



Present Status of HIRFL Complex in Lanzhou

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The 14th International Conference on Heavy Ion
Accelerator Technology (HIAT'18), Oct. 22-26, 2018

Lanzhou, China



Heavy Ion Research Facility in Lanzhou (HIRFL)

The largest ion-accelerator complex in China

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

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

CSRe (9Tm)
2008

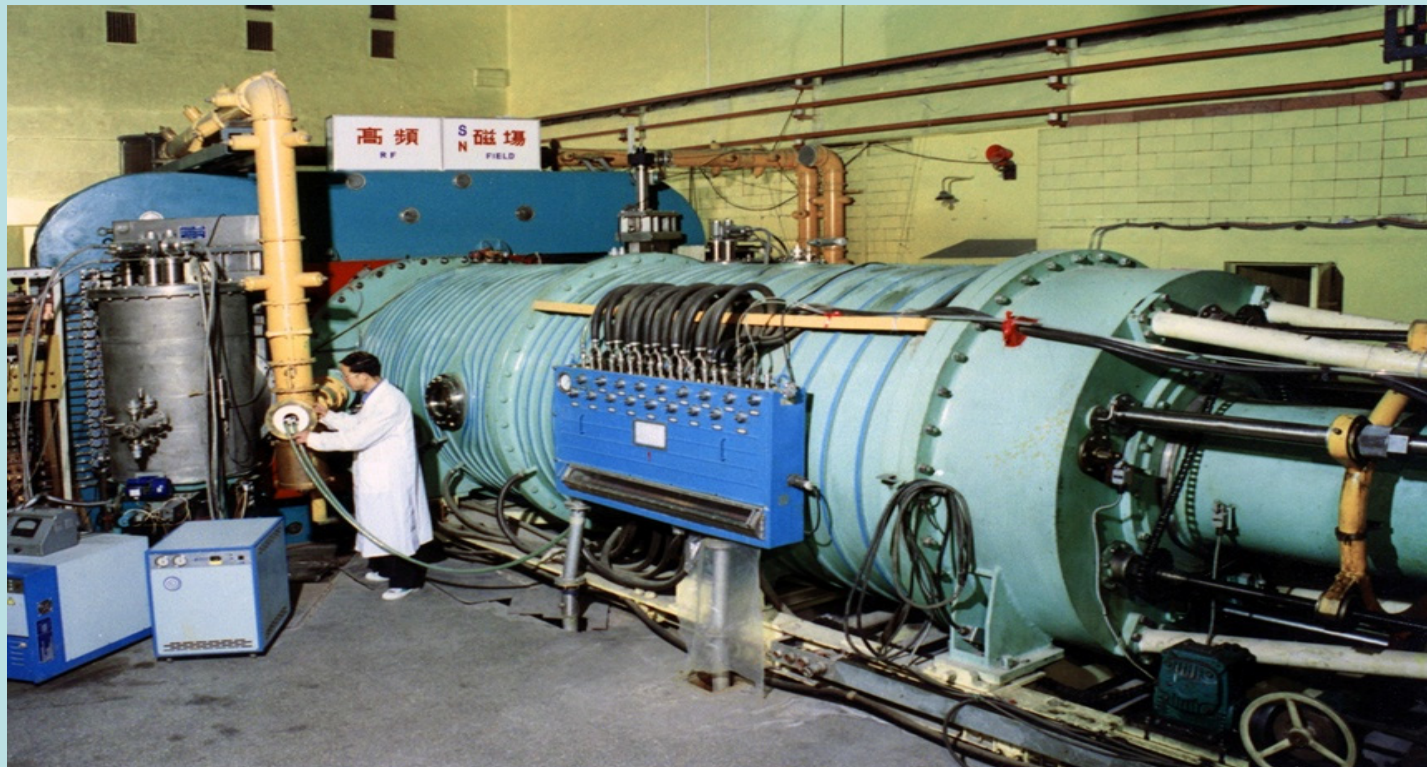
CSRm (11Tm)
2008, 1000MeV/u-C





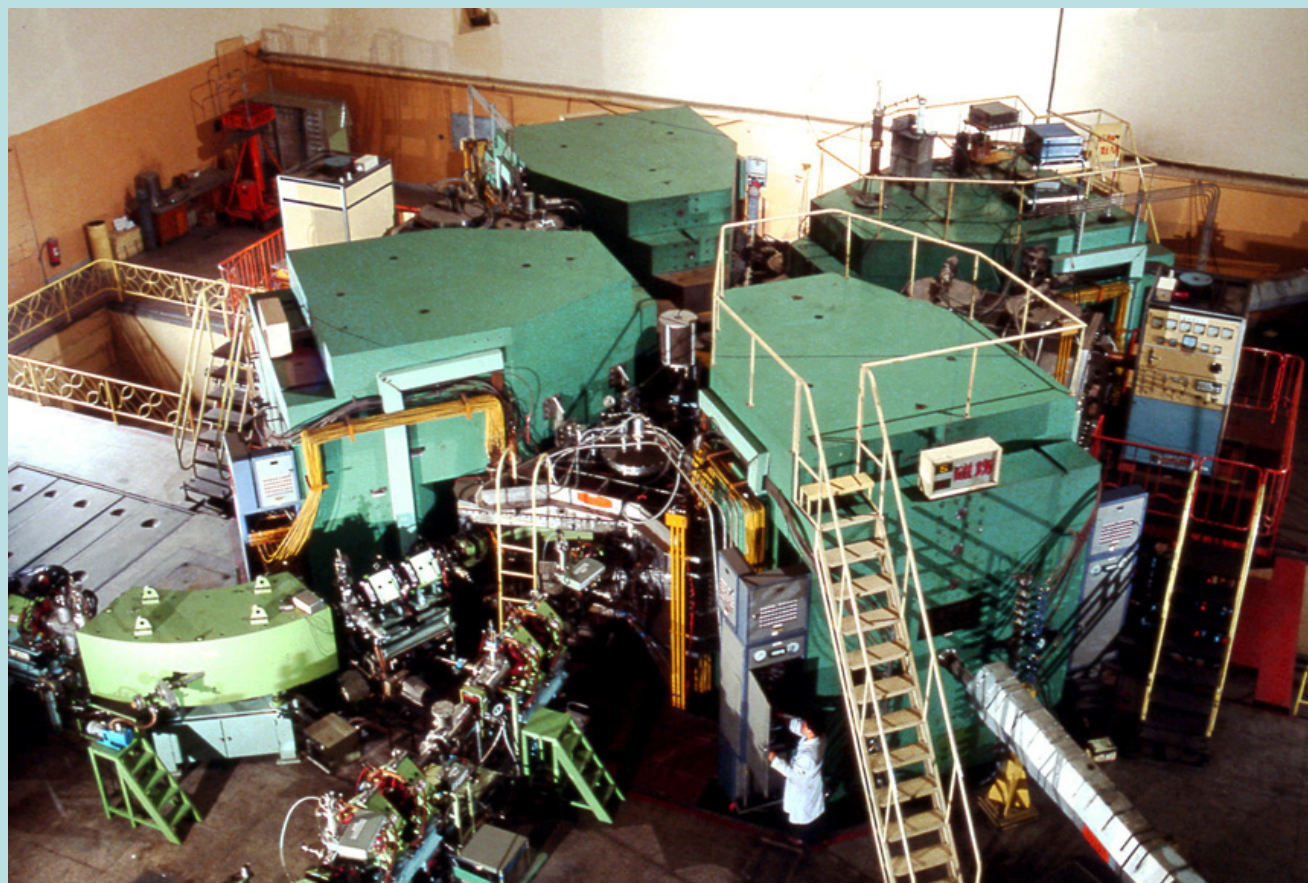
Built in 1961 with the assistance of the Soviet Union, H&He
1970s, upgraded, Carbon~Uranium

$K \sim 69$, $R \sim 0.75$ m, $E \sim 10$ MeV(C), 1MeV/u(U)





1988, $K \sim 450$, $R \sim 3.203$ m, $\alpha \sim \text{U}$, $E : 100$ MeV/u (C), 10 MeV/u (U)





Synchrotron and Storage Rings CSRm & CSRe

CSRm 161.0m, $G_{\max} = 11.3 \text{ Tm}$



CSRe 128.8m, $G_{\max} = 9.0 \text{ Tm}$





CSRm e-cooler
0.5-35kV
0.03-0.5A
0.25→0.15T

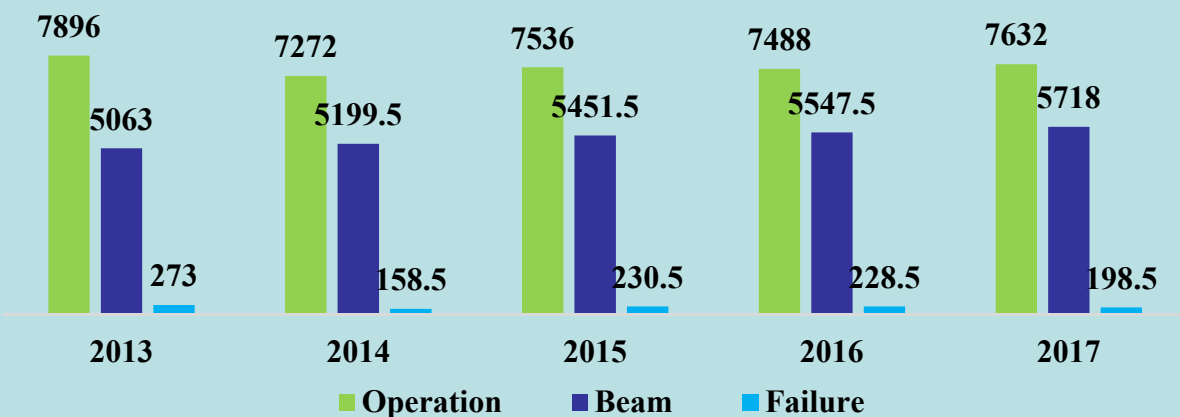


CSRe e-cooler
5-300kV
0.2-3A
0.5→0.15T





Operation Time 2013-2017



Operation budget: **14.68** M\$*5

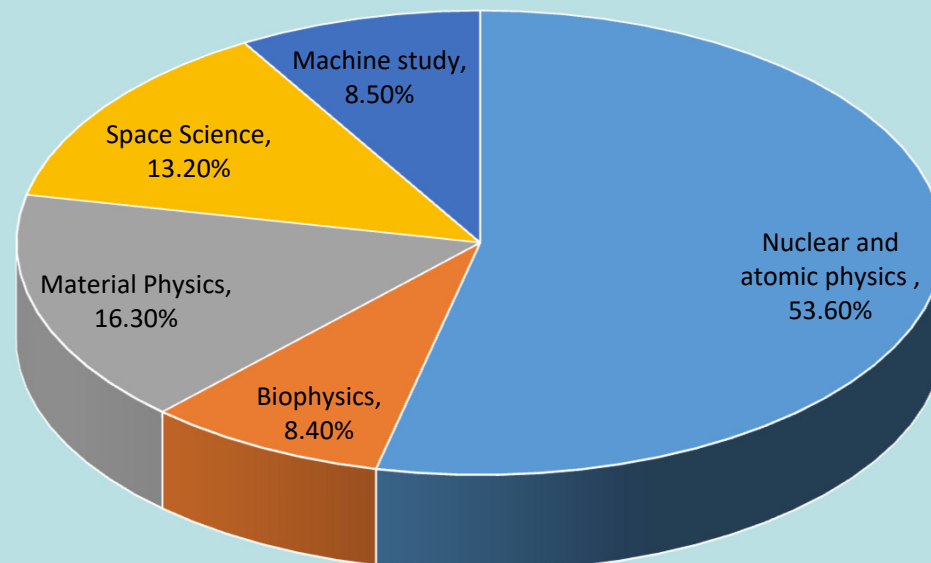
Operation time/a: **7565** h

Beam Time/a: **5273** h

No. Experiments: **910 (+31 MS)**

User institutions: **> 200**

Beam Time Distribution





Chemical Periodic Table

24 elements
~30 isotopes

1 IA IA 1.00794 1 氢 H 0.0899 Hydrogen	2 IIA IIA 9.012182 4 铍 Be 1.85 Beryllium	3 3 IIIA III A 6.941 3 锂 Li 0.53 Lithium	4 4 IVA IV A 9.012182 4 铍 Be 1.85 Beryllium	5 5 VA V A 22.9898 11 钠 Na 0.9712 Sodium	6 6 VIA VI A 24.3050 12 镁 Mg 1.741 Magnesium	7 7 VIIA VII A 55.847 26 铁 Fe 7.86 Iron	8 8 VIIIA VIII 55.847 26 铁 Fe 7.86 Iron	9 9 VIIIA VIII 58.9332 27 钴 Co 8.90 Cobalt	10 10 VIIIA VIII 58.69 28 镍 Ni 8.90 Nickel	11 11 IB IB 63.546 29 铜 Cu 8.96 Copper	12 12 IIB IIB 65.39 30 锌 Zn 7.14 Zinc	13 13 IIIB III A 10.811 5 硼 B 2.535 Boron	14 14 IVB IV A 12.011 6 碳 C 2.62 Carbon	15 15 VB V A 14.00674 7 氮 N 1.251 Nitrogen	16 16 VIB VI A 15.9994 8 氧 O 1.426 Oxygen	17 17 VIIB VII A 18.9984 9 氟 F 1.696 Fluorine	18 18 VIII 0 4.00260 2 氦 He 0.1787 Helium
19 19 IIA II A 39.0983 19 钾 K 0.86 Potassium	20 20 IIA II A 40.078 20 钙 Ca 1.55 Calcium	21 21 IIIB III B 44.9559 21 钪 Sc 3.0 Scandium	22 22 IIIB III B 47.88 22 钛 Ti 4.50 Titanium	23 23 IIIB III B 50.9415 23 钒 V 5.8 Vanadium	24 24 IIIB III B 51.9961 24 铬 Cr 7.19 Chromium	25 25 IIIB III B 54.9381 25 锰 Mn 7.43 Manganese	26 26 IIIB III B 55.847 26 铁 Fe 7.86 Iron	27 27 IIIB III B 58.9332 27 钴 Co 8.90 Cobalt	28 28 IIIB III B 58.69 28 镍 Ni 8.90 Nickel	29 29 IIIB III B 63.546 29 铜 Cu 8.96 Copper	30 30 IIIB III B 65.39 30 锌 Zn 7.14 Zinc	31 31 IIIB III B 69.723 31 镓 Ga 5.91 Gallium	32 32 IIIB III B 72.61 32 锗 Ge 5.32 Germanium	33 33 IIIB III B 74.9216 33 砷 As 5.72 Arsenic	34 34 IIIB III B 78.96 34 硒 Se 4.80 Selenium	35 35 IIIB III B 79.904 35 溴 Br 3.12 Bromine	36 36 IIIB III B 83.80 36 氪 Kr 3.74 Krypton
37 37 IIIB III B 85.4678 37 铷 Rb 1.53 Rubidium	38 38 IIIB III B 87.62 38 锶 Sr 2.6 Strontium	39 39 IIIB III B 88.9059 39 钇 Y 4.5 Yttrium	40 40 IIIB III B 91.224 40 锆 Zr 6.49 Zirconium	41 41 IIIB III B 92.9064 41 铌 Nb 8.55 Niobium	42 42 IIIB III B 95.94 42 钼 Mo 10.2 m Molybdenum	43 43 IIIB III B (97.907) 43 锝 Tc 11.5 Technetium	44 44 IIIB III B 101.07 44 钌 Ru 12.2 Ruthenium	45 45 IIIB III B 102.906 45 铑 Rh 12.4 Rhodium	46 46 IIIB III B 106.42 46 钯 Pd 12.0 Palladium	47 47 IIIB III B 107.868 47 银 Ag 10.5 Silver	48 48 IIIB III B 112.411 48 镉 Cd 8.648 Cadmium	49 49 IIIB III B 114.82 49 铟 In 7.31 Indium	50 50 IIIB III B 118.71 50 锡 Sn 7.30 Tin	51 51 IIIB III B 121.75 51 锑 Sb 6.618 Antimony	52 52 IIIB III B 127.60 52 碲 Te 6.24 Tellurium	53 53 IIIB III B 126.904 53 碘 I 4.92 Iodine	54 54 IIIB III B 131.29 54 氙 Xe 5.89 Xenon
55 55 IIIB III B 132.905 55 铯 Cs 1.87 Cesium	56 56 IIIB III B 137.327 56 钡 Ba 3.78 Barium	57 57 IIIB III B 138.906 57 镧 La 6.7 Lanthanum	72 72 IIIB III B 178.49 72 铪 Hf 13.1 Hafnium	73 73 IIIB III B 180.948 73 钽 Ta 16.6 Tantalum	74 74 IIIB III B 183.85 74 钨 W 19.3 Tungsten	75 75 IIIB III B 186.207 75 铼 Re 21.0 Rhenium	76 76 IIIB III B 190.2 76 锇 Os 22.59 Osmium	77 77 IIIB III B 192.22 77 铱 Ir 22.42 Iridium	78 78 IIIB III B 195.08 78 铂 Pt 21.4 Platinum	79 79 IIIB III B 196.967 79 金 Au 19.3 Gold	80 80 IIIB III B 200.59 80 汞 Hg 13.546 Mercury	81 81 IIIB III B 204.383 81 铊 Tl 11.85 Thallium	82 82 IIIB III B 207.2 82 铅 Pb 11.34 Lead	83 83 IIIB III B 208.980 83 铋 Bi 9.781 Bismuth	84 84 IIIB III B (208.98) 84 钋 Po 9.4 Polonium	85 85 IIIB III B (209.99) 85 砹 At — Astatine	86 86 IIIB III B (222.02) 86 氡 Rn 9.91 Radon
87 87 IIIB III B (223.02) 87 钫 Fr — Francium	88 88 IIIB III B (226.03) 88 镭 Ra 5.0 Radium	89 89 IIIB III B (227.03) 89 锕 Ac 10.07 Actinium	104 104 IIIB III B (261) 104 𬬻 Rf — Rutherfordium	105 105 IIIB III B (262) 105 𬬼 Db — Dubnium	106 106 IIIB III B (266) 106 𬬾 Sg — Seaborgium	107 107 IIIB III B (264) 107 𬬿 Bh — Bohrium	108 108 IIIB III B (269) 108 𬭀 Hs — Hassium	109 109 IIIB III B (268) 109 𬭁 Mt — Meitnerium	110 110 IIIB III B (268) 110 𬭂 Ds — Darmstadtium	111 111 IIIB III B (268) 111 𬭃 Rg — Roentgenium	112 112 IIIB III B (269) 112 𬭄 Cn — Copernicium	113 113 IIIB III B (268) 113 𬭅 Nh — Nihonium	114 114 IIIB III B (268) 114 𬭆 Fl — Flerovium	115 115 IIIB III B (268) 115 𬭇 Mc — Moscovium	116 116 IIIB III B (268) 116 𬭈 Lv — Livermorium	117 117 IIIB III B (268) 117 𬭉 Ts — Tennessine	118 118 IIIB III B (268) 118 𬭊 Og — Oganesson
58 58 IIIB III B 140.115 58 铈 Ce 6.78 Cerium	59 59 IIIB III B 140.908 59 镨 Pr 6.77 m Praseodymium	60 60 IIIB III B 144.24 60 钕 Nd 7.00 Neodymium	61 61 IIIB III B (144.91) 61 钷 Pm 6.475 Promethium	62 62 IIIB III B 150.36 62 钐 Sm 7.54 Samarium	63 63 IIIB III B 151.965 63 铕 Eu 5.26 Europium	64 64 IIIB III B 157.25 64 钆 Gd 7.89 Gadolinium	65 65 IIIB III B 158.925 65 铽 Tb 8.27 Terbium	66 66 IIIB III B 162.50 66 镱 Dy 8.54 Dysprosium	67 67 IIIB III B 164.930 67 铈 Ho 8.80 Holmium	68 68 IIIB III B 167.26 68 铒 Er 9.05 Erbium	69 69 IIIB III B 168.934 69 铥 Tm 9.33 Thulium	70 70 IIIB III B 173.04 70 镱 Yb 6.98 Ytterbium	71 71 IIIB III B 174.967 71 镱 Lu 9.84 Lutetium				
90 90 IIIB III B 232.038 90 钍 Th 11.7 Thorium	91 91 IIIB III B (231.04) 91 镤 Pa 15.4 Protactinium	92 92 IIIB III B (238.03) 92 铀 U 19.07 Uranium	93 93 IIIB III B (237) 93 镎 Np 20.4 Neptunium	94 94 IIIB III B (244) 94 钚 Pu 19.8 Plutonium	95 95 IIIB III B (243) 95 镅 Am 13.6 Americium	96 96 IIIB III B (247) 96 镆 Cm 13.511 Curium	97 97 IIIB III B (247) 97 锫 Bk — Berkelium	98 98 IIIB III B (251) 98 锿 Cf — Californium	99 99 IIIB III B (252) 99 镅 Es — Einsteinium	100 100 IIIB III B (257) 100 镆 Fm — Fermium	101 101 IIIB III B (258) 101 镎 Md — Mendelevium	102 102 IIIB III B (259) 102 镎 No — Nobelium	103 103 IIIB III B (262) 103 镎 Lr — Lawrencium				





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0	Not available by SFC or SSC	1	Limited by SFC-RF frequency <15.5 MHz
1	Available by SFC alone	2	Limited by SFC-B >1T
2	Available by SFC+SSC,same A/Q	1	Available by SSC after stipping.

E(MeV/u)	SFC 0.4	0.6	1	1.5	2	2.5	3	3.5	4	5	6	7	8	9	10
A/Qs	SSC 4.1	6.2	10.4	15.8	21.2	26.7	32.3	38.0	43.8	55.6	67.9	80.6	93.7	107.3	121.4
8	2	2	1	0	0	0	0	0	0	0	0	0	0	0	0
7.75	2	2	1	0	0	0	0	0	0	0	0	0	0	0	0
7.5	2	2	1	0	0	0	0	0	0	0	0	0	0	0	0
7.25	2	2	1	0	0	0	0	0	0	0	0	0	0	0	0
7	2	2	1	0	0	0	0	0	0	0	0	0	0	0	0
6.75	2	2	1	1	0	0	0	0	0	0	0	0	0	0	0
6.5	1	2	2	1	0	0	0	0	0	0	0	0	0	0	0
6.25	1	2	2	1	0	0	0	0	0	0	0	0	0	0	0
6	1	2	2	1	0	0	0	0	0	0	0	0	0	0	0
5.75	1	2	2	1	1	0	0	0	0	0	0	0	0	0	0
5.5	1	2	2	1	1	0	0	0	0	0	0	0	0	0	0
5.25	1	1	2	2	1	1	0	0	0	0	0	0	0	0	0
5	0	1	2	2	1	1	0	0	0	0	0	0	0	0	0
4.75	0	1	2	2	1	1	1	0	0	0	0	0	0	0	0
4.5	0	1	2	2	2	1	1	0	0	0	0	0	0	0	0
4.25	0	0	2	2	2	1	1	1	0	0	0	0	0	0	0
4	0	0	1	2	2	2	1	1	1	0	0	0	0	0	0
3.75	0	0	1	2	2	2	1	1	1	0	0	0	0	0	0
3.5	0	0	1	2	2	2	2	1	1	1	0	0	0	0	0
3.25	0	0	0	1	2	2	2	2	1	1	1	0	0	0	0
3	0	0	0	1	2	2	2	2	2	1	1	1	0	0	0
2.75	0	0	0	1	1	2	2	2	2	2	1	1	1	1	0
2.5	0	0	0	0	1	1	2	2	2	2	2	1	1	1	1
2.25	0	0	0	0	0	1	1	2	2	2	2	2	1	1	1
2	0	0	0	0	0	0	1	1	1	2	2	2	2	2	1
1.5	0	0	0	0	0	0	0	0	0	1	1	1	2	2	2
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
F-SFC	5.59	6.85	8.84	10.82	12.49	13.95	15.28	*16.50	5.88	6.57	7.19	7.76	8.28	8.78	9.25
F-SSC	8.39	6.85	8.84	10.82	12.49	13.95	7.64	8.25	8.82	9.85	10.78	11.63	12.43	13.17	13.87
match	0.5	1	1	1	1	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
F-SFC	9.691	10.11	10.91	11.64	12.33	12.98	13.88	14.72	15.77						

E_k (MeV/u)

F_{rf} (MHz)



* possibly available by SFC-5.49MHz



Present Status of HIRFL Complex in Lanzhou

UPGRADING OF INFRASTRUCTURE





- HIRFL was built-up in 3 periods, lasting about half century.
- Under strong support of the **national maintenance and renovation budget** for large scale fundamental science and technology facilities from CAS, many aspects of the infra-structure of HIRFL were upgraded or renewed to improve the operation stability and reduce the failure time:
 - Power station for SSC and beam lines to terminals
 - Water cooling system
 - Intranet
 - EMC environment of CSRe and RIBLL2
 - Environment control
 - The power supply rooms of CSR
 - New monitoring systems of water-cooling, power station and water leakage detection
 - Radiation protection system





New Power Station for SSC and beam lines to terminals



New grid technology used to improve the reliability, safety and energy efficiency.





Goals

- Pressure stability → $\leq 0.5 \text{ kgf/cm}^2$
- High water resistance → $\geq 1 \text{ M}\Omega \cdot \text{cm}$
- Real-time monitoring.

Actions

- Replace packing pumps by vertical multistage centrifugal pumps
- Centralized management (3 in 1) of Frequency Conversion pumps by PLC
- New RO + EDI with Polishing Resin Bed.

Results

- Pressure stability: $\pm 0.25, \pm 0.1, \pm 0.45 \text{ kgf/cm}^2$
- Inner water resistance: $> 2, 1.2, 3 \text{ M}\Omega \cdot \text{cm}$ (SFC, SSC, CSRm)
- Space saved by 40% for inspection and maintenances
- Power consumption reduce by 11%
- Soft switch on & off of bumps

Real time monitoring device status and parameters, failure alert.....





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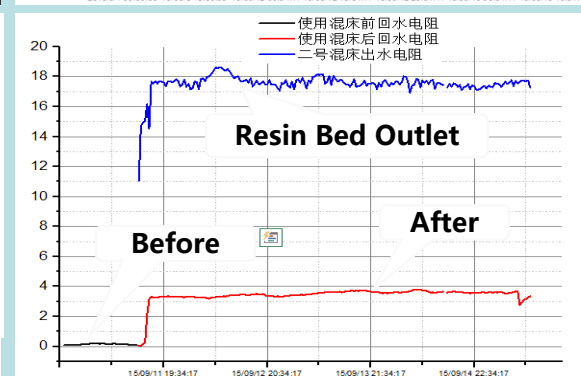
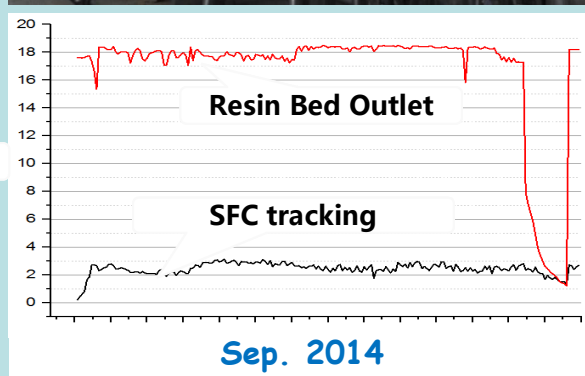
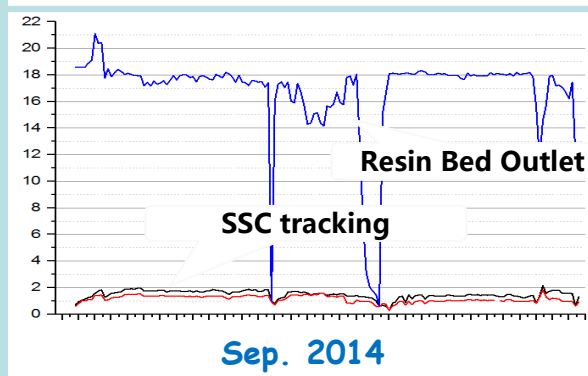
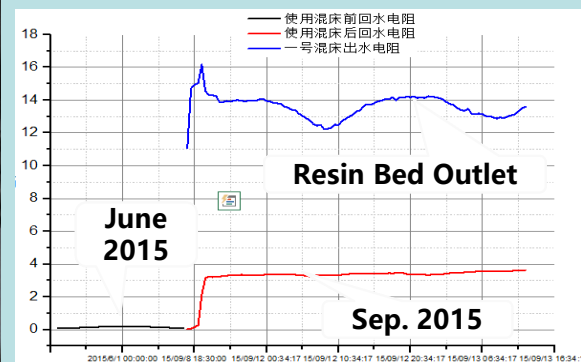
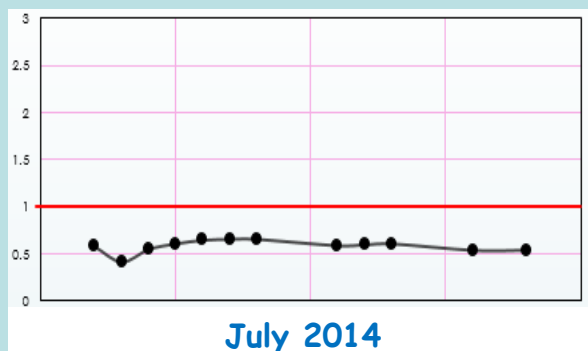
Real time monitoring device status and parameters, failure alert.....





