中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

Status and Upgrade of HIRFL Accelerator Complex at IMP

Youjin Yuan

Institute of Modern Physics (IMP)

Chinese Academy of Sciences

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- Status of HIRFL
- Activities of Upgrading
  - SSC-Linac injector
  - Isochronous mass spectrometry
  - Electron cooling at CSR
  - Laser cooling at CSRe
  - Stochastic cooling at CSRe
  - Upgrade CSRe for experiments
- HIAF project

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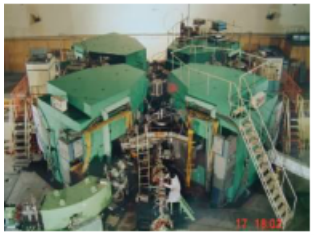
Status of HIRFL: overview



SSC (K=450)

100 AMeV (H.I.), 110 MeV (p)

SFC (K=69)

10 AMeV (H.I.), 17~35 MeV (p)

RIBLL1

RIBs at tens of AMeV

CSRe

RIBLL2

RIBs at hundreds of AMeV

CSR(Cooling Storage Ring)

CSRm

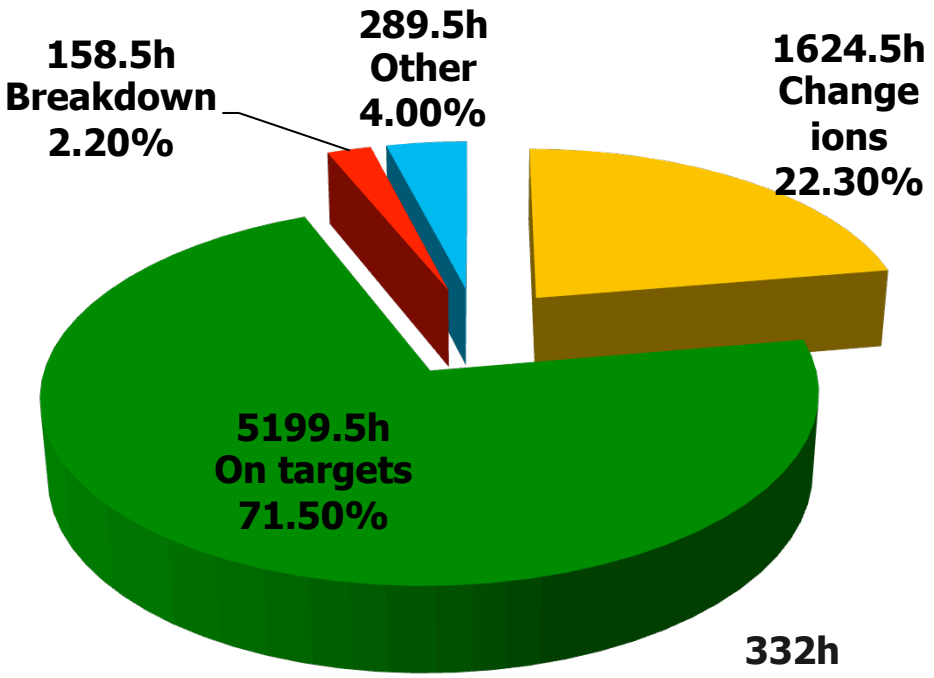
1000 AMeV (H.I.), ≤ 2.8 GeV (p)

Heavy Ion Research Facility in Lanzhou (HIRFL)

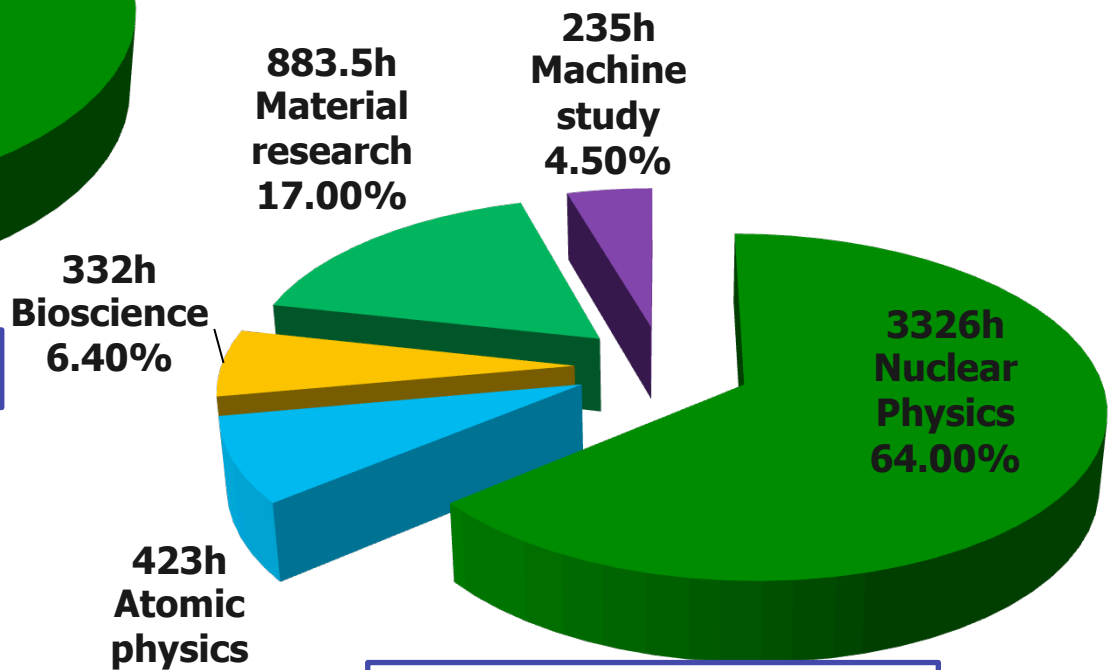
Operation in 2014

No.	SFC			SSC		CSR			
	Ion	Energy MeV/u	Current uA	Energy MeV/u	Current uA	Charge State	Energy MeV/u	Current @ CSRm (uA)	Current @ CSRe (uA)
1	$^{78}Kr^{19+/28+}$	4	4.2				432.5,487	600	Secondary beams
2	H_2^+	10	4				250	30-50	
3	$^{40}Ar^{11+}$	4.8	3. 2						
4	$^{16}O^{6+}$	7	8.5			8+	265,360	600-1000 (4×10^8)	
5	$^{12}C^{4+/6+}$	7	2.3	80.55	0.17				
6	$^{40}Ar^{12+/17+}$	6.17	5	70	0.45				
7	$^{16}O^{6+/8+}$	6.17	5.9	70	0.45				
8	$^{12}C^{4+/6+}$	5.361	2.8	60	0.24				
9	$^{209}Bi^{31+}$	0.911	0.6	9.5	0.04				
10	$^{58}Ni^{19+/25+}$	6.17	1.2	70	0.07				
11	$^{32}S^{9+}$	3.9	1.7						
12	$^{40}Ar^{9+/15+}$	2.794	3	30	0.05				
13	$^{20}Ne^{7+}$	6.17	3.8						
14	$^{16}O^{6+}$	7.5	2						
15	$^{22}Ne^{8+}$	7.5	2.2						
16	$^{86}Kr^{17+/26+}$	2.345	4.5	25	0.13				
17	$^{12}C^{4+/6+}$	4.906	5	54.5	0. 35				
18	$^{36}Ar^{15+}$	8.5	1.9			15+	8.5	300(5×10^8)	
19	$^{14}N^{4+}$	4.5	2.8						
20	$^{40}Ca^{12+}$	5	2						
21	$^{12}C^{3+}$	4.2	5			3+	122.375	270 (6×10^8)	200
22	$^{12}C^{4+}$	7	10			6+	165,300	1500(1×10^9)	
23	$^{40}Ca^{12+}$	4.825	2						
24	$^{209}Bi^{31+}$	0.911	0.3	9.5	0.01				
25	$^{58}Ni^{19+}$	6.3	1.2				467等多种	280(7×10^7)	Secondary beams

Operation in 2014



Operation time distribution

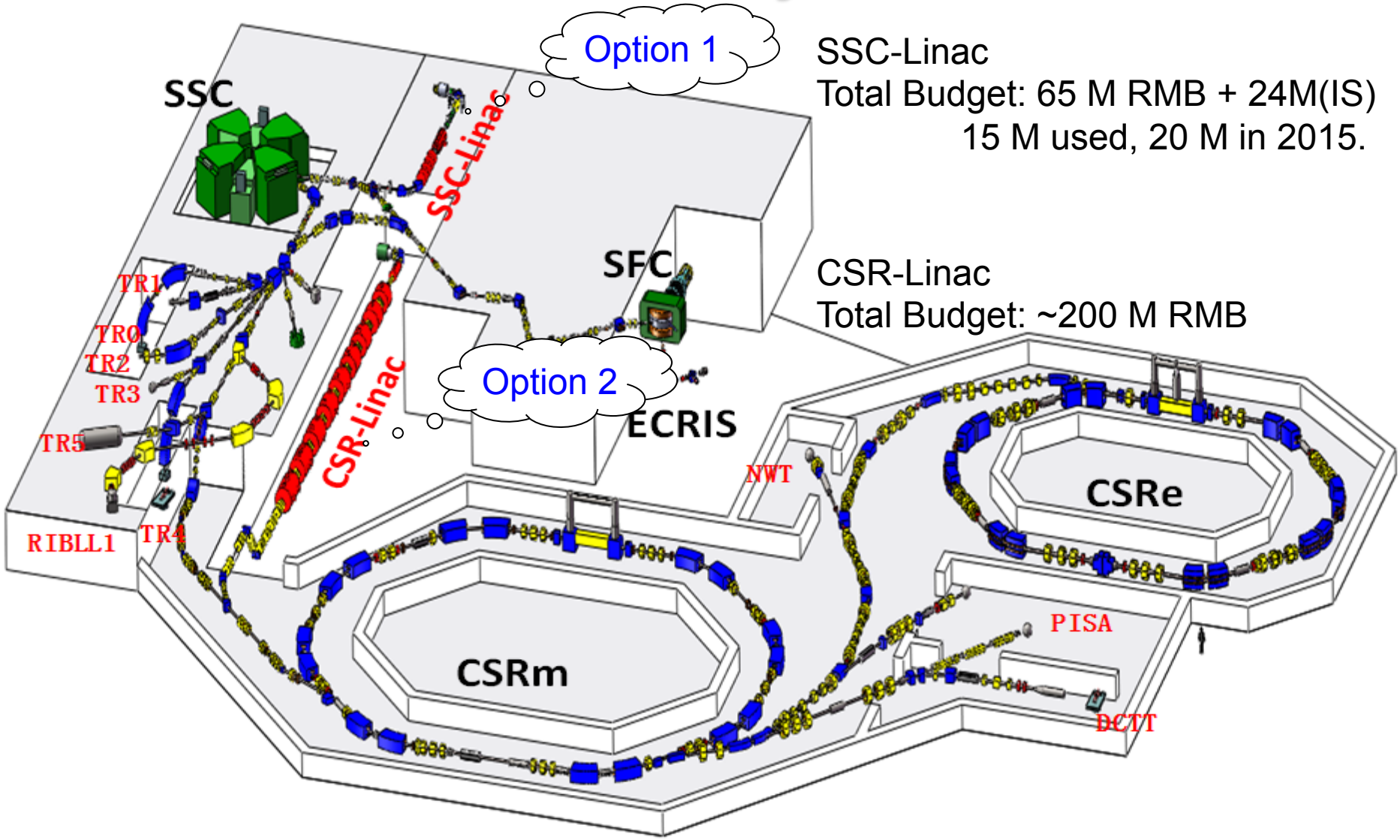


Beam time distribution

- Status of HIRFL
- *Activities of Upgrading*
  - *SSC-Linac injector*
  - Electron cooling at CSR
  - Laser cooling at CSRe
  - Stochastic cooling at CSRe
  - Isochronous mass spectrometry
  - Upgrade CSRe for experiments
- HIAF project

SSC-Linac injector: Overview

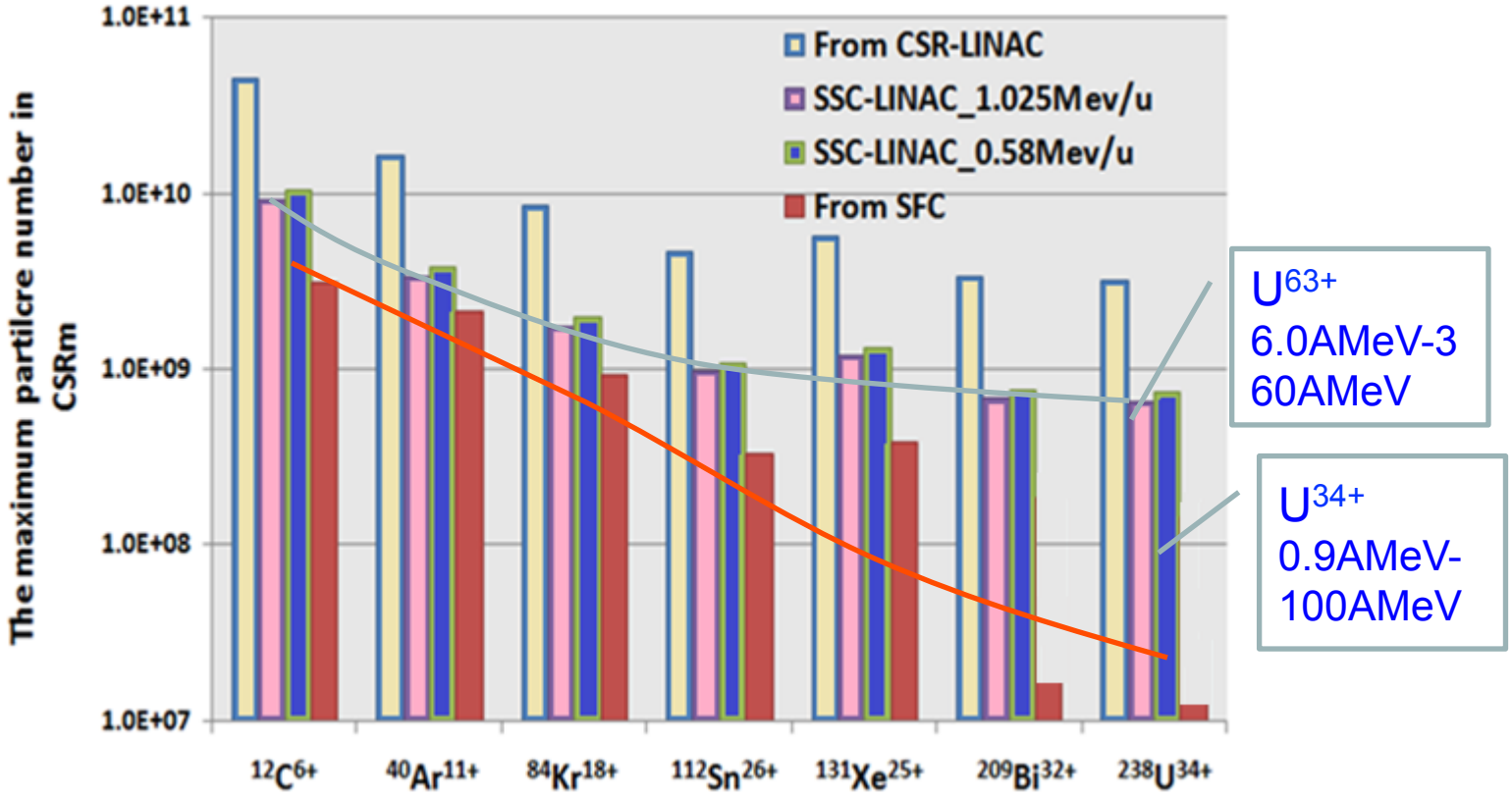
- **New HIRFL with new injectors**



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

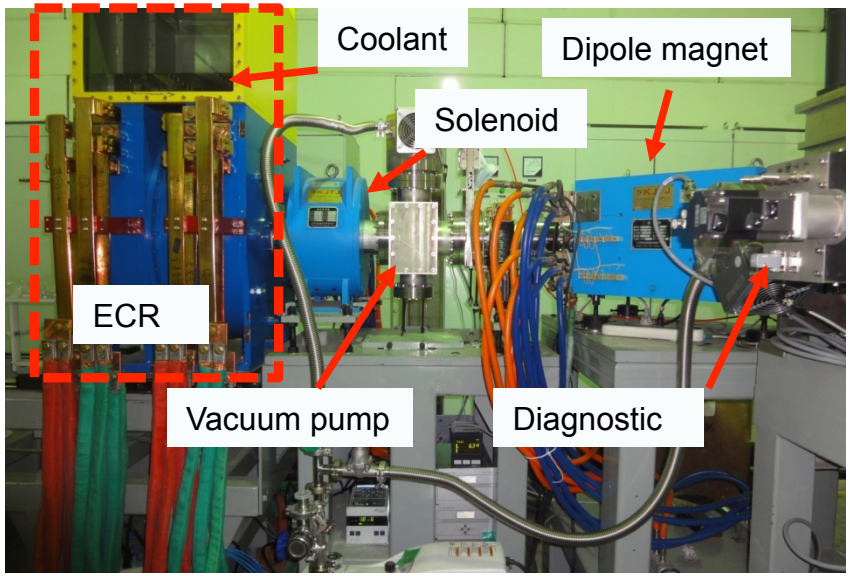
CSR-Linac
Total Budget: ~200 M RMB

SSC-Linac injector: Goal

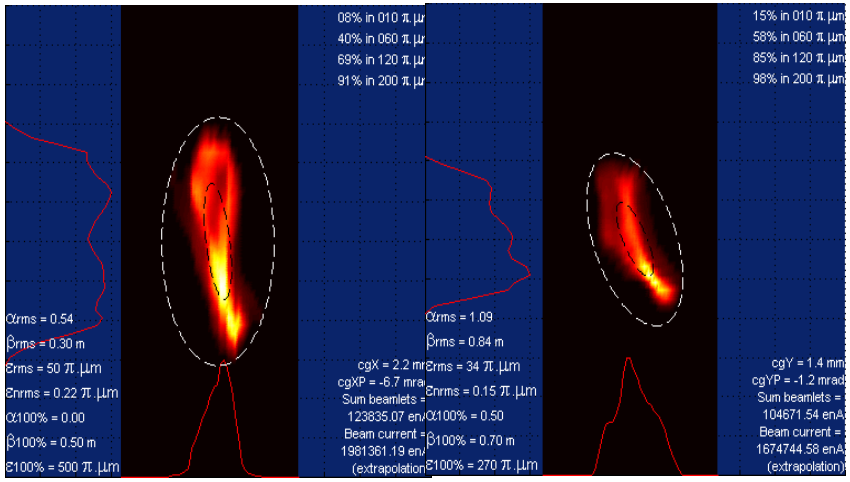


For planned linac injectors, the maximum stored particle numbers in CSRm will be 2 to 15 times the case of the cyclotron injector SFC, especially for much heavier ions, it's possible to reach higher energy in CSRm.

SSC-Linac: Ion Source



ECR ion source



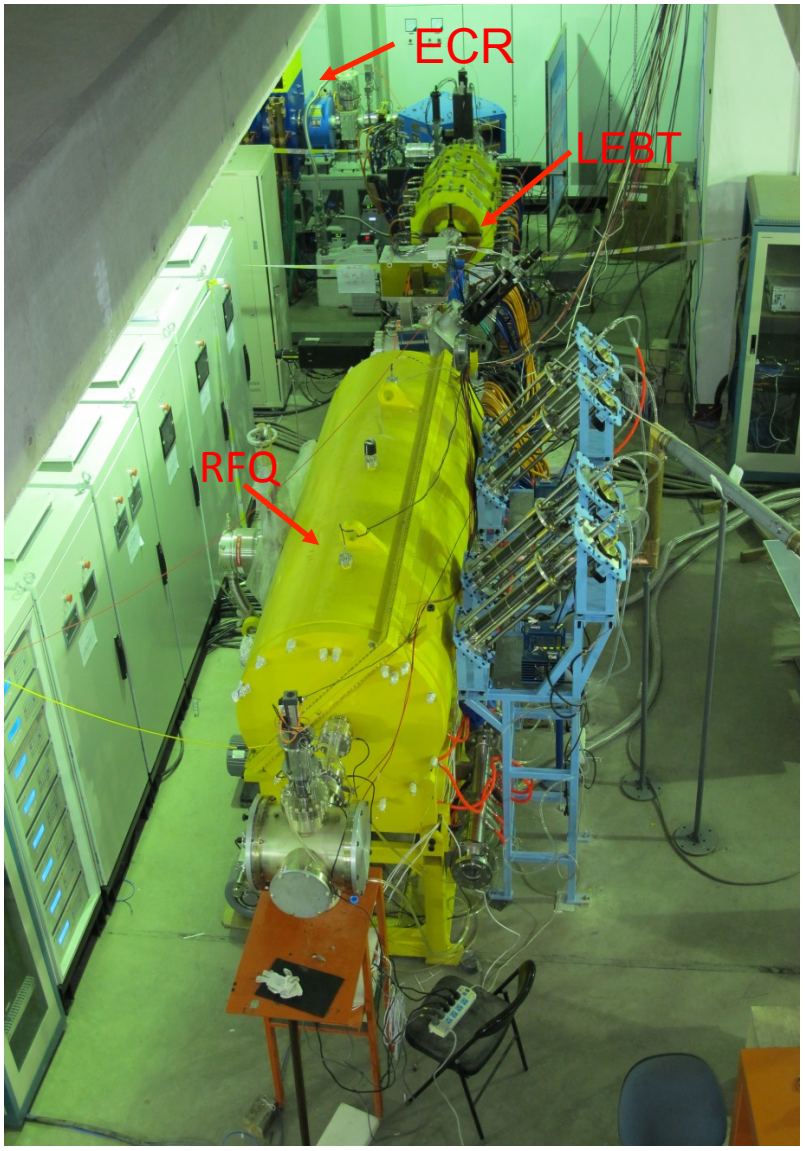
Measured transverse emittance

- High intensity HCI ECR ion source
- Evaporative cooling technology

Beam test results of Ion source

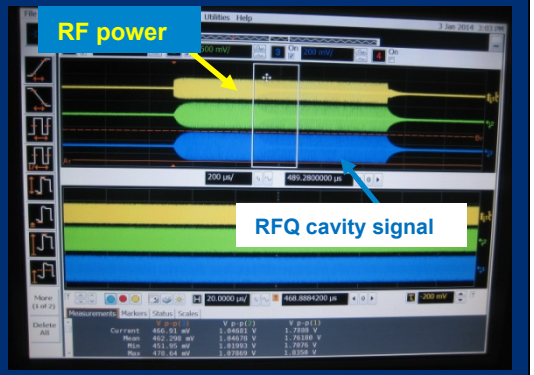
LECR4		
Ion	**charge state**	**I(emA)**
^{16}O	6^+	2110
	7^+	560
^{40}Ar	8+	1717
	9^+	1230
	14+	185
^{129}Xe	20+	430
	27+	135

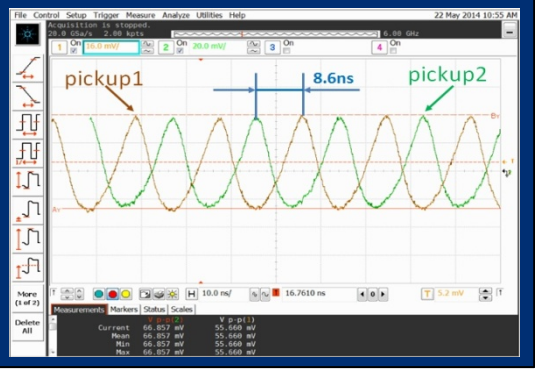
SSC-Linac: Layout and front-end testing



Front end of SSC-Linac

- 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%.





