HIAF front end for transmission and acceleration of 30 pμA $^{238}U^{35+}$

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Daejeon, Korea

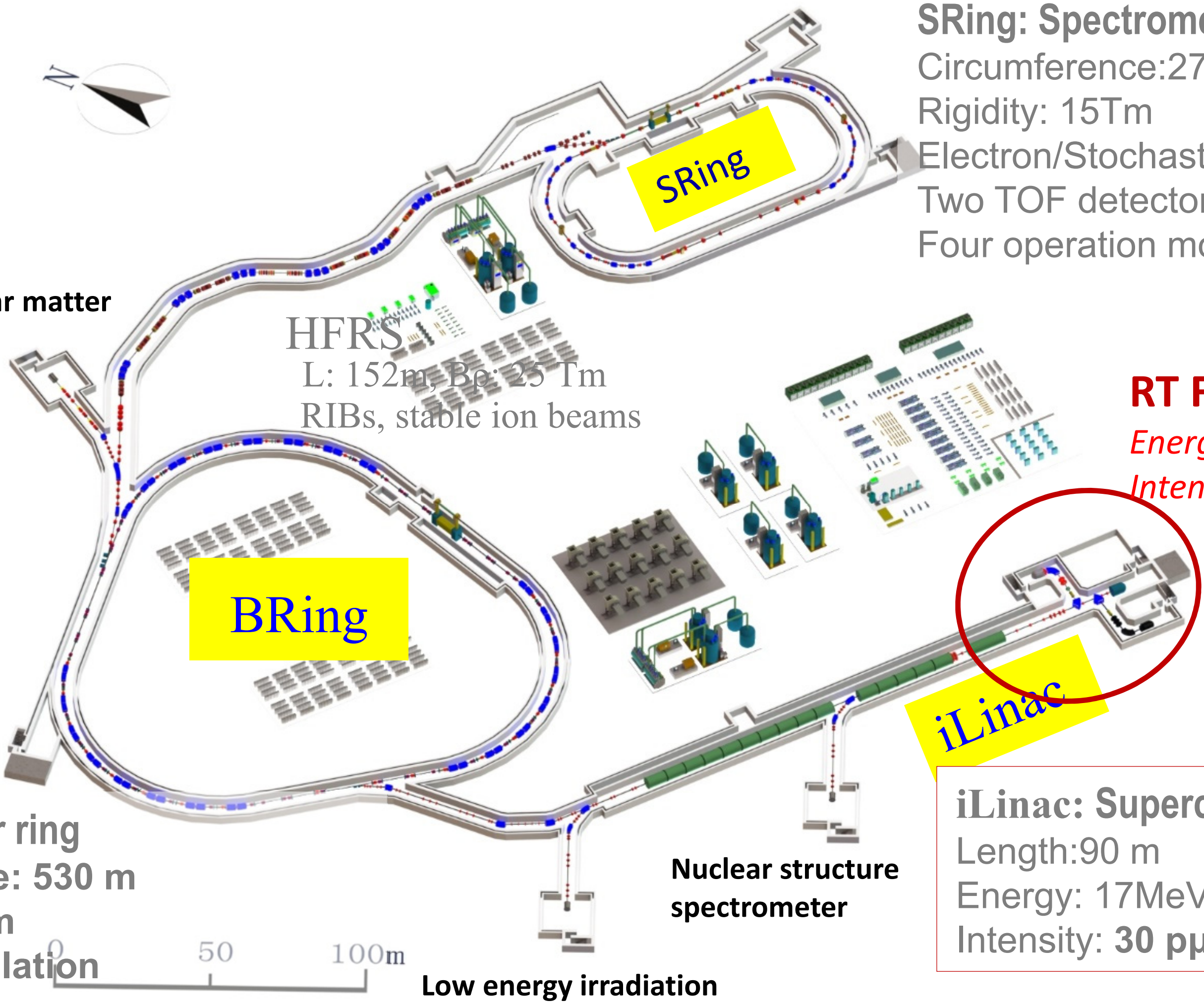
Outline

- Overview
- HIAF Front End：Design and studies
  - High intensity heavy ion beam production and beam quality
  - Beam transport and space charge issues
  - High intensity beam matching with RFQ
  - End-to-End simulation
- Beam commissioning of LEAF
- Summary

Overview

HIAF

2018-2024



External target for RIB

SRing: Spectrometer ring
Circumference:273.5m
Rigidity: 15Tm
Electron/Stochastic cooling
Two TOF detectors
Four operation modes

CEE for HD nuclear matter
Hypernuclear
HE irradition

HFRS
L: 152m, Bρ: 25 Tm
RIBs, stable ion beams

RT Front End
Energy: 0.5MeV/u
Intensity: ***30 pμA*** *($^{238}U^{35+}$)*

BRing: Booster ring
Circumference: 530 m
Rigidity: 34 Tm
Beam accumulation
Beam cooling
Beam acceleration
E=0.8 GeV/u,
I= 1.0×10^{11} ppp（ U^{35+}）

Nuclear structure spectrometer

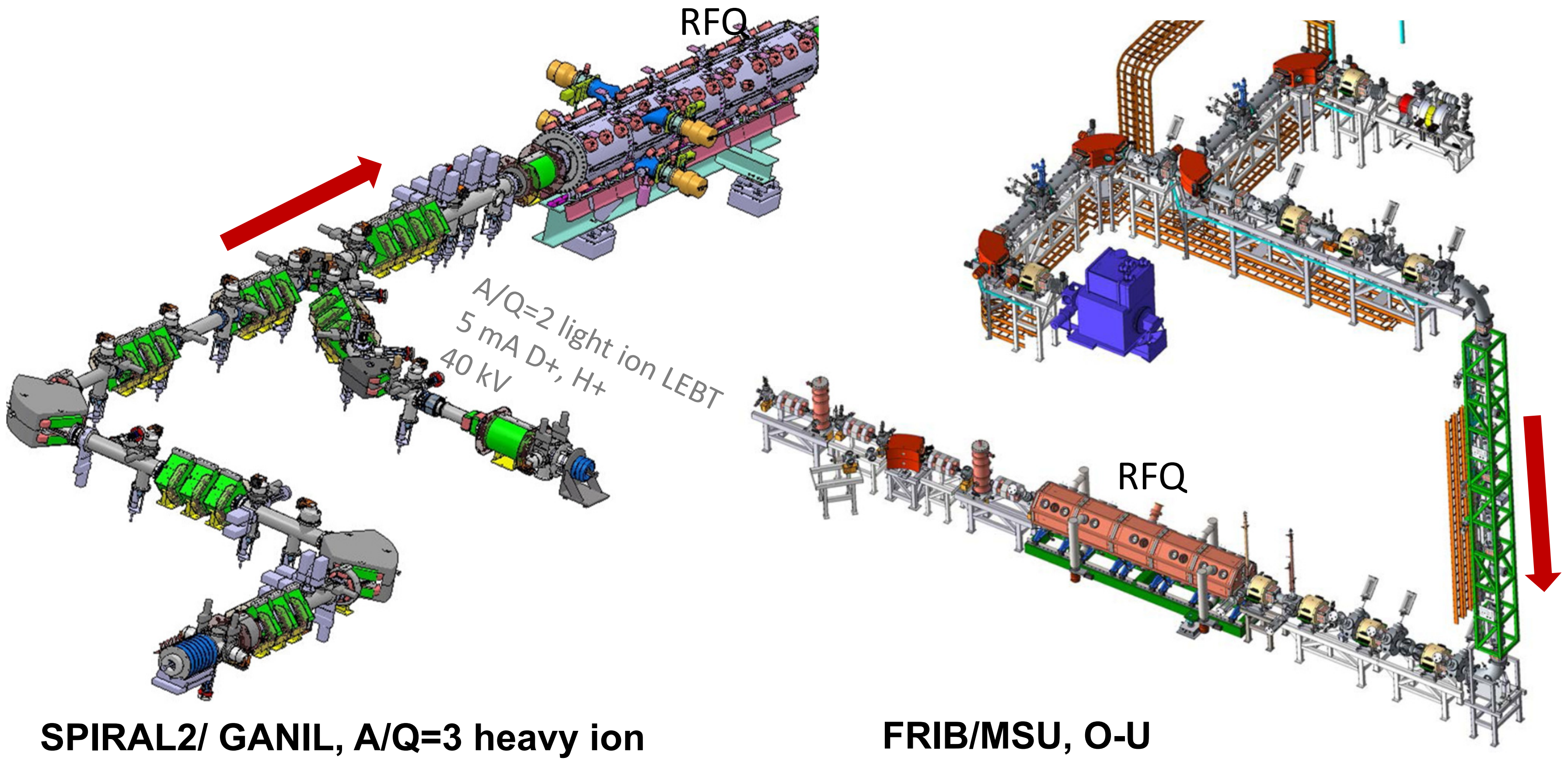
Low energy irradiation and TSR

iLinac: Superconducting linac
Length:90 m
Energy: 17MeV/u($^{238}U^{35+}$)
Intensity: **30 pμA**

The world highest intensity CW heavy ion linac!

Overview

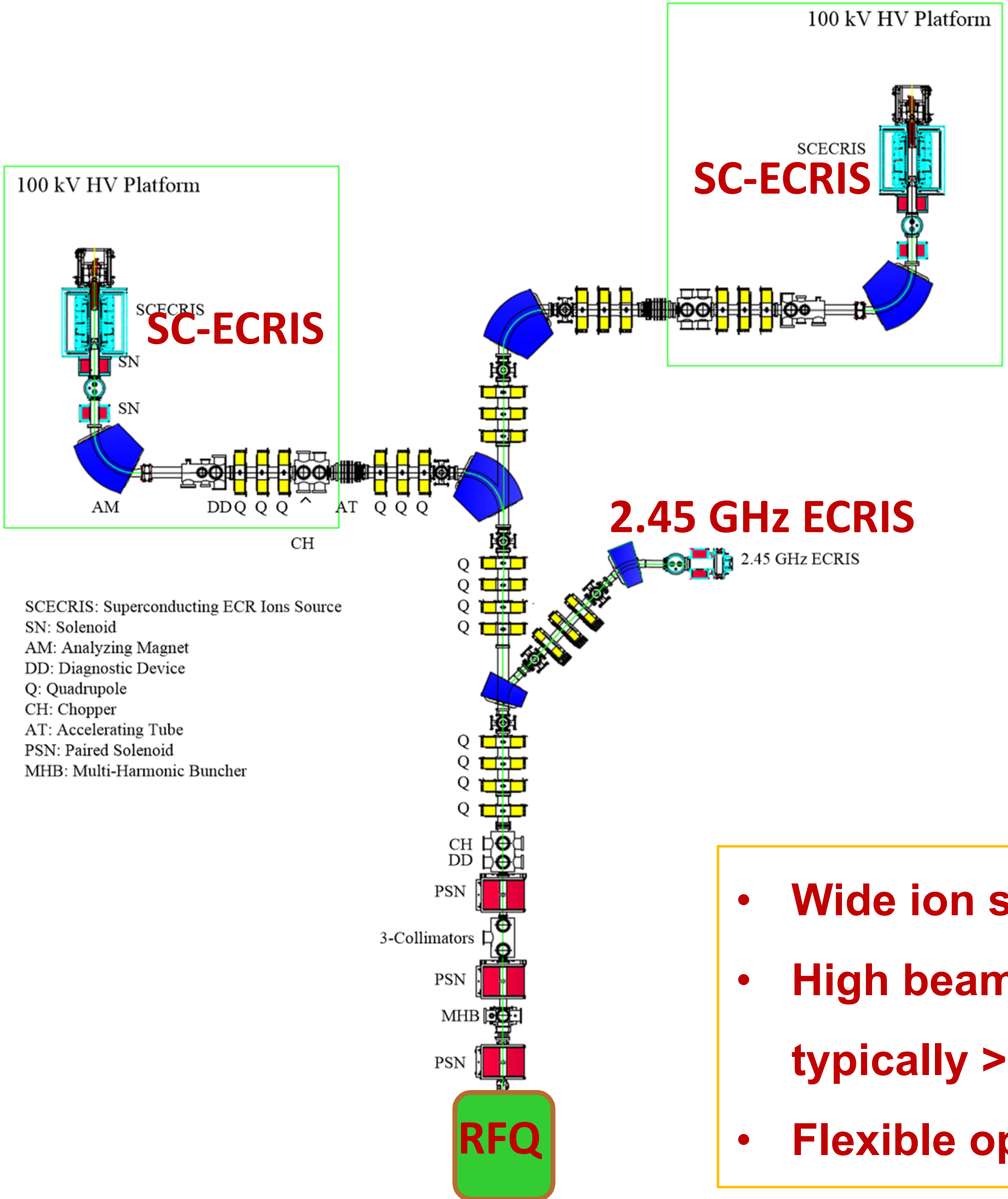
High intensity heavy ion Front End



SPIRAL2/ GANIL, A/Q=3 heavy ion
LEBT up to 1 mA
Typically Ar^{12+} 1 emA/CW

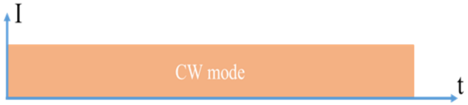
FRIB/MSU, O-U
LEBT up to 350 eμA
Typically $\mathrm{U}^{33+}+\mathrm{U}^{34+}$ 13 pμA /CW

HIAF Front end



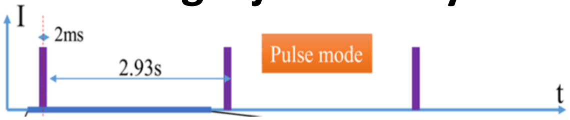
SCECRIS: Superconducting ECR Ions Source
SN: Solenoid
AM: Analyzing Magnet
DD: Diagnostic Device
Q: Quadrupole
CH: Chopper
AT: Accelerating Tube
PSN: Paired Solenoid
MHB: Multi-Harmonic Buncher

CW mode
For iLinac Operation only
Or iLianc + BRing



$^{16}\mathrm{O}^{6+}$	~ 1 emA	$^{209}\mathrm{Bi}^{31+}$	~ 1 emA
$^{129}\mathrm{Xe}^{27+}$	~ 1 emA	$^{238}\mathrm{U}^{35+}$	~ 0.7 emA

Pulsed mode
BRing injector only



$^{16}\mathrm{O}^{6+}$	2 emA	$^{209}\mathrm{Bi}^{31+}$	1.5 emA
$^{129}\mathrm{Xe}^{27+}$	2 emA	$^{238}\mathrm{U}^{35+}$	1 emA

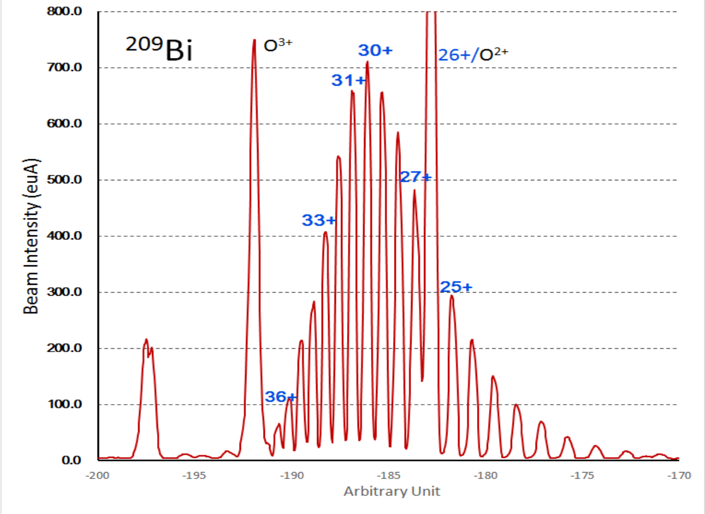
0.3-5 Hz/0.2-2 ms

- **Wide ion species: M/Q: 2~7**
- **High beam intensity: up to 2 emA, typically >1 emA U^{35+}**
- **Flexible operation modes**

Challenges in HIAF Front End

- ☐ High Intensity heavy ion beam production
- ☐ Intense heavy ion beam extraction
- ☐ Intense heavy ion beam transmission with high quality and efficiency
  - ■ Borrowed ideas: Achromatic beam optics, Beam collimation，MHB…
- ☐ Intense heavy ion beam matching to RFQ
- ☐ High Intensity heavy ion beam RFQ

High intensity heavy ion beam production



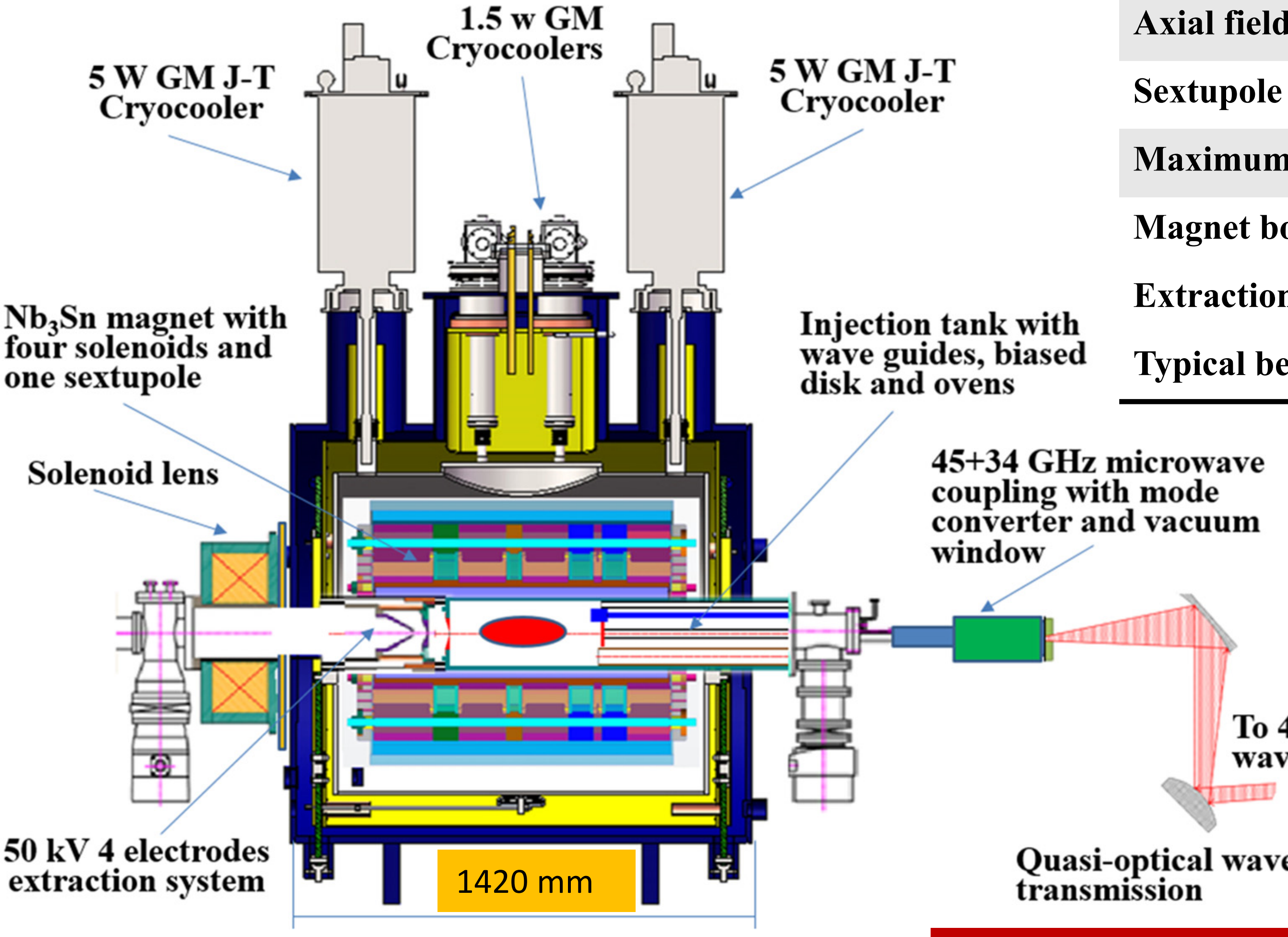
SECRAL I-II beam intensities

Ion Beam	SECRAL I-II (eμA) （2015-2016）	LBNL VENUS beam Intensity 2016 (eμA)
$^{16}O^{6+}$	6700	4750
$^{40}Ar^{12+}$	1420	1060
$^{40}Ar^{16+}$	610	523
$^{40}Ar^{18+}$	5	4
$^{40}Ca^{11+}$	710	400
$^{40}Ca^{14+}$	270	
Xe^{26+}	1100	
Xe^{30+}	320	211
Xe^{42+}	10	1
$^{209}Bi^{31+}$	680	300
$^{209}Bi^{41+}$	100	
$^{209}Bi^{50+}$	10	5
$^{238}U^{33+}$	202	440

The world record beam intensities

High intensity heavy ion beam production

45 GHz FECR



Microwave	45 GHz/20 kW
Magnet conductor	Nb$_3$Sn
Axial fields（T）	6.5/1.0/3.5
Sextupole field （T）	3.8@r=75 mm
Maximum field（T）	11.8 T
Magnet bore（mm）	Ø161~165
Extraction （kV）	50
Typical beam	1.0 emA U^{35+}

$$I \propto \omega^2_{ECR}$$

$$\omega_{ECR} = eB/m_e$$

Goal：>1 emA U^{35+}

Beam extraction

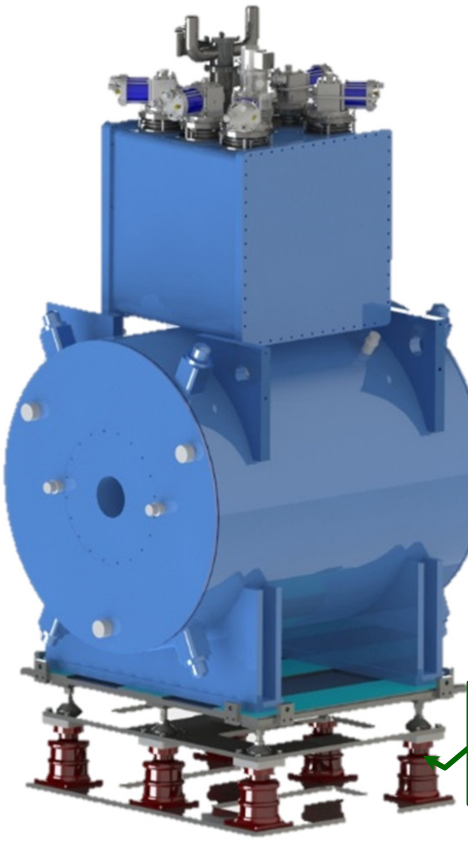
Typical issues:

- ☐ **Emittance growth at extraction**
- ☐ **Beam X/Y phase space coupling**
- ☐ **Space charge influences**

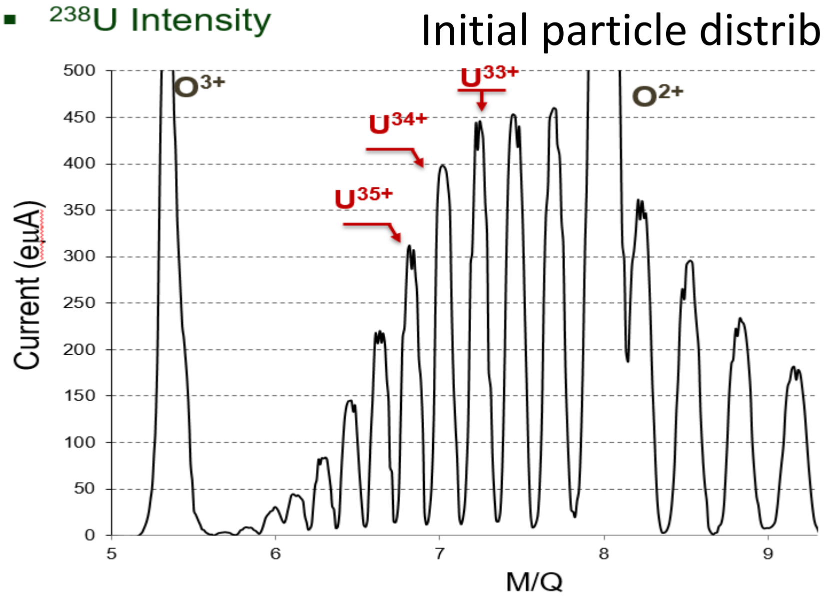
FECR beam extraction

✓Simulated with **IBsimu** code.
✓ Start from an assumed plasma.
✓ Includes magnetic fields in ECR.

