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Manufacturing process and tests of a lower hybrid passive active multi-junction launcher for long pulse experiments on Tore-Supra☆

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ABSTRACT

A new Passive Active Multijunction (PAM) Lower Hybrid heating and Current Drive (LHCD) launcher, has been successfully manufactured and tested on Tore-Supra (TS). The design and the fabrication of this new actively cooled launcher based on the PAM concept, as the present ITER LHCD design, is a major component of the TS CIMES project (Components for the Injection of Matter and Energy in Steady-state), and will play a key role in the TS near term program. To achieve 1000 s pulses with a power flux of 25 MW/m^2 the PAM launcher has been designed for steady state (CW) operation (active cooling) with the objective of coupling 2.7 MW of LHCD power to the plasma at 3.7 GHz with a parallel index $N_{\|} = 1.7 \pm 0.2$. The launcher has achieved its qualifications tests, i.e. low power Radio Frequency measurements, vacuum and hydraulic leak tests, and has been installed on Tore-Supra tokamak in September 2009. It is commissioning on plasma started a month later, quickly achieving its design performance of 2.7 MW on a 35 s pulse. After a technical description of the PAM, this paper presents an overview of the project phases (RF optimization, manufacturing and qualification) and concludes with the first experimental results of the PAM.

1. Introduction

Tore-Supra is the unique Tokamak in Europe with superconducting toroidal magnets. The plasma shape is circular and a pumped limiter is able to extract, in steady state, large heat fluxes of $-10\,\mathrm{MW/m^2}$, but also particles via its pumping ducts. With its superconducting toroidal magnetic field coils and its active water cooled walls (Carbon Fibre Composite for the limiter and stainless steel for the rest of the inner wall), Tore-Supra can, with non-inductive current drive, operate in very long pulses and attain steady state with respect to all plasma and plasma-wall time scales at power exhaust levels above 15 MW [1,2]. So far, discharges lasting 6 min were achieved by injecting 3 MW of LHCD with a non-inductive plasma current of 0.5 MA (i.e. with zero loop voltage) [3], and a total RF power of about 12 MW, 3.5 MW LHCD + 8.3 MW Ion Cyclotron Resonance Heating (ICRH) were coupled during pulses with length up to 8 s ($V_{\mathrm{loop}} > 0$ and $\langle n_e \rangle \sim 4 \times 10^{19}\,\mathrm{m^{-3}}$) [4].

On ITER, LHCD launchers will be exposed to high heat fluxes from plasma radiation and RF power losses in the launcher, with addition of a heavy neutron loading. The neutron energy has to be damped within the launcher to ensure low neutron flux at the back plate. A new concept of multijunction-type launcher has been proposed [5–7], the PAM, which allows an efficient cooling of the whole launcher and damping of the neutron energy. Cooling is provided in the massive walls between the columns of 'active' waveguides.

☆ This paper is dedicated to the memory of Philippe BIBET who designed this Passive Active Multijunction (PAM) project, as well as many other projects, among which the ITER-PAM launcher.

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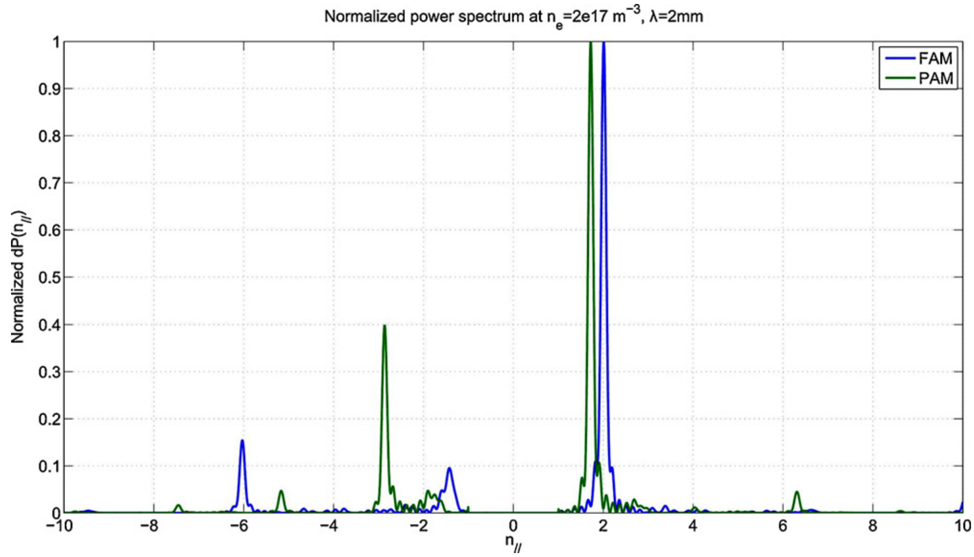

Fig. 1. Normalized to unity power spectrum for the Full Active Multijunction (FAM) and the Passive Active Multij unction (PAM). Plasma edge density is modeled with an electron density of $n_e = 2 \times 10^{17}$ m^{-3} ($n_{ecut.off} = 1.7 \times 10^{17}$ m^{-3}) and a 2 mm scrape-off e-folding decay length. The normalized power directivities are respectively 0.72 and 0.67.

