The Operation Status of HIRFL
Commissioning of HIRFL-CSR
(Heavy Ion Research Facility, Cooler Storage Rings)

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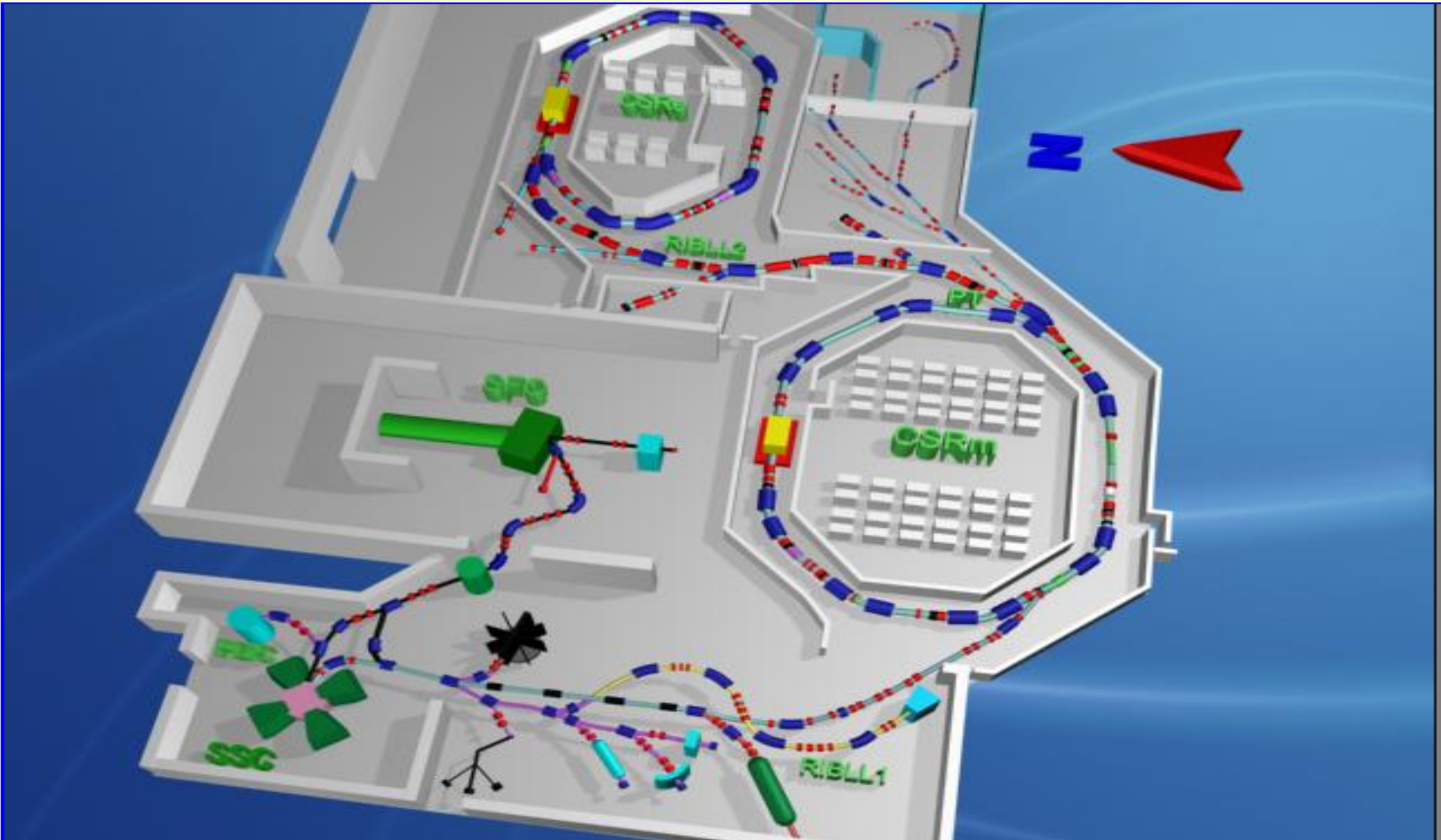
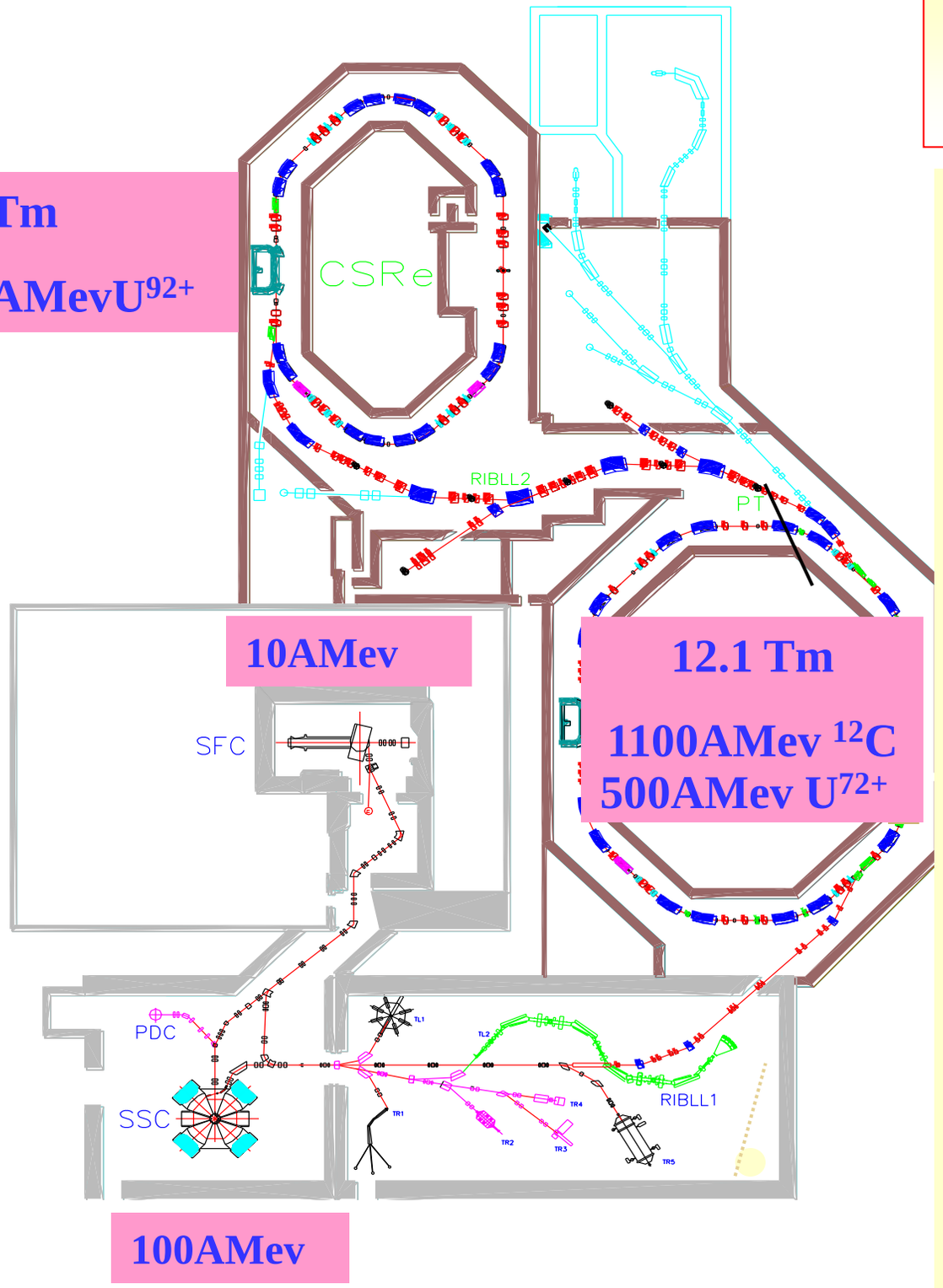
Outline

