Development of CW heavy ion linac at IMP

Xuejun Yin

Accelerator Physics Group,IMP

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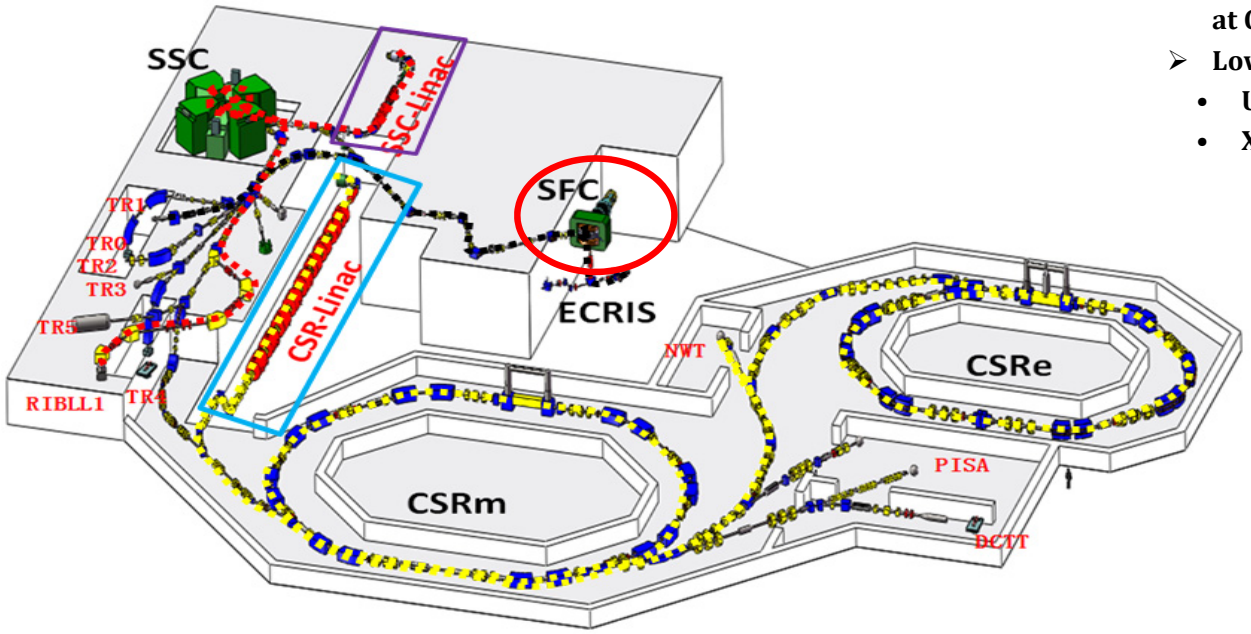
Outline

- Introduction of new injectors for HIRFL
- Design of SSC-Linac
- Development of key components
- Beam commissioning
- Summary

New injectors for HIRFL

- Limited by the only one injector - Spiral Focusing Cyclotron(SFC)
  - ➢No Parallel mode
  - ➢Lack of flexibility



- **HIRFL is long historical standing:**
  - ➢ **Built in 1960s;Upgraded in 1980s&2000s;**
- **Heavy operation duty,**
  - ➢ **>7000 hrs/y**
- **Low energy and Low intensity of heavier ions (1-3 euA).**
  - ➢ **Short lifetime and low accumulated intensity at CSRm**
  - ➢ **Low Q/A→Low extraction energy at CSRm:**
    - **Uranium < 105 MeV/u;**
    - **Xeon < 240 MeV/u.**

