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ROLE OF THE 1+ BEAM OPTICS UPSTREAM THE SPIRAL1 CHARGE BREEDER

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Abstract

The SPIRAL1 charge breeder (SP1CB) is under operation. Radioactive ion beam (RIB) has already been delivered [1] to Physicist for experiments. Charge breeding efficiencies demonstrated high performances for stable ion beams than RIB's. The beam optics, prior to the injection of the 1+ ions into the SP1CB, is of prime importance [2] for obtaining such high efficiencies. Moreover, the intensities of the RIB's are so low, and indeed difficult to tune the SP1CB. A stable beam having a close Brho is required to find out the set of optic parameters preceding the tuning of the RIB. Hence, it has been decided to focus our effort on the control of 1+ beam optics leading to high charge breeding efficiencies whatever the 1+ mass, energy and Target Ion Source System (TISS) used. This contribution will show the strategy undertaken to overcome that problem and the results obtained.

INTRODUCTION

Now, the SPIRAL1 facility has been upgraded and is under operation. Obviously, more time is needed to get a full control over the entire facility as it got more complicated to operate: new Target ion Source System (TISS) [3]; a charge breeder (SP1CB) [4] and reshuffled beam lines. Mainly there are two operational modes for running the facility providing Radioactive Ion Beams (RIB's) to physicist: Shooting Through mode (ST) and 1+/N+ mode [5]. The ST mode carries out the NanoganIII TISS [6] providing RIB's of gas element type transported to the post-accelerator CIME cyclotron [7] through the 6 mm plasma electrode of the SP1CB. The 1+/N+ mode combines the FEBIAD TISS with the SP1CB and has successfully provided a ^{38m}K@9MeV/u beam [8] to physicists in 2019. But challenges ought to be overcome for having a daily routine facility. Indeed, the preparing phase prior to the RIB delivery is too long and a unique set of beam optics parameters must be found for each mode. Concerning the R&D, it is important to understand what are key parameters of the ion beam (Twiss parameters and energy spread) upstream the SP1CB in order to achieve the highest charge breeding efficiency

THE 1+ BEAM LINE

1+ Beam Line Layout

Figure 1 displays the layout of the 1+ beam line. It starts with a combination of two einzel lenses: Einz1 and Einzl2. It is followed by a triplet of magnetic quadrupoles and a magnetic sextupole prior to a magnetic mass analyzing dipole. Next, a triplet of electrostatic quadrupoles is settled just before the 1+ ion injection into the SP1CB. For the diagnostics, there are two beam profilers (upstream PR11 and downstream PR13 the mass analyzing dipole), sets of slits (vertical - horizontal) and one faraday cup CF13 shielded regarding the ion beam extracted backwards from the SP1CB. After the second mass analyzing dipole D3P sorting out the multi-charged ions extracted from the SP1CB, a Faraday cup with a beam profiler is used to check the selected multi charged ion beam intensity and its profile.

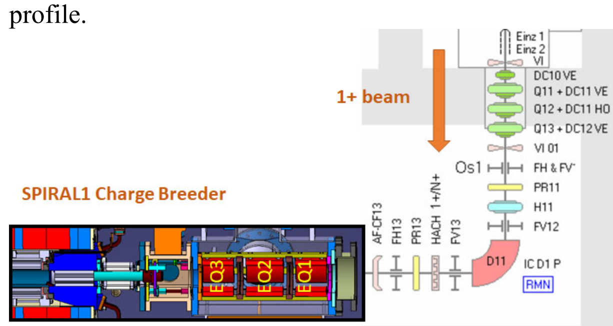

Figure 1: Layout of the 1+ beam line.

