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Design of a continuous wave heavy ion RFQ for BISOL

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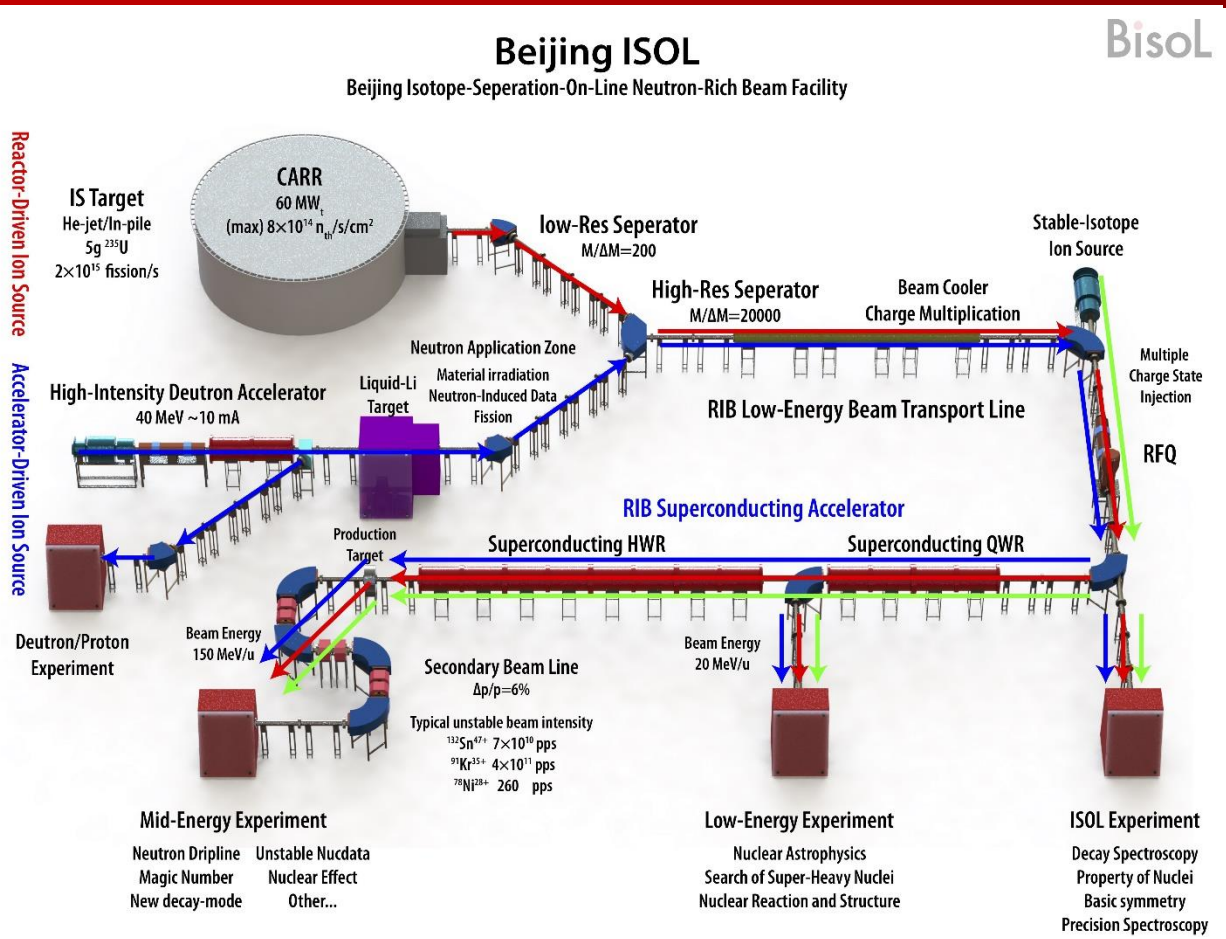
Introduction



Layout of BISOL project

- The facility aims at both basic science and application goals
- Base on both reactor and accelerator-driven systems
- Radioactive ion beams can be accelerated to 150 MeV/u

