Development Towards Intense Uranium Ion Beam Production of the RIKEN 28 GHz SC-ECRIS

G. Q. Saquilayan, Y. Higurashi, T. Nagatomo, J. Ohnishi and O. Kamigaito

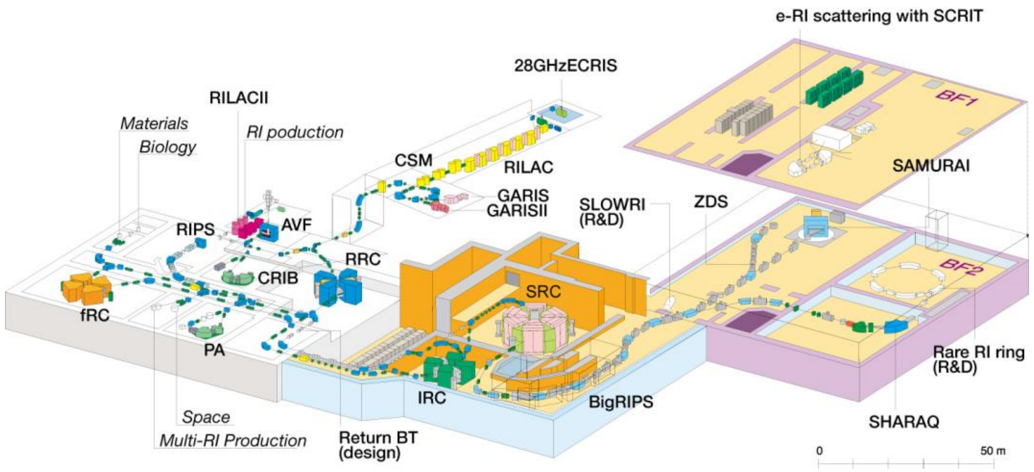
RIKEN Nishina Center for Accelerator-Based Science, Saitama, Japan

OUTLINE:

- Introduction of RIBF and R-28GHz ECRIS
- Uranium Beam Production
- Measurement of Beam Emittance
- Uranium Beam Emittance
  - Effect of Focusing Solenoid Lens
  - Relation to Extraction Current
  - Factors Considered for Beam Emittance Growth
  - Calculation of Ion Source Emittance and Space Charge Effect
  - Discussion
- Summary

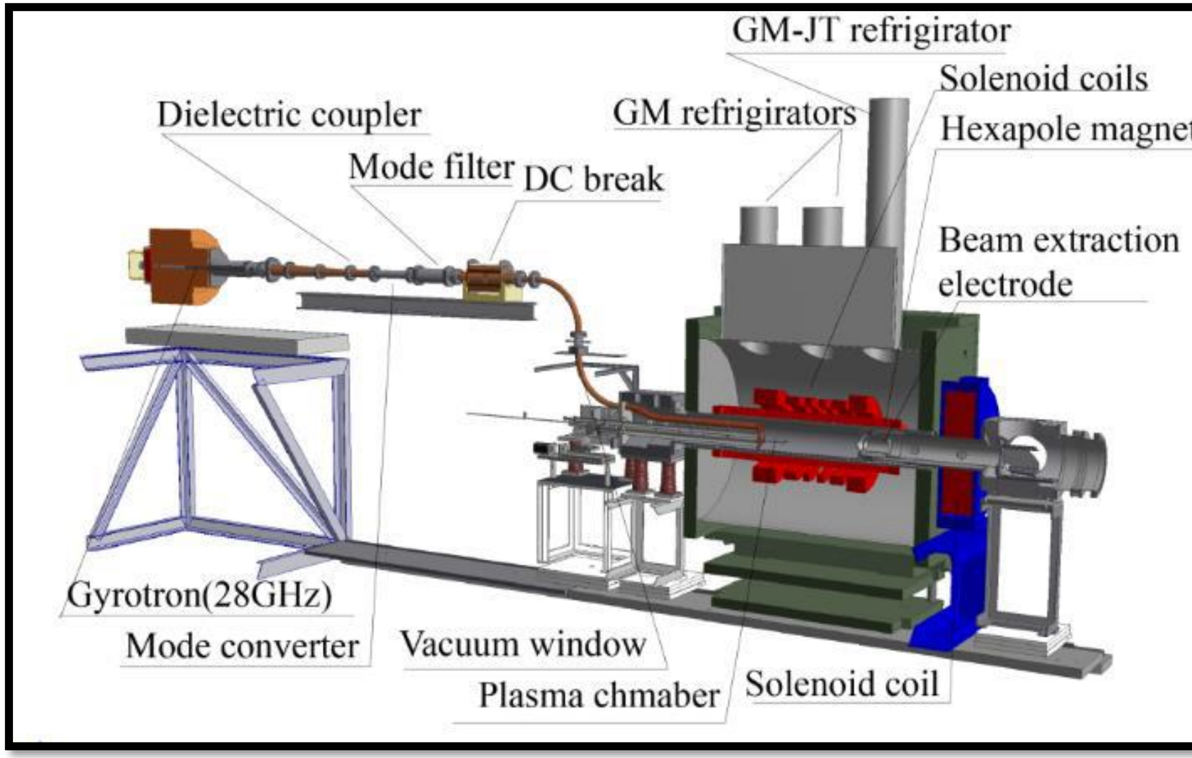
RI Beam Factory (RIBF)

The RI Beam Factory is a heavy ion accelerator complex providing high intensity RI beams for leading research on nuclear physics. To generate intense ion beams for acceleration, a superconducting ECR Ion source was developed for highly charged heavy ion beam production.



Intense uranium beams are necessary for RI beam research

RIKEN 28-GHz SC- ECR Ion source



T. Nakagawa, et. al., Rev. Sci. Instrum. 81 02A320 (2010)
G. D. Alton, D. N. Smithe Rev. Sci. Instrum. 65, 775-787 (1994).

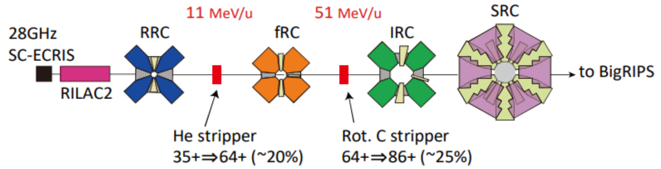
Specifications of the R28GHz SC-ECRIS	
Operational Frequency	28GHz, 18GHz
Max. RF Power	10kW
Magnetic Mirror Fields	3.8 T
Max. Extraction	22kV
Chamber Dimensions	Φ150 mm L 525mm

RI Beam Factory (RIBF)

Future Experiments at RIBF

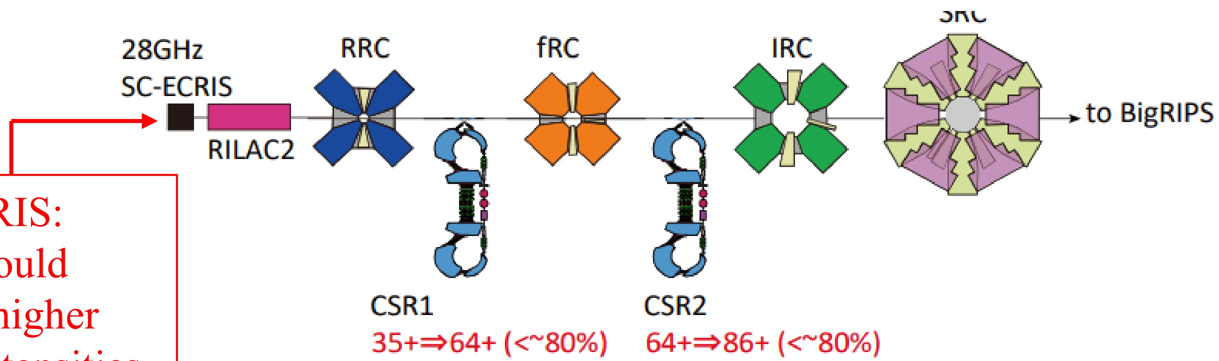
With the demand for future experiments at the RI beam factory requiring intense Uranium beams, development of the R28GHz SC-ECRIS are necessary to supply the required beam intensities.