✓I_{total}: 20 emA
✓I_{U35+}: 2 emA



50 kV insulation columns

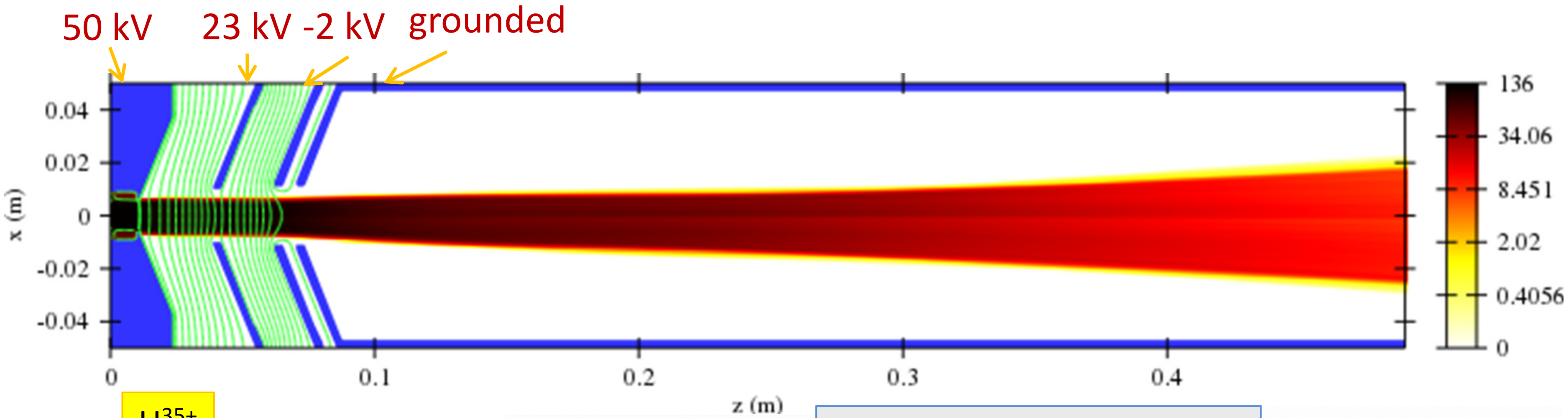


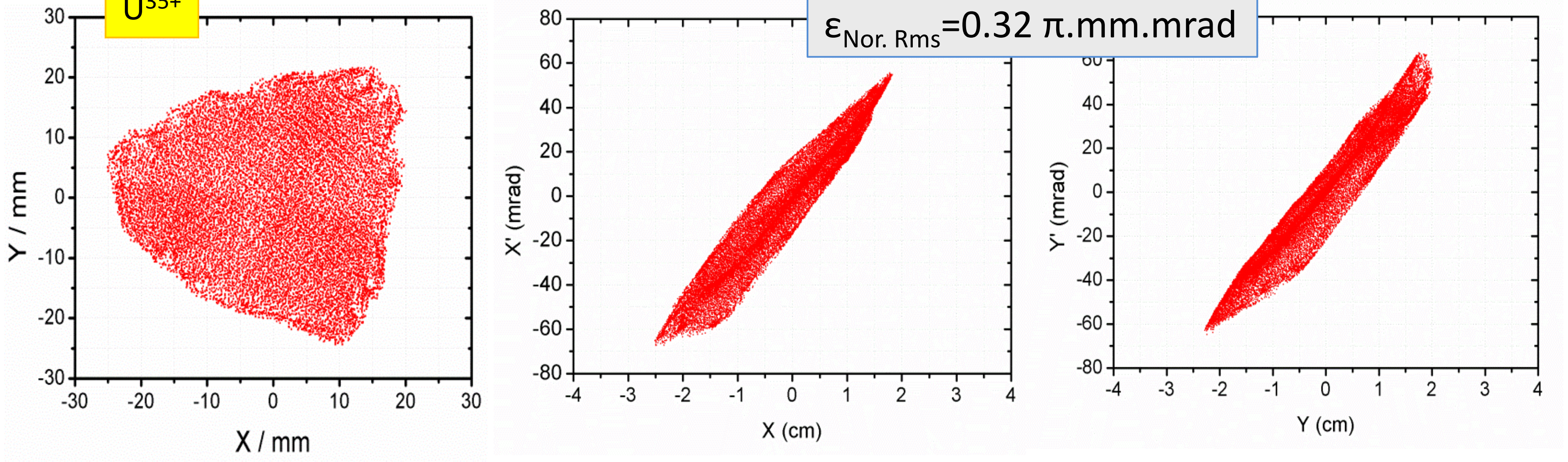
Initial particle distribution

ECR beam quality: emittance growth

- ✓ **Triangular shape due to magnetic field of ion source.**
- ✓ **In-homogeneous density distribution in cross-section.**
- ✓ **Large projection emittance due to high magnetic field at extraction.**

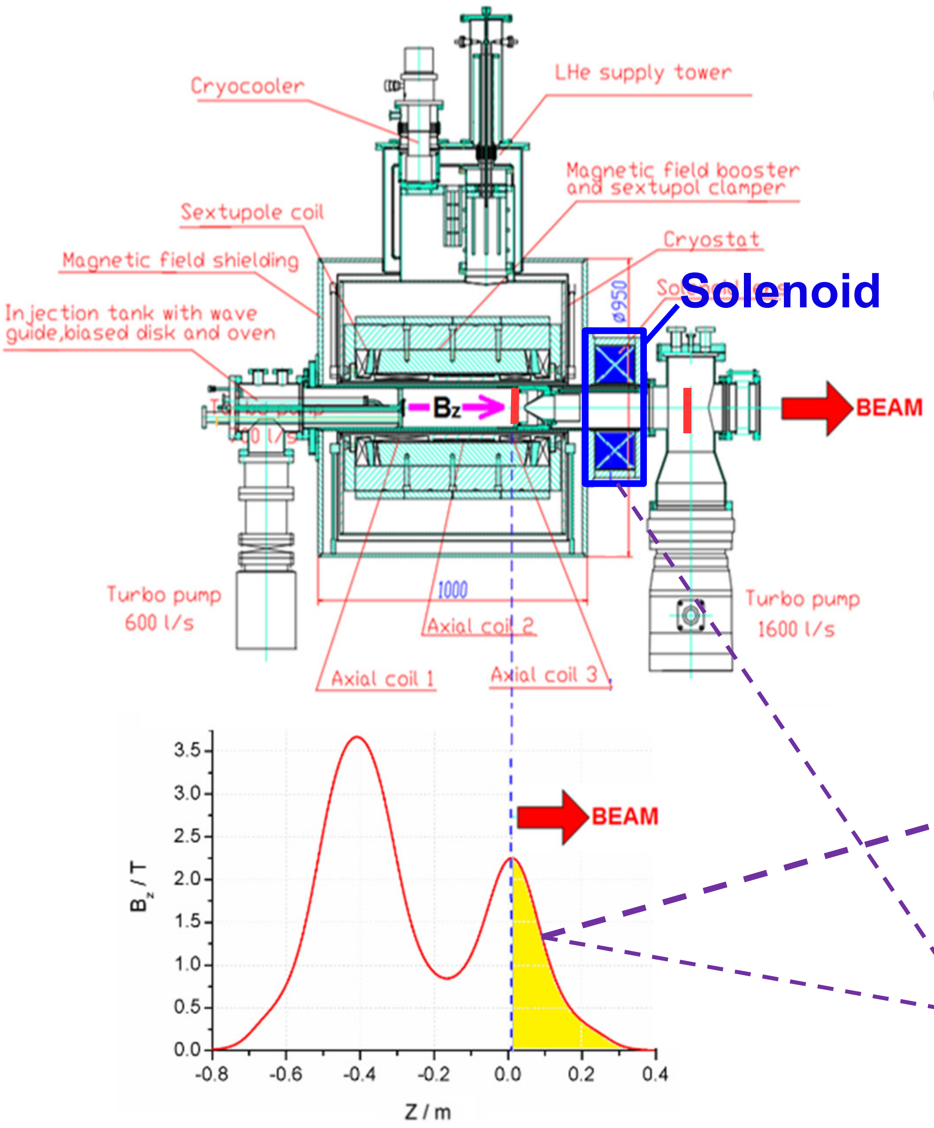
$$\varepsilon_{mag} = 0.032 \cdot (R_{extr})^2 \cdot (\frac{B_{extr}}{M/Q})$$





$\varepsilon_{Nor.\ Rms}$=0.32 π.mm.mrad

ECR beam quality: Coupling



SECRAL schematic view and the axial magnetic field distribution.

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

$$C_1=R_{out}C_0R_{out}^T=\begin{bmatrix}\varepsilon\beta&0&0&\kappa\varepsilon\beta\\0&\frac{\varepsilon}{\beta}+\kappa^2\varepsilon\beta&-\kappa\varepsilon\beta&0\\0&-k\varepsilon\beta&\varepsilon\beta&0\\\kappa\varepsilon\beta&0&0&\frac{\varepsilon}{\beta}+\kappa^2\varepsilon\beta\end{bmatrix}$$

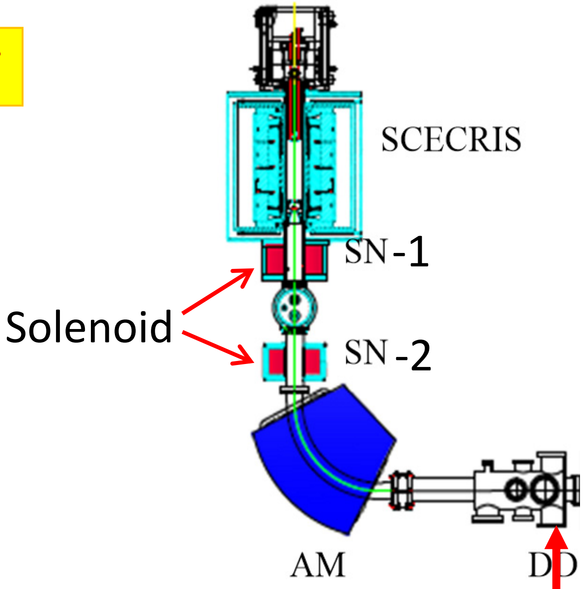
$$\boxed{\varepsilon_x=\varepsilon_y=\sqrt{\varepsilon\beta(\frac{\varepsilon}{\beta}+\kappa^2\varepsilon\beta)}\qquad \varepsilon_{1,2}=\varepsilon_x\pm\kappa\varepsilon\beta}$$

Factor ①: half-solenoid field induced rotational momentum dis-conservation .

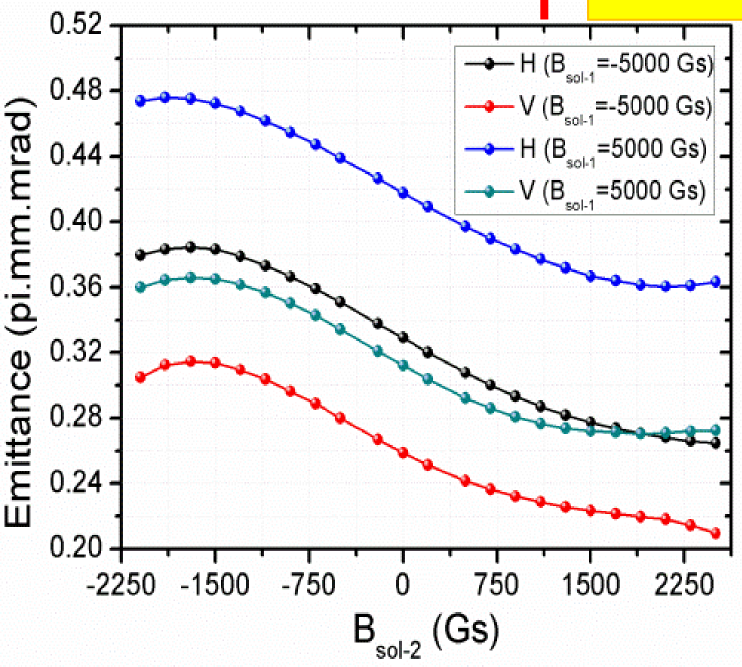
Factor ②: magnetic field induced beam rotation along axis (non-round beam).

ECR beam quality: Coupling

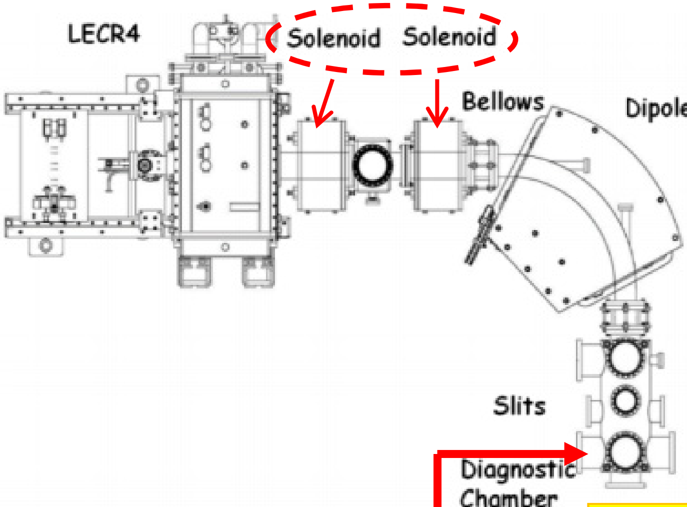
HIAF



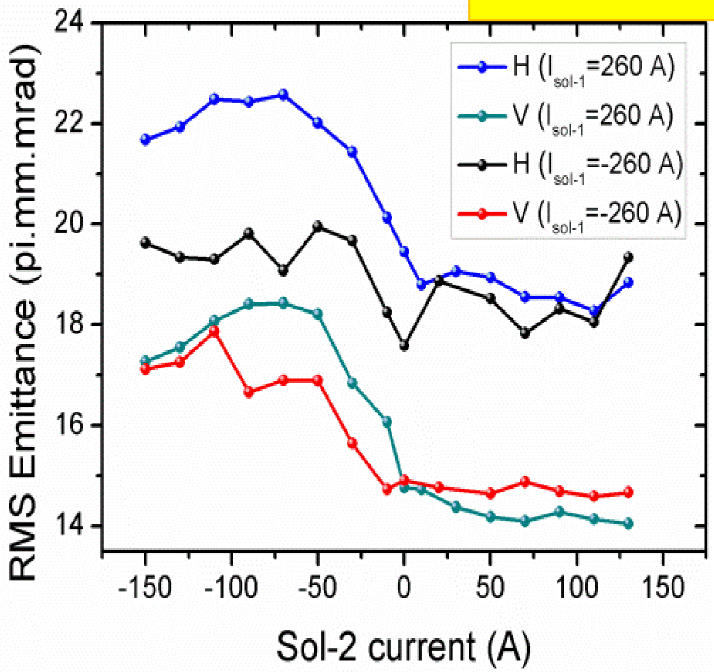
Simulation



SSC-LINAC



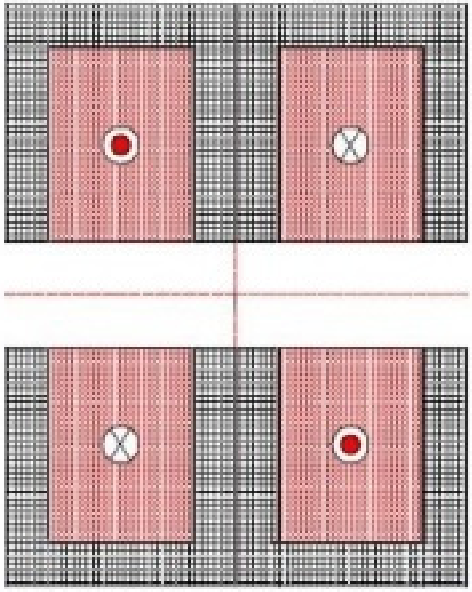
Measurement

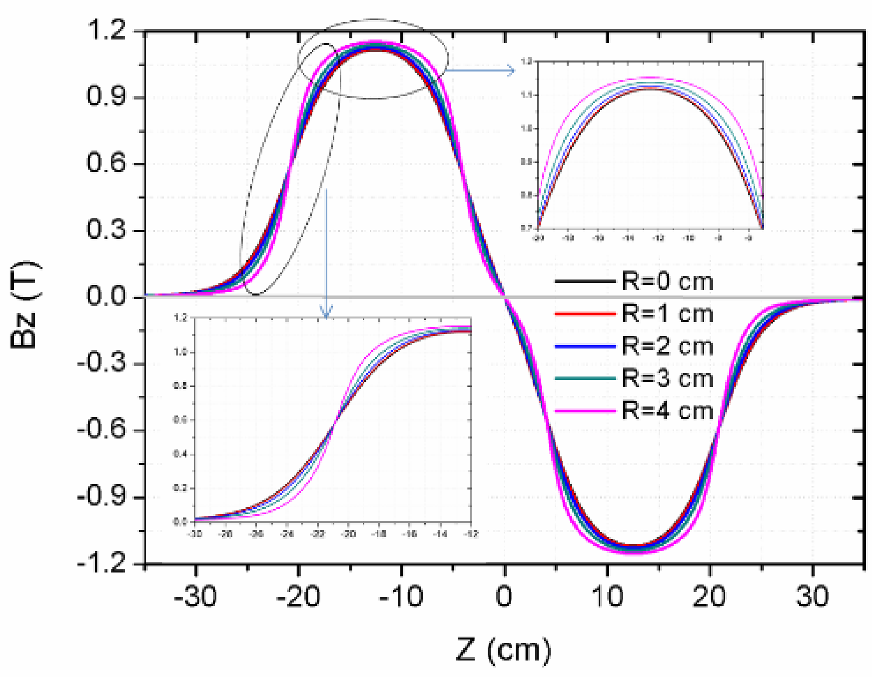


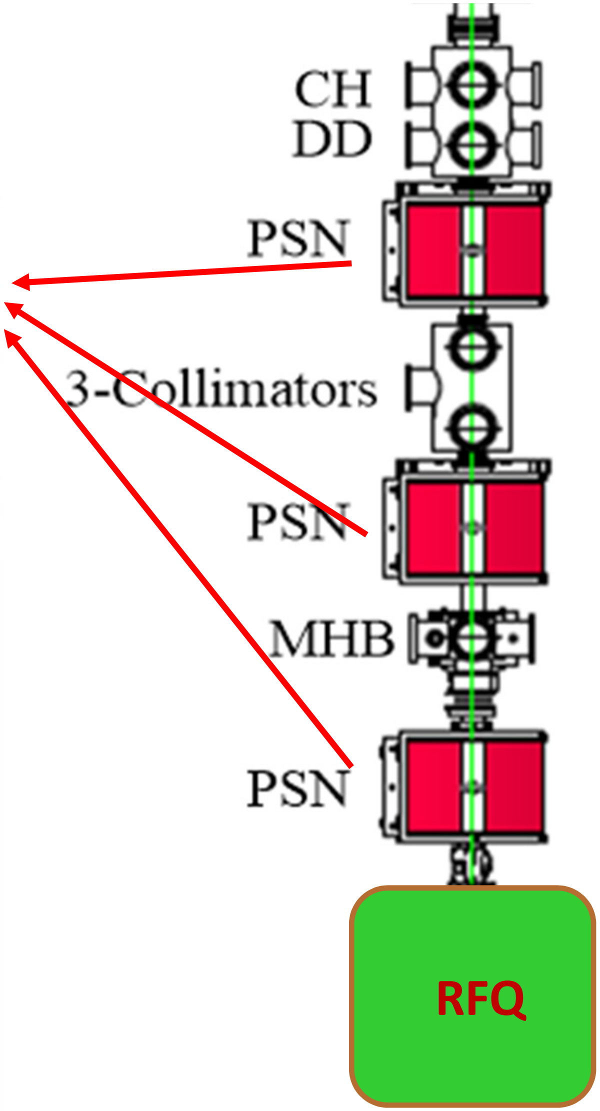
Paired Solenoid: Avoiding coupling

Paired Solenoid

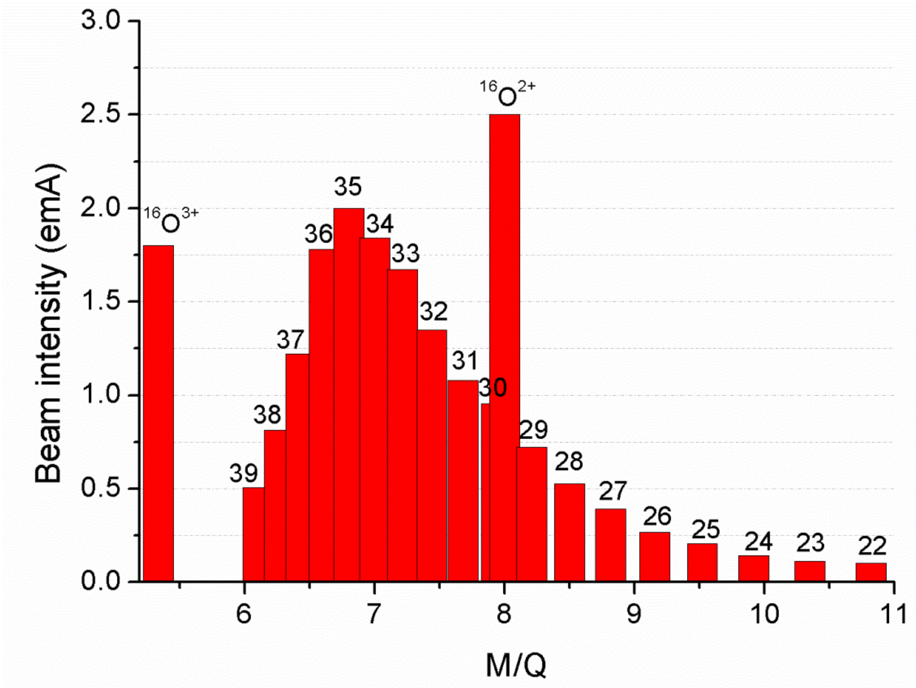
$$R = R_{sol+} * R_{sol-} = \begin{bmatrix} \# & \# & 0 & 0 \\ \# & \# & 0 & 0 \\ 0 & 0 & \# & \# \\ 0 & 0 & \# & \# \end{bmatrix}$$

