ORIC CENTRAL REGION CALCULATIONS*

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Abstract

The central region for the K=100 Oak Ridge Isochronous Cyclotron, ORIC, will be modified to provide better orbit centering, focusing of orbits in the axial direction, and phase selection, in order to improve extraction efficiency, and reduce radioactive activation of cyclotron components. The central region is specifically designed for the acceleration of intense light ion beams such as 60 MeV protons and 15 - 100 MeV alphas. These beams will be used in the production of radioactive atoms in the Radioactive Ion Beam Project at Oak Ridge National Laboratory.

I. RIB PRODUCTION REQUIREMENTS ON ORIC

The Holifield Radioactive Ion Beam Facility, HRIBF, will use the K= 100, Oak Ridge Isochronous Cyclotron, ORIC, as a driver to provide beams of light ions (protons, deuterons, helium, and lithium) ranging from 10 – 65 MeV on target[1]. These will produce proton-rich radioactive atoms for acceleration in the HRIBF 25 MV Tandem. The Target Ion Source on the RIB Platform, presently has a carbon window 170 mg/cm^2 thick. Using the energy loss in this window as a guide, ORIC will need to operate at K≥15 for protons, K≥35 for deuterons and 2-plus helium, and K≥60 with 3-plus lithium. These beams need intensity so as to provide experimenters with sufficient radioactive ions to study nuclear structure and astrophysis. Direct and induced radioactivity produced by these beams, require further constraints on ORIC. The administrative limits for operation as a low hazard facility will be 50μA of 65 MeV protons, and 200μA of 100 MeV alphas. Good extraction efficiency (90+%) is needed to minimize the induced radioactivity produced in ORIC.

II. AN OVERVIEW OF ORIC HISTORY

ORIC was constructed and began operation over three decades ago[2]It was initially used to accelerate light ions. The acceleration of heavy ions in ORIC first took place in 1968[3]. Extraction was achieved by inducing radial oscillations near the center of the cyclotron, and using the precession at 29 in., while ν_r was still $\simeq 1.05$, to increase the radial separation between turns near the deflector septum[4]. In the early 80's, ORIC was converted to be used as a booster for the 25 MV tandem accelerator. A new magnetic field mapping was performed for this conversion in the range of 12–20 kG. This enabled the writing of a set of cyclotron injection/orbit/extraction codes which accurately predicted machine settings for operating the cyclotron in coupled mode for K≥ 60[6]. A new extraction method soon followed. The injected tandem beam had a small emittance, a 6° RF Phase width, and was injected with very good centering. A first harmonic bump was then used at outer radii to produce radial separation closer to the $\nu_r = 1$ resonance, ($\nu_r \simeq 1.017$). These qualities improved the extraction efficiency from a typical 30% to a typical 70%[5] Calculated turn separation at extraction is .1 in.

III. THE PRESENT ORIC CENTRAL REGION

The ORIC central region has been restored to a configuration similar to central regions used before the coupled operations. A PIG ion source is inserted on a radial arm from the North side of the machine. The source, which was modified to use a smaller chimney, can be positioned in both directions in the median plane. The puller, which is a little hook extending out from the dee, can be positioned in one dimension only, along the edge of the 180° dee. It's position in the other direction can be changed by removing the dee and replacing the puller. A radial clipper has been added. It is a small plate with a slot cut axially, that has been mounted on the dee, and runs parallel to the puller. In addition, the source head has been modified so that two plates can be mounted on them to form an axial slit which will restrict the beam axially within the first few turns[7].

Axial focusing in the central region is provided by two separate mechanisms. The first is geometric. The source chimney is set back from the leading edge of the source head. The electric field, which was calculated with RELAX3D[8], penetrates in to the source. Calculations, made with Z3CYCLONE[9], show that this provides axial focusing over most of the gap between the source and the puller when the electric field is accelerating the ions. This axial focusing in the first gap is extremely strong. It over focuses, causing the beam to expand axially. This expansion was measured using marks that a helium beam left on the axial slits, with the axial spread of the beam increasing from .2 in at the source slit to 1.0 in within two turns. The second method of axial focusing comes from rotating the source counter to the direction of the beam rotation[10]. This makes the beam arrive late with respect to the RF at subsequent gaps, providing vertical focusing. To bring the beam back to isochronism after the azimuthally varying magnetic field is strong enough to provide vertical focusing, the magnetic field begins above the isochronism value, returning to isochronism after a few inches, forming a magnetic cone at the center.