Present Scheme:



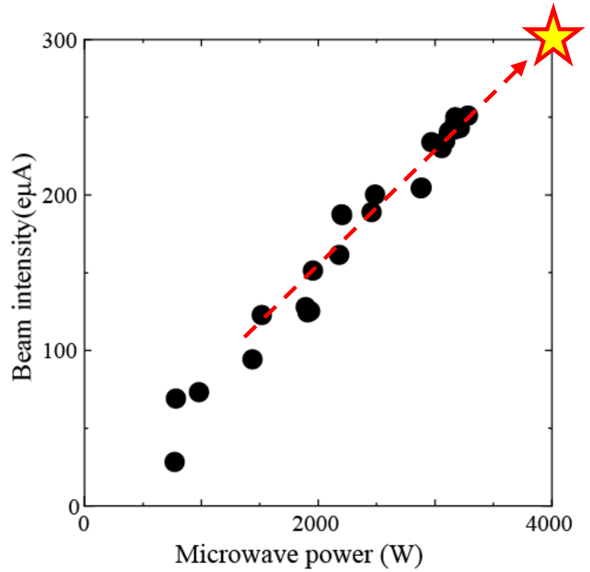
The upgrade of the existing accelerators also requires development of the SC-ECRIS to generate higher beam currents.

Upgrade: H. Imao, JINST 15 P12036 (2020)



SC-ECRIS: U^{35+} should supply higher beam intensities

Required Beam intensity for U^{35+} : ~ 300eμA



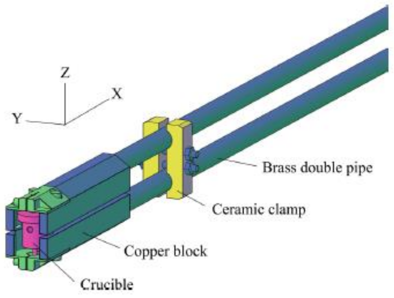
To reach the target beam intensity, SC-ECRIS specifications should be checked.

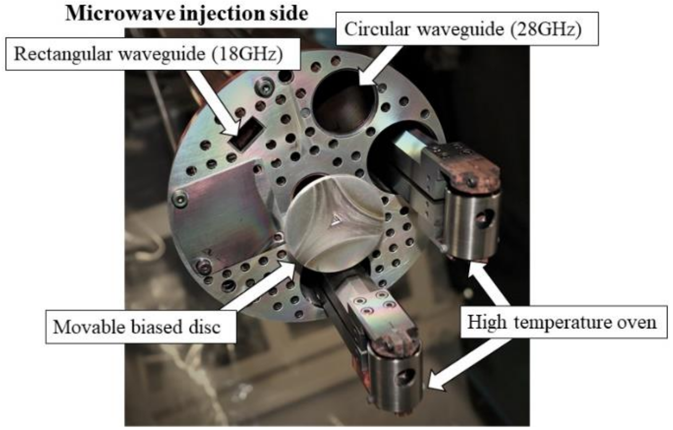
- RF Power and corresponding heat loads
- Material consumption rate for long period operation
- Beam emittance for beam transmission efficiency

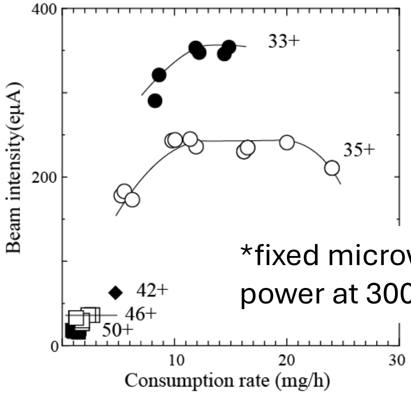
Uranium Beam Production

To increase the beam intensity for uranium beams, the performance of the SC-ECRIS was improved through careful consideration of the High Temperature Oven.

Design considerations:
- Temperature distribution (vapor ejection, blockage, etc.)
- Minimize stress due to electromagnetic forces

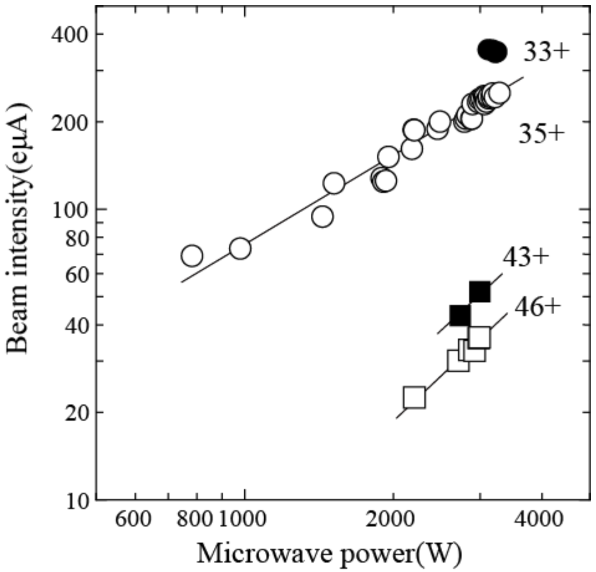






*fixed microwave power at 3000W

Achieved U beam Current:



Through optimization of material consumption rates, currently the achieved beam intensity for U^{35+} is ~250eμA.

Long period beam of 1 month was also possible for U^{35+} (110μA) operated with low consumption rate (2.4mg/h)

As beam development progress towards **higher beam intensities**, this stresses the need to further **study the beam emittance** of the produced uranium beam.

