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Study of ion beam extraction from an ECRIS:

Beam transverse coupling and high-order compensation

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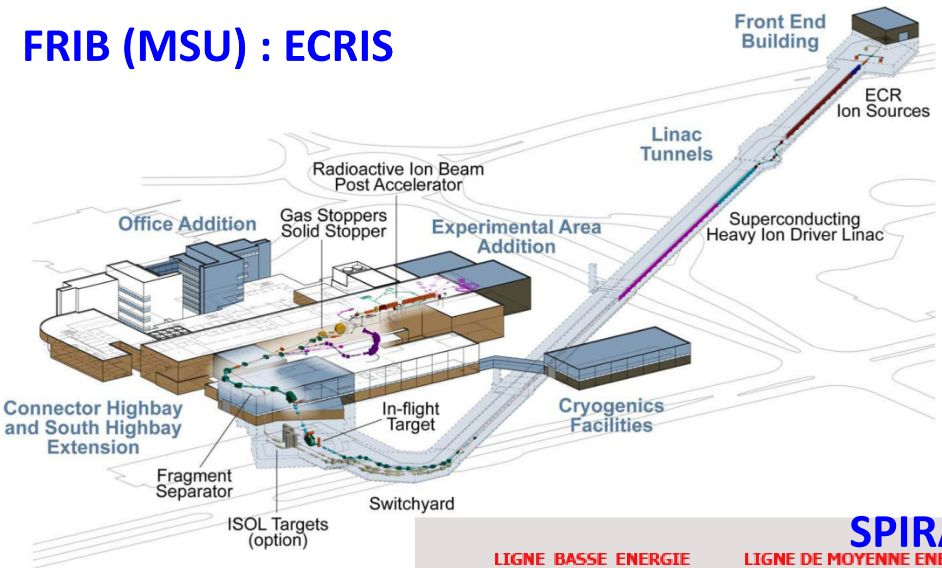
Outline

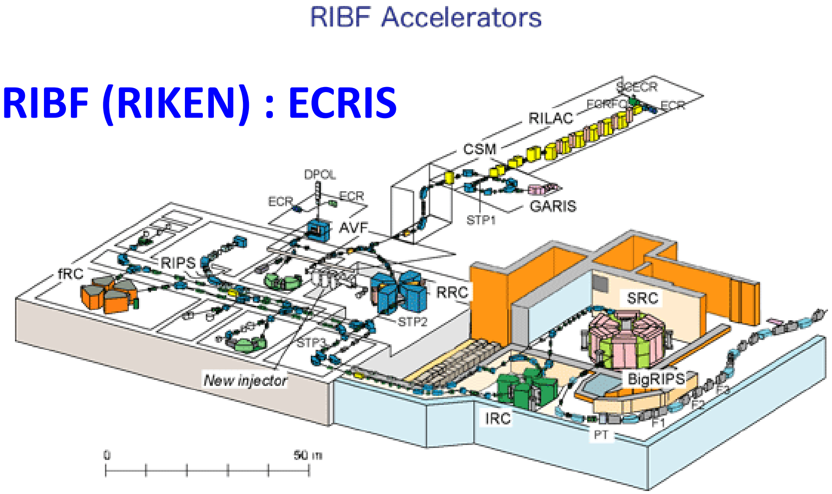
- Backgrounds
- Transverse coupling
  - Coupling induced during beam extraction
  - Coupling effect of a solenoid
- High-order compensation
  - High-order magnetic fields
  - High-order compensation for SECRAL and preliminary results
- An improved design of Q/A selector
- Summary and outlook