The central region is very open, with up to 100° width of RF phase of beam clearing the back of the source. Much of this time spread is lost after the crossing of the $\nu_r = 1$ resonance found at the transition between the magnetic cone and the isochronous field. Depending on the centering of the source, the relative posi-

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tion of the puller, and first harmonic component of the magnetic field added by the innermost harmonic coils, calculations have shown anywhere from 15° – 45° of RF phase of beam orbiting about the center of the cyclotron after this crossing. The ions remaining outside of that time range orbit about the magnetic hills, subsequently returning to the machine center and being lost.

The properties of this open and variable geometry, a wide phase acceptance, a strong variation of centering with phase, and difficulty finding the optimum positions, are counter to those required for consistent, efficient extraction of the beam[11]. Indeed, the good extraction obtained in coupled operation was dependent on both good centering and a small phase width. Recommissioning runs have found the earlier extraction technique easy to reproduce, with 40% extraction efficiency, but the predictions of the cyclotron codes, lacking information about the source, are now only 'ball park' predictions.

IV. CALCULATED MODIFICATIONS TO THE ORIC CENTRAL REGION

Ideally, the installation of a fixed central region, designed to provide good centering, together with slits to provide fine phase selection, would be the best way to provide these qualities consistently for all operating points. This would entail completely redesigning the source for axial insertion, with accompanying changes in the center plug iron. The RF system, which is now used to provide 70 kV at all operating frequencies, would also need to provide a wide range of voltages to accelerate the various combinations of Q/A and E_f/A which are required.

Table I
Operating K Values for the three Pullers

ρ in	V_{dee} kV	p	$^3He^{2+}$	d,$^4He^{2+}$, $^6Li^{3+}$	$^7Li^{3+}$
1.07	70		100		
	66	65			
	54			100	
	47				100
	43	40	60	80	93
1.34	70	40	60	80	93
	43	25	36	50	60
1.69	70	25		50	
	43	15		33	
K to penetrate C window		12	35	32,46,60	70
Lowest K in first harmonic		7.3	16.4	29.2	39.7

Instead of a fixed central region, it is proposed that ORIC operate with a set of modified pullers, each operating over a smaller portion of the operating diagram as if it were part of a 'fixed central region'. With two such pullers, one where the ions have a radius of curvature after the first gap of 1.07 in, and the other 1.34 in, most of the useful part of the first harmonic operating range can be covered. If lower energy beams are desired, a third puller with a 1.69 in radius of curvature could be used. Table I lists the range of K values over which each puller will operate, with the associated accelerating voltage as a function of the Q/A of specific light ions. Also listed are the minimum K values needed for each ion to penetrate the 170 mg/cm^2 Carbon window, as well as the lowest K for which each Q/A can be accelerated using the first harmonic of the accelerating frequency.

The puller itself will be based on a design developed by Blosser and Marti at MSU[12]. The puller is extended to within .4 in of the source. This will create a maximum electric field of approximately 70 kV/cm, which is still below values routinely achieved in other machines. There is still some sparking concern about the puller penetrating between the two source heads. Proper care must be taken in preparing the surface of the puller. If necessary, the source heads will be redesigned to eliminate this overhang. The axial slit has a primary function as a ground post. Also new is an extension of the dummy dee. Previously, the dummy dee was open for the first 6.0 in above and below the cyclotron center. This allowed the insertion and free movement of the source head. but came at the price of deep electric field penetration about either side of the source. The extension restricts the open region from 1.8 in above machine center to 3.0 in below center. While still allowing the insertion and movement of the the source, it, together with the axial slit, provides better definition of the electric field, balancing the gaps on either side of the source as can be seen in Figure 1.