Some heavy-ion RFQs in the world

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Project	Type	Frequency (MHz)	$\frac{Q}{A}$	Current (emA)	Input/output energy (MeV/u)	Power consumption (kW)	Inter-vane voltage (kV)	Vane length (m)	Kp	Q_0	Power consumption (kW/m)	Mode	$\varepsilon_{z,rms}$ (pi·mm·mrad)	$\varepsilon_{z,99.9\%}$ (pi·mm·mrad)	Buncher
GSI-HLI	4-rod	108.48	1/6	5	0.004/0.3	60	55	1.99	-	-	30	cw	0.49	2	No
SSC-LINAC	4-rod	53.667	1/7	0.5	0.0035/0.143	31	70	2.51	1.52	6560	12.4	cw	0.35	3.2	Yes
LEAF	4-vane	81.25	1/7	2	0.014/0.5	54	70	5.98	1.55	16230	9.2	cw	0.10	1.41	Yes
FRIB	4-vane	80.5	1/7	0.45	0.012/0.5	100	60-112	5.04	1.6	16500	20	cw	0.10	1.30	Yes
RISP-RAON	4-vane	81.25	1/7	0.4	0.01/0.5	93.11	50-140	5	1.7	14500	18.8	cw	0.31	-	Yes
SPIRAL2	4-vane	88.05	1/3	5	0.02/0.75	238	100-113	5	1.65	-	47	cw	0.41	-	No
ATLAS	4-vane	60.625	1/7	0.4	0.03/0.296	52	70	3.8	1.67	9873	13.7	cw	0.30	-	Yes

With an external buncher：

pros： Shorten the length and lower the longitudinal transmittance

cons： Overall transmission efficiency is reduced by 20%

Without an external buncher ：

pros： High transmission efficiency

cons： Greater length and the longitudinal transmittance

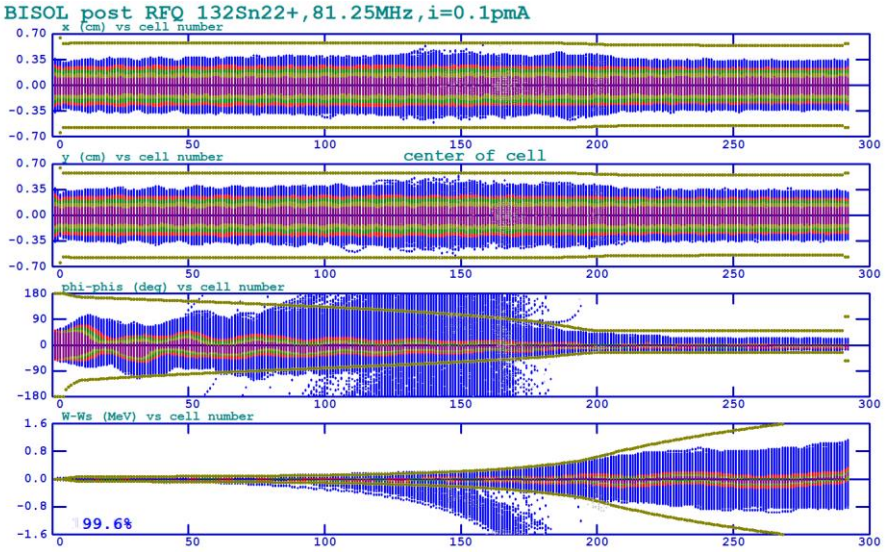
Requirements for the RFQ design

- High transmission efficiency
- Low beam power loss
- Low peak field strength
- Low cavity power consumption per unit length
- Lower the difficulty of RF design
- High beam quality
- Shorten the length of the RFQ

