EMITTANCE MEASUREMENTS AND OPERATION OPTIMIZATION FOR ECR ION SOURCES

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Abstract

Electron Cyclotron Resonance (ECR) ion sources supply a broad range of ions for post acceleration in cyclotrons. Here, an effort to improve the beam transfer from RIKEN's 18 GHz superconducting ECR ion source (SC ECRIS) to the Low Energy Beam Transfer (LEBT) line and an optimization of the performance of the ion source is presented. Simulation studies have shown that less than 20% of the beam is currently transferred. The first goal is to measure the transverse beam emittance in real time. The emittance monitor designed and fabricated for this purpose utilizes a pepper pot plate followed by a transparent scintillator and a CMOS camera for image capture. The second goal is to investigate on dependencies between beam emittance and various operating parameters. To this extent, modifications of the ion source took place, as well as a measurement of the magnetic field inside the ion source. In this contribution the design details of the instrument and a description of the algorithm are presented as well as a typical emittance measurement.

INTRODUCTION

RIKEN's Radioactive Beams Facility (RIBF) utilizes an 18 GHz ion source [1] to produce highly charged ion beams. Firstly for use in the Azimuthally Varying Field (AVF) cyclotron for stand-alone experiments, but also for use in the subsequent Riken Ring Cyclotron (RRC) and the Superconducting Ring Cyclotron (SRC) in case higher beam energies are required, see Fig. 1.

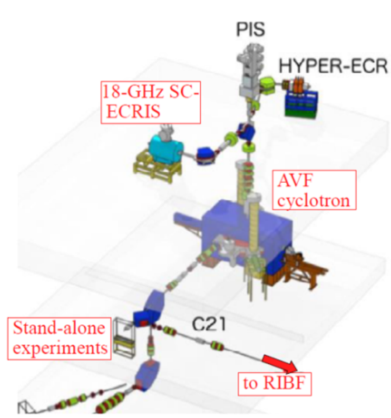

Figure 1: RIBF injector complex including the 18 GHz SC-ECRIS.

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The demand for higher beam intensities and more efficient beam transport triggered simulation and experimental studies into LEBT efficiency and optimization, as well as R&D into the emittance measurement itself.

ECR ION SOURCE DESCRIPTION

The ion source discussed in this paper is based on four superconducting solenoids positioned around a permanent hexapole magnet to generate a mirror magnetic field. An 18 GHz microwave source followed by a Travelling Wave Tube Amplifier (TWTA) is feeding microwave energy into the ion source for plasma generation. The specifications of the 18 GHz SC-ECR ion source are listed in Table 1.

Table 1: Main Parameters of the 18 GHz Superconducting ECR Ion Source

Superconducting material	Nb-Ti
Bore	220 mm
Radius of plasma chamber	70 mm
Length of plasma chamber	378 mm
Length of hexapole magnet	380 mm
$B_{\|}$ (z= - 200 mm)	3.0 T
$B_{\|}$ (z= 0 mm	0.6 T
$B_{\|}$ (z= 200 mm)	2.0 T
Microwave frequency	18 GHz
Microwave power (max)	700 W
Typical extraction voltage	10 kV
Analyzing magnet	
Pole gap	80 mm
Radius of curvature ρ	500 mm
Bending angle	90 degrees
B_{max}	0.15 T
Edge angle	29.6 degrees

Magnetic Field Measurement

To confirm the theoretical magnetic field values and the simulation results a magnetic field measurement was conducted. We used an LP-141 Hall probe to measure the axial field along the centerline of the plasma chamber. One measurement was done with the superconducting solenoid switched off so we were able to discriminate the contribution of the hexapole magnet itself. There is a small fluctuation of the magnetic field, as shown in Fig. 2 on the brown plot, but there was no obvious explanation for this. The field shown by the blue curve is smaller than the design value but this might be due to the imperfect positioning of the probe. Even though lower in absolute terms, the overall magnetic field distribution is suitable for efficient plasma confinement.

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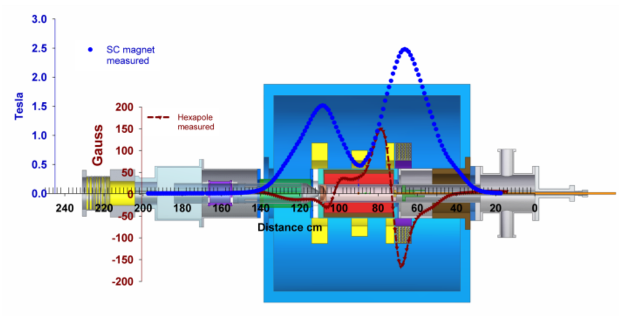

Figure 2: Illustration of the magnetic field distribution.

