JS 19

APPROCHER LES DEUX INFINIS PAR LES ONDES ELECTROMAGNETIQUES

Antennes radiofréquences de fortes puissances pour les expériences sur la fusion nucléaire

High Power Radio-frequency Antennas for Nuclear Fusion Experiments

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Mots clés : antennes radiofréquences, fusion nucléaire. Radio-frequency antennas, nuclear fusion.

Résumé

La maîtrise des réactions de fusion nucléaire pour la génération d'électricité permettrait d'apporter une réponse supplémentaire aux besoins énergétiques à venir. Toutefois, amorcer les réactions de fusion de noyaux atomiques nécessite d'obtenir et de maintenir des plasmas dont les températures sont de l'ordre de la centaine de millions de degrés. Pour obtenir ces températures, des systèmes radiofréquences sont utilisés couramment sur différentes installations expérimentales dans le monde. Selon la fréquence utilisée, les ondes électromagnétiques vont, une fois couplées au plasma, transférer leur énergie de préférence aux ions ou aux électrons. À quelques dizaines de mégahertz, des antennes électriquement courtes sont utilisées pour chauffer préférentiellement les ions du plasma. À quelques gigahertz, des antennes constituées de réseaux phasés de guides d'ondes rectangulaires permettent d'accélérer les électrons afin de maintenir la configuration magnétique sur des durées plus longues. Au-delà d'une centaine de gigahertz, la puissance des ondes électromagnétiques permet d'accélérer et de chauffer les électrons de manière locale dans le plasma grâce à des miroirs réglables. Cet article présente les principaux aspects technologiques de ces antennes radiofréquences sur les expériences actuelles et futures.

Abstract

The goal of nuclear fusion research is to demonstrate the fusion power feasibility for electricity-generation. To achieve the necessary conditions of temperature for fusion reactions to happen, hundreds of millions of degrees plasmas must be generated and sustained, ideally for long durations. For this purpose, antennas delivering few megawatts of radio-frequency (RF) power are commonly used in experimental fusion devices around the world. Depending of the frequency involved, the electromagnetic waves will resonate and transfer their energy mainly with either the ion or electron population of the plasma. In the megahertz range of frequencies, high power electrically short antennas are used to preferentially heat an ion species of the plasma. In the gigahertz range of frequencies, high power rectangular waveguide phased arrays are used to extend the plasma duration. At the hundreds of gigahertz, high power electromagnetic waves which behavior is quasi-optical are launched into the plasma by steerable mirrors for local electron heating. This paper reviews some of the technological aspects of these RF antennas for present and experimental future devices.

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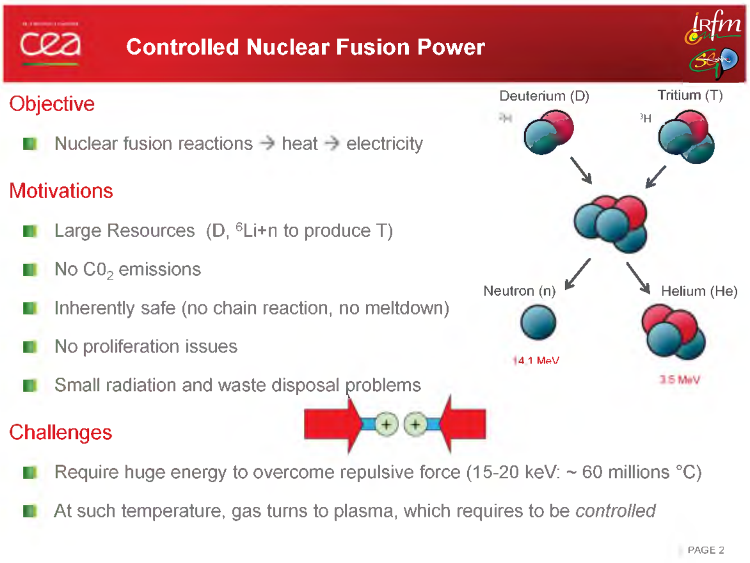


