Radial injection into the superconducting cyclotron at LNS

L. Calabretta, L. Lo'Monaco and D. Rifuggiato
Istituto Nazionale di Fisica Nucleare, LNS - Catania

Abstract

The study of the radial injection of the Tandem beam into the Superconducting Cyclotron is presented. The procedure adopted to achieve the transversal matching is described.

The evaluation of the expected beam loss and of the emittance growth at injection is presented too.

Introduction

The Heavy Ion Facility at L. N. S. in Catania will be based on an injector MP tandem, upgraded to 15 MV, and on a booster, a K = 800 superconducting cyclotron [1].

The tandem beam will be radially injected into the cyclotron, where a stripper foil, located on the hill, increases the charge states of the ions before acceleration. The beam transfer line between the tandem and the cyclotron must perform the phase space rotation of the beam in order to optimize the emittance achromatic matching at the cyclotron stripper [2]. Here we describe the procedure adopted to fix the injection parameters and the diagnostics of the matching line. In order to obtain a good injection, we have to minimize the emittance growth and the beam loss due to mismatch effects. The results of our investigation about this subject are presented here.

Beam injection into the cyclotron

The tandem beam is injected into the cyclotron through a steering magnet, then it crosses the yoke, the cryostat, goes into a valley and reaches hill 3, where the stripper foil is placed, fig. 1). The stripper foil position is the tangent point between the injection trajectory and the equilibrium orbit corresponding to the initial beam energy E_i and to the increased charge state. Due to the cyclotron parameters, radial injection is possible only if the final to initial charge ratio is ≥ 3, tipically $3.5 \div 4$ [2].

When assuming the cyclotron field is constant, in the hard edge approximation it is possible to evaluate the tandem voltage V_{tan} and the injection charge state q_i required to obtain a specified final energy E_f with a final charge state q_s. These data are used as starting values in the following procedure leading to the injection trajectory .

- a- Assuming at first q_s and E_f as those evaluated in the hard edge approximation, the magnetic field map is computed by theoretical simulation up to R = 130 cm. Then it is extended up to R = 250 cm by interpolating the measured fringing field data;
- b- the equilibrium orbit relative to E_i and to q_s is computed;
- c- The tangent point between the equilibrium orbit and the injection trajectory is found.

If the injection procedure does not satisfy specified constraints, we modify some of the main injection parameters, often the tandem voltage or the charge states and start the procedure again.

The following constraints must be satisfied in order that an injection trajectory may be accepted :

- The tandem voltage must be less than 15.5 MV.

- The stripper position must be distant enough from the acceleration gap (4 cm, i.e. $\sim$ 1.5 times the axial gap) in order to avoid the RF heating of the stripper support.

- The injection trajectory must be far enough from the injection channel walls (at least twice the beam envelope).

- The intensity of the final charge state depends on the production efficiency of the injection charge

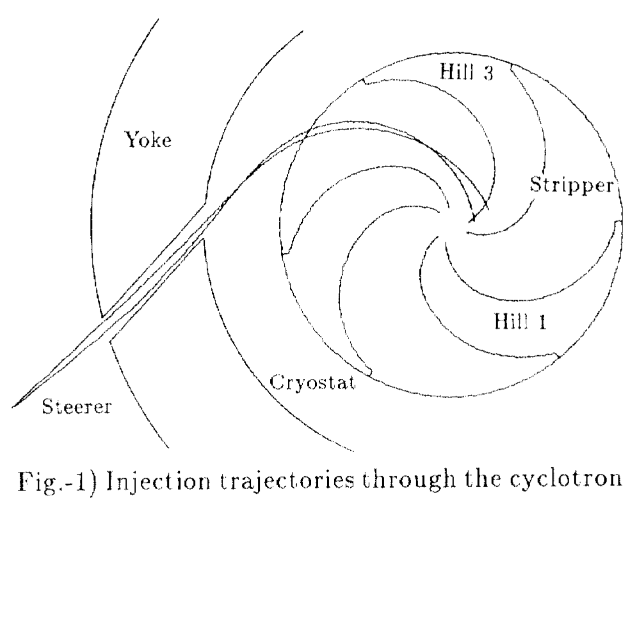

Fig.-1) Injection trajectories through the cyclotron.

state after the tandem stripper, $\eta_t(q_i)$, and of the final charge state after the cyclotron stripper $\eta_{sc}(q_s)$; we consider the global efficiency $\eta_t(q_i) \cdot \eta_{sc}(q_f)$ to be acceptable if its value is $\geq 1.5\%$. This will guarantee beam intensities after the cyclotron stripper higher than 10 nAmpp. Efficiencies are evaluated by semiempirical formulæ [3] which unfortunately can give an error as high as 30 % for some ions.

