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S. Alberti and M.Q. Tran

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T. Goodman, M. Henderson, A. Pochelon, S. Alberti, M.Q. Tran

Centre de Recherches en Physique des Plasmas
Association Euratom - Confédération Suisse
Ecole Polytechnique Fédérale de Lausanne
PPB-Ecublens, CH-1015 Lausanne, Switzerland

Introduction

The objective of the tokamak TCV (Tokamak à Configuration Variable) at the Centre de Recherches en Physique des Plasmas is to study the influence of elongation κ ($\kappa = b/a$ = (half height of plasma /minor radius)) and strong shaping on tokamak performances. The importance of elongation clearly stems out from the various energy confinement scalings which all bear a strong dependence on plasma current I^{α} and elongation κ^{β}, where α and β are of order unity. The maximum current I being a quadratic function of κ, there is a very strong interest in assessing the validity of the scaling laws as a function of κ in particular, but also in general as a function of the plasma shape. Note also the scarcity of the data base in the regime of high elongation ($\kappa > 2$).

Since the plasma in TCV can be created with a large variety of shapes (elongation κ from 1 up to 3, D and inverse-D shapes, etc....), the auxiliary heating must be insensitive to the plasma configuration. Of all the heating methods (Alfvén Wave Heating, Ion Cyclotron Resonant Heating, Neutral Beam Injection, and Electron Cyclotron Resonant Heating (ECRH)), ECRH has the best operational flexibility for heating of a wide-range of different configurations, relying on steerable mirrors to deliver the power locally to the plasma. Moreover, mode control, current drive and current profile modifications by off-axis heating are other features which can be achieved with Electron Cyclotron Wave (ECW).

In this report, we shall present the theoretical predictions for the absorption of and current drive (CD) efficiency due to ECW in TCV (Section 2). The description and the status of the implementation of the ECW system is described in Section 3.

Electron Cyclotron Resonant Heating and Current Drive Calculations for TCV

a) *The Tokamak TCV*

The main characteristics of the tokamak TCV are given in Table I.

Major radius R	0.88 m
Minor radius a	0.25 m
Aspect ratio R/a	3.5
Maximum plasma height 2b	1.50 m
Maximum elongation $\kappa = b/a$	3
Maximum design plasma current I	1.2 MA
Operating Magnetic field B_T	1.43 T

TABLE I
Main Characteristics of TCV

To allow the creation of a large variety of plasma configurations and their control, sixteen independent poloidal coils are installed in TCV (Fig. 1). A set of internal coils connected to a fast power supply will be put into operation to control the plasma position at high elongation [1]. Scenarios for obtaining various plasma configurations have been elaborated. For example, it was shown that ITER-like shapes ($\kappa \sim 2$), fully elongated ($\kappa \sim 3$) as well as multiple magnetic axes configuration [2] (Doublets) could be created in TCV. Experimentally elongation κ up to 2.05 and plasma current of 0.81 MA were achieved [3]. Both limited and diverted plasma were also produced during the different experimental campaigns [4]. More recently, a Doublet configuration was obtained during about 10 ms [2].