Controlled Nuclear Fusion Power

Objective

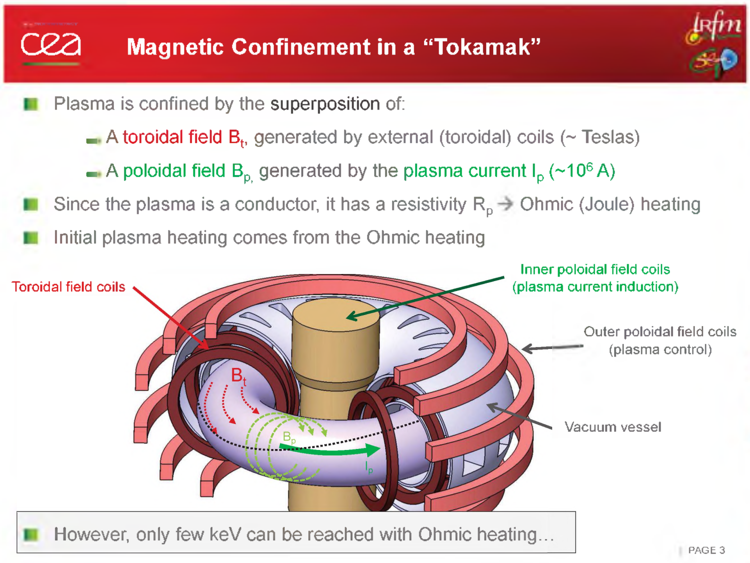
- Nuclear fusion reactions → heat → electricity

Motivations

- Large Resources (D, ^{6}Li+n to produce T)
- No $C0_2$ emissions
- Inherently safe (no chain reaction, no meltdown)
- No proliferation issues
- Small radiation and waste disposal problems

Challenges

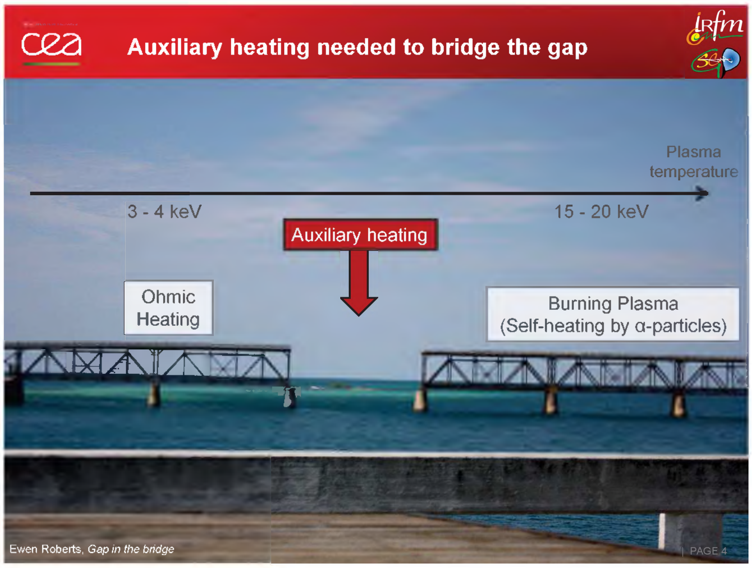
- Require huge energy to overcome repulsive force (15-20 keV: ~ 60 millions °C)
- At such temperature, gas turns to plasma, which requires to be *controlled*



Magnetic Confinement in a "Tokamak"

