Ignitor Project

ICRH Physics in Ignitor

Associazione EURATOM-ENEA sulla Fusione

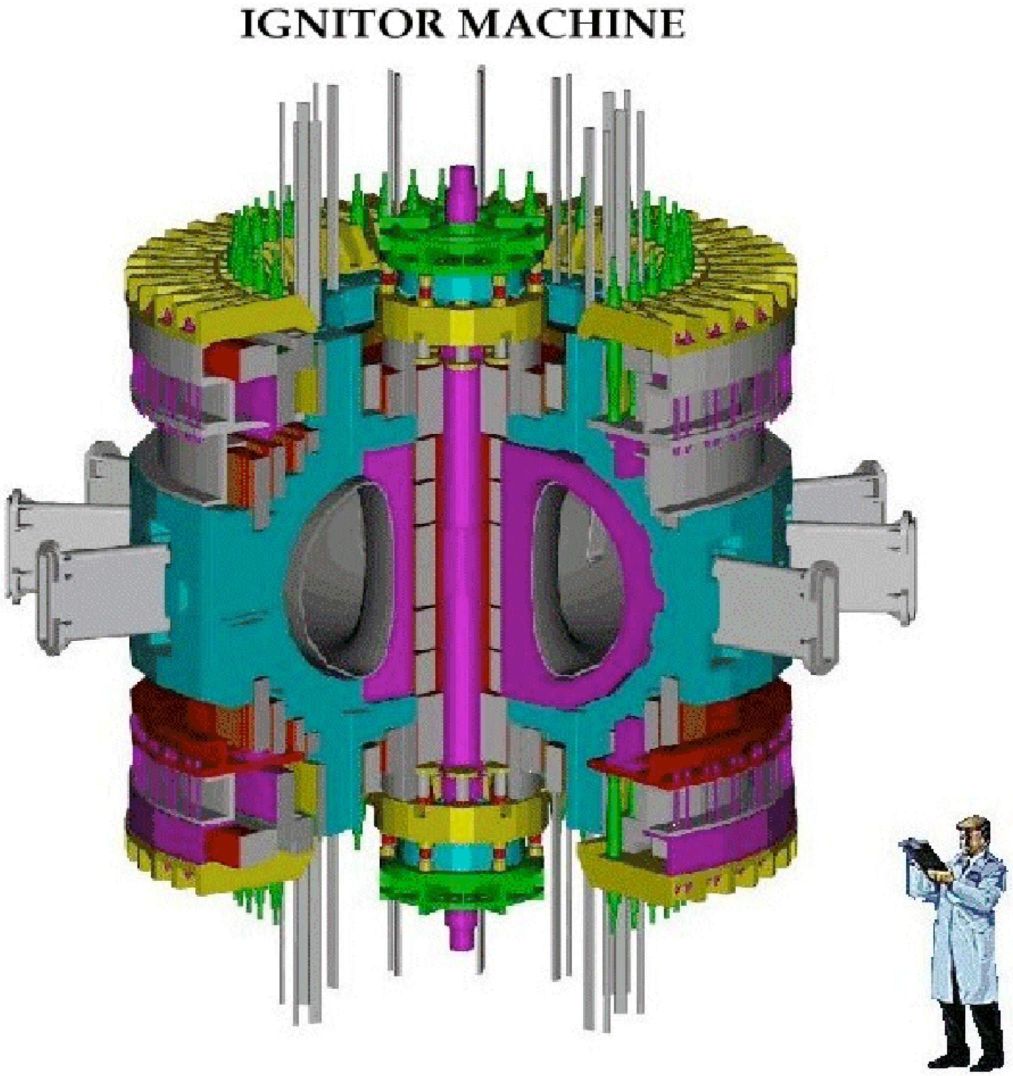
A. Cardinali, F. Bombarda, A. Coletti, M. Sassi, ***Associazione Euratom-ENEA sulla Fusione, Frascati, Italy***
A. Airoldi, G. Cenacchi, ***I.F.P.-CNR Milan, Italy***
B. Coppi, ***M.I.T., Cambridge, MA***
R.V. Budny, ***PPPL, Princeton, NJ***
R. Maggiora, ***Politecnico di Torino, Torino, Italy***

Work sponsored in part by ENEA and CNR of
Italy, and by the U.S. D.O.E.