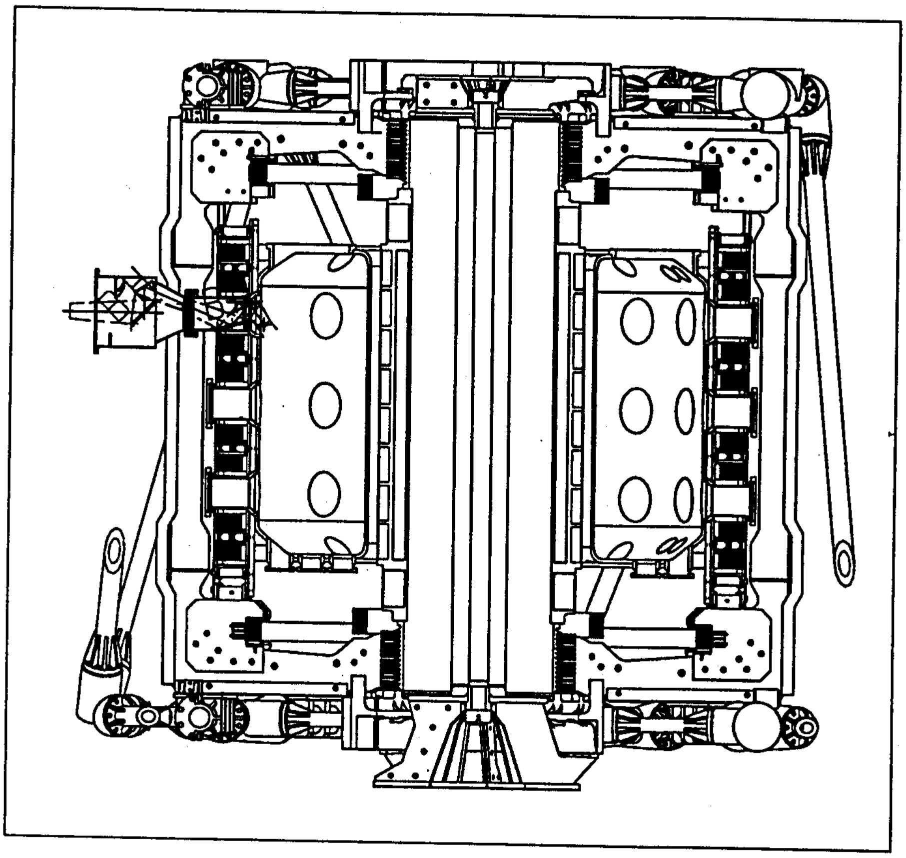


Figure 1

Schematic of TCV. A launcher for the X2 system
is shown on the low-field side on the left of the machine.

b) *Parameters of the ECWS*

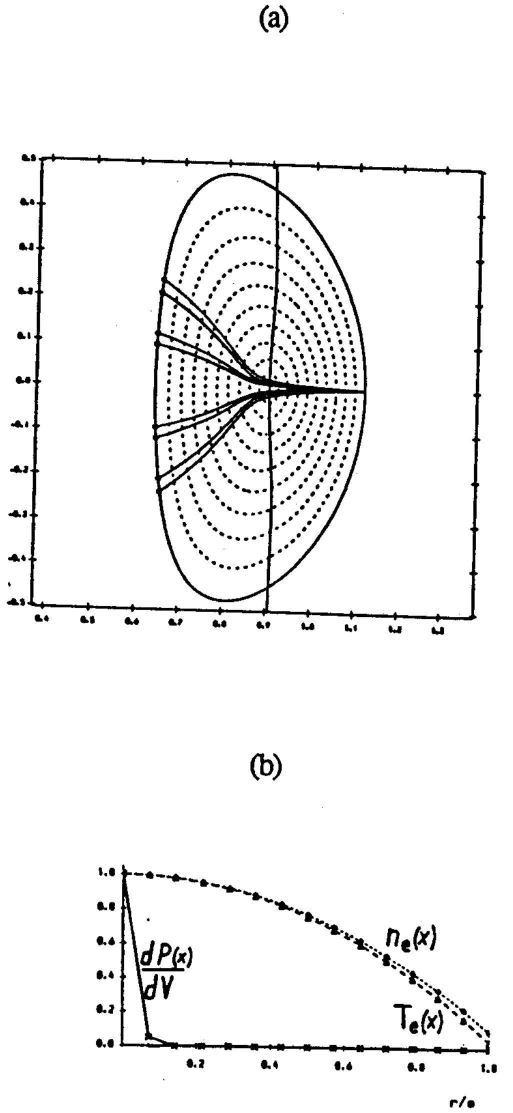
The frequencies of the ECW system have been chosen to maximize the density which can be reached below cut-off. Second harmonic at 82.7 GHz and third harmonic at 118 GHz, both in the extraordinary mode X (called hereafter X2 and X3) allow heating at the operating field $B_T = 1.43$ T in high density plasmas: the cut-off density for X2 and X3 are respectively 4.3×10^{19} m^{-3} and $1.15 \times 10^{20} m^{-3}$. As will be shown in the next sub-section, the use of combined X2 and X3 modes allow to heat plasmas with central density n_{eo} up to 7-8 $\times 10^{19}$ m^{-3}.

