STATUS AND FUTURE PLANS AT LNS CATANIA

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Abstract

The LNS K-800 cyclotron has been operated as a booster of the tandem accelerator until 1999. At the beginning of 2000, the axial injection mode was successfully commissioned and since March 2000 the cyclotron has been working in the stand-alone mode. Transmission measurements through the injection line and the central region are in optimum agreement with the design values. The stand-alone operation allows to achieve a better reproducibility of the beam, moreover the performance of the superconducting ECR source SERSE allows for higher energies and higher intensities. Using phase slits, to reduce the phase acceptance of cyclotron, shorter and cleaner beam pulses are delivered to the users. The upper beam current limit deliverable by the cyclotron is being investigated.

The proposal to modify the K-800 cyclotron in order to allow for the extraction of beams with power of about 20 kW is presented too.

1 INTRODUCTION

The LNS K-800 superconducting cyclotron was commissioned in 1994 and until October 1999 it was operated as a booster of the Tandem accelerator [1]. The beams delivered by the cyclotron are mainly used to perform nuclear physics experiments, investigation on the effects induced by heavy ions on materials. The use of proton beam for radiotherapy is in progress. In the past period above mentioned the Cyclotron was successfully working, becoming more and more reliable.

The axial injection line, axial buncher and central region of the cyclotron were installed at the end of 1999. In January 2000 the first beam axially injected in the cyclotron was successfully accelerated and since that date the cyclotron has been working in the stand alone mode. After a couple of months spent to understand and overcome problems due both to the dark current on the electrostatic inflector and to a vacuum leak in the cooling pipe of the axial buncher, the cyclotron was able to deliver beams to the experiments. Unfortunately, due to serious problems on the electrostatic deflectors (E.D.) we were forced to stop the activity for about 5 months for extra maintenance and E.D. tests [2].

The beams developed to date are shown in Fig. 1. The maximum energies have not yet been reached due to the limit of the maximum electric field achievable by the E.D.

2 AXIAL INJECTION

2.1 ECR Sources

The ion beams injected into the cyclotron are produced by two ECR sources, called SERSE and CAESAR [3]. SERSE is a highly performing superconducting ECR source, constructed in collaboration between our laboratory and the CEA of Grenoble. It is designed according to the concept of the “High B mode”. Both the axial and radial magnetic fields are supplied by three solenoids and a hexapole with superconducting cables. SERSE is able to produce ion beams with high charge states and intensities much higher than room temperature sources. For some light ion beams like O^{8+} the achieved beam intensity is close to 90 μA. This source has been dedicated to the production of heavy ions with high charge states, like F^{8+}, Ni^{26+}, Sn^{31+}, Au^{30+} etc…

The CAESAR source installed in 1999 is a conventional ECR ion source, to be used to produce beams of lighter ions with moderate charge states. It is an upgraded model of the well-known CAPRICE-ECR ion source. A transfer beam line delivers to the cyclotron the beam produced by the two sources. After one year of operation and some modifications on the extraction side of CAESAR we are now able to transfer more than 90% of the beam delivered by both the sources to the faraday cup placed closed to the injection hole of the cyclotron.

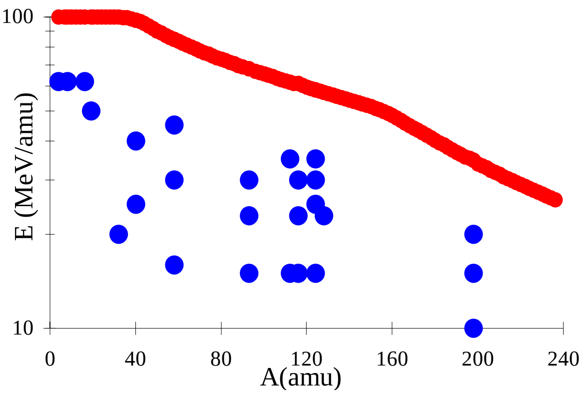

Figure 1: Energies vs. mass of all accelerated ions. The continuous curve is the maximum energy achievable by the cyclotron with axial injection.