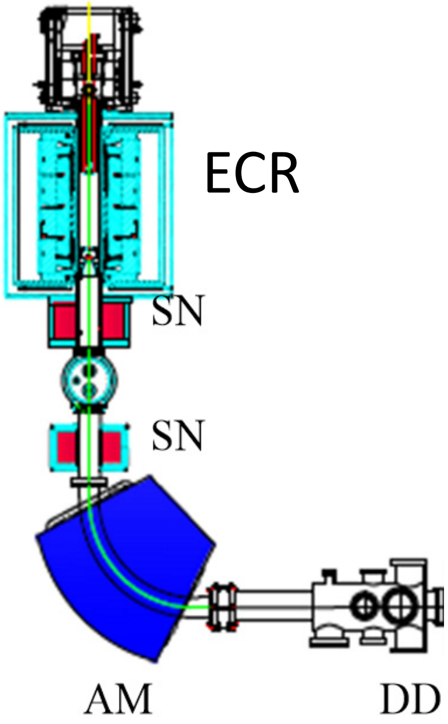






Space Charge effect: Q/A Separation

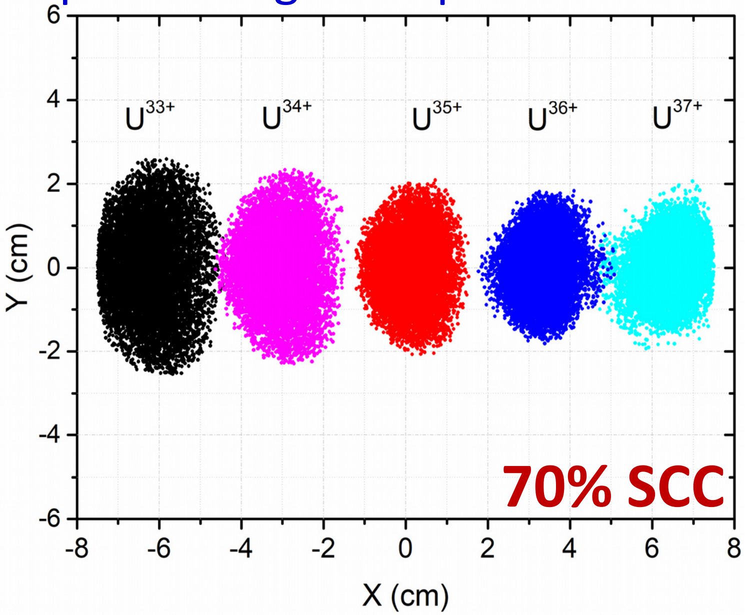


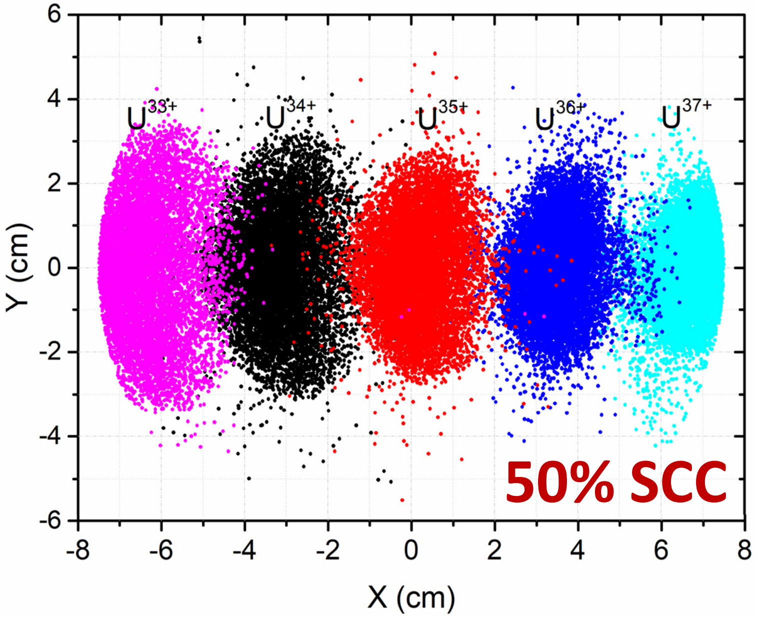


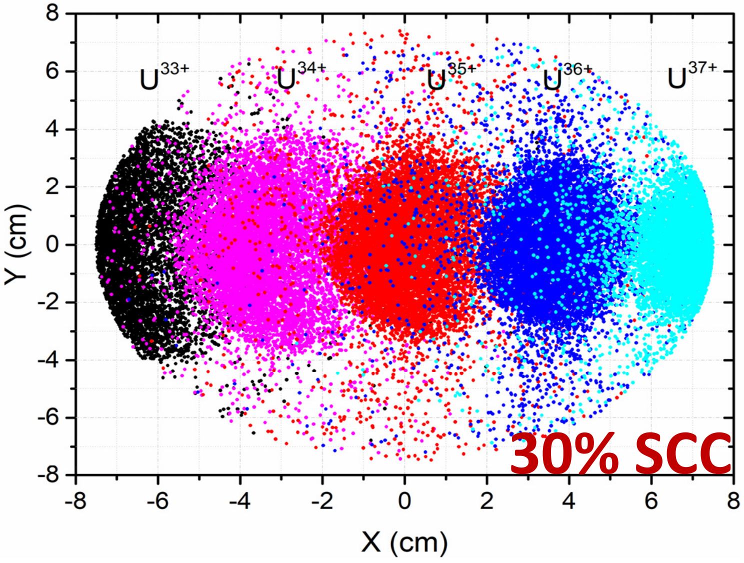
- Objective ion: U^{35+}
- U^{35+} ~ 2 emA, Total current ~ 20 emA.
- Initial mixed beam were simplified to include 20 different ion species
- Assuming all the beams have water-bag distributions with the same Twiss parameters, ~ 0.24 π.mm.mrad.

Space Charge effect: Q/A Separation

- SCC: Space Charge Compensation







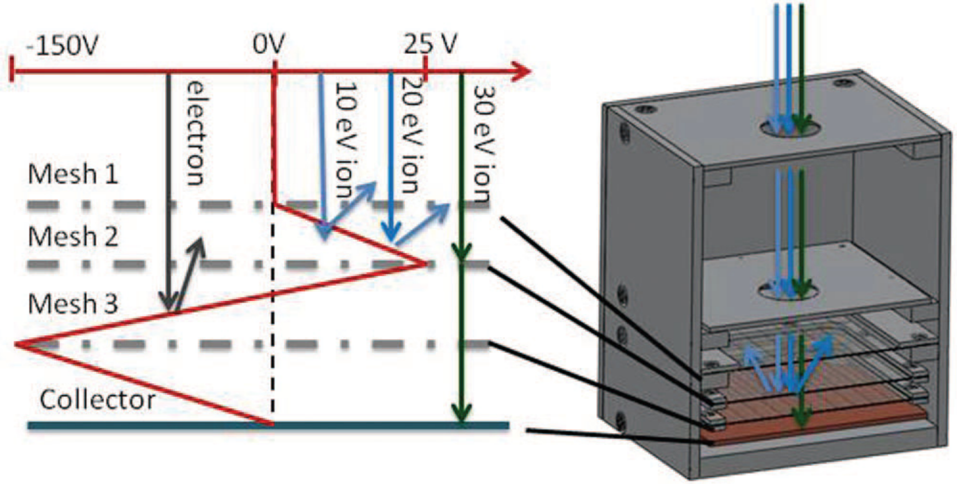
☐ Space charge compensation degree has a vital impact on beam transmission and charge separation.

☐ How much is the SCC factor?

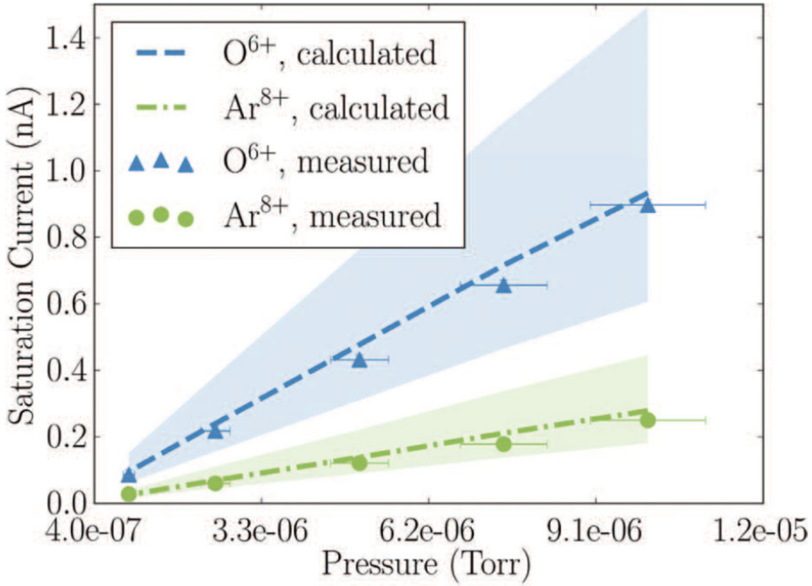
MSU measurement

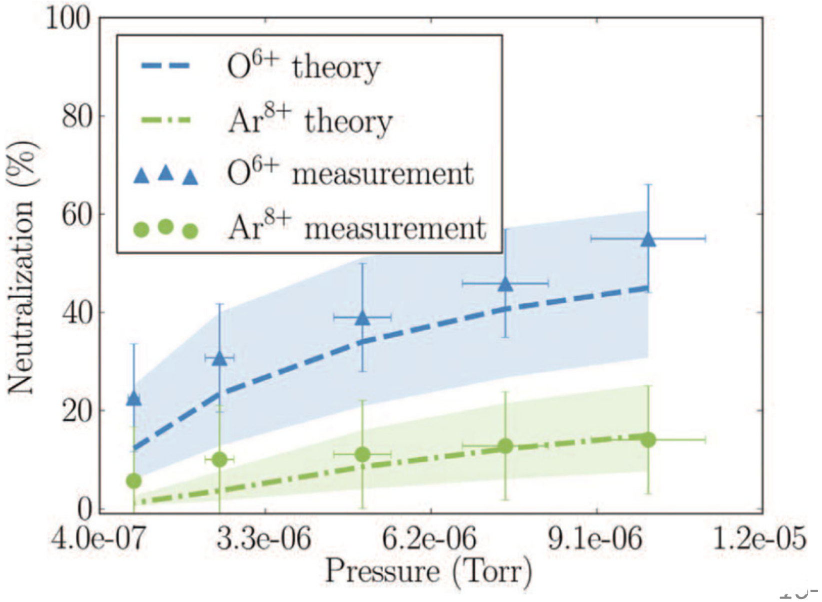
- The measurements suggest overall low neutralization factors (0%–60%).

Retarding field analyzer



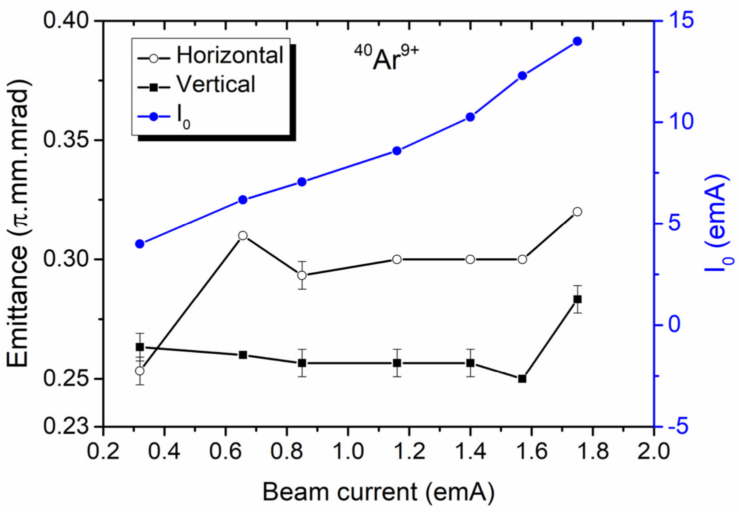
Rev. Sci. Instrum. 85, 02A739 (2014)

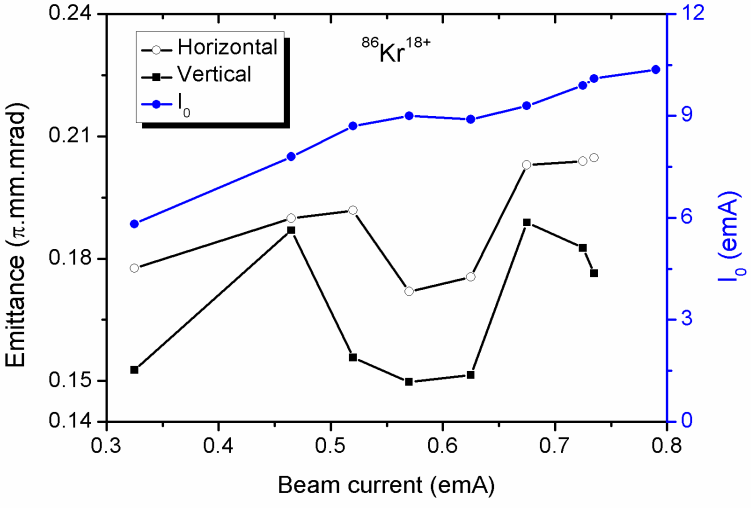




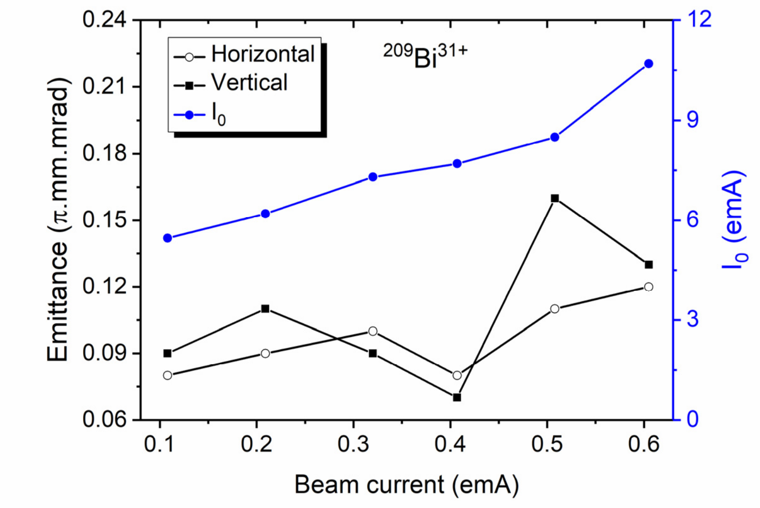
Space Charge effect: How much?

Measurement with SECRAL-II ion source





Measurement with SECRAL ion source



✓ **Beam emittance does NOT increase with beam intensity.**

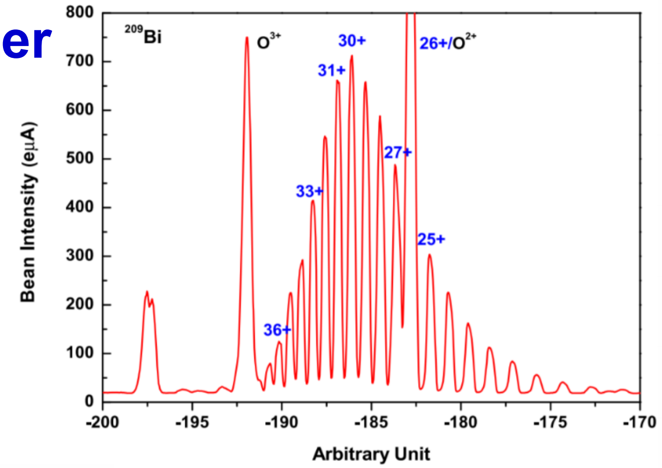
→ good compensation in ECR Q/A analyzer lines.

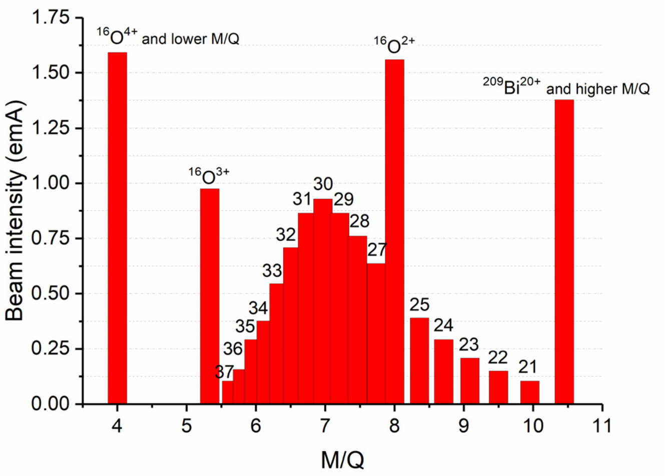
✓ **Beam quality is mainly determined by the ion source tuning and plasma conditions.**

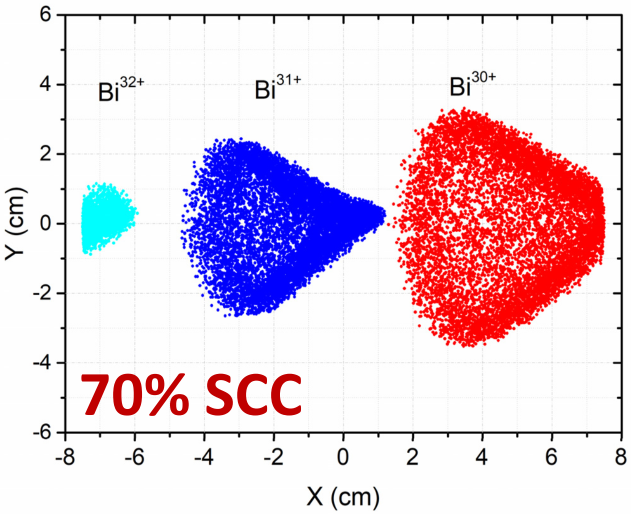
Space Charge effect: How much?

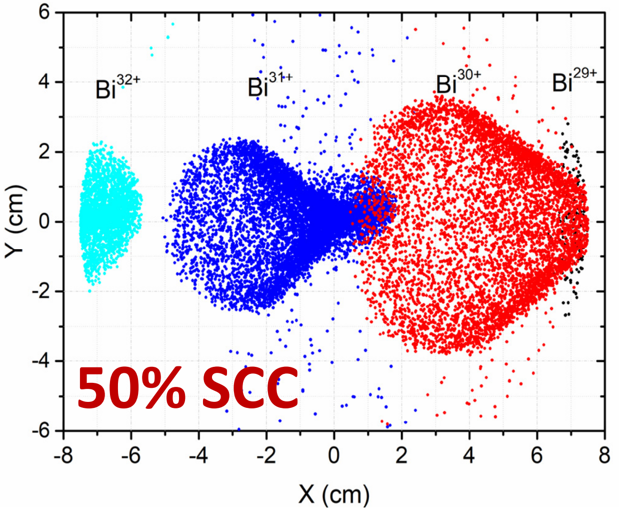
SECRAL Q/A analyzer

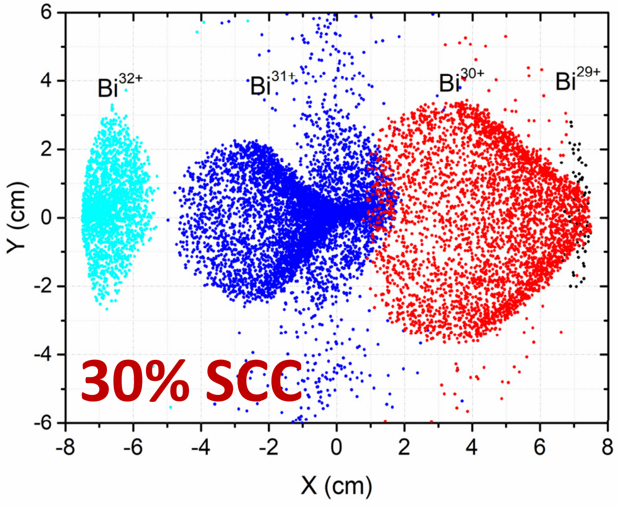
- I_{total}=13 emA,
- I_{Bi31+}=0.65 emA.











Space Charge effect: How much?

