Operation Status and Upgrading of Cyclotrons in Lanzhou

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The 22nd CYC2019, Sep. 27, 2019　　Cape Town, South Africa

CONTENT

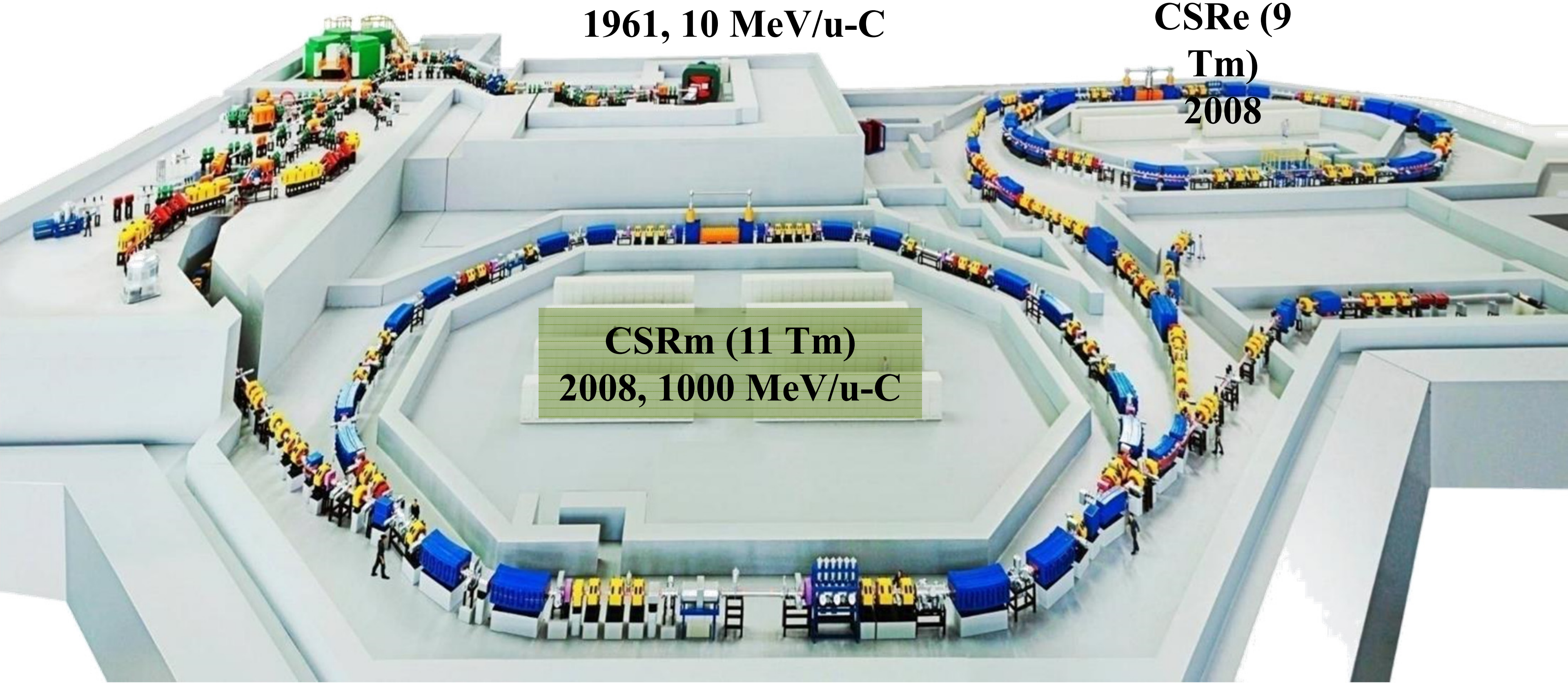
CONTENT

- **Heavy Ion Research Facility in Lanzhou (HIRFL)**
- Overview of HIRFL Operation
- Operation status of the cyclotrons
  - SFC operation status
  - SFC+SSC operation status
- HIRFL Improvement and Upgrade
- Introduction of HIAF and CiADS

Overview of HIRFL

Heavy Ion Research Facility in Lanzhou (HIRFL)

The largest ion-accelerator complex in China



SSC (K=450)
1988, 100 MeV/u-C

SFC (K=69)
1961, 10 MeV/u-C

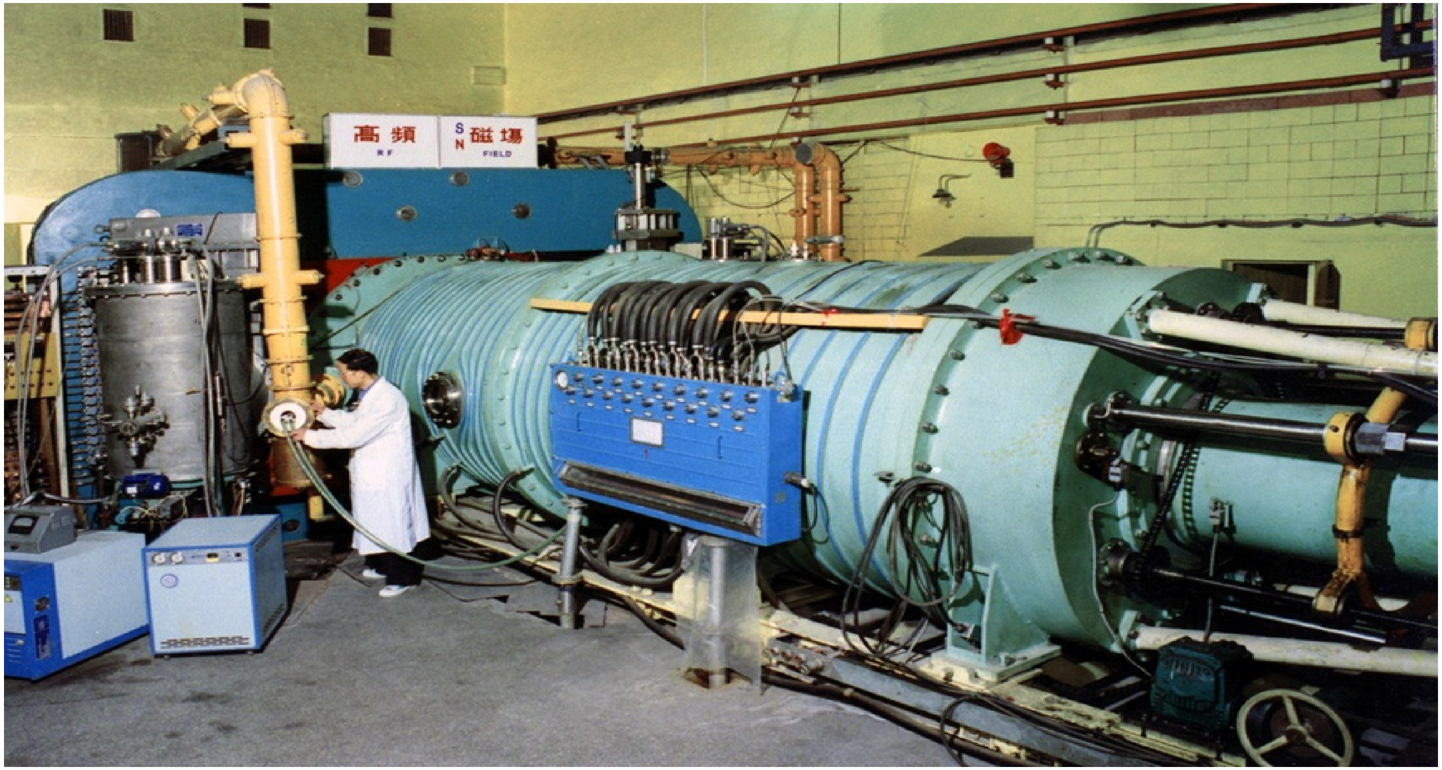
CSRe (9 Tm)
2008

CSRm (11 Tm)
2008, 1000 MeV/u-C

SFC

- Built in 1961: H & He
- Upgraded in 1970s: C~U

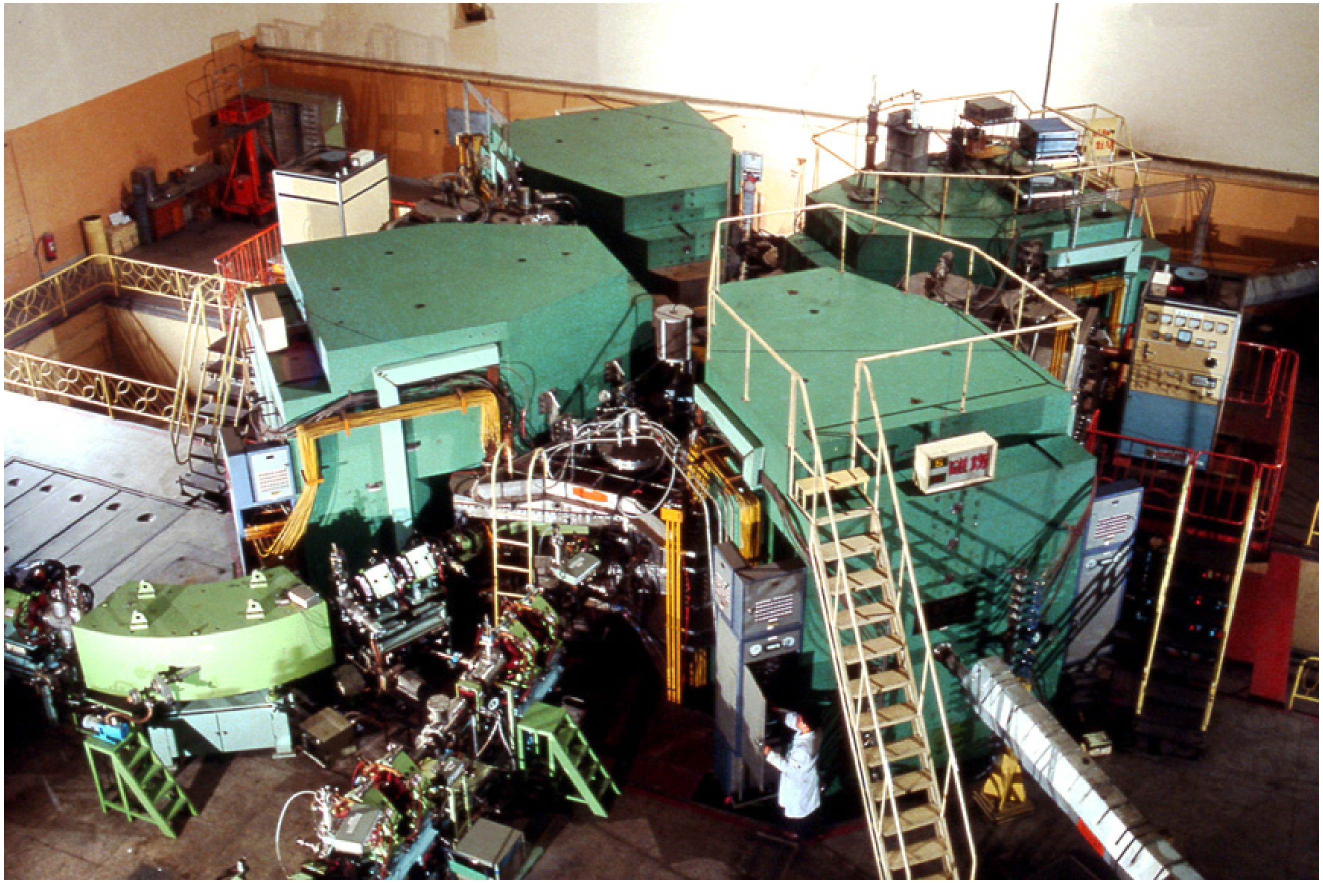
K=69, R ~0.75 m, E ~10 MeV (C), 1 MeV/u (U)



The main cyclotron SSC

Built in 1988:

K=450, R ~3.203 m, He~U, E : 100 MeV/u (C), 10 MeV/u (U)



Synchrotron and Storage Rings CSR

Built in 2008:

CSRm 161.0 m, Bρ_{max}=11.3 Tm

CSRe 128.8 m, Bρ_{max}=9.0 Tm

Beam List with HIRFL

	SFC		SSC		CSR			
					Fast Extraction		Slow Extraction	
Ion species	Energy (MeV/u)	Beam intensity (eμA)	Energy (MeV/u)	Beam intensity (eμA)	Energy (MeV/u)	Beam intensity (ppp)	Energy (MeV/u)	Beam intensity (pps)
H_2^+—Ar	10—1.5	15—1	100—18	2.0—0.1	50—1000	10^7—10^9	600—100	$<10^8$
Ar—Xe	7.0—2.0	7—3	80—20	4.0—0.1	700—230	10^7—10^8	700—230	$<10^7$
Xe—U	3.0—0.9	5—0.5	10—5.0	0.5—0.1	230—100	10^6—10^8	230—100	$<10^7$

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HIRFL operation status 2014-2018