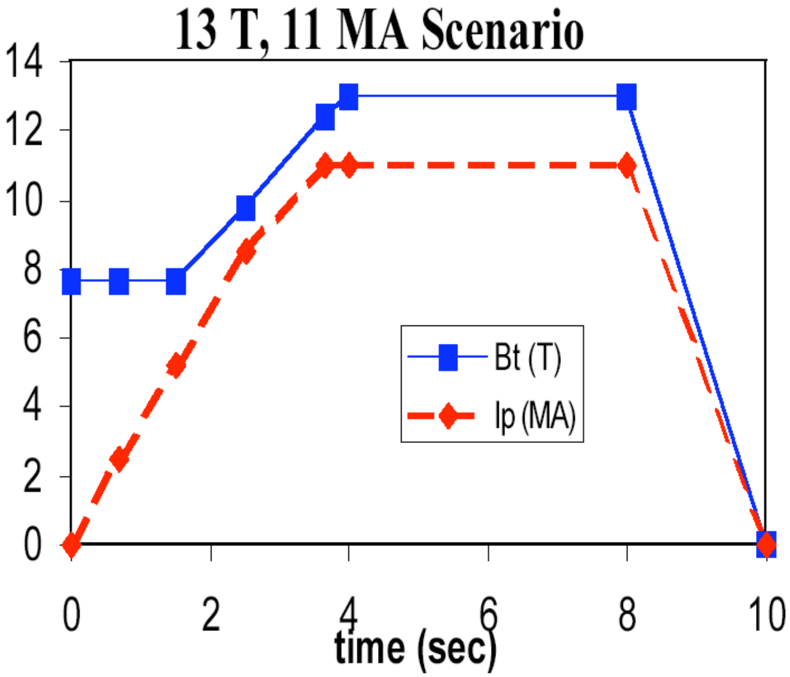
Ignitor Tokamak Facility

- Ignitor is a tokamak characterized by high magnetic field and plasma current.

- The goal of this experiment is to reach the ignition by nuclear fusion of D-T plasmas with ohmic heating only.