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2.2 Injection Line

In figure 2 the layout of the axial injection line is shown. The main elements of the line are 12 solenoids and 4 quadrupoles. The solenoids maintain the size of the beam well confined but provide a weak focusing to minimize the space charge effects and the related emittance growth. The four quadrupoles are installed between the 40° horizontal bending magnet and the 90° vertical bending magnets. By these quadrupoles the beam emittance can be rotated in the phase space to allow for matching to the acceptance of the cyclotron. Although an emittance measurement device is planned to be installed at the matching point before the last 2 solenoids, up to now we operate without it. The standard procedure is to optimize the parameters of the line according to the following procedure:

1. Tuning of the line elements to maximize the beam current at each faraday cup;
2. Tuning of the line elements to maximize the beam current inside the cyclotron.

Using this procedure we are able to transport about 90% of the beam produced by the sources up to the last Faraday cup at the entrance hole of the cyclotron and to accelerate a maximum of 9% of the continuous beam inside the cyclotron with the buncher switched off. This measured value is very close to the calculated value of 35° phase acceptance of the central region.

Some steering magnets are installed along the line although we have never used any of them to optimize the beam transport. Moreover even with B=4.3 T, the maximum field used to date, we have never detected any effects due to the stray field of the cyclotron magnet on the injected beam.

2.3 Axial Buncher and Chopper

The axial buncher consists of a drift tube placed inside the cyclotron 50 cm away from the median plane [4]. The axial buncher is driven by a single frequency in the range 12-50 MHz and it is designed to operate at the same frequency of the cyclotron. The electrode is connected through a 3.5 m coaxial line to a matching box driven by an RF amplifier. Typically a power of 50-100 W is enough to bunch the beam. For some nuclear physics experiments, requiring a longer time separation between bunches, the buncher could be operated also in sub-harmonic mode. In this case a High Energy chopper must be also used to suppress the spurious bunches, due to the multi-turn extraction from the cyclotron. However until now the buncher has been operate at the same frequencies as the cyclotron.

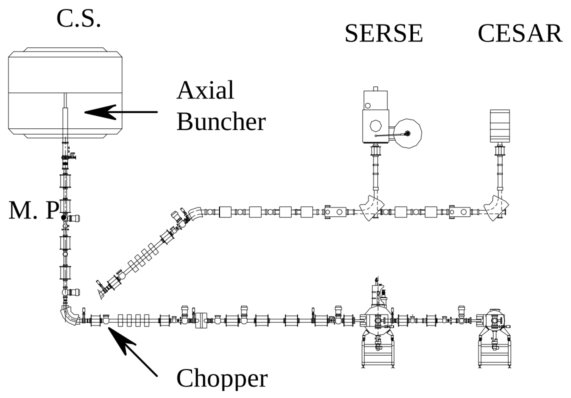

Figure 2: Layout of the axial injection. Radial and vertical view of the two ECR sources are shown.

The operation tests show an increasing factor of the beam current of a factor 4÷5 when the buncher is switched on. These values of bunching efficiencies are in good agreements with the evaluated longitudinal acceptance of the central region which is of 35° RF. Unfortunately, due to a vacuum leak in the cooling line, the buncher was not used for the experiments for a long time. Recently it was disassembled , the cooling system was modified to avoid the vacuum leaks and during the last four weeks it has been working.

Along the injection line, before the 90° vertical magnet, a deflecting plate has also been installed. A pulsed high voltage is applied on this plate to steer the beam: a proper selection of width and repetition rate of the voltage pulse allows for changing the duty cycle of the injected beam into the cyclotron from 100% to 0% in a continuous way. The voltage, delivered by a high voltage supply, is applied to the deflecting plates through a high voltage fast switch, controlled by a TTL signal. A different operation mode consists to drive the plate with a sinus wave RF signal in the 2 MHz frequencies range to chopper the DC beam to deliver beam bunches with 1 MHz rate [4].