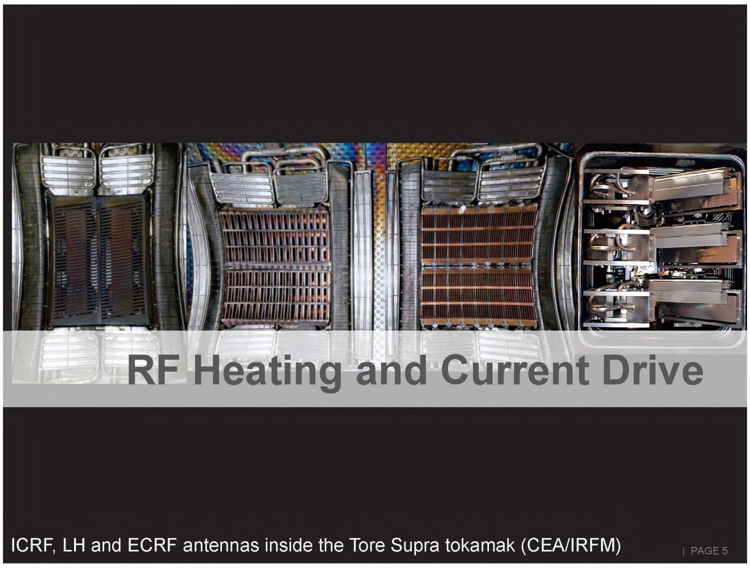
- Plasma is confined by the **superposition** of:
  - A toroidal field B_t, generated by external (toroidal) coils (~ Teslas)
  - A poloidal field B_p, generated by the plasma current I_p (~10^6 A)
- Since the plasma is a conductor, it has a resistivity R_p → Ohmic (Joule) heating
- Initial plasma heating comes from the Ohmic heating

- However, only few keV can be reached with Ohmic heating…



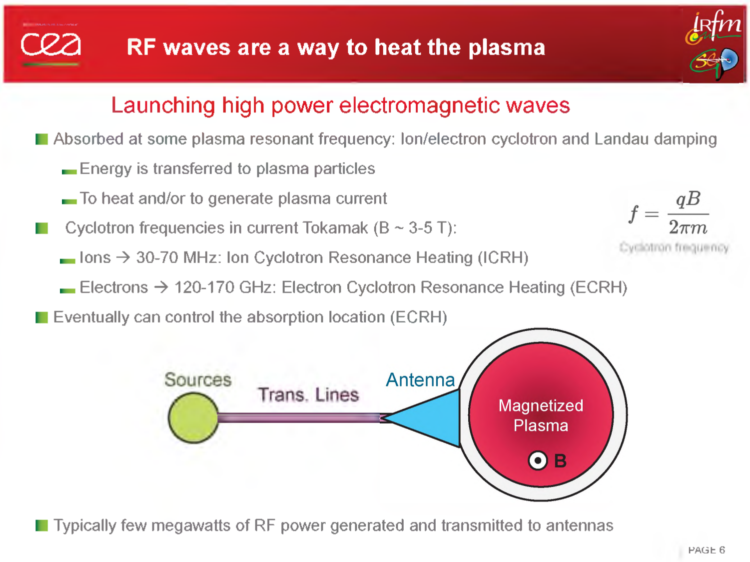
Auxiliary heating needed to bridge the gap

Ewen Roberts, *Gap in the bridge*



RF Heating and Current Drive

ICRF, LH and ECRF antennas inside the Tore Supra tokamak (CEA/IRFM)



RF waves are a way to heat the plasma

Launching high power electromagnetic waves

- Absorbed at some plasma resonant frequency: Ion/electron cyclotron and Landau damping
  - Energy is transferred to plasma particles
  - To heat and/or to generate plasma current
- Cyclotron frequencies in current Tokamak (B ~ 3-5 T):
  - Ions → 30-70 MHz: Ion Cyclotron Resonance Heating (ICRH)
  - Electrons → 120-170 GHz: Electron Cyclotron Resonance Heating (ECRH)
- Eventually can control the absorption location (ECRH)

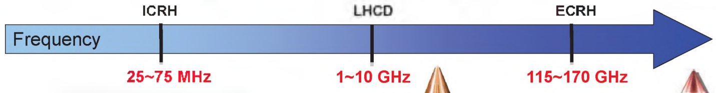
$$f = \frac{qB}{2\pi m}$$

Cyclotron frequency

- Typically few megawatts of RF power generated and transmitted to antennas

Common RF Systems in fusion devices

Ion Heating **I**on **C**yclotron **Res**. **H**eating	**Current Drive** « Lower Hybrid » waves (**LH**)	**Electron Heating** **E**lectron **C**yclotron **Res**. **H**eating