A total power of 3 MW in X2 and 1.5 MW in X3 will be installed. The pulse length of the gyrotron is 2 s, so that the heating pulse is longer than the expected current diffusion time (0.2 s for a 0.2 MA circular plasma, about 1 s for a fully elongated ($\kappa = 3$) 1 MA plasma).

c) *Heating and current drive simulations*

Ray-tracing simulations of the accessibility of the resonance from the low field side of TCV through lateral and top ports (Fig. 1) was computed using the codes BANDIT 3-D [5] and TORAY [6]. The equilibrium magnetic field corresponding to the desired configuration and a parabolic density and temperature profiles were used in the calculations. A value of about 1 keV was used as the central temperature T_{eo} in the Ohmic regime. A RF beam divergence of about 2^o was assumed. In the calculations the accessibilty and heating of plasma configurations with elongation κ of 1 (circular plasma), 2 and 3 were assessed.

Heating at the second harmonic extraordinary mode X2 can be performed in all regions of the plasma by injecting the ECW from the upper lateral and middle ports from the low field side [7] by adjustment of the poloidal launch angle. Technically a system of steerable mirrors could be installed on the low field side of the tokamak. 100% first pass absorption in the central region ($x = r/a \leq 0.4$) is achieved if the density is below cut-off on axis (Fig. 2). An X2 wave launched from an upper lateral port is also efficiently absorbed close to plasma edge ($x \gtrsim 0.7$) for central density above the cut-off density (Fig. 3). The localization of the normalized radius x of the absorption region at different central density is also given in Fig. 3.



Figures 2a) and 2b)

Ray-tracing (a) and power deposition just below cut-off
(f = 82 GHz, $n_{eo} = 4 \times 10^{19} m^{-3}$).