Measurements led to a modification of the ion source. The Einzel lens located downstream of the extraction (purple cylinder) was previously placed in a region where the magnetic field was high. This resulted in a poor performance when the ion beam was focused. After the modification the transport efficiency increased by 50 % for Oxygen beams.

EMITTANCE METER R&D

Hardware Design

The emittance meter development started as a collaboration between RIKEN and CNS [2], and is currently on the 3rd design iteration. The initial design specifications were quite loose in terms of expected emittance values. The design constraints dictated that the pepperpot had to have the largest possible area, whilst being able to fit the monitor onto a DN200 flange. The installation behind a solenoid meant that by varying the solenoid current, the beam size would change dramatically. Thus a large pepperpot area would capture this dependence. Furthermore, the ECR ion source produces a variety of beams with different characteristics, and in some cases higher resolution or higher light yields are required. A single emittance meter cannot address all these needs, so based on the operational experiences from this prototype further modifications are foreseen.

The latest design is shown in Fig. 3 and consists of a thin perforated foil with 0.1 mm pinhole's diameter and 2 mm pitch. A transparent scintillating screen is located 52 mm downstream of the pepperpot. After this a mirror angled by 45^0 is directing the scintillation light towards a camera, through a glass viewport outside of the vacuum chamber. The whole assembly is mounted on a DN 200 flange and can be retracted from the beam line by a stepper motor. The screen to pepperpot distance can be changed by an in vacuum stepper motor from Arun electronics. The pepperpot plate is electrically isolated allowing for beam current measurements via an electrical feedthrough. A custom made Ethernet-based electronic board and software manages the motion control for retracting the device and measuring beam current. The in-vacuum stepper motor is also incorporated in the same control software. In this prototype a Micro Channel Plate (MCP) can be used instead of a Phosphor screen. Phosphor screen tests have shown signs of degradation after long irradiation times or use of heavy ions. In order to protect the screens and the MCP a beam chopper has been employed. It consists of a set of copper electrodes inserted in the beam line that deflect the particle beam when a high voltage is applied. The chopper operation can be synchronized with image acquisition.

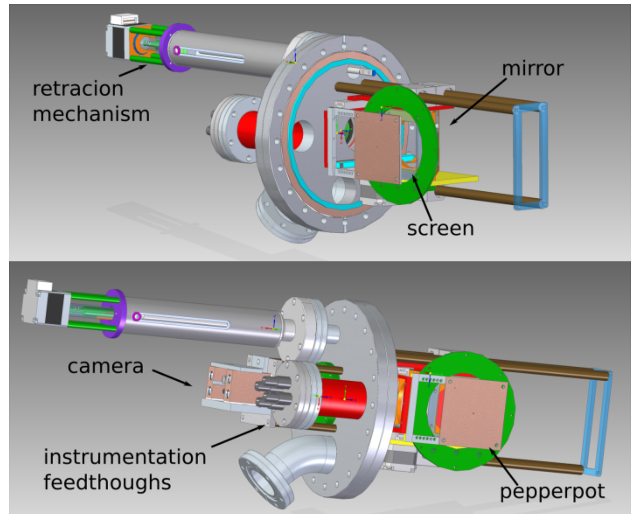

Figure 3: Emittance meter design details.

Software Development

The CMOS camera used in this setup provides real time images to the software-based image processing algorithm that has been developed in Labview, for emittance measurement. The main requirement is to be able to provide emittance data at a reasonable rate to be considered real time, i.e. a few fps. After image acquisition and basic filtering for noise reduction, the algorithm applies a binary image conversion to discriminate the beamlets. A dilation operation increases the size of the beamlets and then this binary image is used to mask the original image. Doing this has the benefits of:

- Masking out all the image apart from the beamlets significantly decreases the numbers of pixels to be processed
- The binary beamlets are larger than the original ones so there is full coverage
- There is no need to threshold the image afterwards. It has been shown that threshold values can affect the emittance measurements [3].

