Results of beam extraction at the Jülich 90 MeV deuteron AEG isochronous cyclotron

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ABSTRACT

The acceptance tests of the Jülich isochronous cyclotron have been completed. Beam matching to the beam handling and monochromator systems is achieved by using two iron channels and an additional electrostatic channel. The measured properties of the extracted beam are in good agreement with the precalculated data.

1. EXTRACTION SYSTEM

A detailed description of the extraction system was given at the 1969 Particle Accelerator Conference, Washington.[1] Due to the high energy gain per turn, the turn separation is 1·5–2 mm at the extraction radius, so that an extraction at $\nu_r > 1$ is possible for external currents in the 10 μA range.

The extraction system consists of three elements (see Fig. 1). The electrostatic deflector, located in a hill sector, covering an azimuthal width of 21°, provides a turn separation of 30 mm at the entrance of the weakening channels. The channels producing a total field screening are combined with a surrounding copper coil, compensating the disturbance of the isochronous field. The focusing channel is mounted in the fringing field of the following hill sector. It is composed of two iron pieces. The first one is defocusing and the second one is focusing in the horizontal direction. By means of an additional electrostatic channel the position of the extracted beam can be kept constant.

2. REQUIREMENTS FOR THE PROPERTIES OF THE EXTRACTED BEAM

The specifications of the external beam have been fixed in a contract with the user of the machine. The most important data associated with the precalculated beam properties will be given below.

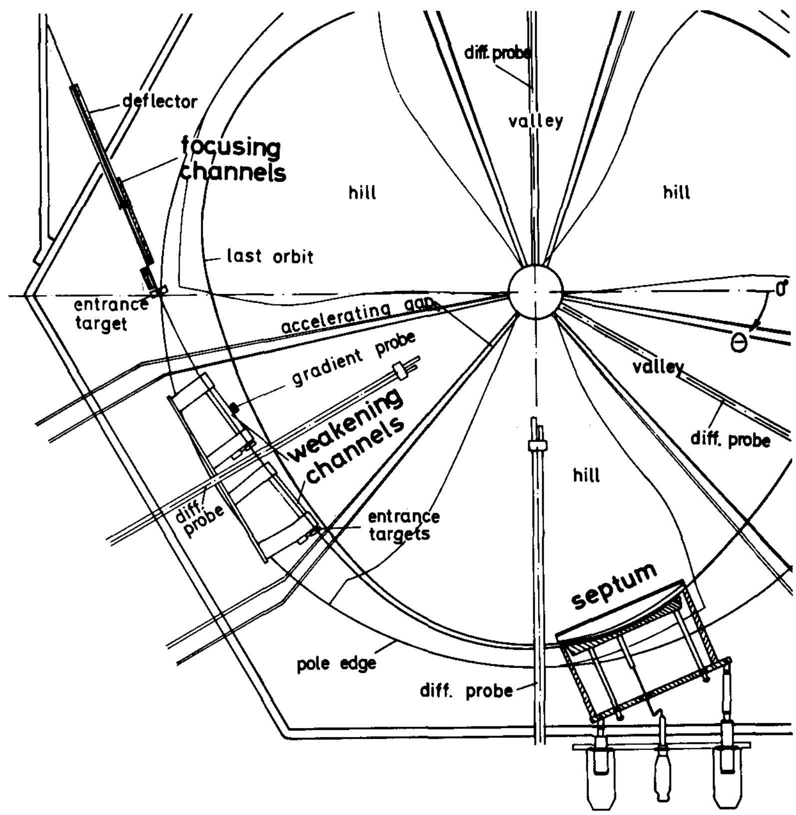

Fig. 1. Horizontal cross-section of the machine, including the extraction system

2.1. *Beam emittance and matching conditions*

The beam emittance defined by an enveloping ellipse at the target point (1·70 m distance from the vacuum tank) has to fulfill the conditions:

$$V_x = \pi \times x \times x' \leqslant 20 \text{ mm mrad (horizontal)}$$

$$V_z = \pi \times z \times z' \leqslant 25 \text{ mm mrad (vertical)}$$

and 80% of the beam intensity must lie within these volumes. Additionally an area has been specified—the 'matching area'—for the horizontal phase space as well as for the vertical phase space, characterised by the condition that 80% of the beam intensities are within these areas.