Shooting Through Mode (ST)

In this mode, the TISS NanoganIII is operated. The specificity is the large emittance of that Electron Cyclotron Resonance (ECR) ion source type. Moreover, the ion beam must be transported across the SP1CB plasma electrode of 6 mm diameter coercing it to be really focused at that location. The experimental data (beam profilers and efficiency of transport) of a stable ion beam of $^{14}N^{3+}$@19.751kV have been considered. As the twiss parameters for the transverse emittances are not known for the NanoganIII ECR ion source, they were let as free parameters. Using the TraceWin code [9], the ion beam envelopes as well as the initial beam twiss parameters are obtained, see Fig. 2. The ion beam is focused, thanks to the coils of the charge breeder, and transported as much as possible across the SP1CB plasma electrode. The calculated transverse emittances of the initial beam is around 106 π.mm.mrad (4 RMS, X and Y planes) and it is a diverging ion beam. The beam profiler values are also replicated. But, to find those results, the TraceWin code applied a factor of 0.6 on the complete magnetic field intensity of the SP1CB. It implies that the simulation doesn't reproduce quite well the measurements. Moreover, in the N+ line (the beam line transporting the multi-charged ion beam from the SP1CB plasma electrode up to the CIME injection), there is a burst of the ion beam envelope in X plane which cannot be really explained. To find out the issue and fix the problem, a pepper-pot emittance meter (Pantechnik type) will be installed in the N+ beam line to constrain the TraceWin simulation. New data will be recorded and compared to the simulations.

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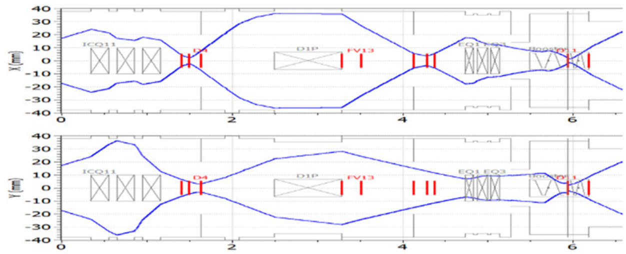

Figure 2: Transverse beam envelopes for the case ST mode and the beam $^{14}N^{3+}$@19.751kV.

Beam Optics for 1+/N+ Mode

For many years, the TISS NanoganIII has been used in combination with a unique set of beam optics suitable for elements up to Brho of 0.136 T.m. Following the upgrade of the SPIRAL1 facility, it is possible nowadays to get RIB's characterized with a $B\rho_{max}$ of 0.22 T.m. The enlargement of Brho involves some restrictions regarding beam optics element in the 1+ beam line. Indeed, the magnetic quadrupoles Q11 Q12 and Q13 cannot be scaled up using the previous beam optics parameters. Henceforth, the idea is to find out a single set of beam optics parameters matching the injection of the SP1CB maintaining as much as possible the SP1CB efficiency over the whole range of Bρ.

Concerning the data, $^{85}Rb^{1+}$ ion has been our probe at different Bρ's defining the 1+ ion beam energy. The two beams were: $^{85}Rb^{1+}$@10kV – Brho = 0.133 T.m (previous beam optics parameters) and $^{85}Rb^{1+}$@27.5kV – Brho = 0.221 T.m. (new beam optics parameters). The $^{85}Rb^{1+}$ ion beam is generated thanks to an ion gun developed at GANIL [2] using a HeatWave pellet [10], up to several hundreds of nA. Fig. 3 shows the SP1CB efficiencies for those two cases.

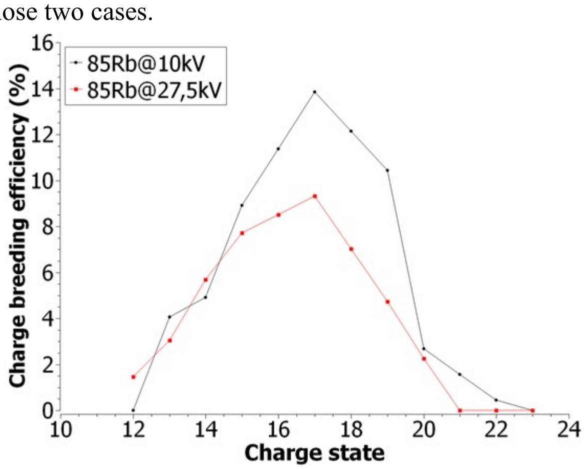

Figure 3: SPIRAL1 charge breeding efficiencies for the mode 1+/N+ and the two cases: $^{85}Rb^{+}$@10kV (black curve) and $^{85}Rb^{+}$@27.5kV (red curve).

