The proton source for the improved CERN synchrocyclotron

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ABSTRACT

The features and performance of the ion source for the improved CERN synchrocyclotron are described together with some aspects of its technological development. The problems of operating the source in the accelerator and of stability are discussed. Finally, a survey of the monobloc construction of the central geometry of the accelerator is given.

1. INTRODUCTION

The proton source which will be used in the improved version of the CERN synchrocyclotron is a conventional cyclotron source, i.e. hot-cathode calutron type. It is mechanically integrated in the accelerating electrode assembly in the central area, the diameter of which is ~120 mm. There are two alternatives in the project for the central area, viz.:

(1) an rf extraction source, with the extraction slit at the potential of the dee;

(2) a pre-acceleration source, in which the source, biased to a positive potential, and a system of symmetrical deflecting electrodes enable a 10 keV beam to be injected into the rf structure in either direction of rotation without moving the source.[1]

The source-electrode assembly will be introduced into the machine by means of a support passing axially through the lower pole-piece. A preliminary experimental study was made to obtain from the pulsed source an extracted instantaneous current inversely proportional to the duty cycle, which, in our case, is 100 times the mean current of a cyclotron source. This current has been obtained, and the study is now being continued with the following aims:

a physical study of the source;

a technological study, with a view to achieving better reliability;

the measurement of the beam emittance according to the extraction optics and the operating status;
the development of the technology of the accelerating electrodes in the immediate vicinity of the source (central area) in relation to the theoretical study of the trajectories, and emittance measurements;
the development of the pre-acceleration source;
a study of the operation of the source in the machine in order to improve the design.

2. THE ION SOURCE

2.1. *The beam intensity*

The source must provide an instantaneous proton current of the order of 50 mA. To achieve this was considered difficult in view of the strong magnetic field (19 kG) and the low rf voltage (30 kV) resulting incidentally in a very small source. Experience, however, has shown that neither the voltage nor the size stood in the way of extracting a beam of this intensity or even a higher one. For a proton source, at least, the diameter of the chimney is irrelevant since, in a strong magnetic field, the ion density in the plasma is unaffected by the size of the column down to a very small diameter, of the order of a few tenths of a millimetre. It is thus possible to employ a very small source provided that sufficient attention is paid to the gas flow impedance which determines the pressure gradient along the plasma column. If, for instance, the gas is introduced near the chimney slit, it is perfectly possible, if necessary, to construct a source with a cross-section of no more than a few square millimetres. It is generally true, in fact, if a study is made of the technology of this kind of source, that the output density and source efficiency are found to increase as its dimensions are decreased. Only the problem of the cathode becomes more difficult as the arc current density is increased: this will be discussed later.

The acceleration voltage, which is lower in a synchrocyclotron than in a cyclotron, is the cause of the serious problem of space charge in the beam. However, regarded strictly from the point of view of the source, to extract a beam with a certain ion density is precisely to compensate its space charge at the plasma surface by means of an electric field. We are not concerned, therefore, with a voltage, but with an electric field, which may be obtained even with a very weak extraction voltage by reducing the distance between the source and the extraction slits. With distances varying between one and ten times the source slit width and with dense plasmas of the order of 1 A arc current per square millimetre, the extracted current is found to vary exponentially with that distance. Saturation occurs when the source-extraction slit distance approaches the size of the slit, i.e. in our case 1 mm, and this sets an initial limit to increasing the intensity by decreasing the distance. There are other limitations too, due to the occurrence of arcing and to the optical properties of the beam, which will be discussed later.

