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Recombination of Analyzed Multiple-Charge State Heavy-Ion Beams Extracted from an ECRIS

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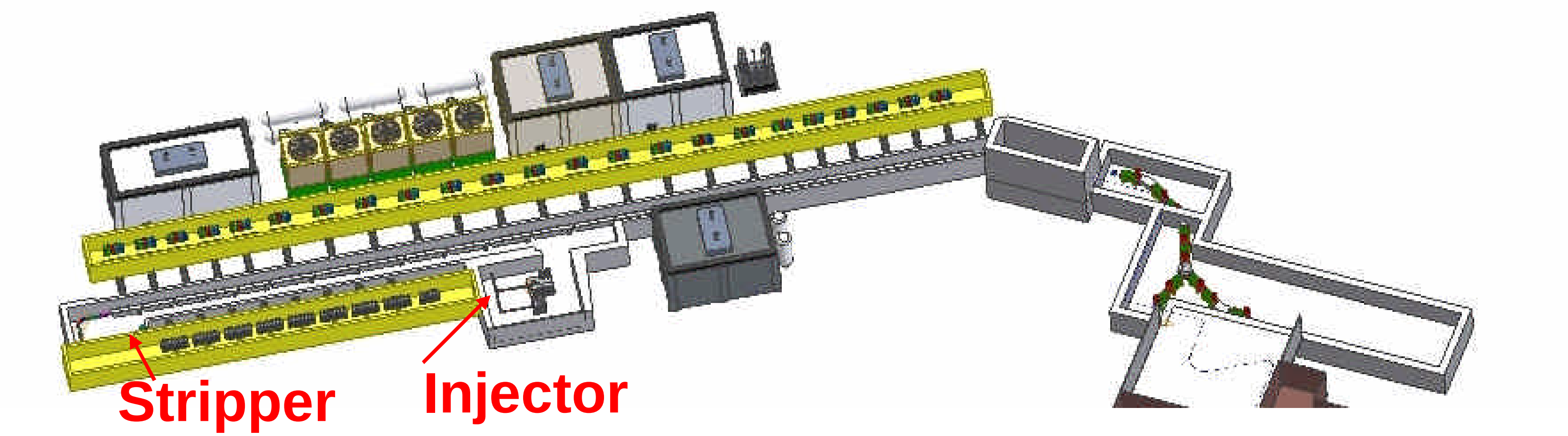
Outline

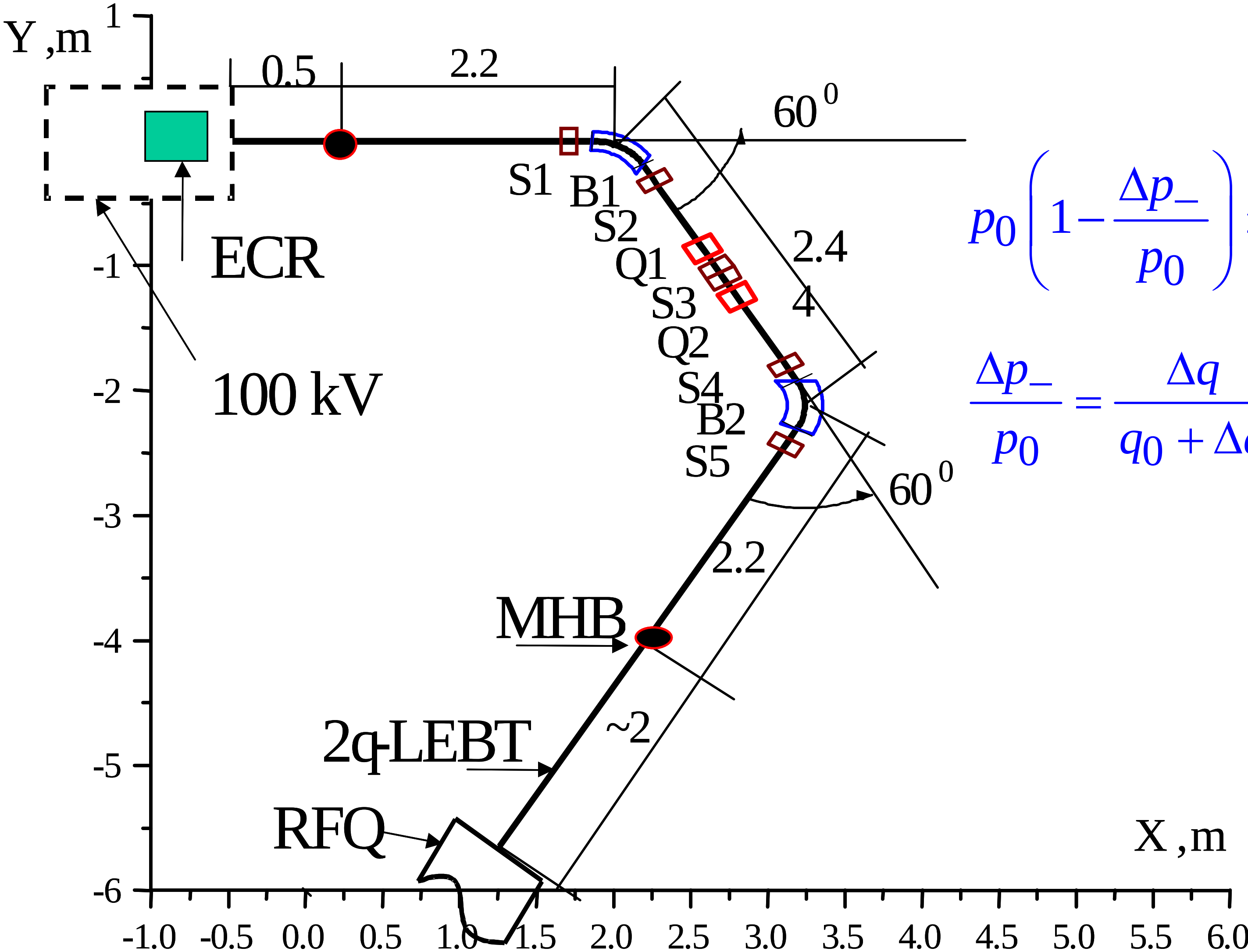
- Motivation
- Short history
- Prototype injector for FRIB
- 2Q-LEBT design
- Experimental apparatus
- Tuning procedure
- Experimental results
- Extended applications
- Conclusion

Facility for Rare Isotope Beams in the U.S.A.

- Beam power – 400 kW
- Ions: from hydrogen to uranium
- Energy: 200 MeV/u uranium, 600 MeV protons
- Total voltage - 850 MV
- Proposed plan for uranium
  - Dual charge state uranium, $^{238}U^{34+}$ and $^{238}U^{35+}$ from the ECRIS, 6 pμA each charge state
  - Accelerate 2q beam up to 17 MeV/u and strip
  - Accelerate 5 charge states of uranium (77+,78+,79+,80+,81+) to 200 MeV/u



Original layout of the injector, developed with COSY

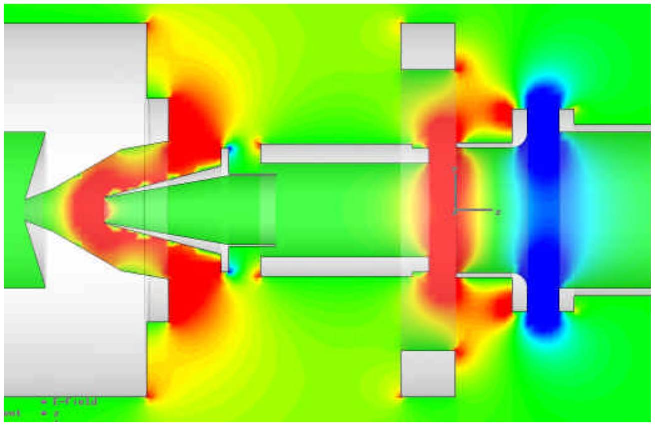


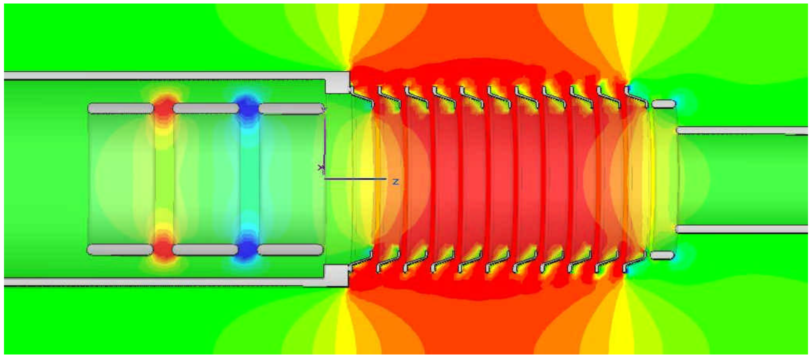
$$p_0\left(1-\frac{\Delta p_-}{p_0}\right)\le p\le p_0\left(1+\frac{\Delta p_+}{p_0}\right)$$

$$\frac{\Delta p_-}{p_0}=\frac{\Delta q}{q_0+\Delta q},\quad \frac{\Delta p_+}{p_0}=\frac{\Delta q}{q_0-\Delta q}$$

