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G. Bodnár[1], S. Bató[1], S. Zoletnik[1], D.I. Réfy[1], M. Brix[2], R. Gomes[3]
and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]Wigner RCP, RMI, Konkoly Thege 29-33, Budapest, Hungary
[2]Euratom/CCFE Fusion Association, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK
[3]Instituto de Plasmas e Fusao Nuclear, Instituto Superior Técnico, Universidade de Lisboa, 1049-001, Lisbon, Portugal
** See annex of F. Romanelli et al, "Overview of JET Results", (24th IAEA Fusion Energy Conference, San Diego, USA (2012)).*

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ABSTRACT

Beam Emission Spectroscopy (BES) is an important method of fusion diagnostic technology. One version of it is the Lithium BES which is widely used for edge plasma density profile and turbulence measurements. Time resolution of the diagnostic is limited by the lithium beam emission and thus the beam current, therefore developments are necessary to improve the beam current.

In 2013, an upgrade of the JET Lithium-Beam injector has taken place. On step of the upgrade was to replace the ion source with a new carbon disk heating type in order to provide longer lifecycle and more extracted ion current with appropiate focusing. The new source needs higher heating power which causes high temperatures in the high voltage, vacuum system environment, and affects stability. The main aim of this paper is to show a mechanical engeneering solution for the increased heating power dissipation in such environment by active cooling elements.

1. INTRODUCTION [1, 3]

The Lithium Beam Emission Spectroscopy (Li-BES) beam diagnostic rates the electronically accelerated alkali beam diagnostics class. This type of plasma diagnostics can simultaneously provide information about electron density profiles, density fluctuations with the help of interaction between the plasma and the injected atomic beam. The ions extracted from a heated ion source and accelerated as well by static electric field produced by two stage ion optics. The ions have to be neutralized to avoid deflection by high magnetic field. The beam atoms collide with the plasma particles, which, among others, excite the valence electrons of the beam atoms. The Li(2p) state emission via de-excitation [4] can be observed by specialized detectors through an optical system. CCD cameras are generally used for low time resolution (~ 10ms) density measurements, while APD (Avalanche Photo Diode) and PMT (Photo Multiplier Tube) detectors are used for fluctuation and fast measurements (~1us).

An upgrade of the KY6 Neutral Li-beam diagnostic took place in 2013, in collaboration between the Wigner Research Centre for Physics (Wigner RCP) and Culham Centre for Fusion Energy (CCFE). It was formulated in the framework of the project that the ion current and the reliability of the recent ion gun was relatively low, and the increase of the beam current is essential to reach the needed performance.

First experiments with a new type of ion source were performed in 2007. During these tests it has been observed that, with the original 13 mm diameter ion source, the maximal extracted current could be 4-5mA. Increasing the surface by a factor of 2 the current could rise even up to 8–10mA.

However, increasing the beam current emitted by the ion source alone is not sufficient, but focusing of the beam to a distance of approximately 4m from the emitting surface -plasma distance- should also be considered. Although a double surface (19 mm diameter) emitter has been already tested in laboratory in 2011. It was found that the beam FWHM diameter at the plasma distance cannot be reduced below 3 cm. Concerns were raised that due to the large observation angle [5] on JET this wider beam would reduce the final spatial resolution achievable with the system, therefore development of a 13 mm diameter ion source was done. Laboratory tests with this ion source were concluded in 2013. They have shown that a 2 cm FWHM ion beam can be formed at the distance of the plasma. As it was shown earlier [1] the neutralized beam has similar diameter. The accelerator system of the beam was kept the same as the original JET Li-beam design, the major development is the new ion source. However, the source technology is substantially different from the original one, which required modifications in the injector system.

2. OVERVIEW OF THE LI-BEAM SYSTEM

The original KY6 Li-beam setup consists of a typically 33keV [5] energy neutral Li-beam injector located on the top of JET tokamak. It shoots vertically down and the beam light is observed through a metal first mirror located behind limiters in the Scrape-Off layer. Light is transmitted through lenses and a set of optical fibers to the diagnostic hall where it is detected by a CCD camera behind a spectrometer and an Avalanche Photodiode array camera (APDCAM) behind interference filter.

