BEAM QUALITY IMPROVEMENT AT JULIC

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Abstract

To improve the external beam quality at JULIC, three different measures have been undertaken: the development of a systematic procedure for beam phase optimization, the precise adjustment of the center region to nominal values as well as the installation of harmonic coils near the cyclotron center and the introduction of two axial phase slits according to calculations for proper axial imaging. Starting with a cyclotron as it was tuned in the former day by day operation, the successive application of the above means resulted in an improvement of the radial emittance by a factor of 2 to 10 mm·mrad and of the energy resolution by a factor of 3 to below $1.5 \cdot 10^{-3}$. The three different means for better machine tuning and their effect on the external beam quality are described.

1. Introduction

The predominant requirement for the ease and quality of most nuclear physics experiments is a good over-all energy resolution. From the accelerator side the inherent energy spread of the beam is of direct concern, whereas the radial beam emittance comes indirectly into play via kinematic broadening in the case of light target nuclei. If we assume that all relevant parameters of a cyclotron are stable in time, three main properties of the accelerating process determine energy spread and radial emittance of the external beam: beam phase along radius, beam phase width, and orbit centering, the latter two being determined in the center of a cyclotron[1]). The energy spread is determined by the first two properties in the case of single turn extraction. The situation gets more complex in the region between single- and multi- turn extraction as in the JULIC case. For the beam emittance the following applies: A broad phase width of the beam burst with respect to the RF results in an inherent spread of the orbit centers, thus deteriorating the radial beam quality. Both a non-optimized beam phase along radius and a broad phase width with respect to the RF give rise to the precessional mixing effect[2]), in the case of a non-well-centered beam with a high number of revolutions to extraction radius. Especially the latter effect is often the reason for a poor radial emittance with poor reproducibility.

At JULIC two special requirements make an improvement of these three properties even more stringent: As was pointed out previously[3]), the overall resolution of the combined and fully matched system, beam line/spectrograph "Big Karl", varies to first order linearly with the radial beam emittance. A non-optimized beam phase along the radius makes macroscopic beam pulsing, performed with axial deflecting plates in the cyclotron center, impossible for desired beam fall off times in the microsecond-region[4]).

2. Beam Phase Optimization

The original trim coil current sets delivered by the cyclotron manufacturer led the beam to extraction radius, but left the job of obtaining an optimal beam phase along the radius to the operator by means of a live display of the beam phase picked up by capacitive probes at 12 radii. This scheme depends on the ability of the operator and the reliability of the phase measuring equipment available at that time at JULIC, and turned out to be impractical in routine cyclotron operation. The analysis of the original trim coil field data[5]) revealed one possible reason for this situation: trim coil fields had only been measured in the radial but not in the azimuthal direction. Therefore, the trim coil functions were not known with the necessary precision. Instead of remeasuring trim coil fields to the necessary extent, the strategy was to make use of the beam phase measurement along the radius. Since each trim coil field (see figure 1) influences the beam phase along radius in a complex way, a systematic mathematical procedure[6]) has to be applied to achieve optimal beam phase along the radius.

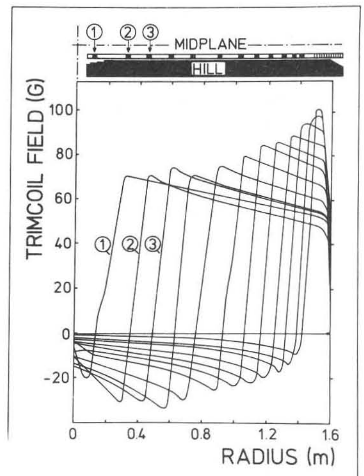

Figure 1
Radial shape of the trim coil fields at $\bar{B}$=13.5 kG, each trim coil being separately tuned to the maximum of 400 Ampère-turns.