SECRAL Q/A analyzer

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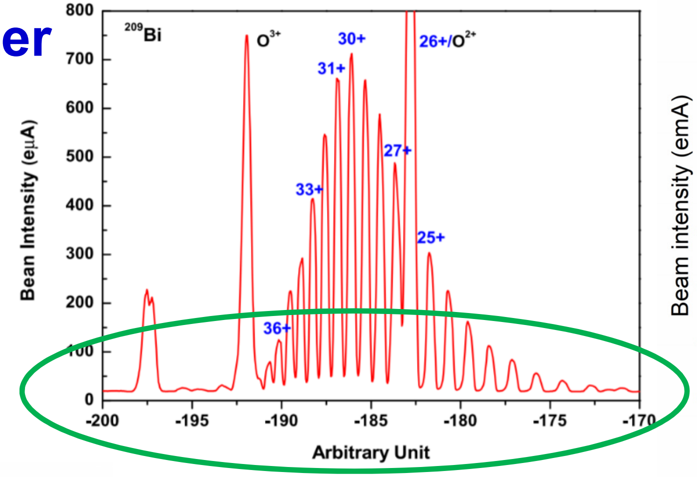
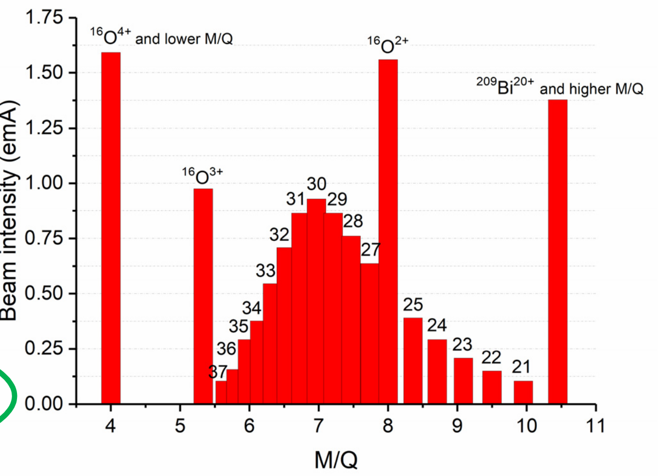
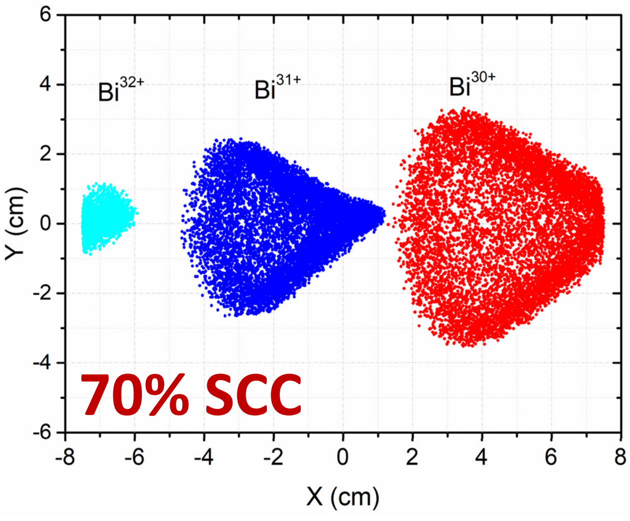
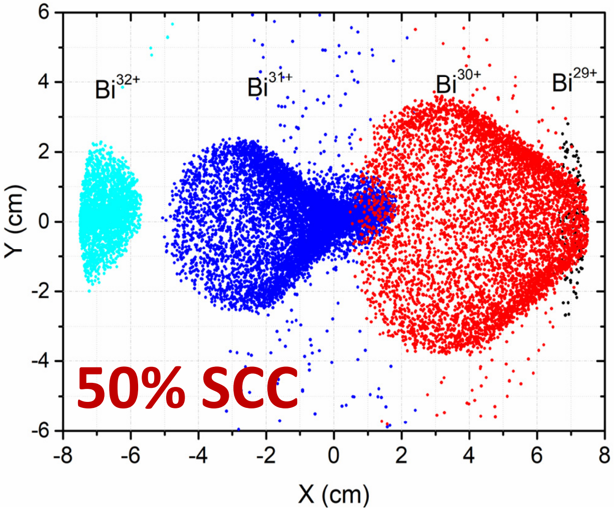


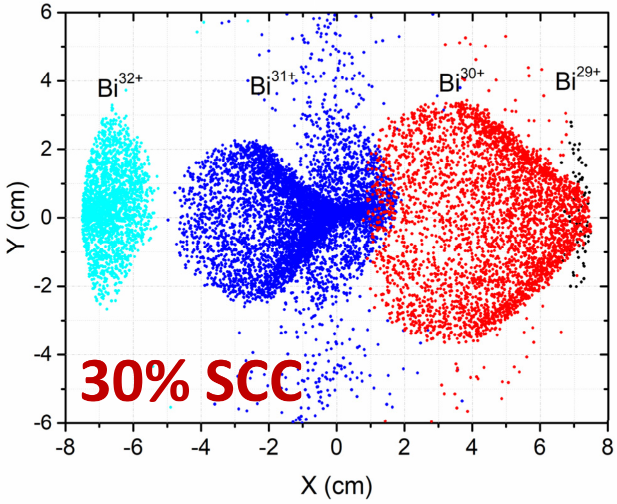




70% SCC



50% SCC

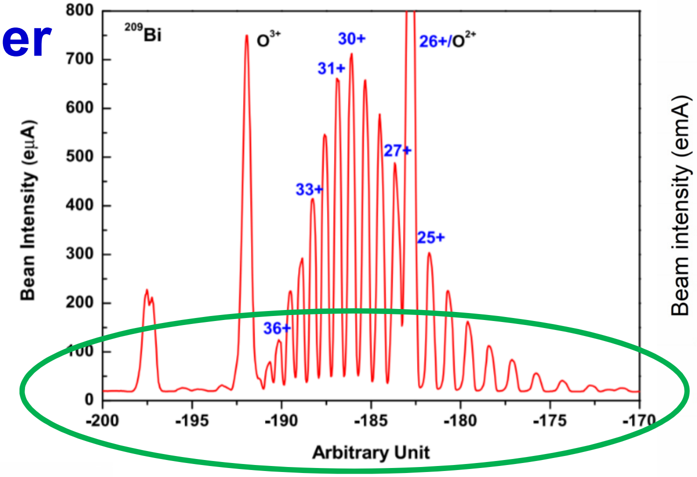


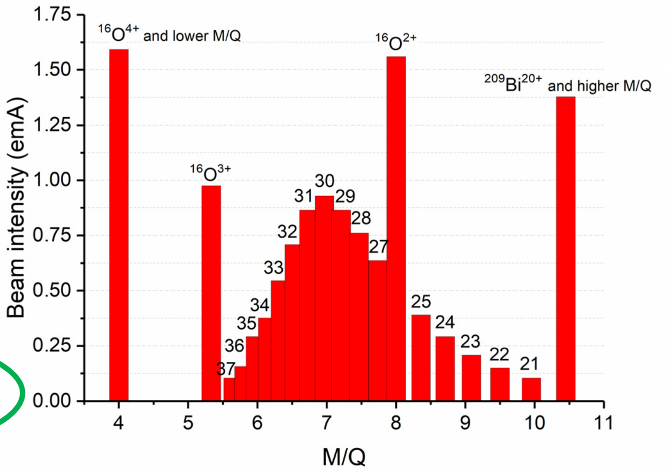
30% SCC

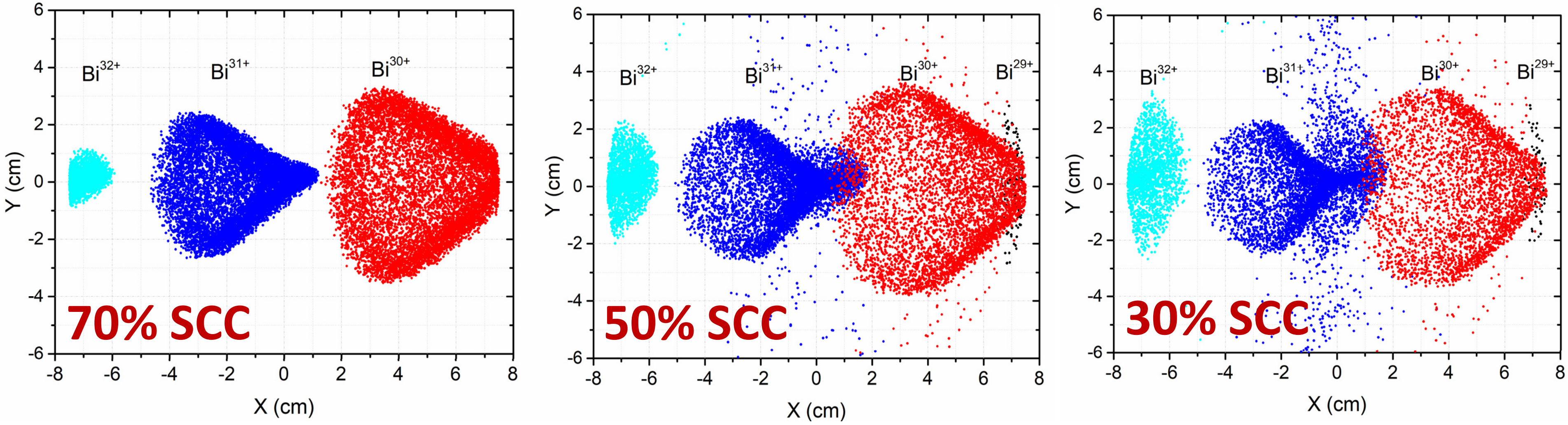
Space Charge effect: How much?

SECRAL Q/A analyzer

- I_{total}=13 emA,
- I_{Bi31+}=0.65 emA.



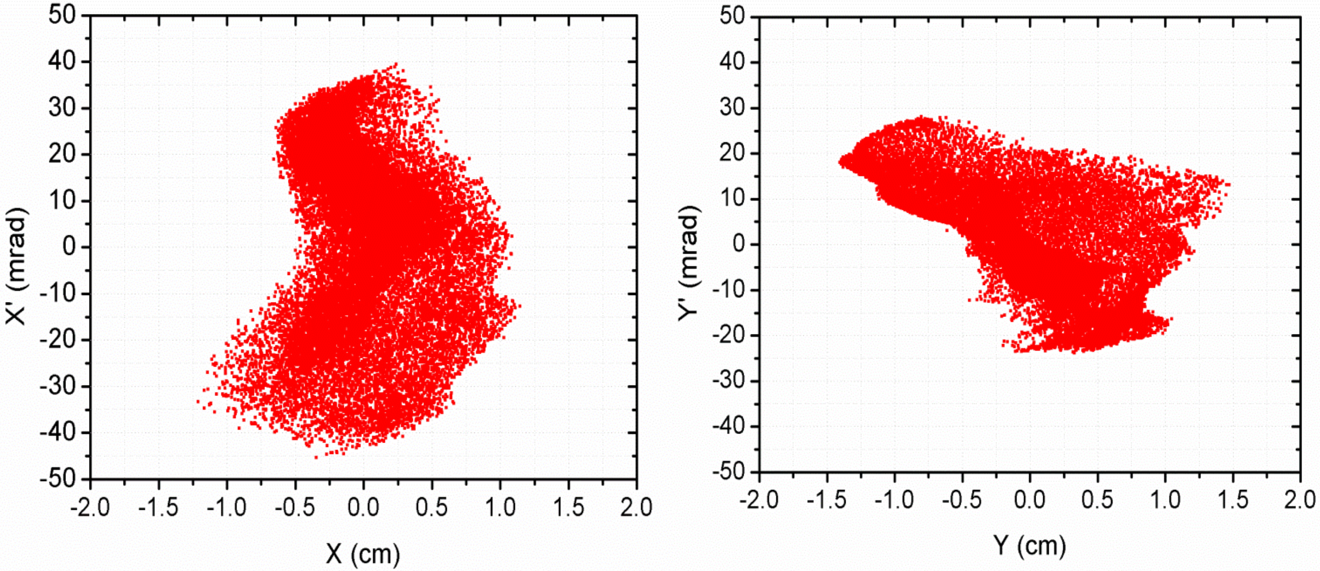




In realistic beam simulations and Q/A analyzer design it is secure to set the overall space charge compensation factor to 70% for intense highly-charged ion beams.

Multi-particle tracking

Phase space distribution after charge selection

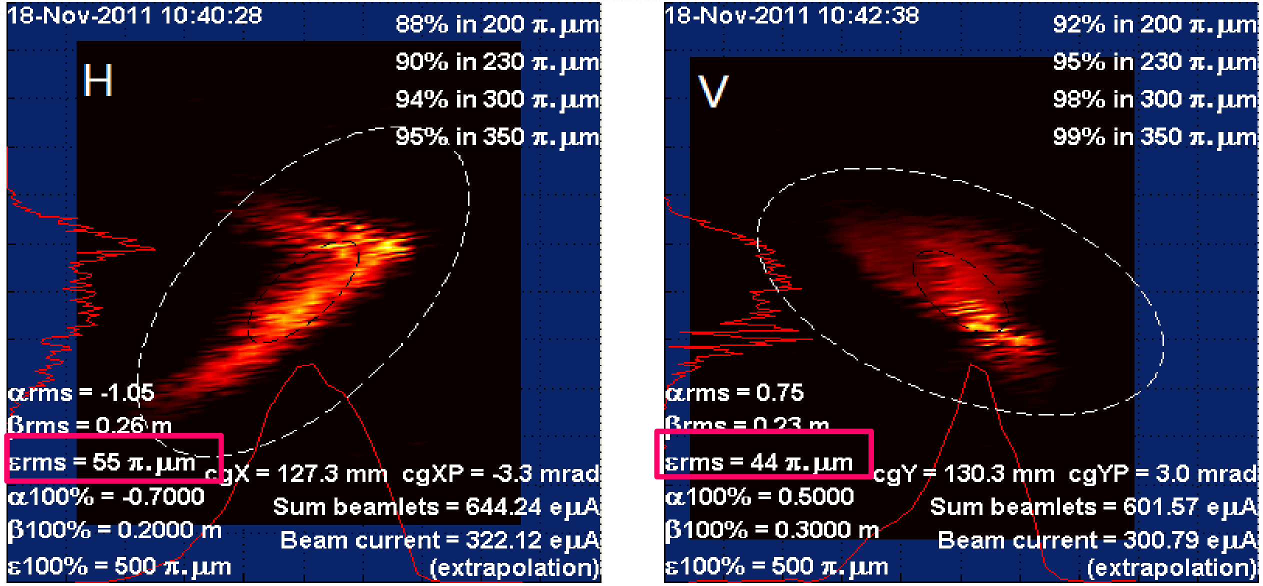


Simulation @FECR

Initial particle distribution from extraction simulation.

$\varepsilon_{X,\ rms}$=0.27 π.mm.mrad
$\varepsilon_{Y,rms}$ =0.21 π.mm.mrad

- B_{extr}=3.53 T



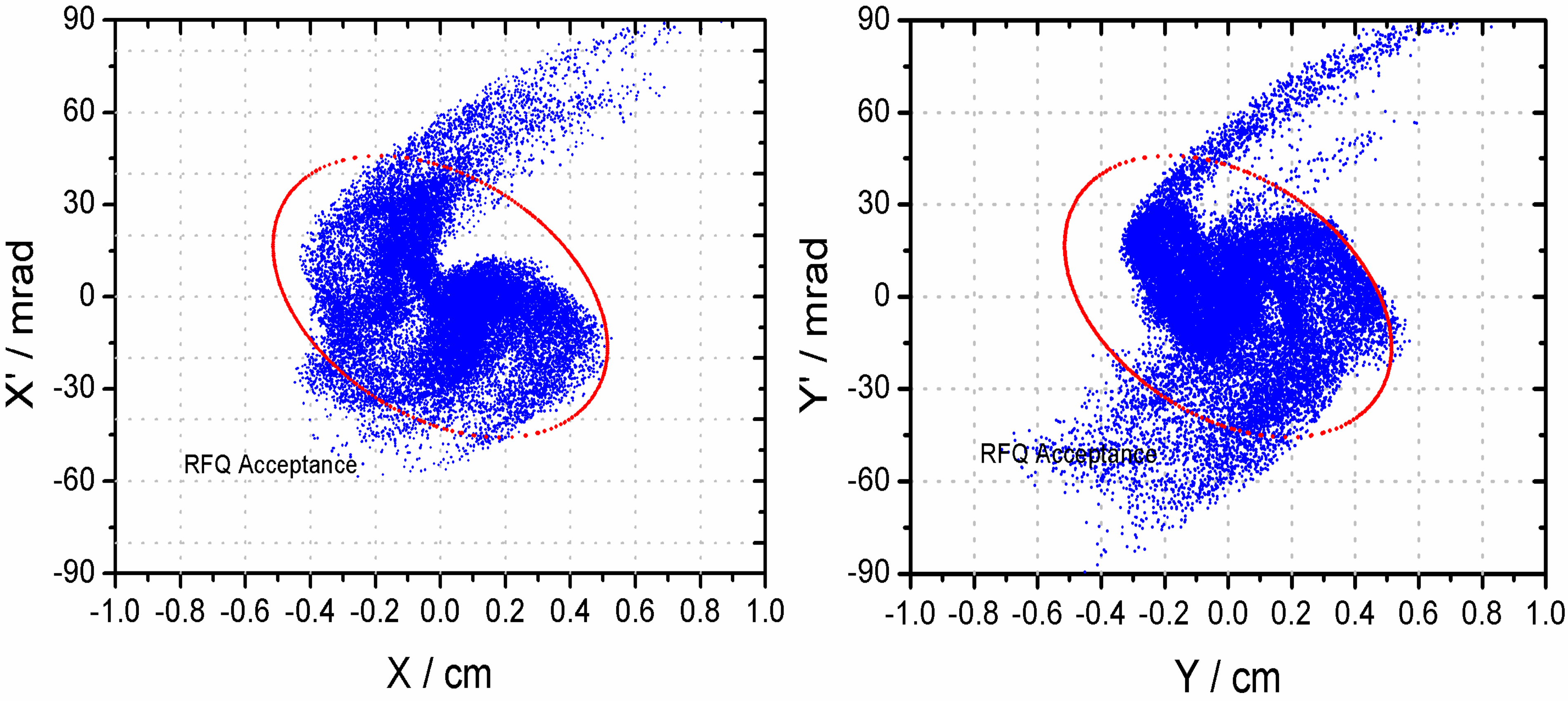
Measurement @ VENUS

$\varepsilon_{X,\ rms}$=0.14 π.mm.mrad
$\varepsilon_{Y,rms}$ =0.11 π.mm.mrad

- B_{extr}~ 2.2 T
- I_{U34+}=311emA
- I_0=7.5 mA

Thyo03_talk @ ECRIS2012

Necessity of beam collimation



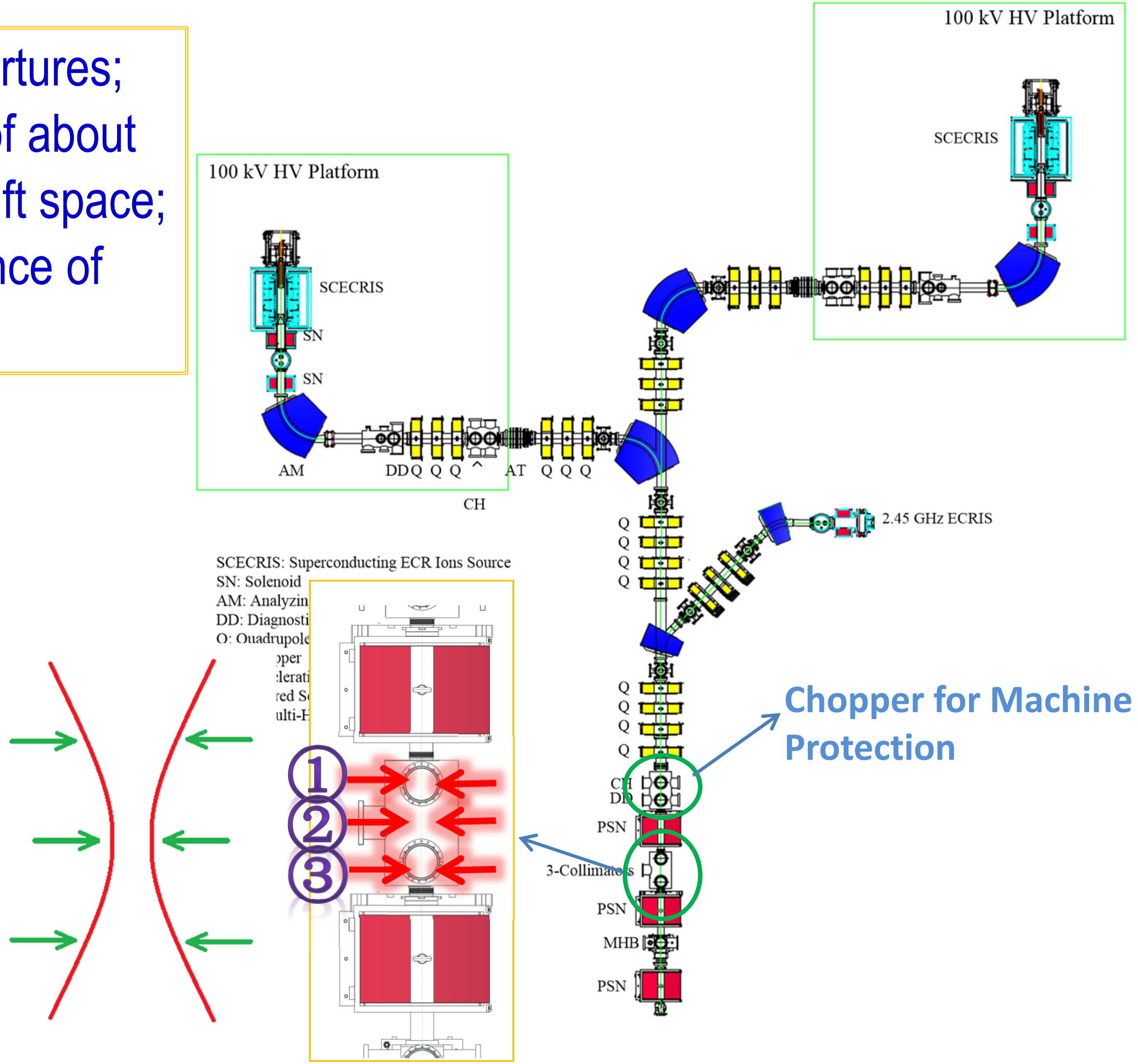
ε_x=0.27 pi.mm.mrad

ε_y=0.31 pi.mm.mrad

Particle distribution at RFQ entrance

LEBT collimation channel

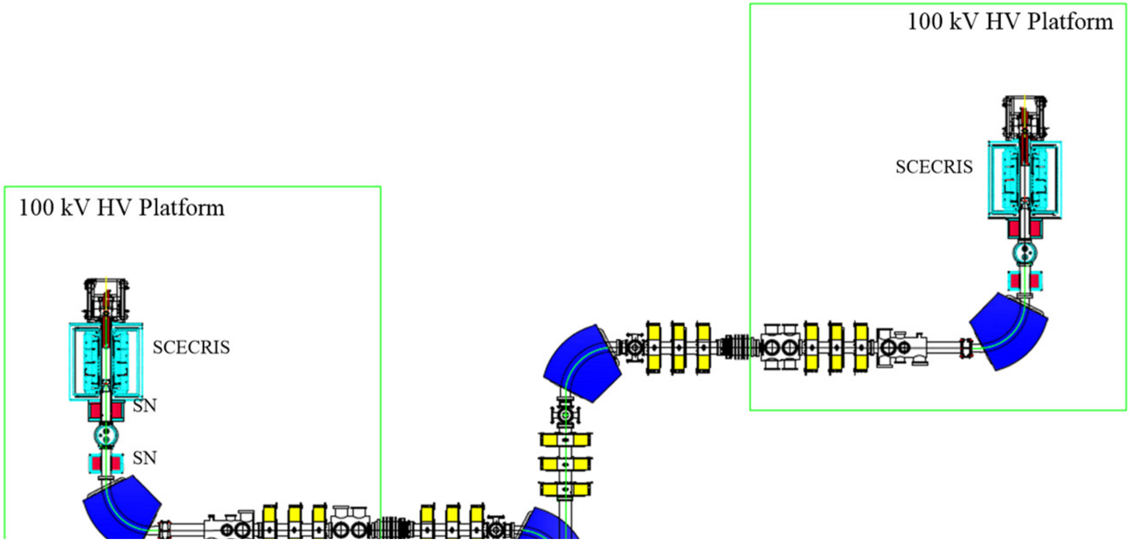
- ✓ 3 successive apertures;
- ✓ Phase advance of about 45 degrees per drift space;
- ✓ Total phase advance of 90 degrees.

