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BENCHMARK ANALYSES OF ELECTROSTATIC DEVICES FOR SPIRAL2-DESIR BEAM LINES

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Abstract

The ISOL facility SPIRAL2 at GANIL, Caen France is in the commissioning progress since 2015. SPIRAL2 will produce a large number of new radioactive ion beams (RIB) at high intensities. In 2023, the DESIR facility will receive beams from the upgraded SPIRAL1 facility of GANIL (stable beams and target fragmentation), from the S3 Low Energy Branch (fusion-evaporation and deep-inelastic reactions). In order to deliver the RIB to the experimental set-ups installed in the DESIR hall, 140 meters of beam line are studied since 2014. The transfer lines are today fully design and component building will start in 2018. Electrostatic devices (quadrupoles, steerers and deflectors) have been intensively study using various tools. This paper will be focus on the detail results of a benchmark using OPERA-3D and COMSOL Multiphysics apply to the DESIR quadrupole conception.

THE DESIR FACILITY WITHIN THE SPIRAL2 PROJECT

SPIRAL2 is a major extension project of the GANIL facility in Caen, France dedicated to the production of heavy ion beams at high intensities and of very exotic nuclides [1]. The SPIRAL2 facility will produce a large number of new radioactive ion beams (RIB) at high intensity. These beams will be produced using a new linear accelerator that will deliver deuterons up to 40MeV at 5mA intensity, protons up to 33MeV at 5mA and ions with A/Q=3 up to 14.5MeV/u at 1mA [2].

The DESIR (Decay, Excitation and Storage of Radioactive Ions) facility will receive beams delivered by the S3-LEB (Low Energy Branch of the new Super Separator Spectrometer) of SPIRAL2 [3]. Nuclides will be produced in fusion-evaporation, transfer and deep-inelastic reactions, and will notably consist in refractory elements. Finally, RIB produced in the fragmentation of high-intensity heavy ions and/or thick targets at the upgraded SPIRAL1 facility will also be available at DESIR [4].

Nuclear physics as well as fundamental weak-interaction physics and astrophysics questions will be addressed by means of laser spectroscopy, decay studies, mass spectrometry and complementary trap-assisted measurements. Experience at other ISOL facilities evidences that ion beams with a high degree of purity are required to push experiments towards the limits of nuclear stability [5, 6, 7].

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140 m long beam lines between S3-LEB, SPIRAL1 up to experimental set-ups in the DESIR hall have been intensively study since 2014 [8] (see Fig. 1).

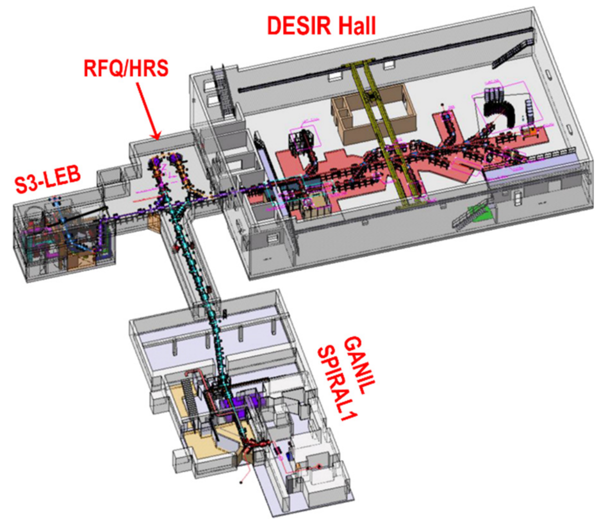

Figure 1: Scheme of the transfer beam line, S3-LEB and SPIRAL1 up to DESIR experimental hall. Designs of the building are not yet fully fixed today.

These beam lines are now started to be built within the collaboration framework between GANIL and FAIR-GSI. Lines have been design in order to accept maximum beam energy up to 60 keV and transverse geometric emittance to 80 π.mm.mrad. Only singly-charged ions will be transported, for which electrostatic devices (deflectors, quadrupoles, steerers) are better suited [8]. Beam dynamics calculations are performed using the CEA TraceWin code [9].

According beam process specifications we have already done the full transfer beam line integration. Coordination system and mechanical standards definition are done in collaboration with the SPIRAL2 Phase1+ system group. IPN Orsay is in charge to make the complete mechanical conception up to 2D detail drawings of optics devices, diagnostics boxes, bellows, pipes, supports, frames.