J. Ohnishi et. al., Rev. Sci. Intrum. 87 02A709 2016
Y . Higurashi, et. al., J. Phys. Conf. Ser. 2743 01205 2024

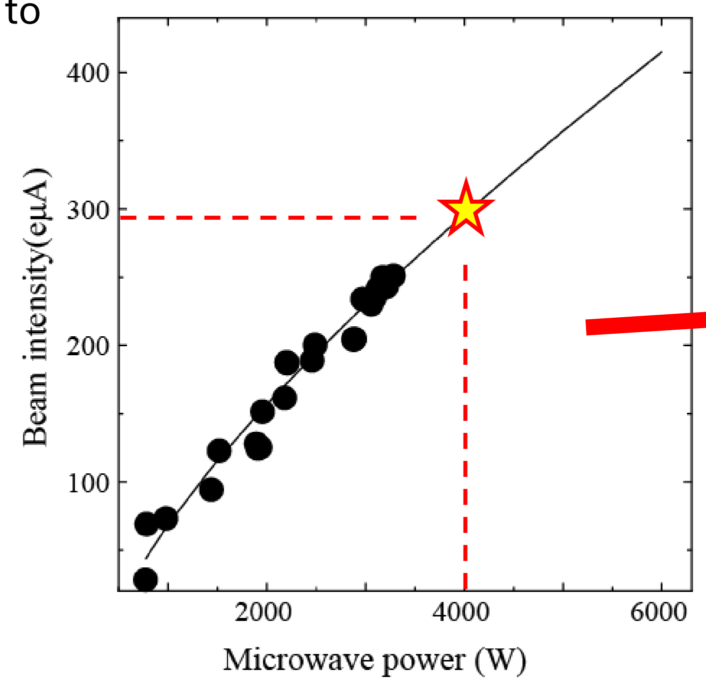
Uranium Beam Production

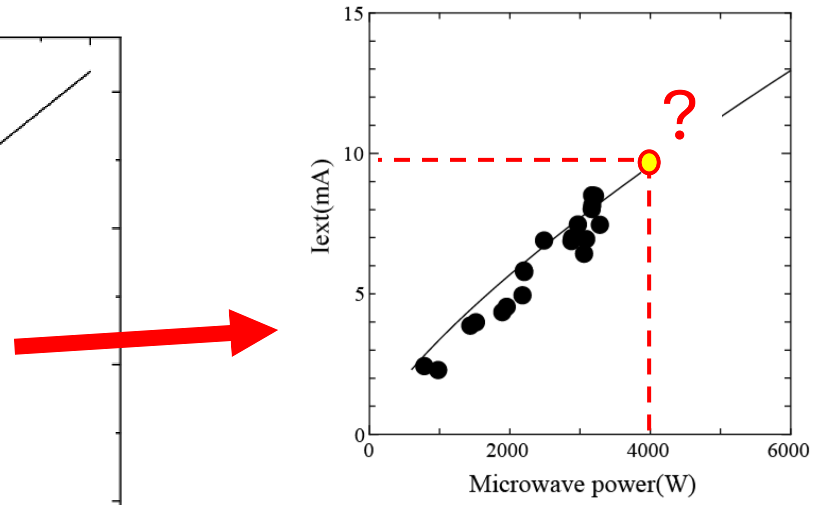
Moving towards the production of high intensity uranium beams using the SC-ECRIS, the important parameters to check is the beam quality.

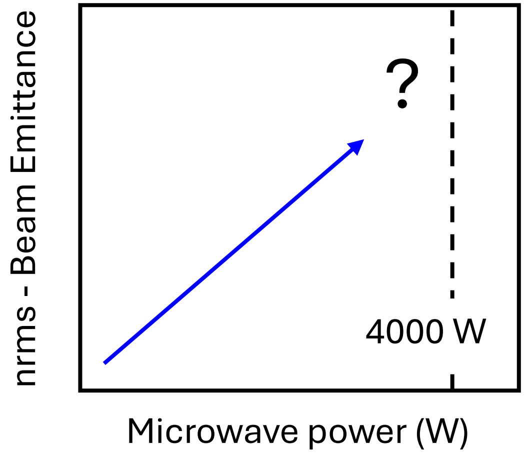
To produce ~300 eμA beam current for U^{35+}, studying the beam optics in the SC-ECRIS is important to ensure proper matching to the low energy beam transport of the accelerator.

- Estimate the extraction current during high intensity beam production
- Investigate the beam emittances

→possible challenges should be confirmed such as beam aberrations caused by co-extracted ion species.







The Measured Beam Emittance

The beam emittance is measured in the downstream region where contribution from different factors can be viewed as:

$$\varepsilon^2_{meas} = \varepsilon^2_{ECRIS} + \varepsilon^2_{Space-Charge} + \varepsilon^2_{other\ effects}$$

Many studies have been made on the emittance from the ion source

The emittance ε_{ECRIS} is mainly influenced by two main factors:

Ion temperature $\varepsilon_{ion-temp} = 0.016 r \sqrt{\left(\frac{kT_i}{M/Q}\right)}$ [π mm mrad]

and

Axial Magnetic Field $\varepsilon_{magnet} = 0.032 r^2 B_0 \frac{1}{M/Q}$ [π mm mrad]

For highly charged ions, $T_e \gg T_i$ we assume the contribution of $\varepsilon_{ion-temp}$ is smaller

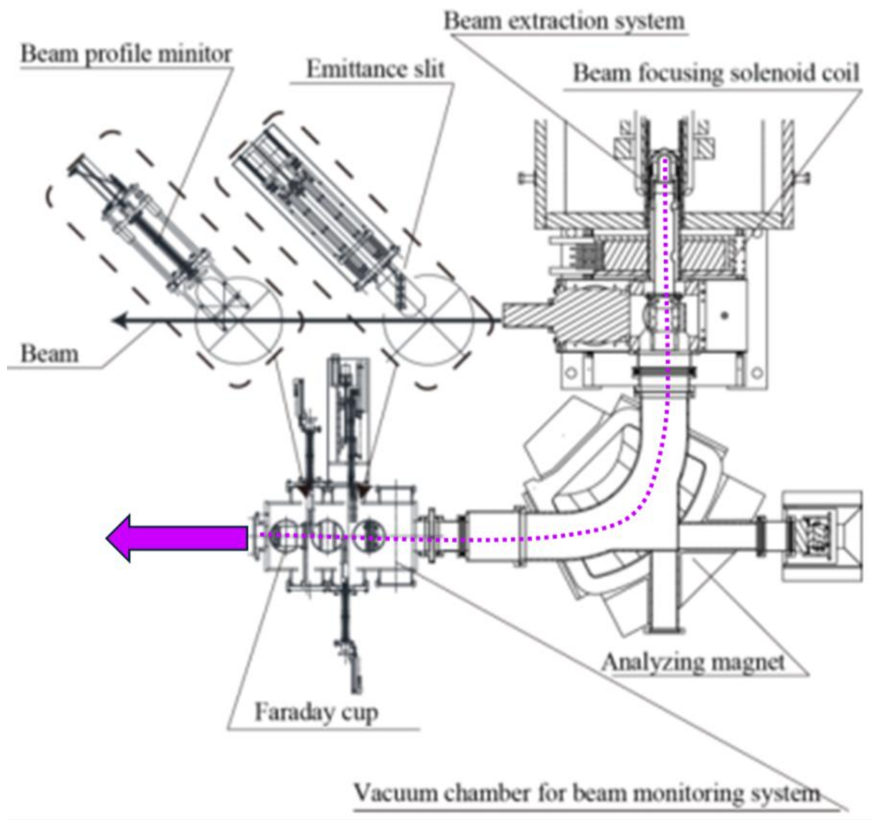
r radius of extraction hole [mm]
B_0 Axial magnetic field strength [T]
kT_i Ion temperature [eV]
M/Q Dimensionless ratio of ion mass [amu] and ion charge state

We consider other effects as influence coming from the beamline during transport.

- Beam Focusing Lenses
- Dipole Analyzing Magnet
- Other beamline components

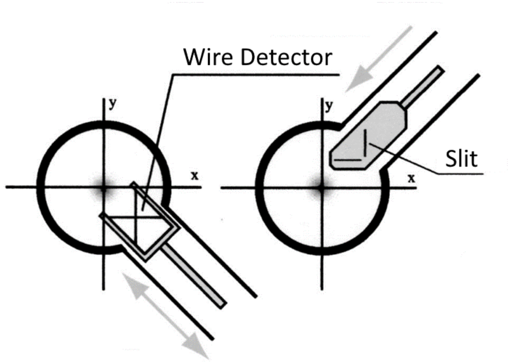
Beam Diagnostics in the R28GHz SC-ECRIS

After the beam extraction and dipole analyzing magnet, the beam diagnostics such as profile monitor (wire type), Faraday cup, and emittance monitoring can be performed.



