BEAM TRANSMISSION EFFICIENCY BETWEEN INJECTOR AND TARGET IN THE GANIL COMPLEX

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Abstract

In order to achieve a maximum transmission efficiency, efforts have been made in three directions : beam measurements, understanding of the physical phenomenon, tuning method. The characteristics of the beam extracted from the three cyclotrons have been measured. The ensuing optical effects are analysed. The tuning of the transport-lines, depending on the characteristics of the extracted beams and the required beam properties on the target, is described.

The GANIL beam-lines are designed in order to perform certain optical functions[1], like betatron and chromatic matching of the beam extracted from the three cyclotrons, betatron and chromatic matching of the beam injected in the SSCs, betatron and chromatic matching of the beam on the target, emittance and energy dispersion measurements[3], emittance and energy dispersion limitation[4]. Since GANIL is running (end 82), efforts have been made to tune the beam-lines so that these optical functions are performed in practise. For this purpose the beam-parameters have been measured, the optical properties of the extraction and injection devices of the cyclotrons analysed, the measurements interpreted and the experimental tuning parameters deduced.

1. CHROMATIC MATCHING OF THE EXTRACTED BEAM

The function of the first section S_{ex} of the beam-line at exit of each cyclotron is to make the beam achromatic. In order to tune this section, the chromatic characteristics of the extracted beam have to be measured. A theoritical estimation of the chromatic terms is not accurate enough, because of the difficulty to measure precisely the field in the whole extraction device of the cyclotron. Two methods are used to match the achromatic conditions : the first method consists in measuring the radial emittance at exit of section S_{ex}, i.e. in section S_{em}, where the beam has to be achromatic, as a function of the gradient of the quadrupoles of section S_{ex}. The achromatic matching is obtained when the radial emittance area is minimum. The second method consists in changing within a few per cent the RF voltage of the cyclotron, i.e. the energy of the extracted beam, and observing simultaneously the radial beam position in section S_{em}, as a function of the gradient of the quadrupoles of section S_{ex}. The achromatic matching is obtained, when the radial beam position in the whole section S_{em} is independant of the energy of the extracted beam. When the achromatic conditions are performed, it has been verified, that any part of the emittance figure has the same energy distribution.

At the present time, the achromatic conditions are achieved at exit of the three cyclotrons. The following table contains the theoretical and experimental values of the chromatic terms T_{16} (in mm per 1000) and T_{26} (in mrad per 1000) at the interfacing point between cyclotron and beam-line.

	Theor. val. [2]		Exp. val.	
	T_{16}	T_{26}	T_{16}	T_{26}
Injector	- 1.9	- 3.3	- 1.8	- 2.8
SSC1	- 0.4	2.3	- 2.1	3.3
SSC2	- 0.4	2.3	- 2.1	3.3

Table 1

The values for SSC1 and SSC2 are equal within the accuracy of the experimental measurements. The chromatic terms seems to be independant from the field level. This point has still to be examined more precisely.

2. CHROMATIC MATCHING OF THE INJECTED BEAM

This question is the inverse one of the chromatic matching of the extracted beam. The function of S_{in}, the last section of the beam-line before the SSCs, is to match the two chromatic terms on the "first orbit". The theoretical estimation of these terms presents the same difficulties as related in the previous paragraph. The method used to match the chromatic conditions consists in minimizing the chromatic oscillation amplitude in the SSCs (frequency $(\nu_r - 1)^{-1}$), as a function of the gradients of the quadrupoles in section S_{in}. At the entrance of section S_{in}, the chromatic properties of the beam are supposed to be well known. In our case, the beam has to be achromatic, i.e. the achromatic matching of the extracted beam has previously to be achieved in section S_{ex} (see preceeding paragraph).

At the present time, the chromatic matching is achieved at injection in SSC1. The following table contains the values of the theoretical and experimental chromatic terms at the interfacing point between the beam-line and the cyclotron, for a beam of 0.72 Tm magnetic rigidity.

	Theor. val. [2]		Exp. val.	
	T_{16}	T_{26}	T_{16}	T_{26}
SSC1	0.9	- 0.5	0.6	- 0.5

Table 2

The two chromatic terms at the chosen interfacing point are slighly dependant of the field level in SSC1, because the focusing in the injection device depends on the magnetic saturation. This does not necessary mean that the chromatic matching on the "first orbit" depends on the field level. Concerning SSC2, the matching parameters are at the present time the theoretical ones. They have to be verified by tests.

