BEAM DIAGNOSTICS IN THE AGOR CYCLOTRON

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Abstract

Using the superconducting cyclotron AGOR at the KVI as an example the beam diagnostics equipment in modern multi-particle, variable energy cyclotrons for research in nuclear physics is reviewed. The experience obtained with the extensive set of diagnostics tools integrated in the design since the start of operation in 1996 is discussed.

INTRODUCTION

The AGOR cyclotron at the KVI is a multi-particle, variable energy AVF-cyclotron [1, 2]. It accelerates ions with charge-to-mass ratio Q/A in the range $0.1 \leq Q/A \leq 1$. The maximum energy per nucleon is, depending on Q/A, determined by either the bending limit $E/A = 600\ (Q/A)^2$ MeV or the vertical focusing limit $E/A = 200\ Q/A$ MeV. The magnetic field, in the range 1.7 to 4T, is produced by two superconducting maincoils, fifteen trimcoils and three fully saturated iron polesectors. The beams from the external ion sources (ECR for heavy ions, multi-cusp source for light ions and atomic beam source for polarised protons and deuterons) are axially injected. The extraction system consists of an electrostatic deflector, two electromagnetic deflectors with dipole and quadrupole windings and a quadrupole channel.

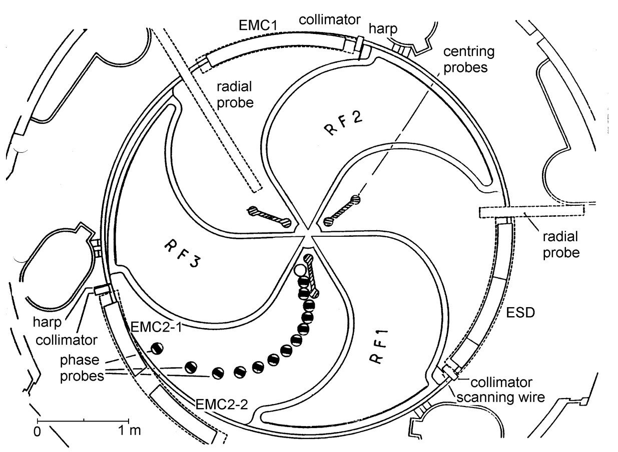

Figure 1: Layout of the AGOR median plane, showing various diagnostic tools and the position of the different extraction elements.
ESD: electrostatic deflector, EMC: electromagnetic channel

Besides the radial probe, the basic diagnostic tool in almost any cyclotron, an extensive set of diagnostics has been integrated in the design (see figure 1) to allow a proper optimisation of beam centring, isochronism and alignment of the beam along the extraction path [4].

BEAM CENTRING

Because of the high magnetic field along the injection path the beam has to be injected exactly on axis. This implies that the orbit of the injected beam is off axis by about 15 mm. The major part of the centring error is corrected by the geometry of the acceleration electrodes in the central region of the cyclotron. The remaining centring error (1 – 2 mm) is corrected with a first harmonic of the magnetic field produced with two of the inner trimcoils [4].

Minimising the centring error is essential to obtain high extraction efficiency and to minimise the radial emittance of the extracted beam. Because of the large phase acceptance (around 30°) the number of turns needed to reach extraction radius varies by about 20, corresponding to several precession periods of the coherent radial betatron motion associated with the centring error. The resulting precession mixing causes a significant increase of the emittance of the beam at the entrance of the extraction system. This leads to reduced extraction efficiency and increased emittance of the extracted beam.

To verify the centring three probes have been installed at azimuths 120º apart to measure the radial turn pattern just beyond the central region of the cyclotron. The use of these probes to optimise the beam centring has turned out to be complicated:

- The observation of the individual turns requires the magnetic field to be tuned such that “turn” focusing is achieved: the number of turns required to reach a given radius has to be independent of the injection phase of the particles. The large phase acceptance allows this to be achieved only approximately, resulting in a small radial intensity modulation rather than separated turns.
- The centring error to be corrected can be as large as the radius gain per turn due to acceleration. Together with the weak turnseparation this makes it difficult to link the turn patterns from the three probes and extract the centring error from the data.

These complications preclude automatic calculation of the centring error from the measurement and thereby its use for the routine operation of the accelerator.