The Li-beam injector is a version of the original ASDEX Lithium beam design [2]. It consists of a thermionic ion source sitting at a Pierce electrode. The ions are accelerated by two additional electrodes and finally neutralized by a sodium vapor cell.

2.1. THE ION-OPTIC IN DETAILS

The thermal source material of the beam is located in Pierce electrode which is the first part of the ion-optic and connected to high voltage of 50–60kV -main voltage. The ions are extracted from the source using an extractor electrode connected to typically 10% lower voltage. The ion current highly depends on the diffusion ability of the emission material and a physical law (Child-Langmuir law) which limits the current via space charge of the ions. The third part of the optic is connected to the ground and can accelerate the ions to the required energy. The so-called deflector plates located after the accelerator electrode, and can provide the possibility of 2 dimensional aiming in plasma; in the original arrangement the KY6 included only one pair of them. [5] On the picture below (Figure 1) the section of the ion-optic is illustrated. The power supply is connected through a CF63 electronic vacuum feedthrough flange. On this stainless steel flange a four-leg mount hang in order to maintain an appropriate distance between the Pierce and the pulling electrode. On the vacuum side of the two feedthroughs copper current connectors are located which ensure the contact with the source. Ceramic disks were used to isolate the elements from each other inside the vacuum.

Aluminum alloys with high Mn or Zn concentration cannot be applied in high vacuum and high temperature environment since their evaporation degrades the vacuum.

The high voltage parts are separated from the ground potential with the help of the main ceramic insulator.

3. OVERVIEW OF THE DEVELOPMENT

A so-called Faraday Cup (FC) is located at the end of the flying tube. By measuring the currents between certain parts of the FC the beam current can be calculated.

With the help of a replica beam, located in the IPP-Garching laboratory, the larger diameter emitter (19mm) tests were performed. During these experiments the presence of less than 1mA current could be measured in spite of the fact that the theoretical value is 10mA with 6mAh capacity. Consequently, approximately 80% of the extracted ions were not be able to enter into the 40mm diameter aperture of the FC which represents the measurement area in the plasma.

While the application of this larger emitter was uneconomical, experiments were started with a new emitter type complex expecting higher efficiency.

In 2012 May in Garching tests were performed with a smaller emitter type (13mm diameter). This type had already been used at COMPASS but it exhausted due to the extensive operation. In that case a sufficient, 2mA current presence could be generated but due to HV problems this value could be reached just on 40kV. During the Garching measurements the extractable ion- current value was 5-5,5mA at an increased 370W heating power, which resulted an amount of 2–3mA on the Faraday-Cup.

To reach higher ion current it has become necessary to increase the heating power by applying a secondary transformer which was able to provide 60–80A instead of the original 33A.

The increased heating power, the closed magnetic shielding around the ion gun and the small area of the heat transfer surfaces result in a much higher temperature environment around the system, which decreases high-voltage stability. The solution was a controllable, active air-cooling system arrangement which utilize pressurized air network present at the tokamak hall.

4. SOLUTIONS

To satisfy the above mentioned requirements the following changes were necessary:

- new emitter complex in order to reach the appropriate ion-current
- secondary transformer to convert the value of heating current from 33A to 60–80A
- heat transfer surfaces and heat sinks of the largest possible size for cooling the parts located on the HV potential
- active sucking-blowing system to flow the fresh air and to ensure the required mass flow to keep the temperature in the safe range
- an extension ring located between the main cylinder and the top plate of the magnetic shield to position the elements of the cooling system and furthermore to ensure the required shielding

4.1. NEW PIERCE COMPLEX

On the illustration below (Figure 2) the arrangement of the Pierce electrode is shown. The Pierce electrode consists of two main parts. The top (1) and the bottom (2) part those are made of stainless steel and are assembled by screws to each other (3) which are ensured against rotating. The emitter surface temperature can reach 1380 degrees Celsius thus the top Pierce includes a Niobium (4) part to withstand high heat load.

