High Heat Flux Testing of components for future fusion devices by means of the facility JUDITH 2

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First wall elements of future fusion reactors like ITER or DEMO will suffer extremely high heat fluxes of up to 20 MW/m^2. In order to assure the performance of these components, electron beam facilities are applied to simulate these high heat loads. The electron beam facility JUDITH 2, located in Forschungszentrum Jülich (FZJ), consists of a powerful electron beam gun (VON ARDENNE-EB-gun), a process chamber with vacuum system, a water cooling circuit (T = 20°C – 100°C) and sophisticated diagnostics. The maximum JUDITH 2 electron beam power is 200 kW at an acceleration voltage between 40 and 60 kV.

This paper presents a summary of characterisation work, concerning beam generation, beam diameter diagnostic, beam scanning methods, calibration techniques and other diagnostics. The generation of heating beam patterns is based on freely programmable figures. These figures consist of points with x- and y- coordinates and different dwell times of the beam. With respect to these figure-points the resulting local power density distribution can be calculated under the assumption of a Gaussian beam profile. Finally some examples of electron beam loading experiments in JUDITH 2 facility with different sample geometries as well as different materials are presented.

Keywords: fusion reactor, tungsten, beryllium, electron beam facility, power density, GAUSS distribution, electron beam diameter, FWHM

1. Introduction

Beryllium, carbon reinforced carbon (CFC) and tungsten alloys will be used as plasma facing materials (PFM) in ITER. Due to its promising material properties, e.g. the good plasma compatibility, relative high thermal conductivity, low atomic number, its high affinity to oxygen as well as the low activation potential, beryllium is foreseen as plasma facing material for the First Wall. However, testing of beryllium components for fusion applications is quite challenging due to its toxicity and the required safety procedures [1]. Beryllium is used for the first wall, the high heat flux components of the divertor will use CFC or W as an armour material. In order to assure the performance under thermal loads at the divertor, high heat flux (HHF) tests are performed for the qualification of W coated tiles and beryllium tile mock-ups. In order to study the armour material combination in a tokamak, the ITER-like Wall (ILW) Project has been launched at JET [2]. In the ILW Project, the JET tokamak will employ tungsten coated CFC tiles for the outer and inner divertor rows. This paper reports demonstration experiments of the qualification tests in the JUDITH 2 facility (**fig. 1**) at FZJ [1, 2, 3] and will give some information about the difficulties during the determination of the electron beam diameter which is an important parameter [4, 5, 7].

2. The electron beam facility JUDITH 2

The electron beam facility JUDITH 2 (**Ju**elich **Di**vertor **T**est Facility in **H**ot Cells, **fig. 1**) is placed in a hot materials laboratory at FZJ and is equipped with a commercial electron beam (EB) generator (high power electron beam gun EH 800 V, VON ARDENNE Anlagentechnik GmbH). This type of EB-gun facility is mainly used for surface heat treatments. The maximum beam power of JUDITH 2 is 200 kW [2, 3, 4].

2.1 Beam gun modes

The acceleration voltage can be adjusted between 40 and 60 kV. The EB-gun of JUDITH 2 has two options of electron beam power regulation. Generally one covers the lower power range up to approx. 30 kW, called TL-mode (**t**emperature **l**imited mode). In the TL-mode the emission of the electrons is controlled by the temperature of the cathode, while the distance of cathode to anode is kept constant. The second mode covers the higher power range between approx. 30 and 200 kW. The high power mode is called SL-mode (**s**pace charge **l**imited mode) [4]. In SL-mode the cathode is kept at maximum temperature. The distance between cathode and anode is labelled d_{ka}. It has been shown by Keusemann [4] that the maximum d_{ka} is reached at 45 mm (45 mm = 100%, position equal to minimum power), while the minimum d_{ka} is close to 15 mm (position equal to maximum power in SL-mode, **tab. 1**). That means in SL-mode the EB power P is proportional to 1/ d_{ka}. The software adjusts the resulting power. In SL-mode the power set points are reached much quicker than in TL-mode. Most tests were done in SL-mode [1, 2].

TL-mode	0 kW to ~30 kW	emission of electrons controlled by temp. of cathode (T_A) with d_{ka} = const., P[kW] is proportional to T_A
SL-mode	~30 kW to 200 kW	P[kW] is proportional to $1/d_{ka}$

Table 1: Composition of possible electron beam gun power modes in JUDITH 2, **TL-mode** = **t**emperature **l**imited mode, **SL-mode** = **s**pace charge **l**imited mode and d_{ka} = distance between cathode and anode.