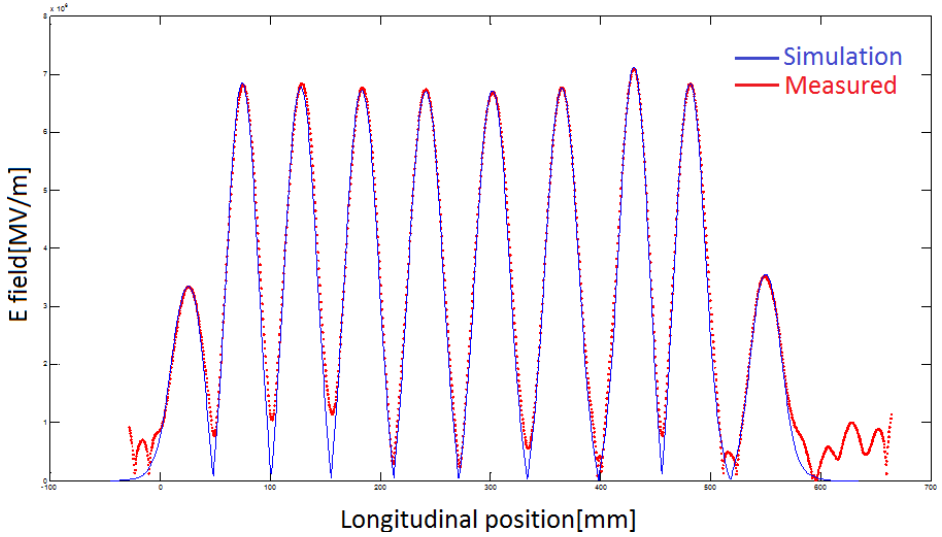
IH-DTL

IH-DTL1

RF measured resualts	
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)

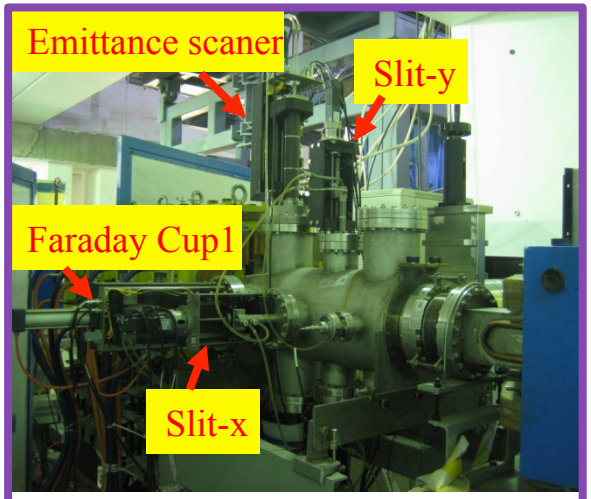
RF coupler

Movable Tuner

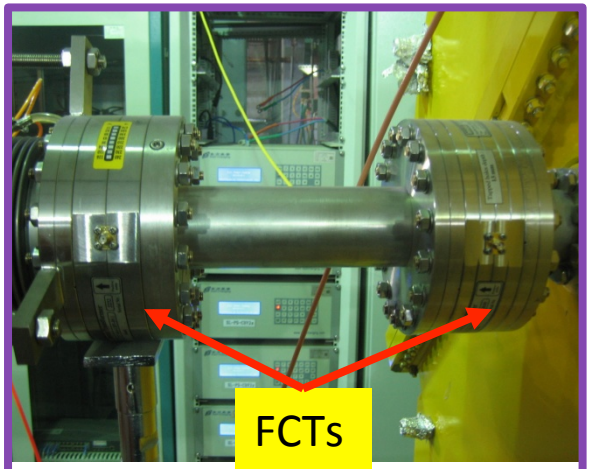


Field distribution along the tank

Beam diagnostic instruments



The transverse emittances are measured by scanners located at the downstream of the analyzing magnet.

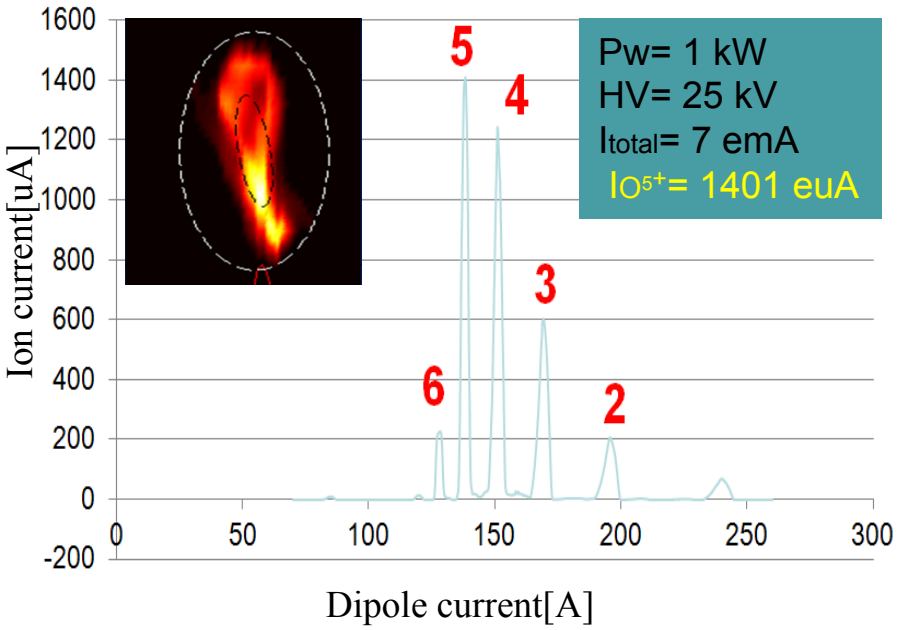


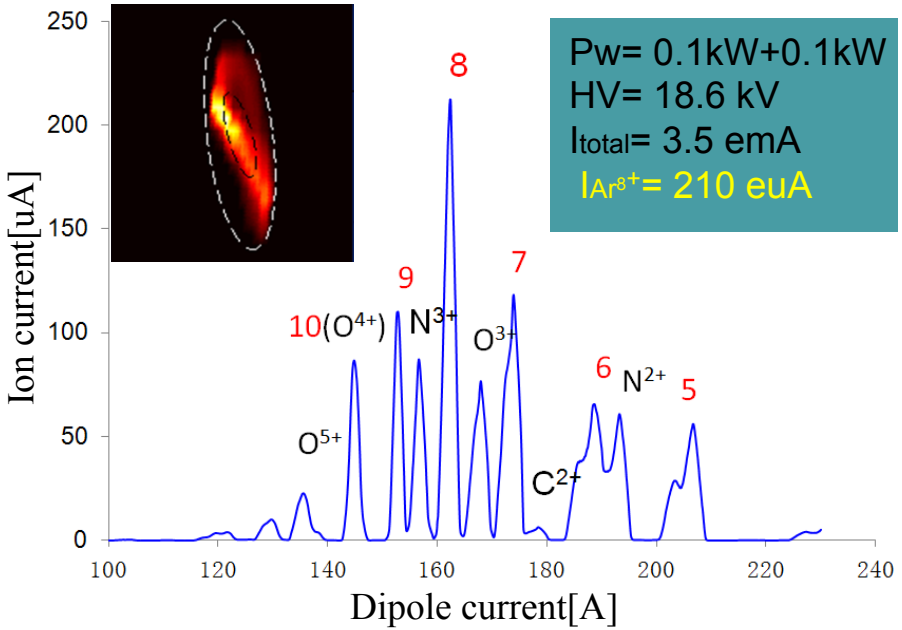
The beam energy is measured using the time of flight (TOF) method with two FCTs (Fast Current Transformer) installed after RFQ.

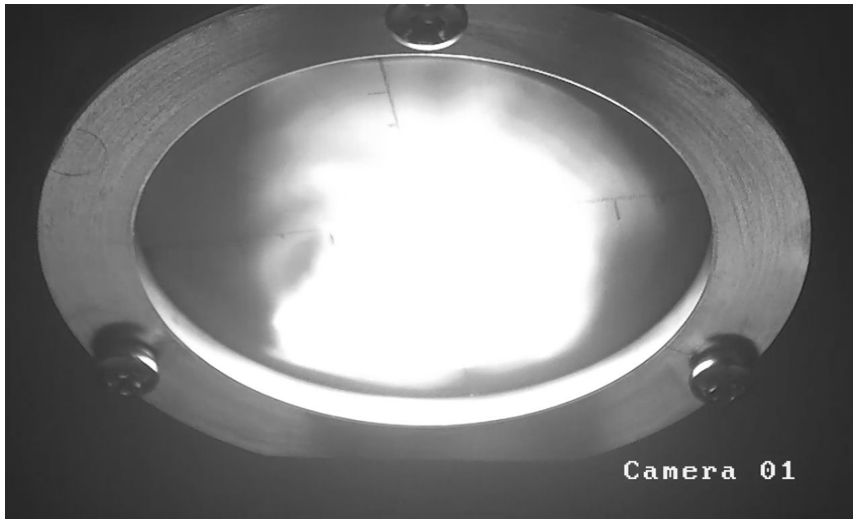
The beam current and transmission are measured by three Faraday cups.

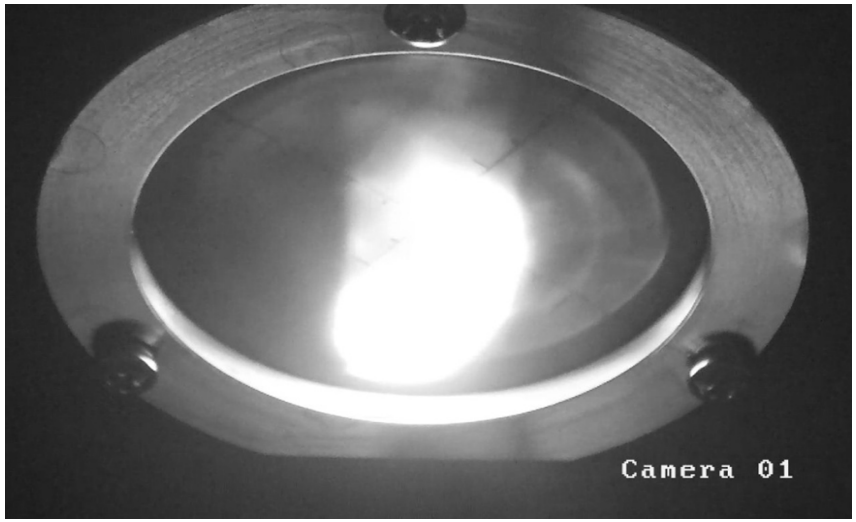
Some beam instruments were developed and applied in the beam commissioning. However, many elements and beam instruments were omitted since the limited funds. The analyzing dipole magnet system and the electrics system for the wire scanner, which were used to measure the energy spread and beam section profile, are not yet available.

Solid core beam of O^{5+}, Ar^{8+}



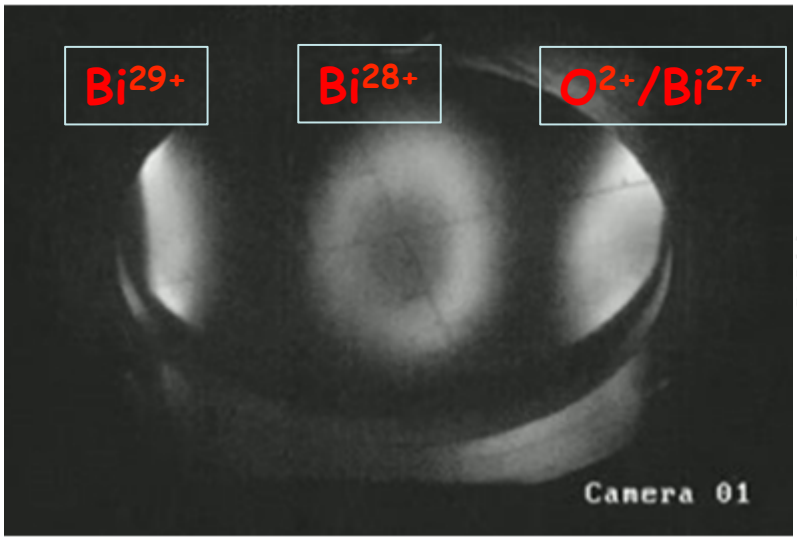


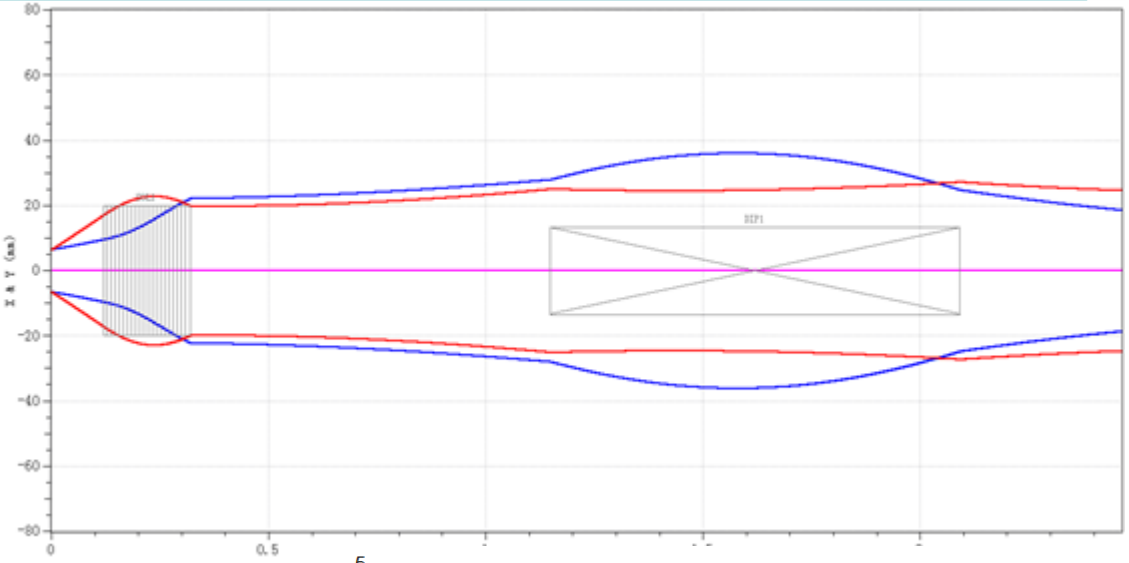




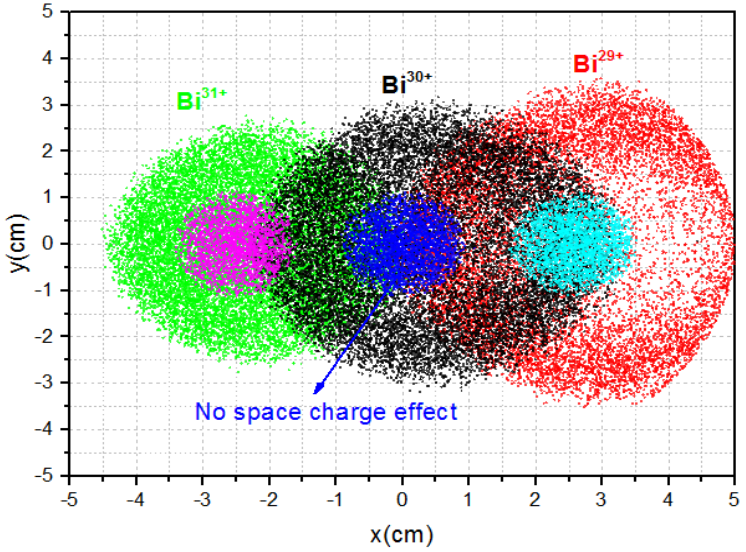
SSC-Linac injector: LEBT

LEBT hollow beam phenomenon and redesign with PIC multiple beam transmission simulation



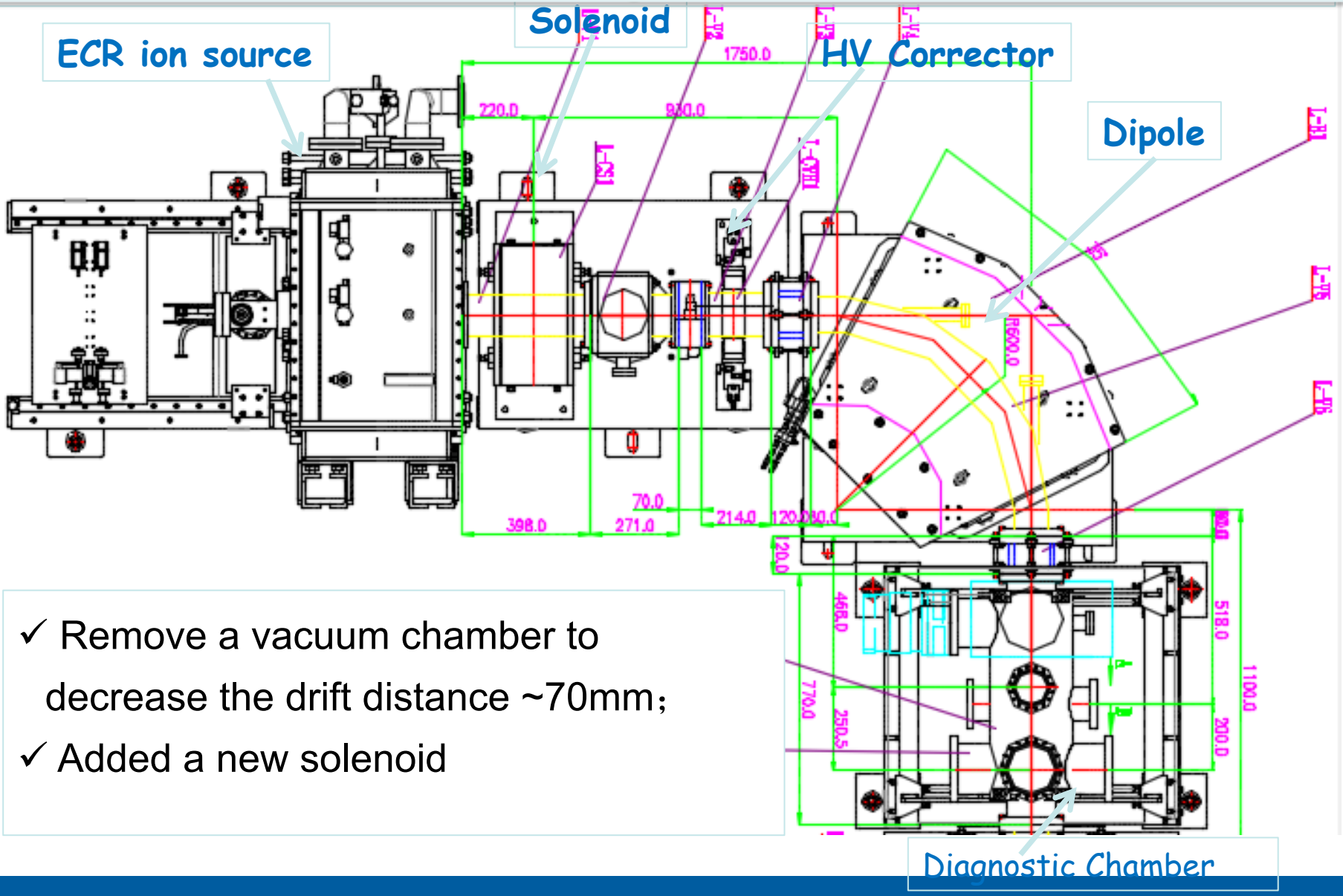


- High charge state
- High intensity Ion beam with multiple ion species and charge states
- High current space charge effect
- Extraction voltage: 23 kV
- I_{total}= 2.4 emA, $I_{Bi^{28+}}$= 20 euA