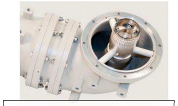
Sources

Tetrodes/Triodes
1-2 MW CW

Klystrons
250-750 kW CW

Gyrotrons
0.2 - 1 MW CW

Trans. Lines



Coaxial Lines
$Ø_{ext}$ ~ 300 mm, 1-2 MW,
3 bars N pressurized

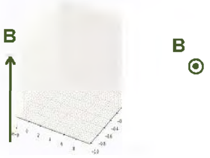
Rectangular Waveguide
~72 x 34 mm, ~700 kW CW,
1-2 bar SF6/N pressurized

Circular corrugated waveguides
$Ø_{ext}$~65 mm, 1-2 MW CW,
Vacuum pumped

Propagation medium: Magnetized Plasma

Radiating medium: Hot Magnetized plasma

- Inhomogeneous (density and magnetic field vary)
- Time and space dispersive
- Non-linear (high electric field)



Approx. in front of the antennas

- ~ lossless, non-dispersive & anisotropic ("cold" plasma)
- From Maxwell equations in Fourier space (**B // z**):

$$\mathbf{k}\times\mathbf{k}\times\boldsymbol{\mathcal{E}}(\mathbf{k},\omega) - k_0^2\,\boxed{\mathbf{K}(\mathbf{k},\omega)}\cdot\boldsymbol{\mathcal{E}}(\mathbf{k},\omega) = \mathbf{0} \qquad \text{where} \quad k_0 = \frac{\omega}{c}$$

$$\begin{pmatrix} \varepsilon_\perp & i\varepsilon_\times & 0 \\ -i\varepsilon_\times & \varepsilon_\perp & 0 \\ 0 & 0 & \varepsilon_\parallel \end{pmatrix} \longleftarrow$$

"Cold" Plasma dielectric tensor
Elements depend on:
- Magnetic field magnitude
- Ion(s) and electron densities
- RF frequency

- Solving for k^2 → 2 « modes » of propagations (also known as *Appleton–Hartree* equation)

→ gives indications on which waves can propagate (or not) and their polarizations

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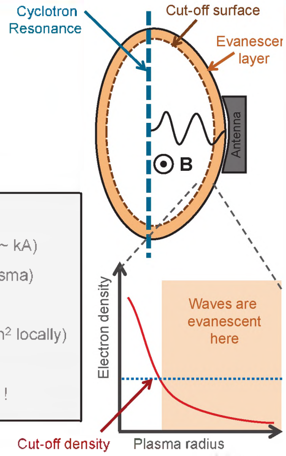
Antenna Design

For a given RF frequency

- Polarization got from the selected plasma wave to excite:
  - Cyclotron damping ~ $\mathbf{E}_{\mathbf{RF}} \perp \mathbf{B}$
  - Landau damping ~ $\mathbf{E}_{\mathbf{RF}} \parallel \mathbf{B}$



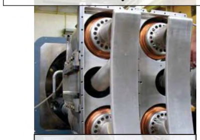
But it's not so easy….

- High RF Power (Electric field up to MV/m, currents up to ~ kA)
- Vacuum (metals only, ceramic eventually far from the plasma)
- CW operation (RF losses → water cooled)
- Compatible with heat flux from the plasma (up to ~ MW/m² locally)
- Launched waves can be evanescent until they reach a *cut-off* density in the plasma → eventually large VSWR !

RF Plasma Heating and Current Drive Antennas

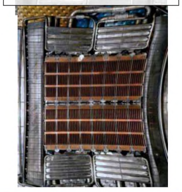
Each frequency range has its own antenna technology

ICRH antenna, with and w/o its "Faraday screen"

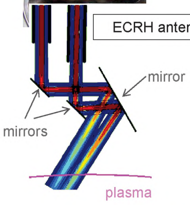


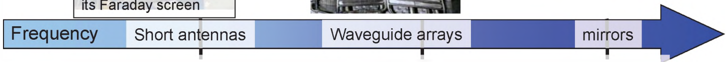
ICRH antenna without its Faraday screen

LHCD antennas



ECRH antenna





25~75 MHz
λ ~ few m

1~10 GHz
λ ~ few cm

115~170 GHz
λ ~ few mm

Ion Cylotron Resonance Heating (ICRH)

