THE PIAFE PROJECT AT GRENOBLE: BEAM TRANSPORT OF A VERY LOW ENERGY RADIOACTIVE BEAM

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Abstract

The aim of the PIAFE project is to produce accelerated beams of neutron rich nuclei by using, in nearby sites, the high flux reactor of the Institut Laue-Langevin and the accelerator complex at ISN. The single ionized fission fragments are accelerated up to 30 keV, analysed by mass before transport in a 400 m beam line to the accelerator. The feasibility of such a transport over a distance as long as 400 m is proven in terms of focusing elements technology, alignment and beam interaction with residual gas and with a very good agreement between experiments and theory . This leads to a simple and cheap solution.

1 THE PIAFE PROJECT

The aim of the PIAFE project [1] is to produce exotic heavy ions from the fission of an uranium target put in the neutron flux of the Laue-Langevin Institute (ILL) reactor. After production, the heavy ions (mass between 80 and 150 amu) will be single-ionized with an energy between 10 and 30 keV. After two successive mass separations, inside the ILL reactor building, beams will be sent towards an outside experimental area where a high resolution mass spectrometer will be installed for spectroscopy (PIAFE1). In a second phase (PIAFE2), the 1+ ions will be transported, then converted to a high charge state by an ECR source and finally accelerated by the SARA accelerator complex at ISN up to, mainly, 10 MeV/amu. A low energy, cheap beam line is needed from ILL to ISN, along about 400 meters. A solution is proposed in this paper.

2 THE TRANSFER LINE

The beam line between ILL and ISN has to fulfill the following requirements: length 400 m, mass 80-150 amu, single charged radioactive ions, energy in the 10-30 keV range, cost as low as possible, maximum transmission. After several iterations the following solution is proposed: ironless magnetic quadrupoles supported by granite girders, CERN like alignment techniques, ionic pumps. The line will be made of 18 m elementary modules. The validation of this solution has been done by experiments on such a module, built at ISN and consisting of: manufacturing of 12 quadrupoles, set up of 3 granite girders (4 quadrupoles per girder), magnetic measurement *in situ* of quadrupole centre, alignment experiments, beam dynamics experiments. These beam experiment results are in a very good agreement with the associated theoretical studies, leading to a reliable and extrapolable model. A very detailed description is given in [2]. To perform this program, several tools have also been developped at ISN: a Rubidium 1^+ source, emittance measurements systems, Faraday cups, profile monitors and an optical matching section (quadrupoles) from the source to the module. More recently, an ECR Rb 1^+ source, coupled with a Wien filter, has been developped for the study of noble gases transport.

2.1 Objectives of the studies

Such a transport is a new thing and specific problems had to be solved:

• A suited and cheap focusing structure had to be defined.
• Alignment must be as simple as possible.
• As the beam rigidity is in the 0.2-0.3 Tm, the Earth magnetic field (and all the other "parasitic" fields) must be taken into account.
• The residual gas will cause beam losses as well as scattering and emittance growth. Both theoretical and experimental studies are needed to know exactly what is the vacuum required in order to maximize the transmission over 400 m.

2.2 Focusing structure

The focusing will be done by a magnetic FODO lattice. This solution is interesting in terms of alignment, cost and safety: all the elements are out of the vacuum chamber where the radioactive beam is transported (even if its activity is low).The quadrupoles are no-iron elements made of four rectangular 0.7 m long copper conductors where a 1500 A current provides a 0.25 T/m gradient. No special machining is needed for copper but only for its support. As there is no remnant field, these quadrupoles are well suited for a low gradient use. The distance between quadrupoles will be 0.8 m. The vacuum chamber diameter is 80 mm. The quadrupoles are installed by sets of 4 on a granite girder put on 3 LEP-kind jacks. One beam position monitor, as well as a steerer, are foreseen every 18 meters. In these conditions, taking the Earth magnetic field deviation effect, the tolerance for quadrupole relative alignment is 0.3 mm RMS.

