THE COUPLING LINE BETWEEN THE TANDEM AND THE SUPERCONDUCTING CYCLOTRON AT THE LNS IN CATANIA

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Summary

The design of the coupling line between a tandem and a superconducting cyclotron is presented. Transversal and longitudinal matching are obtained in a modular way to decouple the two machine and to simplify the set-up and the operation of the beam line.

Introduction

The heavy ion facility at the L.N.S. in Catania will be based on an injector MP Tandem, upgraded to 16 MV and on a booster K=800 Superconducting cyclotron now under construction at the university of Milan[1,2].

The Tandem beam will be injected radially into the cyclotron where a foil stripper, located on the hill, increases the charge states of the ions before acceleration. The final energies of the beam will be 100 MeV/n for fully stripped ligth ions down to 20 MeV/n for uranium, with intensities of $10^{12}\div10^{11}$ pps.

The beam transfer line between the tandem and the cyclotron has been designed in a modular way to simplify the set-up and the tuning. The line is divided in three sections:

i) an analysing section to perform the charge state analysis of the tandem beam;

ii) an achromatic section to produce a double waist of given dimension thus allowing to decouple the two machines for set-up and diagnostic;

iii) a matching section to match the tandem beam to the cyclotron acceptance.

The design goal for the longitudinal phase space is a time focus at the cyclotron stripper foil of ±3° RF with 50% efficiency. This will be obtained with a new Tandem preinjecto (running up to 450 kV), a low energy buncher at the Tandem entrance and an high energy rebuncher in the achromatic section. The general lay-out of the accelerator complex with the main components of the coupling line is presented in Fig. 1. A detailed description of the subsystem is given in the following.

Beam injection into the cyclotron

The radial injection into the cyclotron is performed with a steering magnet, located close to the cyclotron yoke, which controls the deflection of the incoming tandem beam. The beam crosses the yoke and the cryostat, enters in a valley and reaches the hill where the stripper foil is placed, on the equilibrium orbit corresponding to an increased charged state. The injection process is schematically indicated in Fig. 2. where two extreme trajectories are plotted; the needed deflection at the steering magnet is ±2.5°.

The range of the stripper radii is 10÷20 cm; the charge state must be insreased at minimum by a factor 3 (normally 3.5÷4.0) to make possible the injection of the tandem beam. The injection trajectories have been calculated for a large set of representative ions, in a computed cyclotron magnetic field, in order to minimize the width of the injection channel in the yoke and in the cryostat. The optimization of the trajectories with regard also to the radial and azimutal position of the stripping foil will be performed after the magnetic field mapping of the cyclotron.

The beam envelope for a representative ion along the injection trajectory from the steering magnet to the cyclotron stripper foil is shown in Fig. 3. The beam, with an emittance of 15 mm·mrad in both planes, is matched at the stripper to the cyclotron eigenellipses: typical beam size at this location are 2 mm radially and 5 mm axially. The beam is very well confined inside the machine due to the focusing effect of the cyclotron field; the yoke field has instead no focusing effect in both planes so that a strongly convergent beam is required at the steering magnet location. It is therefore necessary to have a large beam size in the focusing elements placed before this magnet.

The use of a magnetic channel in the injection path inside the yoke can reduce, at least in one plane, the size of the beam before the steering magnet as