1. Brief Introduction to HIRFL
2. HIRFL Cyclotron Status and Operation
3. HIRFL-CSR and Its Commissioning
4. Near Future Developments of HIRFL

Heavy Ion Research Facility, Lanzhou,China



HIRFL Layout



- **ECR Ion Source**
- **SFC K=70--10AMev**
- **SSC K=450 –100AMev**
- **CSRm Quasi-synchrotron**
  Intensity: $10^{8\text{-}9}$ pps,
  Circumference: 161 m
- **CSRe: Accel. & Deccel.**
  Intensity: 10^{14} pps
  Circumference: 128 m
  RIB, internal target
  High Resolution Spectrometer
- **CSR budget:42 M$; 2000-2007**

1. HIRFL Cyclotron Status and Operation

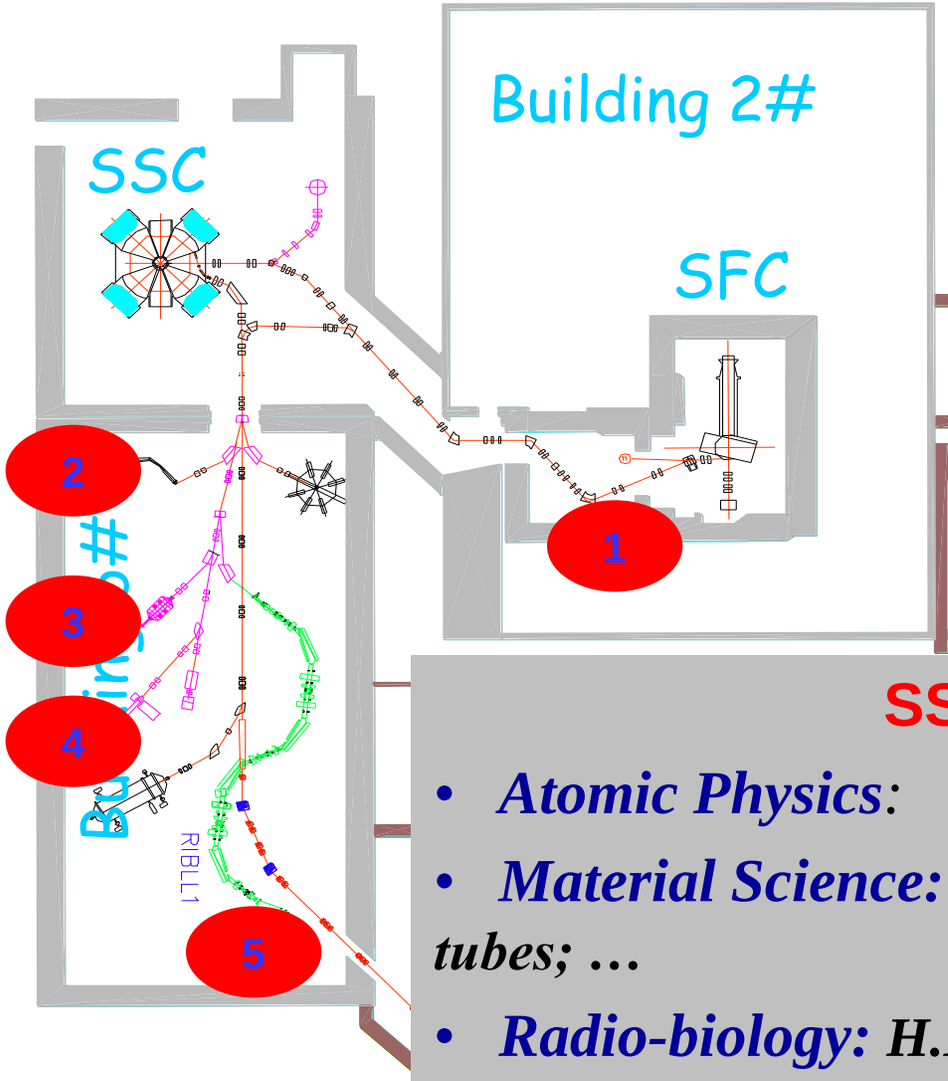
HIRFL LAYOUT

ECR

SFC K=70 (1963-)

SSC k=450 (1988-)

Experiments at HIRFL



SFC: H.I. up to 10 MeV/u

- ***Atomic Physics:*** *Highly charged ions interacting with surfaces;…*
- ***Material Science:*** *functional materials;…*
- ***Nuclear Physics:*** *super-heavy nuclei; drip-line nuclei; γ-spectroscopy of high spin state; nuclear chemistry; …*

SSC: H.I. up to 100 MeV/u

- ***Atomic Physics****:*
- ***Material Science:*** *functional materials; nano-wires & nano-tubes; …*
- ***Radio-biology:*** *H.I. interacting with cells & cancer therapy; mutagenic effects of H.I. irradiation for breeding;…*
- ***Nuclear Physics:*** *RIB physics; nuclear astrophysics;…*

HIRFL operation status 2006-2008

Typical HIRFL operation time distribution in 2006-2008

Operation time distribution	Time (h)	Percentage
Total operation time	7000	100%
Beam time	5500	78.5%
Preparation of beams	800-600	11.5%-8.7%
Failure	700-900	10%-13%