By using the known locations of the pinholes on the pepperpot plate and the distance between pepperpot and screen (or MCP) the divergence can be calculated. The rms emittance is calculated using the locations of the pinholes, locations of the beamspots on screen and the pixel intensity as a statistical weight. One of the issues with the current algorithm is that for every measurement a new beam center is defined based on the masked out central pinhole of the pepperpot. Because of that even if the beam is not centered, it appears centered in the phase space plots. The algorithm also includes the control for the pepperpot movement and current measurements. It is also interfaced to EPICS via the CaLab library [4] so it can request values of other parameters such as magnet current, RF power, temperatures etc.

Experimental Studies

For the calibration of the device when using crystal scintillators, a dummy plate was placed at the position of the crystal with a circular cutout of known diameter. Based on that the pixel/mm ratio was found to be 18.4 pixels/mm. In the here-presented studies a proton beam was used as it can give a higher range of beam currents and does not degrade the scintillators as quickly as heavier ions do. For the current measurements shown here, an Argon beam of 23 μA of current was used. A representative measurement with Ar^{50+} is shown in Fig. 4 below.

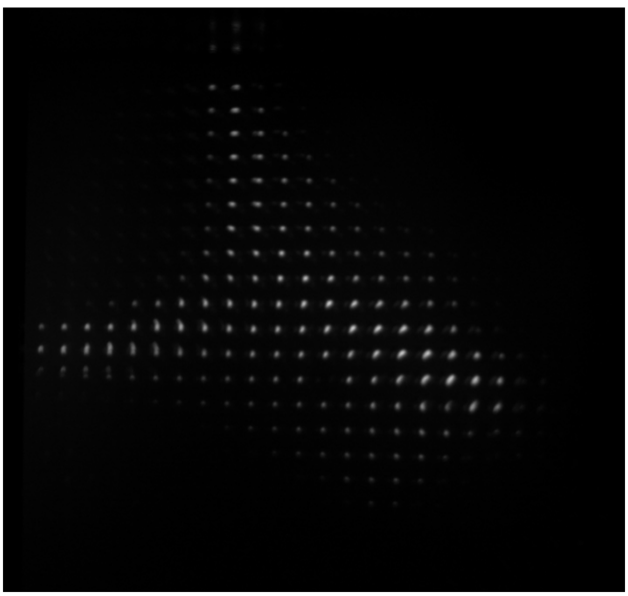

Figure 4: Acquired image of the ion beam on the scintillator.

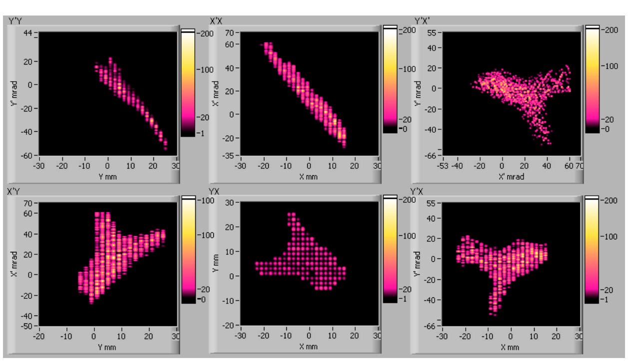

Figure 5: Emittance measurement using Argon.

In Fig. 5 all the combinations among the 4 phase space coordinates X (mm) Y (mm) X' (mrad) Y' (mrad) are plotted for visual evaluation. Typical rms emittance values are: ε_x = 10 mm*rad and ε_y = 34 mm*mrad. As the system is still under development, phase and error estimations have not been completed. Error sources that need to be considered include the position measurement resolution based on the hole size and spacing, angular errors based on camera resolution and calibration, as well as intensity errors from beam, background and camera noise.

Several challenges in the development of this device arise: scintillator performance which varies with different beams species; irregular beam shapes produced by the ECR ion source; different intensity levels for different ion species. This factors will need to be taken into account alongside ion source parameters, camera performance, scintillator degradation, and noise in the image to fully understand the quality of the final emittance monitor.

SUMMARY

A real time emittance monitor was developed specifically for use at the 18 GHz SC-ECRIS, but which shall also be applied to other ion sources of the RIBF once it has been fully characterized. After construction tests have been carried out with 3 prototypes and image analysis algorithms have been improved along measurement campaigns. It was found that the monitor is suitable to perform day to day emittance measurements for a variety of beam species. A detailed characterization and error study is ongoing.

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