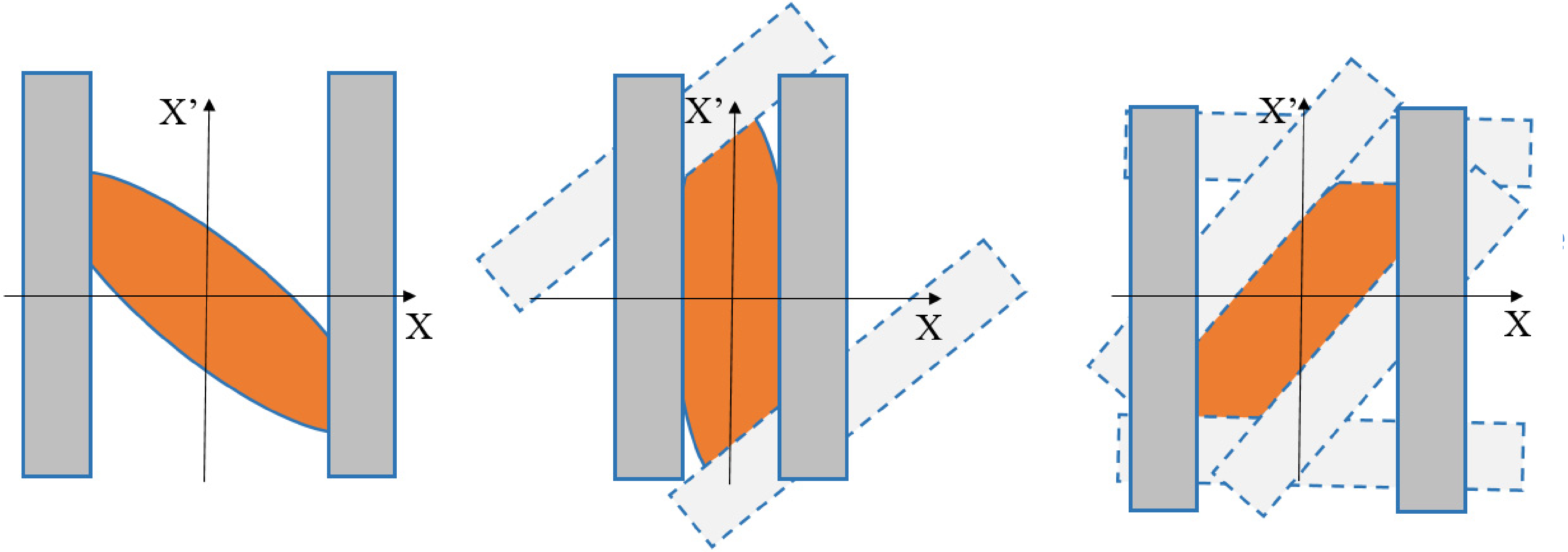


Chopper for Machine Protection

LEBT collimation channel

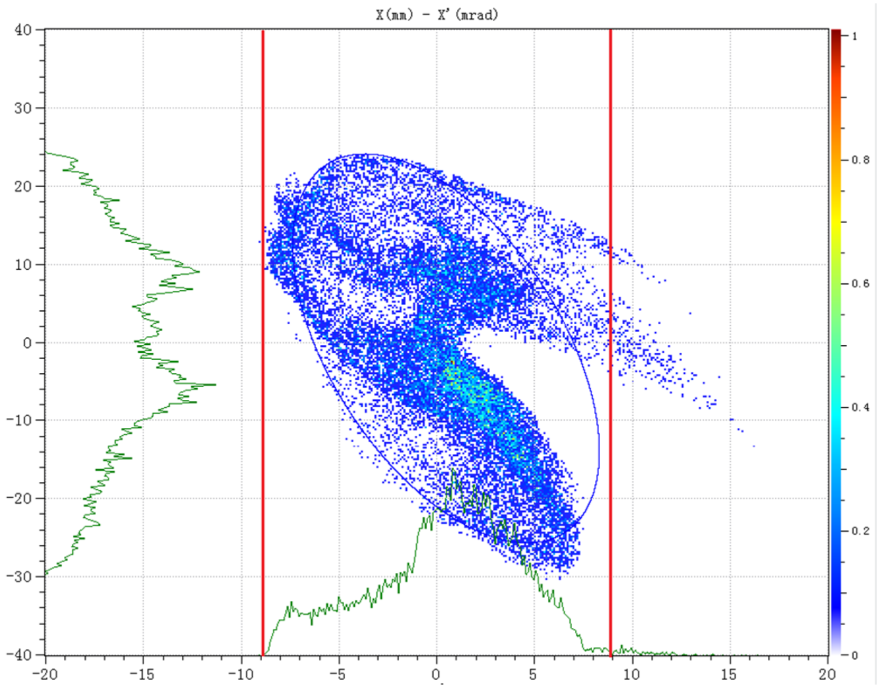
- ✓ 3 successive apertures;
- ✓ Phase advance of about 45 degrees per drift space;
- ✓ Total phase advance of 90 degrees.

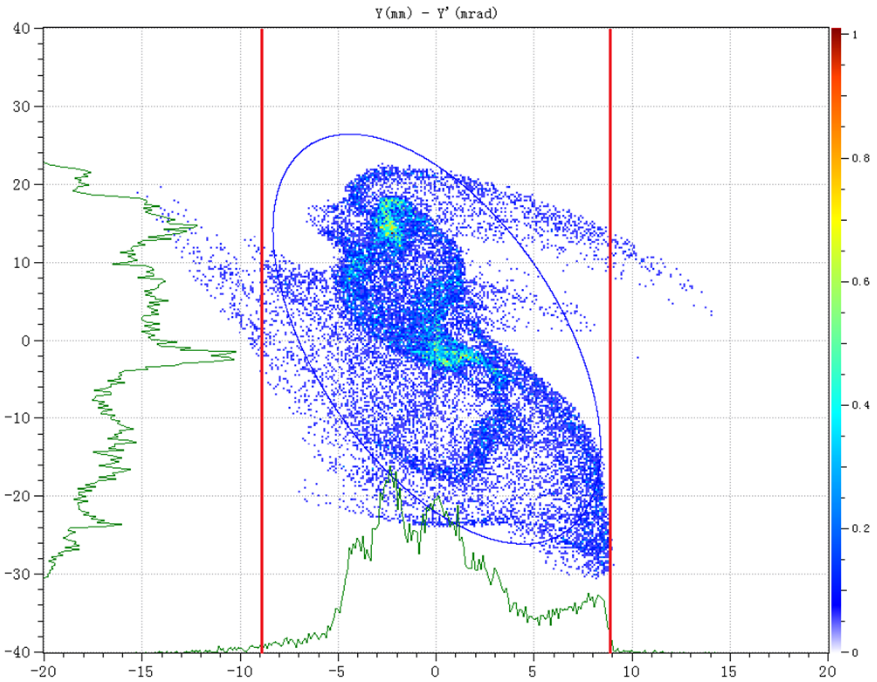




LEBT collimator

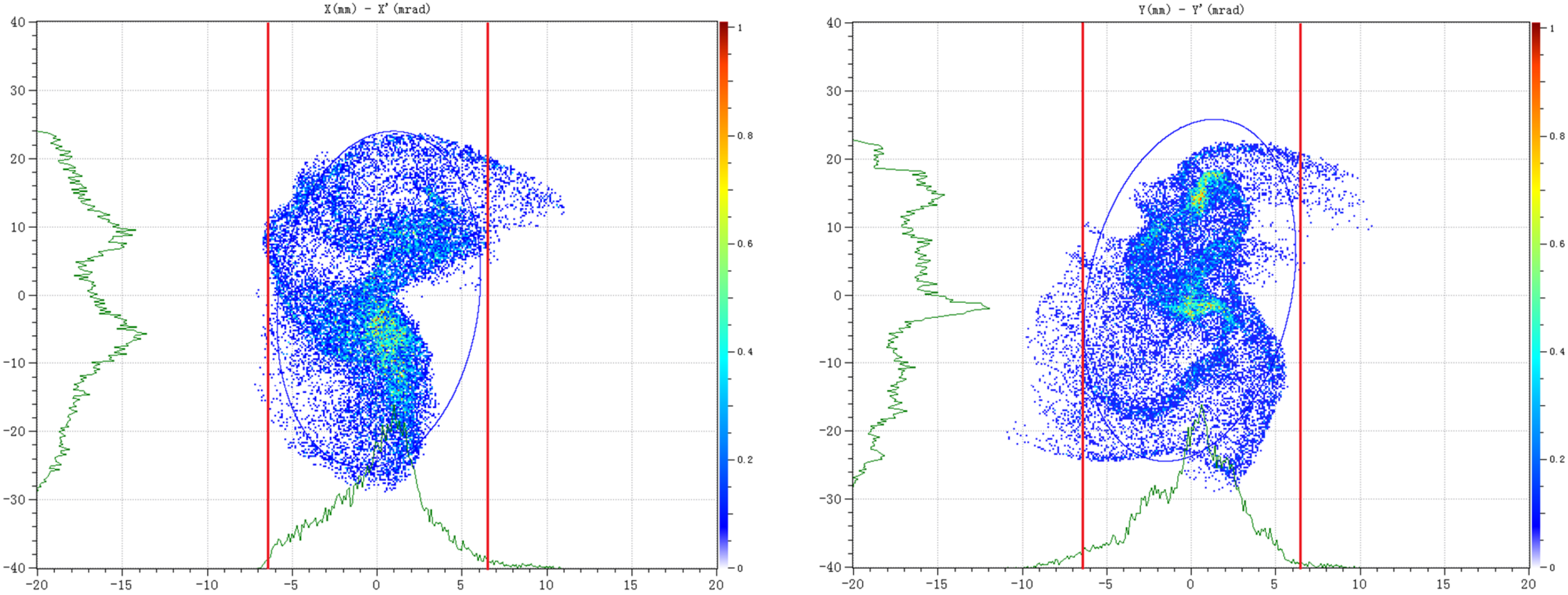
Phase space distribution at the 1st aperture





LEBT collimator

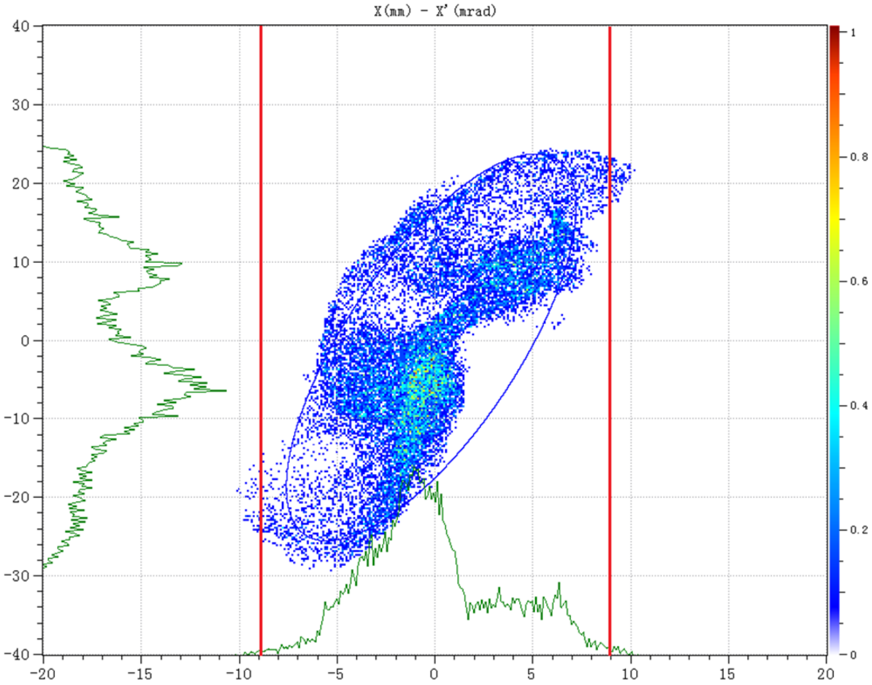
Phase space distribution at the 2nd aperture

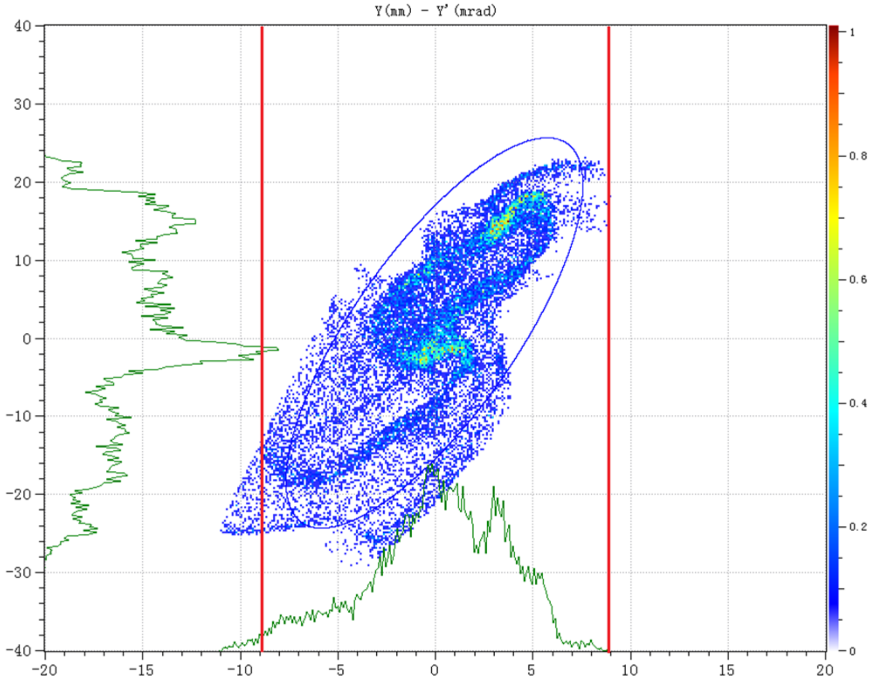


With 1st aperture cut

LEBT collimator

Phase space distribution at the 3^{rd} aperture

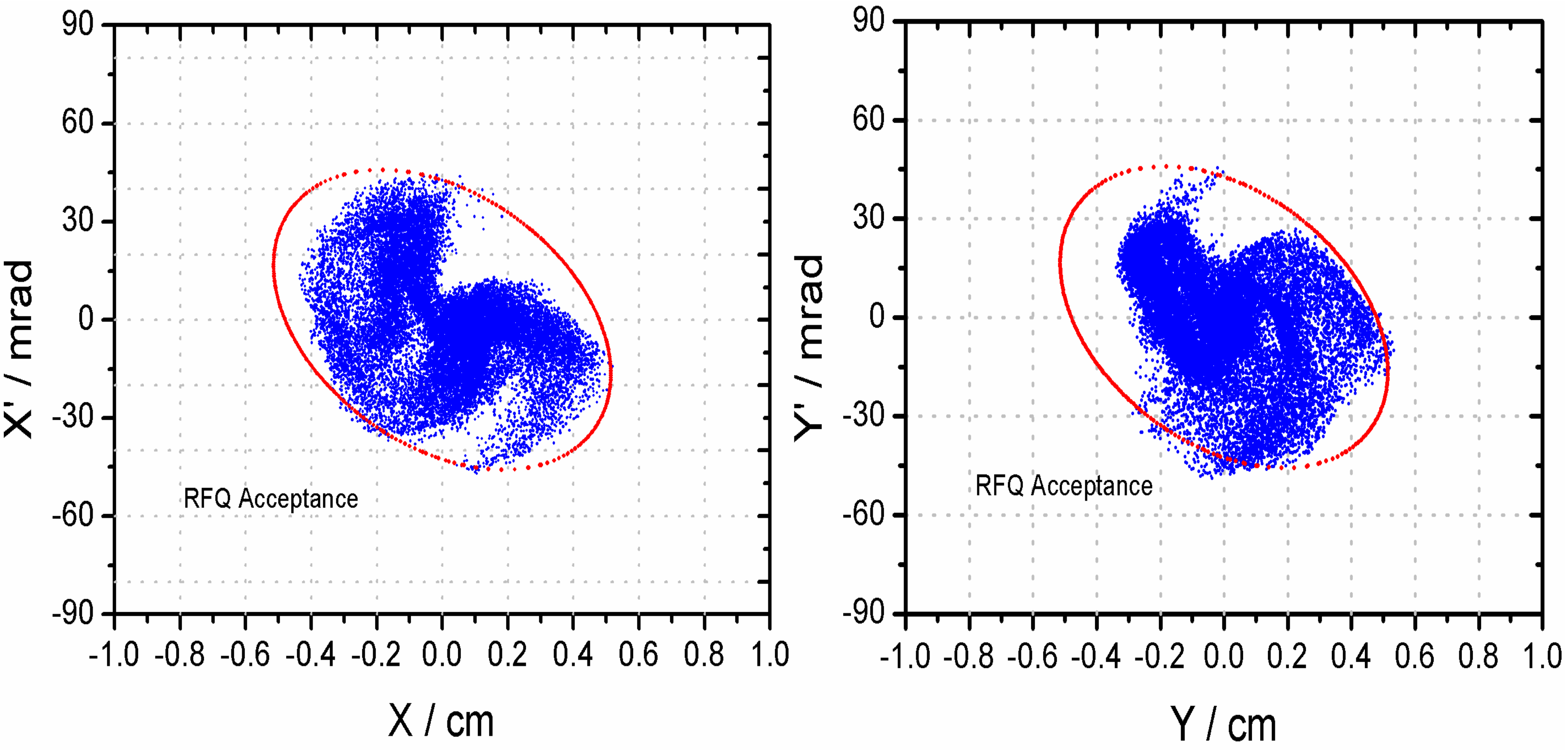




With 1^{st} and 2^{nd} aperture cut

LEBT collimation channel

☐ **20% of the particle tails contribute more than 69% of emittance.**



ε_x=0.16 pi.mm.mrad **ε_y=0.15 pi.mm.mrad**

Particle distribution at RFQ entrance with Collimation cutting in LEBT

HIAF-RFQ

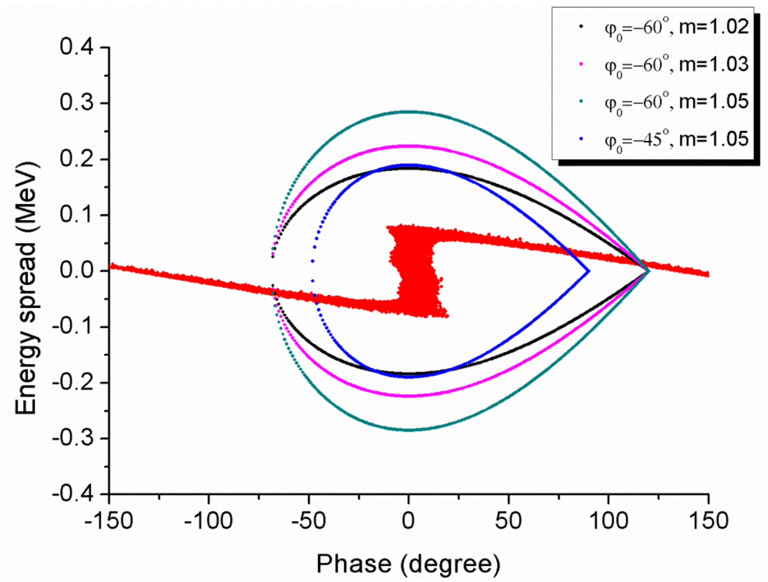
Requirements and strategies:

- ☐ High acceleration efficiency and high transmission.
- ☐ Small Longitudinal Emittance.
  - ➢ External 3-harmonic pre-buncher
  - ➢ Small longitudinal acceptance of RFQ
- ☐ Proper Vane Voltage to minimize the thermal problem for CW beam.
- ☐ Length as short as possible.
- ☐ Traditional design for easily fabricating and tuning— Sinusoidal modulation, constant voltage, constant average radius.
- ☐ Small convergence at entrance for easily matching with LEBT.

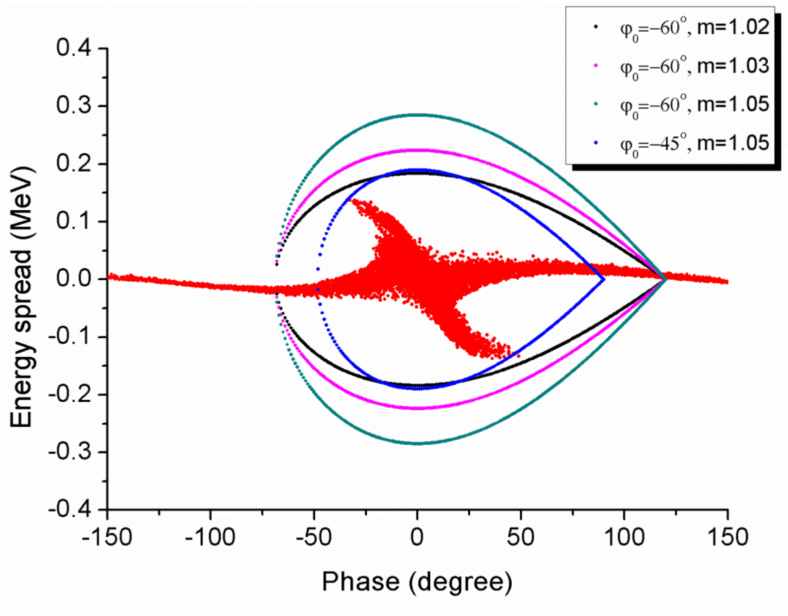
High intensity beam matching with RFQ: Longitudinal

Beam pre-bunching with 3-Harmonic Buncher

Without longitudinal space charge



With longitudinal space charge



Voltage (kV) for three Harmonics:

Longitudinal Space Charge	1st Harmonics (40.625 MHz)	2nd Harmonics (81.25 MHz)	3rd Harmonics (121.875 MHz)
NO	2.66	-1.60	1.46
YES	3.19	-2.26	2.03

- Starting phase and modulation are selected as -60° and 1.02.

