STATUS AND THE FUTURE PLANS OF THE JYVÄSKYLÄ K130 CYCLOTRON

P. Heikkinen, Department of Physics, P.O. Box 35, FIN-40014 University of Jyväskylä, Finland

Abstract

During the last eight years the operating of the K130 cyclotron has exceeded 6000 hours/year. With two ECR ion sources (6.4 and 14 GHz) for heavy ions and one multicusp source for negative hydrogen and deuterium we usually accelerate some 30 different isotopes in a year. Since the modification to accelerate also negative ions in the year 2000 the major upgrading has been done for the ECR ion sources.

Future plans include an upgrade of the injection line optics for higher beam intensities, and the implementation of the fourth harmonic mode for lower beam energies down to about 1 MeV/u. The cyclotron has also been planned to deliver heavy ions for nanometer size beams.

STATISTICS

Since its inception in1993 the K130 cyclotron has been operated for over 64 000 hours, and during 1996-2003 the average running time has been 6740 hours/year. In 2003 the total operating time was 6918 hours, out of which the beam-on-target time was 5485 hours. The rest of the total time consisted of stand by time due to the user, beam tuning and developing. The most intensively used beam was protons (H^-) for 30% of the total. The beam was mostly used for ^{123}I production and for proton induced fission. The second most popular beam was ^{48}Ca (11.7%). Altogether, almost 30 different isotopes were accelerated for experiments and beam development tests in 2003. Figure1 shows the annual operating hours of the Jyväskylä K130 cyclotron since 1992. The actual scientific use started in 1993 when the experimental hall was ready.

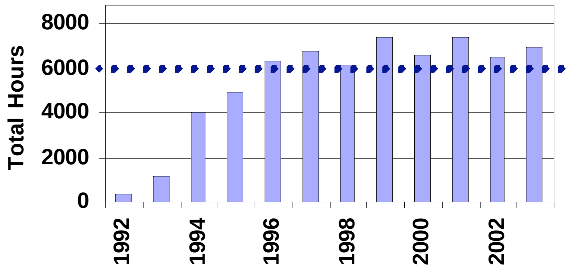


Figure 1: Operation hours of the Jyväskylä K130 cyclotron.

H- ACCELERATION

The first H^- beam was accelerated in August 25, 2000. Our first aim was to accelerate 50 µA of 30 MeV H^- beam, which would be sufficient for ^{123}I production. This was achieved in October, 2000. Today, the maximum extracted current from H^- acceleration at 30 MeV is about 60 µA and it is mainly limited by space charge effects in the injection beam line.

SPACE CHARGE LIMITED BEAM

The intensity of the H^- beam is limited by space charge effects in the injection line. The most used H^- beam energy is 30 MeV, which requires 5.9 kV extraction voltage from the ion source. This is due to constant orbit geometry in the cyclotron. The ion source can deliver more than 5 mA at 5.9 kV, but the maximum current that we have been able to get to the inflector is about 250 µA. In this case the extracted current from the ion source is about 1 mA, which is the maximum that we can get to the matching quadrupoles below the cyclotron. About 0.5 mA of this survives to the next Faraday-cup through the following four quadrupoles and a 90-degree dipole.

The injection beam line for negative ions contains the following elements: solenoid, quadrupole doublet, 30 degree dipole, three solenoids, four quadrupoles, 90 degree dipole, two solenoids. The last solenoid is inside the cyclotron yoke close to the median plane.

Theoretical basis

Assuming a round beam with a uniform current density one can derive a radial transfer matrix[1] for a length of δs without any other focusing than the defocusing force due to space charge.

$$\begin{pmatrix} r \\ r' \end{pmatrix}_{\delta s} = \begin{pmatrix} 1 & \delta s \\ \sqrt{\frac{m}{2q}}\frac{I}{U^{3/2}4\pi\varepsilon_0 r_0^2}\cdot\delta s & 1 \end{pmatrix}\begin{pmatrix} r \\ r' \end{pmatrix}_0$$

where I is the beam current, r_0 is the beam radius, U the accelerating voltage, m and q the mass and charge, respectively. The focusing term suggests the functional dependence of the maximum current from the relevant parameters as

$$I_{\max} \propto \sqrt{\frac{q}{m}}U^{3/2}R^2$$

where R is the beam tube radius. A more detailed description is given in reference [1].

