THE PIAFE PROJECT AT GRENOBLE : BEAM TRANSPORT AND ACCELERATION

J.L.Belmont, J.F. Bruandet, J.M. de Conto, M. Fruneau, G. Gimond, K. Golovanivsky,
E. Liatard, J.M. Loiseaux, H. Nifenecker, A. Savalle, B. Vignon
Institut des Sciences Nucléaires - IN2P3 - Université Joseph Fourier
53, avenue des Martyrs 38026 Grenoble Cedex, France

P. Briand
Centre d'Etudes Nucléaires de Grenoble - DRFMC/PSI
B.P. 85X 38041 Grenoble Cedex, France

ABSTRACT

SARA, the two cyclotrons of the Institut des Sciences Nucléaires de Grenoble (ISN) is close to the Institut Laue Langevin (ILL) high flux reactor. This unique opportunity leads us to the PIAFE project: the exotic atoms - or ions - (fission products: neutron rich nuclei, mass mainly between 80 and 150) should be extracted from an Uranium 235 target put into a 10^{14} neutrons/cm^2/s flux and, after mass separation, should be transported to the cyclotrons and accelerated. We expect from several 10^5 to more than 10^8 ions per second, depending on production rate and energy needed (from 2 MeV/amu to 10 MeV/amu or up to 20 MeV for masses close to 80).

INTRODUCTION

Grenoble is characterized by the existence, in nearby sites, of a possible source of exotic nuclei, the high flux reactor of the Institut Laue Langevin (ILL) and of a low to medium energy accelerator complex SARA, the two cyclotrons of the Institut des Sciences Nucléaires de Grenoble (ISN).

The aim of the "PIAFE" project[1)2)] (in French : Production, Ionisation, Acceleration de Faisceaux Exotiques) is to produce neutron rich nuclei with masses between 80 and 150 and energies between 2 and 10 MeV/amu (up to 20 MeV/amu for masses around 80). The accelerated intensities will depend on the production rates, extraction efficiencies and final energies, and should range between 10^5 and 10^9 particles per second. We have to take into account the half-life times of these elements wich are close to the *second*.

In the following we give a more detailed overview of the project as it stands today, and which may still be subject to change.

Figure 1 shows a sketch of the production, ionization and acceleration complex and expected efficencies.

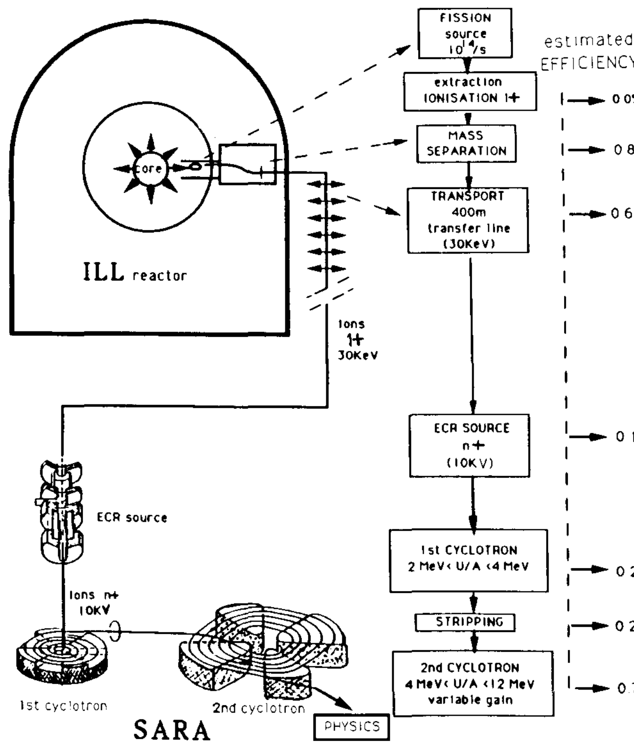

Fig.1. Schematic diagram of the projected production, ionization, acceleration of exotic beams facility P.I.A.F.E. at Grenoble

1 - OUTLINE OF THE EXOTIC ION PRODUCTION

1.1 - The fission source

The fission source should be as intense as possible, conform to security requirements, and as high a proportion of fission fragments as possible should escape from it. To fix ideas we consider an ensemble of ten 100 cm^2 U^{235} layers, with a thickness of 1 mg/cm^2, alternating with 10 mg/cm^2 graphite layers, placed in a 10^{14} neutrons/cm^2/sec flux.

