Study of Analyzing and Matching of Mixed High Intensity Highly Charged Heavy Ion Beams

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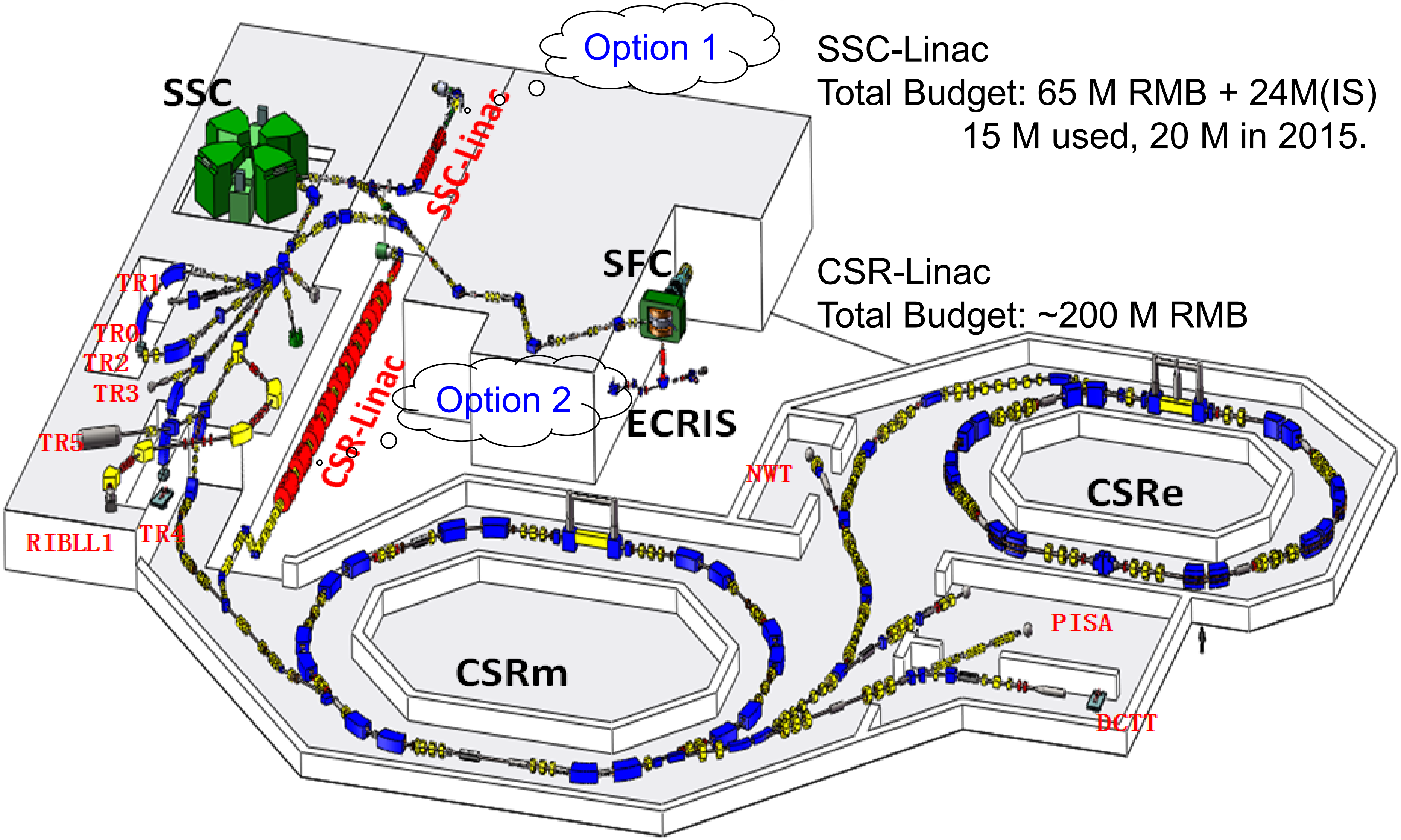
HIRFL: Brief introduction

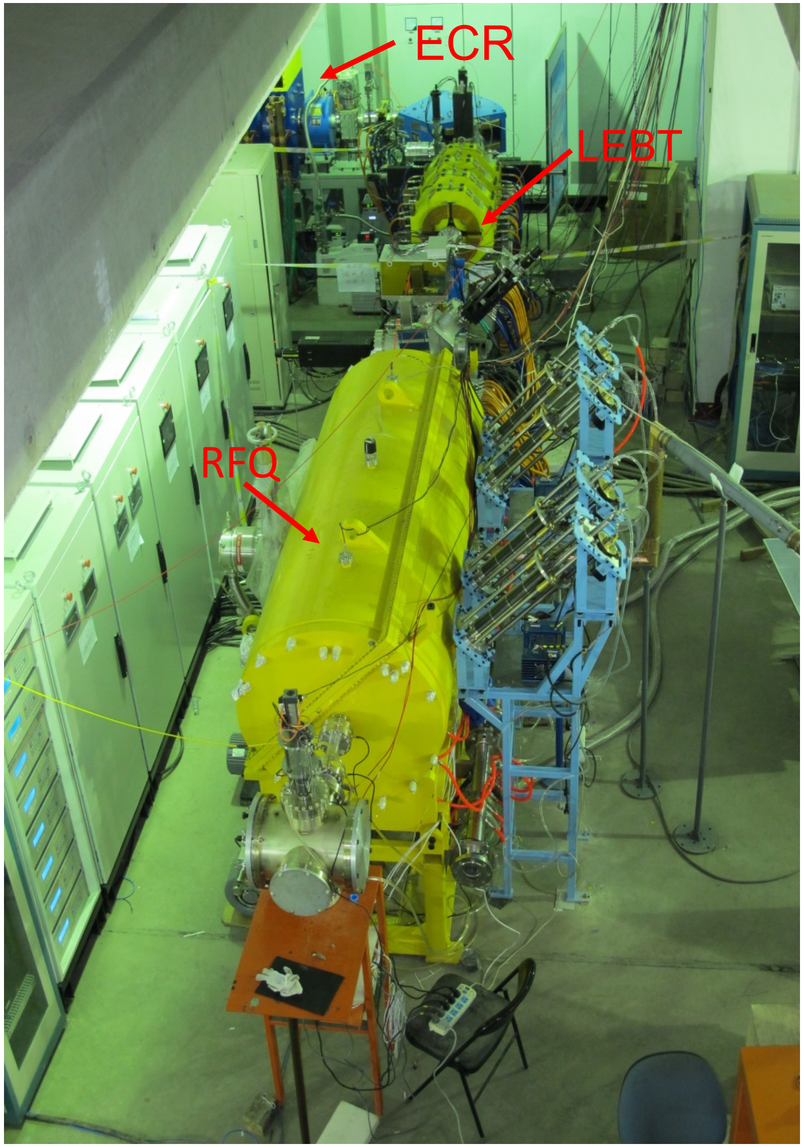
- **New HIRFL with new injectors**



SSC-Linac
Total Budget: 65 M RMB + 24M(IS)
15 M used, 20 M in 2015.

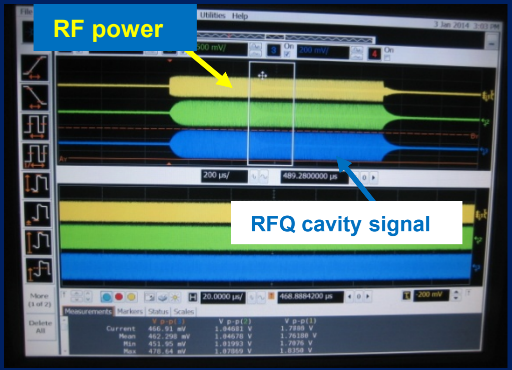
CSR-Linac
Total Budget: ~200 M RMB

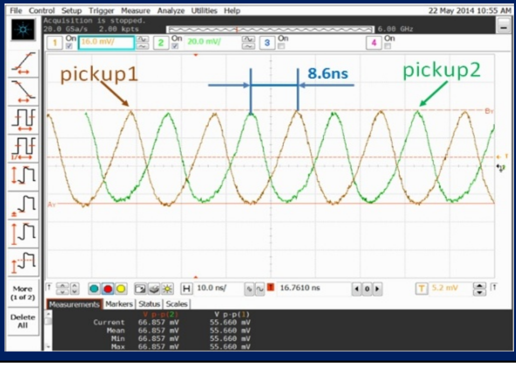
SSC-Linac injector



Front end of SSC-Linac up to RFQ

- 35kW in CW mode has been fed into RFQ successfully.
- $^{40}Ar^{8+}$ ion beam, E=142.8keV/u, I= 198eμA.
- Beam transmission efficiency is 94%.