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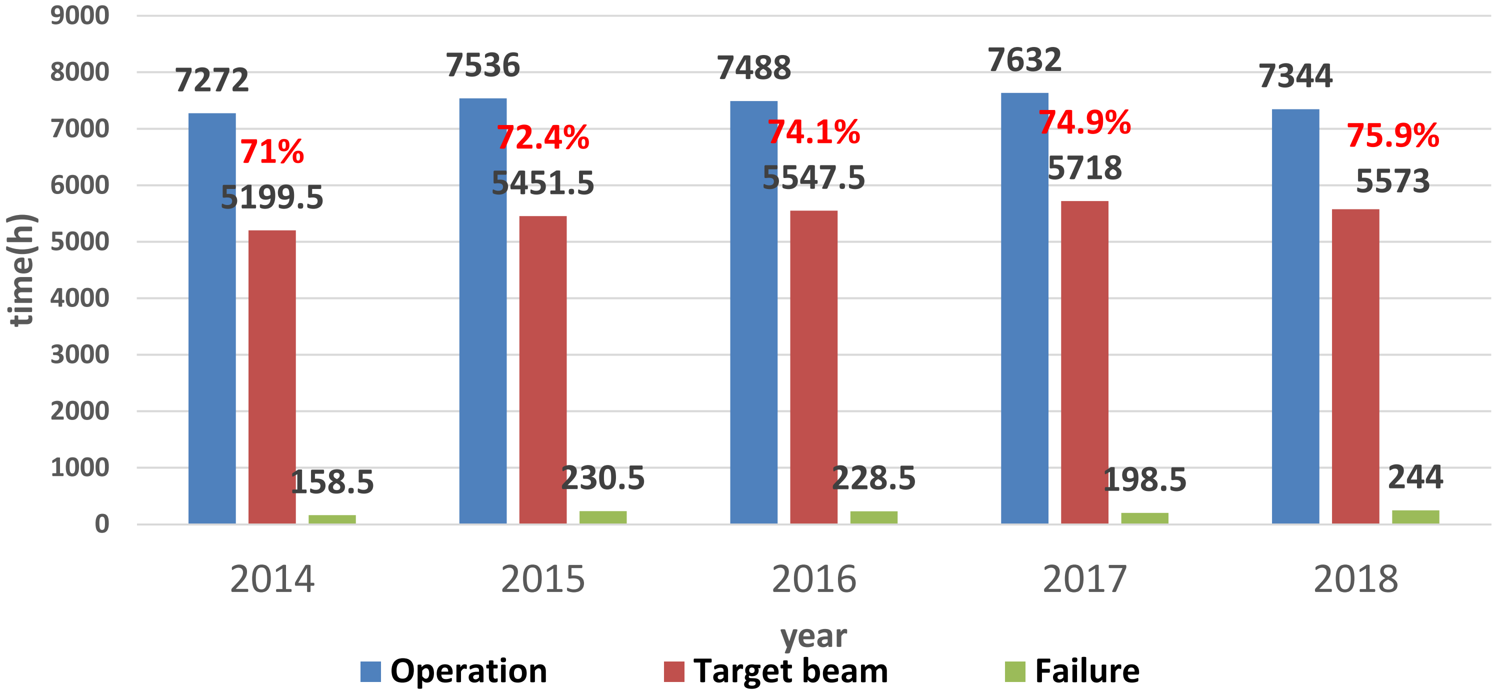

Operation time distribution：

- ◆ Preparation of machine
- ◆ Beam Commissioning
- ◆ Failure during beam on target
- ◆ Beam on target

Cascade Operation Mode:

- ◆ SFC
- ◆ SFC+SSC
- ◆ SFC+CSRm
- ◆ SFC+CSRm+CSRe

Beams accelerated by Cyclotron

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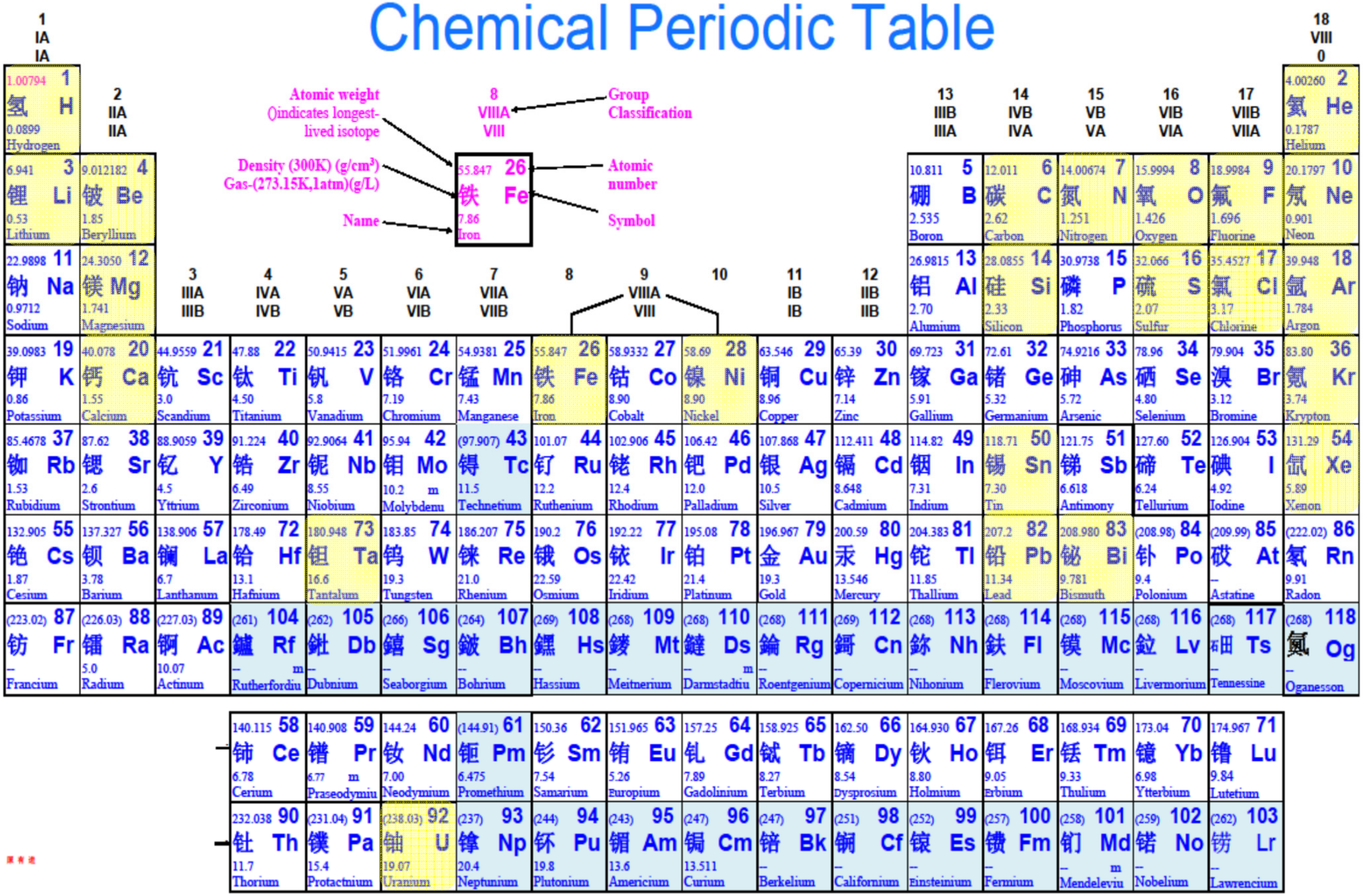

Chemical Periodic Table

Atomic weight ()indicates longest-lived isotope

Density (300K) (g/cm³) Gas-(273.15K,1atm)(g/L)

Name

8 VIIIA VIII

Group Classification

55.847 26
铁 Fe
7.86
Iron

Atomic number

Symbol

1 IA IA	2 IIA IIA	3 IIIA IIIB	4 IVA IVB	5 VA VB	6 VIA VIB	7 VIIA VIIB	8	9 VIIIA VIII	10	11 IB IB	12 IIB IIB	13 IIIB IIIA	14 IVB IVA	15 VB VA	16 VIB VIA	17 VIIB VIIA	18 VIII 0
1.00794 1 氢 H 0.0899 Hydrogen																	4.00260 2 氦 He 0.1787 Helium
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Beams accelerated by Cyclotron & CSR

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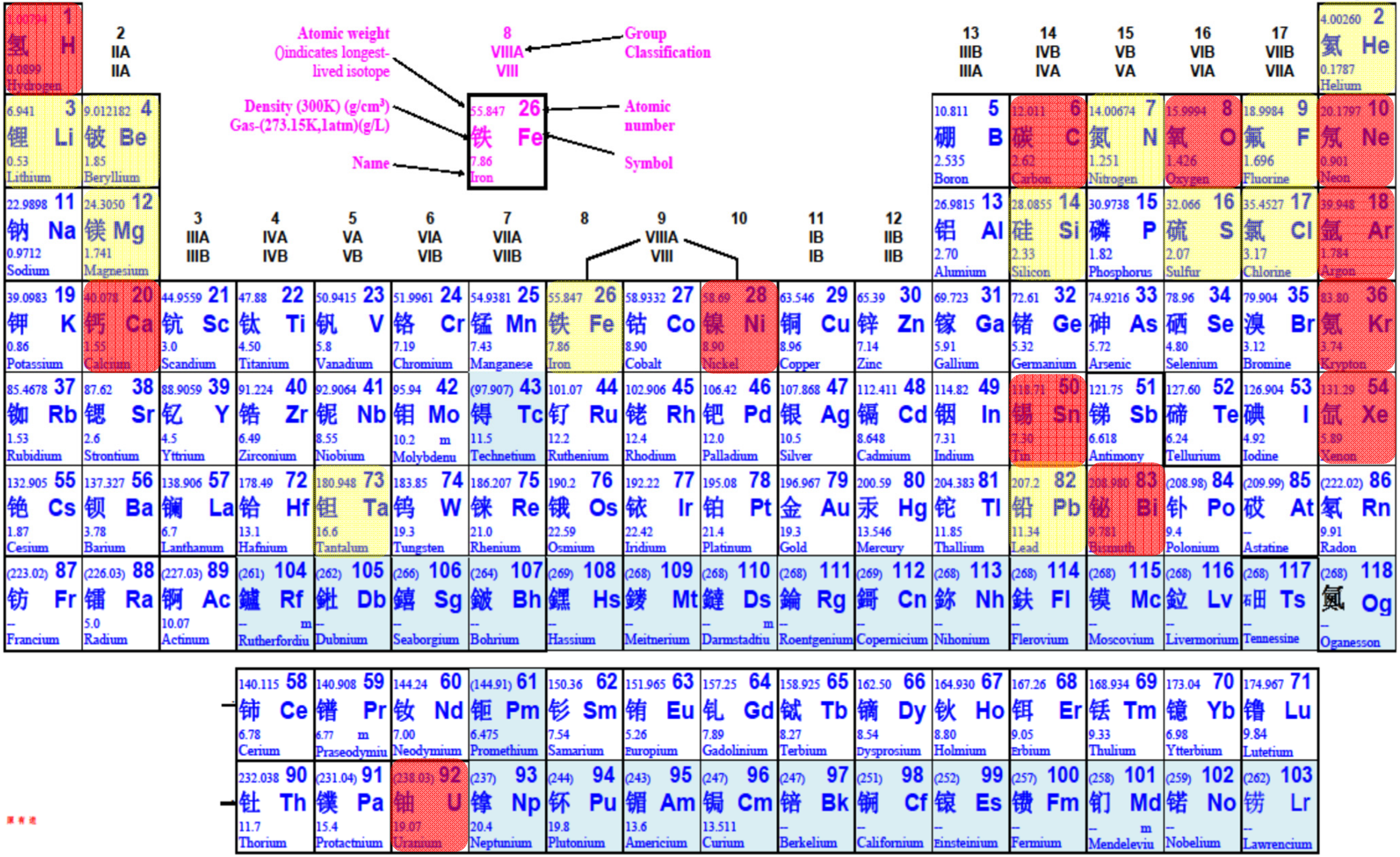

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Typical ions accelerated by HIRFL

Ion Beams	E (MeV/A)			Intensity
	SFC	SSC	CSR	(eμA)
H_2^{1+}	10		400	30
$^{7}Li^{3+}$	9			2.0
$^{9}Be^{3+}$	6.89			0.55
$^{12}C^{5+/6+}$	8.47	100		0.4
$^{12}C^{4+}$	7		1000	3200
$^{26}Mg^{8+/12+}$	6.17	70		0.35
$^{36}Ar^{8+}$	2.0725	22		3.3
$^{36}Ar^{8+}$	2.0725	22	368	650
$^{22}Ne^{7+/10+}$	6.17		70	1700
$^{40}Ca^{12+}$	5.625			3.5
$^{56}Fe^{17+}$	6.3			1.5
$^{58}Ni^{19+}$	6.3		463.36	500
$^{78}Kr^{19+/28+}$	4		487	750
$^{112}Sn^{26+/35+}$	3.7		391	1000
$^{129}Xe^{27+}$	3		235	500
$^{129}Xe^{27+}$	1.844	19.5		0.4
$^{181}Ta^{31+}$	1.193	12.5		0.03
$^{208}Pb^{27+}$	1.1			1.0
$^{209}Bi^{31+}$	0.911	9.5		0.05
$^{209}Bi^{36+}$	2		170	60
$^{238}U^{26+}$	0.81			0.33
$^{238}U^{32+}$	1.22		100	160