Research Aim： Beam &Efficiency

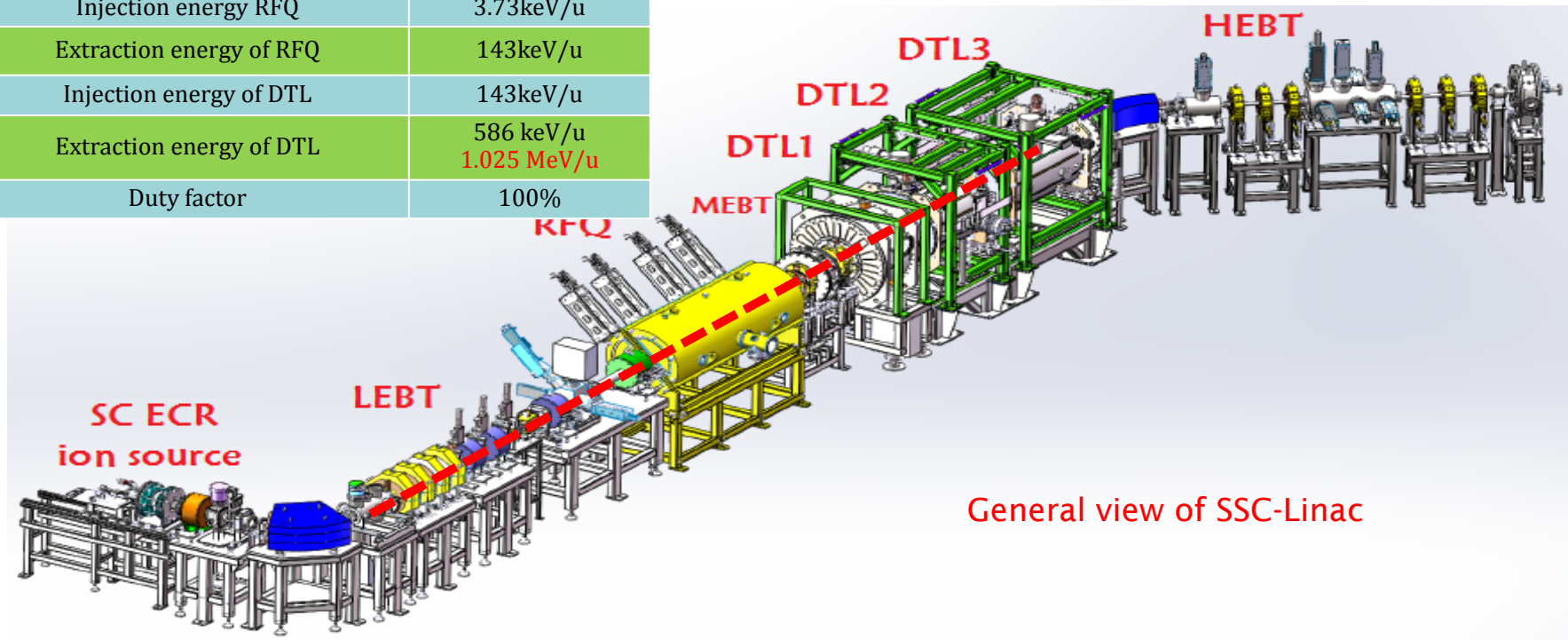
- The transmission of SSC-Linac can be >80%； .
- The total efficiency will be >40%；
- The beam intensity of light-ion will increase 1 ~2 times， the beam intensity of heavy ion will increase 1 ~2 order.

Table1.Comparision of beam current and efficiency before and after upgrade

	SFC+SSC			SSC-Linac+SSC		
I（eμA） / Ion	Injection	Extraction	Efficiency	SSC-Linac	SSC(6.0AMeV)	Efficiency
$^{20}Ne^{5+}$	2.57	0.36	14%	84	33.6	40%
$^{86}Kr^{19+}$	1.5	0.4	26.6%	70	28	40%
$^{136}Xe^{27+}$	2.4	0.7	29%	63	25.2	40%
$^{238}U^{34+}$	0.6	<0.06	10%	21	8.4	40%

Design ion	$^{238}U^{34+}$
Frequency of RF	53.667MHz
Design A/q	7
Extraction voltage of ECRIS	25kV
ε (90%nomalized)	0.6
Injection energy RFQ	3.73keV/u
Extraction energy of RFQ	143keV/u
Injection energy of DTL	143keV/u
Extraction energy of DTL	586 keV/u 1.025 MeV/u
Duty factor	100%

- CW heavy ion linac
- Beam current : ~200eμA for various ions.
- Beam intensity: increase to 1~2 order to inject to SSC for heavier ions.
- $^{238}U^{63+}$ can be accelerated to 360MeV/u by CSRm facility after stripping .