The heating current goes to the CFC heat mushroom (5) through a Wolfram heat wire (6). The heat transfer connection between the Molybdenum cup (8) which includes the emitting material and the heating body is provided by a SiC disk (7). Due to the high heat load Al_2O_3 disks (9) and cylinders- ability of electronically insulation and high melt point- are placed around the heat source.

The thermal expansion plays a significant role thus the connections between the parts are designed with loose fits.

4.2. SECONDARY TRANSFORMER

As a consequence of the potential difference between the transformer on HV potential and its surrounding parts on ground potential the risk of electrical discharges have increased. The transformer was installed in a special resin material on a four-leg transformer plate the way, that the CF63 flange feedthroughs are going through the hole of the transformer in the middle (Figure 3) For the electric connection of the feedthroughs a cable with appropriate cross-section and 100A fuse was used.

4.3. ACTIVE COOLING SYSTEM

While the high magnetic field surrounding the tokamaks can damage electronic devices, it was necessary to develop such cooling system which could operate with the provided pressurized air supply and ensure the required mass flow with an acceptable noise level.

Utilizing the principle of the Coanda effect, (see Figure 4.) with the help of a so-called air amplifier (manufactured by HMC BRAUER LTD) the volume flow rate of the input can be increased even tenfold.

On the input line one of the previously mentioned air amplifier was attached in order to blow the fresh air into the closed sphere. The selected type could multiple the inlet volume flow 5–5.5$\frac{l}{s}$ at 2.76bar to approximately 83$\frac{l}{s}$ on the outlet. The air-flowing was directed to the cooled surfaces by a tube system including Polyamid and Polyethylene parts to avoid electronic discharges. These pipes direct environment temperature (~ 20°C) fresh air to the critical surfaces.

A second Coanda nozzle was placed on the outlet, in the opposite direction, (Figure 4) to ensure the removal of heated up air, and the continuous air circulation.

To accommodate the amplifiers an extension ring was developed, paying attention to magnetic shielding and discharges. The nearest point of the shield could be placed at a distance of minimum 130mm from the HV potential parts (Figure 5)

To monitor the continuous air flow, a pressure switch was attached into the high pressure line which gives an alarm for the operator if the cooling stops. The output air temperature is monitored as well for the same reason.

4.4. HEAT TRANSFER SURFACES MODIFICATION

The dissipation of the doubled heating power requires as large as possible heat transfer surfaces. A cylinder shaped heat sink was designed, manufactured and installed on the high voltage side of the main ceramic isolator, made of aluminum with good heat conductivity (Figure 3). The tests showed that the horizontal top part of the heat sink reached highest temperature, wherefore an additional horizontal heat sink had to be attached. Thermal paste was used between the surfaces to provide good heat contact.

Zirconium bronze parts were brazed directly to the feedthroughs (see Figure 1.) on which two longitudinal heat sink cylinder can be fixed by threaded contact.

5. TESTS BEFORE INSTALLATION

The beam and heating tests were performed at the Wigner RCP, on the JET Li-BES prototype system. All afore-mentioned parts had to be tested prior the installation at JET. The heat sinks, cooling tubes, Coanda nozzles were attached, and the heating was driven by an adjustable 230V/12V transformer (Variac).

Temperature measurement positions can be seen in Figure 4. Table 1 shows the measured temperatures at different times during the heating. From the temperature values one can conclude on which surface reaches highest temperature and needs higher efficiency cooling.

After 6 hours of heating, the equilibrium emitter temperature was 1370°C at 290W heating power. The highest temperature values were detected at points VIII and IX, where the flowing air was hindered by the toroid. It has to be emphasized, that even these locations temperature did not raised above 75°C which is within the operation limits.

6. FIRST TESTS ON JET

As long as JET and the laboratory environments are not identical, we had to face difficulties after installation on JET. High voltage instabilities, e.g. discharges and the leakage of the HV isolators were observed which might correspond to insufficient cooling, which is probably caused by low input mass flow levels from the JET pressurized air supply. We came to this conclusion taking the following considerations.