3 ALIGNMENT

3.1 Quadrupole magnetic measurements

The simplicity of the quadrupoles, as well as the quality of each granite girder is good enough to provide a good relative alignment of 4 quadrupoles, without adjustment system. The straightness and flatness of the girder is about 0.1 mm/m, which is achievable by a standard machining of the granite, for a very reasonnable cost. This property has been checked by measuring the relative position of the quadrupole centres on the 3 girders. A rotating coil has been developped with the following specifications: length 1m, diameter 70 mm, 15 turn/s rotation speed, air bearings, coil made of 30 turns of Litz wire, each wire being made of 10 elementary wires. The coil has been put on the girder. A micrometric table allows the horizontal displacement of the coil. During the coil rotation, the amplitude of the fundamental harmonic of the signal can be writen:

$$V = \alpha I \sqrt{(x-x_0)^2+y_0^2} \quad (1)$$

where I is the current in the ironless quadrupole, x_0 and y_0 the relative horizontal position of the coil centre with respect to the quadrupole center, x the arbitrary displacement given by the micrometric table and α being a proportionnality constant. The procedure is then the following: signal amplitude measurements for a set of different values of x and numerical fit on the previous formula. This gives a precision better than 0.05 mm.

The Earth magnetic dipolar field ($\approx$ 0.5 gauss) displaces the quadrupole centre. For the maximum gradient (0.25 T/m), the effect is 0.2 mm and must be removed . The solution is to make a measure at I=1500A and at I=750A. A simple rule of three gives the value of x_0 and y_0 without the Earth magnetic field. The final results are given figure 1. The achieved RMS value is 0.2 mm for a 0.3 mm required.

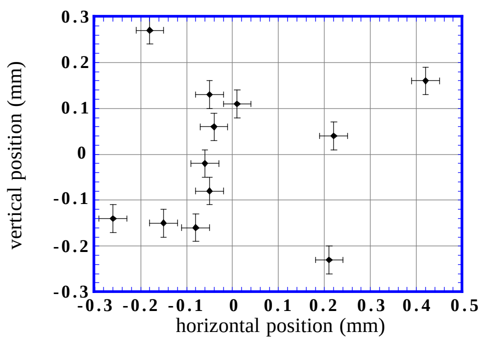

Figure 1: Horizontal and vertical position of the 12 quadrupoles centres of the experimental line. Goal: 0.3 mm RMS. Achieved: 0.2 mm RMS.

3.2 Girder alignment

Following CERN techniques, alignment is quite easy and fast. Each girder is set on three LEP jacks allowing a precise and easy displacement in each direction (horizontal, vertical and longitudinal). A precision support is fixed at each extremity of each girder. For altimetry, a Taylor-Hobson sphere is put on this support and the relative alignment of two successive girders is done by using an optical level. For the position in the horizontal plane, the support has a female part able to receive a digital ecartometer measuring the distance to a streched wire. One must notice that a perfect straightness of the whole line is not needed, but only a good relative alignment of two successive girders. This solution is cheap and simple and the periodic correction of ground motion will be easy.

4 BEAM DYNAMICS

A low emittance ($\pi\varepsilon = 8\pi$ mm.mrad) beam has been used, with an intensity of about 0.5 μA. The main studies have been made with a Rubidium beam and, more recently, with a Krypton beam, showing no difference between alcali and noble gases. Beginning from a good vacuum (10^{-7} mbar is enough for 18 m), a known gas has been introduced in the vacuum chamber, up to 10^{-5} mbar. Transmission and beam RMS size have been measured at the end of the line and compared to theory. The studies have been done at 25 keV and 10 keV.

4.1 Charge exchange

The transmission of a line is given by:

$$\tau = \exp(- 2.65\ 10^{22}\ \sigma LP) \qquad (2)$$

where P is the pressure in mbar, L the length in meters and σ the charge exchange cross section (in m^2), which can be estimated by using the following formula [3], in our range of energy:

$$\sigma \approx 1.43\ 10^{-20}\ q^{1.17}\ I^{-2.76} \qquad (3)$$

where q is the charge of the ions (1 for PIAFE) and I is the first ionization potential of the residual gas (in volts). It must be noticed that σ is independant of the nature of the ions and of their energy.