Since the q_s/q_i ratio and the magnetic fringing field change for different ions and also for different energies, a set of representative ions was chosen to study the whole operating range of the cyclotron (low and high field). The injection trajectories are slightly different for different ions. In table I we list the main injection parameters including the stripper position, R_s and θ_s, and the initial beam direction $\theta - 120^0$, at the steering magnet.

Since higher order effects are negligible, the beam ellipse to be injected at the steering magnet was derived from the eigenellipse at the stripper position and from the transfer matrix. In order to evaluate the transfer matrix elements, we traced the two so called principal trajectories of the beam by integrating the equations of motion along the cyclotron magnetic field. In a similar way we computed the dispersion coefficients R_{16} and R_{26} (see TRANSPORT notation). The values of the ellipse parameters (x, x' and y, y' , see table I) at the steering magnet, together with the dispersion coefficients, were used as input to 'TRANSPORT' code to search for the field values of the matching section line. The matching line was already presented [2]. With respect to those specifications, the distance between the last two quadrupoles is a little shortened in order to minimize the beam envelope inside these quadrupoles.

Moreover the yoke to steerer and steerer to Q16 distances are so large as to place a home developed emittance meter (EM) [4].

Once again we verified that the matching beam line is able to rotate the beam ellipse in the phase space to satisfy the found injection parameters at the steerer position. The characteristics of the steering magnet and of the last two quadrupoles Q15 and Q16 are presented here:

M_{st}:	$L_{eff} = 26$ cm	$\Delta\phi_{max} = 4^0$	$B \cdot \rho = 3\ T \cdot m$
Q16:	$L_{eff} = 20$cm	$\phi = 70$ mm.	$B_{max} = 7.5$ Kgauss
Q15:	$L_{eff} = 30$cm	$\phi = 100$ mm.	$B_{max} = 6.5$ Kgauss

Mismatch effects

The different sources of emittance growth we have considered are :

- angular straggling introduced by the stripper foil;
- emittance to acceptance mismatch;
- chromatism;
- wrong position of the beam centre in the phase space.

The emittance growth due to angular straggling can be minimized but not eliminated. On the contrary, the other effects could in principle be reduced to zero. Since the angular straggling is quadratically added to the beam divergence, in order to minimize its effect we have to obtain a beam divergence as high as possible at the stripper position. Assuming the emittance value ϵ_0=15 mm · mrad, we find the axial envelope is typically 4 mm while the radial one is 2 mm, the divergences are respectively 2.4 and 4.8 mrad. If an angular spread of $1 \div 1.5$ mrad is introduced by the stripper [5], we obtain a $1.20 \cdot \epsilon_0$ emittance growth in the axial phase space and only $1.05 \cdot \epsilon_0$ in the radial space.

We plan to check the correct setting of the matching line by measuring the beam emittance at the steering magnet position with an Emittance-meter (EM). Unfortunately, even though the resolution of the EM is good (0.2 mm., 0.3 mrad) small errors

Table I. Injection and beam parameters at the steering magnet.

Ion	q_i/q_s	V_{tan}	B_0	E_f	θ-120	R_s	θ_s	x	x'	y	y'	R_{16}	R_{26}
		MV	T	$\frac{MeV}{n}$	deg	cm	deg	mm	$mrad$	mm	$mrad$	$\frac{mm}{\%}$	$\frac{mrad}{\%}$
C	1/6	6.	3.13	100.	-0.1	9.2	337.1	21.6	9.4	12.8	10.7	-102.0	-47.2
C	2/6	15.	2.65	67.	-0.7	21.5	320.8	14.0	6.2	6.5	6.0	-69.6	-32.9
O	2/8	6.5	2.2	44.5	-1.4	14.6	320.9	22.1	9.7	4.7	4.0	-65.7	-31.6
Cu	5/21	15.	3.72	60.	1.8	14.0	333.1	17.9	7.8	11.3	10.4	-95.5	-43.7
I	6/28	14.6	4.68	40.	4.0	12.6	332.9	19.3	8.4	11.0	10.8	-96.9	-43.8
I	7/28	15.5	4.65	39.5	2.8	13.9	354.2	14.2	6.4	22.8	20.6	-160.3	-71.5
U	9/34	14.	4.7	16.	4.3	16.6	324.4	17.7	7.7	8.5	8.7	-79.8	-36.2

