SOME ASPECTS OF THE 100 μA OPERATION OF THE SIN INJECTOR CYCLOTRON

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Abstract.- The high current operation of a conventional cyclotron such as the SIN injector depends upon high extraction efficiency and good beam quality. This is achieved with beam collimation in the center region of the cyclotron. The following aspects related to the beam preparation in the center region are discussed: ion source output in the space charge limited case, beam divergence and its dependence upon beam intensity, matching problems. Results of experiments in a test facility are compared to the actual performance in the cyclotron.

1. Introduction.-

The SIN injector cyclotron is a conventional AVF-cyclotron with 2.5m pole diameter designed and constructed by N.V. Philips Gloeilampenfabrieken, the Netherlands and is described in Ref. 1, 2 and 3. It is a versatile and technically complicated machine, because it is operated in two different modes. In the "injector mode" it produces high intensities (typically 120 μA) of 72 MeV protons for injection into the SIN ring cyclotron. In the "variable energy mode" it is used as a source of various beams in the energy range of 10 - 70 MeV for protons, 10 - 65 MeV for deuterons, 20 - 130 MeV for alpha particles and axially injected polarized beams [4].

High current operation results in elevated beam losses and activation levels. Therefore the machine should be simple and the time needed for service and repair short which is in contradiction to the versatility asked for in the "variable energy mode". Our approach to reduce extraction losses has been to increase the ion source luminosity as much as possible and to use collimators to cut down the size of the beam close to the ion source until the beam current is reduced to the level needed. This method is superior to others. Even a perfect design avoiding aberrations would not have given comparable results.

As a first step, vertical collimators were installed in the center region [5], since it was not possible to control the matching of the ion source output to the acceptance of the cyclotron well enough. With this collimator, the ion source exit hole and the phase slit (see fig.1), we have the possibility of forming a four-dimensional frame to define the beam. In a next step, an attempt was made to improve the luminosity of the ion source. Increasing the arc power in the source, however, resulted in a sharp saturation of the beam current. In order to find the cause of the saturation, various properties of the ion source and center region were studied, namely plasma emissivity (described in section 2), optical problems and the matching of the beam (section 3 and 4). As a final step, the extraction septum was adapted to the improved beam quality. Some properties of the septum will be discussed in section 5.

2. Ion source output.-

The ion source is of the Livingston-type (PIG with heated cathodes). The anode bore has 6 mm diameter. The cathodes are LaB6-pellets, one of which is mounted directly onto a tungsten filament (2 mm wire) and can be heated to the temperatures necessary for ignition. The advantage of such a filament is a high lifetime of roughly four weeks in normal operation. The exit opening in the anode is a circular hole with 3 mm diameter.

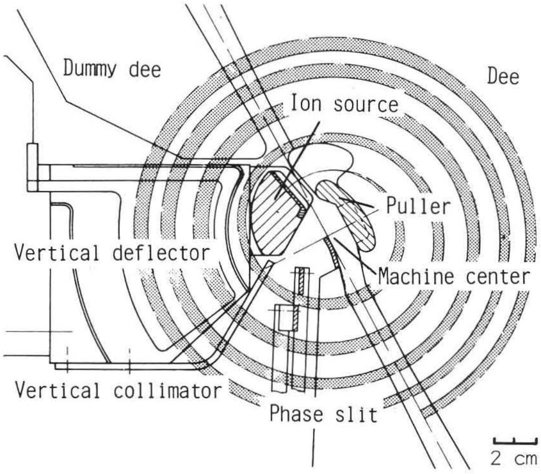

Fig. 1: The center region of the injector cyclotron. The exit opening of the ion source, the phase slit and the vertical collimator form a four-dimensional frame to define the size of the beam.