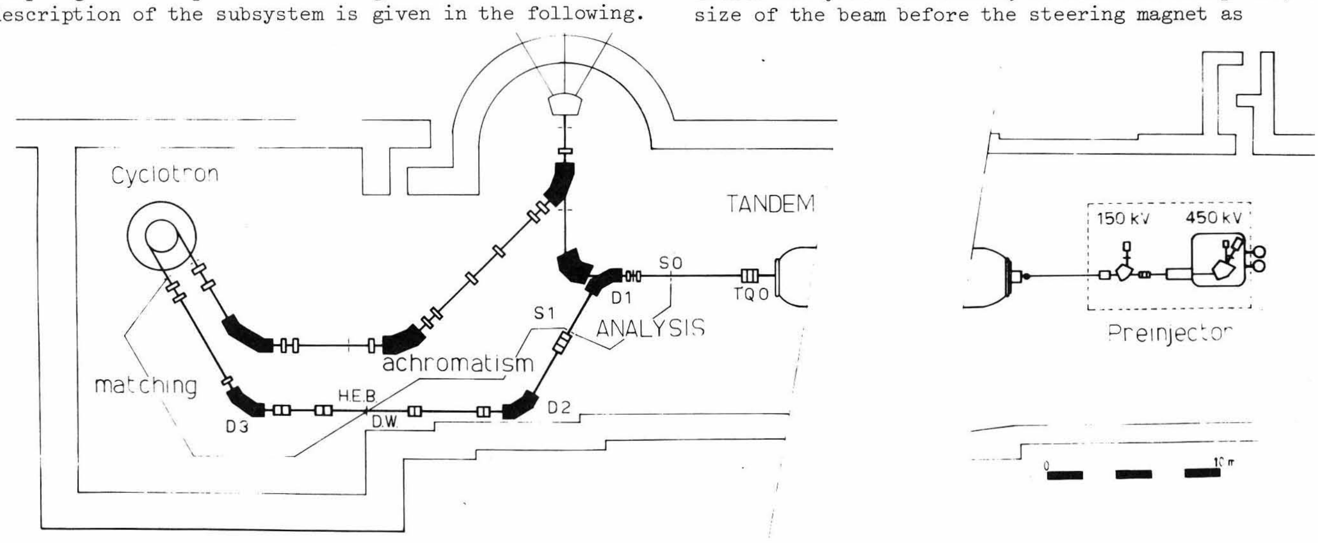

Fig. 1. Lay-out of the beam transfer line between the Tandem and the Superconducting Cyclotron. The new preinjector system is also shown.

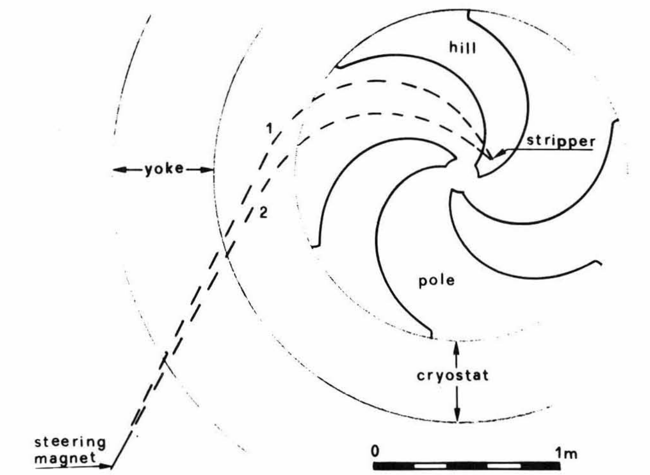

Fig. 2. Scheme of the injection in the superconducting cyclotron. The extreme trajectories are shown.

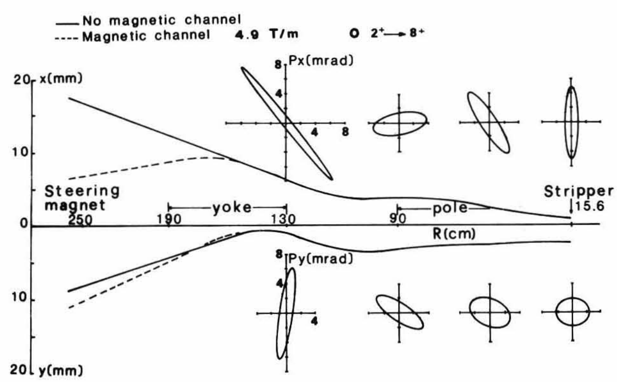

Fig. 3. Beam envelope and phase space ellipse along the injection trajectory from the steering magnet to the cyclotron stripper.

indicated in Fig. 3. The gradient of the magnetic channel scales approximately with the rigidity of the beam. The final choice whether to use or not the magnetic channel will be made after the mapping of the cyclotron field. Preference is obviously given to a solution without magnetic channel; anyway the proposed beam line works equally well in both the cases.