Both charge state distributions are close with FWHM (5 - 6 charge states). They are both peaked on the $^{85}Rb^{17+}$ with charge breeding efficiencies of 13.8% (10kV) and 9.3% (27.5kV) associated with global efficiencies of 70.3% (10kV) and 49.8% (27.5kV) respectively. At the same time, beam profiler values have been recorded to coerce the simulations.

Simulations and Ion Beam Injection into the Charge Breeder

Simulations have been undertaken to find out the new beam optics as well as to learn how the 1+ particles are injected into the SP1CB. For that purposes, two software's have been operated: SIMION [11] and TraceWin [9] to do a complete simulation of the total SPIRAL1 beam line. To note here, simulations are achieved with no plasma model implemented in the SP1CB.

SIMION is employed to generate the ion beam from the ion gun up to exit of the second einzel lens Einz2. One example is displayed on Fig. 4. The geometry included in the simulation is as close as possible to the real one and the voltages applied are exactly those used during experiment.

The twiss parameters are deduced and they will become the input for the TraceWin code. Inside TraceWin, there is a tool box with the different types of optic elements. Beam line has been built to reproduce the 1+ and N+ beam line of the SPIRAL1 facility. For the magnetic as well as for the electrostatic quadrupoles, mass analyzing dipole and einzel lenses, in-house boxes are set in the simulation; gradient (T.m) or voltages are applied to the quadrupoles and the ion beam Brho is used to define the ion beam trajectory inside the mass analyzing dipoles. Finally, evolution of the transverse beam envelopes (in both planes X and Y) can be calculated as well as the beam profiler values. On Fig. 5, in italics and blue are the beam profiler values of experiment and in red are the calculated ones. As it can be seen, values are very close except for the PR13 X one. In that case, experimental beam profile was polluted by a huge background.

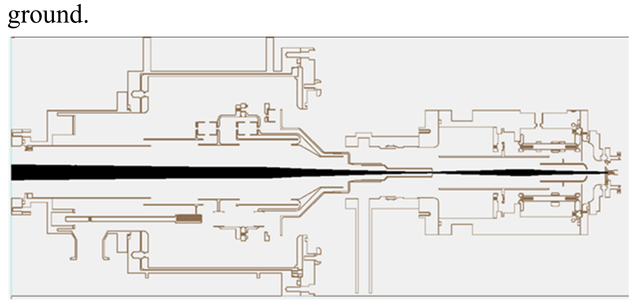

Figure 4: SIMION simulation of 85Rb+@10kV.

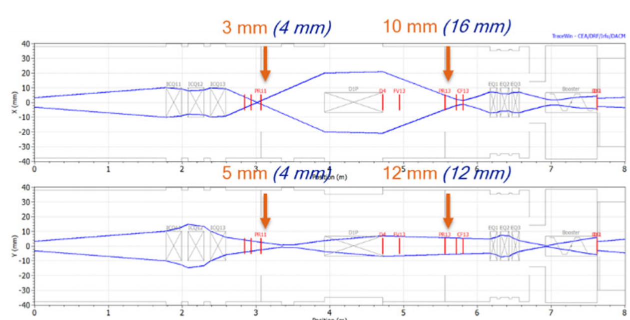

Figure 5: Transverse beam envelopes for the case 1+/N+ mode and the beam $^{85}Rb^{+}$@10kV.

Again, twiss parameters are deduced just at the exit of the EQ3 and inserted as input parameters for the last step of the simulation: evolution of the 1+ beam injected into

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the charge breeder and slowed down. The real 3D magnetic field (coils and hexapole), also containing the fringe field, is included into the SIMION simulation.