In order to produce the highest possible luminosity, one has to ensure that the plasma is intense enough to deliver the space charge limited current in the acceleration gap. The plasma emissivity i.e. the ion current extractable from the plasma, can be measured using a flush-mounted electrostatic probe [6] in the exit hole of the ion surce, as sketched in fig. 2a. For this position of the probe the evaluated ion current corresponds to that from a flat plasma surface in the exit hole. A saturation in the plasma emissivity could be the reason for the observed saturation in current.

Results of measurements in the cyclotron and in the test set up with such a probe are shown in fig. 2b and fig. 3. They can be summarized as follows: 1) The current is roughly proportional to the arc power up to a limit depending upon gas flow. 2) Above 10 ccm/min no saturation was observed with the available arc power, the limit being beyond 18 mA ion current. In the linear part it amounts to 6 mA per 100 watt arc power for this position of the plasma surface (i.e. 85 mA/cm^2).

For the production of 100 µA extracted beam the source is typically operated at about 200 watt arc power at a gas flow of 15 ccm/min. Up to 5 mA have been measured on the first orbit in the machine. From fig. 3 we could expect to extract a DC beam current of up to 12 mA, if the plasma surface were at the measured position, more than 90 % being protons.

3. Divergence of the beam.- The divergence of the beam extracted from the plasma boundary of the source depends on the shape of the equipotential surfaces in the acceleration gap. The equipotential surfaces themselves, including the plasma boundary, are determined in a self-consistent manner by the combination of all extraction parameters like plasma emissivity, the geometry of the acceleration electrodes, the space charge distribution in the beam and the applied extraction voltage V. The emitted ion current I is space charge limited and the Child-Langmuir law may be applied:

$$I = \Pi \cdot (V)^{3/2}$$

The perveance Π includes the influence of the emitted ion current on the plasma boundary and the geometry of the equipotential surfaces in the acceleration gap.

Π is constant only if the plasma boundary is maintained in a fixed position. For a flat plasma surface and a parallel plane geometry, the perveance can be calculated:

$$P_o = \frac{4\varepsilon_o}{9} \cdot \left(\frac{2e}{m}\right)^{1/2} \cdot \frac{\pi a^2}{s^2}$$

where e and m are the charge and mass of the ions, πa^2 is the area of the exit hole and s the width of the acceleration gap. P_o amounts to 0.19 mA/(kV)$^{3/2}$ in our case.

The ratio Π/P_o is a measure of the deformation of the plasma boundary [7]. High values result from high arc power and correspond to a convex plasma surface, a low ratio corresponds to a concave plasma boundary. Since an accurate calculation of the perveance of the actual geometry was not made, the value corresponding to a flat plasma surface cannot be predicted.

The divergence of the beam has been studied in the test facility, which consists of the source and the 'Dee' installed between the poles of a 100 cm magnet to form an exact copy of the cyclotron center region. A DC voltage is applied to the 'Dee' to extract beam from the grounded source. The emitted ion current and vertical density profiles have been measured 180° from the source for variable arc power. The profiles are shown in fig. 4. The divergence was obtained from the profiles assuming a quasi-point source. In fig. 5a the divergence is plotted against the plasma deformation parameter Π/P_o. The focusing action of the concave plasma surface and the defocusing action of the convex surface are clearly seen. In fig. 5b the ratio Π/θ is plotted, which gives a simplified measure of the brightness of the beam. The defocusing action is somewhat compensated by the increase of the ion current.

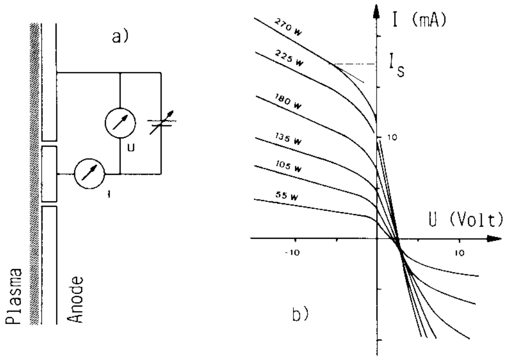

Fig. 2: a) A biased probe was used in the exit opening of the ion source to measure the ion current that can be extracted from the plasma. b) The current I measured on a circular probe with 3 mm diameter as a function of applied bias voltage U for variable arc power. The information on the plasma emissivity is contained in the flat part of the curves. The current would reach a constant value I_s below -5V if the plasma were not deformed by the bias voltage.