SSC-Linac injector: LEBT

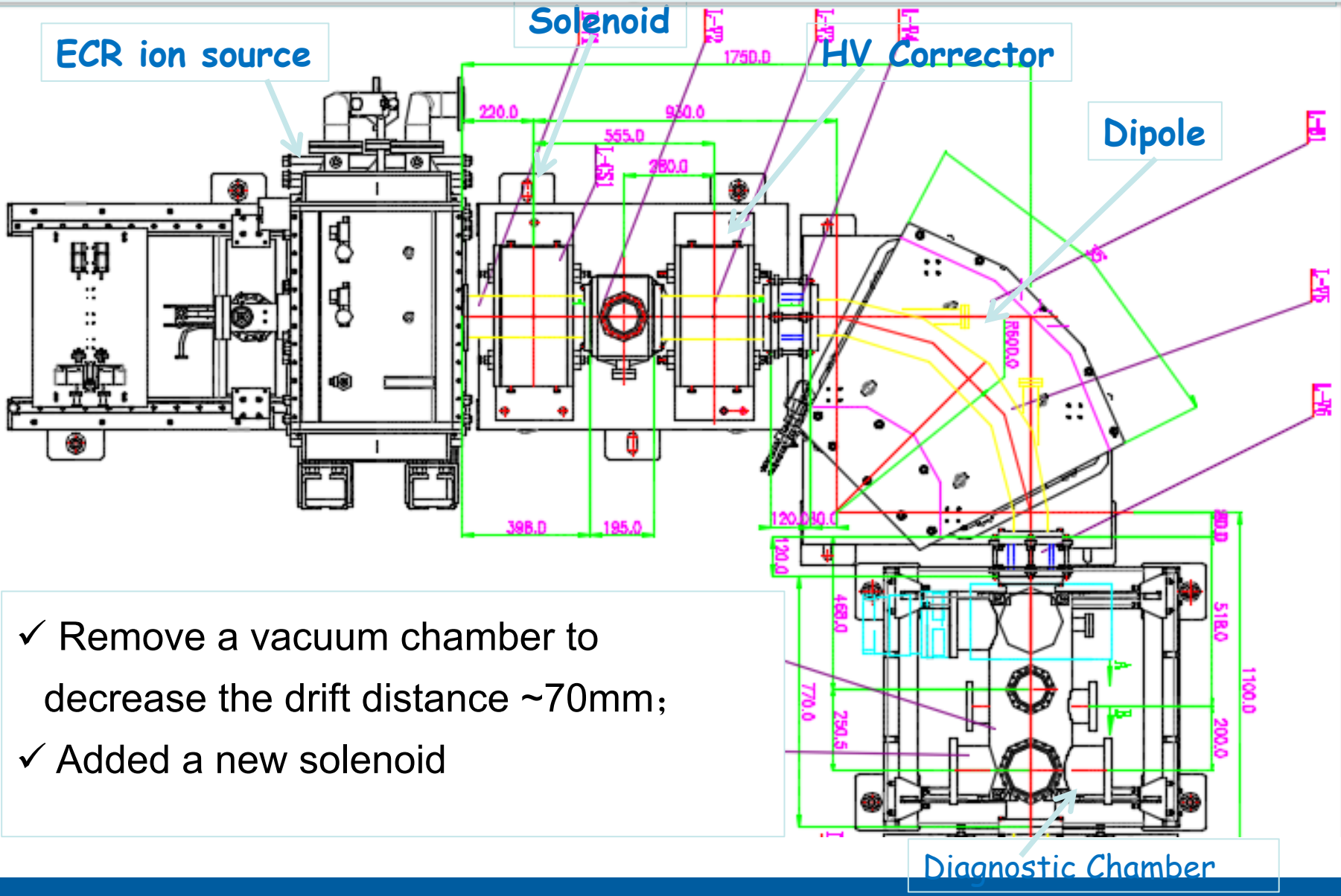
Redesign of LEBT



- ✓ Remove a vacuum chamber to decrease the drift distance ~70mm;
- ✓ Added a new solenoid

SSC-Linac injector: LEBT

Redesign of LEBT



- ✓ Remove a vacuum chamber to decrease the drift distance ~70mm;
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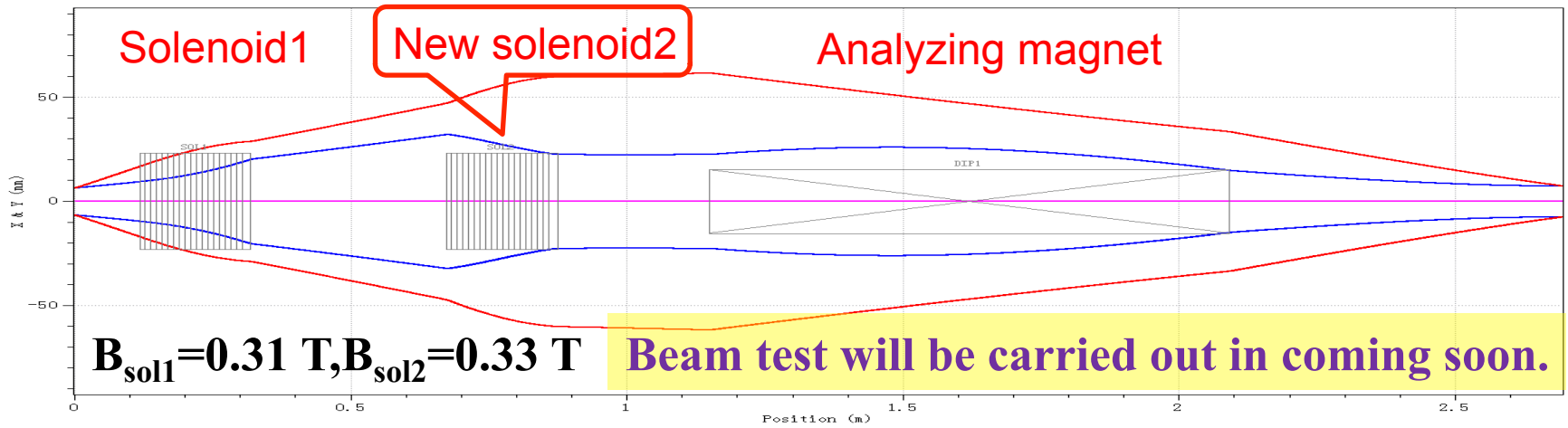
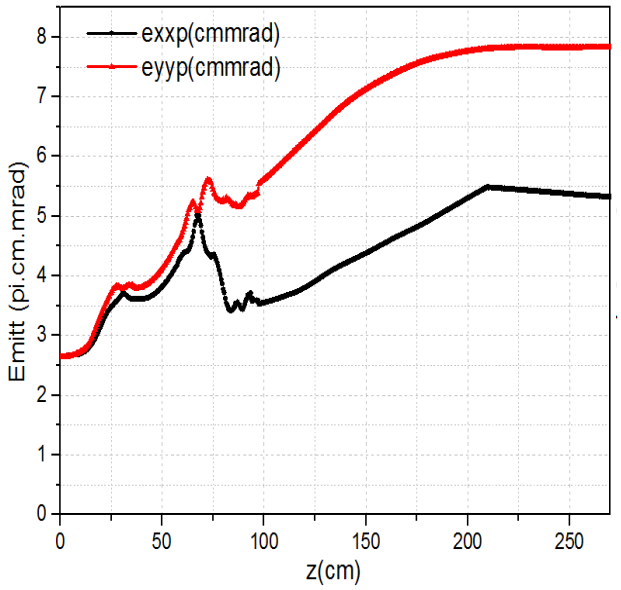
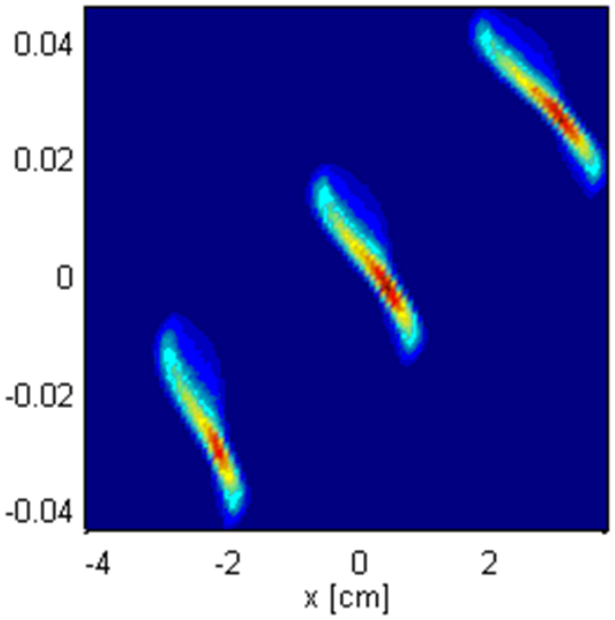
SSC-Linac injector: New LEBT

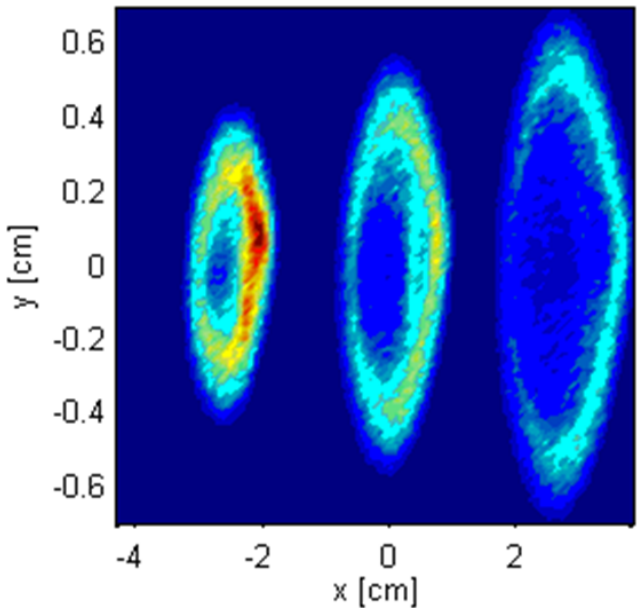


B_{sol1}=0.31 T,B_{sol2}=0.33 T

Beam test will be carried out in coming soon.

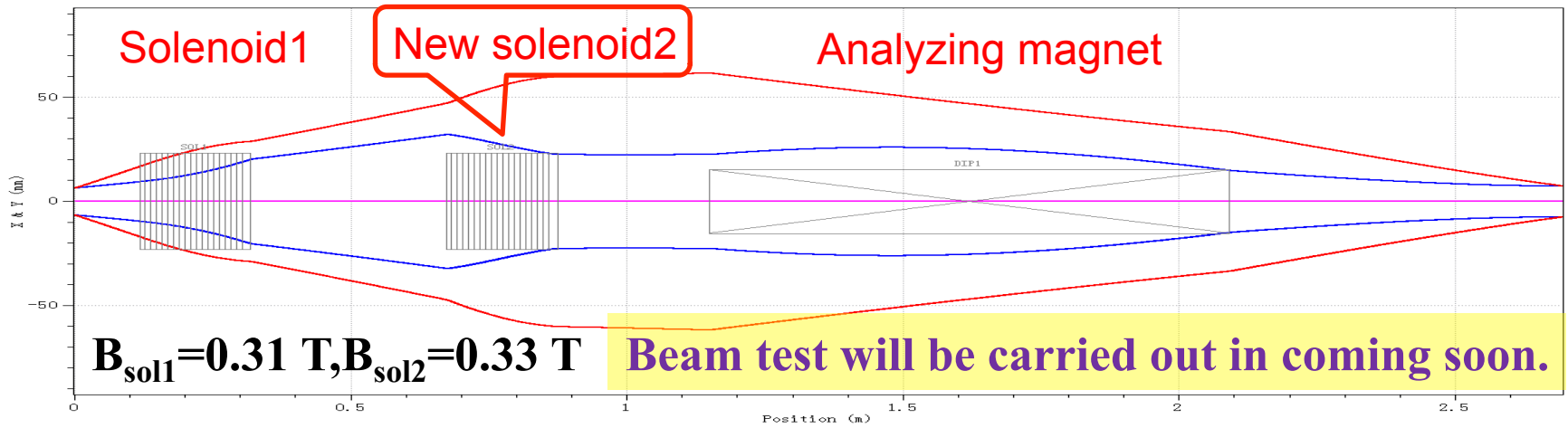






Simulation after optimization of LEBT

SSC-Linac injector: New LEBT



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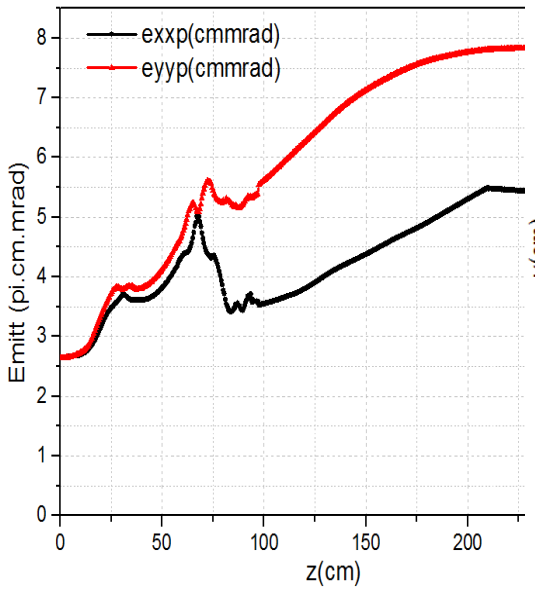

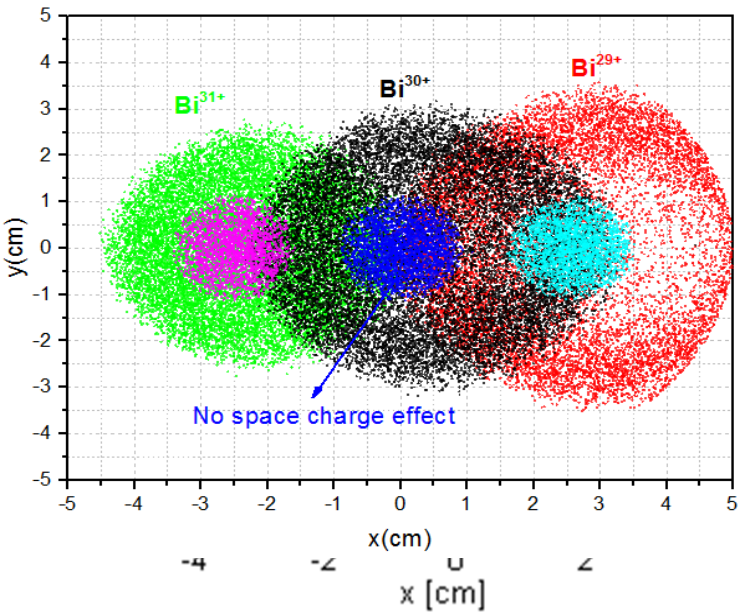

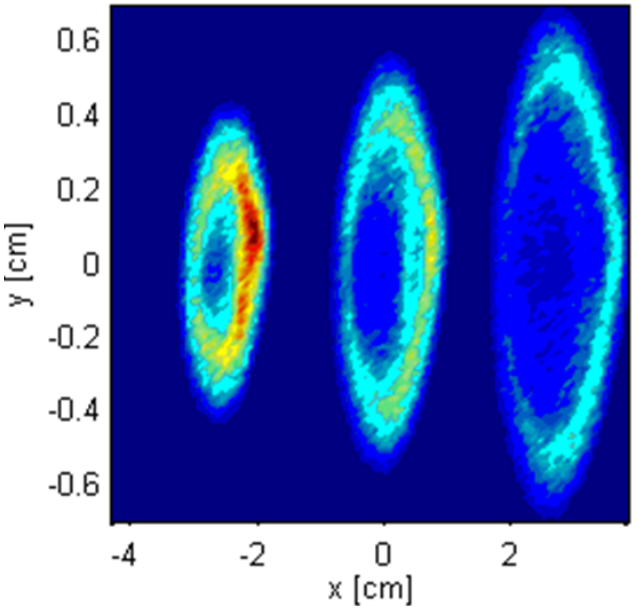

Simulation after optimization of LEBT

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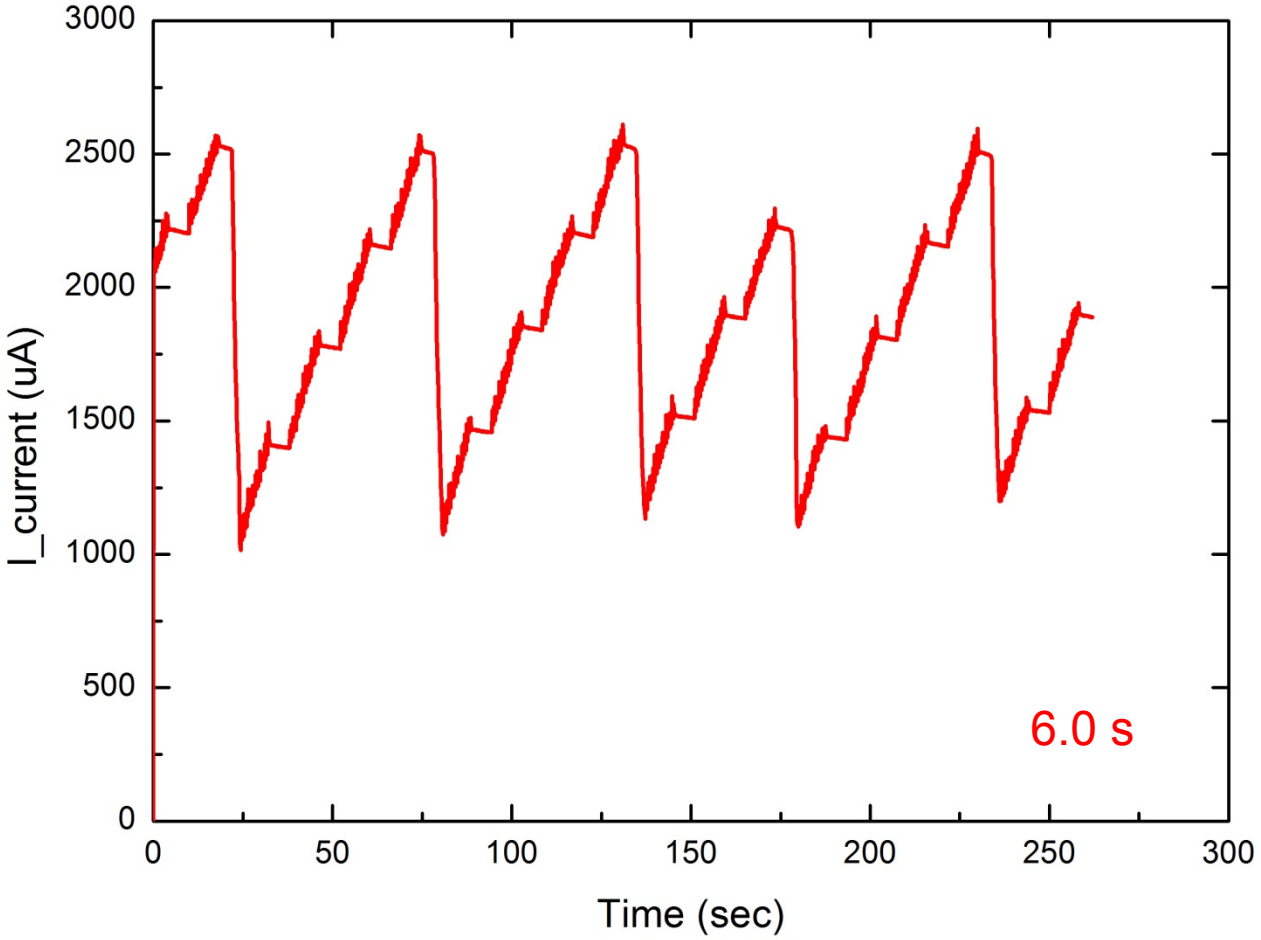
Instabilities of cooled beam

7.0 MeV/u C^{6+} ions was injected with e-cooling continually, particle loss directly around 2.5 mA and the intensity of the beam is limited 10^{10}