2.2 Vacuum chamber

The vacuum chamber of JUDITH 2 was produced by TRINOS Vacuum-Systeme GmbH and is of cylindrical shape with 800 mm diameter and a length of 1800 mm (1200 mm + 600 mm extension, **fig. 1**). A double wall cooling system allows the heat caused by reflected electrons to be dissipated (electron absorption of tungsten is approximately 0.55 [5, 6] and the electron absorption of beryllium is approximately 0.95-0.98). The tested materials and components are mounted on a numerically controlled carrier system (x, y cross-table) fixed to the door of the vacuum chamber. The observation window for the IR camera uses CaF_2 windows. Quartz glass was used for the two-colour pyrometer (**tab. 2**).

The JUDITH 2 facility is equipped with several separate cooling loops. The turbo molecular pumps and the EB-gun are cooled by a 2 kW water circuit [3]. With a flow rate of v_1 = 10 m^3/h up to P_1 = 40 kW of thermal heat can be removed from the wall of the JUDITH 2 vacuum chamber [3]. The second experimental "hot cooling" circuit (water temperature 100°C) with a water flow rate of v_2 = 12 m^3/h at 30 bar is designed to remove up to $P_2 \approx$ 150 kW from active cooled test components.

2.3 Electron Beam control

Guidance and other parameters of the beam are controlled by a tool supplied by VON ARDENNE. All important parameters, such as power, percentage of d_{ka}, acceleration voltage and two lens currents (*L*1, *L*2), as well as process parameters of vacuum pumps and valves are monitored on the PC screen. The pressure in different segments of the vacuum chamber can be measured and has also some influence on the EB-diameter [4].

With the special VON ARDENNE software it is possible to define different kinds of patterns, repeated patterns, let the patterns run on a defined path or simply set single points [2].

The generation of heat load patterns is based on freely programmable figures. These figures consist of up to 2600 points with x- and y- coordinates each, the beam dwell time for these points can be defined between 5 µs and 1 ms . Extensive tests were carried out to characterise the EB-diameter (influence of parameters like EB-power (*P*), acceleration voltage (*U*), lens settings ($L1$, $L2$) and vacuum pressure inside different segments of the EB-gun chamber [4]). As a result of these tests the focused EB-diameter can be adjusted between ~2.6 mm (EB power approx. 15 kW) and ~16.7 mm (EB power approx. 130 kW, **fig. 4**) at an acceleration voltage of 50 kV [4]. The power distribution has been calculated under assumption of a GAUSSIAN beam profile [4]. For example during the tests on the W coated CFC tiles (JET) in the JUDITH 2 facility, a defocused EB-diameter has been used [2]. For the tests on European beryllium mock up (**fig. 2**) a more focused beam has been used [1]. Finally some of the important parameters of JUDITH 2 facility are listed in **tab. 2**. A schematic overview of the testing facility JUDITH 2 is given in **fig. 1**.

max. machine power (VON ARDENNE GmbH, Germany)	P = 200 kW (800 kW down scaled version)
acceleration voltage	U = 40, 50, 60 kV
max. EB scanning area	~ 400 mm x ~ 400 mm
distance EB gun to working plane [4]	1789 mm
2 x water cooling systems	25°C and 100°C up to 30 bar (flow rate up to 200 l/min = 12 m^3/h)
beam dwell time (t_{EBLP})	5.0 µs to 1.0 ms
beam figures (2600 points with x-, y-co-ordinates)	single spot, circular beam, line, meander
vacuum chamber (TRINOS GmbH, Germany)	length 1800 mm, diameter 800 mm
IR camera (FLIR Systems GmbH, Germany)	FLIR SC6000, 3 - 5 µm
window IR camera	CaF_2-glas
mirror IR camera inside vacuum chamber (EDMUND Optics GmbH, Germany)	specially coated float glass with enhanced Aluminium, reflectance wave length (> 94%): 4.0 – 7.0 µm
3 normal pumps (PFEIFFER VAKUUM GmbH, Germany)	2 x for VON ARDENNE EB gun, 1 x booster pump for vacuum chamber
main pump: turbo molecular pump (PFEIFFER VAKUUM GmbH, Germany)	time for vacuum level approx. 45 min, vacuum level approx. 10^{-5} mbar
pyrometer no. 1, MAURER	two colour, spectral range 1.4 – 1.75 µm
pyrometer no. 2 (KLEIBER Infrared GmbH, Germany)	Response time 10 µs (type KMGA 740) 350°C - 3500°C, spectral range 2.0 – 2.5 µm
pyrometer windows	quartz glass, transmission approximately 92% for wavelength 0.17 to 3.8 µm

Table 2: Some information of important JUDITH 2 facility features.