Typical HIRFL beam time distribution in 2006-2008

Beam time distribution	Time (h)	Percentage
Total beam time	5500	100%
Beams for nuclear physics, material science,biophysics,…	3300-3850	60-70%
Beams for CSR commissining and accelerator machine study	2200-1650	40-30%

HIRFL operation status 2006-2008

Typical beams provided by SFC and SSC in recent years

Ion Beams	E (MeV/A)		Beam Intensity (eμA)
	SFC	SSC	
$^{129}Xe^{27+}$	3.0	／	5.0-6.0
$^{208}Pb^{27+}$	1.1	／	0.8-1.0
$^{40}Ca^{12+}$	5.8	/	1.0
$^{20}Ne^{7+}$	7.2	／	10-12
$^{12}C^{4+}$	7.0	／	10-15
$^{26}Mg^{8+}$	6.54	/	2.0
$^{16}O^{6+}$	7.99	/	6-12
$^{40}Ar^{8+}$	2.35	／	6-15
$^{78}Kr^{19+}$	4.0		7-9
$^{238}U^{26+}$	0.81	/	0.33
$^{12}C^{4+/6+}$	7.0	80.5	0.2-0.5
$^{12}C^{5+/6+}$	8.2	100	0.2-0.3
$^{32}S^{11+/16+}$	7.1	82	0.2-0.3
$^{26}Mg^{8+/12+}$	6.17	70	0.3-0.4
$^{40}Ar^{12+/17+}$	7.1	82	0.1-0.3
$^{40}Ar^{8+/15+}$	2.35	25	0.8-1.5
$^{22}Ne^{7+/10+}$	6.17	70	0.2-0.5
$^{58}Ni^{13+/22+}$	4.5	50	0.1-0.2
$^{129}Xe^{27+}$	1.8	19.5	0.6-0.75
$^{36}Ar^{8+}$	2.07	22	2.5-3.5

Improvement of SFC

- **Intense beams from ECR ion source; Upgraded of the axial injection beam line to improve injection efficiency; Built a new SFC vacuum chamber; Improved SFC RF Dee voltage; Power supply and control system upgrading; Optimized tuning.**
- **Beam intensities have been enhanced by a factor 2-10 for light ions such as C, O, Ne, Ar >10 eμA.**

SFC Beam intensity	C 6-7 Mev/u	O 6-8 Mev/u	Ne 6-8 Mev/u	Ar 2-3 MeV/u	Xe 2-3 MeV/u
Before 2004	5 eμA	5.5 eμA	3.7 eμA	3.2 eμA	0.54 eμA
2004—2008	10-15 eμA	6-12 eμA	10-12eμA	10-15 eμA	5-6eμA

- **Some metallic ion beams were delivered, such as ^{26}Mg, ^{40}Ca, ^{56}Fe, ^{58}Ni,^{208}Pb, ^{238}U**
- **Some highly charged very heavy ions were provided such as $^{129}Xe^{27+}$, $^{208}Pb^{27+}$, $^{209}Bi^{31+}$,$^{238}U^{26+}$**

Improvement of SSC

- Intense beams from SFC; Operation of the rebuncher NB1 to improve injection efficiency; Successfully optimization of isochronous magnetic field; Improved SSC RF Dee voltage; SSC vacuum improvement; Power supply, control system and diagnostics upgrading; Optimized tuning.

- SSC beam intensities have been increased by a factor 3-50

SSC Beam intensity	C 80 MeV/u	Ne 70 Mev/u	Ar 22－25MeV/u	Xe 19.5 MeV/u
Before 2004	0.3 eμA	0.15 eμA	0.15 eμA	0.015 eμA
2004－2008	0.3- 0.5 eμA	0.3-0.5 eμA	2.5-3.5 eμA	0.6-0.75 eμA

- The $^{209}Bi^{31+}$ was accelerated to 9.5MeV/u successfully. The next heavy ion scheduled to test is ^{238}U.

- But SSC beam intensity with higher energy(>26MeV/u) is still very low, and very heavy ion beams (such as U) have not been tested.

