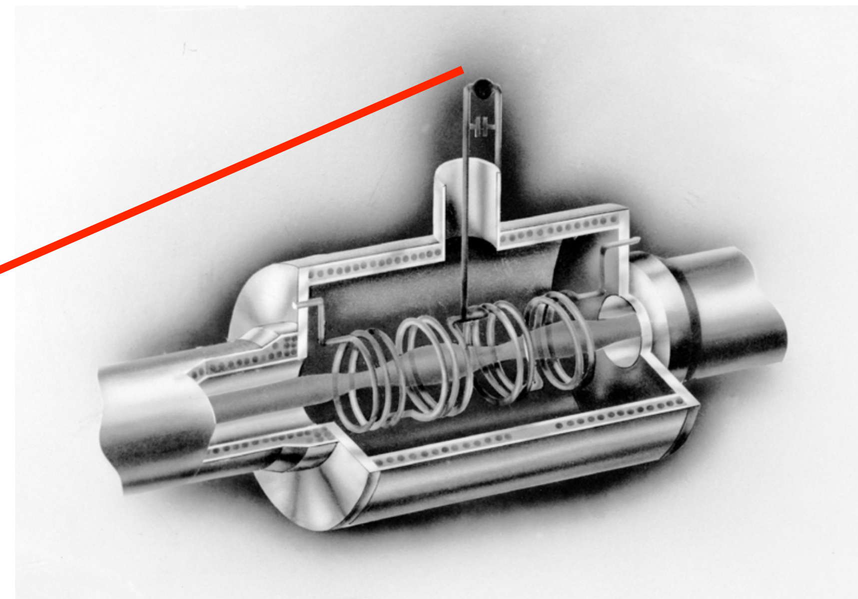
Stix et al, demonstrated efficient heating of magnetically confined plasma with the ICRF "slow" wave (1958-1962)

Extension of the Shear Alfven wave frequency to Ω_i in a "magnetic beach" produced ion tail and neutrons

The B65 Stellarator



B65 Stellarator

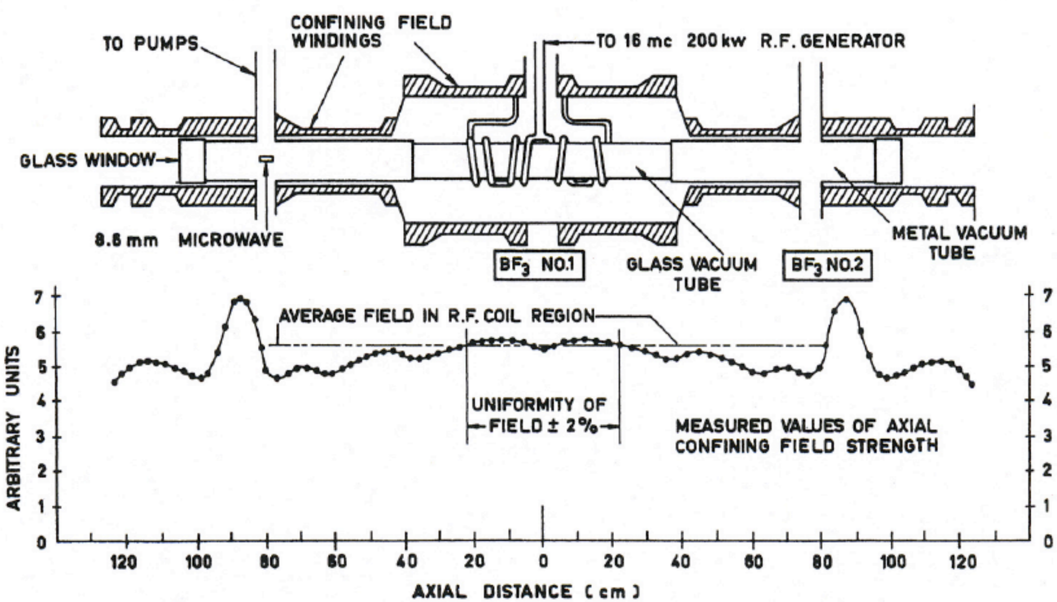


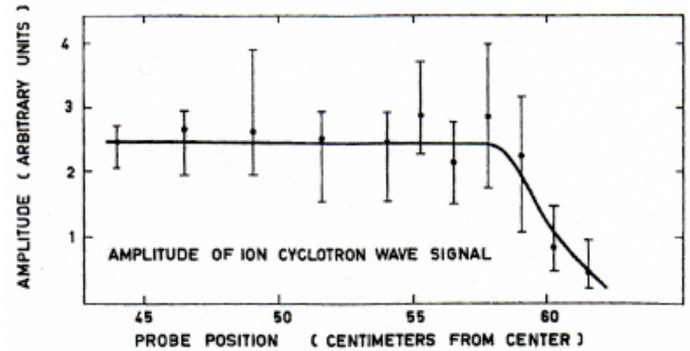
"Stix" Coil

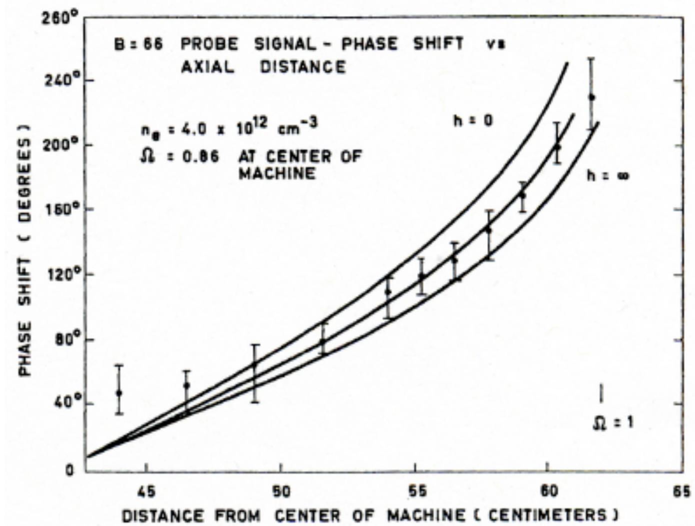
$$\omega \approx k_{\parallel} V_A (1 - \omega/\Omega_i)^{1/2}$$

if $k_{\perp} << k_{\parallel}$

In 1962 W. Hooke et al, verified the dispersion and damping of the ion cyclotron wave in the magnetic beach in the B-66 device







$$\omega \approx k_{\parallel} V_A (1 - \omega/\Omega)^{1/2}$$

where $V_A = c\omega_{ci}/\omega_{pi}$

The ion cyclotron (slow-wave) has practical problems in large tokamaks:

- **Antenna strap spacing too small since $\lambda_{\parallel} \leq 15$ cm**
- **Wave must be launched from inside the torus**

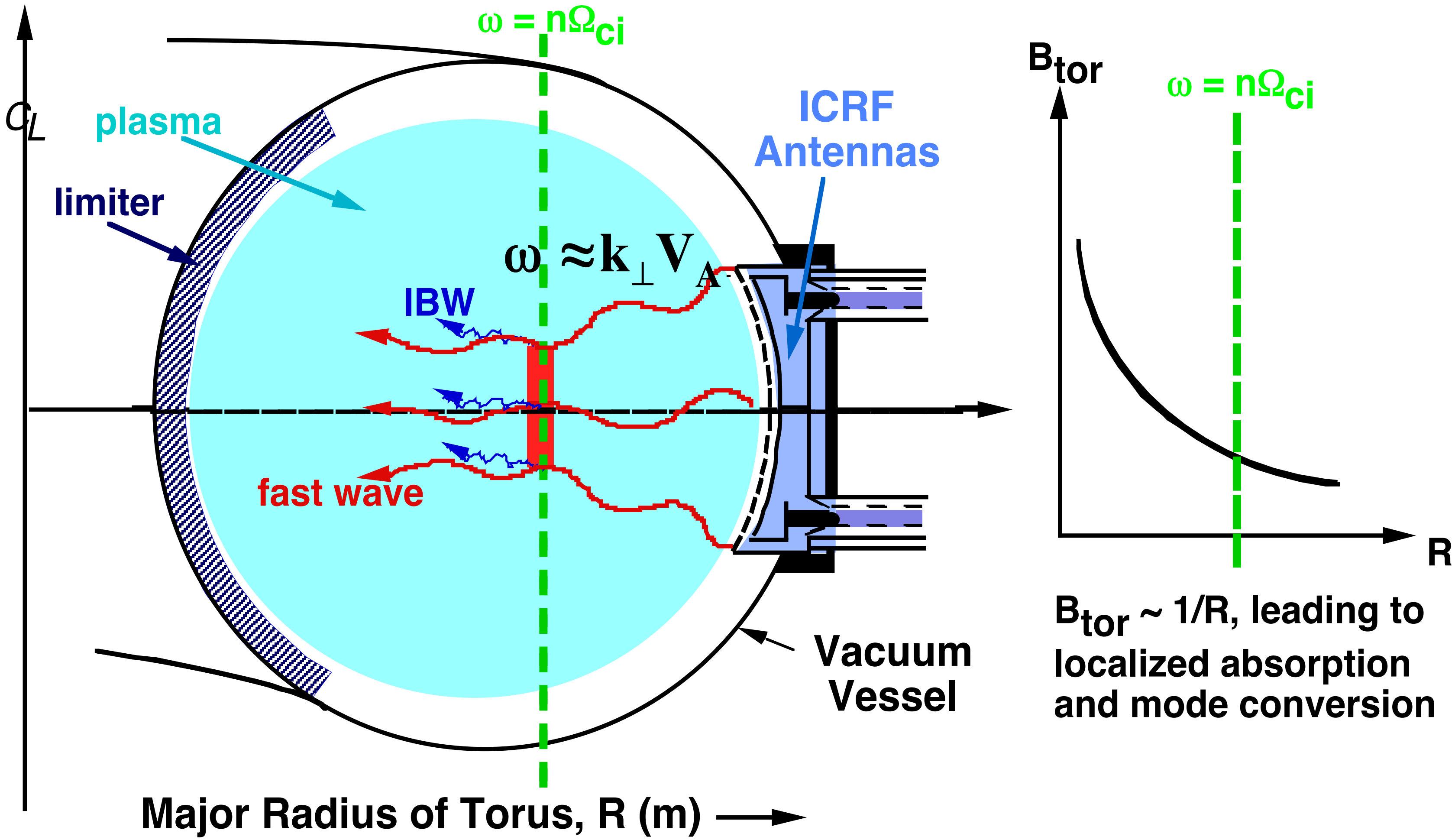
Fast Wave ICRF physics investigated and shown to be viable in tokamaks with good confinement in the 1970s !

➔1970's:

- ✧ ICRH mode-conversion heating in multi-ion species plasmas observed
- ✧ ICRH FW minority heating (ICRF) discovered and was shown to be efficient
  - ➢ Stix' quasilinear theory verified
- ✧ ICRF 2 Ω_i heating observed
- ✧ Ion Bernstein Wave (IBW) dispersion verified (J. Schmitt, 1973) and later found to be excitated by mode conversion from the FW

The Fast Magnetosonic Wave (FW) penetrates large plasmas with $N_{||} \approx 5$ and $\lambda_{||} \approx 0.5 - 1$ m

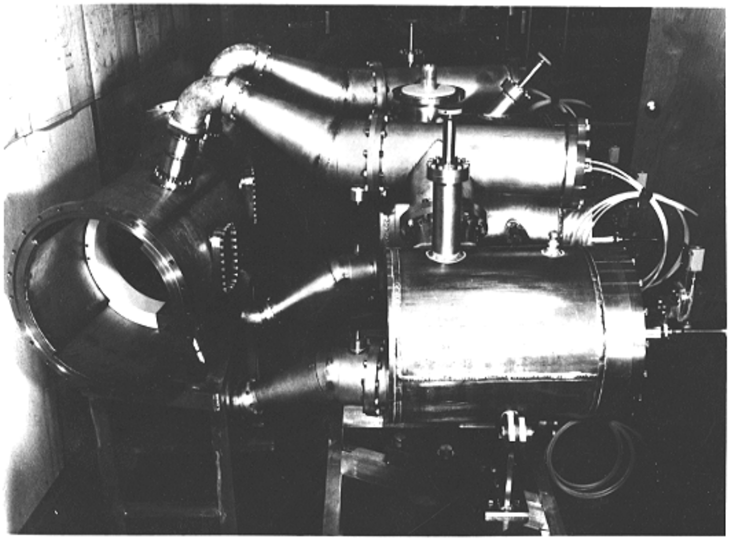
But the wave is RH circularly polarized at Ω_{ci} and may not be absorbed !

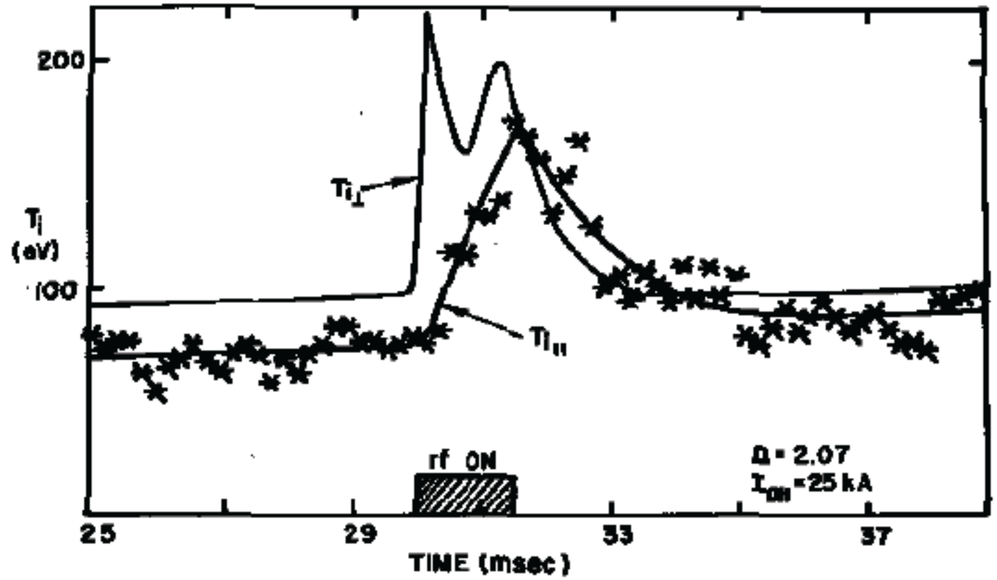


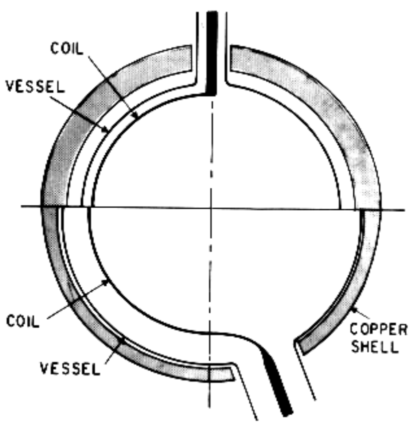
$B_{tor} \sim 1/R$, leading to localized absorption and mode conversion

After J. Hosea, et al

ST Tokamak antenna array with inboard 1/2 Turn elements (circa 1970) to explore Fast Wave launching



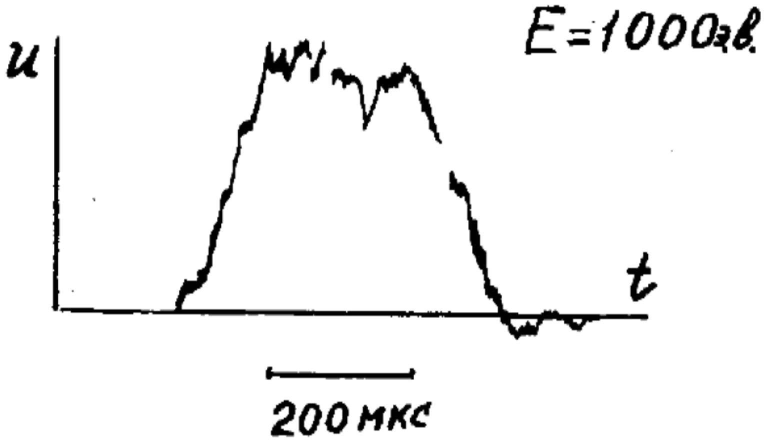




-- Early experiments on the ST tokamak at PPPL established coupling and heating at 2 Ω_D
(J. Adam et al., IAEA, London,1974)
-- Heating subsequently explained as perhaps cyclotron damping of the fast wave on minority hydrogen ions

Minority heating verified by mass sensitive charge exchange neutral diagnosic in the TM-1-Vch Tokamak by V. L. Vdovin and coworkers at the Kurchatov Institute (1976, Grenoble)

V. L. Vdovin et al, in Proceedings 3rd International Meeting on Heating in Toroidal Plasmas, Grenoble (CEA, Grenoble, Vol. 2, pp 349 (1976)).