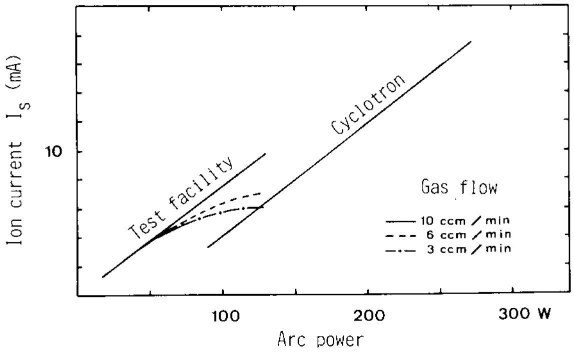

Fig. 3: The current of positive ions, I_s, extracted from a flat plasma surface in the exit hole of the ion source in function of the arc power. The measurements were performed using the arrangement shown in fig. 2.

With the deformation of the plasma surface the emissivity of the plasma changes as well. In the preceeding section it was shown that in our case the ion current would normally increase linearly with arc power. The ion current per unit arc power can be taken as a measure of the plasma emissivity. In fig. 6 it is plotted against the plasma deformation parameter defined above. The fact that it decreases with growing deformation is probably the result of a lower plasma density when the plasma bulges out of the source.

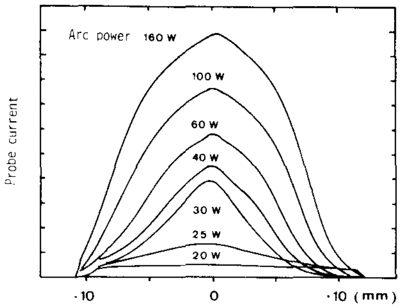

Fig. 4: Beam density profiles 180^0 from the source measured in the test facility using a vertically scanning wire probe. Due to the influence on the plasma surface the angular aperture of the beam first decreases with increasing arc power, then increases after reaching a minimum. At higher arc currents spherical aberration becomes dominant, resulting in a deformation of the shape of the curves.

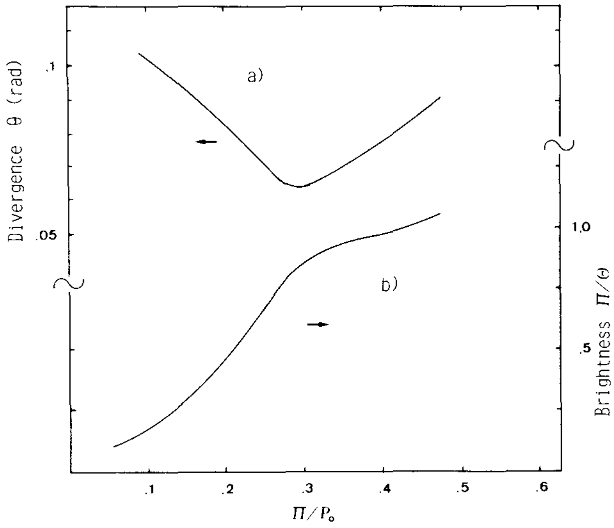

Fig. 5: a) The vertical beam divergence θ (hwhm) obtained from the profiles in fig. 3 is plotted against the ratio of the actual per veance Π to that of a flat geometry P_0. This ratio is a measure of the deformation of the plasma surface.
b) The ratio Π/θ, which gives a simplified measure of the brightness of the beam extracted from the source. (Units $mA/kV^{3/2}\cdot rad$)