For small deviations from the zero beam phase and small current changes, the relation between phase shift and trim coil current variation can be taken as linear in the following form

$$\phi = \begin{pmatrix} \Delta\phi_1 \\ \vdots \\ \Delta\phi_n \end{pmatrix} = \sum_{j=1}^{m} \vec{\pi}_j \cdot \Delta I_j = B \cdot \vec{I} \;, \qquad (1)$$

where $\Delta\phi_i$ are the phase shifts measured at n different radial positions and the ΔI_j are current changes at m different trim coils. Each so-called trim coil vector $\vec{\pi}_j$ represents the phase shift vector, when changing trim coil current number j by 1 A. Small changes in current and phase are assumed for equation (1). Using an iterative procedure, we apply this equation also in the case of large changes in phase or current. For a non-optimal phase vector $\vec{\phi}_1$, we now ask what current change $\vec{I}_1$ is necessary to bring the phase vector close to the zero vector.

If the columns of matrix B, i.e., the trim coil vectors $\vec{\pi}_j$, are linearly independent, a general solution of the problem is given by

$$\vec{I}_1 = -(B^T \cdot B)^{-1} \cdot B^T \cdot \vec{\phi}_1 = C \cdot \vec{\phi}_1 \;, \qquad (2)$$

where B^T is the transpose of B and C is called the control matrix.

The determination of the control matrix C has up

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to now been based mainly on radial field data corrected by beam phase measurements and is therefore afflicted with errors. This, and the fact that the control matrix is applied in the procedure even for rather large current or phase changes, might influence the convergence of the iterative control scheme. Therefore it is necessary to choose the "most orthogonal" set of trim coil vectors. Starting with the first two, determined from the minimum of the inner products of all pairs of the trim coil vectors, each next vector is successively evaluated for being "most orthogonal" to the latter set. This process is stopped, in case the remaining trim coil vectors can "nearly" be composed by linear combinations of the already evaluated set. What "nearly" means has to be estimated from the accuracy in determining the trim coil vectors.

At JULIC a control matrix C_0 was determined from phase as well as field measurements performed at $\bar{B}_0$ = 12.7 kG. The phases were measured at n=12 different radial positions. The distance between each two positions covered about the same number of turns. As "most orthogonal" set, m=7 trim coils were used in the control scheme. Figure 2 shows a typical result of the described control scheme improving the phase along radius in 2 iterations. Even with the fact that the control matrix depends not completely linearly on the field level $\bar{B}$, similar results in less than 4 iterations have been obtained for other field levels just by applying a control matrix $C=(\bar{B}/\bar{B}_0)C_0$.

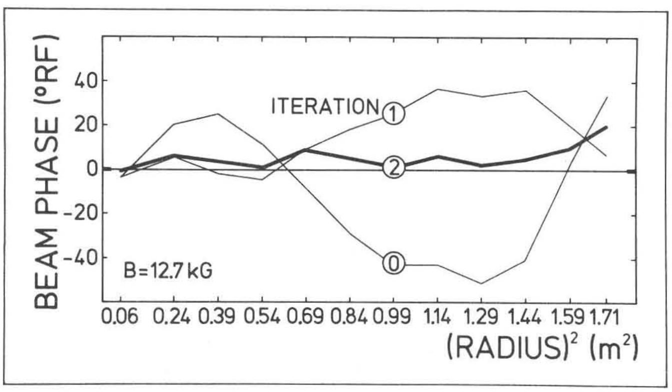

Figure 2
Improvement of beam phase along radius in 2 iterations at $\bar{B}$=12.7 kG (80 MeV deuterons).

Up to now the computer has been used off-line in the control scheme, determining the phases with a radial probe from the time distribution of prompt γ's and changing trim coil currents manually. With the newly installed phase measuring equipment[7], on-line computer control will allow a much quicker iterative control scheme. Computer-aided beam phase determination supported by recent trim coil field measurements, including the azimuthal direction, will facilitate the evaluation of more precise control matrices for different field levels. This we intend to do next.