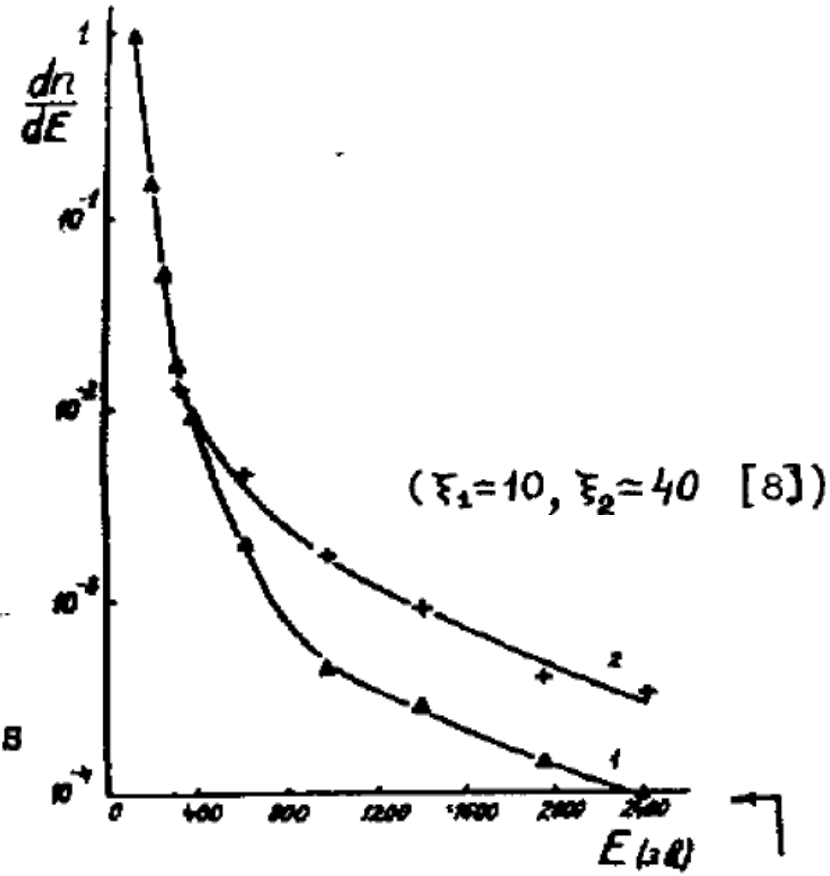
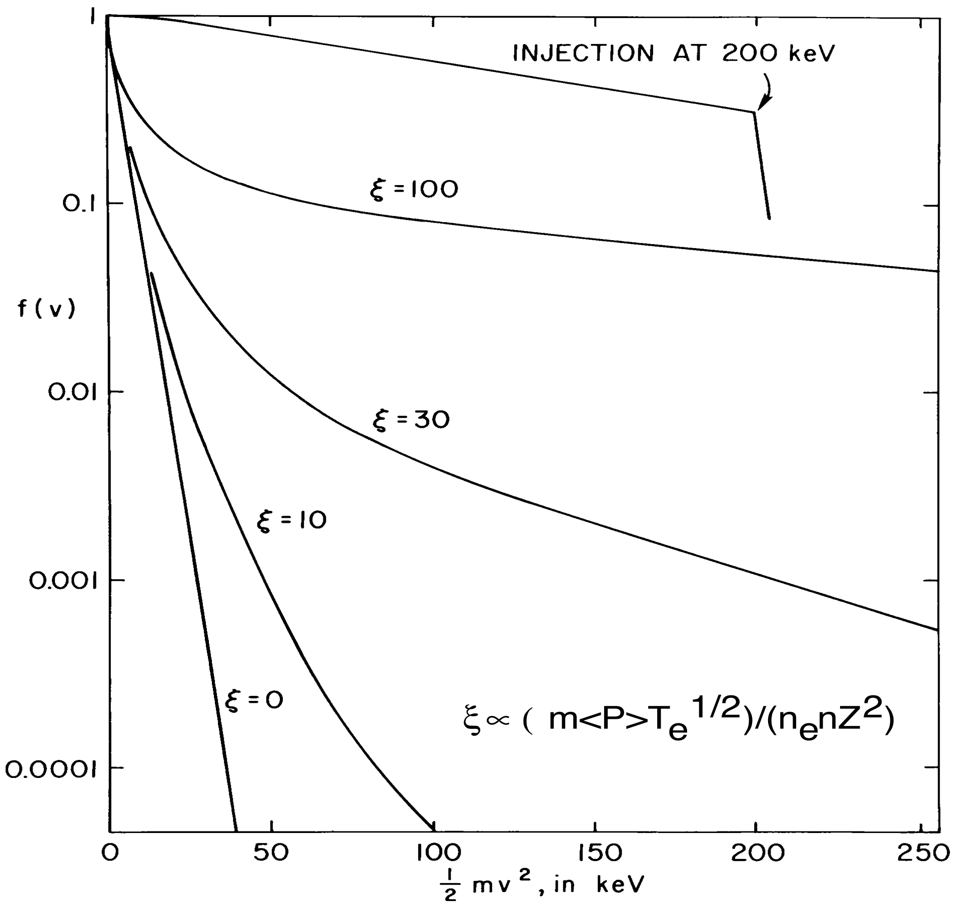


Fig.13. Signal from charge exchange neutral detector at u =1KeV.

Fig.14. Build of a high energy "tail" in the proton (1%) energy distribution in deuterium (99%) for two levels of HF excitation at $\omega = \omega^{H}_{Bi}$.

Minority ion cyclotron heating in a two-ion species plasma was described quantitatively in the 1970s by Stix's theory

Fokker-Planck Energy Distribution Calculated for RF Excitation at the Minority Ion Cyclotron Frequency

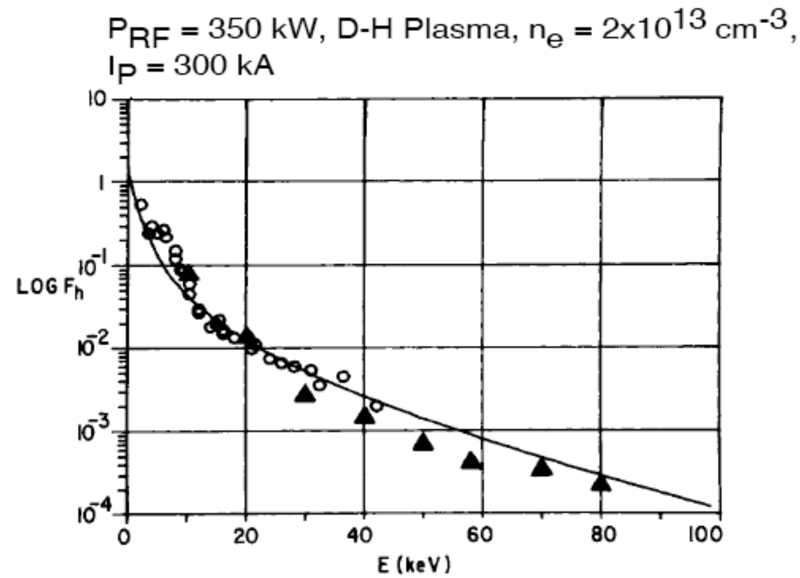


Stix, Nuclear Fusion, 1975

Hosea et al, 1979

PLT Hydrogen Ion Energy Distribution Compared with Theory

P_{RF} = 350 kW, D-H Plasma, $n_e = 2\times10^{13}$ cm^{-3}, I_P = 300 kA



Fast Wave dispersion in cold plasma shows 2 cutoffs (Left and Right hand) and a resonance (ion-ion Hybrid)

Left hand cutoff

Right hand cutoff

$$n_\perp^2 = \frac{(L - n_\parallel^2)(R - n_\parallel^2)}{S - n_\parallel^2}, \qquad n = ck/\omega$$

Ion-ion hybrid resonance

Mode conversion of the FW ($n_\perp^2$=LR/S) into shorter wavelength IBW, ICW (must include thermal effects)

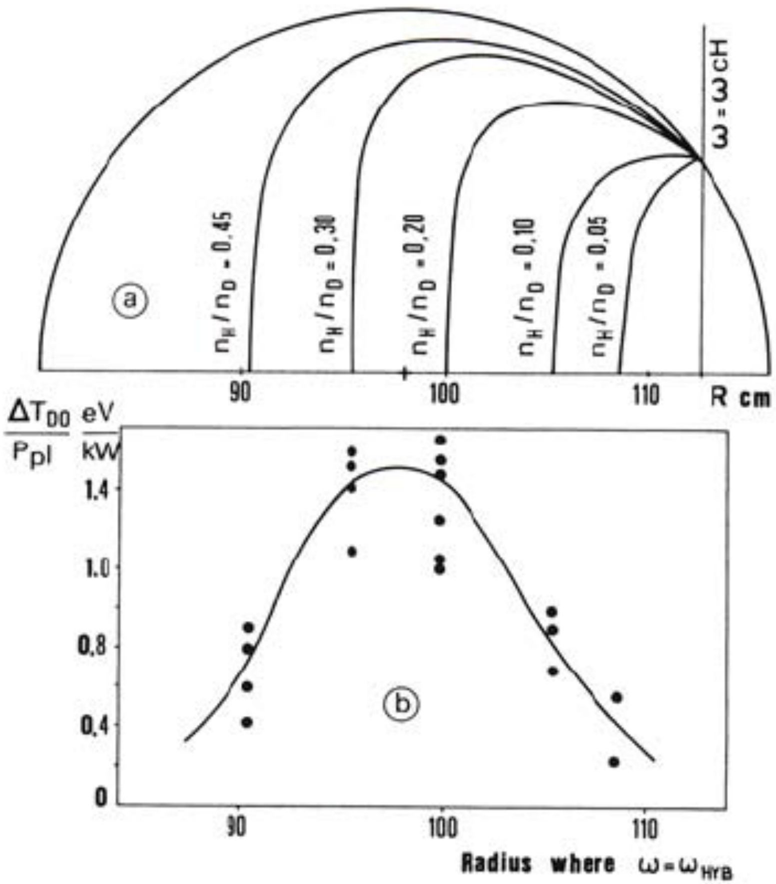
$$R = 1 - \sum_s \frac{\omega_{ps}^2}{\omega(\omega + \Omega_s)}, \quad L = 1 - \sum_s \frac{\omega_{ps}^2}{\omega(\omega - \Omega_s)}$$

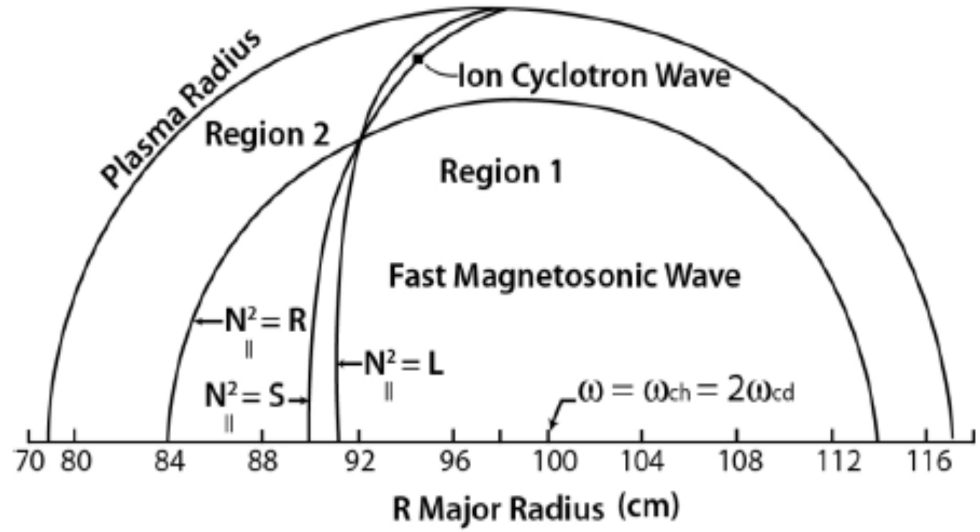
$$P = 1 - \sum_s \frac{\omega_{ps}^2}{\omega^2}$$

$$S = (R + L)/2, \quad D = (R - L)/2$$

$$\omega^2 \simeq k_\perp^2 v_A^2 \left(1 + c^2 k_\parallel^2/\omega_{pi}^2\right)$$

Mode conversion of the Fast Magnetosonic Wave at the " ion-ion" Hybrid Layer in a D(H) Tokamak Plasma





TFR experiment shows heating at the ion-ion hybrid layer for inside launch (J. Adam, 1974)

The case of high "minority" concentration, namely $n_H/n_D = 0.25$; $k_{\parallel} = 15\ m^{-1}$, f = 61MHz :