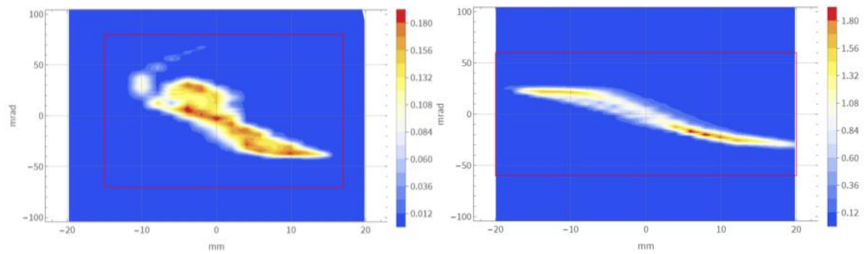
Downstream of the R28GHz ECRIS

Emittance Measurement System (Slit-Wire type)



The emittance monitor is in the beam diagnostics chamber and is a slit-wire type measurement.

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



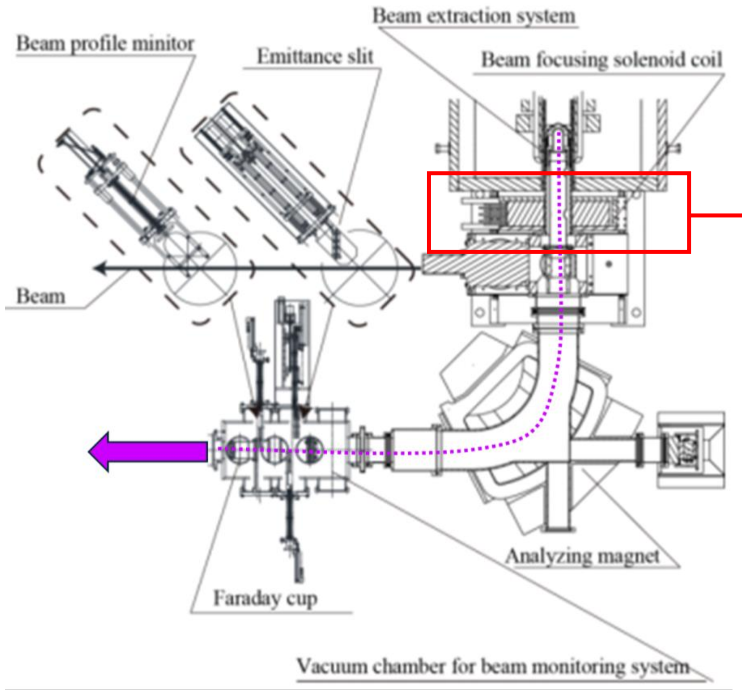
$$\varepsilon_{x-rms} = \sqrt{(\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2)}$$
$$\varepsilon_{y-rms} = \sqrt{(\langle y^2\rangle\langle y'^2\rangle - \langle yy'\rangle^2)}$$

Using movable slits, and wire collectors, the x and y rms emittance are measured obtained.

Beam Emittance of Uranium (U^{35+})

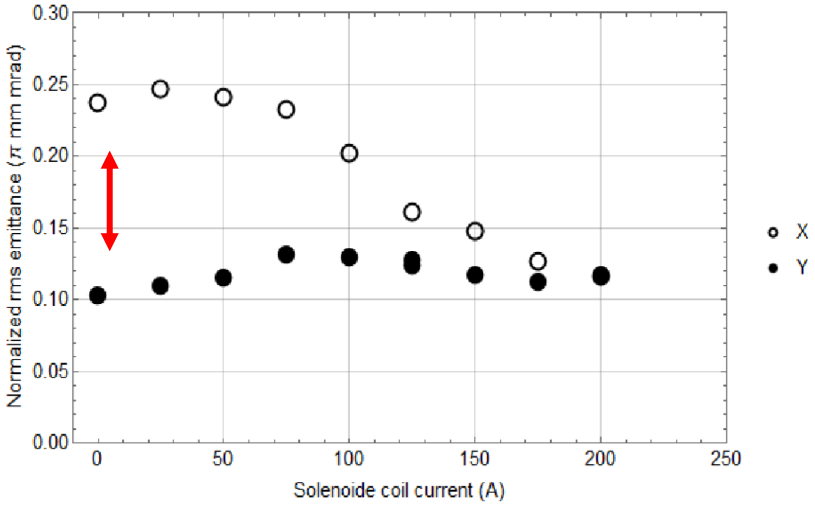
Focusing lens (Solenoid Coil)

After the beam extraction, the beam is focused using a solenoid coil before passing through the dipole analyzing magnet to select the ion charge state.



Y. Higurashi, et. al., 2016 Proc. of ECRIS2016 (Busan) MOBO04

RMS Emittance and Focusing Solenoid Current



In previous studies*, emittance size of the generated beam can be reduced by increasing the focusing solenoid current.

Analyzing the beam emittances, it is important to distinguish the growth factors

$$\varepsilon^2_{meas} = \varepsilon^2_{ECRIS} + \varepsilon^2_{Space-Charge} + \boxed{\varepsilon^2_{other\ effects}}$$

In this case, beam aberration along the beamline can be the cause and the x-emittance should be carefully considered.

This suggests minimal aberration for y-emittance and this can be used to deduce the ε_{ECRIS} and $\varepsilon_{Space\text{-}charge}$

Beam Emittance Growth Study

From the measured beam emittance, if we can assume minimal beam aberration, the major influence would be from the ECRIS and space-charge

$$\varepsilon_{meas}^2 = \varepsilon_{ECRIS}^2 + \varepsilon_{Space-Charge}^2 \cancel{+ \varepsilon_{other\ effects}^2}$$

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

The beam emittance defined by the ECRIS are mainly influenced by:

- Ion Temperature

  *for highly charged ions, this effect is assumed to be minimal.

- Magnetic Field

There have been many ongoing studies on space charge effects and the degree of compensation.

Many model calculations for space charge induced beam emittance growth have already been studied numerically and experimentally where,

The beam emittance was found to be proportional to the total beam current.

$$Total\ beam\ current \propto Beam\ Emittance$$

An example of these model calculations is Y. Batygin's equation on a space charge induced beam emittance

ε_{eff} is the normalized rms beam emittance
K is a constant parameter for the beam shape
z is the drift distance
I is the beam current
I_c is defined as $4\pi\epsilon_0 mc^3/q$.

$$\varepsilon_{eff} = \sqrt{\varepsilon^2 + K\left(\frac{I\,z}{I_c(\beta\gamma)^3}\right)^2}$$

This growth is a function of the beam current.

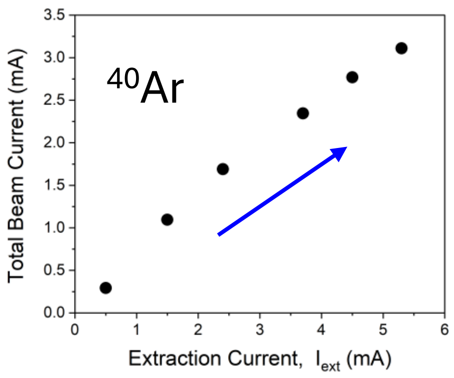
One of our assumptions for the space-charge effect is the correlation to the total beam current.

Y.Batygin, NIM A 772, 93(2015)
D. Leitner, et. al., JINST 6 P07010 (2011)

Beam Emittance of Uranium (U^{35+})

Effect of the Extraction Current

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



$$I_{TOT} = \sum_{q}^{n} I_q \quad \sim \quad I_{EXT}$$

The proportionality of I_{ext} to the total beam current was observed, we investigate further to find a correlation to beam emittance.