The total amount of 1 gram of U^{235} would lead to approximately 10^{14} fissions/sec. This number compares favorably to that expected from a 100 μA beam of 1 GeV protons. The power produced in the target would be about 4 KW, to be compared to more than 20 KW for the proton case. The power dissipation could be used to heat the source up to 2000° C. in order to maximize the diffusion of elements like alkalines and rare gases out of the graphite.

The target heating will probably be the limiting factor of the production rates. Here the thermal neutron production scheme has a distinct advantage over all other competing methods since target heating due to the incident beam is negligible.

1.2 - Ionisation and mass separation steps

The more easily obtained beams should probably be either rare gases or alkalines. Alkalines could be obtained as singly charged ions using the thermoionization effect directly from the source[3)]. Diffusion times of 0.2 s and 0.8 s for Rb and Cs respectively have been reported.

For rare gases one has to rely on a separated ionization step. Rare gases would be pumped through an ionization source of the plasma or ECR type, and singly ionized. Efficiencies in the range of a few percent are expected.

After acceleration by around 30 kilovolts, the singly charged ions should be mass analysed in a standard mass spectrograph, directly situated outside the reactor biologicial shield. It is of great importance to ensure the confinement of dangerous species like Sr^{90} or Cs^{137}.

2 - TRANSPORT

The q = 1^+ ions would be transported under vacuum and focused by quadrupoles from the mass separator output to the SARA site, where they would be injected into the ECR source. The transit time would be, typically, around 1.5 ms for 400 meters.

It is important to reduce, as much as possible, the cost of the transfer line, since it will be the major component of the total cost of the project. A careful optimization of all elements involved in the transfer is needed : Vacuum,number and positions of beam diagnostics, corrections of alignment defects.

Due to the length of the transfer line, rather good vacuum, in the 10^{-7} torr range, is needed. The attenuation of the beam by charge exchange processes during the transport will depend on the nature of the ions.

The total effect of scattering on the residual gas and charge exchange is smaller if we transport (1^+) ions instead of multicharged ions. Due to scattering, the emittance grows during the transport and the aberrations of a long series of lenses disturbs the apparent emittance at the exit. But these effects are without consequence since the 1^+ beam will be injected into the high charge state ECR source of the SARA axial injection system. We consider a scheme in which the beam would impinge on a heated catcher within the high charge ECR source from which the atoms would be evaporated into the plasma. In this way, the emittance would be regenerated, and energy and charge would be adapted to axial injection in the first cyclotron.

During the transfer, the activity of the beam has to be taken into account, for the shortest periods, but it would not exceed 10 microcuries per meter. However careful monitoring should ensure that the beam is not accidently lost, since, in such a case, local activities in the Curie range could be produced. Monitoring should also ensure that no long life chain is sent to the accelerator.

Two schemes of beam handling are proposed.The first scenario is the use of a FODO lattice. The design of any transport line, but especially of a long one, must provide a good acceptance (maximum value of emittance acceptable by the line, for a given geometrical aperture), without being too sensitive to structure defects, like misalignments of quadrupoles. Without defects, the acceptance of a such structure versus the transversal oscillation phase advance μ per cell, is maximum for μ = 76 degrees. However, the misalignment of quadrupoles induces the decentring of the central trajectory of the beam and then decreases the acceptance. In such a case, optimum values for cell length, geometrical aperture and betatron phase advance have to be found. For example, we have considered a 200 m structure made of 3 metre long FODO cells put on 6 meter long girders (4 quadrupoles per girder). The quadrupoles have a transverse positionning precision of 0.3 mm RMS, the girders have an angle positionning precision of 0.15 mrad RMS along the axis and the relative positionning error from girder to girder is 0.9 mm RMS, the geometrical aperture remains 2 * 40 mm.

We intend to use Panofsky style quadrupoles[4] which reduce effects of remanent fields for low field quadrupoles and can give high quality fields without complex machining. We need 500 A in each one conductor coil with 0.4 m long quadrupoles (gradient = 0.36 T/m). With a baked vacuum chamber, a getter pump each 40 m should ensure a 10^{-7} torr vacuum.