It should be remembered that this law of variation is governed simultaneously by the geometrical parameters of the extraction system and by the plasma state. This explains why no perceptible increase is obtained by bringing the extraction slit closer to a low-density ion source, for the plasma is so far behind the source slit that it would be necessary to advance to within a distance much shorter than the width of the slit. Such a procedure would be pointless, since the electric field would not increase any further. This variation is important in our case, and, from a certain source-extraction slit distance onwards, the extracted current can be more rapidly increased by shortening the distance by a given amount than by increasing the voltage in the same proportion, however odd this may seem to the user of a cyclotron source. It should also be noted that, with a distance of two to three times the width of the source slit, the extracted current increases with the voltage as $V^{3/4}$ –very much lower than the normally accepted law of $V^{3/2}$. To our mind, this state of affairs is due to the shifting of the plasma surface, which becomes perceptible when the plasma is dense and the extraction distance is short. As regards arcing, it would be as well to point out that the voltage behaviour in the vicinity of the slit is much better than anywhere else in the accelerator chamber—doubtless because of the ion bombardment which cleans the electrodes—which enables a voltage of 50 kV to be easily maintained over less than 1 mm. In a measurement performed under these conditions, with an arc current of 20 A in a 2 mm diam. column and with an extraction slit at a distance of 1 mm and a potential of 30 kV, a beam of 500 mA was extracted from our source slit of $1 \times 10\ mm^2$. In this experiment, with a duty cycle of 2·5%, the 375 W proton beam easily melted a copper plate 2 mm thick at an angle of 180° as it passed.

2.2. *The emittance of the beam*

At high intensities there is a relationship between the beam optics and its intensity via the shift in the surface of the plasma behind the source slit. The extracted current increases either when this surface retreats under the action of an increasing electric field, or when it advances under the effect of an increasing ion density. Thus the surface of the plasma forms part of the extraction optical system, and, if this system is to be kept constant with an increasing current, either the arc current and the extraction voltage must both be increased, or the distance from the extraction slit must be decreased, while the extraction voltage is kept constant. No precise emittance measurement has yet been performed, but a preliminary experiment with a simplified device consisting of a horizontal collimator placed after 90° deflection in the magnetic field has already shown that, with a constant extraction voltage, the density of the extracted current passes through a maximum when the distance of the extraction slit is varied, while the total current varies monotonically. At this maximum, the slit distance was ~1 mm with a d.c. voltage of 15 kV and the density varied by a factor of 2 when the slit was moved by ½ mm. The position of this maximum also varied with the arc current. This would indicate a very sensitive focusing system, which has to be adjusted if the quality of the beam is to be maintained at the optimum. It is, however, possible that this sensitivity may be less in the accelerator with rf extraction.

2.3 *Technological features*

Our source has, at present, a cylindrical copper chimney 4 mm in internal diameter and eccentrically positioned so that the plasma column which is tangential to the generatrix passing through the slit, is always centred on the filament, regardless of the angular orientation of the slit. In spite of constructional difficulties the head of the chimney carrying the anti-cathode was reduced to the diameter of the chimney in order to eliminate the Penning discharge forming around it when an electrode near the source is biased to a negative d.c. voltage (polarisation of the dummy dee, measurement with a d.c. extraction voltage, pre-acceleration source). This detail is important, since such a discharge tends to falsify the measurement of the extracted current and causes vertical arcing at the slit azimuth, thus preventing the extraction slit from being brought close to the chimney. Attempts will eventually be made to take the anti-cathode via an internal connection to a higher negative d.c. voltage than the arc voltage. Such a polarising of the anti-cathode would double the efficiency of the source and would reduce the plasma oscillations.

