Ion Beam Emittances of Intense Highly Charged Ion Production from the RIKEN 28GHz SC-ECRIS

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ABSTRACT

The RIKEN 28GHz superconducting electron cyclotron resonance ion source (SC-ECRIS) has been developed to produce high intensity multiple charged heavy ions for nuclear physics research at the RIBF. To provide intense RI beams, it is important to evaluate beam quality through emittance measurements to ensure proper matching with the low energy beam transport system of the accelerator. This study focuses on identifying the potential growth factors contributing to the beam emittance growth, observed experimentally in the SC-ECRIS. By analyzing the dependence of the measured beam emittance on the extraction current, space-charge-like emittance growth and an initial beam emittance were determined. Measurements of ion beam emittances from ^{238}U, ^{40}Ar, and ^{136}Xe were compared to investigate the effects of ion velocity, mass-to-charge ratio (M/Q), and to evaluate the consistency with the magnetic field emittance model. The deduced initial ion beam emittance offers valuable insight into the minimum achievable emittance of beams extracted from the ECRIS. Continued investigation into the mechanisms and suppression of space-charge-like emittance growth will be an important step towards realizing the low-emittance conditions for high-intensity ion beam production.

R 28GHz SC-ECRIS

The SC-ECRIS has continuously developed to supply the intense heavy beams,

Specifications of the R28GHz SC-ECRIS

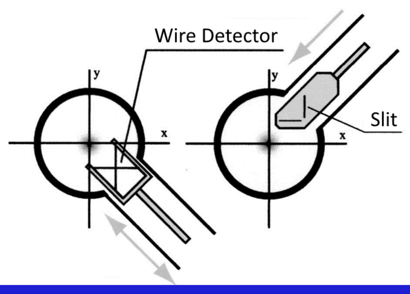
Operational Frequency	28Ghz, 18GHz
Max. RF Power	10kW
Max Magnetic Fields	3.8 T
Max. Extraction Voltage	22kV
Chamber Dimensions	Φ150 mm
	L 525mm

