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CENTRAL REGION UPGRADE FOR THE JYVÄSKYLÄ K130 CYCLOTRON

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Abstract

The Jyväskylä K130 cyclotron has been in operation for more than 25 years providing beams from H to Au with energies ranging from 1 to 80 MeV/u for nuclear physics research and applications. At the typical energies around 5 MeV/u used for the nuclear physics program the injection voltage used is about 10 kV. The low voltage limits the beam intensity especially from the 18 GHz ECRIS HIISI. To increase the beam intensities the central region of the K130 cyclotron is being upgraded by increasing the injection voltage by a factor of 2. The new central region with spiral inflectors for harmonics 1–3 has been designed. The new central region shows better transmission in simulations than the original one for all harmonics and especially for h=2 typically used for nuclear physics. The engineering design for the new central region is being done.

INTRODUCTION

The Jyväskylä K130 cyclotron [1] is a normal conducting multi-particle multi-energy accelerator that has been in operation since 1992. The cyclotron has been used for more than 160 000 hours providing beams from H to Au with energies ranging from 1 to 80 MeV/u. Currently about 3/4 of the running time is used for nuclear physics research and 1/4 for industrial applications. The main application is space electronics irradiation testing, which is done by accelerating ion beam cocktails at 9.3 Mev/u and 16.2 MeV/u [2], while the majority of the heavy ion beams for the nuclear physics program are run at energies close to 5 MeV/u.

The typical injection voltage used for nuclear physics beams is around 10 kV. Such a low voltage limits the available accelerated beam intensity due to several effects. The beams produced by electron cyclotron resonance ion sources (ECRIS) have a strong divergence due to the magnetic field of the ion source and especially when tuned for medium charge states and high intensities, also the space charge effects will limit the beam intensity available for acceleration. Also, typical normalized rms-emittance of a beam produced by modern ECRIS is about 0.1 mm mrad [3], which equates to about a geometric envelope emittance of 200 π.mm.mrad for Ar^{8+} accelerated with 10 kV injection voltage, assuming a KV-distribution. As the K130 cyclotron has an acceptance of 100 π mm mrad part of the beam is obviously lost. All of these effects can be mitigated by increasing the injection voltage. Using the recently commissioned 18 GHz ECRIS HIISI [4–6] at Jyväskylä it has been observed that produced beam intensities of medium charge states such as Ar^{8+} double as source voltage increases from 10 kV to 20 kV. Therefore, a project has been initiated to redesign and upgrade the central region of the K130 by increasing the injection voltage by a factor 2.

PLAN FOR REDESIGN

The K130 has a broad operation range by being able to accelerate particles with two 78° dees with 10–21 MHz RF at a maximum of 50 kV using harmonic modes h =1–3. Injection of beams is done axially using separate spiral inflectors for each of the three harmonic modes. The inflectors can be switched through the axial bore using an automatic changer. The inflector housing is fixed and common to all harmonic modes. Each of the harmonic modes has a fixed design orbit leading to a well-centered acceleration. The injection voltage therefore scales as

$$U_{\mathrm{inj}} = \frac{q}{2m} B_0^2 r_{\mathrm{inj}}^2, \tag{1}$$

where q and m are the particle charge and mass, B_0 is the cyclotron magnetic flux density on axis and r_{inj} is the injection radius. The dee voltage V_{dee} scales linearly with U_{inj} for a fixed design orbit. Only slight centering errors of < 5 mm can be corrected using harmonic coils.

For the upgrade of the central region the fixed design orbits and injection radii are redefined. The original injection radii 13.1, 18.8 and 18.8 mm for harmonic modes 1, 2 and 3 respectively [7] are replaced by 18.5, 26.6 and 26.6 mm – i.e. the radii are multiplied by $\sqrt{2}$. The proportionality constant between V_{dee} and U_{inj} was halved to keep the number of turns in the accelerator almost constant. The magnetic design of the machine was left as originally designed with a 20° integrated phase slip at the central field bump and isochronous field elsewhere until the extraction.

