A new 3MW ECRH system at 105 GHz for WEST

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The aim of the WEST experiments is to master long plasma pulses (1000 s) and expose ITER-like tungsten wall to deposited heat fluxes up to 10 MW/m^2. To increase the margin to reach the H-Mode and to control W-impurities [1] in the plasma, the installation of an upgraded ECRH heating system, with a gyrotron performance of 1MW/1000s per unit, is planned in 2023. With the modifications of Tore Supra to WEST, simulations at a magnetic field B_0~3.7T and a central density n_{e0}~6x10^{19} m^{-3} show that the optimal frequency for central absorption is 105GHz. For this purpose, a 105 GHz/1MW gyrotron (TH1511) has been designed at KIT in 2021, based on the technological design of the 140 GHz/1.5 MW (TH1507U) gyrotron for W7-X. Currently, three units are under fabrication at THALES. In the first phase of the project, some of the previous Tore Supra Electron Cyclotron (EC) system components will be re-installed and re-used whenever possible. This paper describes the studies performed to adapt the new ECRH system to 105 GHz and the status of the modifications necessary to re-start the system with a challenging schedule.

1. Introduction

WEST experiments [2] started in 2017 with a new inertial W-coated divertor and were powered by two RF heating systems, in a frequency range of 55-65 MHz (Ion Cyclotron Resonance Heating) and 3.7 GHz (Lower Hybrid Heating) with respectively 3MW/1000s and 7MW/1000s of power capabilities. The coupling efficiency of the two RF heating systems is strongly dependent on the scrape-off layer parameters. During these experiments, it has been shown, that the H-Mode operational domain was reduced mainly due to difficulties to optimize the coupling efficiency of the RF heating systems to any edge density conditions. Performances were also limited by W (tungsten) core contamination. It is well known that Electron Cyclotron (EC) waves coupling is virtually independent of the edge conditions and that it can be effective in limiting the W accumulation. Therefore its implementation could be decisive in order to increase the performance of WEST operation.

Simulations at a magnetic field B_0~3.7T, a central line integrated density n_{e0}~4.2x10^{19} m^{-3} and a central electron temperature T_{e0}=3keV demonstrated that 3MW of Electron Cyclotron (EC) additional power at a frequency of 105 GHz (O-Mode), can increase the electron temperature by a factor 2.5. A 105 GHz EC system will widen the WEST operational domain and improve the reliability of the experiments. The ECRH project was then launched in April 2021, with the aim of installing three new 105 GHz gyrotrons (1MW per unit), the necessary auxiliaries and to re-use, whenever possible, the previous ECRH system components that were operational before 2011.

In section 2, the gyrotron, designed by KIT and based on the technological design of the 140 GHz 1.5 MW gyrotron for W7-X [3], will be briefly described as well as the new main components ordered for the new system such as a Matching Optic Unit (MOU), an RF load and a cryogen free Super Conducting Magnet (SCM). The section 3 will describe the previous EC system components [4] which can be adapted for EC experiments in WEST with the aim of optimizing both schedule and costs. The current project status is given in section 4. The future prospects are then depicted in the section 5.

2. New components of WEST EC system

The WEST EC project started in April 2021, with the objective to launch the main contracts for the furniture in 2021. Some components from the previous EC system cannot be re-used as the new frequency and pulse duration are not adapted, other components are obsolete as for example the Control Data Access and Communication (CODAC) hardware.

The main new components ordered for the 105 GHz EC system are the gyrotrons and their MOUs, the SCMs, some transmission lines components (RF switches and polarizers) and one RF load 1.5 MW/1000s to commission and condition the gyrotrons before plasma operation.

2.1 Gyrotron and MOU

2.1.1 Gyrotron

The RF design of the new gyrotron has been performed by KIT using a set of relevant codes that have already been validated for the W7-X gyrotron-at 140 GHz, the ITER gyrotron at 170 GHz and the Swiss Plasma Center bi-frequency gyrotron at 84-126 GHz. The industrial manufacturer of these gyrotrons is THALES.

Based on the development of the W7-X 1.5 MW 140 GHz long pulse operation gyrotron (TH1507U), the objective was to design a 105 GHz/1MW/1000s gyrotron for WEST.