- **25 beams provided annually**
- **61 kinds of new beams in the last 5 years**
- **Highlighted:**

challengeable beams with HRIFL

  - ☐ **Ion beam production**
  - ☐ **Cyclotrons as injector for synchrotron**

Time and Type of User Experiments

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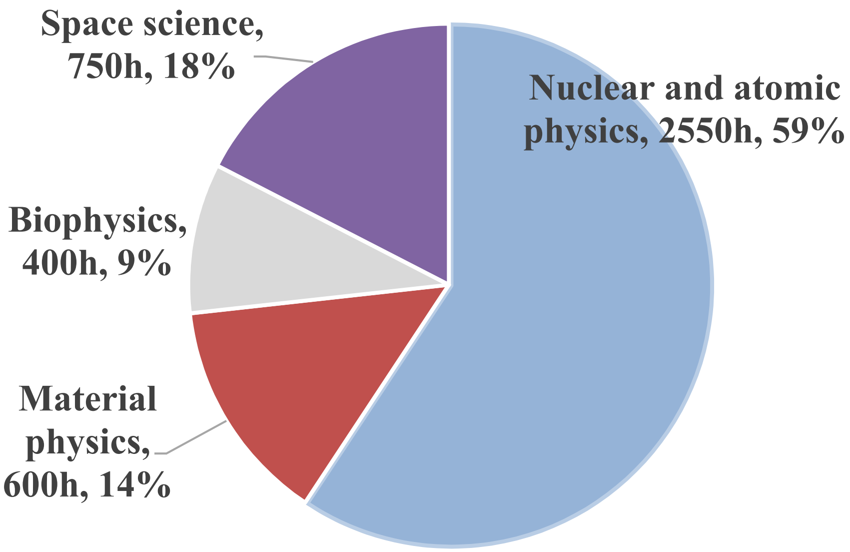
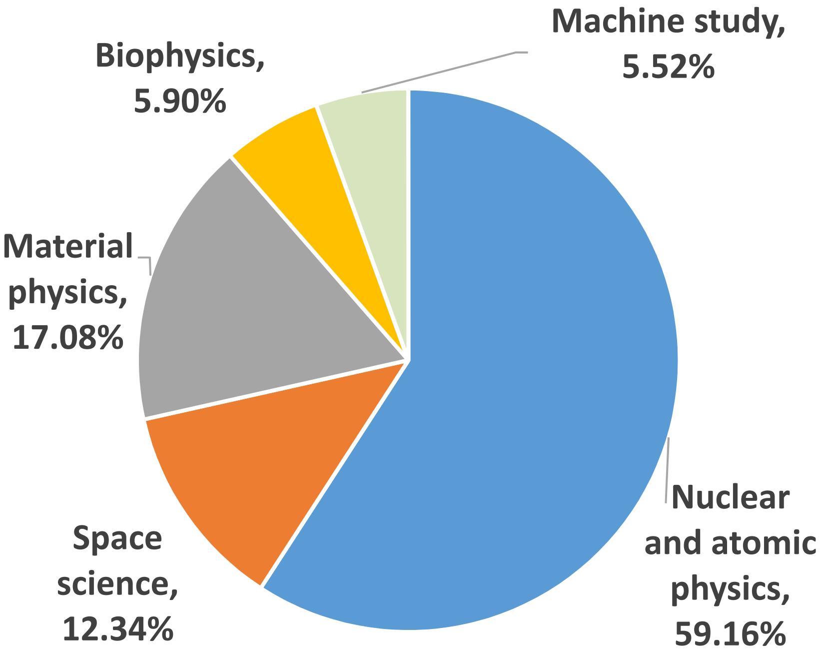
HIRFL completes ~200 experiments/year

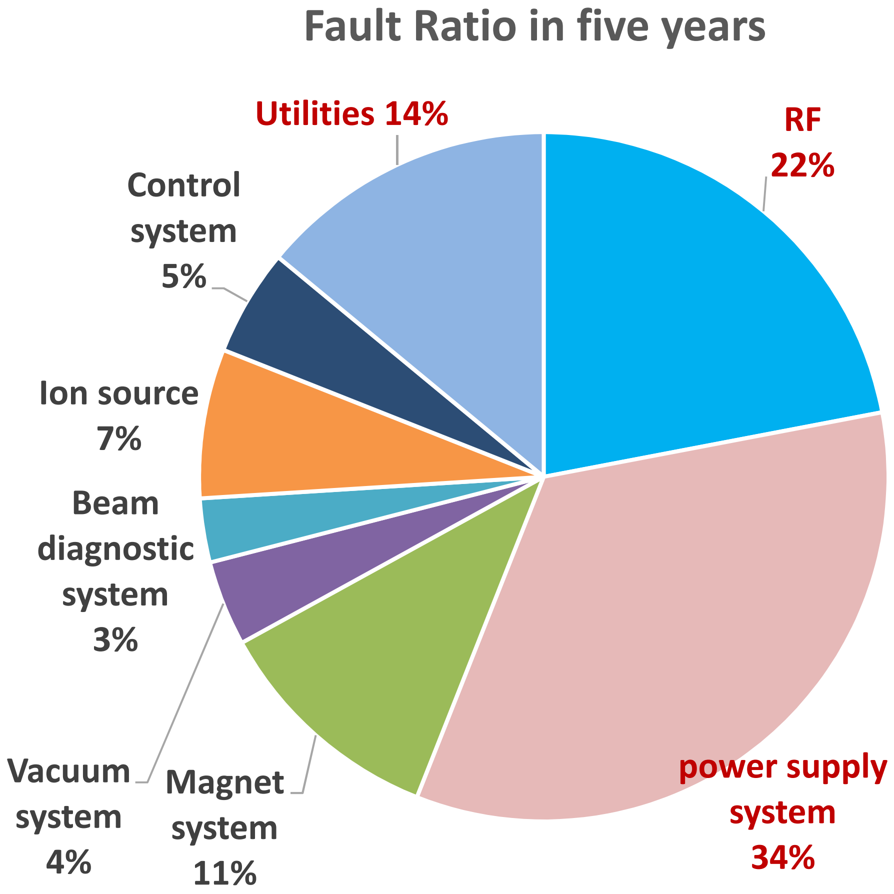
Planned Distribution of Beam Time



Average Distribution of Beam Time in Five Years



Accelerator System Failure



Typically 200~300 hours/year

The RF system

- A 200 kW High Frequency Transmitter
- Two 120 kW High Frequency Transmitters
- A 30 kW High Frequency Transmitter
- Two bunchers