The space behaviour, without magnetic channel, for a set of a representative ions at the steering magnet location is summarized, in the TRANSPORT notation, in Table I. A 15 mm•mrad emittance in both planes has been assumed with an achromatic matching at the stripper to obtain a time focus without straggling. As can be seen in Table I the beam characteristics have a limited range of variation.

Table I . Beam parameters at the steering magnet

Ions	q_f/q_i	E_f	x	θ	y	ϕ	R16	R26
		MeV/n	mm	mrad	mm	mrad	mm/%	mrad/%
N	7/2	100	14	6.2	19	12.4	101	-47
O	8/2	100	18	7.6	9	7.0	70	-32
I	29/7	60	18	7.7	15	10.4	112	-49
U	39/11	20	17	7.1	11	8.3	95	-42
O	4/1	25	18	7.6	6	5.4	65	-30
I	16/4	15	18	7.6	10	7.8	85	-38
U	20/6	5	16	7.0	9	7.0	70	-31

Beam transfer line

The beam line has to satisfy a basic constraint related to the site location. Specifically the cyclotron has to be seen as a bypass between the Tandem and the experimental areas in the direction of the tandem beam. As already mentioned the beam line has been designed in a modular way to decouple the two machines in transversal and longitudinal phase space. This choice was felt unavoidable for a succesfull coupling machines since it allows to perform separate tuning and diagnostic on the two machines.

From the point of view of the coupling the Tandem can be regarded as a virtual source of given emittance, about 15 mm•mrad, almost ind pendent from ion species and energies. The control of the beam size at the Tandem exit can be obtained with a triplet so that it can be assumed at the entrance of the transfer line a double waist of 2 mm in both planes.

A typical beam envelope along the transfer line is presented in Fig. 4, where are also schematically indicated the focusing and diagnostic elements. The beam rigidity of the injected beam is in the range 1÷3 T•m. The wedge dipoles D1÷D3 have a 60° bending angle, a 2 m radius of curvature and 38 mm gap. Two set of quadrupoles, with the same 75 mm aperture, have been chosed with a magnetic length respectively 24 cm and 44 cm and field gradient 18.5 T/m and 16.5 T/m.

Analysing section

Charge state analysis of the tandem beam and control of the tandem beam and control of the tandem voltage are obtained with a dispersive system made up of two quadrupoles and a 60° bending magnet[3]. This system produces an image at the exit slit S1 with a magnification Mx=.8 and a dispersion R16=30 mm/%.

The momentum resolving power of the system is about 2000; the use of logharitmic slit amplifiers, with an intercepted current of few percent, can stabilize the Tandem voltage to better than 10^{-4}.

Achromatic section

This section is designed to produce, at the end, an achromatic double waist of given dimension in both planes. This allow to decouple the two machines for the set-up of the line and for diagnostic. The end of the achromatic section is about midway between the Tandem and the cyclotron so that it is convenient to place here the rebuncher since the achromatic condition assures the decoupling between the longitudinal and the transversal phase space.

The achromatic condition is obtained setting the dipoles D1 and D2 and the triplet TQ1 as a system with antireflection symmetry. The four quads q6÷q9 bring the beam to a double waist with the possibility of a variable size in the range 2÷4 mm. The analysis section and the achromatic system do operate in constant mode i.e. the setting of the elements of the line scale according to the rigidity of the ions. Variation of the beam size respect to the nominal values are in fact easily taken into account. The triplet TQ0 will be used to set the horizontal beam size at the entrance slit S0 to mantain the high resolving power needed for the stabilization of the Tandem voltage. Axial phase space variation are far less important due to the large vertical acceptance of the beam line and are therefore compensated with the quads q6÷q9.

Matching section

This section performs the matching of the double waist and achromatic beam to the cyclotron acceptance here defined at the steering magnet location (Table I).