3. Electron beam characterisation and the expected power density

3.1 Experimental device of the electron beam diameter determination

The determination of the electron beam diameter (d_{EB}) is difficult and very important for the calculation of the absorbed power densities ($p_{ABSORB.,}$ equation 9). **Fig. 2 a** shows the experimental device for the electron beam diameter determination [4]. The two tungsten and three carbon tiles are fitted into a brass rack with screws to guarantee good thermal conduction. The rack stands on an isolated Al_2O_3 plate (electrical isolator). Nevertheless a good thermal conductivity remove the heat - created by the electron beam on the tiles - to the water cooled copper plate below. The sample holder was grounded over a resistor (R = 10 **Ω**). When the electron beam is moved longitudinal over the five tiles the voltage change depends on electron beam hits a W or a Carbon tile (different absorption coefficients, here 2 x tungsten and 3 x carbon, **fig. 2 a, b**).

Assuming a GAUSSIAN profile for the electron distribution in the beam, a transition from one material to the other will create a change in the absorbed current. This current can be measured in combination with the resistor as a voltage drop $\Delta U = R\ I$ (**fig. 2 b**) and can be monitored on the oscilloscope (here YOKOGAWA DL 9000). The assumption of a GAUSSIAN profile can be done because in the nature the most statistical physical processes underlay GAUSS distributions.

3.2 The GAUSS distribution as basic element for electron beam diameter determination

The three dimensional GAUSS distribution is described by equation (1) and the function is exemplarily plotted with a symmetrical standard deviation of $\sigma_x = \sigma_y = \sigma = 5.0$ mm in **fig. 3 b** [4]. The ideal measured signal (ΔU) is equal with the total integral of the GAUSS distribution which is solved and plotted in **fig. 3 a**.

$$f(x,y) = (2\,\pi\,\sigma_x\,\sigma_y)^{-1}\,\exp\{-\,0.5([(x\text{-}x_0)/\sigma_x]^2 + [(y\text{-}y_0)/\sigma_y]^2)\} \qquad (1)$$

$$\Delta U = \text{measured SIGNAL} \sim F(x,y) = \int_{-\infty}^{+\infty}\int_{x_1(t)}^{x_2(t)} f(x,y)\,dx\,dy \qquad (2)$$

The evaluation of the width of the GAUSSIAN profile is done by a special algorithm that creates a 3-dimensional symmetrical GAUSSIAN profile with a predefined start for σ. Then it integrates over both dimensions and compares the integral with the measured signal (**fig. 2 b**, **fig. 3 a**). If the difference is higher or lower than a predefined tolerance, the algorithm changes the standard deviation σ and iterates again. In order to be able to compare the iterated integral with the real signal (**fig. 3 a**) the algorithm normalizes the measured transition without creating exactly the same values for the plateaus [4].

3.3 Full Width at Half Maximum method (FWHM)

The determination of the electron beam diameter can be done by calculation of the **F**ull **W**idth at **H**alf **M**aximum method (FWHM). Under the assumption of symmetric deviation with $\sigma_x = \sigma_y = \sigma$ and with $x_0 = y_0 = 0$ the maximum of equation (1) is determined as:

$$\text{MAXIMUM of } f(x,y) = f(x,y)_{MAX} = (2\,\pi\,\sigma^2)^{-1} \qquad (3)$$