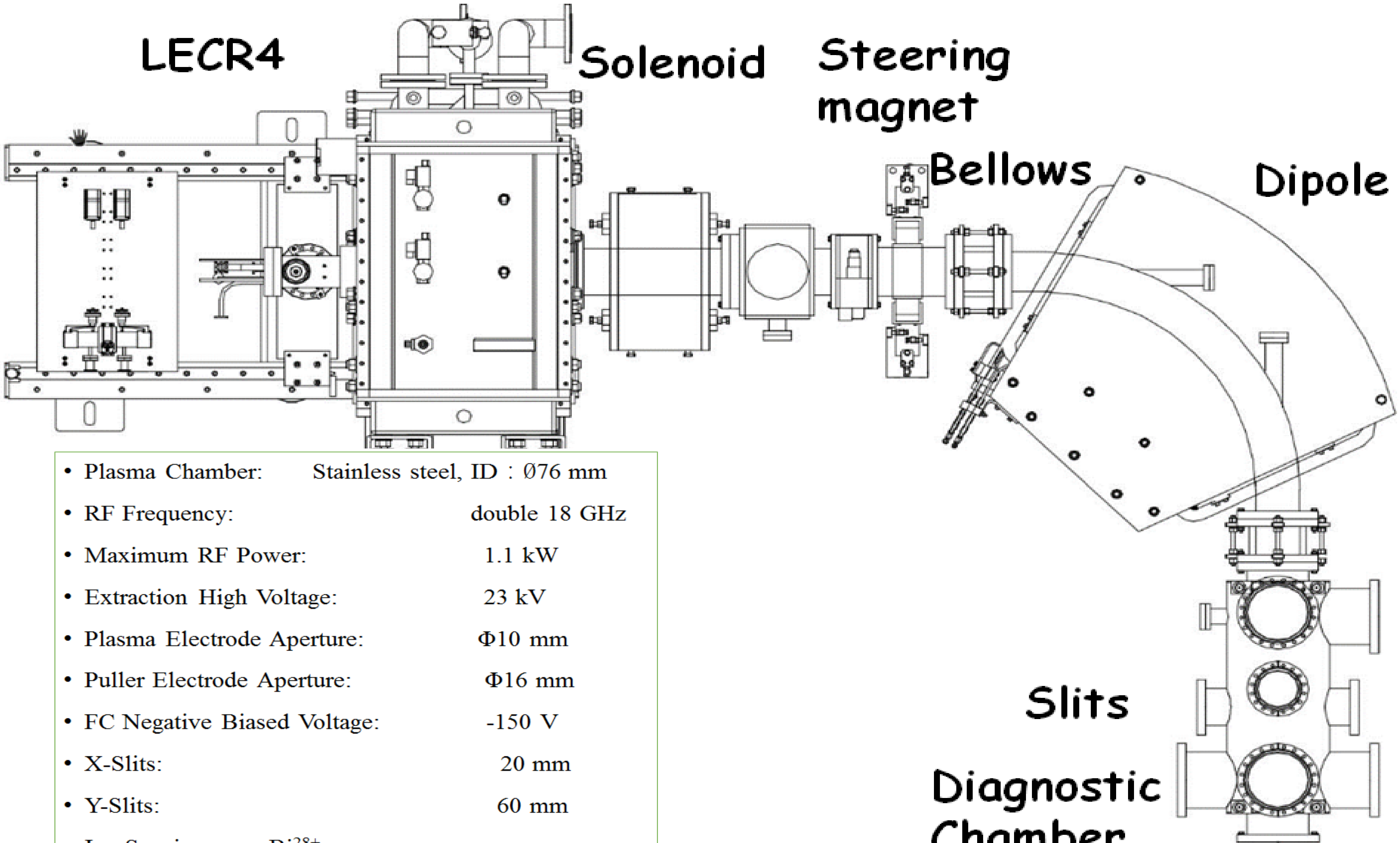




Outline

- Problems in the previous A/Q selection system
- PIC simulation of space charge effects of multi-species ions beam
- Modified A/Q selector for high intense ions beam
- Beam experiments

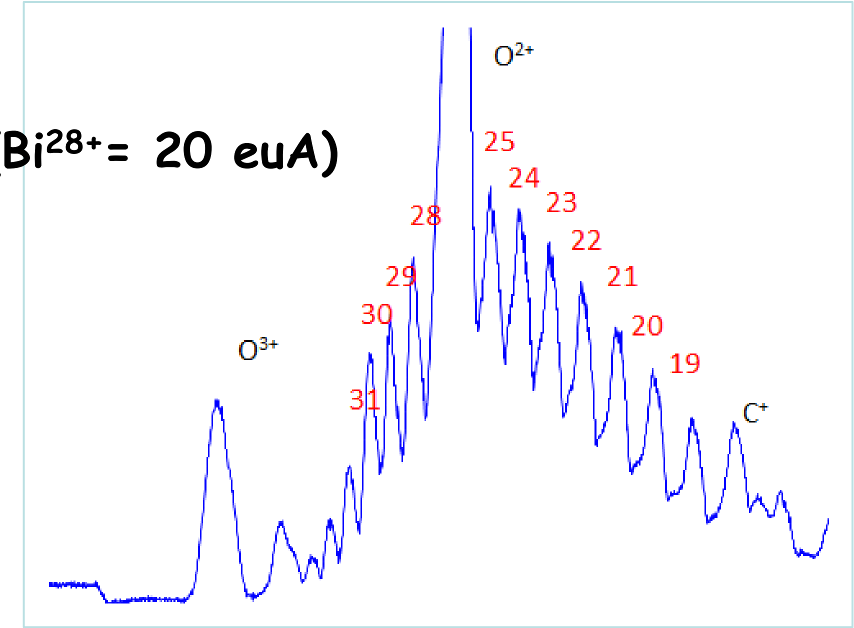
Q/A selector of LECR4



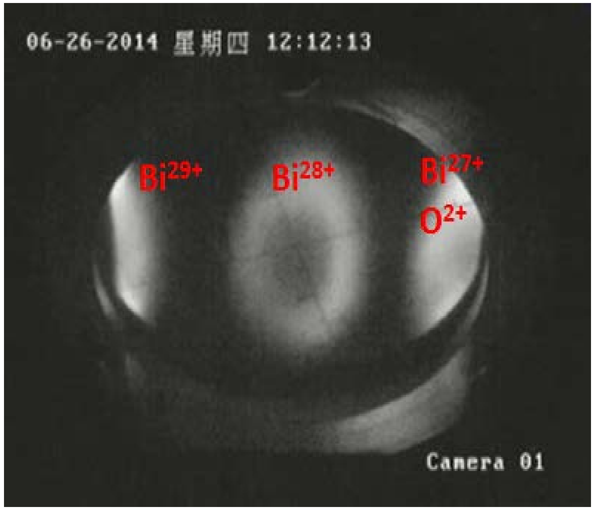
- Plasma Chamber: Stainless steel, ID：Ø76 mm
- RF Frequency: double 18 GHz
- Maximum RF Power: 1.1 kW
- Extraction High Voltage: 23 kV
- Plasma Electrode Aperture: Φ10 mm
- Puller Electrode Aperture: Φ16 mm
- FC Negative Biased Voltage: -150 V
- X-Slits: 20 mm
- Y-Slits: 60 mm
- Ion Species: Bi^{28+}

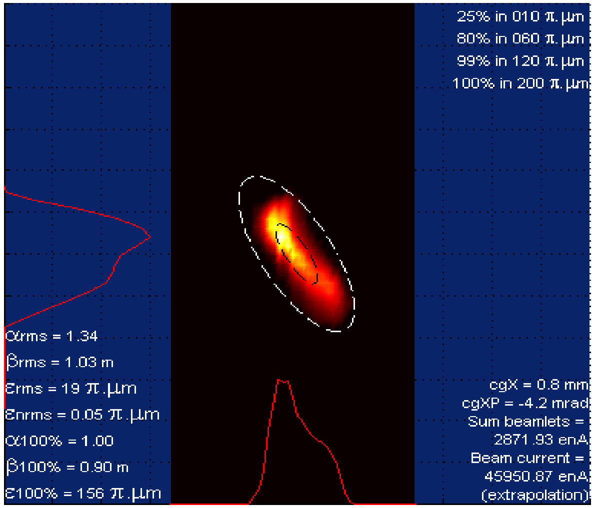
For lower intensity beam

(Bi^{28+}= 20 euA)



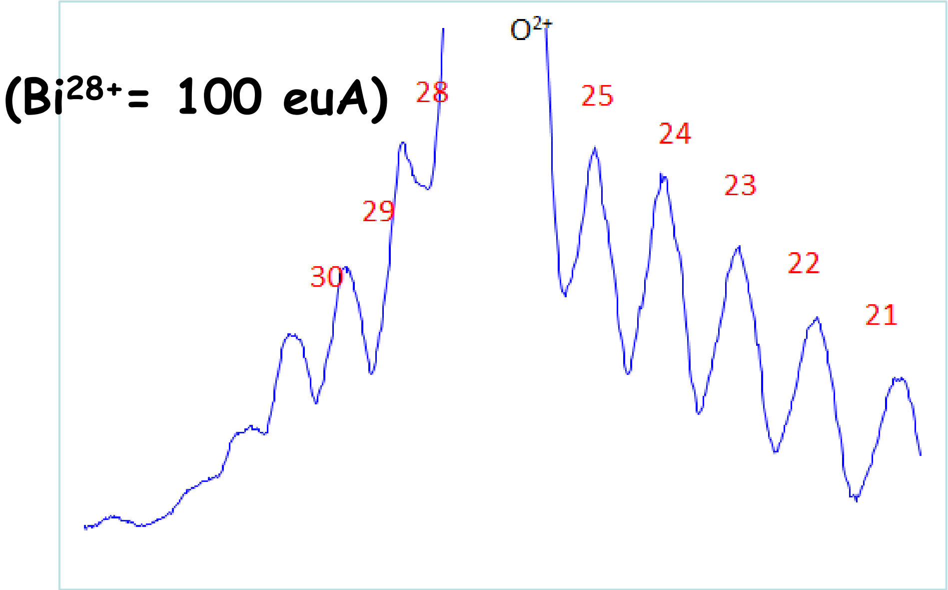
Frequency(GHz)	18
RF power (kW)	0.8
Extraction Voltage (kV)	23
Beam loading (emA)	2.4
Beam current of Bi^{28+} (euA)	20