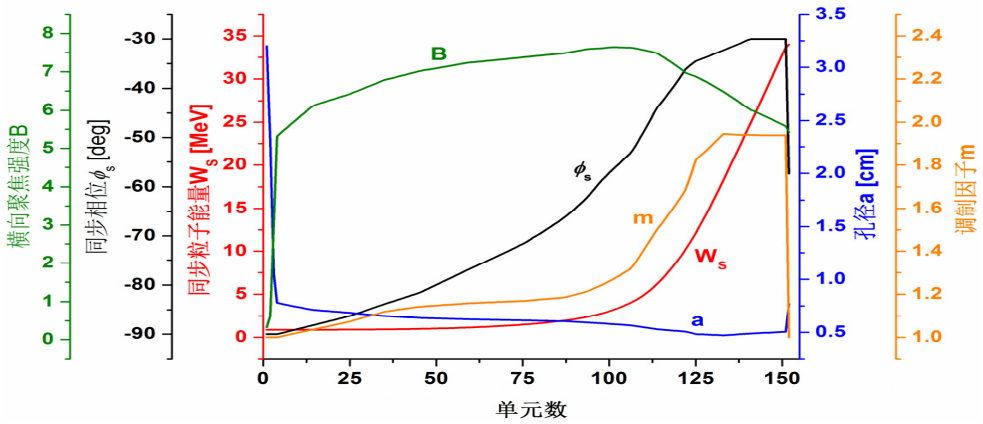


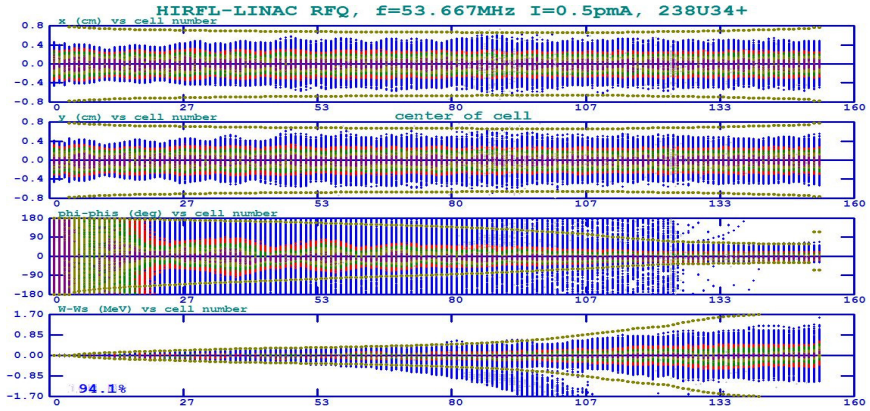
General view of SSC-Linac

Four-rod RFQ(PKU-IMP)

RFQ parameters

Parameters	Value
Operation frequency(MHz)	53.667
Design ions	$^{238}U^{34+}$
Beam intensity(mA)	0.2
Voltage(kV)	70
Max surface field(MV/m)	14.09
Kp value	1.523
Minimum aperture(mm)	4.67
Average aperture(mm)	7.07
Maximum modulation	1.94
Synchronous phase at exit	-30.0
Electrode length(cm)	250.48
Cells number	153
Transmit effeciency(%)	94.5