TRACK model

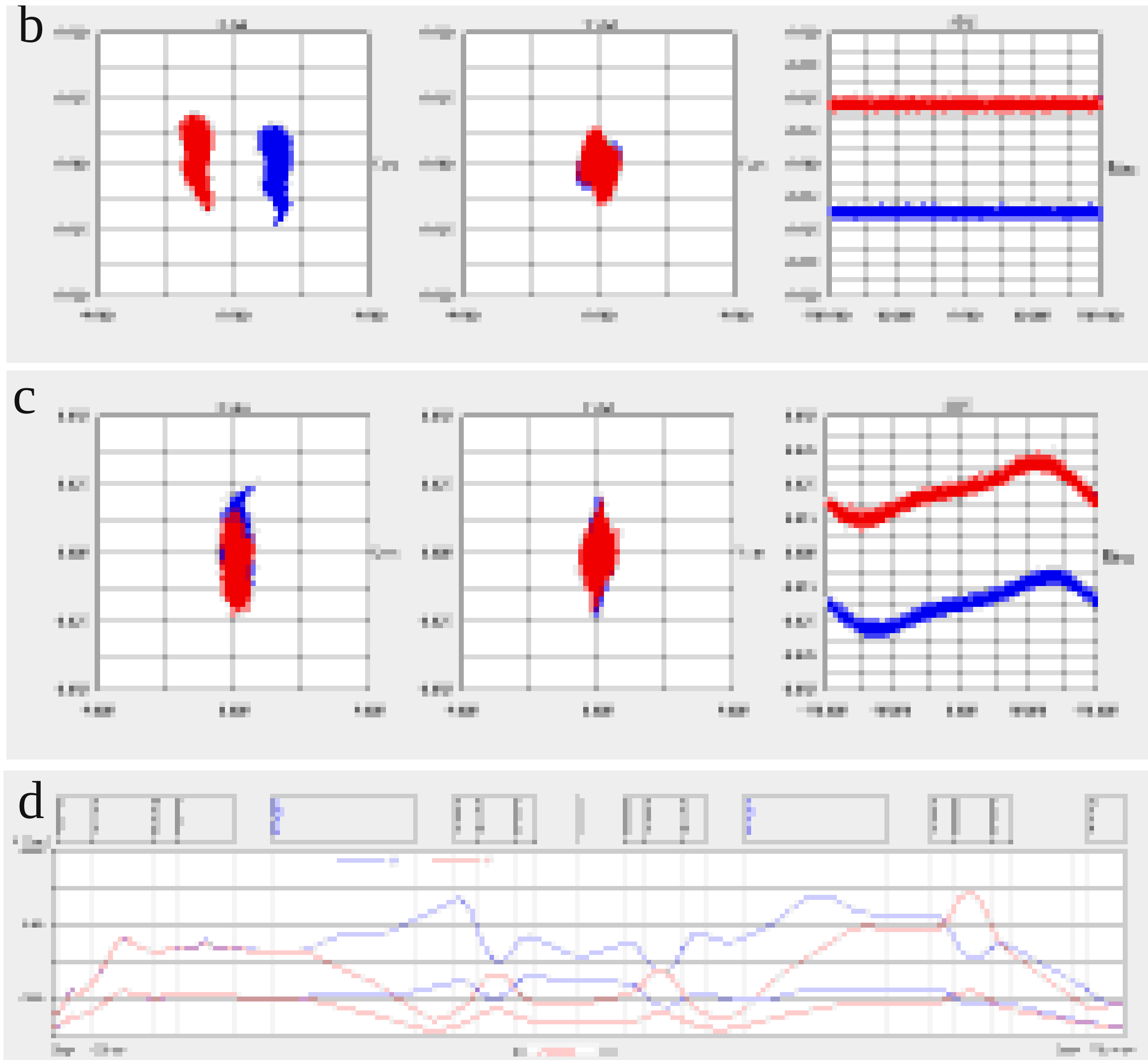
- 3D fields in the ECR extraction region
  - Combined electrostatic and magnetic fields
- Einzel lens
- Accelerating tube
- Bending magnet
  - Edge focusing is essential for high current beams
- Total beam current ~4 mA
  - 17 different q/A



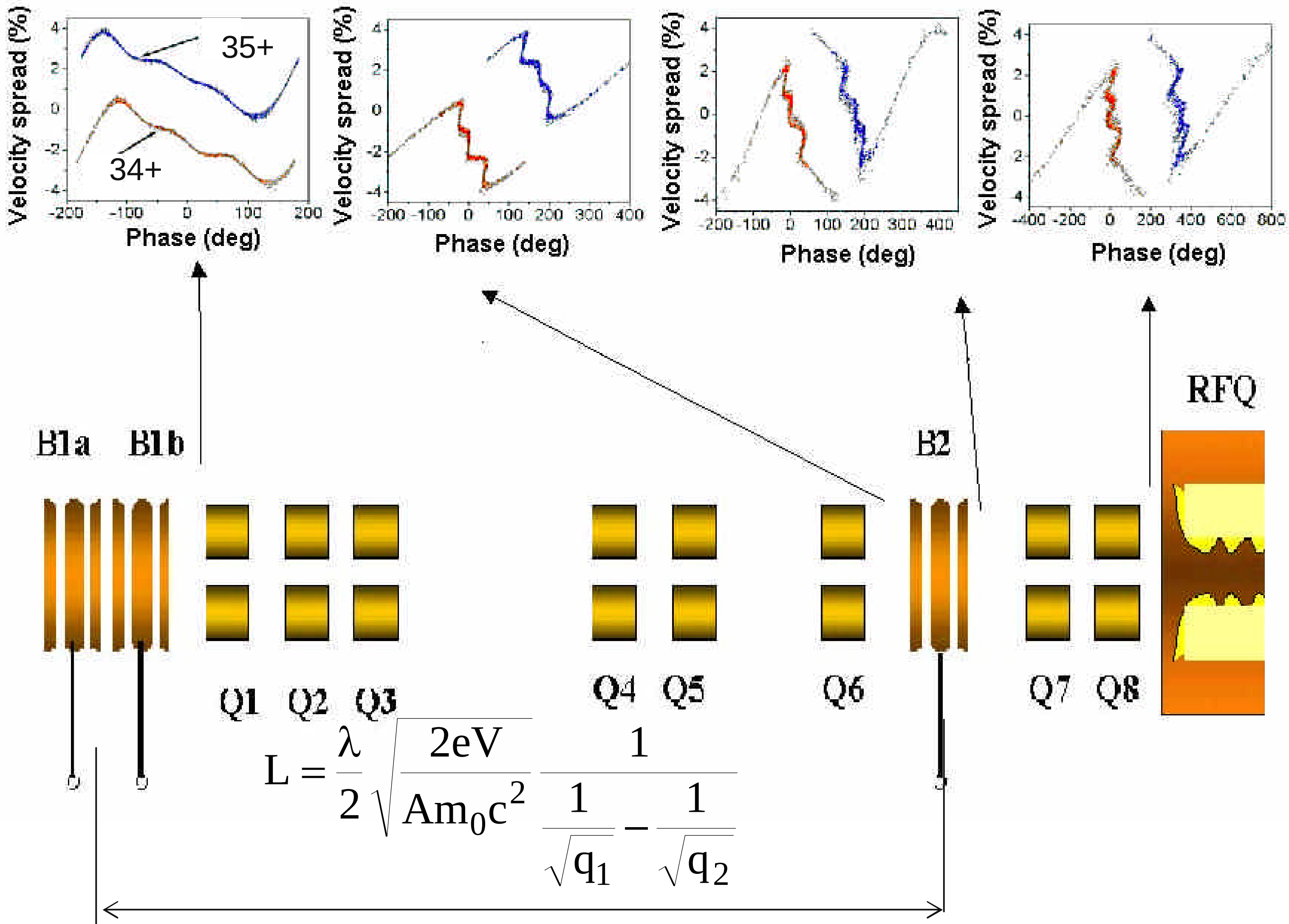


Phase space plots and beam envelope in the 2Q-LEBT

Simulations with the TRACK code

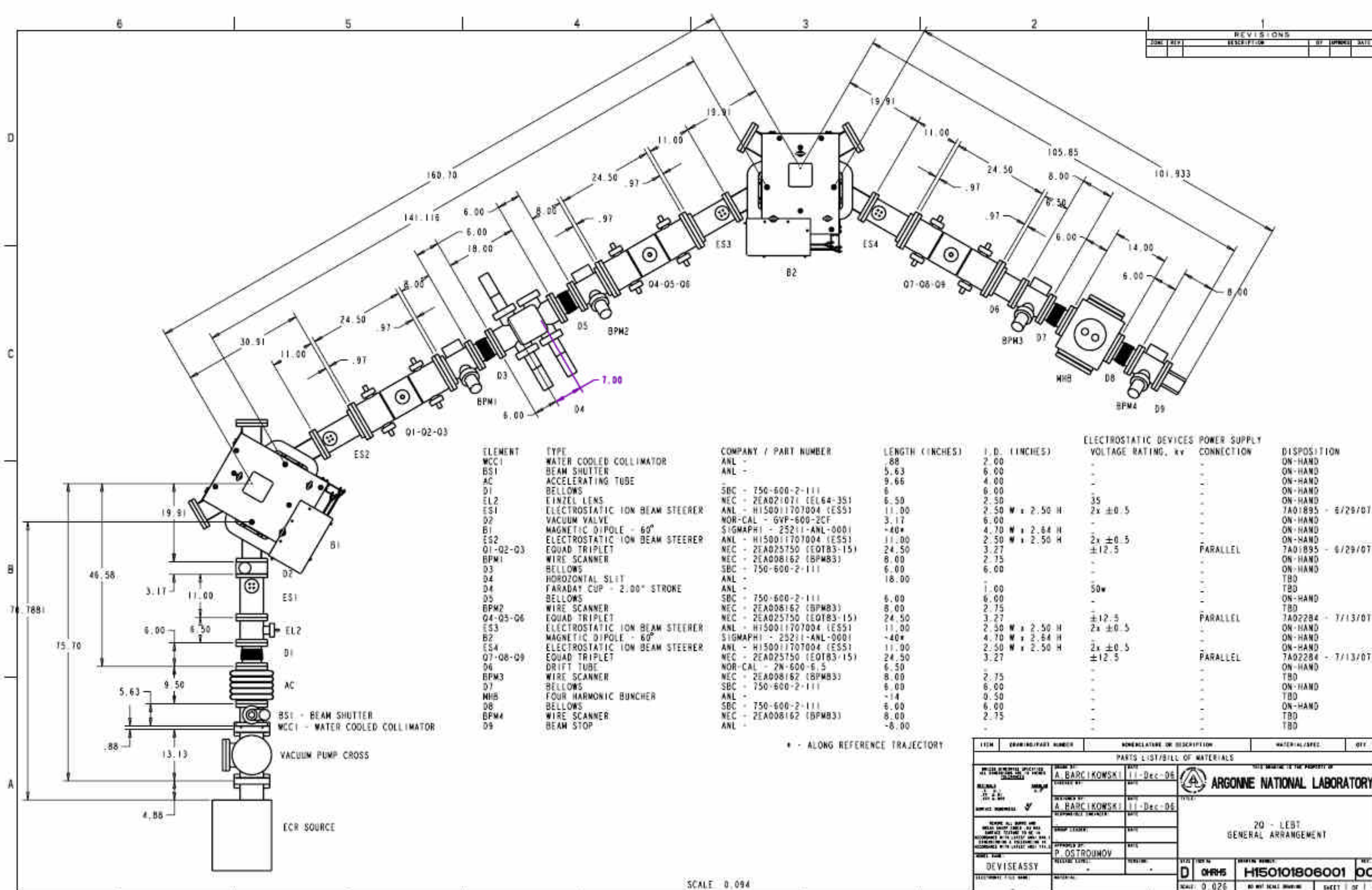


Longitudinal phase space plots of two-charge state uranium beam upstream of the RFQ



$$L = \frac{\lambda}{2}\sqrt{\frac{2eV}{Am_0c^2}}\,\frac{1}{\frac{1}{\sqrt{q_1}}-\frac{1}{\sqrt{q_2}}}$$

