中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

Transverse coupling of ion beams from an ECR ion source

Yao Yang

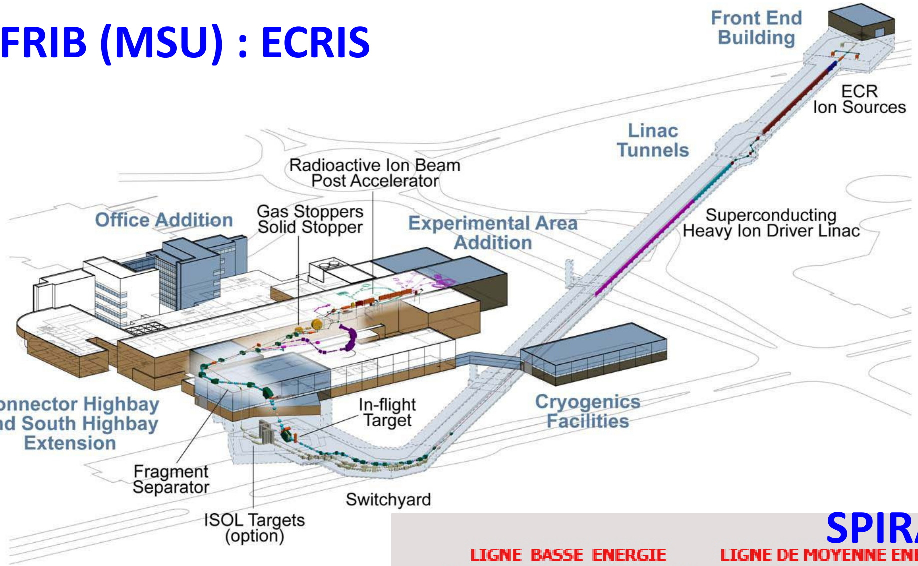
Institute of Modern Physics, CAS, 730000, Lanzhou, China

Outline

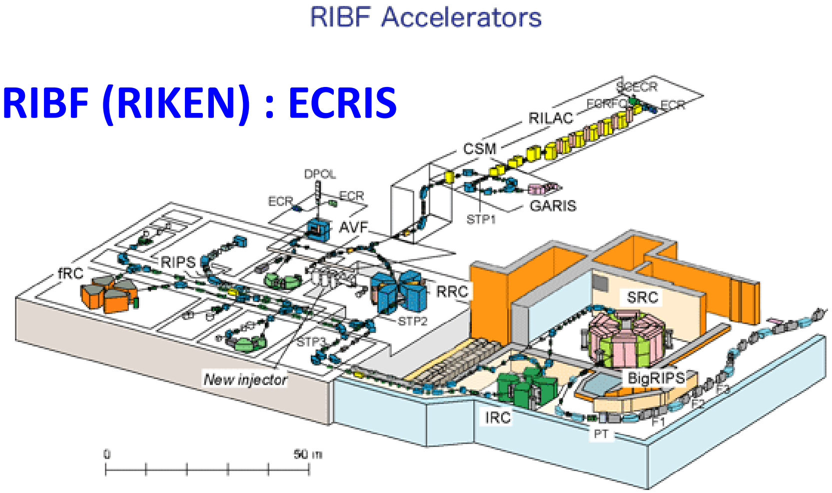
- Background
- Coupling induced during beam extraction
- Coupling effect of a solenoid
- Conclusions and Perspectives