- RO+EDI with Polishing Resin Bed → resistance improved obviously + Less water consumption

Water resistance ($M\Omega \cdot cm$)



SSC (1 resin bed)

- BEFORE: 0.38 — 0.66 $M\Omega \cdot cm$,
- AFTER: 1.2 — 1.7 $M\Omega \cdot cm$,

SFC (1 resin bed)

- BEFORE: 0.4 — 0.72 $M\Omega \cdot cm$,
- AFTER: 2.2 — 3.1 $M\Omega \cdot cm$,

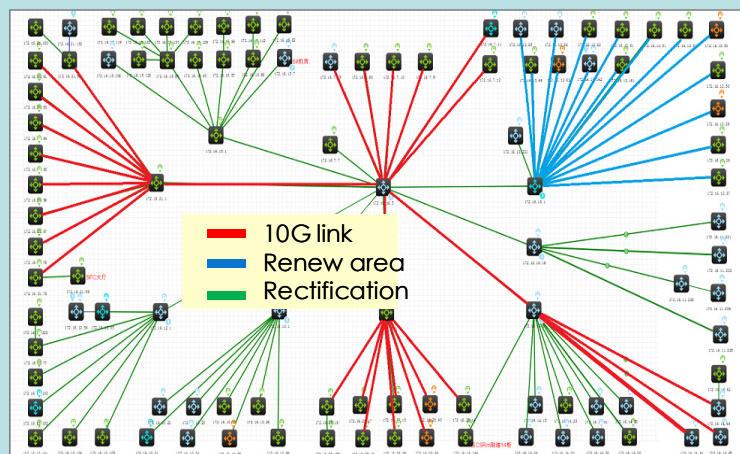
CSR (2 resin bed)

- BEFORE: 0.08 — 0.12 $M\Omega \cdot cm$,
- AFTER: 3.2 — 3.9 $M\Omega \cdot cm$,

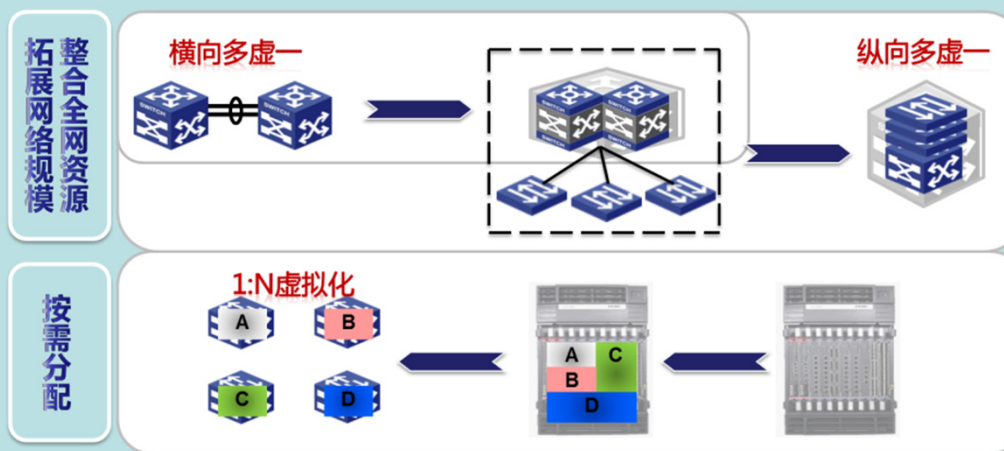




- The backbone: 100 M → 10 G bandwidth
- Physical link network topology optimization
- Network expansion with virtualization tech.



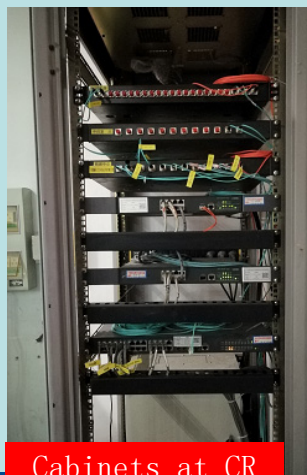
Physical link network topology



Virtualization technology



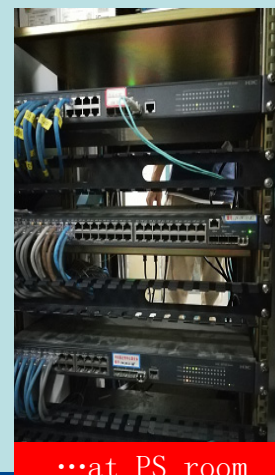
Control room



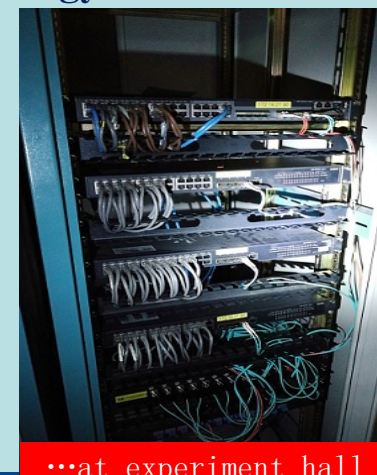
Cabinets at CR



...at SSC



...at PS room



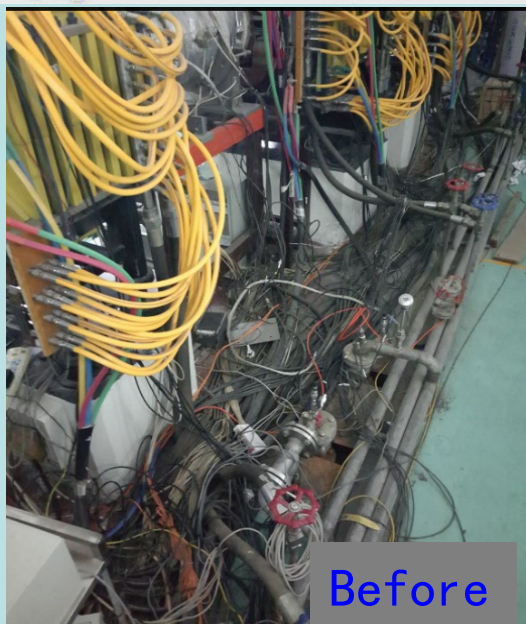
...at experiment hall





- The signal cables and power cables of CSRe and RIBLL2 were rearranged and rewired to reduce the EMI and improve the EMC environment.
- The background noise levels of beam diagnosis and experiment detectors were reduced by more than one order.

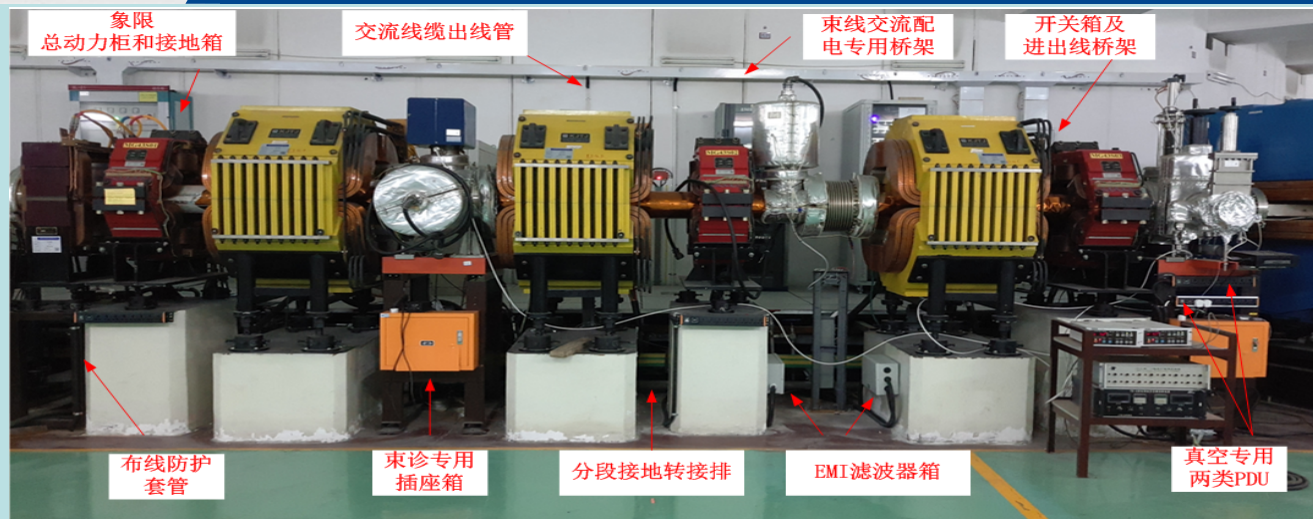




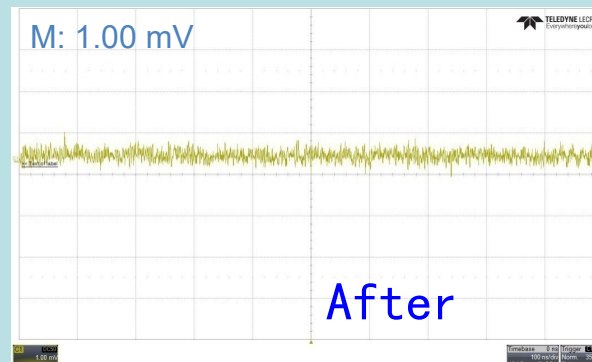
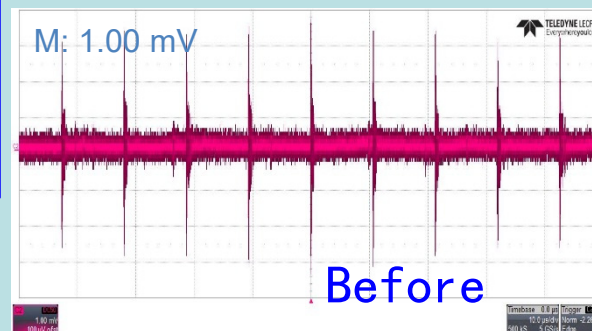
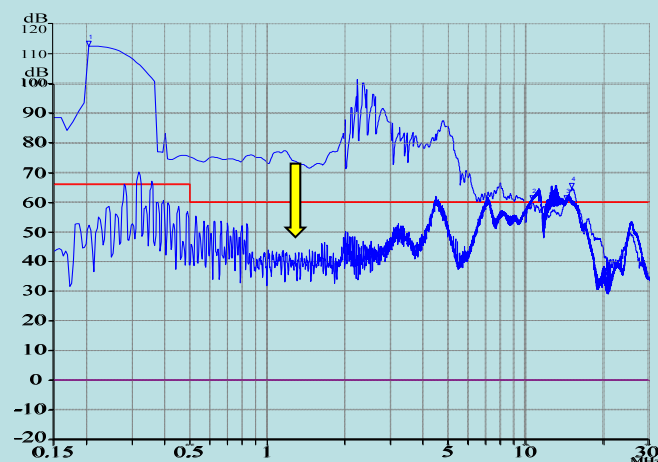
Before



After



- ✓ Overall noise level $< 0.5\text{mV}_{pp}$, reduces (30dB)
- ✓ VN-PE ~ 0 Volt





- **New power supply rooms for CSRm and CSRe inside the CSR hall**
- **New monitoring systems of**
 - **water-cooling**
 - **power station**
 - **water leakage detection**
- **The radiation protection system partly rebuilt.**

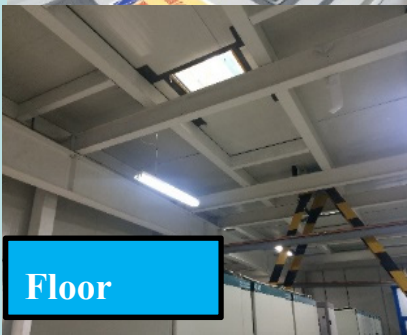




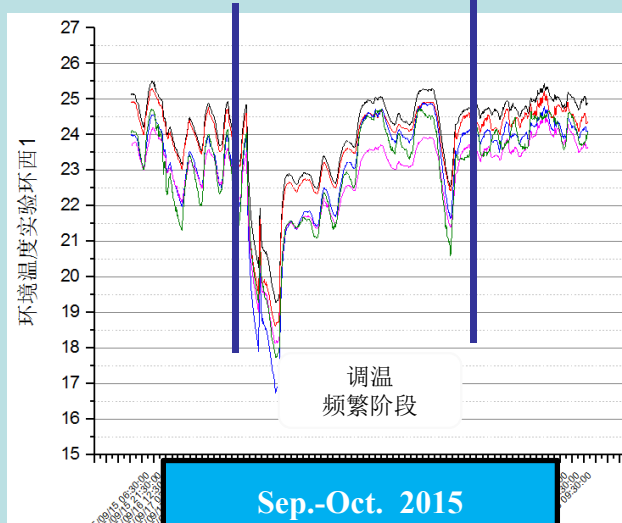
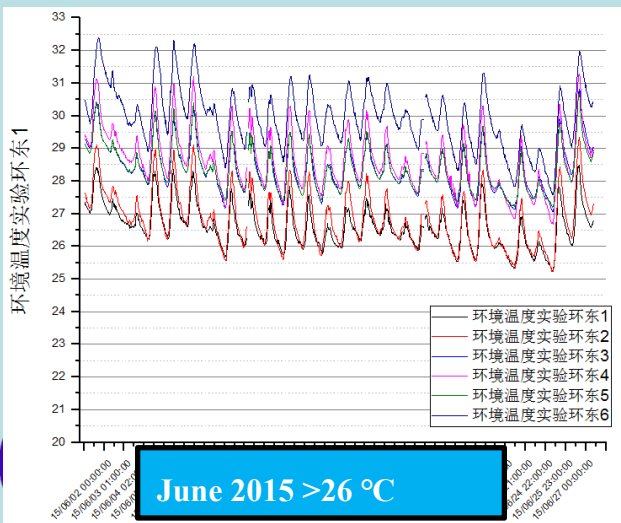
Top view



Conditioner



Floor



Results T/24h

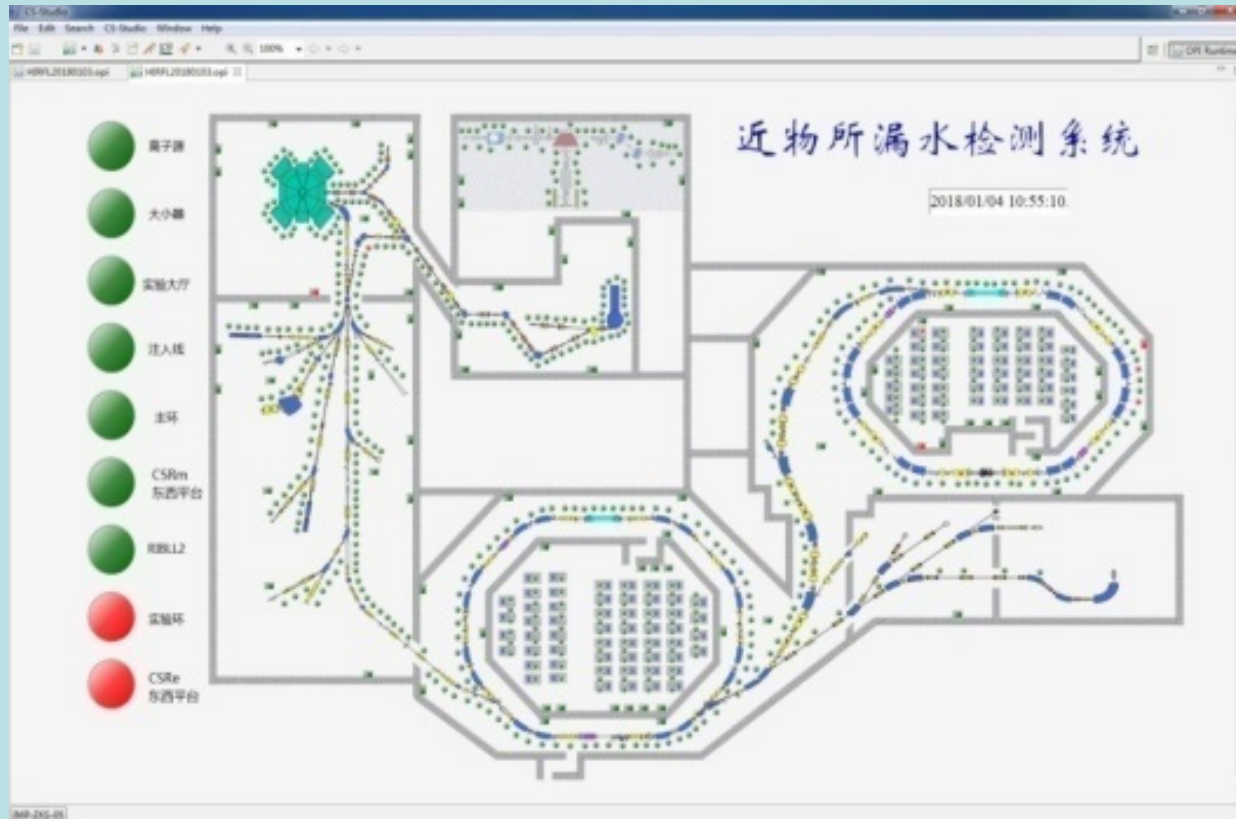
Design: $\pm 2^\circ\text{C}$

Before: $\pm 2.5^\circ\text{C}$

After: $\pm 1.5^\circ\text{C}$

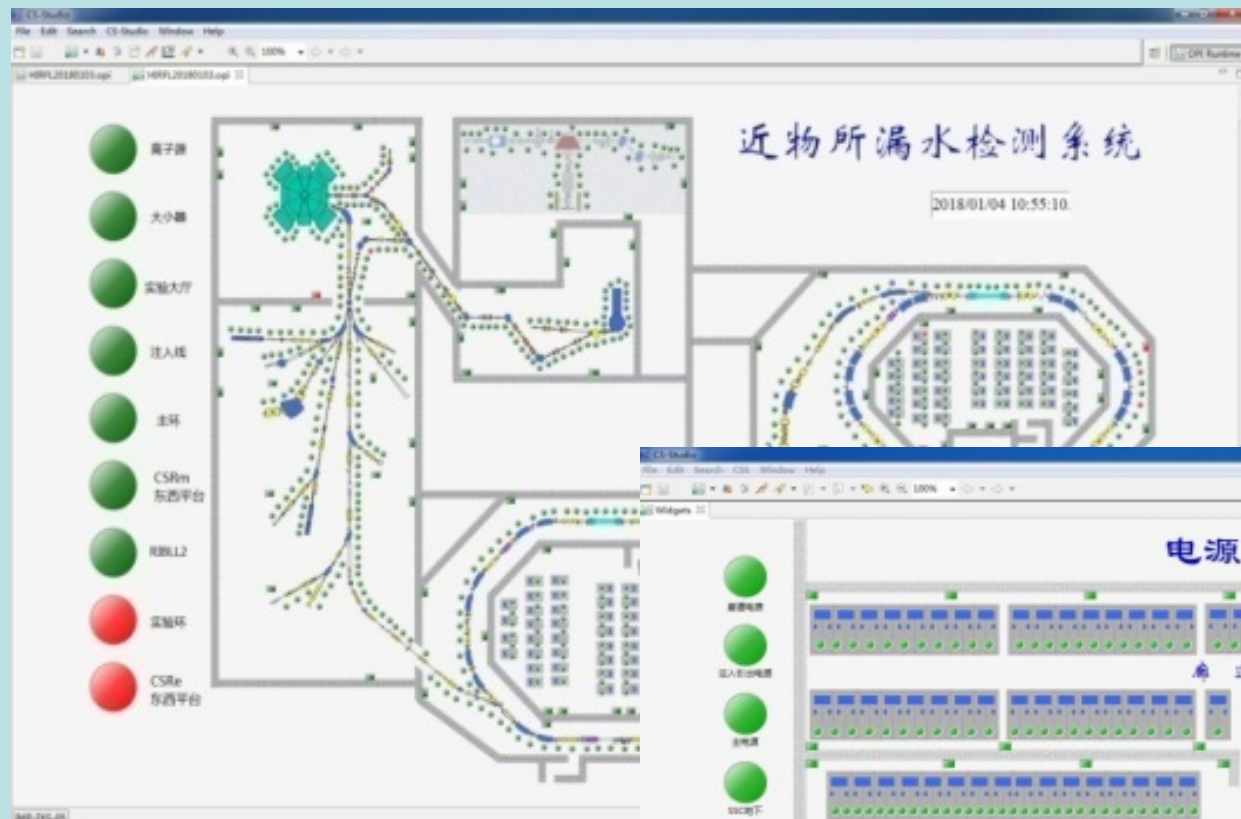


Detection points distributed along beam lines, at PS rooms and terminal areas.





Detection points distributed along beam lines, at PS rooms and terminal areas.





Present Status of HIRFL Complex in Lanzhou

IMPROVEMENT OF PERFORMANCE





- The self-developed distributed control system of HIRFL was developed in many years part by part, and based on many kinds of platforms.
- In last years, the open-source **Experimental Physics and Industrial Control System (EPICS)**, developed at LANL and ANL, was adapted to take over most of the control system of HIRFL.

EPICS

HOME ABOUT NEWS AND EVENTS RESOURCES AND SUPPORT EPICS USERS CONTACT US LOG IN

FREE AND OPEN SOURCE
DEVELOPED COLLABORATIVELY
POWERFUL AND RELIABLE

FREE AND OPEN SOURCE
EPICS is developed as a public open source project. The source code is freely available according to the EPICS Open License.

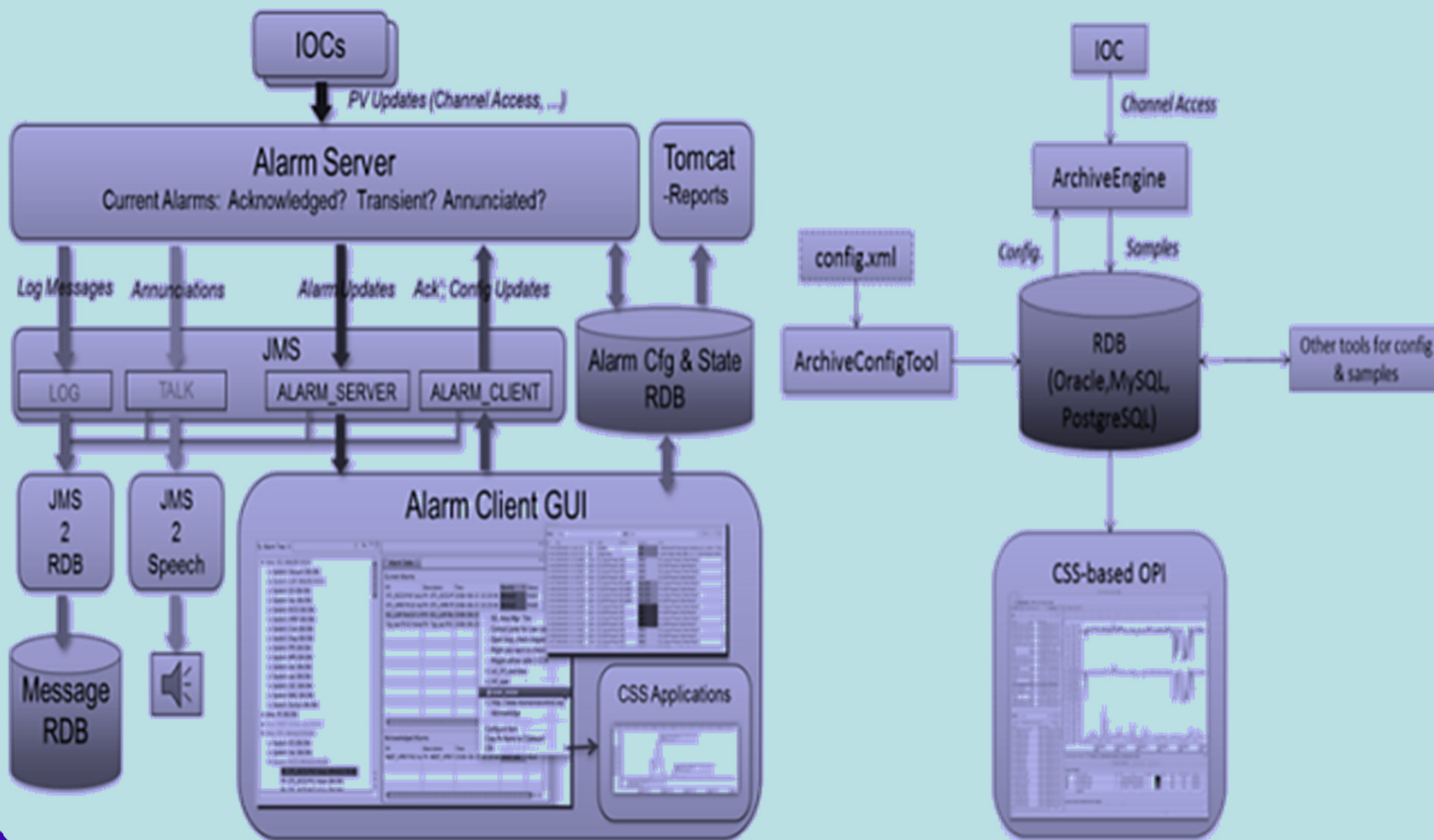
DEVELOPED COLLABORATIVELY
EPICS was created through collaborative contributions from scientific facilities since a long time. It is the preferred choice for complex, large scale distributed control system applications.