Achromatic beam transport system



ELEMENT	TYPE	COMPANY / PART NUMBER	LENGTH (INCHES)	I.D. (INCHES)	ELECTROSTATIC DEVICES VOLTAGE RATING, kv	POWER SUPPLY CONNECTION	DISPOSITION
WCC1	WATER COOLED COLLIMATOR	ANL -	.88	2.00	-	-	ON-HAND
BS1	BEAM SHUTTER	ANL -	5.63	6.00	-	-	ON-HAND
AC	ACCELERATING TUBE	-	9.66	4.00	-	-	ON-HAND
D1	BELLOWS	SBC - 750-600-2-111	6	6.00	-	-	ON-HAND
EL2	EINZEL LENS	NEC - 2EA021071 (EL64-35)	6.50	2.50	35	-	ON-HAND
ES1	ELECTROSTATIC ION BEAM STEERER	ANL - H15001170704 (ES5)	11.00	2.50 W x 2.50 H	2x ±0.5	-	7A01895 - 6/29/07
D2	VACUUM VALVE	NOR-CAL - GVP-600-2CF	3.17	6.00	-	-	ON-HAND
B1	MAGNETIC DIPOLE - 60°	SIGMAPHI - 25211-ANL-0001	~40*	4.70 W x 2.64 H	-	-	ON-HAND
ES2	ELECTROSTATIC ION BEAM STEERER	ANL - H15001170704 (ES5)	11.00	2.50 W x 2.50 H	2x ±0.5	-	ON-HAND
Q1-Q2-Q3	EQUAD TRIPLET	NEC - 2EA025750 (EQT83-15)	24.50	3.27	±12.5	PARALLEL	7A01895 - 6/29/07
BPM1	WIRE SCANNER	NEC - 2EA008162 (BPM83)	8.00	2.75	-	-	ON-HAND
D3	BELLOWS	SBC - 750-600-2-111	6.00	6.00	-	-	ON-HAND
D4	HOROZONTAL SLIT	ANL -	18.00	-	-	-	TBD
D4	FARADAY CUP - 2.00" STROKE	ANL -		1.00	50w	-	TBD
D5	BELLOWS	SBC - 750-600-2-111	6.00	6.00	-	-	ON-HAND
BPM2	WIRE SCANNER	NEC - 2EA008162 (BPM83)	8.00	2.75	-	-	TBD
Q4-Q5-Q6	EQUAD TRIPLET	NEC - 2EA025750 (EQT83-15)	24.50	3.27	±12.5	PARALLEL	7A02284 - 7/13/07
ES3	ELECTROSTATIC ION BEAM STEERER	ANL - H15001170704 (ES5)	11.00	2.50 W x 2.50 H	2x ±0.5	-	ON-HAND
B2	MAGNETIC DIPOLE - 60°	SIGMAPHI - 25211-ANL-0001	~40*	4.70 W x 2.64 H	-	-	ON-HAND
ES4	ELECTROSTATIC ION BEAM STEERER	ANL - H15001170704 (ES5)	11.00	2.50 W x 2.50 H	2x ±0.5	-	ON-HAND
Q7-Q8-Q9	EQUAD TRIPLET	NEC - 2EA025750 (EQT83-15)	24.50	3.27	±12.5	PARALLEL	7A02284 - 7/13/07
D6	DRIFT TUBE	NOR-CAL - 2N-600-6.5	6.50	-	-	-	ON-HAND
BPM3	WIRE SCANNER	NEC - 2EA008162 (BPM83)	8.00	2.75	-	-	TBD
D7	BELLOWS	SBC - 750-600-2-111	6.00	6.00	-	-	ON-HAND
MHB	FOUR HARMONIC BUNCHER	ANL -	~14	0.50	-	-	TBD
D8	BELLOWS	SBC - 750-600-2-111	6.00	6.00	-	-	ON-HAND
BPM4	WIRE SCANNER	NEC - 2EA008162 (BPM83)	8.00	2.75	-	-	TBD
D9	BEAM STOP	ANL -	~8.00	-	-	-	TBD

* - ALONG REFERENCE TRAJECTORY

Prototype Injector for FRIB

1- ECRIS (developed by D.Z. Xie, Rev. Sci. Inst., 73 (2), 2002, p. 531) in HV platform,
2 - 75-kV accelerating tube,
3 - isolation transformer,
4 – 60-deg bending magnet,
5 - Einzel lens,
6 - electrostatic triplet,
7 - electrostatic steering plates,
8 - rotating wire scanner,
9 - horizontal jaw slits,
10 - Faraday cup,
11 - emittance probe.

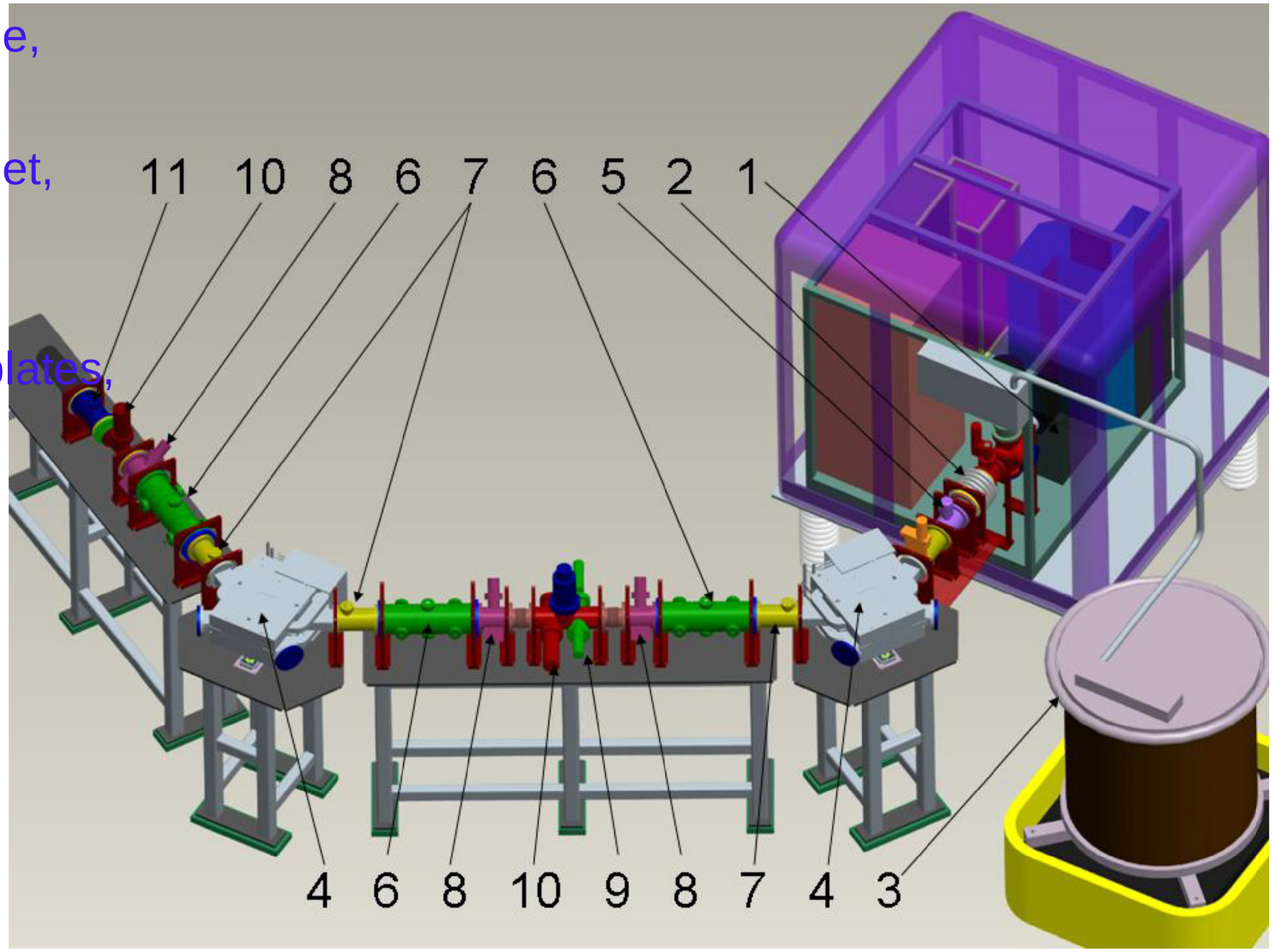
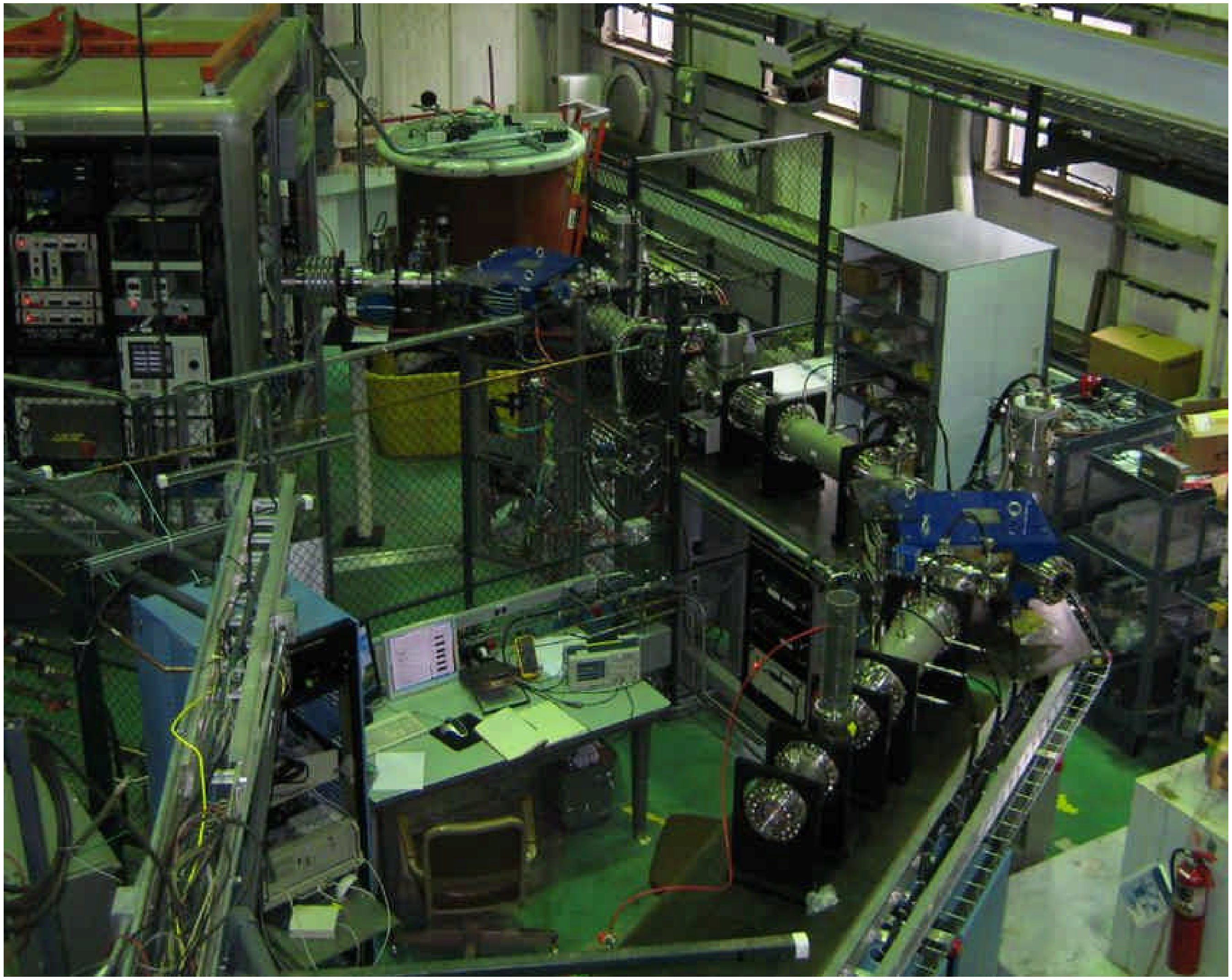