Backgrounds

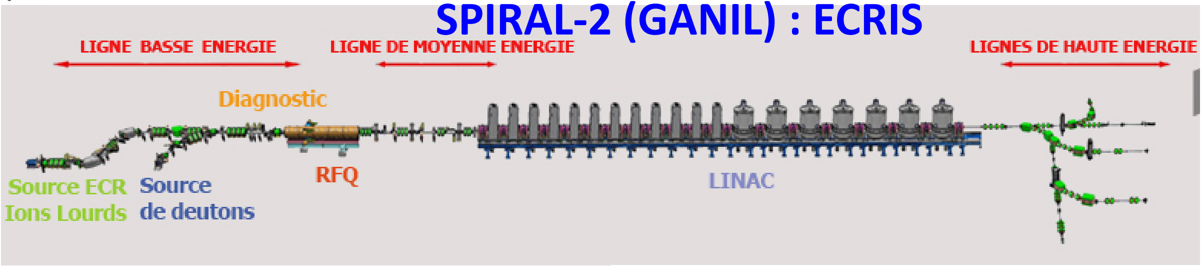
FRIB (MSU) : ECRIS



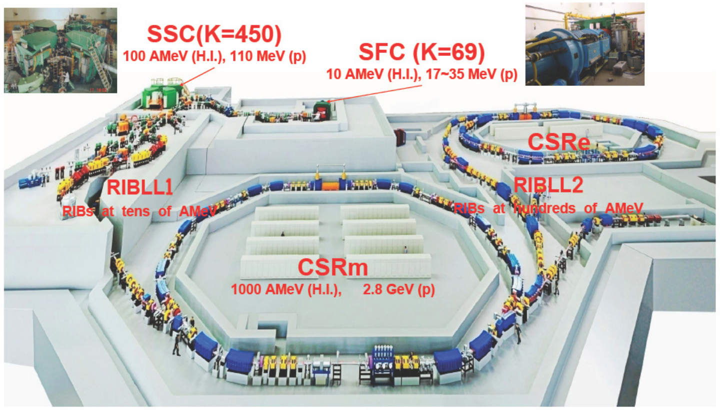
RIBF (RIKEN) : ECRIS



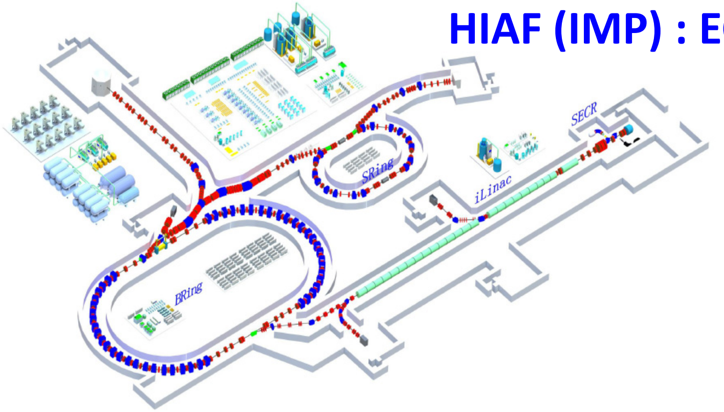
SPIRAL-2 (GANIL) : ECRIS



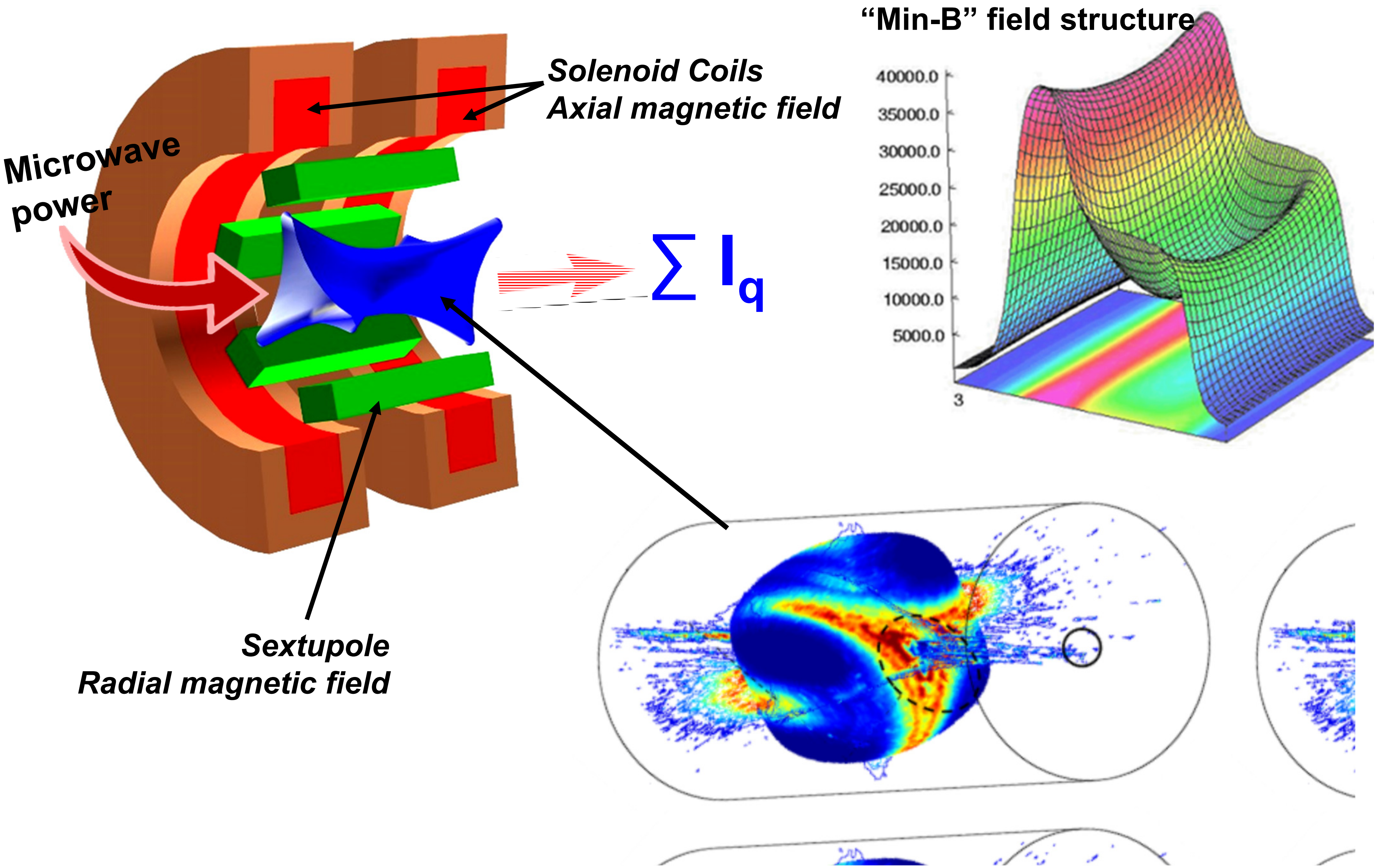
HIRFL (IMP) : ECRIS



HIAF (IMP) : ECRIS



ECR ion source



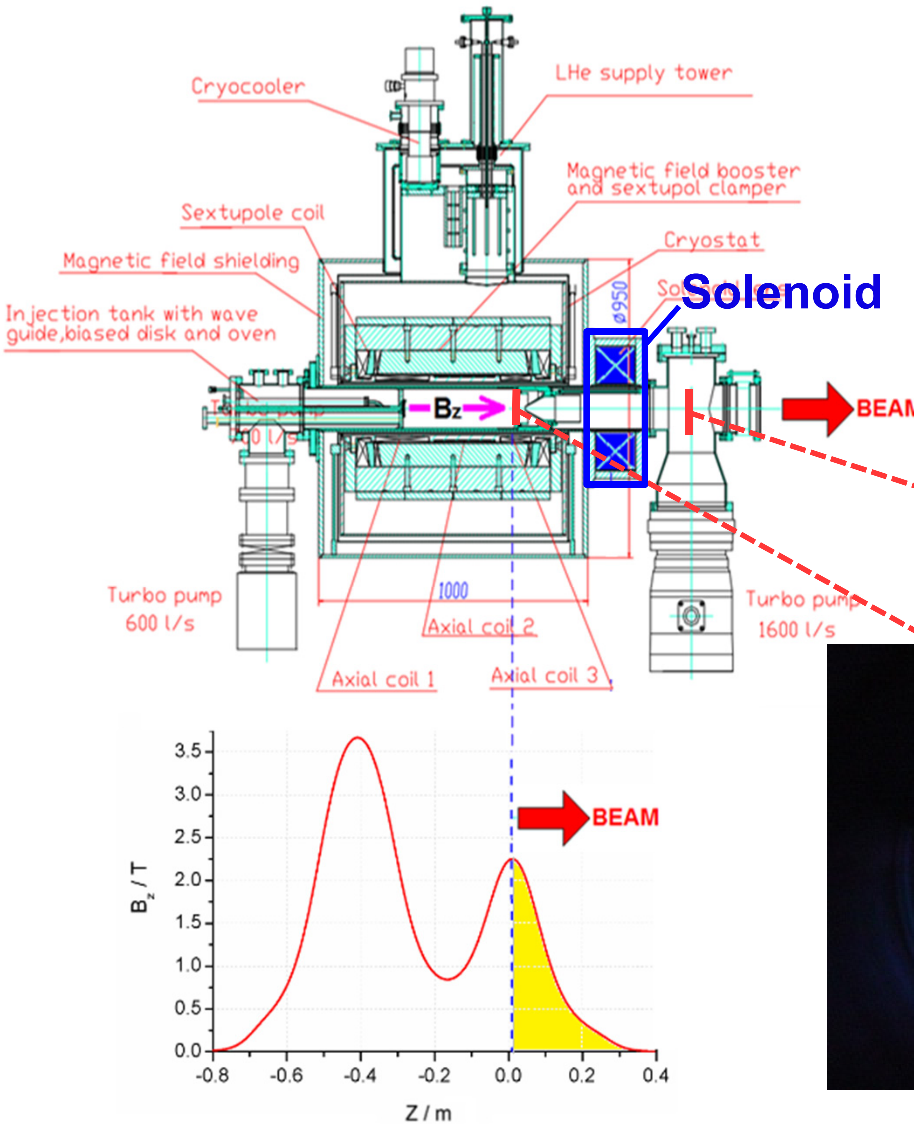
Beam properties from ECR ion sources

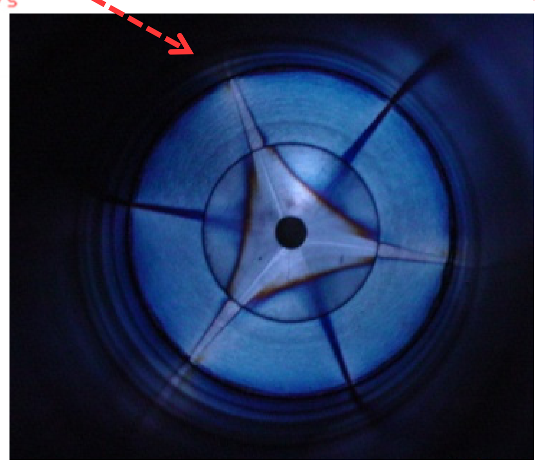
- Particles are extracted and accelerated in a semi-solenoid magnetic field.

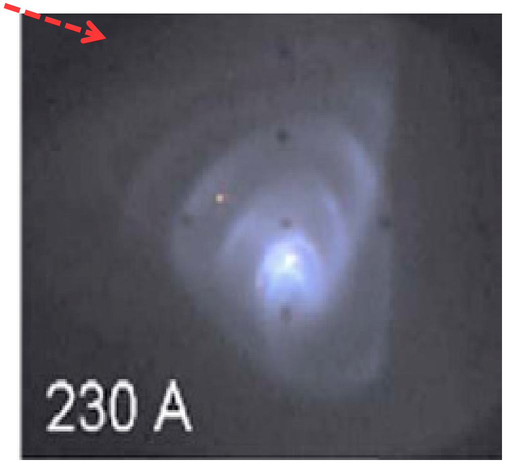
→Transversely coupled beam

- Asymmetric plasma distribution at extraction.

→Inhomogeneous ion density distribution across the extraction aperture







SECRAL schematic view and the axial magnetic field distribution.

Expected 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:

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

Coupling between horizontal and vertical planes results in:

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

equality just for zero inter-plane coupling moments.

Projection RMS emittances:

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

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

4D-emittance:

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

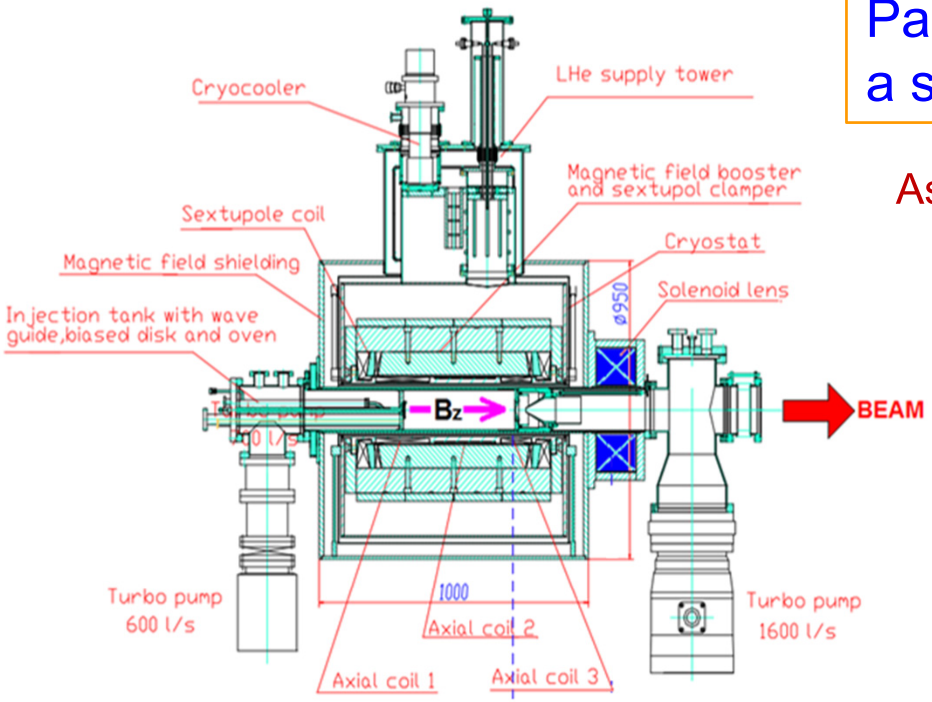
Eigen-emittances:

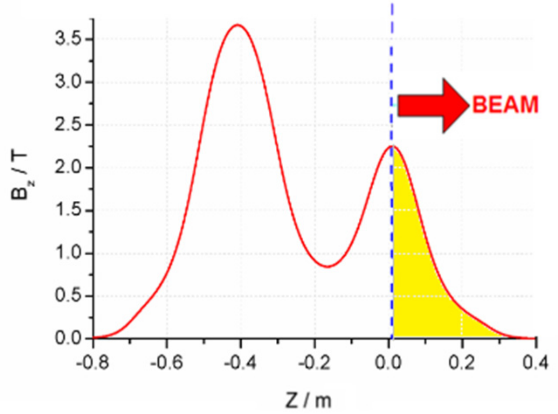
$$\varepsilon_1 = \frac{1}{2}\sqrt{-tr[(CJ)^2] + \sqrt{tr^2[(CJ)^2] - 16\det(C)}}$$

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

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

Coupling induced during beam extraction





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

Assuming a very short solenoid:

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

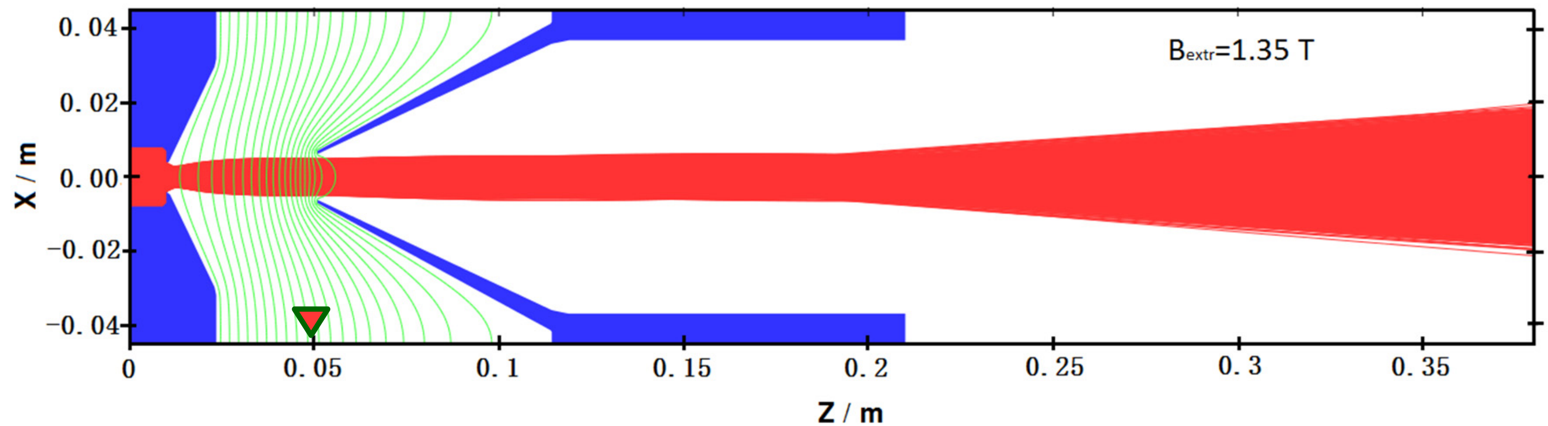
$$C_1 = R_{out} C_0 R_{out}^T = \begin{bmatrix} \varepsilon\beta & 0 & 0 & \kappa\varepsilon\beta \\ 0 & \frac{\varepsilon}{\beta} + \kappa^2\varepsilon\beta & -\kappa\varepsilon\beta & 0 \\ 0 & -k\varepsilon\beta & \varepsilon\beta & 0 \\ \kappa\varepsilon\beta & 0 & 0 & \frac{\varepsilon}{\beta} +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

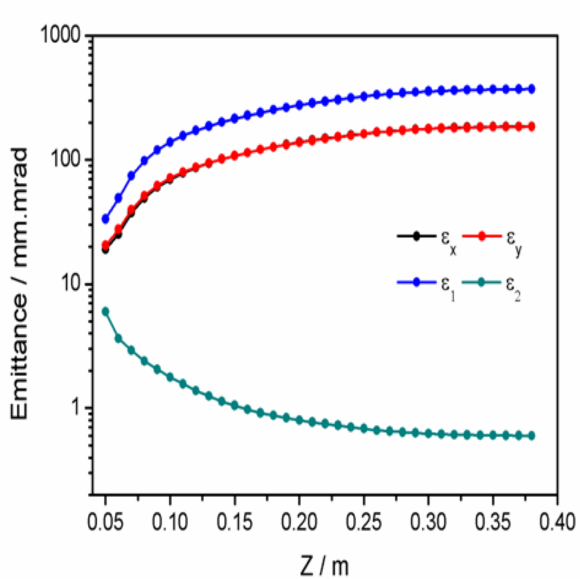
$$\varepsilon_x = \varepsilon_y = \sqrt{\varepsilon\beta(\frac{\varepsilon}{\beta} + \kappa^2\varepsilon\beta)} \qquad \varepsilon_{1,2} = \varepsilon_x \pm \kappa\varepsilon\beta$$

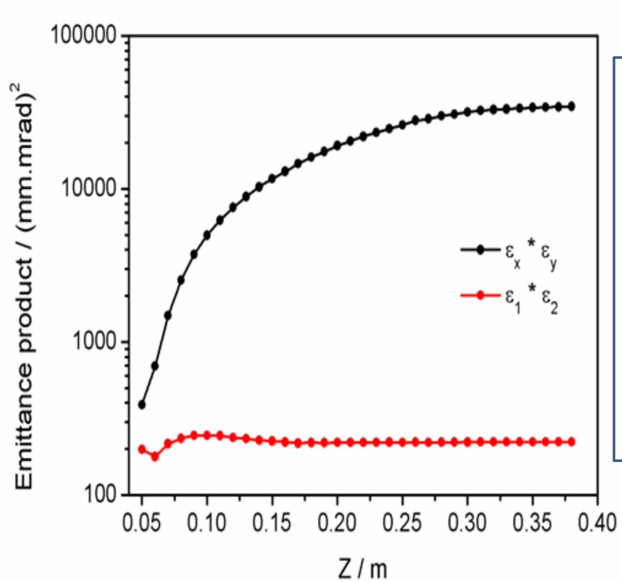
Ion beam is transversely coupled!