POWERFUL AND RELIABLE
The launch of EPICS 7 marks the biggest change of the EPICS code base for over 10 years. The new, feature-rich pvAccess protocol enables many new applications with unprecedented performance and capacity.
[Read more](#)





The structure of new control system



Control and monitor

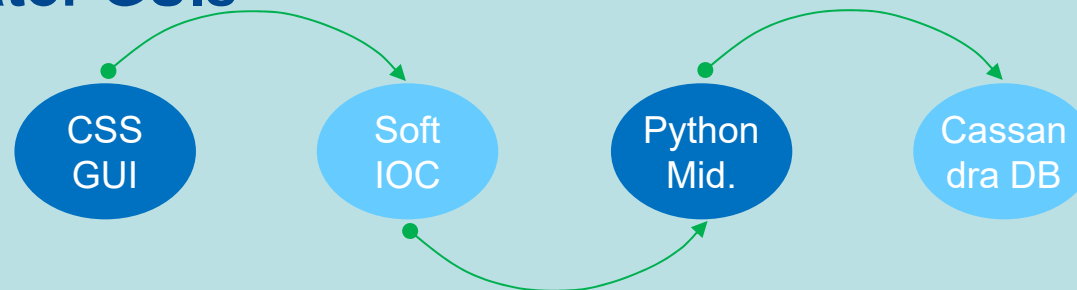
Data Archive





Properties and Results

- Whole substitution of previous system
- Rearranged local controllers and rewire cables
- Big data volume transfer and monitor
- Direct data archive system based on MongoDB, no influence on operator GUIs



- New CSRm injection inflector and User Interface
- New control system for e-cooler instead of the hardware attached one
- The LLRF of cyclotron RF systems and new CSRm RF controller were rebuilt





CSS + Soft IOC + Python **will replace** previous VB Version

HIRFL-CSR Virtual Accelerator

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

Load Acc: Ar 40 氩 12 + of 18 Mass 39.955800165240000

Virtual Accelerator | Ramping Data | RF Data

Save to: **Fast Extraction** **Slow Extraction** **Reload**

Injection	Mid Flat Top	Extraction	Final
Energy[MeV/u]: 6.2180	Energy[MeV/u]: 25.0000	Energy[MeV/u]: 389.2000	Energy[MeV/u]: 400.0000
Part_B_Rho[Tm]: 1.197379527697060	Part_B_Rho[Tm]: 2.412945459508321	Part_B_Rho[Tm]: 10.398402446231275	Part_B_Rho[Tm]: 10.566934296919770
Delt R[mm]: -1.7000	Delt R[mm]: -1.7000	Delt R[mm]: 6.0000	Delt R[mm]: 1.8000
RF Harmonic No.: 2.0000	Frequency[MHz]: 0.845935451689089	RF Harmonic No.: 1.0000	RF Harmonic No.: 1.0000
Frequency[MHz]: 0.428187835377754	Vrf1 [kV]: 1.8000	Frequency[MHz]: 1.319702075978096	Frequency[MHz]: 1.330431287811890
Vrf [kV]: 1.5000	Vrf2 [kV]: 1.8000	Vrf [kV]: 1.5000	Vrf [kV]: 1.5000
Qh: 3.6220	Qh: 3.6150	Qh: 3.6180	Qh: 3.6200
Qv: 2.6100	Qv: 2.6100	Qv: 2.6120	Qv: 2.6100
tau: 1.0000	tau: 0.0000	tau: 0.0000	tau: 0.0000
Time Ext. [Yms]: 3000	Long Q strength: 0.998	Round sections: 8 X 16 Yms	
Time Meas. [Yms]: 10000	Short Q strength: 1.007	Ext. Orbit (%): 60 %	

Calculate Dipole and RF Cavity

Calculate Quadrupoles

Preapre Data

Preapre RF

Delivery Data

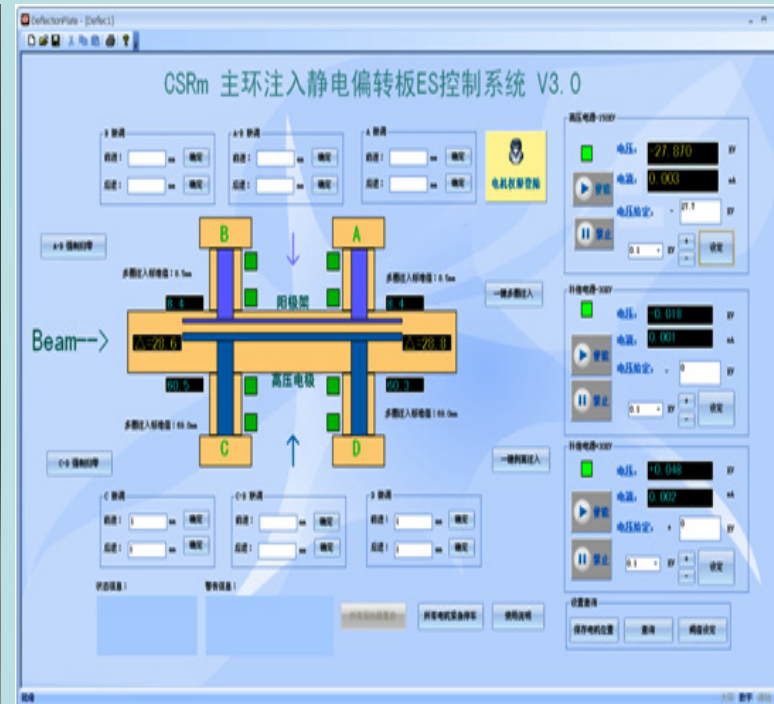
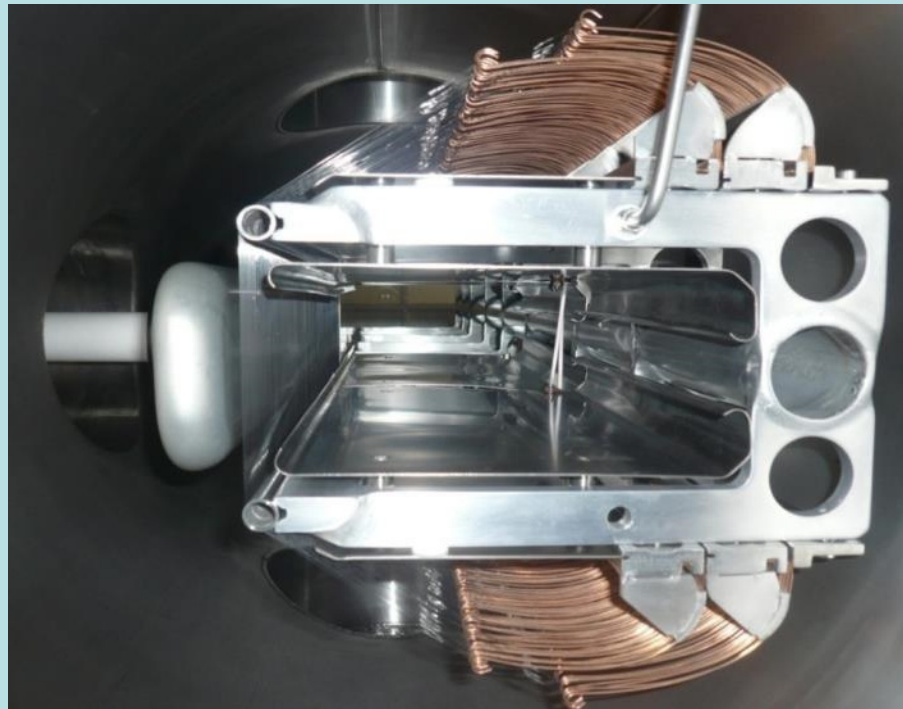
CSRm DC

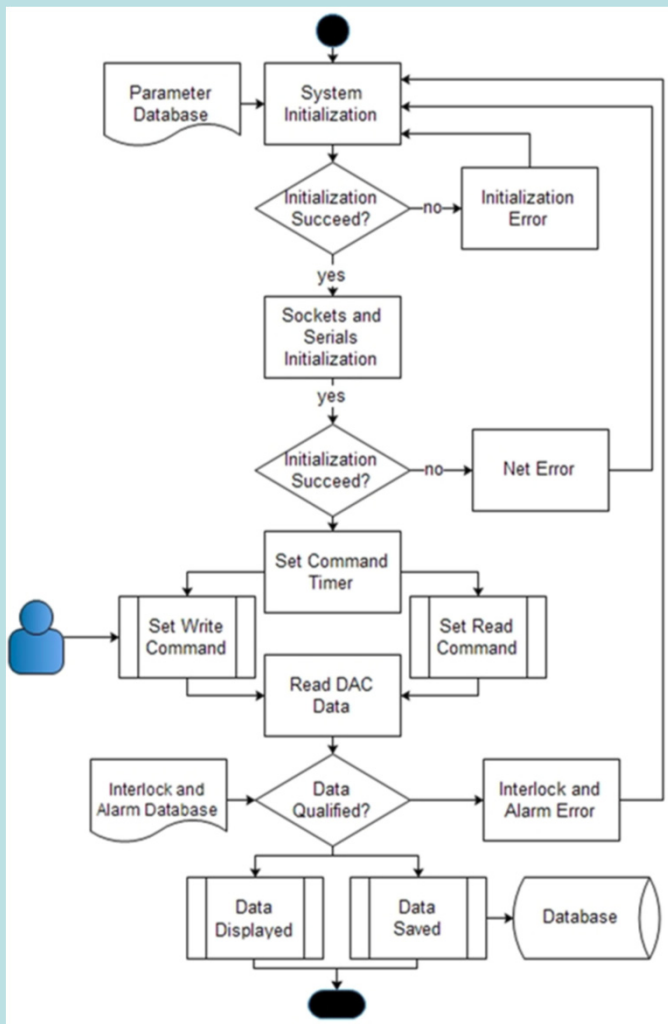
Trigger



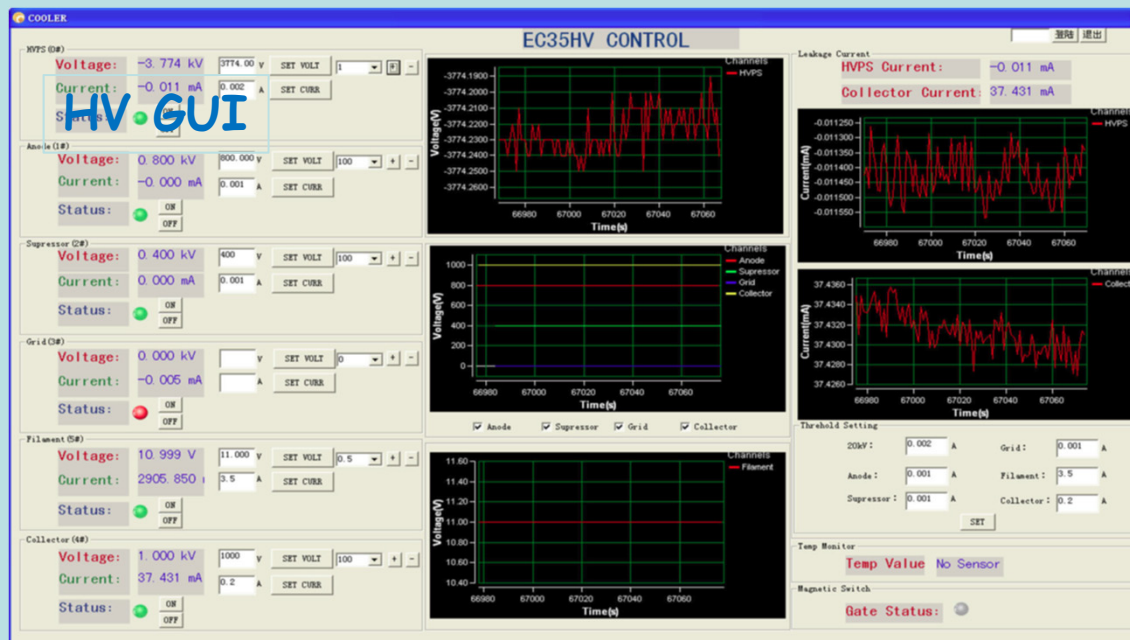
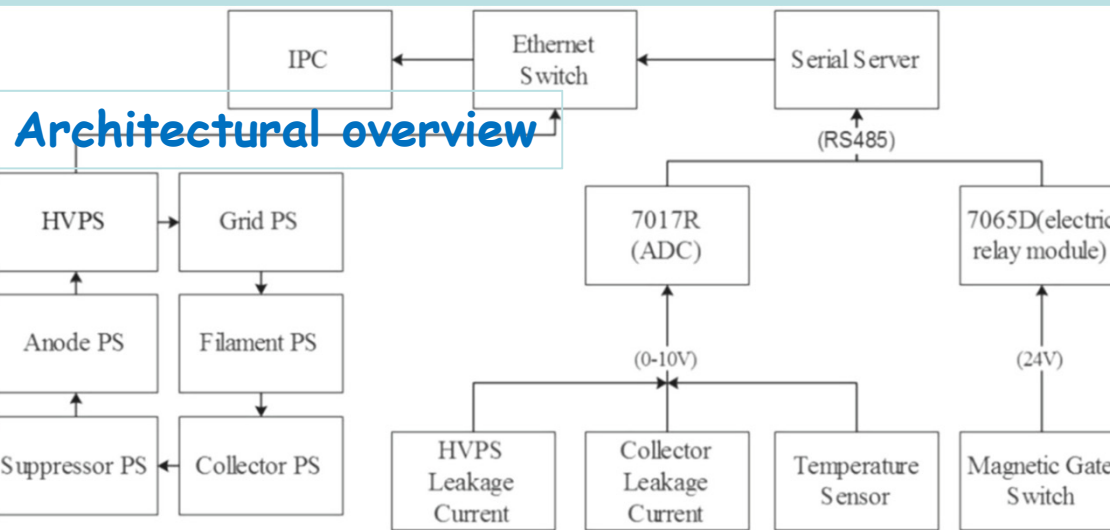


- **New** inflector for both MMI and CEI
- Saving time of breaking of vacuum ($n \times 3$ days/a)





Flowchart of software





- A new generation superconductive ECR source-SECRAL-II as a back-up of the former SECRAL with better performance was constructed and will put into operation this year.
- With new structure, higher magnetic field and works at 18 GHz / 24 GHz microwave frequency, SECRAL-II sets a new beam current record of highly charged heavy ion beams.





- Serial of ECR ISSs. Keep the state of art IS technology and world records.
- New Full SC SECRAL-II as a backup under CAS support
- **(maybe online this year!)**



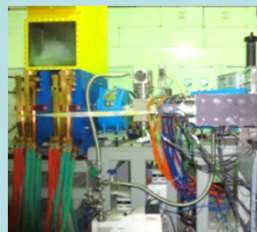
SECRAL-II features (μA)		
Ion	SECRAL-II	SECRAL
O ⁶⁺	6700	2300
Ar ¹⁴⁺	1040	846
Ar ¹⁶⁺	620	350
Ar ¹⁸⁺	15	0.2
Kr ¹⁸⁺	1020	304
Kr ²⁸⁺	146	4
Xe ³⁰⁺	365	360
Xe ³⁸⁺	56	22.6
Xe ⁴⁵⁺	1.3	0.1
Ta ³⁰⁺	375	/
Ta ³⁸⁺	204	/



RT LECR2 & 3
1997-2001
CAS Prize



PM LAPECR2
2004-2006
"Geller Prize"



EV cooling
LECR4
2010-2014



Low RF power
@18 GHz 65

Dual RF feeding
@18 GHz + 18 GHz 180

Low RF power
@24 GHz 242

Dual RF feeding
@24 GHz + 18 GHz 396

New oven & new components
@ 24 GHz + 18 GHz 680

SC SECRAL-II 1000
@24 GHz + 18 GHz

2014-
World
record

2012-2013
World
record

2010-2011
World
record



Full SC SECRAL I&II
2000-2006, 2012-2016
National Prize,
"Brightness Award"

2006

2008

2010

2012

2014

2016

2018



- Serial of ECR ISSs. Keep the state of art IS technology and world records.
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Xe ⁴⁵⁺	1.3	0.1
Ta ³⁰⁺	375	/
Ta ³⁸⁺	204	/

Highly charged ECR ion source development at IMP, L.T. Sun at this conference



RT LECR2 & 3
1997-2001
CAS Prize



PM LAPECR2
2004-2006
"Geller Prize"



EV cooling
LECR4
2010-2014



Low RF power
@18 GHz 65

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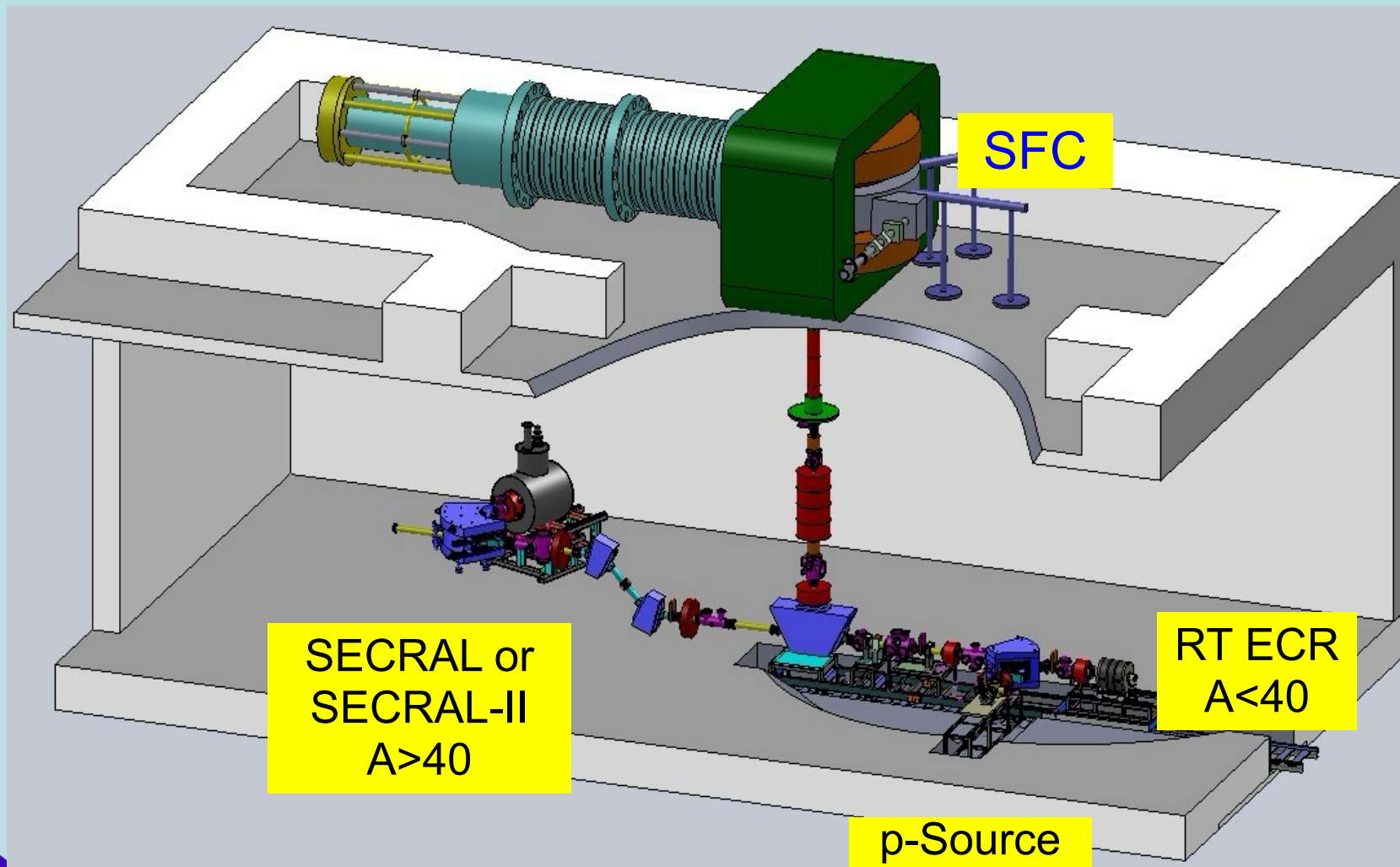
2010

2012

2014

2016

2018





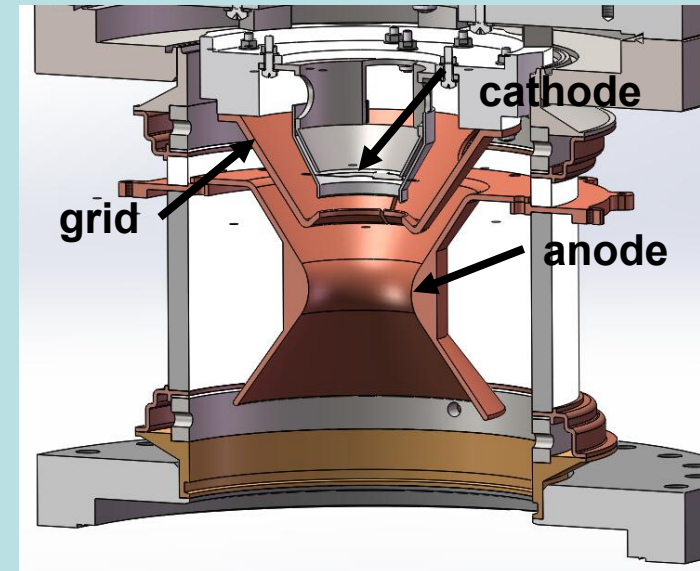
- Pulsed Electron Cooling Experiments of electron cooling with pulsed electron beam are performed for the **1st** time at CSRm.
- New phenomena were observed. Be explained in theory and proved by numeric simulations.
- Important for the cooling of high energy bunched ion beam with high peak current electron cooler, at future ion circular accelerator or colliders.





Pulsed e-Beam

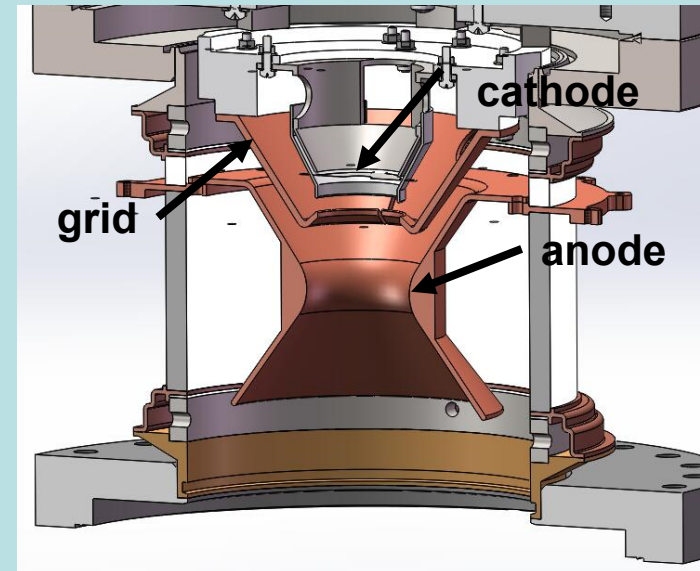
- Grid voltage is used to switch on/off e-beam → pulsed e-beam
- Timing system based on RF signal for synchronization
- DG535 is used to control the delay and pulse width



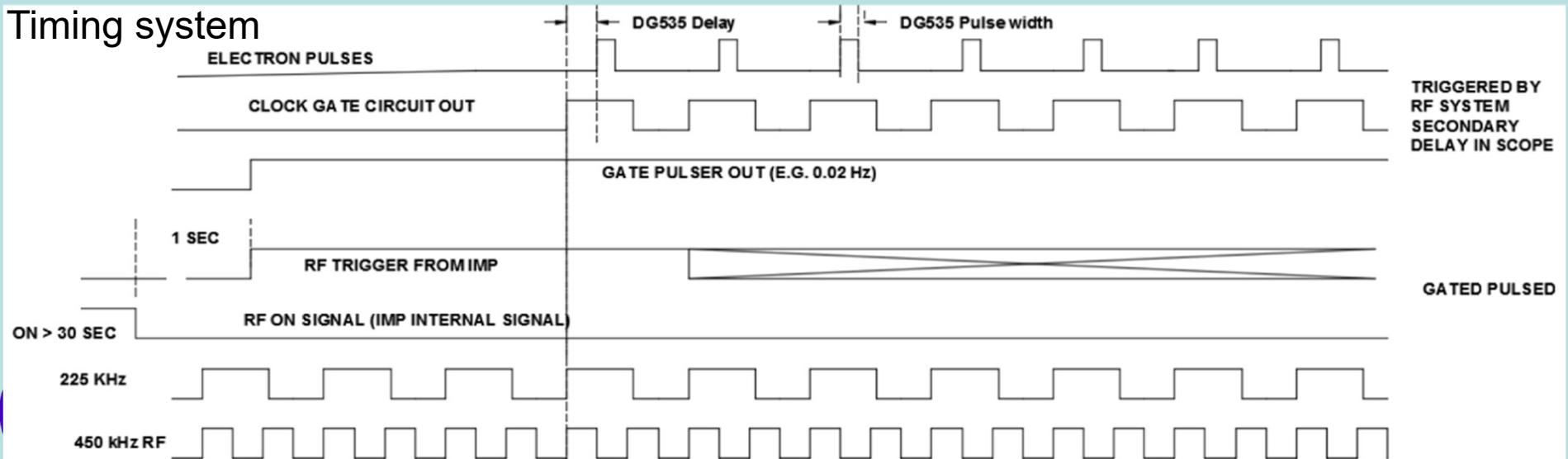


Pulsed e-Beam

- Grid voltage is used to switch on/off e-beam → pulsed e-beam
- Timing system based on RF signal for synchronization
- DG535 is used to control the delay and pulse width



Timing system



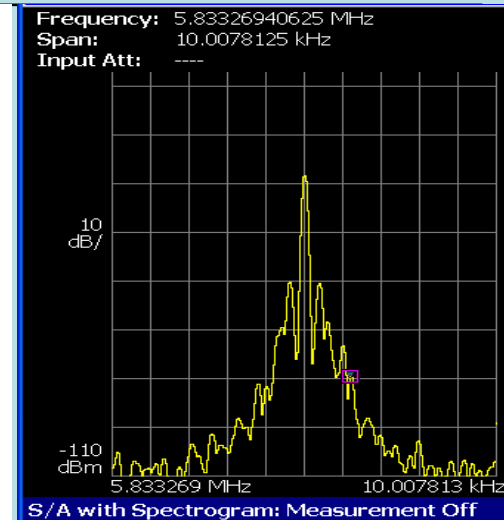
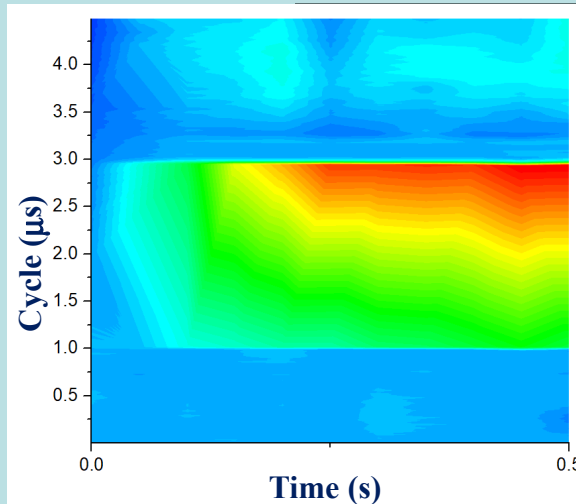


• Coasting ion beam

- Non synchronize heating effect – The freq. of e-beam should be int. or half int. of F_{rev} ion beam for a stable beam.
- Grouping effect – The ion beam cooled to a pulse with the same width of e-beam. The distribution is non-uniform.
- Sidebands – sidebands appears, similar with the synchrotron sidebands.