Mao et al.,

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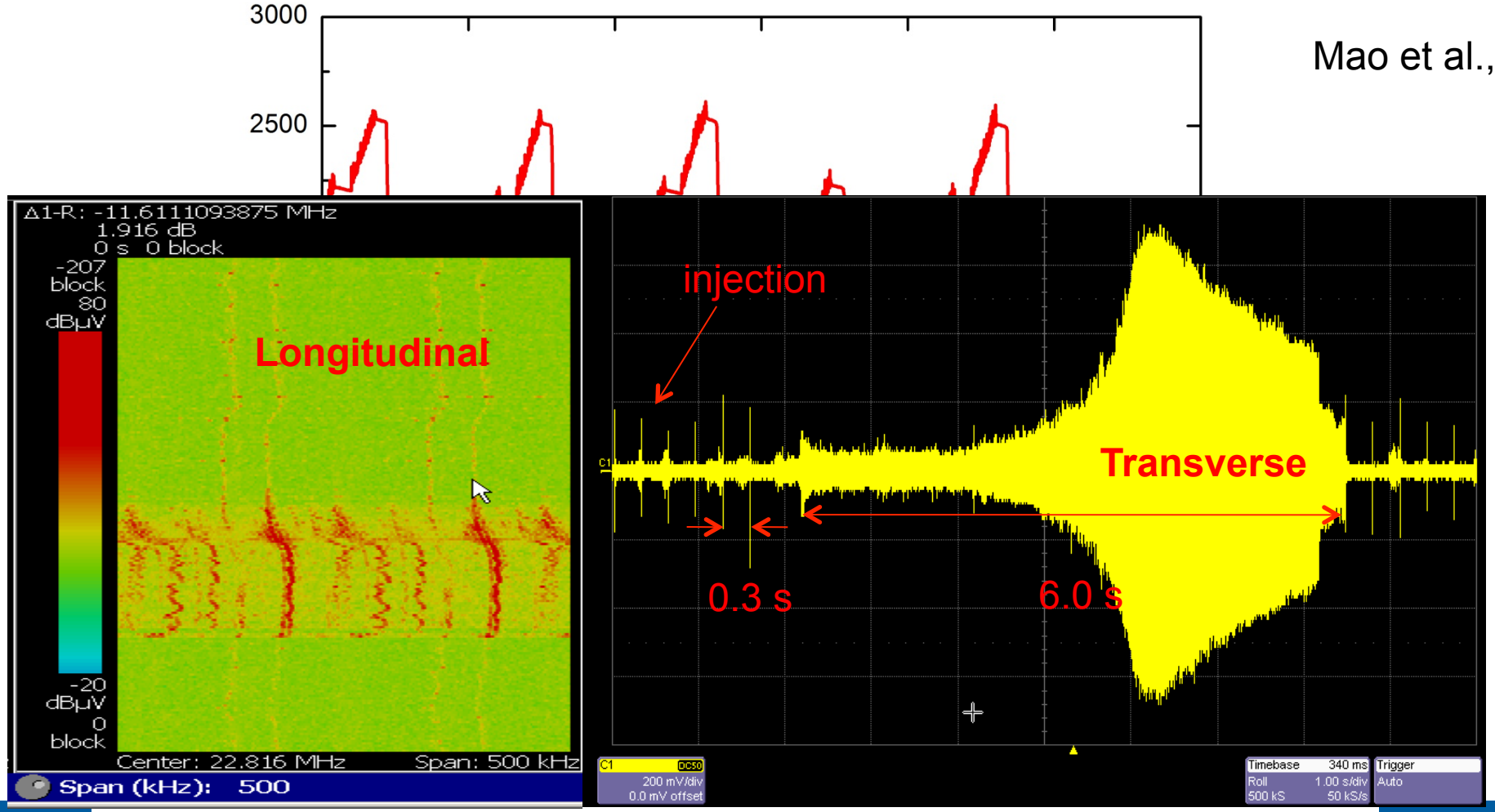
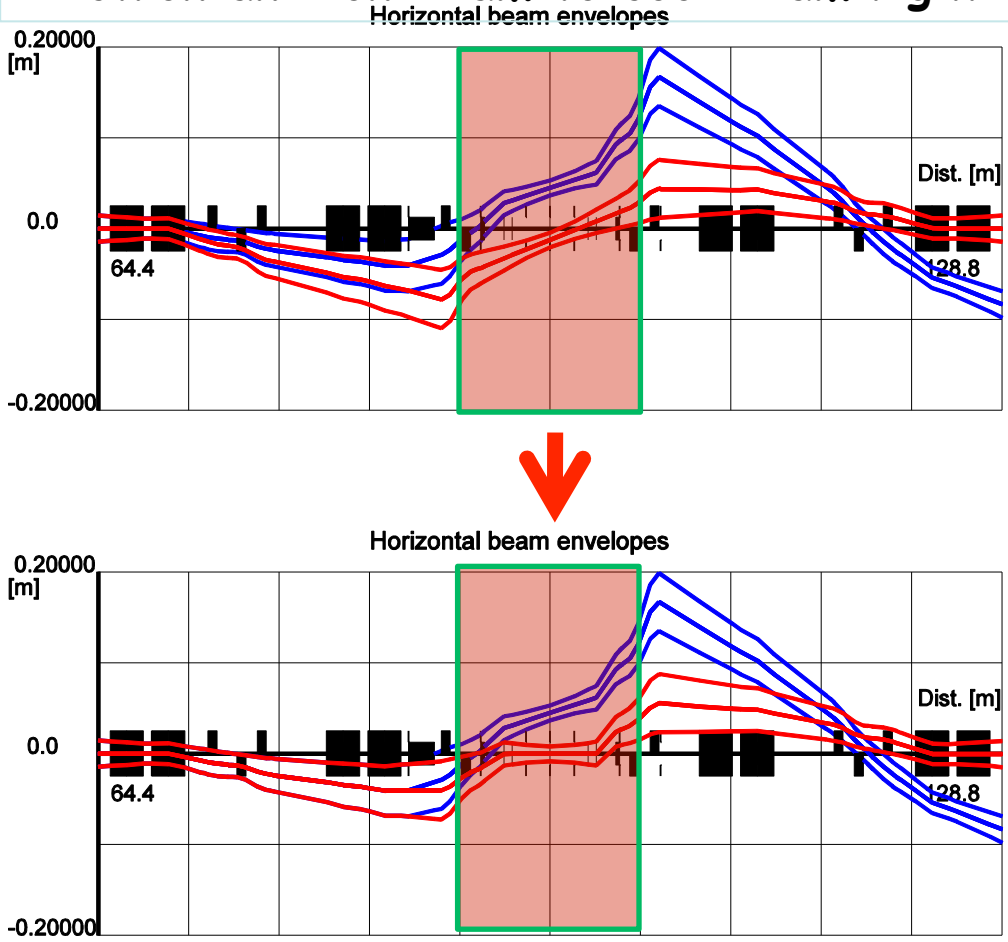
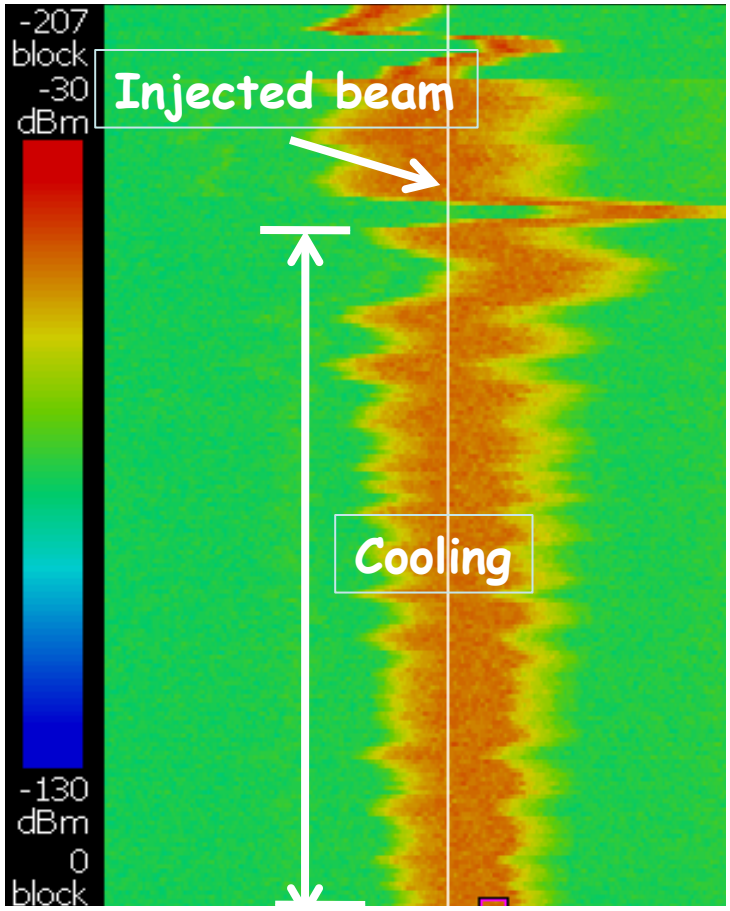


Fixed orbit injection and cooling

A new beam orbit correction is used to ensure an overlap coaxially between electron and ion beam to cool beam right after single-turn injection.

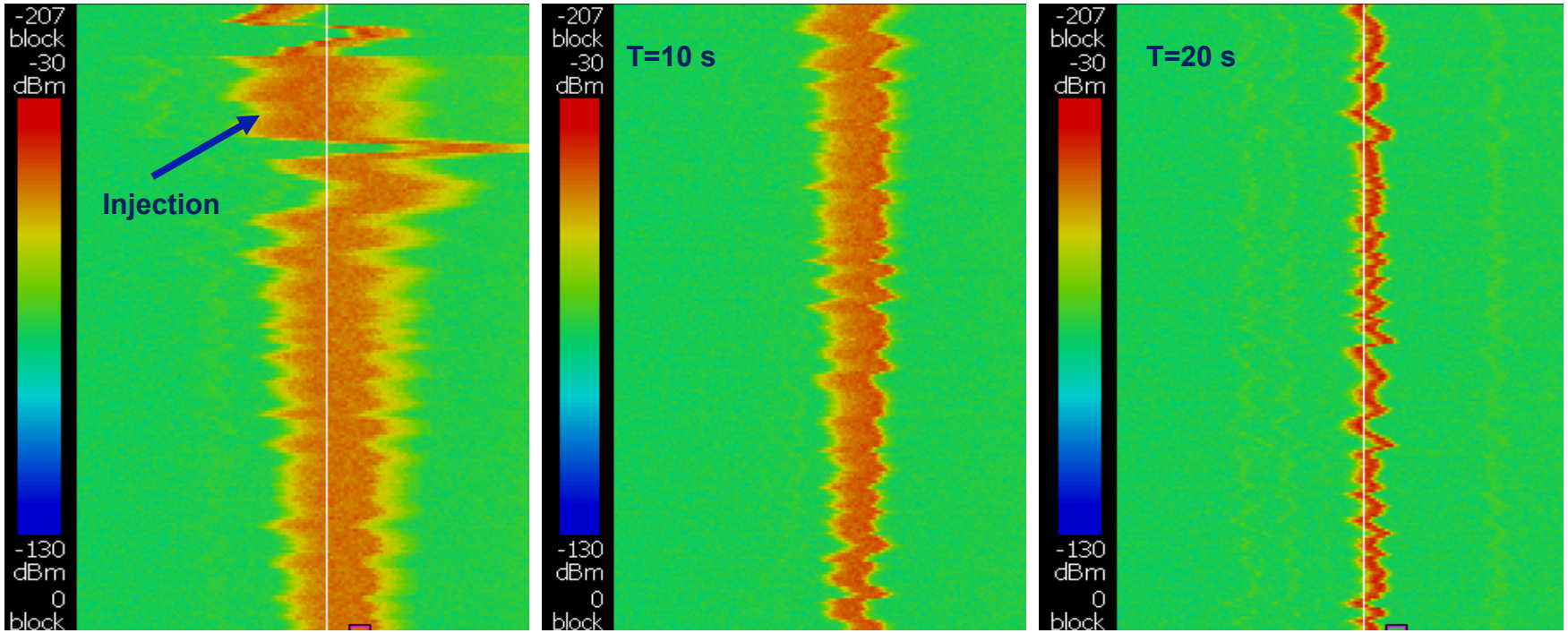




Mao et al.,

Fixed orbit injection and cooling

Ie=320 mA



- Cooling acts just after injection
- Cooling time is still longer then required
- Ripple of PS can be observed (~10^{-4})

Mao et al.,

Other topics

- E-cooling by pulsed electron beam
- High energy e-cooler for HIAF project
  (Mao et al.)

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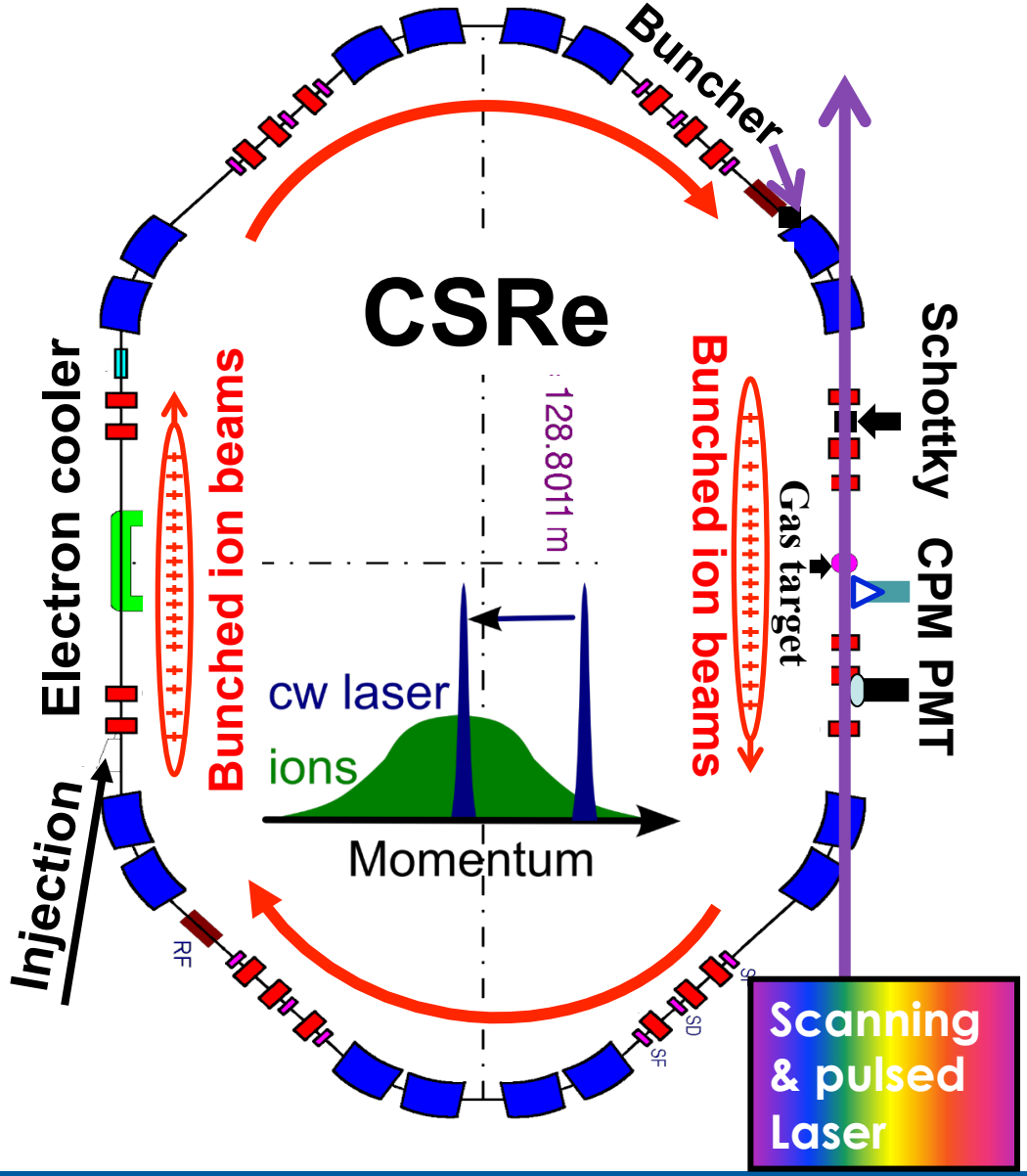
Laser cooling: Main parameters

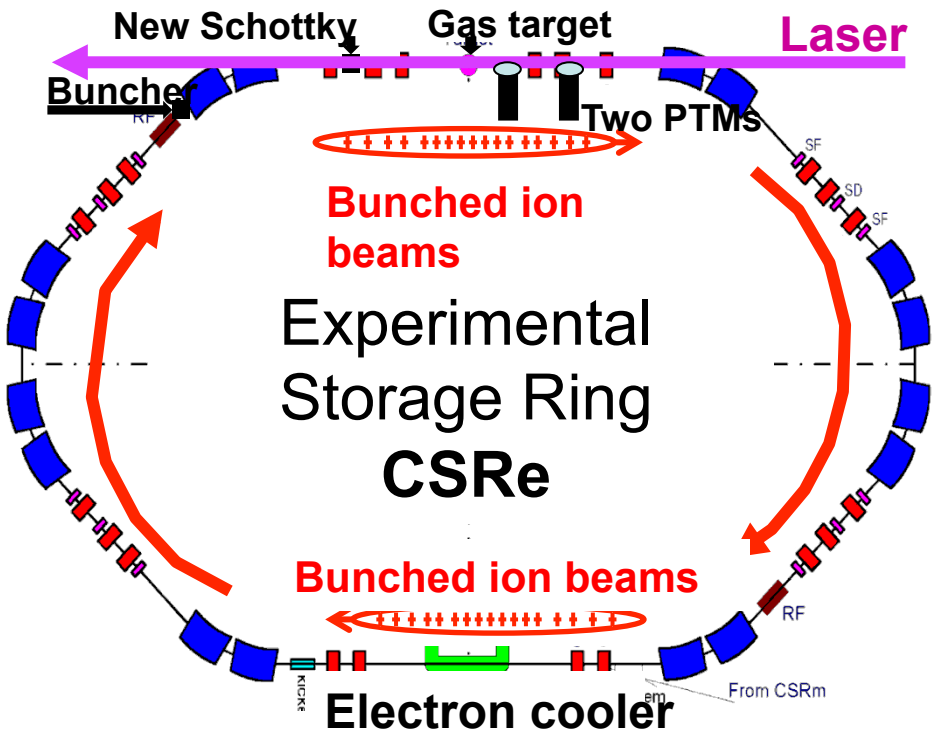


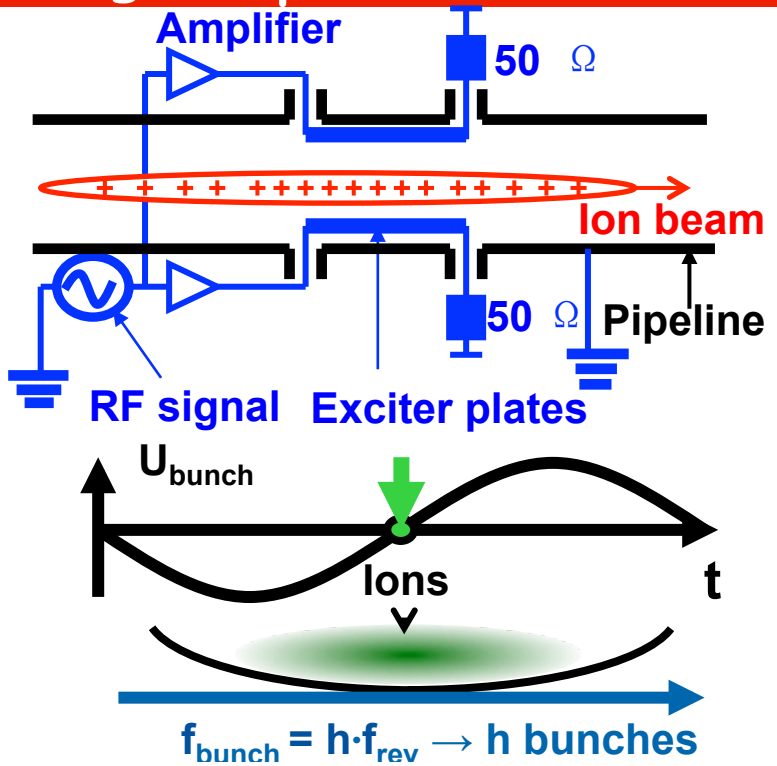
CSRe parameters	
Circumference	128.80 m
Ion species	$^{12}C^{3+}$
Beam energy	122 MeV/u
Relativistic b, g	0.47, 1.13
Revolution frequency	1.088 MHz
Transition energy g_t	2.626
Lifetime of ion beam	~ 20 s
Harmonic number h	10,15, 25
Laser system	
Laser source	cw & pulsed laser
Laser wavelength	$l_{laser} = 257.5$ nm
Cooling transition	
$2s_{1/2} \rightarrow 2p_{1/2}$	$l_{rest} = 155.07$ nm
$2s_{1/2} \rightarrow 2p_{3/2}$	$l_{rest} = 154.81$ nm

Wen et al.,

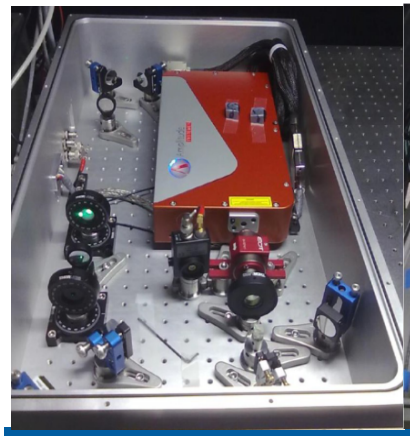
中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