Picture of the front face of the WEST ICRH Antenna during RF tests in vacuum

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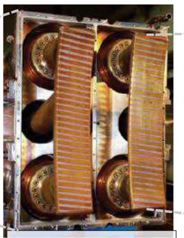
ICRH Antenna: Description

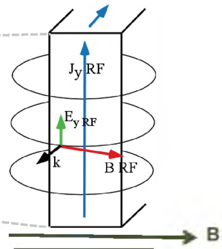
- Antennas are fed by coaxial lines: two conductors (central and external)
- The power is coupled to the plasma through antenna front face
  - A ~ flat plate (*strap*) is connected to the central conductor
  - And short-circuited (after some length) to the external conductor
- RF current flows on the strap → couple to the (fast) plasma wave
- Behind the straps: matching system (inside or outside the antenna)

9" 30 Ω (230 / 140 mm)
pressurised3 bars nitrogen

ICRH antenna
with its Faraday screen
(polarization filter and protection)

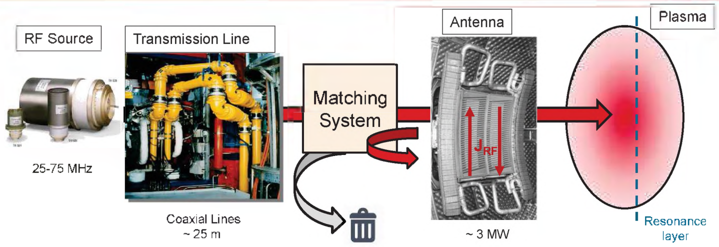


And without
its Faraday screen



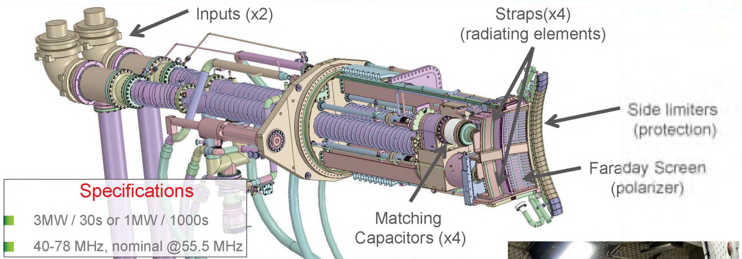
Idealized Strap

ICRH System Example: WEST tokamak



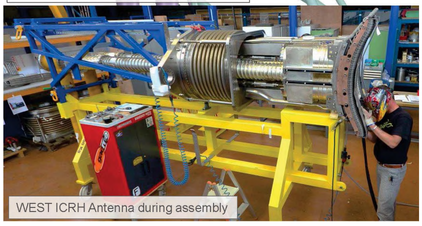
- Only a fraction of the RF power reaching the ICRH antenna is radiated into plasma
- The rest is reflected back to the RF generator (due to load mismatch).
- To prevent this:
  - *matching* elements introduced which make the returning power circulate in a resonant circuit.
  - And/or add elements to re-direct reflected power to dummy loads (dump).