This section has been designed with practically no

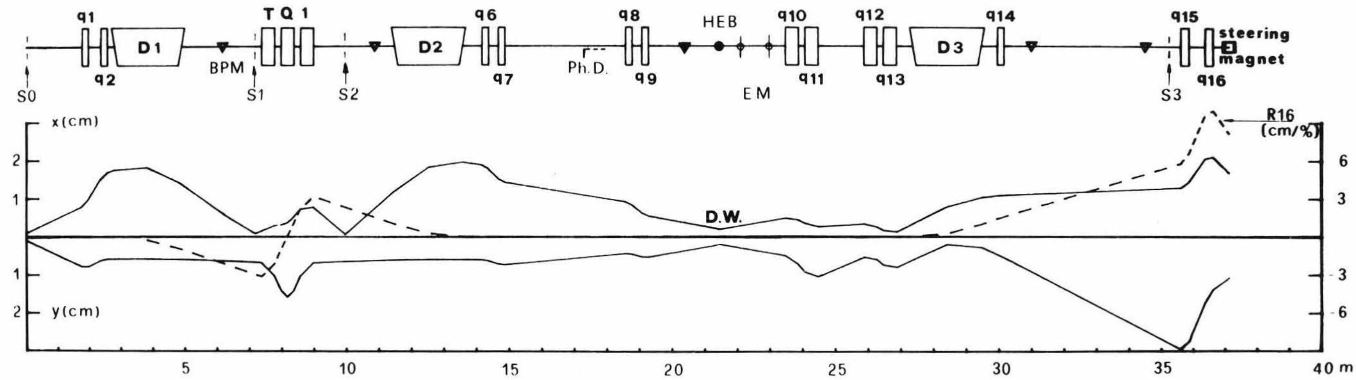

Fig. 4. Beam envelope (for a 15 mm·mrad emittance) and dispersion coefficient along the beam transfer line. Position of beam diagnostic devices are also indicated.

redundance of focusing elements since it has only 7 quads vs the theoretical minimum of 6 quads. Considerable efforts have been made to obtain maximum flexibility without increasing (and overcrowding) the elements

The envisaged solution perform very well under a large variety of input beams (variable size of the double waist in the range 2÷4 mm) and matching conditions (including the option of a magnetic channel inside the yoke). Partial decoupling of the matching has been obtained; the dispersion matching is achieved with the dipole D3 and the quadrupole q14 while the emittance matching is given by the quads q10÷14. The two quads q15-q16 are mainly used to keep the beam size at reasonable values inside the quads. The matching section, with the exception of the quads q15,q16, works practically in a constant mode. This is equivalent to say that the relative variation of the beam characteristic at the steering magnet location can be compensated, for a large part, with just the quads q15-q16.

Diagnostic

The setting and the tuning of the beam line will proceed following the modular design of the system. Beside slits, faraday cups, beam profile monitors (BPM) and emittance meter (EM), placed at the positions indicated in Fig. 4, will be used. The setting of the analysing section will be made maximising the transmission between object and image slit S0÷S1 with the help of a BPM to control the size of the beam. With the same procedure can be checked the correct setting of triplet TQ1 since another image of the slit S0 is formed at the slit S2 (Mx=.6). The two beam profile monitors between D1 and D2 can then be used to obtain information about the beam divergence at the entrance of the line; nominal values at S0 can be obtained, at least in the horizontal plane, by tuning the triplet TQ0.

The achromatism can be checked, in principle, changing the Tandem voltage by 10^{-3} and looking to the invariance of the beam centroid with the BPM placed after the dipole D2. Double waist at the end of the achromatic section will be controlled with an emittance meter.

Control of the matching section is quite more critical due to the difficulty to place diagnostic devices close to the steering magnet and to the low resolution of the devices because of the strongly convergent beam required for the matching. With the rebuncher off, to not introduce significant energy spread, two BPM placed in the drift section after the dipole D3 should be sufficiently to obtain enough information on the transversal matching. Alternatively an emittance meter can be used. Dispersion R16 is measured changing the Tandem voltage by 10^{-3} and looking at the beam displacement.

Fine tuning of the matching section, does require diagnostic measurements inside the cyclotron.

Bunching system

For the longitudinal phase space a design goal of a 6° RF time focus at the cyclotron stripper was set to allow the single turn extraction of the beam and to obtain an energy spread of 10^{-3}.