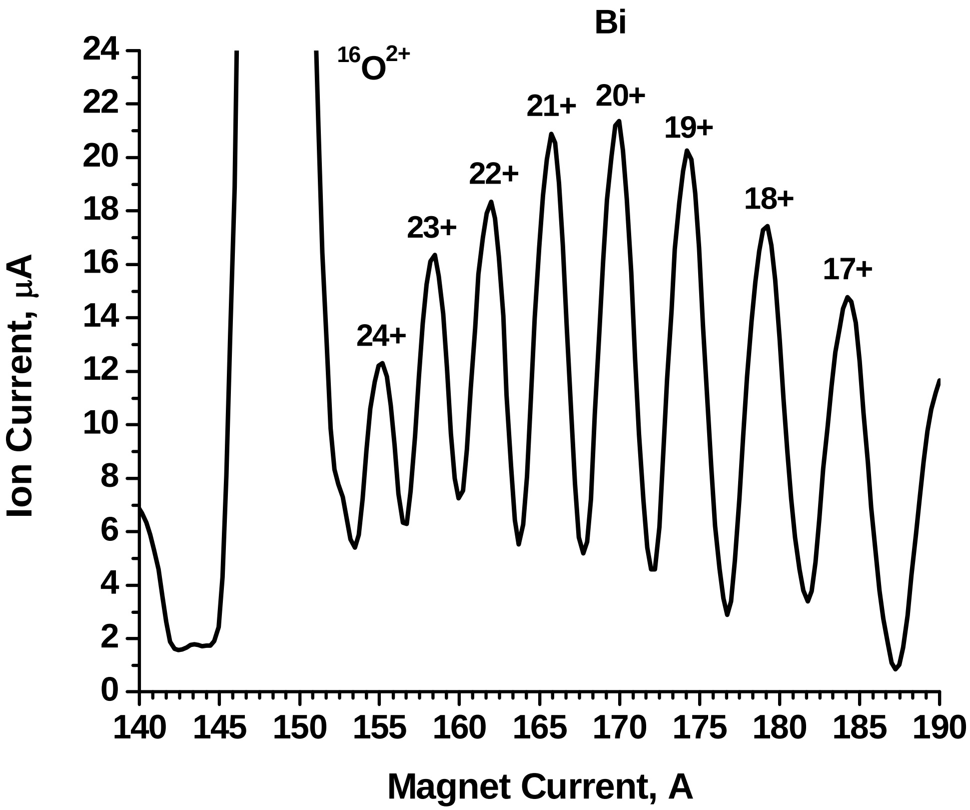
Photo of the injector



Test beam: bismuth

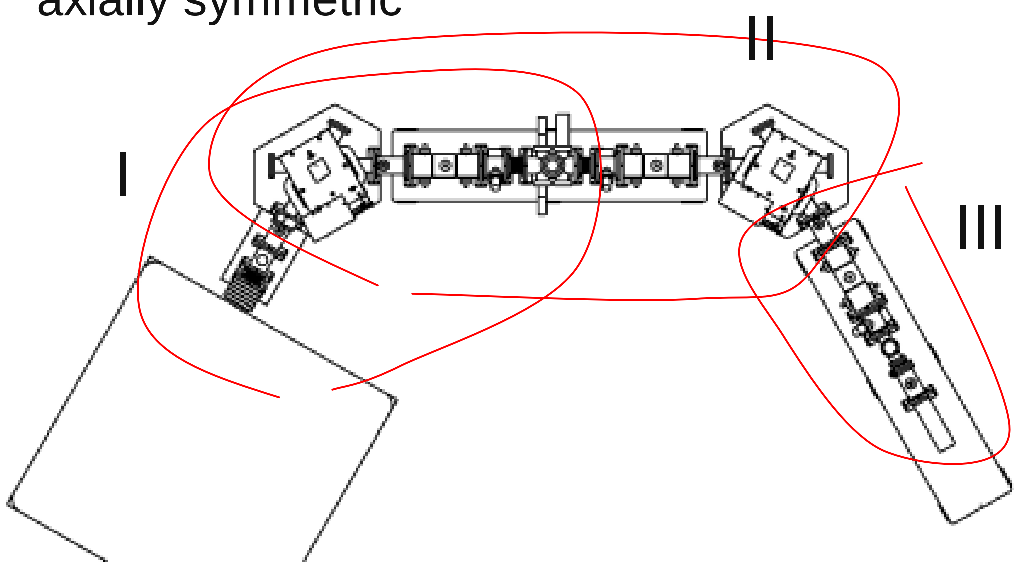
- Simple to produce
- q/A is close to what we expect from VENUS
- Beam current in each charge state ~1 pμA which is easily reproducible
- We are interested in

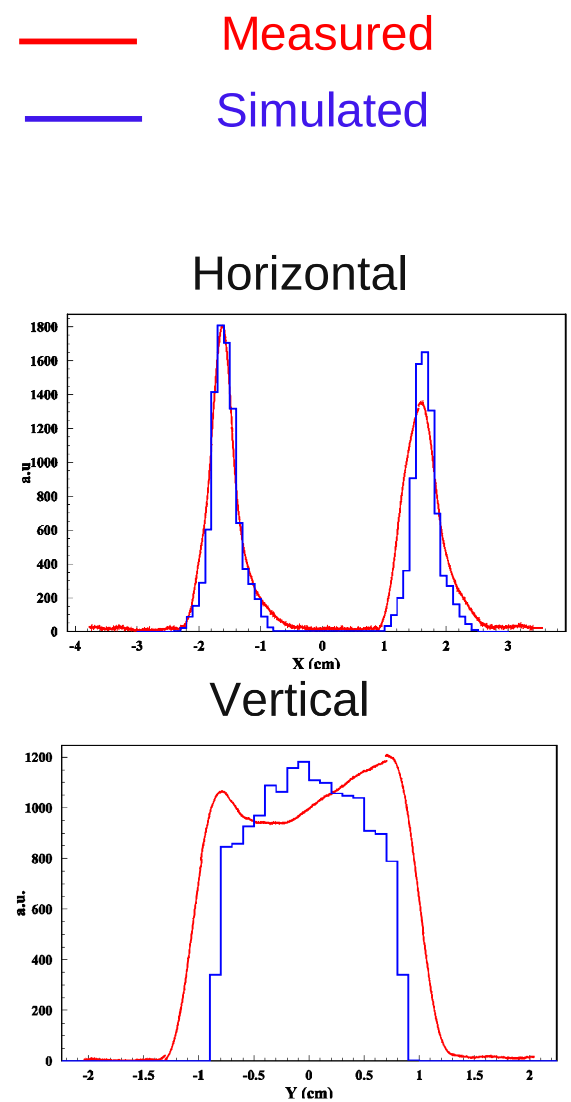
  charge states 20+ and 21+



TRACK fit of the beam initial parameters

- Fitting is based on multi-particle tracking code including space charge and multiple ion species
- 3 stages
  - Find initial beam Twiss parameters at the source exit using measured beam profiles
  - “Symmetric” tune of the achromat LEBT
  - Focusing to the pepper-pot screen
- Fitting results: beam out of the source is not axially symmetric





