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THE MODIFIED CENTER REGION FOR THE PROJECT ISIS AT JULIC

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Abstract.- In the frame work of the project ISIS the isochronous cyclotron JULIC will be adapted to accelerate also heavy ions, produced in an external ECR-source. To realise this goal a new design of the central region of JULIC is necessary. Using a self optimizing computer code the new geometry of the central region was designed for the existing h=3 harmonic mode of RF-system. In connection with plans to enlarge the actual energy range of the JULIC, additionally, similar calculation were carried out anticipating h=2 and 5 harmonic modes of operation.

1. Introduction.- An external ECR-source is the key system for the project ISIS[1] (Injektion Schwerer Ionen nach EZR-Stripping) to enable the acceleration of heavy ions with the isochronous cyclotron JULIC. Such a source provides highly stripped ions with appreciable intensities. Thus it is suited for JULIC, which only can accelerate ions with a charge to mass ratio $Q/A \geq 1/3$. This restriction is due to its special RF-system[2]. The three Dees in the valleys represent at the same time the resonators and are coupled together in the center. From this results the limited operating frequency range of 21-30 MHz and the only mode of operation on the harmonic number h=3.

To match the ECR-Source now under development[3] to the cyclotron a beam preparation, guiding and injection system[4] has been designed. For the final inflection into the cyclotron median plane a hyperboloid type inflector[5] has been chosen. This inflector needs more space than the present Livingston type internal source. The ion start energy enhances from zero to several keV/A. Any modification of the RF electrodes should be restricted only to the Dee tips (Radius $\leq$ 10 cm). These were the main side constraints for the redesign of the RF-center region. The goal to produce beams of as high luminosity as possible led us to prefer the external injection and to abandon the compromise between the internal and external source operation. Therefore, an external light ion source will also be coupled to the external injection system in addition to the ECR-source.

Our users developed a strong demand for energies outside the present operating range of 22.5 to 45 MeV/A. Especially, an extension from 22.5 down to 6 MeV/A is desired for nuclear spectroscopy experiments. This demand could in principle be met by providing a multiharmonic mode of operation at a somewhat extended frequency range. One solution to this, presently in discussion, would mean to decouple the three Dees, drive them separately and to provide a 120^{0} phase shift between every two Dees. None of the technical problems related to the multimode operation has been investigated in detail so far. Nevertheless, the initial solutions to the necessary RF-center modification for h=5 and h=2 harmonic operation are described in this paper. The h=5 mode is necessary to provide lower energies while h=2 would, for instance, push the H^+ and $^3He^{2+}$ beam energies towards the focusing and the bending limit, respectively.

2. Method of calculation.- For an effective design procedure of the center region a self optimizing computer code is needed. Therefore an analytic orbit calculation procedure[6] was used. The magnetic field is assumed to be uniform. The electric field in the accelerating gaps is also uniform but varies in time as a cosine function. Only the particle motion in the median plane was calculated. The emittance was assumed to be $160 \cdot \pi$ mm-mrad[3,4]. For all the calculations we started at the exit of the inflector with an upright phase ellipse with a radial spread of ±1.6 mm and maximum divergence of ±100 mrad. The ellipse was represented by a center particle and 8 particles on its circumference (see the inset in fig.1). Another fixed parameter was the phase width of $\pm 20^{0}$ RF at the exit of the inflector. We expect that the buncher system in the beamline is able to focus the majority of the beam in a time interval which is smaller than 40^{0} RF. The phase width is represented by 3 particles with the phases Φ_0-20^{0}, Φ_0 and Φ_0+20^{0}. The total phase space is thus represented by a total of 3x9=27 particles. The central phase Φ_0 and the geometry of the puller region (coordinates of the inflector and the puller) are the most sensitive free parameters. The fit procedures minimizes the weighted sum of functions which take into account the following beam properties on the turns 2 to 4:

1) Deviation of the mean point (BC in fig. 1) of the centers of gravity of the centers of curvature (six per turn corresponding to 3 valleys and 3 hills) from the machine center (MC in fig. 1) for all the 27 particles. This minimizes the coherent amplitude (distance BC-MC in fig. 1).
2) The spread of the centers of gravity of the centers of curvature (six per turn), that means the radius of a circle which includes all 27 points (see fig. 1). This minimizes the incoherent amplitude for the given emittance and starting phase width.
3) The spread in the radius of curvature of the 27 particles to minimize the energy dispersion and phase width.