However to satisfie the physicist request for a pulse length as short as possible for the extracted beam a more performing bunching system has been designed, able to produce a pulsed beam with 3° RF length over the full range 15÷48 MHz of the cyclotron frequency and with a 60% efficiency.

These performances can be obtained only with a two stage buncher because of non linear effect as source energy spread, energy straggling at the stripper and aberrations at the gap crossing.

A low energy buncher (LEB) is placed at the Tandem entrance and an high energy buncher (HEB), or rebuncher is located midway betxeen the Tandem and the cyclotron (see Fig. 1). The LEB will produce a time focus of 10°÷15° RF at the Tandem stripper to minimize the longitudinal phase space growth produced by the energy straggling at the stripper. The pulse, debunched to 15°÷20° RF, will then brougth by the rebuncher at the final time focus of 3° RF at the cyclotron stripper.

Bunching efficiencies and voltage have been calculated with a raytrace code which take into account all non linear effects with the exclusion of the Tandem jitter. In Table II the calculated bunching efficiencies (η) of the proposed system are listed for a set of representative ions together with the voltages to apply at the two cavity of the LEB (V1,V2) and of the rebuncher (Vr). The rms values assumed for the energy straggling (ΔEstr) at the Tandem stripper is also indicated.

The efficiencies quoted in Table II are given as the beam fraction in ±1.5° RF, $\pm10^{-3}$ momentum spread reduced by 10% to take into account the transparency of the grids used in the LEB. The different efficiency values are mainly due to the aberrations during the gap crossing of the LEB and to the energy straggling of the stripper; for the high energy beam of iodine and uranium a solid stripper has been assumed.

Table II - Bunching efficiencies and parameters

Ions	Vt	q_i	E_{inj}	RF	V1	V2	ΔE_{str}	Vr	η
	MV		KeV	MHz	kV	kV	KeV	kV	%
N	15	2	196	48	0.479	.179	1.5	18	65
O	15	2	224	48	0.544	.203	2.0	26	65
I	15	7	341	33	0.517	.190	21.5	20	56
U	15	11	284	22	0.441	.166	24.8	22	58
C	11	2	196	37	0.659	.248	1.3	23	64
O	6	1	256	22	1.327	.502	2.0	18	57
I	7	4	198	16	0.468	.171	5.9	11	57
U	8	7	253	17	0.441	.166	7.0	10	59