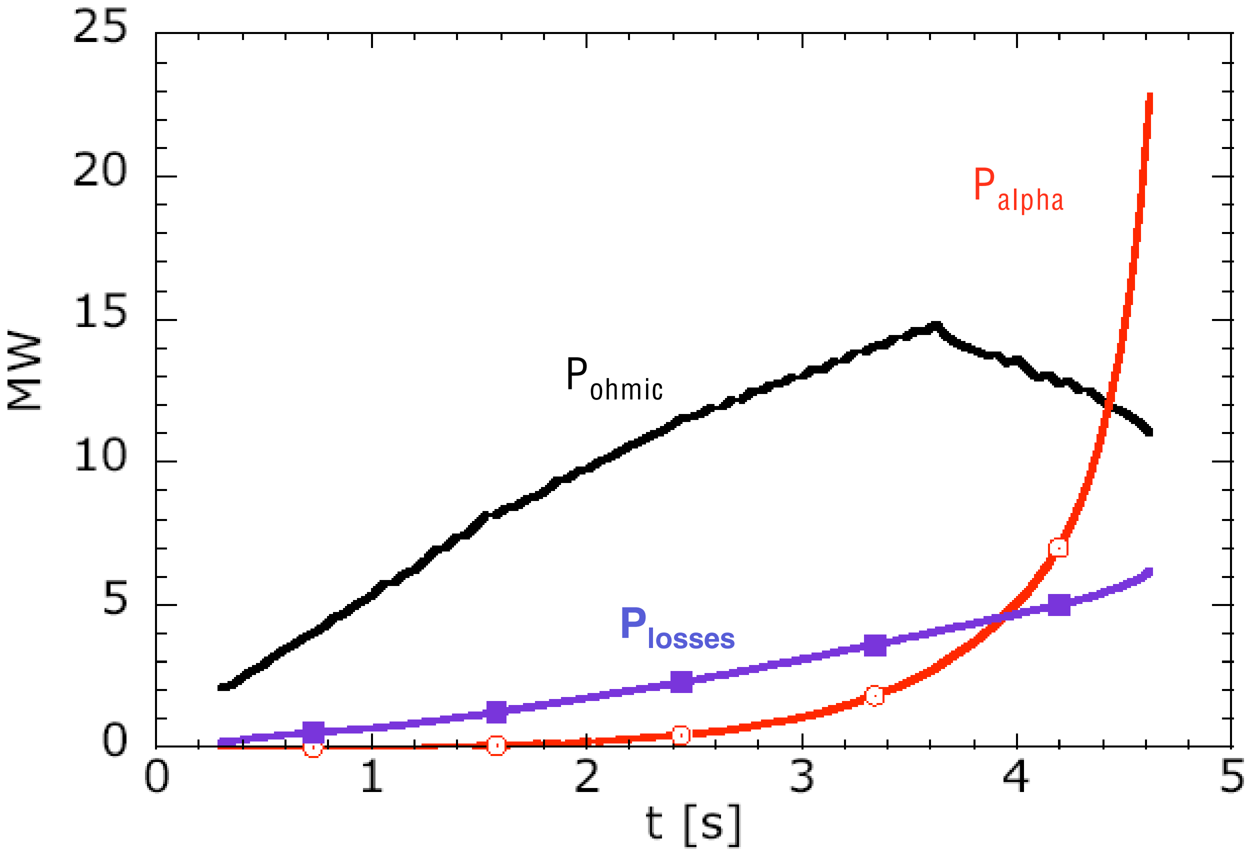
Standard Ignitor scenario



Major radius	R_0	1.32m
Minor radii	a×b	0.47m × 0.86m
Aspect ratio		2.8
Elongation	k	1.8
Triangularity	δ	0.4
Toroidal field	$B_T(R_0)$	13T
Toroidal current	I_p	11MA
Poloidal current	I_ϑ	8 MA
Plasma Volume	V	10 m^3
Plasma Surface	S_a	36 m^2
Safety factor	q_Ψ	3.6
Discharge time	t	(4 + 4)s

Why an assisted ICRH experiment for IGNITOR?

In principle IGNITOR can reach the ignition by operating in ohmic heating regime only.

