

Review of the EU Activities in Preparation of ITER in the Field of EC Power Sources and NB System

T Bonicelli¹, S Alberti⁹, J Alonso⁶, V Antoni², D Bariou¹⁰, P Barabaschi¹, I Benfatto¹, P Benin¹⁰, D Boilson³, A Bruschi¹⁴, M Chantant³, B Chuilon⁷, S Cirant¹⁴, R Claesen¹¹, JJ Cordier³, S J Cox⁷, S Dal Bello², C Day⁴, A De Lorenzi², O Dormicchi¹³, M Dremel⁴, H de Esch³, H Falter⁵, U Fantz⁵, D Fasel⁹, P Franzen⁵, E Giguet¹⁰, E Gaio², T Goodman⁹, R Heidinger⁴, R Hemsworth³, M Henderson⁹, D Henry³, J-P Hogge⁹, S Illy⁴, T T C Jones⁷, M Kovari⁷, C Lievin¹⁰, M Liniers⁶, A Lopez Fraguas⁶, M J Loughlin⁷, D Marcuzzi², C Martens⁵, D Martin⁷, A Masiello², J Milnes⁷, PL Mondino¹, B Piosczyk⁴, T Rzesnicki⁴, S Sandri¹¹, M Santinelli¹¹, E Speth⁵, L Svensson³, A Tanga⁸, G Taddia¹², V Toigo², M Thumm⁴, MQ Tran⁹, C Waldon⁷, Y Xue⁷, PL Zaccaria²

e-mail contact of main author: tullio.bonicelli@tech.efda.org

¹EFDA Close Support Unit Garching, Boltzmannstr 2, D-85748 Garching bei München, Germany

² Consorzio RFX, Associazione Euratom-ENEA sulla Fusione, C.so Stati Uniti 4, I-35126

³ DRFC, Euratom Association CEA Cadarache, France

⁴ Forschungszentrum Karlsruhe, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen

⁵ IPP, Max Planck Institute, Boltzmannstr 2, D-85748 Garching bei München, Germany

⁶ Asociación Euratom/Ciemat, Av. Complutense 22, 28040 Madrid, Spain

⁷ UKAEA Fusion Association, Culham Science Centre, ABINGDON OX14 3DB UK

⁸ ITER IT, Boltzmannstr 2, D-85748 Garching bei München, Germany

⁹ EPFL-CRPP, Association Euratom-Confédération Suisse CH-1015 Lausanne, Switzerland

¹⁰ Thales Electron Devices (TED), 2 Rue de Latécoère, F-78141 Vélizy-Villacoublay, France

¹¹ ENEA Frascati, Via E Fermi 45, 00044 Frascati(Roma) Italy

¹² OCEM, Via 2 Agosto 1980 11, 40016 San Giorgio di Piano (BO) Italy

¹³ Ansaldo Superconduttori SpA, C.so Perrone, Genoa, Italy

¹⁴ Istituto di Fisica del Plasma EURATOM-ENEA-CNR Association, Milano, Italy

Abstract

The European effort for the EC power sources is centred on the development of a 170 GHz, 2 MW, CW coaxial cavity gyrotron of Collector Potential Depressed (CPD) type. 2.2 MW in single mode were demonstrated in short pulse operation on a pre-prototype gyrotron at FZK. Test on the first industrial gyrotron prototype will start before end 2006 in a new full performance EC test facility in Lausanne (CH).

The procurement of the ITER NB system presents several challenges and an extensive R&D programme has been launched. In EU the experimental investigations take mainly place at CEA, Cadarache, where the arc driven source and the concept of an accelerator based on a single gap are pursued and at IPP, Garching, where a RF driven ion source is being developed. For the arc driven source, ITER baseline, the achieved current density is, in long pulses, still lower than the one required for ITER and the Cs consumptions is about three orders of magnitude higher than the one anticipated for ITER. Promising progresses have been made towards a RF driven ion source. Current densities of 330 A/m² in H and 250 A/m² in D were achieved on a small scale source with good reproducibility and operation in D in ITER relevant parameters space was achieved over many pulses. The RF driven ion source can now be considered a valid alternative to the arc driven one. Finally, the limited performances of the existing test facilities do not allow a reliable extrapolation to the ITER scale. The establishment of a full scale test facility has therefore become a centre piece of the European NB development strategy.