Now the <u>half maximum</u> of equation 3 is equal to the GAUSS distribution, this means

$$(4\,\pi\,\sigma^2)^{-1} = (2\,\pi\,\sigma^2)^{-1}\,\exp\{-\,0.5([x/\sigma]^2 + [y/\sigma]^2)\} \qquad (4)$$

and logarithmic calculus for both sides in equation (4) leads to

$$\ln[2] = 0.5([x/\sigma]^2 + [y/\sigma]^2)$$

$$2\,\sigma^2\,\ln[2] = x^2 + y^2 = r^2$$

For the radius (r) inside the symmetric GAUSS distribution it is

$$r = \sigma\,\sqrt{2\,\ln[2]}$$

and under the definition that the electron beam diameter (d_{EB}) is equal to the FWHM it can be written:

$$d_{EB} = \mathrm{FWHM} = 2\,r = 2\,\sigma\,\sqrt{2\ln[2]} \qquad (5)$$

and the standard deviation is

$$\sigma = \mathrm{FWHM} \,/\, (2\,\sqrt{2\ln[2]}\,) \qquad (6)$$

One essential point of equation (5) is that the electron beam diameter (d_{EB}) is a function of the standard deviation (σ) and it can be written FWHM = 2.355 σ. The results for two different acceleration voltages (50 and 60 kV) by using the experimental device of **fig. 2 a** and the FWHM method of electron beam diameter calculation are shown in **fig. 3** [4]. As expected, it could be pointed out that increasing electron beam diameter (FWHM) behaviour is proportional to the increasing machine output power (P).

In addition there are same important parameters which influence the beam shape, they are:
1) Distance from electron beam gun to working plane (z-height in the chamber), 2) Magnetic lens currents $L1$ and $L2$ (unit is [%]), 3) Vacuum pressure inside the chamber, 4) Level of accelerating voltage (U) and 5) Output power (P) [4, 5].

A dependency on pressure is especially crucial for the beam width, considering the fact that an optimum for the pressure does exist. An increasing beam diameter occurs due to stronger influence of space charge for decreasing pressure (COULOMB interaction). On the other hand also an increasing beam diameter occurs for increasing pressure based on stronger scattering procedures with gas atoms inside the vacuum chamber [4, 5].

3.4 Expected power densities

As mentioned before the obtained electron beam diameter can be used to calculate the local power density as a function of the radius (r = FWHM / 2) beginning in the centre of the GAUSS distribution via (P = machine output power):

$$p(r) = P\,(2\,\pi\,\sigma^2)^{-1}\,\exp\{-\,r^2/2\,\sigma^2\} \tag{7}$$

Based on equation (7) with the radius against zero the maximum of incident power density in the centre of the GAUSSIAN beam is [5]

$$p(r = 0) = p_{\mathrm{MAX}} = P\,(2\,\pi\,\sigma^2)^{-1} \tag{8}$$

The incident local power density is reduced due to electron reflection that depends on the absorbing material. For the popular plasma facing materials beryllium, carbon and tungsten the absorption coefficients are $\eta_{\mathrm{Be}} \approx 0.95 - 0.98$, $\eta_{\mathrm{C}} \approx 0.97$ and $\eta_{\mathrm{W}} \approx 0.55$ [2, 5, 6]. In consideration of the absorption coefficient and based on equation (8) the absorbed local power density is determined by

$$p_{ABSORB.} = \eta_{\mathrm{i}}\,P\,(2\,\pi\,\sigma^2)^{-1} \tag{9}$$

The decrease of power density to a fraction of the electron beam spot centre peak value (p_{MAX}) is discussed in detail in [5].

In tests of components it is usually not necessary to know the exact electron beam diameter. Here the electron beam loading (EB) is performed by fast EB beam scanning, distributing the energy on an area that is large compared to the approximate beam diameter. In this case the applied power density (p_1) is simply calculated via the machine power (P), loaded area (A_{L}) and absorption coefficient (η_{i}) like (**tab. 3, 4**) [1, 2]:

$$p_1 = \eta_i\,P\,/\,A_{\mathrm{L}} \tag{10}$$

4. Examples of fusion reactor components for testing in JUDITH 2 facility

In the following two examples of testing campaigns in the JUDITH 2 facility are given and as described before the absorbed power density was calculated with equation (10).

In the frame of the ITER like wall project non destructive tests (NDT) with defocused electron beam in the JUDITH 2 facility were performed on 14 µm W/Re coated CFC G7-like tile (benchmark test) with a absorbed power density of 2.86 MW/m^2 (equation 10) for a loading time of 10.2s (2 cycles, 84 kW, defocused EB, **tab. 3, 4**). The surface temperature reached the 800°C level after two loading cycles and cooled down to 200°C in approximately 5 min. An IR camera (**tab. 2**) based emergency switch-off system was used to protect tiles from overheating due to possible machine failure or operating errors [2].