Backgrounds

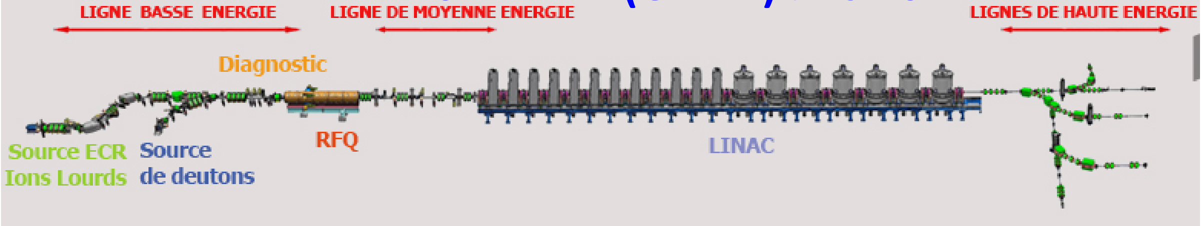
FRIB (MSU) : ECRIS



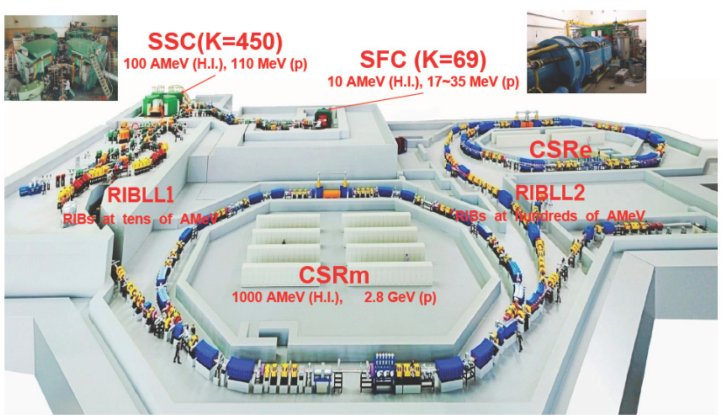
RIBF (RIKEN) : ECRIS



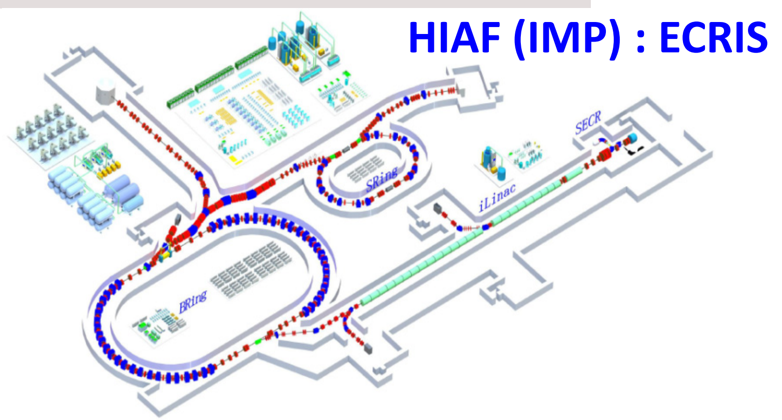
SPIRAL-2 (GANIL) : ECRIS



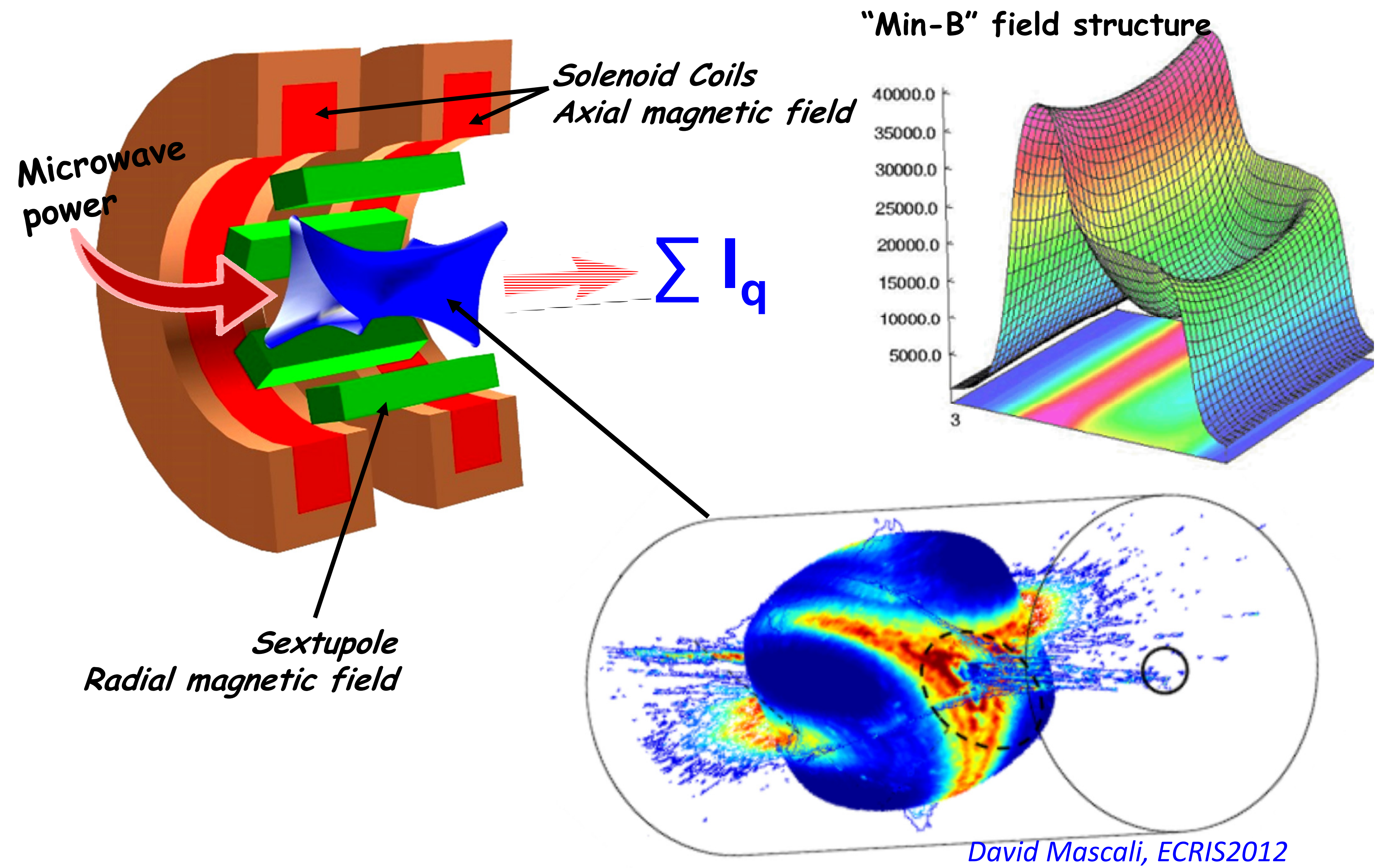
HIRFL (IMP) : ECRIS



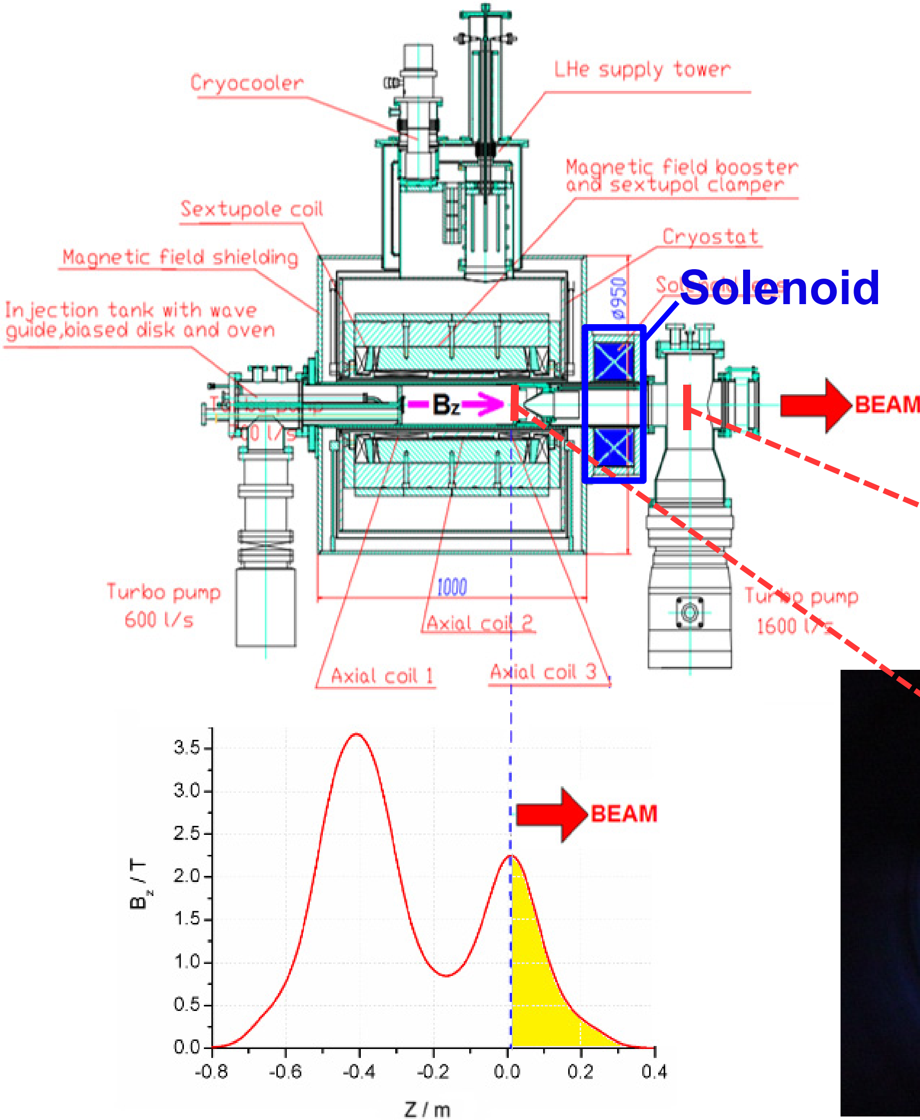
HIAF (IMP) : ECRIS



ECR ion source



Beam properties from ECR ion sources



SECRAL schematic view and the axial magnetic field distribution.

- **Semi-solenoid magnetic field adds an azimuthal momentum to the beam.**

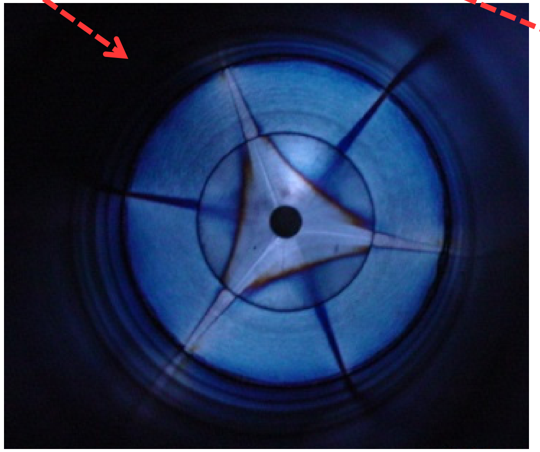
→ Transverse emittance blowup and coupling

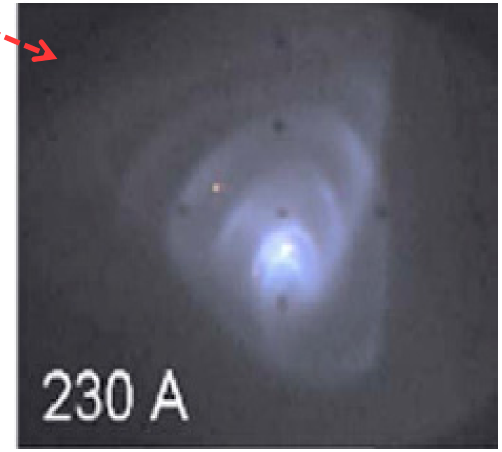
- **Asymmetric plasma distribution at extraction.**

→ Inhomogeneous ion density distribution across the extraction aperture

- **Sextupole field in ion source**

→Triangular beam shape





Predicted emittance of ion beams from ECR

Thermal contribution:

$$\varepsilon_{ther} = 0.016 \cdot R_{extr} \cdot \sqrt{\frac{kT_i}{M/Q}}$$

Magnetic contribution:

$$\varepsilon_{mag} = 0.032 \cdot (R_{extr})^2 \cdot (\frac{B_{extr}}{M/Q})$$

For most ECR ion sources:

$$\varepsilon_{mag} >> \varepsilon_{ther}$$

Asymmetric beam and transverse coupling will make the beam emittance worse!

Projection RMS and eigen-emittances

Beam second moment matrix:

$$C=\begin{bmatrix} <xx> & <xx'> & <xy> & <xy'> \\ <x'x> & <x'x'> & <x'y> & <x'y'> \\ <yx> & <yx'> & <yy> & <yy'> \\ <y'x> & <y'x'> & <y'y> & <y'y'> \end{bmatrix}$$

Projection RMS emittances:

$$\varepsilon_x=\sqrt{<xx><x'x'>-<xx'>^2}$$

$$\varepsilon_y=\sqrt{<yy><y'y'>-<yy'>^2}$$

4D-emittance:

$$\varepsilon_{4d}=\sqrt{\det(C)}$$

Eigen-emittances:

$$\varepsilon_1=\frac{1}{2}\sqrt{-tr[(CJ)^2]+\sqrt{tr^2[(CJ)^2]-16\det(C)}}$$

$$\varepsilon_2=\frac{1}{2}\sqrt{-tr[(CJ)^2]-\sqrt{tr^2[(CJ)^2]-16\det(C)}}$$

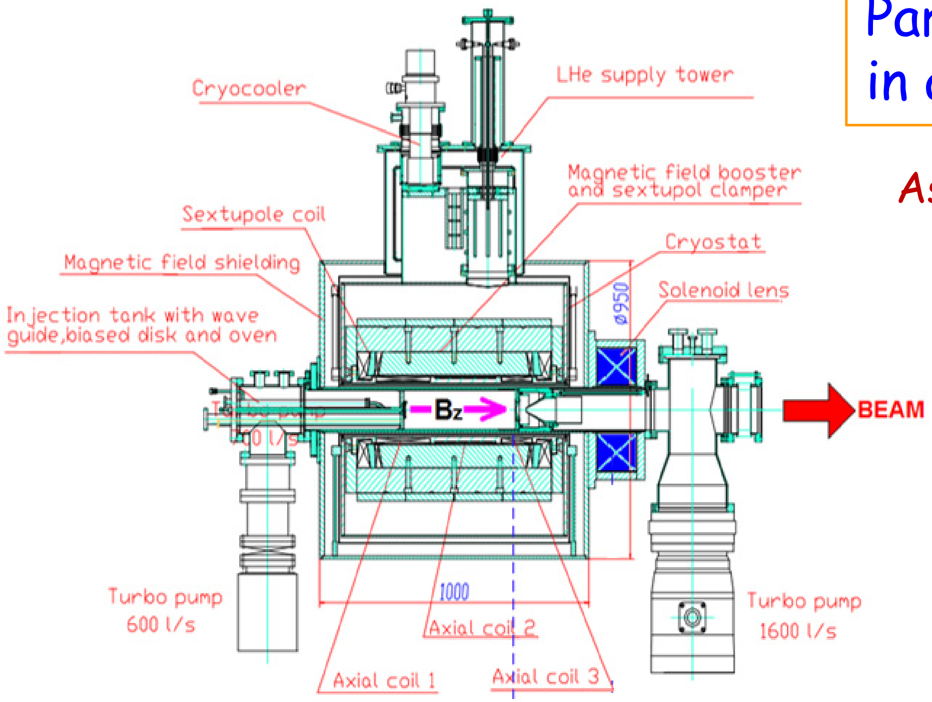
$$J=\begin{bmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{bmatrix}$$

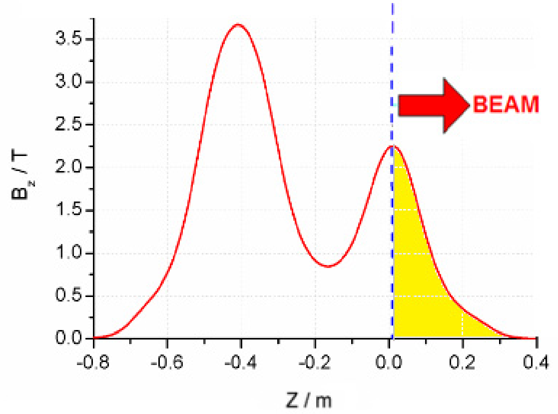
Coupling between horizontal and vertical planes results in:

$$\varepsilon_{4d}=\varepsilon_1\cdot\varepsilon_2\le\varepsilon_x\cdot\varepsilon_y$$

equality just for zero inter-plane coupling moments.

Coupling induced during beam extraction





Particles are extracted and accelerated in a semi-solenoid magnetic field.