In case of the previous arrangement at 200W heating power in thermal equilibrium the beam was in stable state without any additional active cooling system. Since as it was mentioned above the heating power was increased by a factor two thus the temperature increase plays significant role.

The air amplifier is capable of producing 80 l/s volume flow on the output with 5–6l/s, 3 bar pressure air on the input. Measuring both the input (21°C) and the output air temperatures (37°C) the air temperature change was found to be 16°. In thermal equilibrium, assuming that the 300W heating power is dissipated only by the air cooling, one can calculate, that the air flow is maximum ~ 15l/s, which is an over estimation of reality, as long as the heat can be dissipated through thermal radiation as well. This shows that the pressurized air supply has to be improved.

CONCLUSIONS

The engineering integration of a new type emitter complex into JET Li-BES system was supported by the Wigner RCP. This paper mainly focused on the realization of the increased heating power and handling its consequences. An active cooling system was developed, designed, tested and integrated into the JET environment.

The laboratory tests in Wigner RCP demonstrated that the increased heating current and power of the new emitter complex can be satisfied by the secondary transformer. The new cooling system can produce the appropriate mass flow to keep the temperature values in a safe operation range. The increased heating power could be handled.

ACKNOWLEDGEMENTS

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	I	II	III	IV	V	VI	VII	VIII	IX
Time	[°C]								
13:50	40	32	32	31	41	47	66	57	75
15:20	45	34	35	30	40	41	46	50	54
15:42	44	38	30	31	43	47	52	61	67
16:25	53	39	35	34	51	49	51	56	58
16:55	56	39	38	30	50	47	45	60	57
17:55	47	36	32	30	45	49	48	60	59
18:55	49	40	32	30	47	58	54	69	66
19:15	51	40	36	30	49	58	51	62	68

Table 1: Temperature values for each points during the heating, measured at different times.

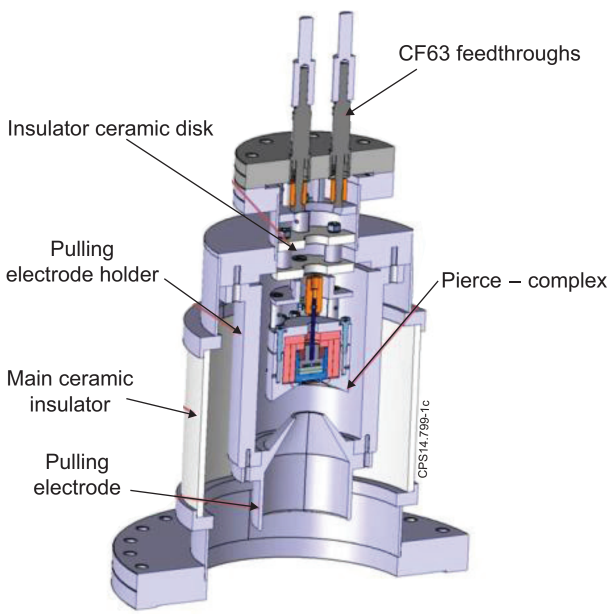

Figure 1: Ion-source and its environments.

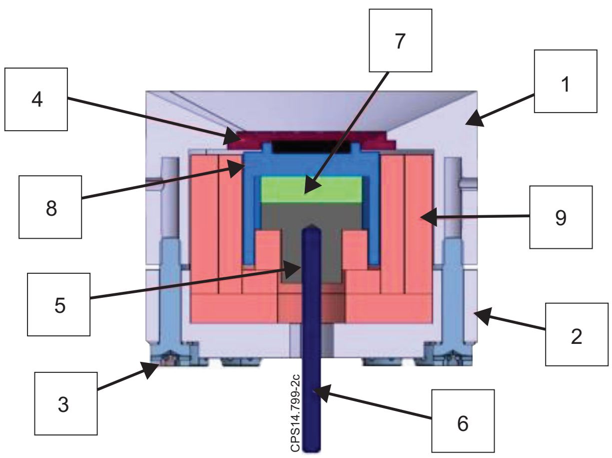

Figure 2: Pierce complex.