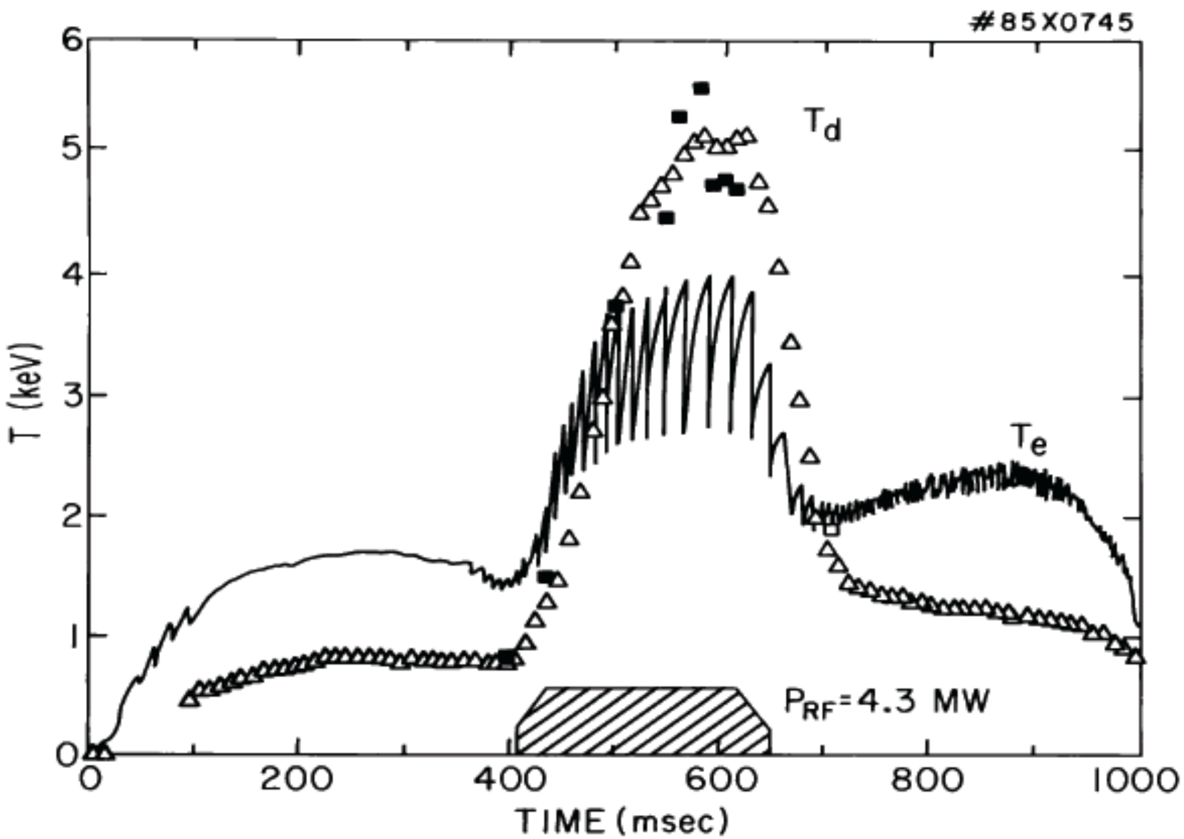
The "mode conversion" regime
J. Jacquinot, et al, PRL 39, 88 (1977)

The history of RF wave propagation and heating experiments in the 1980s was highly successful and verified many aspects of the theory

➔ **1980's:**

- ✧ **ICRH demonstrated at the multi-MW level on PLT**
- ✧ **LH Heating and Current Drive (LHCD) demonstrated**
- ✧ **ECRH demonstrated using the newly developed gyrotron tubes at 28(56) GHz**

ICRF Heating with the Fast Wave to multi-keV temperatures first demonstrated on the PLT tokamak in the 1980s



Deuterium plasma with ^{3}He minority cycloton damping

$n_e = 3.7 \times 10^{13}$ cm^{-3}

I_P = 600 kA

B_Φ = 32.5 kG

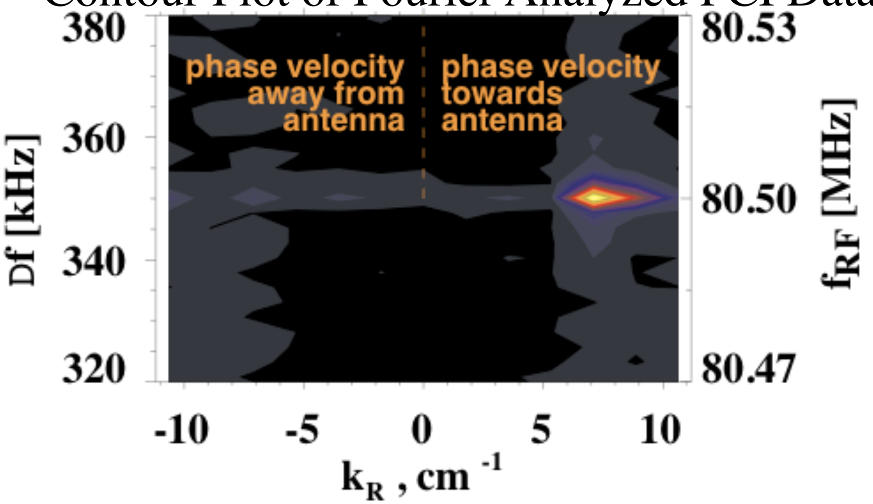
High heating efficiencies (80% or more) established for *minority* heating

Wilson et al., AIP RF Conf./Hosea et al., EPS - 1985

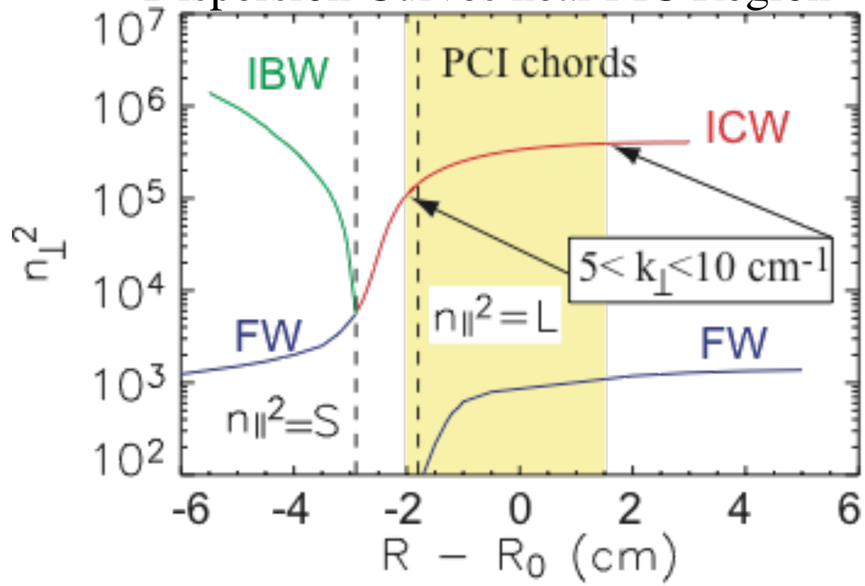
Experimental verification of mode conversion into dominant ICW, rather than IBW, found by the PCI diagnostic

E. Nelson-Melby, M. Porkolab, Y. Lin, *et al*, Phys. Rev. Lett. 90, 155004 (2003)

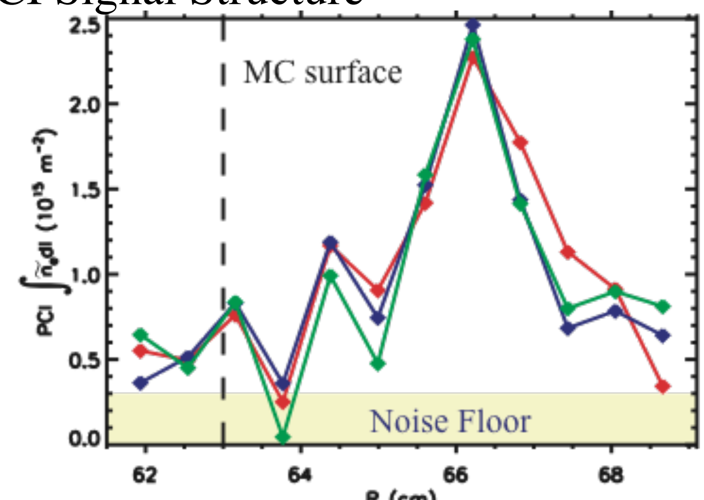
Contour Plot of Fourier Analyzed PCI Data



Dispersion Curves near MC Region



PCI Signal Structure



- **Propagating towards the low field side.**
- **Wavelength shorter than FW, but generally longer than IBW.**
- **On the low field side of the H - ^{3}He hybrid layer.**

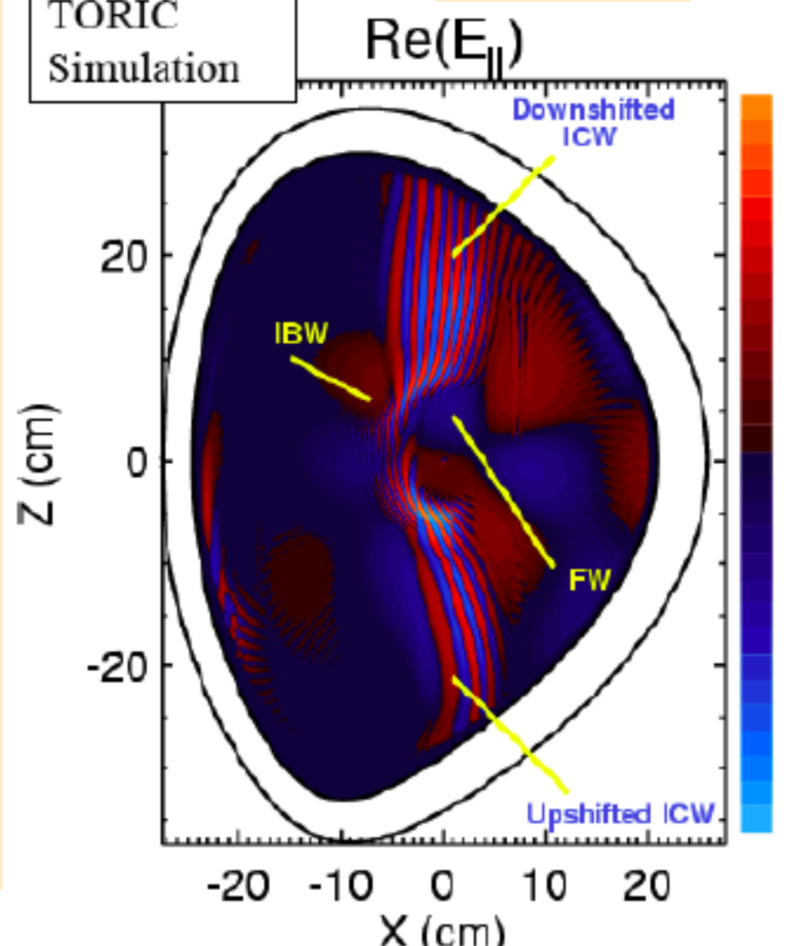
More surprises: in 2003 Phase Contrast Imaging (PCI) on C-Mod, and full wave code TORIC discover ICW predicted by F. Perkins in 1977

(E. Melby, M.Porkolab, et al, PRL. 2003)

Francis (Rip) Perkins in 1977 (Nucl. Fusion **17**, 1197 (1977)) makes new prediction for the mode conversion process in a two-ion component DT plasma with ***magnetic shear***; predicts the importance of conversion into ***the "kinetic ion cyclotron wave", or "ICW"***, and it may well dominate conversion into IBW; paper not understood by the community for 25 years;

ICW has been discovered in Alcator C-Mod by phase contrast imaging (PCI) in 2003 when searching for IBW and the Perkins Theory verified

Bonoli et al



In sheared field off mid-plane, $k_{//} = (m/r)(B_{pol}/B)$ *dominates antenna driven* $k_{//}$

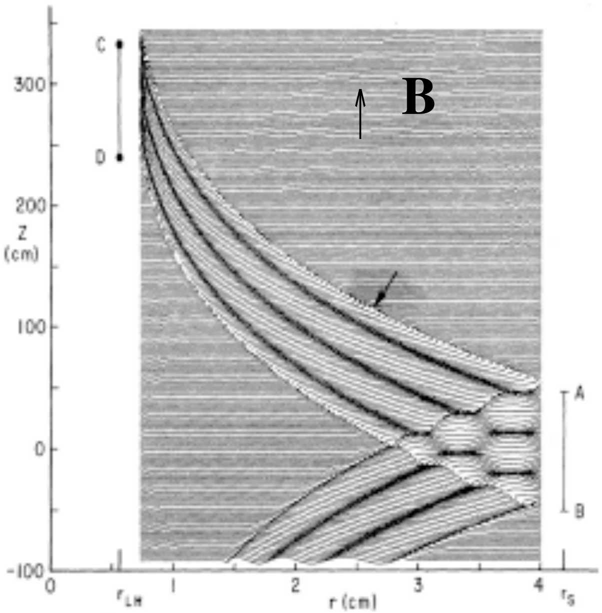
Experiments on RF wave propagation and heating in the 1970s and 1980s demonstrated RF current drive

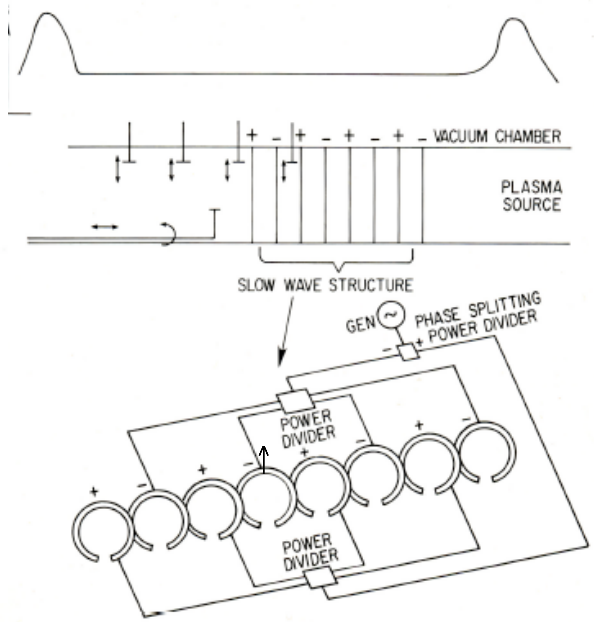
➔ **1970's:**

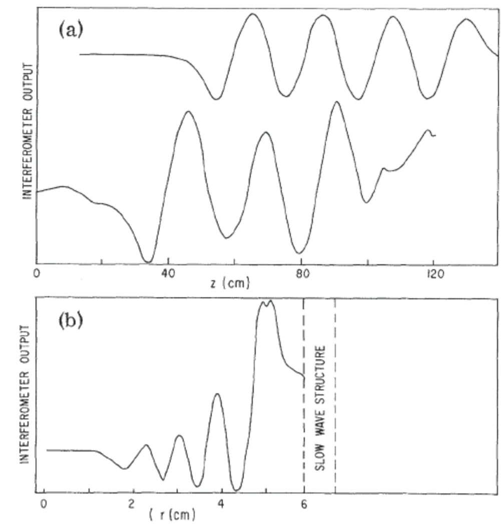
- ✧ **Electron Bernstein wave (EBW) dispersion verified by F. Leuterer**
- ✧ **Nonlinear wave-wave and wave-particle interactions (mode coupling, parametric decay) studied in depth by Porkolab and students (Porkolab, Rev. Mod Physics, 1978; Physics of Fluids, 1977; Nuclear Fusion, 1978)**
- ✧ **Lower Hybrid Wave dispersion verified by Bellan and Porkolab (1975) and later found to be key to efficient current drive in tokamaks (1980s)**