ICRH Antenna Example: WEST Tokamak



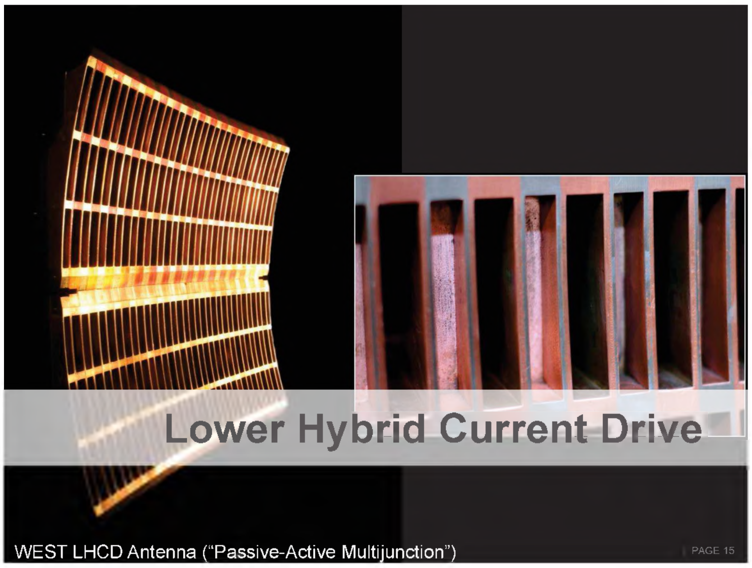
Specifications

- 3MW / 30s or 1MW / 1000s
- 40-78 MHz, nominal @55.5 MHz



WEST ICRH Antenna during assembly

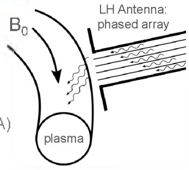
Antenna view inside WEST



Lower Hybrid Current Drive

WEST LHCD Antenna ("Passive-Active Multijunction")

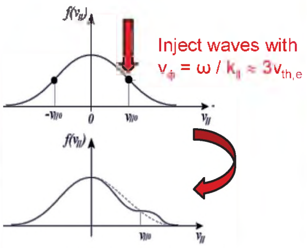
Lower Hybrid Current Drive Principle



RF Plasma Current Drive

- Landau collision-less damping on electrons $v_{\parallel 0} = v_{\phi\parallel}$ (= $\omega / k_\parallel$)
  - Creation of an *asymmetric* tail in electron distribution function
  - Leads to a toroidal momentum asymmetry in the electron population
  - Incremental current carried by e^- produces a net current (10W → ~1A)
  - This goal fixes the toroidal spectrum to launch ($k_\parallel = k_0 c / v_{\parallel 0}$)

Electron velocity distribution



Inject waves with $v_\phi = \omega / k_\parallel \approx 3v_{th,e}$

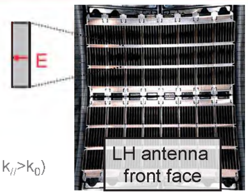
- Particles with $v_{//} < v_\phi$ are accelerated by the wave
- Particles with $v_{//} > v_\phi$ are decelerated by the wave
- But: more particles moving slower than faster

→ more particles accelerated than decelerated

→ net energy is transferred from waves to particles and wave is damped.

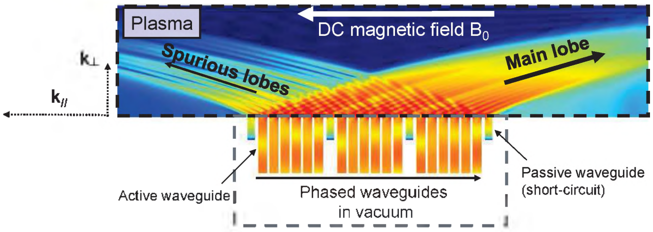
LHCD Antennas

Rectangular waveguides phased array



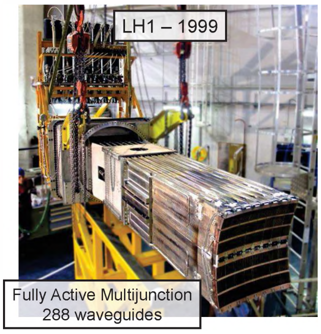
- Rectangular waveguides
  - E-field polarization ~parallel to DC magnetic field
  - High power compatible
- Phased array
  - Excite a field with a high parallel velocity (low $k_{//}$ with $k_{//}>k_0$)
  - The array is finite: excites a spectrum of $k_{//}$
  - NB: $k_{//}>k_0$, so wave is evanescent in vacuum/air

Modeling of the Electric field (norm)



