BEAM DYNAMICS AND ERROR STUDIES OF THE SPIRAL2 DRIVER ACCELERATOR

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Abstract

After a detailed design study phase (2003-2004), the SPIRAL2 project at GANIL (Caen, France) was officially approved in May 2005, and is now in its phase of construction, with a project group including the participation of many French laboratories (CEA,CNRS) and international partners. The SPIRAL2 facility is composed of a multi-beam driver accelerator (5mA 40MeV deuterons, 5mA 33Mev protons, 1mA 14.5MeV/u heavy ions), a dedicated building for the production of Radioactive Ion Beams, the existing cyclotron CIME for the post acceleration of the RIBs, and new experimental areas. In this paper we focus on the beam dynamics and error studies dedicated to the SPIRAL2 accelerator part of the project, from the ECR sources to the High Energy Beam Lines which have been recently updated.

INTRODUCTION

The SPIRAL2 facility is now in its construction phase with huge progress for many parts of the machine as explained in [1]. In parallel, many beam dynamics calculations have been performed in order to extend the possibilities of the accelerator, and to take into account new demands of experimental physics.

As indicated table 1, the Spiral2 accelerator will deliver a huge variety of beams, at various intensities and energies, which constitutes a great challenge.

Table 1: Beam Specifications

beam	P+	D+	ions	ions
Q/A	1	1/2	1/3	1/6
Max. I (mA)	5	5	1	1
Min. output W (Mev/A)	2	2	2	2
Max output W (Mev/A)	33	20	14.5	8
CW Max. beam power (kW)	165	200	44	48

Our beam dynamics reference program is the well known TRACEWIN code [2]. It allows us to simulate the machine from the source to the final target, with a huge number of pseudo-particles. All the simulations can use 3D electromagnetic maps of magnets and cavities which are presently under construction, and the beam optimization uses the set of diagnostics which will be effectively used in the real machine. Moreover we project to incorporate (part of) TRACEWIN into the control system as an essential component of the tuning process.

SPIRAL2 INJECTOR

LEBT Lines and RFQ

The beam dynamics of the LEBT has been explained in detail in [3] and there is no recent modification. However we have investigated in detail the behaviour of the beam for various estimated values of the space charge compensation: this aspect is crucial when we manage the duty cycle and keep perfect bunches with a combination of ECR source, slow chopper and RFQ pulsations.

The 88 MHz 4-vane RFQ accepts charge/mass ratio between 1 and 1/3, and is designed for a very high transmission, in particular in the case of Deuterons at full intensity. We have checked that the 99% transmission was kept with or without space charge.

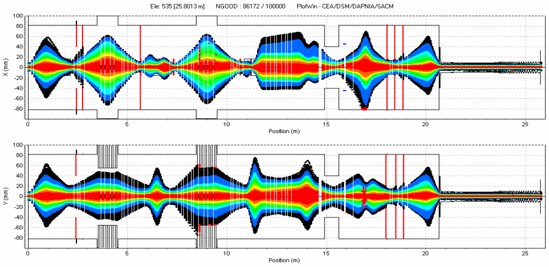

Figure 1: LEBT transport and RFQ acceleration for 1mA 1/3 heavy ions.

MEBT Line

The SPIRAL2 MEBT (Fig. 2) is a complex 8 meters transfer line with the following fundamental functions:

- Transverse/longitudinal matching into the linac
- Fast chopping system and associated beam stop
- Drift for a future connexion of a q/A=1/6 injector
- Movable slits for halo elimination.

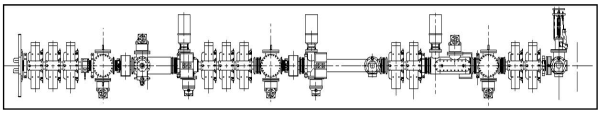

Figure 2: SPIRAL2 MEBT design.

The MEBT beam energy is fixed to 0.75 Mev/u, which corresponds to 7.5 kW for 5mA D+. Beam dynamics have been performed for all types of ions, using particle distributions from LEBTs and the RFQ, using quadrupole and rebuncher 3D maps and with linac matching (fig.3).

Calculations with use of the fast chopper have been performed in parallel with the development of the device.

We have checked that using a static magnetic deviator combined with an RF electric wave did not generate a significant emittance growth (Fig. 4).