Beam extraction simulation for SECRAL

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



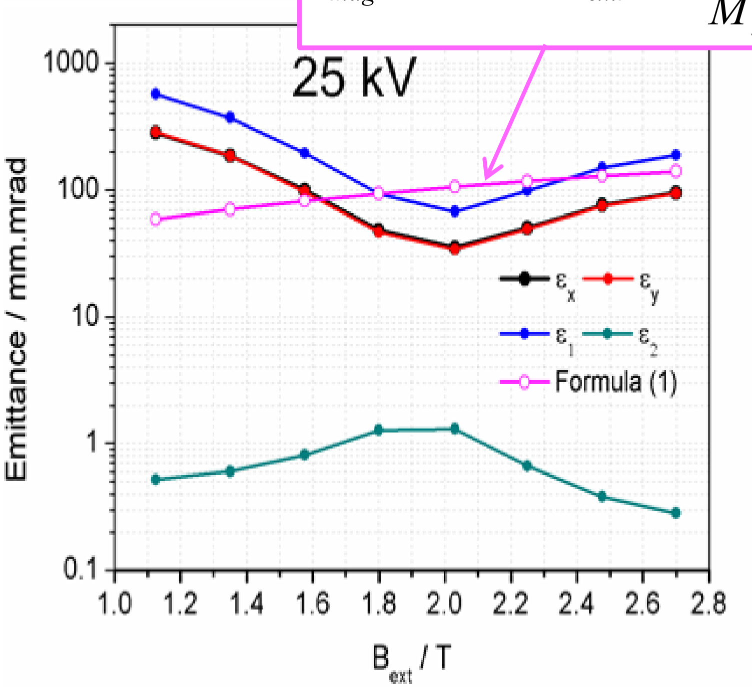


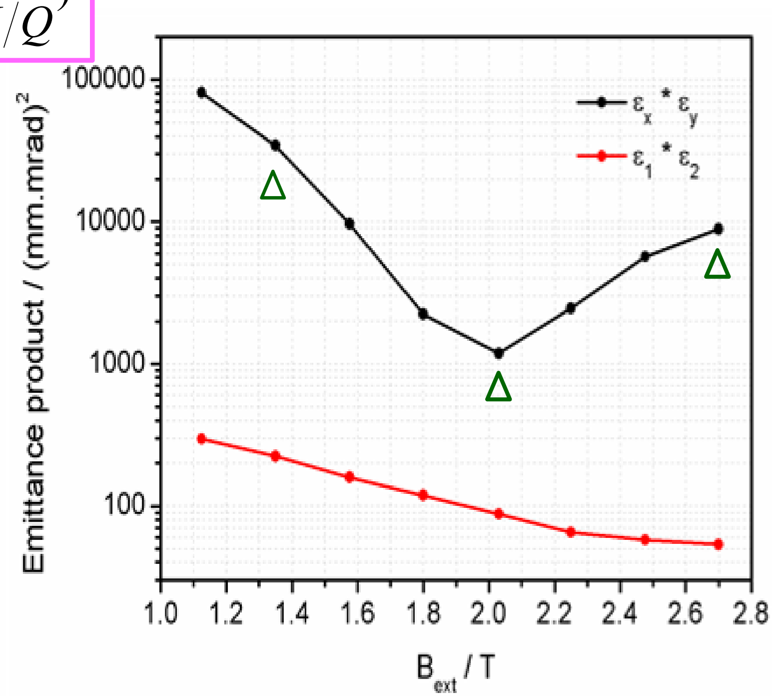


- ✓ Two eigen-emittances heavily separate.
- ✓ Both projection emittances rise up.
- ✓ Constant 4-D emittance (ε_1*ε_2).

Beam emittances VS B_{ext}

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

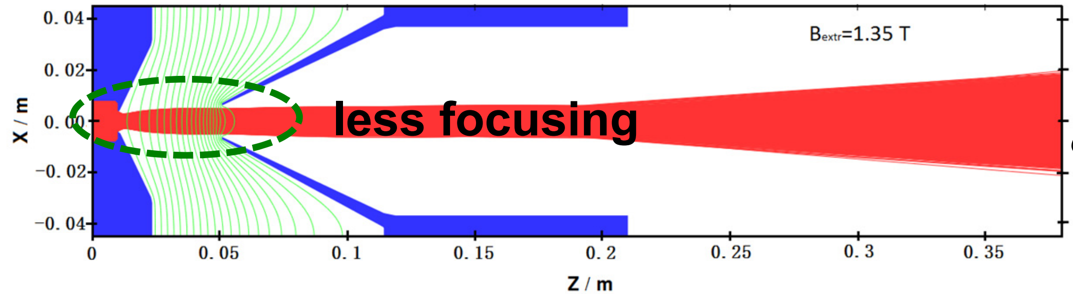




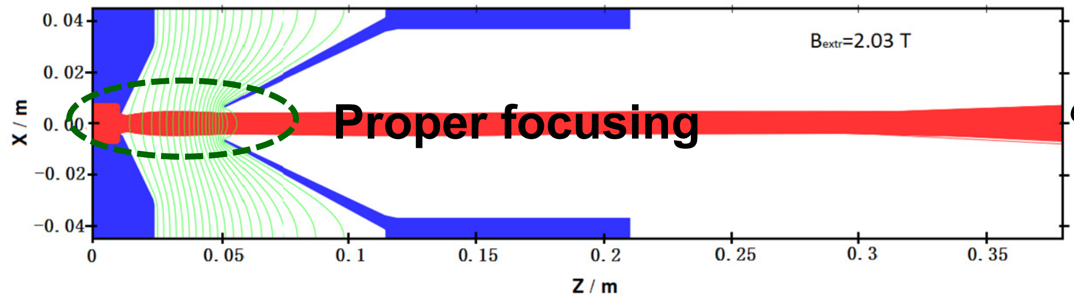
- The projection emittances do not increase with the magnetic field strength proportionally as expected;
- Optimal field (B_{extr}=2.03 T) .
  - $\varepsilon_{x,y}$ reaches minimum;
  - the value of $\varepsilon_x * \varepsilon_y$ is closest to $\varepsilon_1 * \varepsilon_2$;
  - the difference between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

  } The coupling is relatively weak.

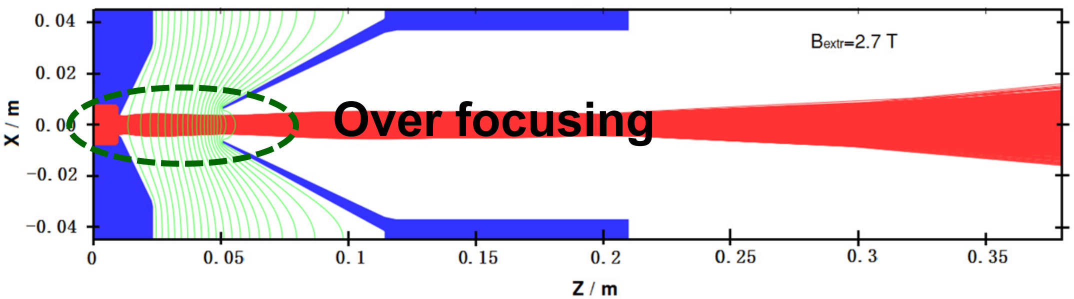
B_{ext} effect on beam formation



$$C_{1.35T} = \begin{bmatrix} 105.9975 & 476.0413 & -0.2120779 & -196.2880 \\ 476.0413 & 2466.011 & 175.0482 & -81.79913 \\ -0.2120779 & 175.0482 & 95.20618 & 432.9456 \\ -196.2880 & -81.79913 & 432.9456 & 2330.547 \end{bmatrix}$$



$$C_{2.03T} = \begin{bmatrix} 13.14704 & 70.28109 & -0.4886135 & -37.11058 \\ 70.28109 & 468.760 & 29.29614 & -22.68711 \\ -0.4886135 & 29.29614 & 11.82261 & 66.22893 \\ -37.11058 & -22.68711 & 66.22893 & 468.3700 \end{bmatrix}$$



$$C_{2.7T} = \begin{bmatrix} 44.9443 & 238.4365 & -1.350854 & -101.0213 \\ 238.4365 & 1465.950 & 87.37357 & -27.78315 \\ -1.350854 & 87.37357 & 44.73177 & 243.2753 \\ -101.0213 & -27.78315 & 243.2753 & 1519.878 \end{bmatrix}$$