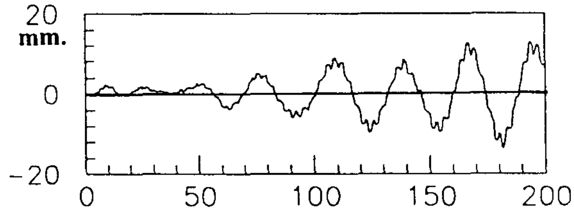

Fig. 2. The central trajectory is plotted along a 200 m FODO structure and for one set of mispositionnings (see text).

The effect of one particular set of mispositionnings is illustrated in figure 2, where the central trajectory is plotted along a 200 m FODO structure: the trajectory draws progressively away from the theoretical axis, reducing the real available acceptance. Corrections can help to compensate that effect.

Figure 3 shows the acceptance of the line **without** mispositionning (maximum at μ = 76 degrees per cell) and **with** mispositionnings of elements: in this case the acceptance is maximum for μ = 40 degrees. A result of the simulations using this configuration is given by figure 4 which shows the acceptance of the line (center of the figure) for 200 sets of mispositionnings. For 1000 sets the confidence level to get at least a reasonably large remaining acceptance available before correction ($\approx 60\pi$ mm.mrad) is 0.999. Simulations performed for many values of μ have shown that the best compromise is always around μ = 40 degrees.

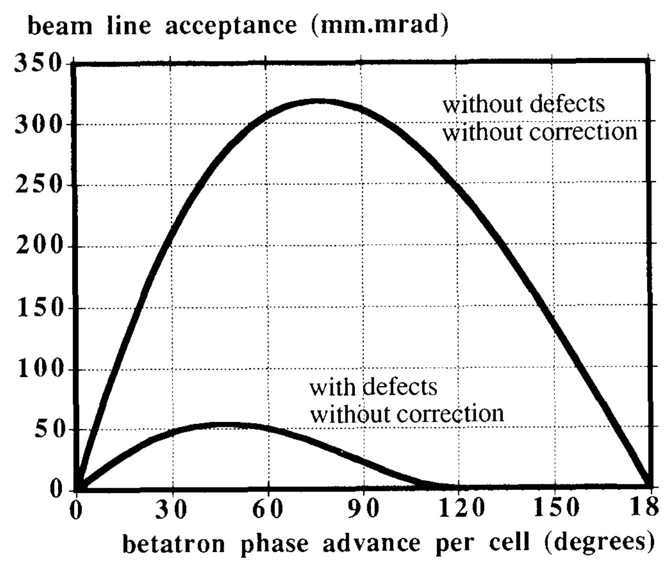

Fig. 3. Acceptance of a 200 m long beam handling made of FODO cells with or without defects on quadrupole positions (see text). Our channel having 400 m we will have to recenter the beam along the path.

The quadrupole alignment of 0.3 mm R.M.S. could be achieved with a method proposed by the SLC[4]: turning off successively the quadrupoles by consecutive pairs procures a set of relations between quadrupole misalignments and beam excentration measured at a few points. These relations permit the estimation of the misalignments. As an example, fig. 5

shows the real and estimated defects with that method over 100 m. The quads are originally decentered by 0.7 mm R.M.S and only three beam position monitors are used.

Another scenario is the use of a high frequency continuous quadrupole guide, working around 0.1 MHz with an electric gradient of around 100 V/cm. It might alleviate alignment problems and should be cheaper if vacuum design remains simple.

We will test these two different schemes of tranfer lines from the ILL to SARA with the aim to minimize the costs.

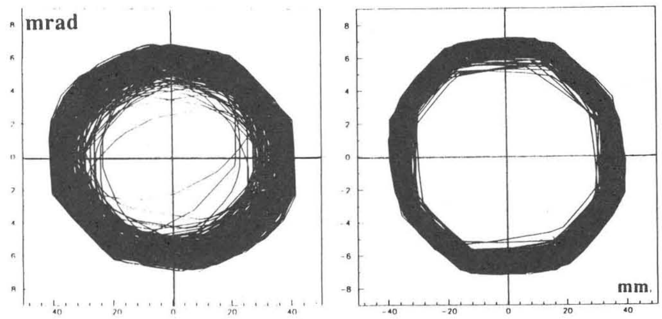

Fig. 4. Acceptances of a FODO 200m long line for 200 sets of mispositionnings (see text for conditions).before and after recentring of the beam after each 50m, taking into account of the 1 mm RMS error of monitor positionning.