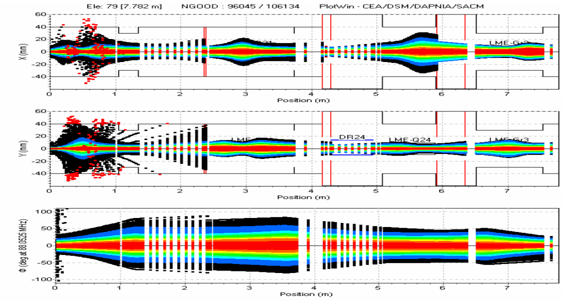

Figure 3: LME nominal (x,y, ϕ) optics for 5mA D+ beam.

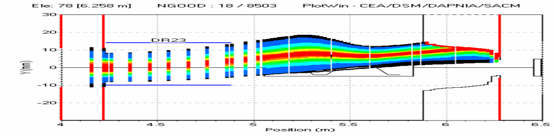

Figure 4: LME fast chopper and beam stopper (7.5 kW).

SUPER-CONDUCTIONG LINAC

The SPIRAL2 linear accelerator [4] is composed of 2 families of 88 MHz SC QWR cavities (β_0=0.07, β_0=0.12), which permits the acceleration of all ions and energies mentioned in table 1. Between each cryomodule, beam focusing is performed by means of 2 warm quadrupoles with short vacuum/diagnostics boxes in between.

Linac Tuning

Thanks to the regular geometry of the linac, it is possible to put the quadrupole strengths in such a way to obtain a continuous phase advance per meter and a continuous transverse focusing channel. We match the beam to the Linac by adjusting the 2 last MEBT quadrupoles and the first Linac doublet (Fig. 5).

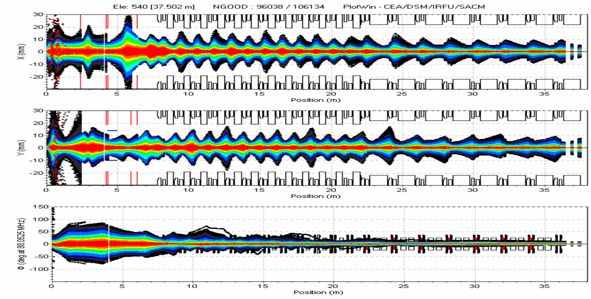

Figure 5: 5 mA D^+ nominal (x,y,ϕ) optics in MEBT and the linac (40 Mev at exit).

The control of the transverse beam matching in the periodic sections is done by using the quadrupolar moment of the Beam Position Monitors. The non interceptive BPMs are located inside the first quadrupole of each lattice, where envelopes are different in x and y. The longitudinal matching is tuned by applying a similar method based on the adjustment of the 3 MEBT re-bunchers, in association with beam phase length diagnostics located in the first Linac periods.

Output Energy Tuning

Physics requirements impose the Linac output energy to be adjustable between 2 and 20 MeV/u, with the beam kept bunched (<0.5ns) at target in some cases. In the low energy cases, the β_0=0.07 cavities are tuned to obtain 2 MeV/u, while β_0=0.12 cavities are off except one or two, in order to keep the beam bunched at the linac exit.

Error Studies

The TRACEWIN code can pilot a heterogeneous collection of computers including PCs and clusters. We use this feature to simulate more than 1400 linacs with 10^6 macro-particles for each one, and study very precisely the losses occurring in the full linac, following the Extreme Value Theory detailed in [5]. For each linac the procedure is the following: the parameters are initialized with theoretical perfect values. A set of random "*static errors*" is applied: cavity/quads misalignments, amplitude errors due to tuning or machining imperfections... and the standard corrections scheme is performed, typically the beam centring with steerers associated with BMPs, beam size adjustment with envelope measurement and quads. In a second step, a set of random "*dynamic errors*" is applied: RF jitter, mechanical vibrations, diagnostic noises or errors…Finally the simulation with 10^6 particles is done from the output ECR source to the linac exit, using a Gaussian initial beam distribution. Most of elements are simulated using a 3D electromagnetic field maps. Then, statistical information concerning emittance growth, centroid behaviour and losses are available. In the case of 5mA 40MeV D^+, average Linac-integrated losses are 0.2W, with 0.26W deviation (Fig. 6).

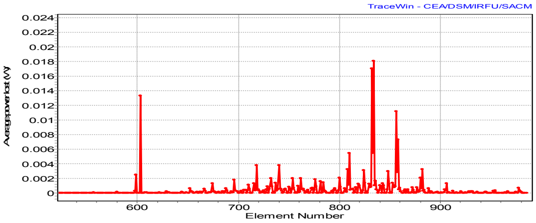

Figure 6: Average beam loss distribution for D^+.

HEBT LINES

HEBT have been recently updated, according to the evolution of physics demands and implantation of buildings and experimental areas:

The "red" production cave (separate building) is dedicated to the production of radioactive nuclides using D+ beam, neutron converter and UCx target production. RIBs will be used in a low energy hall (DESIR) or/and accelerated with the existing CIME cyclotron.