The matching area results from calculations using at first a linear computer code (FEFOK) and secondly the general orbit code (RU3KU), based on the measured magnetic field data. Assuming three neighbouring turns to get into the electrostatic deflector at the same time, the base width of the energy is 0·4%. We supposed an incoherent radial amplitude of 2 mm.

With these assumptions, Fig. 2 shows the motion of the extracted beam in the radial phase space. This was calculated with the linear computer code at the entrance of the electrostatic deflector (θ = 65°), in the middle of the hill sector (θ = 90°) between both weakening channels (θ = 150°), between the defocusing and the focusing part of the focusing channel (θ = 190°) and at the target point.

It is remarkable, that the small phase volume entering the electrostatic deflector increases continuously during the motion. The reasons for this effect are firstly, that the eigen-ellipses entering the electrostatic deflector are cut in the radial direction corresponding to the maximum turn separation and expand during the further motion, and secondly, there is a dispersion due to the energy spread.

Fig. 3 demonstrates the analogous picture for the vertical phase space. In this case the maximum vertical amplitude is given by the 8 mm aperture of the diaphragm, located at the deflector entrance.

The matching areas shown on the bottom of Figs 2 and 3 have been chosen

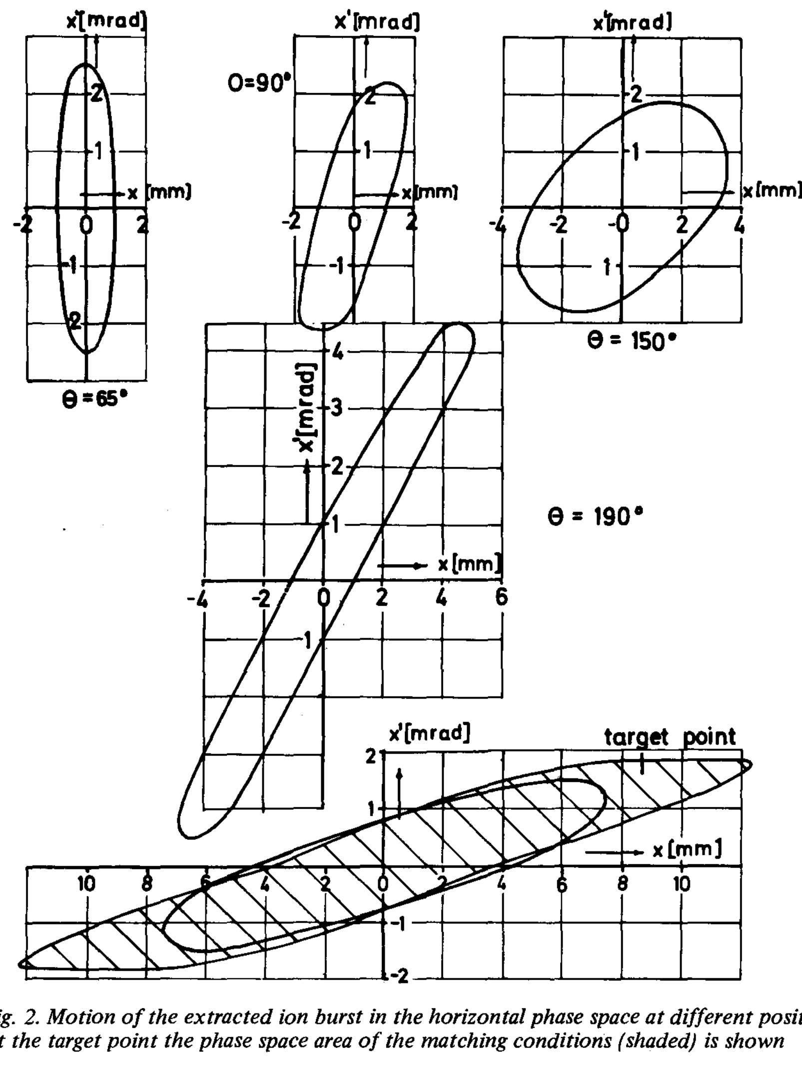

Fig. 2. Motion of the extracted ion burst in the horizontal phase space at different positions. At the target point the phase space area of the matching conditions (shaded) is shown