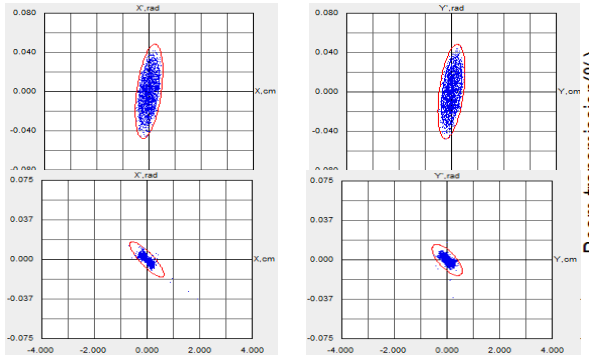


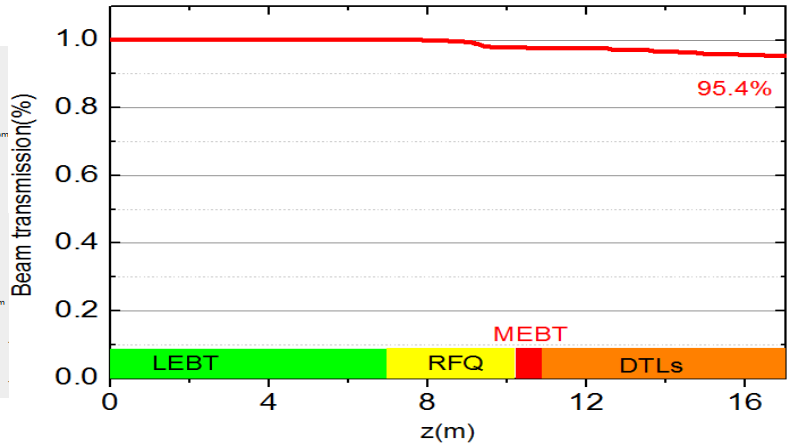
Rebuncher&DTL parameters

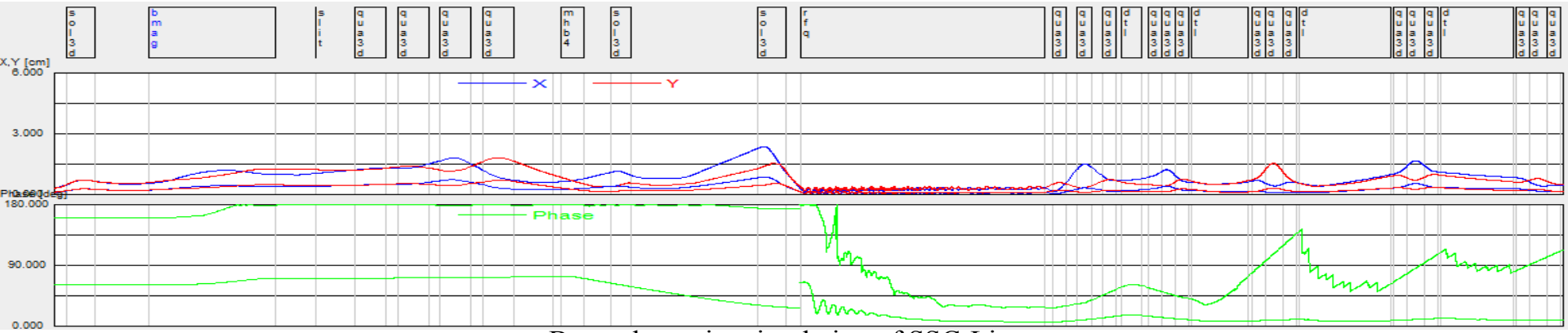
	Rebuncher1	DTL1	DTL2	DTL3
W_{in} (keV/u)	143	143	295	586
W_{out} (keV/u)	143	295	586	1025
Φ_s(deg)	-90	-45~0	-20~-10	-20
Radius of tube (cm)	1.7	1.7	1.8	1.8
Acc. gaps Num.	4	10	12	12
Voltage (kV)	37	165	224	300
RF power(kW)	2	18.4	20.4	40.5
Cavity Length (cm)	20	58.6	102.2	137

End-to-end beam dynamics simulation

- Matched solution
- Optimization
- Beam loss
- Emittance growth

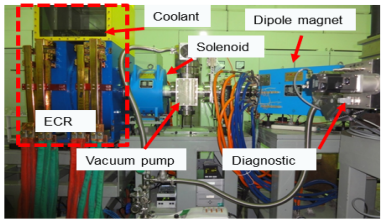




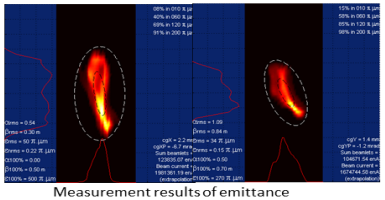


Beam dynamics simulation of SSC-Linac

Development of key components



General layout of Ion source


Measurement results of emittance

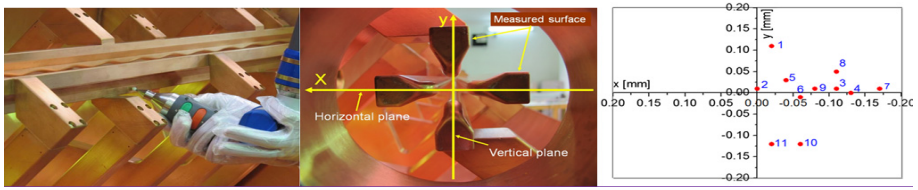
- ➢High charge state room temperature ECR Ion Source.
- ➢Maximum mirror field is 2.3T.
- ➢Evaporative cooling technology is used.
- ➢Beam commissioning of $^{16}O^{5+}$ at 200eμA
- ➢The measured normalized rms emittances were ε_x=0.22p*mm.mrad* ε_y=0.15p*mm.mrad*, respectively.

Beam test results of Ion source

LECR4		
Ion		**I(eμA)**
^{16}O	6^+	1970
	7^+	438
^{40}Ar	8+	1717
	9^+	1075
	11+	503
^{129}Xe	20+	293
	23+	143

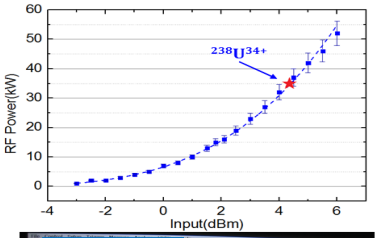
- ●CW 4-rod
- ●Heavy ion
- ●High charge state
- ●Pre accelerating

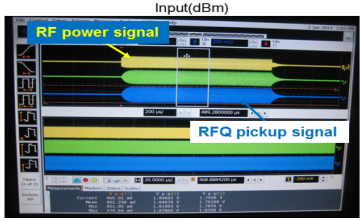
- ✓Fine aligment
- ✓High RF power
- ✓RF stable conditioning
- ✓Cooling design