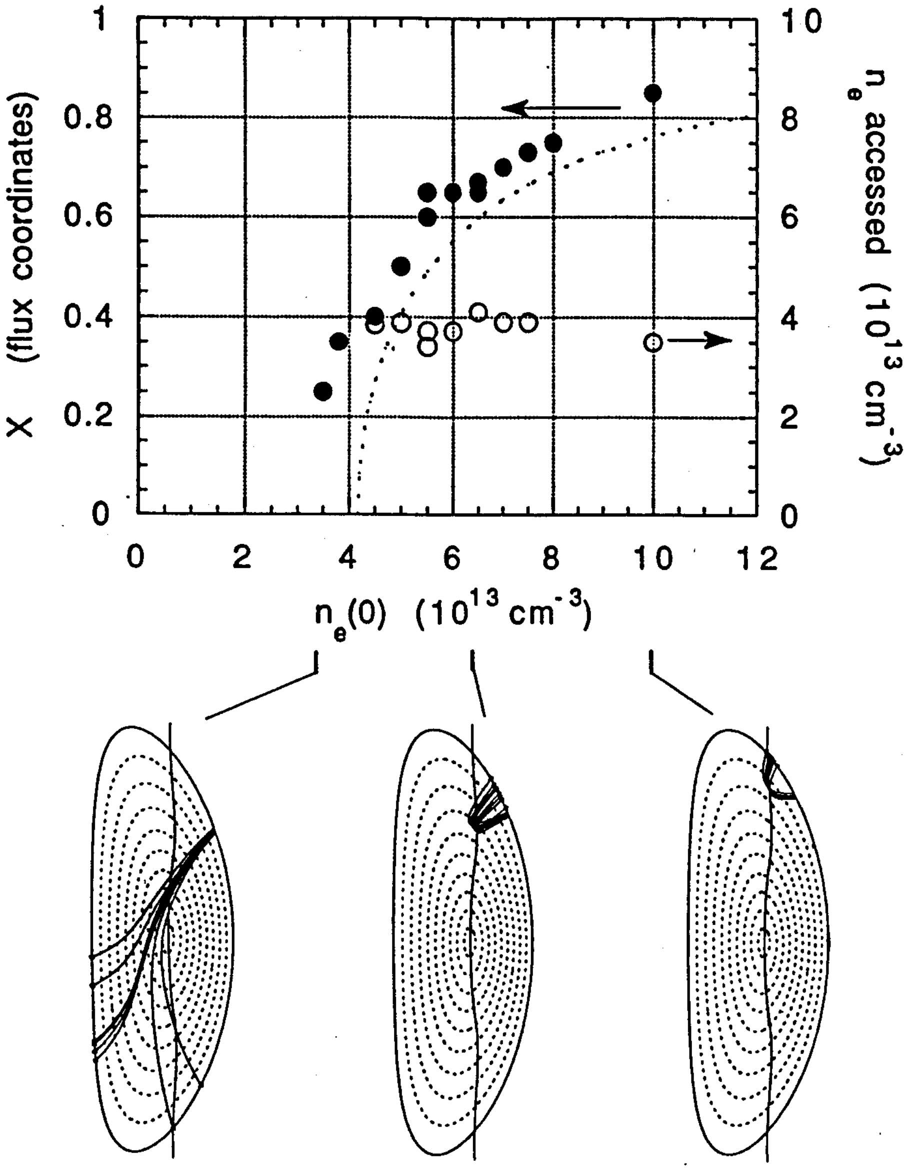


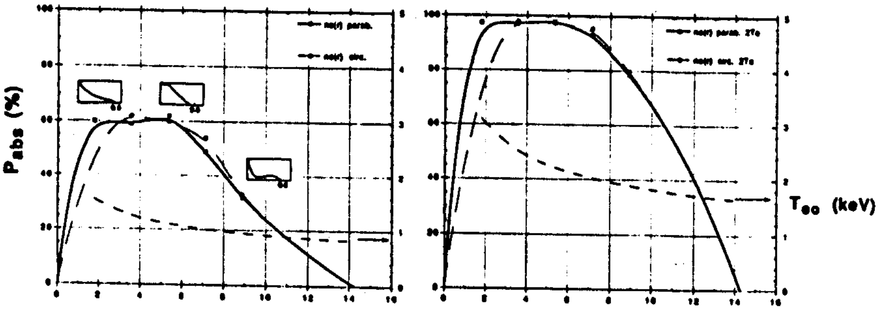
Figure 3
Upper lateral X2 launch into a fully elongated plasma (κ = 3, 82GHz, 1.5T). The position of power deposition is shown as a function of central density. The dotted line represents the flux coordinate, x, of the cut-off density.

Heating at the third harmonic extraordinary mode X3 is used to increase the accessible density. For the TCV plasma parameters ($B_T = 1.43$ T), the optimum frequency range is around 125 GHz with the final frequency choice for the X3 gyrotron being at 118 GHz. Since absorption of third harmonic wave is reduced compared to the one of the second harmonic, it is necessary to increase the path over which the RF beam interacts with the resonant layer. This is achieved by a quasi-vertical launch from a top port (Fig. 1). Moreover, since the optical depth τ of the X3 wave is proportional to $n_eT_e^2$, the interaction should occur close to the temperature maximum. The computed value of the optical depth was found to be in excellent agreement with measurement performed at low power in the tokamak Tore-Supra [8]. With the frequency of the X2 wave being 82.7 GHz, the third harmonic resonance is located on the low-field side of the second harmonic layer. The two layers are separated by $\Delta r/a = 0.2$ and central heating is thus possible using RF waves at both frequencies. This could be exploited in heating scenarios where firstly a low density plasma is brought to high temperature with the help of the X2 and X3 waves and secondly the density is raised and central heating performed by the X3 wave. In such heated plasma, the absorption is nearly complete (>95% for temperature above 2 keV) even at moderate elongation, $\kappa = 2$, and at density n_{eo} less than 4.3×10^{19} m^{-3} (Fig. 4).

Current drive efficiency at the second harmonic was computed using the codes BANDIT-3D and the package CQL3D and TORAY [9]. Both codes show that with electron temperature about 1.5 keV and at an electron density of 2×10^{19} m^{-3}, one can obtain 0.05 — 0.06 A/W, corresponding to a normalized efficiency $\gamma_{20} = n_{eo,20}\, RI_{CD}/P = 0.05$ A/(Wm^2). With the full available power in X2, it is therefore possible to drive the total plasma current for a circular shape plasma. Note however that at the power level P of 3.0 MW non-linear effects might have an influence on the CD efficiency since the ratio P[W cm^{-3}] / n^2_{13} [10^{13} cm^{-3}]^2 (= 10 — 30 W/cm^{-3}) largely exceeds the threshold (0.5 W/cm^{-3}) for electron tail formation given in Ref. 10. This subject is also discussed in Ref. 11.