3. BETATRON MATCHING OF THE EXTRACTED BEAM

In order to fit the acceptance of the beam-line, the betatron emittance parameters, i.e. tilt and ellipticity of the approximate emittance ellipse, of the extracted beam have to be matched at the entrance in the beam-line. For this purpose a special device, consisting of four quadrupoles and three beam-profile monitors, is arranged in section S_{em}. For easier matching, section S_{em} is downstream from section S_{ex}, so that the radial betatron parameters are uncoupled with the chromatic ones. In order to characterize the beam, a special point P was arranged in section S_{em}, where the beam has to present an homothetic horizontal and vertical cross-over. The scaling factor is the square root of the ratio of the emittance area to the theoretical acceptance of the beam-line. In beam-line L1 (between injector cyclotron and SSC1) point P is the object-point of the on-line low-energy analysing magnet ; in beam-line L2 (between SSC1 and SSC2) point P is on the stripper target ; in beam-line L3 (between SSC2 and the experimental area) point P is the object-point of the on-line high-energy analyser. In practise the cross-over is checked on three equidistant beam-profile monitors, installed in a drift-space situated downstream from the four matching quadrupoles. Accurate matching is obtained when $d_1 = d_3$ and $d_2/d_1 = k$, where d_1, d_2 and d_3 are the beam dimensions on monitors 1, 2 and 3, and k is a given constant, depending on the distance between monitor 1 and 3. In addition the beam has previously to be achromatic in section E_{em} (see paragraph 1).

At the present time, the betatron matching is achieved at exit of the three cyclotrons. In L1 the matching depends slightly on the field-level in the injector, even for a standart tuning of the latter. In L2, the matching does not depend on the field-level in SSC1, provided the beam is extracted on the desired turn. In L3, the matching is not reproductible from run to run, because the extraction conditions from SSC2, especially the numbers of turns, are not yet standard.

4. BETATRON MATCHING OF THE INJECTED BEAM

This question is the inverse one of the betatron matching of the extracted beam. The function of S_{in}, the last section of the beam-line before the SSCs, in addition to the chromatic matching function, is to match the two horizontal and the two vertical betatron parameters on the "first-orbit". The method used to match these conditions, consists in minimizing the betatron oscillation amplitude in both directions in the SSCs (frequency $2/(\nu_r - 1)$) as a function of the gradient of the quadrupoles in section S_{in}. At entrance in section S_{in}, the betatron properties of the beam are supposed to be well known. This is the case when the betatron matching of the extracted beam is previously achieved (see preceeding paragraph).

At the present time, the betatron matching at the entrance of the SSCs corresponds to the theoretical values, which have to be confirmed by tests.

5. BEAM MATCHING ON THE TARGET

In the general case the beam on the target is achromatic and has 5 mm in diameter for a horizontal and vertical emittance of 5 π mm-mrad. This squares with the theory. If a smaller diameter is required, it is necessary either to limit the emittance, consequently the intensity, or to find a non standard matching if any exists.

6. GENERAL COMMENT

When the betatron and chromatic matching of the extracted beam is accurate at the interfacing point P (mentionned in paragraph 3), the beam behaviour downstream from P squares with the theoretical estimation. In connexion with this, it must be mentionned that an accuracy better than 1 % of the magnetic rigidity of the beam is necessary, to obtain the accurate quadrupole forces.

7. TRANSVERSE EMITTANCE MEASUREMENTS

Three methods have been considered to measure the transverse emittances in the beam lines[3] : the three distances method, the three (or more) gradients method and the scanning method. At the present time, only the first one is really operational in the three beam-lines. It has still to be used prudently, especially in L1, due to the difficulty of interpretation of the beam profiles, because the particle density distribution in the transverse emittance figures is unknown and in the general case non-uniform. The second method is not easy to use in our case, because the emittance of the beam, especially in L1, is not small enough compared to the acceptance of the beam-lines. So if the gradient is varied, the beam may hit the vacuum pipe. The third method is now in preparation and will be operational near the end of this year.

Figures 3 to 6 show the number of particles in L1 versus the emittance area, limited by the special limitation slits[4].