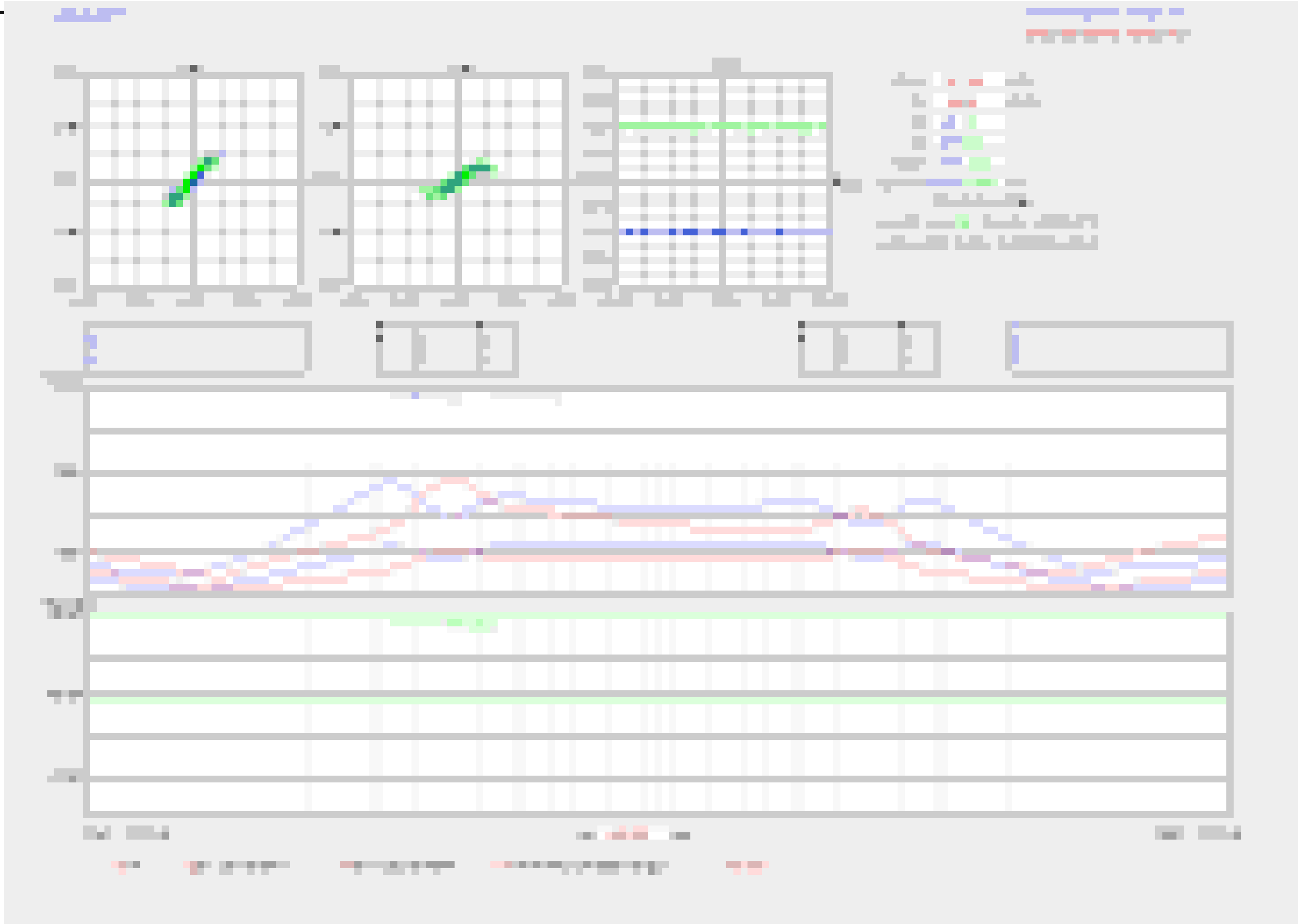
TRACK Fit: Symmetric Beam from M-1 to M-2