2.4 Inflector

The installed inflector is of the spiral kind, with a gap of 6 mm. for the selected injection voltage of 30 kV the maximum required electric field is 22 kV/cm, which gives an exit radius of 17.5 mm ref[5]. On the two electrodes of the inflector a maximum voltage of ±6.6 kV is applied. During the first test of the axial inflector the dark current along the electrodes gradually increased up to high values in only one week. This problem was due to low vacuum in the housing of the inflector, a bad insulation between the electrodes and also between the two cables leading the voltage to the electrodes. After some modifications on this prototype of the inflector the maximum voltages were reached and beams were delivered to the users. Later a new inflector with a better insulation and easier dismounting operation was constructed and is now in operation. During the last five months of operations show the last inflector has proved much better from the electric point of view and the replacement of the electrodes is quite simple. Although it is well working, there is a small area of one electrode which is over heated.

2.5 Central Region

To operate the cyclotron with axial injection it was necessary to disassemble the stripper system and install the spiral inflector, extend the accelerating electrodes of RF cavities towards the center and install the post according to the design of the central region [5]. The central region was designed to operate the Cyclotron in constant orbit mode with harmonic mode of acceleration h=2, which allows for an energy range 8÷100 MeV/amu.

Due to the increased mutual coupling among the RF cavities, the start-up of each cavity after a switch–off is now a bit more difficult. Moreover more discharges occur mainly when the beam is accelerated. We suspect that this is due to over heating of some parts of the inflector electrode or housing which produces impurities emission and discharges.

2.6 Phase Selection

Three movable slits have been installed at a distance of about 20 cm from the center to perform fine phase selection. Each slit consists of a small wedge, with a maximum thickness of 2 mm, that will cut phases according to the simulations made in [8]. They can be used to reduce the phase range from 35° RF (the phase band allowed by the central region) to 6° RF. By reducing the phase range of the beam to be extracted, and making use of the harmonic trim coils to excite the first harmonic resonance, we could increase the separation among the turns to reduce the activation on the deflectors and along the extraction channel. At first, on order to be able to operate at high temperature these slits were made of graphite. Unfortunately graphite caused the RF electrodes to become dirty, and probably a lot of the problem that we had in the past with the electrostatic deflectors were generated by the graphite dust. To solve these problems the graphite slits were replaced by slits made of tantalum.

3 OPERATIONS

For all the ion beams accelerated to date the operating setting of the main coils and trim coils is always very close to the one derived from the magnetic measurements [3]. The differences among the final values of the main coils currents and the calculated ones are of about 0.1-0.3 Ampere, i.e. 0.006-0.02%. This good agreement between the calculated parameters and the operating setting failed only for the ions with q/A=0.5 at energy of 62 MeV/u. In this case there is a difference of about 1 Ampere between the calculated and operating value of the Alfa coil. The disagreement is mainly due to the lack of measured magnetic maps, the working point being just on the lower border of the operating diagram of the cyclotron.

The amplitudes and phases of the centering and extraction first harmonic as well as the RF phases and amplitudes are tuned during operation. Also for these parameters the final values are in good agreement with the expected values.

The injection of the beam into the cyclotron is now quite simple. We optimize the beam current on the last faraday cup of the injection line and we check on a beam stopper, just after the axial buncher, half a meter before the inflector. This beam stopper gives only qualitative information because there is not enough space to install any biased electrons shield. The beam is then measured inside the cyclotron by the radial probe at R=100 mm, the 5th turn. The injection efficiency measured at this position is of about 9% of the continuous injected beam. Typically the whole beam current measured at R=100 mm is accelerated until R=700 mm. After this radius the current measurement of our radial probe is not any longer reliable, due to the strong angle variation of the probe head, which is moving along the median line of the hill, and to the crossing of the region where the beam phase has a strong variation. For these reasons we evaluate the extraction efficiency like the ratio between the extracted beam current and the beam current measured at R=700. The extraction efficiency is generally 30%.