The utilities

- Cooling water system
- Gas supply system
- Power distribution system

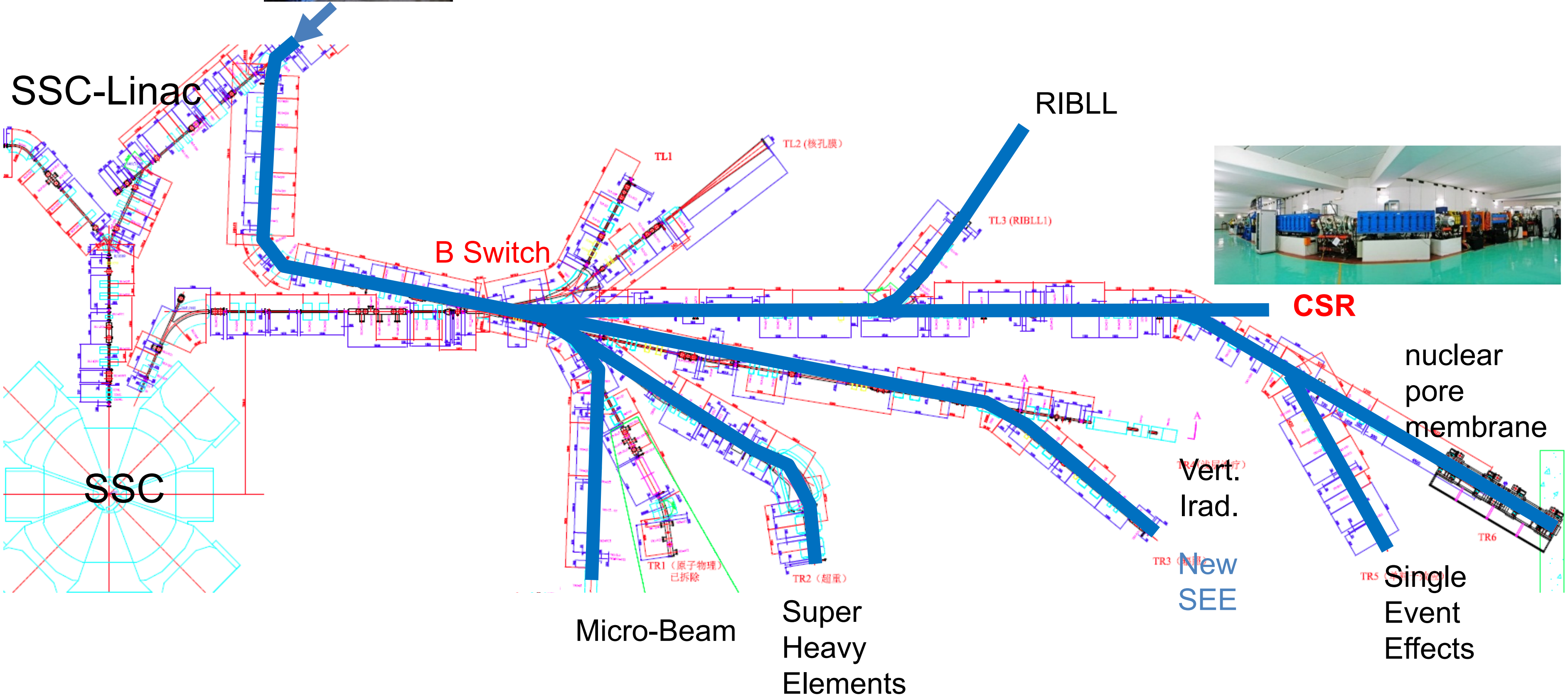
The power supply system

- ~535 different types of power supply

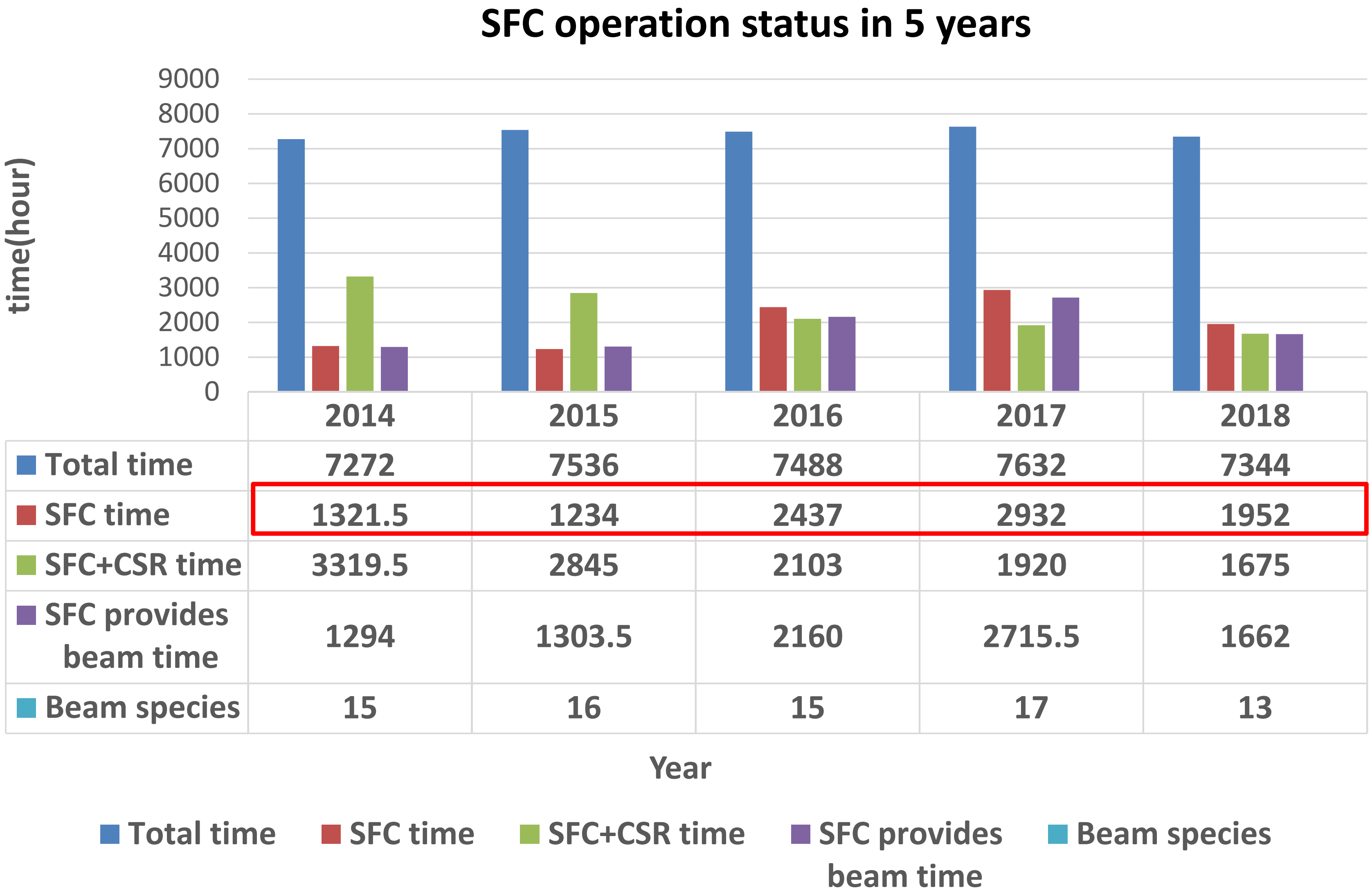
CONTENT

Stand-alone mode of SFC

Distribute beams for 10 experimental terminals



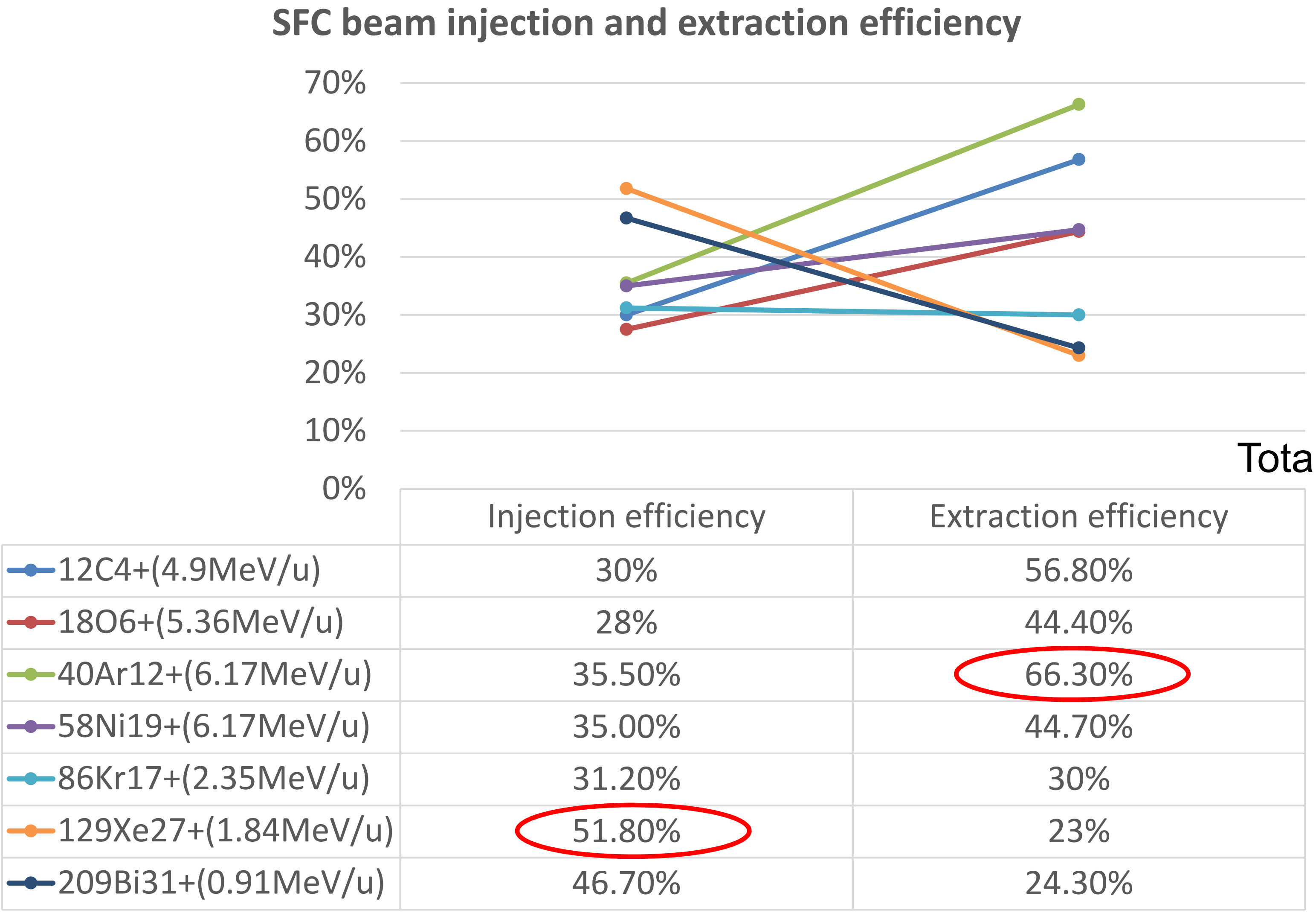
SFC operation status in 5 years



	2014	2015	2016	2017	2018
🟦 Total time	7272	7536	7488	7632	7344
🟥 SFC time	1321.5	1234	2437	2932	1952
🟩 SFC+CSR time	3319.5	2845	2103	1920	1675
🟪 SFC provides beam time	1294	1303.5	2160	2715.5	1662
🟦 Beam species	15	16	15	17	13

🟦 Total time 🟥 SFC time 🟩 SFC+CSR time 🟪 SFC provides beam time 🟦 Beam species

SFC beam injection and extraction efficiency



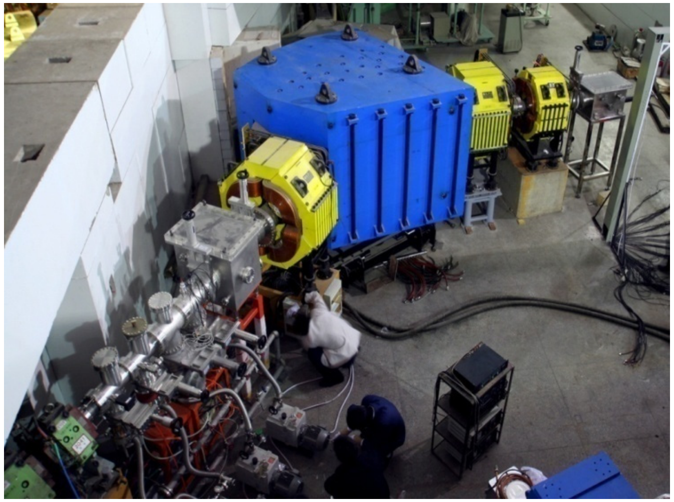
	Injection efficiency	Extraction efficiency
● 12C4+(4.9MeV/u)	30%	56.80%
● 18O6+(5.36MeV/u)	28%	44.40%
● 40Ar12+(6.17MeV/u)	35.50%	66.30%
● 58Ni19+(6.17MeV/u)	35.00%	44.70%
● 86Kr17+(2.35MeV/u)	31.20%	30%
● 129Xe27+(1.84MeV/u)	51.80%	23%
● 209Bi31+(0.91MeV/u)	46.70%	24.30%

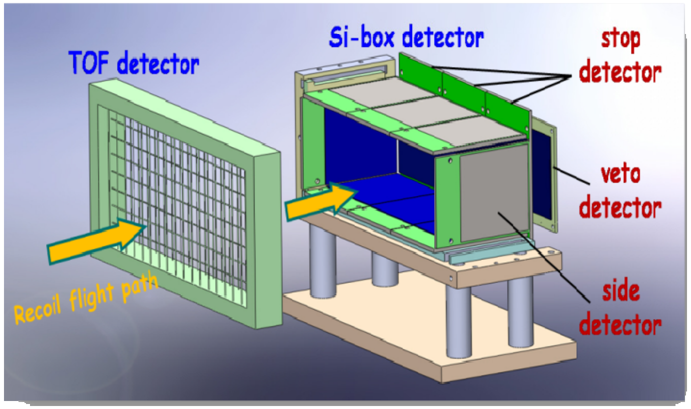
Total Efficiency
>20%

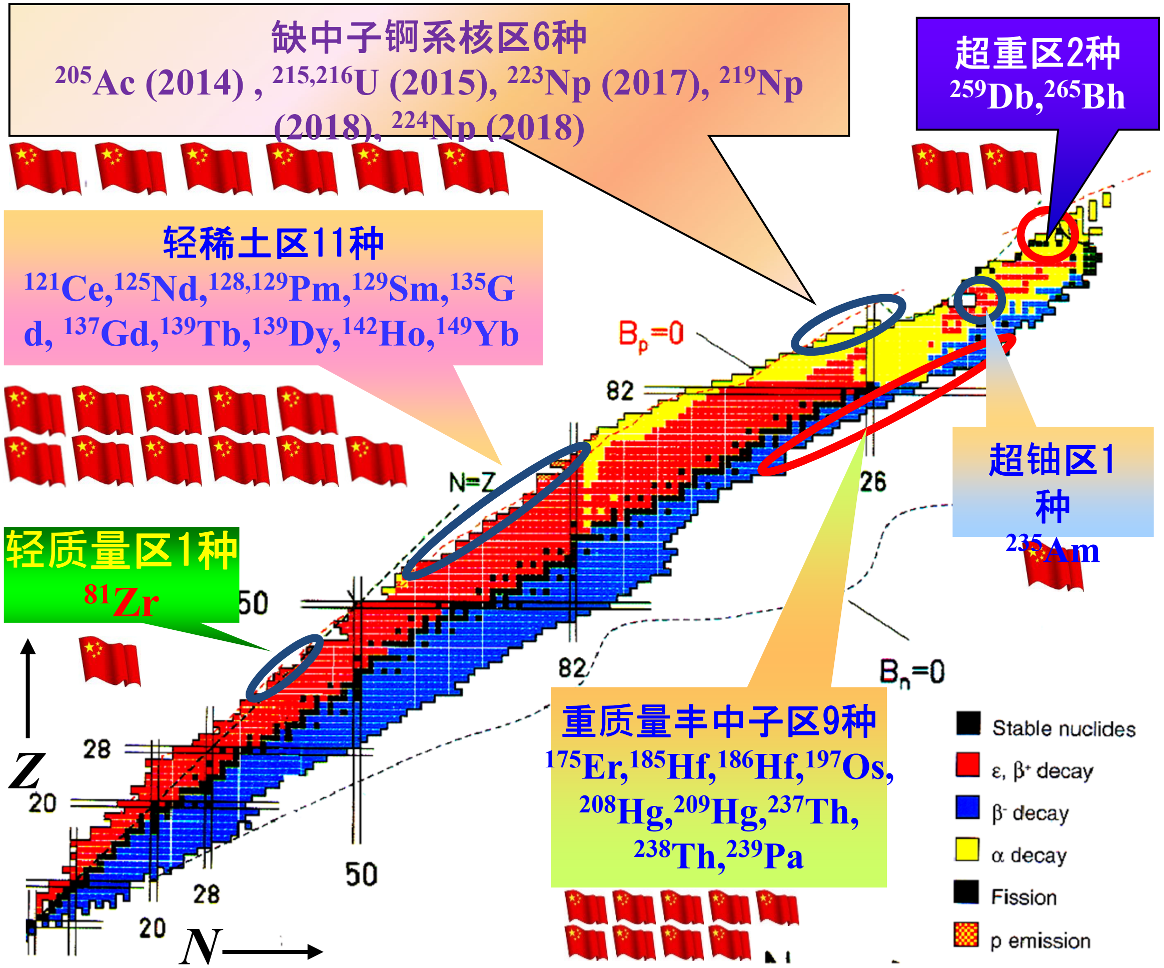
~10%

Physics: new nuclides synthesis

Ar, Ca, S, Mg, Ni and other beams for New Nuclide Synthesis experiments.







缺中子锕系核区6种

^{205}Ac (2014) , ^{215,216}U (2015), ^{223}Np (2017), ^{219}Np (2018), ^{224}Np (2018)

超重区2种

^{259}Db,^{265}Bh

轻稀土区11种

^{121}Ce,^{125}Nd,^{128,129}Pm,^{129}Sm,^{135}Gd, ^{137}Gd,^{139}Tb,^{139}Dy,^{142}Ho,^{149}Yb

轻质量区1种

^{81}Zr

超铀区1种

^{235}Am

重质量丰中子区9种

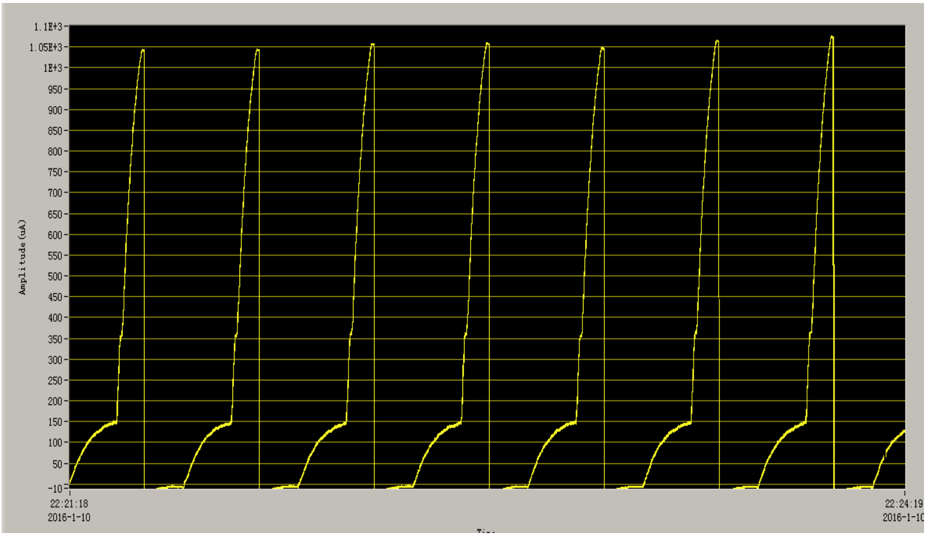
^{175}Er,^{185}Hf,^{186}Hf,^{197}Os, ^{208}Hg,^{209}Hg,^{237}Th, ^{238}Th,^{239}Pa

