ICRH System for the Ignitor Experiment

F. Bombarda[a], A. Cardinali[a], A. Coletti[a], R. Maggiora[b], M. Sassi[a]
[a] *ENEA-UTS Fusione , Frascati , Italy*
[b] *Politecnico di Torino , Turin, Italy*

***Abstract*—An auxiliary Ion Cyclotron Resonance Heating system is included in the design of the Ignitor machine to provide a wider margin of success for ignition and to explore a variety of plasma regimes. Simulations with a full wave code, carried out for deuterium-tritium plasmas and wave frequency $f = 115$ MHz, during the initial magnetic field and plasma current rise, show strong direct ion heating. A modular configuration of the ICRH system has been adopted, operating in the frequency range $f = 70 – 120$ MHz. Two modules, based on 8 generators and 4 antennas, occupying 4 equatorial ports will be installed initially, with the possibility of adding two more antennas.**

Keywords: Ignitor; ignition; ICRH; heating scenarios

I. INTRODUCTION

Ignitor [1] is a high field, high density burning plasma experiment designed to reach ignition by Ohmic heating only. However, both to provide a wider margin of success for achieving ignition and to explore a variety of plasma regimes, a flexible auxiliary Ion Cyclotron Resonance Heating (ICRH) system ($f = 80 – 120$ MHz) is included in the machine design. Neutral Beam Injection is not well suited for a compact machine ($R_0 = 1.32$ m, $a \times b = 0.47 \times 0.86$ m) with high plasma density ($n_0 \cong 10^{21}$ m^{-3}) like Ignitor, while other radiofrequency heating methods, such as Lower Hybrid or Electron Cyclotron Heating at 13 T would require frequencies too high for the presently available sources. Heating by means of ICRH waves, on the other hand, has been successfully tested on a number of existing devices at both low and high density [2], the heating mechanisms are well understood in terms of theory and modeling, the transmitter and coupler technology is relatively well developed; therefore this is the only additional heating system presently considered for the Ignitor experiment.

Ignition can be accelerated significantly by relatively modest levels of ICRH (less than 5 MW, a fraction of the final fusion heating) when applied during the current rise. In addition, ICRH provides a means to control the evolution of the current density profile [3, 4]. An example of RF assisted ignition scenario obtained by numerical simulations carried out with the 1-1/2 D transport code JETTO is shown in Fig. 1 [5]. The most effective boost to the attainment of ignition is provided by more centrally localized power deposition profiles. These ignition scenarios are particularly important as they leave the 4 s flat top of the 13 T magnetic field pulse fully available to study the evolution of the thermonuclear instability or to investigate the properties of the plasma in steady, slightly sub-ignited regimes.

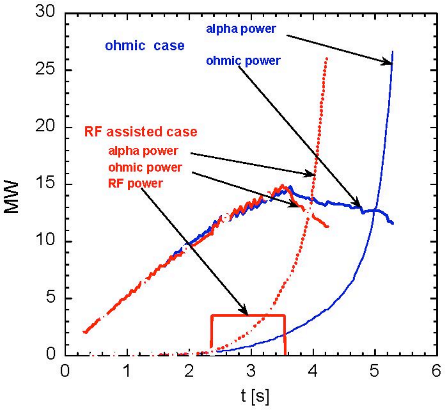

Figure 1. Comparison of Ohmic and RF aassisted ignition scenarios (JETTO code) from [5].

In the JETTO simulations the ICRH injection was treated with a simple model that takes into account the deposition region, time, and total absorbed power, allowing identification of different heating scenarios. In this paper the results of simulations carried out with full wave codes [6] are presented in Section II. These studies support the design effort for the ICRH system that is being carried out by ENEA in collaboration with the Politecnico di Torino. The general scheme adopted for the Ignitor ICRH system is presented in Section III, and a description of the antenna is given in Section IV.

II. SIMULATIONS

The use of ICRH is planned to explore several kind of plasma regimes, but most importantly for the high performance scenarios leading to ignited or slightly sub-ignited conditions. The system therefore is designed to be flexible, as it will operate on plasmas of isotopic composition (D, T), magnetic field and plasma current that vary during the same discharge. The system can operate in a frequency range between 80 and 120 MHz, but for this type of discharges an optimal frequency of 115 MHz is adopted. This frequency corresponds to the 2$^{\text{nd}}$ harmonic of T at the center of the plasma column at 13 T; 3-6

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MW of ICRH power can be coupled to the plasma by means of 2+2 strap antennas occupying 4 large horizontal ports.