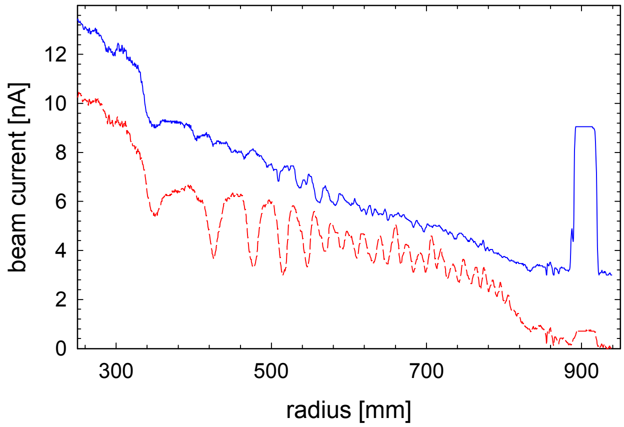

Figure 2: Radial oscillation pattern measured with the radial probe before (dash) and after (full) optimisation of the beam centring. The full curve has an offset of 3 nA. Note the strong influence of beam centring on extraction efficiency (peak at 900 mm).

An alternative method has been developed, which uses the main radial probe in the cyclotron. In front of the probehead a 0.5 mm tungsten wire has been mounted, which intercepts a fraction of the beam just before it hits the stopping block of the probe. In this way information on the current density is introduced in the scans.
The precessional motion induced by the centring error leads to variations in the current density at larger radii, where the turns are no longer separated. The amplitude of these variations is a measure of the centring error and can thus be used to optimise the first harmonic (figure 2).

ACCELERATION REGION

Because of the absence of phase stability the main concern in the acceleration region is to maintain isochronism. Apart from ensuring acceleration up to extraction radius isochronism is important for the extraction process, which uses a precessional motion excited at the passage of the $\nu_r = 1$ resonance. The optimum tuning of this first harmonic strongly depends on the beam phase at the resonance passage and its further evolution in the fringe field up to the entrance of the extraction system.
The radial probe is used to tune the magnetic field such that the beam is accelerated all the way up to extraction. This typically requires an overall field correction $\Delta B/B < 3 \times 10^{-4}$ with respect to the calculated settings. This correction is made with the main coils. For the final optimisation with the trimcoils the beam phase is measured as a function of radius using 13 capacitive pick-ups. Strong perturbations from the RF system have sofar made it impossible to do this in a systematic way. Thanks to the complete saturation of the iron hill sectors the magnetic field has good reproducibility, thus alleviating the need for beam phase measurements during routine operation. A new system has been successfully tested and will be implemented in the near future [5].

The radial probe in the AGOR cyclotron runs along a straight track. This greatly simplifies the mechanical design as compared to the “train”-probes running along a track following a symmetry axis of the cyclotron, which have been installed in other superconducting cyclotrons. The consequences of this choice are:

- No measurement can be performed during the first fifty turns. We do not consider this a handicap, except for the study of vertical beam motion.
- The angle of incidence of the beam on the probe head varies by some ±10° with respect to the optimal right angle. Consequently the efficiency of the current measurement varies with radius. For high energy proton and deuteron beams very little signal is left close to extraction, which seriously complicates tuning. This problem has been partly cured by making the tangential edge of the probe head parallel to the beam direction close to extraction. Comparison of the scans of figures 2 and 3, made with the original and modified probeheads respectively, clearly shows the effect of this.

A good vertical alignment of the beam is important to minimise coherent vertical betatron motion, in particular for beams close to the vertical focusing limit. Like the radial oscillations this leads to reduced extraction efficiency and increased emittance of the extracted beam. The vertical beam position is measured with the radial probe, which can be equipped with a layered head.