On Figure 5: the ion beam is firstly divergent and is focused in both transverse planes to the object plane of the mass analyzing dipole (D1P). After the mass analyzing dipole, ion beam is relatively large in vertical plane but again well focused in horizontal plane to get a good resolution. The electrostatic quadrupole focuses in both planes the ion beam to be transported along the deceleration tube of 28 mm of inner diameter. Figure 6 shows the axial magnetic field and the positions where the 2D transverse 1+ beam profile has been calculated. Figure 7 exhibits how the ion beam propagates inside the SP1CB. From the TraceWin calculation, twiss parameters are obtained just after the EQ3. These parameters are the inputs to the next SIMION simulation for SP1CB injection. The ion beam is smoothly convergent to rush through the deceleration tube into the SP1CB. Till the magnetic field is null, ion beam squeezes (X = 170, 300, 358). As soon as the ions feel SP1CB magnetic field, it explodes (X = 410) and therefore it pinches (X = 500, 541) to turn out to be very small. Entering the plasma core zone (X = 675.6, 700), the monocharged particles of the ion beam are magnetically controlled due to their low energy (star shape owing to the combination of magnetic field produced by hexapole and coils). In reality, this is not the truth because, they collide with charge particles (X^{q+}) of the plasma to be slowed down and captured. Figure 8 shows the same evolution depending on the electromagnetic field in use. The "E+B" case is identical to the one of Fig. 7 c). The "E" case corresponds to the exclusion of the magnetic field and the "B" case represents the withdrawal of the deceleration electric field. From the cases "E" and "B", it is demonstrated that only the combination of both electromagnetic fields leads to the formation of a tiny ion beam transporting the 1+ ions at the right energy (few eV) up to the core of the SP1CB plasma to be efficiently captured and charge bred.

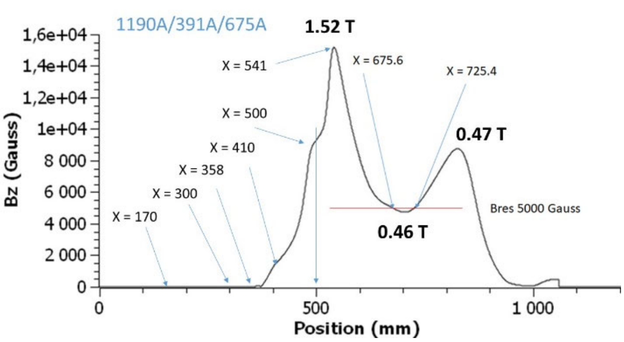

Figure 6: Axial magnetic field profile (Bz in Gauss) with the longitudinal positions corresponding to the Figs. 7, 8 and 10.

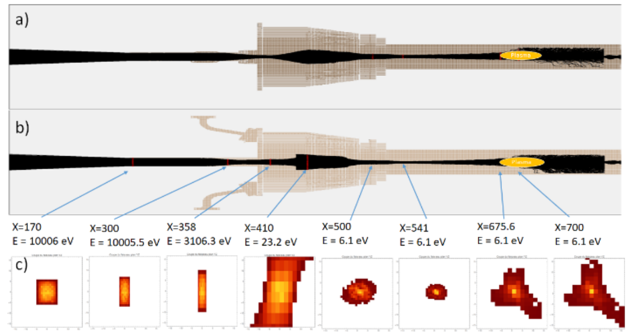

Figure 7: Evolution of the 85Rb+@10kV injected and slowed down into the SP1CB. a) and b) are the pile-up of 1+ trajectories in both transverse planes. c) images representing the evolution of the 2D transverse 1+ beam profile along the SP1CB.

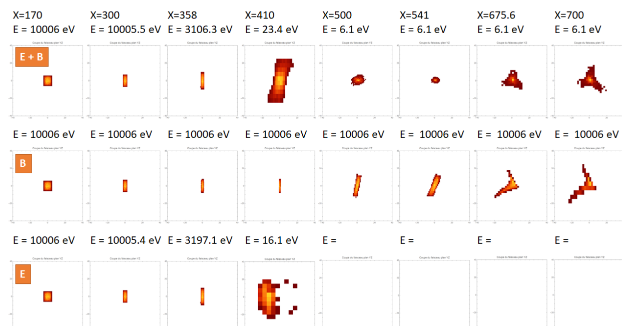

Figure 8: Evolution of the $^{85}Rb^{+}$@10kV injected into the SP1CB for three cases: E+B (both electric field and magnetic field); B (electric field is removed); E (magnetic field is removed).