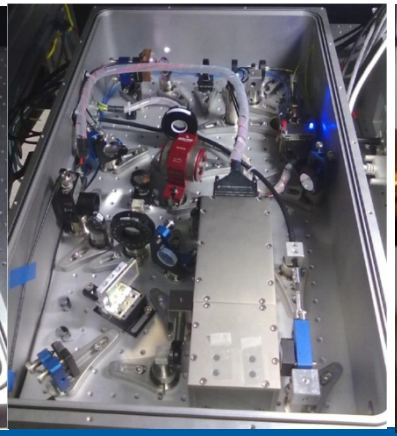
Laser cooling: Experimental setup



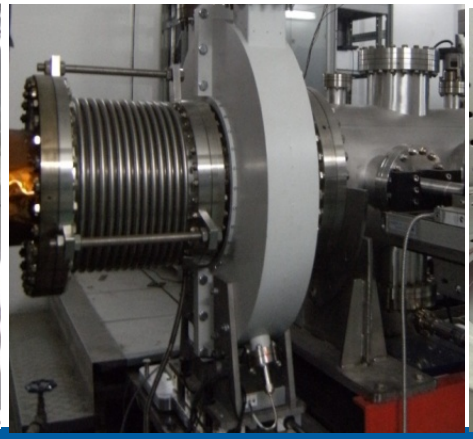


Pulsed laser system, HZDR

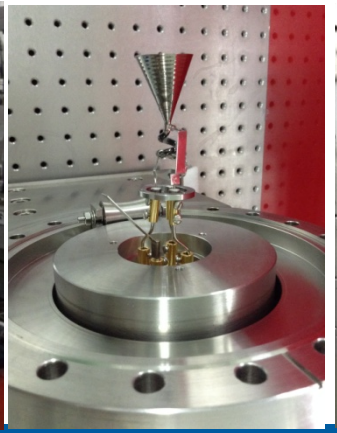




Resonant Schottky

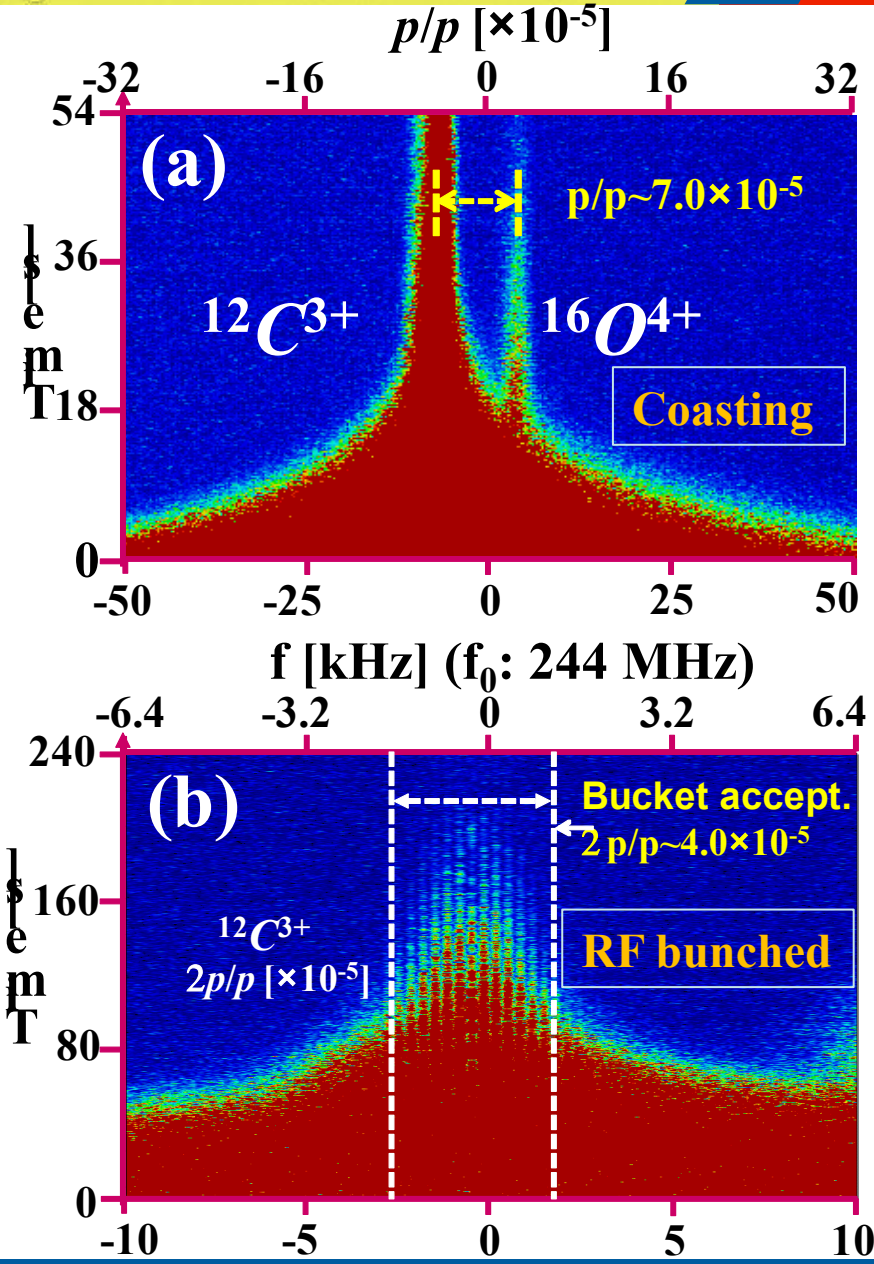


UV-sensitive Channeltron

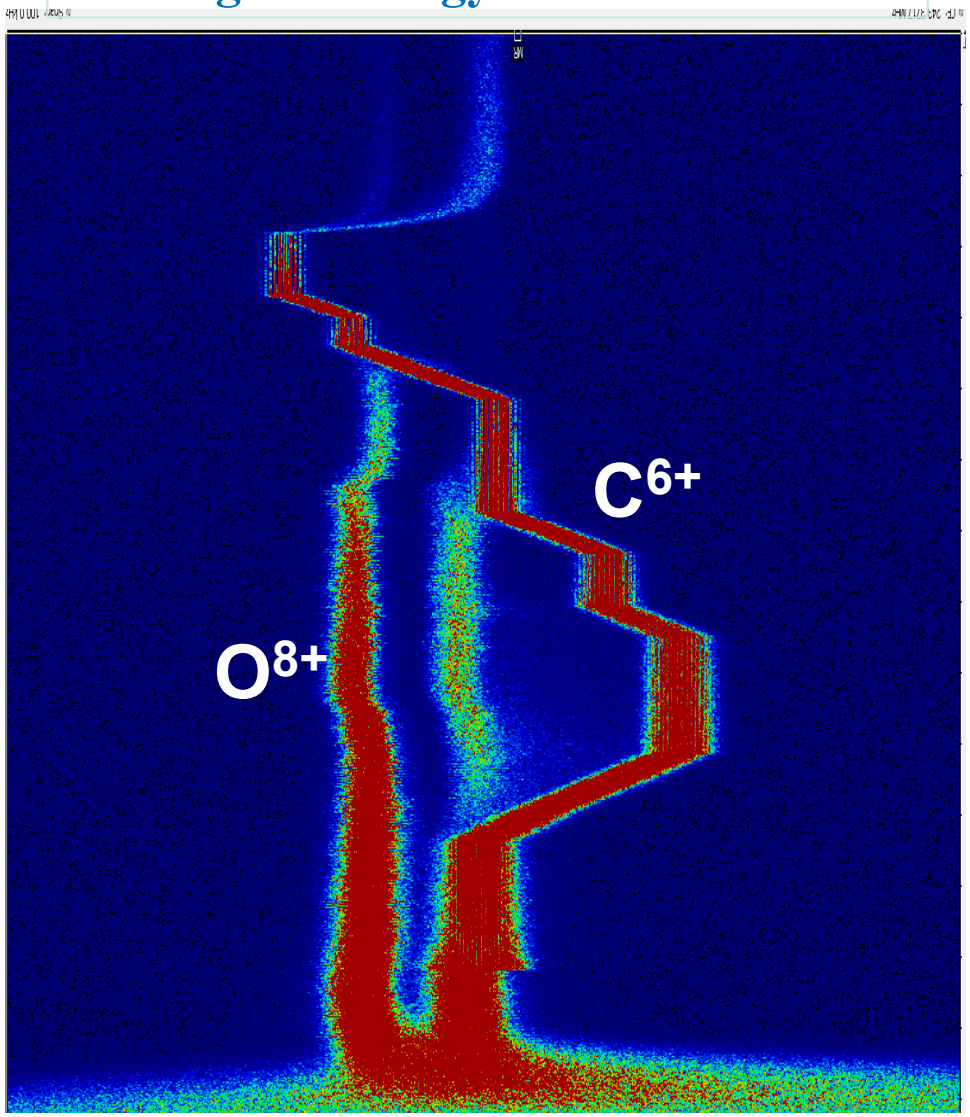


Wen et al.,

Laser cooling: Schottky spectrum

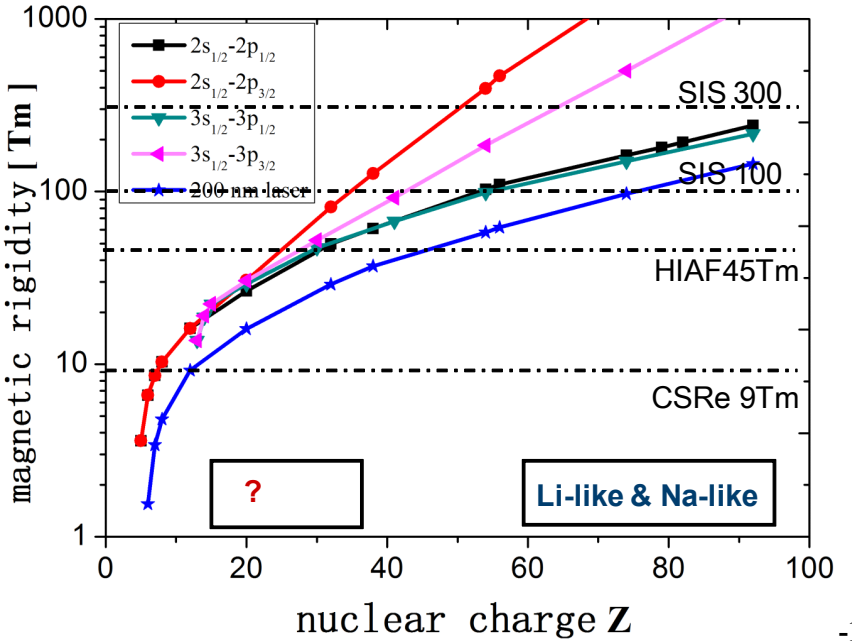


Moving ion energy with RF buncher



Wen et al.,

Laser cooling: Experimental setup test



Lorentz transformation

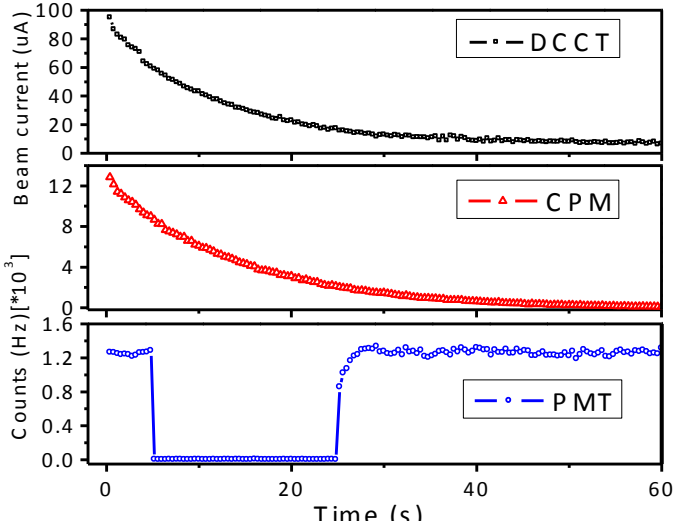
a) ground state transitions of heavy ions be accessed by huge Doppler shift (@ l_{UV} = 257nm)

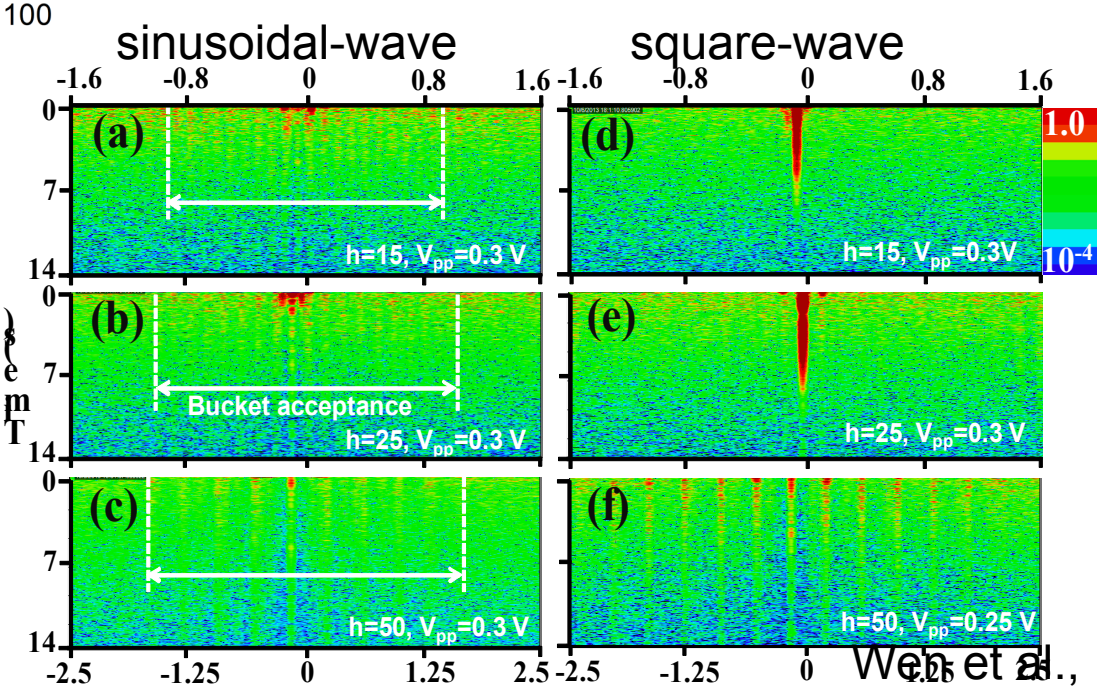
b) one laser for many ion species

c) Laser cooling force increases with beam energy

d) laser spectroscopy will be “free”

Florescence signals by CPM and PMT

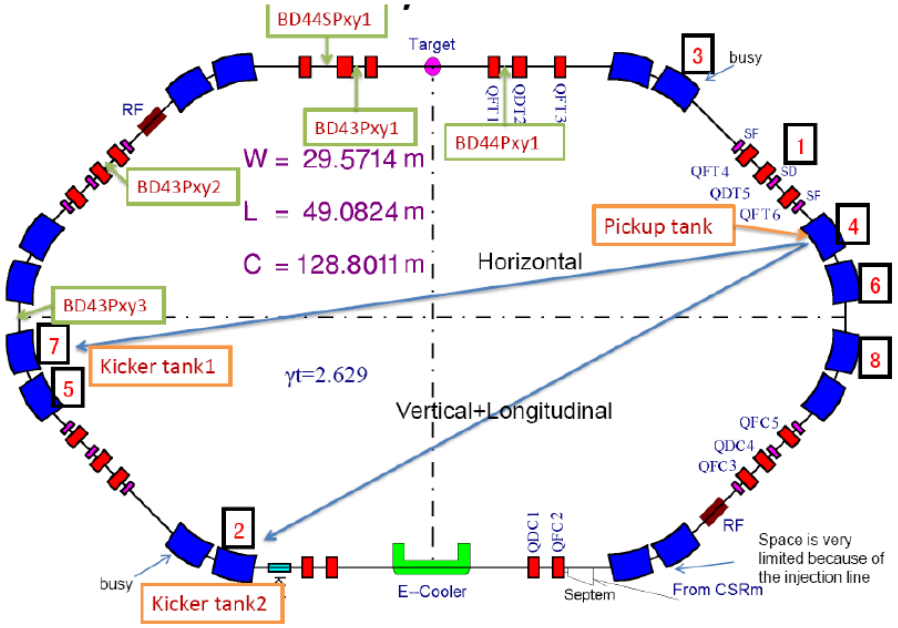


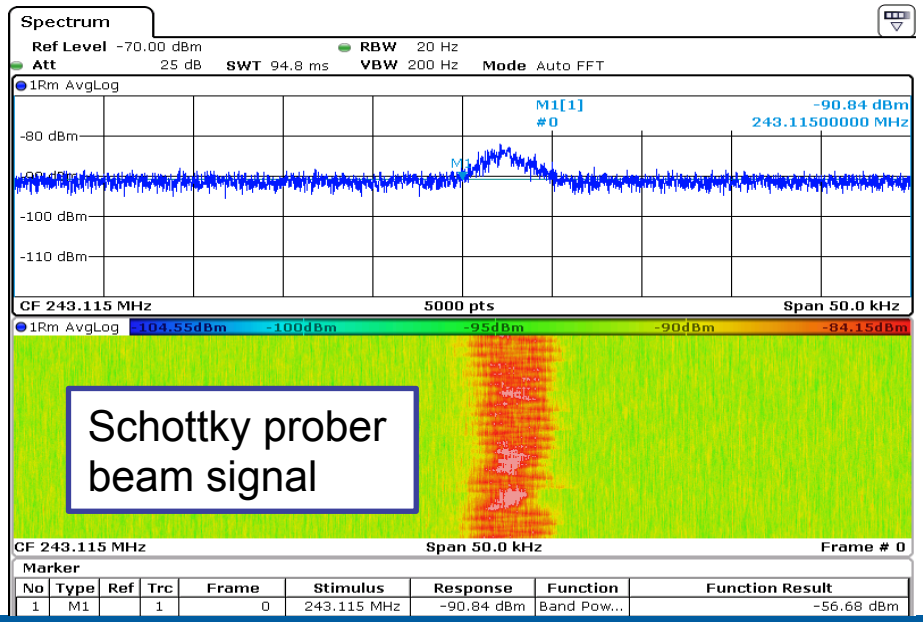


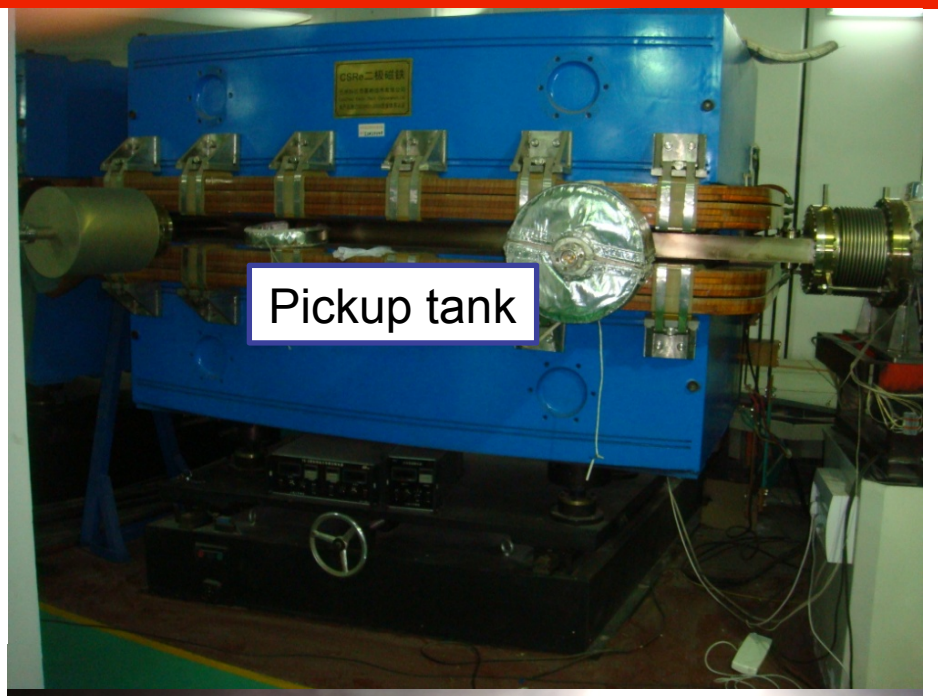
Web et al.,

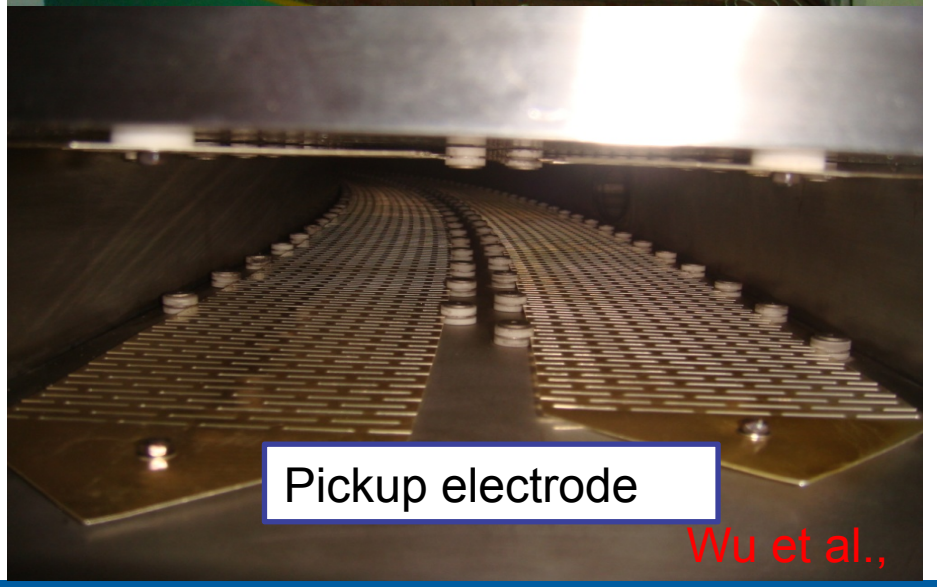
- Status of HIRFL
- *Activities of Upgrading*
  - SSC-Linac injector
  - Electron cooling at CSR
  - Laser cooling at CSRe
  - *Stochastic cooling at CSRe*
  - Isochronous mass spectrometry
  - Other upgrades for CSRe experiments …Upgrade CSRe for experiments
- HIAF project

Stochastic cooling:Overview









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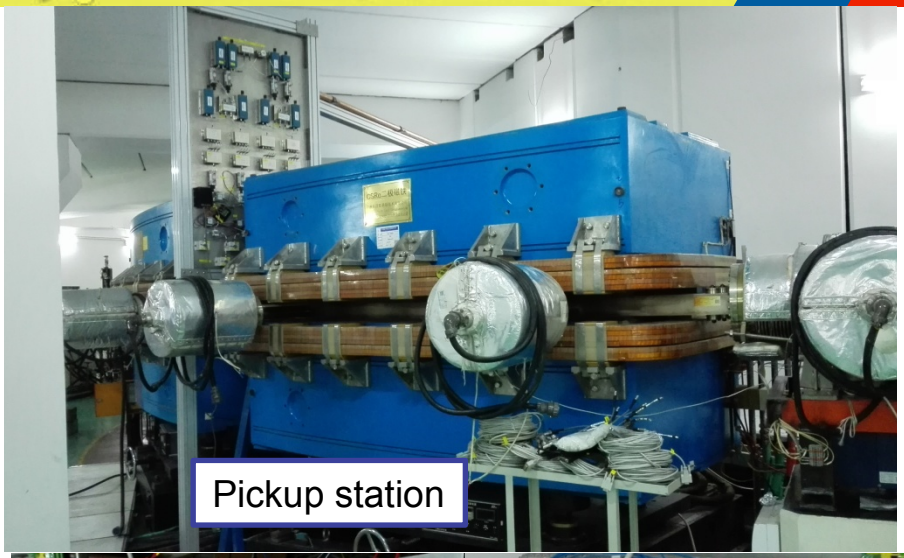
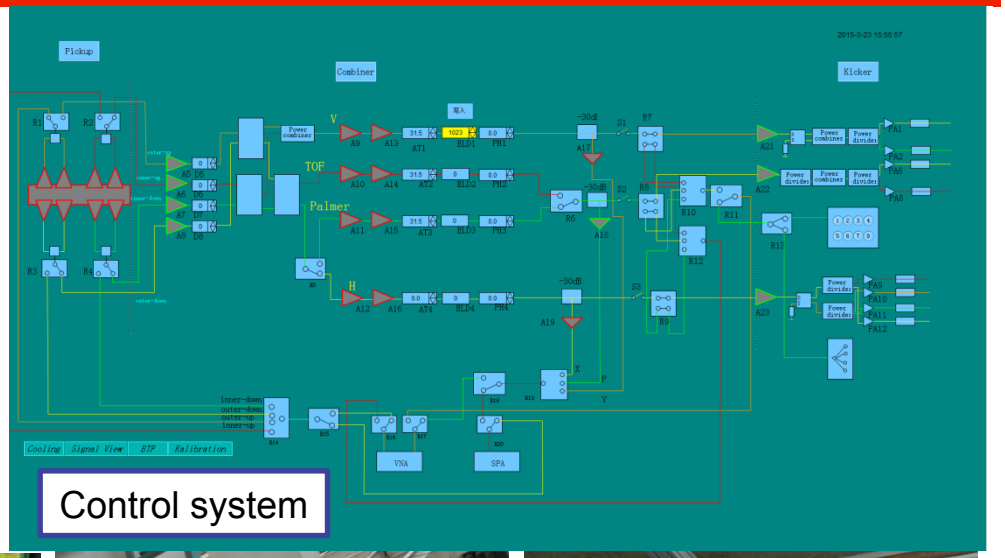
Institute of Modern Physics, Chinese Academy of Sciences