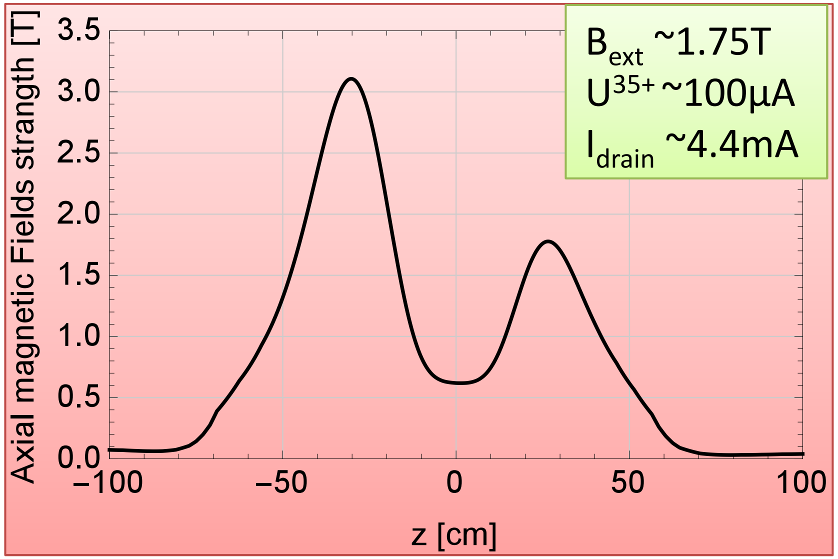
$$\varepsilon_x = \varepsilon_y = \sqrt{\varepsilon\beta\left(\frac{\varepsilon}{\beta} + \kappa^2 \varepsilon\beta\right)} \qquad \varepsilon_{1,2} = \varepsilon_x \pm \kappa\varepsilon\beta$$

The magnetic field can also determine the beam emittances and the transverse coupling by affecting the beam formation in the extraction region.

Beam emittances VS B_{ext}

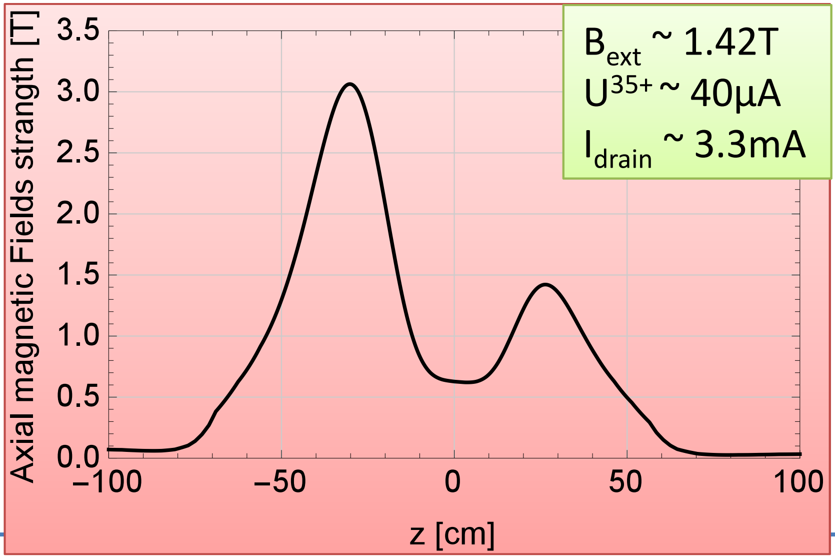
Emittance measurement for RIKEN 28GHz SC-ECRIS

Presented in ICIS'15
by Y. Higurashi from RIKEN



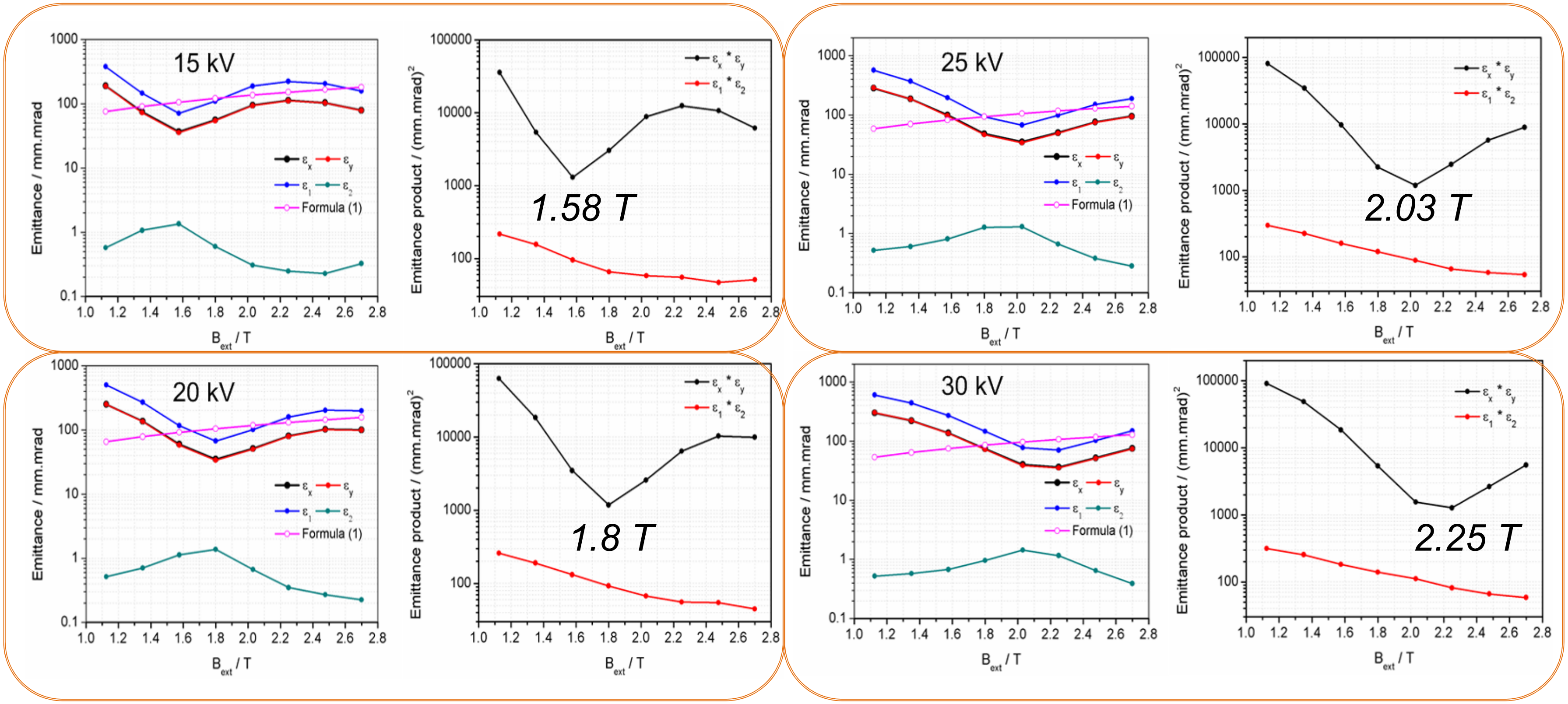
EM Slit measurement			OPERA calculation		
H	V	4D	H	V	4D
290	156	1567	210	172	1459