1. Background

Under the present ITER procurement package sharing, Europe is responsible for one third of the H&CD 170 GHz gyrotrons and all HV power supplies associated with the H&CD system. Europe and Japan share the procurement of the Heating Neutral Beam system, the Indian Participant Team being responsible for the Diagnostic NB. In all areas of participation, the EU Participant Team aims at advancing the technology of each of these subsystems and a robust R&D programme has been launched and pursued under the co-ordination of EFDA (European Fusion Development Agreement).

2. The EU programme for the EC Power Sources

The development of gyrotrons with higher unit power than the ITER reference design was strongly recommended in [1]. The essential arguments for implementing a R&D Programme aimed at developing a 170 GHz, 2 MW, CW coaxial cavity gyrotron are: to reduce the cost of the installation and to allow a compact launcher design and/or increase the power injected in the plasma. The presence of the coaxial insert increases considerably the limit current above which space charge effects become deleterious. In addition, larger cavities can be adopted in order decrease the power density on the walls (typical limit design value 10 MW/m²) without incurring in more severe mode competition problems [2]. 2.2 MW at 165 GHz in single mode were already demonstrated on an experimental gyrotron at FZK [3]. Following this result, a coordinated development programme has been launched under EFDA in co-operation between European laboratories (CRPP, FZK, ENEA-CNR) and industrial partners [4]. The testing up to full power, full pulse length will be performed at a new Test Facility in Lausanne, CH.

The basic target performances of the first industrial prototype are a pulse length of 1 s at an output power of 2 MW.

TABLE I: GYROTRON MAIN DESIGN PARAMETERS

operating cavity mode	TE _{34,19}
frequency	170 GHz
RF output power	2 MW
Nominal beam current	75 A
Nominal accelerating voltage	90 kV
pulse length: τ	3600 s
efficiency	$\geq 45\%$
cavity magnetic field	6.86 T
Window	Diamond (CVD)

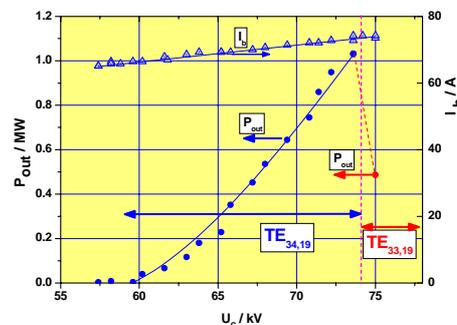


Fig. 1. Microwave output power P_{out} versus U_c . $B_{cav}=6.718$ T and $I_b \approx 65-75$ A

The design and construction of the industrial prototype gyrotron benefit of the experimental studies with a short pulse (\leq few ms) experimental 170 GHz coaxial cavity gyrotron ("pre-prototype") performed at FZK. This pre-prototype utilizes the same TE_{34,19} mode and same cavity with up-taper, launcher and mirrors as designed for the industrial prototype and a very similar electron gun. The results confirm the design even though some discrepancy between the experimental behaviour and predictions of numerical simulations exists. In particular:

- the performance of the electron gun and electron beam has been found to be in agreement with the design objectives as far as the properties are observable during the gyrotron operation;

- unexpected parasitic oscillations were found to be excited around 260 MHz. The shape of the coaxial insert has been modified in the industrial prototype tube, in order to avoid the occurrence of such oscillations or at least to reduce their intensity;
- at the maximum obtainable value of the magnetic field of 6.718 T, an output power of 1.15 MW has been measured with an output efficiency of 20 % (without depressed collector), Fig. 1. The excitation of the nominal mode at 170 GHz has been found to be robust against variations of the operating conditions. However, a discrepancy between the experimental and numerical results concerning the range of oscillation and the mode sequence is still unresolved and needs further investigations;
- the microwave beam is well coupled out of the gyrotron. However, the Gaussian content of the output beam is fairly low. An improved RF output system with larger Gaussian content is under design.