3. Beam Centering

The presence of about 3 mm of radial coherent amplitude gave rise to a first investigation to improve the RF-center region[8] and finally resulted in the decision to use a variable first harmonic in the magnetic field near the cyclotron center as a much more flexible means for beam centering. The use of the first two of the twelve trim coils installed in the 3 hills for this purpose turned out to be not satisfactory with the original power supplies and would have complicated the procedure to achieve an isochronous field. However, between the first and second half of the windings of the first trim coil, there was still enough space for the insertion of separate harmonic coils (see figure 3, left). The radial oscillation frequency ν_r is relatively large (~1.05) in this region; but since the number of turns in the field bump is small, the centering of the beam can be achieved in an easy manner. This was confirmed by orbit calculations, based on field measurements of a proto-type coil in the cyclotron center. As can be seen in figure 3 (right), the introduction of an adequate first harmonic results in a reduction of the radial coherent amplitude from 3 to below 1 mm, sufficiently low in practice.

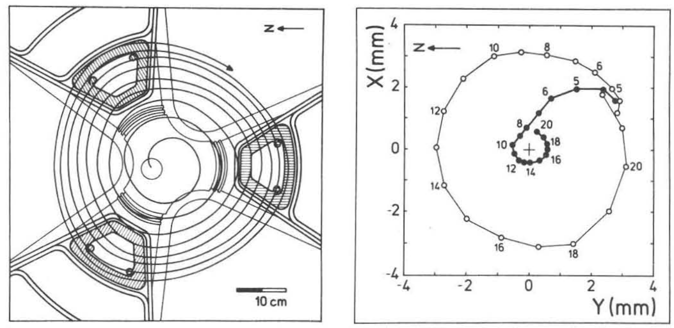

Figure 3
Beam centering with the inner harmonic coils:
left: Location of harmonic coils between the first and second halves of the first trim coil, together with a display of the first 14 revolutions.
right: Movement of the orbit center with (full circles) and without an appropriate first harmonic generated by the inner harmonic coils. Corresponding radial coherent amplitudes are reduced from 3 to below 1 mm.

Parallel to this investigation, a much deteriorated adjustment state of the RF-center just before the annual shut-down in 1976 gave rise to the development of a precise method for observing the RF-center and a clear and easy procedure for its adjustment to nominal values. For the observation of the RF-center under working conditions, a camera support tube has been constructed and is inserted in the central bore of the lower magnet yoke. At its upper end, a glass window carrying an illuminated cartesian coordinate grid is sealed to the lower magnet pole. Since each tip of the three accelerating units (see figures 4 and 5) includes a tip of the inner conductor (Dee) and, on either side, a tip of the outer conductor (Dummy Dee), the revised adjustment procedure starts with the positioning of the separate Dummy Dee tips to their nominal values. Using newly designed coupling plates, which gave the necessary extra degree of freedom (not available up to then), the rest (and main part) of the accelerating units could then easily be matched to the Dummy Dee tips. After this the inner conductor (Dee) of the unit could easily be adjusted with respect to the Dummy Dee tips.

The difference in the adjustment state of the RF-center before and after the adjustment procedure can clearly be seen in the two photographs of figure 4. Additional water-cooling installed at the Dee stems resulted in a reduction of the movement of the Dee tips (caused by RF-power dissipation) from previously up to 2.7 mm to now 1 mm. Various photographs of the center region have been taken in the past two years, especially after removing and remounting the accelerating units. Significant changes have not been observed. The care-

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ful adjustment of the RF-center to the nominal values and the additional cooling at the Dee-stems resulted in much better beam centering, without any first harmonic field in the center, and with a coherent radial amplitude of less than 1 mm.

This result is the reason why the new inner harmonic coils (see figure 3), which in the meanwhile had been installed in new isochronous trim coil plates near the cyclotron center, have been used up to now only in tests and for a repeated measurement of the precessional mixing effect on the external beam quality. The test showed that any radial coherent amplitude up to 5 mm generated on the first orbits can be compensated at small machine radii.

4. Axial Phase Selection

Radial phase dispersion has been calculated to be too small for proper radial phase selection at JULIC.