Assuming a very short solenoid:

$$R_{out} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & -\kappa & 0 \\ 0 & 0 & 1 & 0 \\ \kappa & 0 & 0 & 1 \end{bmatrix} \quad \kappa = \frac{B_{extr}}{2(B\rho)} \quad C_0 = \begin{bmatrix} \varepsilon\beta & 0 & 0 & 0 \\ 0 & \frac{\varepsilon}{\beta} & 0 & 0 \\ 0 & 0 & \varepsilon\beta & 0 \\ 0 & 0 & 0 & \frac{\varepsilon}{\beta} \end{bmatrix}$$

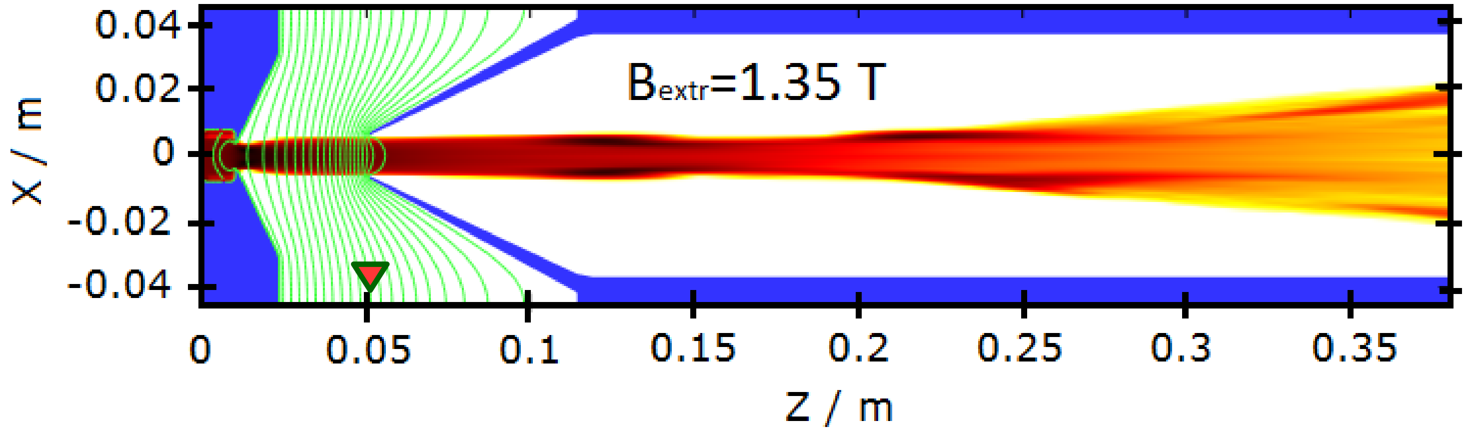
$$C_1 = R_{out} C_0 R_{out}^T = \begin{bmatrix} \varepsilon\beta & 0 & 0 & \kappa\varepsilon\beta \\ 0 & \frac{\varepsilon}{\beta} + \kappa^2\varepsilon\beta & -\kappa\varepsilon\beta & 0 \\ 0 & -k\varepsilon\beta & \varepsilon\beta & 0 \\ \kappa\varepsilon\beta & 0 & 0 & \frac{\varepsilon}{\beta} + \kappa^2\varepsilon\beta \end{bmatrix}$$

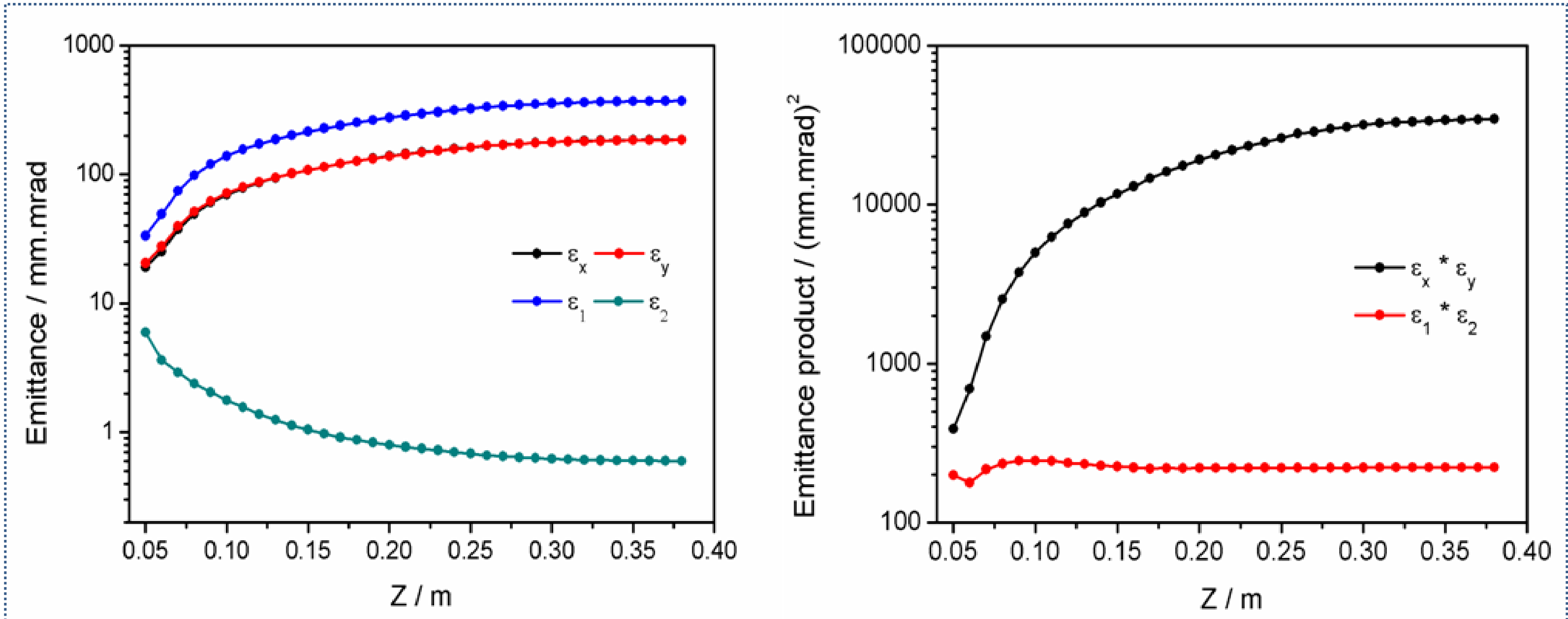
$$\varepsilon_x = \varepsilon_y = \sqrt{\varepsilon\beta\left(\frac{\varepsilon}{\beta} + \kappa^2\varepsilon\beta\right)} \qquad \varepsilon_{1,2} = \varepsilon_x \pm \kappa\varepsilon\beta$$

Ion beam is transversely coupled!

Beam extraction simulation for SECRAL

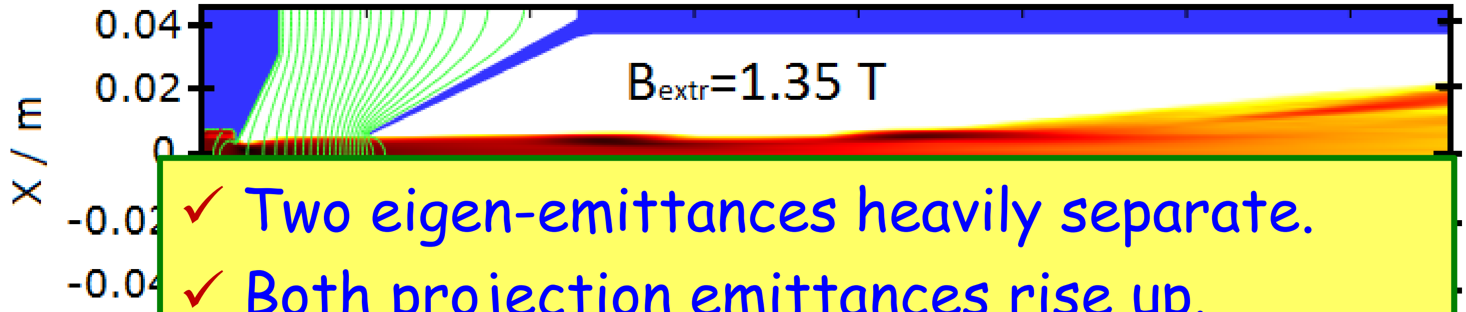
$^{129}Xe^{29+}$, 25 kV, B_{ext}=1.35 T @ **IBsimu** with the magnetic field