Requirements for the RFQ design

Parameter	Value
Reference particle	$^{132}Sn^{22+}$
Q/A	1/6
Frequency [MHz]	81.25
Input beam energy [MeV/u]	0.003
Output beam energy [MeV/u]	0.5
Peak beam current [pmA]	0.1
Duty factor [%]	100
Inter-vane voltage [kV]	70
Kilpatrick coefficient	<1.7
Input transverse nor. RMS emittance [pi mm·mrad]	0.25
Output longitudinal nor.RMS emittance [keV/u·ns]	<0.50
Transmission efficiency [%]	>95

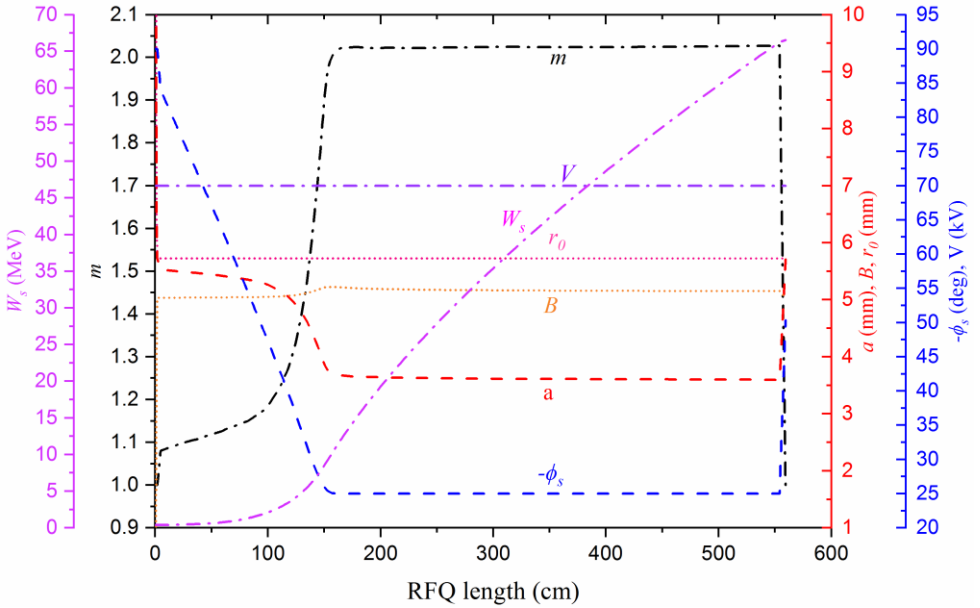
RFQ parameters and beam transmission



Beam transmission along the RFQ

Plots from top to bottom are the beam profiles in x plane, the beam profiles in y plane, the phase width and energy spread versus cell number, respectively.

- a is the minimum radial aperture
- m is the vane modulation factor
- ω_s is the kinetic energy of the synchronous particle
- φ_s is the synchronous phase
- B is the radial focusing strength



Main RFQ parameters

Parameters of beam dynamics design

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Parameter	Value	
Particle	$^{132}Sn^{21+}$	$^{132}Sn^{22+}$
Frequency [MHz]	81.25	
Input energy [keV/u]	3	
Output energy [keV/u]	302	504
Input transverse nor. RMS emittance [pi mm·mrad]	0.20	0.25
Vane length [mm]	3660	5604
Maximum peak surface electric field [MV/m]	17.31	16.70
Kilpatrick coefficient	1.64	1.58
Minimum aperture radius [mm]	3.66	3.60
Average aperture [mm]	5.63	5.73
Synchronous phase [deg]	-90~-25	-90~-25
Modulation factor	1.95	2.07
Output transverse nor. RMS emittance [pi mm·mrad]	0.19	0.19
Output longitudinal nor. RMS emittance [keV/u·ns]	0.31	0.20
Transmission efficiency [%] @elimit=1.5MeV	98.1	95.6