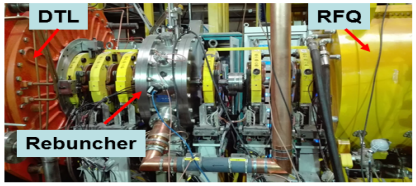
RF conditioning

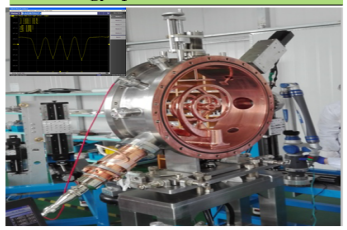
- ◆RF amplifier CW 52kW output
- ◆RFQ conditioning from pulse to CW
- ◆RFQ conditioning at CW 35kW

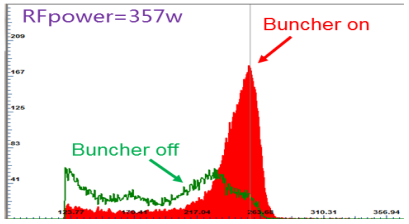




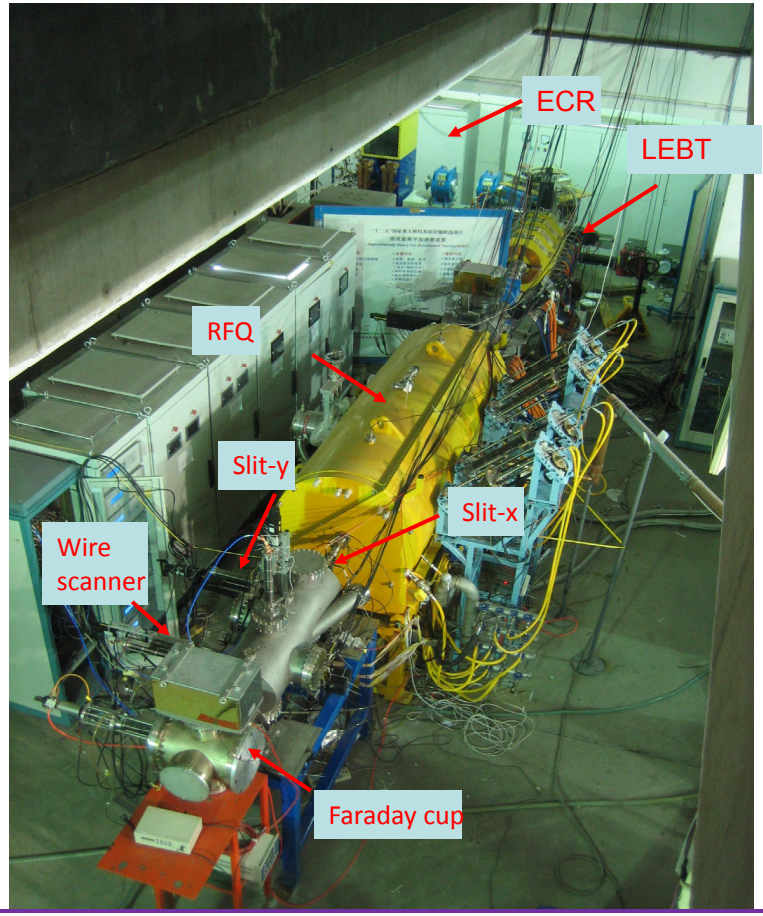
Parameters	Values
Ion	$^{12}C^{4+}$
Power	357W
Voltage amplitude	30kV
Phase	+76°
Phase stability	±<0.5%
Eenrgy spread	±<2%