Simulations

We used the program Trace-3D (PBO-Lab) to study the effect of space charge. Here we give only the main results. Three different focusing schemes were studied: solenoids, FODO quadrupoles and FOFDOD quadrupoles. As the transfer matrix shows there is a strong dependence on the beam size (r^2). The smaller the beam size, the stronger the defocusing force. Therefore it is advantageous to keep the beam size as large as possible along the whole beam line.

In order to be able to compare different focusing schemes we constructed a periodic beam line of given optical elements. The beam line parameters are the distance L between adjacent focusing elements (center-to-center) and the beam tube radius R (= the maximum beam radius). The beam is described by the charge state Q, the mass number A, acceleration voltage U and the beam current I. For each case, the focusing is adjusted to give a periodic solution. The beam is allowed to touch the beam tube. After a certain beam current it is not anymore possible to get a periodic solution: the space charge repulsion is stronger than the focusing force. The simplest case is a beam line consisting of short focusing lenses (Fig. 2).

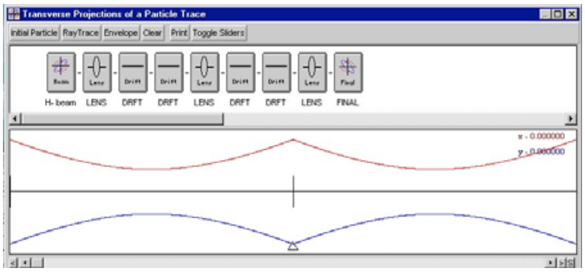
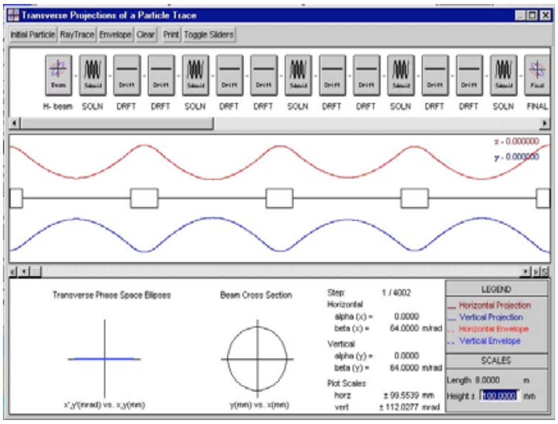


Figure 2: Space charge limited beam focused by short solenoids (thin lenses).



Step: 1 / 4002
Horizontal
alpha (x) = 0.0000
beta (x) = 64.0000 m/rad
Vertical
alpha (y) = 0.0000
beta (y) = 64.0000 m/rad
Plot Scales
horz ± 99.5539 mm
vert ± 112.0277 mrad
Length 8.0000 m
Height ± 100.0000 mm

Figure 3: Space charge limited beam focused by 400 mm solenoids with 100 π mm mrad beam emittance.

The maximum current for thin lenses and negligible beam emittance is

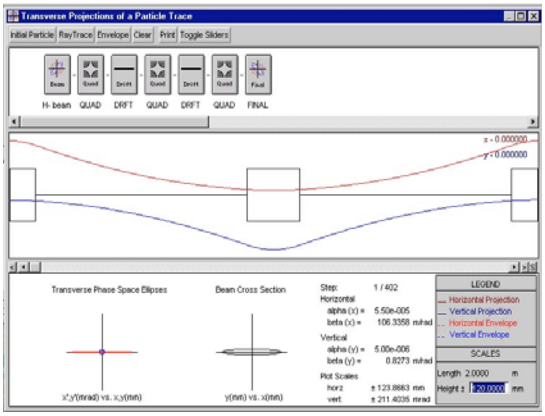
$$I_{\max} = 114.4\sqrt{\frac{Q}{A}}U^{3/2}\left(\frac{R}{L}\right)^2 mA$$