DESIGN PROCESS

The new central region was designed using IBA tracking code AOC [8], which numerically integrates the equations of motion in static magnetic fields and RF electric fields. The 3D magnetic fields were produced using first order expansion of 2D maps measured in the end of 1980s when the cyclotron was built. The electric fields were constructed assuming that $\vec{E}(\vec{r},t) = \vec{E}'(\vec{r})\cos(t)$, where $\vec{E}'(\vec{r})$ is a static electric field computed by Vector Fields Opera [9] and imported to AOC on a set of regular grids in cylindrical coordinates.

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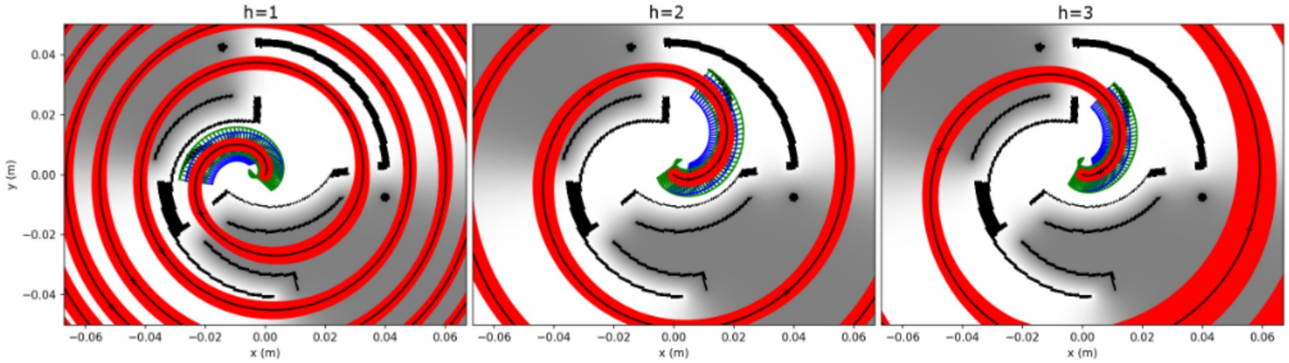

Figure 1: The new central region of the K130 with all three harmonics. The beam depicted in red has a geometrical envelope emittance of 100 π mm mrad at the inflector entrance and all particles are injected at phase 0°. The black line is the reference orbit with particle location at the time of dee voltage maxima marked with a cross.

The new central region design was made using three beams: (1) 30 MeV H^- beam accelerated with the first harmonic mode with $V_{\mathrm{inj}} = 11.5$ kV and $V_{\mathrm{dee}} = 18.1$ kV, (2) 200 MeV $^{40}\mathrm{Ar}^{8+}$ accelerated with $h = 2$ using $V_{\mathrm{inj}} = 20.6$ kV and $V_{\mathrm{dee}} = 24.5$ kV, and (3) 200 MeV $^{40}\mathrm{Ar}^{8+}$ accelerated with $h = 3$ using $V_{\mathrm{inj}} = 20.6$ kV and $V_{\mathrm{dee}} = 36.0$ kV. These beams are representative of typical medium energy, high intensity beams accelerated at Jyväskylä.

The new central region was designed with an iterative process, which started with the original central region geometry. First, on the cyclotron midplane, the injection location and angle leading to a minimum centering error of the accelerated orbit was searched for at the injection phase which leads to the maximum energy gain per turn at high energies. This was done for each of the harmonics, after which the geometry was modified to give space for the beams or to intentionally change the orbits by changing the acceleration gap angles and thus avoiding collimation. This process was repeated until a satisfactory solution was acquired.