Same method can be applied to the case of $^{85}Rb^{+}$@27.5kV. But a new beam optics has been found to overcome the magnetic quadrupole (Q11 – Q12 – Q13) restriction. Indeed, to determine the new values of magnetic optic elements, it is scaled regarding Bρ's. As the $^{85}Rb^{+}$@10kV and $^{85}Rb^{+}$@27.5kV are characterized by Brho of 0.133 T.m and 0.221 T.m respectively, the currents applied to the magnetic elements must be multiplied by a factor 1.66 (ratio of square root of the acceleration voltages $\sqrt{\frac{27.5}{10}}$). So a new beam optics has been calculated and tested experimentally. Figure 3 displays the charge state distribution (CSD) of charge bred ions (red curve) at this new energy. Figure 9 is totally similar to Fig. 5. Some discrepancies can be noticed:

- for X beam envelope, global shape is quite comparable except at the end where the beam explodes into the SP1CB
- for Y beam envelope, it blows up after the first magnetic triplet, similarly it is huge passing through the EQ2 before being pinched while entering in the SP1CB

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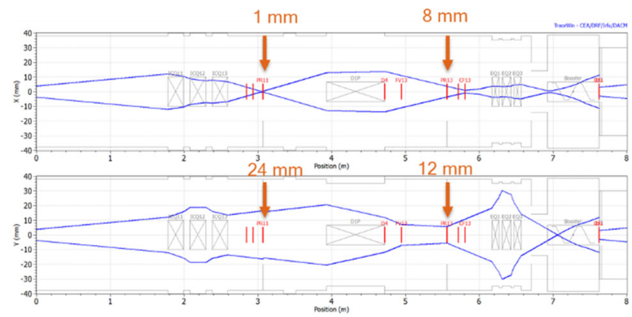

Figure 9: Transverse beam envelopes for the case 1+/N+ mode and the beam $^{85}Rb^{+}$@27.5kV.

But the value of the beam profiler on PR13 are quite similar for both cases prior to the injection inside the SP1CB: X plane 10 mm (10kV) – 8 mm (27.5kV) and Y plane 12 mm (10kV) – 12 mm (27.5kV). Figure 10 displays equivalent behavior regarding Fig. 7. The 2D transverse profiles have comparable shapes at the same locations. But, as it is larger in Y plane (cf. above), it looks likewise in Fig. 9. As the beam in Y plane is a bit larger than the deceleration tube inner diameter, there is some losses which can explain the decrease of the global efficiency in that case (Fig. 3 red curve).

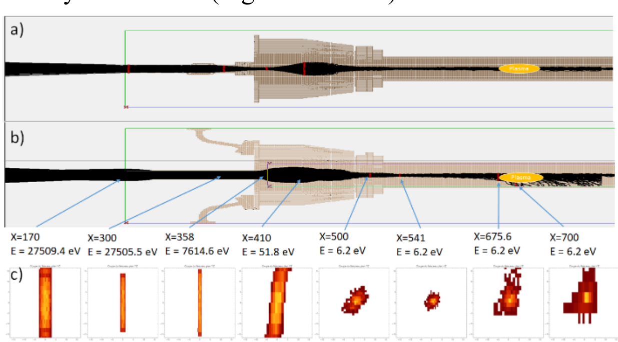

Figure 10: Evolution of the $^{85}Rb^{+}$@27.5kV injected and slowed down into the SP1CB. a) and b) are the pile-up of 1+ trajectories in both transverse planes. c) images representing the evolution of the 2D transverse 1+ beam profile along the SP1CB.

Blind Tuning Test

What is it important to know for this type of facility is the fact that the RIB's are orders of magnitude lower in terms of intensity than stable beams. So, it is not possible to tune the beam optic elements likewise the SP1CB using a classical faraday cup. So the typical method to adjust such a beam, is to use a stable one with an intensity in the range of hundred nA or more. The process is to sweep from the stable ion beam to the RIB by scaling the magnetic optic elements with the Brho and the electrostatic optic elements with the energy corresponding for the 1+ ion beam to the acceleration voltage.