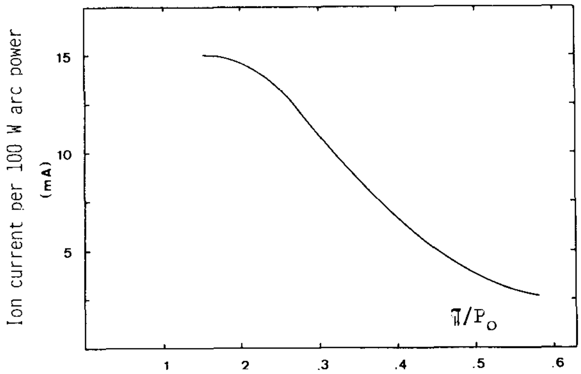

Fig. 6: The ion current per unit arc power plotted against the plasma deformation parameter Π/P_0. The curve gives the plasma emissivity, if the plasma boundary is at the corresponding location.

4. Matching of the beam

4.1 By center region design.- It is beyond the scope of this paper to present details of the center region design. The corresponding work has been described extensively by Baan et al. [1] and by v.Nieuwland et al. [2]. Only a few general remarks shall be given here.

A proper design of the center region includes the following properties: 1) Horizontal and vertical emittance areas should correspond to eigenellipses of the betatron oscillation at radii where the (phase dependent) electrical focusing can be neglected. 2) The orbits should be equally well centered for all particle phases. In our machine, as in every conventional cyclotron with multiturn extraction, a mismatch in either one of these properties will result in an increased size of the beam and in higher extraction losses.

Several tunable parameters, like Dee-voltage magnetic field in the center and ion source position serve to correct the behaviour of the beam. However, as shown in the previous section, the starting conditions change with arc power and the burning of the ion source plasma. In addition, the focusing in the center region depends upon the phase of the particles and might change due to erosion of the puller or the ion source exit opening. Therefore it will obviously be very difficult to achieve a proper matching and for successful high current operation it will be necessary to remove the unmatched part of the beam by means of collimators in the center region.

4.2 Radial collimation.- The radial size of the beam can easily be controlled by the exit opening of the ion source and the phase slit in the first orbit (see fig. 1). Although the slit is not optimally positioned for this purpose, a positive effect on the extraction efficiency can be observed when its width is reduced. The mismatch in the radial phase-space, however, is not very serious due to the strong radial focusing in the center. The slit is not very effective in reducing the phase width of the beam. Especially at high intensities the phase selectivity is lost because of the divergence introduced from the source.

4.3 Vertical collimation.- Several factors lead to a more severe mismatch in the vertical plane. In the 'injector mode' the cyclotron is operated in the third harmonic at a RF-frequency of 50 MHz and the transit time in the acceleration gap is about 100° RF. Depending on the phase of the particles, this results in a strong defocusing action in the acceleration gap which is added to the divergence of the beam from the source. The vertical focusing in the center is rather weak and depends again on the phase of the particles. Vertical collimation is therefore extremely important in our case.

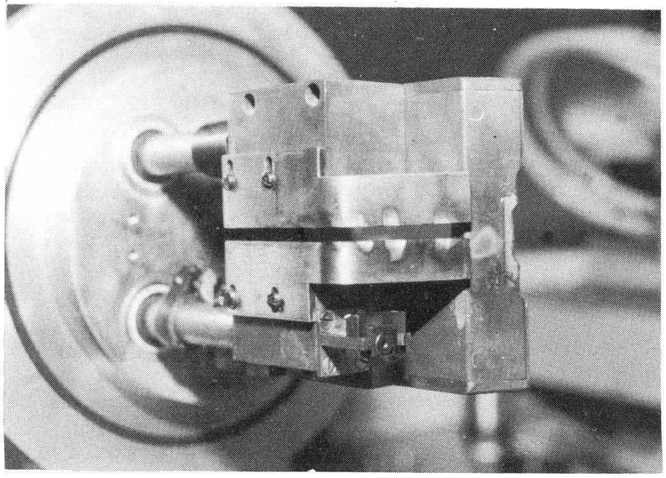

Fig. 7: Ion source with the vertical collimator mounted on the ion source body. The exit opening of the source is behind the edge on the right side of the picture. A large portion of the beam must be removed by the collimator because of the divergence from the source and insufficient vertical focusing.