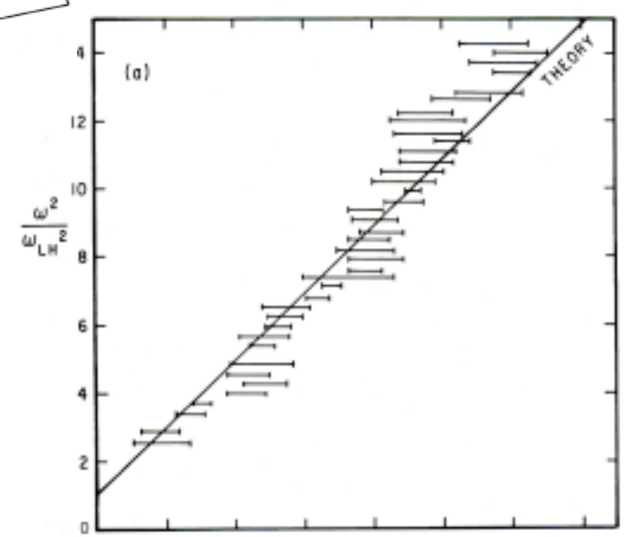
Lower-Hybrid Wave Dispersion and Accessibility Verified

Bellan and Porkolab (PRL 34, 124 (1975))







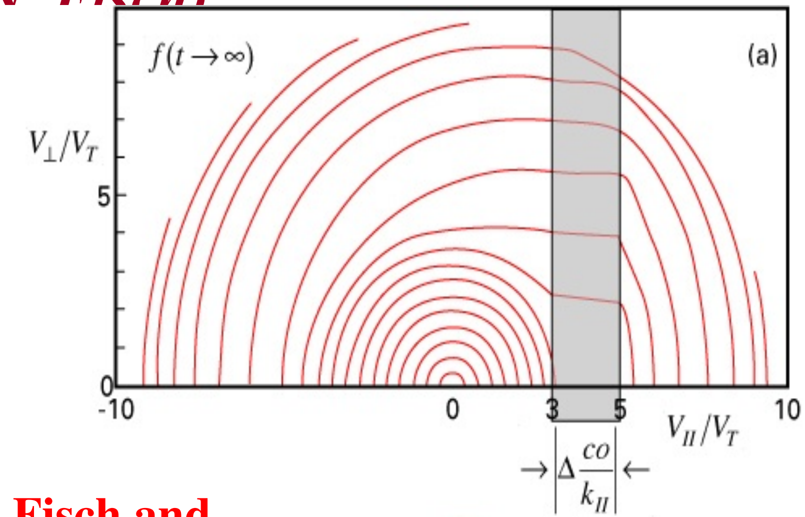


$(m_i/m_e)(k_z^2/k^2)$

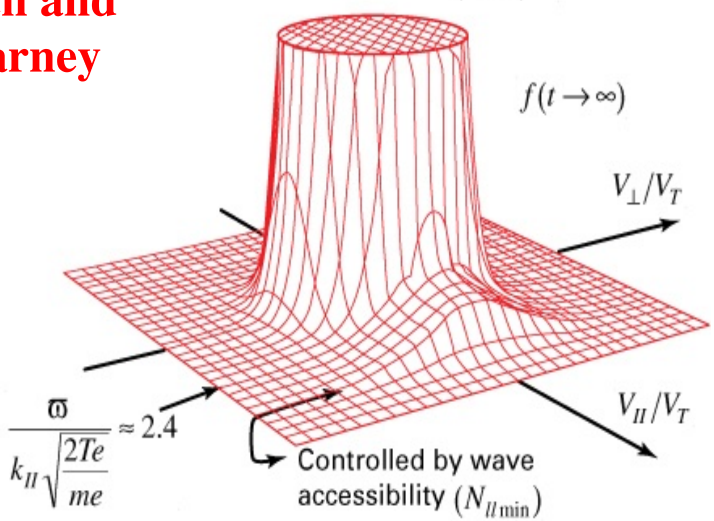
$$\omega^2/\omega_{LH}^2 = 1 + (m_i/m_e)(k_z^2/k^2)$$

$$\omega_{LH}^2 = \omega_{pi}^2/(1+\omega_{pe}^2/\omega_{ce}^2)$$

Principle of Lower Hybrid Current Drive established late 1970s and 1980s: asymmetric LH wave packet creates one sided plateau on the electron distribution whose velocity moment corresponds to net current (N. Fisch)



Fisch and Karney



Maximum $n_{||}$ penetrates until it is Landau damped on electrons at the quasi-linear plateau break point, typically

$v_{min} = c/n_{||max} = 2.4v_{te}$ where $v_{te} = \sqrt{2T_e/m_e}$

Or, typically, $n_{||max} = 7/\sqrt{T_e(keV)}$

Minimum accessible value of $n_{||}$ (Golant, Troyon) determines maximum value of the quasi-linear plateau, $v_{max} = c/n_{||min}$ which determines maximum current drive efficiency, η_{CD}

Thus, **window of penetration** is limited to

$$\frac{\omega_{pe}}{\omega_{ce}} + \left[1 + \frac{\omega_{pe}^2}{\omega_{ce}^2}\left(1 - \frac{\omega_{ce}\omega_{ci}}{\omega^2}\right)\right]^{1/2} \leq n_{||} \leq 7/\sqrt{Te(keV)}$$

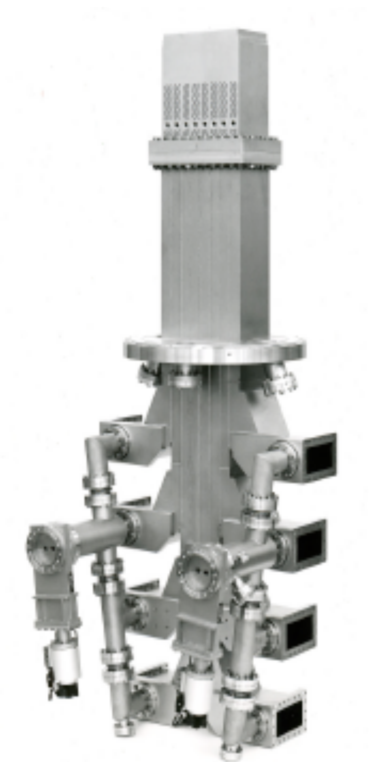
Or for $\omega_{pe}^2/\omega_{ce}^2 \approx 1$ about 12 keV !

Higher magnetic field is beneficial !

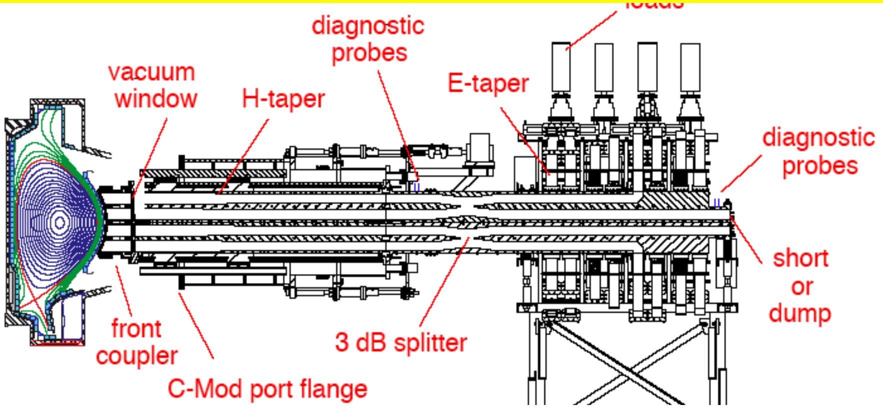
Typical slow wave structure for launching lower hybrid waves is a phased waveguide array (“grille” or grill *) in the 1-8 GHz range

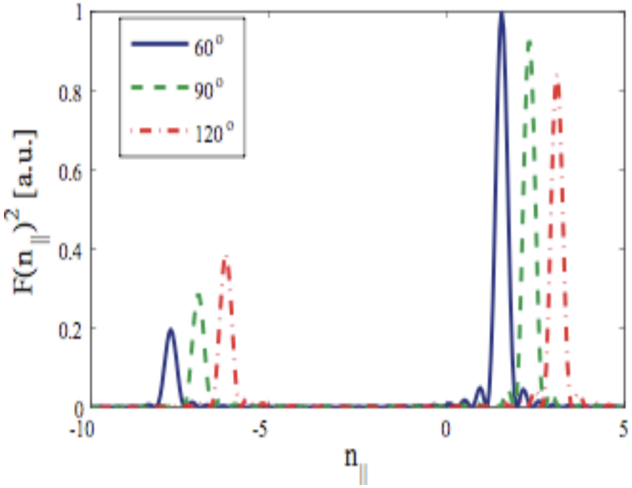
** GRILL concept developed in Grenoble, Garching, Princeton and MIT and coupling theory formulated by M. Brambilla*

ASDEX design (after F. Leuterer, 1980s)



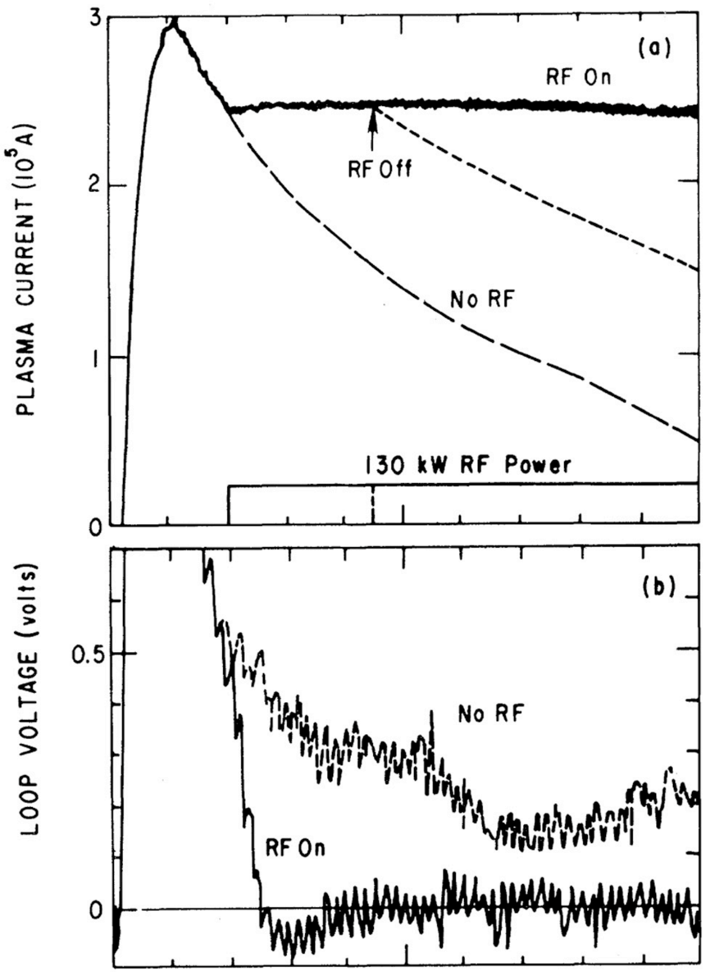
Alcator C-Mod, 2008-2012, Parker et al

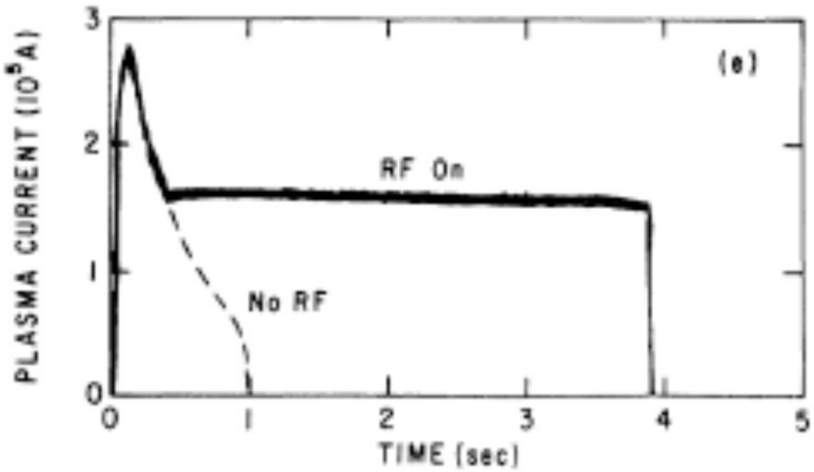




Some Early Lower Hybrid Current Drive Results on PLT

S. Bernabei, et al., Phys. Rev. Letts. 49, 1255 (1982)



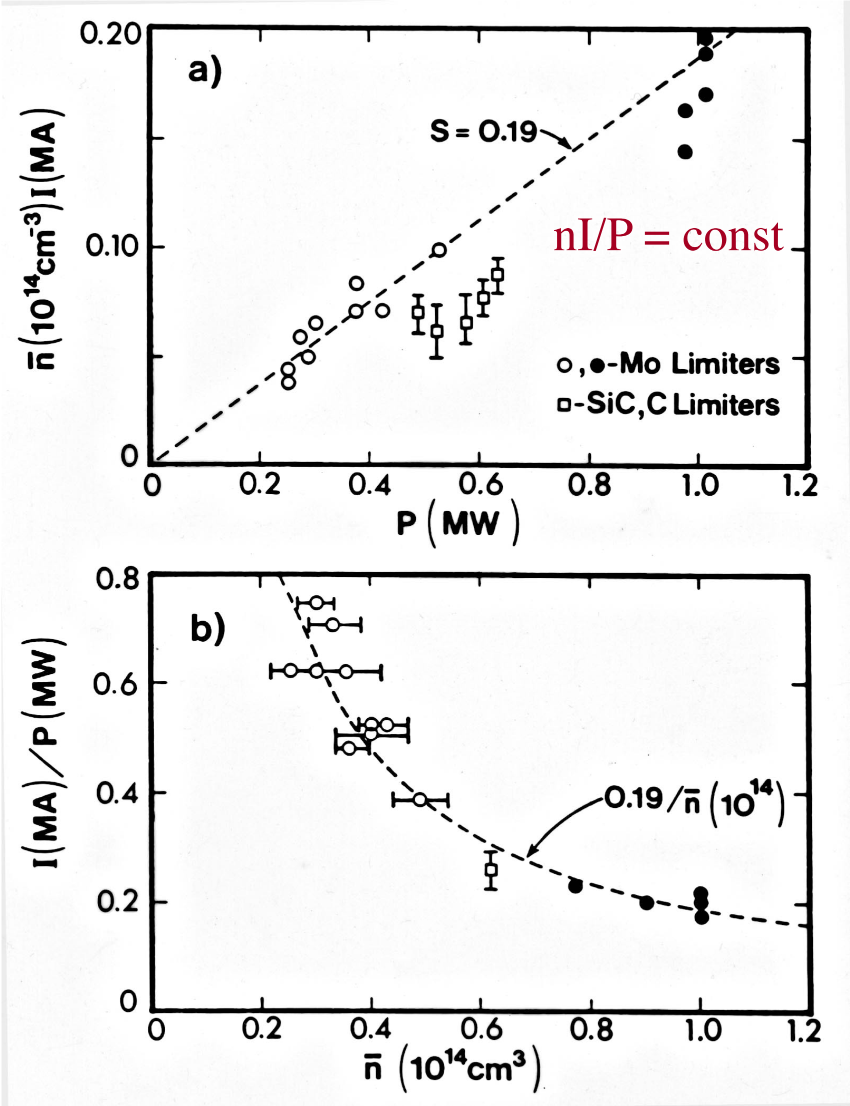


A"density limit" of about 0.8 x10^{19} m^{-3} was observed in nearly all experiments at f=0.8 GHz