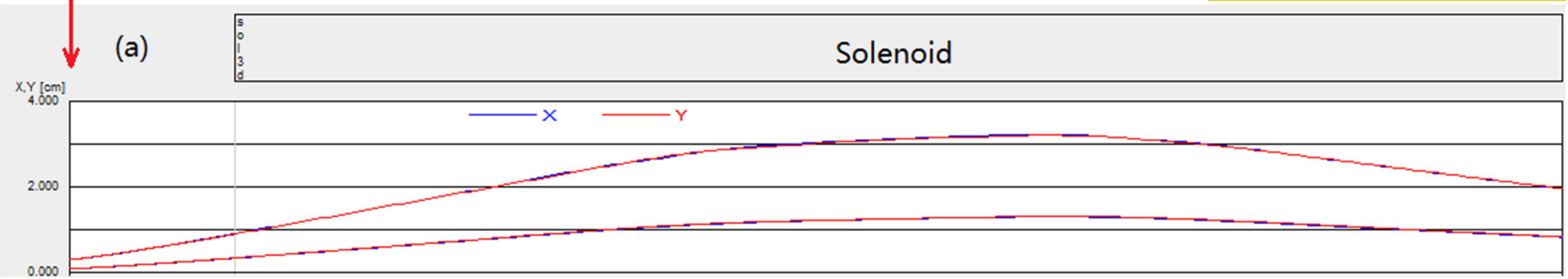
High intensity beam matching with RFQ: Transverse

Steep convergence VS Smooth convergence at RFQ entrance

Beam back-tracking from the entrance of the RFQ electrode

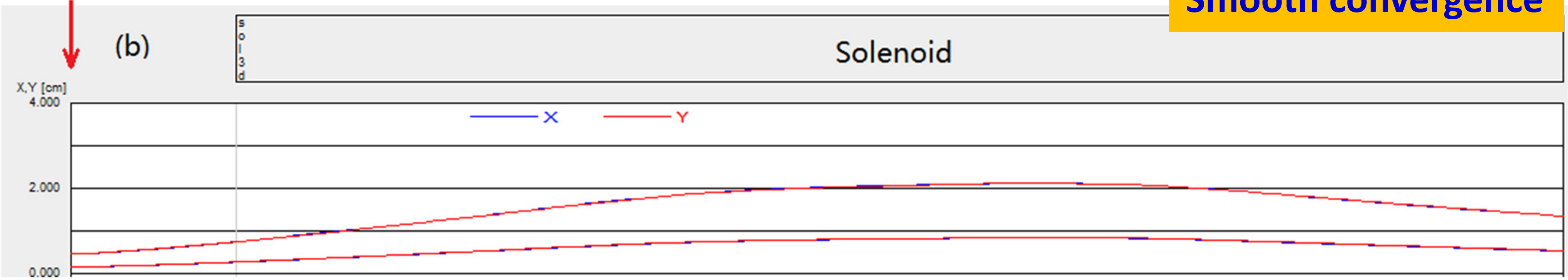
RFQ electrode entrance

Steep convergence



RFQ electrode entrance

Smooth convergence

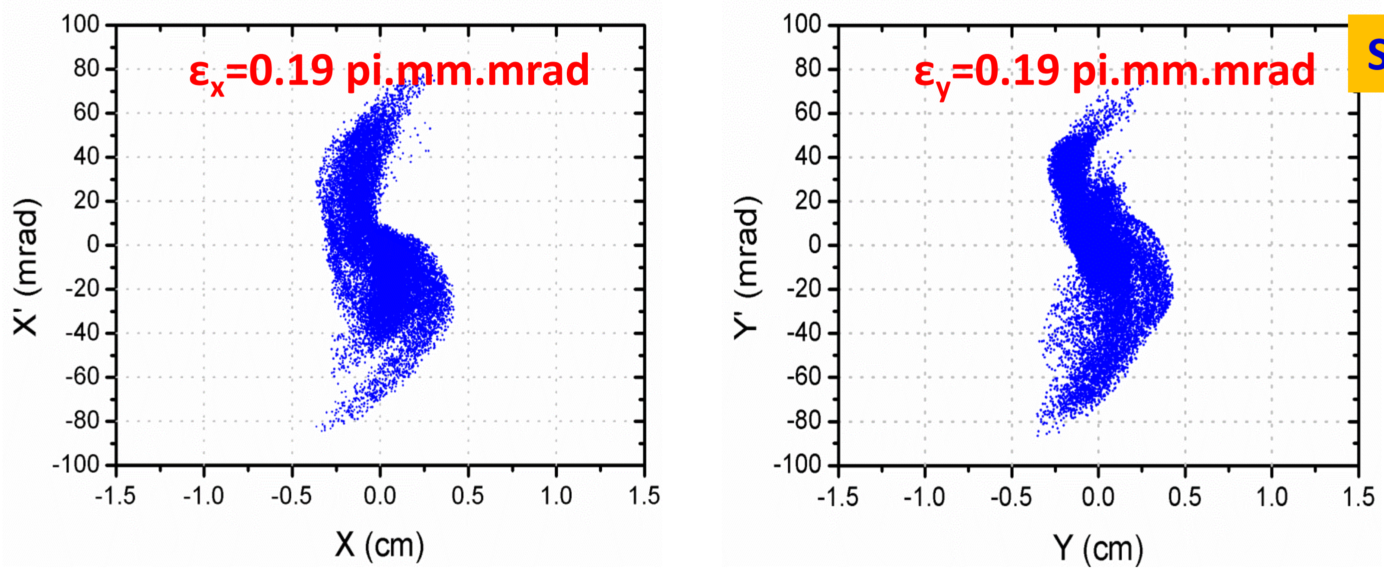


(a) RFQ matching TWISS parameters: alpha~ 0.63, beta~5.92 cm/rad
emittance growth: 4.6%

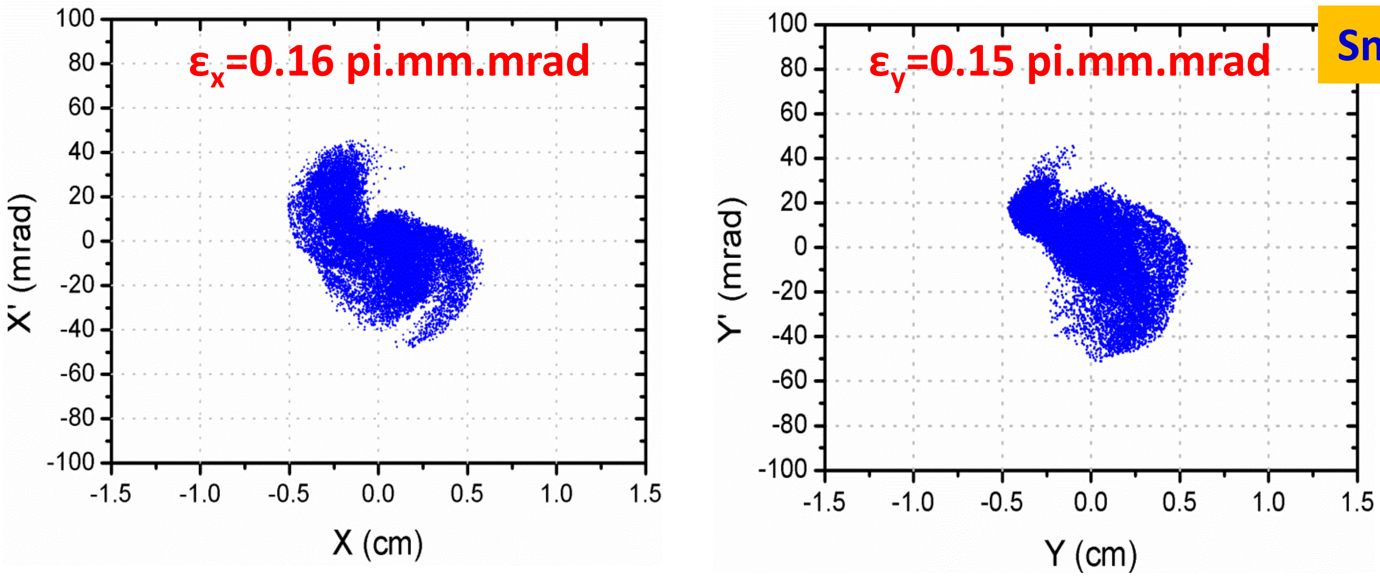
(b) RFQ matching TWISS parameters: alpha~ 0.39, beta~12.06 cm/rad
emittance growth:0.24%

High intensity beam matching with RFQ: Transverse

Steep convergence VS Smooth convergence at RFQ entrance



Steep convergence



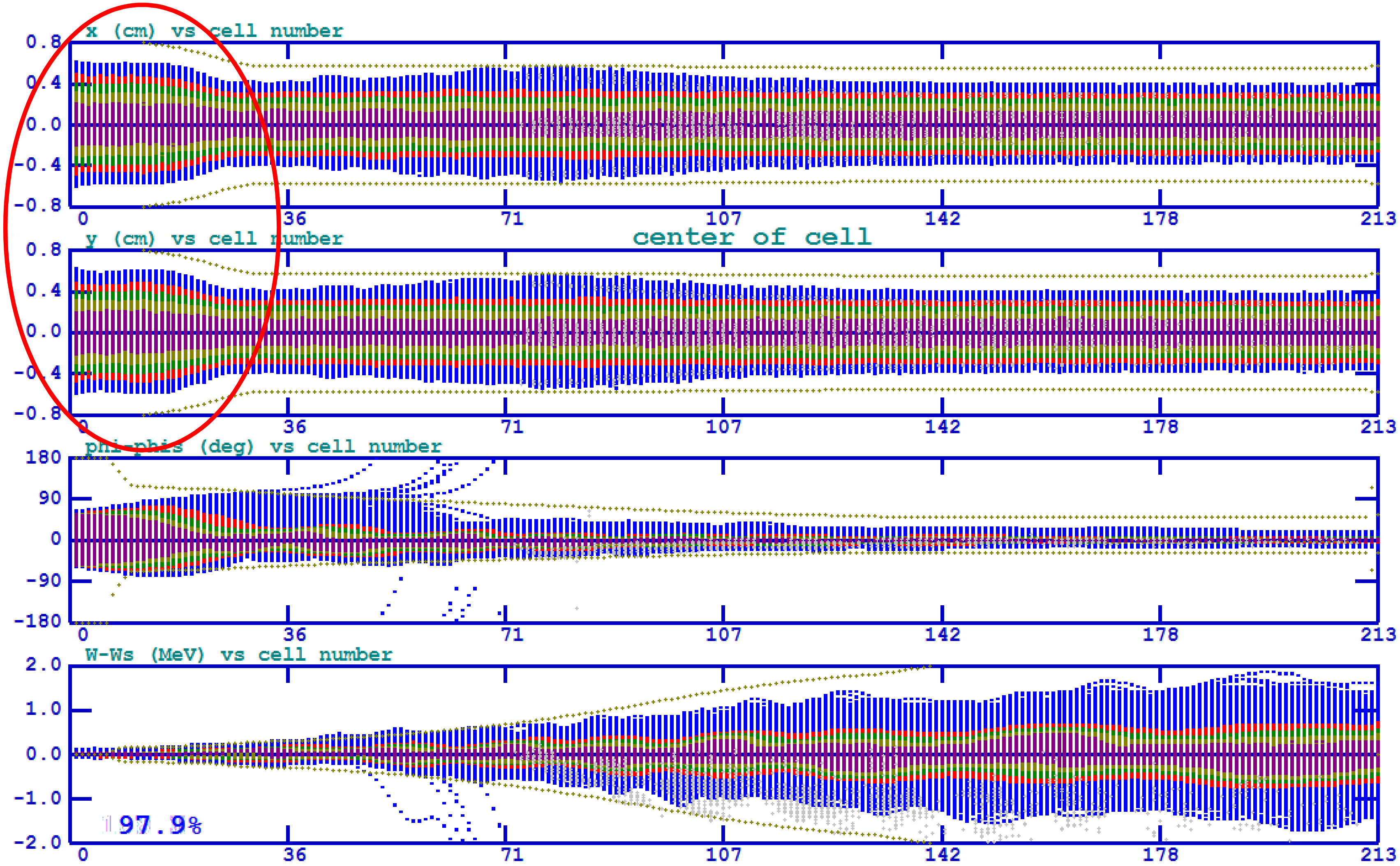
Smooth convergence

RFQ beam dynamics

	HIAF-RFQ
Design M/Q	2~7
Frequency (MHz)	81.25
Resonance cavity	4-vane
Input/Output energy (MeV/u)	0.014/0.5
Max. vane voltage (kV)	70
Max. Kilpatrick Coefficient	1.57
R_0 (mm)	5.758
Synchronous Phase	**-60° ~ -26°**
Modulation Factor	**1.02~2.03**
Acceptance TWISS α/β (cm/rad)	**0.39/12.05**
Radial Matcher cell	**6**
Length (cm)	623.9
Overall acceleration efficiency	**81.3%**
$\varepsilon_{z,rms}$ (keV/u.ns)	0.33
$\varepsilon_{z,99.9\%}$ (keV/u.ns)	6.40
$\varepsilon_{x,rms}/\varepsilon_{y,rms}$ (π.mm.mrad)	0.152/0.146
$\varepsilon_{x,99.9\%}/\varepsilon_{y,99.9\%}$ (π.mm.mrad)	1.407/1.343

RFQ beam dynamics

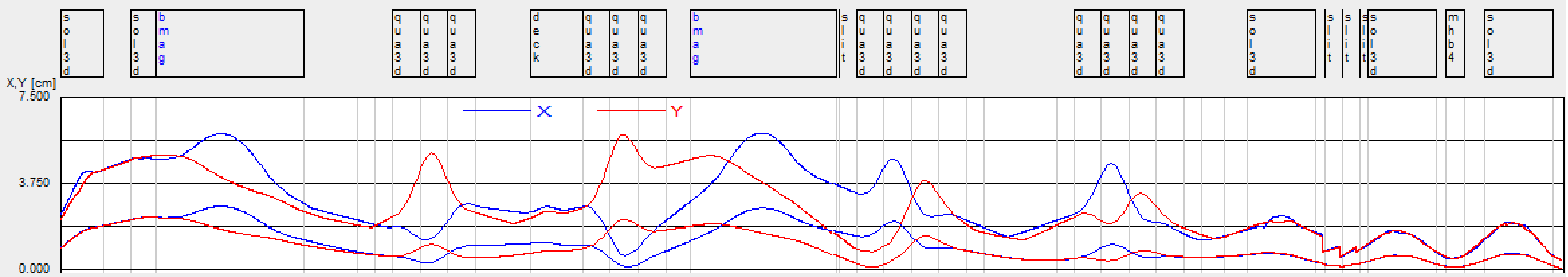
@ rfqgen



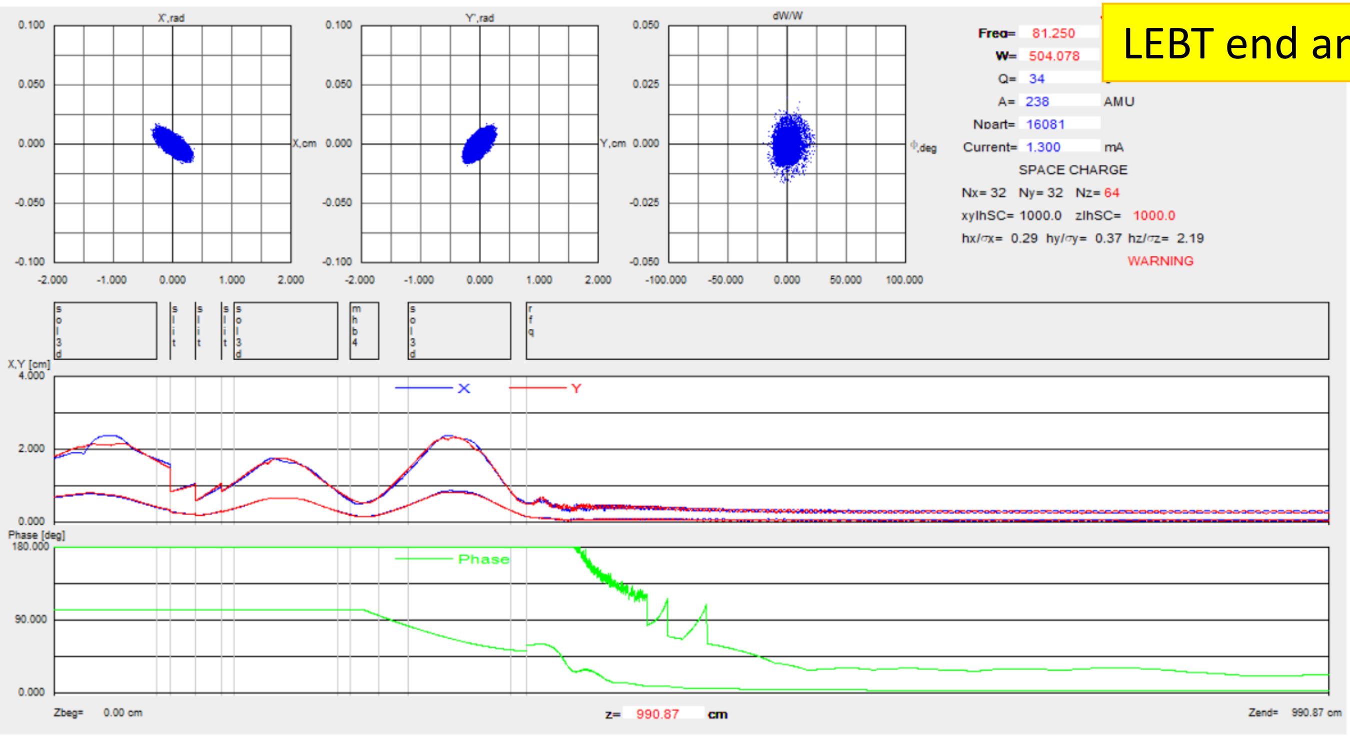
End-End Simulation for HIAT FE

- ☐ Initial particle distribution from extraction simulation.

LEBT



LEBT end and RFQ



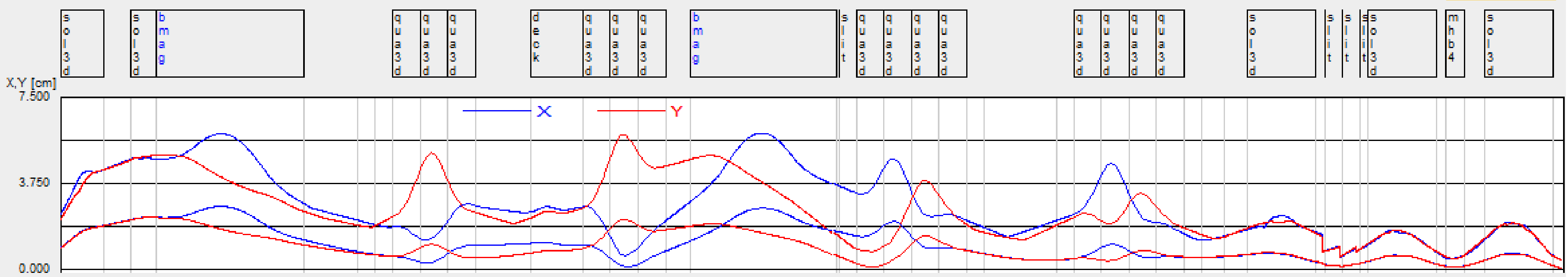
Freq= 81.250
W= 504.078
Q= 34
A= 238 AMU
Npart= 16081
Current= 1.300 mA
SPACE CHARGE
Nx= 32 Ny= 32 Nz= 64
xylhSC= 1000.0 zlhSC= 1000.0
hx/σx= 0.29 hy/σy= 0.37 hz/σz= 2.19
WARNING

Zbeg= 0.00 cm
z= 990.87 cm
Zend= 990.87 cm

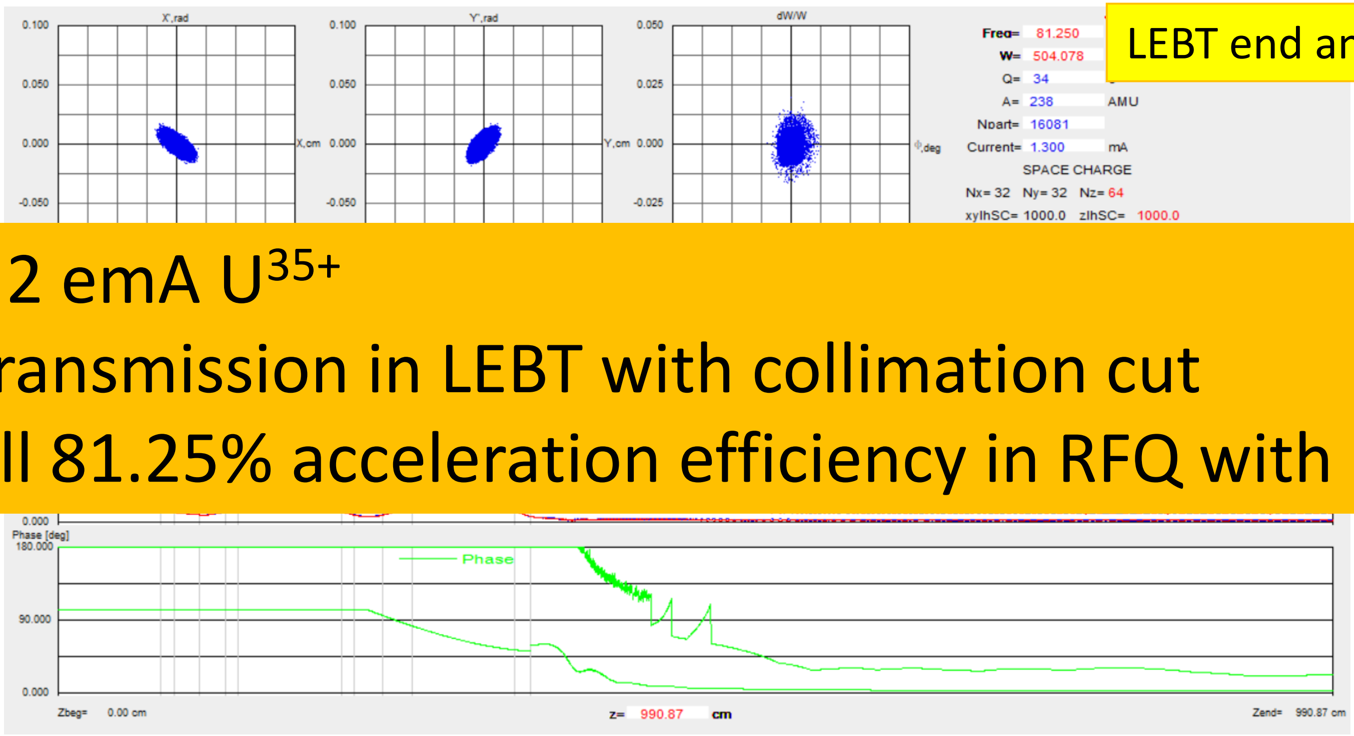
End-End Simulation for HIAT FE

☐ Initial particle distribution from extraction simulation.