κ = 2

TeOH 2 × TeOH



κ = 3

TeOH 2 × TeOH

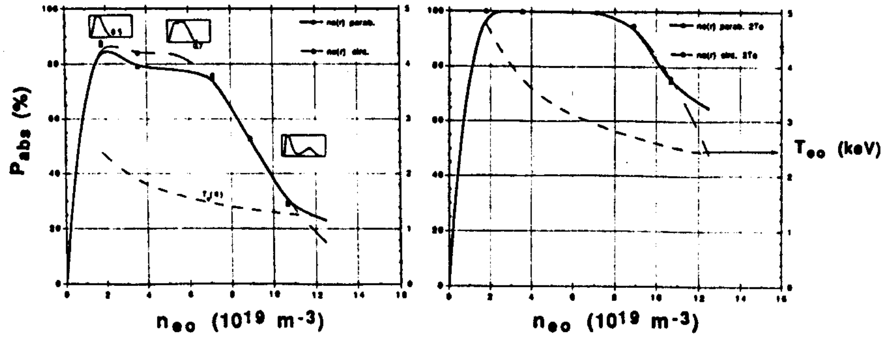


Figure 4

First pass absorption at third harmonic X3 at ohmic temperature (TeOH ~ 1 keV) and at twice this temperature (2 keV). The dashed line (------) shows the target plasma temperature.

The Electron Cyclotron Wave System

The Electron Cyclotron Wave System (ECWS) [12, 13] is distributed in three clusters delivering 1.5 MW each, two clusters being at 82.7 GHz and the third one at 118 GHz. The system is designed to meet the following physics requirements. For the X2 system the RF beam must be elliptically polarized and be steerable in the poloidal direction (between about -7^{o} and -55^{o} to reach the center of the plasma for all elongations from an upper lateral port) and toroidal direction (in the same range) for current drive. The design beam divergence in the plasma from the launcher is 2^{o} — 3^{o}. For the X3 system, the antenna shoud be movable in the radial direction to adjust the beam location with respect to the resonance layer in the plasma.

An evacuated transmisson line (0.5 MW per line) was chosen because of the requirements caused by the design of windows capable of handling high power in long pulse.

Each cluster of 3 gyrotrons is energized by a single regulated high voltage power supply (RHVPS) delivering 85 kV and 80 A. The RHVPS is a solid state power supply based on the Pulse Step Modulator technology developed and built by Thomcast AG [12, 14].

a) *The X2 system at 82.7 GHz*

The gyrotrons are manufactured by Gycom and deliver 0.5 MW in pulse of 2 s and are described in Ref. 15. They were developed from the existing short pulse (0.5 s) 0.5 MW gyrotrons made by Gycom. The cavity mode is the $TE_{10,4}$, which is converted internally into a mode which is compatible with the use of a BN window (Diameter: 104 mm) which is cooled at the edge by water. This mode is then converted to a Gaussian beam matching the input of a 63.5 mm diameter corrugated waveguide. The design beam diameter at 1/e in power is 20.4 mm; the measured values show some asymmetry in the beam shape with two values for the diameter across two perpendicular axis, respectively 22.9 mm and 20.4 mm The matching optics include two focussing mirrors and two flat, corrugated mirrors used as polarizers [16]. The whole optics is enclosed in a vacuum vessel. The stray RF beam is absorbed by plates coated with TiO_2 (Thickness: about 0.3 mm). High power measurements of the Gaussian content η_g of the beam after the matching optics gives a value around 95%. The power measured after two meters of corrugated waveguide is 552 kW for a beam current and voltage of 70 kV and 22.5 A, respectively.

The schematic of the transmission line is presented in Fig. 5. The typical length of a full line is about 30 m. The main elements are straight sections of Al corrugated waveguides, miter bends with and without power monitor, bellows, DC breaks, pumping Tee, microwave switch and a high power load capable of sustaining 0.5 MW in pulse of 2 s. These components have been designed and manufactured by Spinner Gmbh (Germany) and General Atomic (USA). The computed ratio of transmitted power to input power is 95% The waveguides have lengths up to 2.1 m and are supported at distance about 3 m using simple holders on which the waveguides rest. The alignment was performed using a simple three axis laser device and was referenced to fixed points with respect to the tokamak. The burn patterns obained at the input of the transmission line and at its end are shown in Fig. 6. They are well centered and show no deformation along the line. High power test of the line was performed first with the line under air, then in vacuum. In test under atmosphere, 0.5 MW was transmitted through the whole line during pulse of 0.1 s without any need of conditioning and without arcing. The measured ratio of the input power to the transmitted power is estimated around 93%. The line was then pumped down using a 500 l/s turbo-molecular pump located at the vacuum vessel of the matching optics unit (another turbo-molecular pump is located near the tokamak, downstream from the microwave switch but was not used in this experiment). Typical base pressure is in the range of 4×10^{-5} mbar after one day of pumping. At the time of writing of this paper about 310 kW was transmitted through the line into the load during pulses of 2s. We are presently extending the total energy delivered to the load aiming towards the full specifications, namely 0.5 MW, 2 s. In this process, a conditioning is necessary since the large energy (in the order of 0.6 MJ) absorbed in the load gives rise to a pressure increase in the line ($\Delta p = 10^{-3}$ mbar).