Later experiments at 2.45 GHz observed a density limit of 4x10^{13} m^{-3}, while at Alcator-C at 4.6 GHz, in D the density limit arose to above 1x10^{20} m^{-3}, and in FTU even higher at 8 GHz

LCHD efficiency and frequency scaling with density was firmly demonstrated on Alcator-C at densities up to $n_e = 10^{20}$ m^{-3}

M. Porkolab, et al, Phys. Rev. Lett. 53, 450 (1984)



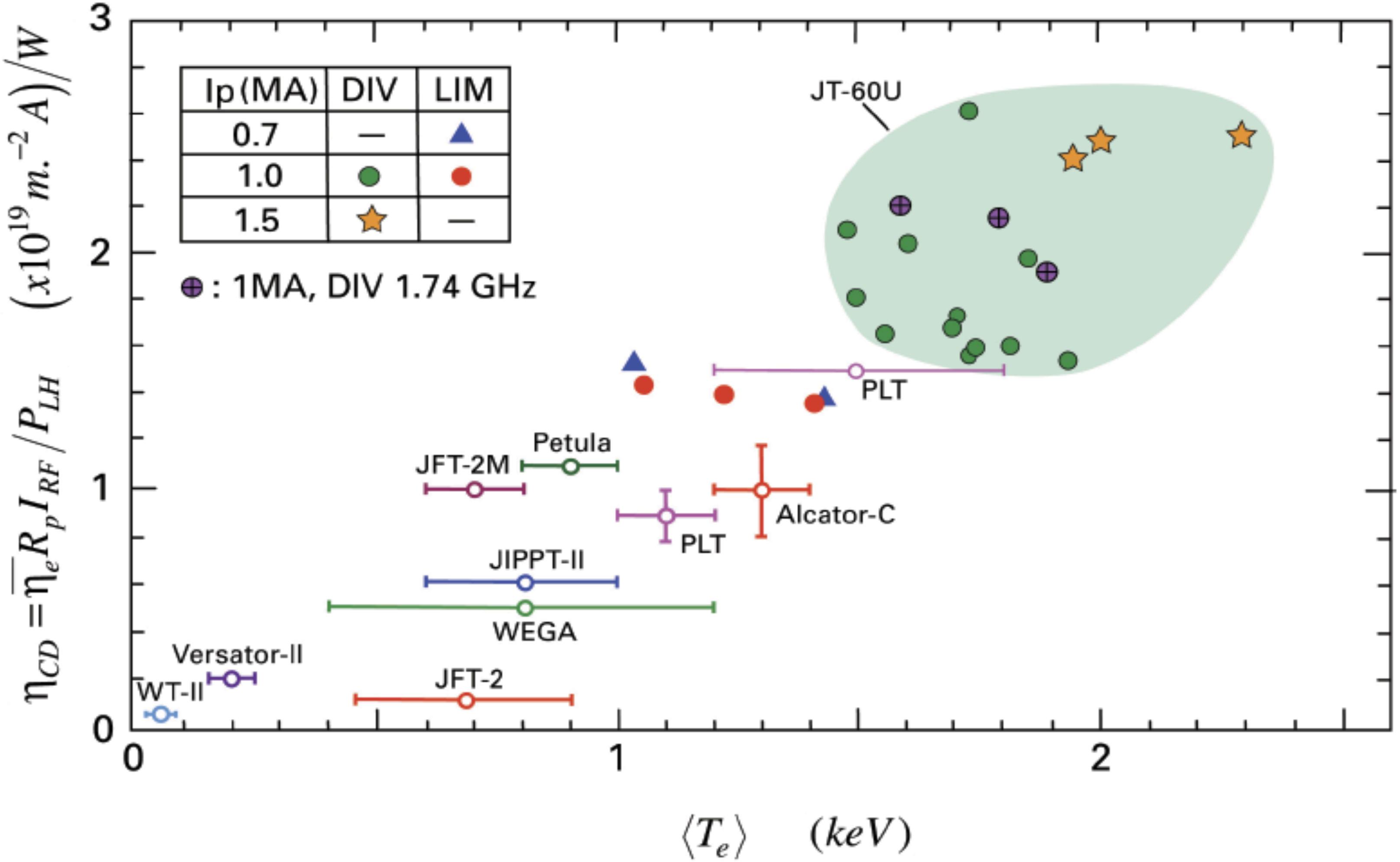
f = 4.6 GHz

A frequency (~ 5 GHz) should be suitable for LHCD in ITER (and DEMO) to operate at densities ~ (0.8-2)x10^{20} m^{-3} at B_T= 5.4 T and avoid absorption by alphas

Theory predicts : $nI/P = f(T_e)/n_{||}^2R$

Lower Hybrid Current Drive (LHCD) efficiency increases with electron temperature

$n_{e20}I_{MA}R_m/P_{MW} = 0.01T_e$ (keV)



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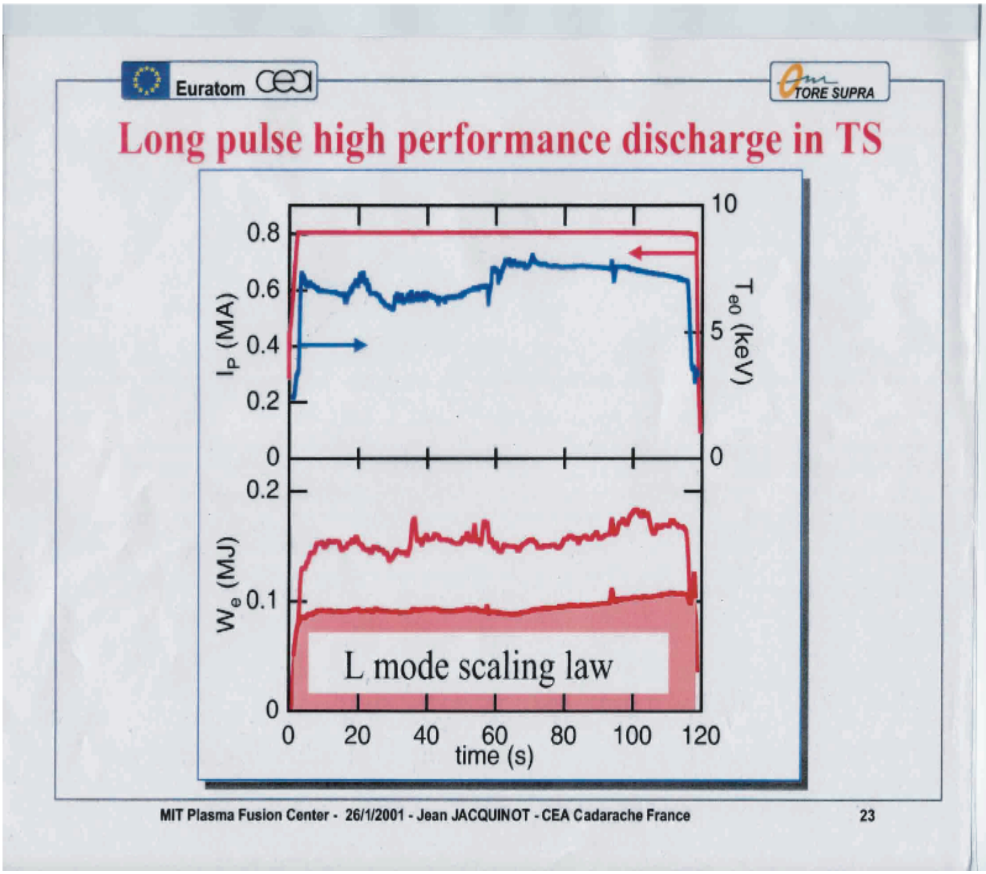
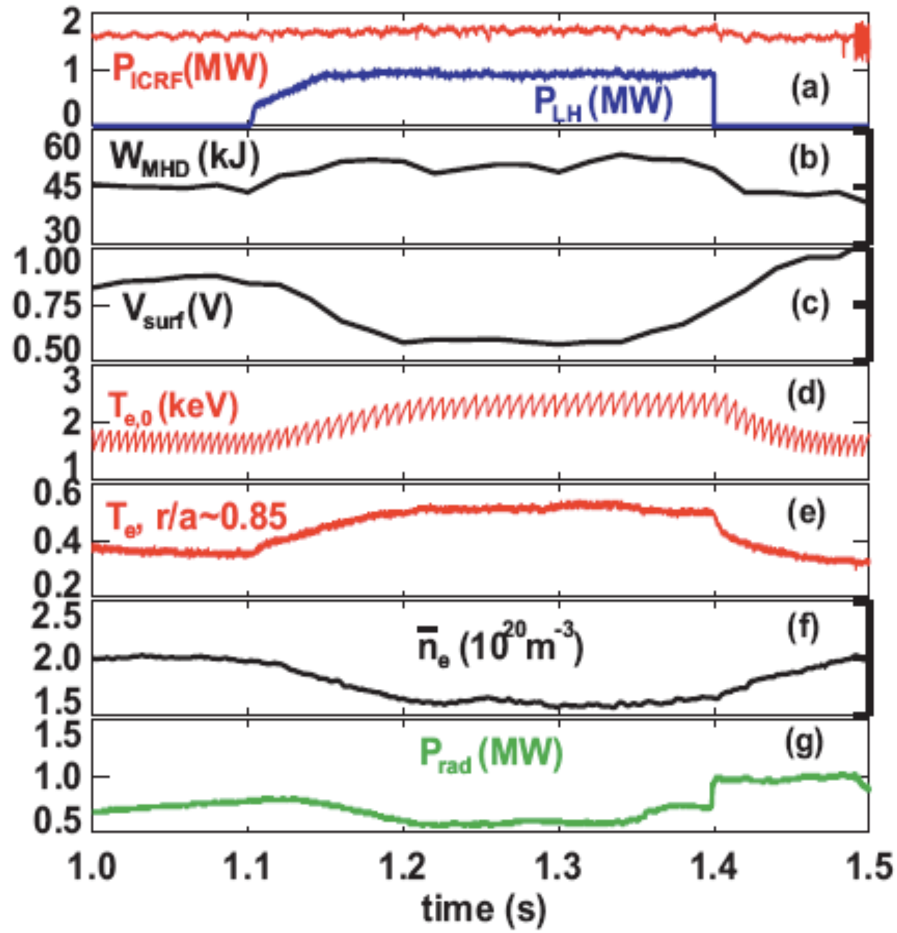
-Tore Supra demonstrated 2 minute LHD pulses at steady state in 2001
-LHCD has been coupled successfully to H-mode plasmas in Alcator C-Mod at ITER relevant parameters (B=5.4 T, n_e= $0.8 \times 10^{20} m^{-3}$)

Alcator C-Mod

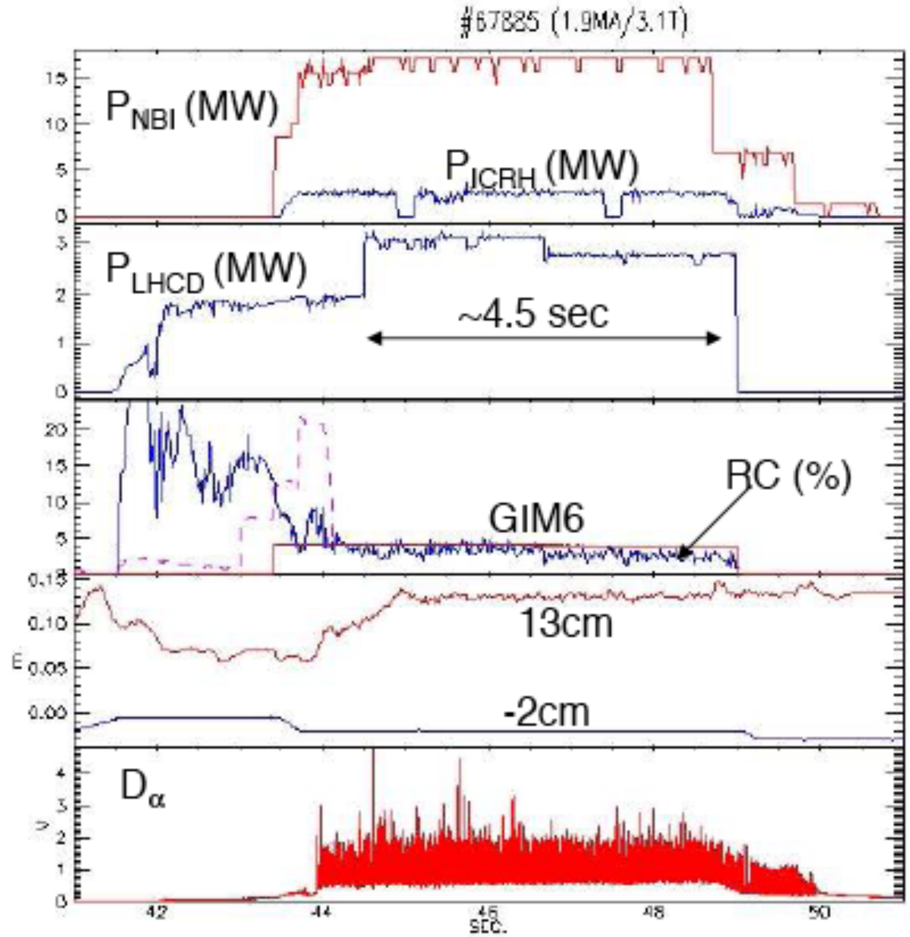


C-Mod H mode with LHCD/ICRF



LHCD Coupling into ELMy H mode with 15 cm gap in JET successful with gas puff assist

Long distance (15 cm) LH coupling in JET Advanced Tokamak scenario at high Triangularity using local D_2 puff (3 MW for 4.5 sec)