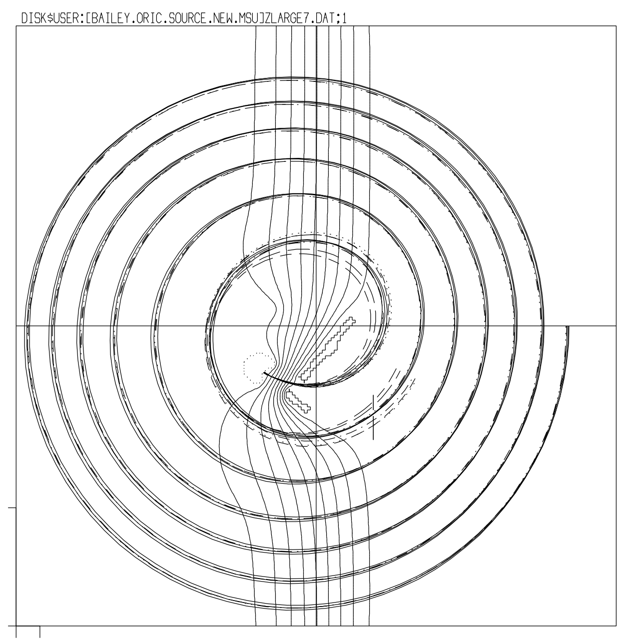

Figure. 1. Central Region Orbits with the New Puller. Depicted are the source, puller, and radial clipper protrusions in the median plane with electric field 10% equipotential lines. The axial slit restricts the gap on the source side above the centerline. Overlaid on the electric field are orbits for central rays for starting times from 200° to 270° RF, as well as displaced rays covering the radial phase space about the central ray which passes through the radial clipper.

The short and well defined gap between the source and puller, .46 in including the knife edge source slit, serves to reduce the energy and centering spreads in the ion beam. There is still enough centering spread that the radial clipper can make a coarse phase selection, as shown in Figure 1, where central rays for starting RF times of 200°, 220°, 240°, 265° and 270° are shown being stopped by the clipper. The central ray, together with parallel rays displaced ± .01 in and rays diverging ± 90°, all with the starting time of 252.5° RF, are shown passing through the slit in the clipper. For this calculation, the starting times of 245° and 260° begin to slip beam through the slit. Thus, for the K=75 Q/A=1/2 operating point, the clipper will cut out all beam except ±8° about a starting time 17.5° before the peak of the accelerating voltage. This phase cut is not enough to provide single turn extraction, but will provide a well centered beam which will pass through the $\nu_r = 1$ resonance, and improve the extraction efficiency. Further reductions in phase will require the use of additional phase slits.

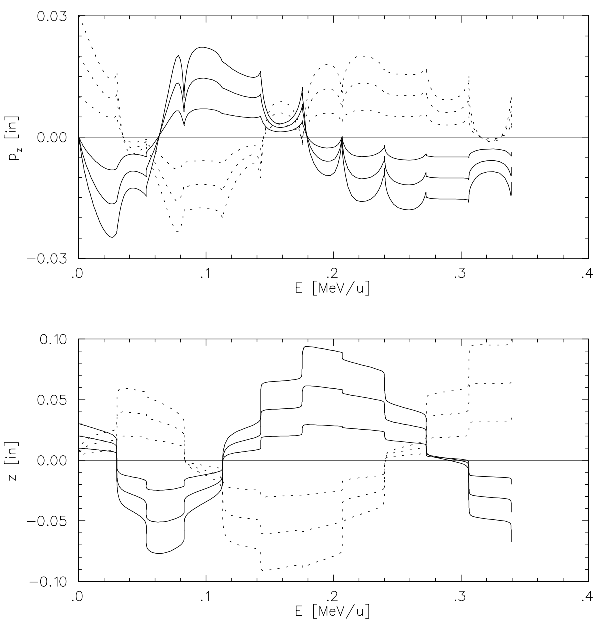

Figure. 2. Axial Motion of the Central Ray from Figure 1. For these starting conditions, z≤ .03 in., and p_z≤ .03 in. the motion is linear. (Momentum is converted to cyclotron units by dividing by mω.) Outside of this range it is nonlinear. The axial slit, set at ± .1 in., will pass this range, cutting the rest.

The axial motion is depicted in Figure 2, where z and p_z are plotted versus energy for the first six turns, for three parallel rays displaced in z, and three diverging rays with no z displacement. This motion is linear, except for the outermost orbits, which have small nonlinearities. Calculations starting with larger values of z or p_z quickly become nonlinear. The axial slit, which covers the first five turns will collimate out the nonlinear beam if the slit is set at ± .1 in. Notice the rapid change in p_z in the first accelerating gap, which is the geometrical focussing discussed earlier.

The central region presented here will be implemented in ORIC over the next year.

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