To establish the power deposition profiles, two codes have been utilized, which solve an integro-differential wave equation that model the plasma-wave interaction. The equation is solved in 1D space (slab approximation) or 2D (toroidal geometry accounting for the real magnetic field equilibrium configuration). The boundary conditions are chosen considering the wave field at one boundary as radiated by the antenna, and on the other boundary as required by the regularity of the solution on the torus axis. The power deposition profiles have been estimated for five different values of the external magnetic field (9, 10, 11, 12, and 13 T), and a fixed frequency of 115 MHz. This range of magnetic fields corresponds to the time interval from 2 to 5 s of the pulse. The resonance locations as a function of magnetic field are listed in Table I. The ICRH power is delivered to different ion species during the magnetic field ramp from 9 to 13 T. At lower field (9 to 10 T) 2nd harmonic heating on D is predominant, and ion absorption is very strong (of the order of 80%). At higher field the 2nd harmonic of T enters the plasma while the D resonance moves out and the 1st harmonic of D is on the high field side of the plasma column.

TABLE I. RESONANCE LOCATIONS AT 115 MHZ

B (T)	H/D/T	T/^{3}He	D
9	1st/2nd/3rd at $x\approx0.5$	2nd/1st at $x\approx-0.5$	
10	1st/2nd/3rd at $x\approx0.9$	2nd/1st at $x\approx-0.25$	1st at $x\approx-0.95$
11	Out of reson.	2nd/1st at $x\approx0$	1st at $x\approx-0.75$
12	Out of reson.	2nd/1st at $x\approx0.2$	1st at $x\approx-0.6$
13	Out of reson.	2nd/1st at $x\approx0.4$	1st at $x\approx-0.4$

This analysis has highlighted certain issues that need to be further investigated. One is the role played at lower fields by small amounts of H in the plasma; another is that of fusion α-particles on the absorption of ICRH (recall that from the ICRH point of view, the α-particle is like deuterium); and finally, the presence of spurious harmonic layers of deuterium localized at the plasma edge in front of the antenna, in particular for $B \approx 10$ T.

TABLE II. CHARACTERISTICS OF A SINGLE MODULE

Operating Frequency Range	80- 115 MHz
Max RF power at 115 MHz	3.2 MW (at the generators)
Max RF power at 80 MHz	8 MW (at the generators)
Pulse duration	4 sec
Type of RF generators	Cavity coupled RF tetrode
Type of RF antennas	Four strap antennas
N° of generators per module	4
N° of antennas per module	2

III. ICRH SYSTEM ARCHITECTURE

The ICRH system for Ignitor is being designed as a highly flexible, modular system, able to perform under a wide range of operational plasma scenarios, to comply with remote handling installation and maintenance requirements, and also to allow future power upgrades. The use of standard, commercially available components has been preferred, if possible. The system architecture is based on modules having the characteristics listed in Table II, while the main electrical scheme of a single module is shown in Fig. 2.

The power of the 4 generators is distributed over two antennas (8 straps), in order to keep the maximum electric field in the vacuum region of the straps and transmission line below 5 kV /cm. The power splitting is performed through standard 3dB hybrid junctions that, with proper phase adjustment, allow the necessary insulation of the generators with respect to the reflected power of the plasma.

A set of four 9 1/16” coaxial rigid line transfers the power from the generators to the antennas; standard components like stub tuners and adjustable line stretchers are used for matching. A set of eight Vacuum Transmission Lines (VTL), including the feedthrough transitions, transfer a total power of about 3.2 MW (400kW per unit at 115 MHz) inside the load assembly, through 2 ports.

The main advantages of choosing 30 Ω impedance in the VTL are that the RF power transmission efficiency is maximized and therefore the distribution of the electric field inside the VTL is optimized; and the maximum electric field threshold to avoid discharges at plasma vacuum pressure is increased, in agreement with the Paschen law.

The configuration of each module allows a full phase control of the straps (poloidal and toroidal) through a proper PLL phase control in the low level stage of the generators.

Two modules, composed by 8 generators and 4 antennas, deliver the requested RF power of 6.4/16 MW at 115/80 MHz. At first, only four antennas will be installed, leaving the possibility of adding two more in the six large equatorial ports allocated to the ICRH system.

Fig. 3 gives a preliminary configuration of the coaxial feedthrough. Work is in progress to better define details of its construction using a FEM code (ANSYS) analysis to meet the requirement of limiting the electric field to < 5 kV/cm. Fig. 4 shows that the present configuration is not far from reaching the final goal.

IV. ANTENNA DESIGN

The limitation imposed on antenna design by the vacuum chamber and access ports configuration make the antenna geometry more complex, and this constitutes a challenge for the numerical simulation and the successive analysis.