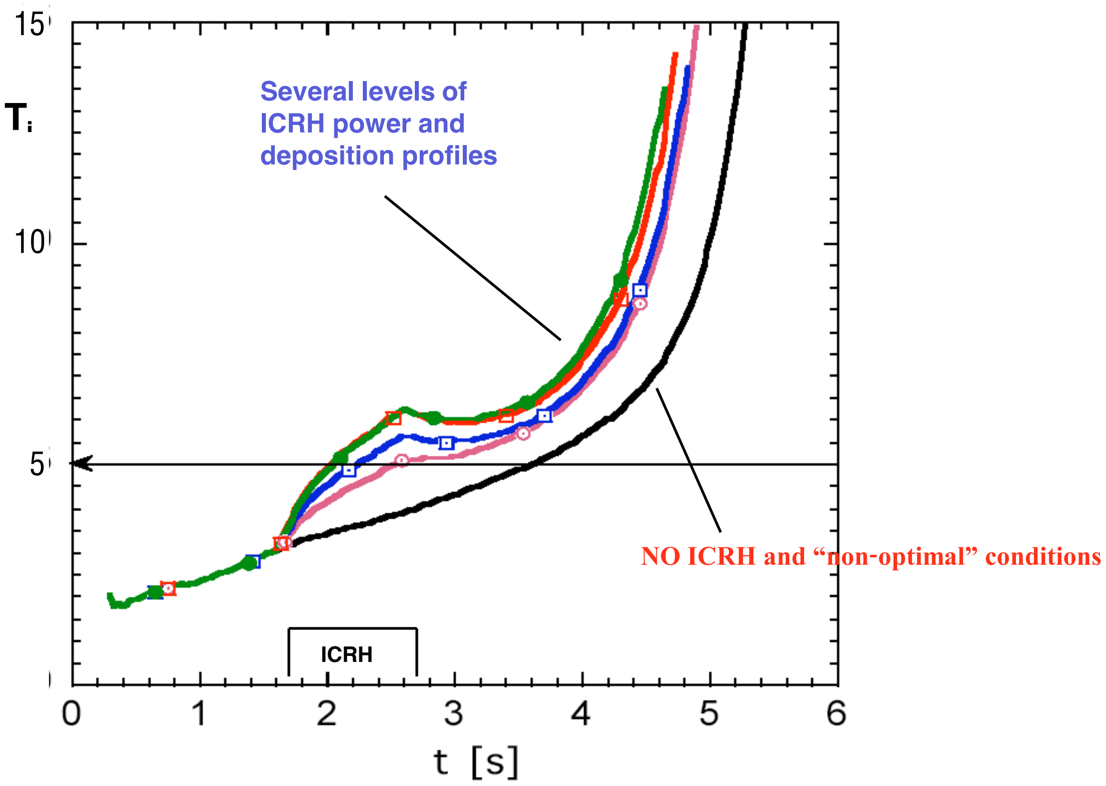


Time evolution of Ohmic, alpha powers and radiation losses (Impurity radiation, bremsstrahlung and synchrotron), in an "*optimized*" case using the Coppi-Mazzucato model. The simulation by JETTO is stopped when ignition is attained.

I-Reasons for an assisted ICRH experiment for IGNITOR

The attainment of ignition with ohmic heating alone under realistic conditions for the high density regimes that characterize the Ignitor experiment involves the optimization of the rate of increase of the plasma density while both the toroidal field and the plasma current are ramped up.

A deviation from the optimal conditions such as the presence of an impurity content producing a Z_{eff} value greater than 1.5, or a fuel composition different from 50/50% D-T leads to require the assistance of the Ion Cyclotron.



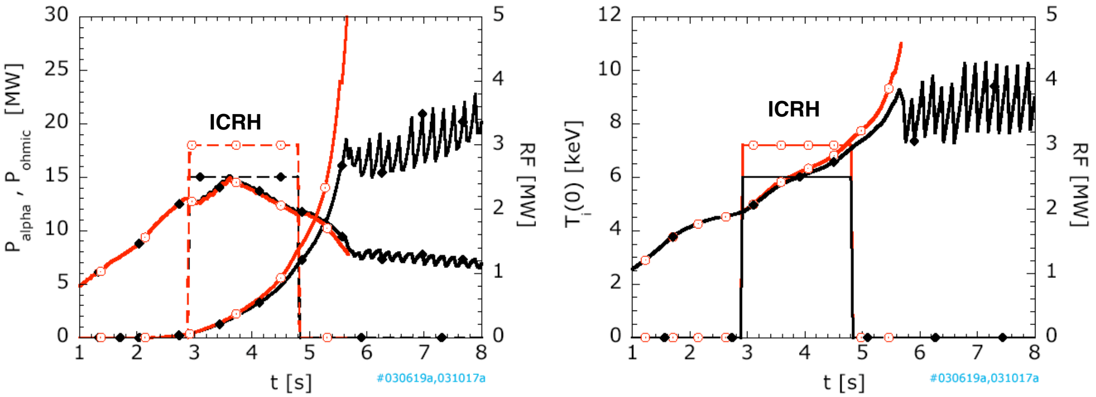
Several levels of ICRH power and deposition profiles

NO ICRH and “non-optimal” conditions

When the heating power is injected during the current ramp-up (from 1.8sec to 2.8sec), the attainment of ignition is accelerated.

II-Reasons for an assisted ICRH experiment for IGNITOR

- The onset of saw-tooth oscillations can be avoided by RF heating in the current flattop.



This is an example which shows as the application of 3MW (from 3 to 5 sec of the discharge time) of ICRH avoids the triggering of the saw-tooth oscillation.