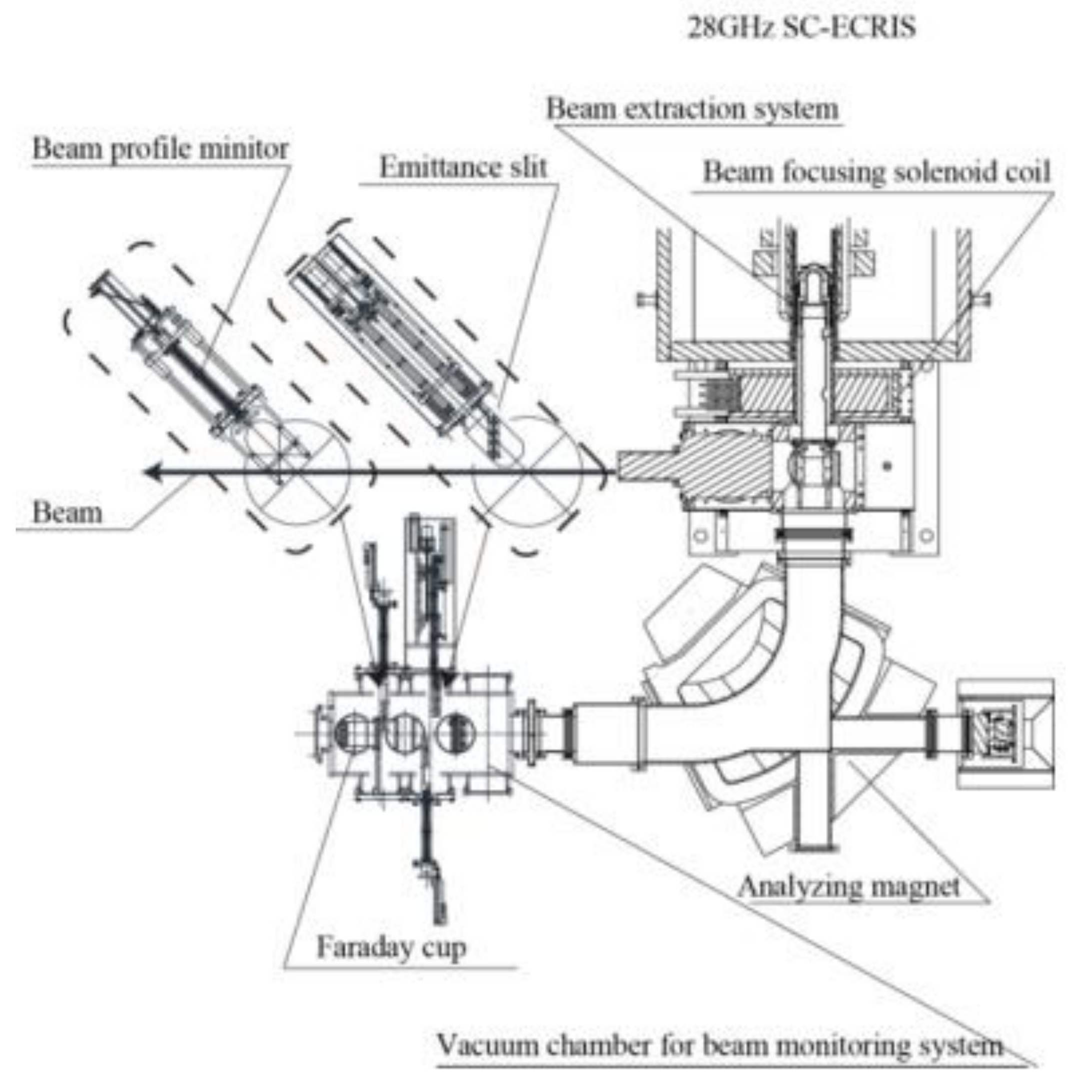
After beam extraction and bending magnet, the beam diagnostics: profile monitor (wire type), Faraday cup, and beam emittance monitoring system are set.

Emittance Measurement System

(slit-wire type)

Slit to wire: 140mm
Slit width: X – 0.7 mm
Y – 1.0 mm





T. Nakagawa, et. al., Rev. Sci. Instrum. 81 02A320 (2010)

BEAM EMITTANCE GROWTH FROM ECRIS

The normalized beam emittances (π mm mrad) is measured from the downstream region and a simplified contribution from different factors can be viewed as:

G. Q. Saquilayan, et. al., Proc. of ECRIS2024 (Darmstadt) M0A3

$$\varepsilon^2_{meas} = \varepsilon^2_{ecris} + \varepsilon^2_{space-charge} + \varepsilon^2_{other}$$

Diagnostics System

Defined by the ECRIS:
- Ion temperatures
- Magnetic Field Confinement

Space charge effects that occur in the low energy region of beam extraction

Beamline aberration and other unknown causes

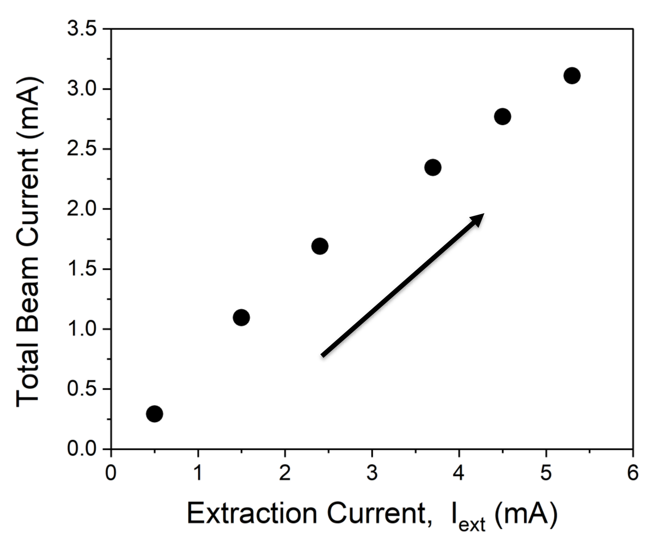
Extraction Current Dependence:

One of the parameters that has been observed to have a large influence on the beam emittance is the extraction current.