Injector: Beams for CSR

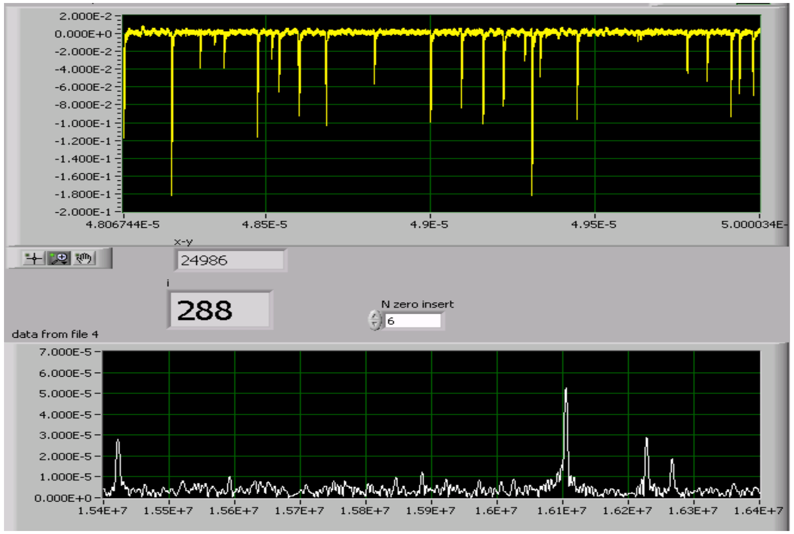
SECRAL: $^{112}Sn^{26+}$ 61 euA

SFC: $^{112}Sn^{26+}$ 2 euA/3.7 MeV/u

CSRm: $^{112}Sn^{35+}$ 1000 euA/401 MeV/u



CSRm-DCCT beam signal



x-y 24986

i 288

N zero insert 6

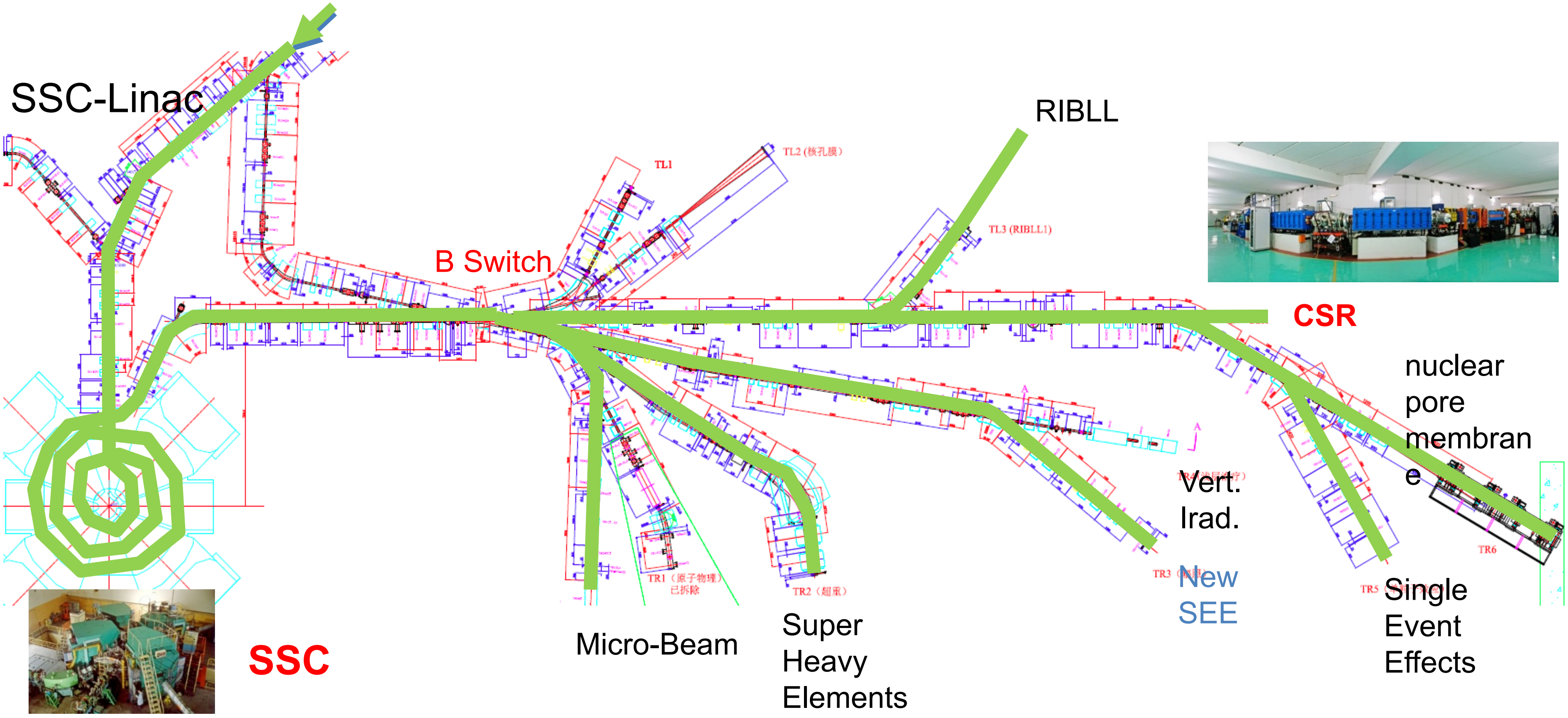
data from file 4

Data collected by CSRe detector

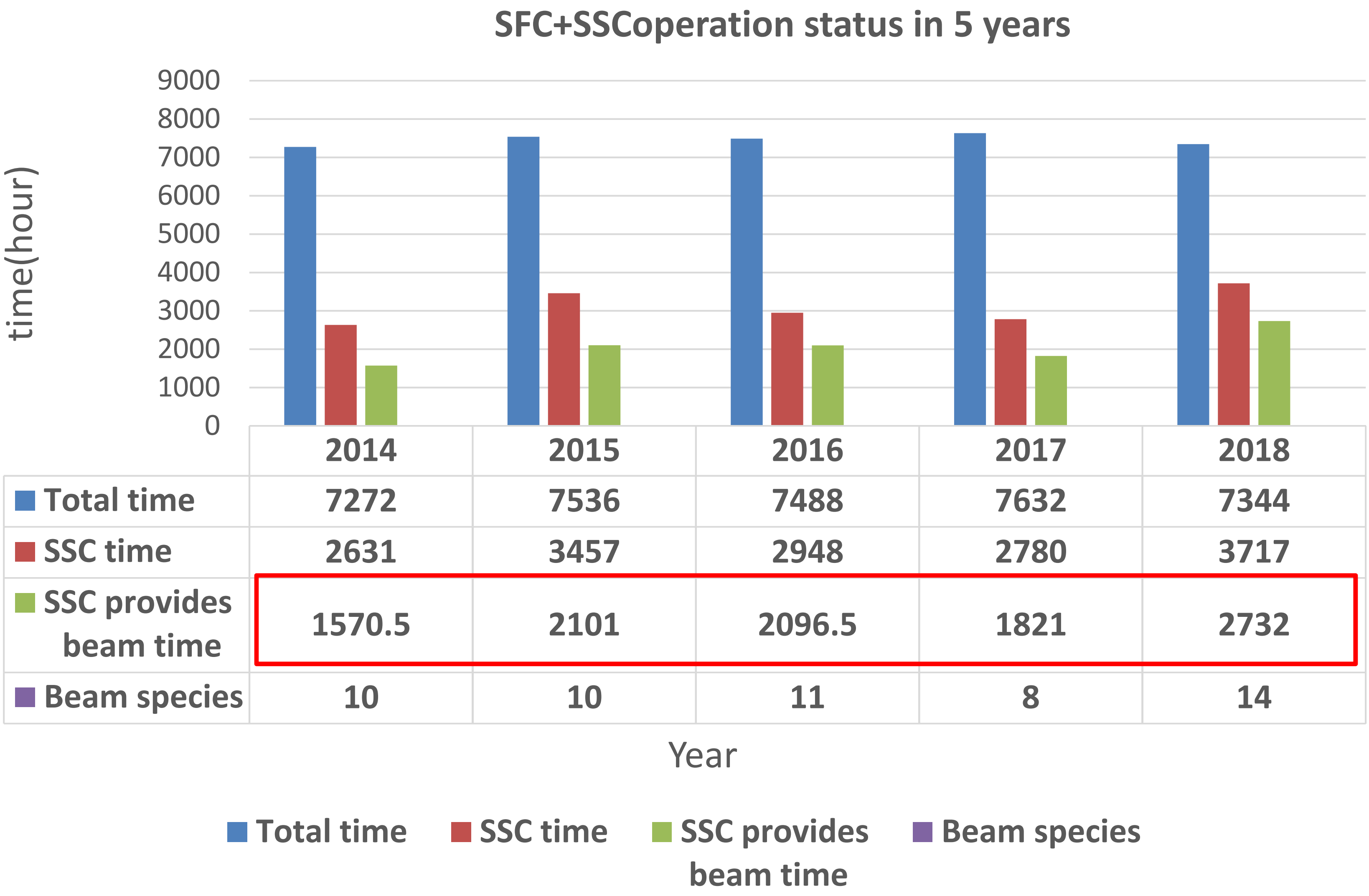
CONTENT

SFC+SSC Coupled Operation Mode

SFC+SSC provides beams for 8 experimental terminals

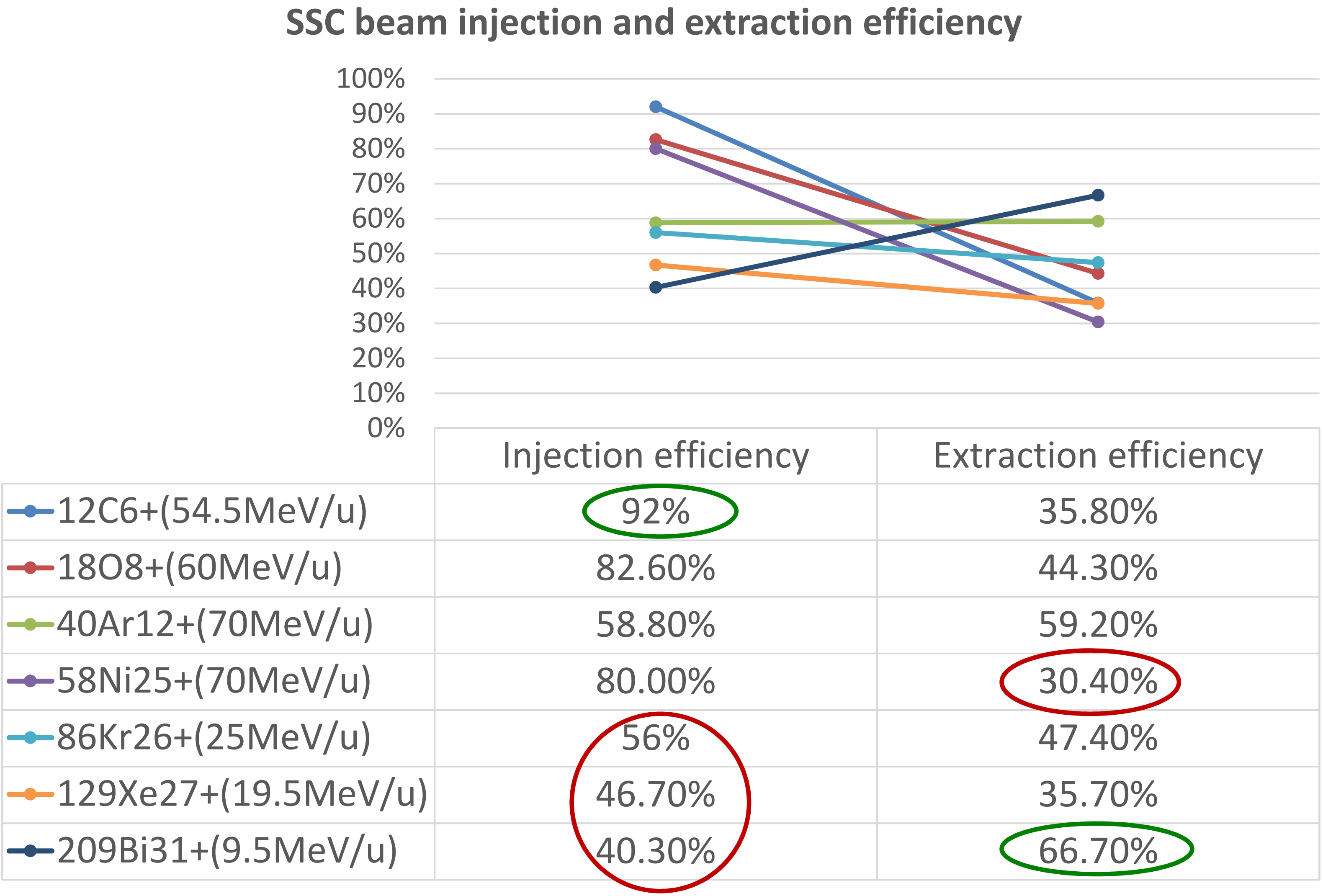


SFC+SSC operation status in 5 years



	2014	2015	2016	2017	2018
🟦 Total time	7272	7536	7488	7632	7344
🟥 SSC time	2631	3457	2948	2780	3717
🟩 SSC provides beam time	1570.5	2101	2096.5	1821	2732
🟪 Beam species	10	10	11	8	14

SSC beam injection and extraction efficiency



	Injection efficiency	Extraction efficiency
12C6+(54.5MeV/u)	92%	35.80%
18O8+(60MeV/u)	82.60%	44.30%
40Ar12+(70MeV/u)	58.80%	59.20%
58Ni25+(70MeV/u)	80.00%	30.40%
86Kr26+(25MeV/u)	56%	47.40%
129Xe27+(19.5MeV/u)	46.70%	35.70%
209Bi31+(9.5MeV/u)	40.30%	66.70%