Initial design

With an external buncher

Comparison at the entrance of the RFQ

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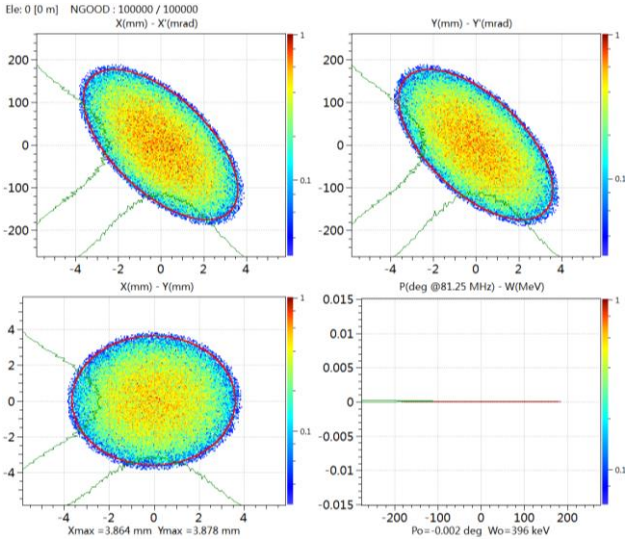
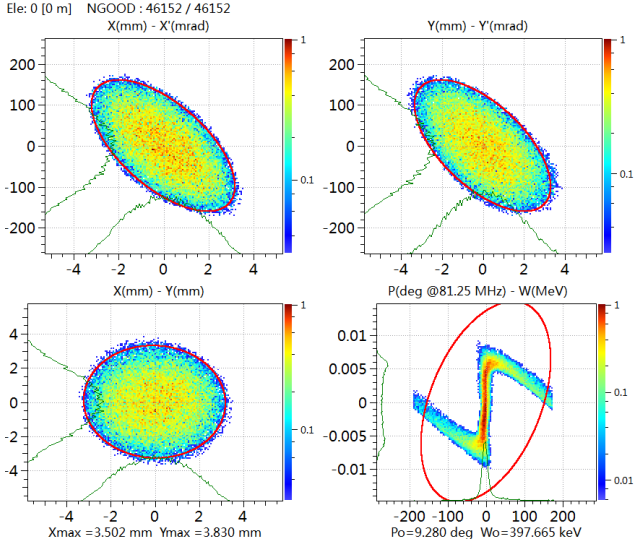
Without buncher