HIRFL-CSR operation status-2009

The typical beam provided by HIRFL-CSR in 2009

	Beam	Energy (MeV/u)		
		SFC	SSC	CSR
1	$^{12}C^{4+}$	7.0	/	150~300
2*	$^{129}Xe^{20+}$	1.67	/	/
3	$^{78}Kr^{19+/28+}$	4	/	205~450
4	$^{86}Kr^{17+/26+}$	2.35	25	/
5*	$^{12}C^{5+/6+}$	7.34	85	/
6	$^{13}C^{5+/6+}$	8.47	100	/
7*	$^{209}Bi^{31+}$	0.91	9.5	/
8*	$^{16}O^{6+/8+}$	7.72	90	/
9	$^{19}F^{7+}$	6.6	/	/
10	$^{40}Ca^{12+}$	5.8	/	/
11	$^{36}Ar^{8+/8+}$	2.07	22	/
12*	$^{58}Ni^{19+/24+}$	6.59	75.3	/
13	$^{58}Ni^{15+/24+}$	4.53	50	/
14*	$^{20}Ne^{7+/10+}$	7.4	85.75	/
15	$^{9}Be^{3+/4+}$	6.89		
16	$^{40}Ar^{8+/15+}$	2.353	25	/

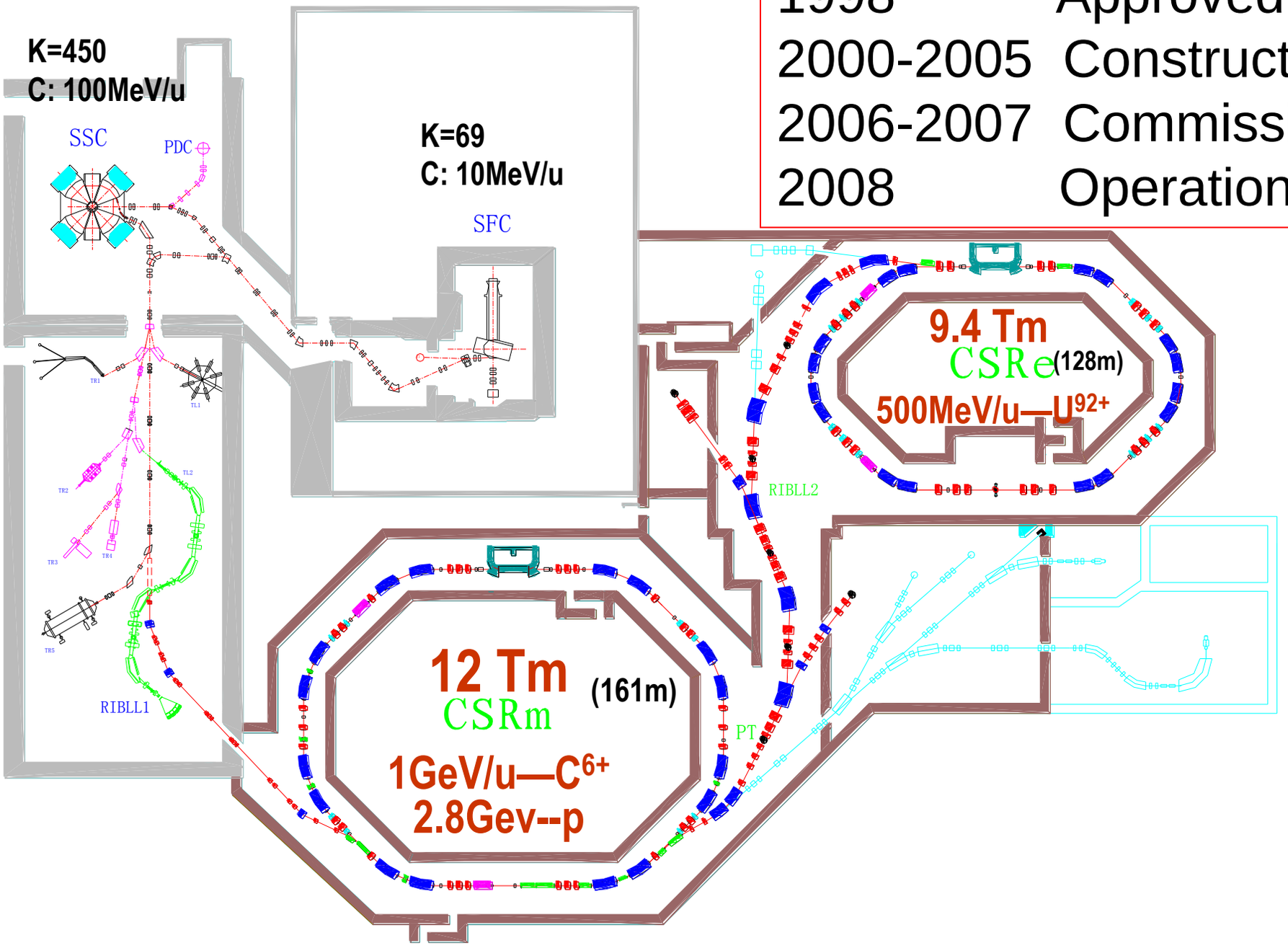
HIRFL-CSR operation status of 2009

2008.12.21---2009.12.21

Operation time distribution		Time Hours	Percentage
Total operation time		7155.1	100.0
Failure		733.6	10.3
Preparation of beam		1233.6	17.2
Beam time		5188.3	72.5
	Nuclear physics	2355.9	45.4
	Irradiation	983.9	19.0
	Biophysics and cancer therapy	1079.4	20.8
	machine study	769.0	14.8