III-Reasons for an assisted ICRH experiment for IGNITOR

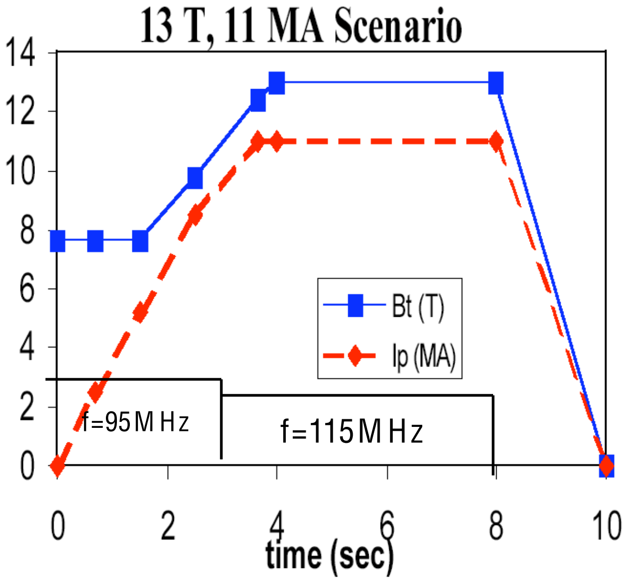
- When ignited the alpha power grows steadily reaching values unsustainable by the machine structure. A possible way to control the thermonuclear instability is the following:
  - Puffing gas (^{3}He) and changing the fuel composition when for example the averaged electron temperature overcomes a fixed value.
  - The lower tritium content causes, afterwards, a reduction in the alpha power.
  - If the reduction of the alpha power is too big, use the ion cyclotron heating as a boost given to the temperature to remain in sub-ignited conditions.

There is an intrinsic difficulty for the ICRH experiment in the ignited scenario due to the fact that the field is ramping-up from 9 to 13 T

- We have established that
  - The frequency f=115 MHz is a good choice when the ICRH timing is t_{ICRH}>3sec (the end of the ramp-up and flattop), which corresponds to a magnetic field included between 11-13Tesla.
  - For timing <3sec and fields 9-11 Tesla a good frequency choice could be f=95MHz.

At f=115MHz with 11T<B<13T, and at f=95MHz with 9T<B<11T, infact,the first harmonics of ^{3}He and the 2nd of T resonate in the central part of the plasma between 0<r/a<0.4, this guarantees central power deposition,
while the first and second harmonics of D are outside the plasma or in the very edge (1rst D) in the high field side.

B(Tesla);f=115MHz	H/D/T	T/He^3	D
9	1rst/2nd/3rd at xÅ0.53	2nd/1rst at xÅ-0.56	Out of res
10	1rst/2nd/3rd at xÅ0.90	2nd/1rst at xÅ-0.33	1rst at xÅ-0.95
11	Out of res	2nd/1rst at xÅ-0.08	1rst at xÅ-0.76
12	Out of res	2nd/1rst at xÅ+0.16	1rst at xÅ-0.58
13	Out of res	2nd/1rst at xÅ+0.40	1rst at xÅ-0.39

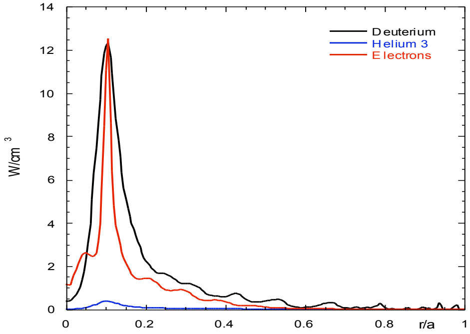


We show here a Quasi-Linear Power Deposition Profile in the case B=11T (t=3sec) and f=115MHz, ^{3}He (2%) minority heating obtained by using the full wave code “TORIC” coupled to the Fokker-Planck solver SSQLFP.

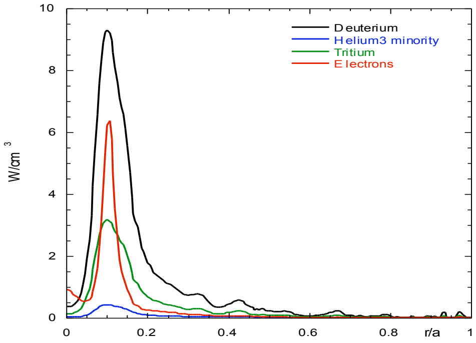
- It has been chosen this heating scheme (minority heating via ^{3}He) because is very efficient in giving energy at the plasma bulk population, and at the same time allows to control the TI by injecting ^{3}He.