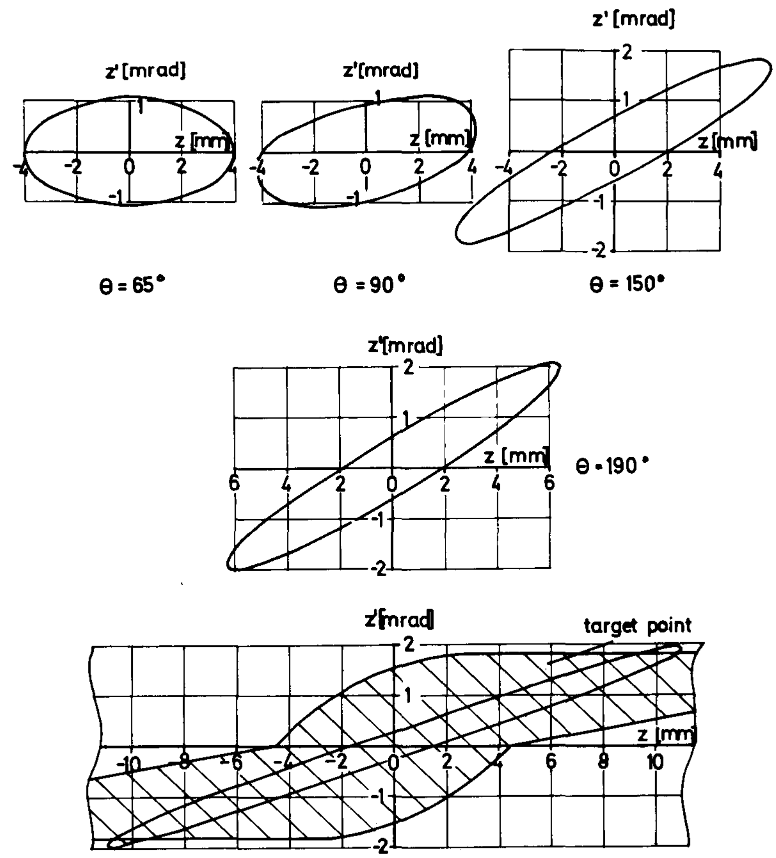

Fig. 3. Motion of the extracted ion burst in the vertical phase space at different positions. At the target point the phase space area of the matching conditions (shaded) is shown

somewhat larger than the calculated phase volumes, taking into account that the orientation of the phase volumes vary with energy and kind of particles.

For an adequate beam matching to the beam handling and monochromator systems, the target point is matched by using the deflector inside the focusing channel. The possible variation of the beam angle is ±3 mrad.

2.2. *Extraction efficiency and stability of the external current*

The extraction efficiency T has to be 50% at least, in order to limit the activation of the machine. T is given by

$$T = \frac{I_{ex}}{I_{int}} \tag{1}$$

with I_{ex} = extracted currents,
I_{int} = beam current at 1/4 extraction radius (380 mm).

The fluctuation of the external beam current has to be smaller than ±10%.

The beam losses in the septum and the corresponding transparency of the deflector have been estimated, assuming a cosine distribution $F(\Delta\varphi)$ of the ion pulse, with a base width of $2\Delta\varphi_m$. The maximum and minimum turn separation of a coherent oscillating beam (A_c = coherent amplitude, ν_r = oscillation number) is given by

$$\Delta S_{\substack{max\\min}} = \Delta r \pm 2\pi A_c(\nu_r - 1) \tag{2}$$

with Δr = turn separation due to the energy gain per turn.

Considering a finite phase width of the ion pulse, Δs depends on the phase $\Delta\varphi$:

$$\Delta S_{\substack{max\\min}} = \Delta r \pm 2\pi\, A_c(\nu_r - 1)\ .\cos\left[2\pi(\nu_r - 1) \times\ n(\Delta\varphi/2)^2\right] \tag{3}$$

with n = total number of turns. $\Delta\varphi = 0$ represents the central phase. The resulting transparency of the electrostatic deflector, with the septum thickness d, is given by

$$T_{s\,\substack{max\\min}} = \int_{-\Delta\varphi_m}^{+\Delta\varphi_m} (1 - \frac{d}{\Delta s_{\substack{max\\min}}(\Delta\varphi)})F(\Delta\varphi)\ .\ d\,(\Delta\varphi) \tag{4}$$

For the 45 MeV deuterons case, the results are shown in Fig. 4 for different phase widths of the beam.