2. HIRFL-CSR and its Commissioning

1998	Approved
2000-2005	Construction
2006-2007	Commissioning
2008	Operation



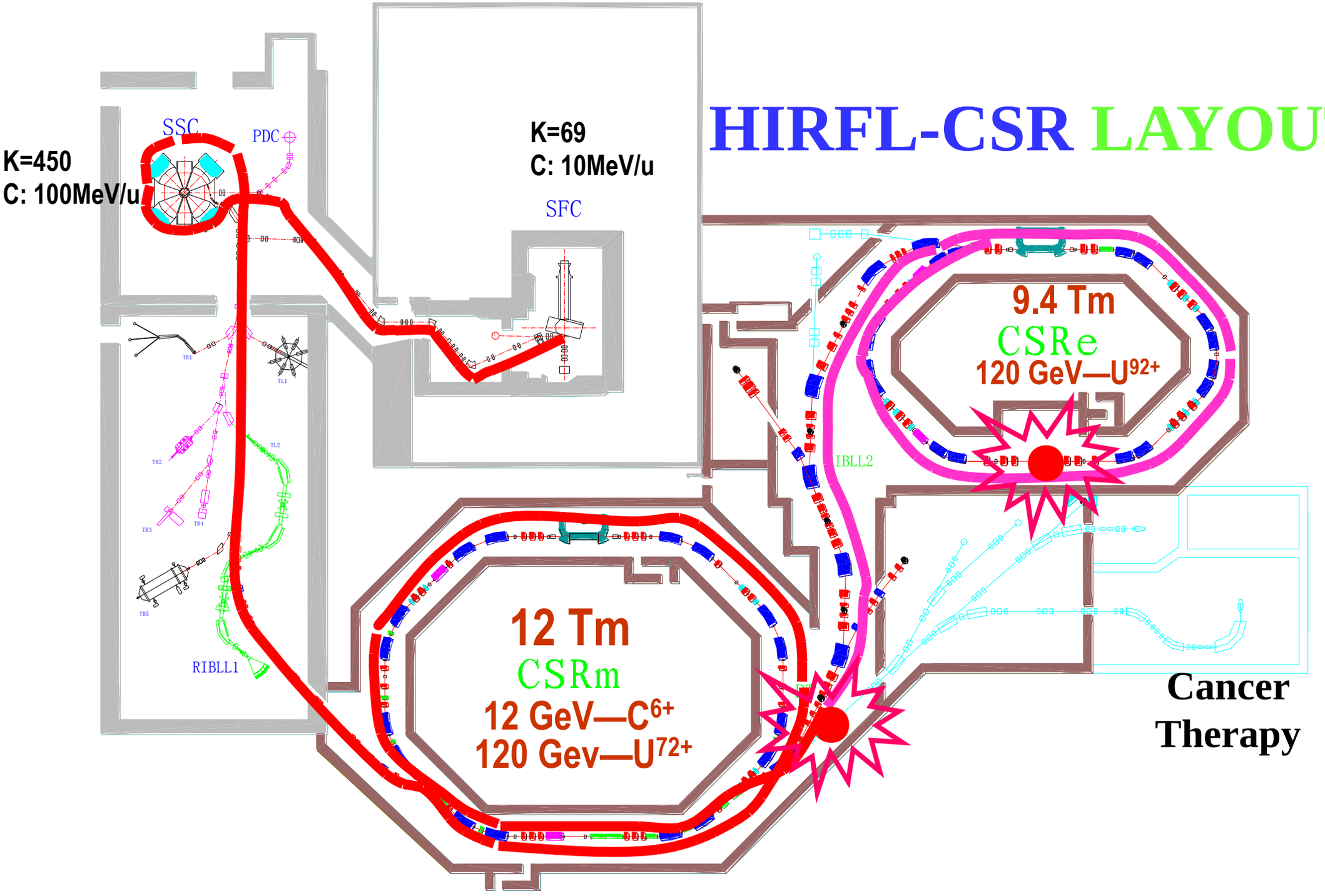
Pre-accelerator system of CSR

A< 40