In the second example an actively cooled (100°C, 30 bar) European First Wall beryllium mock up was tested in JUDITH 2 under "steady state" loading conditions (MARFE tests = **M**ultifaceted **A**xisymmetric **R**adiation **f**rom the **E**dge = 1.75 MW/m^2 for 10 s at 1000 cycles, **tab. 3, 4**) [1]. A picture of the European beryllium mock up -manufactured by the CEA Grenoble- is shown in **fig. 5**.

Mock-up type	size A_L [m^2]	heating time t_H [s]	cool-down time Δt[s]	cycle no.	max. temp. T_{MAX} [°C]
Tungsten coating CFC, G7-like, JET	0.0162 (135 x 125 mm^2)	10.2 (10.0 µs)*	30.6	2	800
European beryllium mock up	0.0192 (240 x 80 mm^2)	10.0 (5.0µs)*	90.0	10^3	329 (<555)

Table 3: Two examples of typical mock ups in electron beam facility JUDITH 2 [1, 2], here * is the beam dwell time.

Mock up type	input power P[kW]	input power density p_0 [MW/m²]	absor. coefficient η_i	absorbed power density p_1 [MW/m²]	U [kV]
Tungsten coating CFC, G7-like tile, JET	84.0	5.19	0.55	2.86	50
European beryllium mock up, F4E	35.4	1.84	0.95	1.75	40

Table 4: Two examples of typical mock ups in electron beam facility JUDITH 2 [1, 2].

Failures of the mock ups during JUDITH 2 electron beam loadings are determined by measuring the surface temperatures with an IR camera (**tab. 2**). As shown before an increase in surface temperature above special temperature level over normal is considered possible failures (hot spots).

5. Summary and outlook

A first fundamental method to measure the electron beam profile for high power electron beams is presented in this paper (**fig. 2 a**) [4]. It could be pointed out that the electron beam distribution and thus the power density distribution in an electron beam can be assumed to be in form of a GAUSSIAN profile (**fig. 3 b**). It was shown that the determination of the electron beam diameter can be done by calculation of the Full Width at Half Maximum method (FWHM, **fig. 3 b**, **4**) [4]. The method showed that the beam shape depends on various parameters, namely adjusted machine power (*P*), acceleration voltage (*U*), distance from electron beam gun, magnetic lens currents *L*1 and *L*2 and vacuum pressure.

It has to be said that a new method to measure the profile of high power electron beams has been developed and is taken out to a patent [7]. In contrast to the former first fundamental "milestone" method (**fig. 2 a**, [4]) it is now possible to observe the complete electron beam profile (total integral of GAUSS distribution) "in-situ" very fast. Also possible is visualising the beam shape changes when e. g. changing focusing magnetic lens currents ($L1$, $L2$) or the vacuum level. With the new method [7] it is possible to measure in-situ the sum of 20 electron beam diameters in a time less than a few minutes with a statistical standard deviation of $\sigma^* \approx 0.2$. In addition to the new method [7] combinations of different GAUSS distributions in the same electron beam can be handled. This topic is one object of the actual research.

The first wall quality mock up tests with the powerful electron beam facility JUDITH 2 (**fig. 1**) are part of qualifying process of high heat flux components for ITER and JET (**fig. 5**, **tab. 3, 4**) [1, 2].

Acknowledgement

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6. References

[1] C. Thomser, A. Schmidt, B. Bellin, A. Buerger, J. Linke, M. Roedig, F. Zacchia, High heat flux testing of beryllium components with improved diagnostics, (in press) SOFT 2010.

[2] A. Schmidt et al, First demonstration of non-destructive tests on tungsten- coated JET divertor CFC tiles in electron beam facility JUDITH 2, Phys. Scr. T138 (2009) 014034.

[3] P. Majertus et al, The new electron beam test facility JUDITH 2 for high heat flux experiment on plasma facing components, Fusion Engineering and design 75-79 (2005) 365-369.

[4] S. Keusemann, Feasibility study for the simulation of transient thermal events on plasma facing materials with electron beams, Master thesis, RWTH Aachen, 2008

[5] Th. Loewenhoff, T. Hirai, S. Keusemann, J. Linke, G. Pintsuk, A. Schmidt, Experimental simulation of Edge Localised Modes using focused electron beams - features of a circular load pattern, Journal of Nuclear Materials (in press), 2010.

[6] M. Roedig, W. Kuehnlein, J. Linke, M. Merola, E. Rigal, B. Schedler, E. Visca, Investigation of tungsten alloys as plasma facing materials for the ITER divertor, Fusion Engineering and Design 61-62 (2002) 135-140.