The amount of stray microwave losses has been evaluated to be around 8 % of P_{out} . Efficient internal absorbers (water loads) for the stray radiation have been tested. The collector will dissipate a power of 2.4 MW during nominal operation at constant RF output power and it is expected to be one of the most critical parts of the 2 MW gyrotron. In order to spread the power on a larger collector area, a set of coils is installed to sweep the beam [5]. An optimal sweeping frequency of 7 Hz was determined. The average power density does not exceed the critical value of 500 W/cm² and the resulting peak temperature will be 270°C, which is an acceptable value. Further improvements are under study to take into account the extra load (up to ~3.4 MW) on the collector during the modulation of the RF output power. The first prototype gyrotron [6] is presently under advanced state of assembly, Fig. 2, and its delivery is expected by end of September 2006. The superconductive magnet must comply with tight tolerances on the alignment of the magnetic and mechanical axis, which should be maintained also after quenches. The superconducting magnet operates at a nominal field of 6.86 T at the cavity centre. The system has been designed for an additional 5% operating margin so the maximum operating field at cavity is 7.2 T, corresponding to a maximum field of 8.16 T on the superconductor. The SCM is now under advanced stage of manufacturing and assembly and it is expected to be delivered before the end of 2006. Two 2 MW dummy loads are also being procured. The first one targeted for the initial short-pulse, SP, operation and the second load intended for the later tests in CW. The two versions, SP and CW, have identical electromagnetic design and differ only in the heat removal. The load is made of a spherical cavity, 600 mm inner diameter, with partially reflecting walls. Absorption occurs in a thin ceramic layer, plasma sprayed on the internal walls, which determines the effective wall reflectivity. An appropriate dispersing mirror opposite to the input beam, in combination with the spherical shape and the proper selection of wall reflectivity, provides uniformity in heat loading of the walls [7]. The final PS scheme adopted for the Test Facility [8], Fig. 3, is composed of a Main High Voltage Power Supply (MHVPS) and a Body Power Supply (BPS), based on several identical series connected "low voltage" IGBT modules. A thyristor crowbar (HVC) provides additional, full back-up protection, to the one granted by the MHVPS. Compared to the ITER requirements, the sinusoidal modulation frequency of the BPS output voltage is increased to 5 kHz (instead of 1 kHz), with the possibility of operating at 10 kHz. To limit the collector loading, the MHVPS can switch on and off the beam current at 5 kHz, synchronously with the BPS. It was found out that the IGBT-based MHVPS was less expensive than the reference ITER scheme (thyristor converter and high voltage IGBT protection switch) in case of the 2 MW RF. A similar solution may be convenient also for the ITER case. The BPS is based on a fully solid state design which replaces the traditional power vacuum tubes solutions used for this kind of application. This novel scheme [9] provides higher reliability, at lower investment and maintenance costs. The BPS has passed successfully a comprehensive factory testing programme. For example, in case of 5 kHz

sinusoidal modulation of the output voltage with 25 kV peak-to-peak, the maximum phase shift is 10° and the THD is 1.9 % (specified 5%). Sinusoidal modulation at 10 kHz, above specifications, is also very satisfactory (THD = 4.9%). The -3 dB bandwidth is beyond 30 kHz.



Fig. 2. First Industrial 170 GHz, coaxial cavity gyrotron prototype

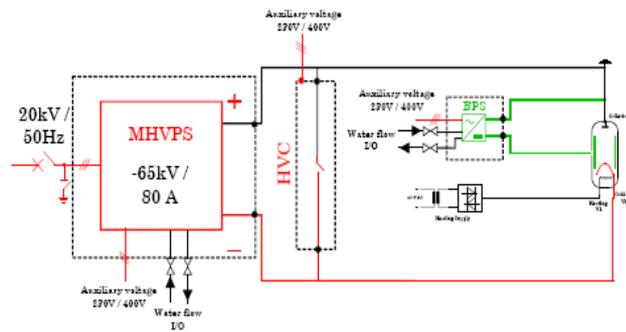


Fig. 3. Power supply scheme adopted for the EC test facility

The EC source development is centred around the construction and testing of three prototypes (typically 1s, 100s and then CW as target pulse capacity) before launching the procurement for ITER. The development phase should be completed, with the final tests on the third prototype, by mid-2013 when the ITER series production should start [6].