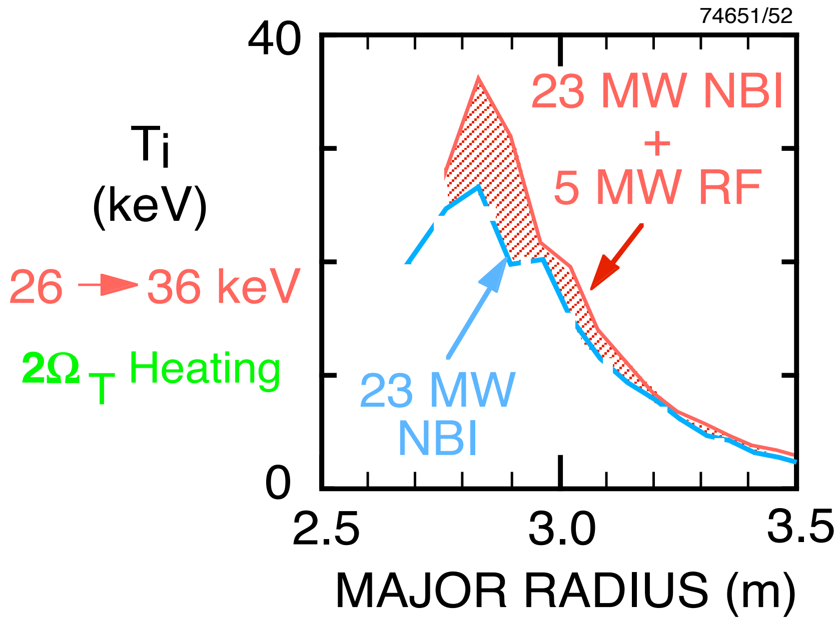
Progress on LH coupling to ELMy H-mode

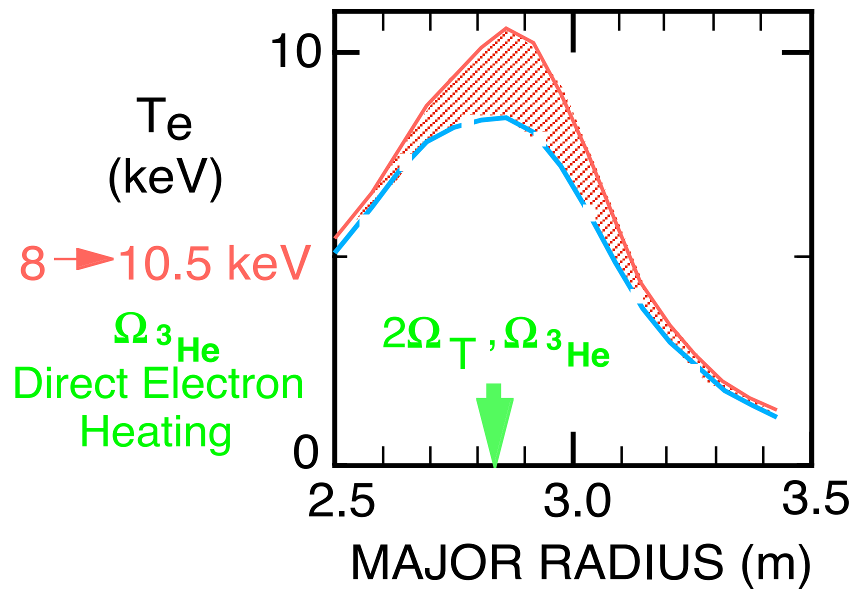
The 1990s saw reactor relevant RF performance in TFTR, JET and JT 60

➔ **1990's:**

- ✧ **ICRF heating demonstrated in DT plasmas in JET and TFTR**
- ✧ **LHCD demonstrated at the MW level and in some cases for hours**
- ✧ **FWCD, ECCD and ICRF MCCD demonstrated**
- ✧ **O-X-B mode conversion to EBW and heating demonstrated in W7-AS**

ICRF Produced Significant Increase In Central Ion And Electron Temperatures In D-T Plasmas





- Plasma reactivity increased 10% with RF
- 2% ^{3}He added to increase RF single pass absorption

Taylor et al., IAEA, 1994

ICRF Heating of D-T Plasmas

Four ICRH schemes have been examined in D-T plasmas

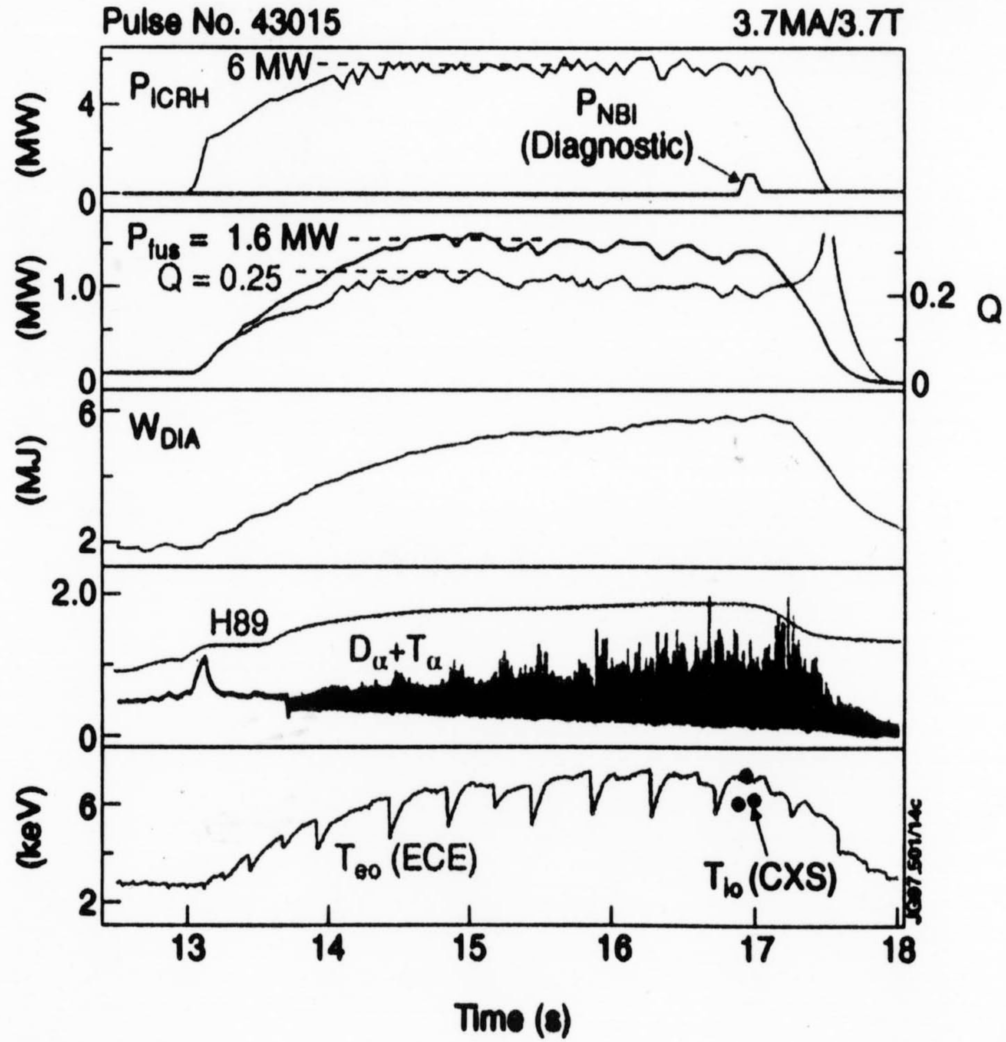
- Bulk ion heating with deuterium minority heating (D)T

Record Q=0.22 in steady-state

- Other schemes studied:
- – Second harmonic tritium heating
- – ^{3}He minority heating (^{3}He)DT
- – Tritium minority heating (T)D

Excellent agreement with PION code predictions: extrapolates well for efficient bulk ion heating on way to ignition in ITER

After D.F.H. Start, 1999, JET Start (CD1/2)



More recent RF results from JET are summarized in review article J. M. Noterdaeme et al, Fusion Science and Technology, Vol 53, Chapt. 9, pp. 1103-1151, May 2008.

In the 2000s the physics of profile control with RF is explored and preparation for testing ITER relevant RF launchers is underway

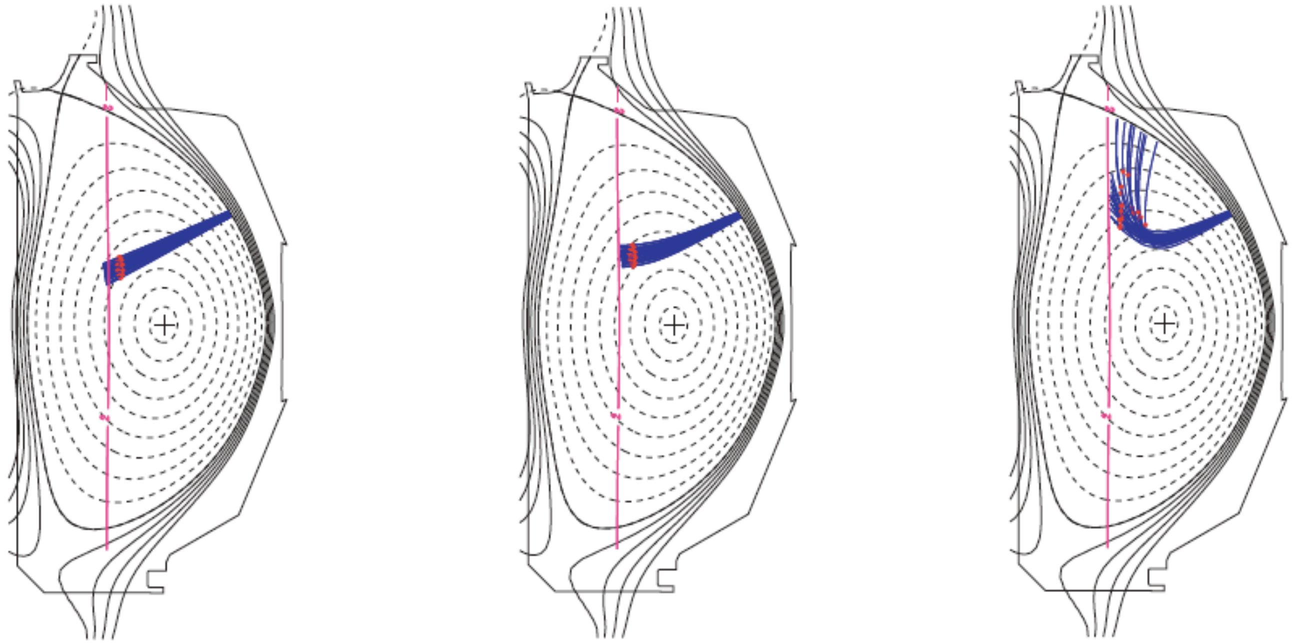
➔2000 - 2009:

- ✧ FWCD, ECCD physics quantified at the MW level
- ✧ ECCD used successfully to stabilize neoclassical tearing modes (NTMs)
- ✧ Sawtooth stabilization by MCCD, ICCD shown to be effective
- ✧ High Harmonic Fast Wave (HHFW) absorption on beams and electrons elucidated
- ✧ Plasma rotation and ITB formation due to ICRF heating without significant momentum input under study (C-Mod, JET, Asdex-U)
- ✧ Full Wave Code iterated with FP code in the ICRF and LH regimes successful
- ✧ Modern relativistic ray tracing codes combined with FP code used in the EC regime
- ✧ Measurement of the absolute ICRF wave amplitudes by Phase Contrast Imaging

Verification of ECH and ECCD, were presented in 2003 APS DPP review talk by Ron Prater, and a review of NTM stabilization with ECCD was presented in recent APS talks by LaHaye and Konemen

- TORAY-GA calculations for DIII-D; B_T = 1.7 T, T_e (0) = 5 keV, f_{EC} = 110 GHz

R. Prater



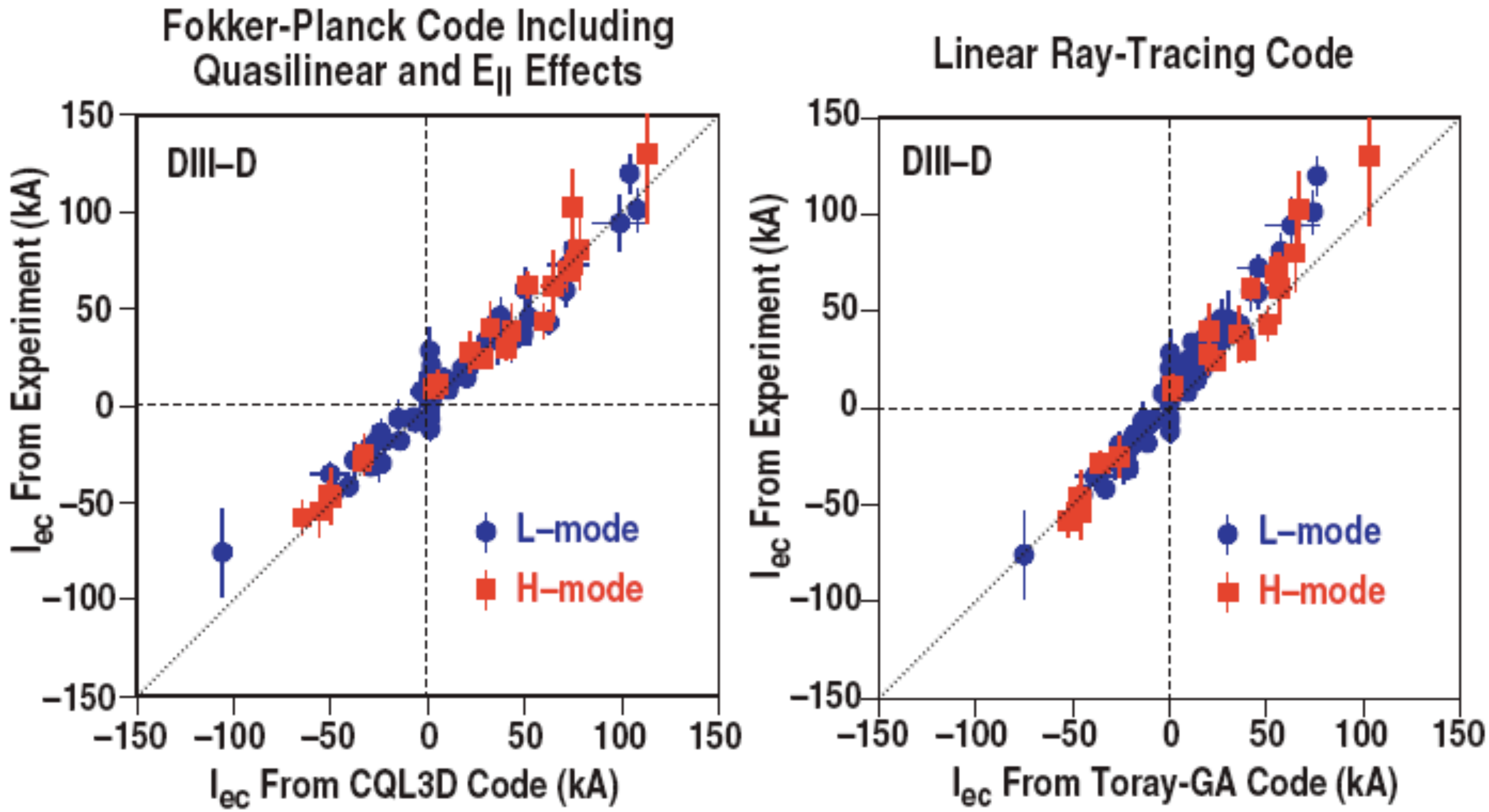
n_e (0) = 3 × 10^{19} m^{-3} | 8 × 10^{19} m^{-3} | 11 × 10^{19} m^{-3}