One constraint was to re-use the WEST High Voltage Power Supply (HVPS) which limits the cathode voltage to -55kV and the maximum beam current to 45A for each gyrotron. As the gyrotron has a depressed collector, each gyrotron will be equipped with an adapted Body High Voltage Power Supply (BHVPS) at +35 kV and a crow bar (CB) to protect the tube in case of arcing. The optimization of the 140 GHz design for 105 GHz by re-using the validated components in existing W7-X tubes or minimizing the modifications was a key point to:

- reduce the risks associated to this project,
- optimize the schedule (the objective is to start the operation of the first gyrotron in 2023),
- minimize the cost of the gyrotron.

The CVD diamond window thickness will be very close to that of the W7-X gyrotron while the collector will have the same geometry as the 170 GHz gyrotron (TH1509). To avoid high localized loads on the collector, it will be equipped with a transversal and a vertical beam sweeping systems; the transversal sweeping systems will be provided by KIT [5]. All other components of the gyrotron, the gun, the beam tunnel, the cavity and the launcher have been optimized to avoid mode competition, backward waves and to keep the ohmic wall loading at a reasonably low value < 1.08 kW/cm^2.

The RF design, delivered by KIT in October 2021, has margin, with an RF power at the exit of the cavity of 1.30 MW. It has been shown in multimode simulations, that interaction with the counter-rotating mode ($TE_{-20,8}$) is more favourable in order to avoid a major redesign of the electron gun. In order not to reverse the orientation of the quasi-optical coupling system, the magnetic field is reversed compared to the TH1507, TH1509 and TH1510 gyrotrons. The main parameters of the TH1511 gyrotron for WEST designed by KIT are summarized in Table 1.

Table 1. WEST gyrotron parameters

Design Parameter	**Value**
Operating frequency	104.92 GHz
Operating cavity mode	$TE_{-20,8}$
Magnetic field	-4.13 T
Cathode voltage	-55 kV
Body Voltage	+23 kV
Accelerating voltage	78 kV
Beam current	45 A
RF power at cavity exit	1.30 MW
Gaussian mode content	98.85%
Max Ohmic loading of cavity wall	1.08 kW/cm^2
Interaction efficiency	~ 28,5%
Global efficiency (w depressed collector)	~ 40%

The RF design of the quasi-optical launcher has been experimentally validated by KIT using a dedicated $TE_{-20,8}$ mode generator at 105 GHz and low power tests with an aluminium launcher mock-up. The results confirmed the robustness of the RF design with a very good agreement between simulation and measurement scalar correlation coefficient: 96.6 %. (see figure 1).

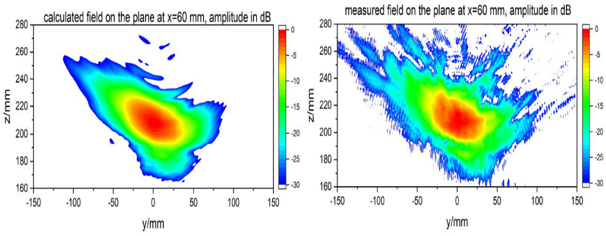

Fig. 1: Comparison between the calculated launcher output field on the left hand side and the measured field on the right hand side at 60 mm from the gyrotron axis

The final design of the quasi optical mode converter has demonstrated an excellent performance with a calculated Gaussian mode content of 98,85% and stray radiation in the quasi-optical system estimated between 1 to 1.7%. (see figure 2)

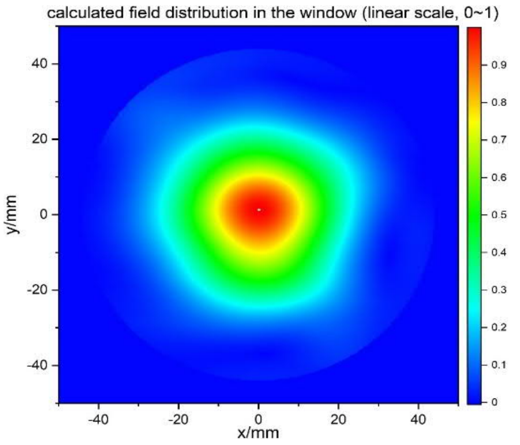

Fig. 2: Results of the field distribution at the outptut window with the quasi-optical converter new design for the $TE_{-20,8}$ mode for theWEST gyrotron.