The axial focusing is guaranteed by the restriction to positive phases at the center of each gap.

The design parameters have been divided in two categories i.e. the ones describing the geometry and the others describing all the other quantities. Out of the geometrical parameters the following were set free in the fit procedure: the coordinates of the point and the angle at which the beam leaves the inflector, the distance between the inflector and the puller electrode, the angle of the puller edge, and the coordinates describing the geometry of 2nd to 7th gap.

3. Design for the h=3 harmonic mode.- In connection with the project ISIS the work concentrated on the design for the existing h=3 harmonic mode. The non-geometrical parameters, fixed or free, in the above described calculation are given in table 1. The resulting design and its quality is explained by means of the figures 1 through 3.

Table 1: The non geometrical parameters used in the calculation. For the free parameters the final results are given.

Parameter	Type	Value
Horizontal emittance	fixed	$\pi\cdot 1.6\cdot 100$ mm-mrad
Center phase at start	free	-103^{0} RF
Phase width at start	fixed	$\pm\ 20^{0}$ RF
Injection energy	free	3.9 keV/amu
Dee voltage	free	41.3 kV
Resonance frequency	fixed	29.5 MHz for d^+
Magnetic field	fixed	1.28 Tesla

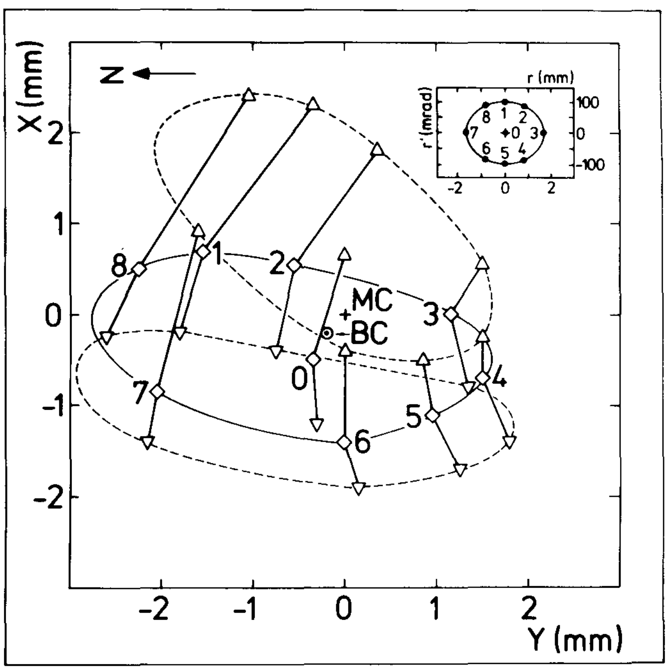

Fig. 1: Centers of gravity of the centers of curvature representing 9 particles (labelled 0 through 8) on the starting ellipse (see inset) at three different starting phases (◇:ϕ_0, Δ:ϕ_0+20°RF, ∇:ϕ_0-20°RF) during the 4th revolution. BC=beam center; MC=machine center.

The numbers 0 through 8 in figure 1 refer to the start ellipse in the radial plane (see inset of the fig. 1), representing the center and the circumference of the ellipse, respectively. The points corresponding to the circumference of the ellipse have been interconnected separately for each of the three starting phases ϕ_0 and $\phi_0 \pm 20^0$ RF. The resulting figure nearly reproduces itself after each revolution following the second and displays three ellipse like curves. The distance between the machine center, MC, and the mean point of the 27 particles, BC, is a measure of the coherent amplitude. The half of the maximum distance across the figure gives an estimate of the incoherent amplitude. These two quantities correspond to the first two fit functions described in the previous section.