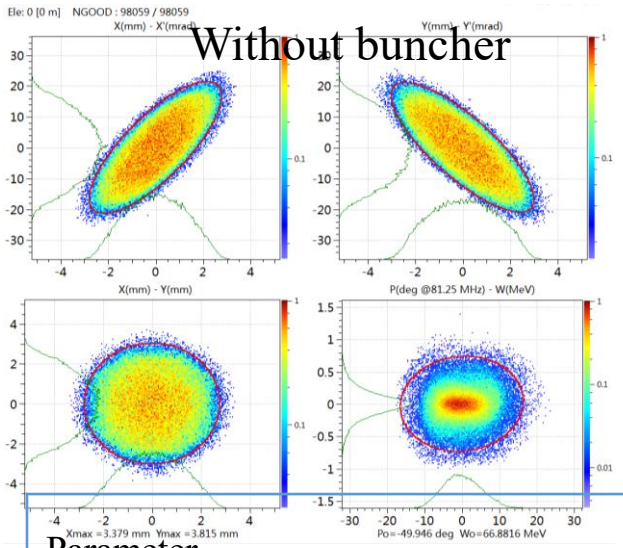


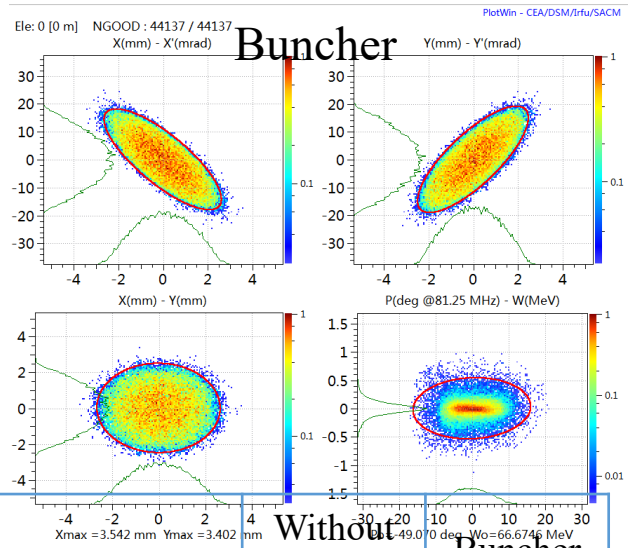
Buncher



Parameter	Without buncher	Buncher	Unit
Input transverse α_i	0.758/0.758	0.791/0.783	-
Input transverse β_i	0.0258/0.0258	0.0253/0.0261	mm/mrad
$\boldsymbol{\varepsilon_{x,norm,rms}}$	0.25	0.20	mm·mrad
$\boldsymbol{\varepsilon_{y,norm,rms}}$	0.25	0.20	mm·mrad
$\boldsymbol{\varepsilon_{z,rms}}$	0	0.20	deg·MeV
$\boldsymbol{\varepsilon_{x,norm,99.9\%}}$	1.45	1.19	mm·mrad
$\boldsymbol{\varepsilon_{y,norm,99.9\%}}$	1.45	1.28	mm·mrad
$\boldsymbol{\varepsilon_{z,99.9\%}}$	-	3.36	deg·MeV

Comparison at the exit of the RFQ





Parameter	Without buncher	Buncher
Particle	$^{132}Sn^{22+}$	
Output energy [keV/u]	506	504
Vane length [m]	6.57	5.60
Output transverse nor. RMS emittance [pi mm·mrad]	0.23	0.19
Output longitudinal nor. RMS emittance [keV/u·ns]	0.31	0.20
Output longitudinal emittance [keV/u·ns] @99.9%	5.33	5.31
Output longitudinal emittance [keV/u·ns] @98.0%	3.11	2.24
Output longitudinal emittance [keV/u·ns] @95.0%	2.18	1.45
Output longitudinal emittance [keV/u·ns] @90.0%	1.50	0.95
Transmission efficiency [%]	98.1	95.6