[7] A. Schmidt, A. Buerger, Verfahren und Vorrichtung zur Ermittlung eines Elektronenstrahldurchmessers, applying for a patent (no. 102010025123.2), 25.06.2010.

7. Figures

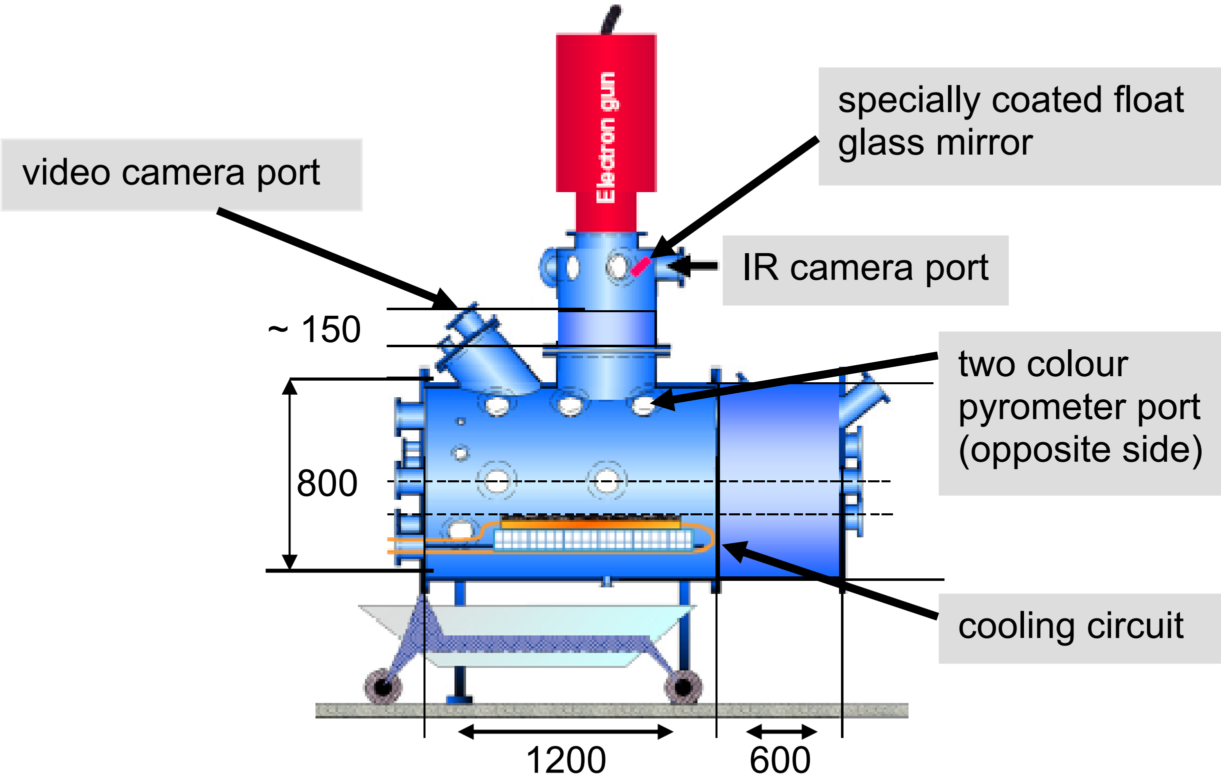

Fig. 1: Schematic diagram of JUDITH 2 electron beam facility [1 to 6].