Fit criteria:
Symmetric Beam from M1 to M2 with respect to the Mid-plane

Fit parameters:
Strengths of the 6 Quads of T1 and T2

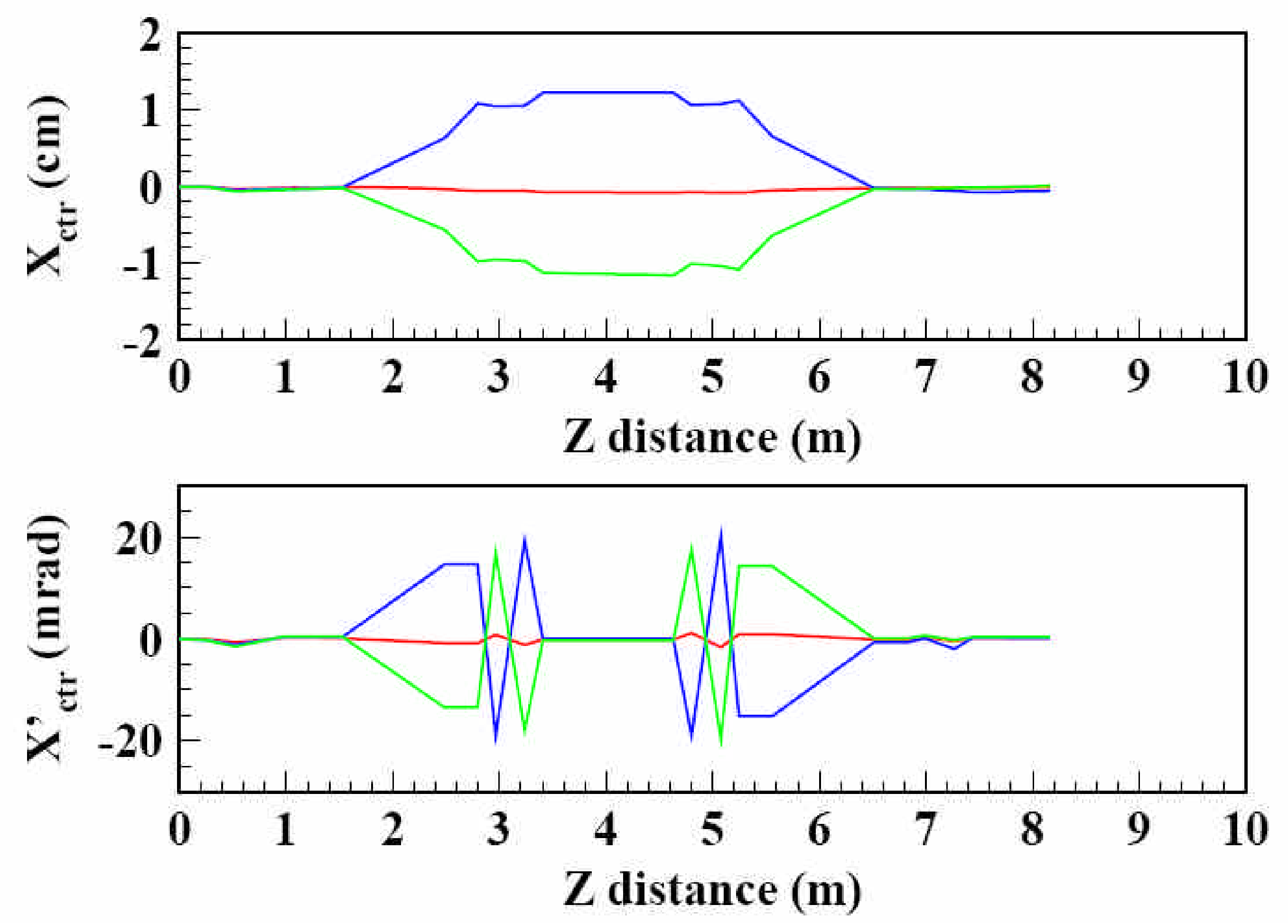
Fit type: 22

Results:
RMS envelopes are ~ 100% symmetric
Max envelopes are OK

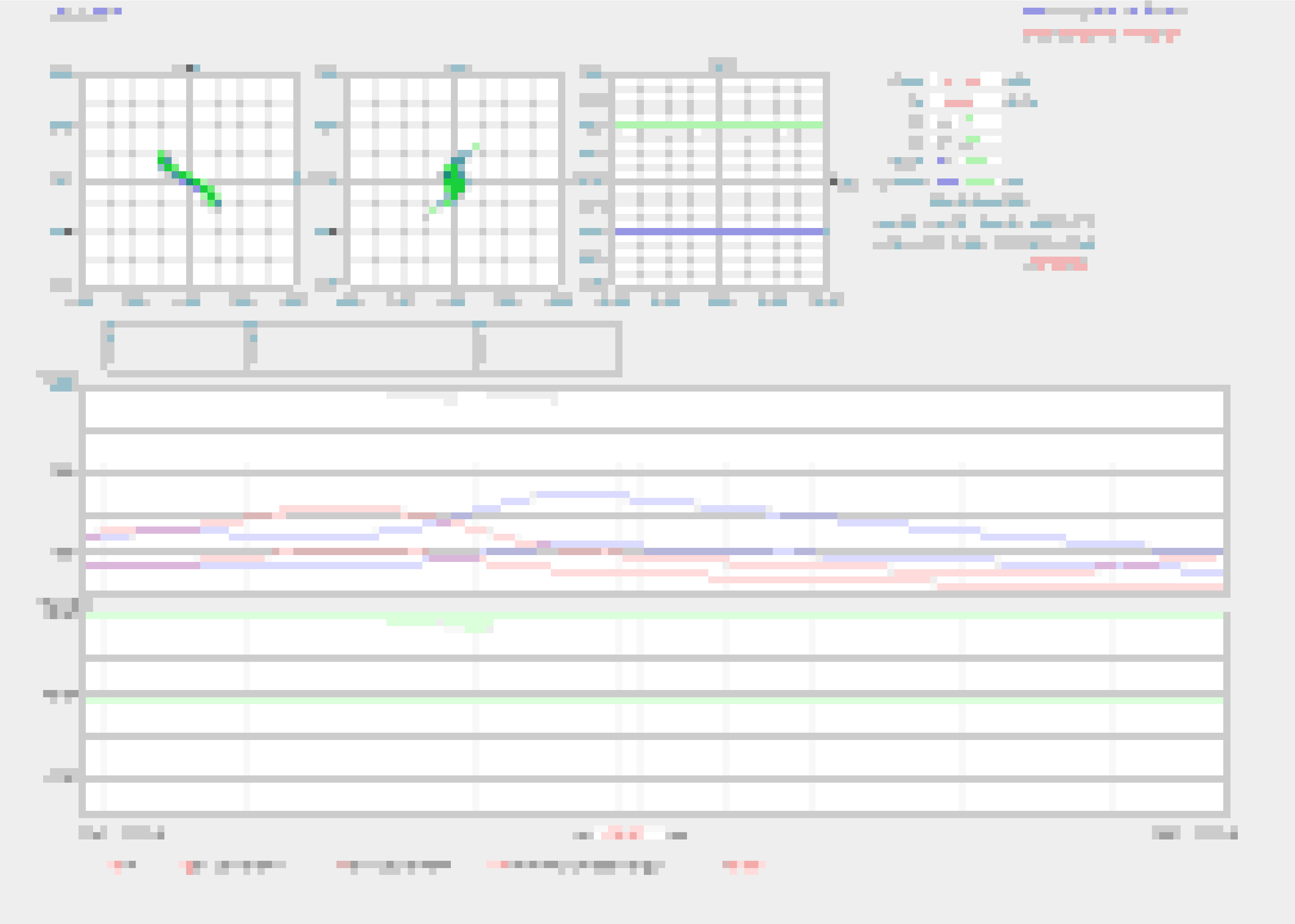


Quad strengths: Q1=3.312, Q2=-2.589, Q3=1.847, Q4=1.794, Q5=-2.595, Q6=3.372 kV

Obtain zero angular dispersion in the symmetric tuning



TRACK Fit: Well Focused Beam on the Pepper-Pot



Fit criteria:
Well focused beam on the Pepper-Pot in both X and Y planes

Fit parameters:
Strengths of the 3 Quads of last triplet T3

Fit type: 2

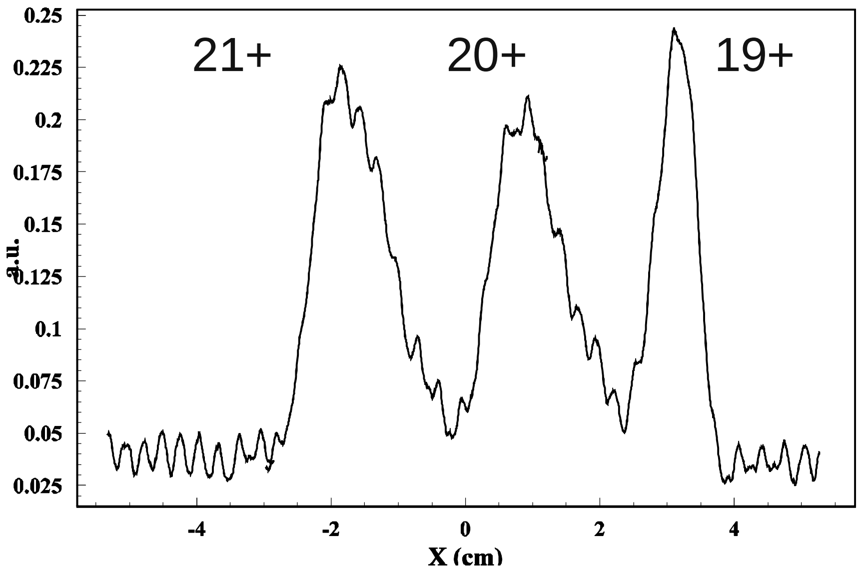
Results:
Beam better focused in Y. Beam is distorted, more in Y.

Quad strengths: Q7=2.487, Q8=-3.225, Q9=3.743 kV

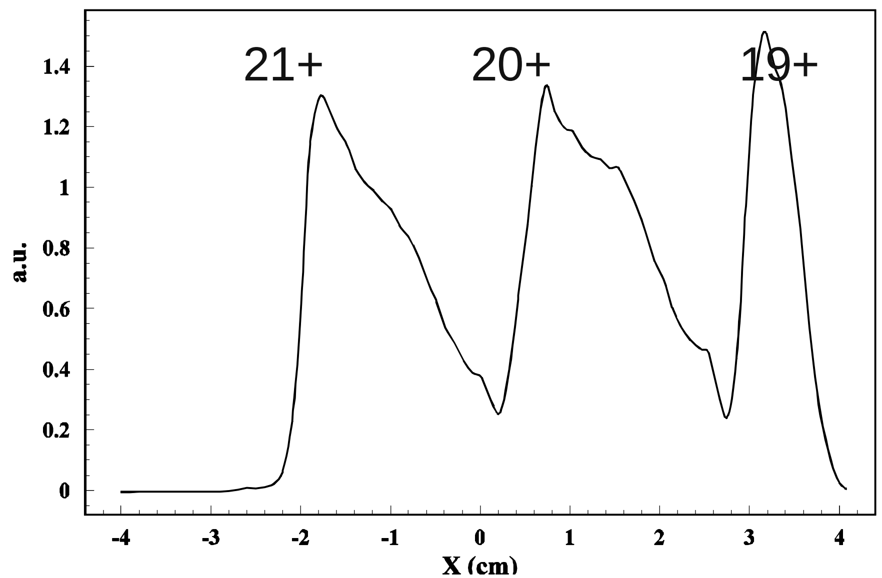
Tuning the achromatic condition

- Using BPM and slit scan zero angular momentum between the triplets
  - Requires some tweaking of quadrupole fields with respect to the pre-calculated values

Rotating wire



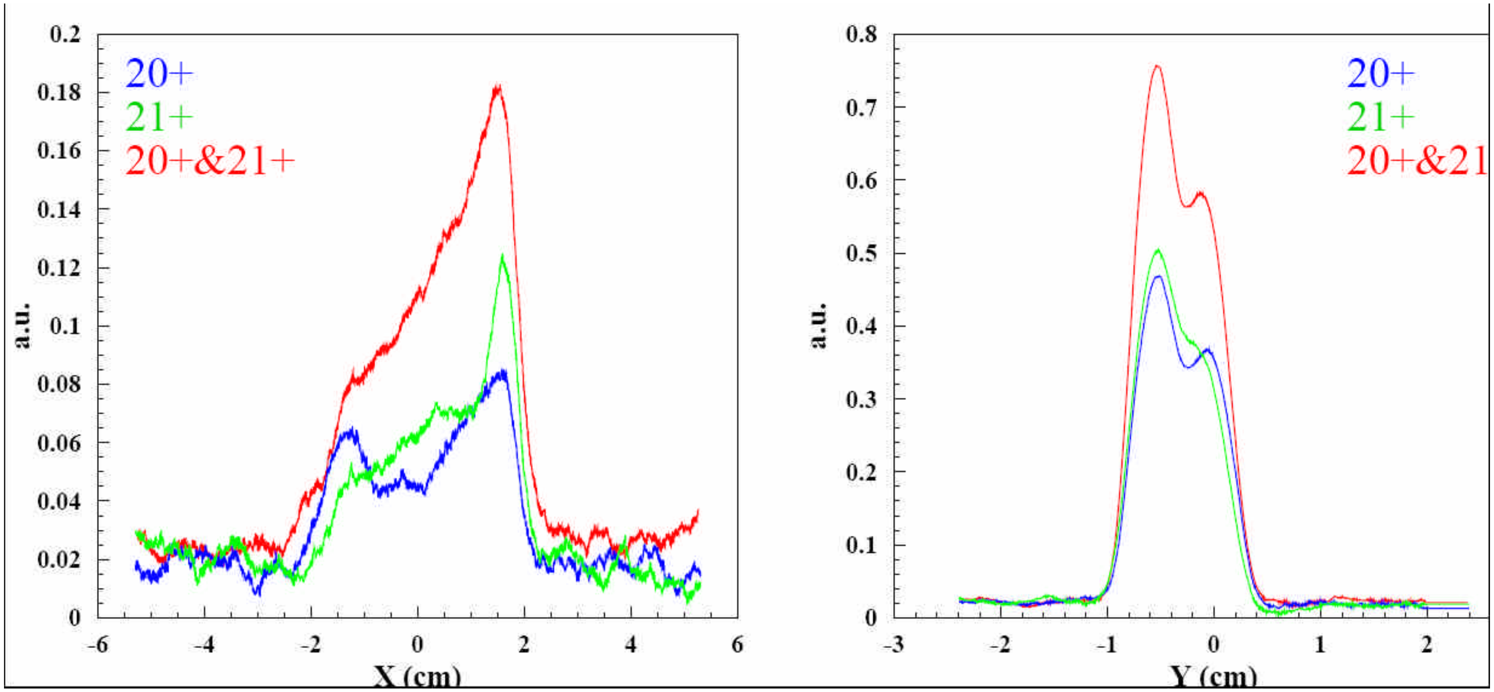
Slit scan



BPM-2 Profiles

- Transmission is close to ~100%

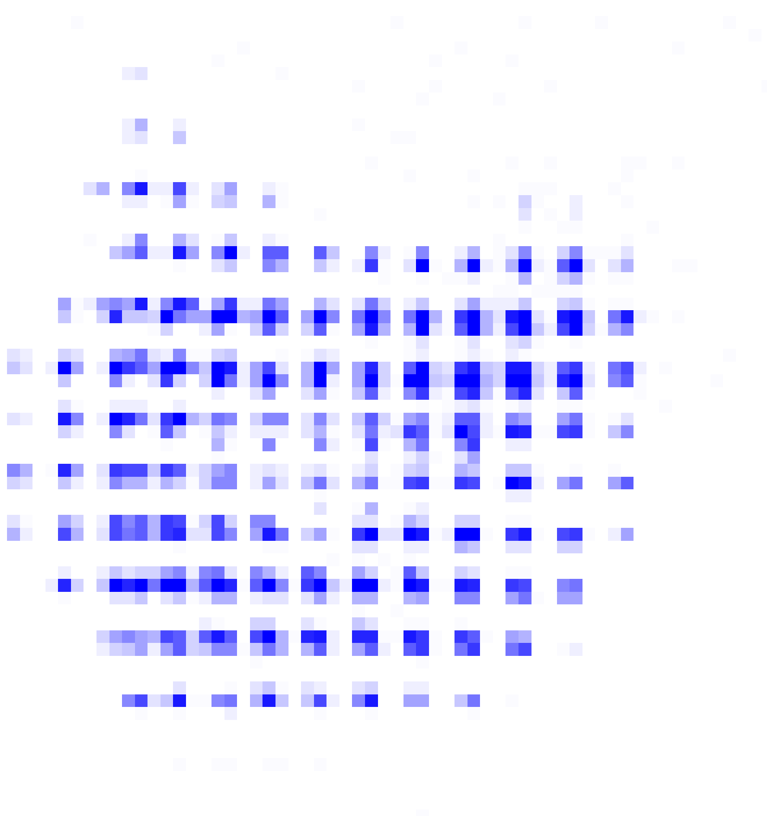
$$I_{20+} = (20.9 \pm 0.2)\,\mu A, \quad I_{21+} = (21.3 \pm 0.2)\,\mu A$$
$$I_{20+,21+} = (42.1 \pm 0.4)\,\mu A$$