LEBT



LEBT end and RFQ



Freq= 81.250
W= 504.078
Q= 34
A= 238 AMU
Npart= 16081
Current= 1.300 mA
SPACE CHARGE
Nx= 32 Ny= 32 Nz= 64
xylhSC= 1000.0 zlhSC= 1000.0

Zbeg= 0.00 cm
z= 990.87 cm
Zend= 990.87 cm

- Initial 2 emA U^{35+}
- 80% transmission in LEBT with collimation cut
- Overall 81.25% acceleration efficiency in RFQ with MHB

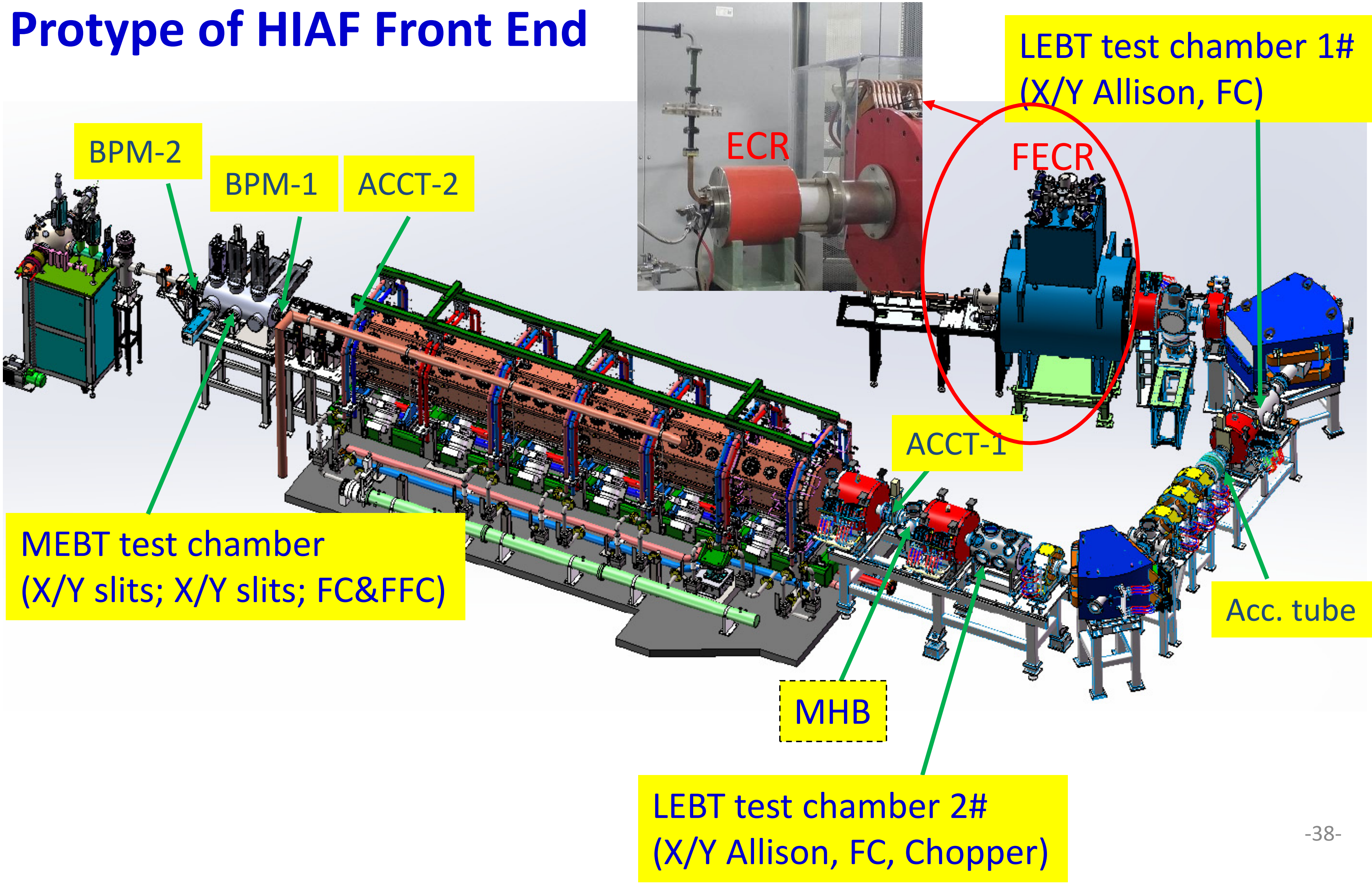
End-End Simulation for HIAT FE

Simulation with different SCC factor in LEBT

- SCC: Space Charge Compensation

SCC	Collimator	η_{LEBT}	η_{RFQ}	η_{Total}	$\varepsilon_{x\ LEBT}$	$\varepsilon_{y\ LEBT}$	$\varepsilon_{x\ RFQ}$	$\varepsilon_{y\ RFQ}$	$\varepsilon_{z\ RFQ}$
95%	withou	100%	68.8%	68.8%	0.23	0.21	0.16	0.15	0.34
	with	80%	79.9%	63.8%	0.16	0.14	0.15	0.14	0.33
70%	without	100%	67.0%	67.0%	0.27	0.31	0.15	0.15	0.33
	with	80%	81.3%	65.0%	0.16	0.15	0.15	0.15	0.33
50%	without	100%	65.4%	65.4%	0.28	0.31	0.18	0.16	0.32
	with	80%	80.0%	64.0%	0.18	0.17	0.17	0.15	0.32
25%	without	100%	62.1%	62.1%	0.31	0.35	0.19	0.17	0.32
	with	80%	76.8%	61.4%	0.19	0.20	0.19	0.16	0.32
0%	without	99.4%	60.3%	60.0%	1.02	0.92	0.18	0.19	0.30
	with	80%	74.6%	59.7%	0.22	0.21	0.18	0.18	0.30

Protype of HIAF Front End



ECR

FECR

LEBT test chamber 1#
(X/Y Allison, FC)

BPM-2

BPM-1

ACCT-2

ACCT-1

MEBT test chamber
(X/Y slits; X/Y slits; FC&FFC)

Acc. tube

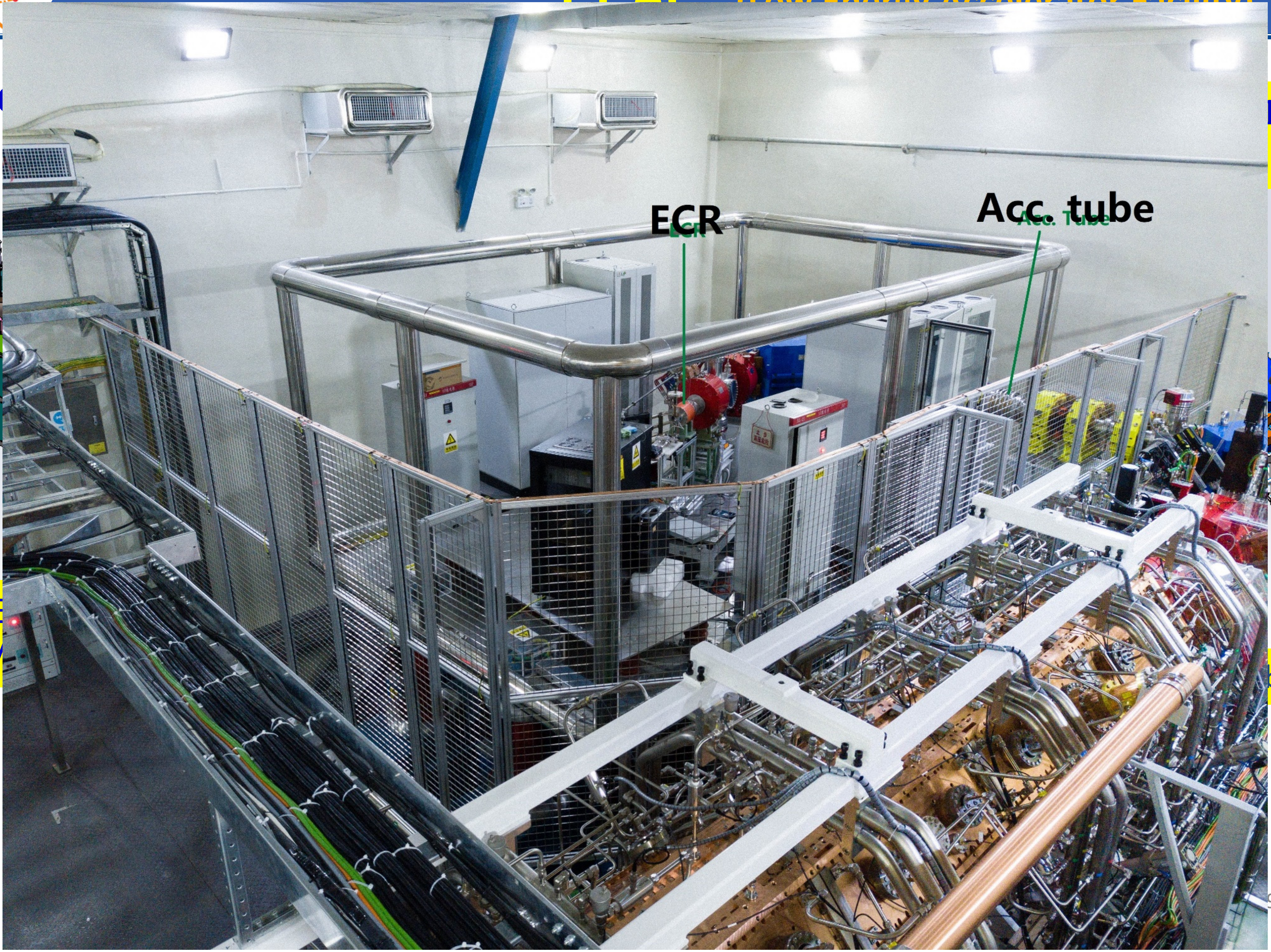
MHB

LEBT test chamber 2#
(X/Y Allison, FC, Chopper)

LEAF (Low Energy Accelerator Facility)

Pr

1#



ME
(X/

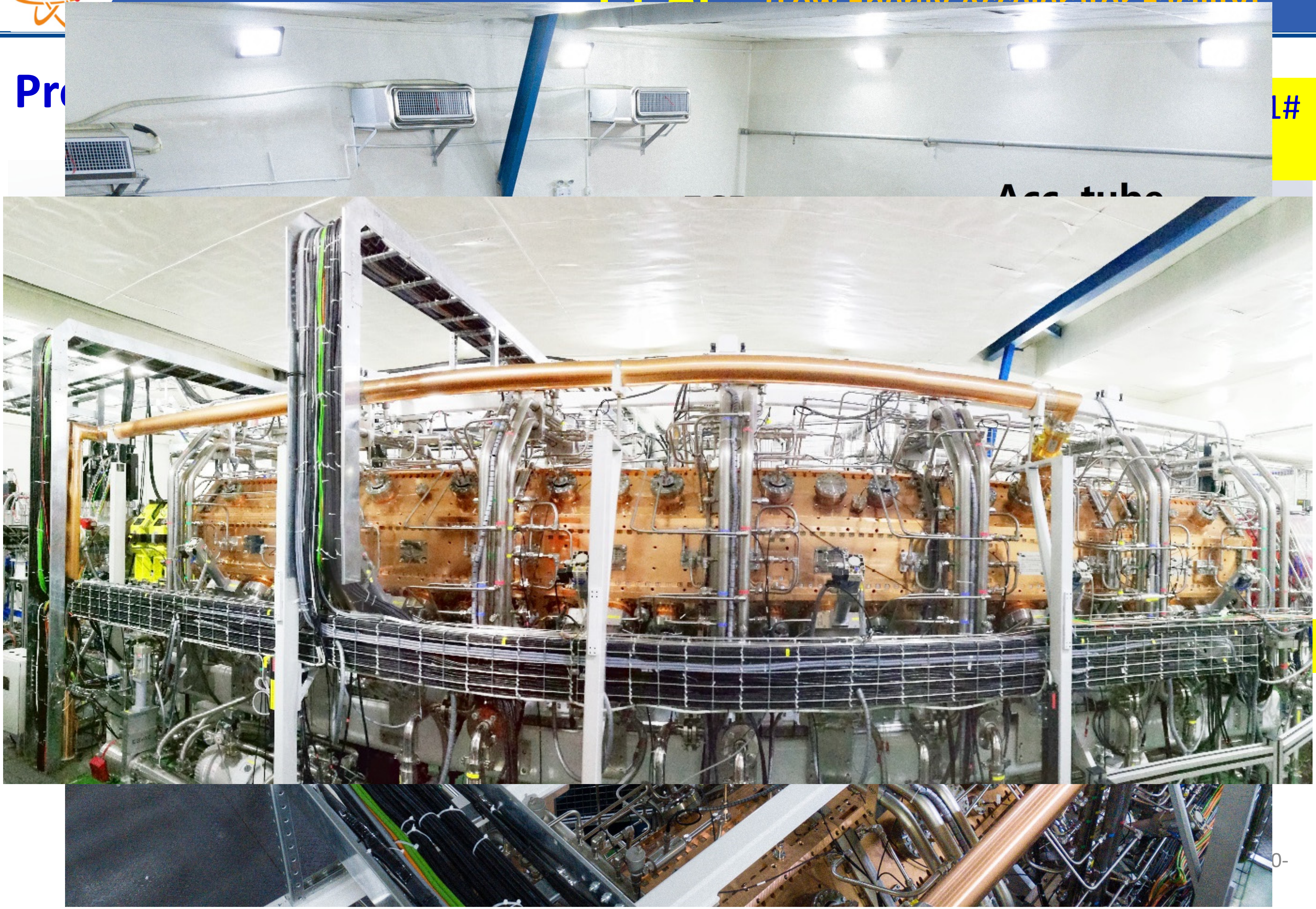
be

LEAF (Low Energy Accelerator Facility)

Pr

L#

Acc. tube

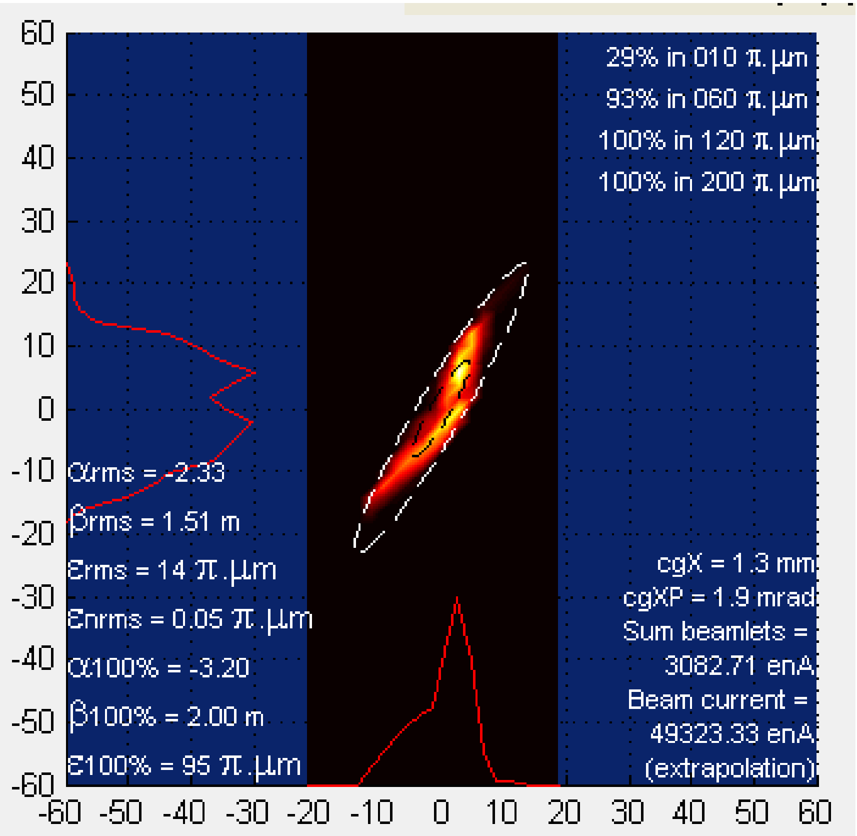


First beam test of LEAF

ECR beam

- $^4He^{1+}$
- Beam intensity: ~ 88.8 euA
- Pencil beam

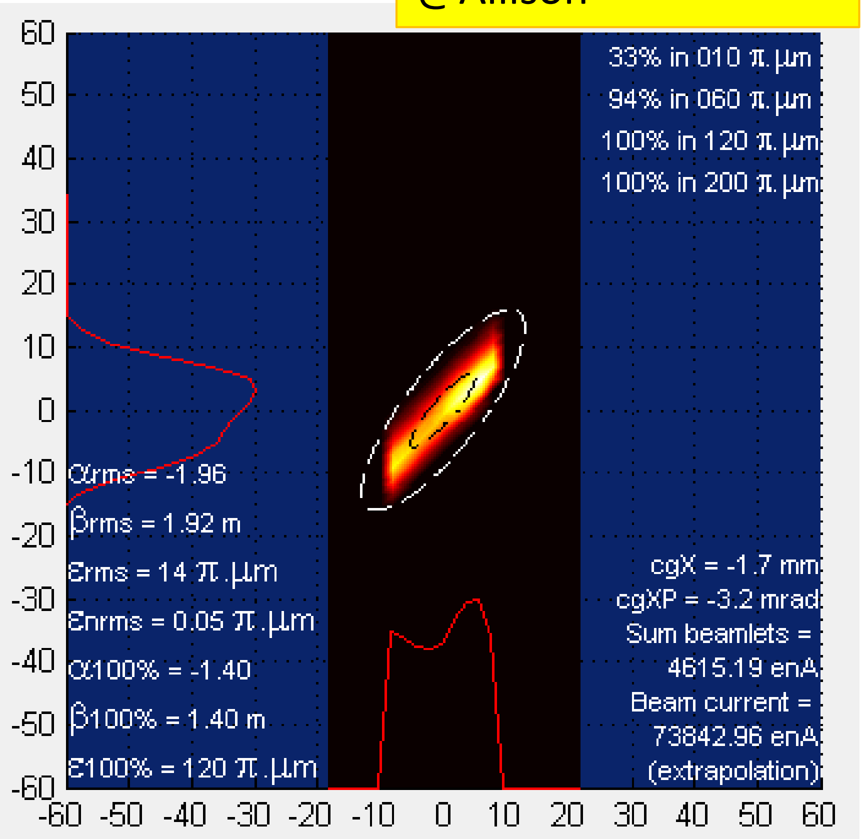
LEBT test chamber 1#
@Allison



29% in 010 π.μm
93% in 060 π.μm
100% in 120 π.μm
100% in 200 π.μm

αrms = -2.33
βrms = 1.51 m
εrms = 14 π.μm
εnrms = 0.05 π.μm
α100% = -3.20
β100% = 2.00 m
ε100% = 95 π.μm

cgX = 1.3 mm
cgXP = 1.9 mrad
Sum beamlets = 3082.71 enA
Beam current = 49323.33 enA (extrapolation)



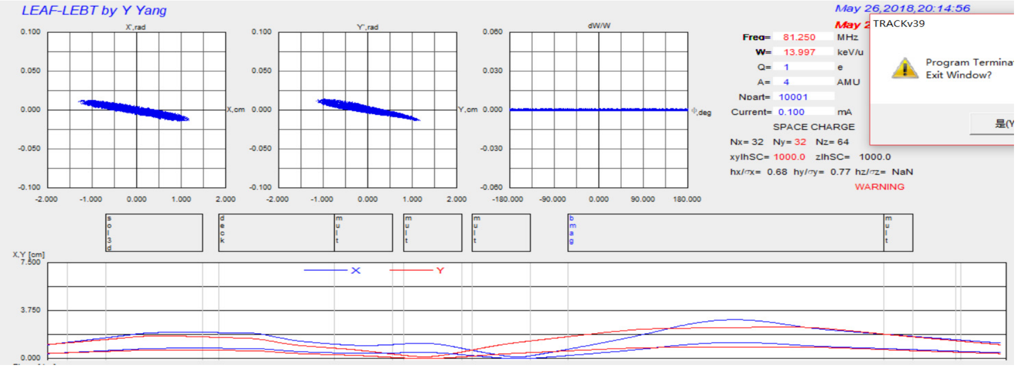
33% in 010 π.μm
94% in 060 π.μm
100% in 120 π.μm
100% in 200 π.μm

αrms = -1.96
βrms = 1.92 m
εrms = 14 π.μm
εnrms = 0.05 π.μm
α100% = -1.40
β100% = 1.40 m
ε100% = 120 π.μm

cgX = -1.7 mm
cgXP = -3.2 mrad
Sum beamlets = 4615.19 enA
Beam current = 73842.96 enA (extrapolation)

First beam test of LEAF

LEBT beam transmission → Axisymmetric beam



May 26,2018,20:14:56

TRACKv39

Program Termina
Exit Window?

Freq= 81.250 MHz
W= 13.997 keV/u
Q= 1 e
A= 4 AMU
Npart= 10001
Current= 0.100 mA

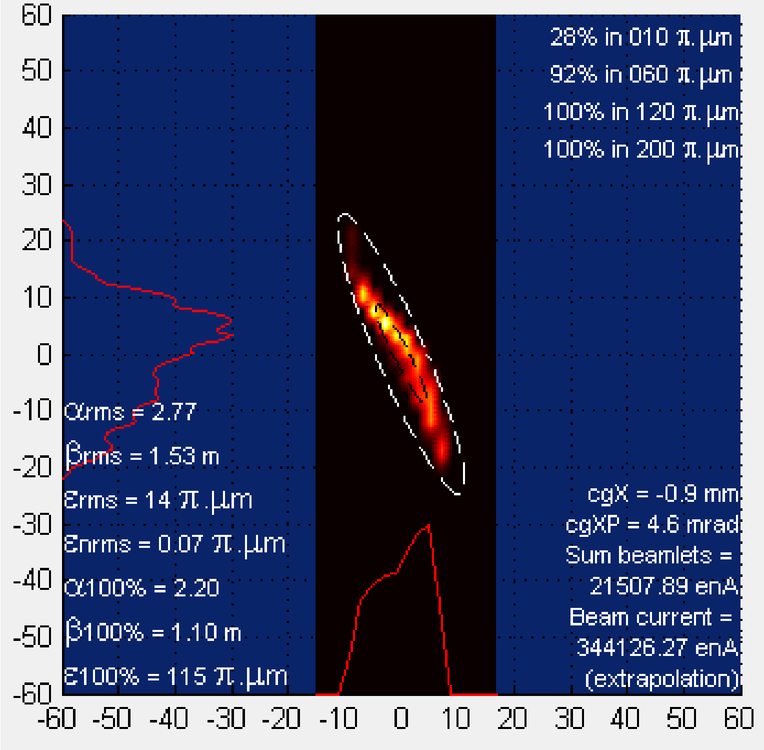
SPACE CHARGE

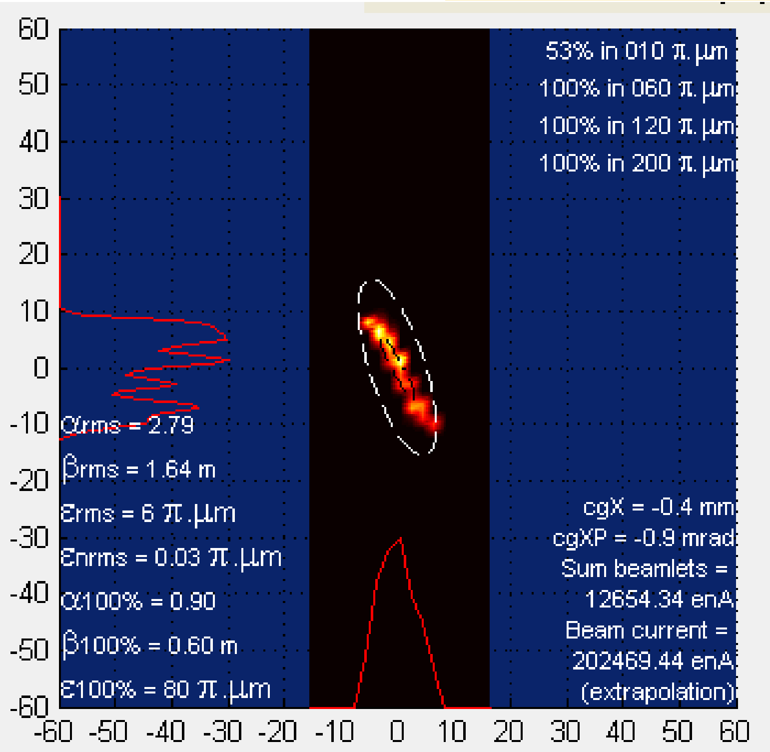
Nx= 32 Ny= 32 Nz= 64
xylhSC= 1000.0 zlhSC= 1000.0
hx/σx= 0.68 hy/σy= 0.77 hz/σz= NaN