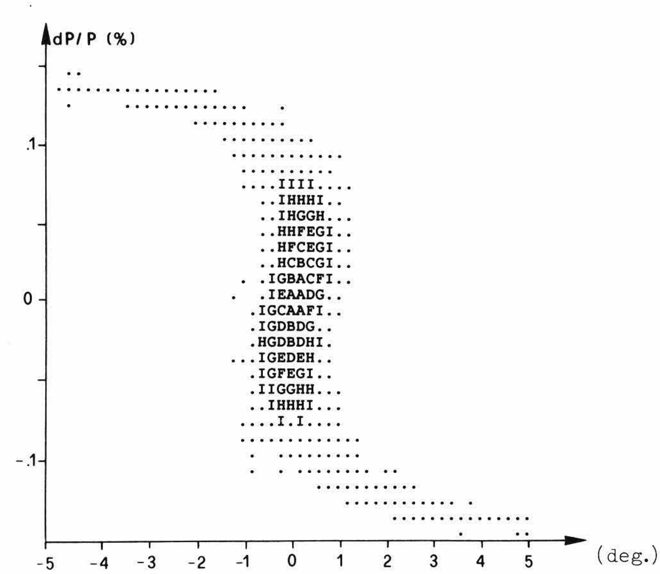

Fig. 5. Longitudinal phase space at the S.C. stripper

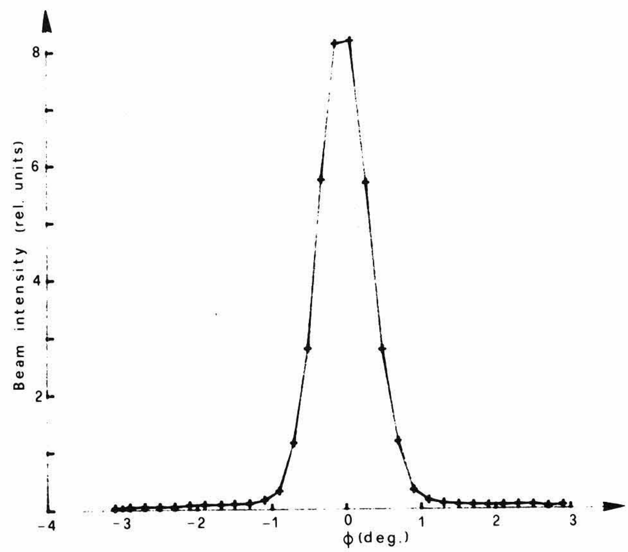

Fig. 6. Beam intensity at the cyclotron stripper

In Fig.5. is presented a typical longitudinal phase space at the cyclotron stripper as calculated by the computer code. As can be seen in the figure (obtained tracking 10000 ions) the requirements of a 3° RF pulse length is met with an associateed momentum spread of $\pm 10^{-3}$. The intensity distribution is plotted in Fig.6

The FWHM of the pulse is lower than 1° RF; however a 0.5° RF has to be added quadratically to take into account the residual Tandem phase jitter not compensated by the control system (see later). No significant change of the efficiency, as can be estimated from the figure, is anticipated.

Low Energy Buncher

The LEB is a double drift buncher consisting of two λ/4 cavities driven respectively in first and second harmonic. Several laboratories use this device although at lower and generally fixed frequency.

To reduce the disuniformity of the accelerating electric field, grids made of 20 microns tungsten wire, spaced 3 mm, are used in the gaps. The grids reduce the beam intensity by about 10%; the expected life time should be at least one mounth.

In order to obtain a good time focus at the stripper a new 450 kV preinjector will be installed[4].

The energy spread of the source and the voltage instabilities will be reduced to a level of $\sim 10^{-4}$. The high voltage will allows to select the appropriate value of $\beta\lambda/2$ for the injected beam to match the drift tube length of the buncher. Also the transmission through the Tandem will be improved. The two cavities of the LEB are made of aluminum and the expected quality factor is Q=2000; a 50 watt solid state broad band amplifier is sufficient to give the 1.5 kV peak voltage required.

High Energy Buncher

The HEB is a resonator with a drift tube working in the frequency range 60÷200 MHz. The operation in fourth harmonic mode has been chosen to minimize the peak voltage amplitude while still providing a good linearity in the working region (±30°). The drift tube length is a 63 mm to match the average $\beta\lambda/2$ value of the injected beam; for stripping radii in the cyclotron in the range 10÷20 cm the $\beta\lambda/2$ value in RF degrees is in the range 120°÷240°. The HEB is a λ/4 resonator based on a similar design realized at Chalk River[5].

The expected quality factor of the cavity (copper made) is Q≐5000; for a peak voltage of 30 kV a power of about 1 kW should be sufficient to drive the rebuncher.

Diagnostic

The tuning of the LEB is made possible through monitoring of the pulse shape close to the HEB position.

A μchannel plate will be used as a time detector for the ions of the beam. The signal will be send to a TAC acting as stop while a reference RF phase signal will be used as start. Few minutes, to accumulate about 100.000 events, are required to obtain a good resolution for the pulse shape. The phase jitter introduced by the tandem will be controlled by a capacitive pick-up probe (PhD in Fig. 4) detecting the central phase of the beam. The phase shift of the probe respect to a reference RF phase will be send as a feedback to the LEB.

Measuring the left-rigth difference of the current i.e. the beam centroid shift due to the longitudinal momentum variation and at the high dispersion value at the slit S3 the correct phase shift between the LEB and the HEB will be controlled. The resolution of this device is critical due to the large size of the beam at this position.

Status

The magnetic components of the beam line, with the exception of quads q15-q16, have been ordered and will be delivered at the end of '86. The LEB is under construction and the final design of the HEB has been completed. Diagnostic devices for the transversal and longitudinal matching are under development.

It is planned to install part of the beam line (up to and including the dipole D3) in '87; this allow to test completely the first two section of the beam transfer line and the low energy buncher as well as the diagnostic devices.

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