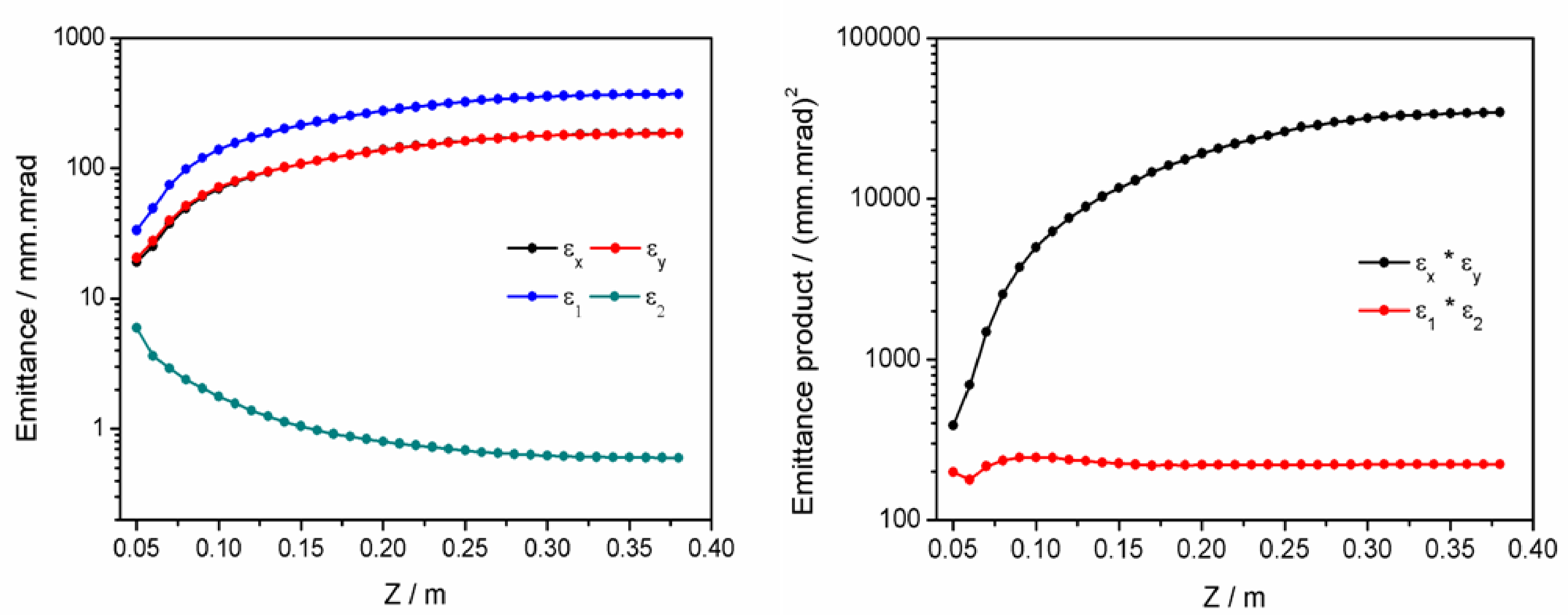


Beam extraction simulation for SECRAL

$^{129}Xe^{29+}$, 25 kV, B_{ext}=1.35 T @ **IBsimu** with the magnetic field

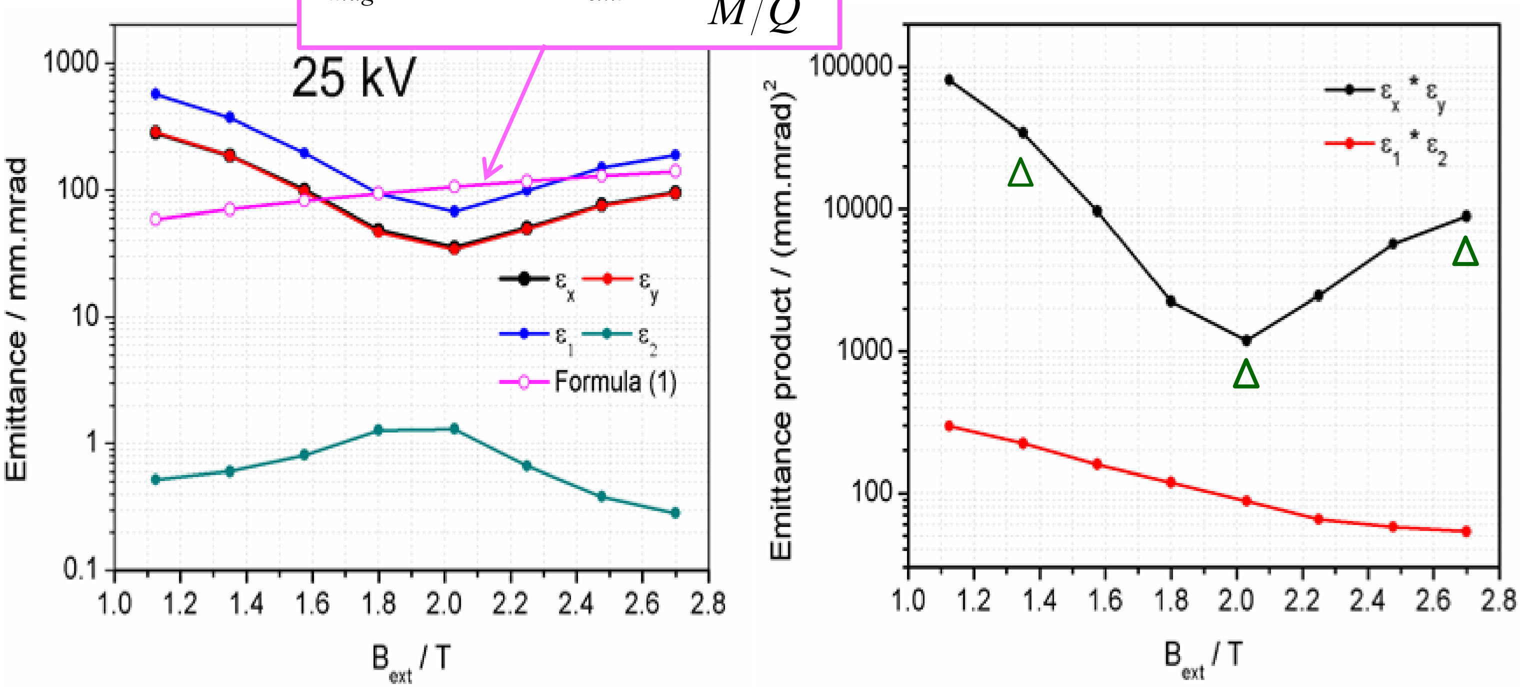


- ✓ Two eigen-emittances heavily separate.
- ✓ Both projection emittances rise up.
- ✓ Constant 4-D emittance ($\varepsilon_1 * \varepsilon_2$).



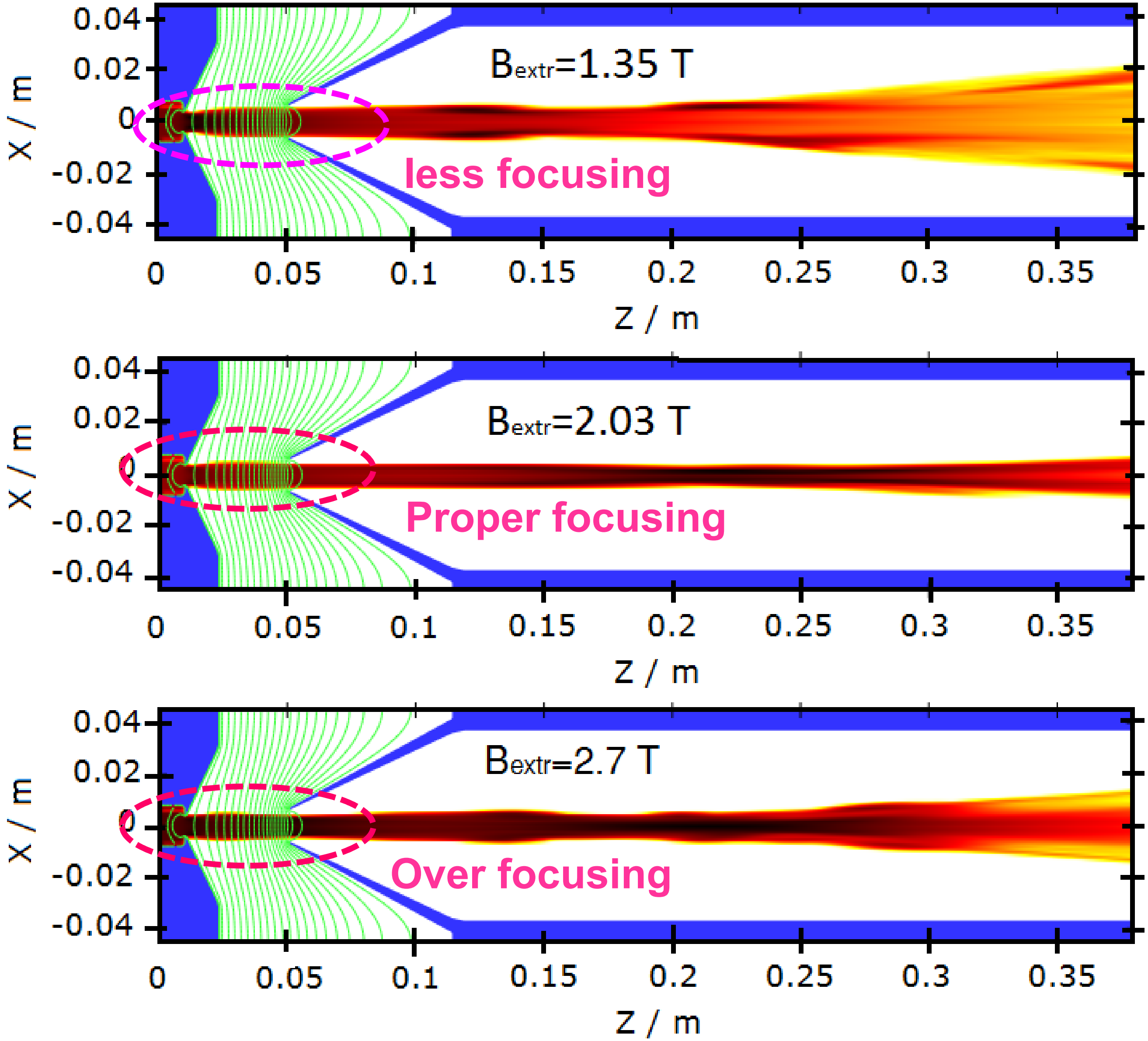
Beam emittances VS B_{ext}

$$\varepsilon_{mag} = 0.032 \cdot (R_{extr})^2 \cdot \left(\frac{B_{extr}}{M/Q}\right)$$



- The projection emittances do not increase with the magnetic field strength proportionally as expected;
- Optimal field (B_{extr}=2.03 T) → The coupling is relatively weak.
  - $\varepsilon_{x,y}$ reaches minimum;
  - the value of $\varepsilon_x * \varepsilon_y$ is closest to $\varepsilon_1 * \varepsilon_2$;
  - the difference between ε_1 and ε_2 is smallest.

B_{ext} effect on beam formation



$$\varepsilon_x = \varepsilon_y = \sqrt{\varepsilon\beta\left(\frac{\varepsilon}{\beta} + \kappa^2 \varepsilon\beta\right)}$$

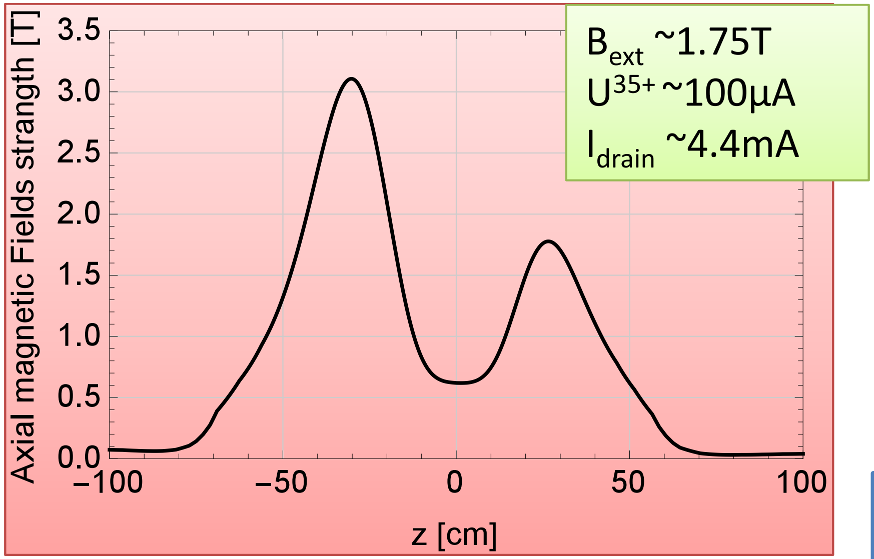
$$\varepsilon_{1,2} = \varepsilon_x \pm \kappa\varepsilon\beta$$

- Magnetic field in the extraction region determine the beam emittances and the transverse coupling by
  - Adding a azimuthal momentum to the beam.
  - Affecting the beam formation .