The launcher consists of four mirrors and meets all the physics specifications given above. The mirrors are made out of OFHC copper except for the last one which is TZM. TZM, a Molybdenum alloy, is selected since it has low sputtering and good electrical and thermal properties and is machinable. During a 2 s pulse at 0.5 MW, the temperature increase of the TZM mirror is about 470 ^{o}C, but due to the low duty factor (about 0.3%) the mean temperature is computed to be around 110 ^{o}C with radiative cooling only. The characteristics of the output beam from the launcher were measured at low power and good agreement was found between theory and experiments.

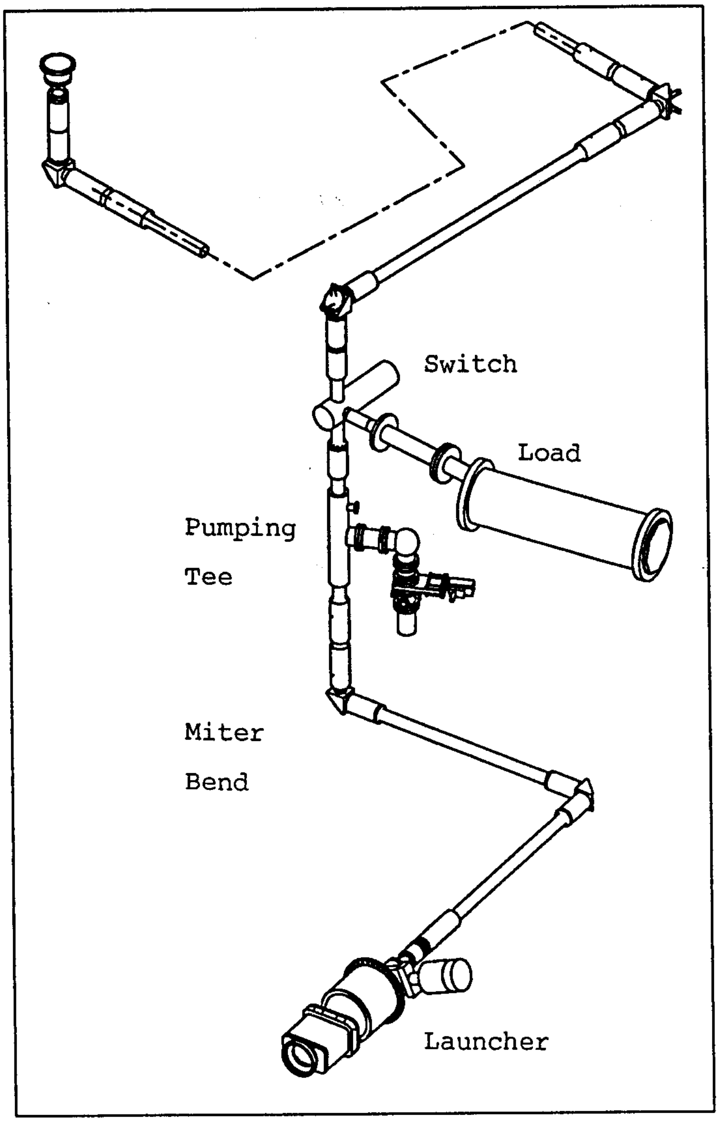
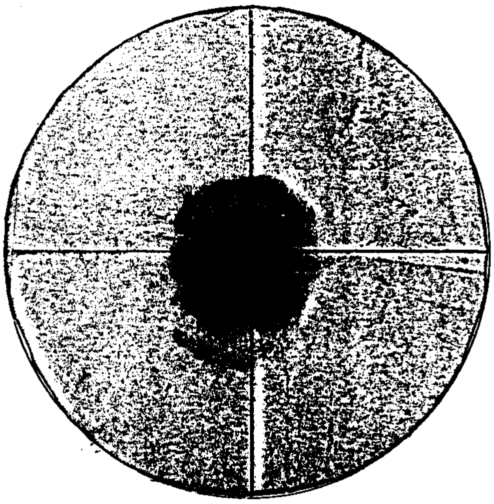