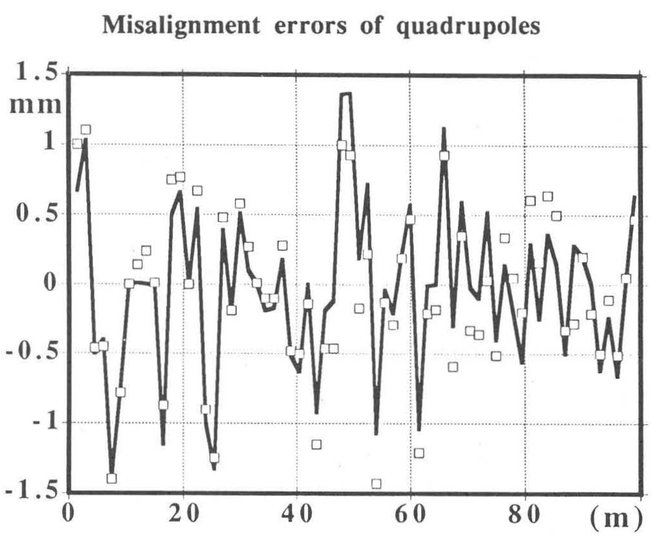

Fig. 5. Example of a simulation of a set of misalignments of quadrupoles over 100 m : real values (arbitrary linked by a solid line) and estimated values (square points) (see text for conditions)

3 - TRANSFORMATION OF THE 1^+ BEAM.

The q/A value of injected ions inside the first cyclotron must be higher than 0.15. In order to couple the 30 keV ion beam to an ECR Ion Source (ECRIS) plasma, we project to implant radioactive ions into a catcher outgassing because of its high temperature : thermal atoms immediately after desorption are facing a magnetized plasma.

Due to the characteristics of the injection line into the first cyclotron, the voltage of the ECRIS cannot exceed 10 Kilovolts. The 1^+ beam will have a rigidity close to eight times that of multicharged ions. We are studying two solutions for changing the 1+ beam into a high charge one

In the first solution the 30 keV 1^+ beam (rigidity ≈ 0.3 T.m) crosses transversely the magnetic field (0.06 T) in the central part of a first ECRIS[6]. After exit from the catcher the atoms will be singly ionized again inside this first ECRIS, working with two 2.45 GHz cavities,where the plasma could have the rather high density of 10^{12} cm^{-3} and which serves as a large first stage of a high performance 16 GHz ECRIS.. The plasma of the 2.45 GHz source could be guided to the 16 GHz ECRIS by a magnetic field smoothly and continously increasing from the first source to the second one.

In a second solution, the 1^+ beam is injected in the 16 GHz ECRIS axis through the extraction electrodes: it is decelerated from 30 keV to 20 keV and slightly focused by the magnetic field at the other side of the source where we put the catcher. In this design the exotic atoms after desorption from the catcher facing the plasma should be multiply ionized. These multicharged extracted ions and 1+ beam travel in opposite directions and are easely separated by a small magnet close to the extraction.

The global efficiency of the ECRIS, for a given final charge state is estimated to be around 15 %. The time delay induced by the ionization process in the ECRIS has been measured to be less than 1 ms per charge unit[4], i.e. between 20 and 30 ms for the ions of interest here.

4 - ACCELERATION

The SARA acceleration complex has two cyclotrons, one compact with K = 88MeV and one of the separated sector type with a K = 160 MeV.

The multiply charged ions are injected into the first cyclotron and the energies produced range between 1.9 and more than 4 MeV/amu, depending upon the charge states.