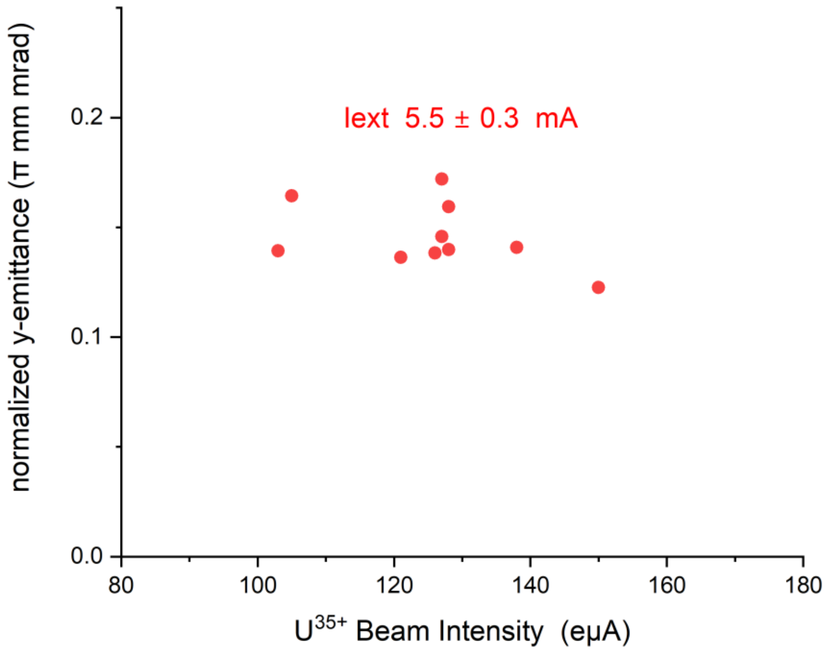
We aim to have use a semi-empirical method to extract information (about space charge effects) from the relation of the extraction current I_{ext} and the nrms beam emittance.

The fixed extraction current condition suggests a constant total beam current which results in low variation in beam emittance, even over 100 ~ 150 eμA

nrms y – emittance measurement and Beam Intensity of U^{35+}

Notes on the ECR Parameters:

- Same magnetic field configuration(B_{min} ,B_{ext} ,...)
- Microwave Power was at 3 – 4 kW



The growth in emittance size is more influenced by the extraction current than U^{35+} ion beam intensity.

Beam Emittance of Uranium (U^{35+})

Effect of the Extraction Current

Having observed the influence of I_{ext} to the beam emittance, It was found that emittance size become much larger for higher extraction current.

If the total current (as indicated by I_{ext}) is reduced, the beam emittance become smaller.

Based on our assumptions for the measured beam emittance,

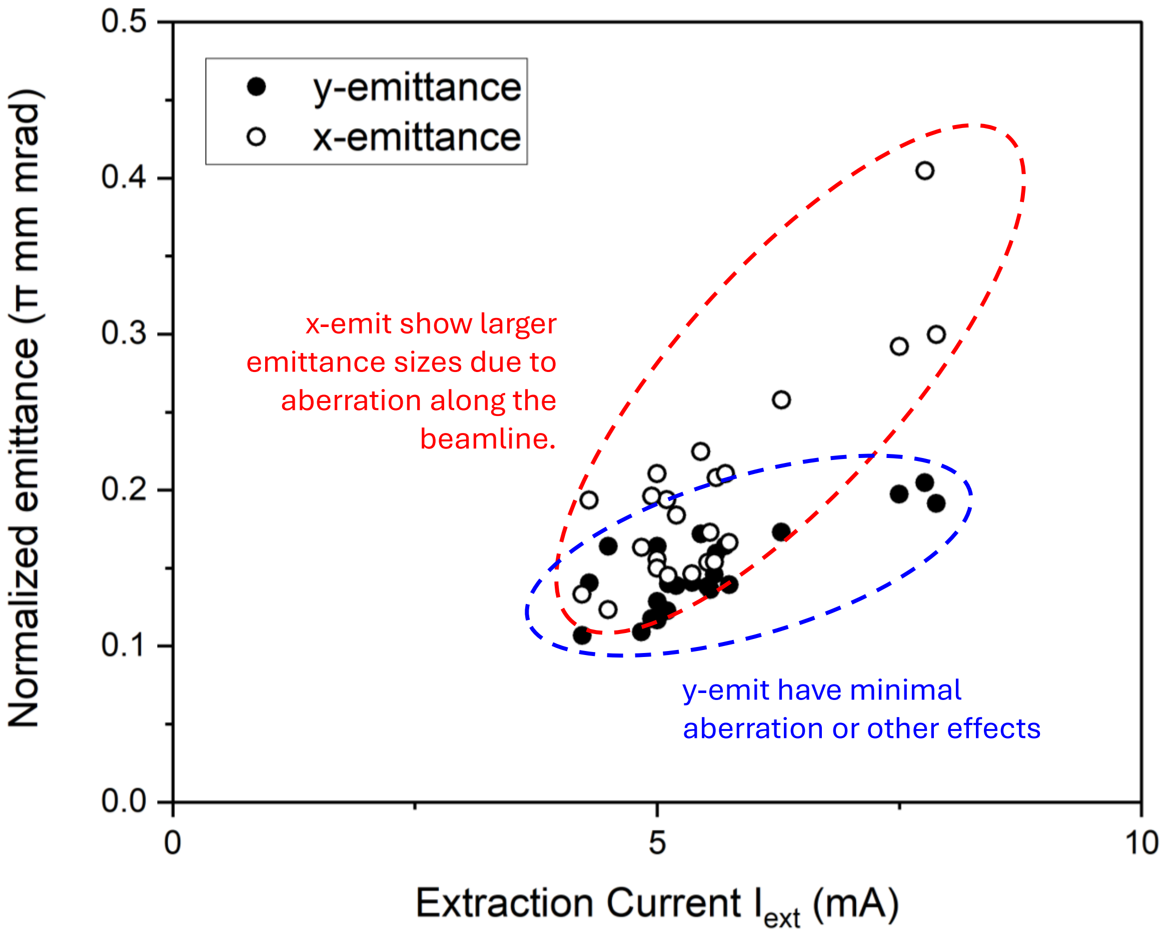
$$\varepsilon_{meas} = \sqrt{\varepsilon_{ECRIS}^2 + \varepsilon_{Space-Charge}^2}$$

and with $\varepsilon_{space-charge} \propto I_{\text{TOTAL}}$, we to estimate the total beam current with the extraction current so that,

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

where ε_0 is an initial emittance

$then\ if\ Iext \sim 0$ then we can assume that $\varepsilon_{meas} = \varepsilon_0$



From here, it can be possible to estimate the emittance of both the ion source and its growth due to space charge.