The proportionality of I_{ext} to the total beam current was observed, $I_{ext} \sim I_{tot} = \sum_q^n I_q$

which is a used an indicator for the total beam current

Sum of all produced ion currents for ^{40}Ar with respect to I_{ext}



Space-charge-like effects:

From the dependence of the extraction current I_{ext} on the measured beam emittance, a smaller I_{ext} (or total current) shows smaller beam emittances.

Assuming negligible effect coming from beamline aberration, etc.,

$$\varepsilon_{meas} = \sqrt{\varepsilon^2_{ECRIS} + \varepsilon^2_{Space-Charge}}$$

and with $\varepsilon_{space-charge} \propto I_{total}$

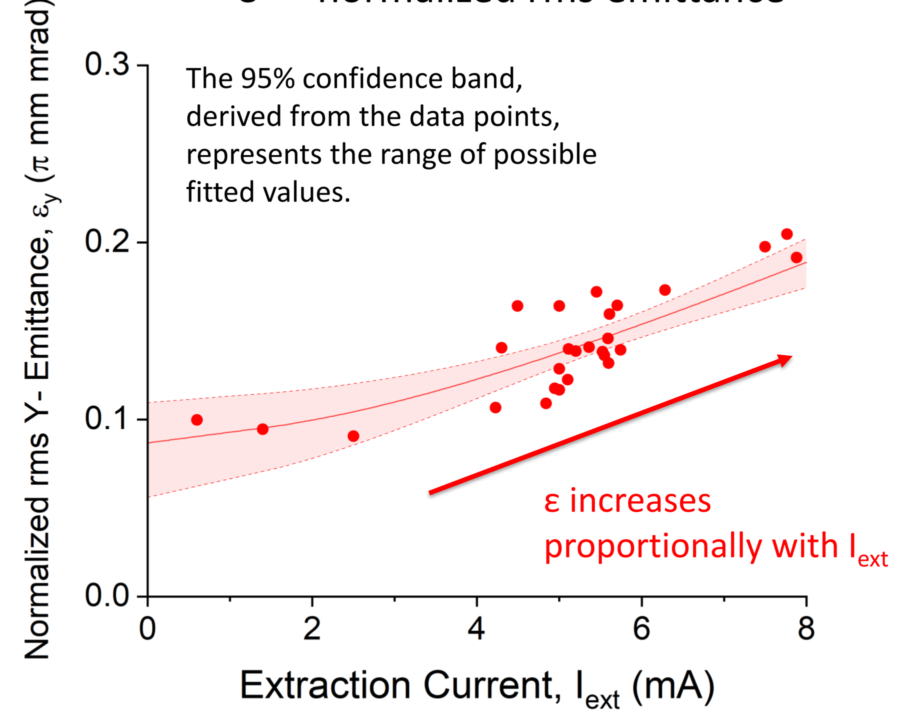
$$I_{total} \approx K\, I^2_{ext}$$

$$\varepsilon_{meas} = \sqrt{\varepsilon_0^2 + K(I_{ext})^2}$$

where ε_0, is an initial beam emittance

And K is a parameter describing the beam

^{238}U^{35+} normalized rms emittance