3. The EU programme for Negative Ion Based NB system

The ITER NB system performances are well beyond the ones achieved so far by any negative ion based system, Table II. The objective of the R&D being performed in Europe and Japan is to prove the concepts for the negative ion source and the 1 MV accelerator. Though good progresses have been made, no ion source or accelerator has yet achieved simultaneously all the parameters required in the ITER specification.

3.1 SINGAP Accelerator

The ITER baseline design for the accelerator is based on the MAMuG concept consisting of 5 grids, forming 5 acceleration stages of 200 keV, with distances (typical) 86, 77, 68, 59 and 50 mm. During the past few years, Europe, at CEA Cadarache, has developed the SINGAP accelerator concept [10, 11]. In the 1 MV test stand at Cadarache, the ion source is installed at ground potential and the negative beam is accelerated towards a positive electrode at high positive potential, the inverse of the ITER arrangement. In SINGAP the full acceleration of the ion beam to 1 MeV is achieved mainly in a single gap, ≈ 350 mm long. The SINGAP concept would bring substantial simplifications to the NB system, for example in the design of the HV bushing and transmission lines and services to the accelerator. In addition, beam steering (ITER requires vertical steering of ± 10 mrad) can be achieved in SINGAP by simply displacing the post-acceleration (grounded) grid instead of moving the complete accelerator, as is necessary with the MAMuG concept. This was proved experimentally with very good agreement being found between prediction and experiment. The best performance ITER

relevant pulse, using only one aperture in the pre-accelerator, was at 727 keV with a current density, in D^- , of 123 A/m^2 (total accelerated current 18.5 mA). The divergence in the horizontal and vertical directions was 3.9 mrad and 5.5 mrad respectively. The main technological difficulty posed by the SINGAP design is probably related to the electrons generated in the accelerator ($\approx 2.7 \text{ MW}$ at an average energy of $\approx 760 \text{ keV}$) which would cause additional stresses on the beam line components, in particular on the neutraliser leading edges with peak power densities (over very small areas) of $25\text{-}30 \text{ MW/m}^2$. New systems to deflect and dump the electrons are now under design [12]. The additional heat on the cryopump caused by the X-rays produced by the dumped electrons and by back scattered electrons has been evaluated and additional screens proposed that ensure no critical conditions occur. An important issue identified in Cadarache is the large dark current flowing between the grounded vessel and electrodes whose origin is not fully understood. The dark current impairs considerably the experimental activities due to the limited current, 100 mA, available from the 1 MV power supply at Cadarache. After adequate conditioning, good voltage holding (with no discharge in the ion source) up to 940 kV across the 350 mm gap was nevertheless achieved but only at a pressure around the accelerator (0.07 Pa), higher than that predicted for ITER (0.03 Pa). A programme aiming at studying the reasons for the dark current and at identifying mitigating or suppressing measures has now been launched.

It is recognised that the validation of the SINGAP concept needs experimental results at higher currents and it is now planned to test the SINGAP concept in co-operation with the Japanese Home Team in the test facility at Naka where a -1 MV power supply with a current capability of 1 A (limited to $\approx 0.5 \text{ A}$ at the accelerator) is available. Those tests could be performed in the first half of 2007.

3.2 EU ion source development

The main specifications, to be maintained stably on long pulses, of the ITER NB ion sources are summarised in Table III. Two concepts for the negative ion sources are being considered for ITER: the multi-cusp arc discharge source, which is the ITER baseline design, where the plasma is produced by an arc discharge in a chamber provided with directly heated tungsten filaments, and the RF driven ion source. In both sources, caesium is injected to enhance the negative ion production. In Europe, the arc driven option is being studied in CEA, Cadarache, using the KAMABOKO III source, designed and built in Japan, with a maximum acceleration voltage of $\approx 30 \text{ kV}$, with the main aim to achieve long pulse operation. Stable operation was demonstrated for 1000 s pulses both in H^- and D^- . On the other hand, while current densities of $>280 \text{ A/m}^2$ H^- and of $>200 \text{ A/m}^2$ D^- were achieved in short pulse operation, the maximum accelerated current density in long pulses of H^- was $\approx 160 \text{ A/m}^2$ on the calorimeter [13], below the ITER requirements. The consumption of Cs was found to be more than three orders of magnitude higher than it is expected for ITER [14, 15]. It is found that the Cs is “blocked” on the chamber walls and on the plasma grid in a mixture with the tungsten evaporated from the filaments. A possible solution of this problem, presently under study, is to use filaments made of thoriaated tungsten, which operate at a significantly lower temperature than pure tungsten for the same specific electron emission. The development of the alternative RF ion source concept is pursued in Europe at IPP, Garching. Compared to the arc driven source, the RF ion source is not affected by the evaporation of tungsten from the filaments. Maintenance requirements are also reduced, since there is no need of regular replacement of the filaments. Tests are performed on three experimental facilities:

TABLE II – ITER NB REQUIREMENTS AND EXISTING NEGATIVE ION BEAM SYSTEMS

ITER	JT-60U	LHD
16.5 MW	1.6 MW	5.7 MW
1 MeV	360 keV	184 keV
3600s	20 s	120 s @ 0.2 -0.3 MW

TABLE III: – ION SOURCE MAIN ITER SPECIFICATIONS

D ⁻ current density	200 A/m ²
Uniformity	± 10 %
Filling Pressure	< 0.3 Pa
Co-extracted electrons	$I_e/I_{D^-} \leq 1$
Maintenance frequency	< 2/year
Cs consumption	“low”, e.g. 10 g for 6x10 ⁶ s operation

- BATMAN: principle studies, high current densities for short pulses (< 4 s) on small scale source (extraction area up to 100 cm²);
- MANITU: long pulse experiments on a PINI size source (188 cm² extraction area);
- RADI: plasma homogeneity of a large RF source (1/2-size ITER source, full width and half height) presently without extraction.

Stable and reliable operation in deuterium within the required parameter range (current densities >200 A/m², electron/ion ratio <1) at a source filling pressure of 0.3 Pa. was achieved on BATMAN as shown in Fig. 4. The electron/ion ratio was below one, with minimum values of about 0.8 and with ion current density above 200 A/m². The plasma grid temperature was kept within 120 – 150 °C with a “cold” source body (30 °C – 50 °C). The medium size source on MANITU reached long pulsed operation both in H (600 s) and D (≈200 s). The pulse length is limited by the increase of the electron current, see Fig. 5, which is thought to be caused by the continuous increase in temperature of the uncooled plasma grid mask changing the Cs coverage of the plasma grid and/or the plasma grid mask. A cooled grid mask is now being procured. Deuterium operation in MANITU started only at the end of July (2006). Electrically measured accelerated D⁻ current densities of about 120 - 130 A/m² have been achieved for pulses of up to 190 s; the electron current however was not stable and increased during the pulse to an electron/ion ratio of about 3. Work is now in progress to optimise operation in deuterium. The RADI experiment is dedicated in particular to the study of uniformity in large sources. Operation started before summer 2006 and no relevant results have been produced yet. At present there is no extraction/acceleration capability on RADI, therefore the extracted current densities and the amount of co-extracted electrons cannot be directly investigated. The uniformity of the large RF source will be initially deduced from measurements of the plasma characteristics and the negative ion density in the source. It is proposed to upgrade the test facility to allow to run the plasma source for an extended time and to extract beam throughout the plasma pulse for 10 s every 160 s of source operation. The Cs consumption for the RF source has not yet been fully assessed, but there are strong indications that the Cs consumption is considerably lower than the one found for the arc driven source. Contrary to the arc driven source, there is also no indication of increasing Cs consumption with increasing pulse length. In view of the very good progresses made, the RF ion source is now a serious candidate for the ITER NB system.

3.3 NB Design and NB Test Facility

In the last few years, an extensive activity promoted and co-ordinated by EFDA and carried out by six EU Associations (CEA, CIEMAT, FZK, IPP, ENEA-RFX and UKAEA), [16], has been performed in Europe aimed to:

- a) revise and update the NB injector design for ITER

- b) bring the design of RF driven ion source and SINGAP accelerator to the same level of detail of the reference design (arc driven and MAMuG respectively)
- c) adapt the design of the NB system to a generic full scale Test Facility.