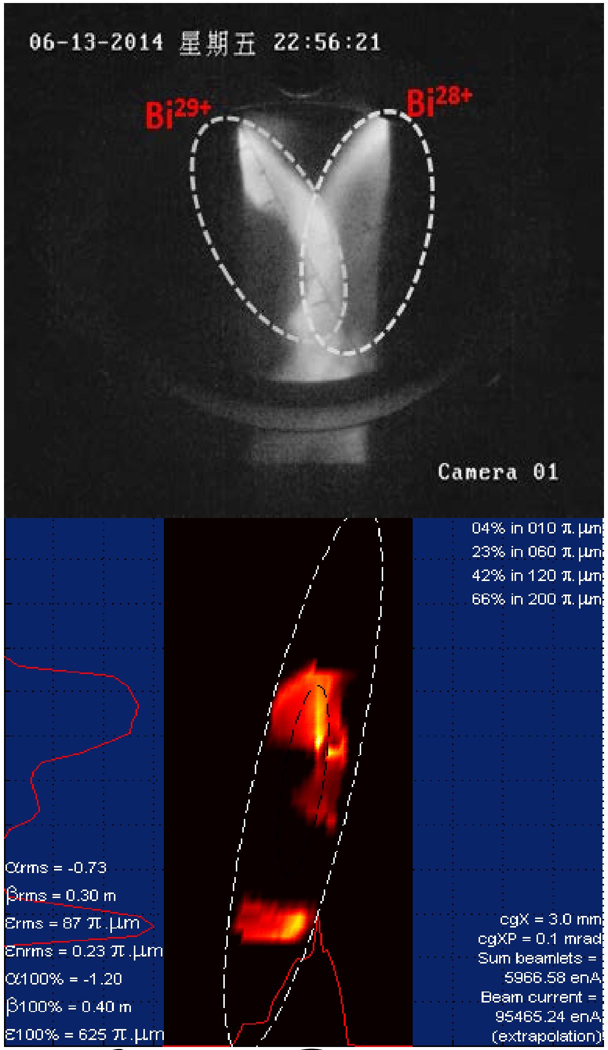




In case of low intensity, the beam hollow appeared

For higher intensity beam





Frequency (GHz)	18
RF power (kW)	0.8
Extraction Voltage (kV)	23
Beam loading (emA)	5.8
Beam current of Bi^{28+} (euA)	100

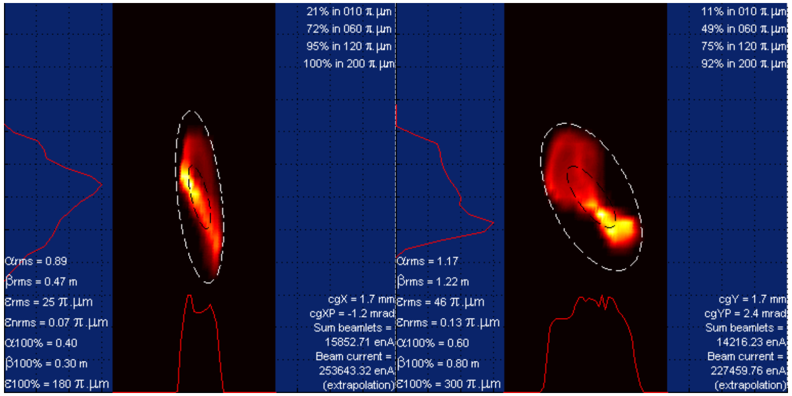
The total beam current of 5.8 emA from ECRIS, and the target beam (Bi^{28+}) cannot be clearly separated

Outline

- **Problems in the previous A/Q selection system**
- **PIC simulation of space charge effects of multi-species ions beam**
- **Modified A/Q selector for high intense ions beam**
- **Beam experiments**

Beam parameters of LECR4

Ar^{8+}= 210 euA



Estimated beam parameters at the exit of LECR4

	Case1 (0euA)	case2 (70euA)	case3 (210euA)
β_x (mm/mrad)	0.13	0.1447	0.39
α_x	-0.45	-0.736	-1.38
β_y (mm/mrad)	0.11	0.1631	0.32
α_y	-1.53	-2.14	-5.3

$\varepsilon_{x,rms}$=25 π um $\varepsilon_{y,rms}$=46 π um

- The beam parameters are calculated indirectly according to the measured beam emittances at the slits position.
- The beam parameters is variable for different ion species and different ion source conditions.
- Parameters above is only used in the following simulation as reference, which is in reasonable range.

The initial beam is asymmetrical at the exit of LECR4

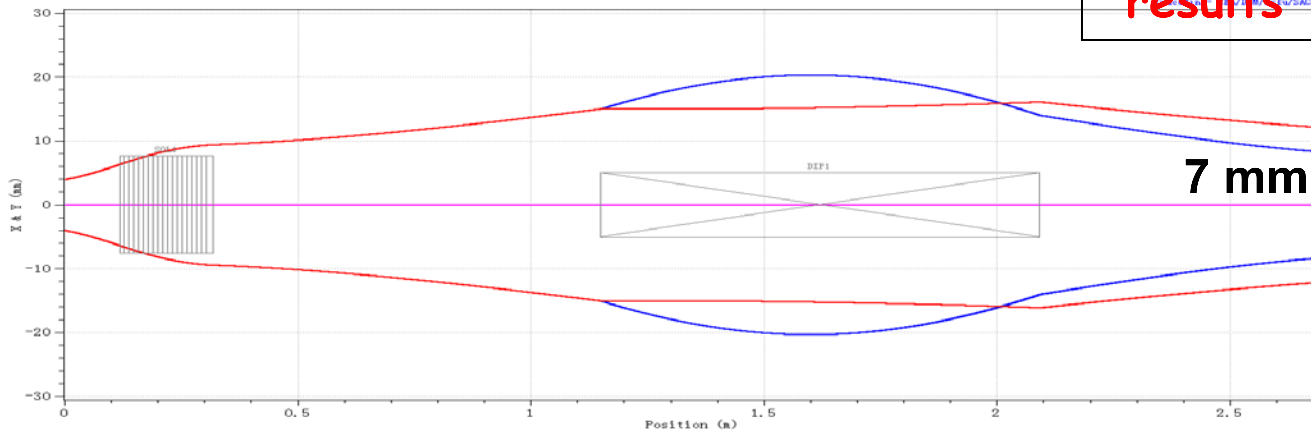
Beam matching conditions

Original case: Symmetrical input beam

Tracewin results

Twiss parameters

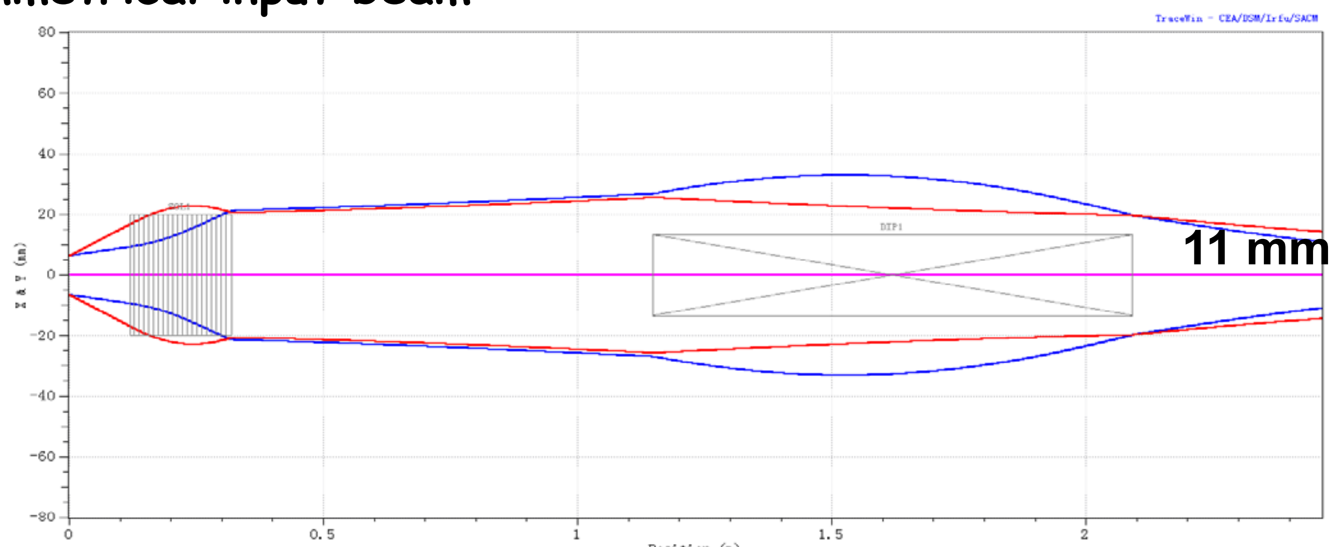
AlphaX	-0.5	
BetaX	0.15	mm/pi.mrad
AlphaY	-0.5	
BetaY	0.15	mm/pi.mrad



Updating case: Non-symmetrical input beam

Twiss parameters

AlphaX	-1.38	
BetaX	0.4	mm/pi.mrad
AlphaY	-5.3	
BetaY	0.4	mm/pi.mrad



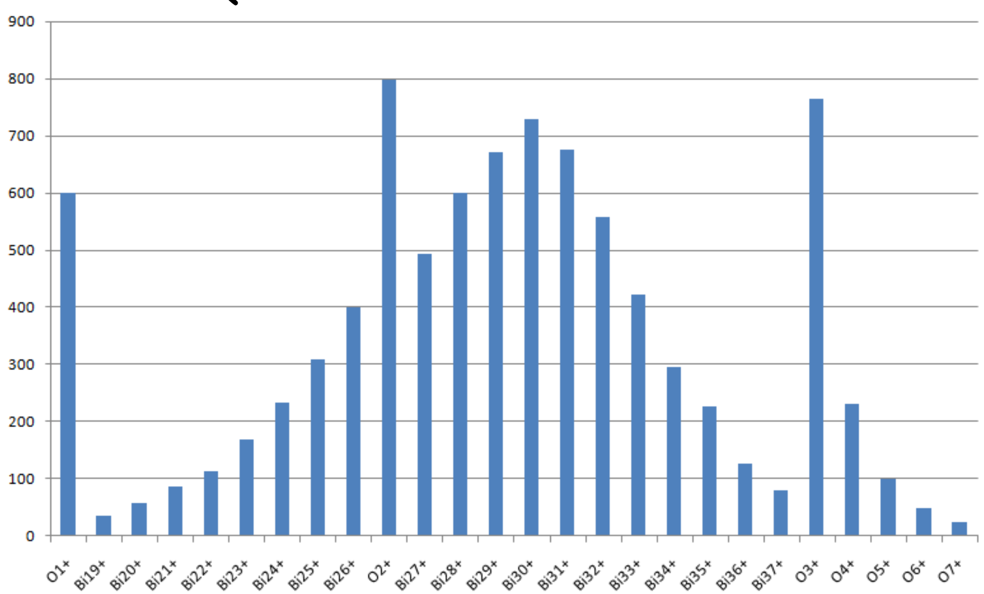
This lattice design is not optimized for non-symmetrical input beam

The PIC tracking

Revised BEAMPATH

- The Tracewin code is used for single beam.
- The PIC code has been developed based on Beampath for simulation of high intense mixed heavy ion beams.