Such test has accomplished successfully using the two isotopes of the rubidium: ^{85}Rb (stable) and ^{87}Rb (stable like because its half-life is 4,92×10^{10} years). The abundances of ^{85}Rb and ^{87}Rb are ~72.2% and 27.8% respectively. The ion gun delivered ion beam intensities of ~300 nA of ^{85}Rb and 120 nA of ^{87}Rb well mass resolved. The test has been done at acceleration voltage of 10 kV and using He as buffer gas for the SP1CB. The full SPIRAL1 was tuned for getting a charge bred beam of $^{85}Rb^{19+}$ (Brho = 0.0305 T.m) from $^{85}Rb^{1+}$ (Brho = 0.1332 T.m). At same acceleration voltage, the Bρ's of the $^{87}Rb^{1+}$ and $^{87}Rb^{19+}$ ion beam become 0.1347 T.m and 0.0309 T.m (ratio of square root of the masses $\sqrt{\frac{87}{85}}$) meaning a factor of 1.0117. Figure 11 shows the CSD of charge bred ions. They are both peaked on the $^{85}Rb^{17+, 18+, 19+}$ ions with a maximum charge breeding efficiency of 12.2% ($^{85}Rb^{17+}$) and 10.2% ($^{87}Rb^{18+}$) associated with global efficiency of 70.6% (^{85}Rb) and 53.6% (^{87}Rb) respectively. The SP1CB as well as 1+ and N+ beam lines were tuned exactly in the same manner. Only the magnetic optic elements were scaled regarding the Bρ's ratio above. The ΔV value remained constant to 5.4V (ΔV is the additional voltage applied on the ion gun to get energy enough for the Rb^{1+} beam to be efficiently captured by the SP1CB plasma).

That result goes to prove that bling tuning is possible as long as the relative Brho difference is of the order of few %.

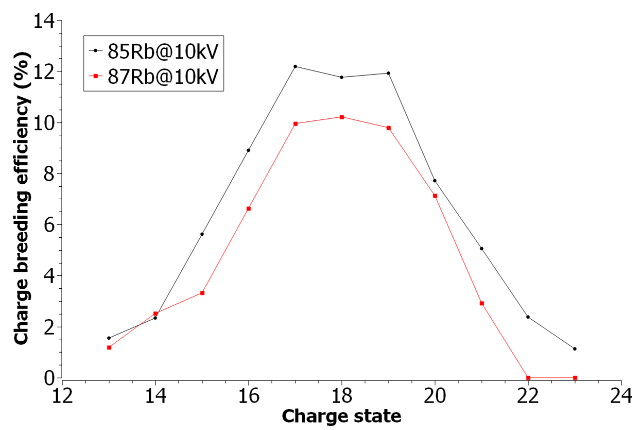

Figure 11: Charge state distribution of ^{85}Rb (black) and ^{87}Rb (red) charge bred ions at 10keV of total energy.

CONCLUSION

That paper focuses on the beam optics. Concerning the ST mode, more work and diagnostic is requested to better understand why TraceWin code must decrease the magnetic field of the SP1CB by a factor 0.6 to reproduce the experimental beam profiler values. A pepper-pot emittance meter type will be mounted in the N+ beam line to constrain the TraceWin simulation. One additional work to be achieved is to seek if there is a possible optimization between the three electrostatic quadrupoles and the magnetic field created by the SP1CB coils such that the transmission across the SP1CB plasma electrode can be increased.

About the 1+/N+ mode, a new beam optics has been found to overcome the limitation of the magnetic quadrupoles (Q11 Q12 Q13) designed previously to go up to Brho of 0.136 T.m instead of the current maximum Brho of 0.22 T.m. That new beam optics leading to close performances of the SP1CB shows a similar propagation of the ion beam inside the SP1CB. It has been established that

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both deceleration electric field and magnetic field are requested to transport 1+ incoming ions to the core of the SP1CB plasma. Next work will be the validation of that new beam optics over several ion beams of Na and K at few different energies covering the full range of Bρ's available at the SPIRAL1 facility. Finally, the final validation will be achieved using the TISS FEBIAD in the 1+/N+ mode.

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