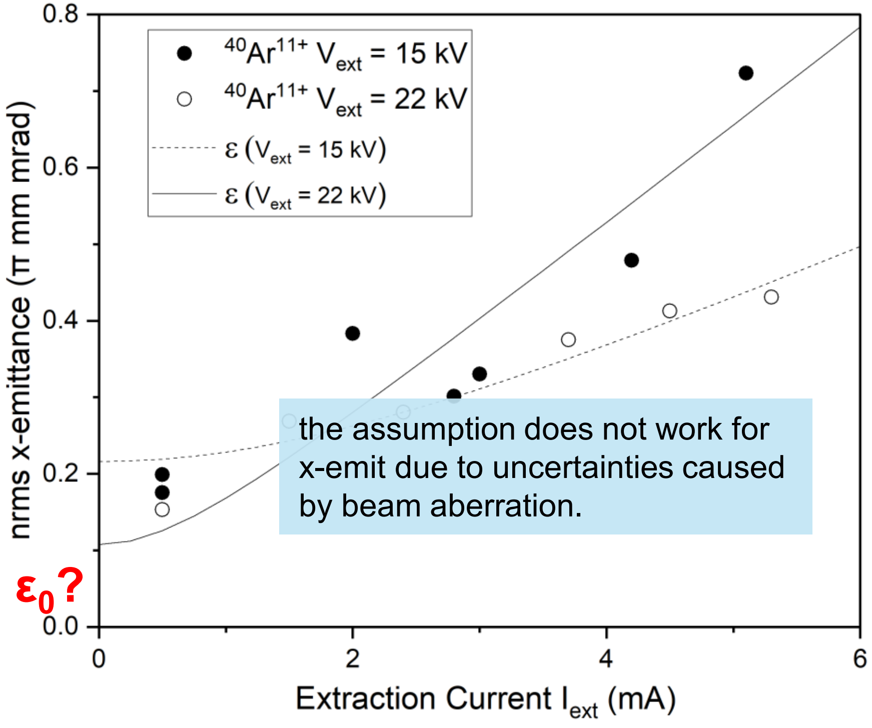
Beam Emittance Growth Study

Velocity Effect

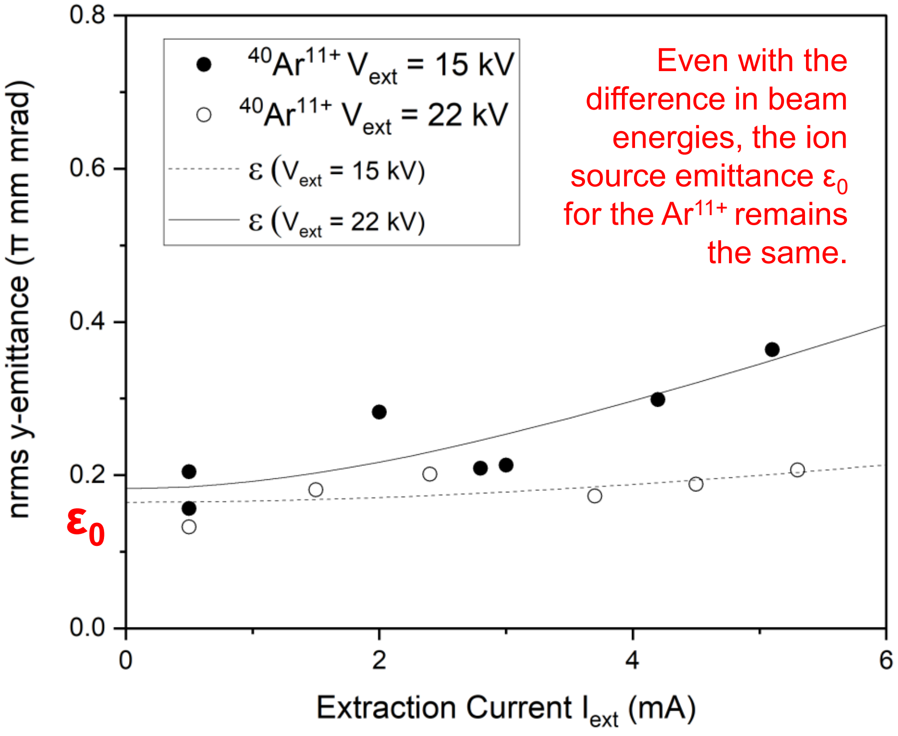
To test this idea, a test beam $^{40}Ar^{11+}$ ion beam was used to investigate the relation of beam emittance to extraction current. Data for the normalized beam emittance was collected with V_{ext} at 15kV and 22kV.

The beam current was fixed at 20μA

nrms x - emittance



nrms y - emittance



By calculating the ε_0 when I_{ext} =0, we evaluated an emittance ε which relates a space charge growth

With different V_{ext} for the Ar^{11+} ion beam yields different beam energies, we can observe the **velocity effect** on the emittance growth.

This offers a useful method to estimate both the **ion source emittance** and **space charge growth.**

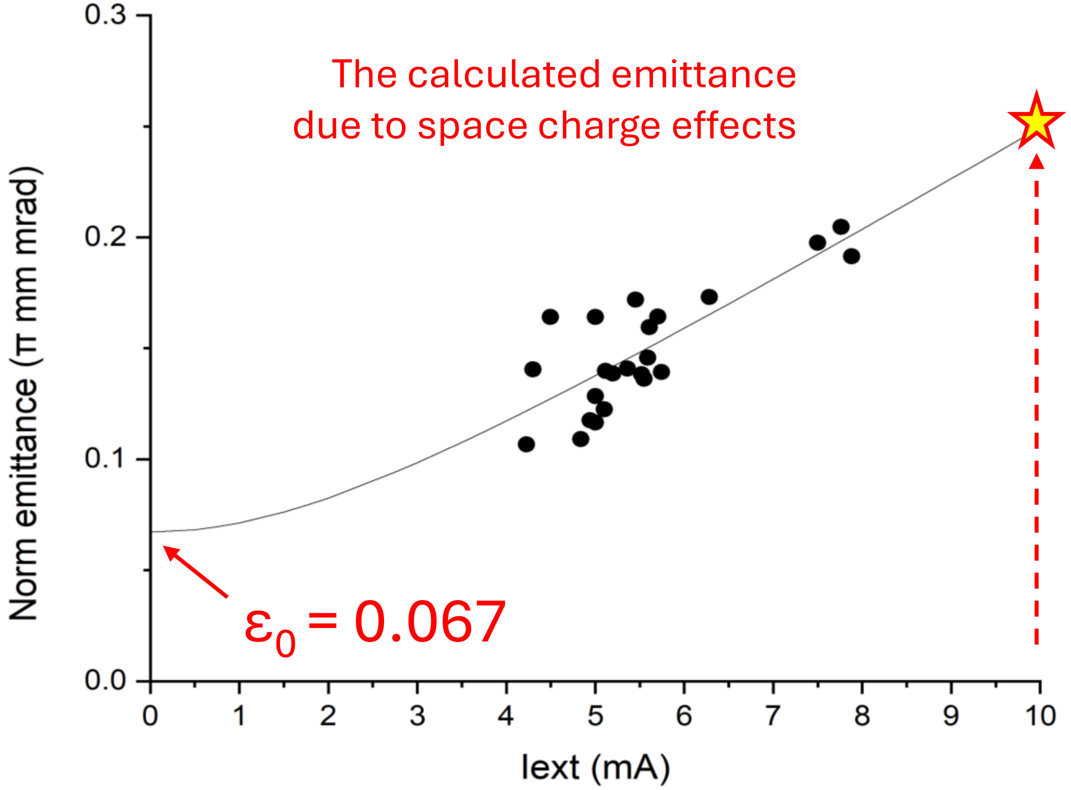
G.Q. Saquilayan, et. al., J. Phys. Conf. Ser. 2743 012081 2024

Measurement of Uranium (U^{35+}) Beam Emittance

Emittance Growth by Space-Charge

Coming back to the beam emittance measurements of the uranium U^{35+} beam, we used the same method to estimate an initial beam emittance and the growth due to space charge effects.

nrms y – emittance for U^{35+}



We have estimated the initial emittance to be $\varepsilon_0 \sim 0.067$, and a growth tendency was evaluated. This allows the estimation of the 10mA extraction current beam emittance to reach up to 0.25 π mm mrad.

Based on the results; to minimize the emittance growth due to space charge,

- **low total beam current condition** — We need to properly optimize the ECR conditions systematically (microwave power, consumption rate, magnetic fields, etc)
- **space charge compensation** — For even higher beam intensity, space charge effects will be larger so compensation should be considered

Although low total beam current may be difficult to achieve high beam intensity, an optimization map for beam intensity and space chage compensation mechanisms are being considered.

Beam Emittance Measurements

Measured Initial Emittance and the Magnetic Field Emittance

From the estimated values of an initial beam emittance ε_0, we make a comparison with the magnetic field emittance.