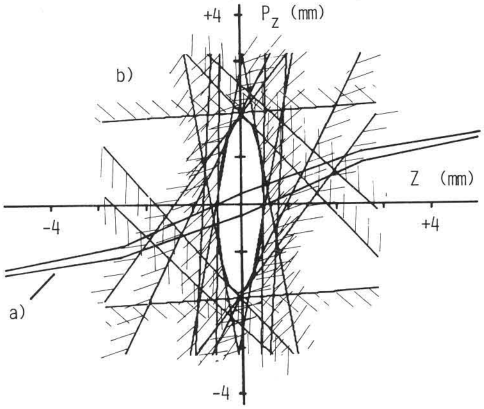

Fig. 8: Vertical phase space area 90° from the source. a) Uncollimated beam as measured in the test facility. b) Shadow of the vertical collimator for subsequent crossings. The shadow lines have been obtained from calculations of the trajectories in the center region.

The transmitted part of the beam matches the eigenellipse of the vertical motion in the cyclotron. This part only can be accelerated and extracted without significant beam loss.

The vertical collimator is shown in fig. 7. It has an aperture of 7 mm and covers about 10 revolutions. Made out of 5 mm thick copper, it is mounted onto the ion source body from where it is indirectly cooled. The effect on the beam is demonstrated in fig. 8. The transmission through the collimator is rather low. It ranges between 5% and 20%. As expected from the divergence measurements described in section 3, it becomes smaller with increasing arc power. The current transmitted through the collimator can be considered as a direct measurement of the brightness of the beam. It is plotted in fig. 9, for easy comparison with fig. 5b, against the plasma deformation parameter Π/P_0. Here Π has been calculated from the current I measured on the first orbit and the Dee-voltage V_{Dee} averaged according to the space charge law. With an acceptance between -80° and -20° starting phase, as found in center region calculations, we get

$$\pi = \frac{I}{1/2\pi \int_{-80^\circ}^{-20^\circ} (V_{Dee} \cos x)^{3/2} \, dx}$$

The current saturates at the same value of the ratio Π/P_0 as would be expected from the curve in fig. 5b. The brightness does not decrease with increasing arc power.

4.4 Vertical collimation as a means to reduce the phase width of the beam.- The strength of the vertical focusing by electric fields in the center region, and therefore the amplitudes of vertical oscillations, depend upon the phase of the particles. If a collective oscillation is introduced in the center, e.g. by changing the vertical position of the ion source, the collimator will act selective on certain phases. This effect can efficiently be used to reduce the phase width of the beam which improves further the quality at the cost of a moderate loss in intensity. A typical measurement of this effect is shown in fig. 10.

4.5 Methods to improve the matching and the brightness of the beam.- In the preceeding sections it was shown that the observed saturation is caused by the combination of the divergence from the source, the vertical mismatch and the collimator. In order to increase the beam current at the saturation level an attempt was made to either improve the matching or the perveance of our geometry.

The exit hole of the ion source is tapered. The angle of the tapering influences both properties. Changing the angle from 90° to 120° gave 1.5 times more beam current without affecting its quality. Going beyond 120° gave even higher currents, but the brightness of the beam was diminished because the reduction of the phase width by vertical collimation became less effective.

Opening the aperture of the vertical collimator would give about the same result. The intensity increases at the cost of a deterioration of the beam quality. The brightness diminishes because the reduction of the phase width is lost.