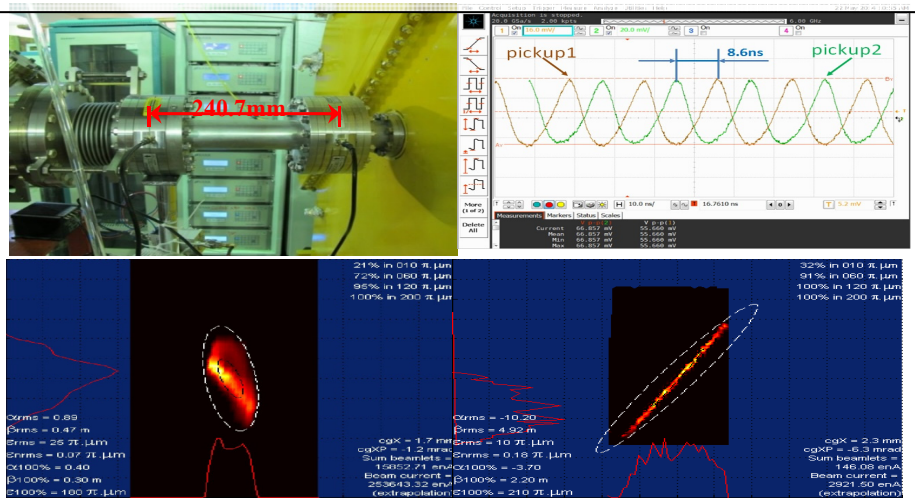




Beam commissioning of RFQ

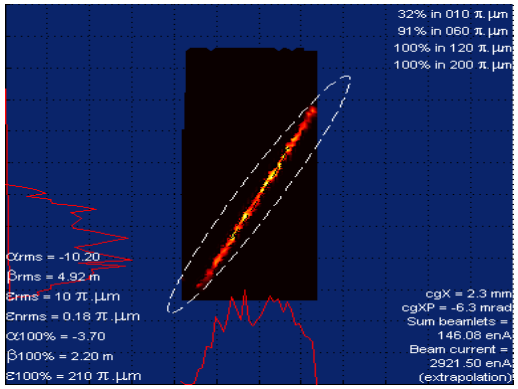


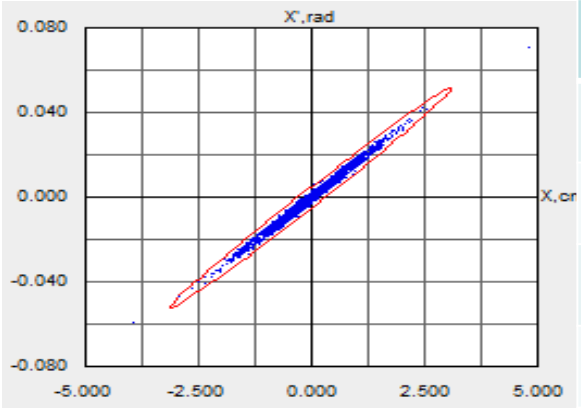
Parameters	Values
Ion	$^{16}O^{5+}$
Beam current	170uA
Input /Output energy	3.7/142.8keV/u
ε_{xnrms}	0.18mm·mrad
Transmission	>90%
Accumulated OP Time	500h



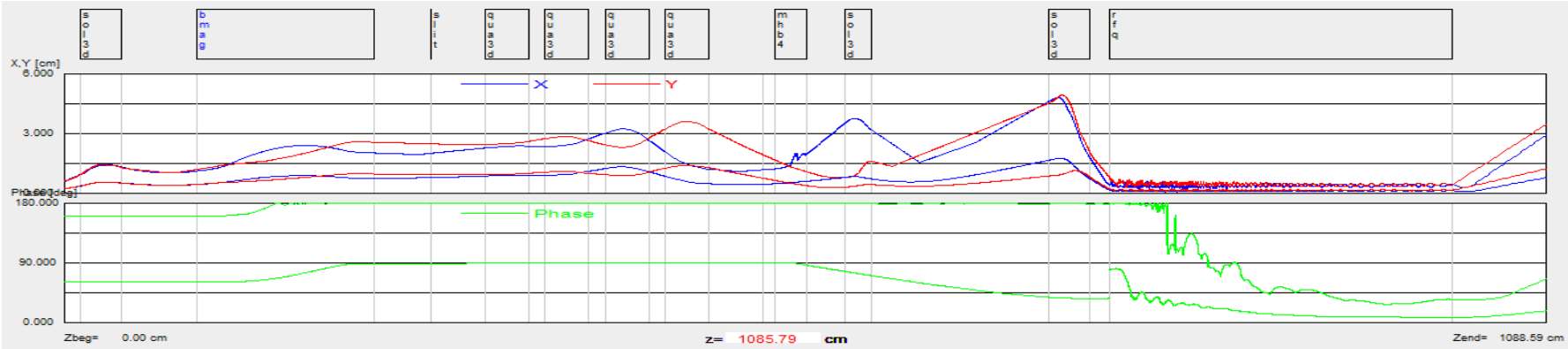
Measured transverse emittance and beam signals

Code benchmarking and beam experiment with RFQ[1]