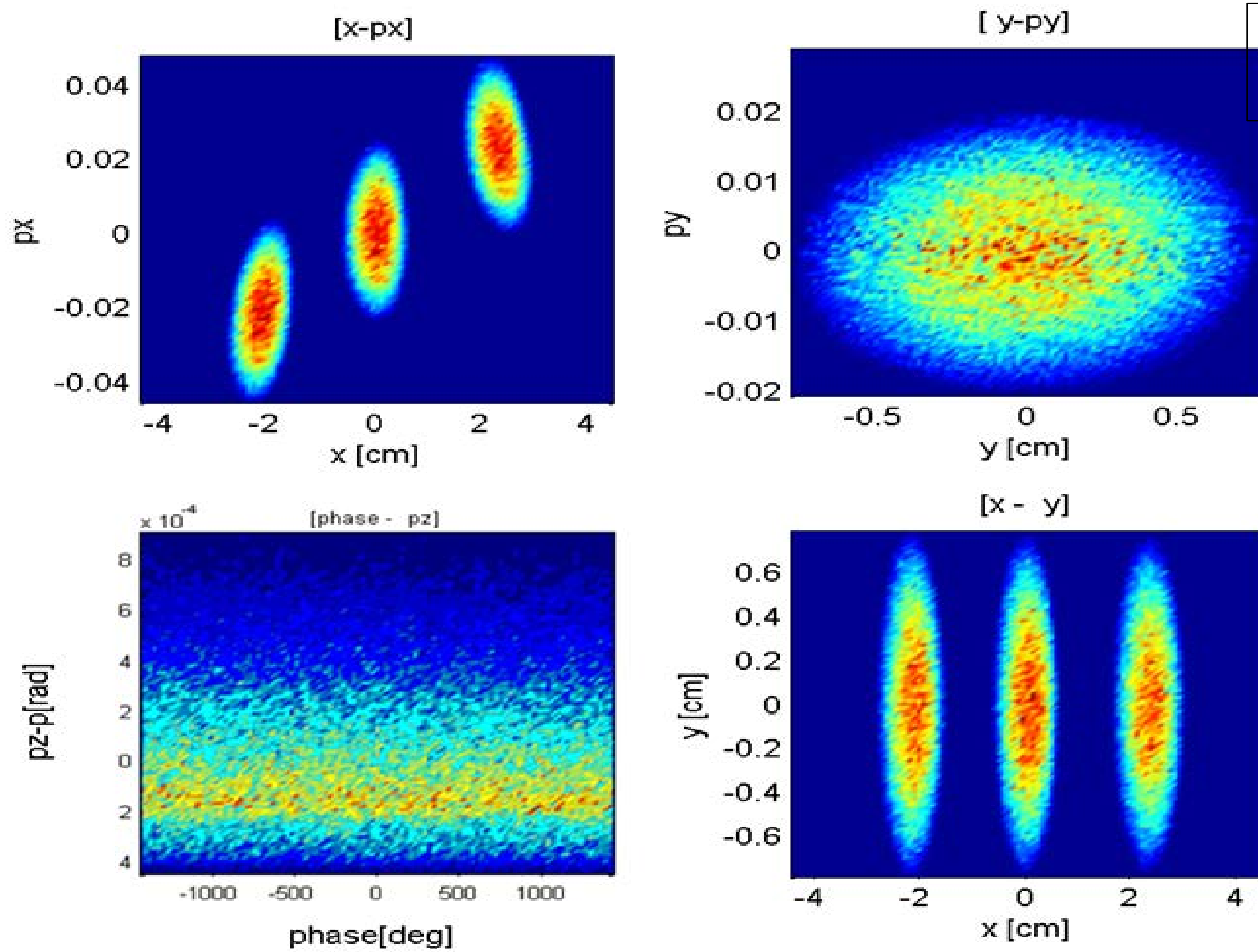
The intensity distribution of different Q/A ions in the simulation



The initial beam includes 26 different Q/A values, Bi^{19+} to Bi^{37+} and O^{1+} to O^{7+}, according to the measurement results of LECR4.

Symmetrical w/o space charge

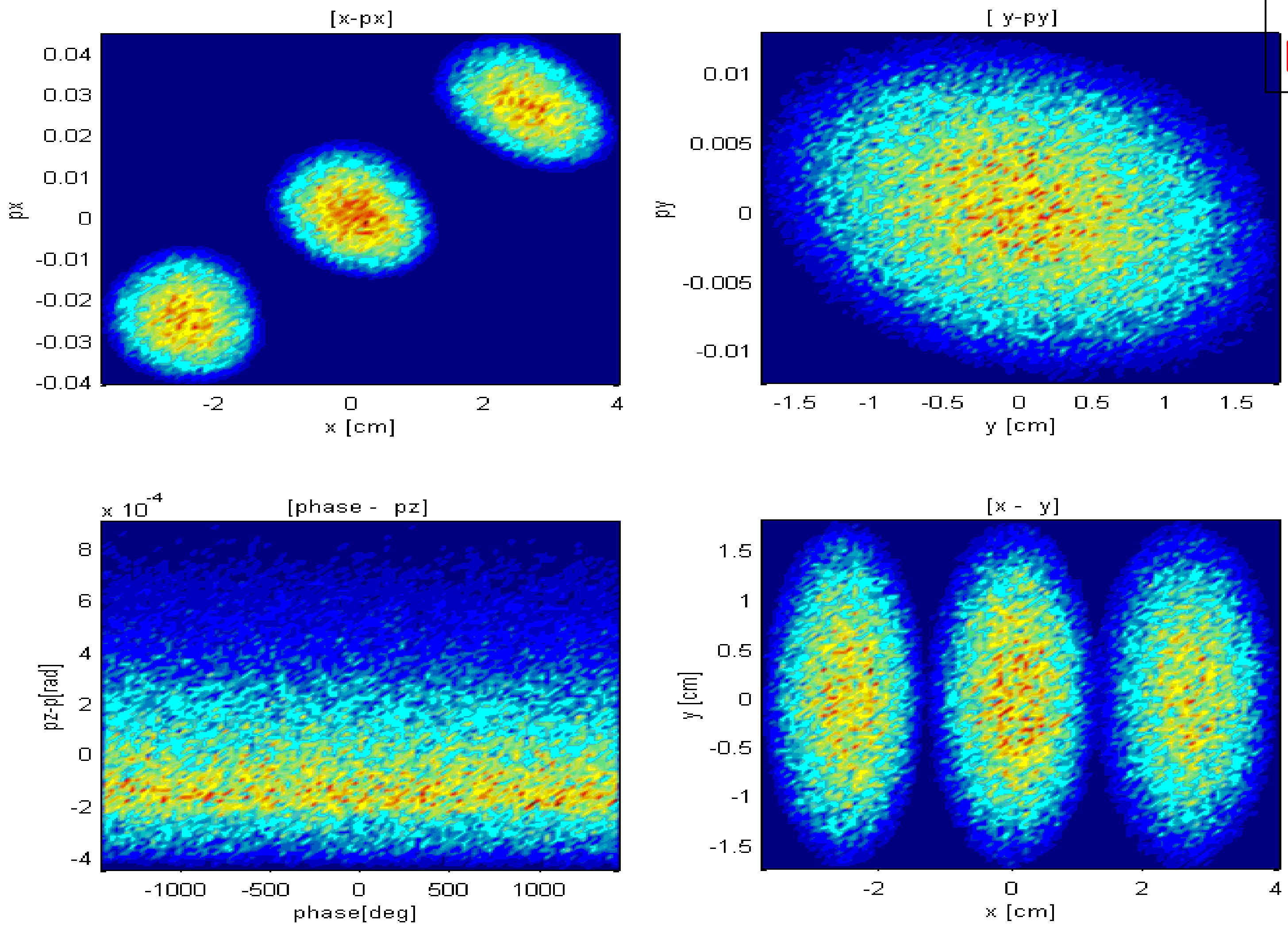
Revised BEAMPATH



In case of symmetrical input beam without space charge, the target beam can be separated clearly and the beam size is about 7 mm at the slits