Beam emittances VS B_{ext}

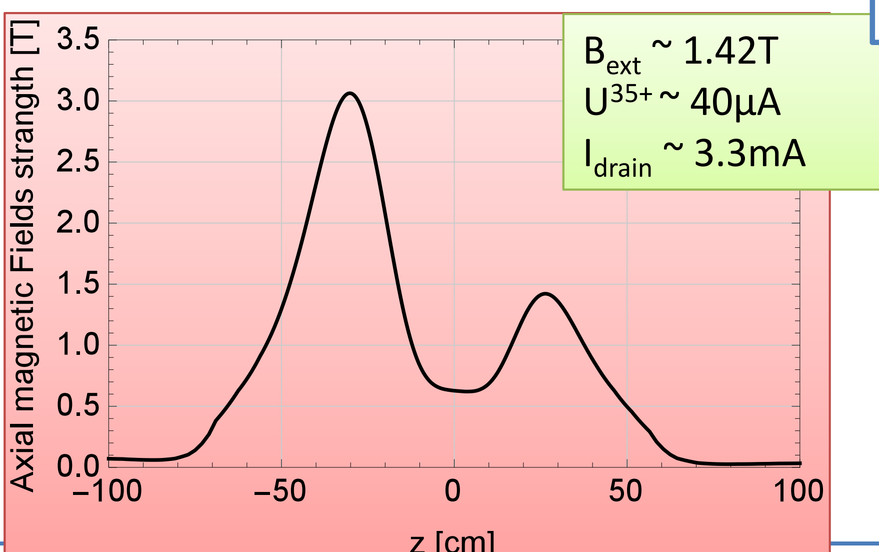
Emittance measurement for RIKEN 28GHz SC-ECRIS

Presented in ICIS'15
by Y. Higurashi from RIKEN



EM Slit measurement		
H	**V**	**4D**
290	**156**	**1567**

The emittance with lower B_{ext} is larger than that with higher B_{ext}.

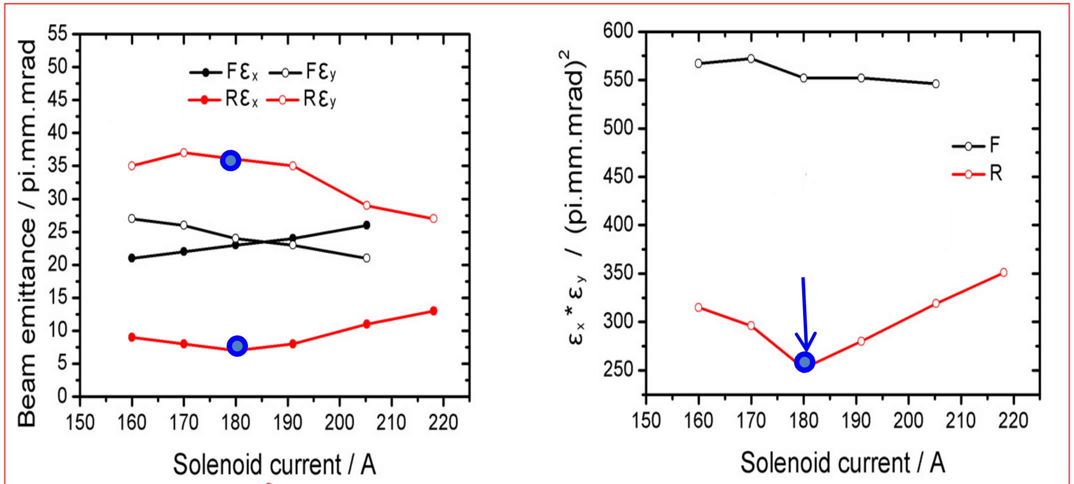


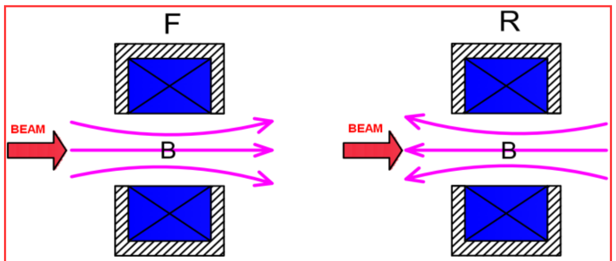
EM Slit measurement		
H	**V**	**4D**
377	**214**	**3476**

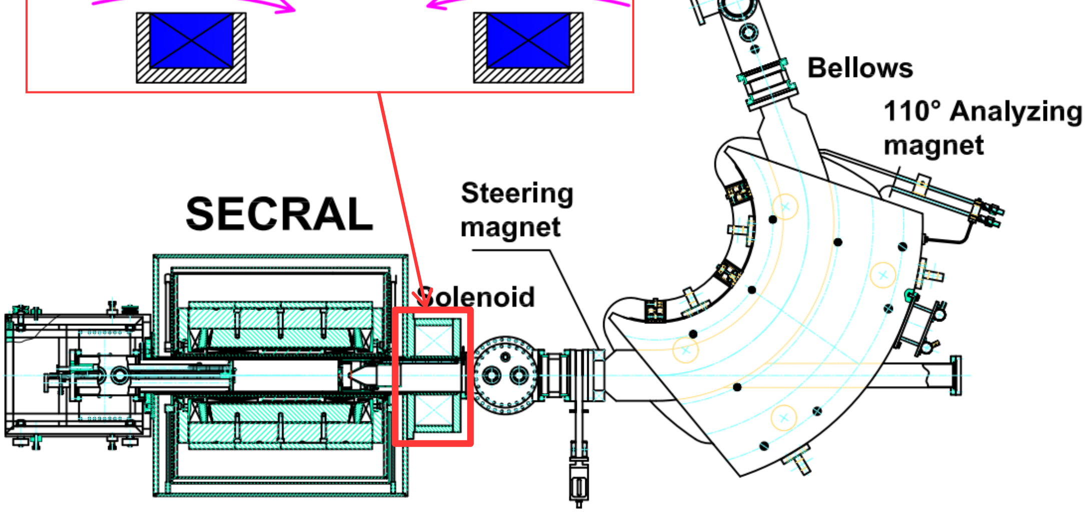
Coupling effect of a solenoid

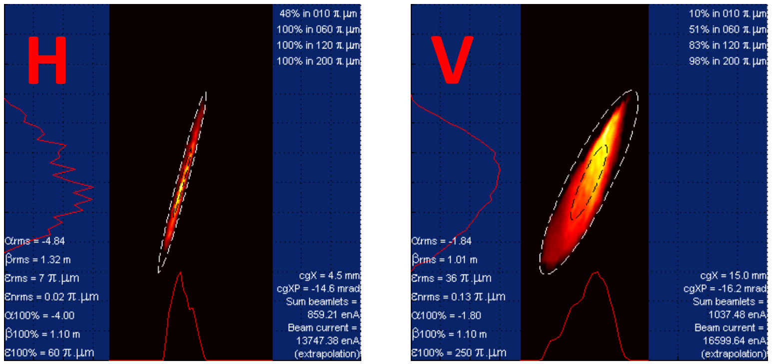
Beam emittance measurement for SECRAL

- Beam: $^{209}Xe^{29+}$;
- Extraction voltage: 25 kV;
- Load current: I_0=0.95 emA;
- Beam current: I_{29+}~19 emA









$I_{solenoid}$=-180A

Transfer matrix of a solenoid

$$R_{sol} = \begin{bmatrix} \cos^2(kz) & \sin(2kz)/2k & \sin(2kz)/2 & \sin^2(kz)/k \\ -k\sin(2kz)/2 & \cos^2(kz) & -k\sin^2(kz) & \sin(2kz)/2 \\ -\sin(2kz)/2 & -\sin^2(kz)/k & \cos^2(kz) & \sin(2kz)/2k \\ k\sin^2(kz) & -\sin(2kz)/2 & -k\sin(2kz)/2 & \cos^2(kz) \end{bmatrix}$$

$$R_{sol} = \begin{bmatrix} \begin{matrix} \cos(kz) & \sin(kz)/k \\ -k\sin(kz) & \cos(kz) \end{matrix} & 0 \\ 0 & \begin{matrix} \cos(kz) & \sin(kz)/k \\ -k\sin(kz) & \cos(kz) \end{matrix} \end{bmatrix} \begin{bmatrix} \cos(kz) & 0 & \sin(kz) & 0 \\ 0 & \cos(kz) & 0 & \sin(kz) \\ -\sin(kz) & 0 & \cos(kz) & 0 \\ 0 & -\sin(kz) & 0) & \cos(kz) \end{bmatrix}$$

Focusing **Rotation**

$$k = \tfrac{1}{2} B_0 / B\rho_s$$

Beam rotation angle in a solenoid: $\Theta = \kappa L_{eff} = \dfrac{B_{max}}{2(B\rho)} L_{eff}$

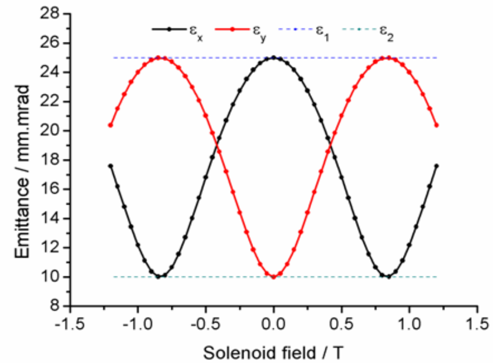
Non-round beam through a solenoid

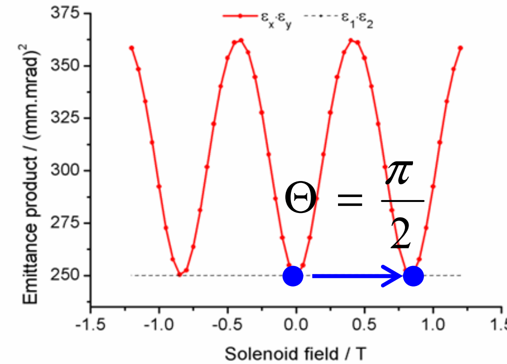
$R_x=R_y$

$\varepsilon_x=25$ mm.mrad

$\varepsilon_y=10$ mm.mrad.

$$C=\begin{bmatrix}10 & 65 & 0 & 0\\ 65 & 485 & 0 & 0\\ 0 & 0 & 10 & 65\\ 0 & 0 & 65 & 432.5\end{bmatrix}$$