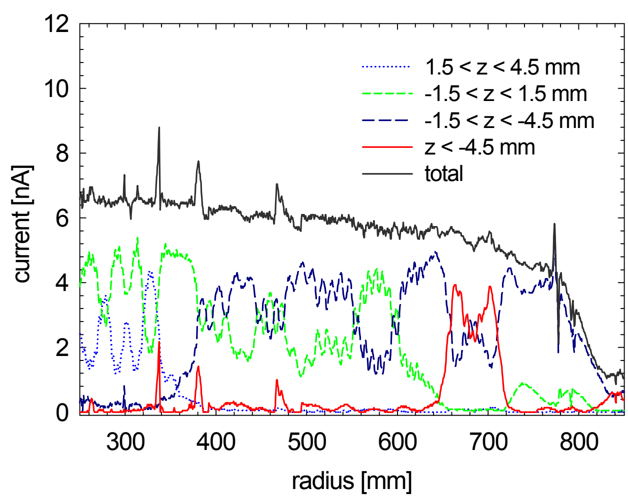

Figure 3: Vertical beam motion measured with the radial probe. Coherent vertical betatron motion caused by off-midplane injection and large-scale motion caused by coil misalignment are observed.

The measurements of the vertical beam position have been crucial for understanding the behaviour of beams close to the vertical focusing limit. Localised vertical beam losses and large vertical excursions of the beam have been observed (figure 3). Comparison of the measurements with calculations showed that the most likely cause of these excursions is a vertical misalignment of the superconducting coils by about 0.6 mm, despite the fact that the alignment of the coils was made on the basis of field measurements.

EXTRACTION

In superconducting cyclotrons the extraction system has to guide the beam through an extensive fringe field region with large gradients. Consequently the extraction system extends over almost 360° and consists of several elements. These elements provide bending and horizontal focusing along the extraction path but also perturb the beam motion in the acceleration region, in particular near the $\nu_r = 1$ resonance. As this resonance is used to properly position the beam at the entrance of the extraction system, the field perturbations of the extraction elements have to be compensated with correctors integrated in the different elements.

The extraction system of the AGOR cyclotron consists of electrostatic and electromagnetic elements (figure 1), in contrast to other superconducting cyclotron where also magnetostatic elements are used. A quadrupole doublet (QP) in the beam exit port of the magnet is not displayed. The position of all elements can be adjusted to the extraction trajectory of the various beams. For the ESD also the curvature can be adjusted. In total the extraction system (exc. QP) has 18 adjustable parameters. Optimisation in this large parameter space is only possible thanks to detailed tracking calculations for some twenty typical beams throughout the operating range.

To verify the proper settings diagnostics measuring the radial beam profile all along the extraction path is needed, starting at the entrance of the first extraction element.

At the entrance of each element a beam profile monitor (either scanning wire or harp) and a collimator with current readout have been installed. The profile monitors do not operate satisfactorily for the high-energy proton and deuteron beams, which make up for almost 80 % of the beamtime:

- The strong magnetic field (up to 4.1 T) in which they are placed suppresses the delta electron emission, which normally strongly increases the signal, despite the fact that the wires have been tilted with respect to the magnetic field.
- The typical beam current of ≤10 nA is at least one order of magnitude lower than anticipated during the design stage. This is due to the good beam quality and the large acceptance of modern experimental set-ups, resulting in higher transmission and lower luminosity.

The collimators, however, provide a workable alternative. When the beam “touches” the walls of the collimator (20 mm tungsten) the current on the collimator strongly increases due to delta electron emission, thus allowing the optimum setting of the preceding element to be found rather easily.

At the exit of ESD, EMC1 a beam current measurement is made with a radially scanning probe intercepting the beam. This measurement is used to optimise the transmission through the extraction system.

At the exit of EMC2 no current measurement has been installed, the measurement at the machine exit, beyond the quadrupole channel was considered sufficient. Operation experience has shown that a beam intensity measurement at this location would be very helpful as a diagnostic tool. The installation of such a measurement is planned. However, the compactness of the cyclotron complicates the design.

CONCLUSION

In the design of the AGOR cyclotron a complete set of beam diagnostics has been integrated to allow optimisation of all the relevant tuning and beam dynamics issues: beam centring, isochronism, radial and vertical motion and extraction settings. At the beamintensities foreseen in the design these operate well after minor modifications, with the exception of the phase probes. Exploitation of the results from the centring probes has turned out to be impractical for routine operation; an alternative using the main probe has been developed. At the actual intensities, at least one order of magnitude lower than anticipated, operation of the beamprofile monitors along the extraction path is insufficient for light ions. A satisfactory work-around for this problem has been found.

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