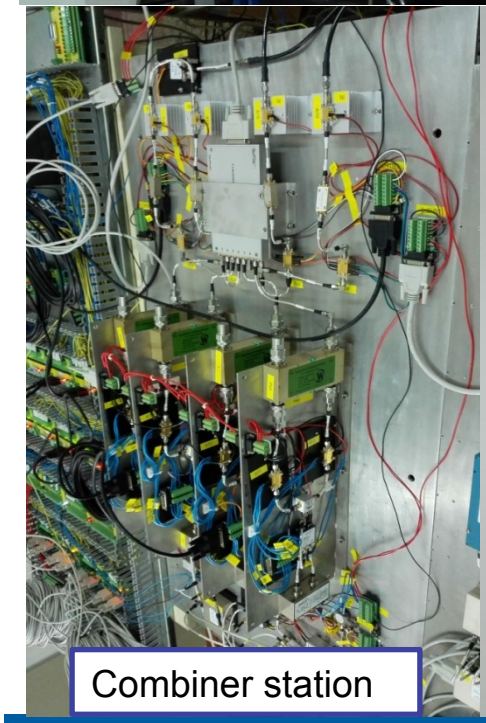
Experimental setup



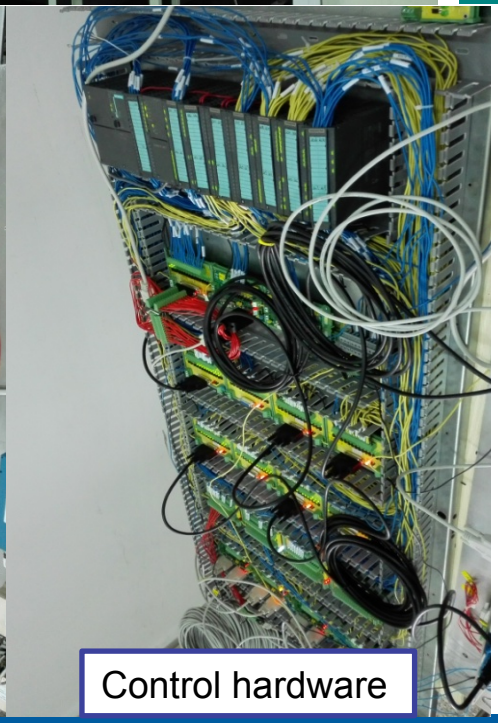
Pickup station



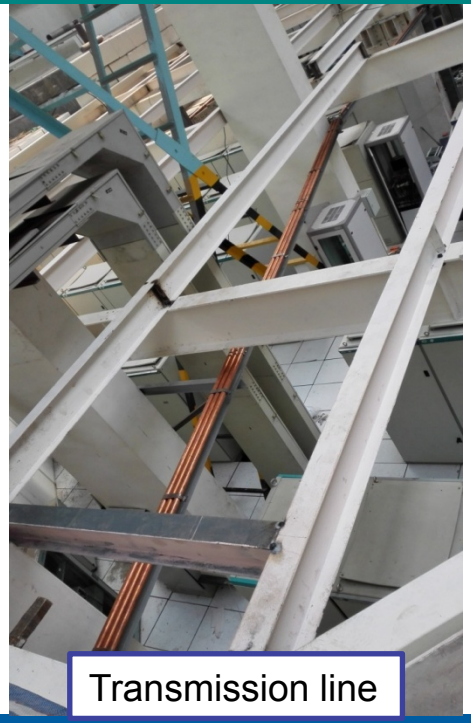
Control system



Combiner station



Control hardware



Transmission line

Wu et al.,

Power amplifier

- Status of HIRFL
- *Activities of Upgrading*
  - SSC-Linac injector
  - Electron cooling at CSR
  - Laser cooling at CSRe
  - Stochastic cooling at CSRe
  - *Isochronous mass spectrometry*
  - Upgrade CSRe for experiments
- HIAF project

Isochronous mass spectrometry

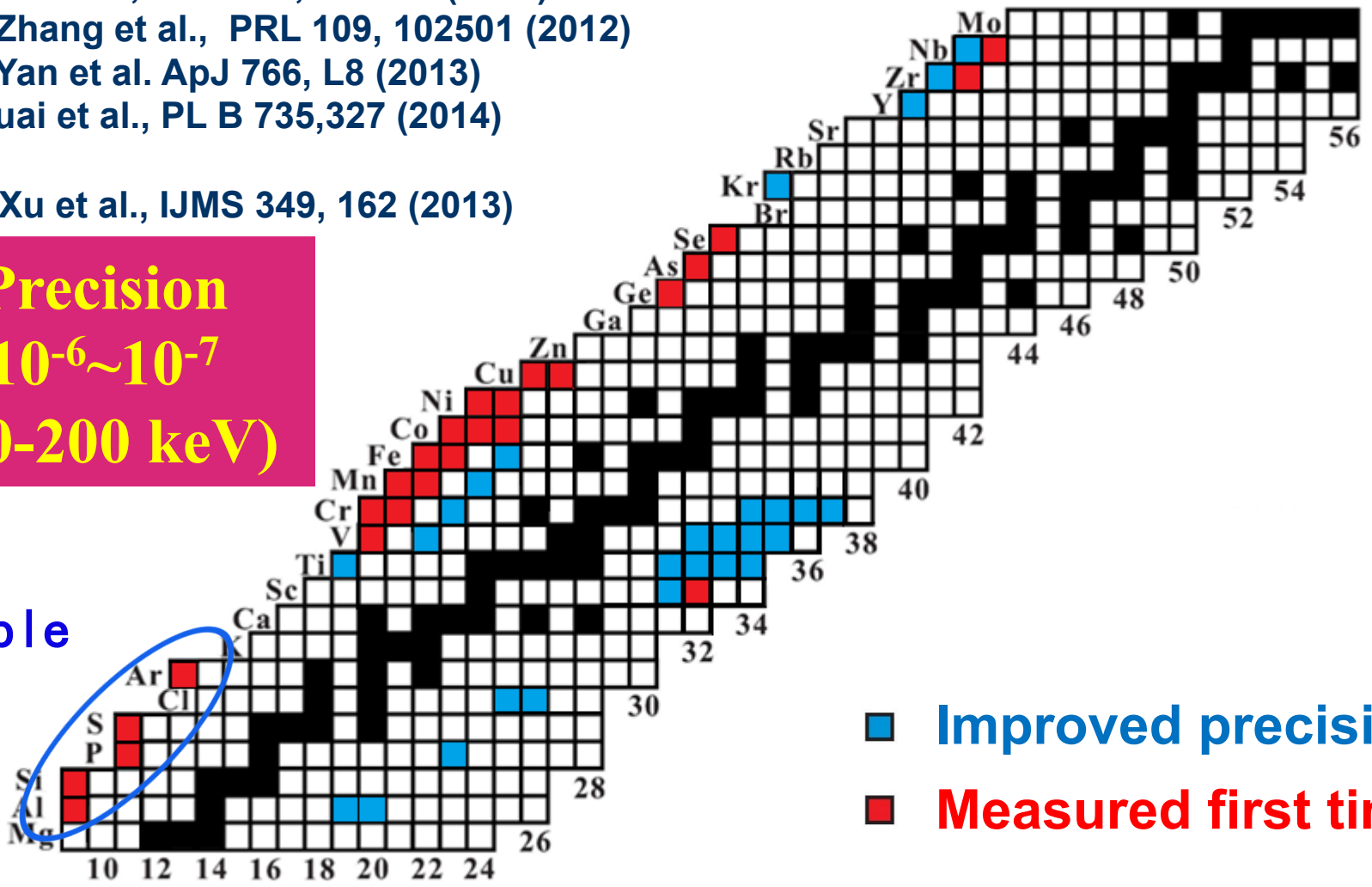
Beams: ^{78}Kr, ^{58}Ni, ^{86}Kr,^{112}Sn,^{58}Ni, ^{36}Ar

X. L. Tu et al., PRL 106, 112501 (2011)
Y. H. Zhang et al., PRL 109, 102501 (2012)
X. L. Yan et al. ApJ 766, L8 (2013)
P. Shuai et al., PL B 735,327 (2014)

H. S. Xu et al., IJMS 349, 162 (2013)

Precision
10^{-6}~10^{-7}
(20-200 keV)

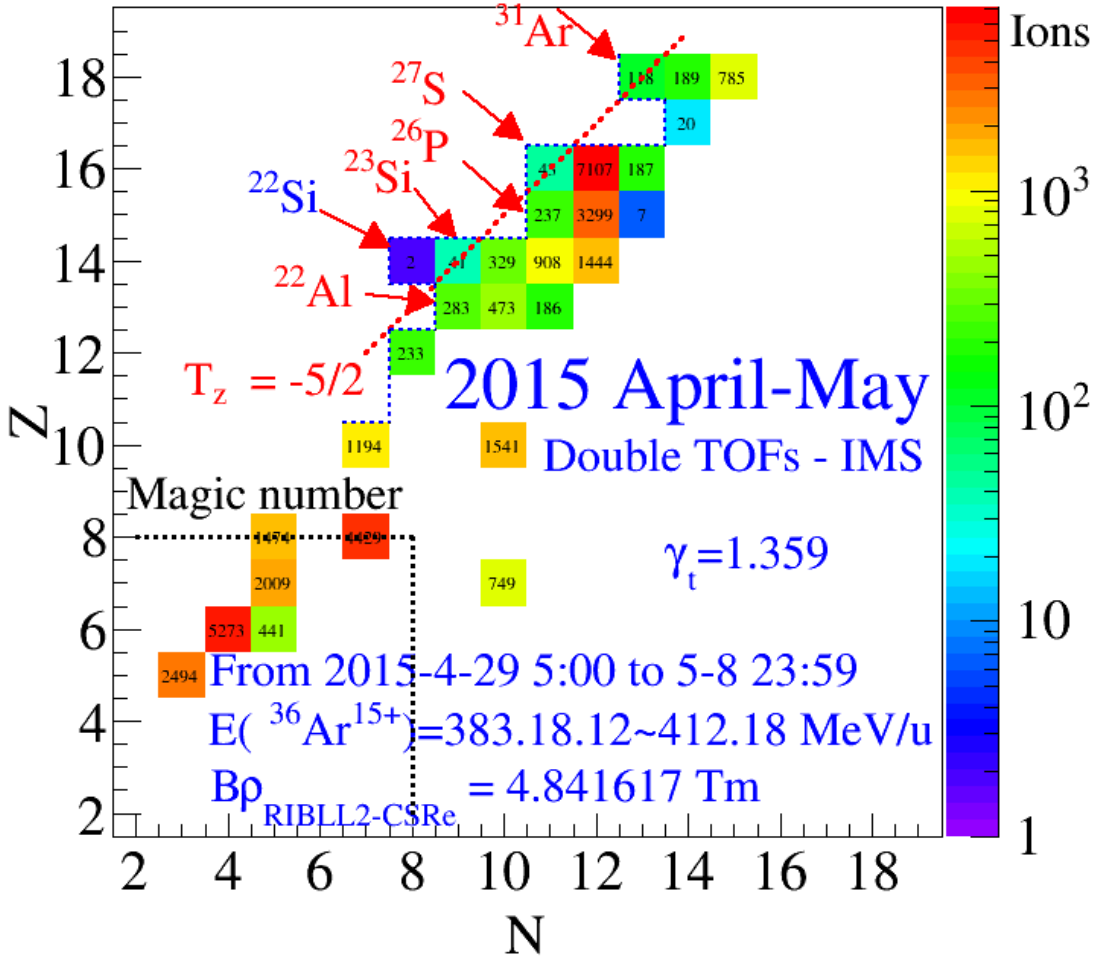
Double TOF



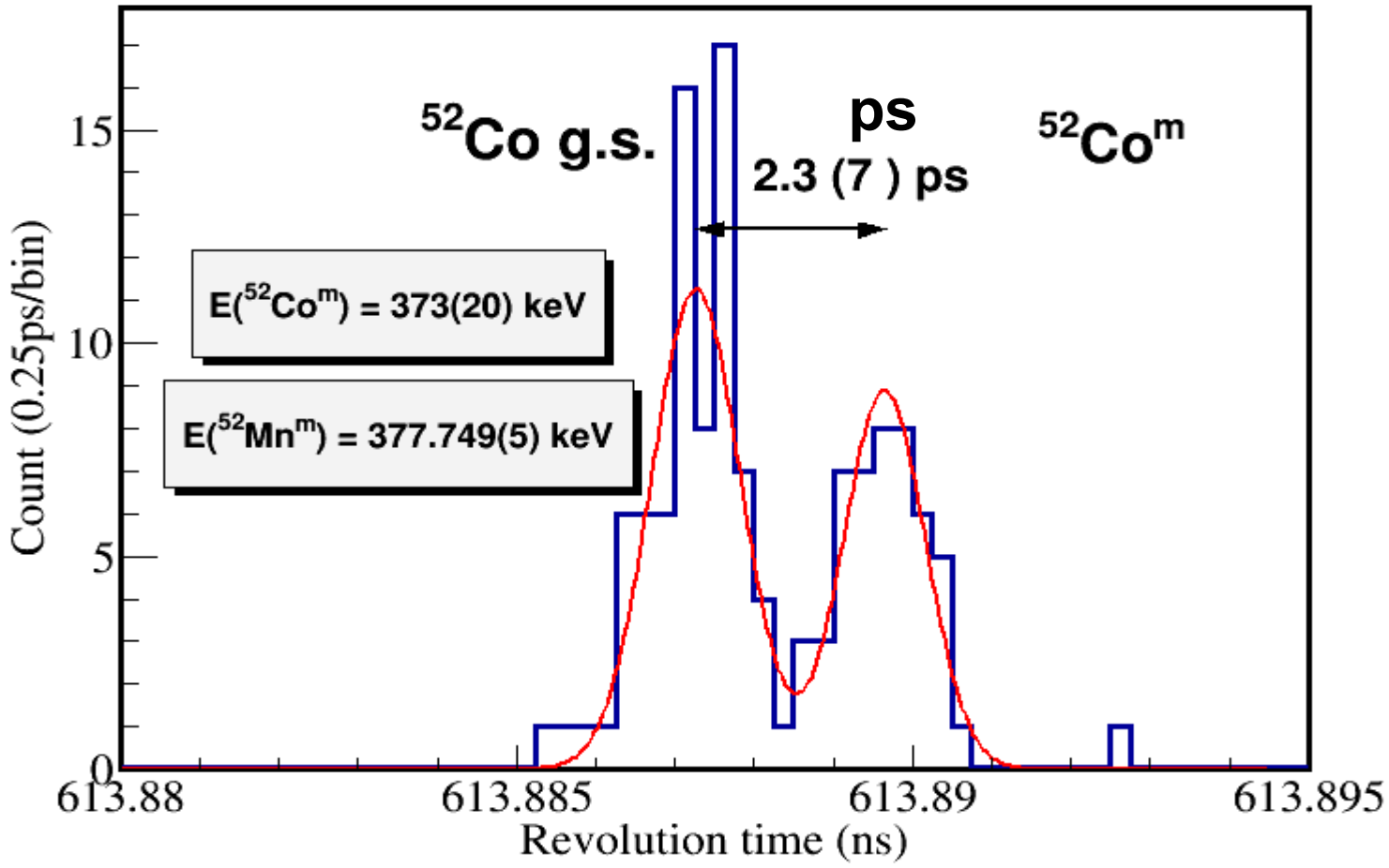
- Improved precision
- Measured first time

Recent results (double TOF)

Mass measurement of ^{26}P, ^{22}Al, ^{31}Ar, ^{27}S, ^{23}Si. First double ToF experiment.

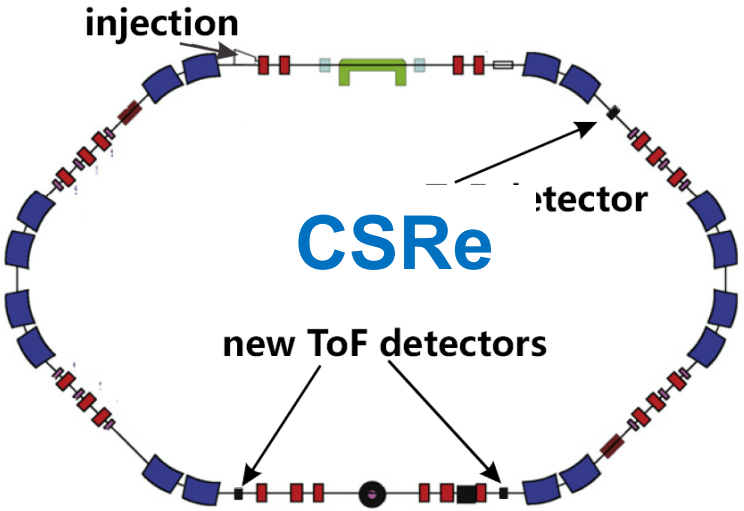


Highest resolving power of single ToF IMS

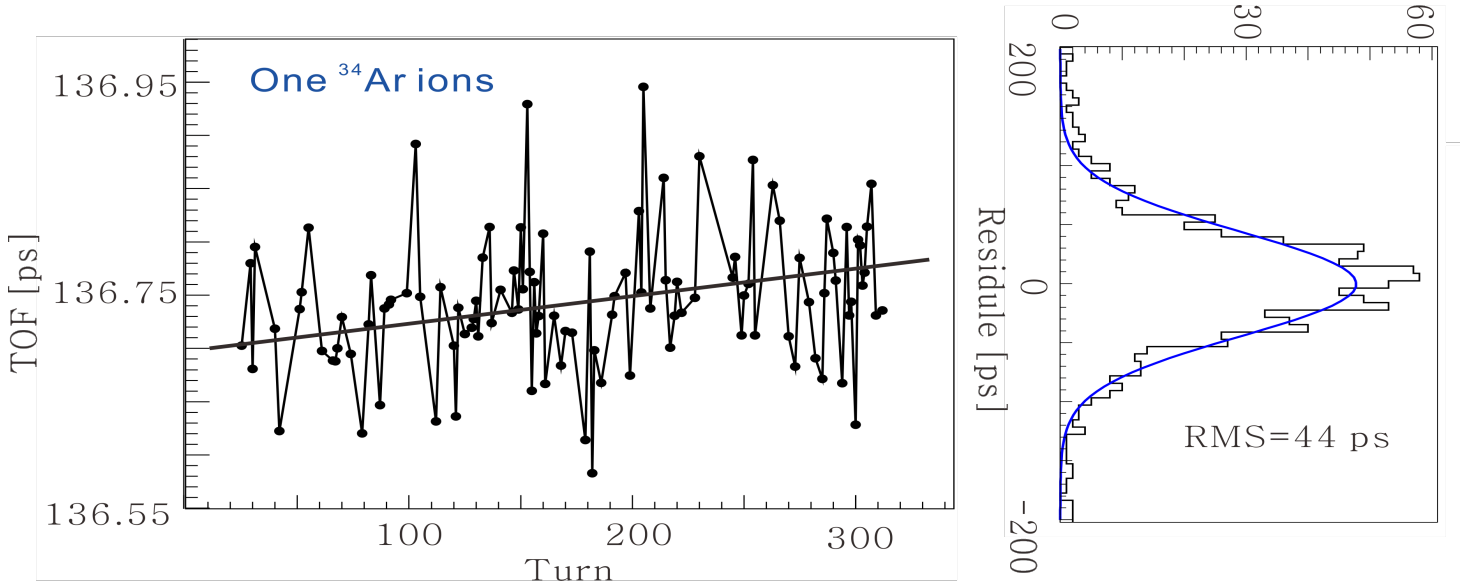


$$\frac{m}{\Delta m_{(FWHM)}} \approx 300{,}000$$

Best performance ToF detectors

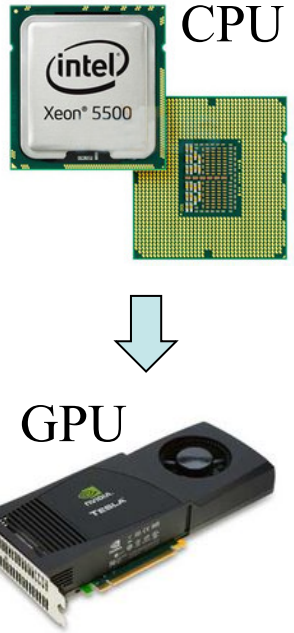


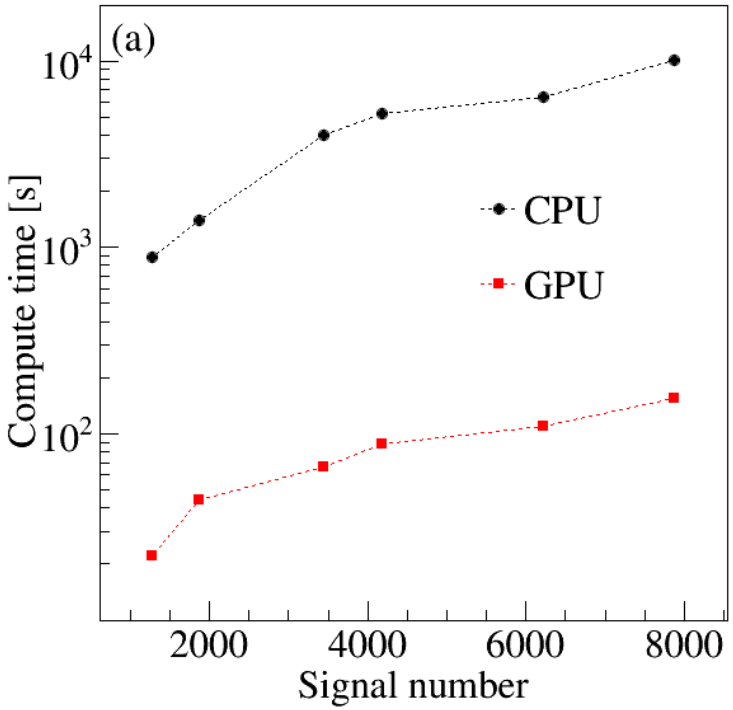
1. intrinsic resolution of TOF detector: **30 ps**
2. accuracy of velocity measurement: **10^{-4}**

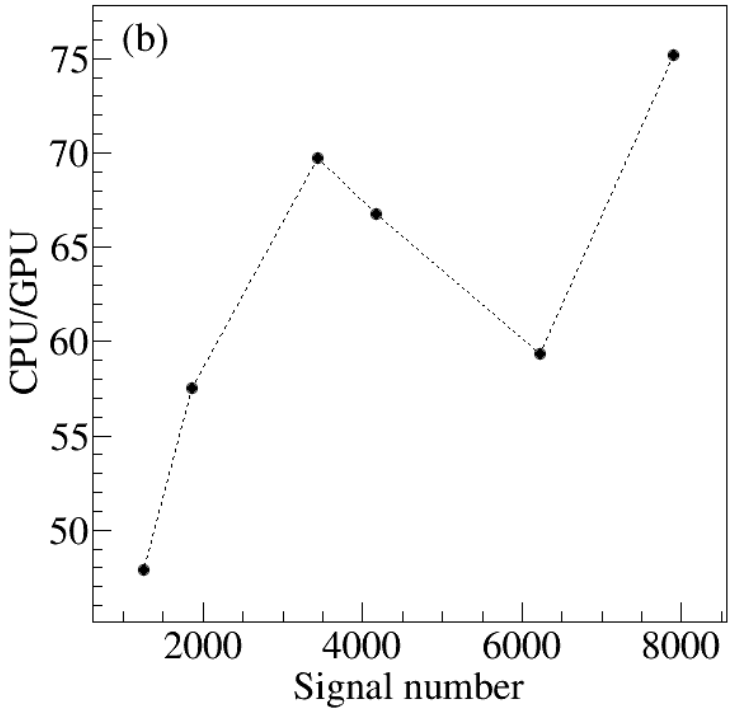


Realize real-time data analysis for each injection.