The Super Separator Spectrometer (S3) is dedicated to experiments using heavy ion beams from LINAC (super-heavy and very-heavy nuclei, spectroscopy at and beyond the drip-line, isomers and ground state properties…)

Neutrons For Science hall (NFS) is dedicated to cross-section measurements (TOF or irradiation techniques) and fundamental physics. It concerns transmutation of nuclear waste, design of future fission and fusion reactors, nuclear medicine and tests and development of new detectors.

SRI facility is dedicated to atomic physics research.

HEBT lines are designed with a limited number of repeated structures:

- Matching sections composed of 4 quadrupoles, used at Linac exit, for the beam dump, and at the entrance of each experimental room,
- Triplet sections for transport, with repetitive transverse waists and periodic envelopes,
- Achromatic double deviations for beam distribution and protection of targets against energy fluctuations.

HEBT beam dynamics scheme is such that we have always the same radial envelopes, up to a homothety, according to the type of beam and the final energy (fig. 7). In some cases, very short bunch time lengths are needed on target (<0.5 ns for $S^3$and NFS). We will use a set of 2 SC cavities (probably β_0=0.07) installed between triplet sections, where the beam diameter is minimum. The SPIRAL2 beam dump is located in the straight line of the LINAC. For safety and radioprotection reasons, beam dump entrance is located around 6meters from the last matching quadrupole. An optimized beam-dump geometry profile limits the power deposition density to 400W/cm² and permits a 200kW beam (5mA D^+, 40MeV), although we will always limit the duty cycle to around 5% during the tuning of the accelerator.

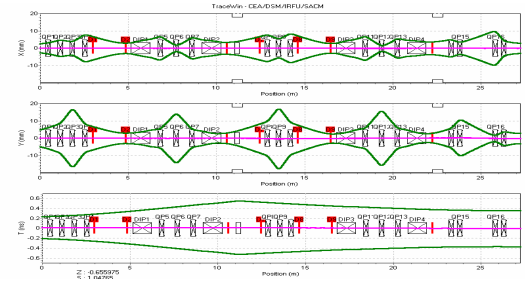

Figure 7: 5rms HEBT envelopes of Q/A=1/3 1mA ion beam at 14.5MeV/u between linac and S^3.

Ideally, HEBT beam error and beam loss studies must be done for all beam lines, all species and for minimum and maximum energies. By decreasing artificially the beam tube diameter, the worst case appears to be the 33MeV protons beam: beam losses are located in the middle of triplet sections, where the vertical envelope is maximal, and also at the output of the re-buncher. (Fig.7).

Recent activation calculations confirm that dose rate obtained with stainless steel vacuum chamber would be higher than with aluminium, for deuterons or even protons. Moreover, the decrease after beam put off is much favourable in the case of aluminium. In order to permits hands-on maintenance and reduce exposure, we are looking carefully at the best compromise in term of beam tube diameter and material, collimators and beam loss monitors along the HEBT lines.

OPERATION MODES

It is fundamental to protect the machine from thermal and activation problems during the tuning as well as at full nominal beam power. The best way is certainly to dispose of a dedicate software/hardware which gives successive authorizations to increase the beam power, depending upon the part of the machine we consider.

However in the case of SPIRAL2, the problem is very complex, because it also depends of the type of accelerated beam (D+, p+…) and of the required final energy. Moreover we have many possible paths for the beam (2 ECR sources, many experimental halls…) and we must distinguish various types of targets (with or without neutron convertor in the red cave for example…)

In order to have a clear idea of what we are doing during the tuning and avoid dangerous mistakes, we propose to introduce a “tuning mode 3D-Matrix”, with 3 axis corresponding to the following basic modes:

- The “beam-type mode”, corresponding to the type of beam we want to accelerate,
- The “machine-path mode”, corresponding to the path of the beam and the intermediate beam stop or final target we consider,
- The “beam-power mode”, corresponding to a maximum authorized beam power at a given step.

Once the 3D (sparse) matrix obtained is filled according to the relevant combinations, and given a beam type at a given final energy, we can extract the corresponding 2D matrix automatically and determine the succession of safe steps to increase the beam power along the machine.

CONCLUSION

Beam dynamics calculations for the SPIRAL2 driver accelerator have been performed on various aspects, with results giving more and more confidence in the machine capability to ensure a safe and flexible beam operation. Further studies are on-going, especially concerning the final definition of the HEBT lines, the management of operation modes, and the role to be played by the TRACEWIN code into the control-command process of the real machine.

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