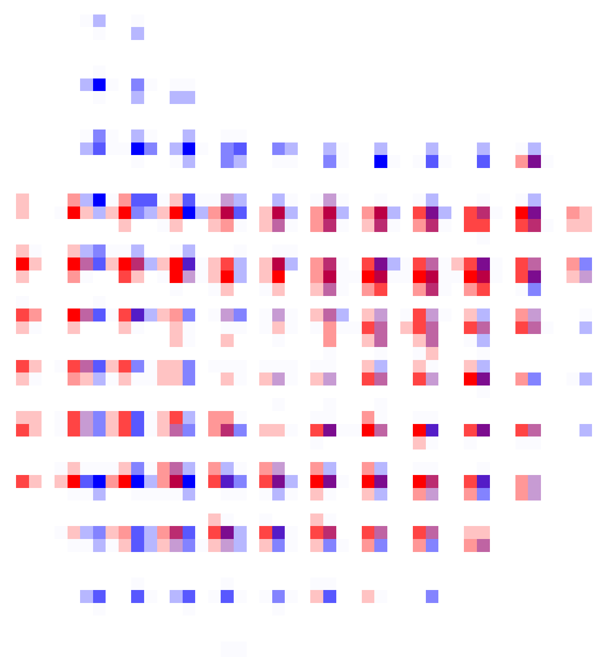
Pepper-Pot Images: 2Q (20+&21+) versus Q1(20+) + Q2(21+)

- Calculated tune, beams are not well combined

20+ & 21+



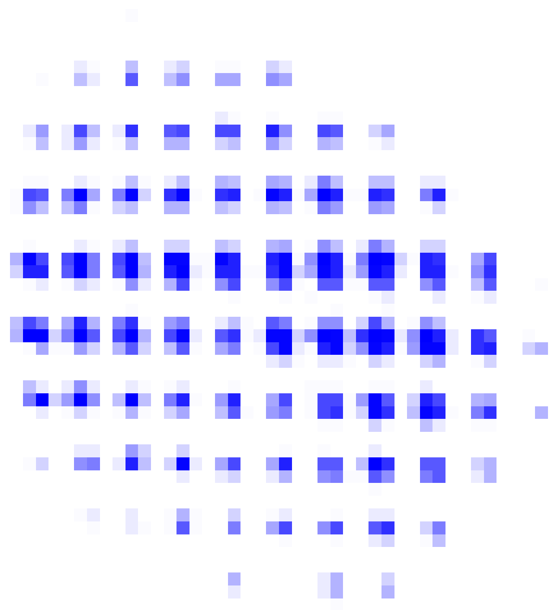
20+ + 21+



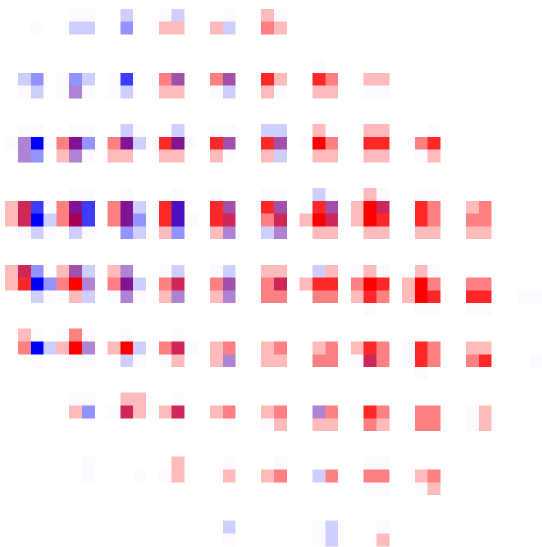
Pepper-Pot Images: 2Q (20+&21+) versus Q1(20+) + Q2(21+)

- Modified tune: minimize angular dispersion
  - Setting of 4 quads are changed by ~5% - 8% with respect to the pre-calculated values

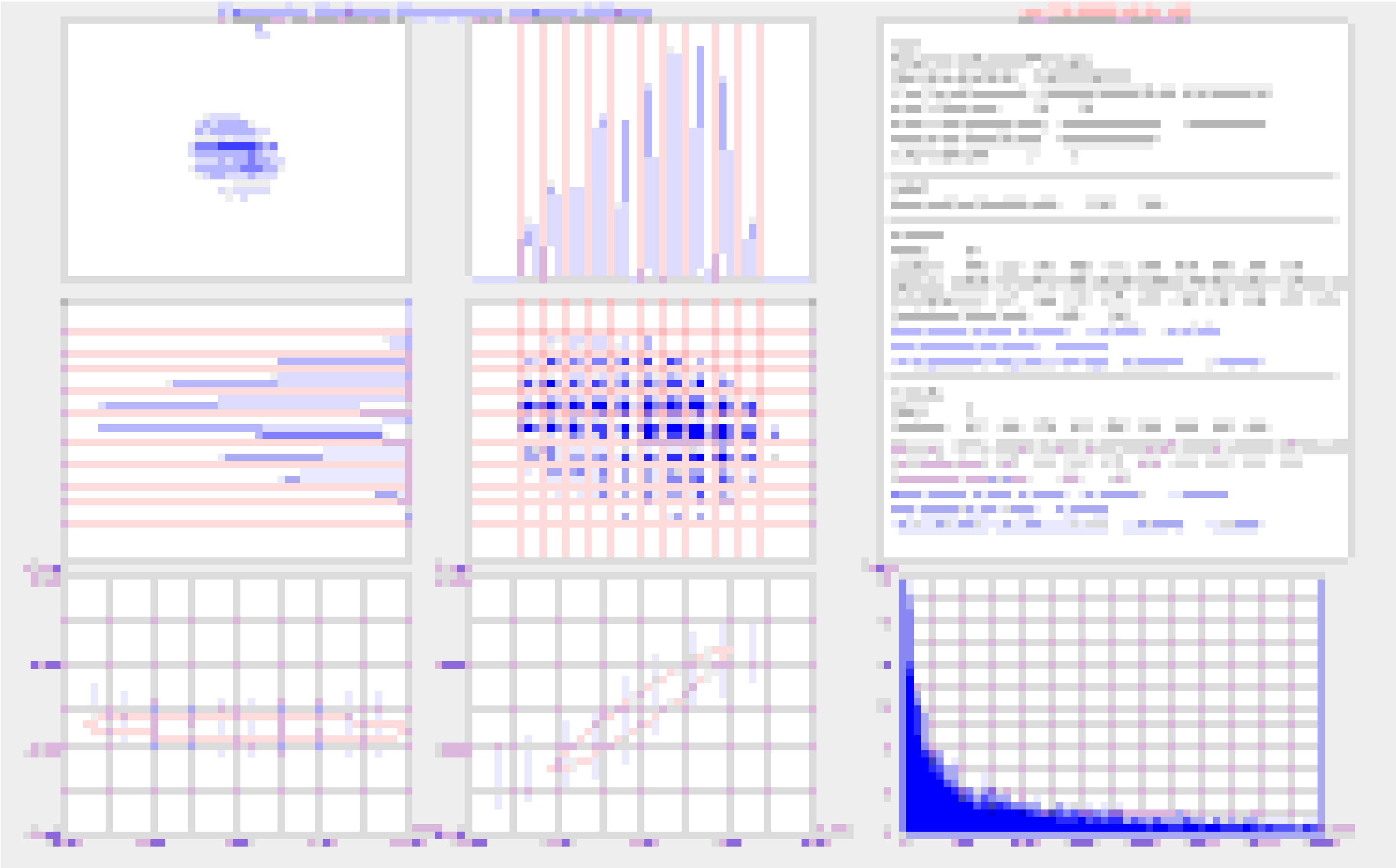
20+ & 21+



20+ + 21+

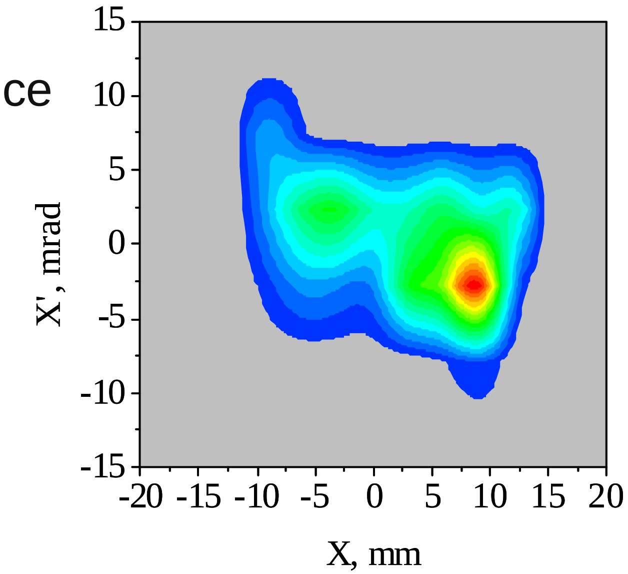


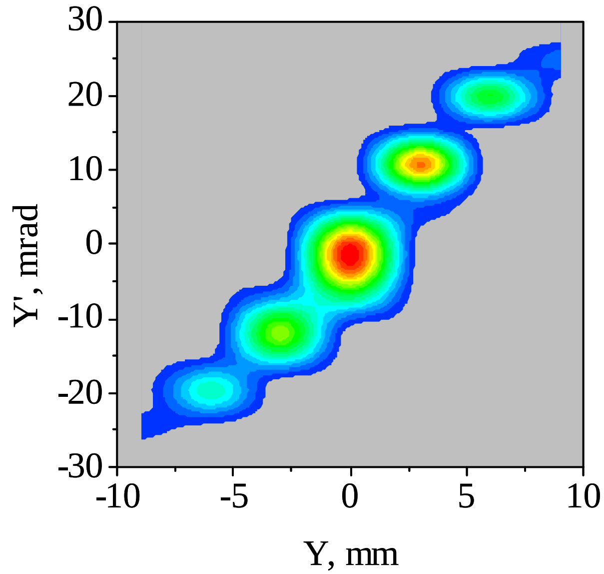
Pepper-Pot Images: 20+&21+ (File: 2.png, Gain:~400 -default)