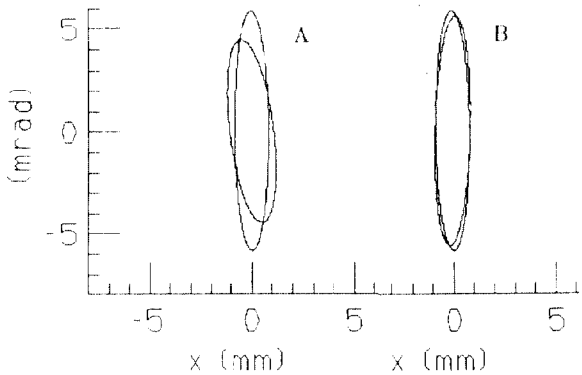

Fig.-2) Radial beam ellipses at the stripper.
A) emittance beam measured at steerer;
B) Beam size measured by the moving probe.

in the evaluation of the ellipse slope at the steerer position are amplified at the stripper. In fig. 2A) we show two different emittance ellipses at the stripper. They are produced by two ellipses at the steerer which are indistinguishable within the resolution of our EM device. In the worst case shown, 25% of the beam is out of the ideal emittance (assuming uniform intensity inside the ellipse), and this unmatched part of the beam (called 'loss' from now on) will be filamented over a larger emittance area ($\sim 2\epsilon_0$). In the axial plane these mismatch effects are smaller due to the beam size at the stripper position (beam 'loss' $\sim$ 18%, $\epsilon = 1.7\epsilon_0$). In fig. 3) we show a typical beam envelope along the injection trajectory and also after the stripper position up to hill 1 (see fig. 1)), where the beam can be detected by a moving probe. The position resolution of the probe in the radial plane is about 0.5 mm. If this probe is used to check the injection conditions, we expect a maximum beam 'loss' in the radial plane of about 8 % and $\epsilon = 1.45\epsilon_0$, see fig. 2B).

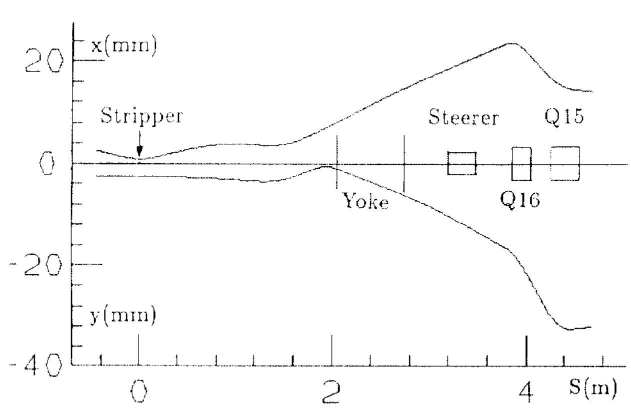

Fig.-3) Beam envelope from the steerer to the moving probe crossing the stripper position. The stripper is out, the charge state is q_i.

In order to check the dispersion coefficients at the steerer position, we plan to increase the tandem voltage by 0.2% and to measure the beam shift (about 12 $\div$ 32 mm) by the EM. Since the beam momentum spread introduced by the rebuncher is $\pm$ 0.1%, the evaluated residual dispersive effect at the stripper is negligible ($R_{16} \leq 1$ mm/%).

The last problem we investigated is related to the position of the tangent point between the injection trajectory and the equilibrium orbit. We expect that we could place the centre of the beam at the correct position by setting properly the steering magnet parameters. Let us suppose to check the trajectory position by the probe once again; if we assume a 0.5 mm error in radius position, the betatron oscillation of the centroid increases the emittance to $2.5\epsilon_0$ and causes a beam 'loss' of $\sim$ 39%. Fortunately, as said before, we can move the beam to a different radial position by using the steering magnet so as to minimize this effect. However, in doing so we would also introduce a 1$\div$1.25 mrad angular shift (referred to 0.5 mm radial shift), and this produces a beam 'loss' of 21%, filamented on an emittance area of $1.37\epsilon_0$.

Conclusions

We plan to use an emittance meter placed near the steering magnet to check the beam chromatism and to set the matching line. Using only this diagnostic device, we expect a beam 'loss' of 50% at most. This can be reduced to 26% if a moving probe is used to check the position and the beam envelope. Matching in the axial plane is possible using only the EM device, the beam 'loss' being of $\sim$ 18%. If the probe will measure the axial beam size with an accuracy better than 1 mm., we expect to reduce the axial mismatch.

References.

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