Non-symmetrical w/o space charge

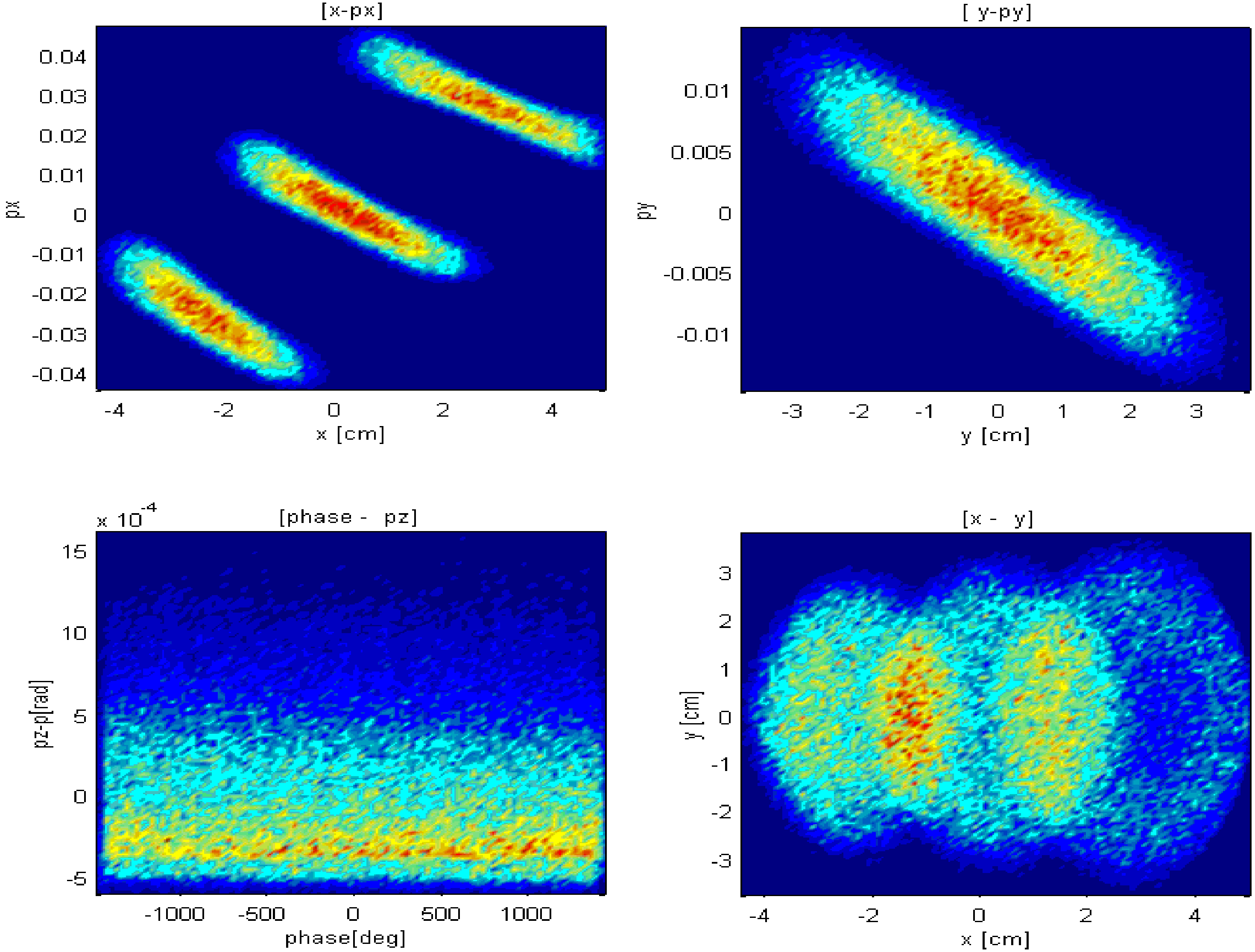
Revised BEAMPATH



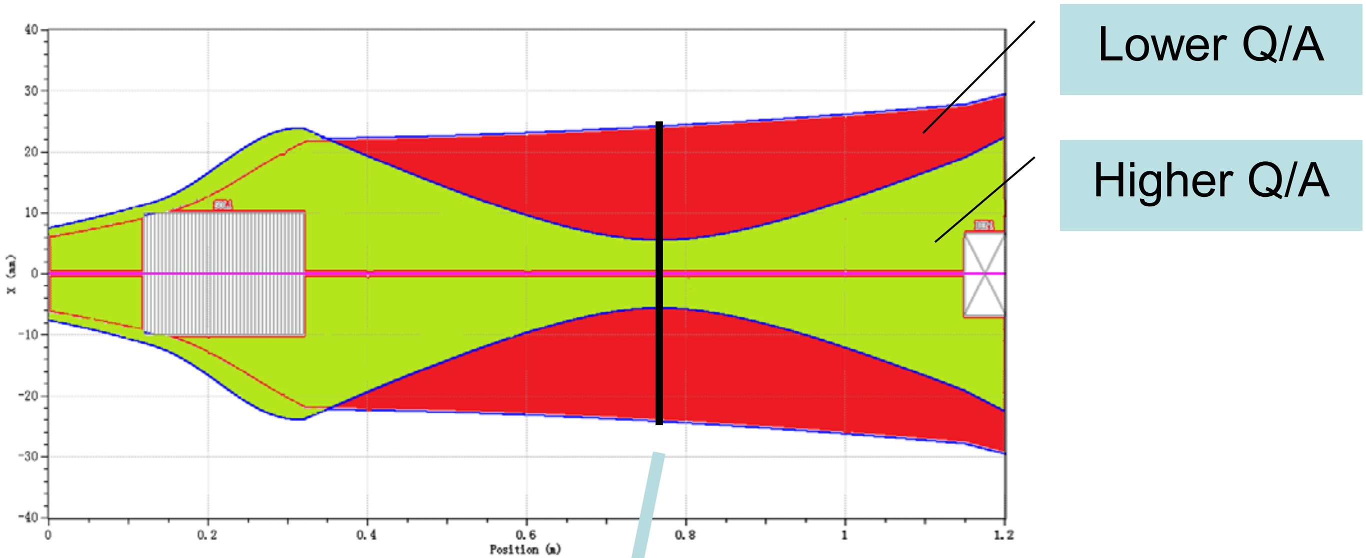
In case of no space charge, the target beam can still be separated clearly

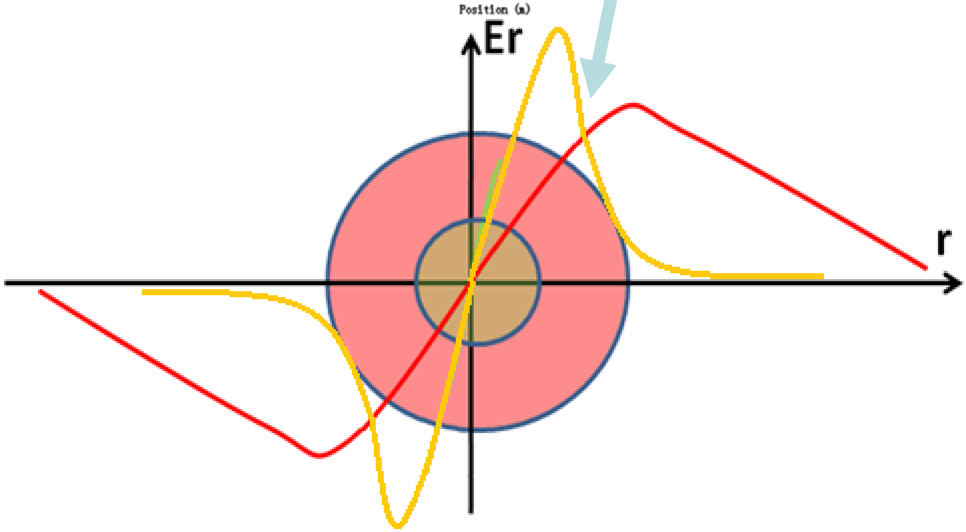
Non-symmetrical with space charge

Non-symmetrical input beam with beam current of 5.8 emA and space charge neutralization degree of 0.82; beam hollow appeared.



An explanation of “hollow”





Space charge force distributions

The sharp focused higher Q/A beam components pushed the lower Q/A beam radially outwards to form the beam “hollow” of desired beam.

Outline

- **Problems in the previous A/Q selection system**
- **PIC simulation of space charge effects of multi-species ions beam**
- **Modified A/Q selector for high intense ions beam**
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Considerations of Q/A selector on high intensity low energy heavy ion beams

- **Momentum resolution**
  - **The distance between heavy ions with the adjacent charge state at the slits position is larger than the beam size.**

$$\Delta x \approx (1+\frac{L}{\rho_0})\cdot\frac{B\rho-(B\rho)_0}{B_0}$$

- **Acceptance**
  - **The maximum acceptance of Q/A selector, and the beam size at the slits meets:**

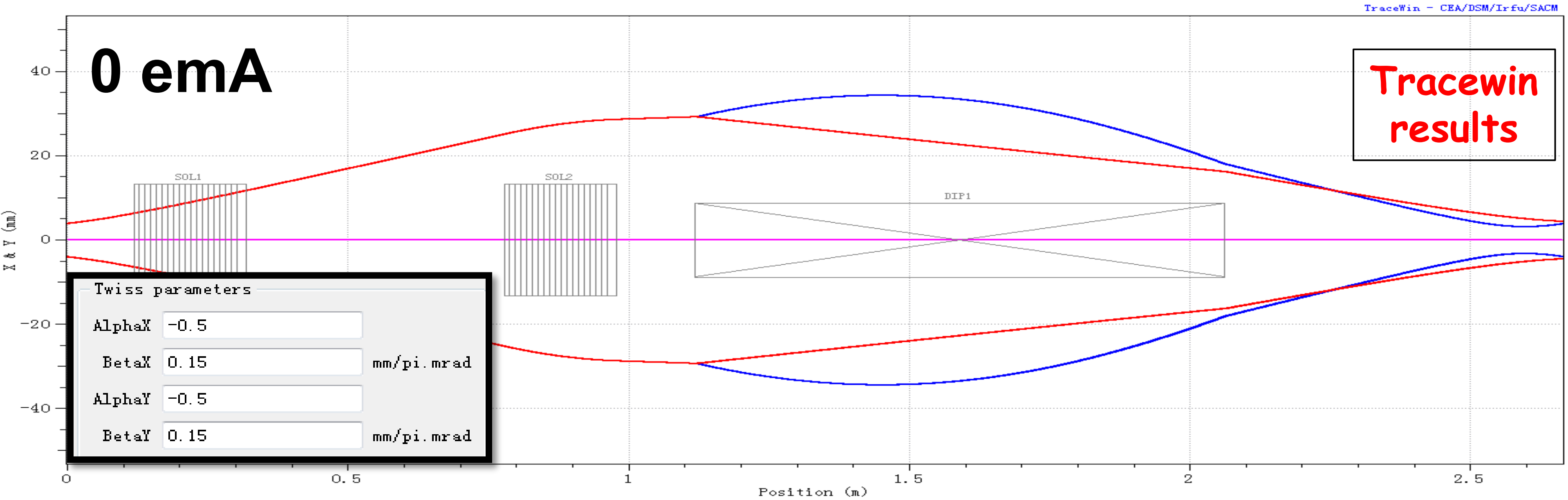
$$\sigma_{beam}=\sqrt{\varepsilon_{x,\mathrm{total}}\cdot\beta_x}<\Delta x/2$$