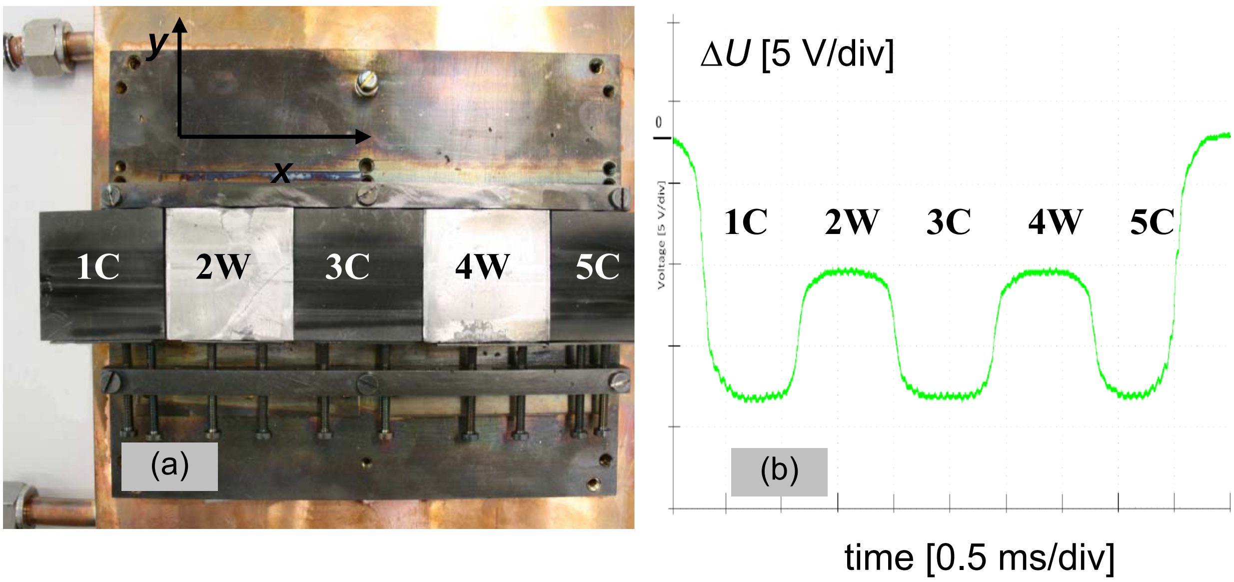

Fig. 2: Carbon and tungsten experimental set-up (a) and the measured signal (b) [4].

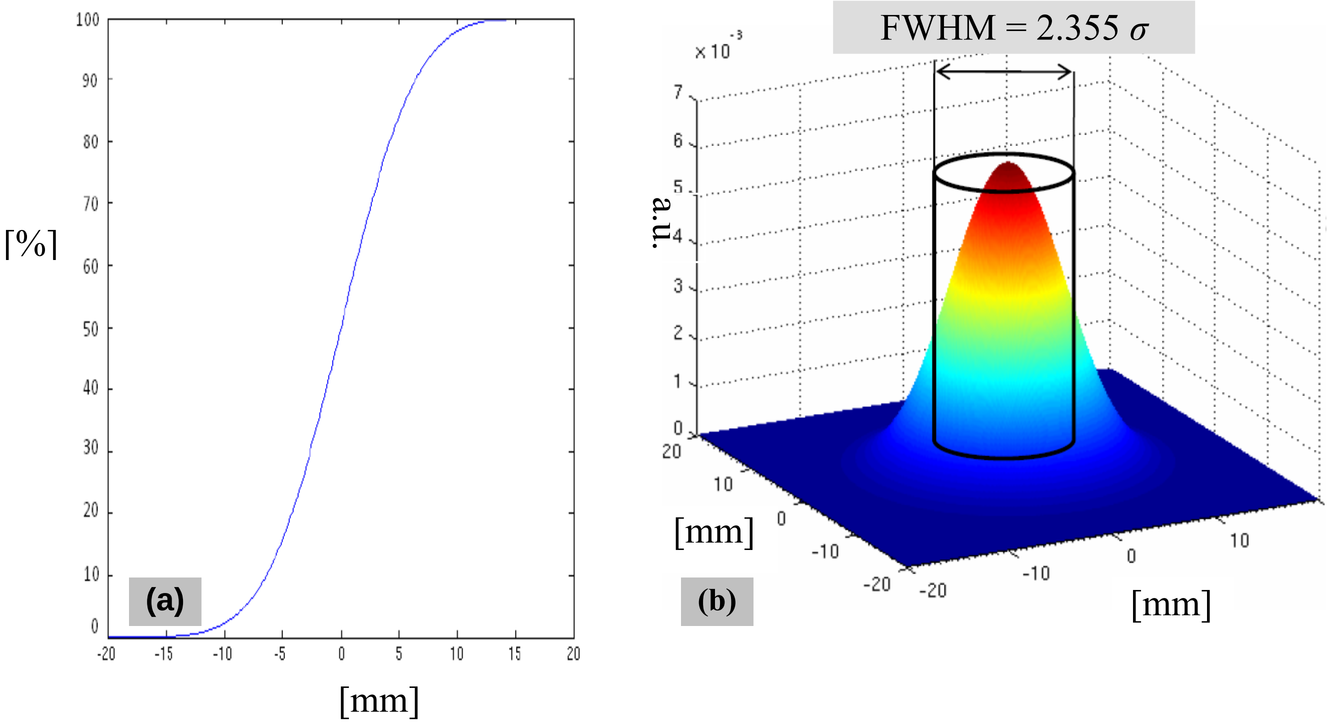

Fig. 3: GAUSS integral (a) and corresponding GAUSS distribution (b), $x_0 = y_0 = 0$ and $\sigma_x = \sigma_y = \sigma = 5.0$ mm [4].