Before the tuning of SSC1 was standard, the emittance of the extracted beam was different from run to

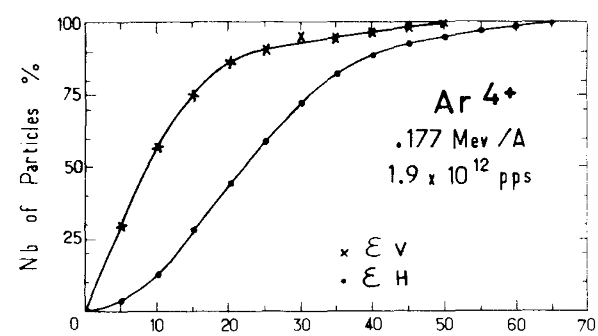

Fig : 3 Emittance π . mm.mrad

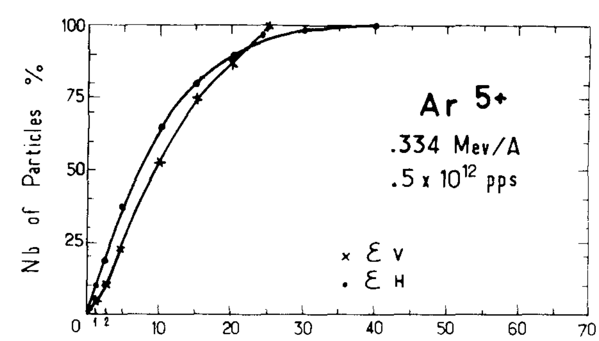

Fig : 4 Emittance π . mm.mrad

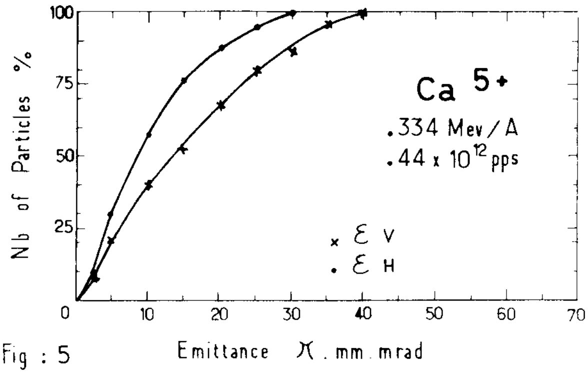

Fig : 5

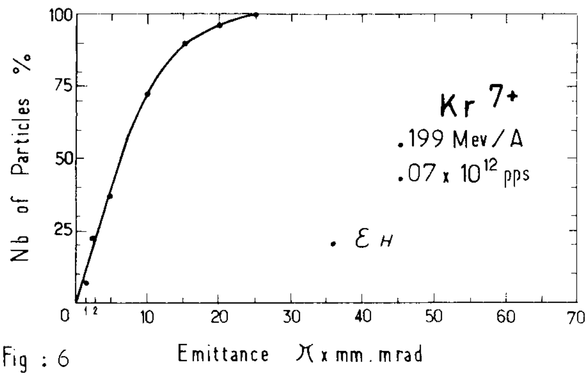

Fig : 6

run and its area was rather smaller than the theoretical value. Since it is standard, the emittance measurement has only been performed on a Ar^{16+} beam of 3,5 MeV/A. The horizontal and vertical emittance areas are found to be in the order of 12 π mm-mrad.

The tuning of SSC2 is not yet standard. Nevertheless a typical emittance area, measured on a 44 MeV/A Ar^{16+} beam extracted from SSC2 is 6 π mm-mrad horizontally and 3 π mm-mrad vertically at $1.75.10^{11}$ pps and 2.5 π mm-mrad in both directions at $7.8.10^{10}$ pps.

8. ENERGY DISPERSION MEASUREMENTS

The energy spread of the beam extracted from the injector is measured in the on-line analyser of L1 (resolution = 5.10^{-3} total* energy width, with an emittance of 40 π mm-mrad). The energy spread of the beams extracted from the SSCs is measured in the on-line analyser of L3 (resolution = 5.10^{-4} total* energy width, with an emittance of 5 π mm-mrad).

Typical values of the energy spread measured in the three beam-lines are shown in tables 7 to 9. Concerning table 7, it has to be mentionned that in order not to reduce the injection efficiency in SSC1, it is absolutely necessary to tune the injector cyclotron so that its beam has a total* width of the energy spread smaller than $1.4.10^{-2}$. The theoretical acceptance of SSC1 is in the order of 10^{-2}.