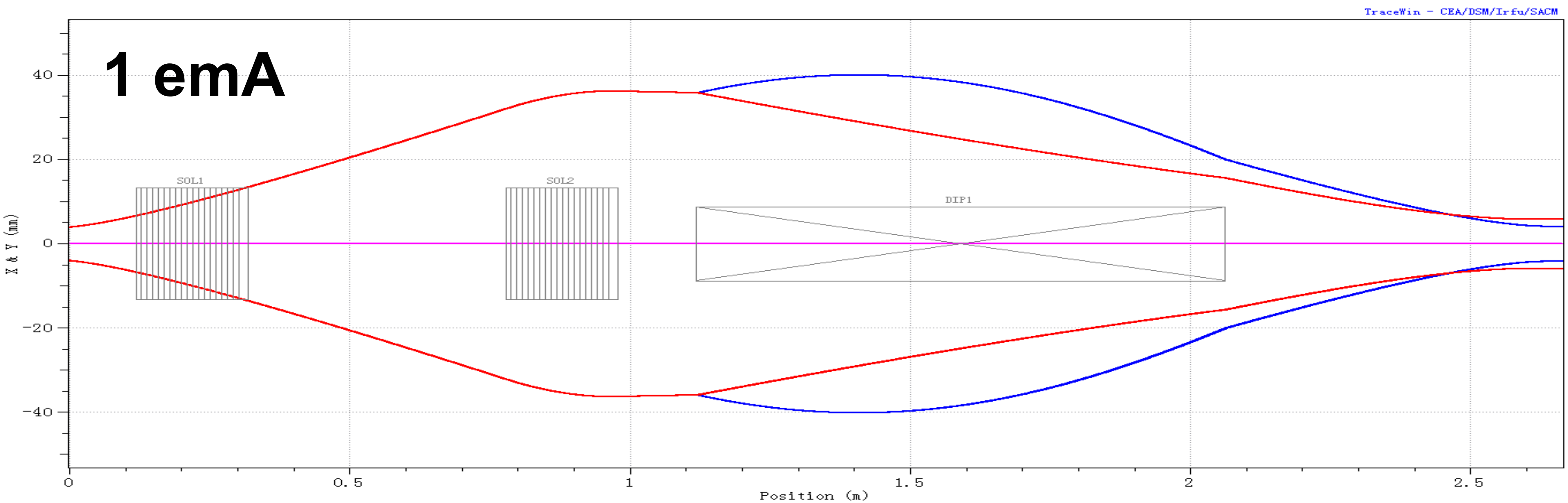
- **Space charge judgement**
  - **The effect of the space charge on the momentum resolution and transmission**

Single solenoid ➔ Double solenoid scheme

- Separated functions,
  - The first solenoid: control beam size in the beam channel, for the good transmission efficiency
  - The second solenoid: control the beam waist position and reduce the field strength of the 1st solenoid, suppressing the "short foci" effect.
- Opposite polarity,
  - Eliminate the beam coupling in the transverse phase space.

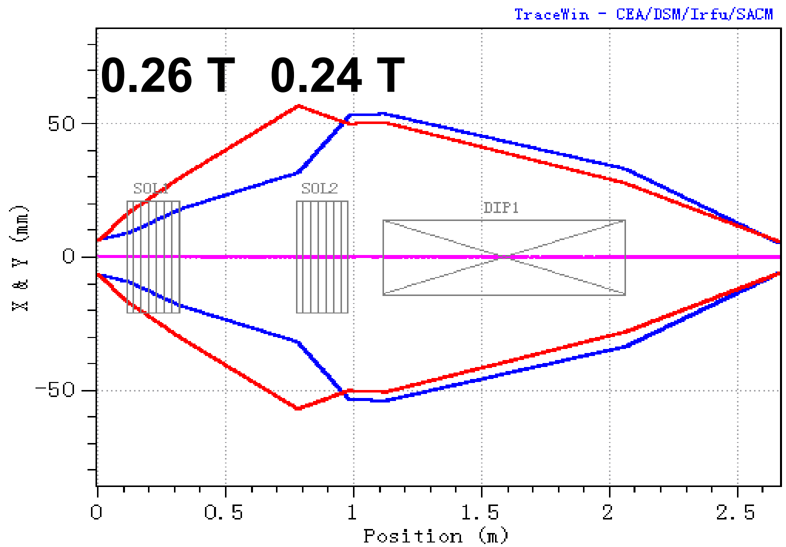
Case1: Symmetric input beam



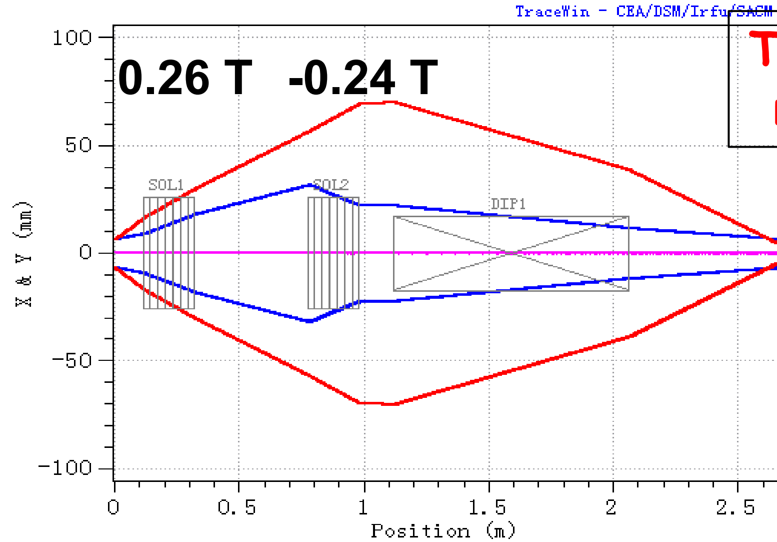


Case2: Non-symmetric(0 emA)