The project EXCYT and radioisotope production require a beam power as high as 1 kW. This pushes us to investigate the maximum beam power deliverable by our cyclotron. For this reason a fixed probe has been installed at radius 600 mm, and in the near future another one will be installed at the extraction radius. These fixed probes consist of a piece of titanium able to flip by 90° on the median plane when a small coil is fed by a current pulse. An opposite current pulse puts the probe out of median plane. The probes are much more resistant than our radial probe and could measure and receive beam currents of some μA.

Accelerating beam current of some μA at 60 MeV/u implies handling powers of some kW. These beams can cause serious activation and eventual melting of the E.D. and of the acceleration chamber.

To investigate on the maximum beam current and evaluate the transmission factors involved in the injection, acceleration and extraction we operate with beams delivered by the source with a maximum intensity but reduced by a pepper pot to an intensity of 1%. In this way we handle beams with full emittance but low power. Injection and acceleration tests confirm that about 9% of the continuous beam injected inside the cyclotron is accelerated until radius 700 mm. Attenuation by pepper pot reduces by a factor 100 the current density and the space charge effects. The beam current accelerated inside the cyclotron is far away from the critical current, which cancel the vertical focusing. However, the space charge effects due to beam intensities of 40-80 μA of fully stripped ions could increase the emittance of the beam along the injection line, mainly along the last meter inside the cyclotron yoke where the beam is focused to 2-4 mm. This effect was investigated using a simple electrostatic chopper placed in the injection line, which changes the duty cycle of the beam from 100% to 0.% with continuity. For our test a pulse length of 10 μs was delivered with a repetition rate of 1 KHz, duty cycle 1%. Test performed with a beam current of 3-4 μA(Fluorine) show very small effects (1-3%), while a test with 37 μA of Nitrogen beam shows a reduced injection efficiency of about 30%. In future we have to investigate if it is possible to compensate for the space charge effects with a different tuning of the line.

4 UPGRADING OF THE CYCLOTRON

As before explained the main limit to deliver high intensity beams by our cyclotron is due to the extraction process, which is accomplished by two electrostatic deflectors. Assuming that in future we can reach the extraction efficiency of 60%, by increasing the gap of the E.D. to 6 mm, when delivering a beam of 1 kW to the user, about 650 W will be dissipated on the E.D. The activation of E.D.and of the cyclotron in general when operating with this high power becomes serious and the reliability of all the devices decreases too. So we believe that the maximum deliverable beam power from our cyclotron could not exceed 1 kW. The EXCYT facility, under construction at our laboratory, and the research on the radioisotope production could be significantly upgraded if a primary beam with a 20 times higher power would be available. To deliver light ion beams with high power we propose to accelerate ions with charge state q_{ac}=Z-1, Z being the charge of the nucleus.

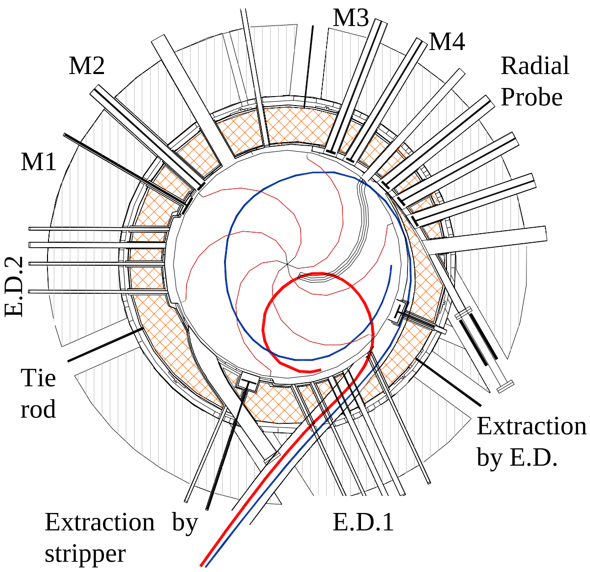

Figure 3: Layout of the cyclotron and the extraction trajectories of $O^{7+\rightarrow 8+}$ (line blue) and of $H_2^+ \rightarrow$ proton