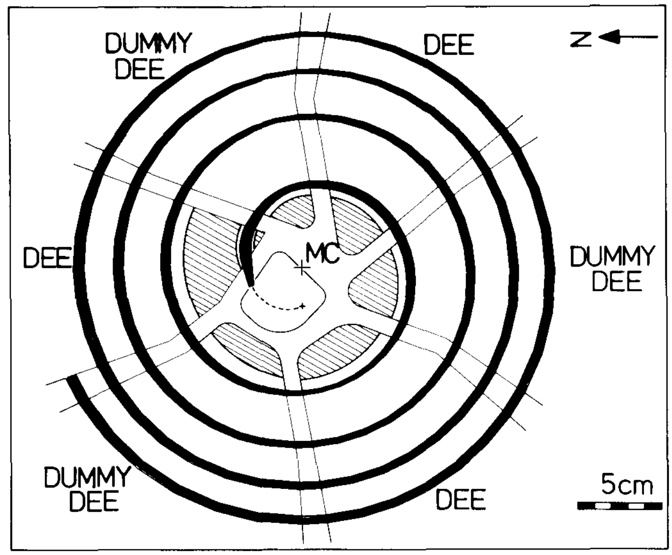

Fig. 2: Structure of the RF-center region together with the orbits of 27 particles (resulting in a black beam region) for a radial emittance of 160·π mm-mrad and a starting phase width of ± 20° RF.

Fig. 2 shows the first orbits in the median plane for all 27 particles together with the fitted geometry of the accelerating gaps and the inflector. There is sufficient space for the inflector and the necessary Dee and Dummy Dee-posts (hatched regions).

For a check of the quality of the design there is a variety of other representations among which we chose the plot of the beam phase versus gap number given in figure 3.

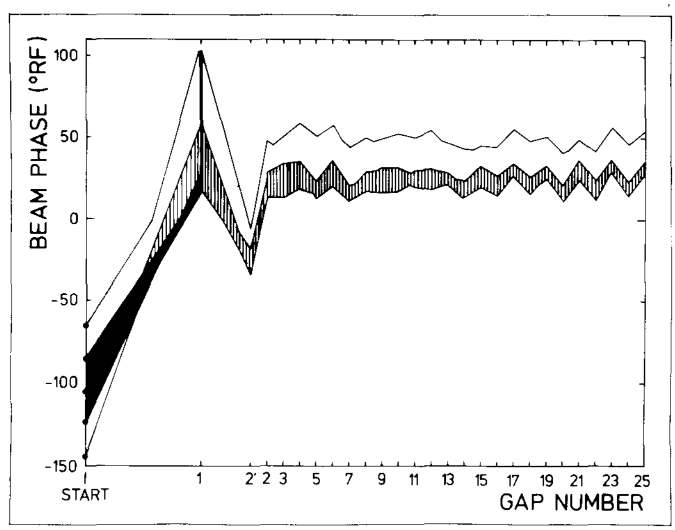

Fig. 3: The blackened region corresponds to the central particles with starting phases of $-(103\pm20)^0$ RF. The vertically hatched region shows the broadening caused by an emittance of 160·π mm-mrad. The outmost lines are the envelopes for phases of $-(103\pm40)^0$ RF and the same emittance.

It shows clearly a very rapid motion of the particles in the time coordinate (phase) during the first two gap transitions. The starting phase ϕ_0 (see table 1) is extremely negative and the particles leaving the inflector are first decelerated. The particles with starting phases from -83° to -123° RF but identical spatial coordinates are focussed in time within the first gap. The blackened area, for instance, shows this effect for particle no. 0 starting from the center of the ellipse. The first gap acts as a rather strong buncher for these particles. The particles on the circumference of the phase ellipse are overfocused during the first gap crossing (blackened and vertically hatched area up to label 1) but get focussed again between the first and second gap (lable 2', vertically hatched area). This second focussing effect results from adequate path length variations in the section between first and second gap and corresponds to the broadening of the beam in this section which can clearly be seen in figure 2. After the second gap the phase band remains practically constant with a width of about 10° RF. The outmost lines show the envelopes for starting phases between -63° and -143° RF, i.e. a starting phase width of ± 40° RF and the same emittance. Since, all these particles are accepted by the cyclotron but have only a moderate beam quality, the bunchers in the beam line should focus them into a desired phase width of ±20° RF.