DIII-D NATIONAL FUSION FACILITY

123-09/RP/jy

Measured ECCD on DIII-D agrees with theory

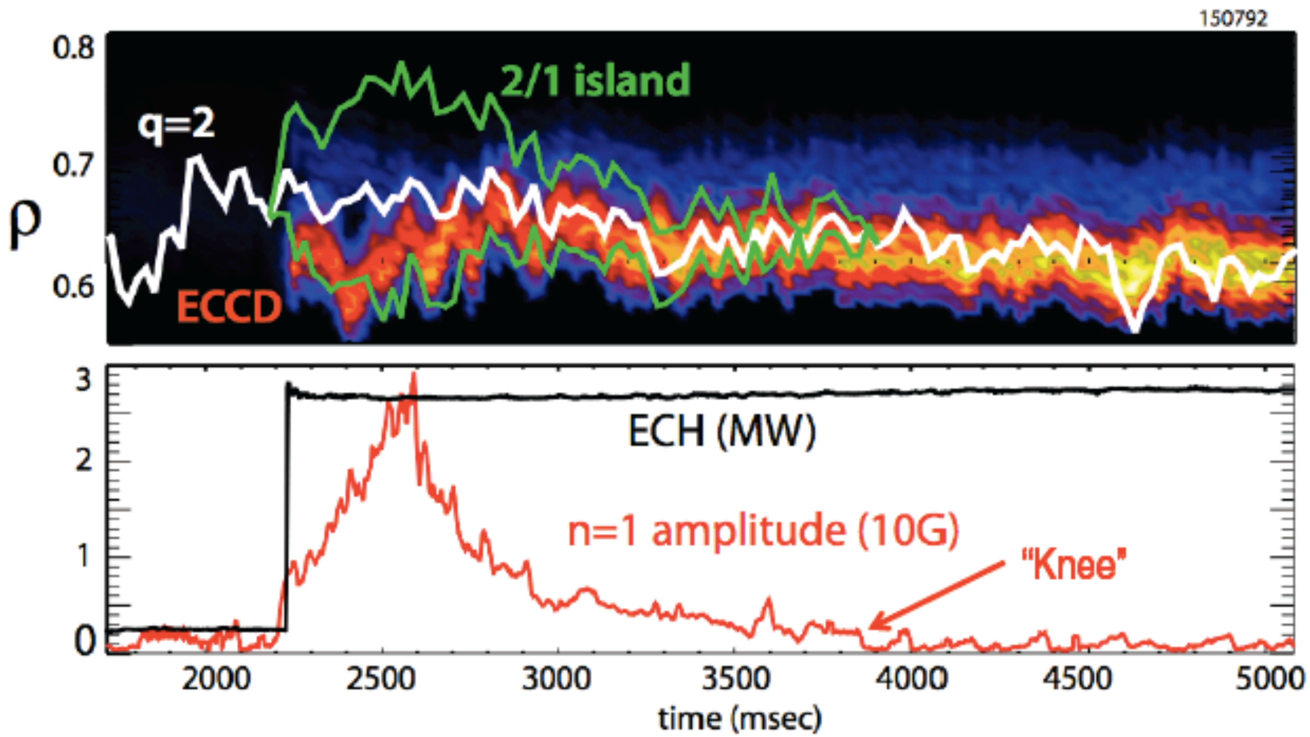
(Ron Prater)



123-09/RP/jy

Successful 2/1 Neoclassical Tearing Mode (NTM) catch and subdue demonstrate on DIII-D with ECH current drive

(E. Kolemen, APS 2012) (Similar results on ASDEX-U)



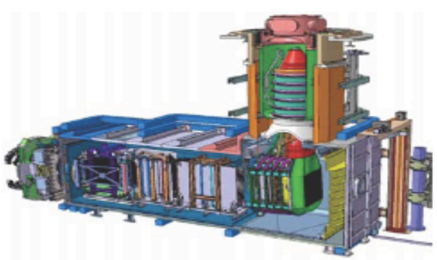
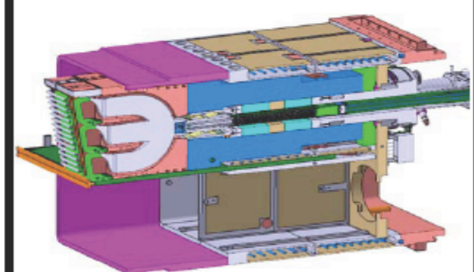
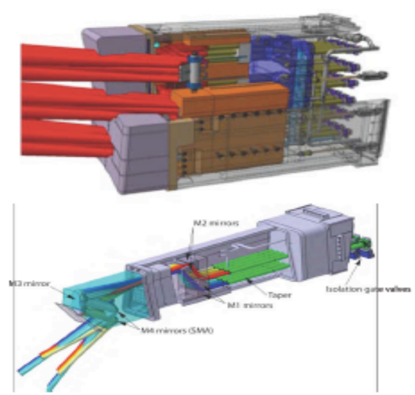
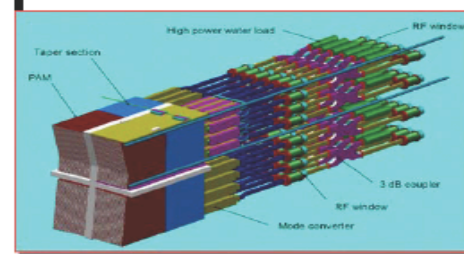
- Peak mode amplitude is reduced; without ECCD, mode reaches ~40 G and locks with loss of H-mode
- The mode is eventually brought to full suppression

The design of ITER RF systems and antennae is underway

(Courtesy of M. Henderson, 39th IRMMW-Thz meeting)

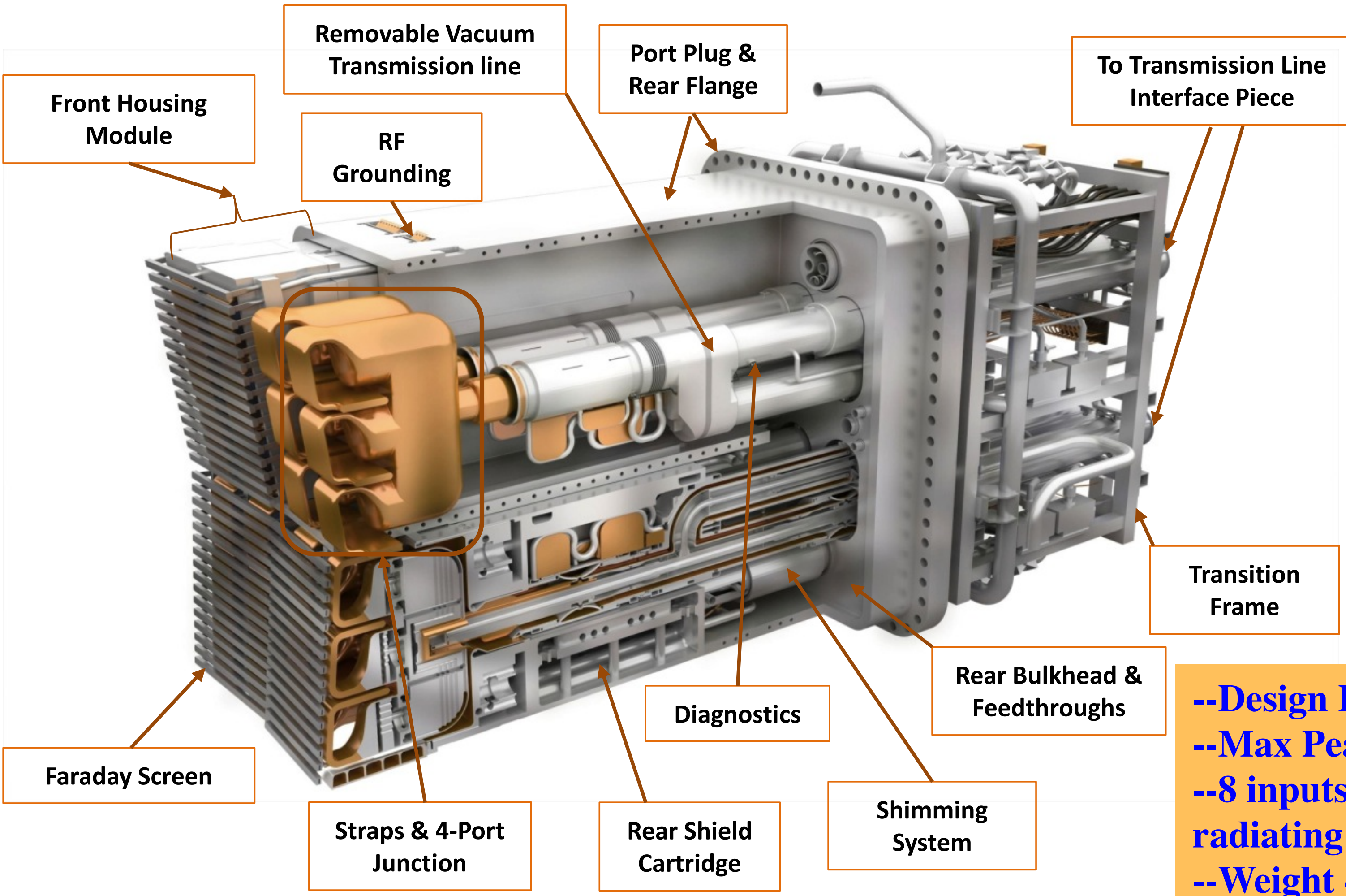
ITER H&CD Systems

All four heating systems envisioned for ITER in preparation for DEMO

NB	IC	EC	LH
Neutral Beam	Ion Cyclotron 40-55MHz	Electron Cylotron 170GHz	Lower Hybrid **5 GHz**
			
33MW +17MW	20MW +20MW	20MW +20MW	0MW +40MW
Plasma Rotation for stabilizing RWM	Bulk ion heating	Localized and steerable H&CD	Off-axis bulk current drive

Need a variety of "tools" to optimize the operating scenario for DEMO

1/4 scale cross section of a proposed ITER ICRF antenna has been built and tested in JET; new improved design may emerge



Tetrode Developed by CPI

Thales, France developing "Diacrode"

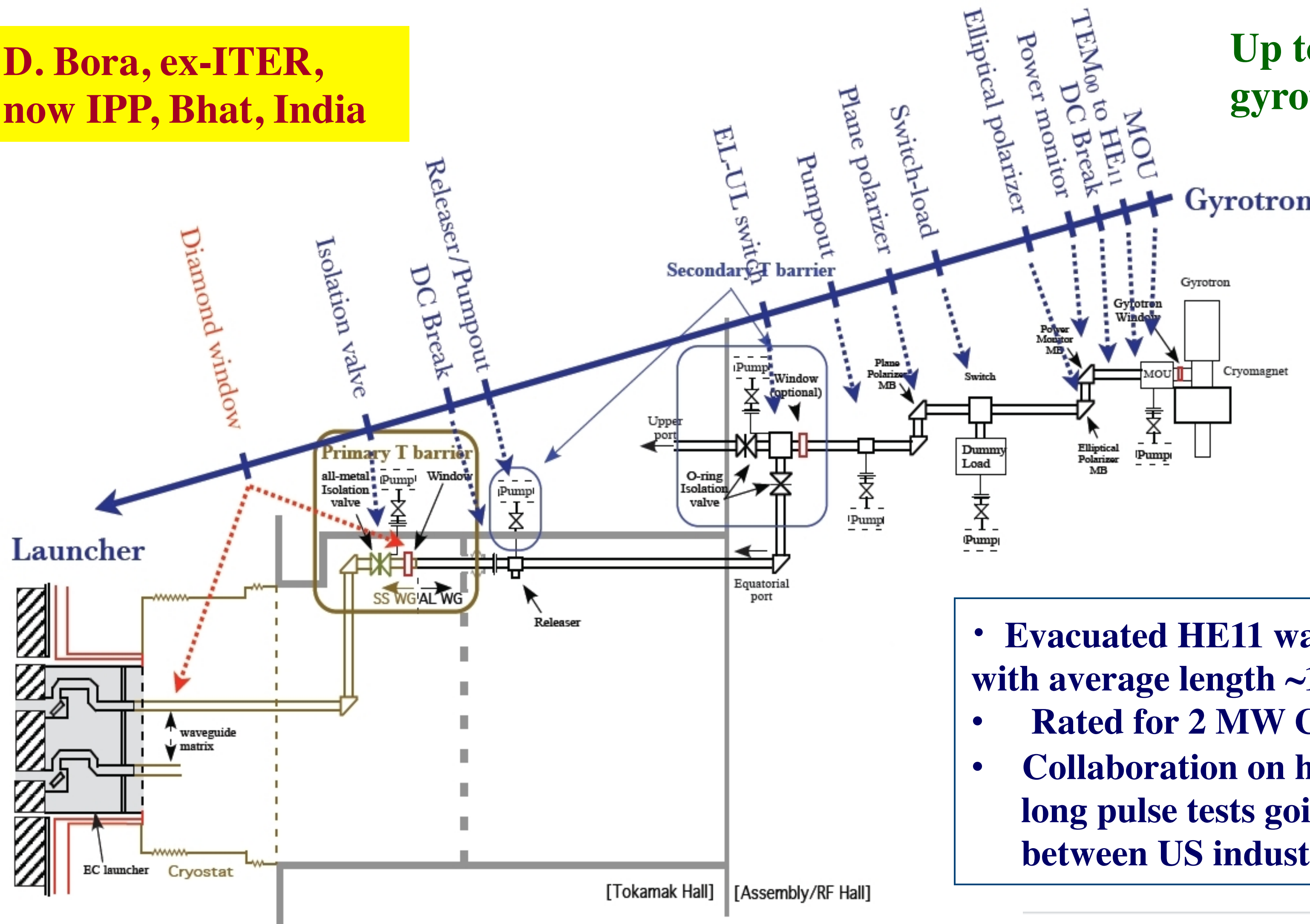
--Design Power: 20 MW
--Max Peak Voltage 45kV
--8 inputs connected to 24 radiating straps
--Weight 45 ton
--2 antennas located in equatorial ports

Courtesy D. Bora, Sorrento RF Conf. 2013

ITER ECH transmission line (160 m long) layout and launcher design complex (ongoing debate about optimum location of steerable mirror launchers at Sorrento RF 2013)

D. Bora, ex-ITER, now IPP, Bhat, India

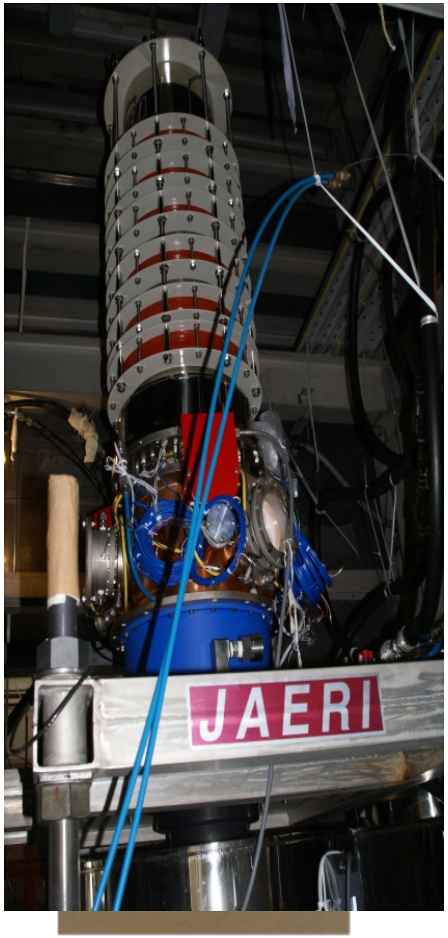
Up to 24 TL on the gyrotron side



- **Evacuated HE11 waveguides with average length ~160m.**
- **Rated for 2 MW CW operation**
- **Collaboration on high power long pulse tests going on between US industry and JAEA**