The antenna design is based on performance evaluation obtained with the TOPICA© simulation suite (TOrino Polytechnic Ion Cyclotron Antenna code). The code was extensively tested and validated against commercial codes (in vacuum), against the ICANT and RANT3D codes (where

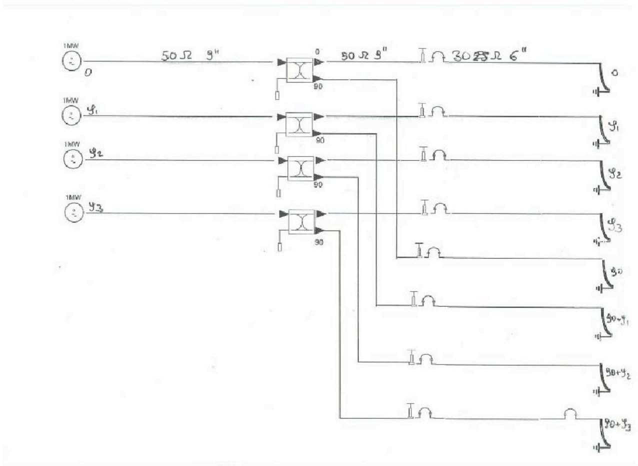

Figure 2. Main electrical scheme of a single module

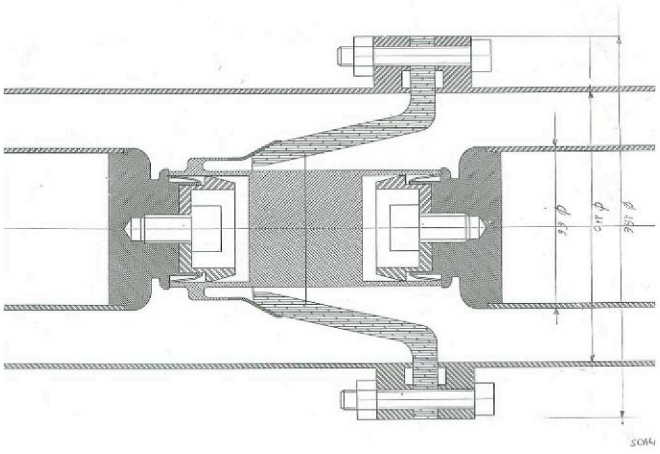

Figure 3. Preliminary configuration of the coaxial feedthrough.

applicable), against measurements of in-house and external mockups, and against data in literature.

The problem is addressed numerically via the integral-equation (IE), Method of Moments (MoM) formulation; accuracy in the geometrical representation is critical; for this reason sub-domain basis functions (rooftop) are required to properly discretize the current on the 3D general antenna geometry. A full-wave modelling of the plasma-facing antenna components is adopted; the magnetized plasma geometry is simplified to 1D "slab" geometry, suited for determining the antenna near-field behaviour and the antenna input impedance.

The antenna analysis and design rely heavily on numerical simulations that are based on an existing version of a computational core for the evaluation of the MoM matrix entries.

The IGNITOR reference antenna structure was analyzed, characterized by four driven ports. Effect of all parameters was carefully investigated.

The computational core simulation-control parameters assessment has allowed the electric and geometrical modelling of the complex Ignitor 4-port antenna, and the determination of the antenna parameters influence with respect to the design specifications. Currents, Standing Wave Ratio and maximum transmitted power have been accurately evaluated in the complete range of operating frequencies, demonstrating that the ICRH antenna system for the IGNITOR experiment satisfies the design requirements.

A complete thermomechanical assessment has also been carried out. In the final design, shown in Fig. 4, all the first wall elements, such as the Faraday shield, can withstand thermal loads, both in normal operating conditions and in case of disruptions, and electromagnetic loads due to eddy and halo currents. Compliance with Remote Handling assembly and maintenance has been assured.

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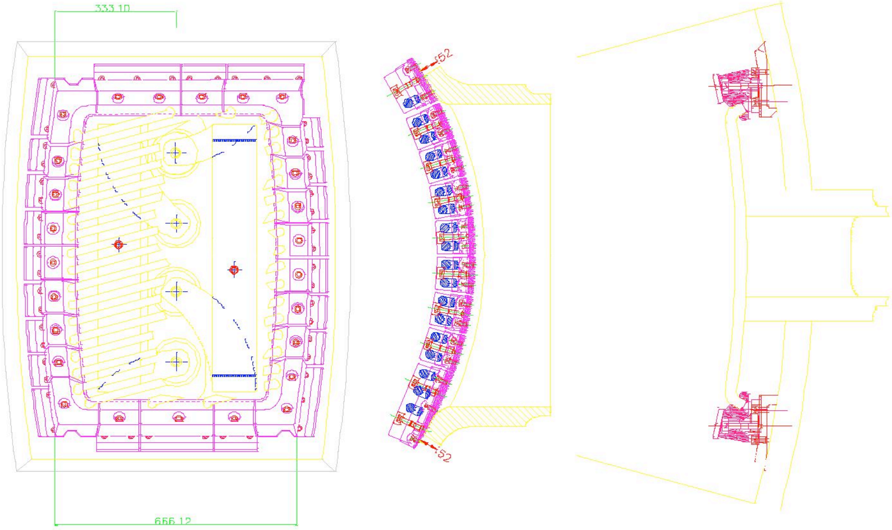

Figure 4. Front, side and top views of the Ignitor four strap antenna.