Beam transmission with different codes

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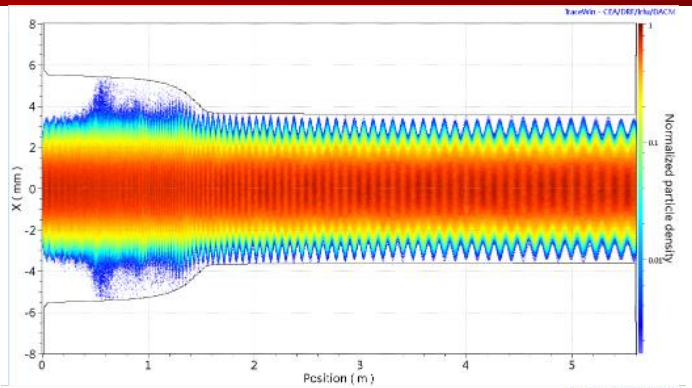
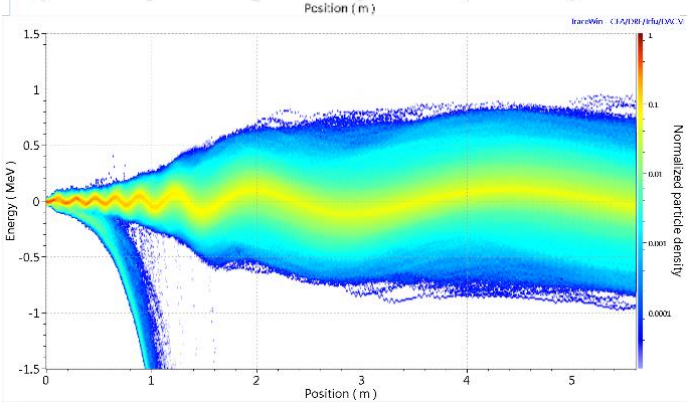
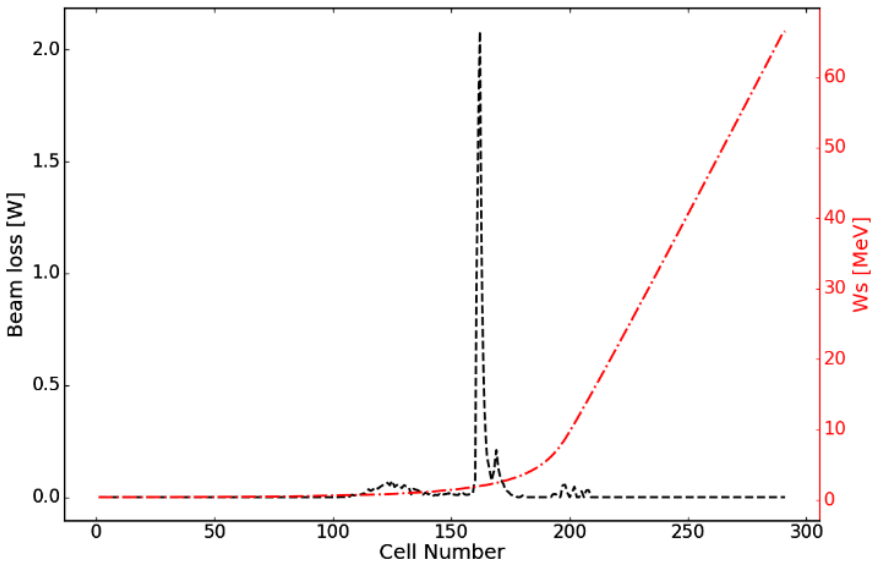
Parameters	Parmteqm	TraceWin	Impact-T	Unit
Macro-particle number	46152			-
Beam current	2.2			emA
Input transverse α_i	0.791/0.783			-
Input transverse β_i	0.0253/0.0261			mm/mrad
Input nor. rms emittance	0.20/0.20			mm·mrad
Input nor. rms longitudinal emittance	0.20			deg·MeV
Output energy	66.67	66.55	66.66	MeV
Output transverse α_o	1.30/-1.26	1.38/-1.23	1.30/-1.16	-
Output transverse β_o	0.24/0.21	0.26/0.21	0.26/0.21	mm/mrad
Output nor. rms transverse emittance	0.19/0.19	0.19/0.19	0.20/0.21	mm·mrad
Output longitudinal α_o	-0.07	-0.003	-0.05	-
Output longitudinal β_o	29.85	27.86	26.69	deg/MeV
Output nor. rms longitudinal emittance	0.77	0.94	0.95	deg·MeV
Output longitudinal emittance @99.9%	20.50	20.44	23.42	deg·MeV
Transmission efficiency	95.6 @elimit=1.5MeV	92.8(Acc.)	93.3(Acc.)	%

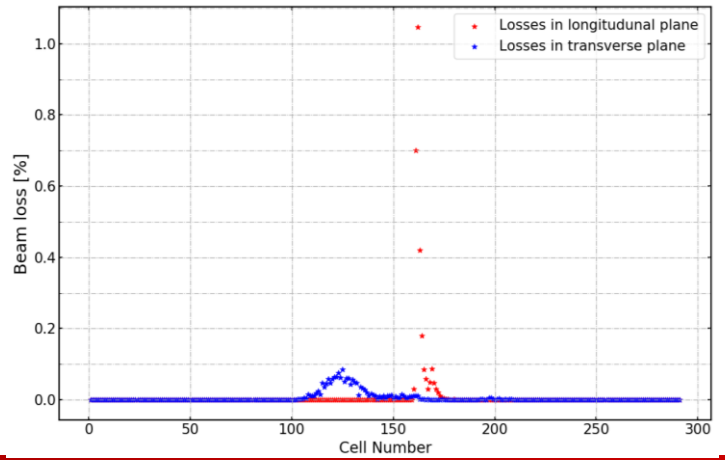
Beam loss-TraceWin

- The beam loss mainly occurs between the 100th to 180th unit, which belongs to the gentle buncher section. At this time, the beam energy is low, and the maximum beam loss power consumption is about 2W.