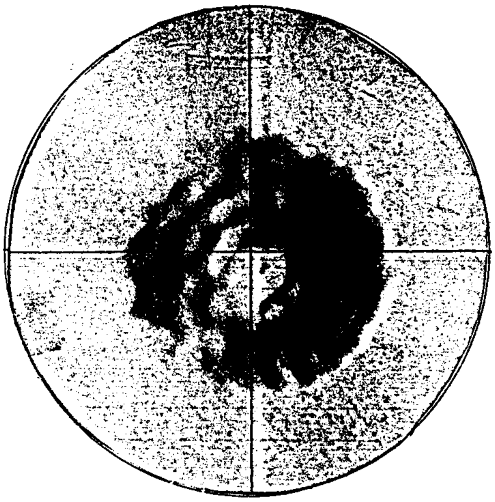
Figure 5

Schematic of the transmission line from the MOU to the launcher at TCV.

(a) at input



(b) after 20 m



Figures 6 a) and b)

Burn patterns in unevacuated transmission line.

Presently the first cluster is already installed and experiments could be performed as the commissioning of the gyrotrons and the transmission lines progresses.

b) *The X3 system at 118 GHz*

The main element of the X3 system is the 118 GHz gyrotron, for which a development programme is running in collaboration between the Associations CEA-Cadarache (France), CRPP (Switzerland), FZK (Germany) and the industry Thomson Tubes Electroniques (France). The parameters of the 118 GHz gyrotron are given in Table II. This tube will be used for the ECWS of both TCV and the CEA superconducting tokamak Tore-Supra (TS), for which the specification on pulse duration is 210 s.

Frequency	118 GHz
Output power in a HE_{11} waveguide	0.5 MW
Pulse length	2 s (for TCV) 210 s (for TS)
Cathode voltage	80 kV
Modulation anode voltage	30 kV
Electron beam current	22 A

Table II
Characteristics of the 118 GHz gyrotron

A description of the gyrotron design and the status of the high power tests are given in Ref. 17. The main design features of the tubes are: operating mode $TE_{22,6}$, window: sapphire cooled at the edge by liquid Nitrogen [18], pattern at the window: gaussian, spent electron beam swept along the collector. The coupling of the output beam into a corrugated waveguide (diameter: 63.5 mm) is performed via a matching optics consisting of three mirrors, two polarizers and a focussing mirror. We have recently achieved 0.5 MW as measured in a calorimeter after 2 m of corrugated waveguide in pulses of 2 s. During these tests no attempt was performed to maximize the efficiency. In spite of this, the measured efficiency is about 28%, close to the minimum specified value of 30%. The optimization and characterization of the prototype gyrotron is presently underway and factory acceptance test is foreseen in the very near future.

Conclusion

The main features of the ECRH and ECCD on the tokamak TCV were reviewed. Numerical calculations show that good absorption is achieved at X2 (82.7 GHz) and X3 (118 GHz). The implementation of the ECWS requires the development of long pulse gyrotrons at both 82.7 GHz and at 118 GHz. Of significant importance is the development programme related to the 118 GHz which paves the way to the obtention of CW gyrotron at higher power level. Test on TCV is expected in the next months.

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The design, fabrication and operation of the ECWS have benefitted form the expert work and assistance of all the engineers and technical teams of the CRPP. The participation of Dr. I. Roy (Kurchatov Institute, Russian Federation) during part of the high power test of the first cluster is gratefully acknowledged. The measurement of the output pattern from the Gycom gyrotron was performed by M. S. Wochner (FZK).

The development of the 118 GHZ gyrotron is performed in the frame of a joint contract between Associations Euratom - CEA Cadarache, Euratom - Confédération Suisse, and the industry Thomson Tubes Electroniques. The project has benefitted from the active contribution of FZK and the contribution of Prof. M. Thumm and M. O. Braz is gratefully acknowledged.

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