Magnetic Field Emittance:

$$\varepsilon_{magnet} = 0.032 r^2 B_0 \frac{1}{M/q}$$

r radius of extraction hole
B_0 Axial magnetic field strength
M/q Mass-Charge ratio

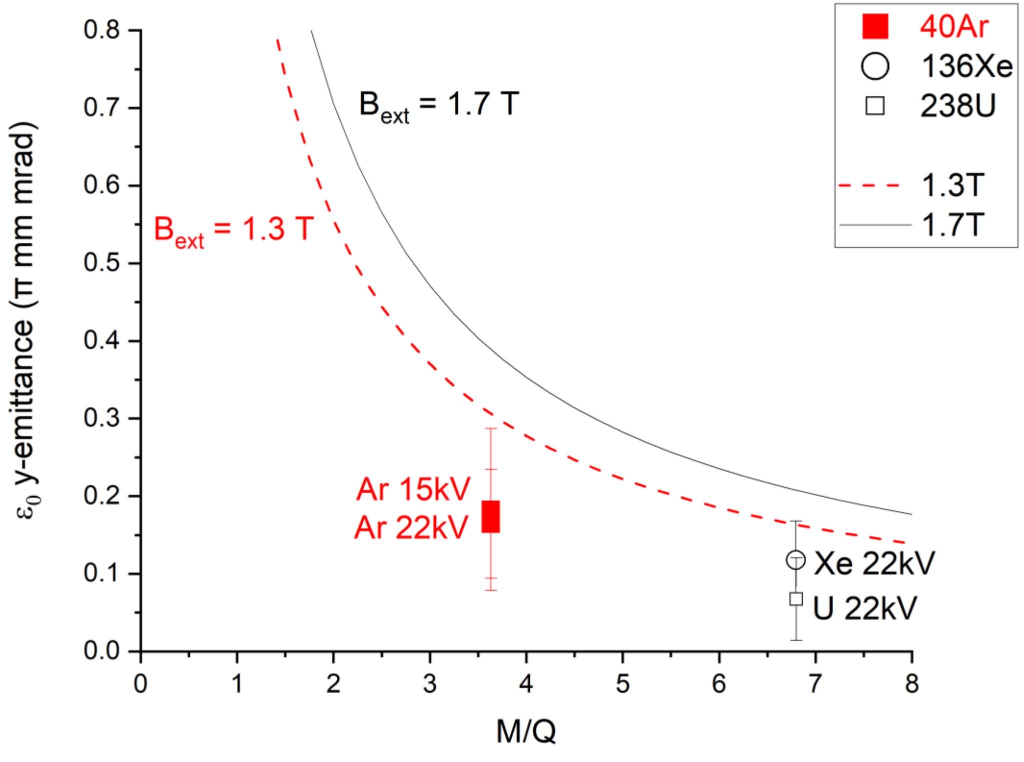
This magnetic emittance is caused by the angular momentum of ions in the extraction magnetic field

Other ion species ($^{40}Ar^{11+}$, $^{51}V^{13+}$, $^{136}Xe^{20+}$ and $^{238}U^{35+}$) were calculated for the ion source beam emittance ε_0 .

- Compared to the magnetic field emittance, the experimentally obtained emittances were found.

  *This have also been observed in other laboratories

- Heavier ion species are observed to have lower beam emittances.



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

Beam Emittance Measurements

Initial Beam Emittance and the Magnetic Field Emittance

For the case of uranium and xenon having the same M/Q, there is a small difference between the obtained beam emittances.

Magnetic Field Emittance:

$$\varepsilon_{magnet} = 0.032 r^2 B_0 \frac{1}{M/q}$$

r radius of extraction hole
B_0 Axial magnetic field strength
M/q Mass-Charge ratio

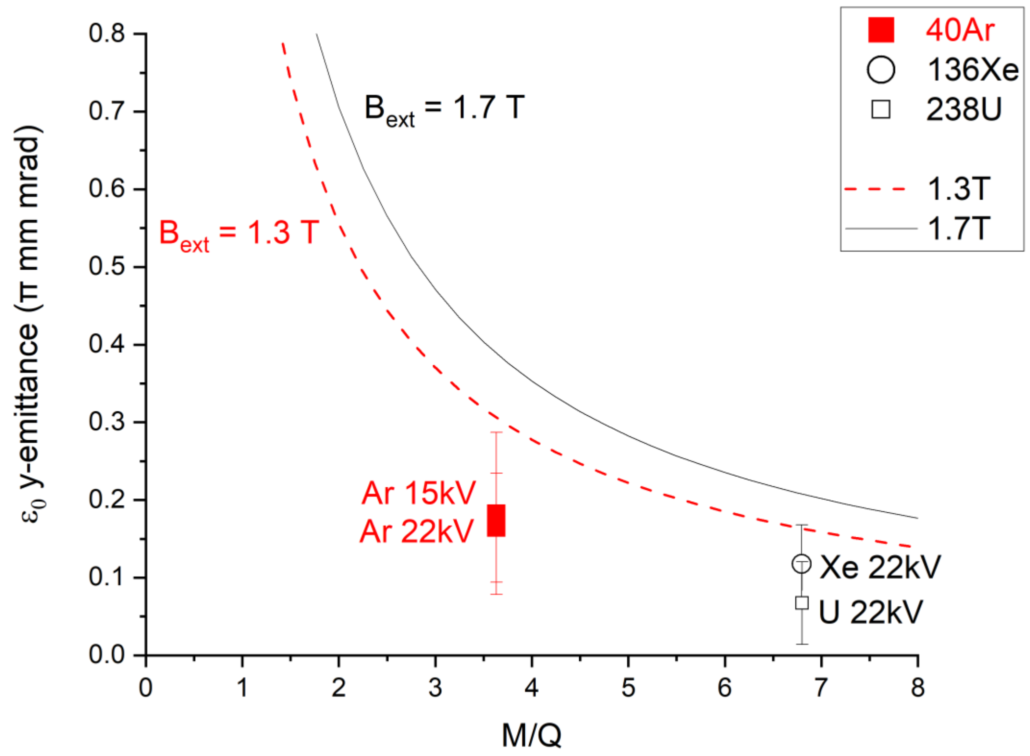
This emittance equation assumes a uniform distribution with r defined as the beam size

~ extraction aperture
Aperture radius: 5 mm

Ion	V_{ext}(kV)	M/Q	ε_0
$^{136}Xe^{20+}$	22	6.8	0.13
$^{238}U^{35+}$	22	6.8	0.06

r Effective Beam size
4.0
2.7

Effective beam size r, is evaluated from ε_0 having the assumption of I_{ext}=0



Since the ECRIS extracts multiple ion charge species, the assumption of a uniform beam distribution may lead to some over estimation or difference with the actual beam size.

Beam Emittance Growth

Beam Emittance of Uranium (U^{35+}) and Xenon (Xe^{20+})

The measured nrms emittances of xenon and uranium are shown over the range of extraction current.

From the obtained ε_0, the emittance due to space charge for beams with the same M/Q shows similar growth.

Ion	V_{ext}(kV)	M/Q	ε_0	K
$^{136}Xe^{20+}$	22	6.8	0.13	**6.0E-4**
$^{238}U^{35+}$	22	6.8	0.06	**5.0E-4**

*derived from magnetic field emittance

r Beam size
4.0
2.7

The K parameter is evaluated from ε_0.