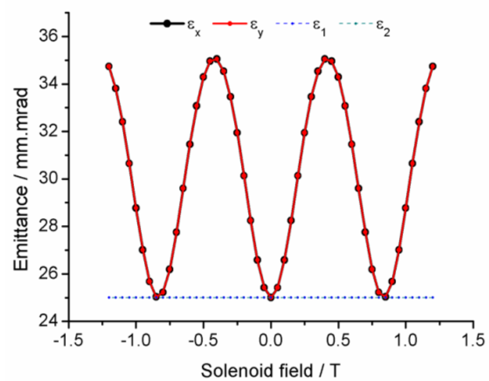


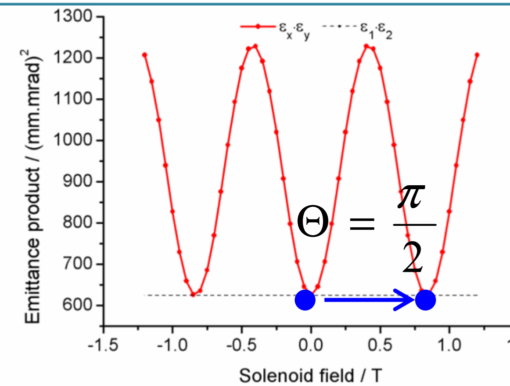


$R_x\neq R_y$

$\varepsilon_x=\varepsilon_y=10$ mm.mrad

$$C=\begin{bmatrix}10 & 65 & 0 & 0\\ 65 & 485 & 0 & 0\\ 0 & 0 & 20 & 65\\ 0 & 0 & 65 & 242.5\end{bmatrix}$$



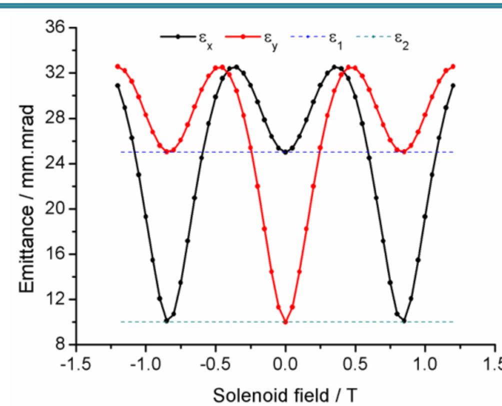


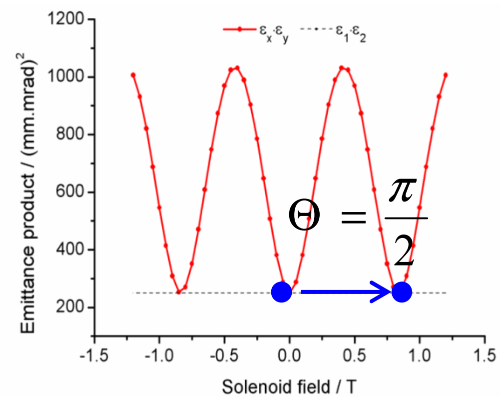
$R_x\neq R_y$

$\varepsilon_x=25$ mm.mrad

$\varepsilon_y=10$ mm.mrad.

$$C=\begin{bmatrix}10 & 65 & 0 & 0\\ 65 & 485 & 0 & 0\\ 0 & 0 & 20 & 65\\ 0 & 0 & 65 & 216.25\end{bmatrix}$$





$B\rho=0.0479$ Tm

$L_{eff}=0.18$ m

Coupling effect of a solenoid

The rotation effect of a solenoid field brings a periodic coupling to a non-round beam.

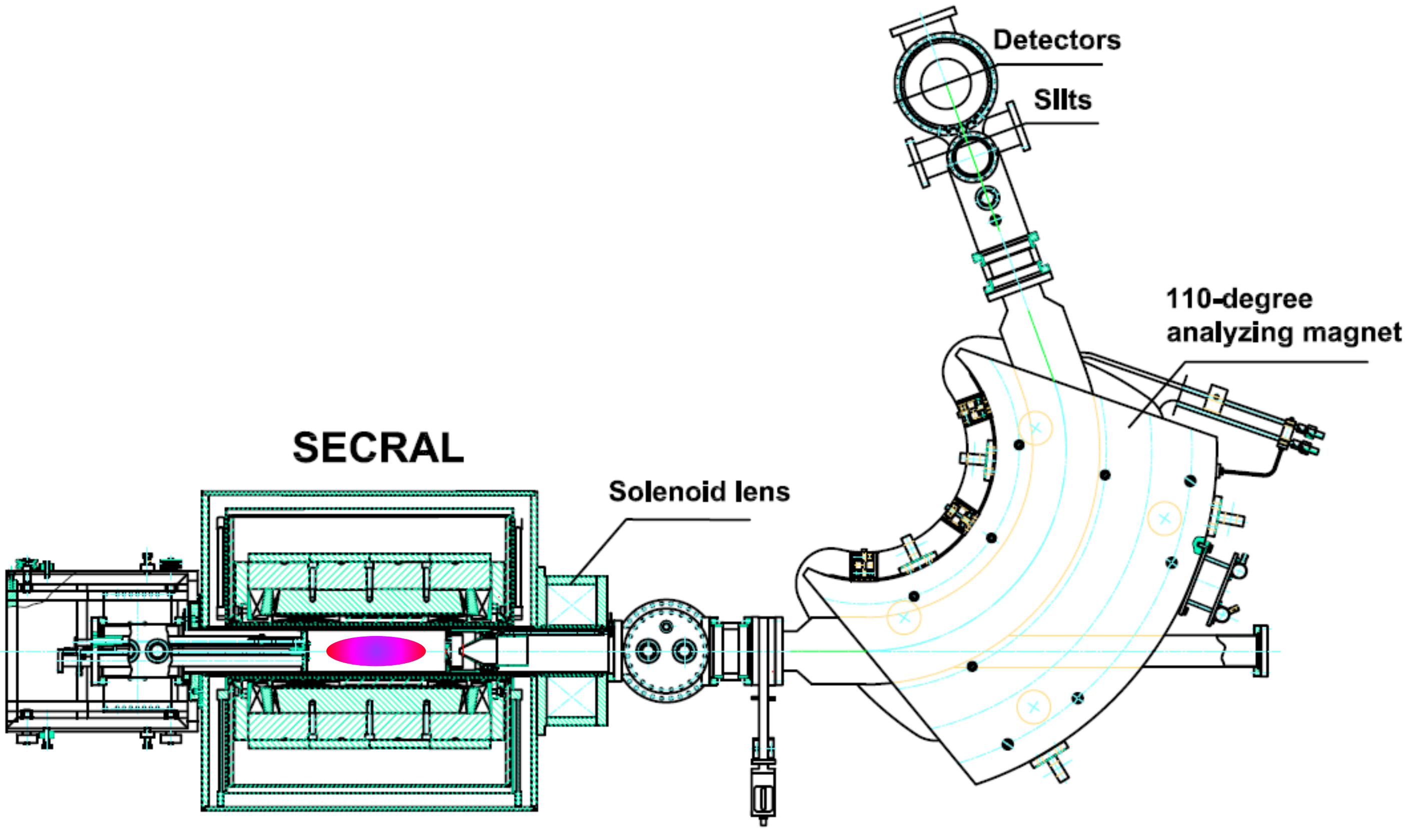
When $\Theta = n \cdot \frac{\pi}{2}$ $\quad n = 0, \pm 1, \pm 2, \pm 3, \cdots$ the beam is uncoupled.

Horizontal and vertical planes exchange while $n = \pm 1, \pm 3, \pm 5, \cdots$

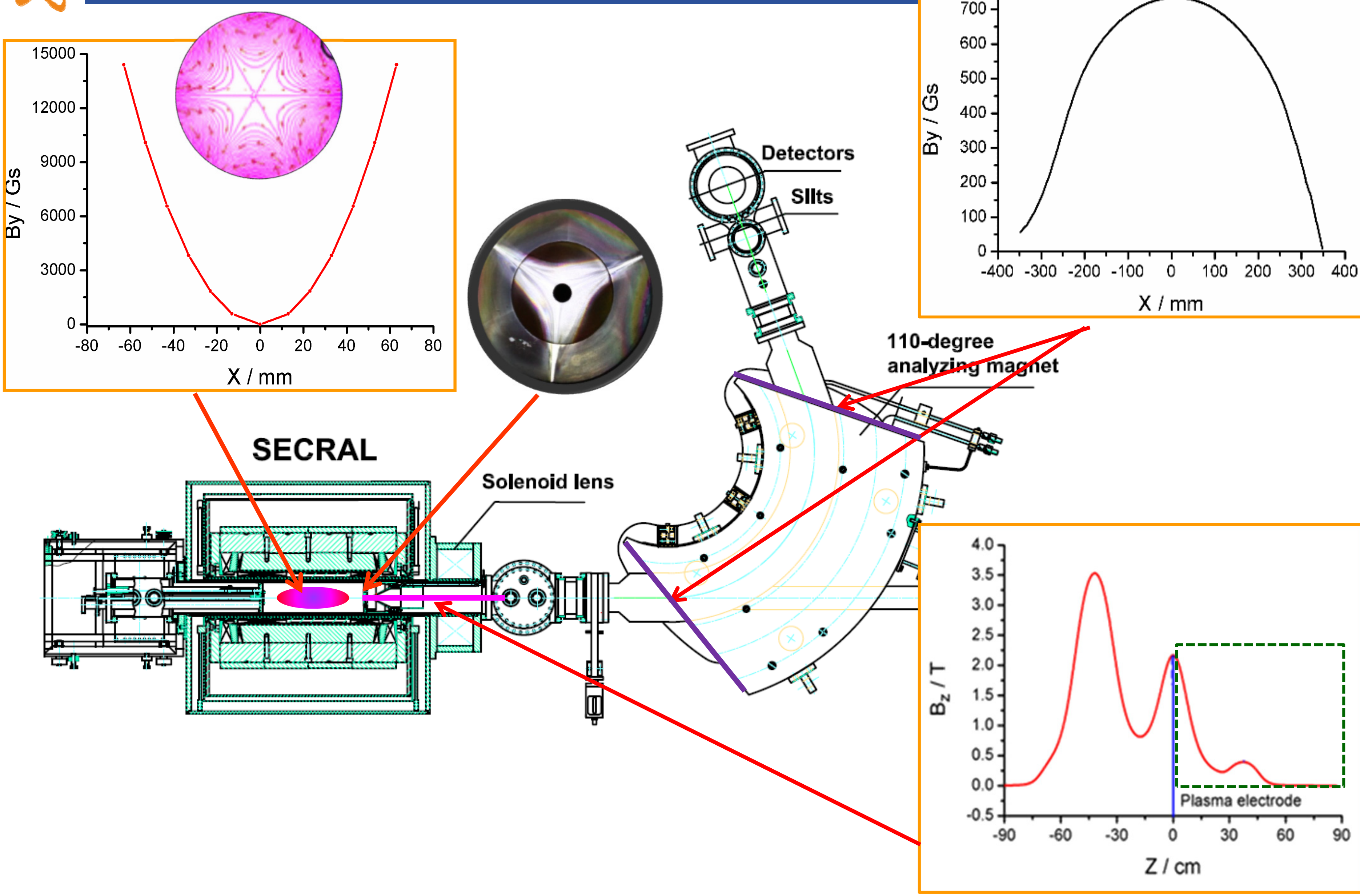
With regard to the experimental result with SECRAL:

- Ion beam extracted from the ECR ion source is not round.
- The solenoid after the ion source could disentangle the coupling (when $I_{solenoid}$= -180A) by compensating the beam rotation (not rotational momentum) created by the semi-solenoid field in the extraction region.
- However, the coupling induced during beam extraction can not be removed unless in an opposite magnetic field of the same the particles experienced while they were extracted or by using a skew quadrupole (or a skew triplet).