Exp. Parameters

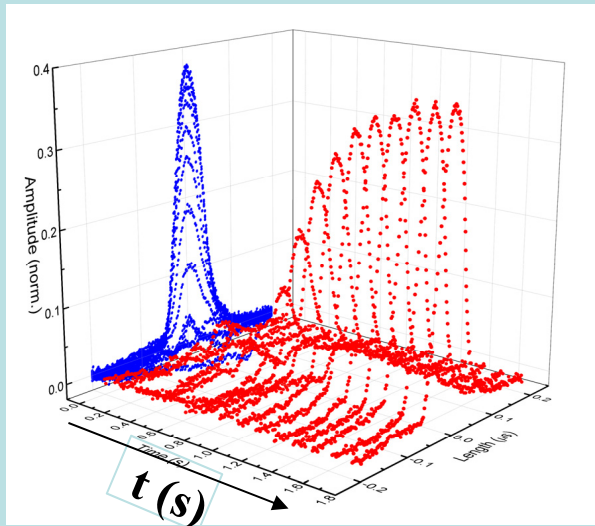
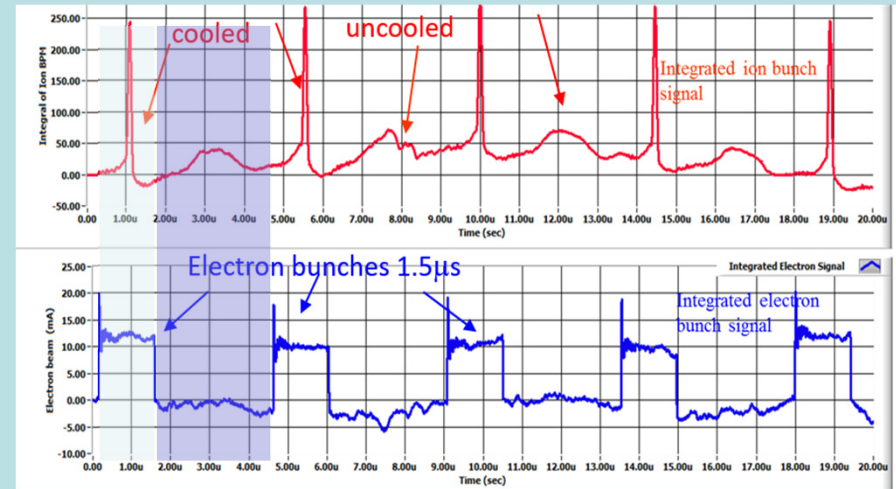
7.0 MeV/u C ⁶⁺	Coasting	Bunched
Particle number	5.0 x 10 ⁸	1.3 x 10 ⁸
Emittance (RMS)	*/*	*/*
dp/p (RMS)	2.0 x 10 ⁻⁴	7.0 x 10 ⁻⁴
Bunch length (RMS)	*	~135 ns
RF voltage	*	1.0 kV
h	*	2
E-beam current (peak)	30 mA	65 mA
E-beam diameter	~30 mm	~25 mm
Pulse width	0.5-3.0 μs	0.5-3.0 μs
Rising/falling time	10 ns	10 ns



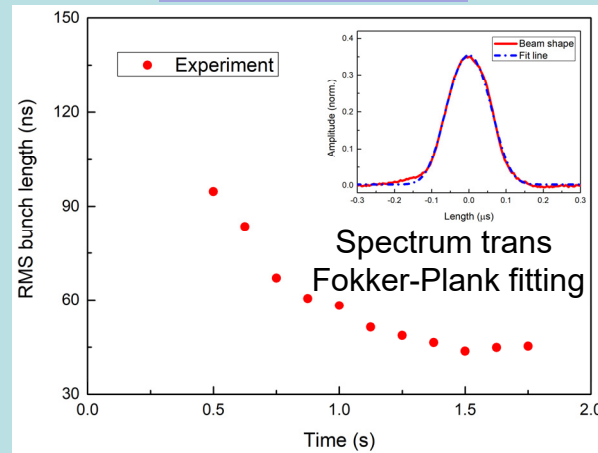


- **Bunched ion beam**
 - Cooled and uncooled ions
 - The pulse width of e-beam is larger than the ion bunch length
 - Bunch shape evolution

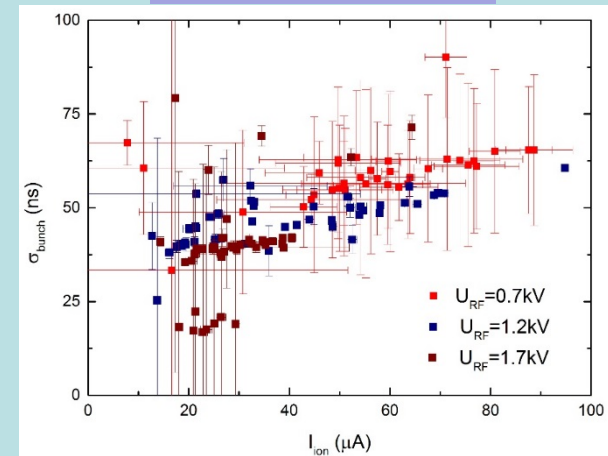
Integrated BPM signal



Cooling process

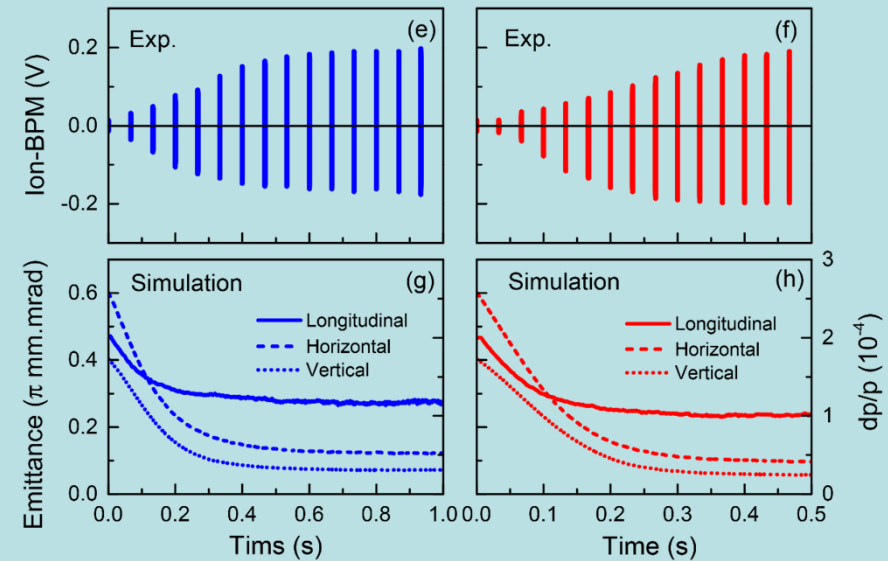
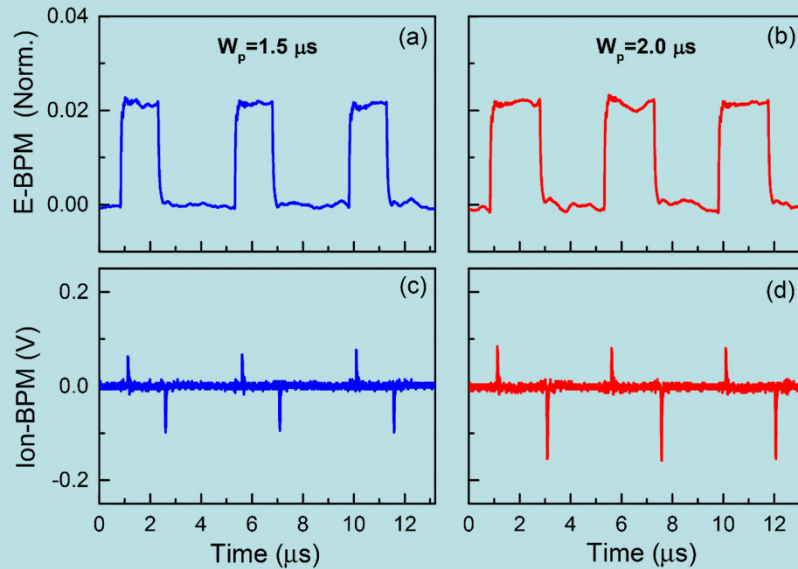
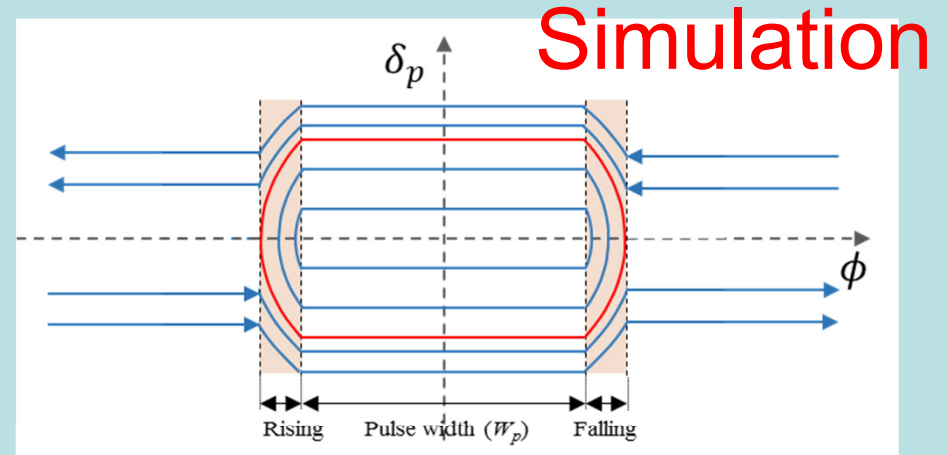


Final bunch length





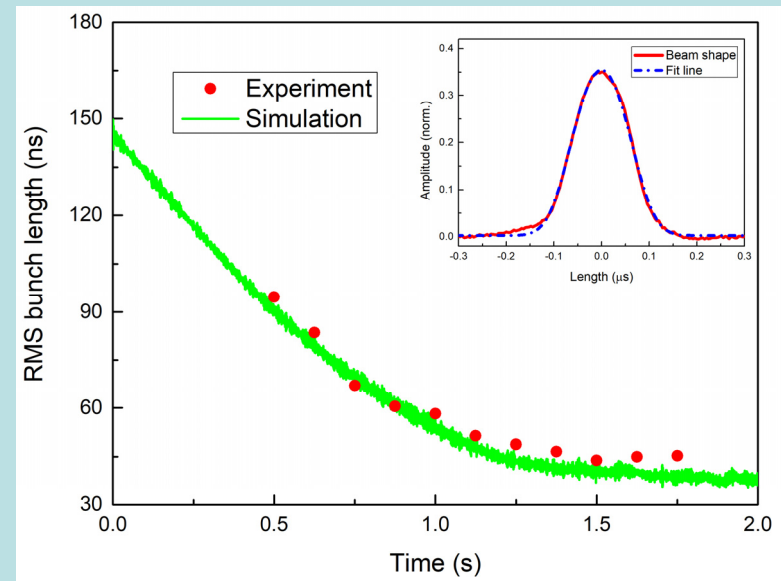
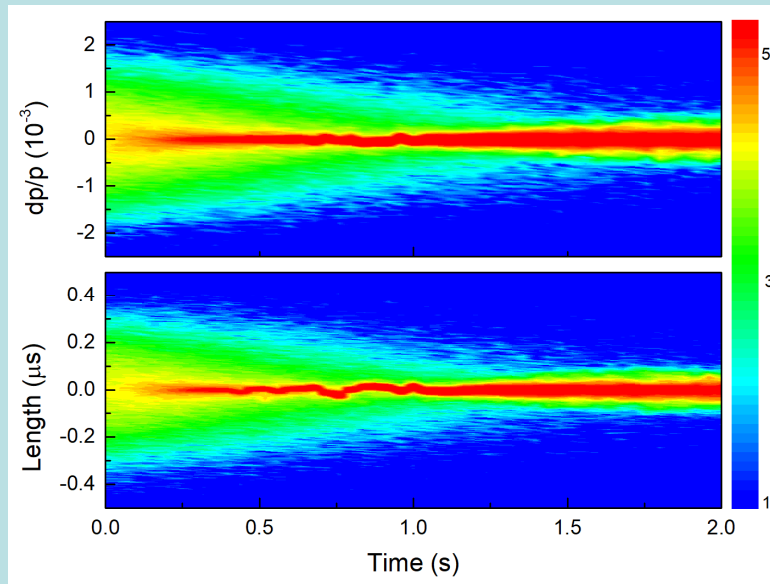
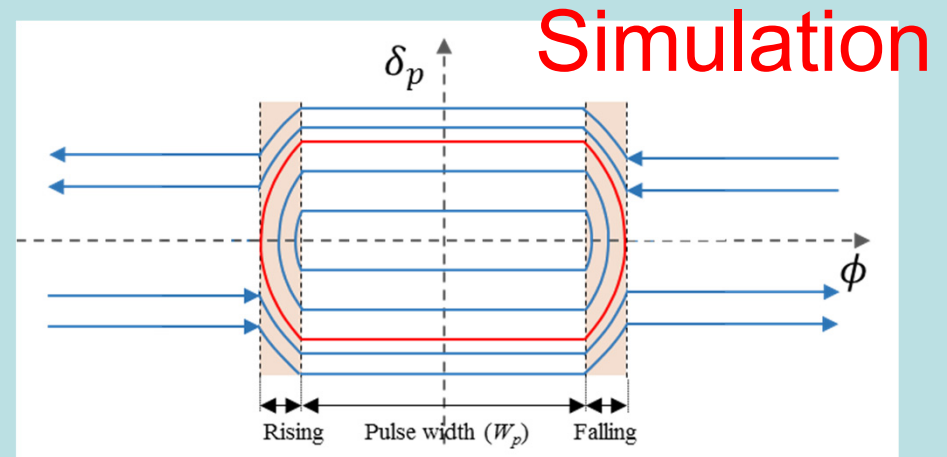
- **Simulation on Coasting Beam**
 - **e-bunch formed a barrier-bucket-like potential well**
 - **BPM signals in one cycle used**
 - **Good agreement with the meas.**





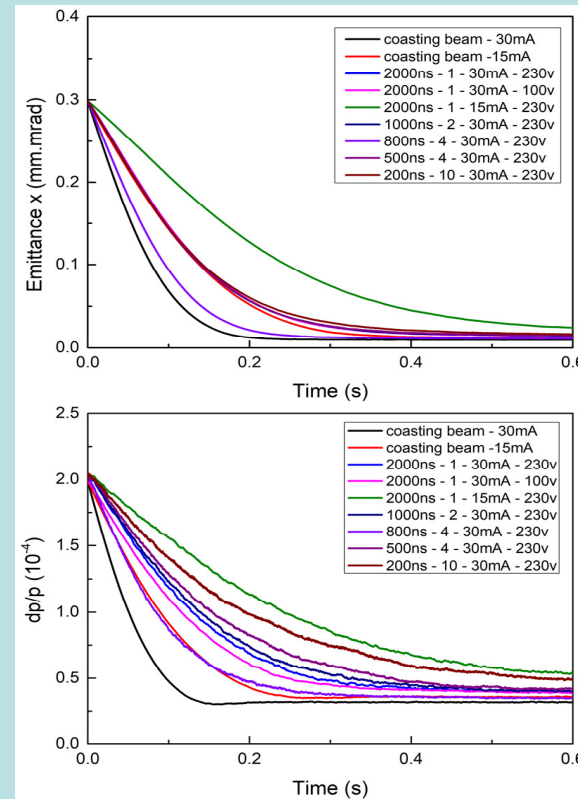
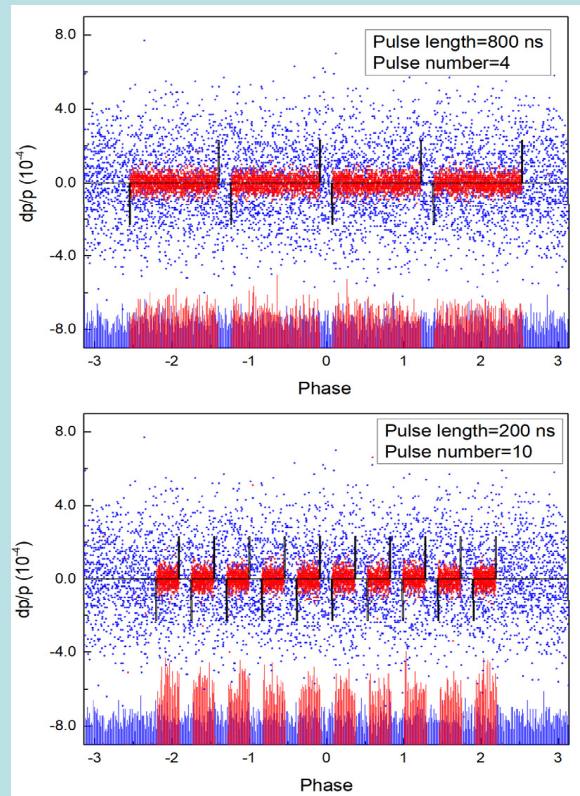
Simulation on Bunched Beam

- **e-bunch formed a barrier-bucket-like potential well**
- **Good agreement with the meas.**
- **Similar cooling process with the exp. of DC e-beam cooling**



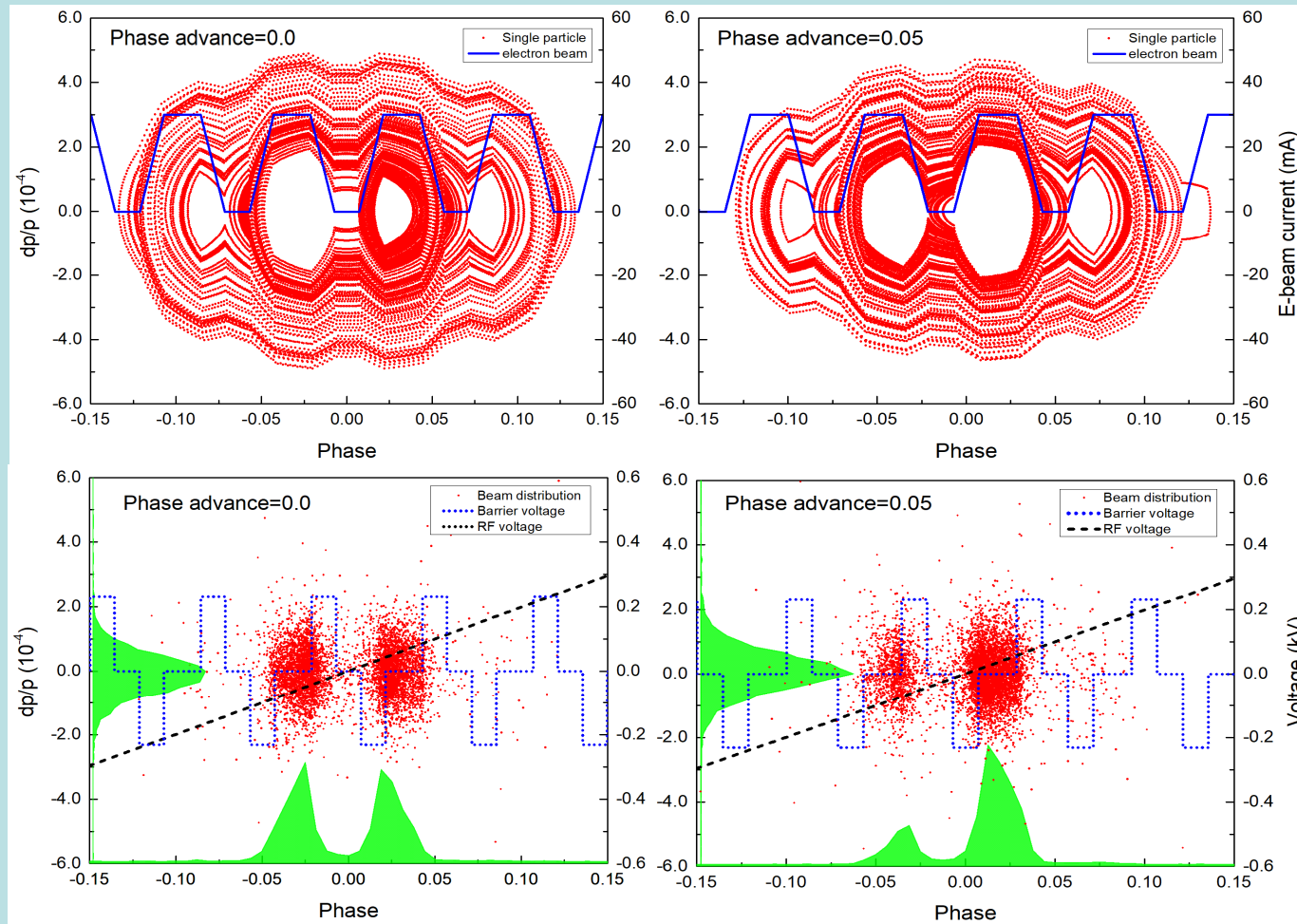


- **Multi-pulsed e-beam on coasting ion beam**
 - The ion beam is been cooled to many pulses
 - The comparison between different pulsed e-beam (No. bunches, length, duty factor, e-current)





- Short pulsed e-beam (15 ns) on bunched ion beam
 - RF bucket modulated by the barrier voltage of e-pulses





- The performance of RIBLL2 as an in-flight separator of relativistic projectile fragments was gradually improved.
- There are 8 beam profile detectors newly installed along RIBLL2 for both horizontal and vertical profiles.
- In the joint efforts of experimental teams, RIBLL2-ETF is capable of identifying clearly all ions up to $Z=30$, with the combination of the TOF and the MUSIC detectors.
- Future upgrading of RIBLL 2 was planned.



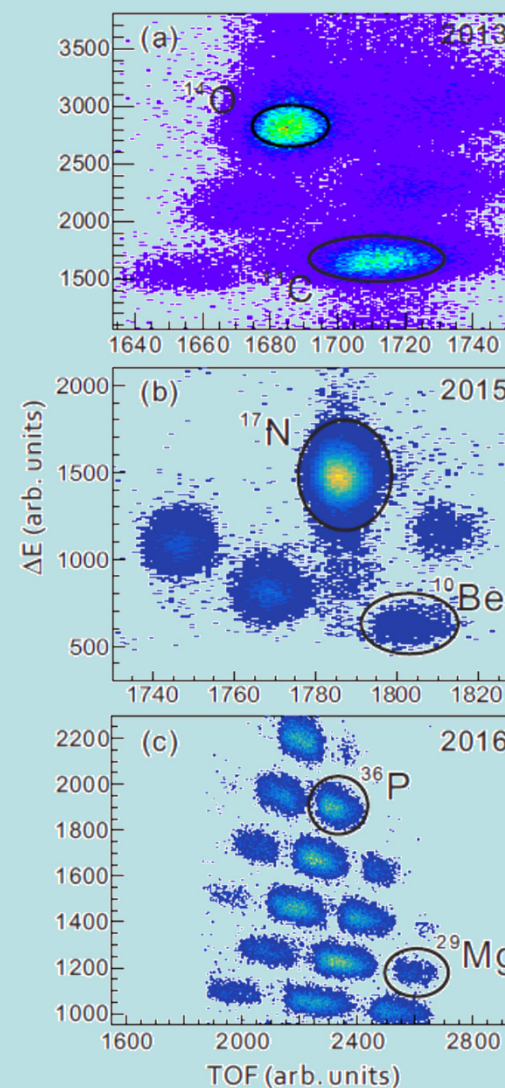
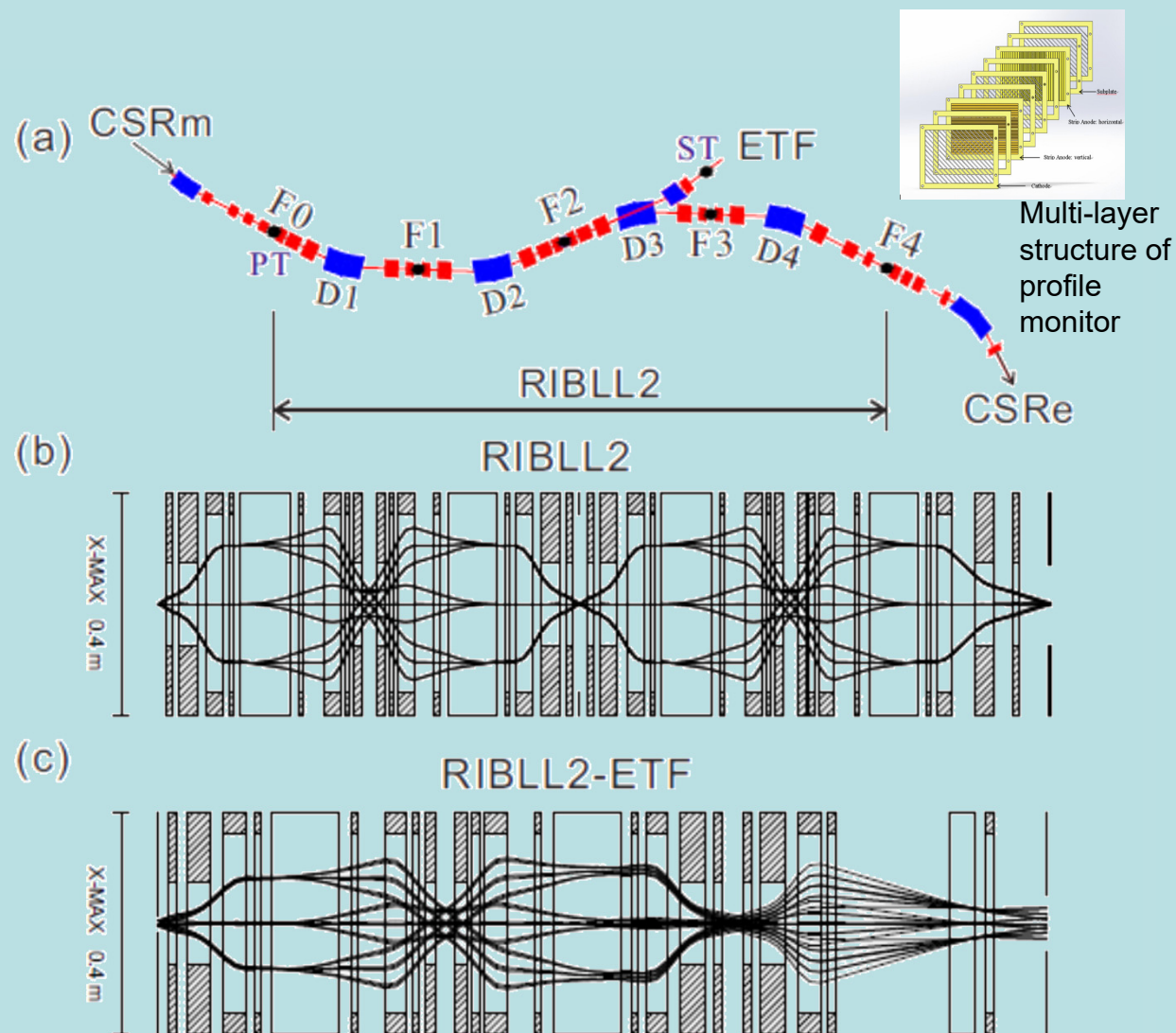


FIG. 1: (Color online) (a) A schematic layout of the RIBLL2

FIG. 2: (Color online) Typical particle identification plots of the ^{16}O , ^{18}O and ^{40}Ar fragments in three experiments performed in 2013 (a), 2015 (b) and 2016 (c), respectively.

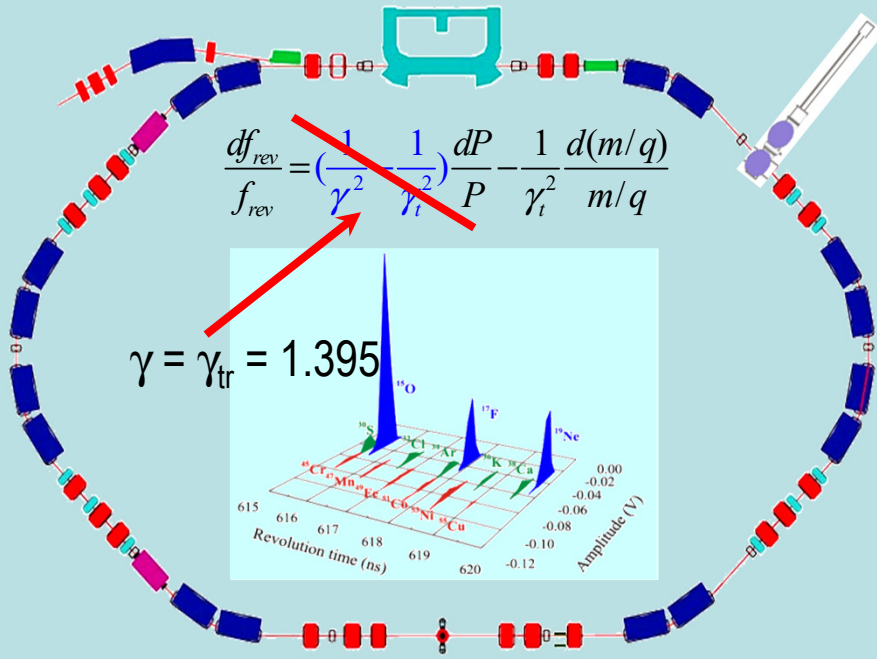


- State-of-art mass resolution of storage rings with unique two-TOF velocity measurement setups.
- Following the ISO mode mass spectrometry at ESR@GSI, we explored deeply the mass spectrometry at CSRe.
- With the improvement of EMC environment and **new dipole PS** at CSRe, the signal-noise ratio was significantly improved.
- With the new idea of two-TOF detector at storage rings (**Unique**) to measure the velocity of ions, the transition energy (γ_t), as a function of the closed orbit length or momentum deviation, can be measured precisely using the time spectra data of the ions cycling in CSRe.
- The transition energy function can be monitored and optimized **online** to ensure stable and good isochronous condition.
- With the quadrupole magnets and sextupole magnets corrections, a mass resolution of 1.71×10^5 (FWHM) was reached.
- **Nonlinear optimization** with higher order magnet field was planned.