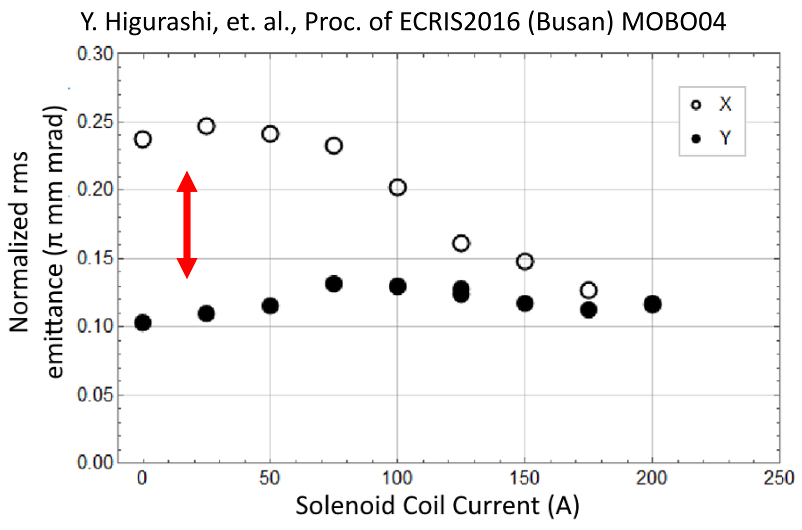
Considering the ε_y nrms emittance with minimal aberration effects, a space-charge-like growth was fitted based on the measurements.

Other Contributions on Beam Emittance:

In previous studies, a large disparity between the x and y beam emittances were observed. This difference could be suppressed by using stronger focusing of the solenoid lens.

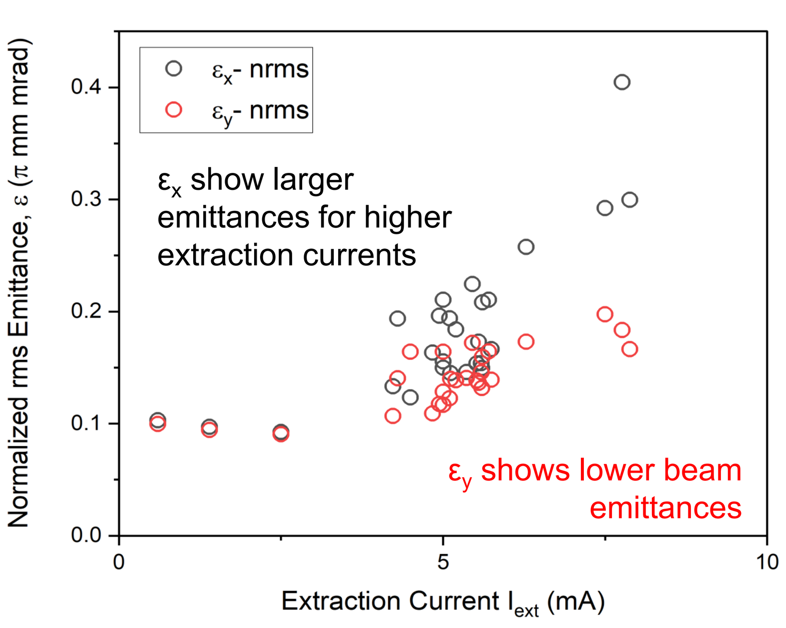
Beam current: ~ 100 μA
I_{ext} : ~4.8 mA

Y. Higurashi, et. al., Proc. of ECRIS2016 (Busan) MOBO04



Observed difference between x and y beam emittance:

^{238}U^{35+} normalized rms emittance



Despite compensating using the solenoid lens, an obvious difference is observed between ε_x and ε_y at larger I_{ext} (greater than 4 mA).

Discrepancies can be due to:
- Beam path deflections in the x-direction
- Variation in initial trajectories (ECR extraction)

Initial Beam Emittance:

Continuing with the same assumption for,

$$\varepsilon_{meas} = \sqrt{\varepsilon_0^2 + K(I_{ext})^2}$$

then as I_{ext} approaches 0

the nrms emittance should show that $\varepsilon_{meas} \approx \varepsilon_0$

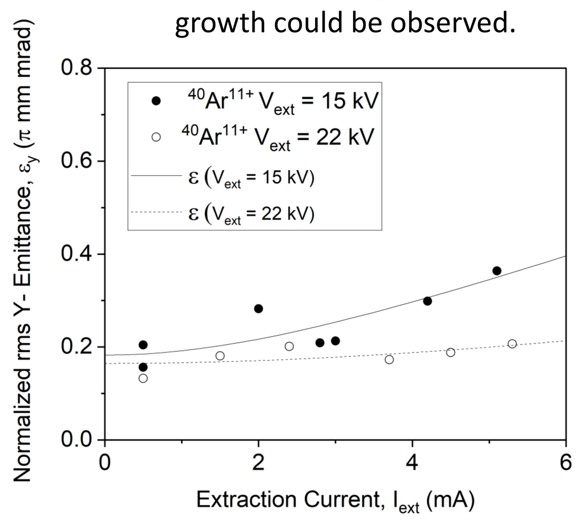
This initial emittance ε_0 should be related to the extracted emittance from the ECRIS.

Velocity Effect:

G.Q. Saquilayan, et. al., J. Phys. Conf. Ser. 2743 012081 2024

Evaluating the space charge growth and initial beam emittance was investigated previously with ^{40}Ar^{11+} to show a velocity effect in the emittance growth.

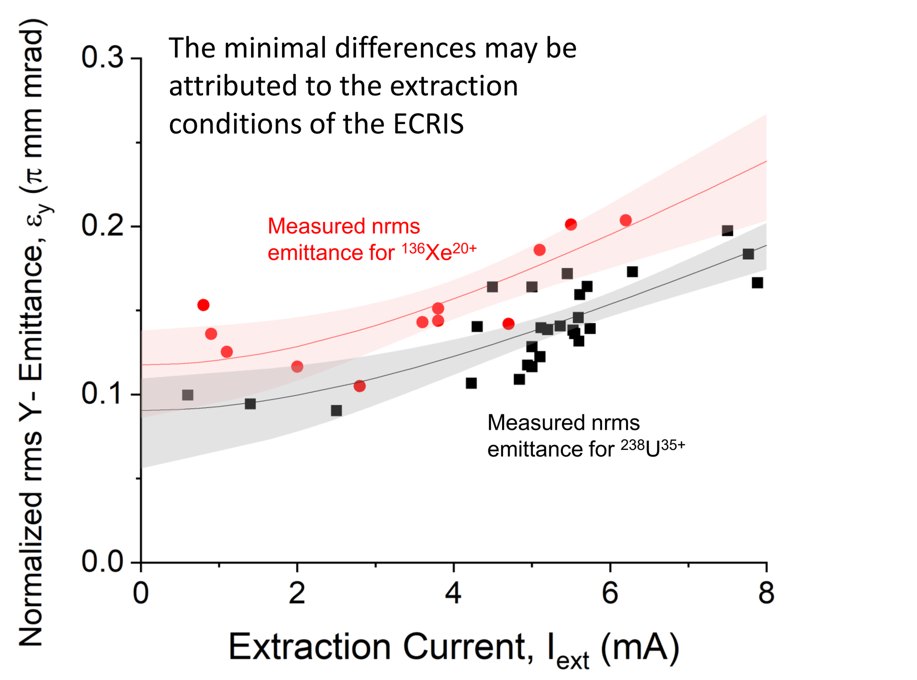
Using similar ECRIS conditions but with extraction voltages, the difference in emittance growth could be observed.



