EPJ Web of Conferences **147**, 04001 (2017) DOI: 10.1051/epjconf/201714704001
EC-19

Summary of papers on technology

Burkhard Plaum[1,*]

[1]Institut für Grenzflächenverfahrenstechnik und Plasmatechnologie, Universität Stuttgart, D-70569 Stuttgart, Germany

Abstract. The contributions on technology are summarized.

1 Gyrotrons

Gyrotron development was with 15 submitted abstracts the largest technology topic on the workshop, which shows that the microwave tubes are still the most challenging components in all EC heating systems.

The development status of the Russian ITER gyrotron was reported by D. Denisov. The Russian tube produces 0.96 MW at the MOU output at ITER relevant pulse lengths (up to 3600 s). Another series of gyrotrons developed by the Russian Gycom company for frequencies in the range of 105 GHz to 140 GHz was presented by E.M. Tai.

The European ITER gyrotron status was reported by G. Gantenbein. After successful tests with a short pulse tube, a 1MW CW prototype was built and tests started in the beginning of 2016.

J. Jelonnek presented the design status for a European 240 GHz coaxial cavity gyrotron for Demo. Several topics, like frequency step tunability and a multistage depressed collector were discussed.

A proposal of mode selection criteria for a 255 GHz gyrotron for the Korea demonstration power plant (KDEMO) was discussed by A. Sawant. The power will be > 1 MW with a conventional cavity operating at the $TE_{55,13}$ mode.

Numerous presentations came from IPR colleagues about the domestic gyrotron development in India. NK. Singh gave an overview of the 42 GHz, 200 kW Gyrotron, which is developed by IPR for use at the Tokamaks SST1 and ADITYA. The development of an anode modulator power supply (AMPS) with a crowbar protection system for 82.6 and 42 GHz gyrotrons was reported by N. Rajanbabu.

An overview of the ITER-India EC RF source package was given by S.L. Rao. It consists of the delivery of two 1 MW/3600 s gyrotron tubes operating at 170 GHZ. It also includes the development of a Gyrotron test facility (IIGTF).

The IIGTF was presented by V. Rathod. It includes power supplies, a crowbar protection system, a dummy load, beam diagnostic systems and cooling systems.

S. Dilip reported on the prototype development of the body power supply for the IIGTF. It has the capability to modulate the cathode and body potentials simultaneously and will be realized using cost-effective high voltage solid state switches. A. Sharma presented the RF Beam diagnostics for the IIGTF. It uses thermography with an IR camera and a software module to retrieve the phase of the output beam. These data are used to characterize the output beam of the gyrotron in order to minimize the spurious modes in the transmission line.

An overview of the local control unit for the IIGTF was presented by R. Shah. The prototype of the LCU will have programmable controllers, which will allow the gyrotron operation through a graphical user interface (GUI). In the final version, the software will be compatible with the ITER CODAC core system (CCS).

In conclusion of the gyrotron related contributions, it can be said, that one problem is the fact, that there is no series production of fusion relevant high-power/high-frequency gyrotrons. This is mostly because the frequencies (which are defined by the magnetic field), are always increasing. This implies the need for higher order cavity modes, which have increased requirements for the internal mode converter and might be sensitive to mode competition.

Also, the supporting technologies like power supplies, crowbars and control systems need to be constantly adapted for the changing requirements. Thus, they are often developed in-house by the fusion research institutes.

One suggestion to work towards a series production and better competition among manufacturers would be to standardize the parameters, most notably the frequencies of gyrotrons. This would imply non-optimal frequencies in some cases (along with decreased heating efficiency) while the advantage would, in the long term, be reduced prices and improved reliability of the tubes. Considering the current experiments, one can already see a tendency into this direction, since 105, 140 and 170 GHz are already used by more than one fusion experiment.

Another topic is frequency tunability. Challenges here are the design of broadband windows (e.g. Brewster windows) and the dependence of the output power on the frequency. Finally, for Demo it will be necessary to increase the efficiency beyond the 50%, which are typically achieved today. Thus, advanced depressed collector configurations will remain an important issue.

* Corresponding author: plaum@igvp.uni-stuttgart.de

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2 Launchers

Another important topic was the development of ECRH launchers. There are two competing technologies: A front steering launcher has movable mirrors close to the plasma. One example is the upper ECRH launcher for ITER, which was presented by D. Strauß. It is designed by a European consortium and will allow to use 8 beamlines with 1 MW each for MHD control. In total, 4 upper launchers are foreseen. It was stated, that the main design issues are mostly on the administrational level from the ITER side, which makes the launcher design a *moving target*. Another presentation was given by H. Mistry about an ECRH launcher for the SST-1 tokamak at IPR, which operates at 42 and 82.6 GHz and has a steering range of ±20°.

