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BEAM LOSS MONITORING THROUGH EMITTANCE GROWTH CONTROL AND FEEDBACK WITH DESIGN

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Abstract

Beam intensities and powers being increasingly strong, installations increasingly large, the need to reduce losses and costs (i.e. dimensions) becomes essential. Improvements are possible by increasing the acceptance in the two transverse planes. We investigate the solution to control the beam line acceptance by measuring the emittance growth and a feedback with the design, e.g. pole shape and high-order modes of the fields. This is possible with detection of very low intensities of the halo and beam loss monitoring.

INTRODUCTION

A new focusing unit based on a quadrupole doublet structure has been constructed at the Institut Pluridisciplinaire Hubert Curien (IPHC). The prototype with a 0.5 m long quadrupole doublet structure was developed to study some key issues for the transport of low energy ion beams with the electrostatic quadrupole technology. The typical application is the transport of radioactive ion beams (RIB), as SPIRAL 2 and DERICA projects [1-2]. Despite the low current intensity and standard loss level of 10^{-4}, cumulative contamination can limit access and reduce operability [3].

An experimental campaign was carried out in order to analyse key problems related to the design and operations. The results and the difficulties encountered in characterizing the performance of the doublet are reported with emphasis on low current intensity measurement (tail and halo of the beam), and 2D transverse emittance figures with non-standard elliptical shape.

DESIGN OF THE QUADRUPOLES

High-Order Modes Analysis

The prototype is an operational beam transport module with an optical structure based on an electrostatic quadrupole doublet (FODO structure with successive quadrupoles noticed Q1 and Q2). The design and manufacture of the prototype and especially the poles were carried out under a research contract between the CNRS and the SIGMAPHI company [4]. The pole design is carried out following an analysis of the fields and a decomposition by Fast Fourier Transform (FFT) of the higher-order multipoles (HOM). The harmonics are extracted from the field map, Fig. 1, integrated on the axial position with OPERA3D in order to evaluate their importance over the full length of the doublet with respect of the main quadrupole component A_2.

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Higher-order field components generate optical aberrations and limit beam transport. The different coefficients and the first, third and fifth order forces/aberrations can be easily calculated with different codes as Cosy-infinity, OPERA3D, etc. with more or less precision.

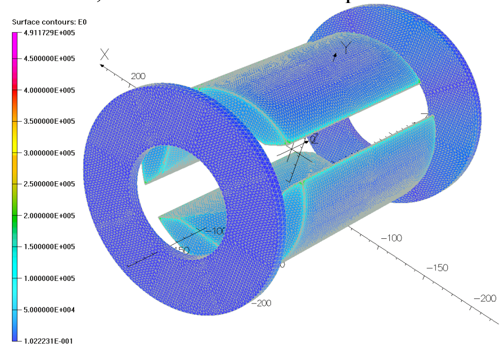

Figure 1: Numerical 3D Model with Field Map on The Surfaces of The Quadrupole and Two Collimator Rings.

Design Optimization

The method consists in minimizing some of the integrated high-order field components at a radial position, typically chosen to 50-75% and here 80% of the aperture because this corresponds to the filling of the beam. Pole design optimization is performed with specific objective functions and design variables in the Optimizer module of the OPERA3D code, and allowing automatic tasks and time savings. Our objective functions are defined by the integrated quadrupole component (A_2) which must be kept constant and several unwanted HOMs which must be minimized. It is a determining factor for particles passing close to the tips and for the beam halo which can be used as a signature of the performance. The construction is controlled by the minimization of a few integrated components, mainly the dodecapole (12 poles, component A_6), the duodecapole (20 poles, component A_{10}), and the 28 poles (component A_{14}) because they tend to defocus the beam and lead to aberrations, see Fig. 2.

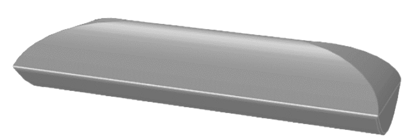

Figure 2: Optimized Pole Design Obtained from The Original Shape and Additional Geometric Constraints Leading to Smoothing the Profile and Minimizing Some Harmonics.

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Beam optics calculations are performed with the TraceWin code [5]. The result of the transverse distributions in 2D phase-space for a 34 m long virtual beam transport line is shown in Fig. 3. The optical structure is composed of six-unit cells of identical doublets. The initial Gaussian distributions have a marginal emittance of 80 π mm.mrad and are truncated at ±3 rms in the transverse planes.

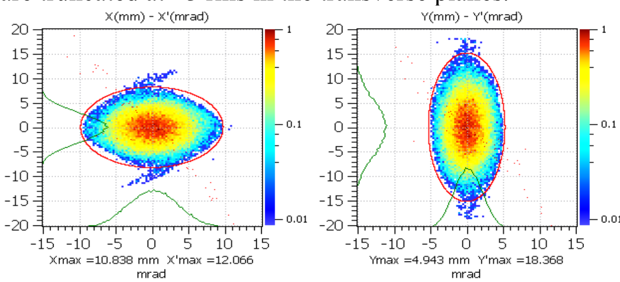

Figure 3: Transverse Trace-Space Distributions Simulated In X-X' and Y-Y' Planes at the Exit of a 34 M Long Virtual Beam Transport Line. The Red Ellipses Indicate The 3-Rms Emittances.