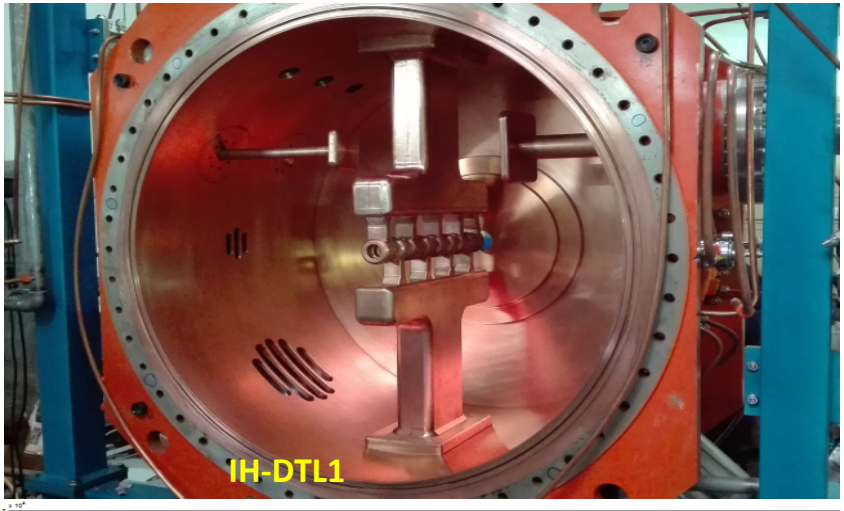
RFQ		
Parameter	Simulation	Experiment
ε_{rms}[mm·mrad]	0.176	0.18
α	-10.23	-10.20
β[mm/mrad]	6.1	4.92



[1] X.J.Yin,Y.J.Yuan,J.W.Xia, *et al.*, Phys. Rev. Accel. Beams 19, 010402 (2016).

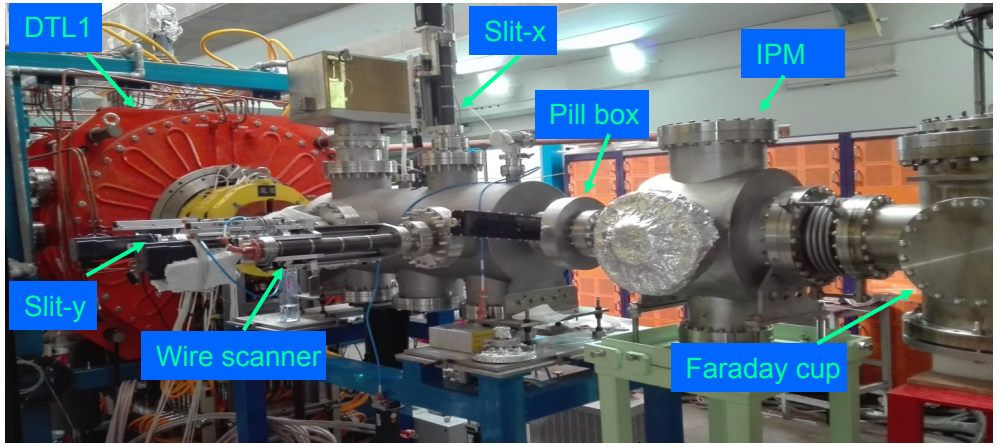
- CW mode
- High Intensity
- High efficiency
- Compact

RF measured results	
Frequency[MHz]	53.667
Q0	10200 (Designed 12400)
Fixed tuner[mm]	150
Tuning range[MHz]	1.4
Moveable tuner[mm]	100
Tuning range[kHz]	140
Power[kW]	18.2(Calculated)