After finding the well-centered reference orbits the spiral inflectors were designed to deflect a particle propagating along the axis of the accelerator to the desired orbit. The original inflectors of the K130 were made according to the analytic Belmont-Pabot formula [10]. This time the inflectors were designed in AOC using a numerical model producing the deflecting electric field in the particle tracking routine. The difference of the inflectors produced by this method when compared to Belmont-Pabot solution is that the gap between the inflector electrodes can remain constant even with a nonzero tilt parameter k. The tradeoff is that with a constant gap the inflector will be longer in length as a fraction of the electric field is used to adjust the horizontal turning radius. In this case the constant gap solution was found to have a higher transmission. For each of the inflectors there is an infinite number of solutions that deliver the beam to the desired orbit. For the K130 the largest bending radius A was chosen, which produces an inflector that both fits within the central region case and avoids affecting the accelerating field distribution. The tilt parameter k and the rotation θ were found to deliver the reference particle to the centered orbit. The inflector gap height and width were chosen to have the same values as in the original inflectors, 5 and 10 mm respectively. The inflector parameters selected for the new central region are shown in Table 1. The physical models of the inflector geometries built from the solved central trajectories were trimmed in length to take in account the effects of the fringe field. At the start of the inflector the length was trimmed to achieve centering of the reference particle inside the inflector and at the end trimming was done to minimize the vertical oscillation of injected particle around the midplane. For example, for the second harmonic inflector the calculated centering error within the inflector is less than 0.15 mm and the vertical oscillation in the acceleration region is less than 0.2 mm. The engineering models for the inflectors were produced using a custom computer program defining the geometry in the openly documented IGES file format [11].

Table 1: The New Spiral Inflector Parameters

Harmonic mode:	**1**	**2**	**3**
Spiral height A (mm)	36	45	34
Tilt parameter k	0.497	0.560	0.604
Injection radius (mm)	18.5	26.6	26.6
Gap height (mm)	5	5	5
Gap width	10	10	10
Maximum V_{inj} (kV)	31.8	42.0	28.6
Maximum V_{sprl} (kV)	±4.41	±4.67	±4.21

The central region geometry with the inflectors and the beams for all three harmonics are presented in Figure 1. The transmission of a KV-distributed beam with a geometrical envelope emittance of 100 π mm mrad injected at the inflector entrance at phase 0° is 99 %, 93 % and 98 % through the inflectors and central region for harmonics 1–3 respectively. For a beam with 125 π mm mrad emittance the corresponding transmissions are 87 %, 82 % and 88 %. For a 100 π mm mrad emittance beam with a phase distribution of 0–360° (DC beam) the transmission is 10 %, 14 % and 12 % for the different harmonics. The transmission is mainly limited by the loss of vertical focusing outside the 56° acceptance of h =2–3 modes and 46° acceptance of h =1 mode as presented in Figure 2. The transmission of the DC beam is therefore somewhat better than of the original central region (9 %) for the same geometrical emittance beam [7].

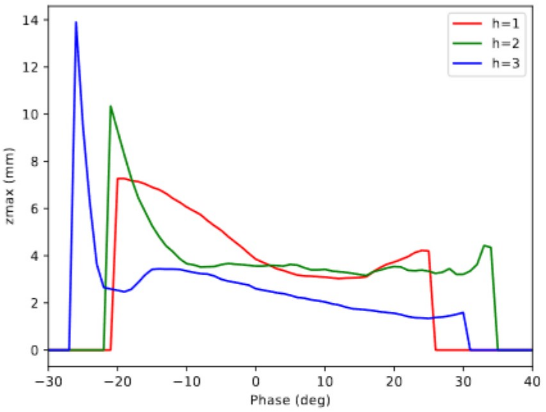

Figure 2: The maximum vertical position of a particle launched at the end of the inflector off the midplane, at z = 1 mm as a function of the starting phase. A non-zero value is shown only for particles reaching the extraction. Zero phase refers to the phase producing the highest energy gain per turn for a particle launched on the midplane.