where U is given in kV. If the thin lenses are replaced by real solenoids (length 400 mm) and a realistic beam emittance (100 π mm mrad) is used, the maximum current becomes

$$I_{\max} = 140\sqrt{\frac{Q}{A}}U^{3/2}\left(\frac{R}{L}\right)^2 mA.$$

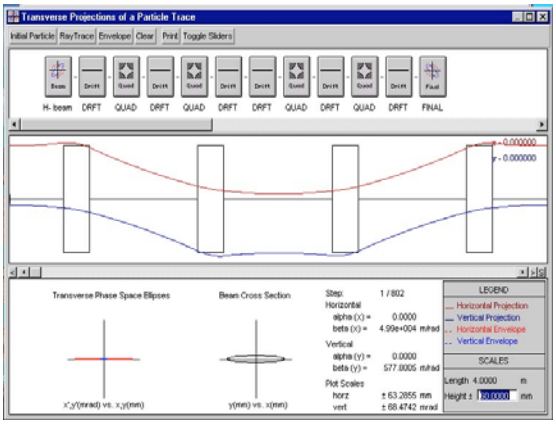
The slight increase in the maximum current clearly comes from longer focusing elements, i.e. the relative distance with only Coulomb repulsion is shorter. The result is consistent with our experience. The parameters in the solenoid section of the injection line (three solenoids) are: R = 50 mm, L = 2000 mm, U = 5.9 kV. These parameters give 1.25 mA which is practically what we have been able to measure after the solenoid section.

Two most common quadrupole structures are FODO and FOFDOD structures. With these structures the beam dimension in one direction is very small. Especially in the FOFDOD structure the beam is narrow in one dimension between the two D quadrupoles.



Step: 1 / 402
Horizontal
alpha (x) = 5.50e-005
beta (x) = 106.3358 m/rad
Vertical
alpha (y) = 5.00e-006
beta (y) = 0.8273 m/rad
Plot Scales
horz ± 123.8863 mm
vert ± 211.4035 mrad
Length 2.0000 m
Height ± 120.0000 mm

Figure 4: Periodic solution in a FODO structure.



Step: 1 / 802
Horizontal
alpha (x) = 0.0000
beta (x) = 4.99e+004 m/rad
Vertical
alpha (y) = 0.0000
beta (y) = 577.0005 m/rad
Plot Scales
horz ± 63.2855 mm
vert ± 68.4742 mrad
Length 4.0000 m
Height ± 80.0000 mm

Figure 5: Periodic solution in a FOFDOD structure.

The maximum currents for these structures become

$$I_{\max} = 29.5\sqrt{\frac{Q}{A}}U^{3/2}\left(\frac{R}{L}\right)^2 mA$$

for the FODO structure and

$$I_{\max} = 17.2\sqrt{\frac{Q}{A}}U^{3/2}\left(\frac{R}{L}\right)^{2} mA$$

for the FOFDOD structure. Also for other quadrupole structures the beam dimension in one direction usually becomes small causing strong defocusing due to space charge.

Actions against space charge

As is seen in the maximum current equations above, the ways to increase the space charge limit are:

1. Add more focusing elements (L^{-2})
2. Use larger beam tube (R^2)
3. Use higher extraction voltage from the ion source ($U^{1.5}$)
4. Replace quadrupoles by solenoids

Case 2 would mean building a totally new injection line and case 3 would require a new central region and the inflector for the cyclotron. Our intention is to add some new solenoids (case 1) and to replace two matching quadrupoles by one solenoid (case 4). The remaining two quadrupoles cannot match the beam emittance totally into the acceptance of the cyclotron, but for space charge limited beams the gain using a solenoid instead of quadrupoles is larger than the beam loss due to poorer emittance matching. We have also an alternative plan to place the multicusp ion source closer to the cyclotron, i.e. below the cyclotron using a +/- 90 degree dipole. Of course, this would mean a limited access to the ion source compared to the present situation where the ion source is in a separate room and can be accessed while the cyclotron is in use.