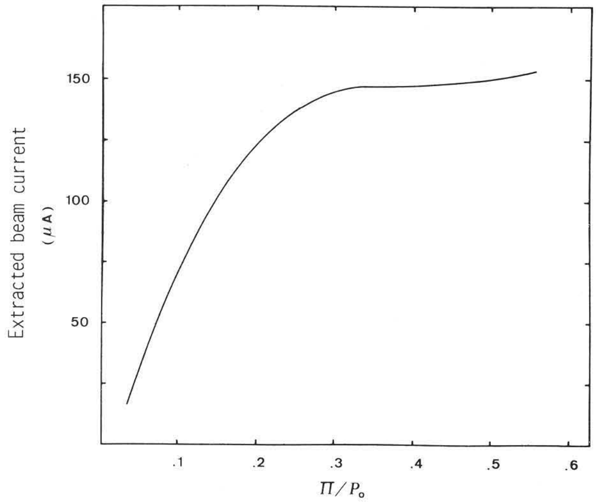

Fig. 9: Ion current transmitted through the vertical collimator and the phase slit plotted against the plasma deformation parameter Π/P_0. The current after collimation is a measure of the brightness of the beam. The trend agrees well with the expectation from fig. 5b, which was based on divergence data.

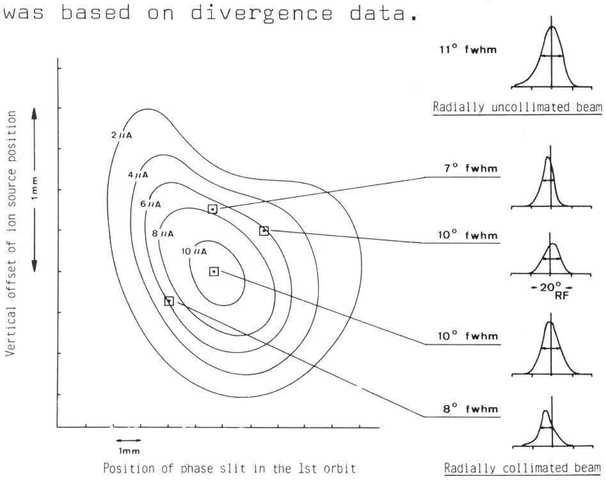

Fig. 10: The beam intensity and phase width in the cyclotron is shown for various combinations of phase slit position and vertical offset of the ion source. The measured time structure data shown on the right demonstrate that the vertical collimator can also be used as an effective tool to reduce the phase width of the beam, as explained in the text.

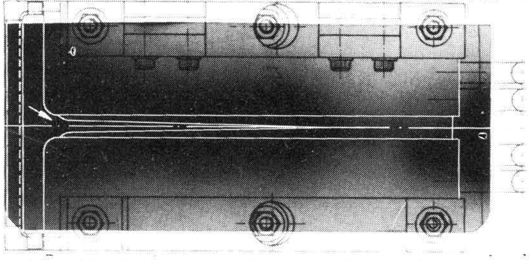

Fig. 11: Radiogram of a septum that was used before installation of the vertical collimator The beam enters from the left side. The blackening at the entrance edge shows that most of the beam losses do not occur in the V-cut of the septum but at the entrance edge due to excessive vertical size.

5. Extraction system.- As pointed out before, in high current operation it is necessary to reduce extraction losses and therefore the activation of the machine as well as the thermal load on the extraction elements. Extraction losses can be due to the following reasons: 1) The size of the beam is larger than the acceptance of the extraction channels. 2) Septum losses which depend on the thickness of the septum and the radial gain per turn in the precessional motion. 3) Shadow losses along the channels which depend on the beam quality. In the conventional cyclotron without separated turns, losses cannot be completely avoided, but extraction rates above 80% can be expected if the first kind of beam loss is avoided. Due to precessional mixing, however, errors in the center region, e.g. the mismatch shown in fig. 8, can easily result in an extremely bad beam quality, so that a substatial part of the beam is lost at the extraction channels.