WARNING

Transmission efficiency ~ 100%

LEBT test chamber 2#
@Allison





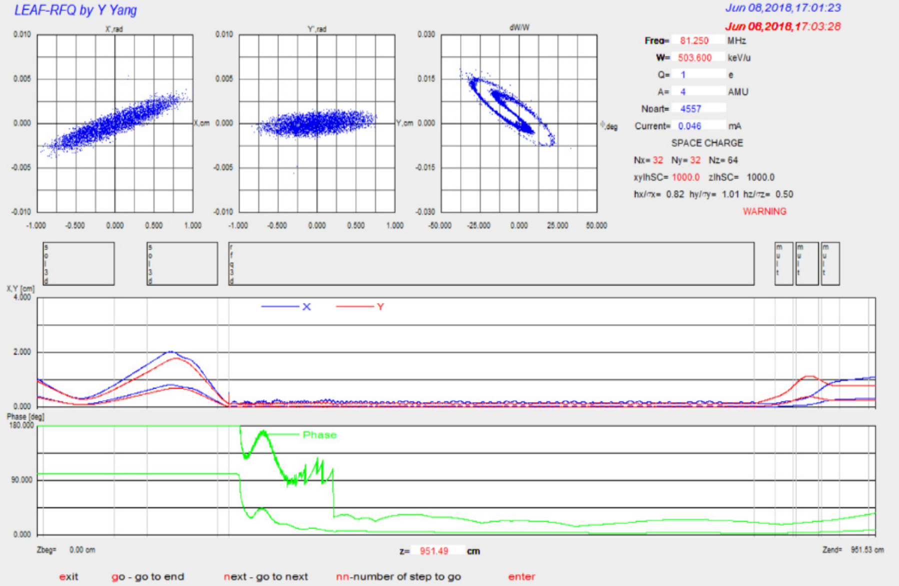
First beam test of LEAF

RFQ

Beam simulation @ TRACK

@ without MHB

- Transmission efficiency ~ 99.2%
- Acceleration efficiency ~ 45.6%



Jun 08,2018,17:01:23

Jun 08,2018,17:03:28

Freq= 81.250 MHz

W= 503.600 keV/u

Q= 1 e

A= 4 AMU

Npart= 4557

Current= 0.046 mA

SPACE CHARGE

Nx= 32 Ny= 32 Nz= 64

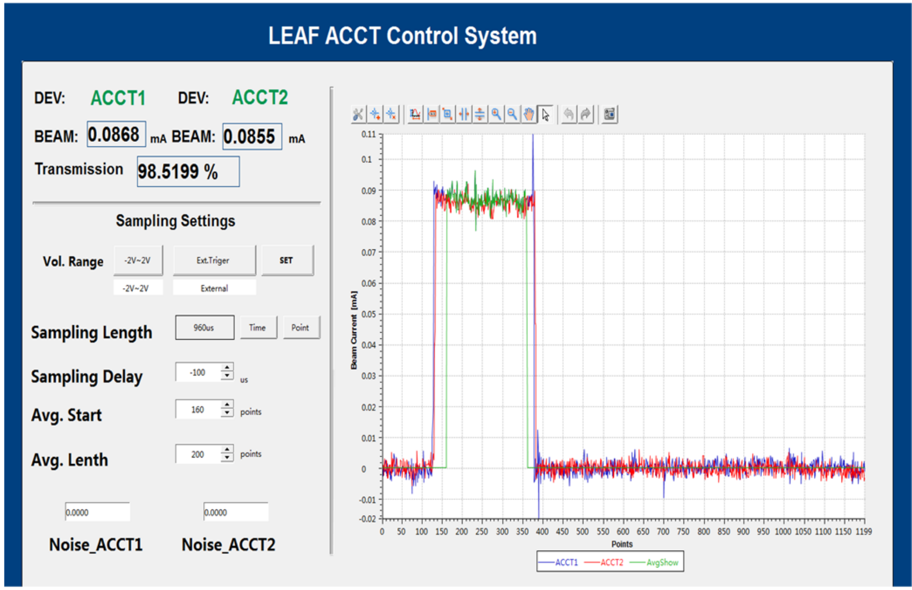
xylhSC= 1000.0 zlhSC= 1000.0

hx/σx= 0.82 hy/σy= 1.01 hz/σz= 0.50

WARNING

Measurement

- Transmission efficiency ~ 98.5% (I_{ACCT-2} / I_{ACCT-1})
- Acceleration efficiency ~ 46.5% (I_{FC} / I_{ACCT-1})



LEAF ACCT Control System

DEV: ACCT1 DEV: ACCT2

BEAM: 0.0868 mA BEAM: 0.0855 mA

Transmission 98.5199 %

Sampling Settings

Vol. Range -2V~2V Ext.Triger SET

-2V~2V External

Sampling Length 960us Time Point

Sampling Delay -100 us

Avg. Start 160 points

Avg. Lenth 200 points

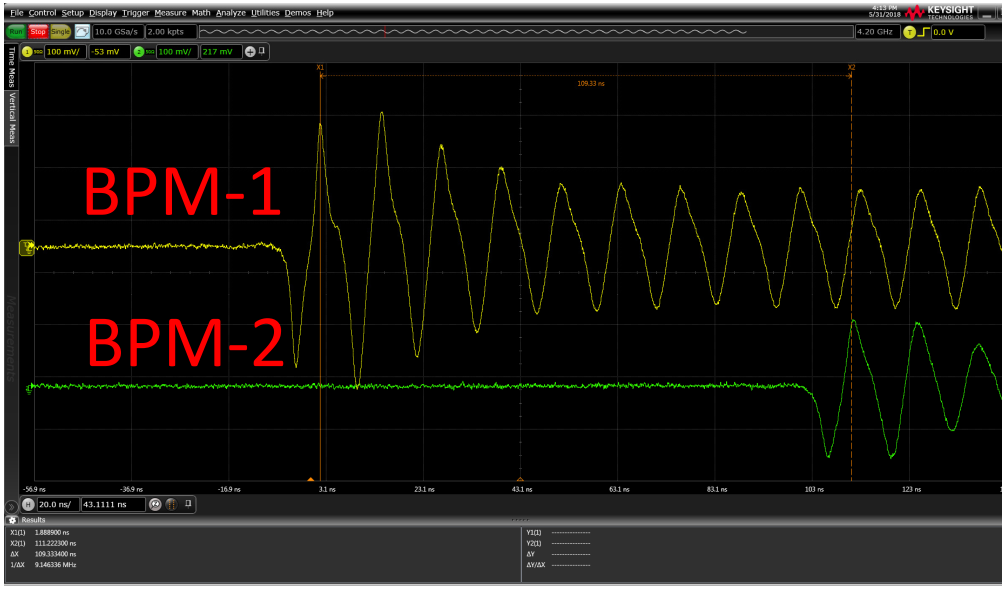
0.0000 Noise_ACCT1

0.0000 Noise_ACCT2

ACCT-1 & ACCT-2

First beam test of LEAF

Beam Energy



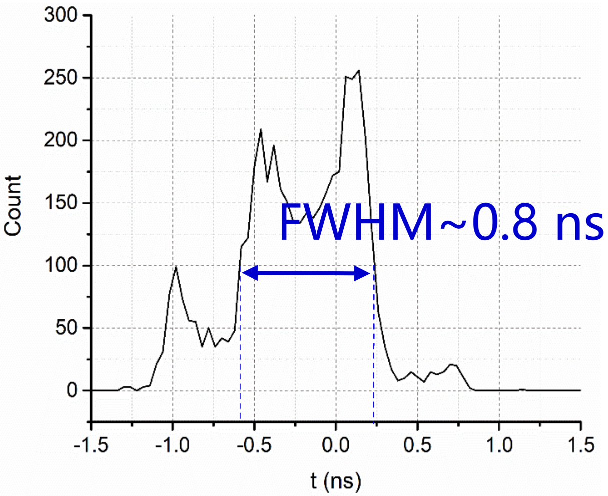
X1(1) 1.888900 ns
X2(1) 111.222300 ns
ΔX 109.333400 ns
1/ΔX 9.146336 MHz

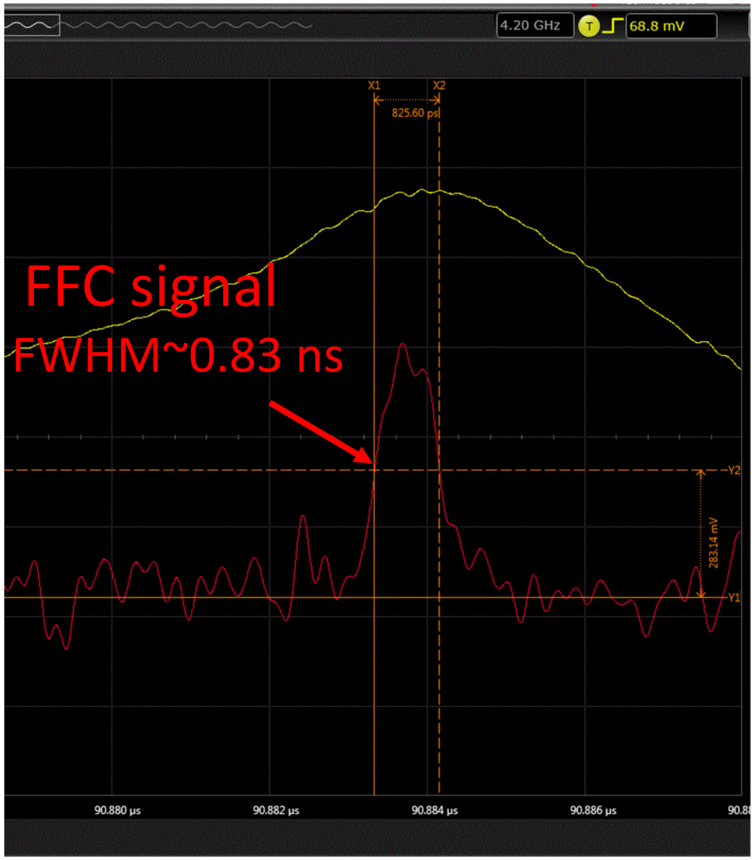
Y1(1) --------------
Y2(1) --------------
ΔY --------------
ΔY/ΔX --------------

TOF: Distance ~ 1.0689 m

→ Energy ~ **0.5±0.001 MeV/u**

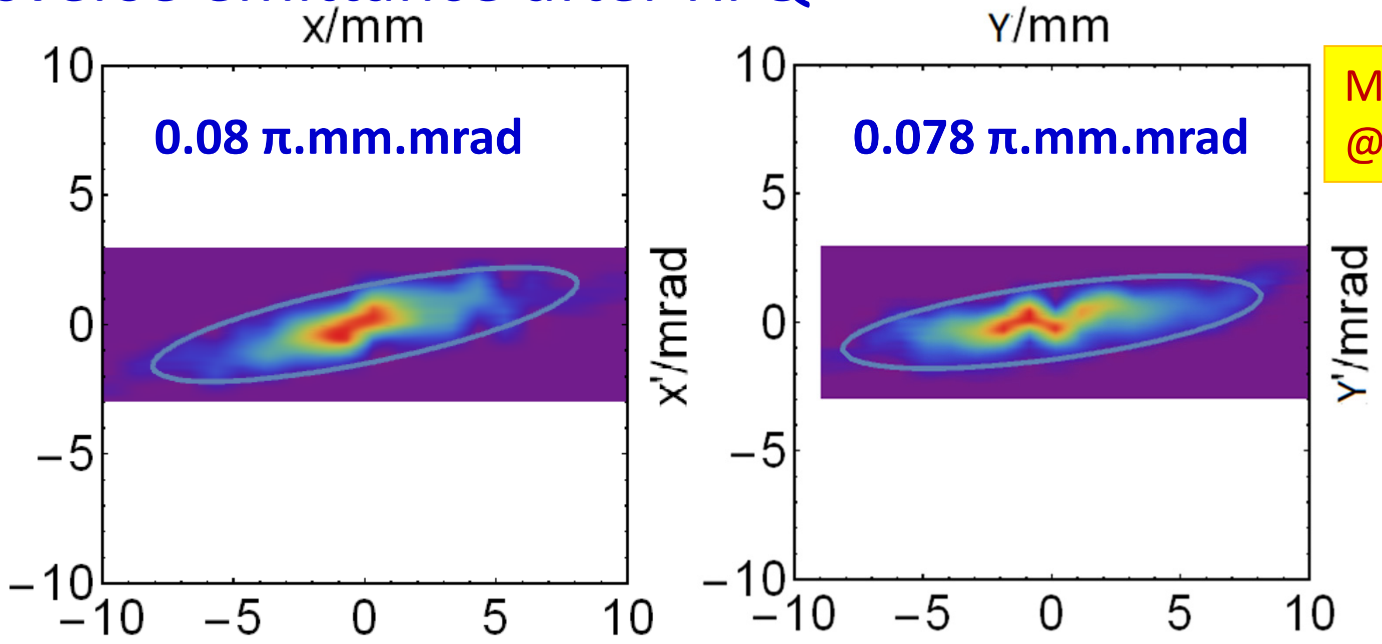
Bunch length





First beam test of LEAF

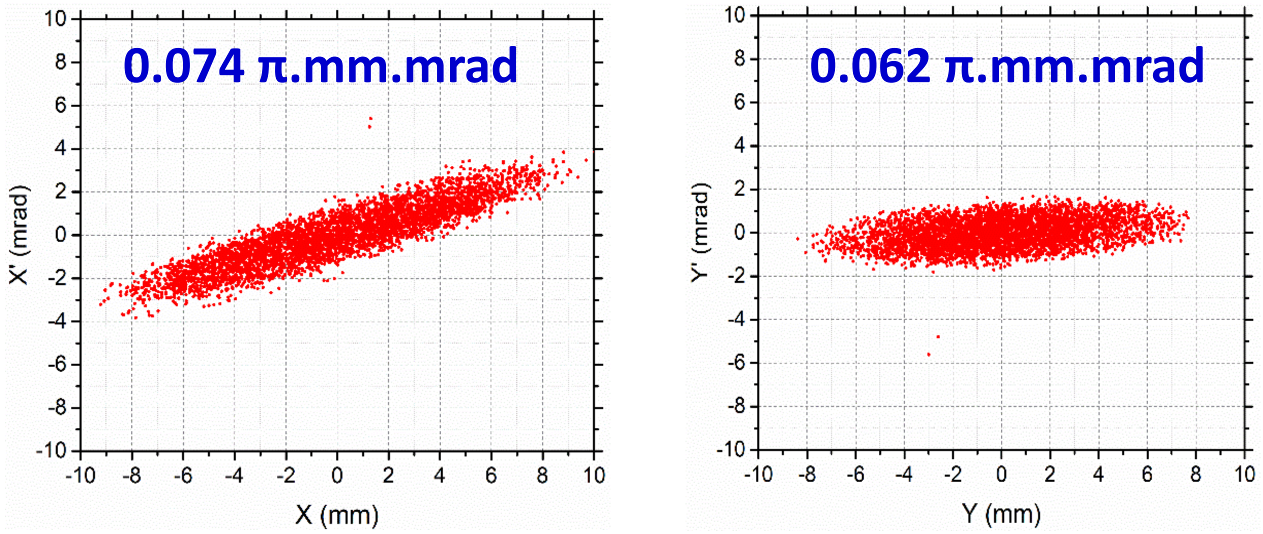
Transverse emittance after RFQ



0.08 π.mm.mrad

0.078 π.mm.mrad

Measurement
@ slit+slit+FC



0.074 π.mm.mrad

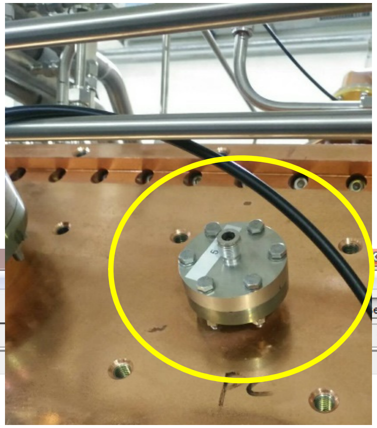
0.062 π.mm.mrad

TRACK simulation

First beam test of LEAF

RFQ CW commissioning @ 200 eμA He^{1+}

Transmission ~ 97%, Acceleration ~ 50%



CS-Studio

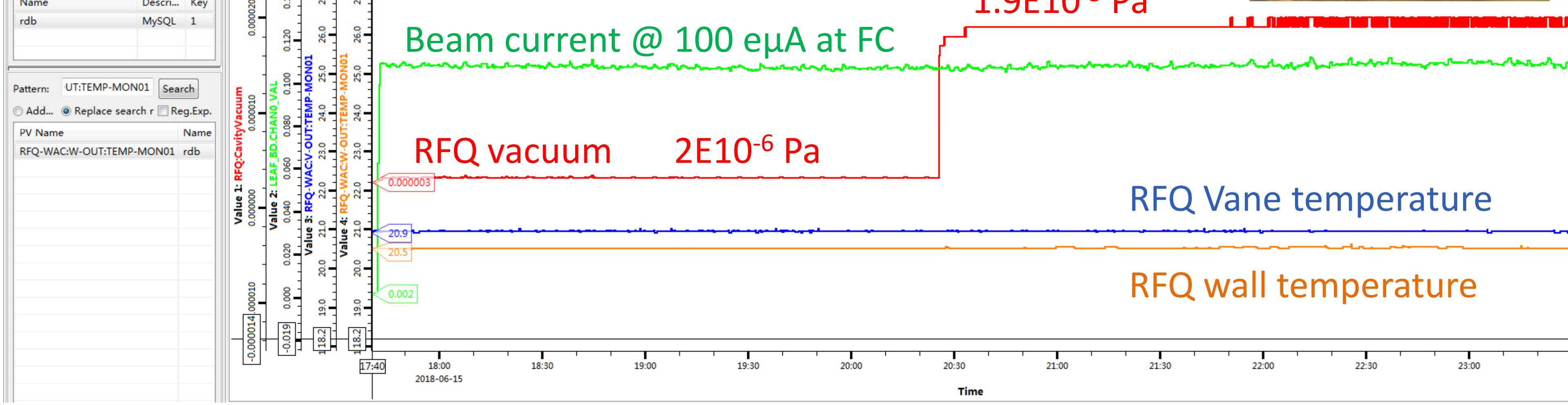
URL: jdbc:mysql://90.0.11.11:33(

Name	Descri...	Key
rdb	MySQL	1

Pattern: UT:TEMP-MON01

○ Add... ● Replace search r ☐ Reg.Exp.

PV Name	Name
RFQ-WAC:W-OUT:TEMP-MON01	rdb



1.9E10^{-5} Pa

Beam current @ 100 eμA at FC

RFQ vacuum 2E10^{-6} Pa

RFQ Vane temperature

RFQ wall temperature

6 Hr

Summary

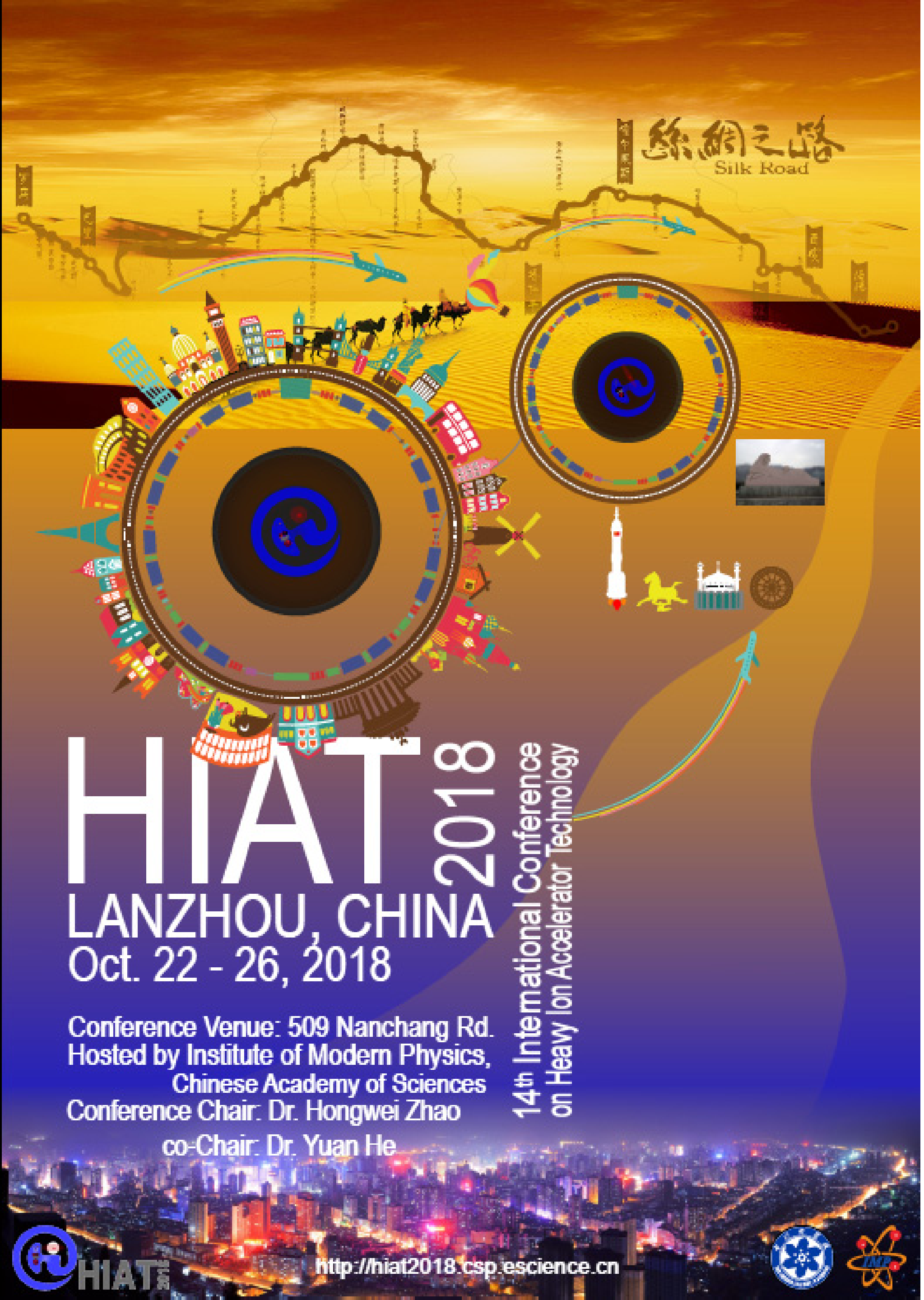
☐ Design of HIAF front end was completed based on studies of ion source beam quality, space charge effect in low energy beam transport, high intensity beam matching with RFQ.

☐ Beam simulations show that the present design is robust to transport and accelerate very high intensity beams of highly-charged heavy ions.

☐The LEAF has been successfully commissioned and accelerated beams to the energy as expected, satisfying the design specifications, which provides a good basis for HIAF Front end.

Acknowledgement

- LEAF Team Members
- Brahim Mustapha



HIAT 2018

LANZHOU, CHINA

Oct. 22 - 26, 2018

14th International Conference on Heavy Ion Accelerator Technology

Conference Venue: 509 Nanchang Rd.
Hosted by Institute of Modern Physics,
Chinese Academy of Sciences
Conference Chair: Dr. Hongwei Zhao
co-Chair: Dr. Yuan He

http://hiat2018.csp.escience.cn

Thank you for your attention!

HIAT 2018

Lanzhou, China

Oct. 22-26, 2018

http://hiat2018.csp.escience.cn/dct/page/1