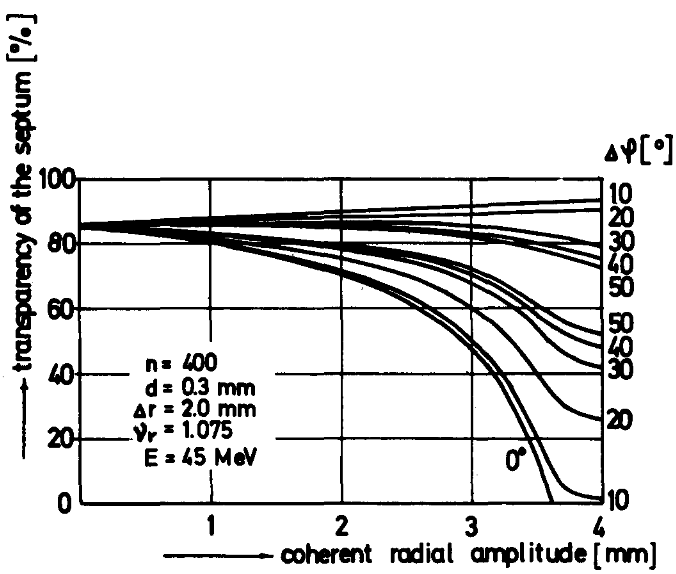

Fig. 4. Calculated maximum and minimum transparency of the septum for different phase widths of the beam

For a coherent radial amplitude of 3 mm and a phase width of 20°, e.g. the transparency of the electrostatic deflector is between 60% and 80%.

In this case the fluctuation of the external beam current is larger than ±10%.

This happens if, due to fluctuations of the frequency, the magnetic field, or the rf voltage, the total number of turns changes within the range of a ν_r-period.

Consequently the required stability of the external current can be achieved by:

(a) the coherent radial amplitude has to be within a range of 1 mm,
(b) the phase width of the beam has to be large,
(c) the total number of turns has to be enlarged in order to get complete precessional mixing,
(d) the stability of the machine parameters has to be such that the change Δn of the total turn number is small compared with the turn number of a radial oscillation period:

$$\Delta n < \frac{1}{5}\,\frac{1}{\nu_r - 1} \tag{5}$$

It is quite difficult to fulfil condition (a). Machine operation based on condition (c) results in an increased beam emittance, as will be demonstrated by experiment (see Section 3.1).

The only practicable solution of this problem is a sufficient machine stability providing:

$$\left(\frac{\Delta f}{f}\right) + \left(\frac{\Delta B}{B}\right) < \frac{1}{\pi n h}\sqrt{\frac{3\Delta n}{2n}} \qquad \frac{\Delta U}{U} < \frac{\Delta n}{n} \tag{6}$$

with h = 3 (rf–Mode number),

$\frac{\Delta f}{f}$ = relative frequency fluctuations

$\frac{\Delta B}{B}$ = relative magnetic field fluctuations,

$\frac{\Delta U}{U}$ = relative Rf-voltage fluctuations.

For ν_r = 1·075, n = 400 we obtain

$$\frac{\Delta f}{f} < 2{\cdot}5 \times 10^{-5}$$

$$\frac{\Delta U}{U} < 7 \times 10^{-3}$$

2.3. *Energy resolution*

The guaranteed energy resolution of 0·3% *FWHM* is based on the well-known internal beam properties associated with calculations, pointed out in Section 2.1.

3. RESULTS OF BEAM MEASUREMENTS

3.1. *Phase space measurements*

All phase space areas have been measured by means of the emittance-measuring equipment of the Institute for Nuclear Physics of KFA Jülich.[2] As an example, Fig. 5 shows the measured current density distributions as a function of x' for

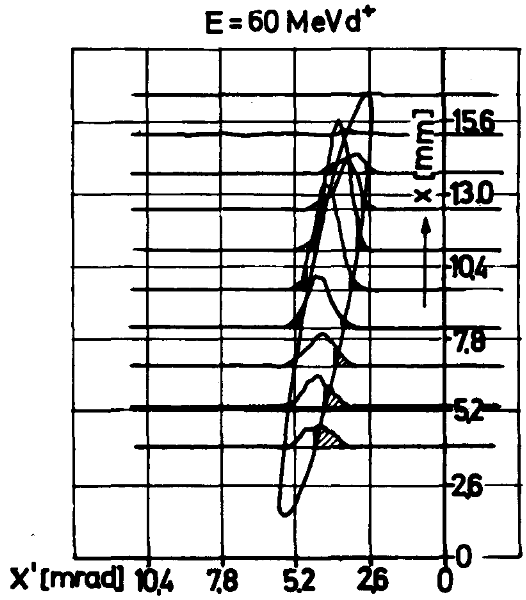

Fig. 5. Current density measured by means of the emittance-measuring device. The ellipse with V_x = *18 mm mrad demonstrates the part of the beam fulfilling the matching conditions*

different x-values. To examine the matching conditions, an ellipse with V_x = 18 mm mrad representing a part of the matching area (see Fig. 2) is projected into this figure. This ellipse demonstrates directly the part of the extracted beam, fulfilling the matching conditions. The result is, that more than 85% of the beam intensity lies within the ellipse.