A major technological difficulty stems from the filament since, at the arc current densities needed its useful life is very much shorter than in a cyclotron source. If ionic wear is considered roughly the same in both cases for the same average current, an additional amount of wear must be added in the case of the synchrocyclotron due to sublimation. This becomes predominant since the temperature of the filament is markedly higher. We use filaments (Fig. 1) machined by spark-erosion in order to locate the hot point under the plasma column accurately. This is important, for a difference in cross-section of a few per cent in the filament branches is quite enough to displace the hot point outside this zone, and thus shorten the useful life considerably. In spite of a detailed study of the shape of the filament, its life remains short (80 h) in the case of small filaments (2 mm thick) giving high efficiency. If the life is to be lengthened, it is essential to increase the size of the filament and thus give it a larger emissive area, necessitating a heavier arc current for the same plasma density. In our case, for example, the useful life can be increased to 200 h if a 4 mm thick filament is used. A coaxial filament would give an even longer useful life but, if an arrangement is required which combines the conflicting demands of a reduction in the emissive area and an increase in the useful life, an indirectly heated cathode has to be employed. Our prototype (Fig. 2) has a cylindrical cathode of the same cross-section as the plasma column, the end of which is heated to the desired temperature by electron bombardment from a hollow cylindrical filament surrounding it at a distance of 0·5 mm. The bombardment must be perpendicular to the magnetic field to prevent arcing, which makes it very difficult for the electrons to reach the cathode. In fact, such a bombardment is theoretically impossible if the local magnetic perturbation set up by the current heating the hollow filament is not taken into consideration. In order to obtain the bombardment a d.c. voltage is applied to the cathode, with the filament earthed. When the arc pulse appears, it short-circuits this voltage across a resistance and takes the cathode to arc voltage. The temperature of the cathode is therefore a function of the duty cycle. This is of no significance with a low duty cycle and may be compensated for by an increase in the polarisation voltage in the case of a higher duty cycle. However, this effect renders the system totally impossible with a duty cycle of 100%. With this system we hope to obtain a useful life of about one month with an arc current density of 1 A/mm^2. The cathode can wear out longitudinally over a length of 5–6 mm without any change in the conditions for striking the arc since the shape of the assembly is cylindrical. The filament, which is at a lower temperature than the cathode, does not wear out. In spite of a great number of technological difficulties, the source has already operated with this cathode system at previously unattained efficiency—a result, however, which was not entirely unexpected since the emissive area is only 3 mm^2 as against the 9 mm^2 of the smallest filament we have realised.

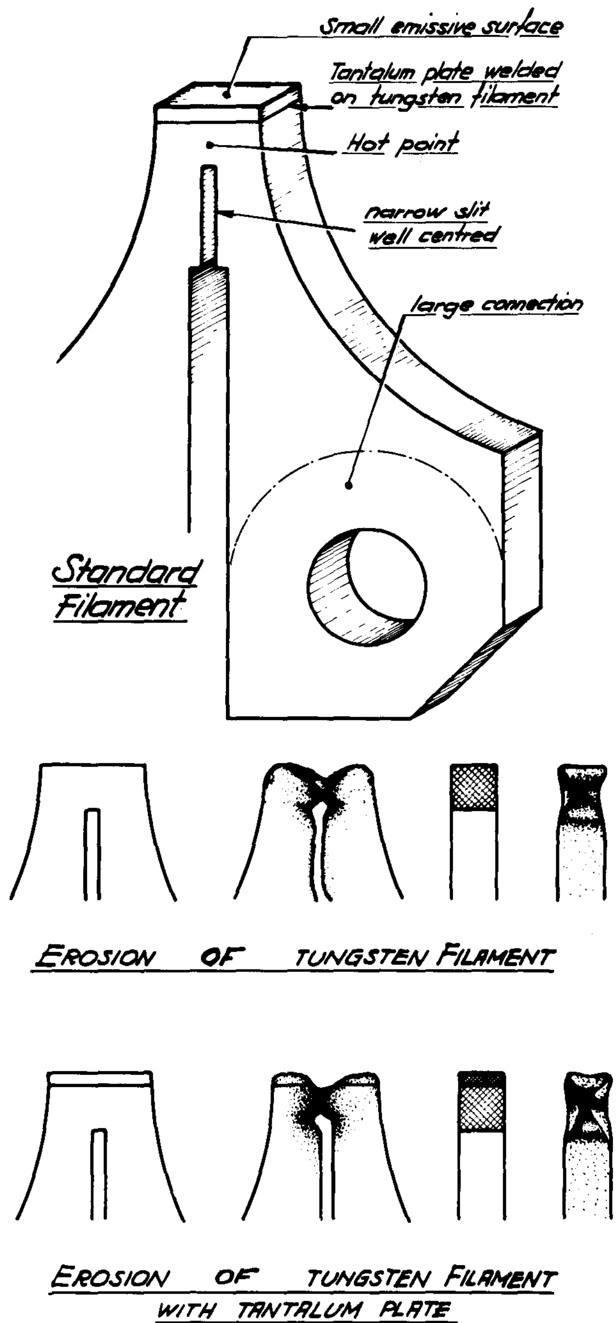

Fig. 1. Standard filament used in the CERN Central Region Model. Its design establishes a compromise between a small emissive surface (9 mm^2) and a reasonable mean lifetime. For the small duty cycle envisaged (~1%) the wear is predominantly due to sublimation. The filament with the tantalum plate (operating temperature ~2300°C) has the longest lifetime (~80 h) and a final section before breakage (hatched) orientated vertically, as compared with the horizontally orientated section of the pure tungsten filament (operating temperature ~2500°C) are shown