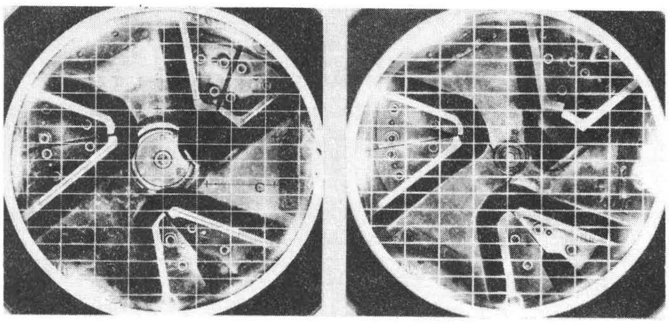

Figure 4
Adjustment state of the RF-center before and after the new adjustment procedure (see Figure 5 for further explanation)

Axial phase selection has the advantages that the optimum position of the slits can be calculated in a simple way and that their radial positioning in the cyclotron is much less critical[6].

The criterion for an optimum radial/azimuthal position of two axial phase slits is the following: The transformation of the particle coordinates in axial phase space from slit 1 to slit 2 given in the form

$$\begin{pmatrix} Z_2 \\ Z_2' \end{pmatrix} = M \cdot \begin{pmatrix} Z_1 \\ Z_1' \end{pmatrix} \qquad (3)$$

should be independent of Z_1' for the desired phase. Therefore matrix element m_{12} should vanish and the slit height of slit 2 should be $h_2 = m_{11} \cdot h_1$ for optimum transmission.

Matrices M have been evaluated for an adequate set of RF-phases from numerical calculations of the axial particle movement. For this, electrical as well as magnetic field data have been used. For a technically possible solution, attention was directed to the azimuths of the center-line of the 3 Dees to use the driving mechanism of the so-called Dee-targets for positioning. As is shown in figure 5, a solution has been found for slits on the first and fourth turn in the center SE- and N-Dee, respectively, for -49° RF initial phase, which is the highly populated desired phase. The corresponding magnification m_{11} turned out to be nearly 1, so that slits of equal height $h_1=h_2=h$ have been used.

Figure 6 (left) shows the results of acceptance calculations for different initial phases. Corresponding center position phases on the fifth turn are given as well. They describe the actual development of the beam phase during the first revolutions much better than the normal phase definition. The definition of the center position phase[9] uses the azimuth of a particle with respect to the actual orbit center instead of the azimuth with respect to the cyclotron center. The acceptance calculation reveals a second maximum for later phases. But in this region, characterized by the dashed line, particles are probably not accelerated. This was confirmed by the results of beam phase distribution measurements (see figure 6, right). The result of axial phase selection with 2 slits (curve 3) is in agreement with the calculation, reducing the phase width (FWHM) from 14 to 7° RF. The transmission through both slits was measured to be around 10%. Phase distribution 2 clearly tells that the insertion of just one slit has no relevant effect on the phase width.

5. Successive Beam Quality Improvement

The iterative procedure for beam phase optimitization along radius and the axial phase selection have successively been applied using a beam of 60 MeV deuterons at JULIC. The beam was well centered; the evaluation of turn pattern measurements showed a radial

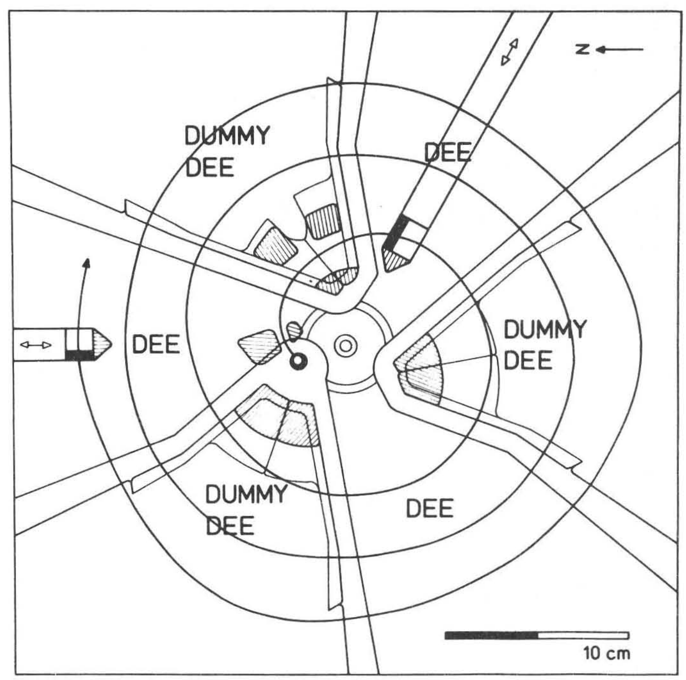

Figure 5
Location of first and second axial phase slit in the SE- and N-Dee on the first and fourth revolution, respectively, together with a display of the RF-center.