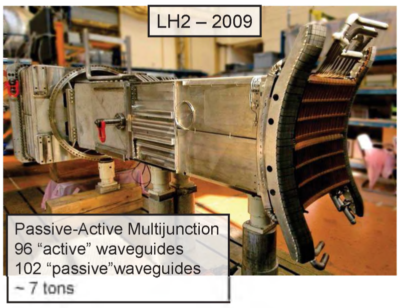
LHCD Antennas Example: WEST

- Two LHCD antennas installed
- Increase the plasma discharge duration from ~10 s to ~1000 s
- Up to 6 MW launched to the plasma
- Actively water cooled



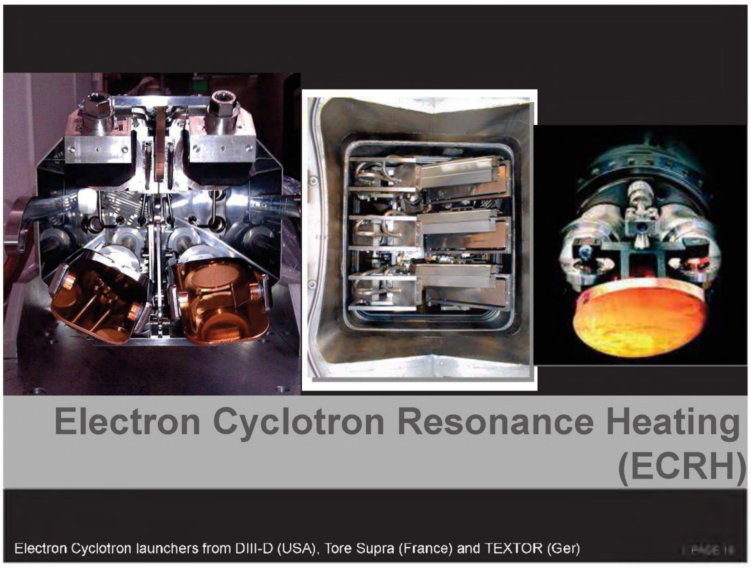
LH1 – 1999

Fully Active Multijunction
288 waveguides



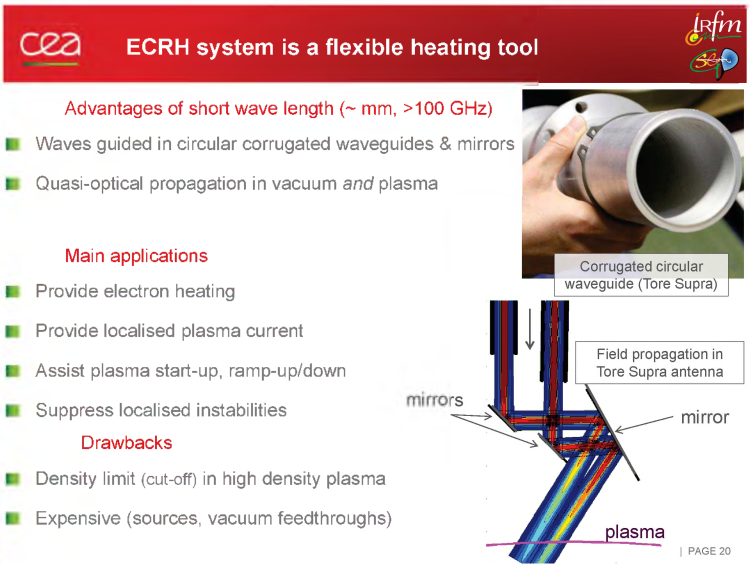
LH2 – 2009

Passive-Active Multijunction
96 "active" waveguides
102 "passive"waveguides
~ 7 tons



Electron Cyclotron Resonance Heating (ECRH)

Electron Cyclotron launchers from DIII-D (USA), Tore Supra (France) and TEXTOR (Ger)



ECRH system is a flexible heating tool

Advantages of short wave length (~ mm, >100 GHz)

- Waves guided in circular corrugated waveguides & mirrors
- Quasi-optical propagation in vacuum *and* plasma