An example of this kind is given in fig. 11. It shows a radiogram of a septum which has been in use before the vertical collimator in the center region was installed in 1976. From the blackening it is clearly seen that beam is lost at the wrong place, due to a beam size larger than the vertical aperture of the septum. The extraction rate was only 60% at that time, but could be raised to above 85% after installation of the collimator. Beam lost at the apertures of the extraction channels is as low as 2% today.

A further increase in the extraction efficiency could be achieved by changes to the septum itself. It is a copper septum and in the new version it is made out of one piece to avoid alignment problems. Its thickness was reduced to 0.15 mm. This raised the extraction efficiency to 93% at typical horizontal and vertical beam qualities of 3 π and 2 π mm mrad, respectively. Up to 190 μA of 72 MeV p have been extracted with this septum. The power limit is discussed in a separate publication [8].

Acknowledgments.- Last but not least it should be added that a successful operation is not achieved by a good design alone. Merits deserve P.van der Starre, S. Bohr, H. Einenkel, P. Meyer, A. Rölli and K. Weber for their careful maintenance and technical improvements on the machine, and S. Drack and the operation personnel for their continuous effort to achieve a perfect tuning of the cyclotron. The improved septum was skilfully manufactured by the SIN mechanical workshop. The radiogram was made by R. Kramer.

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8. W. Joho, this conference

" DISCUSSION "

H.W. SCHREUDER : Did you do charge state analysis in the data from the test set-up ?

Th. STAMMBACH : With sufficiently high arc power about 90 % of the total ion current are protons.

O.C. DERMOIS : Did you include the influence of the first transition lens in the emittance of your source ? We found that the shape of that lens has a large influence.

Th. STAMMBACH : It is correct that the field shape in the acceleration gap gives a defocussing action in addition to the "blow up" of the beam from the source with high arc current. The measured emittance area is the result of the field under influence of the space charge of the beam and, such, includes both effects.

G. DUTTO : Did you notice a difference in peak current (instantaneous over the cyclotron phase acceptance) between the source in the model with DC extraction and the source in the cyclotron with RF extraction ?

Th. STAMMBACH : No, the total ion current measured in the test facility and in the cyclotron agrees quite well, if we scale according to the space charge law and integrate over the calculated phase acceptance.

R.C. ROGERS : In the plan view of the collimator, what is the angular location relative to the ion source slit ? Was this an optimized location ?

Th. STAMMBACH : It is about 230° from the ion source aperture. The position is not optimized but is determined by practical considerations.

G. DUTTO : I would like to comment on the improvement of the brightness of the source which is extremely important for high intensity machines. At TRIUMF, we found a saturation effect similar to yours. It is our experience that the optimization of the region between source and puller has to be done extremely carefully in order to keep the brightness as high as possible.

" DISCUSSION " (continued)

Th. STAMMBACH : The rather large effect of the tapering angle on the ion source exit hole, described in the paper, also demonstrates the importance of this optimization.

M. REISER : It appears from your results that the current at full energy is limited by space charge effects near the ion source, not by septum losses or the longitudinal space charge limit that Dr. JOHO talked about. Is this correct ?

Th. STAMMBACH : The current is not really limited by the space charge effect. It is rather the luminosity that is limited by this effect. Reducing the collimation in the centre region i.e. enlarging the beam defining frame, provides higher beam currents as long as one is willing to accept more tails in the beam and higher extraction losses. The thermal limit of the septum has not been reached yet.

W. JOHO : Comment : Longitudinal space charge forces do not limit the current. They prevent separated turns in the Philips cyclotron at currents above a few μA. Extraction is thus limited by the thickness of the septum to about 93 %.

D.A. LIND : Comment : Ion electrostatic waves in magnetically confined arcs are needed to react on ions. Thus, the extraction RF field must have comparable frequency. Such frequencies are about 2 ω_{ci}. ω_{ci} is cyclotron ion resonance frequency.

(see paper "RF field effects on the cyclotron arc source", this conference).