The above example is chosen for a less favourable case, i.e. the setting of the machine parameters was not optimal. For those energies and particles investigated a machine parameter adjustment could be found fulfilling the matching conditions.

In Fig. 6, three measured phase ellipses are given. They are obtained in such a way, that each measured density curve is reduced by 10% in reference to the maximum intensity. By this means more than 80% of the total intensity remains in the rest area.

The top of Fig. 6 shows a horizontal phase volume with a very large V_x = 50·2 mm mrad. The corresponding extraction efficiency was 35%. The result was obtained by detuning the accelerating frequency, $\Delta f/f = 4 \times 10^{-5}$. Due to the resulting precessional mixing, the extraction efficiency is small and the emittance is very large. On the other hand, no fluctuations of the beam intensity were observed.

In the centre of Fig. 6, a phase volume with V_x = 12·6 mm mrad is given. For this a careful adjustment of the machine parameters was made. In this case the

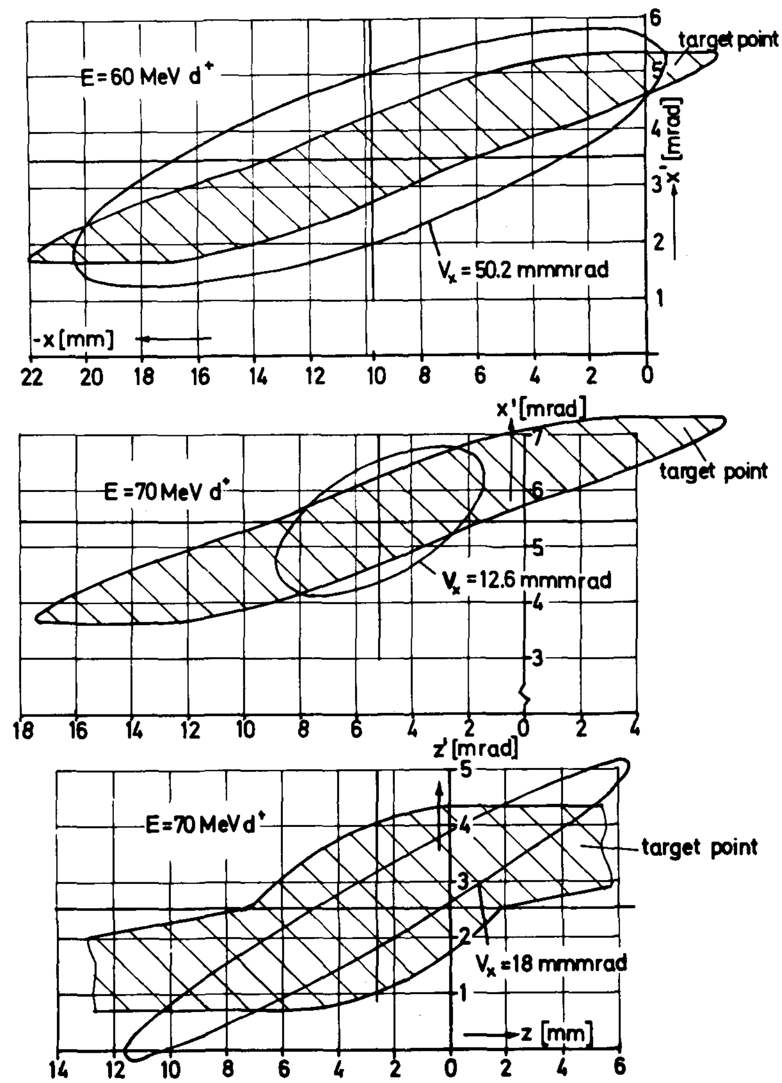

Fig. 6. Examples of measured phase volumes for different machine parameter settings

horizontal beam extension at the target point was only half of the calculated value (Fig. 2). Because the calculated beam width, due to the dispersion effect (for an energy spread of ±0·2%) increases by a factor of two, we expect in this case an energy resolution of about 0·2%.