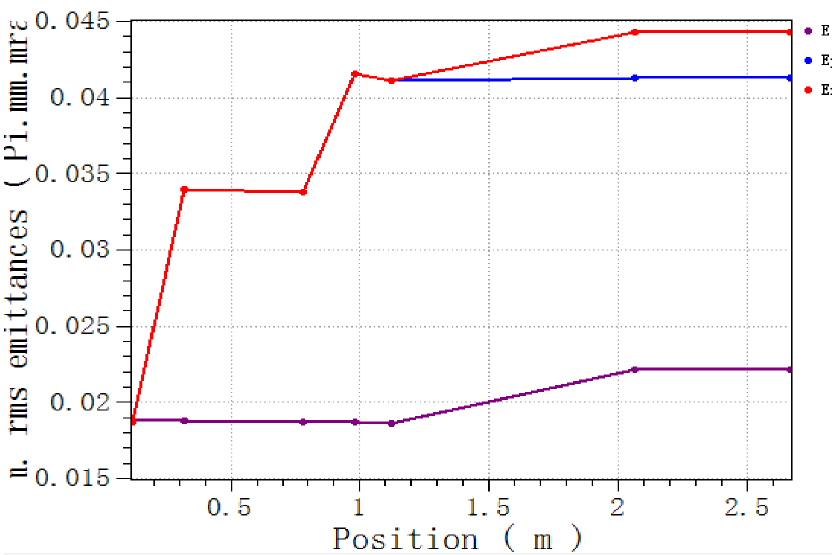
Double solenoid with same polarity

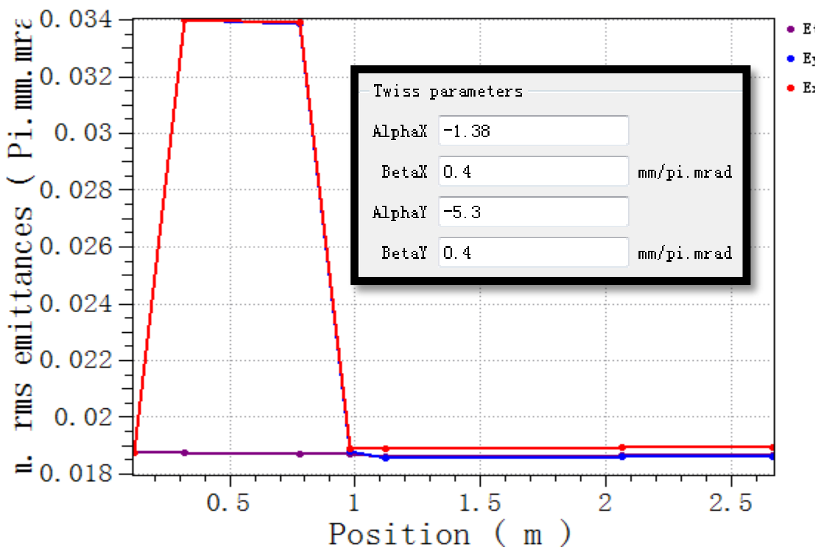


Double solenoid with opposite polarity



Tracewin results

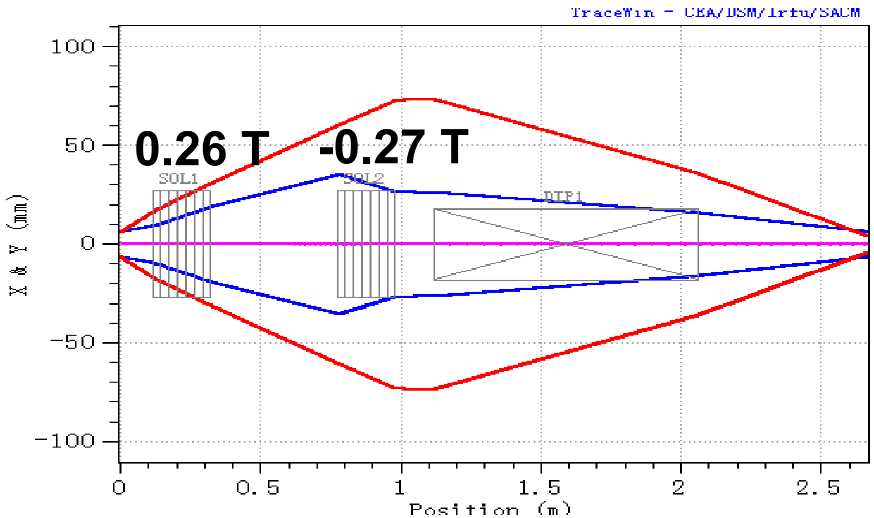


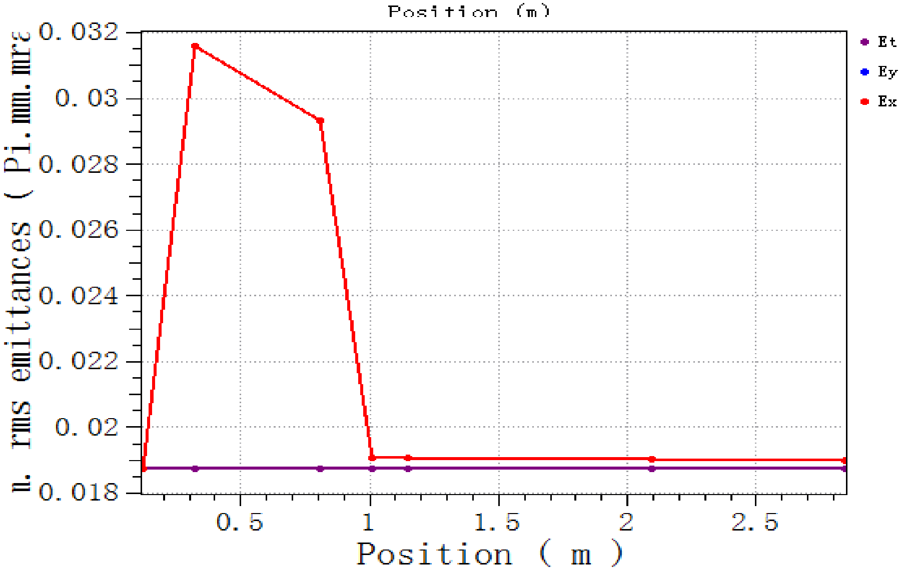


Case2: Non-symmetric(1 emA)

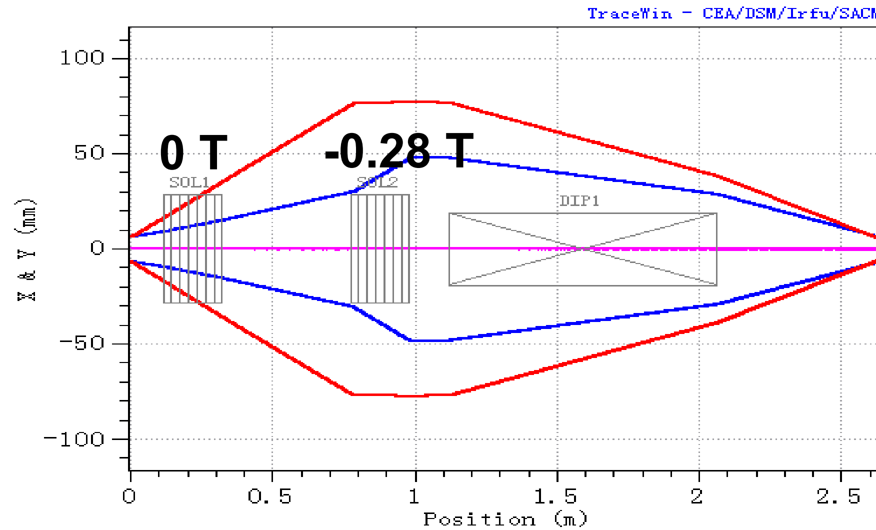
Tracewin results

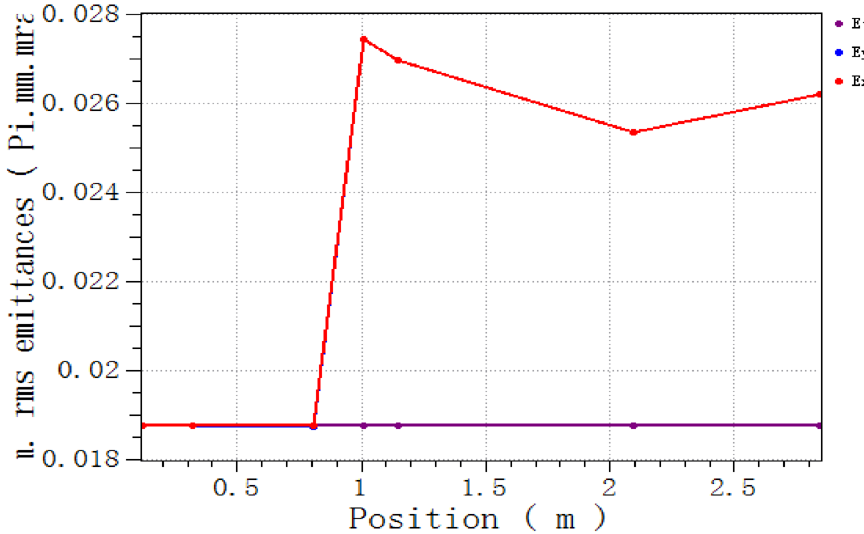
Double solenoid with opposite polarity





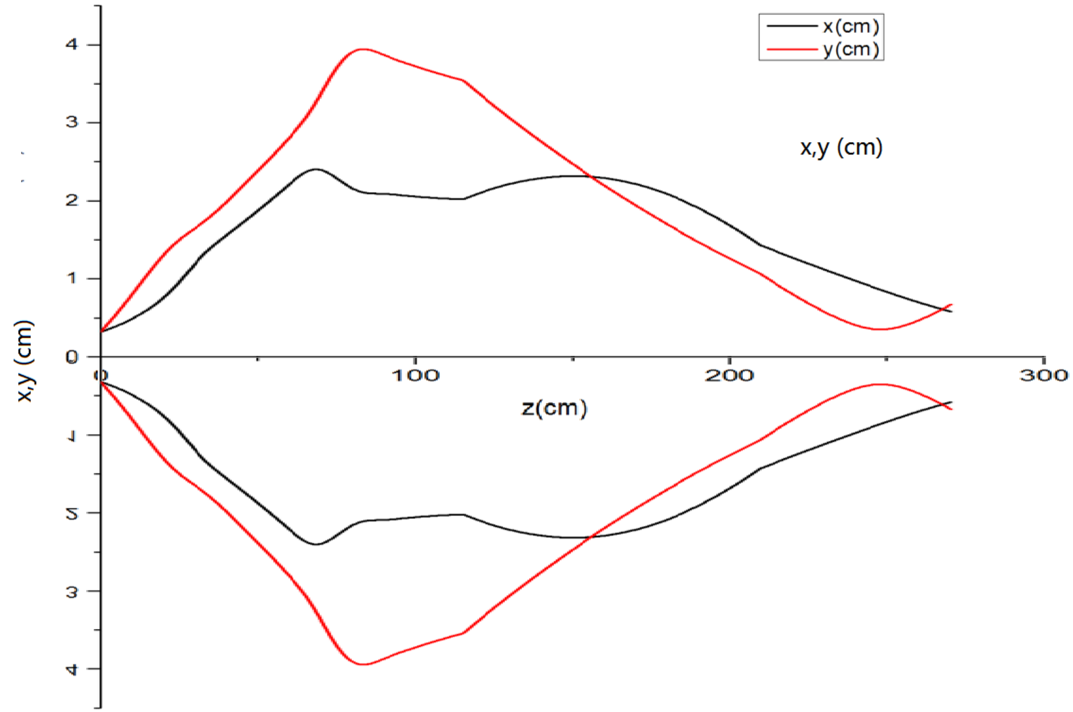
Single solenoid





PIC tracking(1 emA)