These ions could be extracted using a stripper foil, which increases the charge state up to q_{ex}=Z, then the orbit radius changes and after 1 turn the beam escapes from the pole region [6]. According to the focusing limit of our machine, K_{foc}=200, the maximum energies achievable for light ion are 80÷87.5 MeV/a.m.u. At these energies the ions become fully stripped, with a stripping efficiency of 100%. Adjusting the position of the stripper foil in azimuth and radius it is possible to deliver all the ion beams of interest through a new extraction beam line. A typical extraction trajectory for the case of $O^{7+ \rightarrow\ 8+}$ is shown in Fig. 3. Of course a new cryostat taking account of the new extraction trajectory, is needed.

A different family of trajectories are also possible if the selected charge state for acceleration of ion is q_{ac}=Z/2 and the charge state after the stripper is q_{ex}=Z. Of course it is necessary to achieve a final energy high enough to guarantee stripping efficiency of 100% for the charge state q_{ex}=Z. For our machine the maximum energies achievable are 50 MeV/amu for all the ions up to Calcium. Moreover also the H_2^+ and the D_2^+ molecular beam can be extracted by stripping. In this case in fact the stripper foil breaks the molecules and produces 2 nuclei, which have a magnetic rigidity two times less than the accelerated beam. There is only a difference for the case of H_2^+. In this case the charge to mass ratio is q/A=0.5, and the maximum final energy is 100 MeV/amu. In fig. 3) the drawing of the K800 cyclotron with the extraction by stripper trajectories for the $H_2^+ \rightarrow P$ case and the $O^{7+} \rightarrow O^{8+}$ case are shown. It is evident that the new cryostat needs a proper and different penetration hole through the cryostat, while the existing radial injection channel becomes unnecessary.

A lot of work has been done to find out the radius and azimuth of the stripper that allows to have the different extraction trajectories for H_2^+ and the light ions inside one extraction channel with minimum differences. The main difference between the two trajectories of extraction are the position of the stripper foil. For the extraction q=Z/2→Z the stripper foil must be placed in a hill, while for the other extraction q=Z-1→Z is placed in a valley.

According to this perspective we propose to modify our cyclotron to allow for stripper extraction, building a new cryostat, complete of a new set of superconducting coils and two extraction channels. One channel similar to the present one, which allows the extraction of all the ion beams with low power (<50 W) by E.D. These beams are generally used to perform nuclear physics experiments at intermediate energies and low beam current is normally required. The additional extraction channel will be provided to allow for the extraction by stripping of ion beams with power of 10-20 kW. The design of the extraction channel requires a stress analysis of the cryostat structure to evaluate the maximum size of each penetration across the cryostat. Both these types of trajectories can be delivered through the new extraction channel. But it is evident that the extraction path of the trajectories Z-1→ Z are longer and there are more interference with the existing extraction channel and other devices of the machine. The extraction channel and the construction of the new cryostat could be strongly simplified if only the trajectories of the kind Z/2 → Z are extracted. The main modifications of the magnetic configuration will be:

- increase the distance between the two section of the main coil α to have more room for the beam and for a thicker median plate of the cryostat;
- larger extraction channel and penetration holes to get better performances of the cyclotron;
- use of impregnated coils, like for Agor cyclotron;
- replacement of the inner CuBe tie rods with a different compression system;
- new kind of nitrogen shields to reduce the Liquid Nitrogen consumption;
- replacement of the cryogenic lines with new ones.