High-Power Gyrotrons for Fusion Plasma Applications

Karlsruhe Institute of Technology



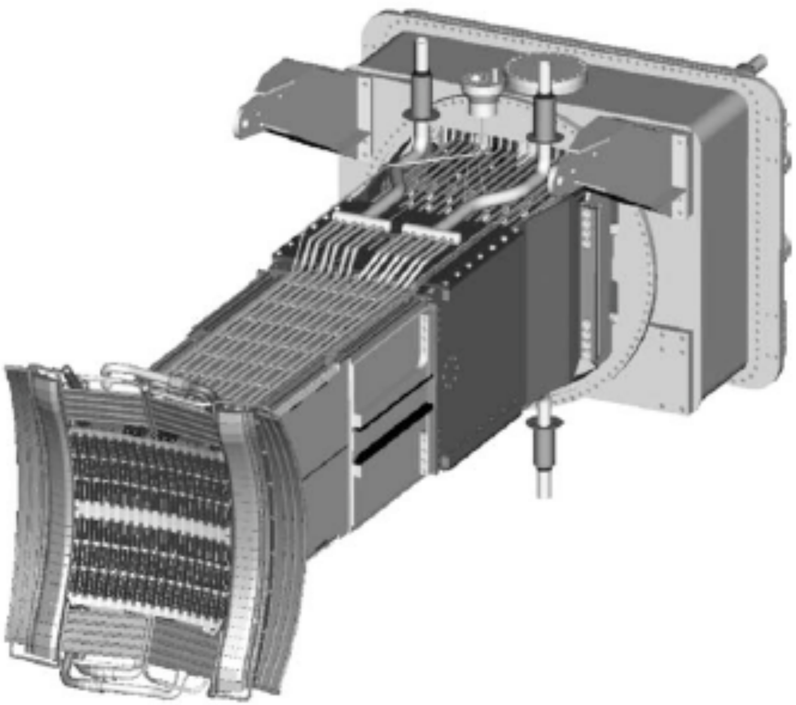
ITER: TOSHIBA/JAEA (JA)
170 GHz, 1 (0.8) MW
800 (3600) s, 55 (57) %

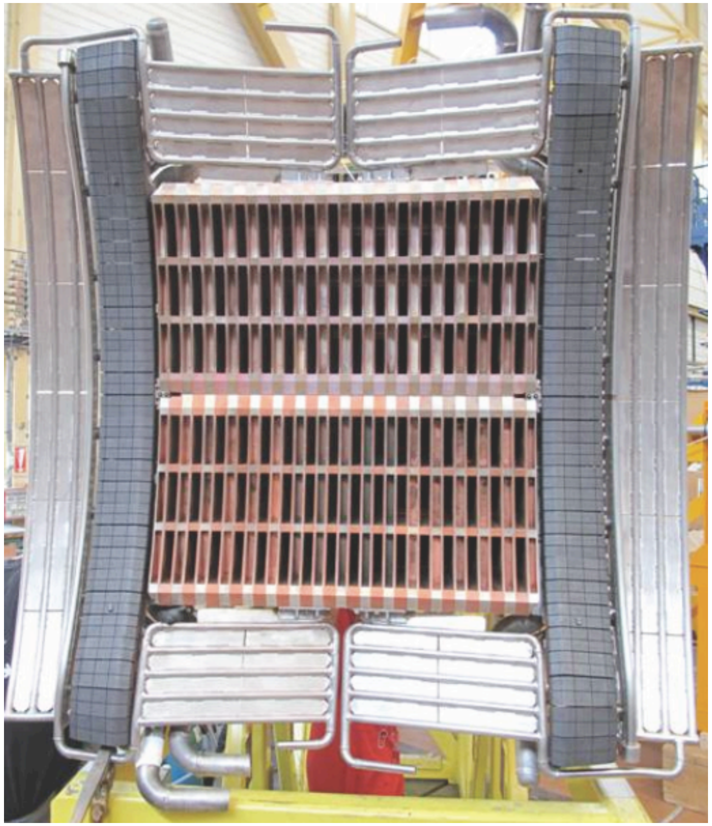
ITER: GYCOM/IAP (RF)
170 GHz, 1.05 (0.83) MW
116 (203) s, 52 (48) %

W7-X: CPI (USA)
140 GHz, 0.9 MW
1800 s, 35 %

EU: Short pulse prototype, to be refurbished. Tests of new gun and launcher design on short pulse tube with good results

ITER ¼ antenna size prototype LHCD PAM antenna has been built and is being tested in Tore Supra



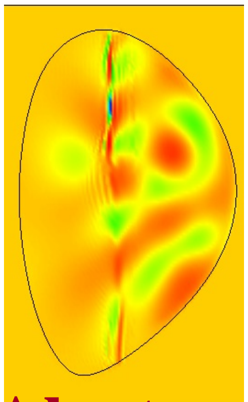


TORE SUPRA

--The ITER prototype passive-active (PAM) launcher installed in Tore Supra and tested; (P. Bibet, 1995)
--Results outstanding after second day of commissioning:
0.45 MW coupled for 4.5 second with low reflectivity

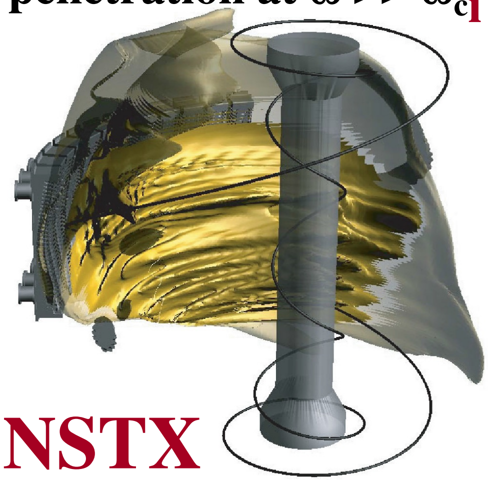
High Power Computing resources enabled validation of RF physics models in tokamak plasmas over a 100-X increase in *frequency* (40 MHz to 5 GHz) (curtesy: P.T. Bonoli)

ICRF Heating at $\omega \sim \omega_{ci}$



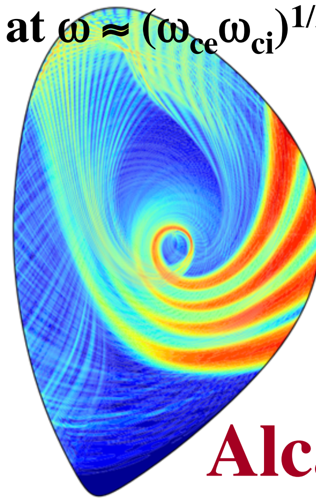
Alcator

Surface wave excitation and penetration at $\omega >> \omega_{ci}$



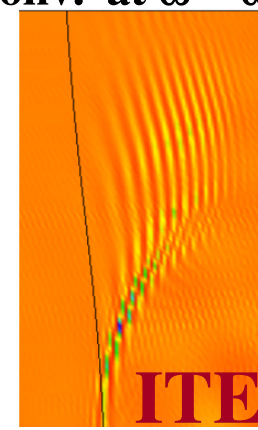
NSTX

LH Wave propagation at $\omega \approx (\omega_{ce}\omega_{ci})^{1/2}$



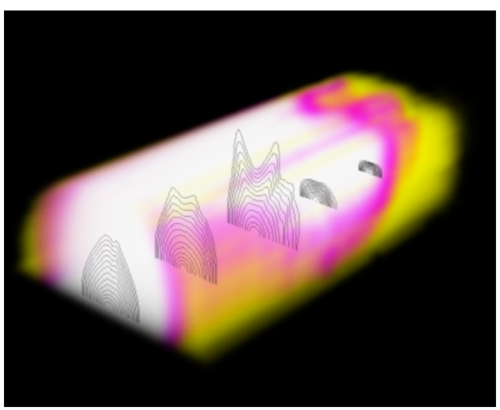
Alcator

ICRF mode conv. at $\omega \sim \omega_{ci}$

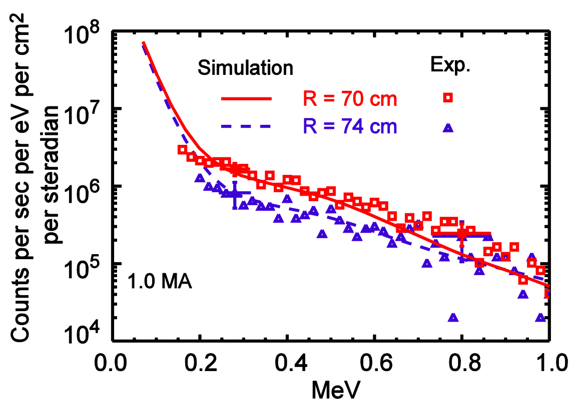


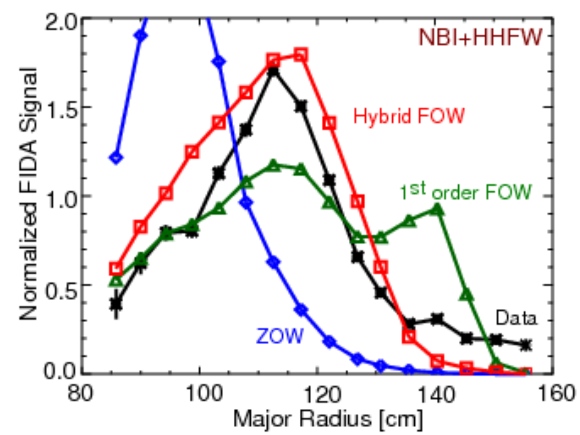
ITER

Gigaflop → ***Teraflop*** → ***Petaflop***



ICRF-generated ion distribution

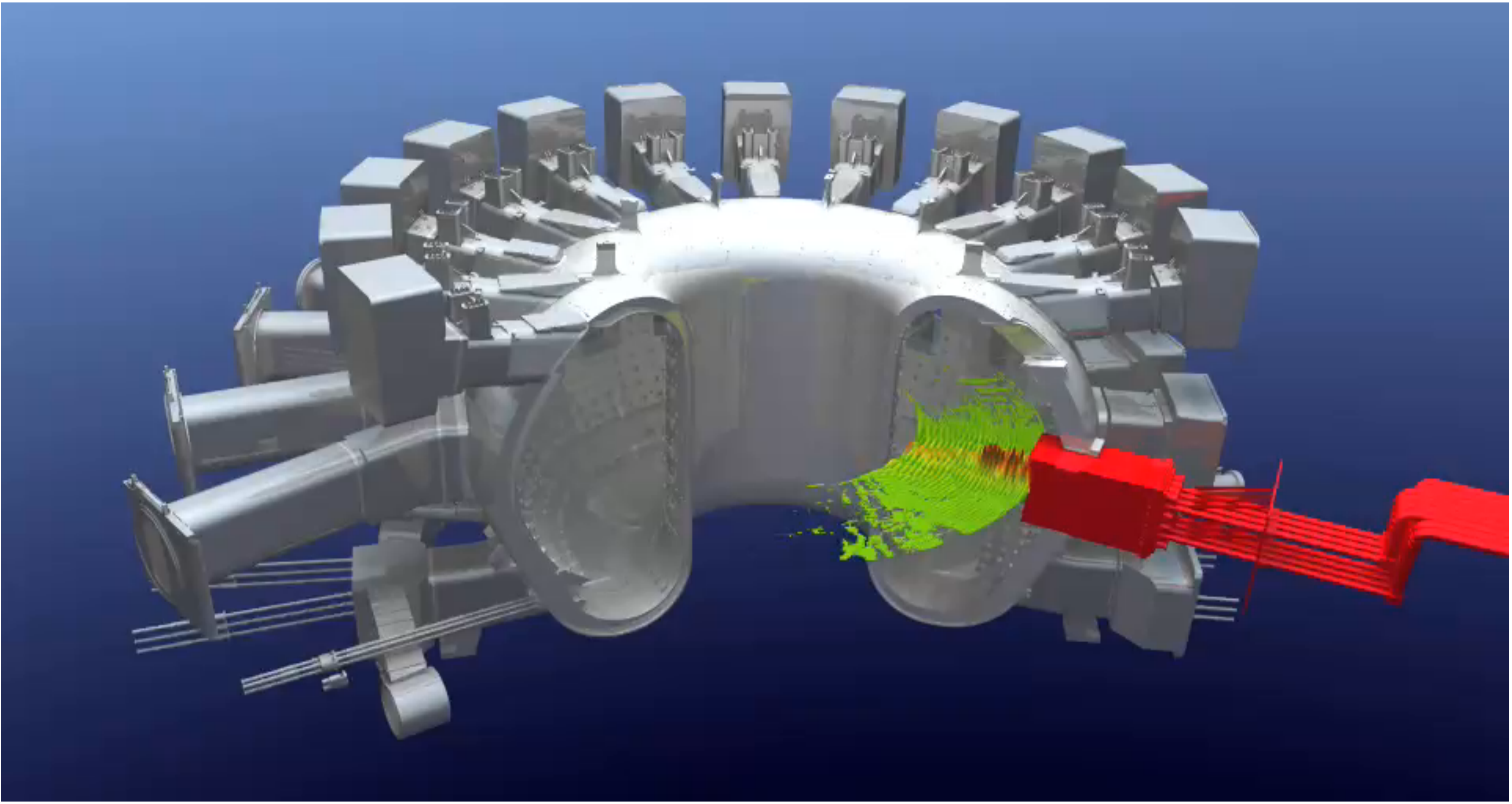




Validation of ICRF-generated distributions against expt

Animation of the ICRF Fast Wave Propagation in ITER type plasma from AORSA full wave code

Fred Jaeger, et al, ORNL



SUMMARY and the FUTURE

- Enormous progress in the last 5 decades in understanding RF wave physics in magnetically confined plasmas; collaboration between European and US scientists was critical to this progress, and now world-wide collaboration ensures further rapid growth of this field of science and technology

- Important applications to transport physics still need to be resolved, for example RF induced plasma rotation, stability control with localized current drive, formation of AT steady state tokamak at ITER and DEMO relevant parameters, reliable non-inductive startup, reduced impact of RF sheaths (metallic impurities), coupling through long scrape-off layer, etc

- Integration of *RF* and *Alpha Particle Physics* with technology in ITER, and beyond in DEMO toward an economically attractive fusion reactor

- Innovative technology development played a key role; more needs to be done for reliable and robust performance in ITER and DEMO