The gyrotron and MOU procurement contract was signed with THALES in December 2021. The Factory Acceptance Test (FAT) of the first gyrotron is expected in March 2023, with a delivery of the first gyrotron and its MOU in April and May 2023 respectively.

2.1.2 MOU

The MOU is part of the THALES contract. The RF optical design (number, shape and position of the mirrors) was conducted by the Swiss Plasma Center (SPC), whereas THALES is responsible for the technical design and the manufacture. It consists in one tiltable mirror which can compensate for a possible microwave beam misalignment and a second fixed mirror that focusses the beam at the 63.5 mm corrugated waveguide input. All the MOU components are water cooled to be compatible with the 1MW/1000s requirement.

2.2 RF load

Due to the space allocated to the WEST ECRH transmission line, it was decided to install one RF load for the three gyrotrons with a succession of RF switches. (see figure 7).

The RF load (see Table 3) has been designed by Calabazas Creek Research (CCR) [6] and the contract was signed in February 2022. The RF input is adapted to the 63.5 mm corrugated input transmission line and a mitre mirror is optimized to focus the beam on a revolving reflector. The size of the load is ~1.8 m high and ~0.9 m large including the supporting structure.

The fabrication is on-going and the delivery of the load is expected to be delivered in October 2022.

Table 3. RF load specifications

Parameter	**Value**
Operating frequency	105 ±10 GHz
Peak power	1.5 MW
Pulse duration	1000s
Nominal reflected power (HE_{11} mode)	<1%
Polarization	Compatible with various linear polarization
Pressure level after conditioning	< 10^{-4} Pa

2.3 Cryogen free superconducting magnets

During the RF design of the gyrotron, the magnetic field profile was provided by KIT.

The strategy to mitigate risks, to avoid over-costs, and optimize the schedule lead, as for the gyrotons, to the selection of the design close those of the SCM used at W7-X and at the SPC in Lausanne.

The contract for three units and their power supplies was signed with Cryomagnetics in February 2022 and the first SCM is expected to be delivered in March 2023 (see Figure 8).

3. Modifications of Tore Supra EC system for WEST

The EC WEST project, launched in 2021, due to an aggressive schedule and cost saving requirements, it is necessary to re-use as many components of the previous 118 GHz EC System as possible.

3.1 HVPS system

3.1.1 Cathode High Voltage Power Supply

The existing Main High Voltage Power Supply (MHVPS) is adapted to the gyrotron requirements. Nevertheless, the gyrotron RF design has been driven by the MHVPS nominal specifications.

Two HVPS are dedicated to the ECRH system with a capability of -65 kV/90 A each. In this configuration, two gyrotrons will be connected to the same HVPS, limiting the maximum beam current to 45A per unit. Each HVPS in series with a regulator using a tetrode constitute the system called the MHVPS. The regulator is acting to limit the ripple of the cathode voltage and to protect the gyrotron in case of arcing. In this configuration the cathode voltage cannot exceed -55 kV. The modified MHVPS results are shown in Table 4.

Table 4. Results of tests on load of the WEST MHVPS

Parameter	**Value**
Maximum voltage	-55 kV
Maximum current	90A
Ramp up (0 to -55kV)	3 ms
Ramp down (-55kV to 0)	100 µs
Cathode voltage shut off (arc)	13 µs
Ripple at 55kV	330V (0.6%)

3.1.2 Body High Voltage Power Supply

The gyrotron will be equipped with a depressed collector to increase the efficiency and limit the collector power loading.

In order to start with the gyrotron commissioning as soon as possible, the technical concept is to associate a Technix power supply available on the market (35kV/143 mA) with a crow bar (CB) to protect the gyrotron in case of arcs with a time response < 10 µs. The CB is developed by JEMA company. In this configuration it could be difficult to modulate the BHVPS (also the MHVPS) as the time responses of both BHVPS and MHVPS are in the range of 5 ms. The CB will only act as a protection system to shut off the BHVPS in case of arcs. The MHVPS and BHVPS arrangement is shown in figure 3.