Total Efficiency: >20%

Physics: Ion Beams for RIBLL1

He, C, O, Ne, Si, S, Ar, Ni and other beams for RIBLL1

中国原子能科学研究院
中核集团 CHINA INSTITUTE OF ATOMIC ENERGY

MICHIGAN STATE UNIVERSITY

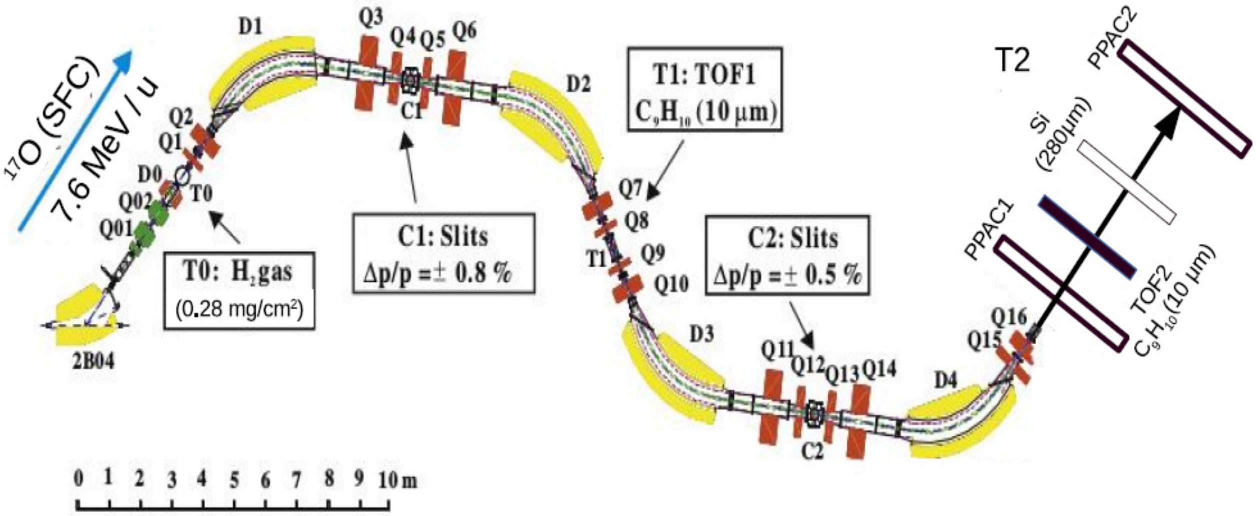
GSI

RIKEN

INFN Istituto Nazionale di Fisica Nucleare

BERKELEY LAB

GANIL spiral2 laboratoire commun CEA/DSM



Radioactive Ion Beams Line in Lanzhou (RIBLL1)

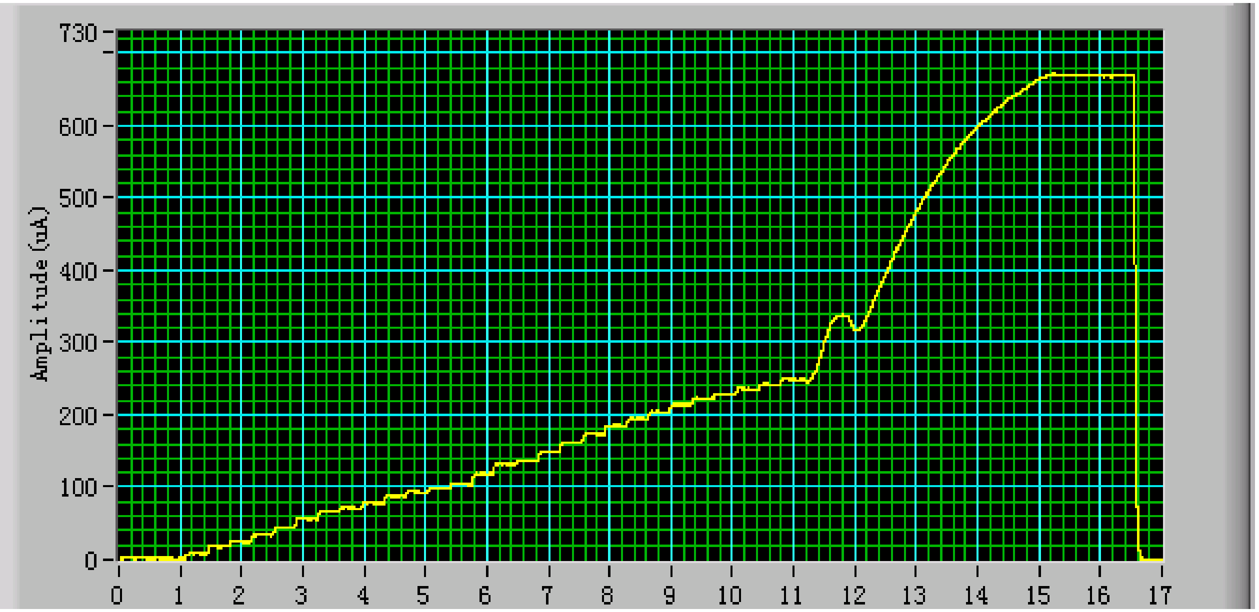
Injetor: beams for CSR

ECR: ^{36}Ar^{8+} 259 euA

SFC: ^{36}Ar^{8+} 16 euA, 2.0725 MeV/u

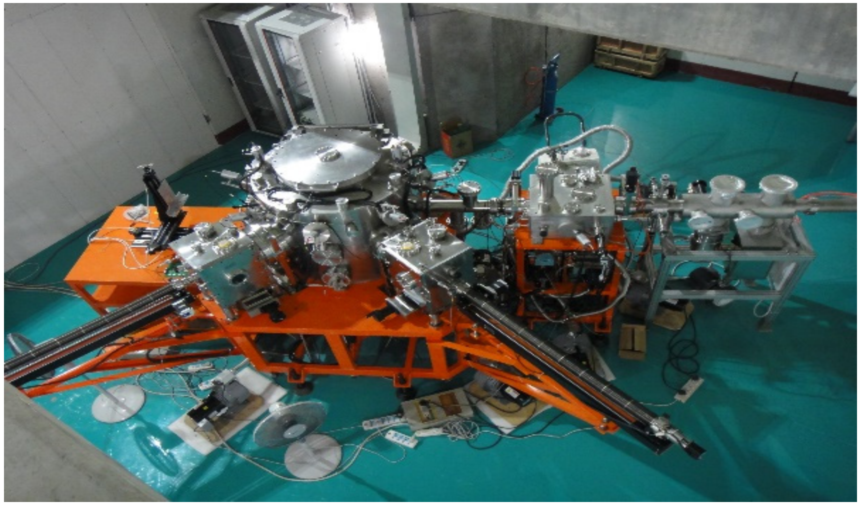
SSC: ^{36}Ar^{8+} 3.5 euA, 22 MeV/u

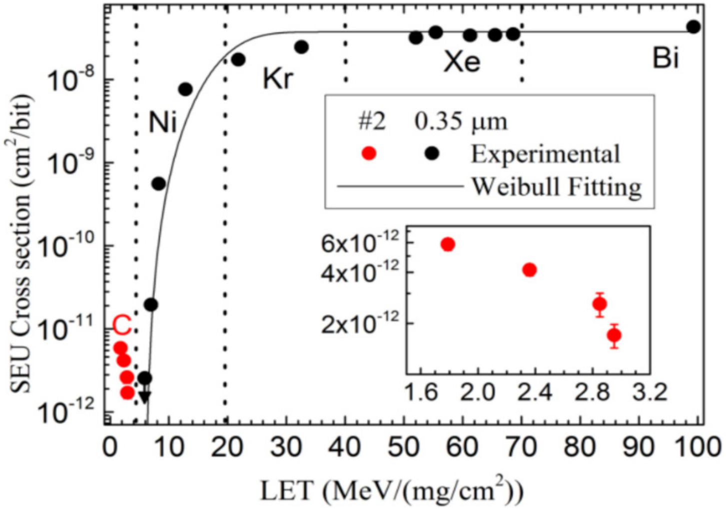
CSRm: ^{36}Ar^{8+} 680 euA, 368 MeV/u

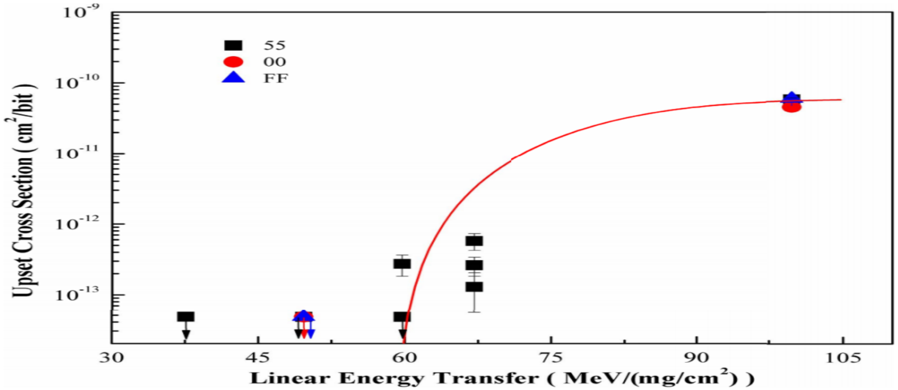


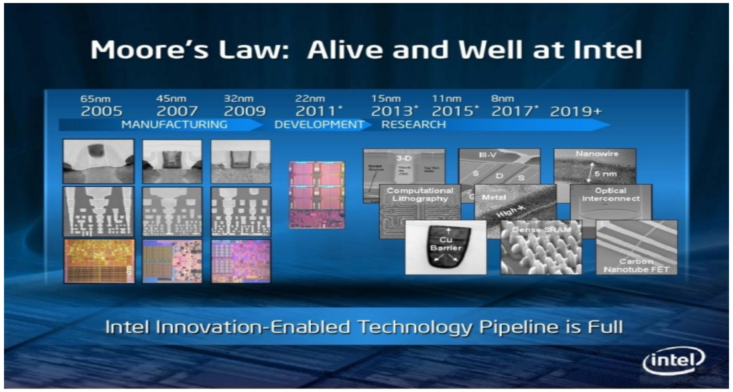
Applications: Single event effect experiment

Kr, Bi, Ta, Xe and other beams for the single event effect study









Moore's Law: Alive and Well at Intel

Intel Innovation-Enabled Technology Pipeline is Full

CONTENT

- Heavy Ion Research Facility in Lanzhou (HIRFL)
- Overview of HIRFL Operation
- Operation status of the cyclotrons
  - SFC operation status
  - SFC+SSC operation status
- **HIRFL Improvement and Upgrade**
- Introduction of HIAF and CiADS

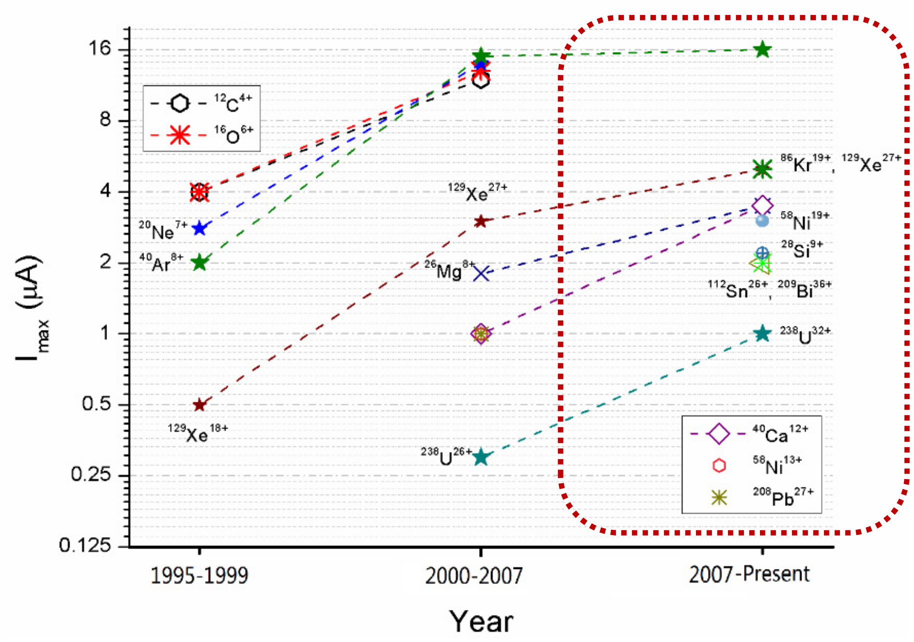
Why?

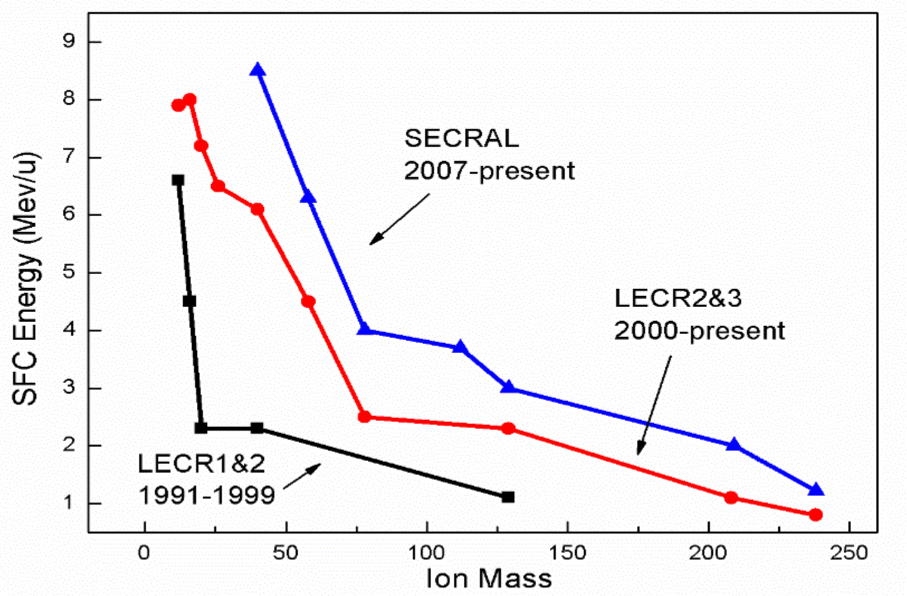
- HIRFL facilities cover the history of half century
  - Hardware degrading
  - Technology advancement
  - Experiment needs
- Cascade operation limits HIRFL performance
  - SFC is the only working horse for all purposes
  - SFC+SSC coupled efficiency
  - CSR needs more intense injection beams
- Gain
  - More beam time (doubled)
  - More powerful: SSC and CSR
  - Enable more physics

Main Improvement and Upgrade

- New superconducting ECR ion source SECRAL-II→ higher q and Iq, continuous operation without LHe refilling
- Improvement of SFC vacuum chamber, 3×10^{-7} mbar → 5×10^{-8}mbar
- Buncher between SFC and SSC, SSC beam intensity increased by a factor of 2
- Replacement of SSC injection and extraction magnetic elements reduces the machine failures caused by the aging coils
- EPCIS control upgrade
- Power supply system upgraded to digital controlled
- SSC High Frequency Power Source Changed from Electron Tube Amplifier to Solid State Amplifier, LLRF system digitized.