The vertical phase ellipse given on the bottom of Fig. 6 is V_z = 18·4 mm mrad. Generally, the vertical phase space is relatively independent of the particle energy and the settings of the machine parameters.

3.2. *Measured current density and extraction efficiency*

Fig. 7 shows a typical current density curve, measured in the extraction region. From this plot we estimated a coherent radial amplitude of 2·8 mm. The fact that individual turns can be seen indicates a good beam quality.

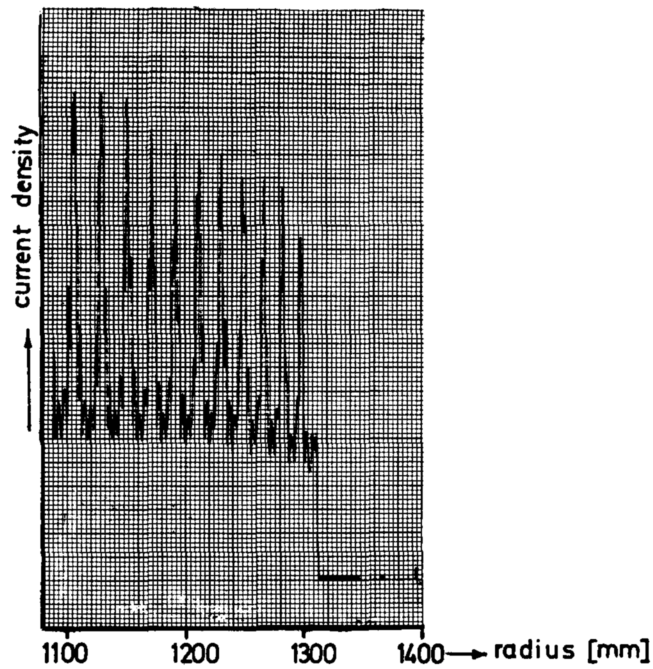

Fig. 7. Current density near the extraction radius in the case of an adequate machine parameter adjustment

This effect is not surprising, considering that the time distribution of the ion pulse (of 20° phase width) is approximately a cosine distribution; consequently, 70% of the pulse intensity is within a phase interval $\Delta\varphi = \pm 5°$, and therefore in a radial interval of 2·8 mm. This value is comparable with the turn separation of 2 mm due to the energy gain per turn. The measured extraction efficiency defined in Section 2.2, is between 50% and 65% and depends mainly on the machine parameter adjustment, and also on the energy and the beam current. In agreement with Fig. 4 the maximum transparency of an 0·3 mm tungsten septum is about 80%. In general, the best extraction efficiency coincides with the best beam quality of the extracted beam.

Originally, the frequency stability of the self excited rf-system was about 5×10^{-5}, a factor of two less than the required tolerance value, given in relation (6). As a consequence, it was difficult to fulfil the demand for the stability of the extracted beam current. After damping the mechanical vibrations of the vacuum tank, induced by the vacuum pumps and the cooling water, the fluctuation of the external beam current was smaller than 3%.

3.3. *Septum and extracted currents*

The amount of the extracted beam current is only a question of the power dissipation at the septum. We described a septum design[1], consisting of an 0·2 mm tungsten foil and some carbon pieces in front of the tungsten foil, just outside the electric field. The power dissipation of this septum design was favourable, but it showed a tendency to arc over during operation. This arcing effect was caused by the carbon particles deposited on the high voltage electrode.

After that we tested several arrangements based on thin tungsten wires cooled by radiation. Tests with specially shaped tungsten wires, 0·3 in diam., were relatively successful.

Currently, an 0·2 mm tungsten foil, sealed on a watercooled copper support is under construction and will be tested in September this year.

ACKNOWLEDGEMENT

The authors would like to thank the Institute for Nuclear Physics of KFA Jülich, especially Prof. Mayer-Böricke for making the results of beam emittance available.

DISCUSSION

Speaker addressed: P. Wucherer (A.E.G.)

Question by G. Hendry (Cyclotron Corporation): What is the maximum beam power that you have extracted?
Answer: Last week we got 14 μA of 60 MeV D^+. Tests of the septum are still being performed.

REFERENCES

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2. Kuhlmann, W., Bojowald, J., Mayer-Böricke, and Reich, J., 'Emittance measurements at the Jülich isochronous cyclotron', Proceedings of this Conference, p. 348.