This paper will be focus exclusively on the design study of the standard electrostatic quadrupole for the DESIR project.

QUADRUPOLE CONCEPTION

Making use of the knowledge and long experience on electrostatic devices [10, 11, 12], we have studied and designed all optics elements with respect to the maximum beam emittance and energy required at DESIR. The transfer lines will have around 70 quadrupoles. It is therefore justified to have as simple as possible and robust device in order to full-fill the working condition at GANIL.

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For the 60 keV mono-energetic beam, maximum potential in the quadrupoles will be |3200| V. We will use quadrupoles with aperture to R = 50 mm, electrode length to 175 mm with a circular shaping to R' = 57.5 mm (reduce cost compare to hyperbolic shape). We will have also two grounded rings 2 mm thick, 100 mm in aperture located at 27.5 mm to the electrodes. Figure 2 shows the mechanical design of the electrostatic quadrupole.

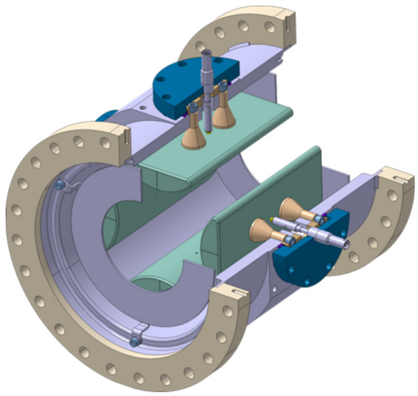

Figure 2: 3D design of the electrostatic quadrupole inside the vacuum chambers.

Blocks of quadrupoles will be assembling in order to form doublet or triplet. The mounting procedure is fully validated.

THEORETICAL QUADRUPOLE

At the centre of a pure quadrupole with radius R oriented along the z beam axis, the potential and transverse electric fields are given by :

$$V(x,y,z)=\frac{V_0}{R^2}(x^2-y^2) \quad (1)$$

$$E_x=-\frac{2V_0}{R^2}x\ ,\ E_x=\frac{2V_0}{R^2}y \quad (2)$$

With the quadrupole length L and $k=\sqrt{G/B\rho}$ where $G=V_0/(\beta c\times R^2)$ expression of the first order matrix is:

$$\begin{pmatrix} \cos(kL) & \sin(kL)/k & 0 & 0 & 0 & 0 \\ -k\times\sin(kL) & \cos(kL) & 0 & 0 & 0 & 0 \\ 0 & 0 & \cosh(kL) & \sinh(kL)/k & 0 & 0 \\ 0 & 0 & k\times\sin(kL) & \cosh(kL) & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & L/\gamma^2 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (3)$$

BENCHMARK OF THE ELECTROSTATIC QUADRUPOLE

From Design to Solver

Using the mechanical conception, a simplify design of the quadrupole is produced in step format which contain the vacuum chamber, the four electrodes and the two grounded rings. All unnecessary details like screws, screw holes, voltage connectors are cancelled. Step file is imported directly in OPERA-3D [13] and COMSOL Multiphysics [14].

Using geometric tools of both tools, external parallelepiped and central tube of 3cm radius oriented along quadrupole axis are created. All pieces can be filled by air in our context. Then limits conditions are applied with essentially grounded (V = 0) and ±4 kV for the electrodes. Surface and volume mesh is applied to the system using preferentially tetrahedral. We tried to apply as close as possible mesh parameters in both simulation tools especially for the central part of the quadrupole around the beam direction, rings and electrodes. For COMSOL Multiphysics, 1397274 nodes number are produced and 1387011 for OPERA-3D. Finally, solving process is done. It must be notice that methodology of the mesh and solving parametrization is significantly different between the two simulations tools. COMSOL Multiphysics is 100% GUI, OPERA-3D is also GUI but it can be execute as a standard programming language (like python or proprietary language) which can be more convenient. On the same computer, mesh and solving steps have been taken 5 times more with COMSOL 5.3 compare to OPERA V18R2 (respectively from around 35 min. and 7 min).

Field Analysis

Field-maps have been extracted from both simulation tools with the same linear (X,Y,Z) range. As an example, Figure 3 shows the relative difference between the two codes and theory (see Eq. (2)) for the horizontal transverse electric field at the centre of the quadrupole.