To increase the size of the penetration holes across the cryostat a thicker median plate is mandatory. So the size of the main coils has to be reduced to increase the distance from the median plane. This implies that the current density has to be increased. But at the same time the modification has to be as small as possible to keep the form factor of the coils as close to the present one as possible. The main modification to the alpha coil is the increased distance from the median plane, which changes from 62 to 80 mm. This could be done by removing the layer nearest the median plane side. The coil beta could remain exactly the same. Assuming the new size for the coil alfa, we evaluated the new form factor and the currents required for the main coils alfa and beta and the trim coils to achieve the isochronous magnetic field for a set of characteristic ions and energies.The result is a little increase (about 2-4%) of the currents on alfa and beta coils, while for the trim coils current the differences are consistent with the maximum operation currents of the trim coils.

4.1 Maximum Beam Power Deliverable

The K-800 cyclotron has an RF system and a magnetic field able to be tuned in a large frequency range, then the K-800 upgraded cyclotron could be able to accelerate any kind of particle with any q/m ratio. In particular the light ions could be produced and accelerated with the charge state q=Z-1 and at energies of about 80 MeV/amu or alternatively the charge state q=Z/2 could be selected. In this case, although the maximum energies achievable are lower, 50 MeV/amu, the beam current deliverable by the source are 4-8 times more intense.

The maximum beam power for protons, Oxygen, Carbon Nitrogen and Neon ions deliverable from the upgraded K800 proposed are presented in table-1. The final beam power have been evaluated according both to the measured beam current deliverable by SERSE, and to the measured efficiencies of injection, bunching and acceleration. Although the upgrading proposal is attractive there is the negative feature of a necessary stop of the cyclotron activity for a period of 12-15 months to replace the existing cryostat with the new.

Table 1: Beam power deliverable by upgraded k-800

Ions	$q_{ac}\rightarrow q_{ex}$	Emax MeV/u	I_{source} μA	I_{acc} [§] μA	P_{ex} kW
O	7→8	87.5	200	60	12
N	6→7	85.7	200	60	12
H_2	1→2	100	1000	300	60
D_2	1→2	50	1000	300	60
^{16}O	4→8	50	400	120	24
^{20}Ne	5→10	50	300	90	18
^{40}Ca	10→20	50	150	45	9

[§] Transport efficiency 90%, Injection efficiency with Buncher on 36%, acceleration efficiency 95%

5 CONCLUSION

The present status of the K-800 cyclotron allows to deliver all ion beams from proton to Gold. Unfortunately the maximum energies are not yet reached due to the maximum voltage reachable by our electrostatic deflectors. The tests of acceleration of choppered beam with current peak of some μAmpere confirm that there are not any problems of space charge and of emittance acceptance inside the machine. The small losses of about 5% during the acceleration process are due to the stripping of ions beam with the residual gas inside the vacuum chamber. The measured vacuum inside the machine is $1\div4\times10^{-4}$ Pascal and must be improved to reduce the machine activation when beam power of some kW will be accelerated. To overcome the limit in maximum voltage and to deliver beam with power of 500-1000 W new cooled E.D. are under construction.

Anyway we believe that our cyclotron could deliver a beam power of 10-20 kW even of ions as heavy as Calcium with extraction by stripping.

REFERENCES

[1] L. Calabretta et al., proc. XIV I.C.C.A, Cape Town (1995)

[2] M. Re et al., “Breakdown mechanism on Electrostatic deflectors”,this proc.

[3] S. Gammino et al., proceedings XV I.C.C.A, Caen (1998) p. 413

[4] A. Caruso et al., “The Radiofrequency Pulsing System at INFN-LNS” this proc.

[5] D. Rifuggiato et al., proc. XV I.C.C.A, Caen (1998), p. 646

[6] L. Calabretta and D. Rifuggiato, proc. XV I.C.C.A, Caen (1998) p.665