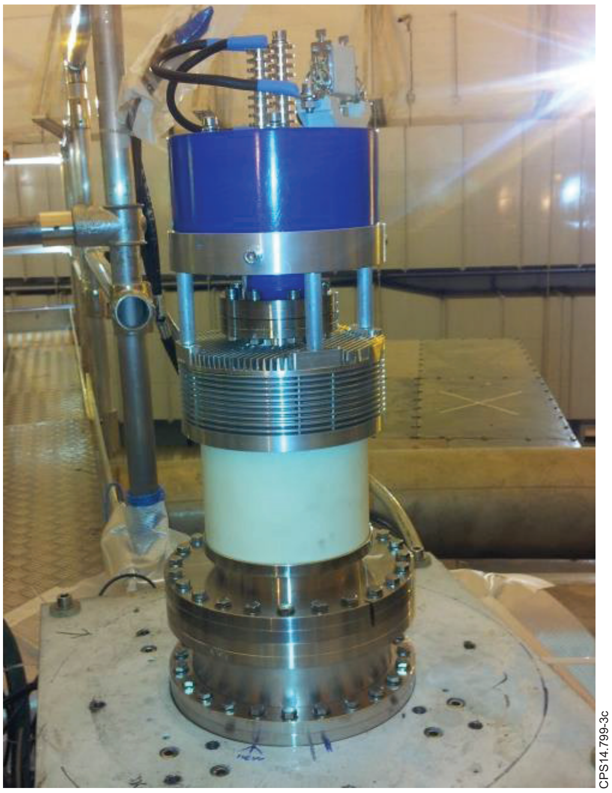

Figure 3: Secondary transformer in resin with heat sinks for efficient cooling after installation.

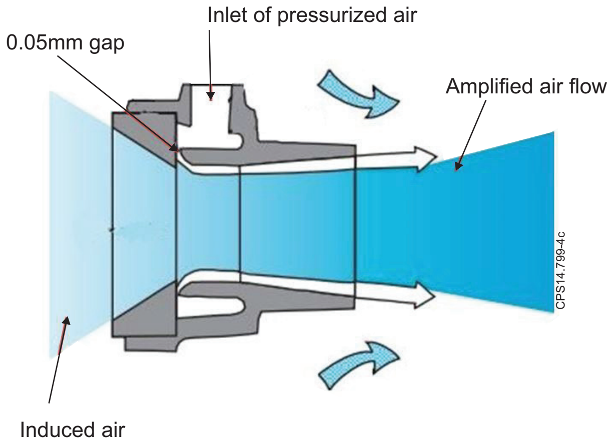

Figure 4: Air amplifier and the Coanda effect.

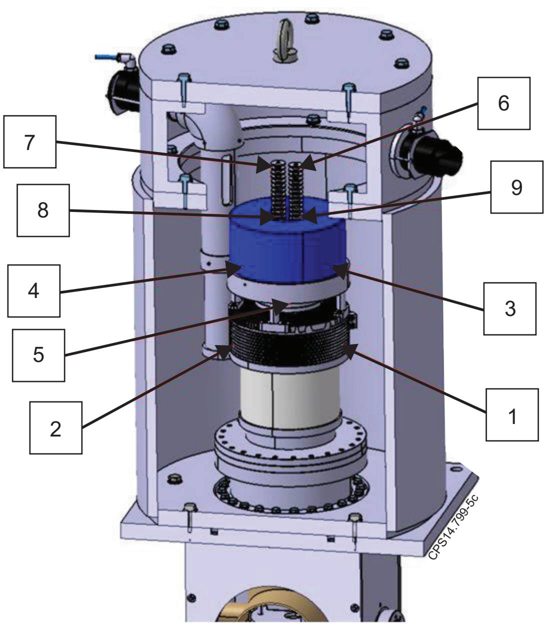

Figure 5: Cooling inside the magnetic shield.