Beam parameters

LabView emittance



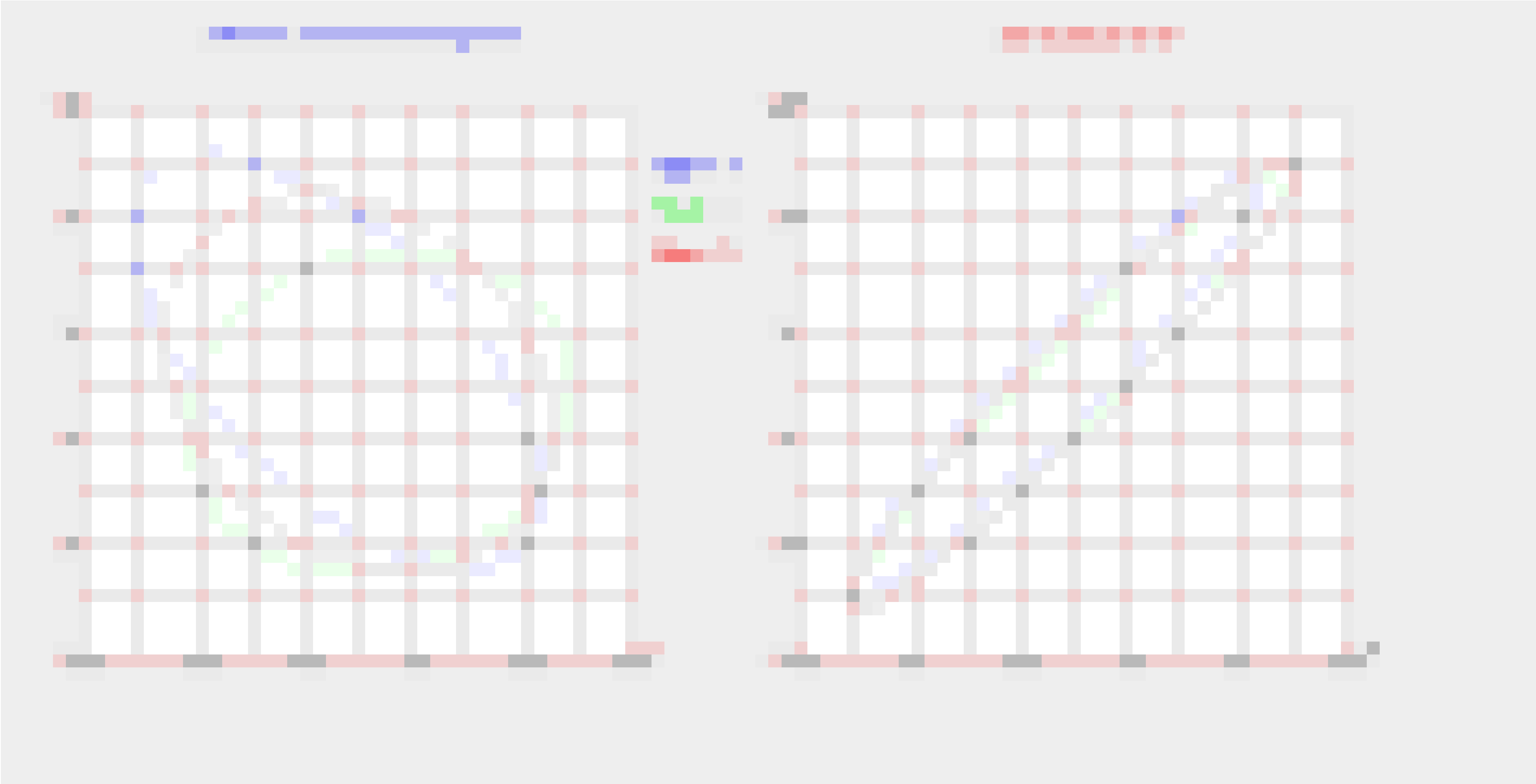


Parameter	$^{209}Bi^{20+}$	$^{209}Bi^{21+}$	$^{209}Bi^{20+}+^{209}Bi^{21+}$
ε_X (π μm)	0.092	0.081	0.087
α_X	0.816	-0.125	0.259
β_X (mm/mrad)	2.93	3.17	2.68
ε_Y (π μm)	0.055	0.059	0.057
α_Y	-2.92	-3.33	-3.32
β_Y (mm/mrad)	0.78	0.90	0.90

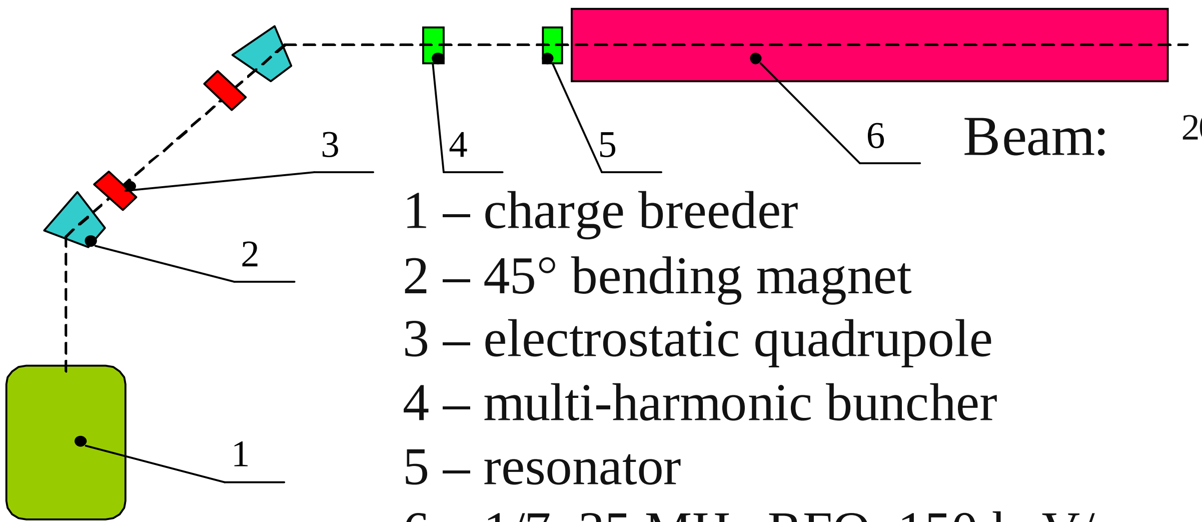
*4*RMS ellipses*

xx'

yy'

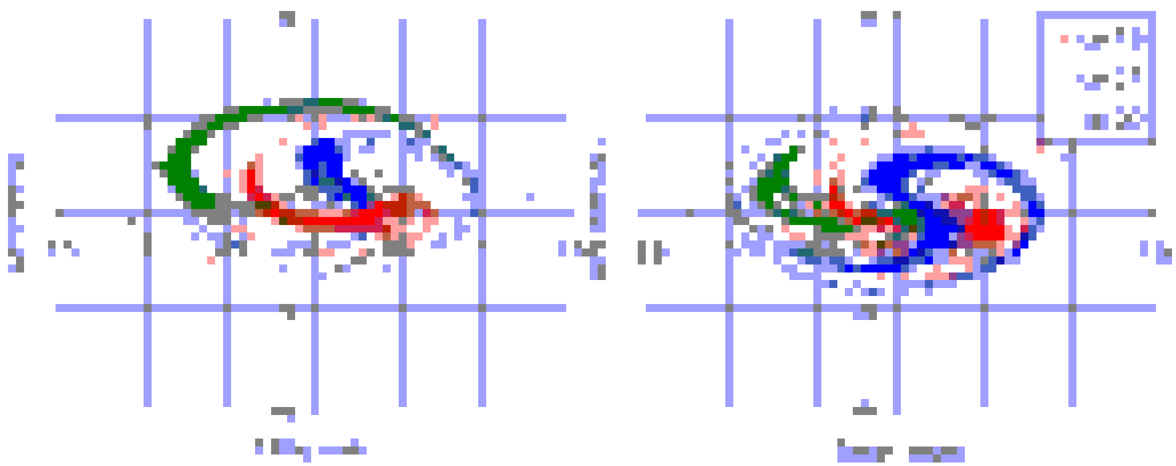


Application of multi-q beams after the charge breeder, enhance RIB intensity by factor of ~2.8



Beam: $^{200}Au^{19+,20+21+}$, $\Delta q/q=10\%$

1 – charge breeder
2 – 45° bending magnet
3 – electrostatic quadrupole
4 – multi-harmonic buncher
5 – resonator
6 – 1/7, 35 MHz RFQ, 150 keV/u



Summary

- combination of two charge states of heavy-ion beams in the phase space is demonstrated
- Application of a multi-particle code with multi-parameter fitting capabilities was essential for our experiments
  - Beam diagnostics (WS, emittance probes) provide input data for the fitting code
- Further improvements are possible in the horizontal plane:
  - Better matching into the first bending magnet
  - Use sextupoles for beam optics correction
- Extraction, analysis and combination of several charge states of heavy-ion beam is a powerful method to enhance beam intensities of both driver accelerator and post-accelerator based on charge breeders