High-order magnetic fields

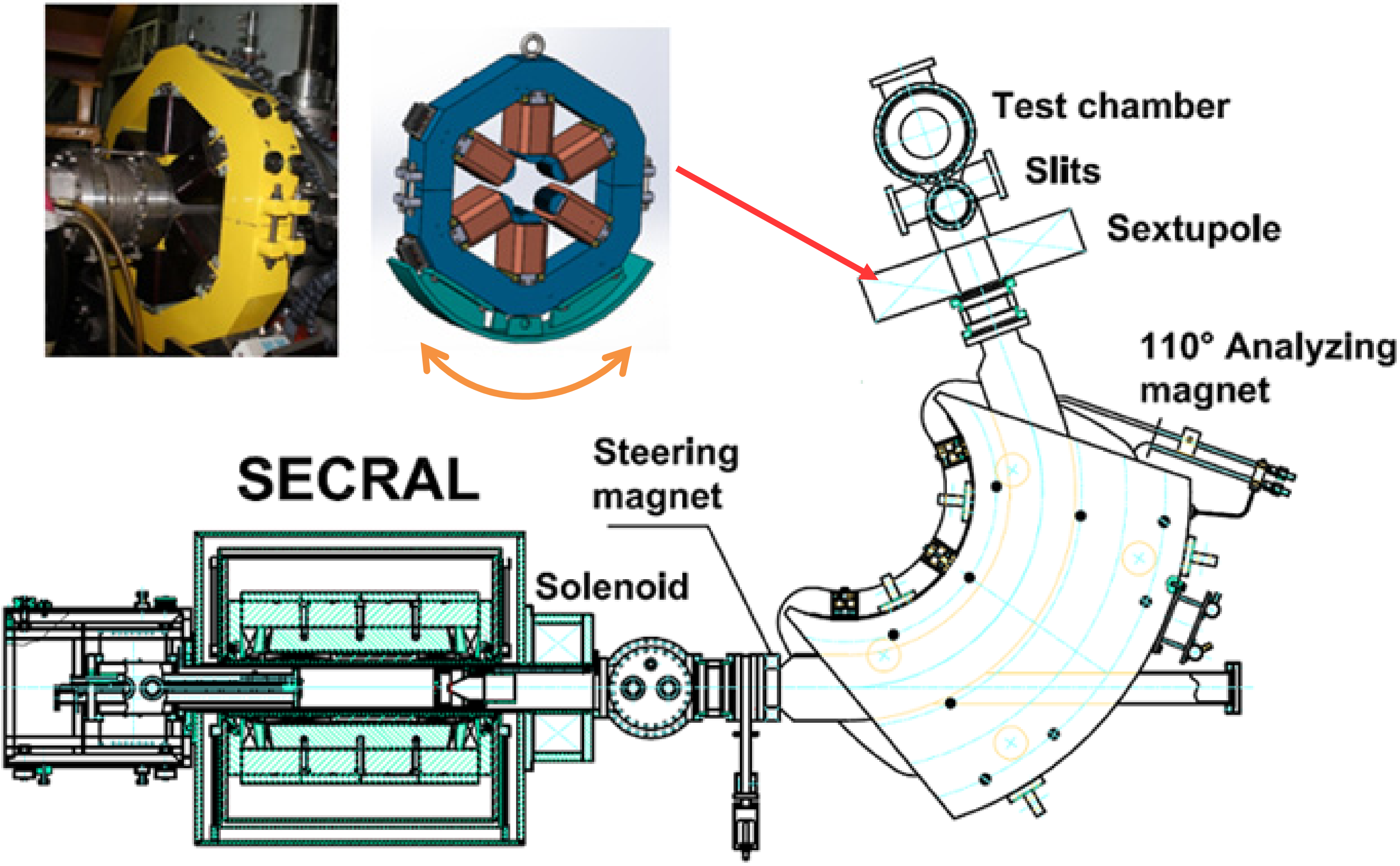


High-order magnetic fields



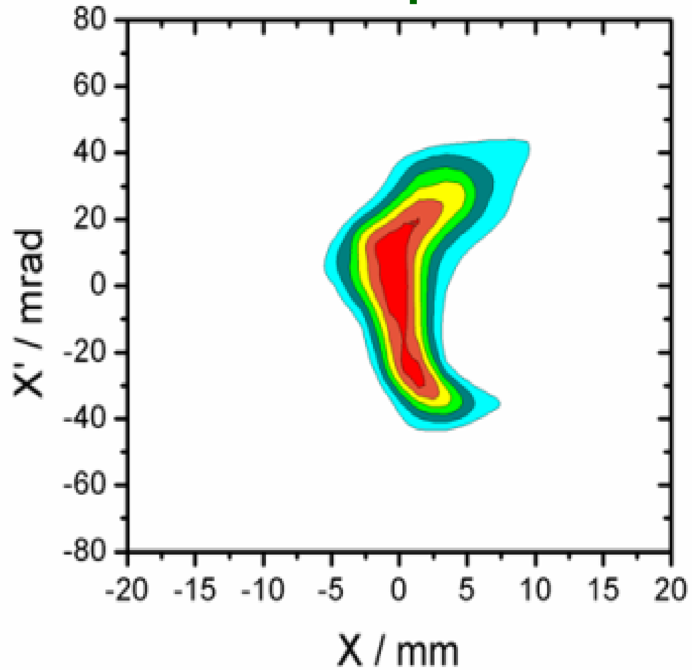
Sextupole compensation for SECRAL

Experimental setup

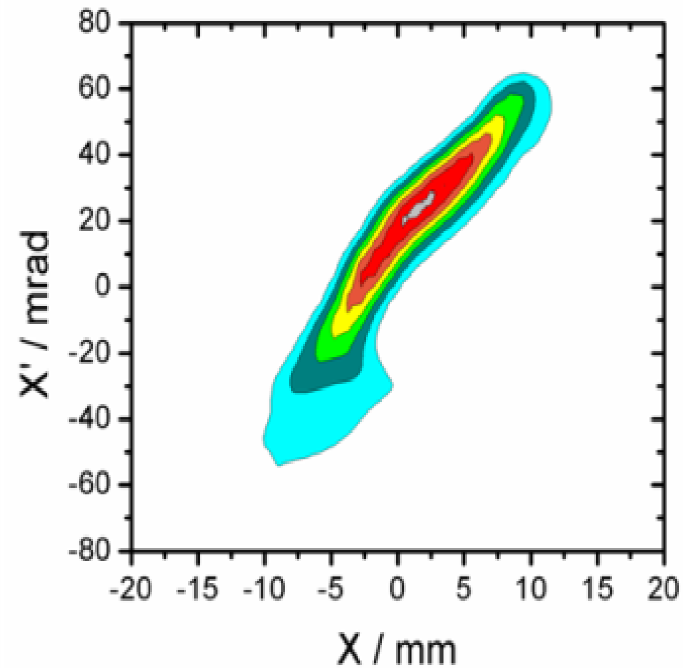


Preliminary results

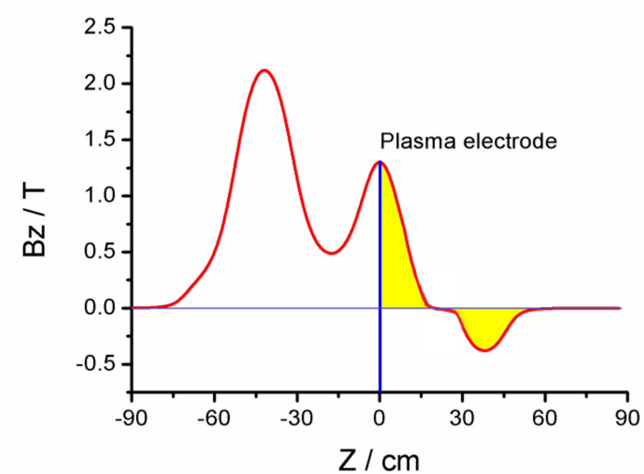
Before compensation



After compensation



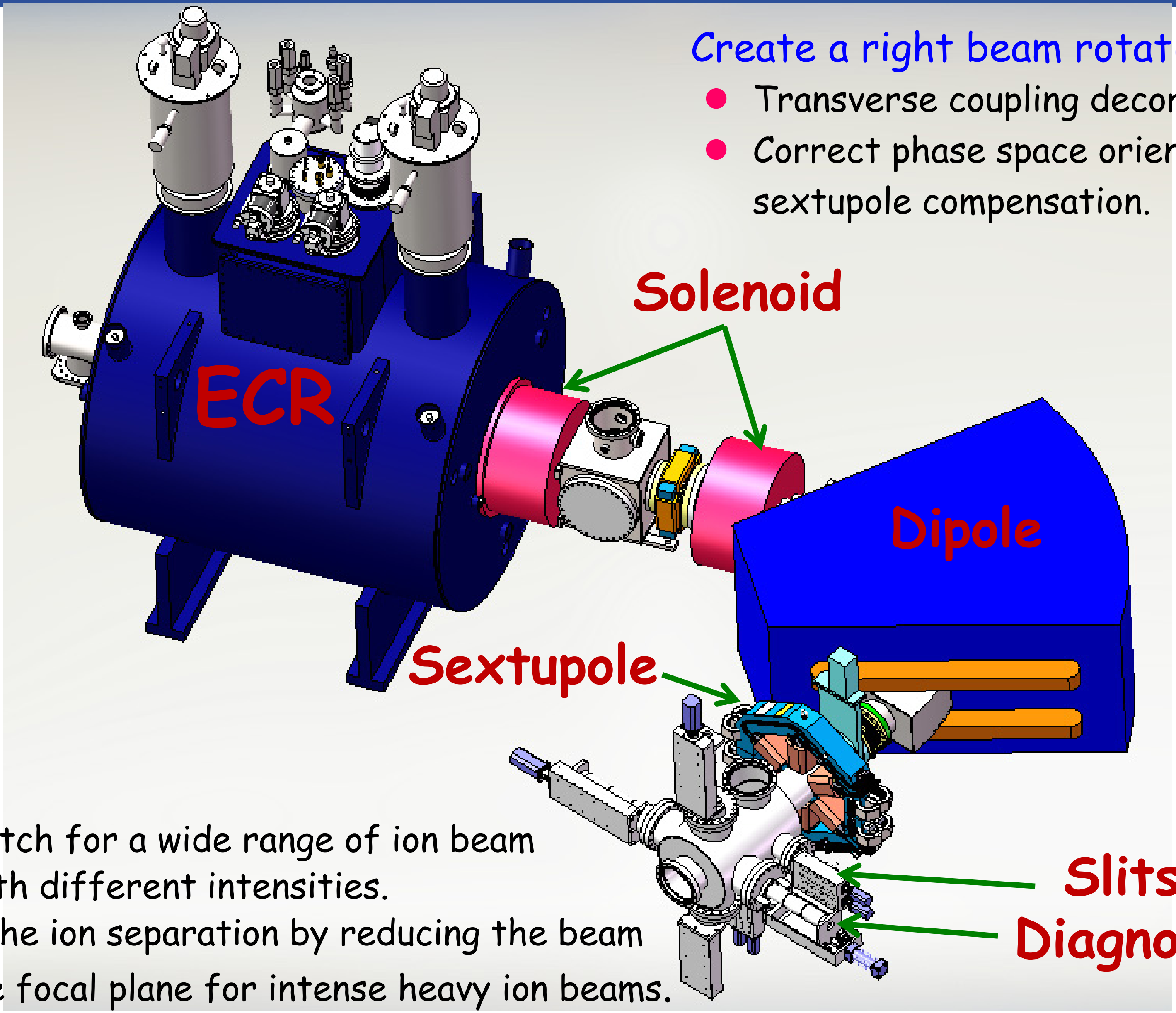
- $^{16}O^{3+}$
- Solenoid current ~ -160 A
- Polarity of sextupole: NEGTIVE