coherent amplitude below 1 mm. The extraction system was not touched throughout all steps. But it has to be emphasized that for reproduction of the best result in each step, small changes in frequency and RF-amplitude had to be applied, probably due to long term instabilities, especially of the RF-amplitude.

In each step above the external beam quality was evaluated from emittance measurements[10] and from recordings of deuteron spectra under 10.5° with a Ge(Li)-detector at a scattering chamber. The figures for the energy resolution in table 1 have been calculated

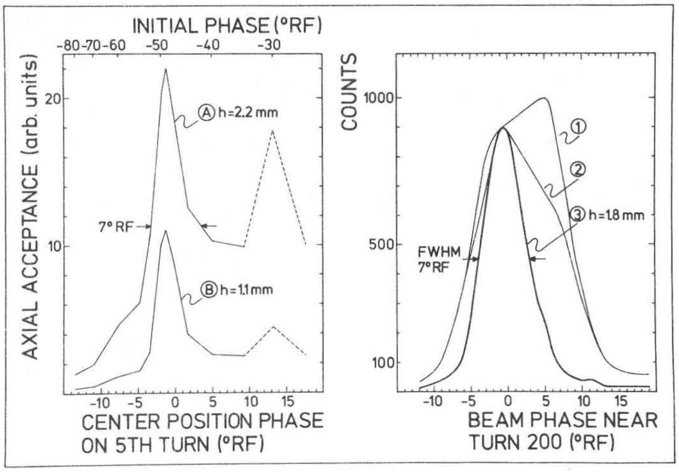

Figure 6
Axial phase selection:
Left: Axial acceptance of the two phase slits calculated for h=2.2 and 1.1 mm slit height (A,B) versus initial and center position phase on the fifth turn
Right: Beam phase distribution measured with the prompt-γ method near turn 200 for no slit 1, first slit 2 and both slits 3 being inserted. Both slits have the same aperture of h=1.8 mm.

from deuteron spectra using a pure Au-target (0.2 mg/cm^2) and taking into account energy loss straggling through the target, the exit foil of the scattering chamber and the entrance window of the detector. For a visual presentation of the results, spectra from a combined (C_2H_2+Au)-target (see figure 7) have been measured. The improvement of energy resolution (peaks C, Au), as well as of radial emittance (peak H) via the corresponding angular beam width reduction at the target, can clearly be seen. For the latter, one should notice that, in terms of base width, the angular opening of the detector with respect to the target was about 7 mrad, whereas the angular beam width varied from 14 to 6 mrad between step 0 and 3. The first two inserts in the spectra of figure 7 give clearly the difference of beam phase along radius in the first two steps. Quantitative results for each step are given in table 1. The overall factor of improvement is larger than 2 for the radial beam emittance and larger than 3 for the beam energy width.

6. Conclusion

With beam phase optimization, beam centering and phase selection, the measures have been taken at JULIC which, in principle, are necessary to optimize the acceleration process of a cyclotron with respect to external beam quality. Further beam quality improvement is now mainly expected from further stabilization, especially of the accelerating frequency and the RF-amplitude