	1272 signals	1870 signals	3543 signals	4177 signals	6232 signals	7896 signals
CPU	862	1380	3972	5208	6406	10066
GPU	18	24	57	78	108	134

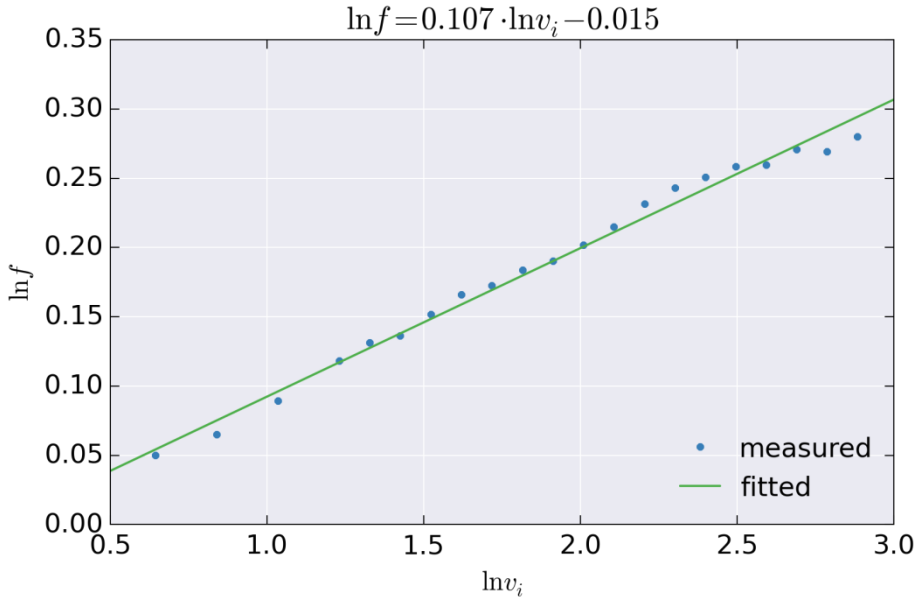


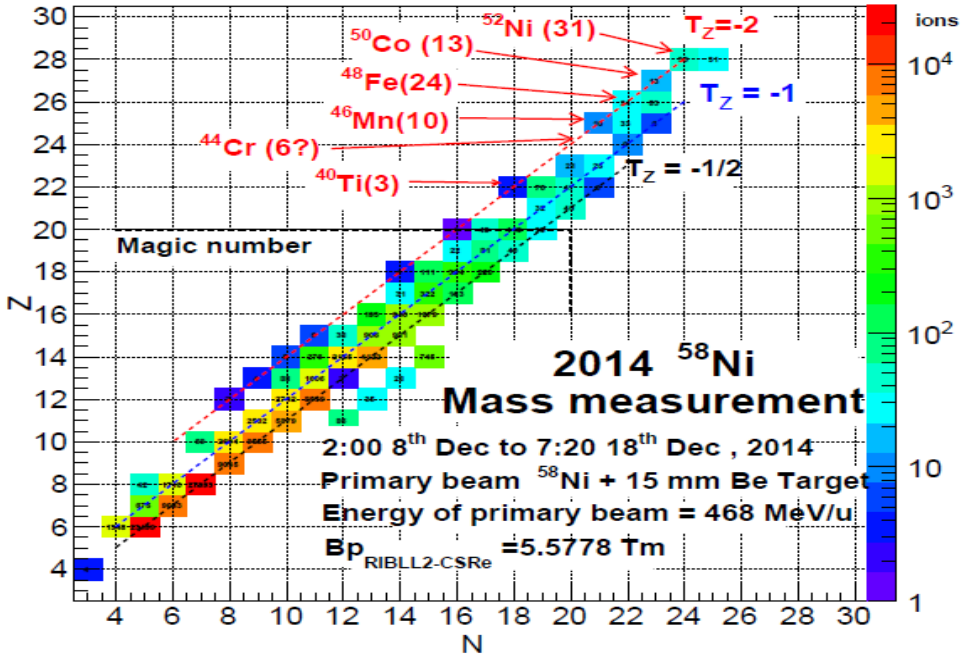




Transition energy and isochronicity measurement by e-cooler

Measured γ_t: 1.403, Setting: 1.400





- Status of HIRFL
- *Activities of Upgrading*
  - SSC-Linac injector
  - Electron cooling at CSR
  - Laser cooling at CSRe
  - Stochastic cooling at CSRe
  - Isochronous mass spectrometry
  - *Upgrade CSRe for experiments (a list)*
- HIAF project

Upgrade CSRe for experiments

- Modification/redesign of RF Cavity for Barrier Bucket accumulation
- Deceleration research for lower energy HCI exp.
- Double ToF IMS study
- E-cooler: fixed orbit inj. and cooling; new HV
- Upgrading of control, BD, PS systems
- Improvement of EMC environment (+BINP)
- Dynamic vacuum collimation study

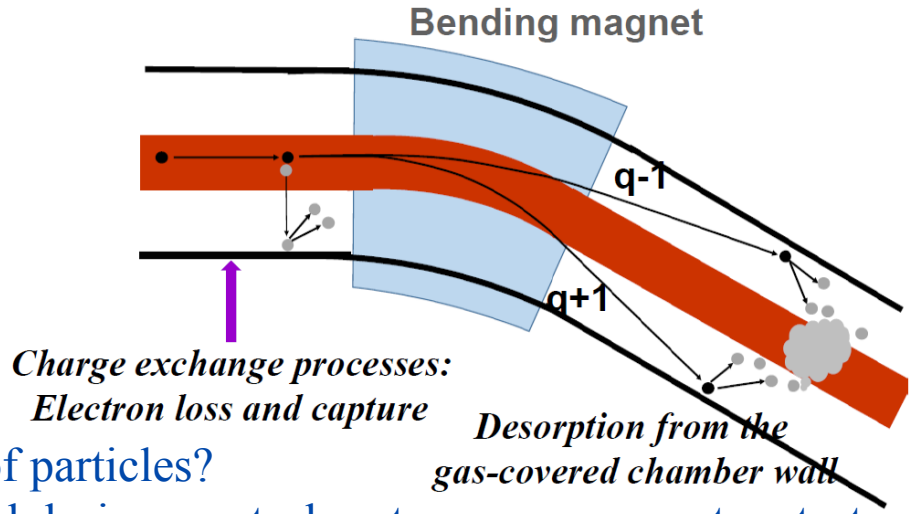
Collimation at CSRm

To maintain extra-low and stable vacuum pressure

Beam loss mechanism:

Charge exchange of intermediate charge state ions ($^{238}U^{34+}$) **due to collision**

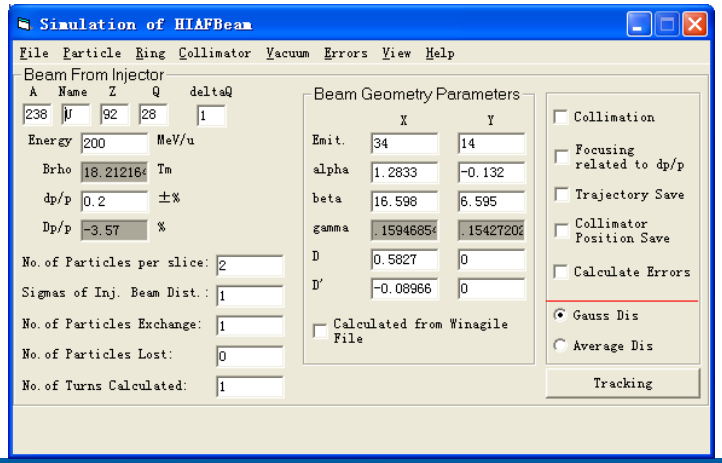
$$U^{34+} + X^{n+} \rightarrow U^{35+} + X \quad \text{Stripping}$$
$$U^{34+} + X^{n+} \rightarrow U^{33+} + X \quad \text{Capture}$$

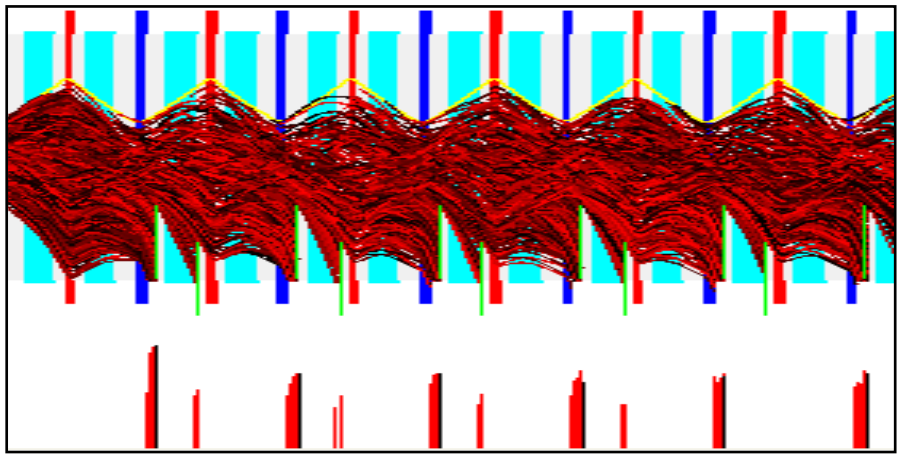


Challenges:

- How to get the high collimation efficiency?
- How to optimize lattices for different types of particles?
- How to design the collimator? the mechanical design, control system, vacuum system test.

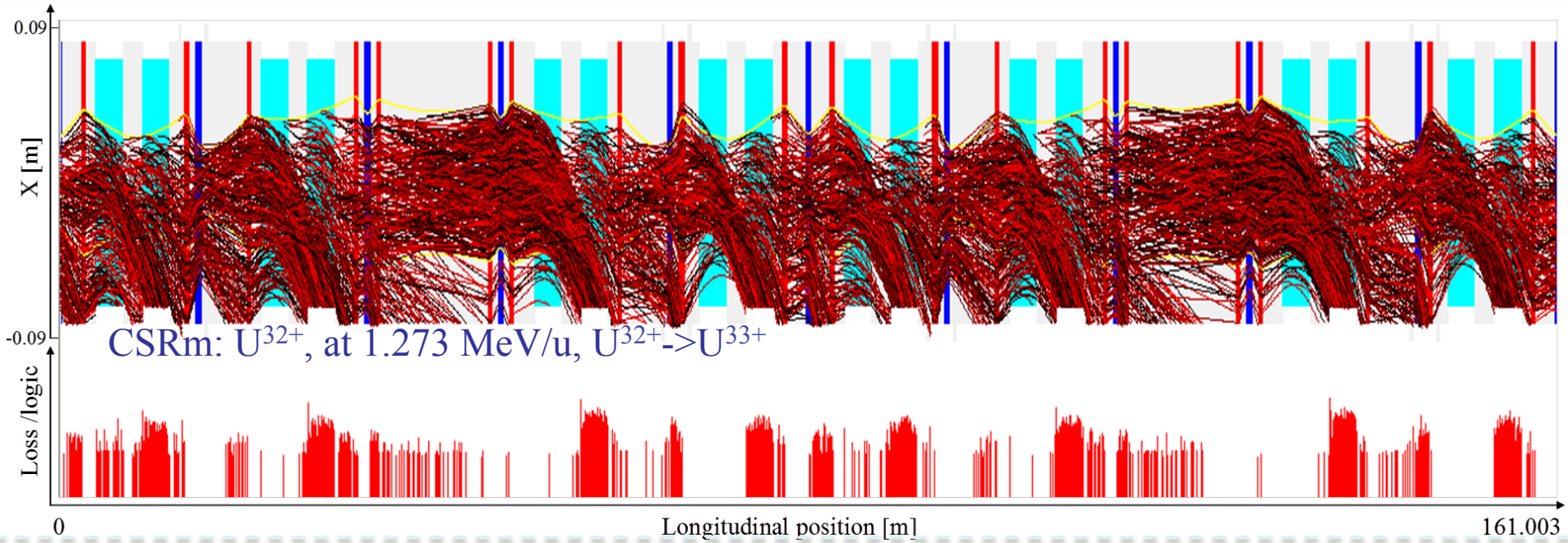
A dedicated dynamic vacuum simulation code HIAF-DYSD has been developed for the optimization of dynamics design.



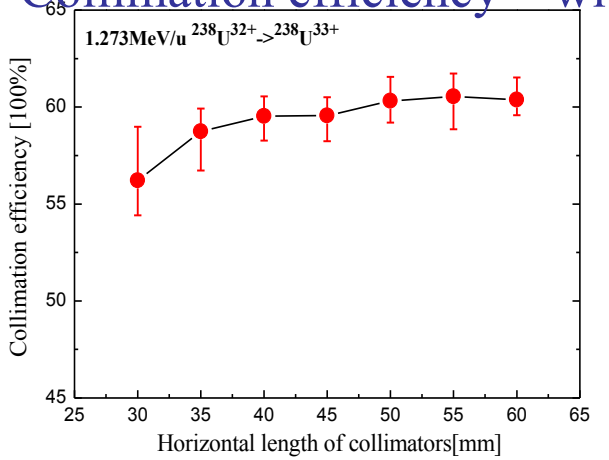


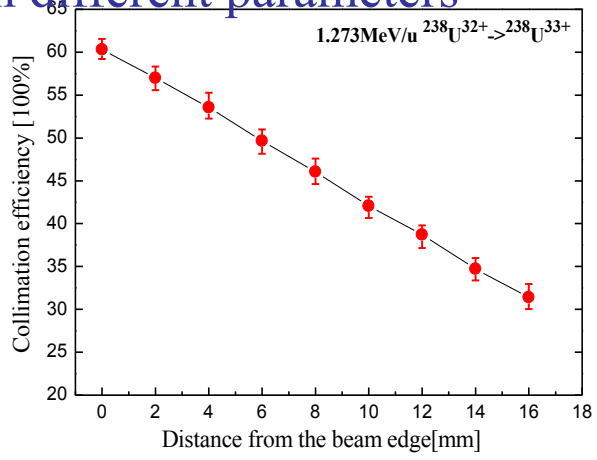
Collimation at CSRm

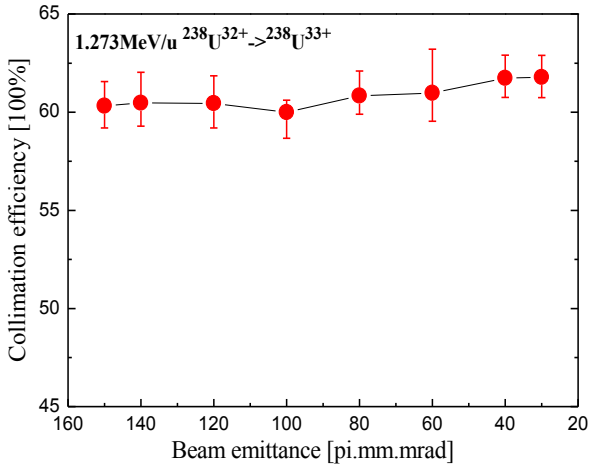
Study of collimation efficiency with different parameters



Collimation efficiency – with different parameters







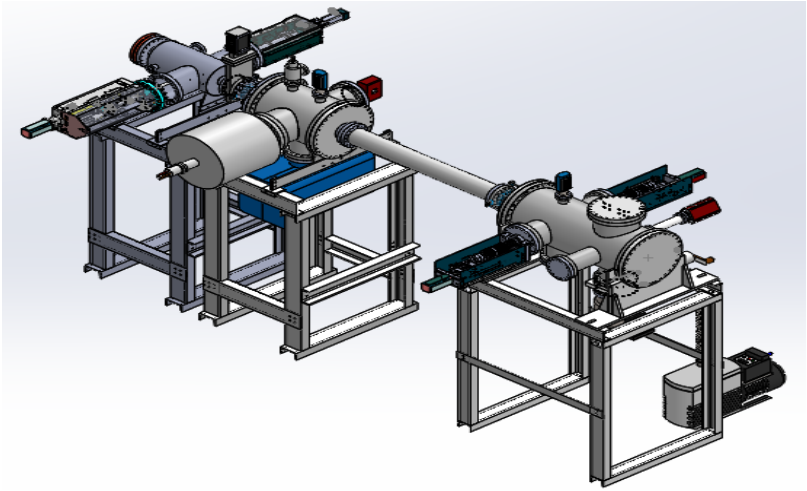
Collimation at CSRm

Preparation of desorption and collimation study experiments

First step - Test platform

Desorption measurement

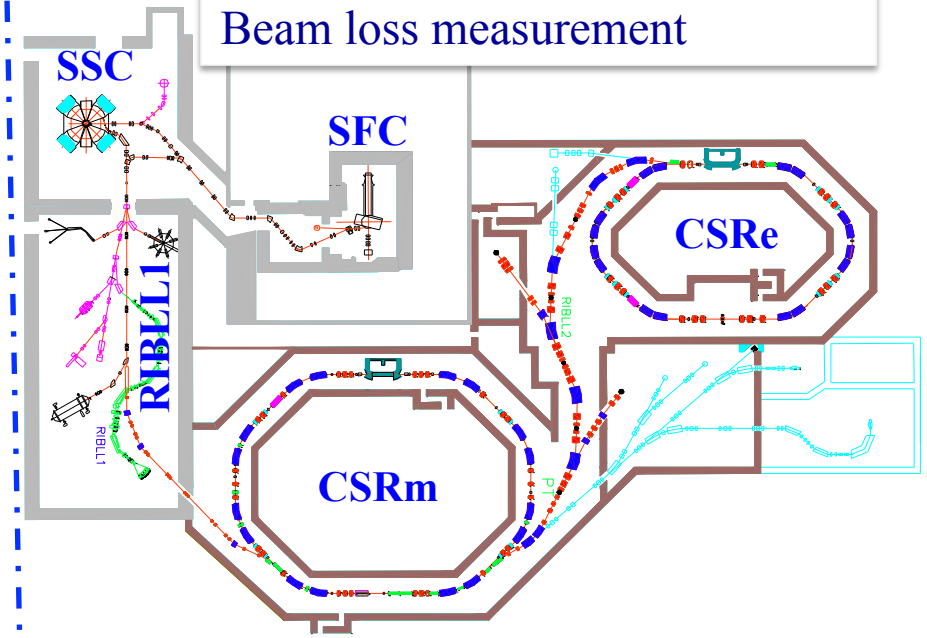
Install at PISA or E-point



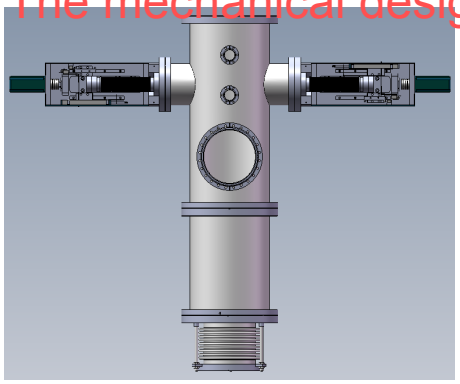
Second step –

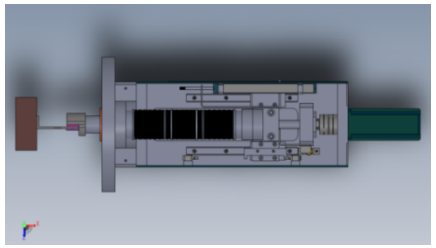
Collimator prototype of CSRm

Beam loss measurement

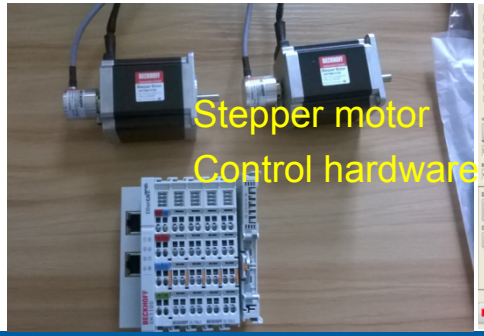


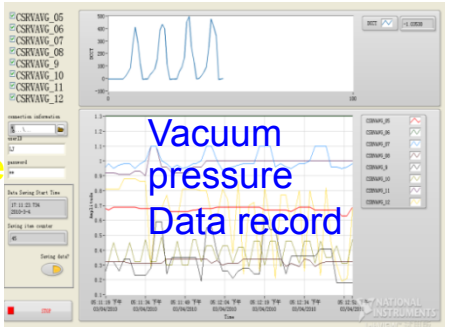
The mechanical design has been finished





Fabrication of hardware components





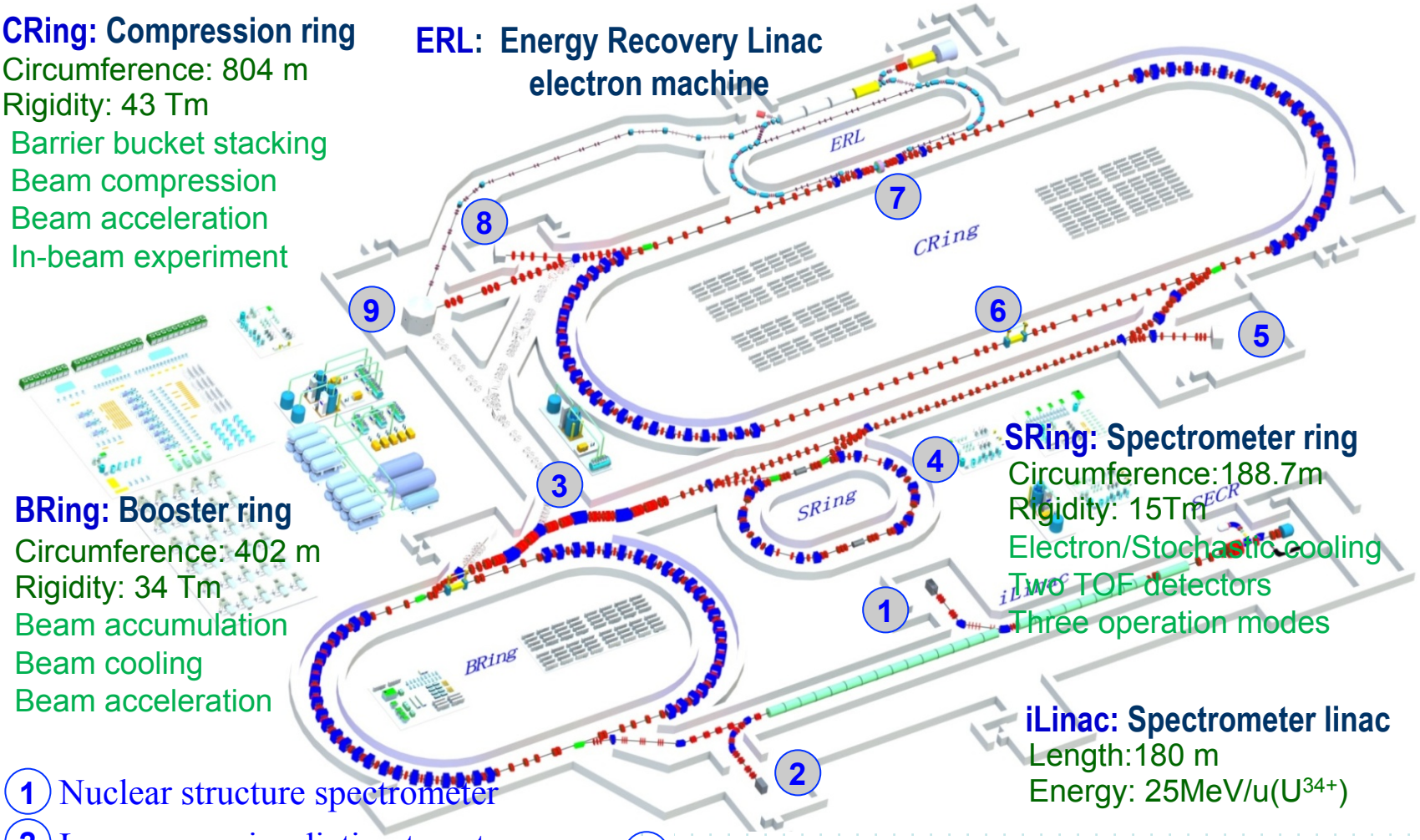
- Status of HIRFL
- Activities of Upgrading
  - SSC-Linac injector
  - Electron cooling at CSR
  - Laser cooling at CSRe
  - Stochastic cooling at CSRe
  - Isochronous mass spectrometry
  - Upgrade CSRe for experiments
- *HIAF project*