3. THE STABILITY AND OPERATION OF THE SOURCE IN THE ACCELERATOR

The ion source always gives a misleading impression of simplicity and, what is worse, it can work in conditions very far indeed from the optimum setting. The usual result is that, when operated in the accelerator, it is empirically adjusted, and the setting may therefore be poor, from the point of view either of the useful life, or of the brilliance. Moreover, the setting will always be poor if the source parameters are varied solely by observing the effect of these variations on the accelerated beam. This is due to the accumulation of deviations from ideal operating conditions when attempts are made to optimise on too large a number of parameters. For this reason, we think that the source adjustments should be dissociated from the machine performance in order to rationalise their mutual relationship. To put it a different way, the source itself must first be adjusted to give a beam of a certain brilliance which from previous experience is required by the accelerator. This presupposes, on one hand a knowledge of the characteristics of the source and on the other that these characteristics are

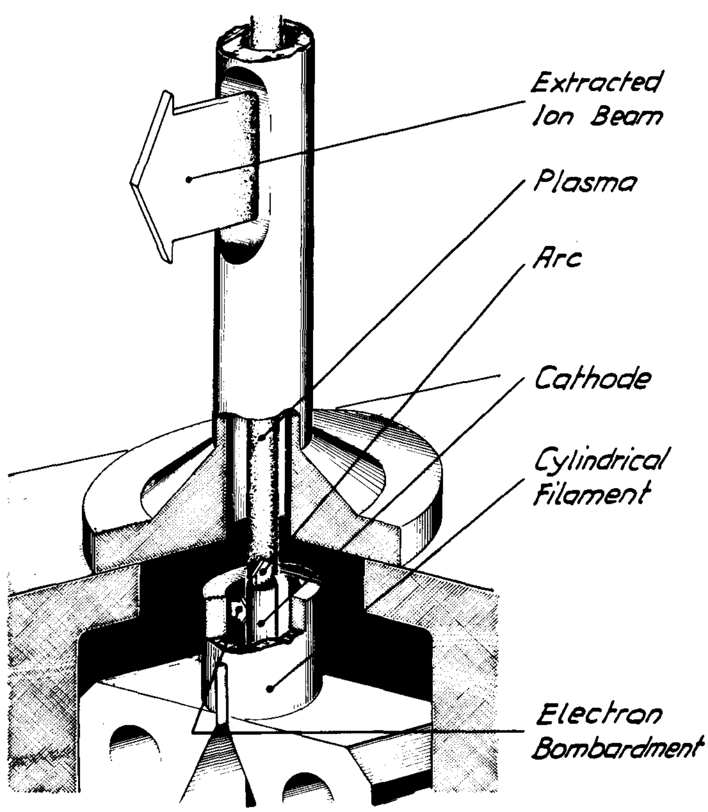

Fig. 2. Indirectly heated cathode under study. Emissive surface 3 mm². The electrons emitted from the inner surface of the cylindrical tungsten filament raise the temperature of the central tantalum cathode by bombardment following complicated trajectories across the magnetic field without striking any arc. The problem consists in heating the cathode at its upper end, which permits the cathode to be worn longitudinally from above and increases the lifetime

stabilised. Stabilisation is important because the source can be affected by long-, medium-, and short-term fluctuations of various origins. Slow drifts stem from wear on the filament and variation in the gas flow which is sensitive to ambient parameters. Fast fluctuations form the characteristic 'hash' of sources in a magnetic field. In our source, medium-term fluctuations display a curious periodicity of two seconds, but are less troublesome than the other two types because their amplitude is not so great.