EXPERIMENTAL INVESTIGATIONS

High performance transport requires preservation of the transverse phase-space distributions and large acceptance conditions, i.e. with the highest ratio of beam filling to quadrupole aperture. Differential measurements are carried out with two emittance scanners in order to evaluate the emittance growth for different beam sizes, i.e. for several fillings of the first quadrupole aperture of the doublet. Both emittance scanners were calibrated in a preliminary experiment [6]. The first device is a commercial 4D pepperpot system from Pantechnik (EM1), and the second one is an "Allison" type 2D scanner (EM2) developed at IPHC [7].

Experimental Setup

The experiment is performed at the ARIBE test facility operated by the CIMAP laboratory and GANIL, Caen. The beamline delivers $^{40}Ar^{8+}$ beam. The test bench with the quadrupole doublet structure was installed at the extremity of the beam line. The facility delivers a 15 keV/q $^{40}Ar^{8+}$ beam with an intensity typically between 100 nA and 1 µA DC. The beamline is equipped with an ECR ion source, several dipoles (D), quadrupoles (Q), and steering magnets. The experimental setup including a vertical slit (FV), the quadrupole doublet (Q1 and Q2), the emittance meters (EM1 and EM2), and their location are shown in Fig. 4. FV slit combined with a defocused beam upstream allows the selection of a uniformly distributed beam sample for the purpose of the quadrupole aperture filling. The settings of Q1 and Q2 quads are fixed in order to allow successive focusing on the two emittance scanners. The settings of Q2 allow an adequate focusing on the emittance-meters located downstream.

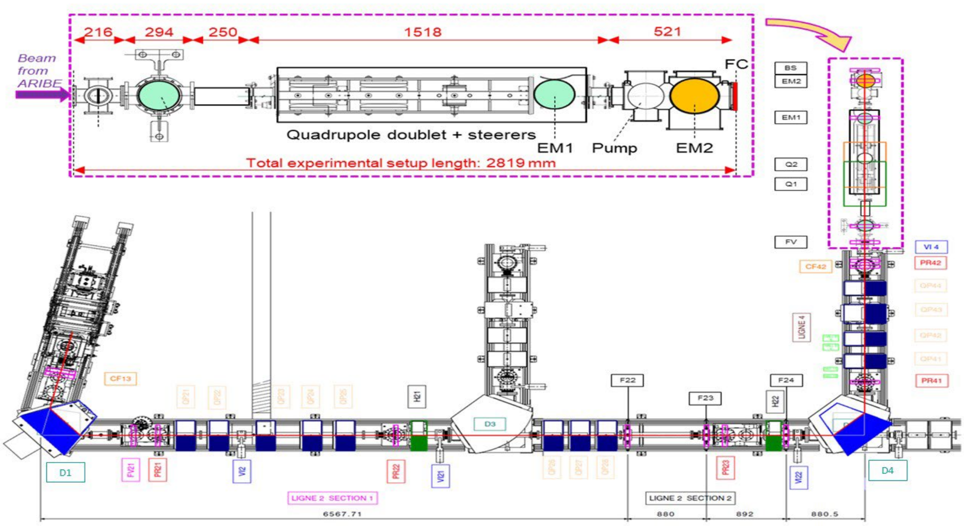

Figure 4: Experimental Setup on the ARIBE-D4 Beamline. The ECR Ion Source is Positioned Before the First Dipole Magnet (D1), Followed by D3 and D4 Dipole Magnets and Other Equipment as Slits (Fi), Profilers (Pri), and Faraday Cups (Cfi). The End of the Line is Identified by a Vertical Slit (FV) at the Interface with the Test Bench.

Control of the Quadrupole Filling and Transverse Distribution

The quadrupole filling is fixed by the vertical slit aperture (FV), and is evaluated by the geometry and the vertical beam waist at the position of PR42. The evaluation is complemented with TraceWin simulations to define the several beam optics settings. Figure 5 shows the simulated vertical beam distributions at the entrance of the slit and of Q1. The slit is set to a ±10 mm opening corresponding to a vertical size of ±33 mm (FWHM) at Q1 and resembling a uniform distribution. The error concerning the filling is a few percent over the range of variation between 20 and 80%.

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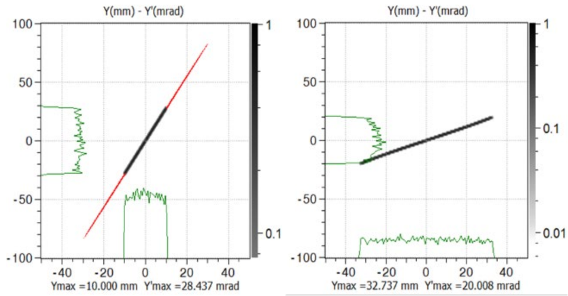

Figure 5: Vertical Distributions at the Entrance of the FV Slit (±10 mm aperture) and of the Q1 Quadrupole According to The Simulations. Red Points Indicate the Particles That Have Been Intercepted by The Slit.