Some studies were performed with bunched beams. With h = 2, for example, a transmission of 46 % was achieved (a gain factor of 3.5 compared to a DC beam) without considering the space charge effects. With the space charge model of AOC turned on one could evaluate the throughput of the bunched beam taking in account the repulsive space charge forces. Unfortunately to evaluate the maximum transmission with space charge a global optimization should be done to the injection line by adjusting the initial phase space distribution, bunching parameters and focusing between the buncher and the inflector. Due to the computation time of such a calculation it has not yet been done.

The centering of the injected beam with h = 2 and h = 3 is presented in Figure 3. The central region has been designed to minimize the centering error of the reference orbit, the orbit injected at the center of the inflector. The reference orbit is drawn in black. It can be seen that the centering error is of the order of 1 mm. The rest of the 100 π mm mrad beam is drawn in red. For the h = 2 the maximum centering error within the beam is $<$ 5 mm, which enables an efficient extraction of the accelerated beam from the cyclotron. The h = 1 case is simiar. On the other hand, for the h = 3 case the beam contains particles with centering errors of up to 25 mm. This is not due to the new central region design as the same is also observed for the original central region, but it is an effect that takes place because in the case of h = 3 the phase advance within a single dee is $3 \times 78° = 234°$. Once the phase advance is larger than 180° small errors in particle phase become amplified causing the centering error to grow. The large centering error spread causes losses in the extraction, which is a known problem on the K130 with h = 3. The effect could be corrected by decreasing the dee angle in the central region, but this would decrease the energy gain per turn of the already critical h = 1 case. Therefore, for now the dee angle originally selected for the K130 is accepted as a compromise.

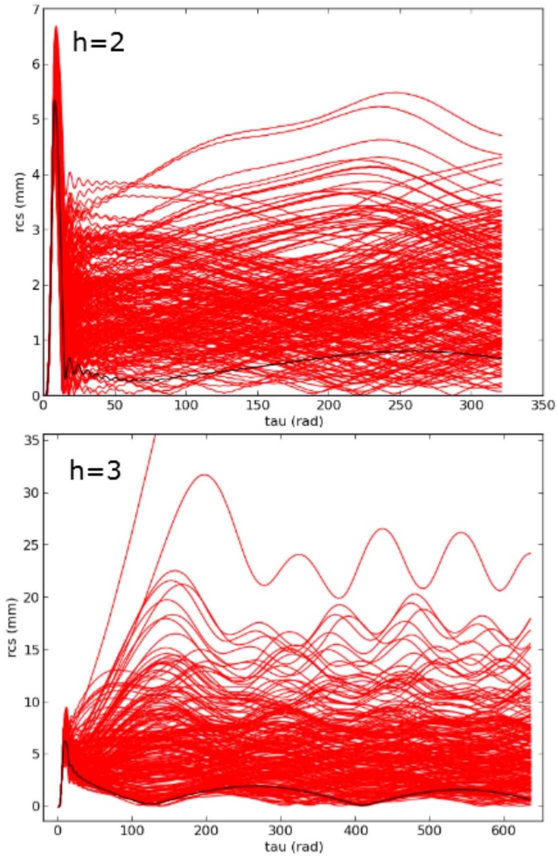

Figure 3: Centering of the full injected beam for h = 2 and h = 3. The reference orbit is drawn in black.

OUTLOOK

The physics design of the new central region is mostly done. Some simulation studies with space charge and bunching are still being made, but it is expected that no changes will be made to the design presented in this paper. Therefore, the engineering design for the project is already being made. The number of modified parts due to the redesign is rather small. The inflectors and their supporting structures, the central region case, the dee and the dummy-dee tips and the upper magnetic steel plug need to be remade. The magnetic upper magnetic steel plug is made of two parts with the outer one being fixed and acting as a part of the vacuum chamber. The inner part of the plug is removed together with the inflector by the inflector changer. Currently the aperture in the outer part is ⌀70 mm, but the h = 2, largest of the new inflectors will require a free space of at least ⌀75 mm to fit through. The engineering and machining of the new parts should be done during the first months of 2020 allowing the experimental characterization and commissioning of the new central region during 2020.

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