These walls are terminated by 'passive' waveguides which have a short length equal to a quarter of guided wavelength (~24 mm). This arrangement ensures a regular array of waveguides facing the plasma, which is necessary for launching a wave with the required parallel index and high power directivity. The main drawback of this design is the reduction of the total radiating surface since the 'active' waveguides is the same as the "passive" waveguides surface. The expected coupled power (2.7 MW) for this launcher was estimated according to the following considerations. We assumed the same power density in the active waveguides (25 MW/m^2) than that obtained for the previous multijuctions launchers on Tore Supra for pulse length of several seconds on a large database (337 pulses). This power density was even achieved for pulse length of 30 s. Much higher power density (75 MW/m^2) was obtained on the 8 GHz PAM launcher of FTU [8,9] but on a shorter time scale (0.9 s). Apart of the pulse length, the favorable frequency scaling (probably a consequence of the multipactor effect limiting the transmitted power) explains the difference between these two experiments. For ITER [10], a lower hybrid launcher designed for 20 MW of LHCD power is foreseen at 5 GHz, considering a power density of 33 MW/m^2.

To be able to run plasmas in steady state at acceptable temperatures levels, water cooling must be implemented as close as possible to the grill mouth. This ensures enough clearance at the grill mouth for an efficient water cooling circuit located at the back of the passive waveguides. The technology used to realize the PAM is roughly the same employed in previous conventional Fully Active Multi-junction (FAM) launchers [11] developed for Tore Supra, being also similar to the one proposed for the earlier ITER design:

- Use of copper + stainless steel sheets joined by explosive diffusion bonding.
- Assembling by brazing of the copper parts.
- Electron beam welding of the stainless steel parts.
- Tungsten inert gas (TIG) welding of stainless steel piping.

PAM design allows efficient cooling of the front launcher. Its thermal constant time is 30 s in striking contrast to the 200 s for the previous FAM launcher. Simulated launched spectrum by the ALOHA [21] code for both launchers is plotted in Fig. 1. The width of the waveguides have been optimized in order to use the whole space available in the equatorial Tore-Supra port and consequently to reduce the power density within the launcher. Consequently the $N_\parallel$ peak range is 1.72 ± 0.28 compared to 2.03 ± 0.34 for the previous FAM launcher. Lower $N_\parallel$ values are expected to be more efficient for current drive [12]. The N_y flexibility is roughly the same for PAM and FAM. The power directivity (defined here as the ratio between the power in the positive $N_\parallel$ and the total launched power) is 67% for the PAM, to be compared to the 72% for the FAM, Fig. 1. The theoretical figure of merit for lower hybrid current drive may be written in the following form: $\eta = N_\parallel{}^{-2}$. The lower the $N_\parallel$ is, the higher the current drive efficiency η is. This is favorable for the PAM compared to the FAM.

2. PAM launcher description

The new launcher, illustrated in Fig. 2, is composed of two main RF components: (1) the PAM and (2) the Mode Converter (MC) which is bolted to the PAM rear flange.

At the CIMES project completion [13] 7 MW injected power of LHCD at 3.7 GHz will be available on Tore Supra to drive more than 0.8 MA at an average volume electron density of 2.3×10^{19} m^{-3}. This amount of power will be delivered through a combination of two launchers: the standard FAM launcher [6] and the new PAM launcher. Both launchers are fed by 8 klystrons each, whose power is split by two via hybrid junctions (3 db couplers). 16 BeO

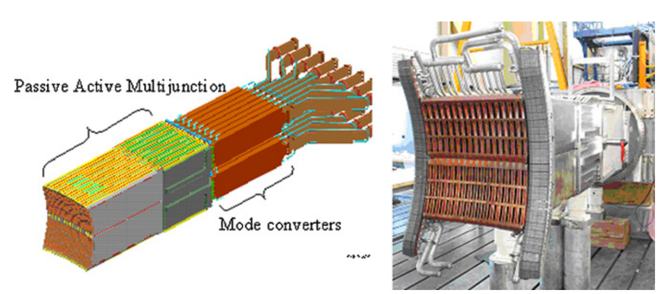

Fig. 2. PAM launcher equipped with its side protections on the equatorial lateral side of the front face and with its vacuum flange at the back. The structure is composed of two components bolted together: (1) the Passive Active Multi-junction (PAM) and (2) the Mode Converters.