Both converges to similar ε_0

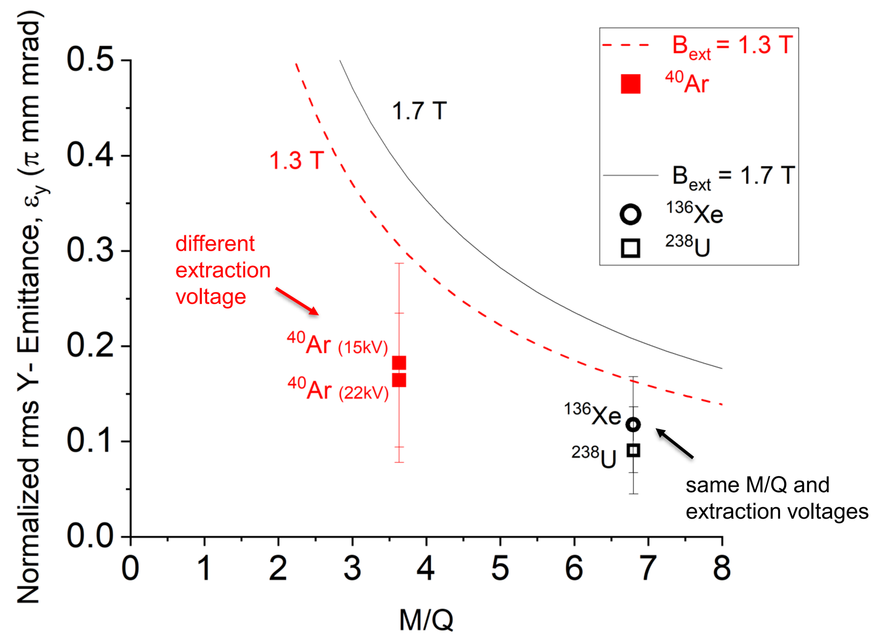
Conditions with same mass-charge ratio M/Q:

Comparing ion beams of ^{238}U^{35+} and ^{136}Xe^{20+} having the same M/Q, the initial emittance ε_0 and emittance growth ε show similar values.



Consistency with the Magnetic Field Emittance

The beam emittance from the ECR extraction has been known to be greatly influenced by the induced rotation by the magnetic field at the extraction region.



Magnetic Field Emittance:

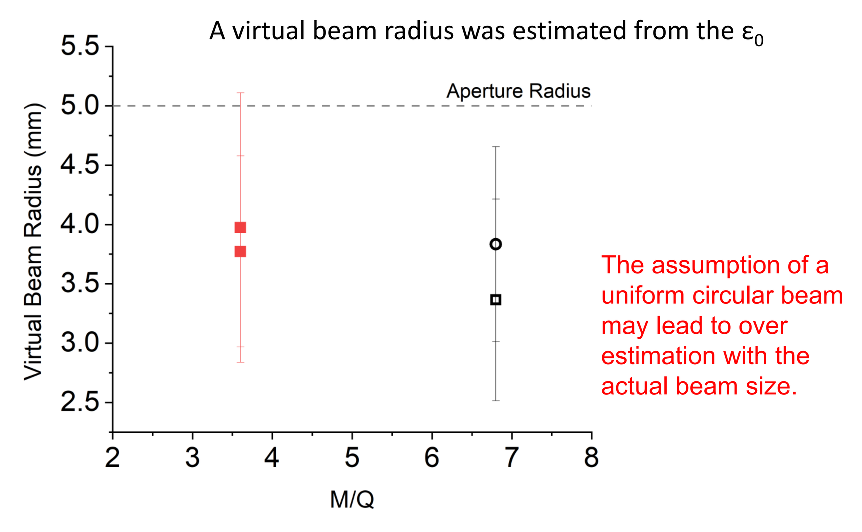
V. Mironov, Phys. Rev. ST Accel. Beams 18, 123401 (2015)

$$\varepsilon_{mag} = 0.032 r^2 B_0 \frac{1}{M/Q}$$

r — radius of extraction hole
B_0 — magnetic field strength at extraction
M/Q — Mass-Charge ratio

This emittance equation assumes a uniform distribution with r defined as the beam size. (Extraction aperture radius = 5 mm)

A virtual beam radius was estimated from the ε_0



Actual beam emittances may be lower than the measured values

SUMMARY

Factors influencing beam emittance growth were investigated experimentally through normalized root-mean-square (rms) emittance measurements, with particular focus on its dependence on the extracted beam current. Contributions from an initial beam emittance, space-charge-like growth and other effects were examined under various conditions, including the velocity effect, ion beams with same M/Q ratios and comparisons with the magnetic field emittance model. Understanding these contributions can guide strategies on suppressing the emittance growth and reevaluating the ECRIS extraction system towards high intensity beam production.