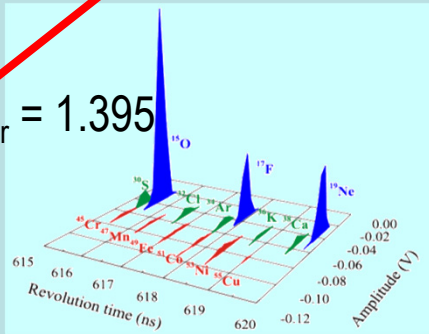


Single TOF ISO mode mass spectrometry @CSRe



$$\frac{df_{rev}}{f_{rev}} = \left(\frac{1}{\gamma^2} - \frac{1}{\gamma_t^2} \right) \frac{dP}{P} - \frac{1}{\gamma_t^2} \frac{d(m/q)}{m/q}$$

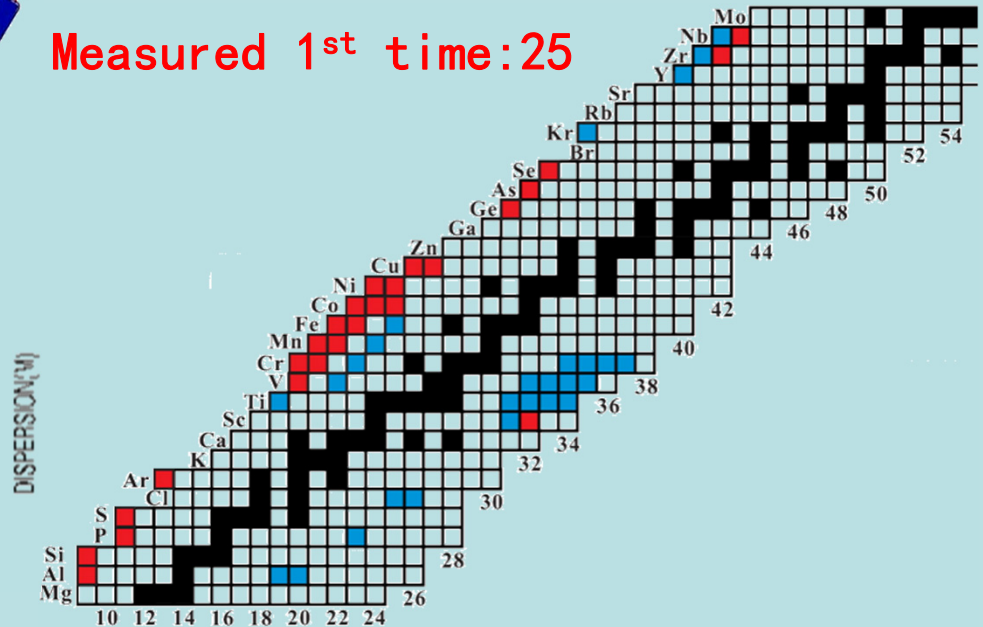
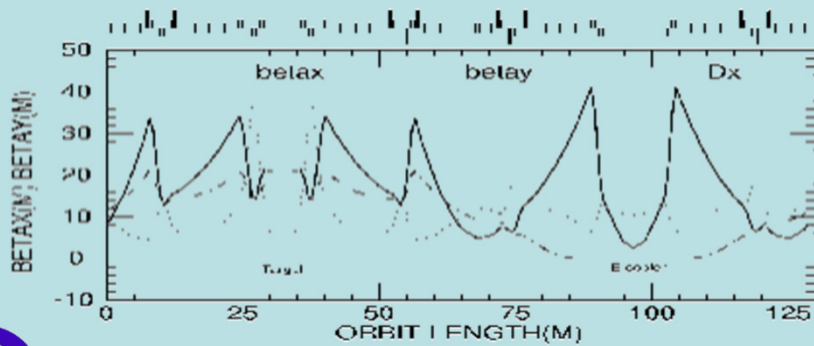
$$\gamma = \gamma_{tr} = 1.395$$



$\Delta m/m \sim 10^{-5} \sim 10^{-6}$

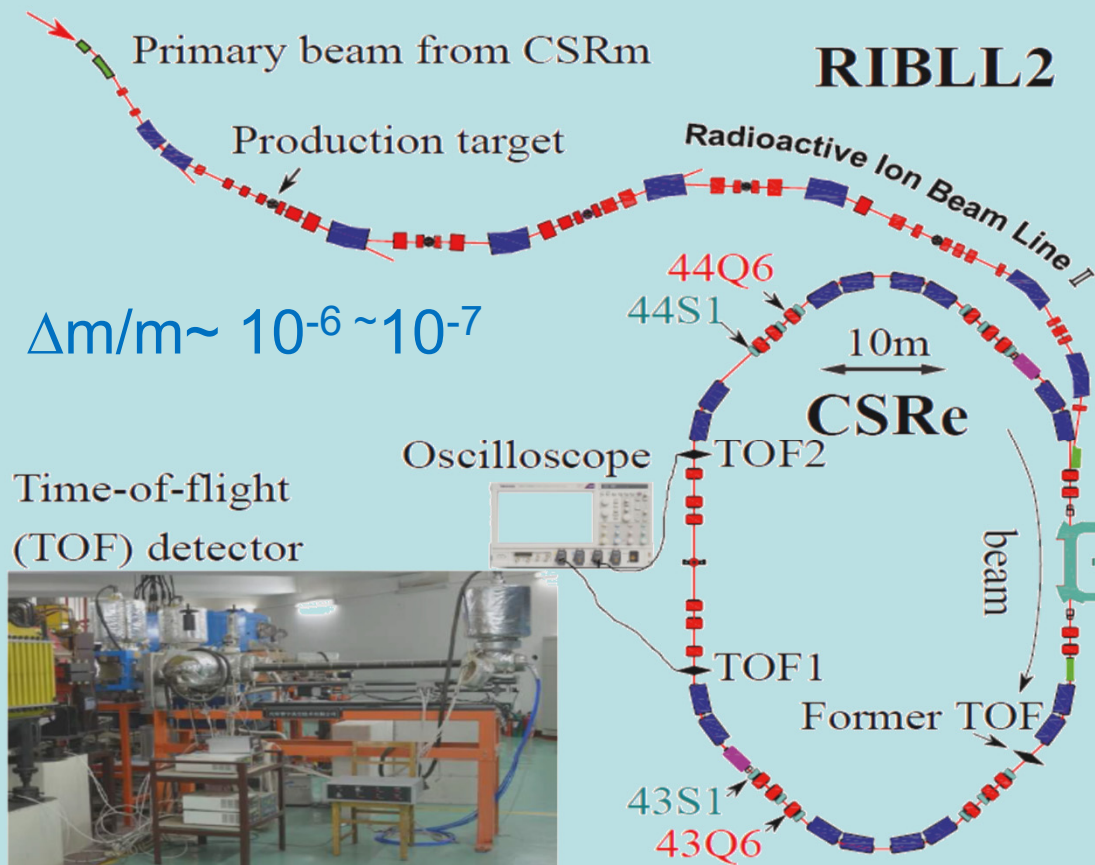
Precision improved: >50

Measured 1st time: 25



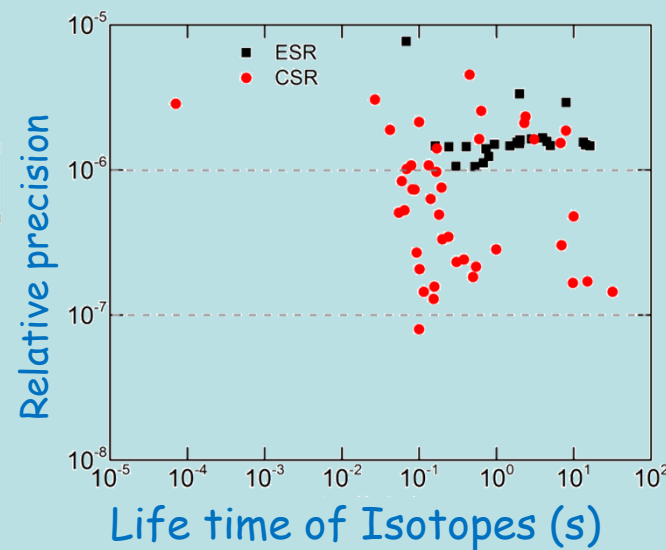
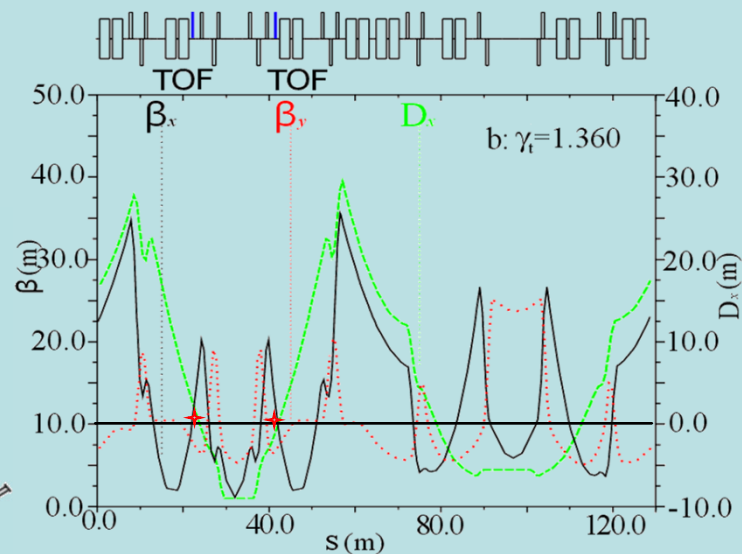


Unique Double TOF ISO mode mass spectrometry
Highest mass precision in storage rings
shortest life time rare isotope with precise mass



$$\Delta m/m \sim 10^{-6} \sim 10^{-7}$$

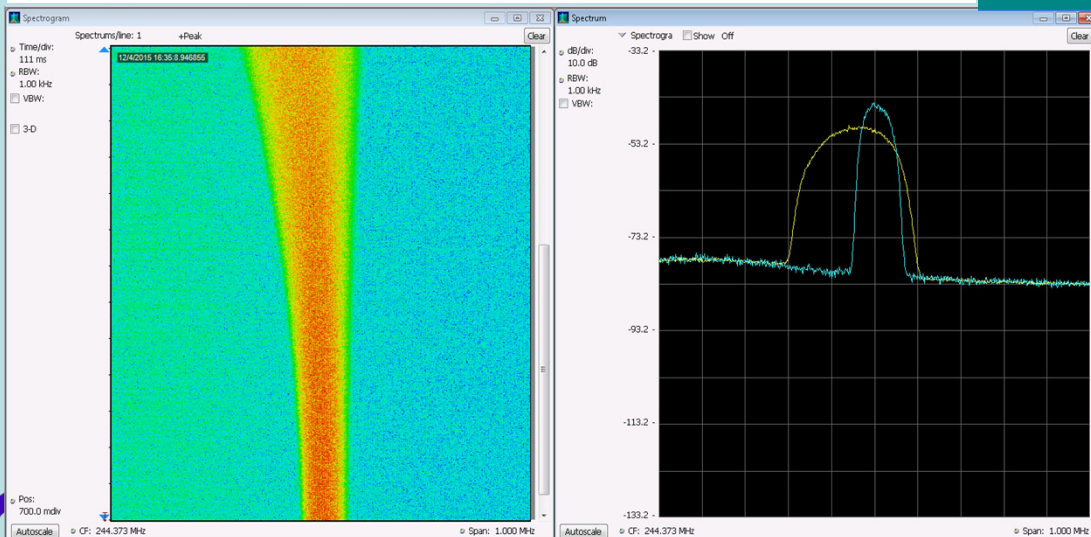
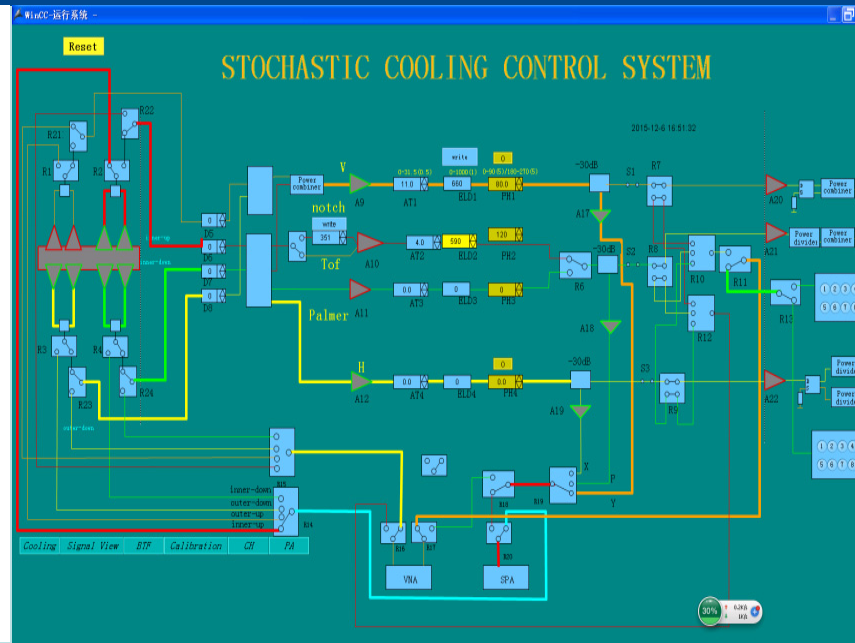
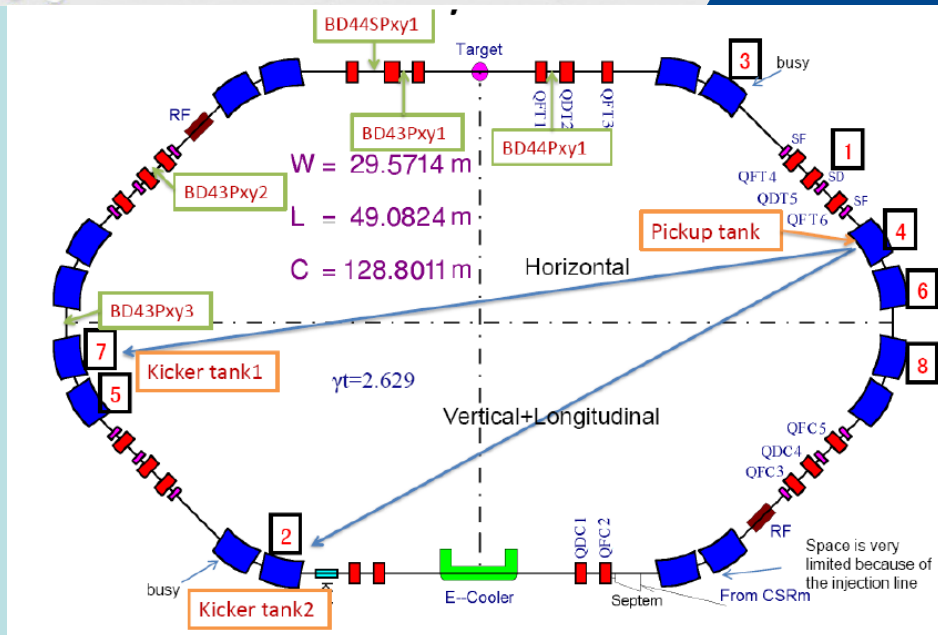
Time-of-flight
(TOF) detector





- Stochastic Cooling and Laser Cooling are realized in CSRe, which will help to extend the research ability of nuclear and atomic physics at CSRe.
- The beam after target with large emittance and momentum spread can be cooled down in seconds by stochastic cooling with slot line pickup and kickers.
- Stochastic cooling will be used in the Schottky Mass Spectrometry (SMS) experiments.
- The relativistic Li-like O^{5+} beam, with energy of 280 MeV/u, was cooled by CW laser of wavelength 220 nm recently. It's up to now heavy ions with **highest charge state** and **highest energy** that ever been laser cooled.





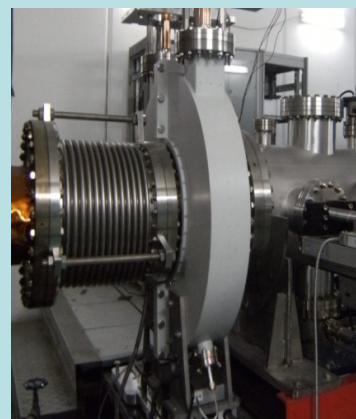
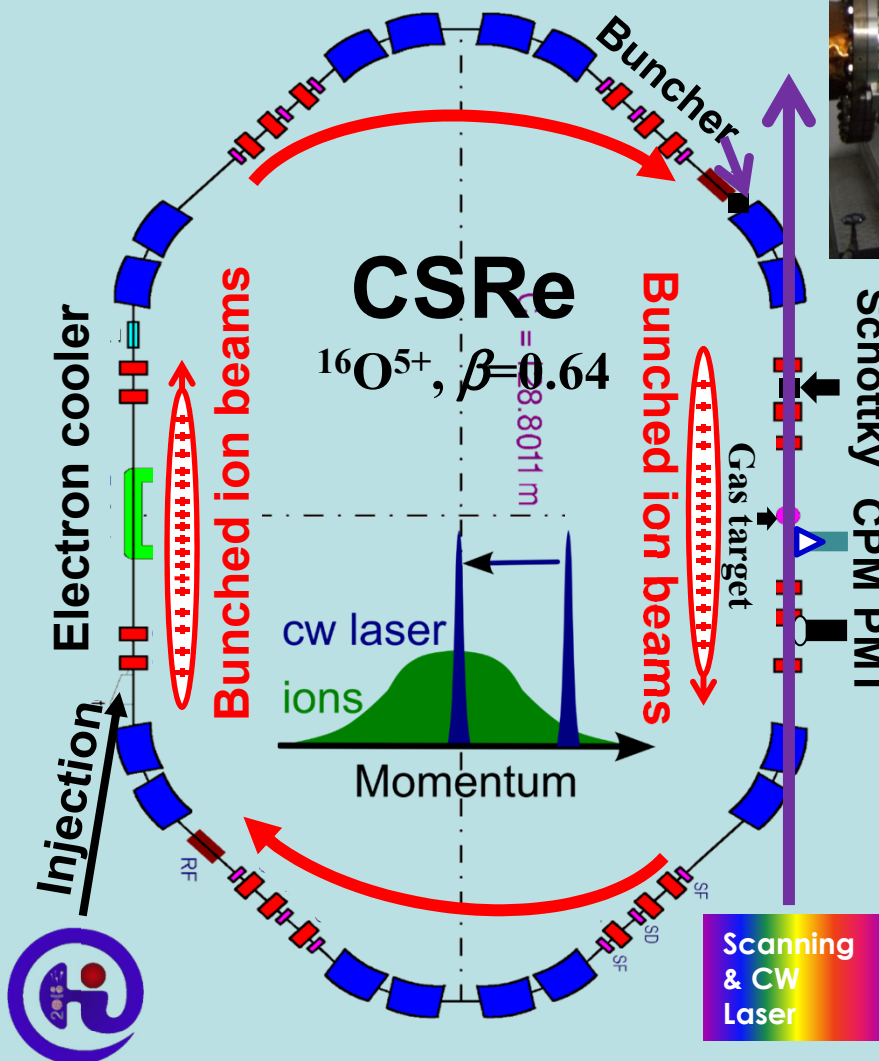
Longitudinal beam signal (380 MeV/u $^{12}\text{C}^{6+}$)



Pickup electrode

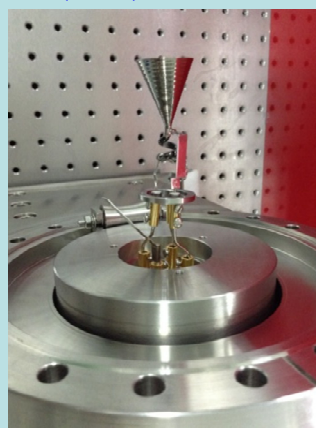


It's just a beginning...



F. Nolden, et al.,
NIMA, 659(2011)69-77

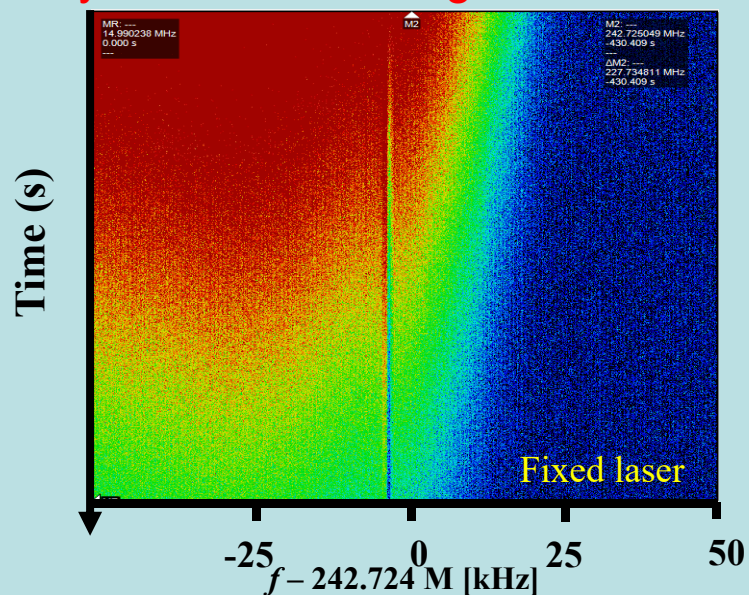
W. Wen et al., NIMA,
711(2013)90-95



CSRe parameters	
Circumference	128.80 m
Ion species	$^{16}\text{O}^{5+}$
Beam energy	275 MeV/u
Relativistic β, γ	0.64, 1.30
Revolution frequency	1.491 MHz
Transition energy γ_t	2.629
Harmonic number h	10, 15
Laser system	
Laser source	CW laser
Laser wavelength	$\lambda_{\text{laser}} = 220 \text{ nm}$
Laser power	$P_{\text{laser}} = 40 \text{ mW}$
Scanning range	$\Delta f_{\text{laser}} = 20 \text{ GHz}$
Cooling transition	
$2S_{1/2} \rightarrow 2P_{1/2}$	$\lambda_{\text{rest}} = 103.76 \text{ nm}$
$2S_{1/2} \rightarrow 2P_{3/2}$	$\lambda_{\text{rest}} = 103.19 \text{ nm}$

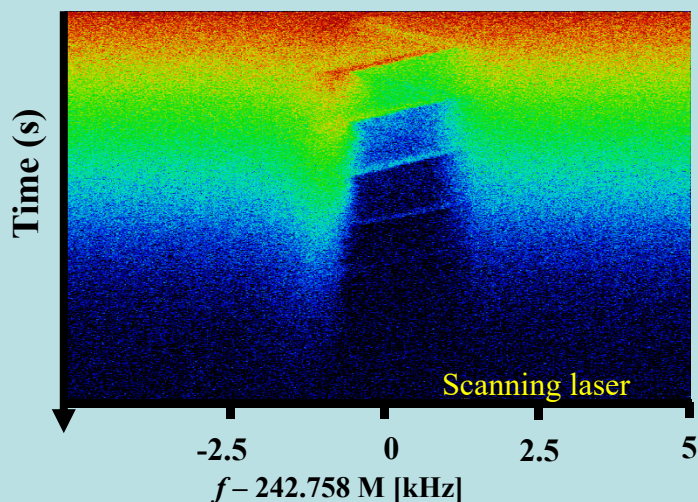


Preliminary results: Coasting beam with fixed laser



Laser force range: $\Delta p/p \approx 1.0 \times 10^{-7}$

Preliminary results: Coasting beam with scanning laser

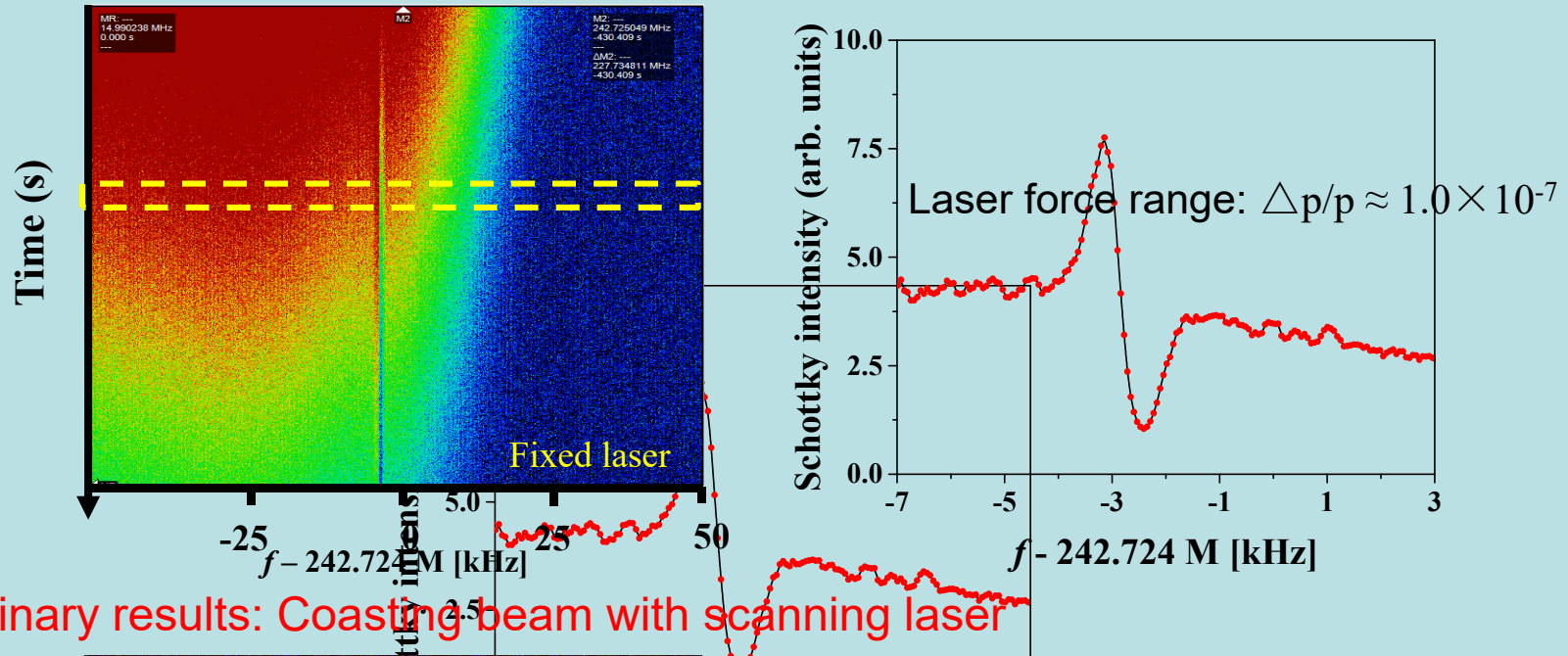


Laser scanning range: $\Delta p/p \sim 10^{-4}$

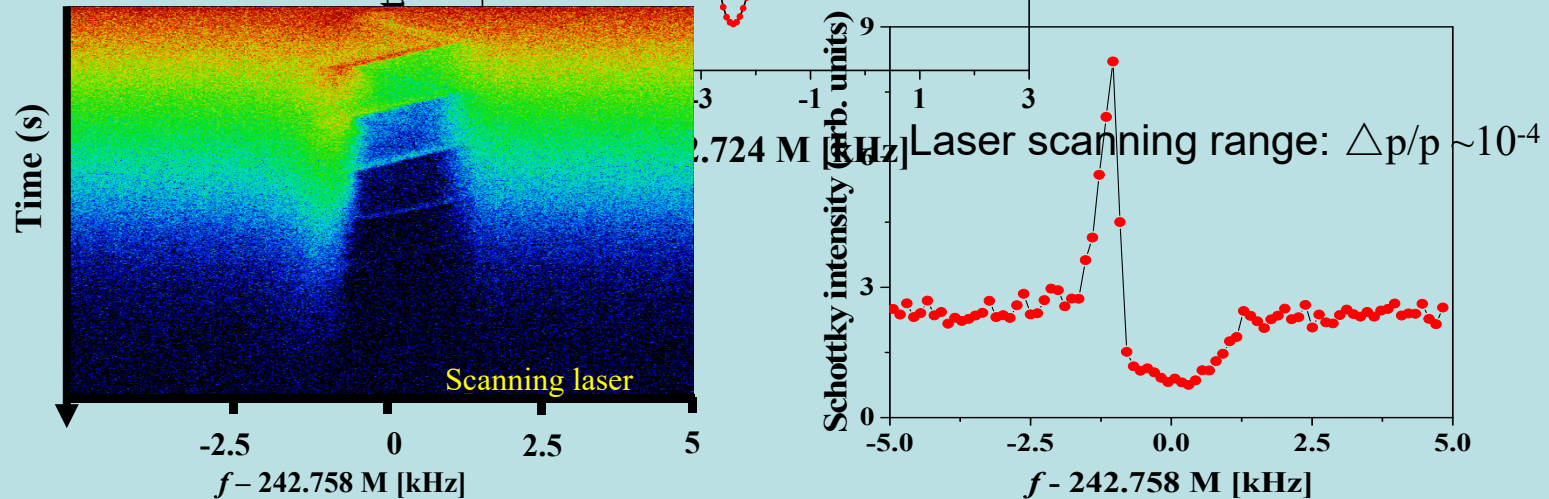




Preliminary results: Coasting beam with fixed laser

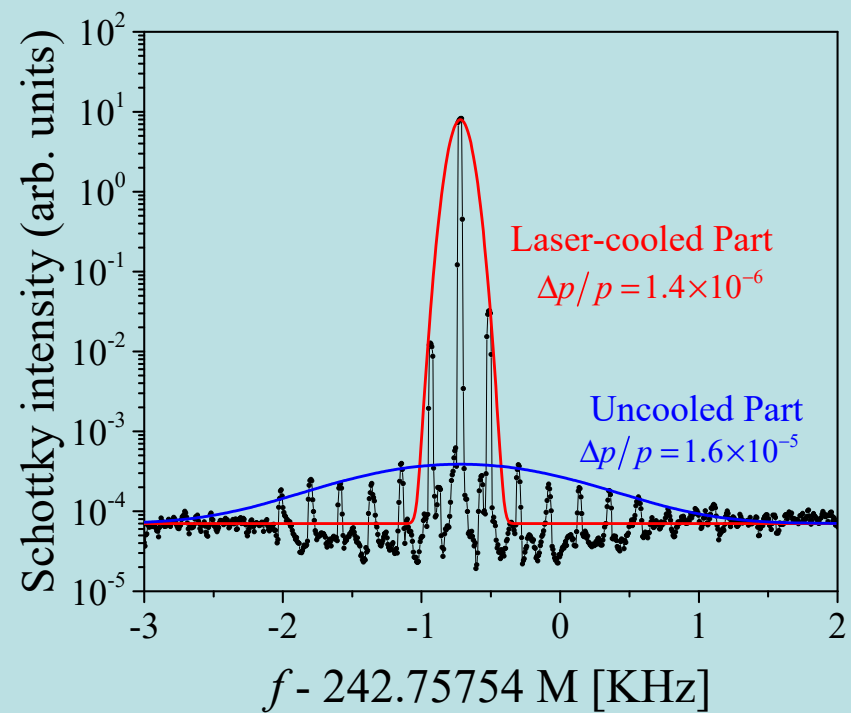
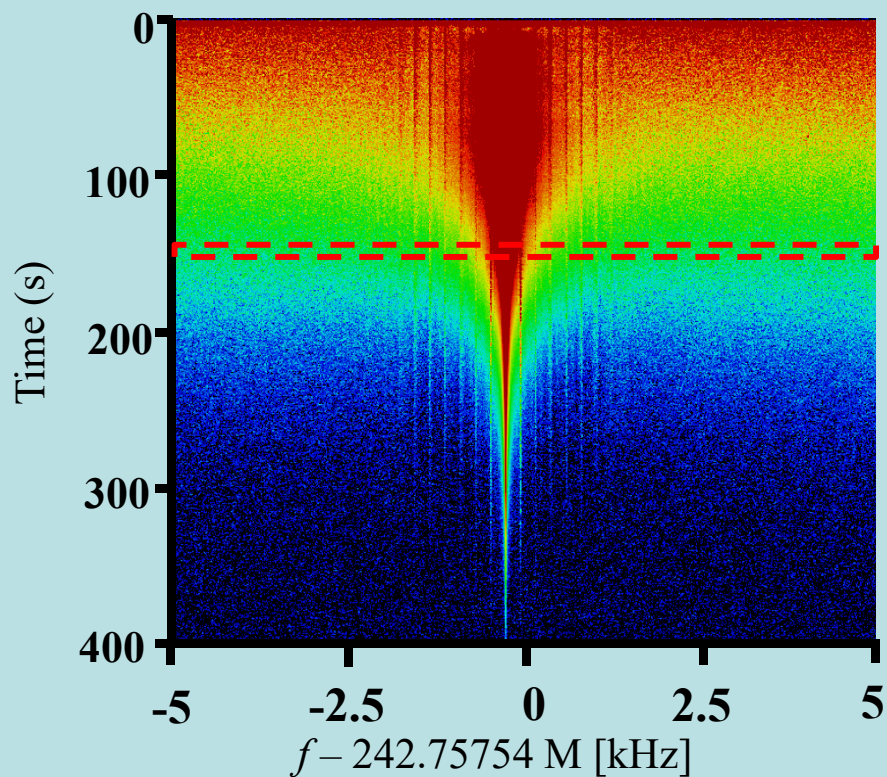