中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

Layout of HIAF

CRing: Compression ring
Circumference: 804 m
Rigidity: 43 Tm
Barrier bucket stacking
Beam compression
Beam acceleration
In-beam experiment

ERL: Energy Recovery Linac electron machine



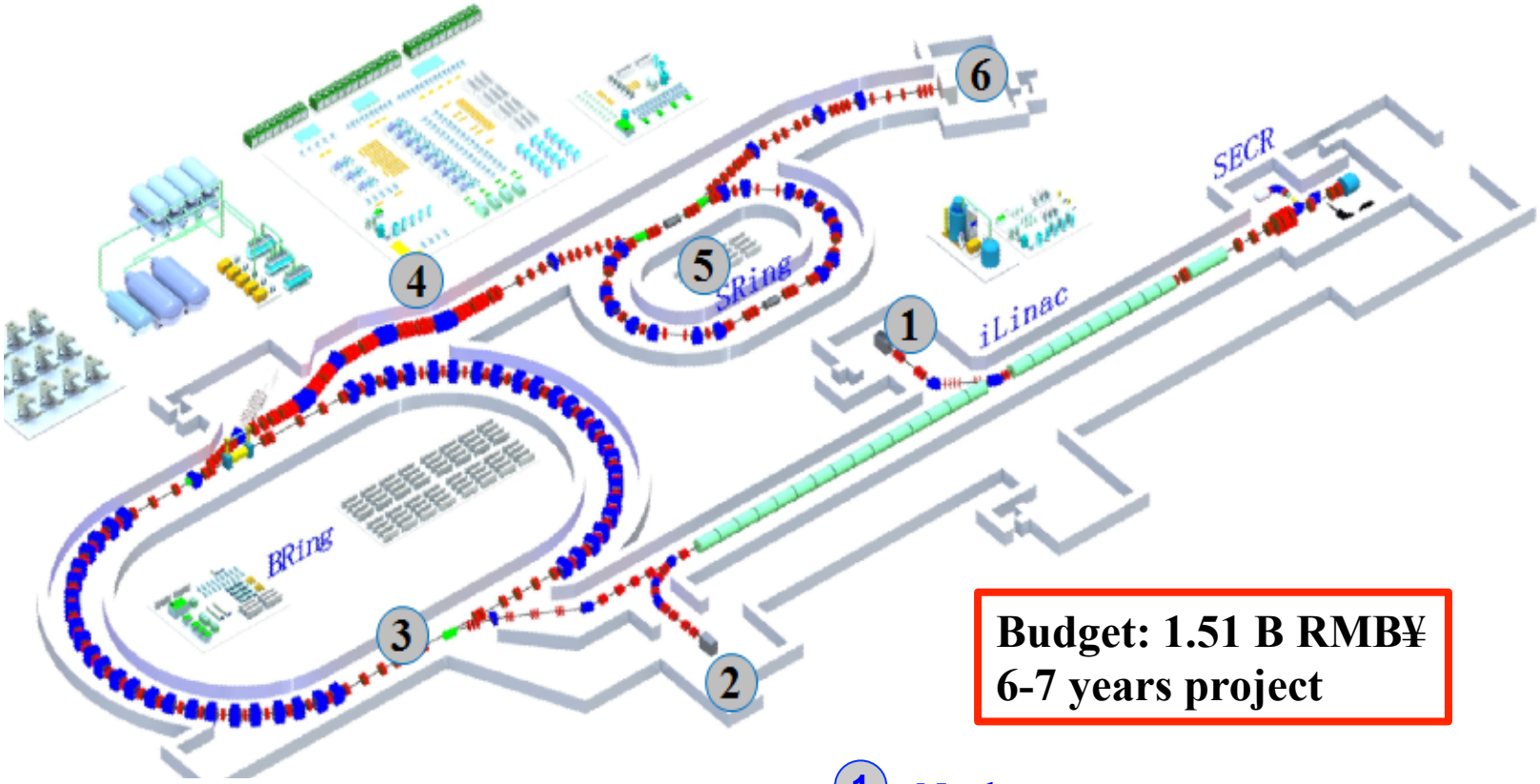
BRing: Booster ring
Circumference: 402 m
Rigidity: 34 Tm
Beam accumulation
Beam cooling
Beam acceleration

SRing: Spectrometer ring
Circumference:188.7m
Rigidity: 15Tm
Electron/Stochastic cooling
Two TOF detectors
Three operation modes

iLinac: Spectrometer linac
Length:180 m
Energy: 25MeV/u(U^{34+})

1. Nuclear structure spectrometer
2. Low energy irradiation target
3. RIBs beam line
4. High precision spectrometer ring
5. External target station
6. Electron-ion recombination spectroscopy
7. Electron-Nucleus Collision (ENC)
8. High Energy Density Physics target
9. High energy irradiation target

First phase of HIAF

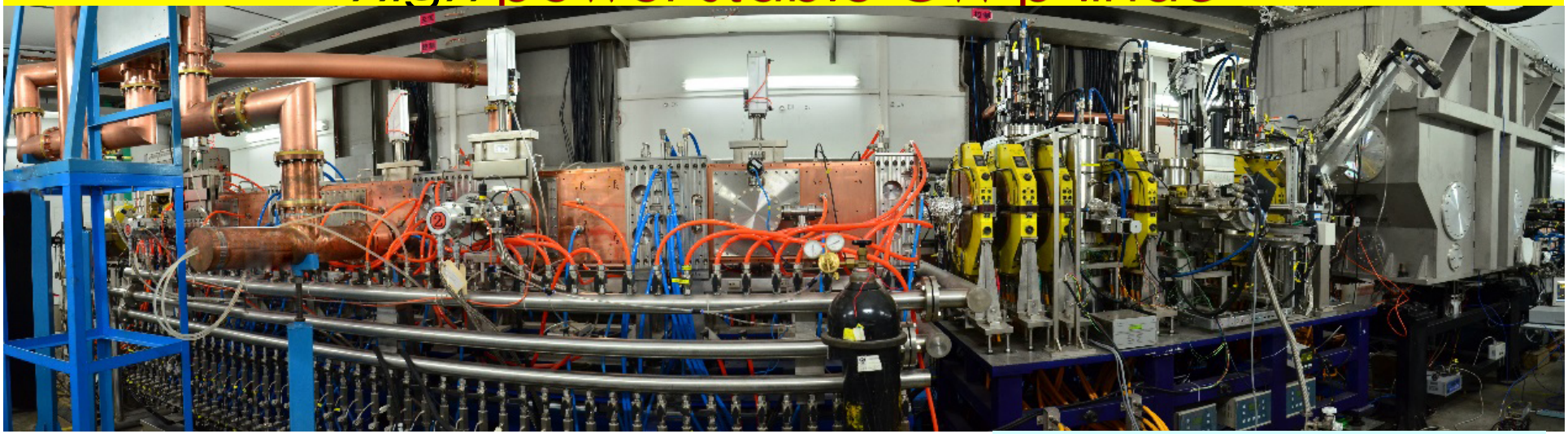


Budget: 1.51 B RMB¥
6-7 years project

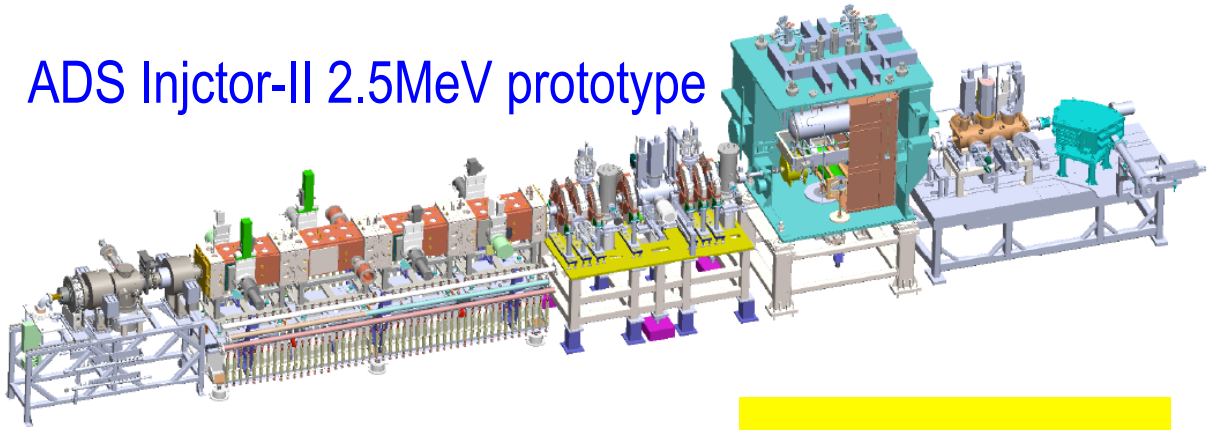
	Ions	Energy	Intensity
SECR	U^{34+}	14 keV/u	0.05 pmA
iLinac	U^{34+}	17 MeV/u	0.028 pmA
BRing	U^{34+}	0.8 GeV/u	~1.4×10^{11} ppp

1. Nuclear structure spectrometer
2. Low energy irradiation target
3. Electron-ion recombination spectroscopy
4. RIBs beam line
5. High precision spectrometer ring
6. External target station

ADS Injector-II
High power stable CW p-linac



ADS Injctor-II 2.5MeV prototype



Feb 2015 RFQ+TCM:
2.55MeV/11mA, CW, 1hr

~200 hrs, CW～12hrs

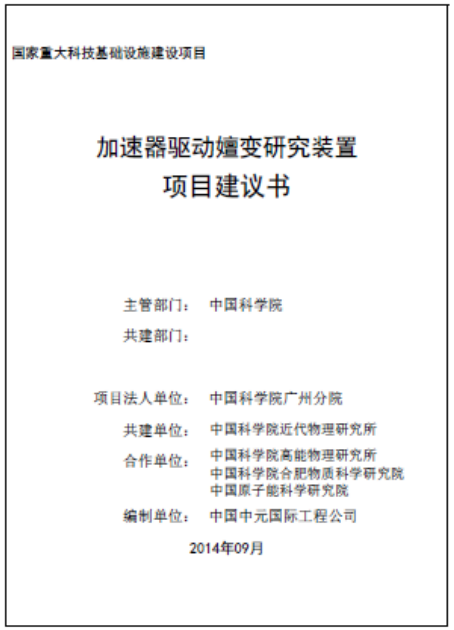
CW 28kW

Physics Design and proprosal

Be proved soon, 1.8 B RMB

Goal: Beam Power 250MeV@10mA, Heat Power: 10MW

Tech. Solution: SRF p-linac+ pellet fluid target + LBE reactor



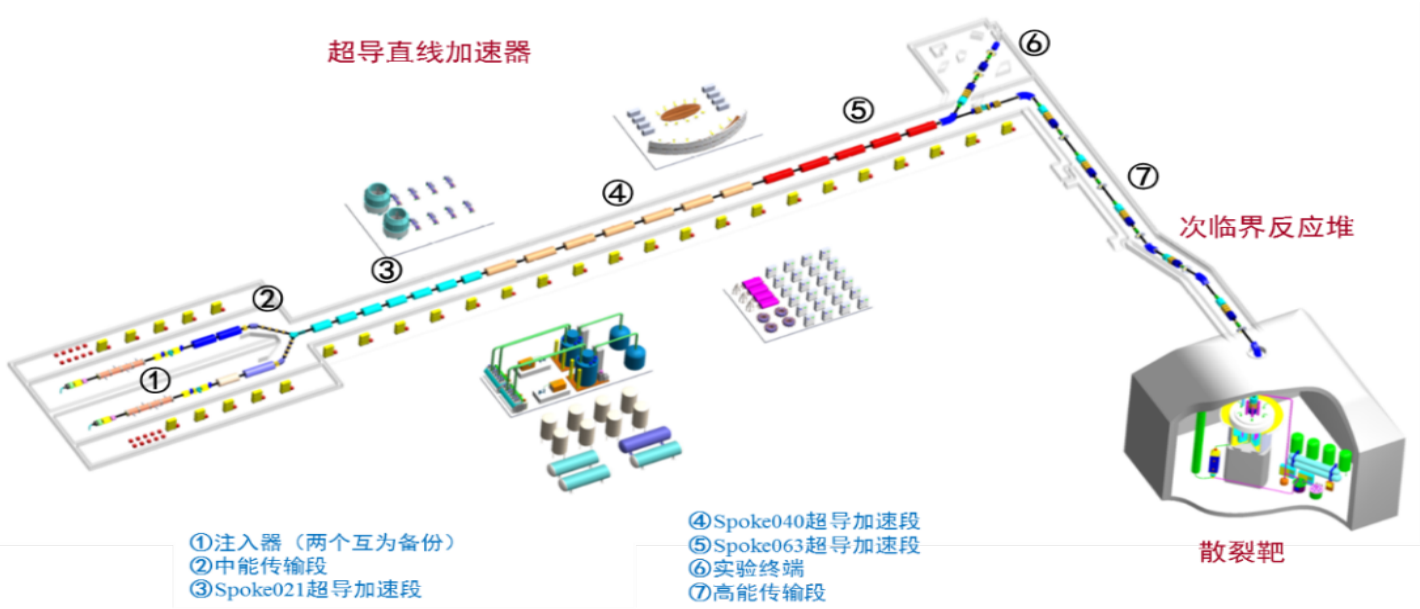
国家重大科技基础设施建设项目

加速器驱动嬗变研究装置
项目建议书

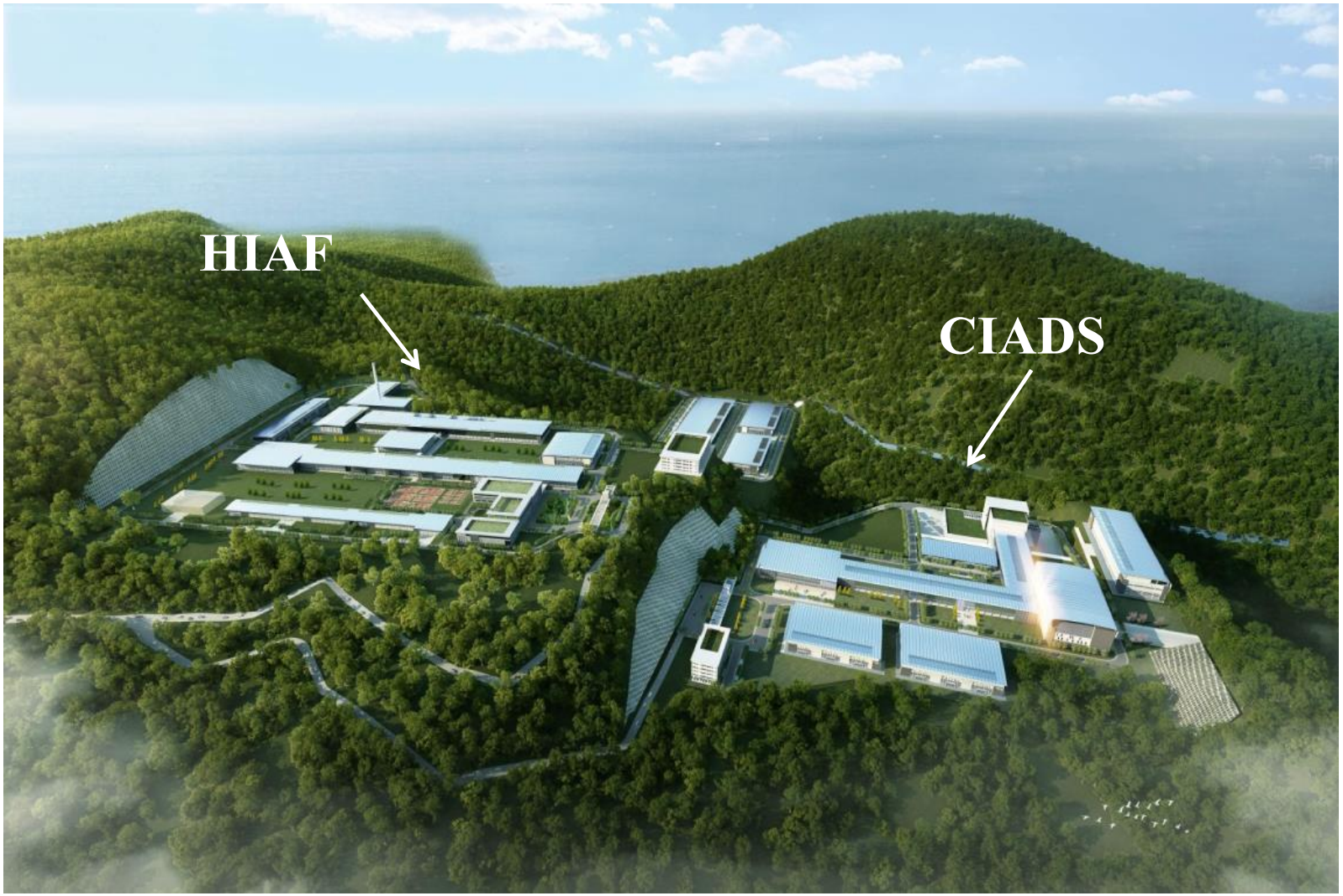
主管部门： 中国科学院
共建部门：

项目法人单位： 中国科学院广州分院
共建单位： 中国科学院近代物理研究所
合作单位： 中国科学院高能物理研究所
中国科学院合肥物质科学研究院
中国原子能科学研究院
编制单位： 中国中元国际工程公司

2014年09月

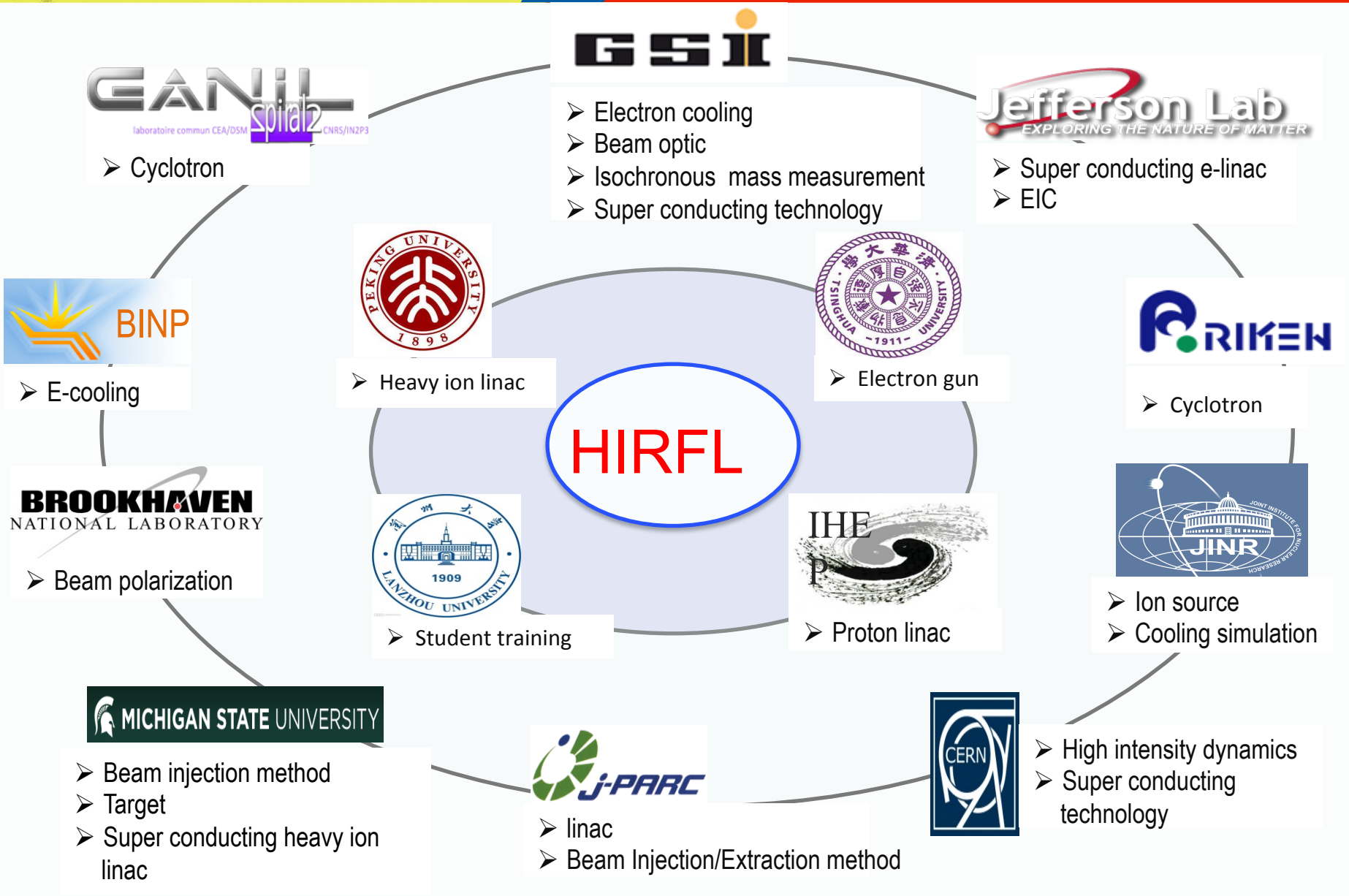


HIAF and CIADS projects



Huizhou, Guangdong

Collaborations



Thanks for your attention!