9. BEAM CHARACTERISTICS AND TRANSMISSION EFFICIENCY OF THE BEAM-LINES

Tables 7 to 9 show the characteristics of the extracted beams of various ions and energies and the corresponding transmission efficiency of the beam-lines. These tables call for three comments :

- The three tables and each line in each table are independant one from the other, except the following ones (7/1, 8/1, 9/1), (7/3, 8/3, 9/3) and (7/5, 8/5, 9/6). The reasons are mainly :

Most of the measurements have been performed at different days. In addition, some measurements have been performed during operation runs (7/3, 7/7, 7/10, 8/3, 8/4, 8/6, 8/7, 9/2, 9/3, 9/4, 9/5, 9/8), the other ones during runs devoted to beam studies, when the beam was matched according to special criteria, like high intensity (7/5, 7/10, 8/5, 8/6, 9/6), low-energy spread (8/8), or best transmission efficiency (7/4, 7/6, 7/8, 7/9).

- Concerning table 8, the transmission efficiency factor includes the stripping efficiency. Now, some values of the transmission efficiency are low, because the optimum thickness of the stripping foil could not be used, in order not to reduce the accelerated beam current in SSC2. When the thickness of the stripping foil is increased, the energy spread increases and the ensuing phase length at input in SSC2 increases. Tests have to be made to measure firstly the particle distribution in the longitudinal emittance figure as a function of the stripper foil thickness and secondly the longitudinal acceptance of SSC2.

- In SSC1 the longitudinal acceptance problem has been solved simply by tuning the injector so that the total* width of the energy spread of the extracted beam is smaller than $1.4.10^{-2}$.

The symbols and the unities used in tables 7 to 9 are :

W = beam energy (MeV/A)
I = beam intensity at extraction (10^{12} p.p.s.)
E_H = horizontal emittance area of the injected beam (π mm-mrad)
E_V = vertical emittance area of the injected beam (π mm-mrad)
w = total* width of relative energy spread (per 10^3)(w_i before stripper ; w_o after stripper)
r = transmission efficiency of the beam-line (per cent)(r_3 of L3 ; r_4 of L3 + beam-line on exp. area)
r_s = theoretical stripping efficiency[5] (per cent)
e^s = thickness of the stripper-foil ($\mu g/cm^2$).

Table 7

L1		W	I	E_H	E_V	w	r
7/1	O^{3+}	0.494	5.40	40	40	14	84
7/2	Ar^{4+}	0.177	1.90	40	40	13	85
7/3	Ar^{4+}	0.177	0.80			13	78
7/4	Ar^{4+}	0.250	4.70	40	40	13	90
7/5	Ar^{4+}	0.250	7.66			13	60
7/6	Ar^{5+}	0.334	0.50	40	25	13	∿100
7/7	Ar^{5+}	0.334	0.85			13	75
7/8	Ca^{5+}	0.334	0.44	40	30	15	∿100
7/9	Kr^{7+}	0.199	0.07	25	20	14	∿100
7/10	Kr^{7+}	0.199	0.36			14	90

(*) 95 % of the particles.

Table 8

L2		W	I	e	r_s	ε_H	ε_V	w_i	w_o	r
8/1	$O^{3+/8+}$	6.90	3.23	30	99.6					65
8/2	$Ar^{4+/14+}$	2.20	0.50	30	36.2			3.4		77
8/3	$Ar^{4+/14+}$	2.20	0.40	30	36.2					77
8/4	$Ar^{4+/16+}$	3.48	1.56	30	37.4	12	12	4.0	4.2	77
8/5	$Ar^{4+/16+}$	3.48	3.00	30	37.4					
8/6	$Ar^{5+/16+}$	4.65	0.88	50	48.0			4.0	4.8	85
8/7	$Kr^{7+/26+}$	2.73	0.27	30	24.2			4.0	4.9	
8/8	$Kr^{7+/26+}$	2.73	0.20	30	24.2			2.5	3.7	

Table 9

L3		W	I	ε_H	ε_V	w	r_3	r_4
9/1	O^{8+}	93.7	1.25			1.7	95	
9/2	O^{8+}	93.7	0.62			1.7	95	90
9/3	Ar^{14+}	27.2	0.06			3.9	63	
9/4	Ar^{16+}	44.0	0.08	2.5	2.5	2.0	∿100	95
9/5	Ar^{16+}	44.0	0.18	6.0	3.0	6.6	90	80
9/6	Ar^{16+}	44.0	0.43				94	80
9/7	Ar^{16+}	60.0	0.23				∿100	95
9.8	Kr^{26+}	34.5	0.04			2.0	95	80

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