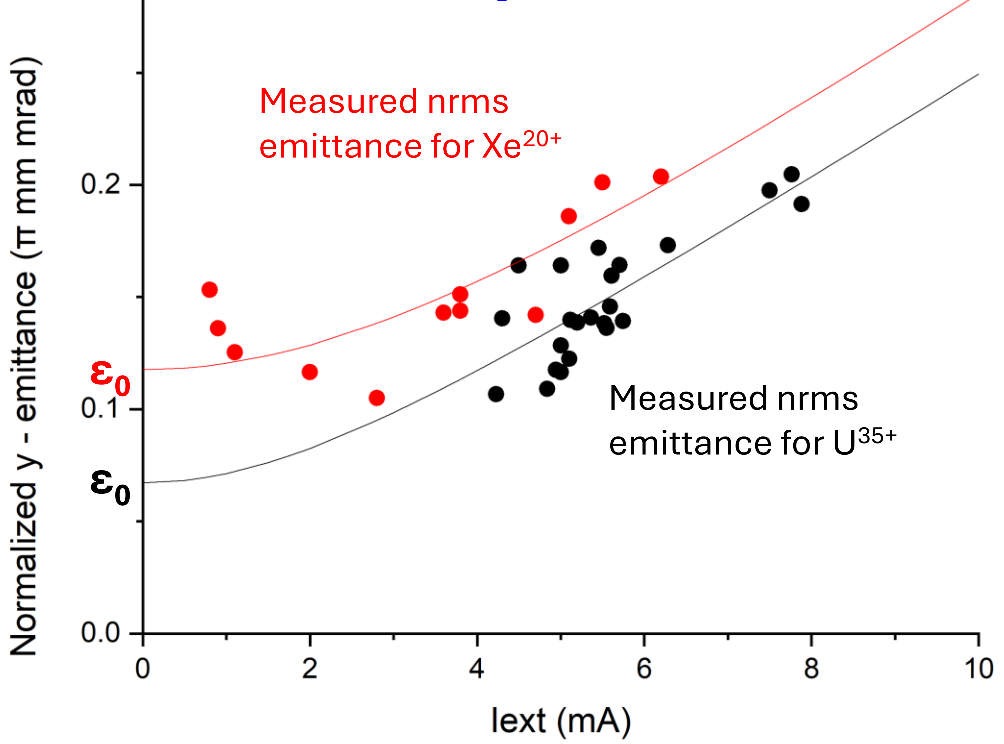
$$\varepsilon_{meas} = \sqrt{\varepsilon_0^2 + \underline{K(I_{ext})^2}}$$

K parameter relates to the initial beam distribution.

relating to space charge

Xenon beam shows small difference in K values with the uranium beam.

From experimental results, we can observe that the xenon beam emittance values are a little larger than the uranium beam.



Additional experiments are needed to confirm the difference in space charge between the two ion beams.

Beam Emittance Growth

Consider the conditions for ^{40}Ar, ^{136}Xe and ^{238}U beams where the ion source and space charge emittance are estimated from,

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

For the case of Ar^{11+}, the different extraction voltages imply different velocity conditions but ion source emittance ε_0 is almost the same.

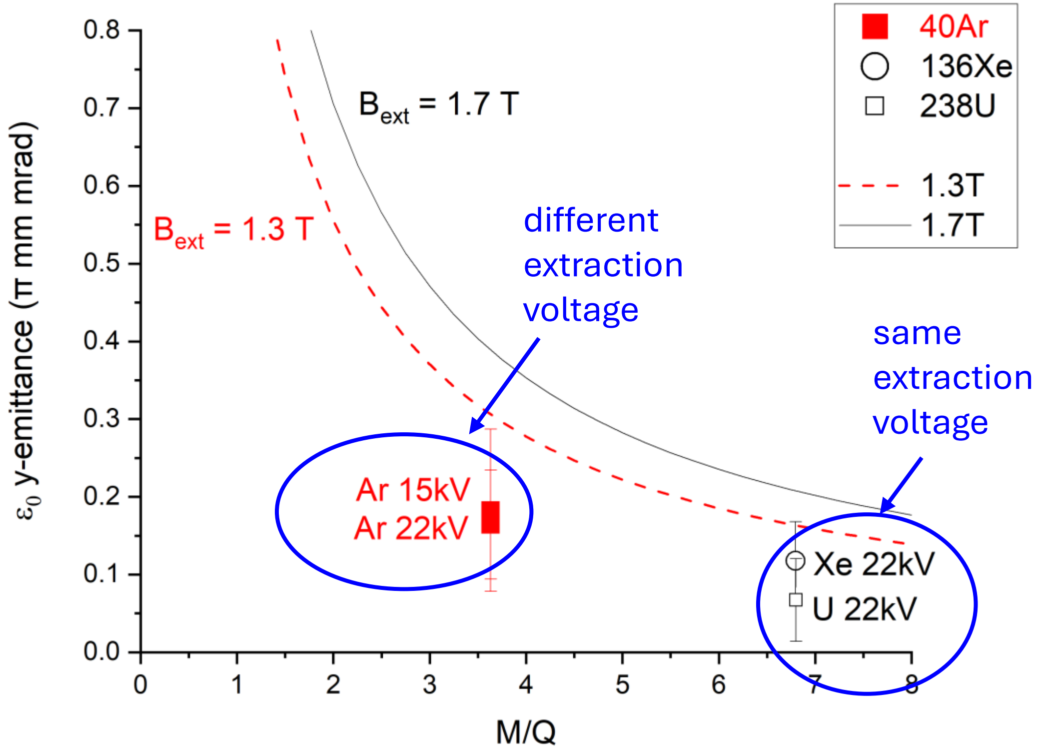
Ion	V_{ext}(kV)	M/Q	ε_0	K
$^{40}Ar^{11+}$	15	3.6	0.18	3.43E-3
$^{40}Ar^{11+}$	22	3.6	0.16	0.51E-3

The difference in K parameter shows the velocity effect with higher beam energy having lower space charge effects.

For U^{35+} and Xe^{20+} having the same M/Q and the same extraction voltage, observe differences in the initial beam emittance.

Ion	V_{ext}(kV)	M/Q	ε_0	K
$^{136}Xe^{20+}$	22	6.8	0.13	6.7E-4
$^{238}U^{35+}$	22	6.8	0.06	5.7E-4

There are small variations in the space charge growth as indicated by the evaluated K parameter.



Summary

Development of R28GHz SC-ECRIS towards intense uranium ion beam production, with a beam requirement of ~300eμA for U^{35+}, is currently ongoing. As progress moves towards more intense beams, the study on beam emittance growth aims to provide a semi-empirical method to estimate the beam emittance for the target beam requirements.

- Factors that influence the beam emittance growth are investigated.

$$\varepsilon^2_{meas} = \varepsilon^2_{ECRIS} + \varepsilon^2_{Space-Charge} + \varepsilon^2_{other\ effects}$$

- The extraction current I_{ext} was observed to greatly influence the beam emittance, this tendency was used to investigate growth factors that relates to the ion source and space charge effects. Assumptions were made which gives a simple relation for the measured emittance and extraction current:

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

- The beam emittance for uranium U^{35+} beam was analyzed and a value for an initial beam emittance (emittance defined by the ion source) was found to be about 0.067 π mm mrad. This allowed the estimation of a **beam emittance reaching 0.24 π mm mrad for the extraction current 10mA**.

Summary

- From the semi-empirical method aiming to estimate the emittance growth, a value that corresponds to the influence of the ion source was obtained. Comparison to the magnetic field emittance shows lower values from experimental measurements. This may be due to assumptions based on a uniform beam radius and further investigation on the effective beam size for single ion species is necessary.

- Beam emittance growth relating to a space charge effect was evaluated through analyzing the effect of the extraction current. This emittance growth and relation to different beam conditions such as a velocity effect and beams with same M/Q were investigated. Experiments to investigate the influence of space charge effects are still ongoing.

Thank you for your attention