Preliminary results: Coasting beam with scanning laser





Preliminary results: Laser cooling of bunched ion beams



Only part of the $^{16}\text{O}^{5+}$ ions were laser-cooled

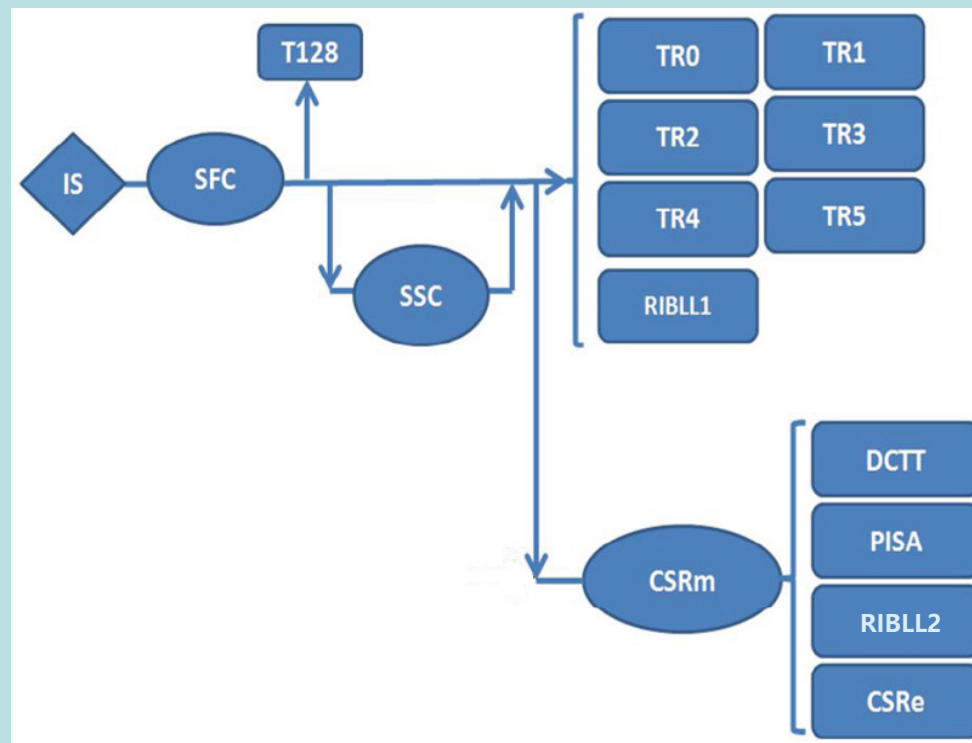




Present Status of HIRFL Complex in Lanzhou

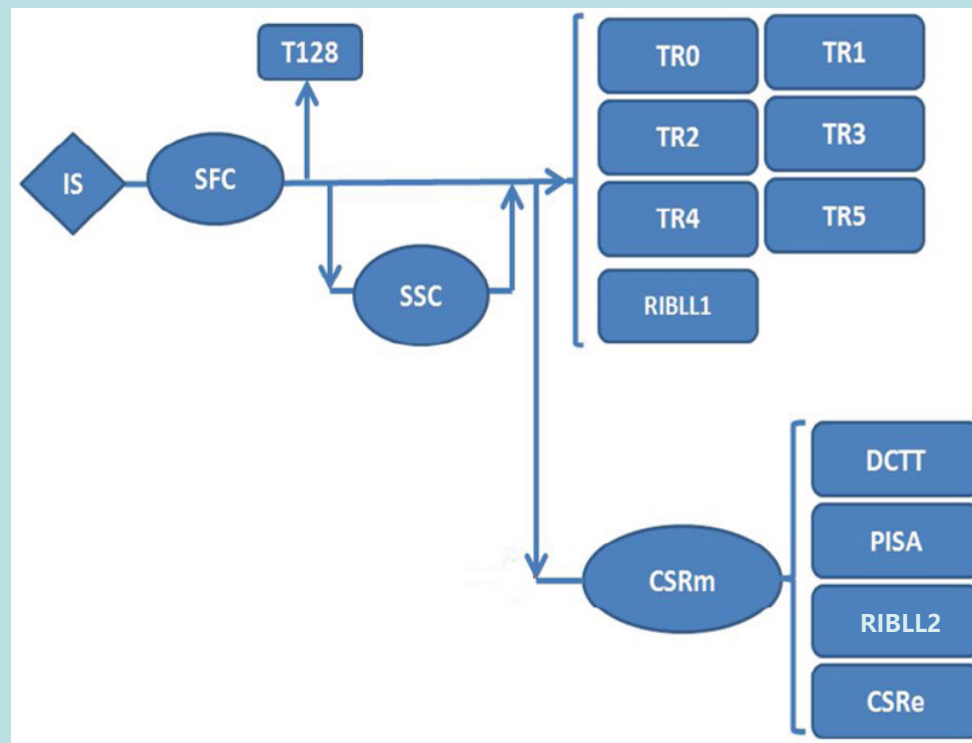
FUTURE DEVELOPMENTS





Operation modes of HIRFL with new injectors





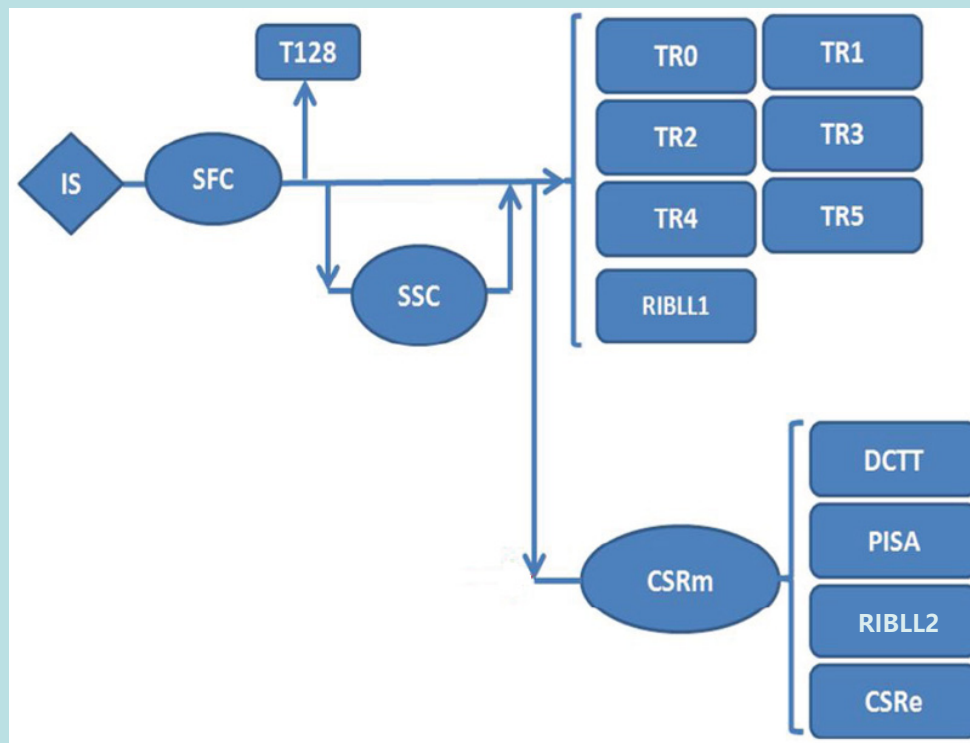
Operation modes of HIRFL with new injectors





- Parallel operation modes of HIRFL.

- Enough maintenance period for injectors
- More total beam time



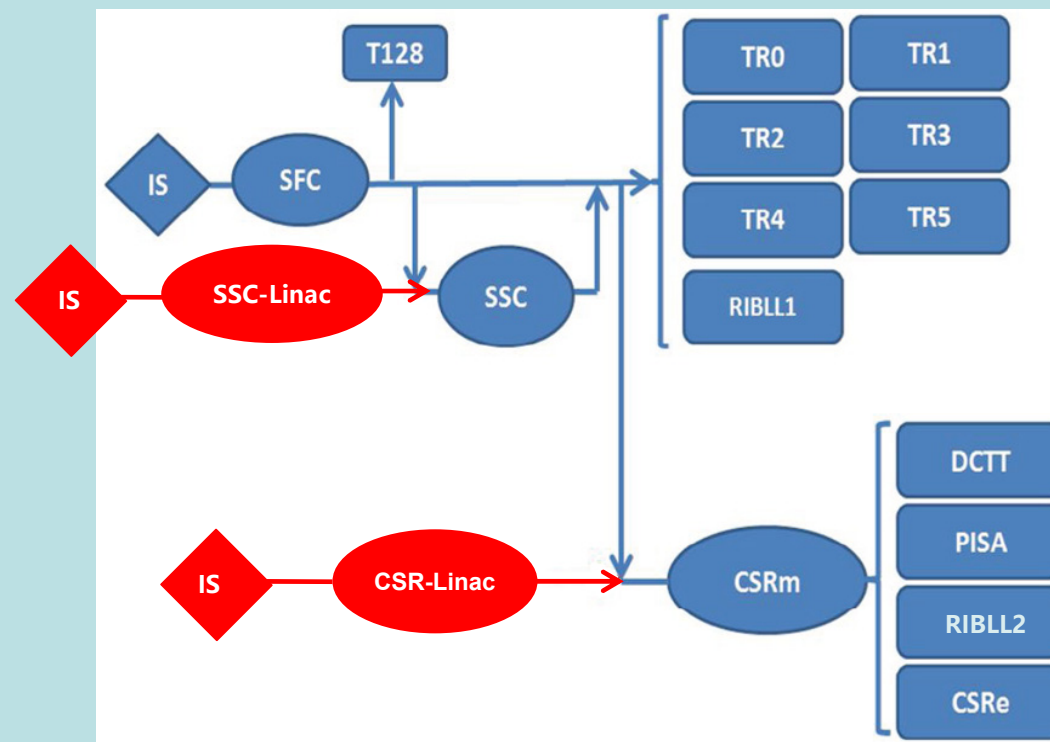
Operation modes of HIRFL with new injectors





- Parallel operation modes of HIRFL.

- Enough maintenance period for injectors
- More total beam time

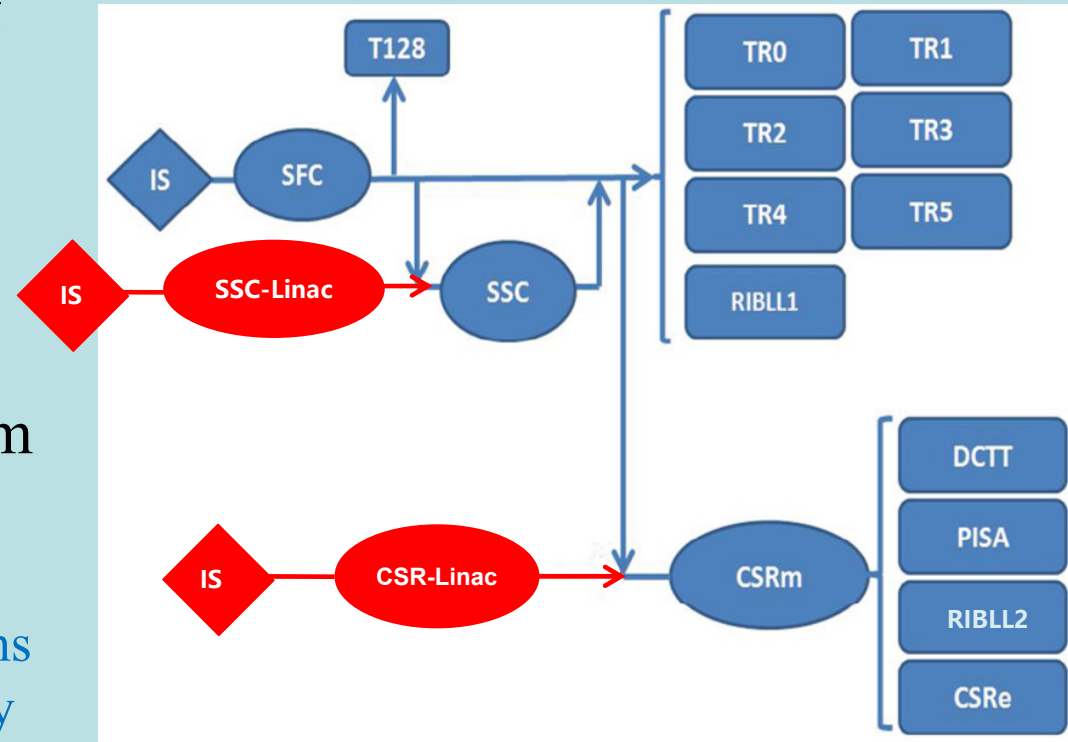


Operation modes of HIRFL with new injectors





- Parallel operation modes of HIRFL.
 - Enough maintenance period for injectors
 - More total beam time
- High beam transmission efficiency from IS to CSRm and intensity.
 - Enough energy/ intensity to get highly charged heavy ions for higher accelerated energy by CSRm.
 - Short accumulation time → higher repetition rate of CSRm.



Operation modes of HIRFL with new injectors



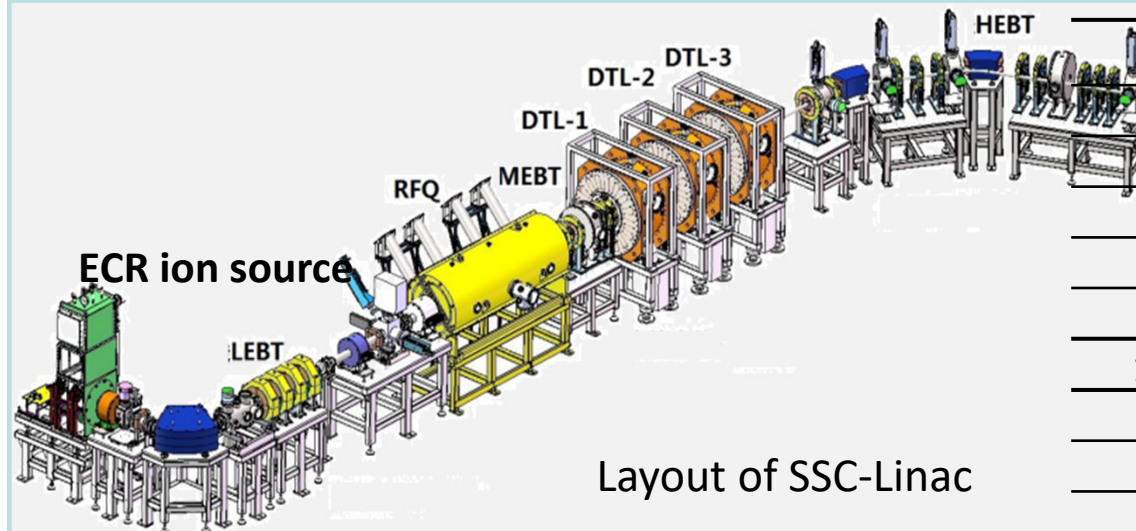


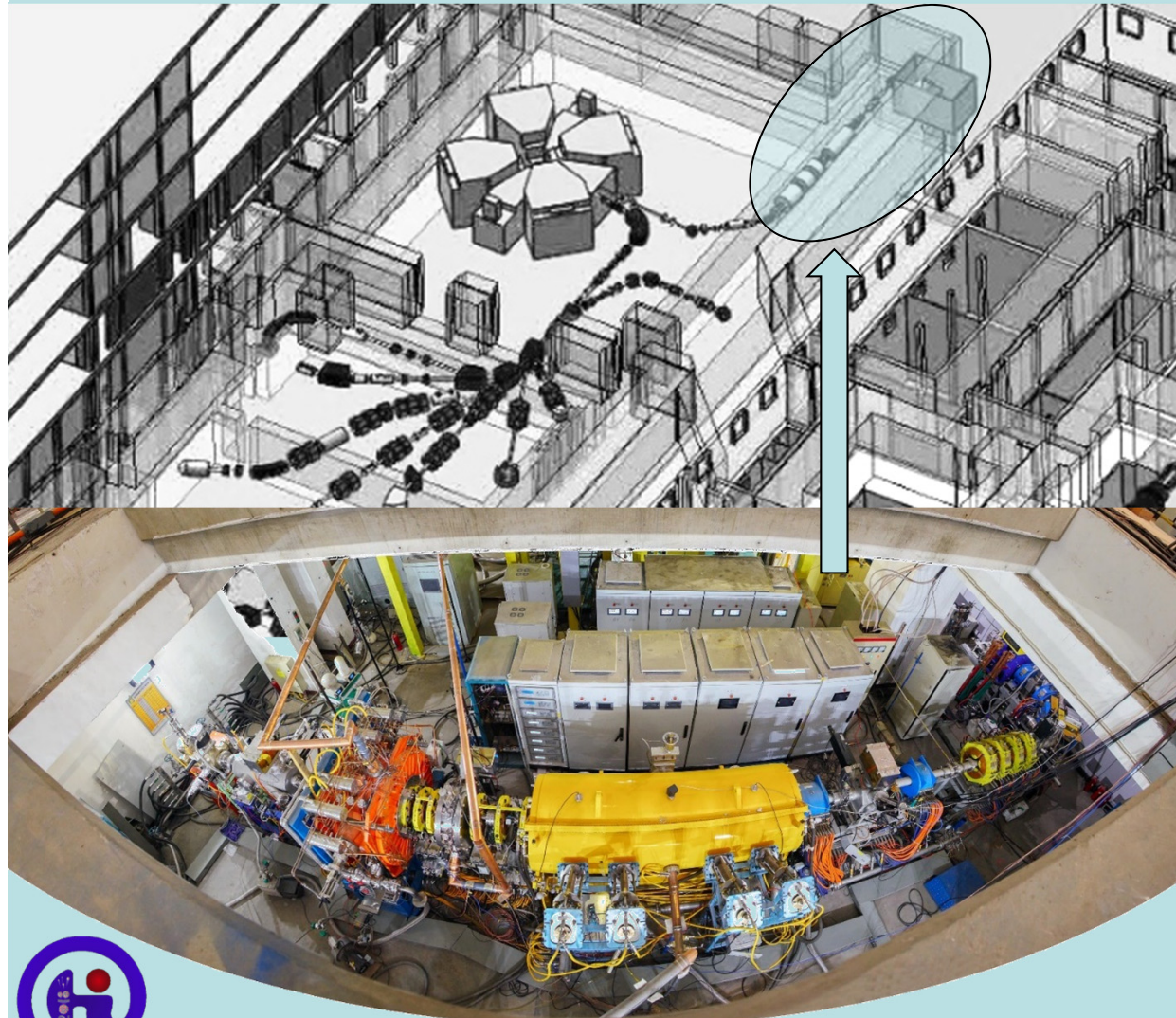
New high intensity heavy ion injector of SSC

- Extraction energy:
1.025MeV/u → 10.7MeV/u(SSC) → CSRm
0.576 MeV/u → 5.97 MeV/u(SSC) → CSRm
- Beam current : 5~30μA for various ions.
- Beam intensity: increase 1~2 order for SSC.
- $^{238}\text{U}^{35-72+}$ can be accelerated to 487MeV/u by CSRm after stripping.

Main parameters of SSC_Linac

Parameters	Values
Design ion	$^{238}\text{U}^{34+}$
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	0.5mA
IH-DTL	KONUS
Frequency	53.667MHz
Input energy	0.143MeV/u
Output energy	1.025MeV/u





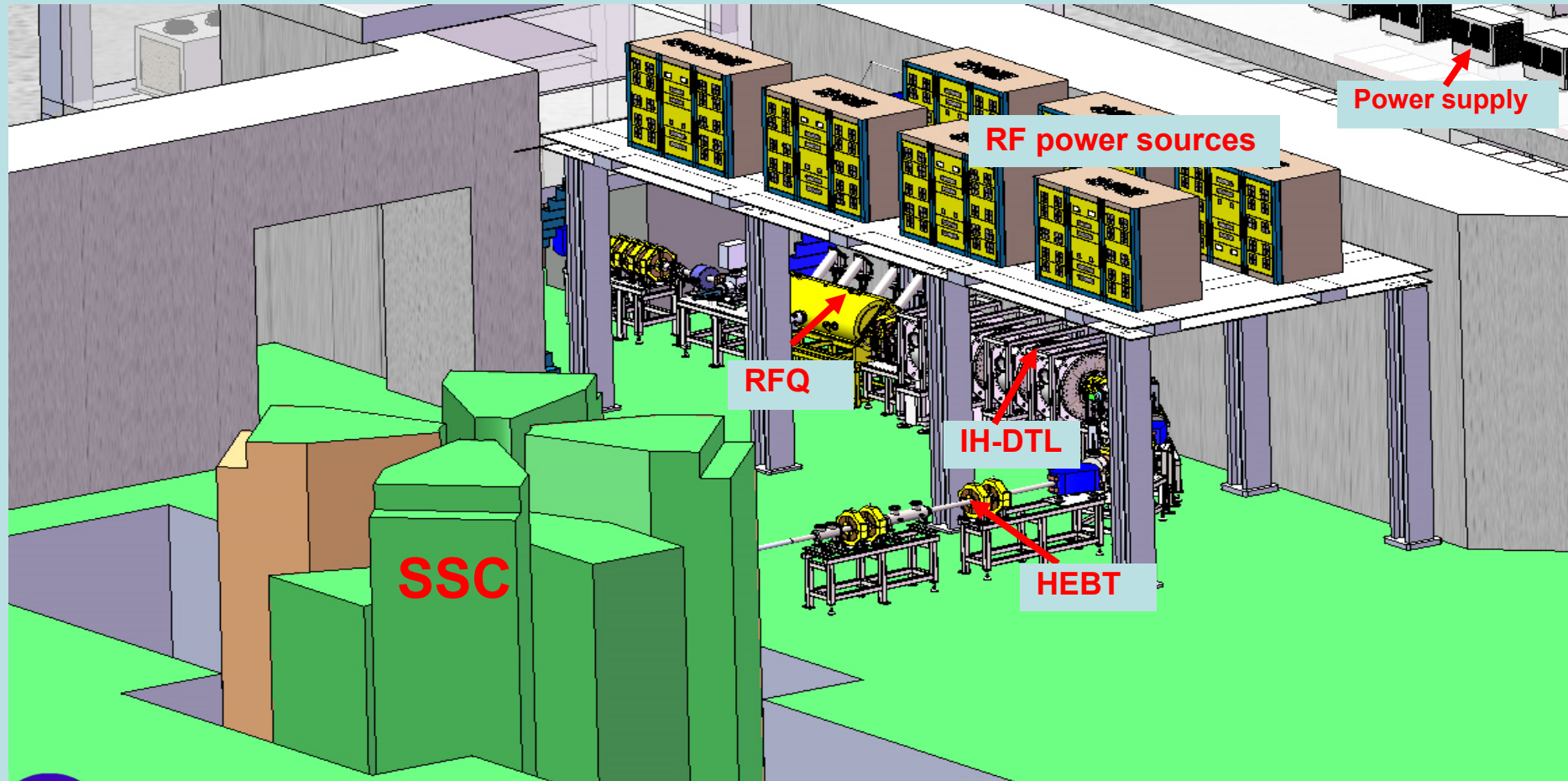
- Beam test of IS+LEBT+RFQ+DTL1 is done
- DTL2 be installed this month
- DTL34 ordered