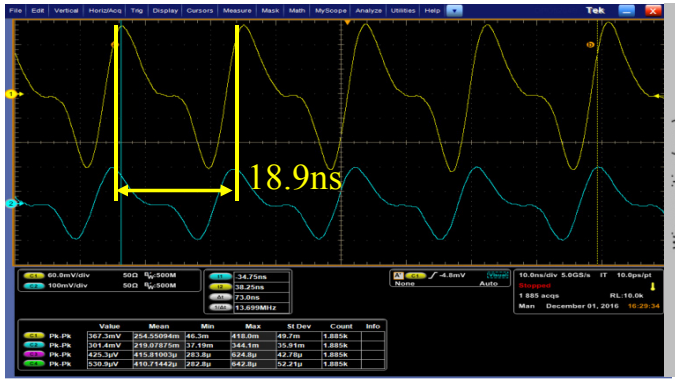


Field distribution along the IH-DTL1

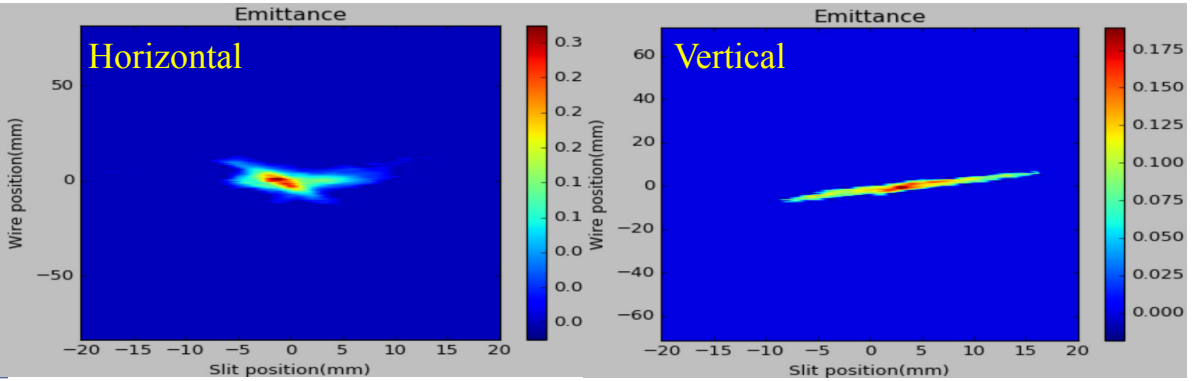
IH-DTL1 Beam Commissioning



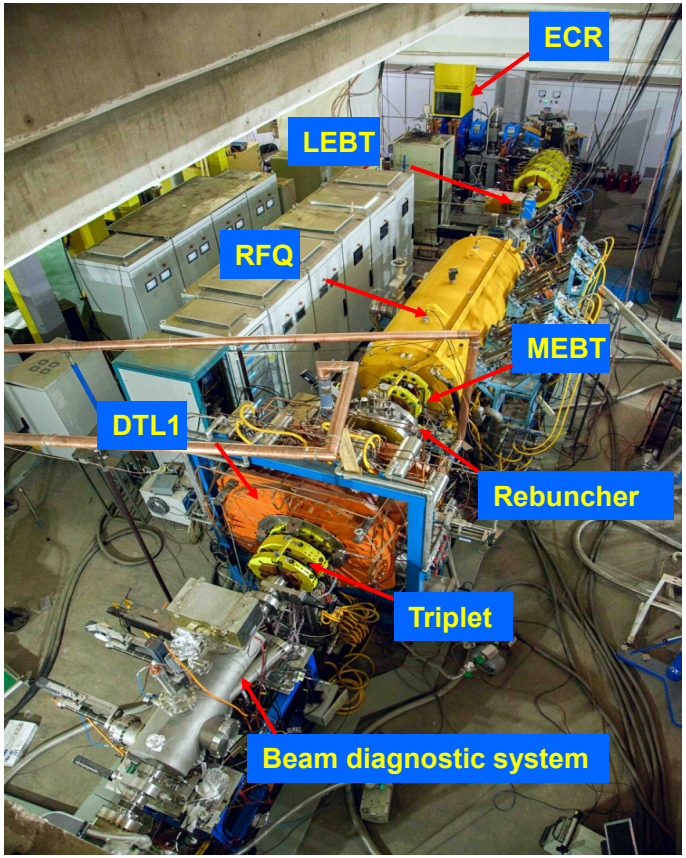
Parameters	Values
Ion	$^{16}O^{5+}$
Beam current	70uA
Input energy	142.8keV/u
Output energy	295.6keV/u
ε_{xnrms}	0.18mm·mrad
ε_{ynrms}	0.14mm·mrad



Particle energy measurement by TOF method



Measured emittance at the DTL1exit



SSC-Linac layout

- Beam commissioning: $^{16}O^{5+}$,$^{12}C^{4+}$, $^{16}O^{4+}$& $^{209}Bi^{30+}$
- Beam energy 295.6keV/u
- Beam transmission > 70%
- DTL2(576keV/u) will be finished in 2018

Beam experiment resualts

Parameters	Values	
Frequency	53.667MHz	
Input energy	3.7keV/u	
Output energy	295.6keV/u	
$\varepsilon_{x\ nrms}$	0.18mm·mrad	
$\varepsilon_{y\ nrms}$	0.14mm·mrad	
Energy spread	±<2%	
Ion	**I(eμA)**	
	INPUT	**OUTPUT**
$^{12}C^{4+}$	45	37(DTL)
$^{16}O^{5+}$	184	170(RFQ)
	100	70(DTL)
$^{40}Ar^{8+}$	220	198(RFQ)
$^{209}Bi^{30+}$	42	12(RFQ)

Summary

- The CW heavy ion linac.
- 4-rod RFQ and IH-DTL.
- Beam commissioning of SSC-Linac.
- Challenges in the design and operation of CW machine.
- Long term operation
- High current beam dynamics study.
- Code benchmarking on space charge effect.

Thank you for your attention !