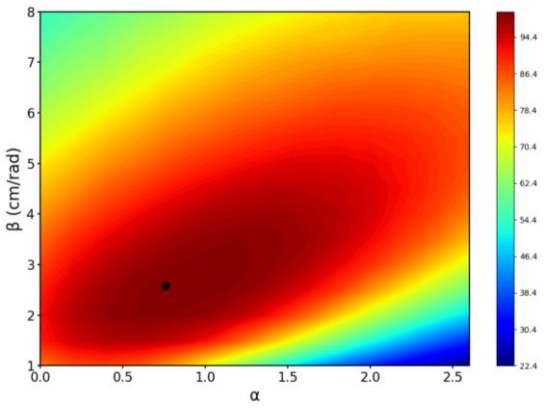




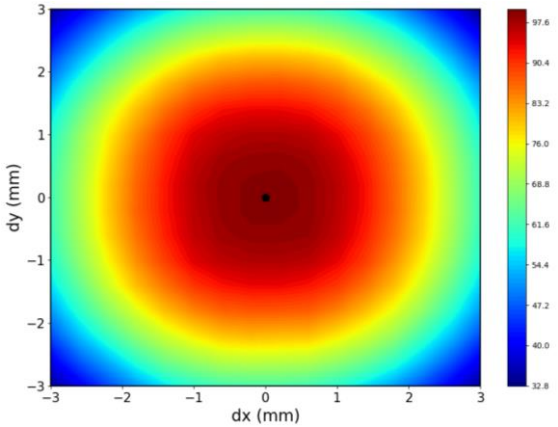




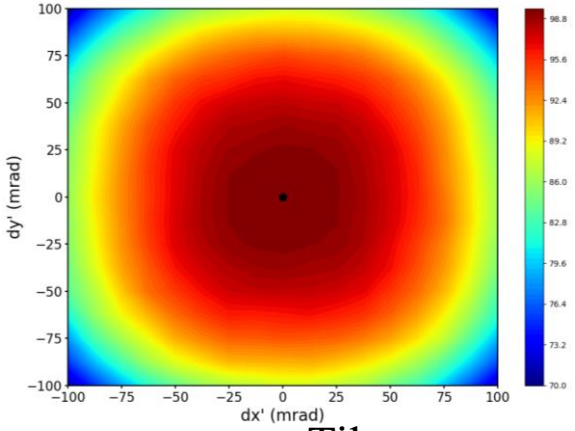
Errors study



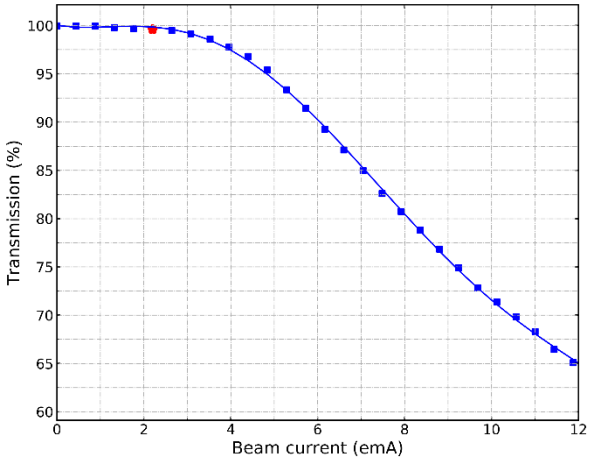
Twiss



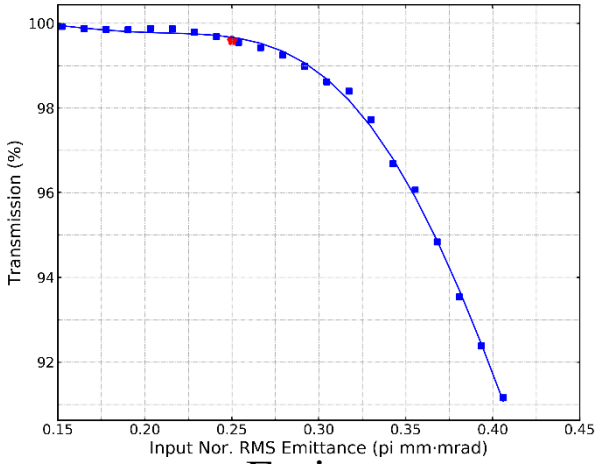
Offset



Tilt



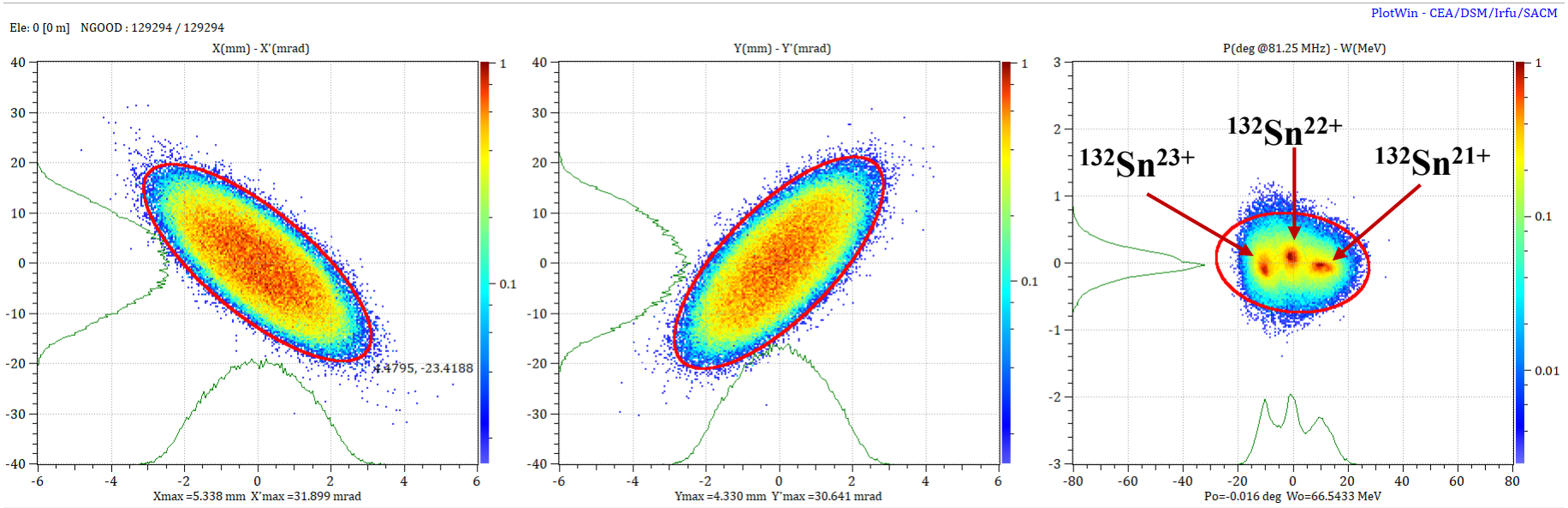
Current



Emittance

The results of error analysis show that this design is not very sensitive deviations from the ideal input beam parameters.

Multi-charge-state beams acceleration-Impact-T



Phase space of multi-charge-state beams at the exit of the RFQ

Parameters	$^{132}Sn^{21+}$	$^{132}Sn^{22+}$	$^{132}Sn^{23+}$	Unit
Output energy	66.48	66.59	66.56	MeV
Output nor. rms longitudinal emittance	2.13			deg·MeV
Output longitudinal emittance @99.9%	8.99			keV/u·ns
Output longitudinal emittance @99.0%	5.32			
Acc. Efficiency @elimit=1.5MeV	93.1	93.4	93.6	%
	93.4			