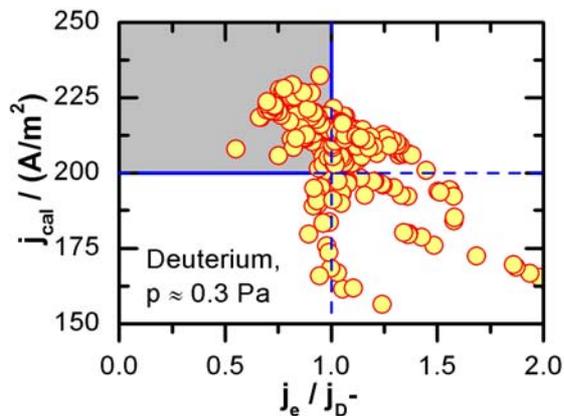


Fig. 4. RF ion source: pulses in ITER parameter range

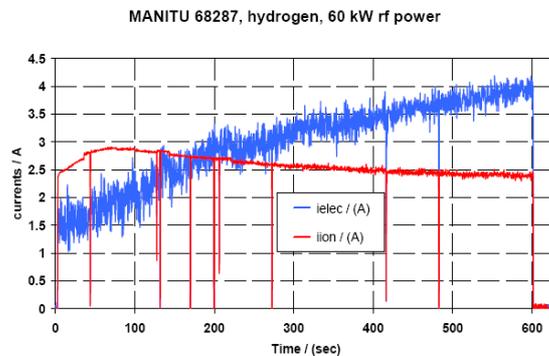


Fig. 5. RF ion source: long pulse operation

Among the main results of the EU activities was a technical proposal for a change of the ITER reference power supply scheme [17]. All electric devices part of the ion source power supplies are removed from the High Voltage Deck (HVD) in SF₆ and located in a new deck that is air insulated for -1MV to ground and placed at the beginning of the transmission line. This scheme has the following main advantages: reduction of the number of 1 MV insulation transformers from eight (four of them rated for 1 kHz) to one (at 50 Hz), much easier maintenance and troubleshooting of the ion source power supplies, simplification of design and reduction of weight and size of HVD in SF₆ located near the tokamak. The proposal is now being discussed with the ITER parties and it has a good chance to be adopted.

The existing 1 MV test facilities have performances very limited compared to the ITER nominal ratings:

- 1 MV, 1 A (operated at 0.5 A), H⁺, 2 s (target limit) in Naka, Japan
- 1 MV, 0.1 A, D⁻, 2 s (target limit), in Cadarache, France

The ITER NB injector will accelerate 40 A, D⁻, to 1 MeV, for 3600 s.

It is generally appreciated that a full scale test bed is a necessity: to fully develop the ion source and the accelerator at the level required for ITER. Some of the specific issues requiring experimental investigation on a full scale test facility are:

- achievement of the specified negative ion yield and Cs consumption
- studies of source uniformity
- high voltage holding (both the beam source and the power supply systems)/ dark current
- effect of residual magnetic field on the beam trajectory
- studies of phenomena associated with high accelerated currents (optics, space charge, beamlet-to-beamlet interaction, etc.)
- test of beam line components at full power, including power deposition from any co-accelerated electrons and X-rays
- beam neutralisation studies and measurements at full power
- residual ion dump proof of correct operation
- integrated tests of the power supplies (essential to ensure reliability during operation)
- final verification of overall reliability of the NB system.

Negotiations are being carried out with the ITER Parties to establish the NB test facility in a site in Padua, Italy. It is also proposed to include in the NBTF a full scale ion source test facility. This can be ready before the 1 MV test facility allowing the development of the full scale ion source to start early

4. Conclusions

Good progresses have been made in all the areas of the development of the EC sources and good cooperation has been established amongst the European laboratories and Industrial Partners under EFDA coordination. The first industrial prototype of the coaxial cavity gyrotron is being delivered at the EC test facility and testing with RF power will start early in 2007. For the ITER NB system, both concepts for the ion source have demonstrated to fulfil requirements on current density, pressure, power and low electron co-extraction. Long pulses in RF sources (IPP, Garching) and improved spatial uniformity in arc driven sources [18] have recently been achieved. Stable long pulse, uniformity and low Cs consumption are still to be demonstrated. The development of the two alternative accelerator designs has made some steps forward but the performances achieved are still far from the ITER parameters, mainly because of the limitations of the available test beds. The complexity of the NB system demands the construction of a full scale test facility to develop the critical components and test the NB system before operation on ITER.

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