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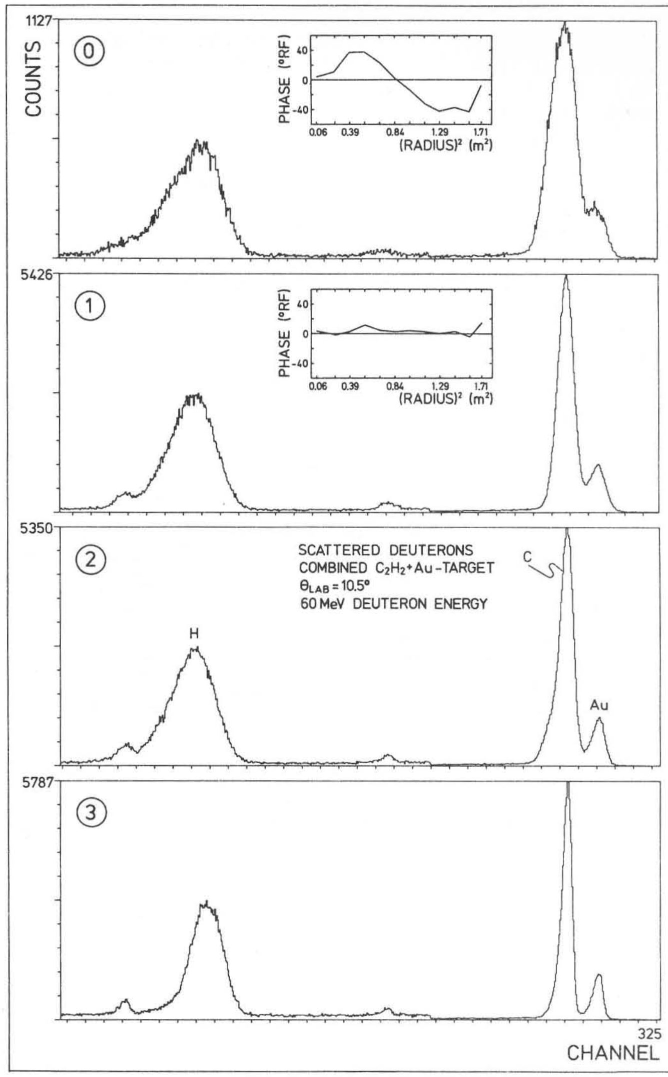

Figure 7
Successive beam quality improvement:
Deuteron spectra taken from a combined (C_2H_2+Au)-target at 60 MeV incident deuteron energy. Numbers in circles are explained in Table 1 and correspond to those in Figure 6, right. The inserts show beam phase along radius.

Table 1
Results of Successive Beam Quality Improvement

STEP	$\Delta\phi$ FWHM (°RF)	ε_x* (mm·mrad)	$\Delta E/E$ FWHM x10^3	EXTR. EFF. (%)
0 "BAD" PHASE ALONG RADIUS	14	23.5	5.0	30
1 "GOOD" PHASE ALONG RADIUS	14	19.4	3.2	47
2 1st AXIAL SLIT	14	15.0	3.2	60
3 1st and 2nd AX.SLIT	7	10.0	1.4	75

*radial emittance for approximately 90 % beam intensity

References

1) H.G. Blosser, Proc. 5th Int. Cyclotron Conf., Oxford (1969), p. 257

2) H. Thimmel, Interner Bericht AEG-TELEFUNKEN Nr. E4/E 33.03/73 (1973)

3) J. Reich, S. Martin, D. Protić and G. Riepe, Proc. 7th Int. Conf. on Cyclotrons and their Applications (Birkhäuser, Basel, 1975), p. 235

4) R. Brings, N. Dolfus and P. Wucherer, Annual Report 1977, IKP-KFA, Jül-Spez-15 (1978), p. 125

5) H. Scharlemann, Technischer Bericht AEG-TELEFUNKEN Nr. 1005 (1968)

6) G.C.L. van Heusden, EUT Thesis, Eindhoven (1976)

7) W. Bräutigam, K. Kennepohl, M. Herschbach and J. Reich, these proceedings

8) J. Linz, P. Wucherer and J. Reich, Proc. 7th Int. Conf. on Cyclotrons and their Applications (Birkhäuser, Basel, 1975), p. 279

9) W.M. Schulte, H.L. Hagedoorn, these proceedings

10) J. Bojowald, H. Borsch, W. Kuhlmann, J. Reich and A. Retz, AIP Conf. Prof. No. 9 (1972), p. 399

0018-9499/79/0400-2011$00.75