Emittance Growth Measurements in The Presence of Perturbations

The obtained results from the EM2 measurements are shown in Fig. 6. As expected, the beam emittance increases with slit opening, and optical aberrations increase with filling of the quadrupole but also in the presence of misalignment between the ECR ion source and the prototype. A misalignment induces an offset in position and angle in the transverse phase plane, and a shift of the emittance figure. It can be produced by faulty steering, internal electrical disconnections, voltage drop (large beam partially colliding with the poles), and charging of floating surfaces inside the vacuum chamber. Another scenario that needs to be studied in more detail is the possibility of a partial discharge between several poles due to the large beam filling.

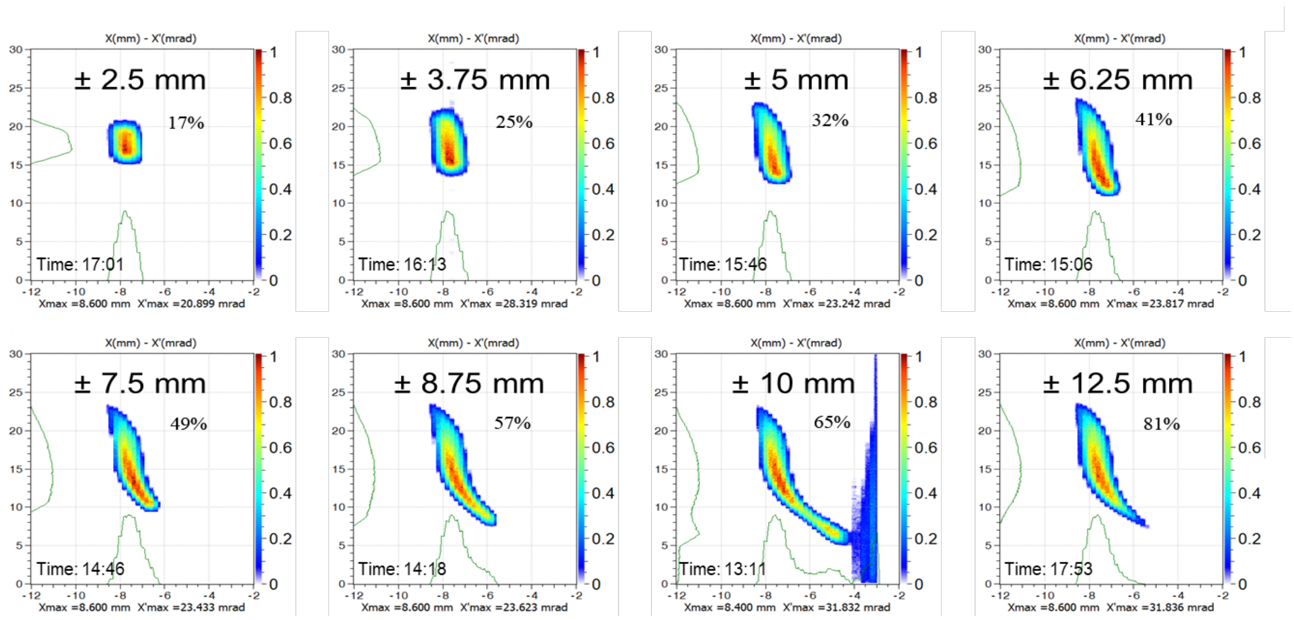

Figure 6: Emittance Measurements in 2D (Y-Y' vertical plane), with Different Slit Apertures and Q1 Quadrupole Fillings (± half openings of FV slit and percentages of filling).

DISCUSSION

One of the main challenges in evaluating the performance of the quadrupole doublet was related to the measurement of the signature of the HOM field components in the tail and the halo of the beam and to detect the emittance growth. During the experiment, the resolution of the beam current intensity measurements was limited to 1pA. This barrier should clearly be pushed back in the future to allow the evaluation of emittance growth with better precision [8]. Some typical numbers defining the halo are the particle count that is less than 10% of the total, distributed over more than 60% of the area of the 2D beam emittance figure, with less than 10^{-5} of the total beam current intensity at 5-rms for a Gaussian distribution [9-11]. When measuring such low intensities, the signal to noise ratio becomes crucial and therefore the identification of the background noise (BGN), the filtering of the signal keeping most of the halo will require further effort to improve emittance growth measurements.

CONCLUSION

A low-energy ion beam transport prototype including a quadrupole doublet has been realized after optimization of the quadrupole structure design. The experiment carried out with the doublet structure on a low energy ion beam line has revealed the limits of the measurements of the trace-space distributions currently possible and necessary to evaluate the tiny emittance growth generated by a unit optical cell. The importance of the signal analysis and image reconstruction was demonstrated because classical statistical tools were not entirely satisfactory. Although current PS specifications indicate a high stability and 10^{-5} load regulation, behaviour under load variation, with current injection into the electric circuit, induced voltage transients, and the use of a resistive load (bleeder resistor) must be investigated in more detail. This will allow control of the pole potential even with beam losses and inter-pole effects.

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