- Civil construction start this summer
- Commissioning start by end of 2019



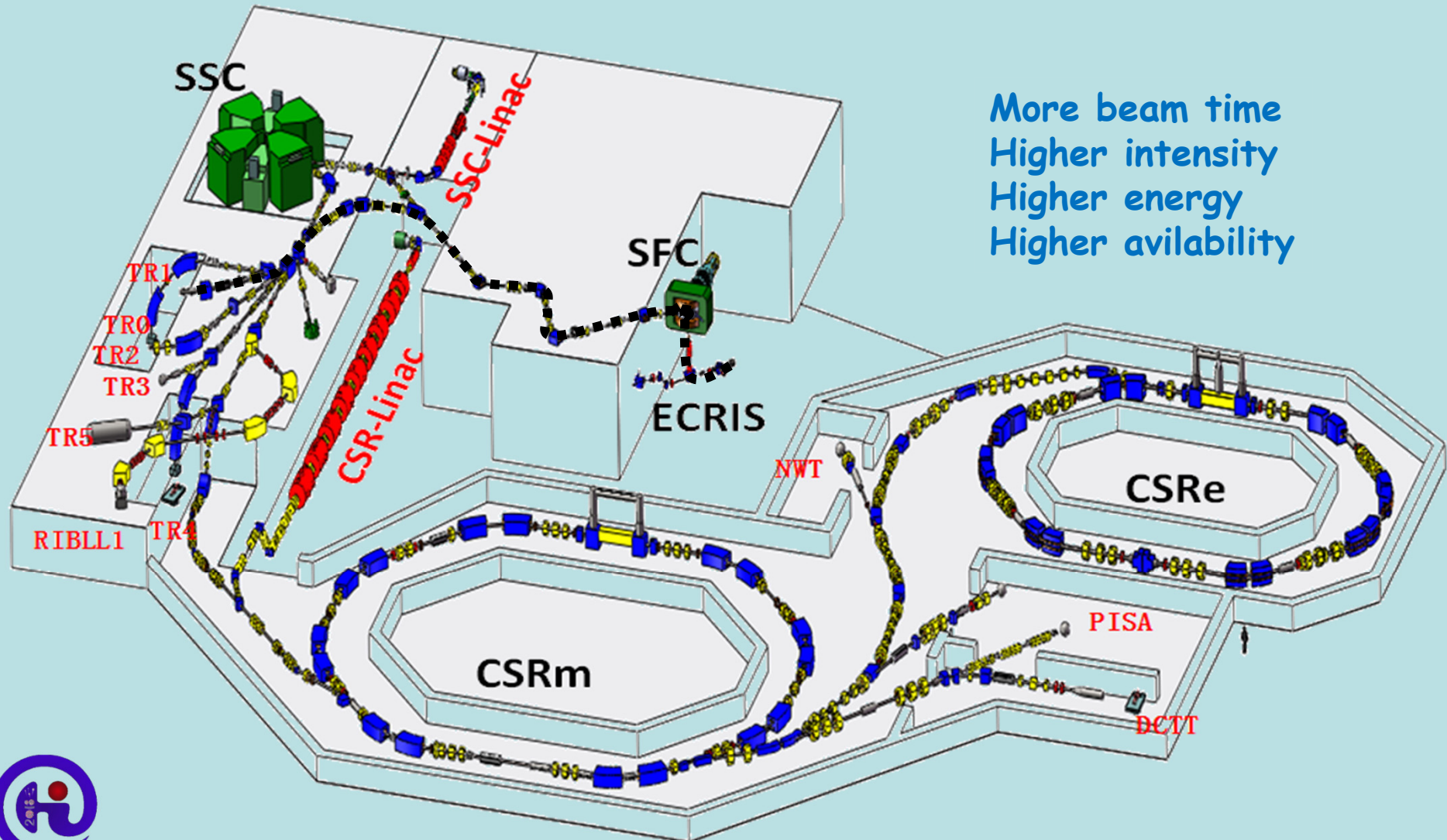


- Platform for RF generators, right up the cavities, 80 m²
- New building outside SSC hall for PS, water cooling etc. ~400 m²





SFC



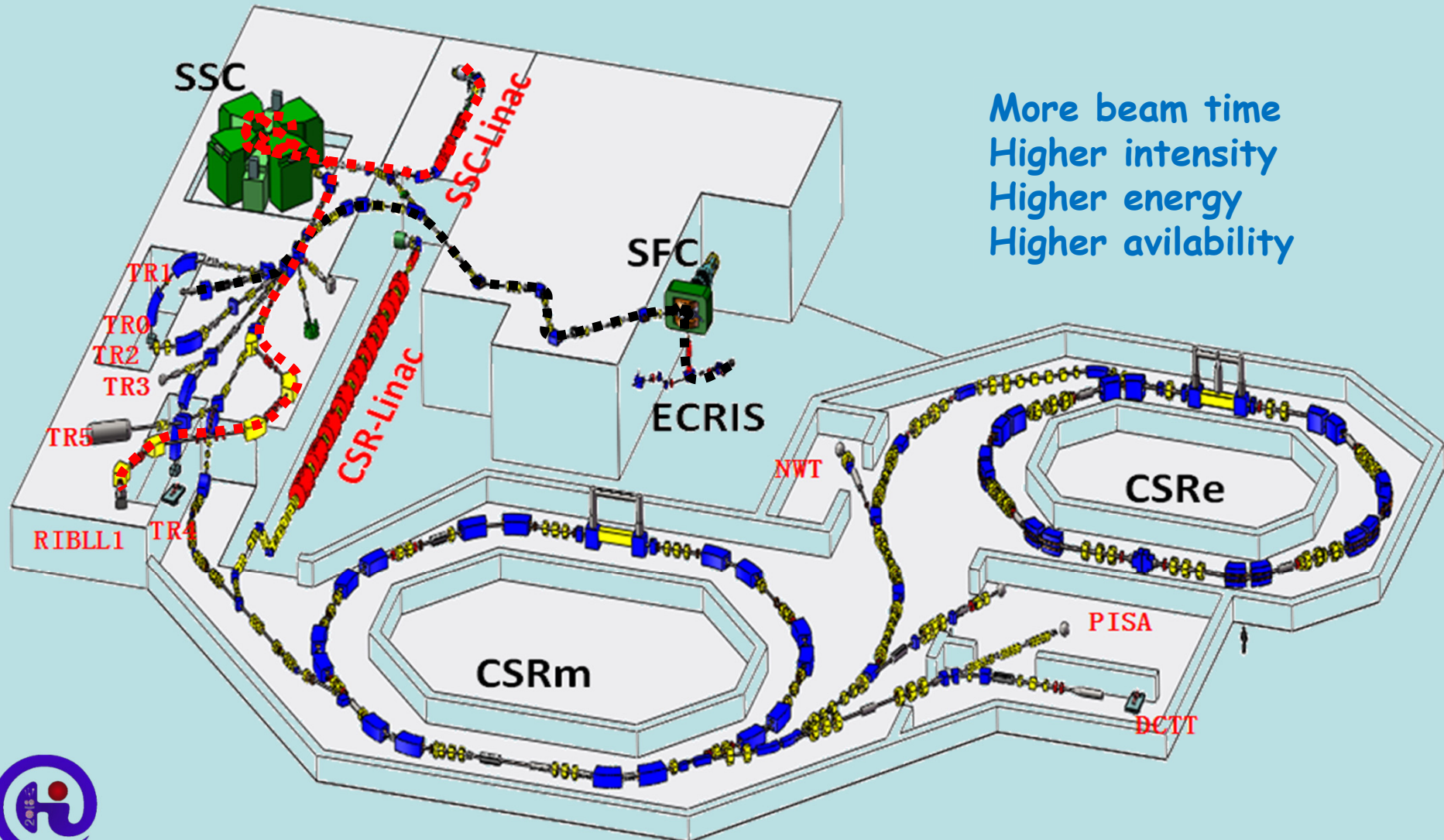
More beam time
Higher intensity
Higher energy
Higher availability





SFC

SSC-Linac



More beam time
Higher intensity
Higher energy
Higher availability

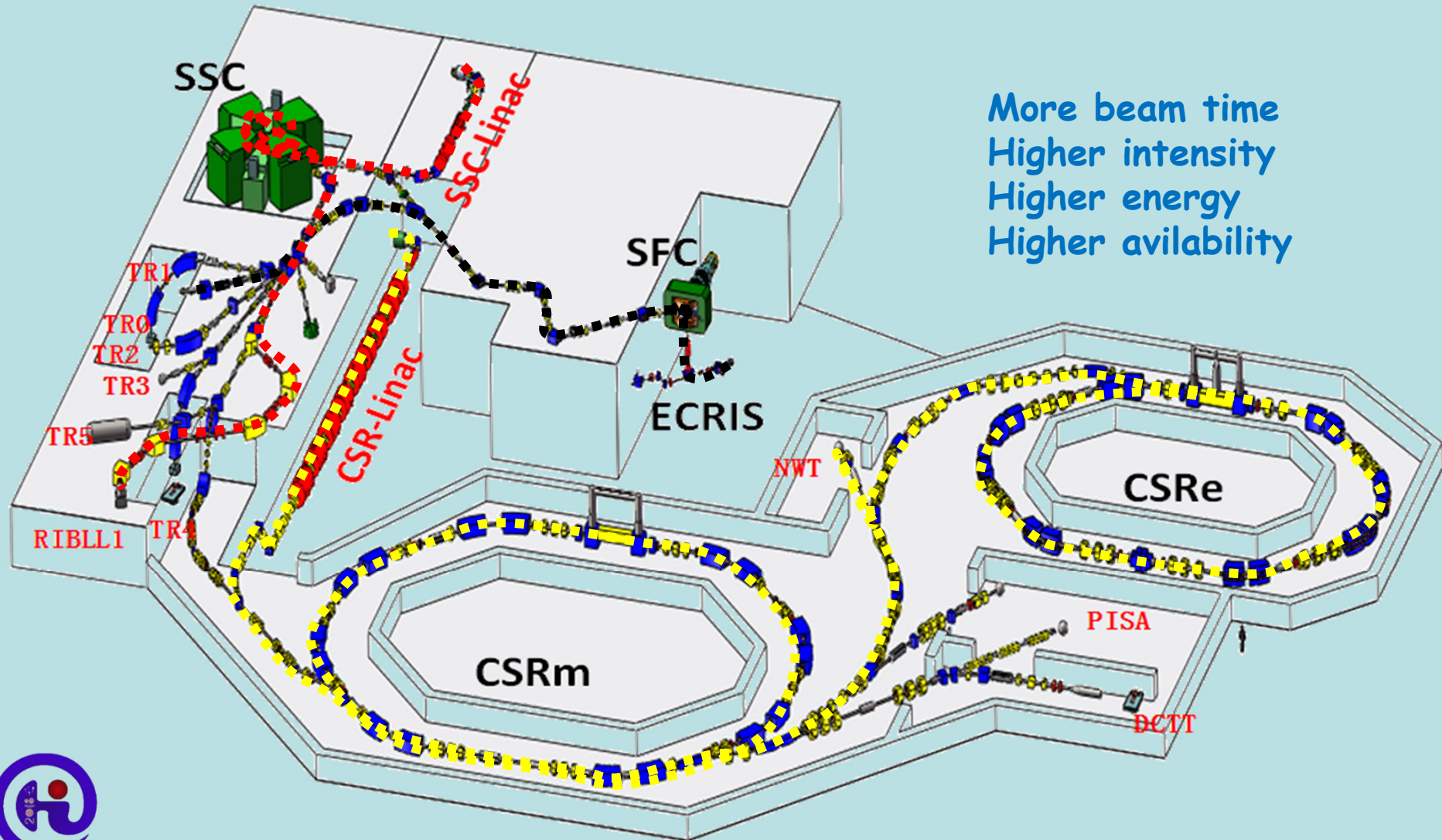




SFC

SSC-Linac

CSR-Linac



More beam time
Higher intensity
Higher energy
Higher availability



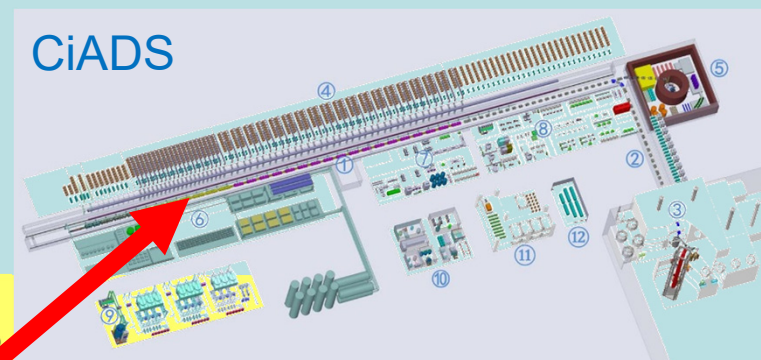


Recent and future projects based on HIRFL

Cancer therapy



CiADS

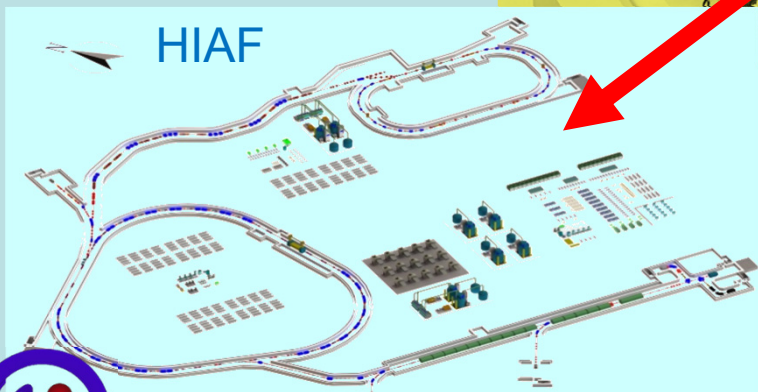


SFC (K=69)
10 AMeV (HL), 17~35 MeV (p)



Talk by Z.J. Wang
at this conference

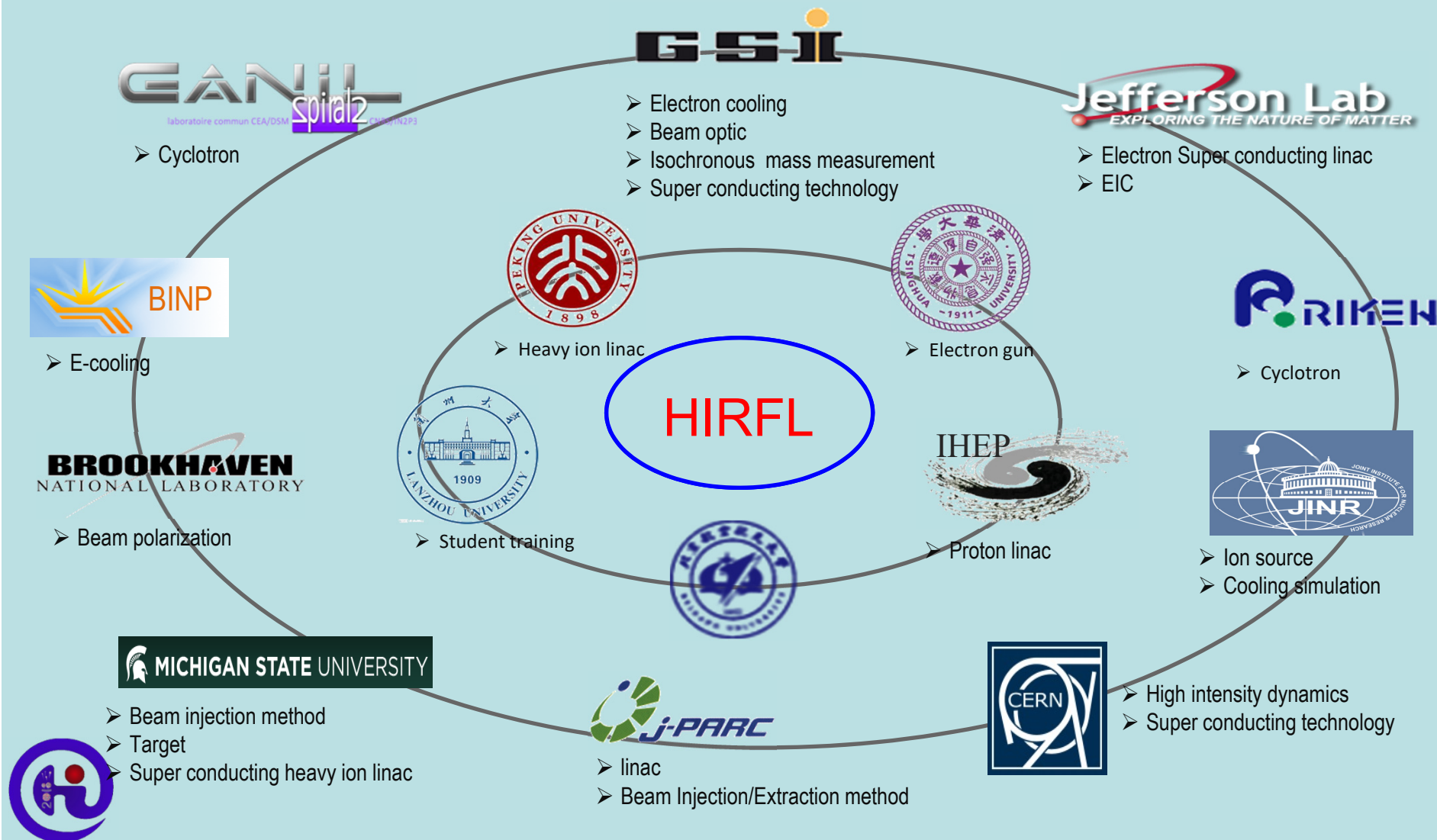
HIAF



Talk by J.C. Yang at this conference



Thanks for the **50 years cooperations** of all our friends!





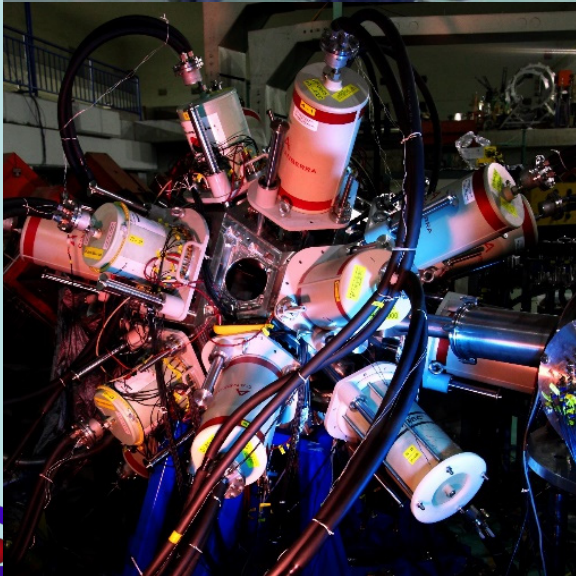
Present Status of HIRFL Complex in Lanzhou

**Thanks for your
attention!**





RIBLL



Online γ detector



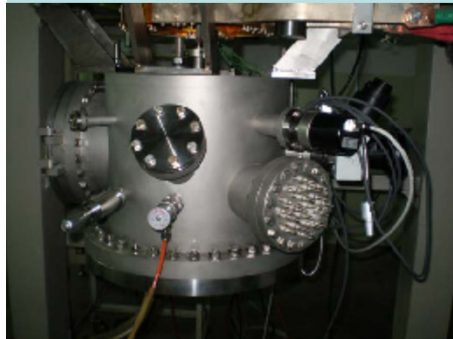
Micro-beam





Characteristics:

1. Energy selection
2. Vertical irradiation
3. Focusing micro beam
4. Two foci: one in vacuum the other in the air



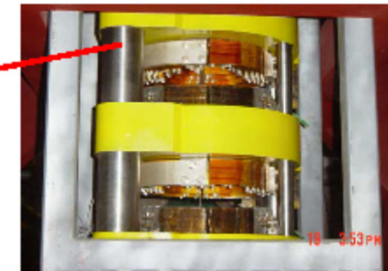
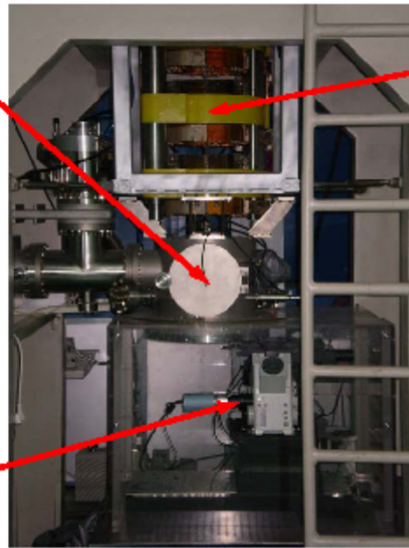
Vacuum Chamber for material irradiation



Microbeam facility on the first floor
(upper part)



Inverted microscope for cell irradiation



Quadrupole triplet, Φ 15mm
L = 100mm, G = 123 T/m

Facility in the cellar
(lower part)

$^{12}\text{C}^{6+}$ 80.55MeV/u

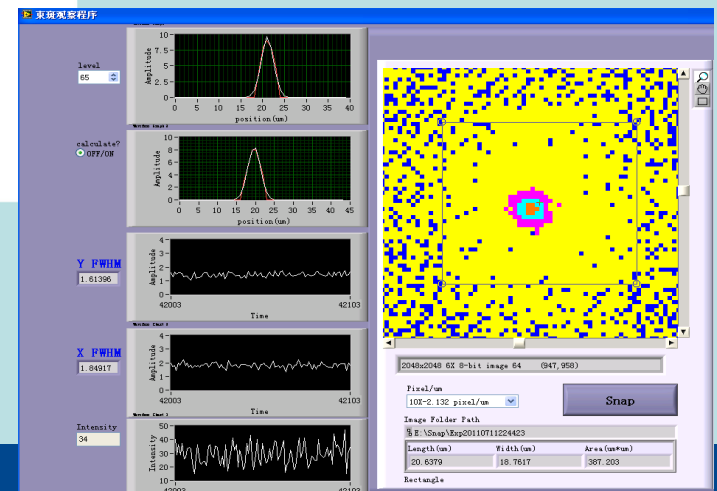
Ion hitting rate 1~1200/s controllable

FWHM beam spot $< 2\mu\text{m}$ in air

$< 1\mu\text{m}$ in vacuum



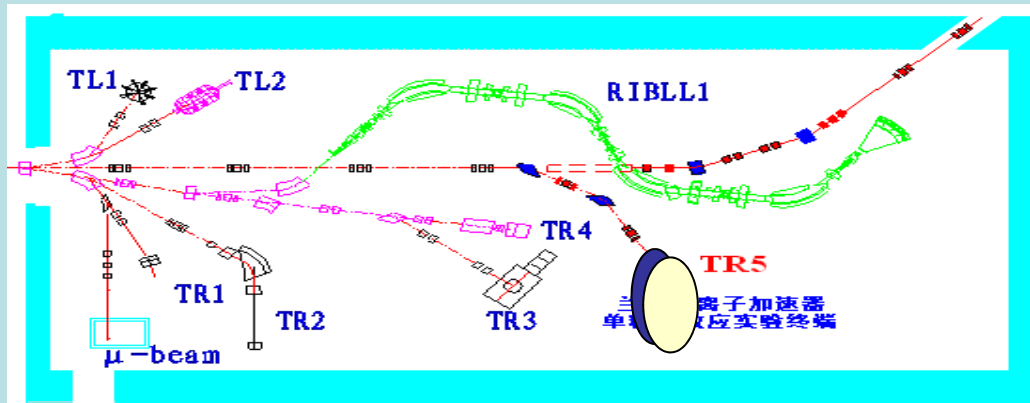
HIAT2018, Oct.22-26, 2018, Lanzhou





New single event effects terminal

- 700 hours/year for SEE (Single Event Effects) researches (2010-2014)
- Improving the accuracy and efficiency of ground simulation for space radiation
- Increasing reliability for electronic device evaluations



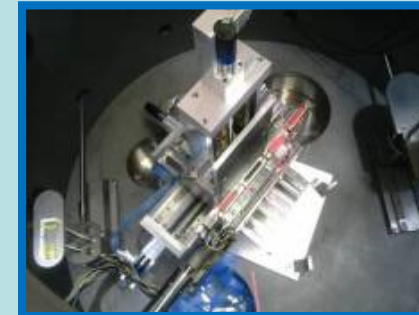
TR5 terminal for SEE research at the HIRFL experiment hall



Main Chamber



Pre-vac chamber

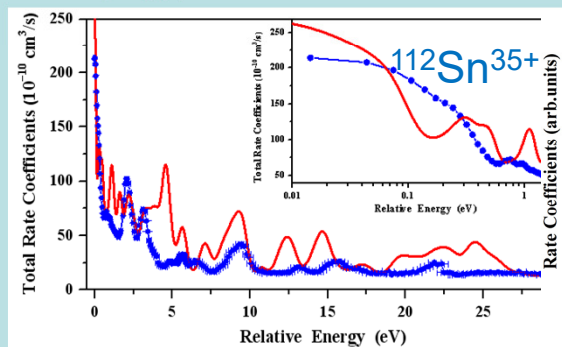
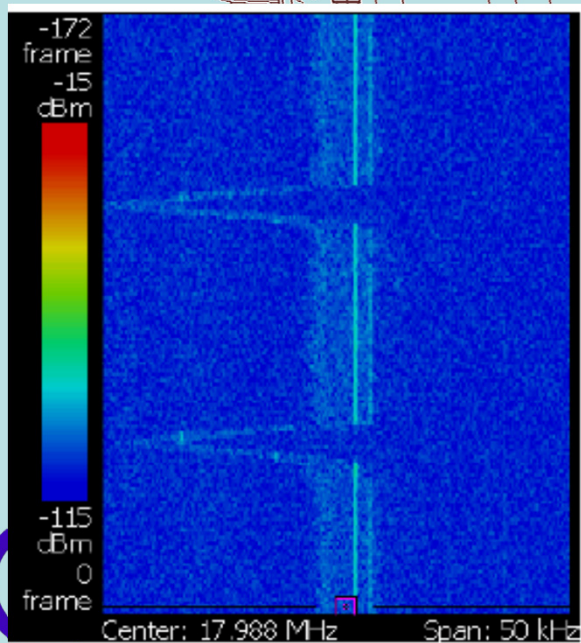
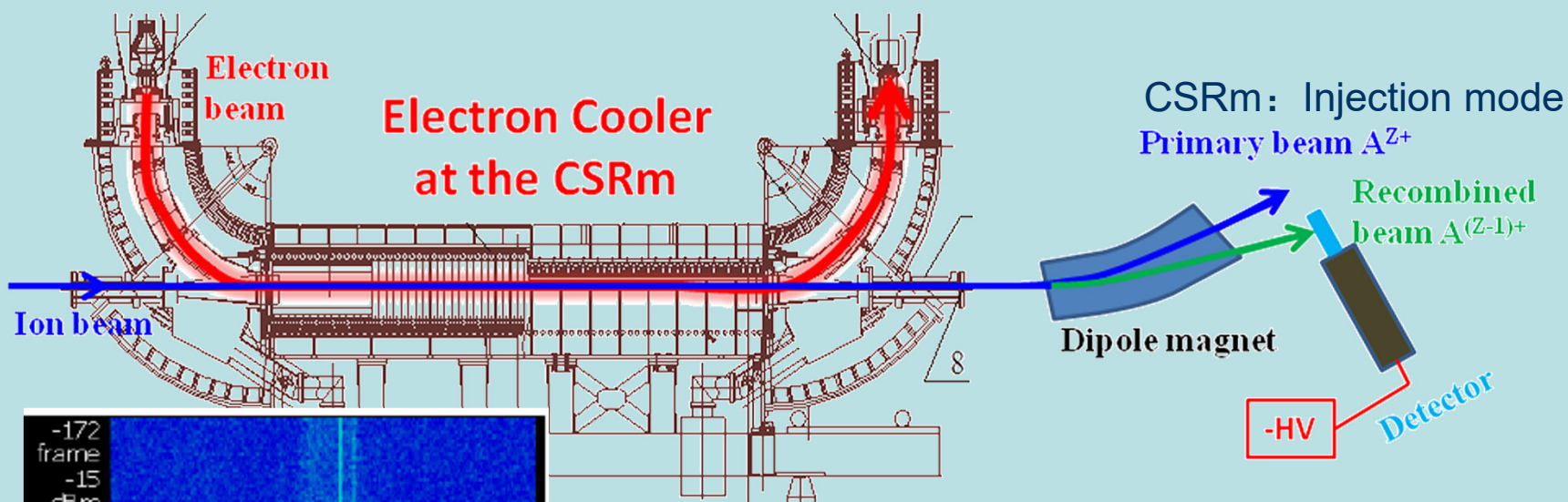


4-dimensional sample holder

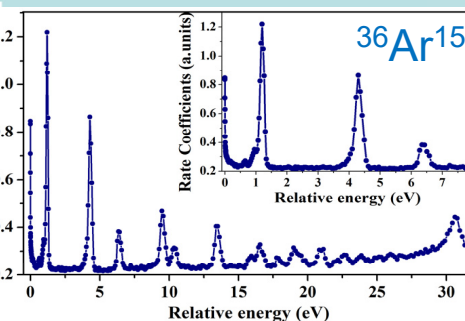




Operation mode: ECR+SFC+CSRm, Beams: C, Ar, Xe, Sn...