Revised BEAMPATH



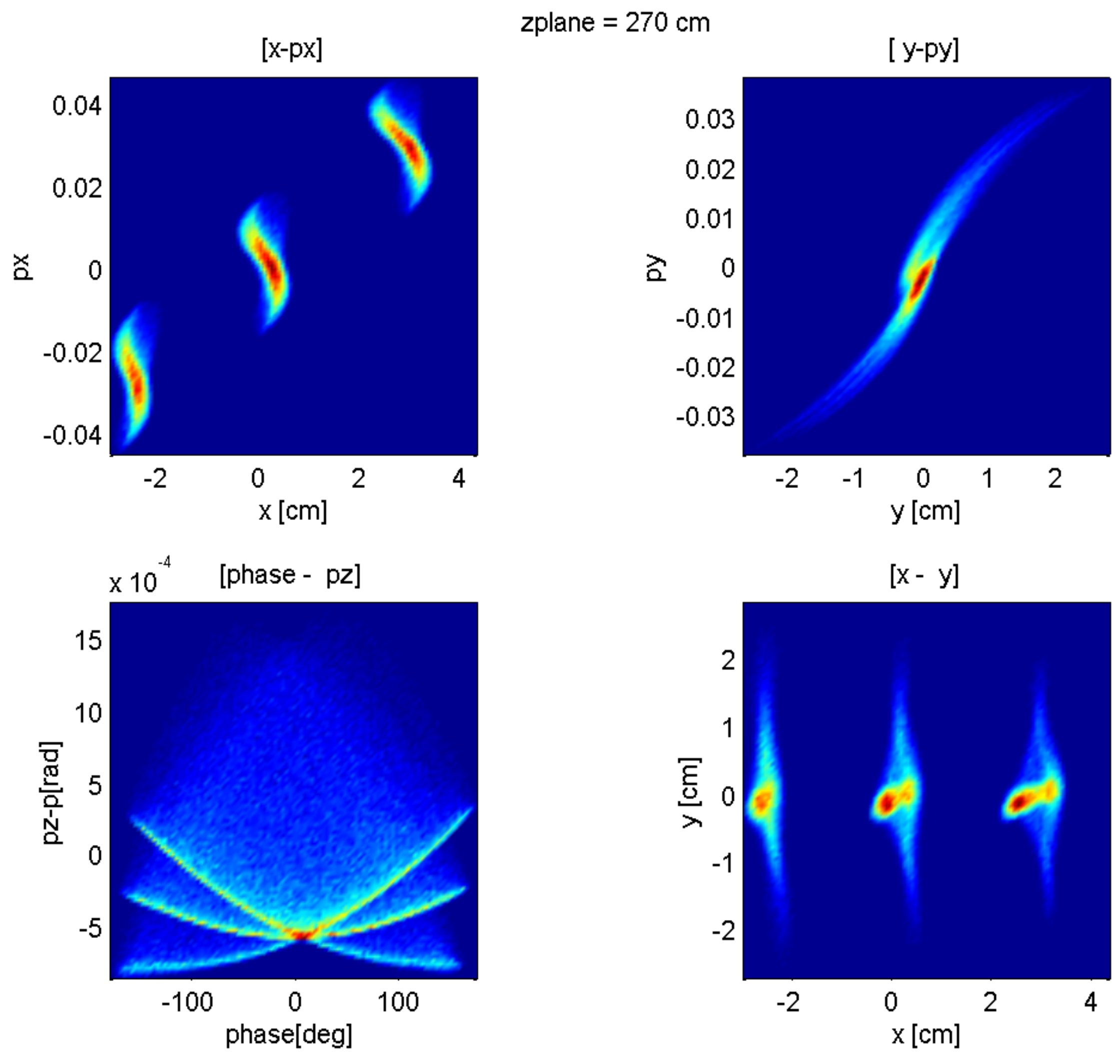
Beam profile along Q/A selector

- The total beam current is set to 1 emA
- 26 Q/A ion species
- The target beam can be separated clearly and the beam size is smaller than 10 mm at the slits.

B_{sol1}=0.31 T
B_{sol2}=-0.36 T

PIC tracking(1 emA)

Revised BEAMPATH



- The vertical emittance growth of ~100%, horizontal emittance growth of ~50%.
- The field strength of the second solenoid increase by 33% compared to that for single ion species.
- Serious distortion in the x-y space, the effect of high-order nonlinear space charge of mixed heavy ions beam cannot be ignored.

Outline

- Problems in the previous A/Q selection system
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- Modified A/Q selector for high intense ions beam
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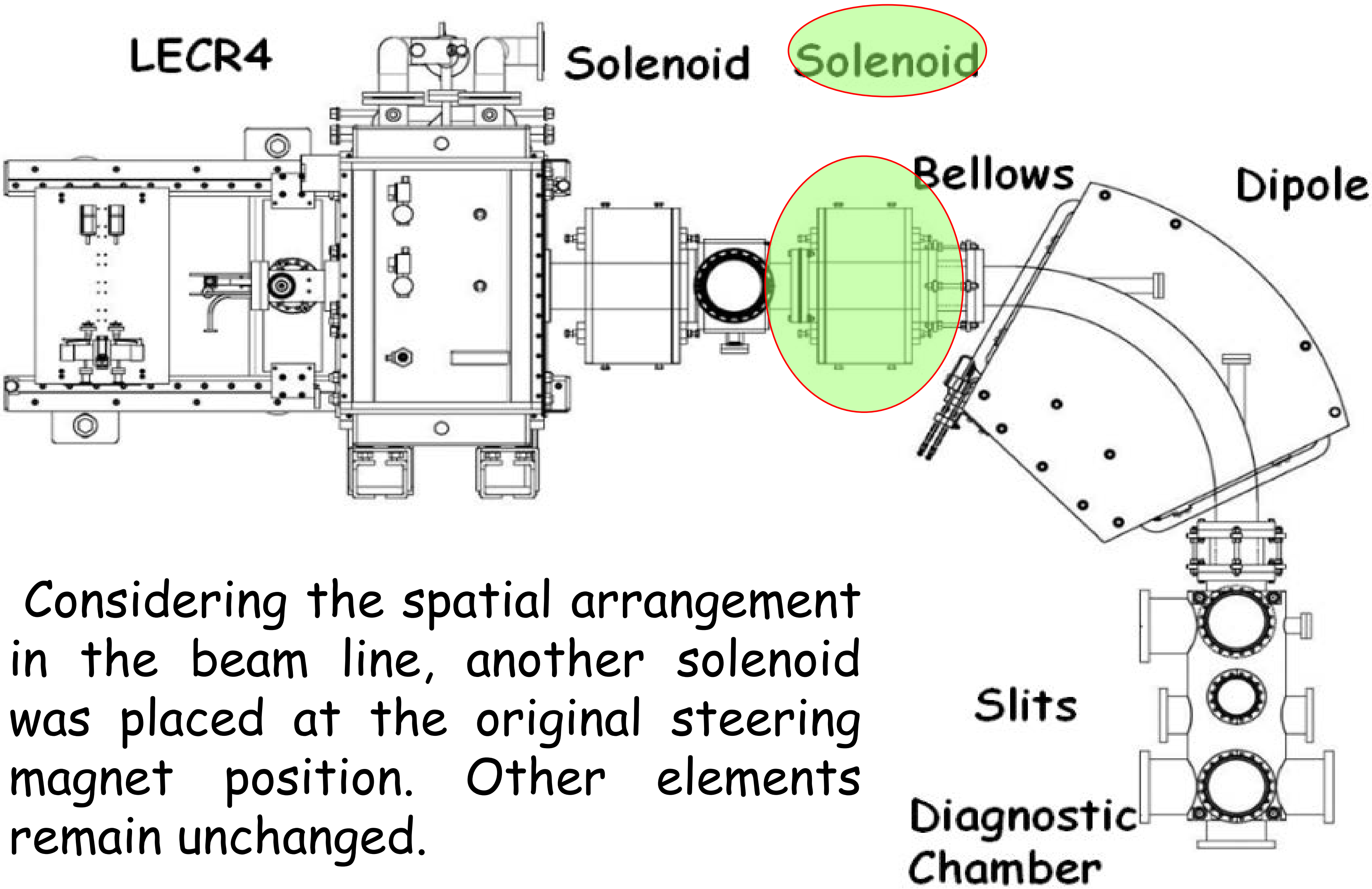
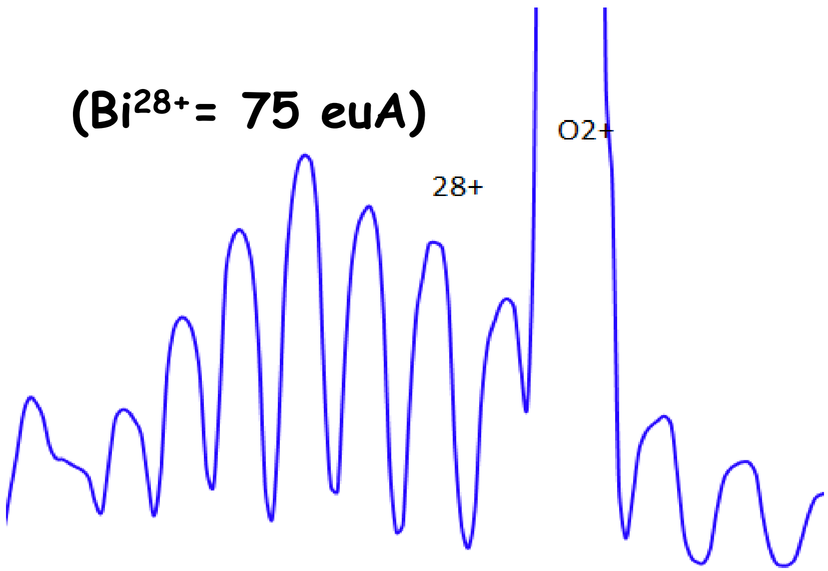
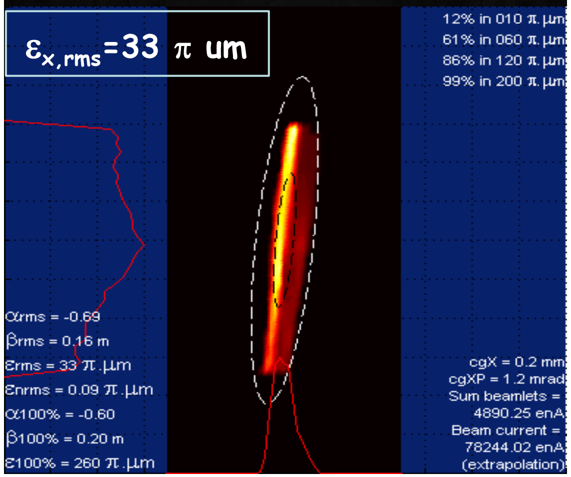
Modified Q/A Selector

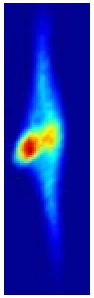


Considering the spatial arrangement in the beam line, another solenoid was placed at the original steering magnet position. Other elements remain unchanged.

Experimental Results







Frequency (GHz)	18
RF power (kW)	0.8
Extraction Voltage (kV)	23
Beam loading (emA)	5.5
Beam current of Bi^{28+} (euA)	75

- The experimental results has a good agreement with the PIC simulations.
- Serious distortion in x-y space, the effect of high-order nonlinear space charge of mix heavy ions beam cannot be neglected.

Summary and outlook

- **For high intensity high charge state ECRIS that required by future heavy ion accelerator projects, Q/A selector is still very challenging task.**
- **Space charge field of mixed heavy ion beams plays key role in the beam "hollow" formation.**
- **Double solenoid scheme is proved to be able to eliminate the beam "hollow" formation and reach good momentum resolution.**

Thanks for your attentions!