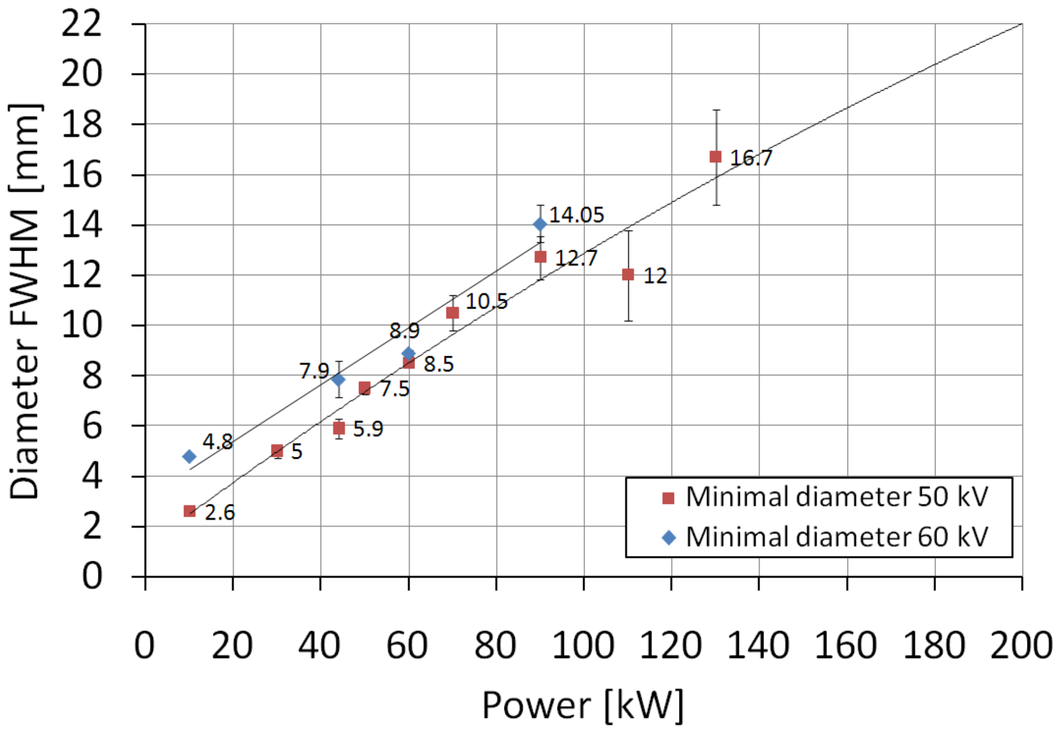

Fig. 4: Minimal electron beam diameter at FWHM depending on JUDITH 2 output power and different acceleration voltage levels of 50 and 60 kV [4].

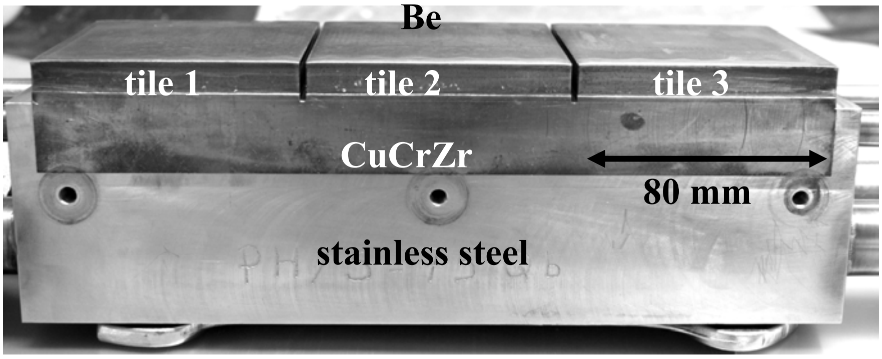

Fig. 5: European beryllium mock up for first wall qualification tests for ITER [1].