Main applications

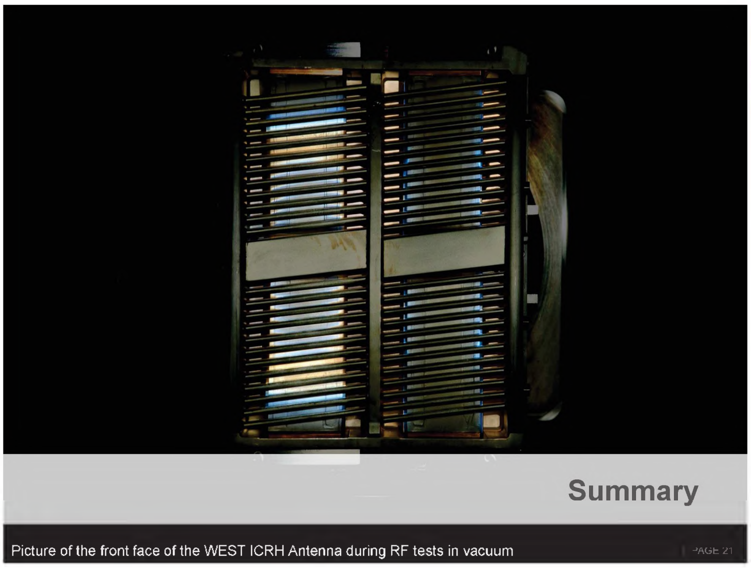
- Provide electron heating
- Provide localised plasma current
- Assist plasma start-up, ramp-up/down
- Suppress localised instabilities

Drawbacks

- Density limit (cut-off) in high density plasma
- Expensive (sources, vacuum feedthroughs)

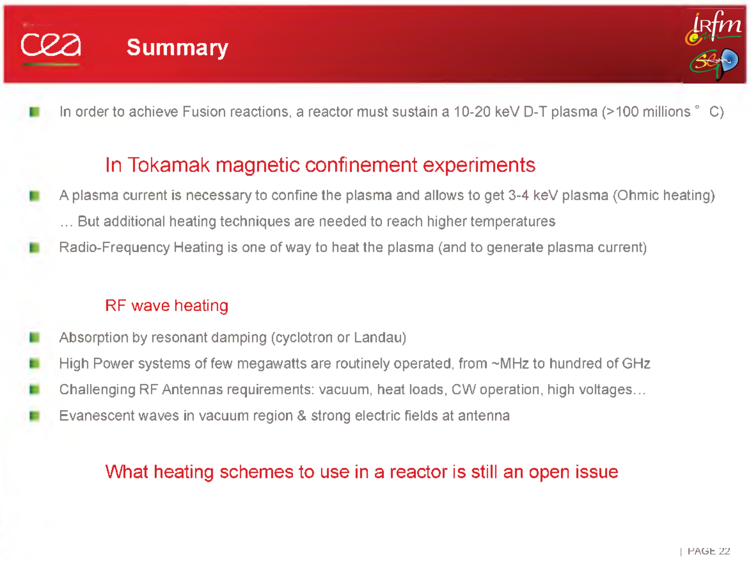
Corrugated circular waveguide (Tore Supra)

Field propagation in Tore Supra antenna



Summary

Picture of the front face of the WEST ICRH Antenna during RF tests in vacuum



Summary

- In order to achieve Fusion reactions, a reactor must sustain a 10-20 keV D-T plasma (>100 millions ° C)

In Tokamak magnetic confinement experiments

- A plasma current is necessary to confine the plasma and allows to get 3-4 keV plasma (Ohmic heating)
  … But additional heating techniques are needed to reach higher temperatures
- Radio-Frequency Heating is one of way to heat the plasma (and to generate plasma current)

RF wave heating

- Absorption by resonant damping (cyclotron or Landau)
- High Power systems of few megawatts are routinely operated, from ~MHz to hundred of GHz
- Challenging RF Antennas requirements: vacuum, heat loads, CW operation, high voltages…
- Evanescent waves in vacuum region & strong electric fields at antenna

What heating schemes to use in a reactor is still an open issue

Summary

Thank you for your attention

Inside the WEST vacuum vessel (CEA/IRFM)