- In the figures below the power gain by species (in Watt/cm^3) is shown vs r/a.
  - The figure a) refers to a plasma composition D(100%)-^{3}He(2%),
  - The figure b) refers to a plasma composition D(70%)-T(28%)-^{3}He(2%),
  - The figure c) refers to a plasma composition D(50%)-T(40%)-^{3}He(2%).

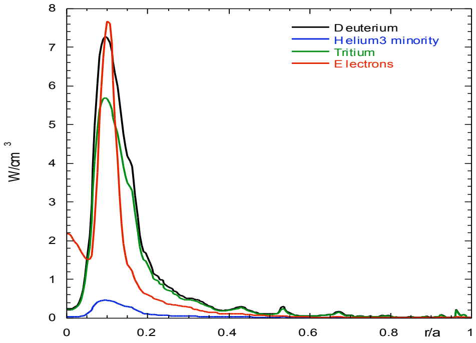
a



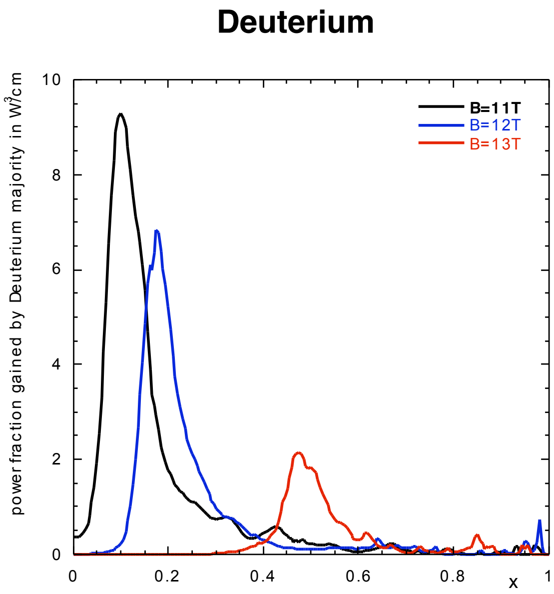
b

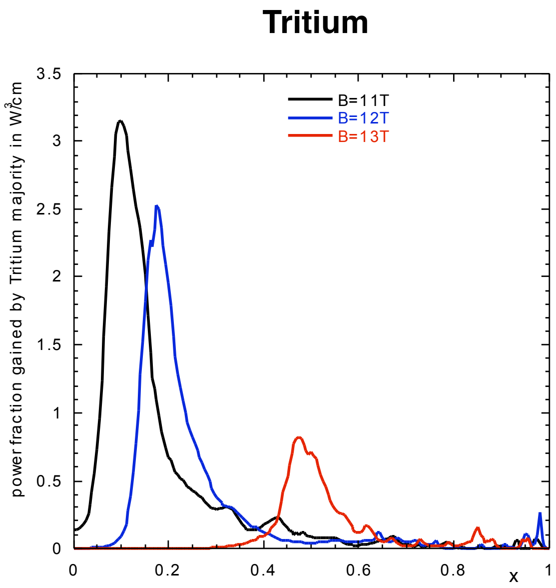


c



Here we show the evolution of the QL Power Deposition Profile during the field ramp-up from B=11 to 13 Tesla


Deuterium


Tritium

•Power gain by Deuterium (left) and Tritium (right) after collisional transfer (from energetic minority ^{3}He ions to majority species)

- •for B=11T (black line),
- •for B=12T (blue line),
- •for B=13T(red line)

in the case of D-T (50%-48%) mixture with 2% of ^{3}He minority.

The Ignitor antenna design

(courtesy of R. Maggiora, Politecnico di Torino)

- The ICRH system is structured with a modular configuration and launches the power into the plasma through RF strap-antennas based on 4 straps, grouped in two poloidal pairs, per port.