As a first step, we introduced a slow regulation (elimination of medium and fast fluctuations seems to be a more difficult problem) in the main parameters: I_{arc}, V_{arc} and gas flow. This system has advantages, at least one of which was not expected, i.e. an increase in the useful life of the filament. The others are:

the automatic starting-up of the source by setting reference values and simple triggering;

the stability of the beam from the beginning to the end of the filament life without any action being necessary on the part of the operator;

the facility for carrying out experiments in order to study characteristics by the elimination of the internal $V_{arc}\,I_{arc}$ coupling.

In a second stage there would have to be a rational correlation between parameters (characteristic follower) so as to have only one control button—that for the brilliance. It would be possible to conceive of a third stage in which the brilliance, in its turn, would become a function of certain qualities desired in the accelerated beam. Such a mode of operation seems well suited to on-line computer control but could be brought about by more conventional means.

4. THE CENTRAL GEOMETRY

Because of its effect on the beam optics, the position of the extraction slit must be precisely positioned in relation to the source, and thus it is impossible to fix the slit on the dee. In a first experiment, we fixed the slit on the dummy dee, for which there is a precise mechanical reference, and connected it to the dee by flexible contacts. Thus the source could be adjusted in relation to the slit. Since this assembly worked well, we were encouraged to extend this method to the electrode assembly in the centre of the machine, and this gave rise to the 'central geometry', fixed to an axial support.[2] There are many arguments favouring this construction, including:

the positioning of the source-extraction slit assembly in relation the magnetic centre;

the need to reverse the direction of rotation of the beam which can be performed by using two mirror-symmetric central geometries for rf extraction;

a fixed size and location of the conical acceleration electrodes defining the very narrow dee gap at the centre (4 mm)·

the shape of the electrodes can easily be changed in the light of further study and development;

the possibility of servicing the source without exposure to radioactivity.

The central geometry consists of a cylindrical assembly, 120 mm diam., containing the electrodes and the source. This monobloc assembly is inserted and removed via an axial support. The electrodes are rigidly interconnected by insulators and are connected to the dee and the dummy dee by flexible contacts. The axial support enables the whole of the central geometry arrangements to be

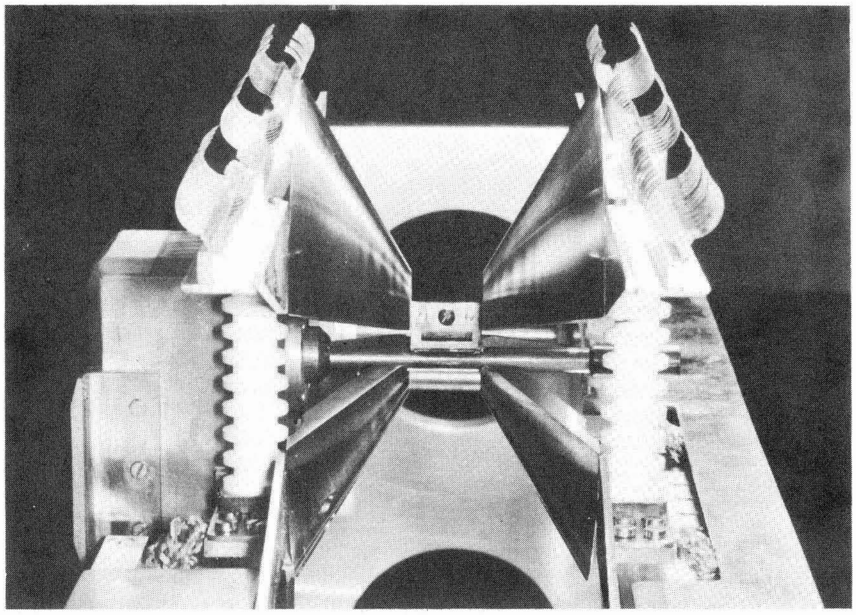

Fig. 3. Central assembly for rf extraction used in the CERN Central Region Model. The mechanically integrated construction of the source, puller and conical accelerating electrodes with rf contacts to the main dee are shown

moved in relation to the centre of the machine without causing any magnetic perturbation, and also allows the source to be moved in relation to the centre of electrodes. A prototype of this geometry has operated perfectly in our Central Region Model, a small 20 MeV synchrocyclotron (Fig. 3).

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