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



EM Slit measurement			OPERA calculation		
H	V	4D	H	V	4D
377	214	3476	249	201	2755

Under different extraction voltages

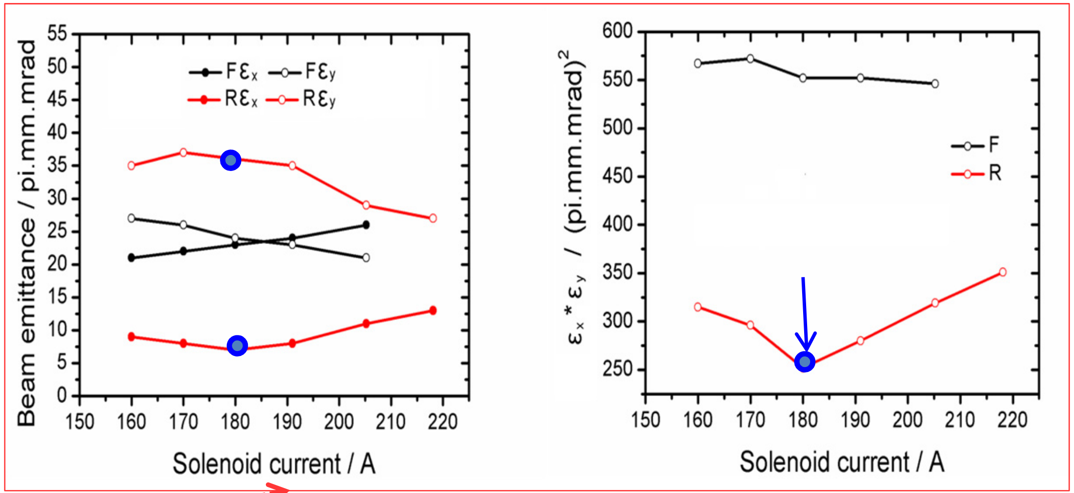


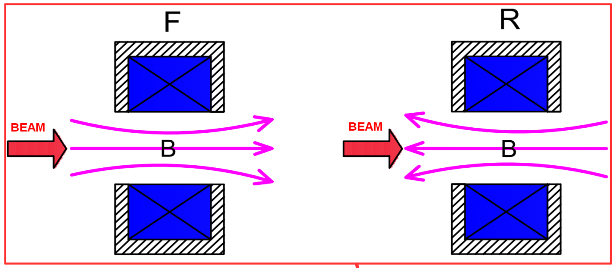
- The 4-D emittance decreases with increasing the extraction magnetic field.
  - ✓ the beam size at the location of the grounded electrode is focused to be smaller with a larger magnetic field, helping to avoid the large-radius aberration in the einzel lens and improve the beam quality.