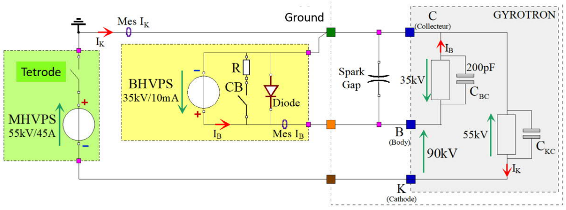

Fig. 3: MHVPS on the left-hand side (WEST HVPS system associated with the tetrode) in green. In the yellow part, the BHVPS system composed of a Technix power supply (+35 kV/143 mA) and a CB to shut-off the body voltage with a response time < 10 µs.

3.2 Launcher

Tore Supra was equipped with an equatorial ECRH launcher with six fixed mirrors (M1) and three steerable mirrors (M2) [4], all actively cooled and capable of handling 400 kW/210s (see figure 4). The M1 shape was originally optimized for a frequency of 118 GHz. In addition to the water cooled mirrors, six non-actively cooled stainless steel corrugated waveguides are also part of the In Vessel components, and the launcher structure is in direct view of the plasma.

Because of the aggressive schedule of the project, the first gyrotron will start operation in WEST experiments with the existing Tore Supra launcher. For this purpose the modifications with this extisting launcher are minimized: the mirrors are not modified, the stainless steel waveguides are not water cooled and the launcher front face is not protected from plasma loading.

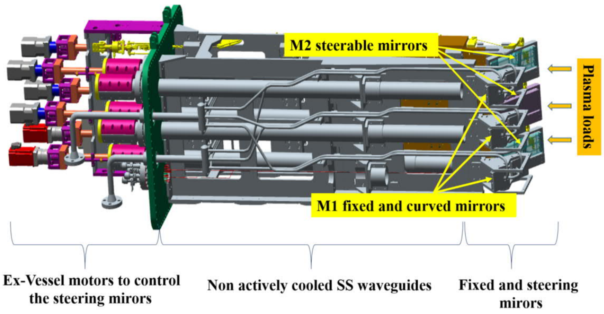

Fig 4. General view of the existing EC launcher

With the objective to re-use the previous launcher for first EC experiment, a thermal and thermal-structural analysis in the WEST configuration has been carried out with ANSYS 2021R2. The goal was to assess if this launcher can be used at 105 GHz, with the original curvature of the fixed mirror M1, and sustain both thermal loads from plasma radiation and EC power. Extensive thermo-mechanical analyses with ANSYS simulations have been performed on all launcher components with two models.

The first simulations were focussed on the thermal structural analysis of the mirrors which are actively cooled but nevertheless limited by the incident ECRH power. The mirrors are made of pure cooper assembled on actively cooled stainless steel heat sink thanks to explosion welding. For the simulations, the launcher working conditions are taken into account with an inlet temperature water of 100°C, 3.3 MPa of pressure, and flow rates of 0.71 m^3/s for the steerable mirrors and 0.96 m^3/s for the fixed mirrors. The maximum temperature considered in the water cooling loop is 150°C and during the cooling time after each pulse, the bulk temperature goes back down from 150°C to 100°C. The absorbed value in the mirrors taken into account was considered to be 0.3% of the incident power. The peak intensity is higher on mirror M1 (beam is more focused than on M2). To avoid any risks of creep, the temperature is limited on the copper part of the mirror to 400°C. Figure 5 shows the parametric study as a function of the number of possible cycles, pulse duration and the incident ECRH power e.g the launcher can handle 1MW of RF power during 10 s and 1000 cycles (being limited by mirror M1).

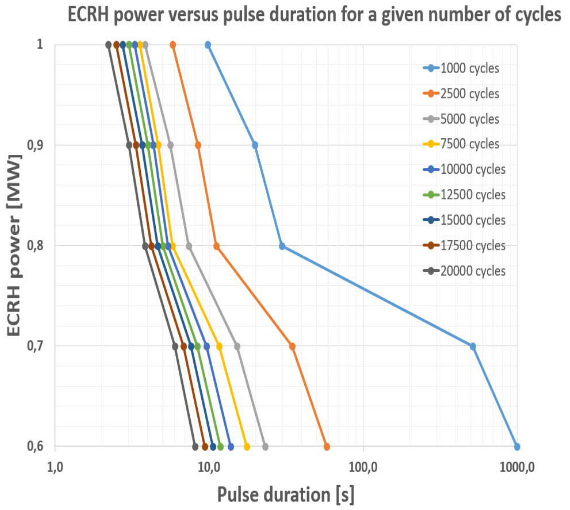

Fig 5. Limitation of the EC launcher per line depending on cycle number, pulse duration and EC power

The second model was focussed on the thermal analysis on non actively cooled mirror supports and limited by the total radiated plasma power. The supports on the launcher mirrors are made of 316L stainless steel and are not hidden from plasma loads. The maximum acceptable temperature of the structure taken into account is 550 °C to prevent creep in the material. The limitations are described in figure 6. The study also revealed that some parts of the existing launcher (bearings for steering mirror movement) needed to be replaced before its installation in WEST, even if the radiated power is limited.