In order to get more realistic electrical field distributions three dimensional relaxation calculations have been performed. From these calculation attenuation coefficients in the 1st up to 4th gap have been evaluated and taken into account in the present work. A general orbit integration will be the final step on the center region design.

4. Results concerning multimode operation.- The basic philosophy in the design was to reach as early as possible nearly scaled orbits referring to the h=3 mode and to use the same inflector. The method of calculation and the fitting procedure were as already described except that an appropriate 120°-phase shift was applied between every two Dees. Table 2 compares the essential parameters and results for h=2,3 and 5 harmonic mode.

The phase width $\Delta\phi_0$ at the inflector exit was held constant (see table 2) assuming constant efficiency of the beam line buncher system. The resulting starting phase ϕ_0 for h=2 and h=5 is larger (particles start later) and therefore the bunching effect (phase compression) of the first gaps is weaker and consequently the phase width, $\Delta\phi$, after the 25th gap is larger.

Even allowing for bad centering in the fit the radius R_{out} where the beam leaves the inflector could not be held constant for the different modes. Consequently, the radius R_{in} describing the location of the axis of the vertical beam line also changes.

Table 2: Essential parameters and results for different harmonic modes. R_{out} radius where beam leaves the inflector; R_{in} radius where beam enters the inflector (axis of vertical beam line); ϕ_0 mean starting phase; $\Delta\phi_0$ starting phase width; $\Delta\phi$ resulting phase width after the 25th gap; Ac, Ai coherent and incoherent beam amplitude calculated for the 4th revolution.

Parameter	Type	h = 2	h = 3	h = 5
R_{out} (cm)	free	2.6	3.2	4.3
R_{in} (cm)	result	1.7	2.1	2.5
ϕ_0 (°RF)	free	-74	-103	-95
$\Delta\phi_0$ (°RF)	fixed	40	40	40
$\Delta\phi$ (°RF)	result	32	10	20
Ac(cm)	result	0.04	0.03	0.05
Ai(cm)	result	0.27	0.26	0.32

Figure 4 shows the beam envelopes in the median plane up to the 3rd gap for the three different harmonic modes. These results demonstrate that with respect to the RF-center region only a kind of puller change is necessary for a mode change.

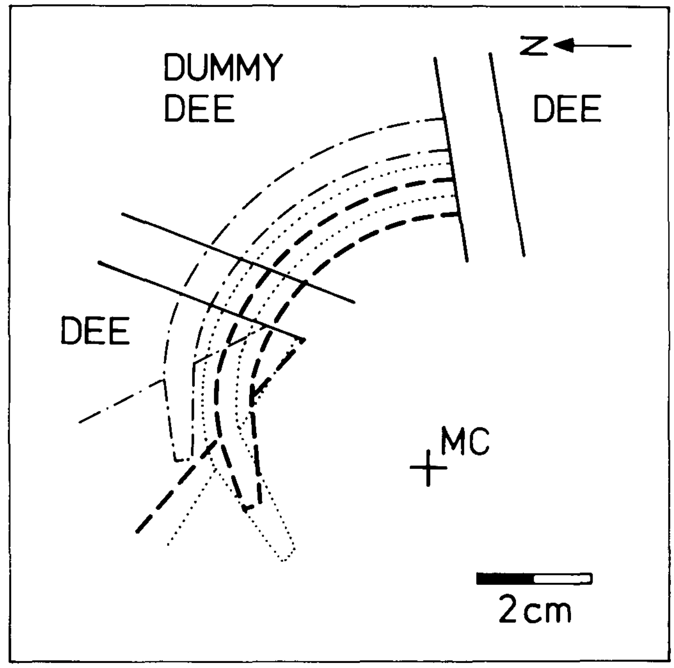

Fig. 4: Beam envelopes up to the 3rd gap and the varying first gap geometry for different harmonic modes (..... h = 2, --- h = 3, -·- h = 5). MC = machine center.

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