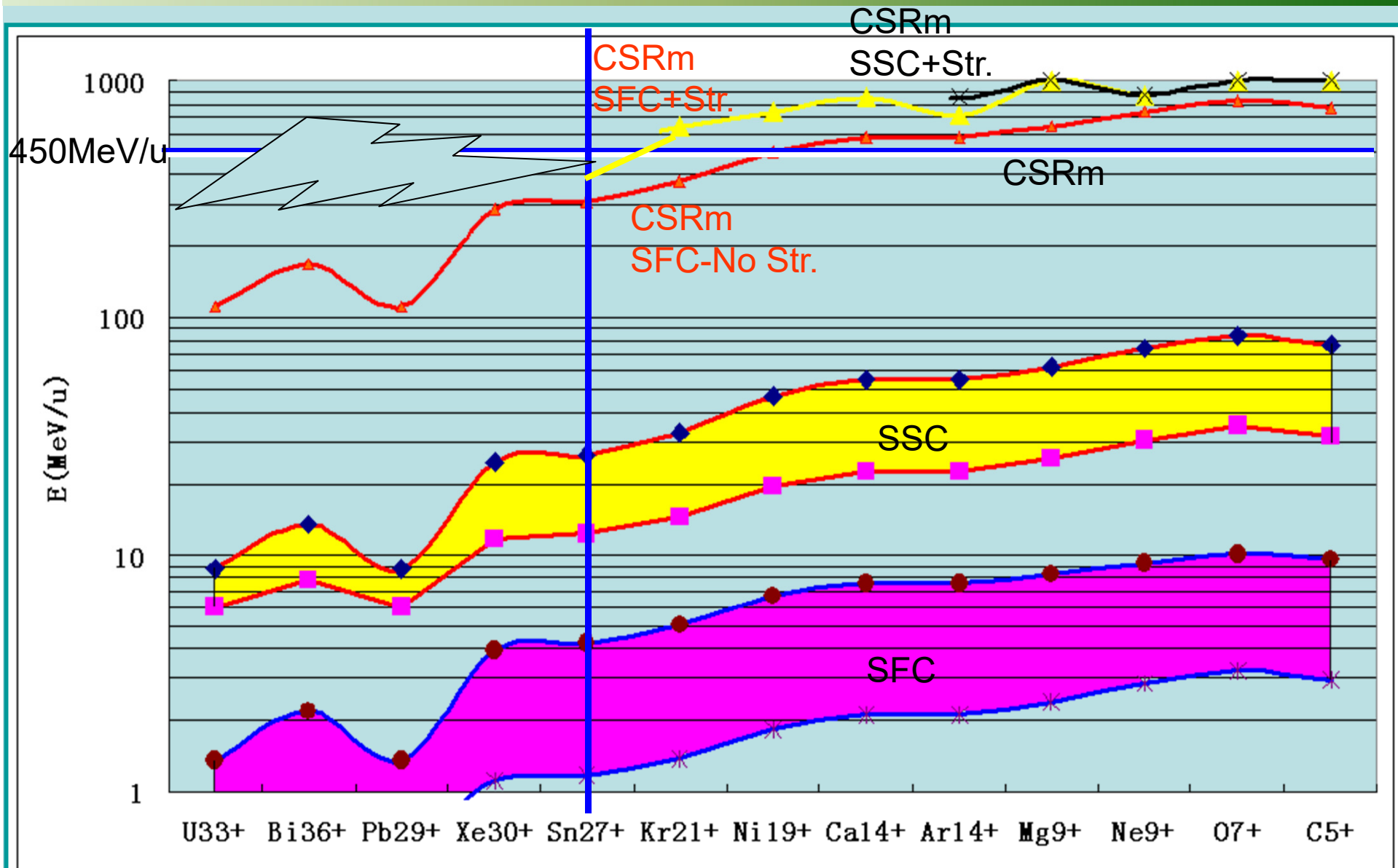


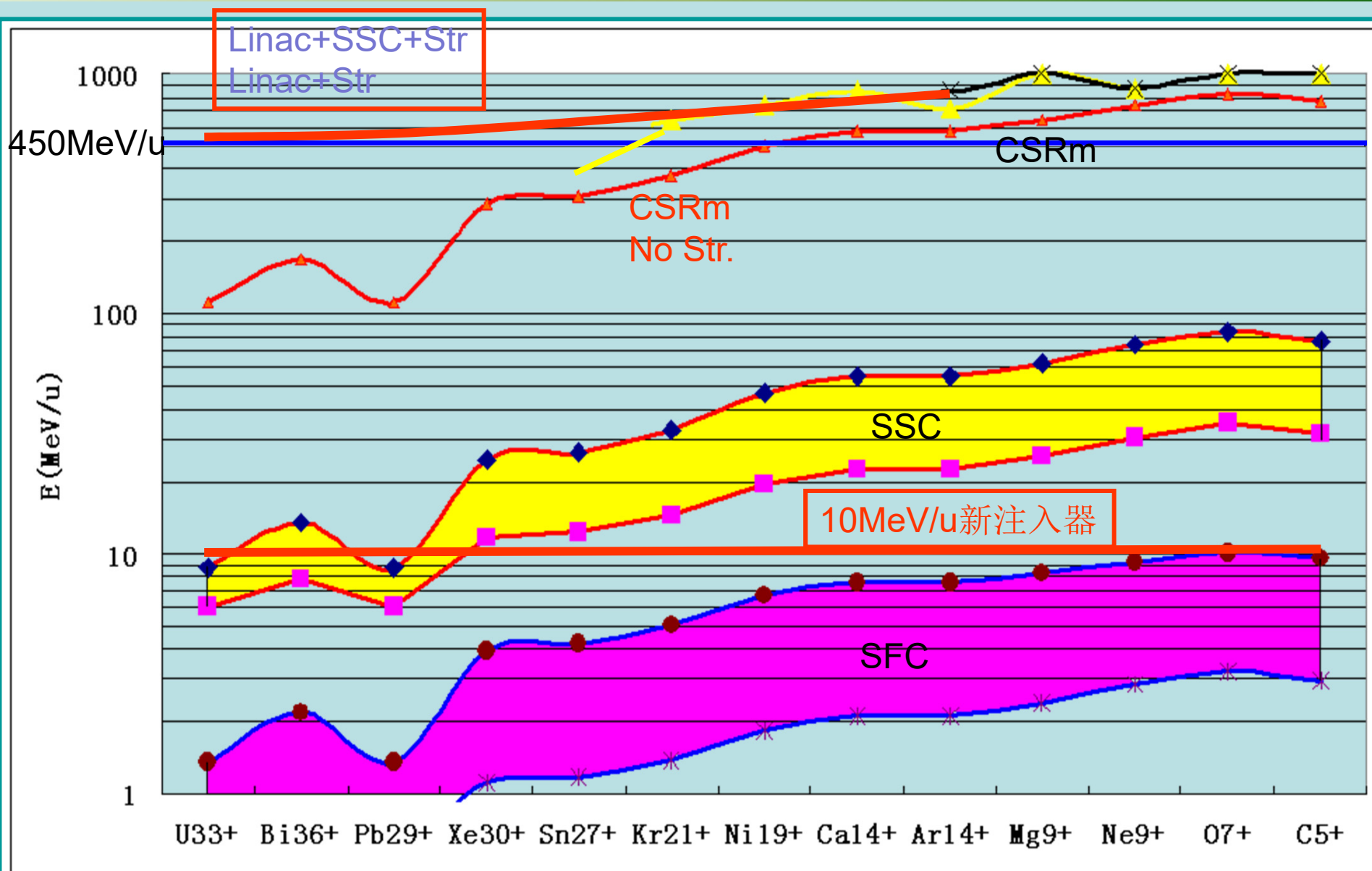
DR of $^{112}\text{Sn}^{35+}$, 10. 2012



DR of $^{36}\text{Ar}^{15+}$, 07. 2014

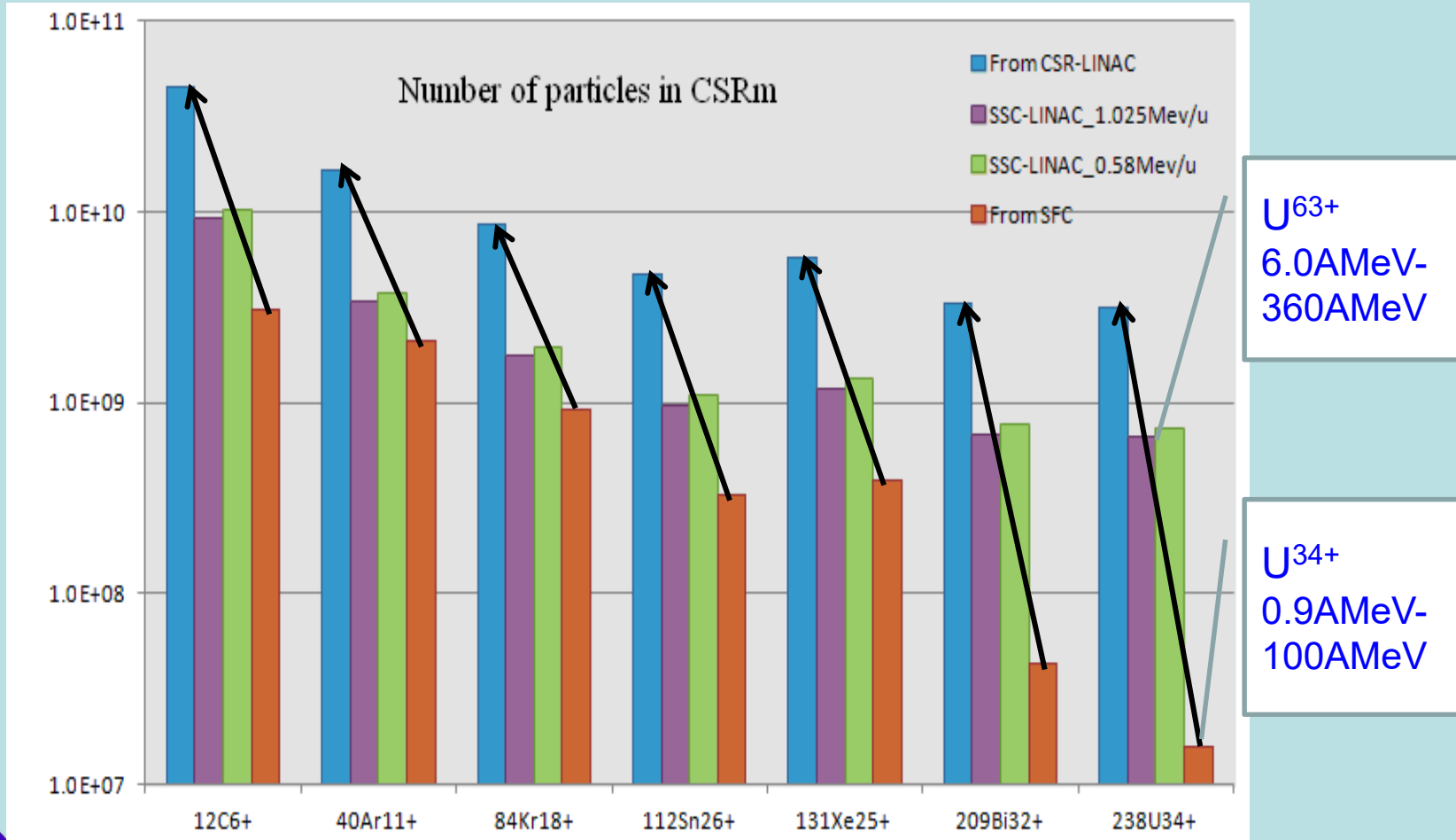
Detuning e-energy for DR cross section measurement





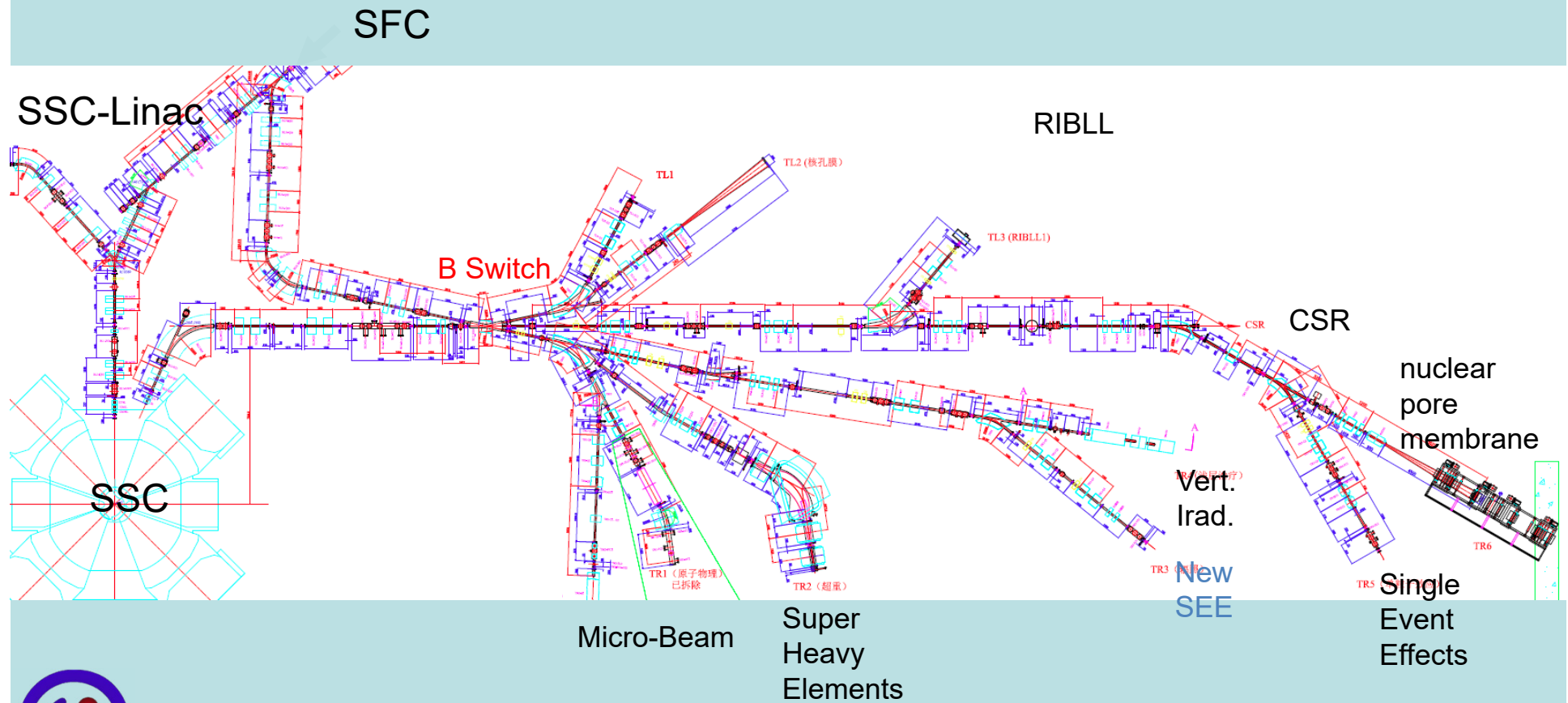


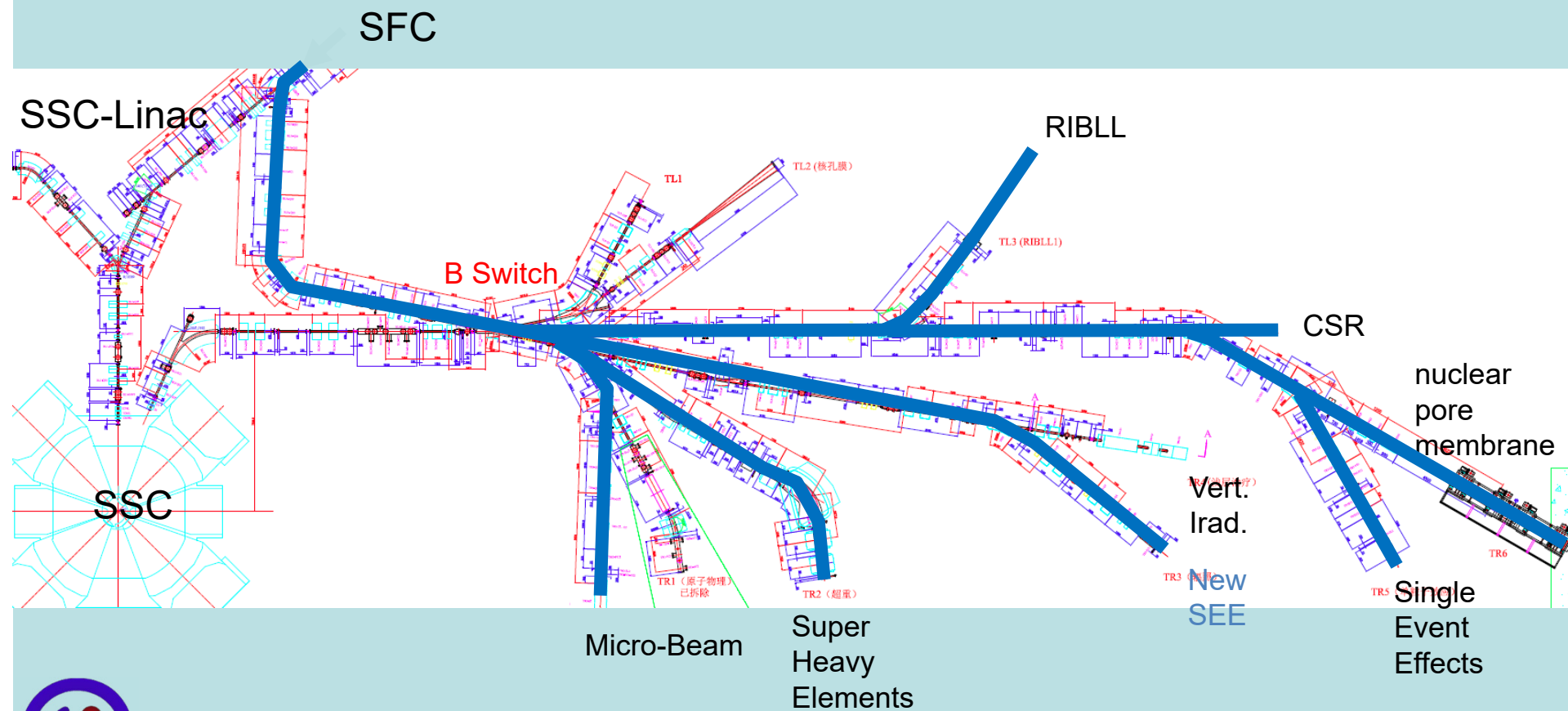
- The number of ions in CSRm can be increased by 10~200 times
- The repetition cycle time can be reduced by ~30%



Estimated maximum number of stored particles at CSRm with various injectors



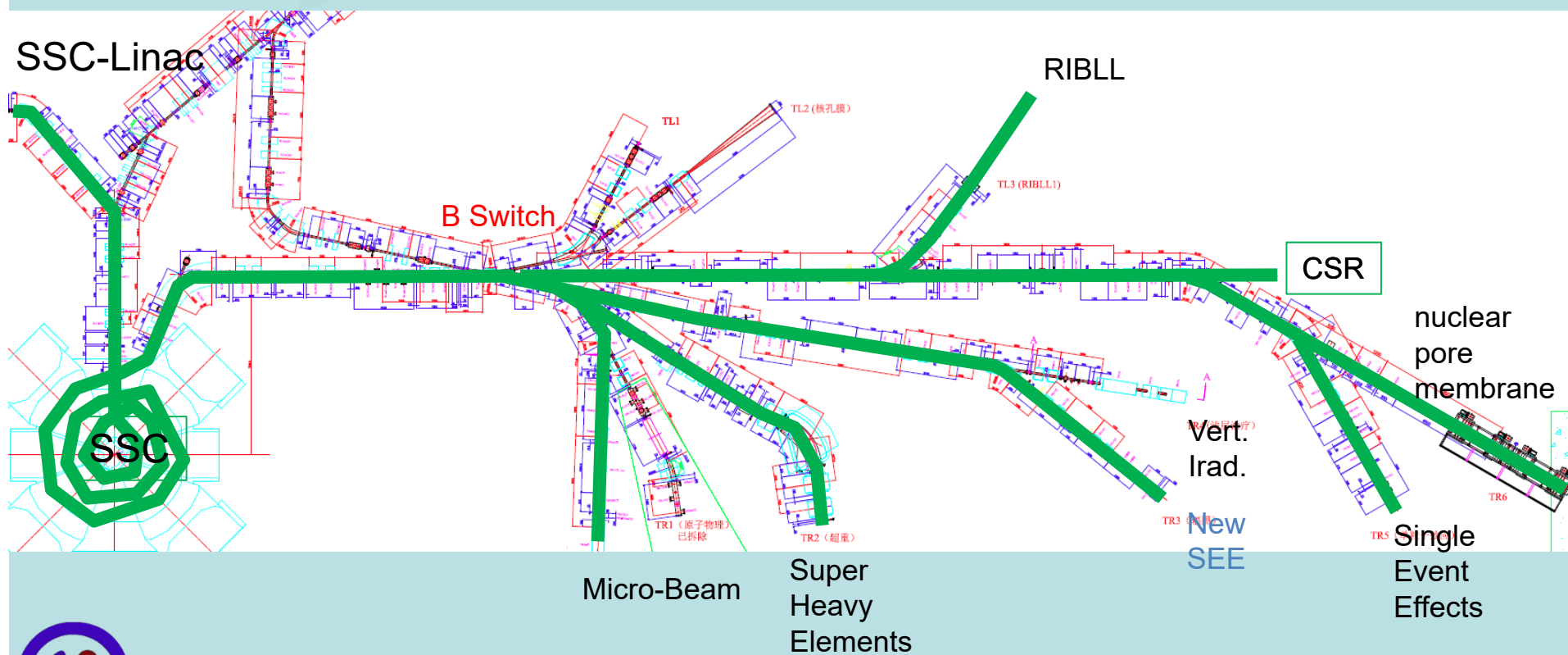








SFC

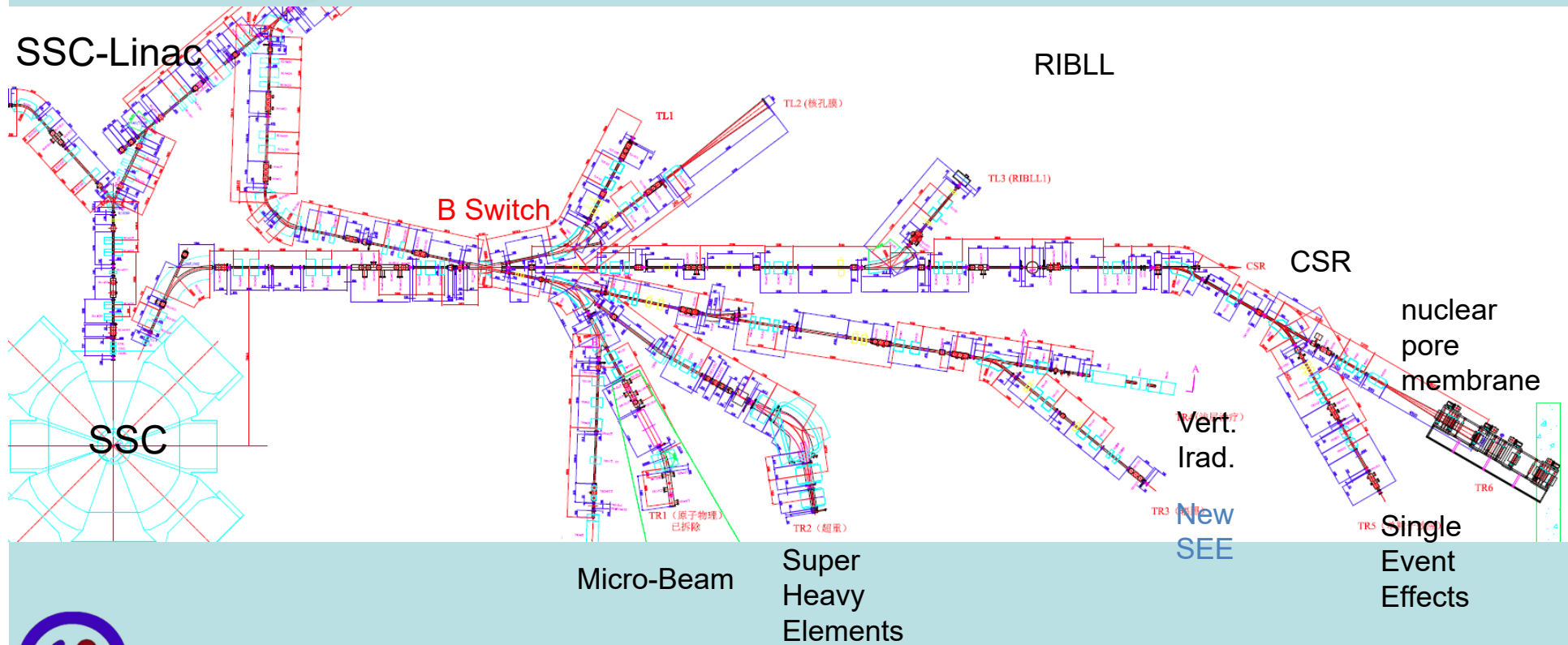




Parallel Operation with 2 Injectors

SFC

SFC alone + (SSC-Linac+ SSC)

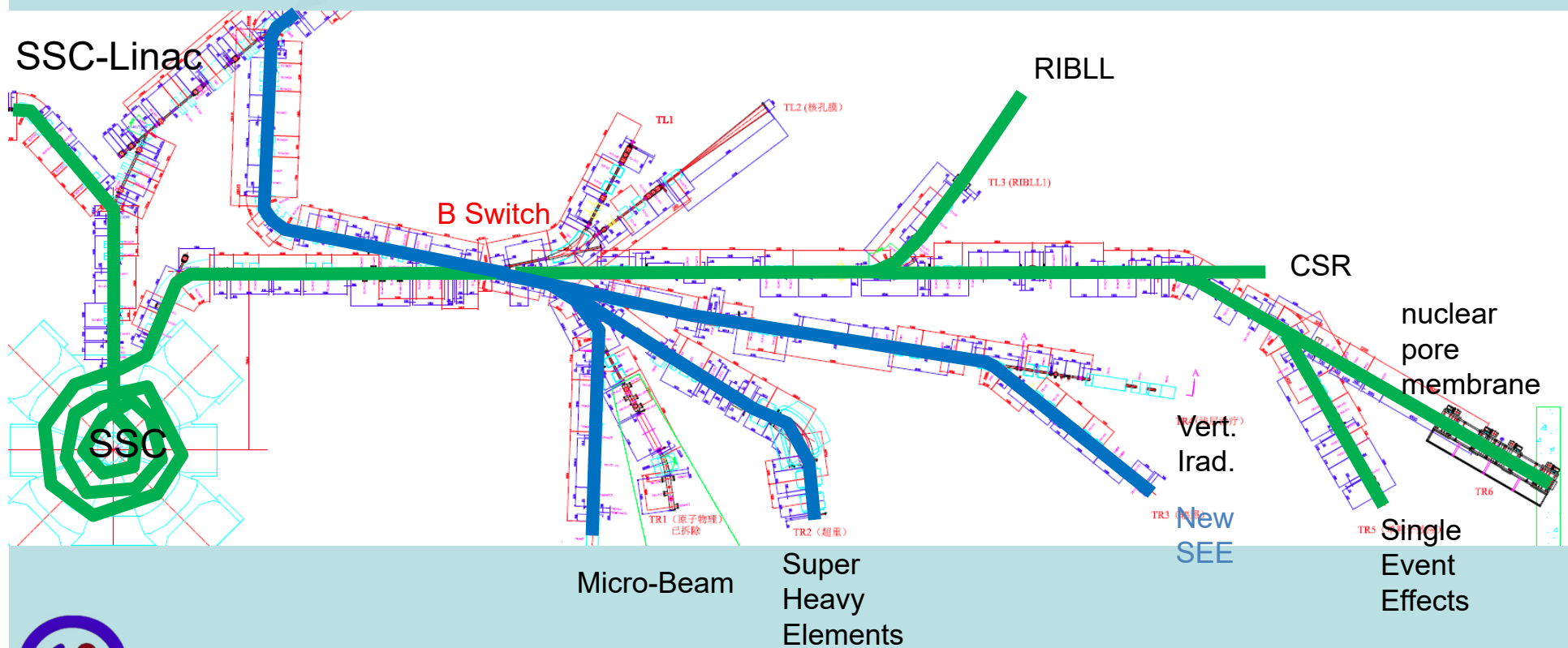




Parallel Operation with 2 Injectors

SFC

SFC alone + (SSC-Linac+ SSC)





THE END