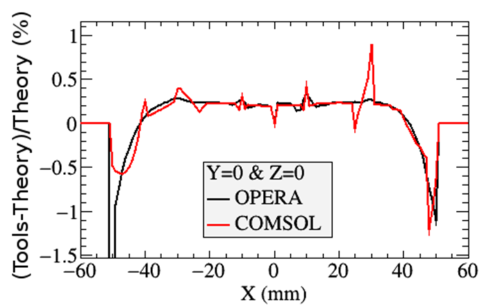

Figure 3: Relative difference between the two codes and analytic calculation of the horizontal transverse electric field at the centre of the quadrupole.

Very good agreements are observe for the field results in all region of interest where the beam will be transport. Some small discrepancies can be observed at some point like limits surface of pieces and they are almost due to the type of the solver taken by OPERA-3D and COMSOL Multiphysics. The logic of the mesh process optimization is a little bit different between the two simulation tools.

From the field-maps, we have determine the electric length of the quadrupole. For OPERA, we obtain 193.6 mm, and 194.3 mm for COMSOL. Therefore less than 0.4% discrepancies occurs which is fully satisfactory.

Beam Tracking Analysis

The beam tracking is performed with TraceWin. Field-maps generated with OPERA and COMSOL are converted in the TraceWin format with the same methodology and directly insert in the TraceWin input. In the same way we define a pure electrostatic quadrupole with previously calculated electric length surrounded by two symmetrical drift in order to ensure the same full length of the simulated

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field-maps to 500 mm along the beam axis. The input beam is a 60 keV of $^{122}Sn^{1+}$ with 80 π.mm.mrad emittance which is the fixed maximum emittance for DESIR beams. Finally we compare all results along the beam axis and at the end of this simple line. As an summary we give in Table 1 the beam characteristics obtained at the end of the 500 mm long section.

Table 1: Beam characteristics obtain at the end of the 500mm long section calculated using TraceWin code for the field-maps extracted from OPERA and COMSOL and for a pure theoretical electrostatic quadrupole.

	Type	OPERA	COMSOL	Pure
	E mean (keV)	60.0001152	59.9999208	60.0000005
(X,X')	Eps norm (pi.mm.mrad)	0.013711	0.013711	0.013707
	Eps geo (pi.mm.mrad)	13.337389	13.337454	13.333360
	Beta	0.094655	0.094633	0.093395
	Gamma	11.318832	11.360737	11.583817
	Alpha	-0.267177	-0.274052	-0.286127
(Y,Y')	Eps norm (pi.mm.mrad)	0.013714	0.013714	0.013707
	Eps geo (pi.mm.mrad)	13.340191	13.340315	13.333361
	Beta	4.932287	4.955376	4.901282
	Gamma	33.188874	33.462525	32.506369
	Alpha	-12.755276	-12.838200	-12.582642
	RMS X (mm)	1.124	1.123	1.116
	RMS X' (mrad)	12.287	12.309	12.428
	RMS Y (mm)	8.112	8.131	8.084
	RMS Y' (mrad)	21.042	21.128	20.819
	RMS E (eV)	1.209	1.229	1.202

We can observe that particles tracking is in excellent agreement between the OPERA-3D and COMSOL Multiphysics field-maps and the pure electrostatic quadrupole. Small discrepancies around 1% occur on the sizes and Twiss parameters. We can conclude that in our working range at DESIR, the pure hard-edge electrostatic quadrupole is validated.

CONCLUSION

We have presented here an introduction of the DESIR project. DESIR will be a new and extended experimental area dedicated to the study of the fundamental properties of new exotic radioactive nuclides to be produced at SPIRAL2-GANIL. This paper is focused on a dedicated study of the electrostatic quadrupole which will be used in this project. Large number of units will be built in the collaboration framework between GANIL and FAIR.

In this paper we have presented the calculation results of a benchmark using two simulation tools : OPERA-3D and COMSOL Multiphysics. In the DESIR working range, a very high agreement have been obtain between the two calculations as well for the field-maps and the particles tracking for a typical beam which will be transport in the DESIR transfer beam lines. We have also notice that the mesh calculations and field solving is five times better using OPERA-3D compare to COMSOL Multiphysics with very close constraints and parameters.

Same methodology of studies will be taken for the already design DESIR deflectors and in the near future accelerator project in which IPN Orsay will be engaged.

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