An improved design of Q/A selector

Create a right beam rotation angle

- Transverse coupling decorrelation.
- Correct phase space orientation for sextupole compensation.



- ✓ Optics match for a wide range of ion beam species with different intensities.
- ✓ Improve the ion separation by reducing the beam size at the focal plane for intense heavy ion beams.

Summary

- Magnetic field in the extraction region determine the beam emittances and the transverse coupling by adding a azimuthal momentum to the beam & affecting the beam formation .
- A solenoid can lead to periodic coupling for an initially non-round beam due to its rotation effect.
- Experiments have verified the validity of sextupole compensation, but it is vital to create correct phase space orientation at the location of the sextupole.
- Using TWO SOLENOIDs in the Q/A selector could be an improved scheme.

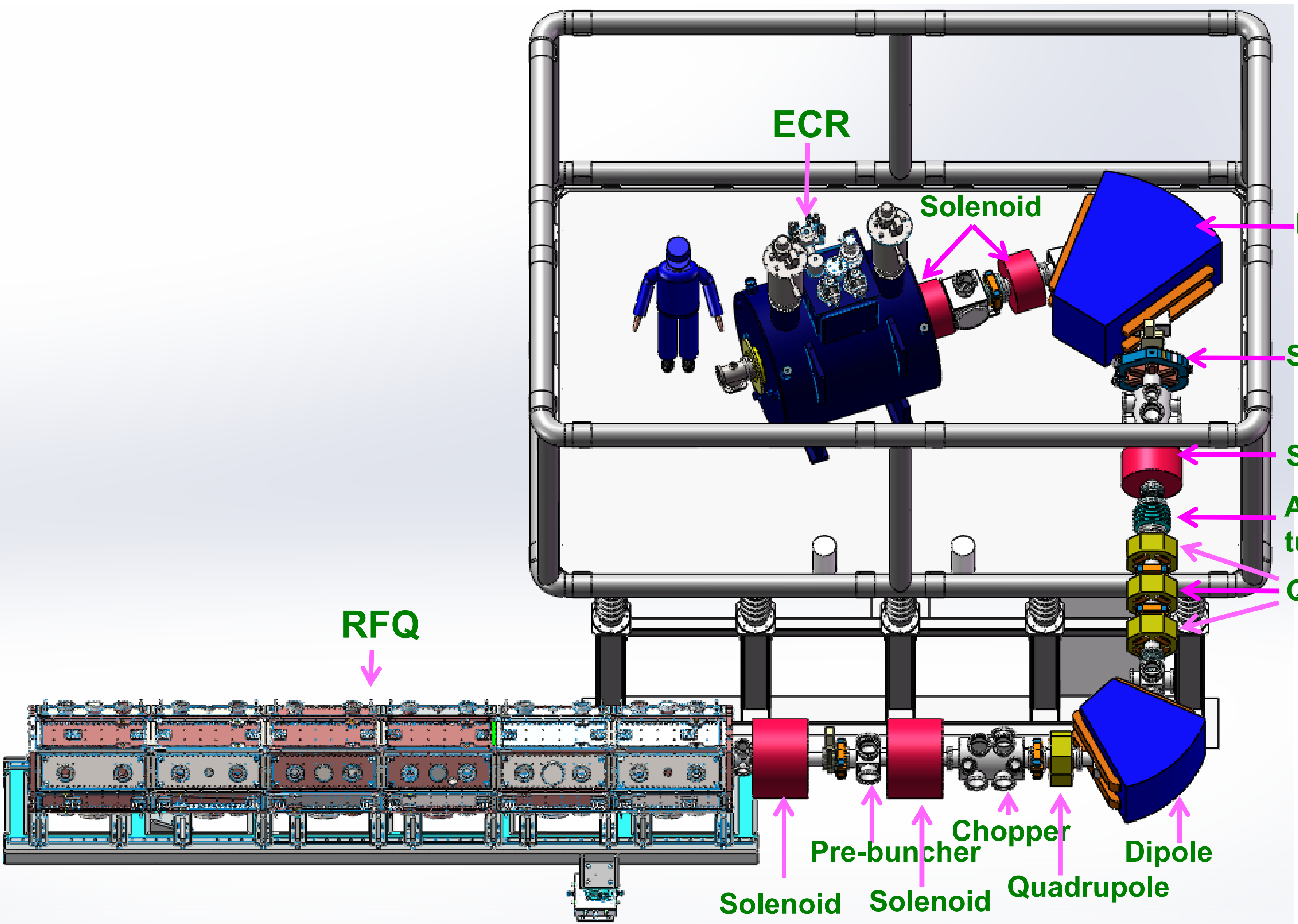
Outlook

- Beam quality measurements using a pepper-pot scanner are very essential.
- Further experiments on high-order compensation are planned.
- Improved scheme by using TWO SOLENOIDs to create a right beam rotation angle should be verified by detailed simulations.

Thanks for your attention!

谢谢！

Layout of LEAF



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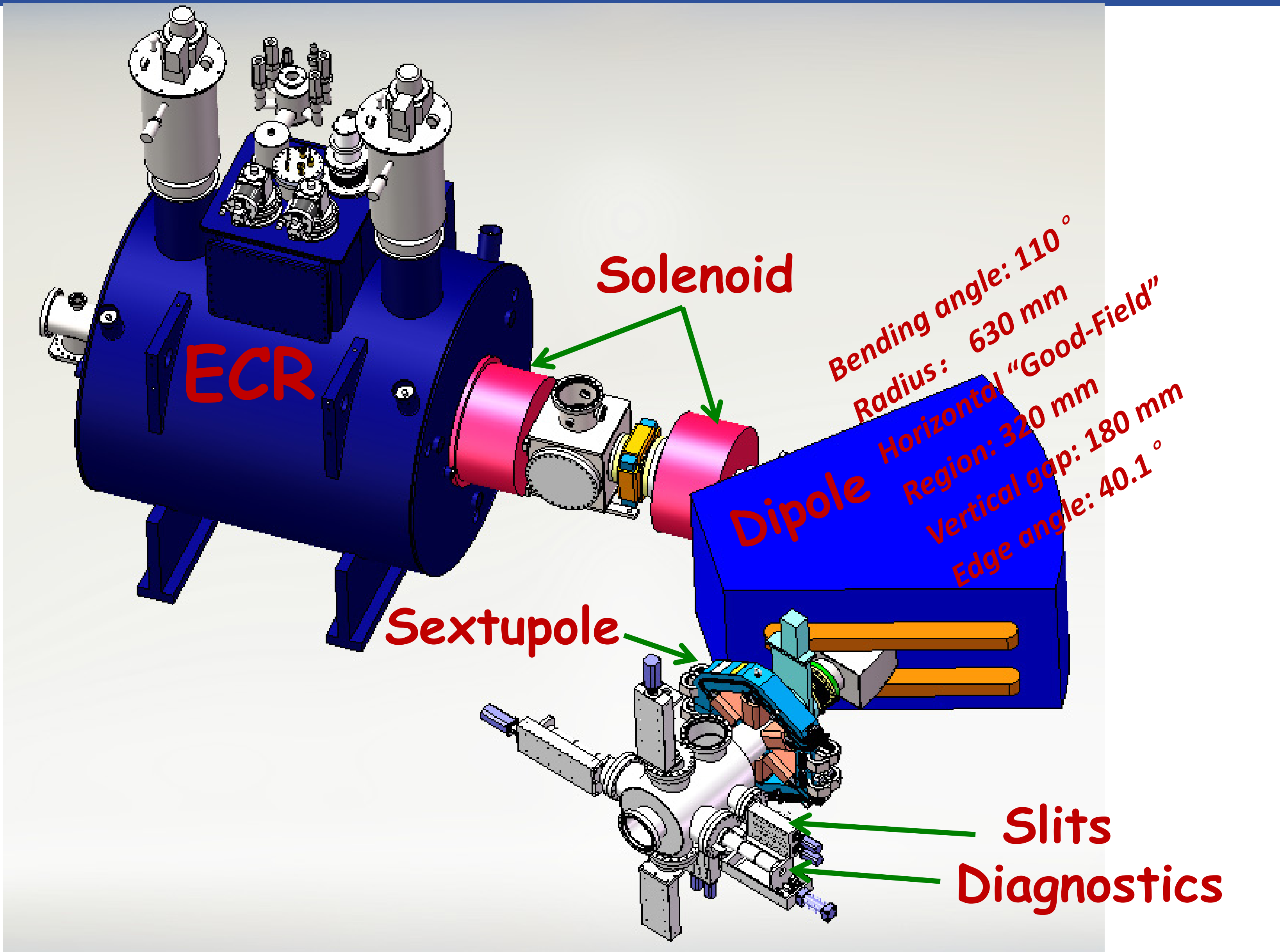

An improved design of Q/A selector

TWO SOLENOIDS:

- ✓ Optics match for a wide range of ion beam species with different intensities.
- ✓ Improve the ion seperation by reducing the beam size at the focal plane for intense heavy ion beams.
- ✓ Creat a rihgt beam rotation angle
  - Transverse coupling decorrelation.
  - Correct phase space orientation for sextupole compensation

I_0: 15 emA; I_{U34+}: 2 emA
HV: 50 kV; SCC: 70%