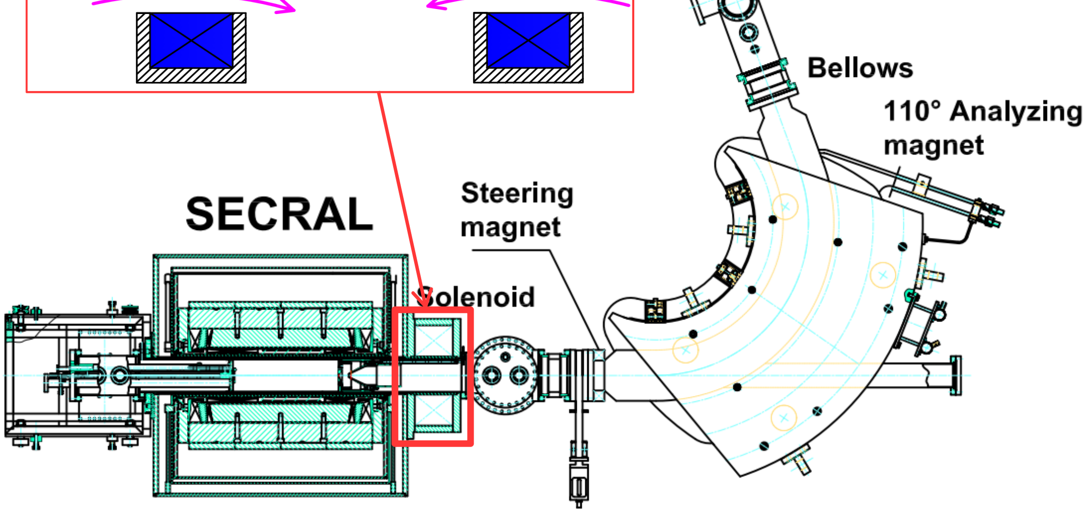
Coupling effect of a solenoid

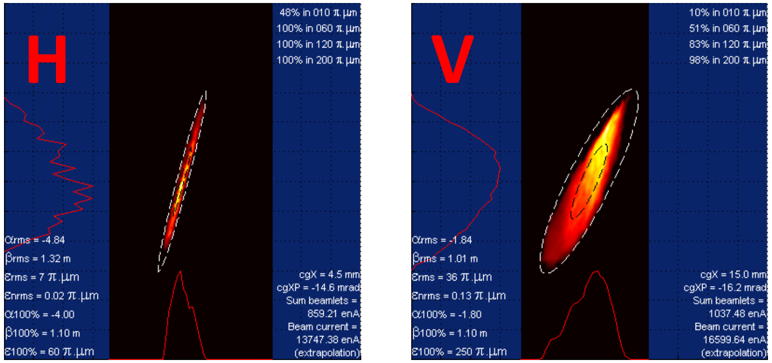
Beam emittance measurement for SECRAL

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









$I_{solenoid}$=-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**

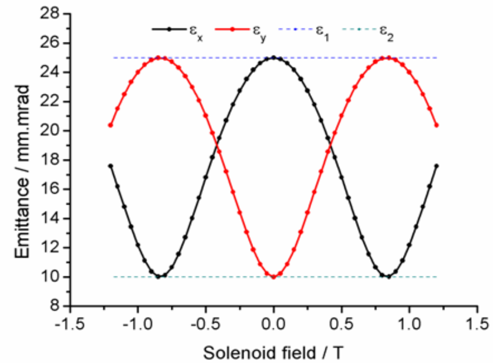
$$k = \tfrac{1}{2} B_0 / B\rho_s$$

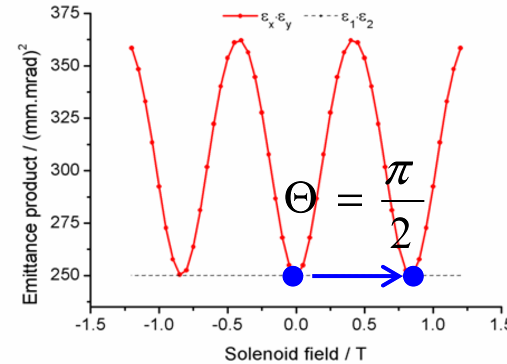
Beam rotation angle in a solenoid: $\Theta = \kappa L_{eff} = \dfrac{B_{max}}{2(B\rho)} L_{eff}$

Non-round beam through a solenoid

$R_x=R_y$
ε_x=25 mm.mrad
ε_y=10 mm.mrad.

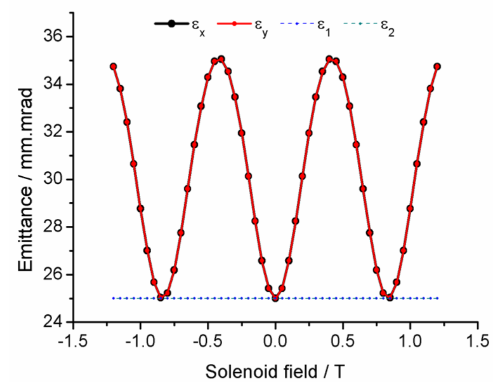
$$C=\begin{bmatrix}10 & 65 & 0 & 0\\ 65 & 485 & 0 & 0\\ 0 & 0 & 10 & 65\\ 0 & 0 & 65 & 432.5\end{bmatrix}$$

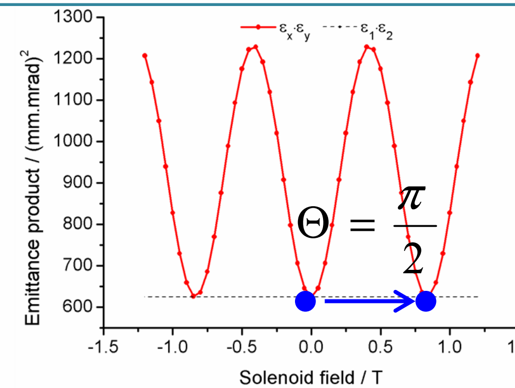




$R_x \neq R_y$
$\varepsilon_x=\varepsilon_y$=10 mm.mrad

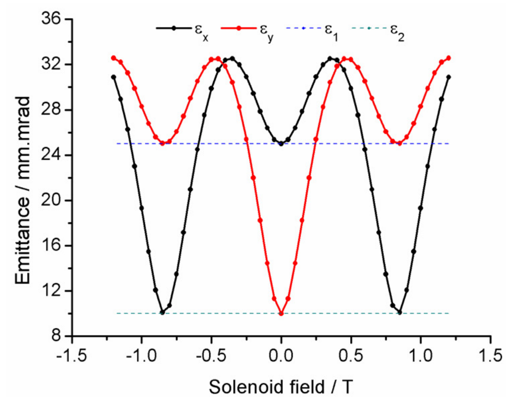
$$C=\begin{bmatrix}10 & 65 & 0 & 0\\ 65 & 485 & 0 & 0\\ 0 & 0 & 20 & 65\\ 0 & 0 & 65 & 242.5\end{bmatrix}$$

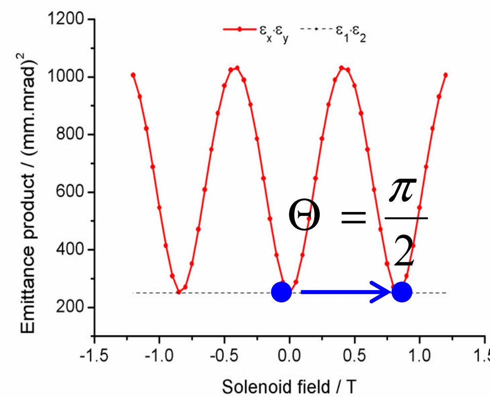




$R_x \neq R_y$
ε_x=25 mm.mrad
ε_y=10 mm.mrad.

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





$B\rho$=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 by compensating the rotation caused by the semi-solenoid field in the extraction region.
- However, the coupling induced during beam extraction can not be removed unless a skew quadrupole (or a skew triplet) is used.

Conclusions

- A strong coupling in the transverse space will be induced through the semi-solenoid field in the extraction region.
- The magnetic field in the extraction region can also determine the beam emittances and the transverse coupling by affecting the beam formation.
- A solenoid can lead to periodic coupling for an initially non-round beam due to its rotation effect.

Perspectives

- Experiments and test on the emittance with a pepper-pot scanner are essential.
- Decoupling method should be introduced in the beam matching from the ion source to the downstream accelerators (RFQs, cyclotrons) to reduce the projection emittances.
- The understanding of the ion source beam quality will be very helpful to the design of the ECR beamlines.

Thanks for your attention!

谢谢！