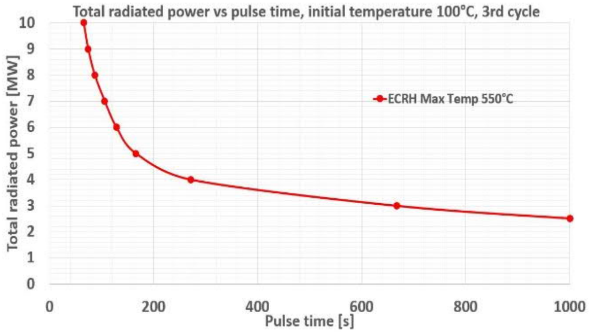

Fig 6. Total radiated power acceptable for the ECRH launcher front face as a function of pulse duration (10MW/65s or 2.5MW/1000s)

The existing launcher will sustain 1MW/10s without major modifications in WEST configuration but for a very limited number of cycles. The existing launcher will be used for the start of the EC system on WEST with some additional diagnostics (see section 4) to assess the loads and check the limits. Following this assessment and a review with EC European experts, the technical solutions, the costs and the schedule to fabricate a new launcher compatible with three 105 GHz 1MW/1000s gyrotrons has been evaluated.

In parallel, the appropriate range of EC wave injection angles for WEST (with ray-tracing REMA code) has been determined and compared with the mechanical launcher limits [7].

3.3 RF transmission line components

The previous ECRH system was equipped with 63.5 mm corrugated waveguides and mitre bends produced by General Atomics (GA). The mitre bend mirrors are water cooled whereas the waveguides are not. Regarding recent findings of the overheating of the transmission lines for long pulse operation [8], it will be necessary to cool down the transmission line components. Some studies are on going to adapt cooling channels to the existing transmission line for the WEST EC system. The transmission line will be re-used as well as the mitre bends and power monitored mitre bends (i.e. with power monitoring feature). The latter will be recalibrated and RF components adapted to 105 GHz will be used. The adaptation of the waveguides to a specific cooling system is on-going.

The transmission line arrangement has been completely redesigned with the new components, and taking into account the differences between the old and new systems:

- three gyrotrons instead of two,
- new interfaces,
- the MOU is not equipped with polarizers, (GA mitre bend polarizers will be installed)
- installation of one load for three gyrotrons.

The transmission lines layout, still subject to small modifications, is shown in figure 7. To have the possibility to use one load for three gyrotrons, remotely controlled RF switches have been ordered to GA in April 2022. The components are expected to be delivered in January 2023.

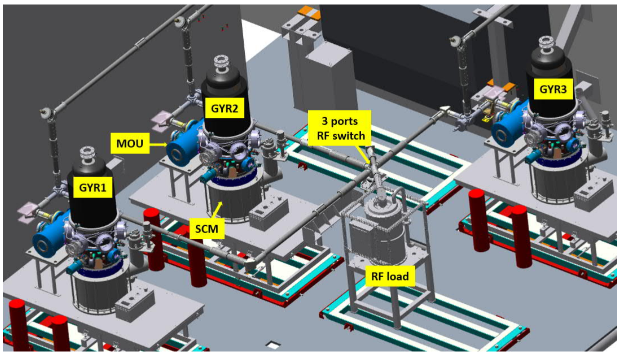

Fig 7. Status of the new WEST ECRH transmitter with three TH1511 new gyrotrons and their MOUs, SCMs, RF loads and the layout of the transmission line

4. Status of the project (September 2022)

The project has been launched in April 2021 and the main contracts have been signed. The schedule of the project is very tight. Nevertheless, the risks, costs and schedule have been mitigated by using proven components and relying on the experience of the EC community.