Upgrade Impact to HIRFL





Gain:

- Higher beam intensity
- Heavier ion beams (H~U)
- Higher energies

HIRFL with new injectors

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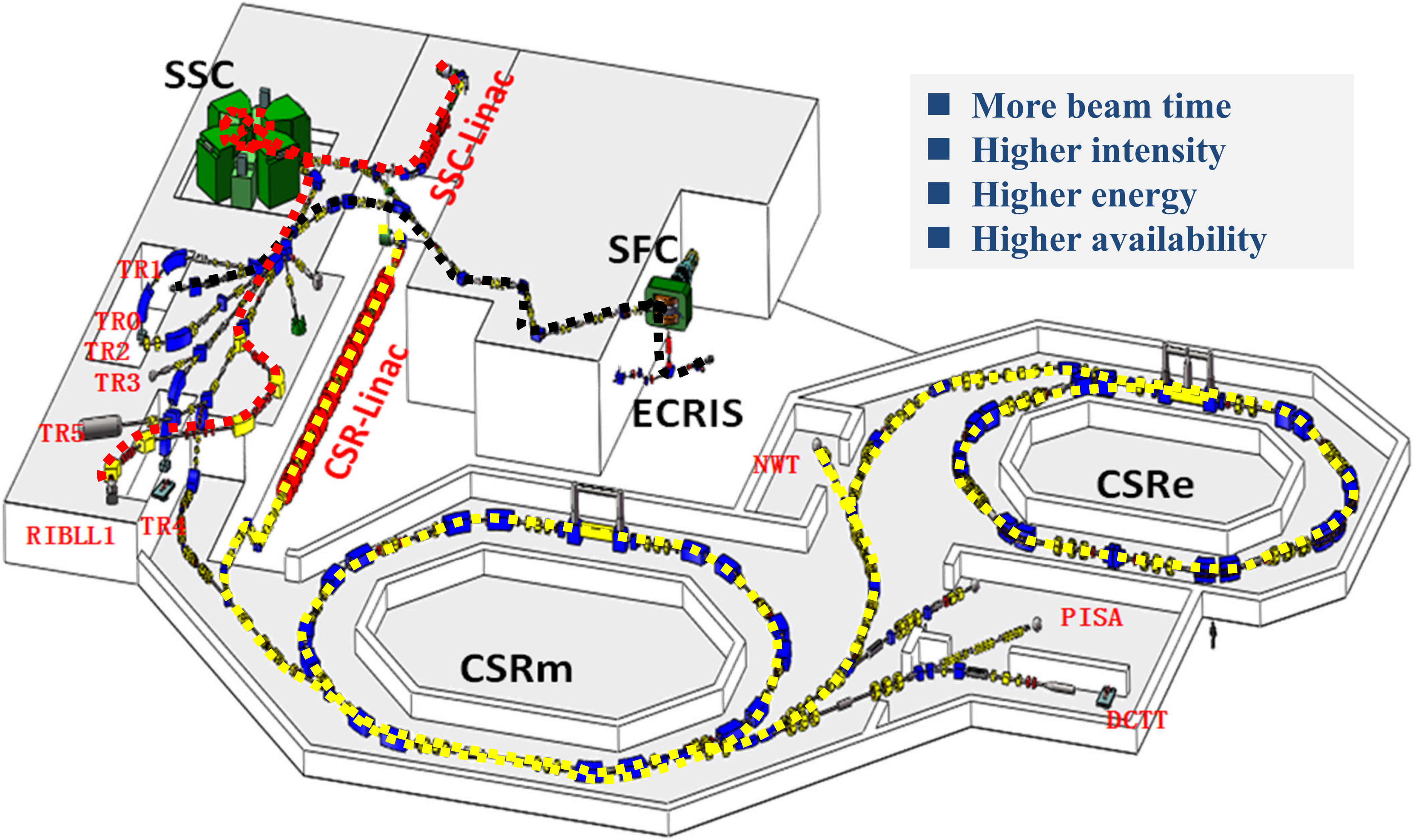
SSC-Linac **CSR-Linac**

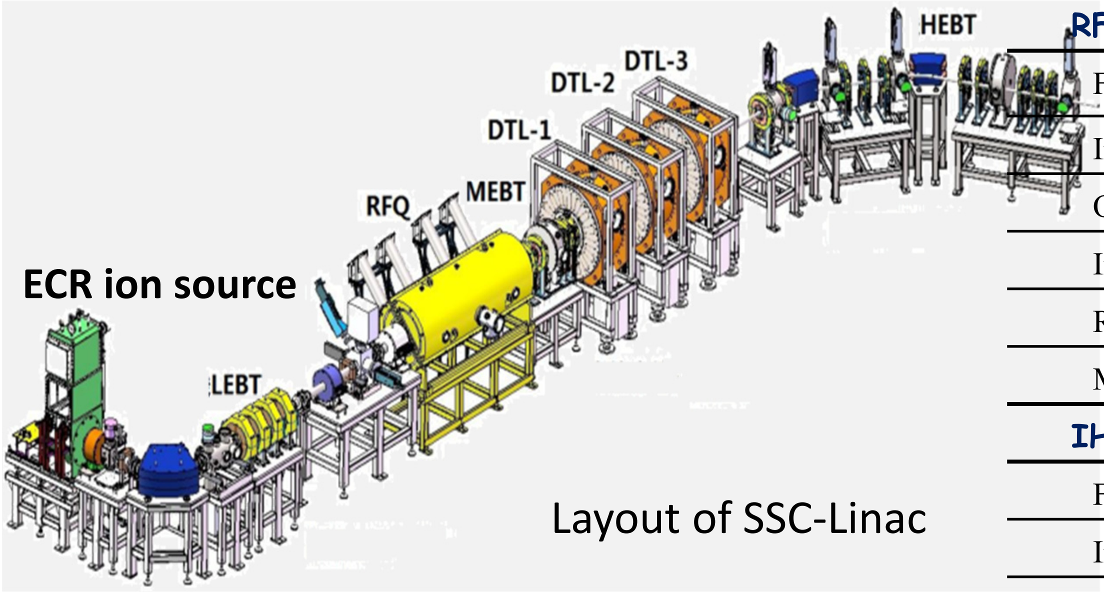


- More beam time
- Higher intensity
- Higher energy
- Higher availability

SSC-Linac: Overview

New high intensity heavy ion injector of SSC

- Extraction energy:
  - Phase I: ~0.7 MeV/u → 5.97 MeV/u(SSC)→CSRm
  - Phase II: ~1.0 MeV/u→10.7MeV/u(SSC)→CSRm
- Beam current : 5~30eμA for various ions.
- Beam intensity: increase 1~2 order for SSC.
- $^{238}U^{35\text{-}72+}$ can be accelerated to 487MeV/u by CSRm after stripping.



Layout of SSC-Linac

Main parameters of SSC_Linac

Parameters	Values
Design ion	$^{238}U^{34+}$
ECR ion source	
Extraction voltage	25kV
Max. axial injection field	2.3 T
Microwave frequency	18GHz
RFQ	4-rod
Frequency	53.667MHz
Input energy	3.728keV/u
Output energy	143keV/u
Inter-electrode voltage	70kV
RF power	35kW
Max. current	0.5emA
IH-DTL	KONUS
Frequency	53.667MHz
Input energy	0.143MeV/u
Output energy	1.025MeV/u

Beam Commissioning Progress

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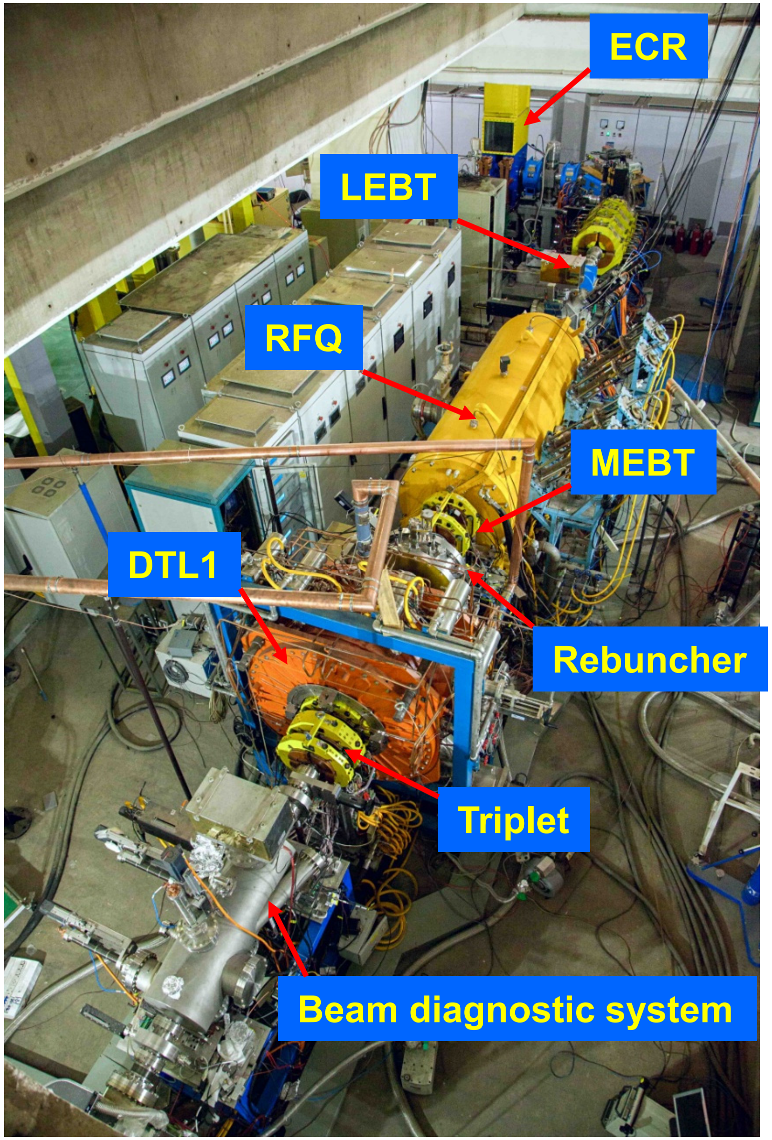

SSC-Linac layout

- ➢Beam commissioning: $^{16}O^{5+}$,$^{12}C^{4+}$, $^{209}Bi^{30+}$&$^{238}U^{35+}$
- ➢Beam energy 295.6keV/u
- ➢Beam transmission > 70%
- ➢DTL2(576keV/u) has been finished in 2019

Beam experiment resualts

Parameters	Values
Frequency	53.667 MHz
Input energy	3.7 keV/u
Output energy	295.6 keV/u
$\varepsilon_{x\ nrms}$	0.18 π.mm·mrad
$\varepsilon_{y\ nrms}$	0.14 π.mm·mrad
Energy spread	<±2%

Ion	I(eμA)	
	INPUT	OUTPUT
$^{12}C^{4+}$	45	37
$^{16}O^{5+}$	184	170
	100	70
$^{40}Ar^{8+}$	220	198
$^{209}Bi^{30+}$	42	12
$^{238}U^{35+}$	7.0	4.5

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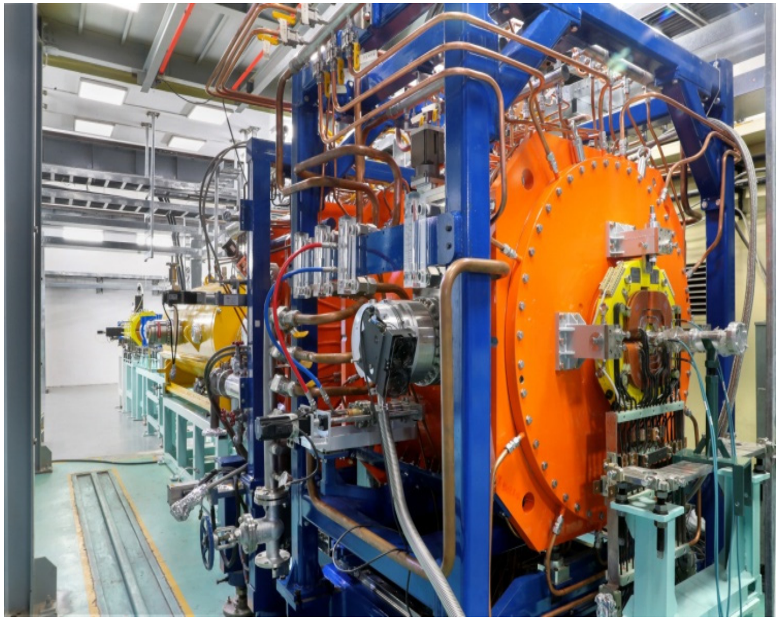
Field installation and progress