The other option is the remote steering launcher, which uses a waveguide with imaging properties and has the steering mechanism several meters away from the plasma. One remote steering antenna is developed for Wendelstein 7-X and was presented by C. Lechte.

While remote steering launchers have clear advantages, especially in reactor-like conditions or if space is limited, the disadvantage is the limited steering range.

3 Complete systems

An overview of the conceptual design of the Demo EC system was presented by S. Garavaglia. The Demo reactor will, in comparison with ITER, require higher power at higher frequencies. The requirements regarding the flexibility are, however, less strict since Demo will be a fusion reactor prototype. Starting with the baseline design “EU DEMO1 2015”, the requirements for the EC system are a power of 50 MW at 170 and 204 GHz. The power per tube is 2 MW and the reference efficiency is 60%. For the launcher, only the remote steering type (see Section 2) and the open ended waveguide (without any steering) were discussed. Calculations of the current drive efficiency with the TORBEAM code were discussed as well as the impact on the tritium breeding ratio. For the transmission line, an evacuated quasi-optical line was suggested and different configurations were investigated with respect to the system reliability.

J.H. Jeong presented the development status and plan of the KSTAR ECH system in Korea. In addition to the systems running at 84 and 110 GHz (short pulse) and 170 GHz (cw), a new system, which will deliver 3 MW at 105 and 140 GHz will be installed. The presentation included an overview as well as a description of the power supplies.

4 Other Topics

The issue of stray radiation in plasma vessels was discussed by J. Osterbeek. The radiation consists mainly of non-absorbed ECRH beams, which become an isotropic radiation background after many wall reflections. The second source is the synchrotron radiation of the plasma itself, which becomes important at high electron temperatures. The unwanted effects of stray radiation are heating of components and potential damage of sensitive diagnostic elements. After an introduction to the topic, the bolometers, which will be used as stray radiation monitors in ITER, were presented.

The design of external mode converters for the Indian 42 GHz gyrotron was presented by K. Sathyanarayana. The gyrotron outputs a TE_{03} mode, while at the output of the converter chain, the HE_{11} mode is required. First, the TE_{03} mode is converted to a TE_{02} and then to a TE_{01} mode. These converters change only the radial indices of the modes, and are therefore rotational symmetric structures with a varying diameter. The TE_{01} mode in the smooth wall waveguide is degenerate with the TM_{11} mode, and the azimuthal indices differ by one. This means, that the TE_{01} mode will be fully converted to the TM_{11} mode in a bend with a constant curvature after certain angle. The $TM_{11} \rightarrow HE_{11}$ conversion is done by increasing the corrugation depth continuously from zero to $\lambda/4$. While such oversized converters have been designed for many years, they required dedicated computer codes, which calculated the mode conversion. Full-wave solvers could not be used for 3D structures, which have dimensions of many wavelengths. However, today it is possible to design such oversized components with a commercial general purpose tool.

Diagnostic components for ECRH systems also need to be adapted to the changing requirements, most notably higher power, longer pulse lengths and two (or more) frequency operation. B. Plaum presented a number of different developments from this area. Different coupler techniques, which are necessary for power monitoring, were extended for operation at 105 and 140 GHz in ASDEX-Upgrade. Grating couplers for quasi-optical systems were discussed as well as hole couplers, which can be integrated into mitre bends of waveguide transmission lines. Special arrangements of hole couplers can, together with a suitable signal analysis, used as simple detectors for spurious modes. Also, a 1 MW calorimetric dummy load was presented, which works reliably under atmospheric pressure.

The experimental verification of Gaussian beam coupling into HE_{11} transmission lines at 400 GHz was reported by M.S. Choe. Although the coupling of Gaussian beams into waveguides is established technology, the significantly higher frequency implies stricter requirements for the machining accuracy and the measurement equipment. The measured results are in good agreement with Surf3D simulations, which were used to design the coupling mirror.

A report on the instrumentation and control system architecture for the ECRH system for the tokamak SST-1 was given by H. Patel. The developments include a two level interlock system with fail-safe logic where slow signals in millisecond scales are processed by software, while hardware interlocks operate on microsecond timescales.