In addition to new solenoids in the injection line we most probably need to install a new solenoid also into the axial hole. Now we have one 400 mm solenoid outside the yoke and one 400 mm solenoid as close to the median plane as possible. There is space available for one extra solenoid between the buncher and the last solenoid.

FUTURE PLANS

In addition to increasing the space charge limit in the injection line as described above we plan to extend the available beam energy range down to about 1 MeV/u by adapting the fourth harmonic mode. Now harmonic modes h = 1, 2 and 3 are used and the lower limit for the beam energy is 2 MeV/u. During this process we have also a possibility to make the central region better for the present use of the cyclotron, namely more efficient central region for high-energy light ion beams (h = 1) without forgetting the heavy ions. In the original design the cyclotron was optimised mainly for heavy ions (h = 2 and 3).

Nanobeams

Nanometer sized proton beams have been used for lithography with electrostatic accelerators[2]. Our new experimental material physics group (professor Harry J. Whitlow) plans to use also heavy ions from the cyclotron. The proton beams up to 1 MeV will be accelerated with a Tandem accelerator. Heavier particles need higher energies and therefore the K130 cyclotron will be used if we can solve some problems concerning the beam spot size. The required beam intensity is very low. Therefore we can decrease the beam emittance by strong collimation. The optics for 1 MeV protons works[2]. The most critical point is the beam energy spread, which together with strong aberrations in the final focus triplet makes the beam spot larger. The natural energy spread of a cyclotron beam (0.5 – 1 %) is far too large, and it must be decreased by energy selection with a slit in a focal point where dispersion is large.

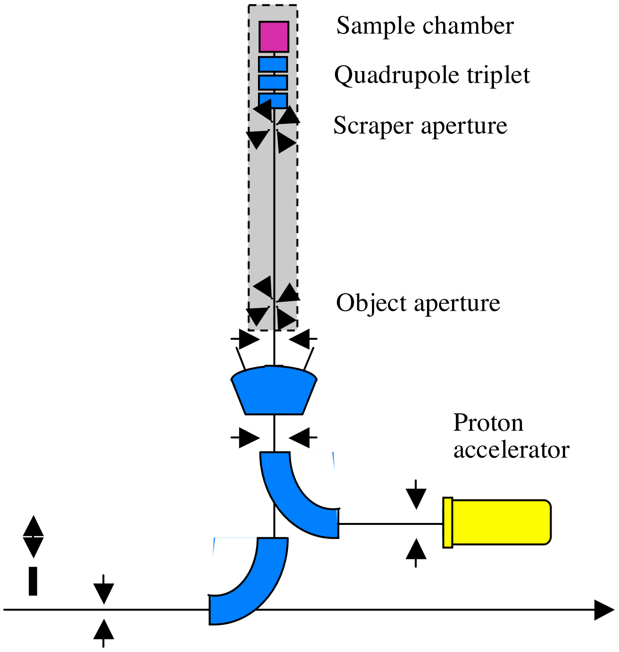


Figure 6: A schematic layout of the nanobeam facility. The 8 m long structure from the object aperture to the sample chamber must be installed on a vibration-damped platform.

REFERENCES

[1] P. Heikkinen, "Space Charge Dominated Beam Transport in the K130 Cyclotron Injection Line", NUKLEONIKA 1003;48 (Supplement 2):S21-S24.

[2] H. J. Whitlow, M. L. Ng, V. Auželytė, I. A. Maximov, J. A. van Kan, A. Bettiol and F. Watt, "Lithography of High Spatial-density Biosensor Structures with sub-100 nm Spacing by MeV Proton Beam Writing with a Minimal Proximity Effect", Nanotechnology 15 (2004) 223.