In parallel to the re-design of the system, an extensive work is on-going with the CODAC: hardware and software must be upgraded to match WEST features and requirements. The vacuum system of the transmission line and the cooling system of the components (gyrotrons, RF load, MOU, transmission line…) is under work. The oil tanks located beneath each gyrotron have undergone a preliminary design phase and the procurement is on going.

Some design work to adapt the new components to the EC installation is still in progress but the main technical choices are validated and contracts are signed.

The Tore Supra launcher is also under modification and tests. The development of the software to pilot the steering mirrors with the right injection angles is in progress and calibrations will be performed in a vacuum tank at the operational temperature (70°C) [9] before its installation on WEST. Some diagnostics (thermocouples) to monitor the temperature of the components (waveguides, mirrors) will be installed to guarantee the safety of the components and validate the simulations.

Finally, another part of the project consists in the modification of the EC installation with respect to the French regulation safety laws in a complex environment (X-rays production, magnetic field, electromagnetic waves, high voltage and high current environment, high microwave power). In addition to manage the modifications necessary to protect both workers and materials, the documentation will be prepared and presented to the safety authority to get a formal authorisation to operate.

A simplified schedule (see figure 8) shows that the first gyrotron could ideally be commissioned in 2023 on load.

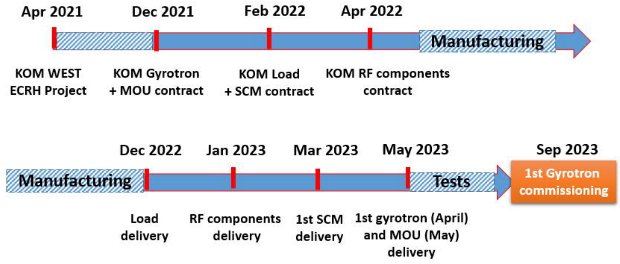

Fig 8. Simplified schedule of the WEST EC project

5. Prospects

The EC system will start plasma operation in 2024 with the first gyrotron and the existing launcher. In parallel to the EC system designed in 2021-2022 (gyrotrons, RF components, generator implantation and existing launcher), some studies are foreseen to fabricate a 3MW/1000s launcher with the fixed curved mirrors designed for 105 GHz, fully compatible with the gyrotron specifications and able to sustain the plasma loads.The schedule to operate the 2nd and 3rd gyrotron and the installation of a new launcher will be optimized with respect to the experimental WEST schedule and the ressources allocated to the project.

Acknowledgements

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References

[1] A C C Sips et al., *Plasma Phys. Control. Fusion* **50** (2008) 124028 https://doi.org/10.1088/0741-3335/50/12/124028

[2] J. Bucalossi et al., *Nucl. Fusion* **62**, 042007 (2022). https://doi.org/10.1088/1741-4326/ac2525

[3] K.A. Avramidis et al, Towards a 1.5 MW, 140 GHz gyrotron for the upgraded ECRH system at W7-X, *Fusion Eng. Des.* **164** (2021) 112173. https://doi.org/10.1016/j.fusengdes.2020.112173

[4] C. Darbos et al, The 118-GHz Electon Cyclotron Heating System on Tore Supra, *Fusion Eng. Des.* **56.** https://doi.org/10.13182/FST09-A9174

[5] S. Illy, et al.Optimized vertical collector sweeping for high power CW gyrotrons using advanced current waveforms, *43rd International Conference on Infrared*, Millimeter and Terahertz Waves, 9-14 September 2018, Nagoya, Japan (2018)

[6] L.Ives et al, 1.5 MW CW RF loads for Gyrotrons, *21st joint workshop on electron cyclotron emission (ECE) and electron cyclotron resonance heating (ECRH),* 20-24 june 2022

[7] T. Fonghetti et al, Operational domain for the new 3MW/1000s ECRH System on WEST, *21st joint workshop on electron cyclotron emission (ECE) and electron cyclotron resonance heating (ECRH),* 20-24 june 2022

[8] T.Kobayashi et al, High power experiment and heat load evaluation of transmission line for the ECH/CD system in JT-60SA, *Fusion Eng. Des.* **175** (2022) 113009. https://doi.org/10.1016/j.fusengdes.2022.113009

[9] J.M.Bernard et al, New High Power CW Test Facilities for ITER ICRH components testing, *AIP Conf. Proc.* 1406, **49** (2011). https://doi.org/10.1063/1.3664926