The experimental results are given in table 1, in good accordance with theory.

Residual gas	σ theorical (10^{-20} m^2)	σ measured (10^{-20} m^2)
Nitrogen	4	7.4
Argon	4.2	7.1
Xenon	8.1	14.7
Helium	0.5	2.1

Table 1: Charge exchange cross section for a Rubidium 1^+ at 25 keV.

The dependence with energy has been studied for Rubidium against Argon and is related figure 2. According to (3), the energy dependence is very low. It must be noticed that an 80% transmission has been obtained at 3 keV over 18 m.

Experiments with a Krypton beam have given quasi-identical results, showing the independance with the nature of the beam.

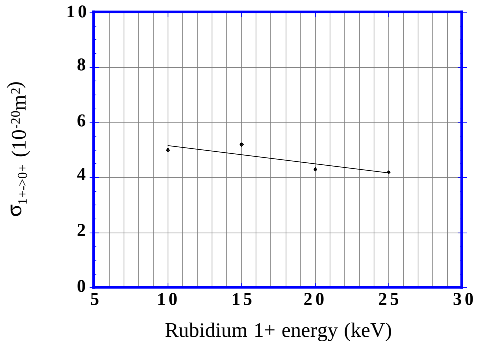

Figure 2: variation of cross section with energy (Rb 1+ against Argon).

4.2 Emittance growth by scattering

Extensive theoretical studies have been made on scattering [4] and can be summarized as follows:

• The interaction potential between an ion and an atom of the residual gas is a screened Coulomb potential [5]:

$$V(r) = \frac{e^{-r/a}}{r} \qquad (4)$$

• A classical treatment in the center of mass ion/atom is deduced and gives the deflection angle θ versus the impact parameter b.

• A statistical treatment is done by calculating the RMS value of each random deflection. Then the variation of beam matrix (correlation matrix) is calculated and transported along the line.

• Finaly, for a long periodic line of length L, the RMS emittance growth is characterized by its RMS value [4]:

$$\sigma_\varepsilon = \chi\ P\ \langle G\rangle\ L \int_{b_0}^{+\infty} b\theta^2(b)db \qquad (5)$$

<G> is a constant depending of the optics (it is analogous to the mean value <H> used in emittance calculation in synchrotron light sources). The integral characterizes the RMS value of each interaction, where b_0 depends of the angular acceptance of the line (the ions having an impact parameter b lower than b_0 are lost). P is the pressure and χ is a proportionnality constant. For a short line (18m), this formula has to be slightly corrected to include the non constantness of the acceptance.

Table 2 shows the theoretical and experimental results for a pressure of 2 10^{-5} mbar after 18 m.

Gas P= 2 10^{-5} mbar	Emittance growth Theoretical (πmm.mrad)	Emittance growth experimental (πmm.mrad)
Nitrogen	9	9
Argon	13	8
Xenon	17	19
Helium	5	2.2

Table 2: Emittance growth after 18 m.

It can be deduced from these results that charge exchange is the dominant process. A good transmission (> 95%) will be achieved with 5 10^{-8} mbar over 400m.

4.3 Non-linearities

The quadrupole linearity has been studied. It has been seen that the beam profile remains very pure after 18 m. For a longer distance, a reduced Differential Algebra software has been developped to show the very small effect of these non-linearities[5].

5 VACUUM

The needed pressure is a few 10^{-8} mbar. This can be easily done by using one ionic pump (45 l/s) every 18 m, after an obvious good cleaning of the chamber. The pumping scheme will be as follows: pre-pumping by turbo pumps without the beam, pumping with ionic pumps when the radioactive beam is present, keeping all the activity inside the chamber.

CONCLUSION

A strong coupling between theory and experiment on a rather long prototype have proven the feasability of the transport by giving a well proven model and without exhibiting unforeseen problems. Moreover, the size of the experiment has given a credible and very low value of the cost.

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