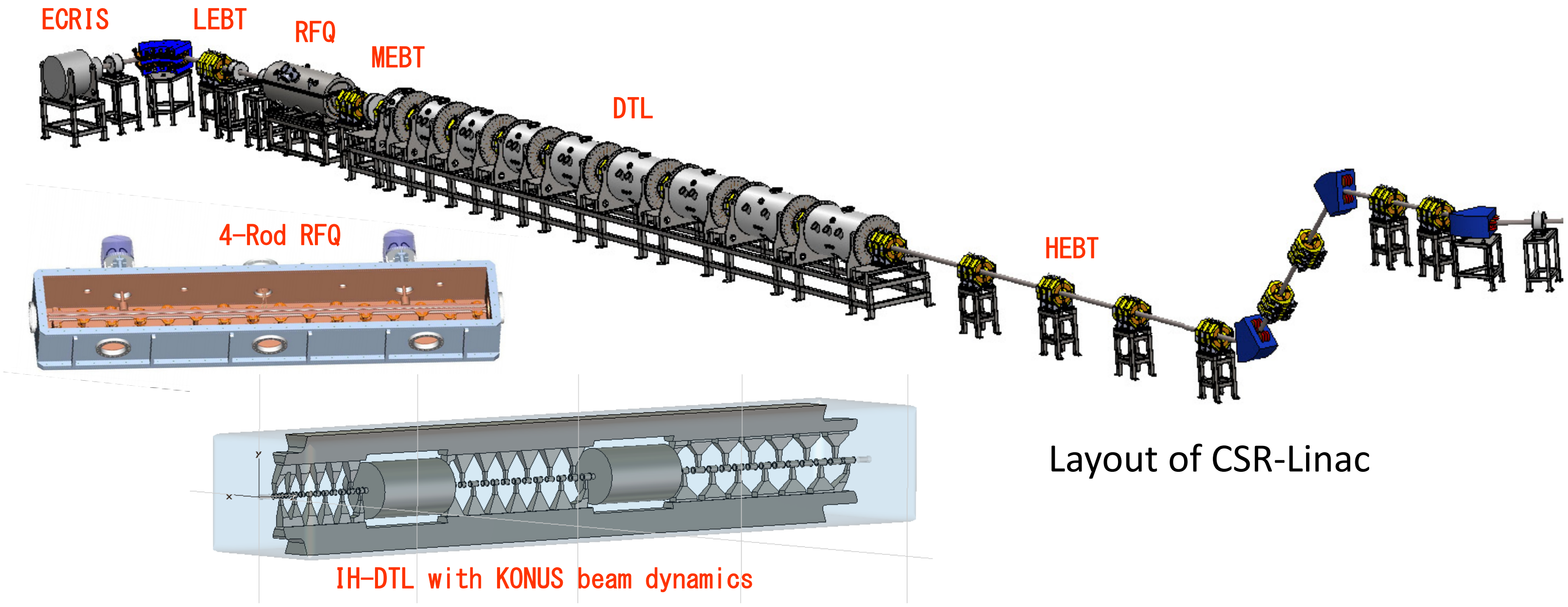
- 2019.09.30 On-site installation completed
- 2019.10.15 Joint commissioning of systems
- 2019.10.31 Linac beam commissioning
- 2019.11— Joint beam commissioning of Linac and SSC

CSR-Linac Overview of Design

The CSR-LINAC :

- carbon to uranium up to 7.272 MeV/u
- Beam current: 1-10 pμA
- Beam intensity: 1~2 order to CSRm for heavier ions

Q/A	1/3 - 1/7	-
Emittance(norm, 99%)	0.88	$\pi.mm.mrad$
Frequency	108.48/216.96	MHz
Beam current	3	emA
Duration	3	ms
Repetition	10	Hz
RFQ input/output energy	4/300	keV/u
DTL input/output energy	0.3/7.272	MeV/u
Transmission(design)	90	%



Layout of CSR-Linac

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Bird view of HIAF and CiADS Campus

HIAF Overview

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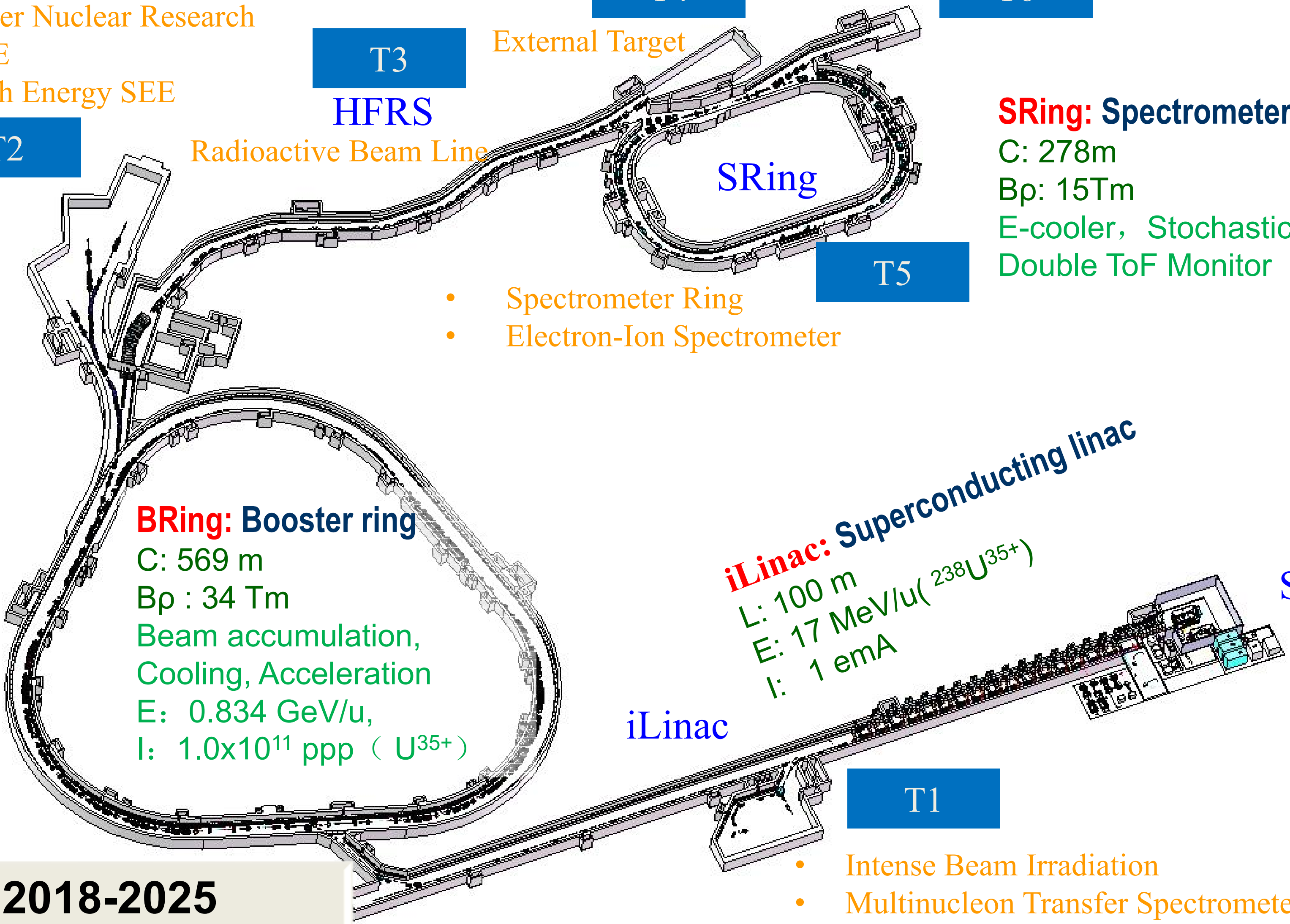


- Super Nuclear Research
- CEE
- High Energy SEE

T2

T3

HFRS

Radioactive Beam Line

T4

External Target

T6

HEDM

SRing

SRing: Spectrometer ring
C: 278m
Bρ: 15Tm
E-cooler，Stochastic cooling
Double ToF Monitor

T5

- Spectrometer Ring
- Electron-Ion Spectrometer

BRing: Booster ring
C: 569 m
Bρ : 34 Tm
Beam accumulation,
Cooling, Acceleration
E：0.834 GeV/u,
I：$1.0x10^{11}$ ppp（U^{35+}）

iLinac: Superconducting linac
L: 100 m
E: 17 MeV/u($^{238}U^{35+}$)
I: 1 emA

SECR

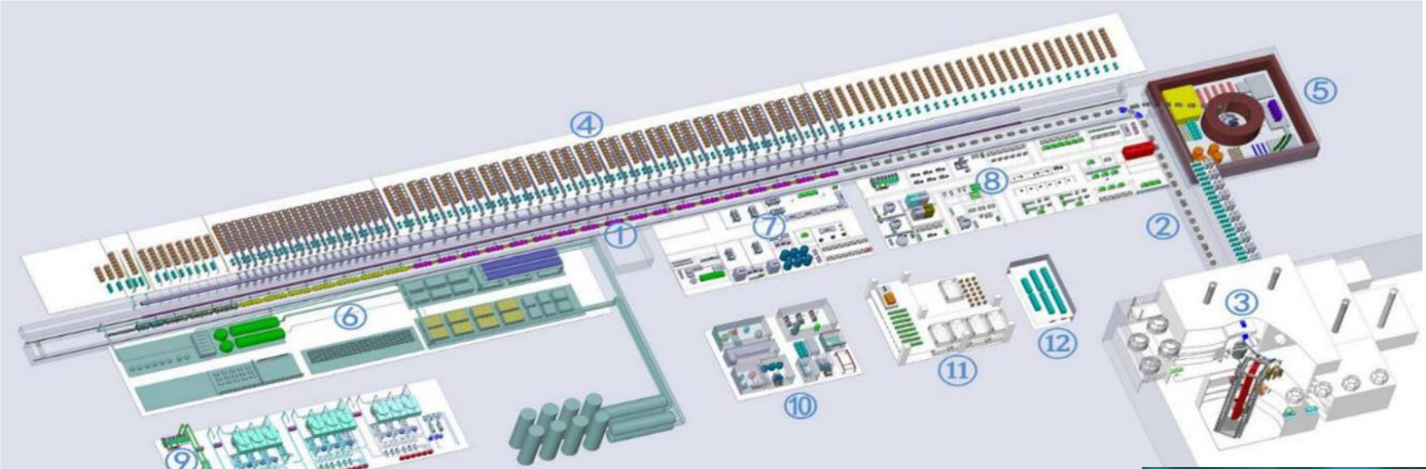
iLinac

T1

- Intense Beam Irradiation
- Multinucleon Transfer Spectrometer

HIAF: 2018-2025
Budget: ~1.6+1.2 B CNY

CiADS Overview



☐ **CiADS Main Parameters:**

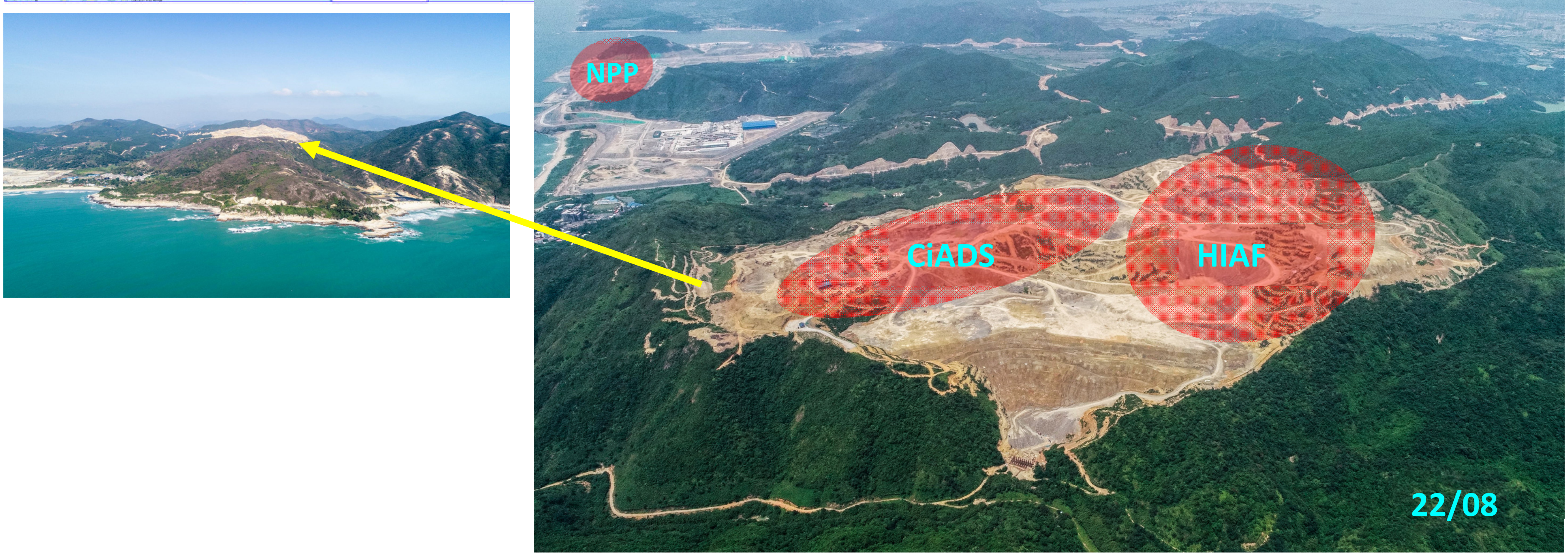
- High CW Power (>2.5 MW, >500 MeV) SC-LINAC
- High Power (>2.5 MW) Spallation Target
- Sub-Core (<10 MW_{th})
- Coupling all Components → Full System (~10 MW)

☐ **CIADS Budget & Time Schedule :**

- 1.8 + 1.25 +1.0 B CNY
- 6 years （2019—2025）

HIAF + CiADS

- Approved in Dec. 2015
- Responding institute: IMP
- Location: Huizhou, Guangdong Prov.
- Ground breaking in August 2018
- To be completed in 2025



Thanks for your attention！