- The system is designed to operate in the frequency band 80 - 120 MHz.

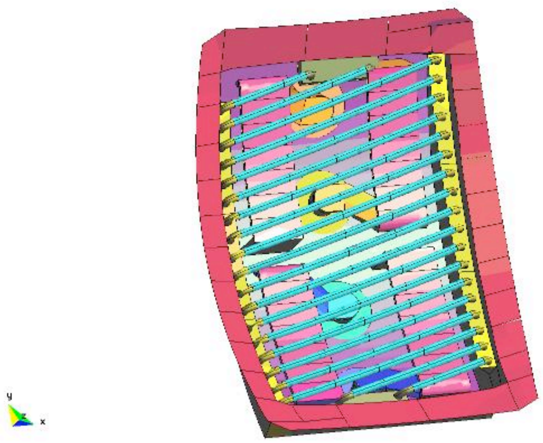
- Each module consists of 4 high power generators whose power is split over two ports (8 straps) in order to keep the maximum electric field (especially in the vacuum region of the straps and transmission line) below 5kV/cm.

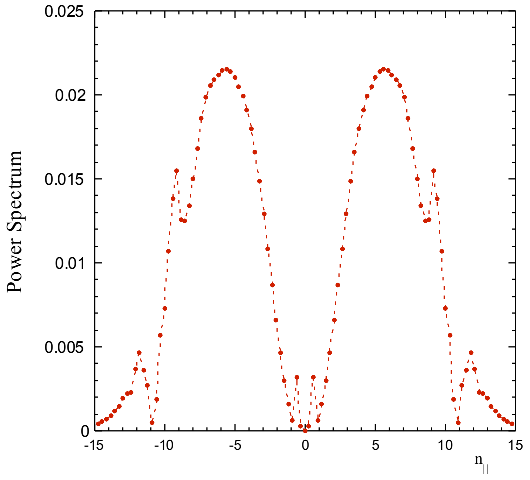
- A 30 W vacuum transmission line, including the feed-through, transfers the power to each strap. The RF configuration of the modules allows a full phase controls (toroidal and poloidal) of the straps though a Phase Lock Loop (PLL) control.

- Each module that feeds 2 ports can deliver up to 3.2 MW (at the generator) at f≤120 MHz (1.6MW per port) and up to 8MW (at the generator) (4MW per port) at lower frequencies ≥80 MHz.

- Therefore, two modules, distributed over 4 ports, can deliver a global power of about 6.4 MW at 120 MHz and 16 MW at 80 MHz.

4 straps antenna





Conclusions

- In the IGNITOR ignited D-T scenarii, the ICRH heating system has been considered essentially for 3 reasons:
  - The boost given to the plasma temperature in the ramp-up phase accelerates the ignition time when a deviation from the **"optimal conditions"** such as the presence of impurities (producing a Z_{eff} value greater than 1.5), or a fuel composition different from 50/50% D-T leads to a delay or to an obstacle in reaching the ignition.
  - Applying auxiliary heating at the flattop, can be a treatment or can suppress the saw-tooth oscillations that may be excited.
  - A possible way to control the thermonuclear instability is to act by adding ^{3}He to the D-T mixture and injecting ICRH to maintain the evolution of the shot in a sub-critical stage.

- The "ICRH-TORIC" code which solves the full wave equation coupled with the 2D Fokker-Planck solver has been used in order to study the absorption of the ICRH and to define the power deposition profiles in the plasma when the external magnetic field is ramping-up from 11 to 13 T (3-5 sec of discharge time) in presence of a D-T mixture,.
- These result are used as input data for a transport code like (JETTO or PTRANSP) to study the evolution of the plasma parameters during the RF pulse.
- A design of the antenna and a project of the transmission line which considers a frequency range 80-120MHz and a total power at the generators included between 6.4-16 MW has been considered.
- These features of the ICRH system is compatible with the ICRH physics, in particular
  - Two operational frequencies have been considered 95 and 115 MHz
  - The power delivered at the plasma to reach the gloal has been calculated to be <5MW