The second cyclotron acts like an amplifier with a gain in energy given by the square of the ratio of extraction and injection radii. The present gain is equal to 5.4. This gain is not optimum for physics with exotic beams since it gives a *lower* limit of achievable energies of 10.3 MeV/amu. (1.9 * 5.4). We plan to modify the extraction system in order to make the gain continuously varying between 2.1 and 4.1 (see figure 6). The gain variation would be obtained by a change of the extraction radius. The energy change will be much easier and quicker, not far from that of a tandem !

The idea is simple but we have to remove one of the two RF resonators and to replace it by a movable electrostatic extractor positionned at the needed radius, used to push the beam into the septum magnet after the next magnetic sector. If we succeed in putting this magnet in two articulated parts (and may be in reinstalling the second cavity at 90° with respect to the first one) we will obtain the full range of energy gain : 2.1 to 5.4. The first harmonic due to this design could be easely compensated by correcting coils[7].

Factors limiting the masses accelerated by the second cyclotron are the stripping efficiency and the maximum of the rigidity accepted at the injection by this machine (K = 33MeV). Figure 6 shows energy ranges of the machines for Xenon.

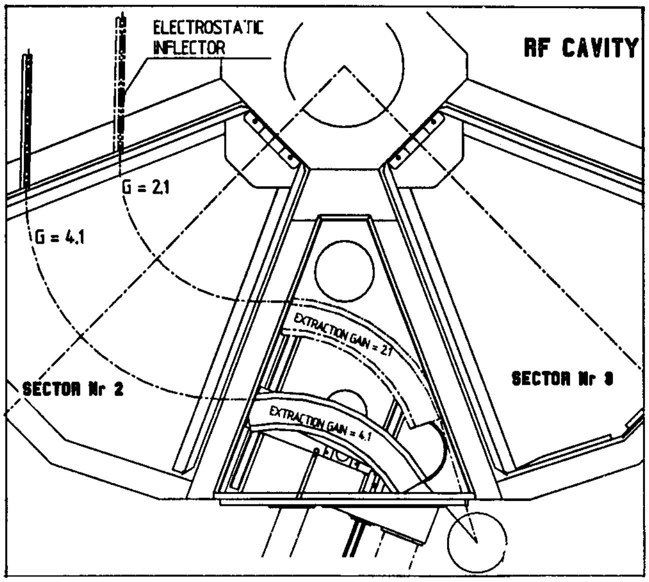

Fig. 6. The proposed extraction system allows the second cyclotron having a continuously varying gain between 2.1 and 4.1.

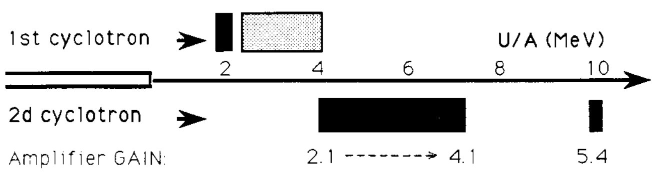

Fig. 7. Energies for Xenon.4 MeV/amu is directly obtained with the first cyclotron. Presently energy gain G of the second cyclotron is G = 5.4, allowing only 10.5 MeV/amu. It is expected a variable extraction : $2.1 < G < 4.1$ allowing to cover the energy range of 4 to 7.8 MeV/amu (and 10.5). Because stripping effect is not large enough, only 1.9 MeV/amu from the first cyclotron can be injected in the second one.

Nucleus	$T_{1/2}$ sec.	Usable beam First cyclotron	Usable beam Second cyclotron
Rb^{93}	0.58	2.10^{9}	3.10^{8}
Kr^{93}	1.29	9.10^{7}	$1.7\ 10^{7}$
Cs^{142}	1.8	2.10^{9}	$3.4\ 10^{8}$
Cs^{144}	1.02	$1.7\ 10^{8}$	3.10^{7}
Xe^{144}	1.2	2.10^{7}	$3.4\ 10^{6}$

Table 1 - Estimated usable beam intensities ion pps at the output of the first and second cyclotrons.

CONCLUSION

The association of the high flux reactor of the ILL to the SARA accelerator system opens the perspective of intense neutron rich isotope beams, with masses between 80 and 150 and intensity of exotic ions gets 10^{9}pps (see table 1).

Development work has been started on different critical points of the project : in-pile fission source, transfer line and injection of a singly charged ion beam into a high charge state ECR source.

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