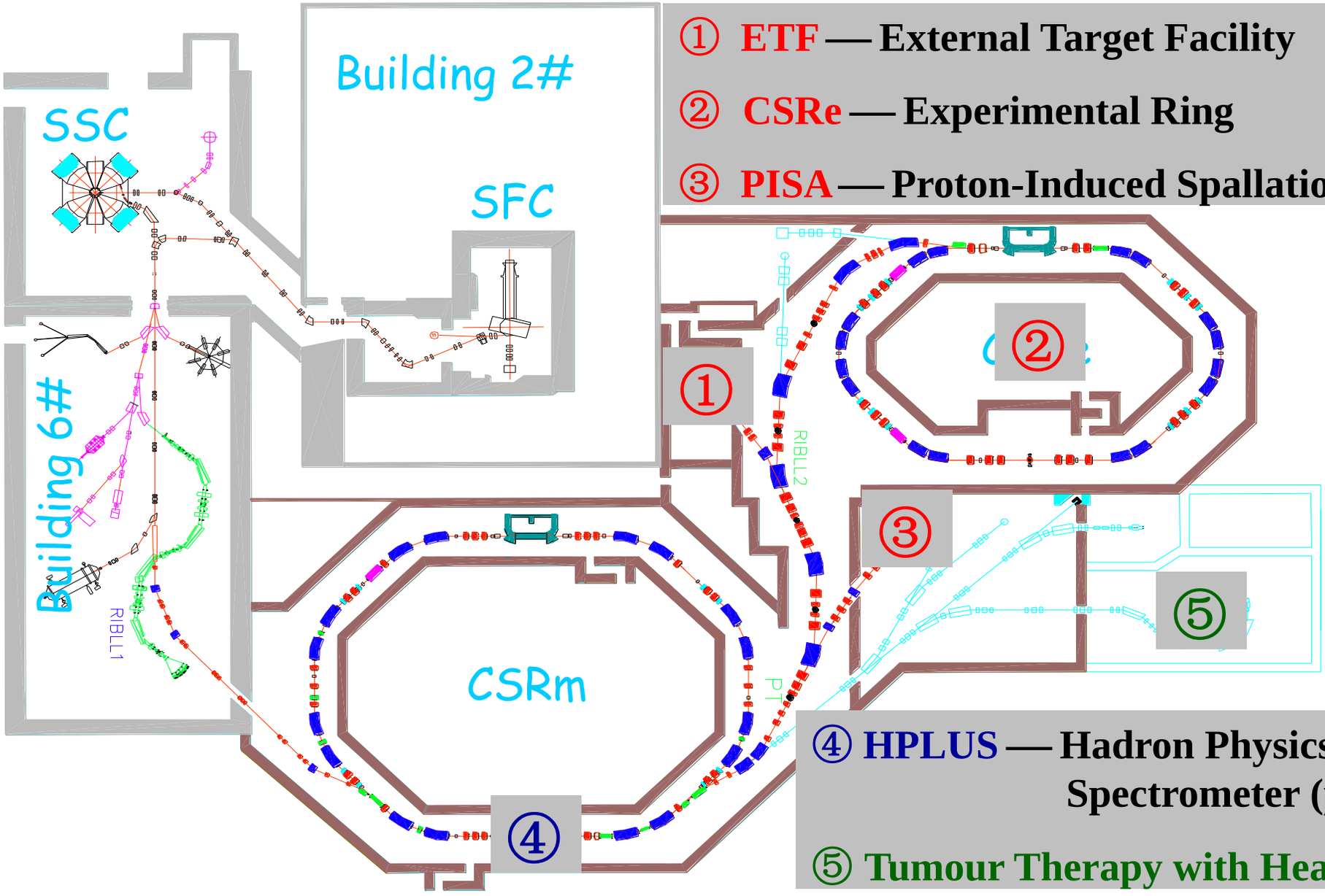
A≥ 40

CSRm

HIRFL-CSR LAYOUT



Experiments at CSR



① **ETF** — **External Target Facility**

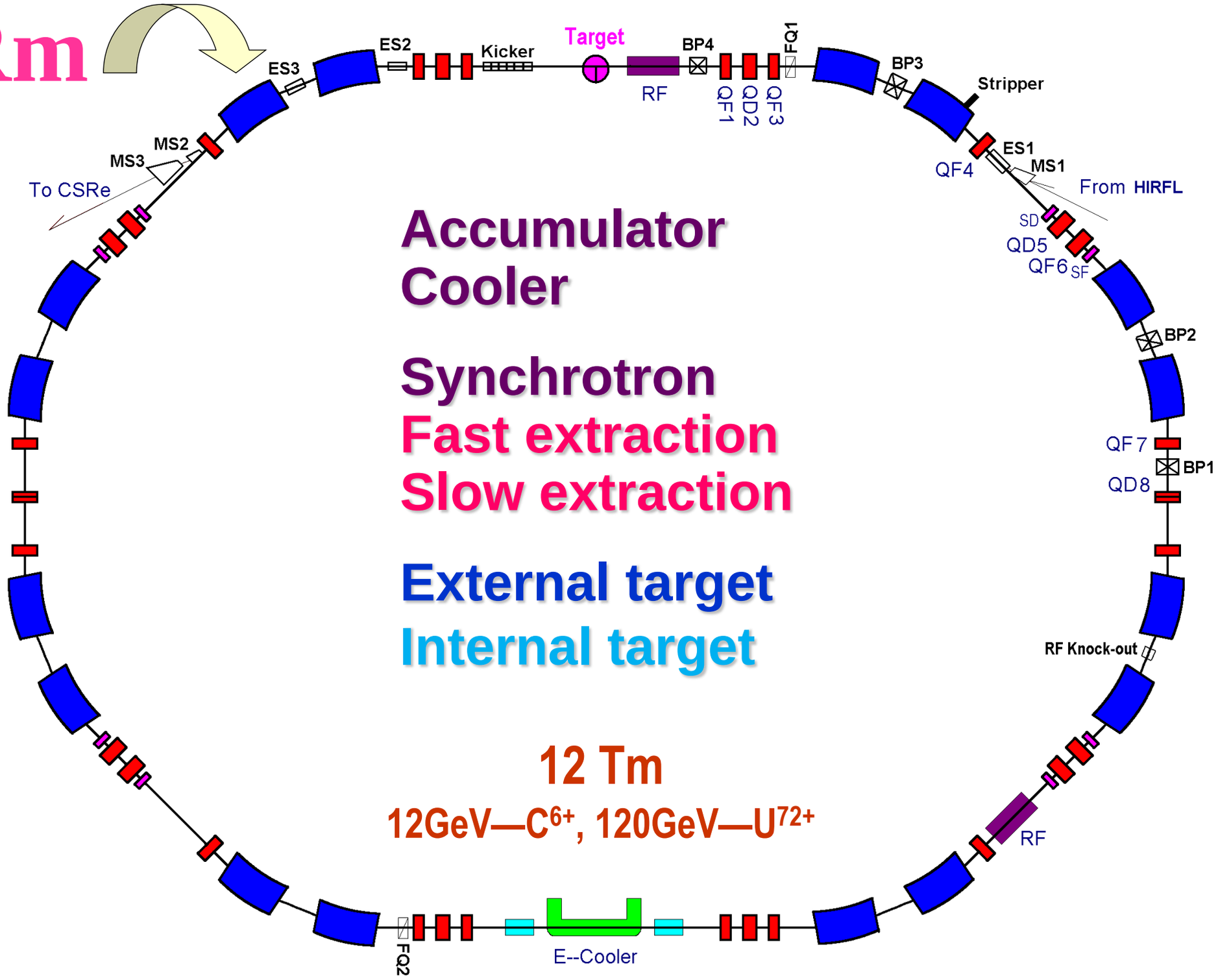
② **CSRe** — **Experimental Ring**

③ **PISA** — **Proton-Induced Spallation Apparatus**

④ **HPLUS** — **Hadron Physics LanzhoU Spectrometer (planned)**

⑤ **Tumour Therapy with Heavy Ions**

CSRm



Accumulator
Cooler

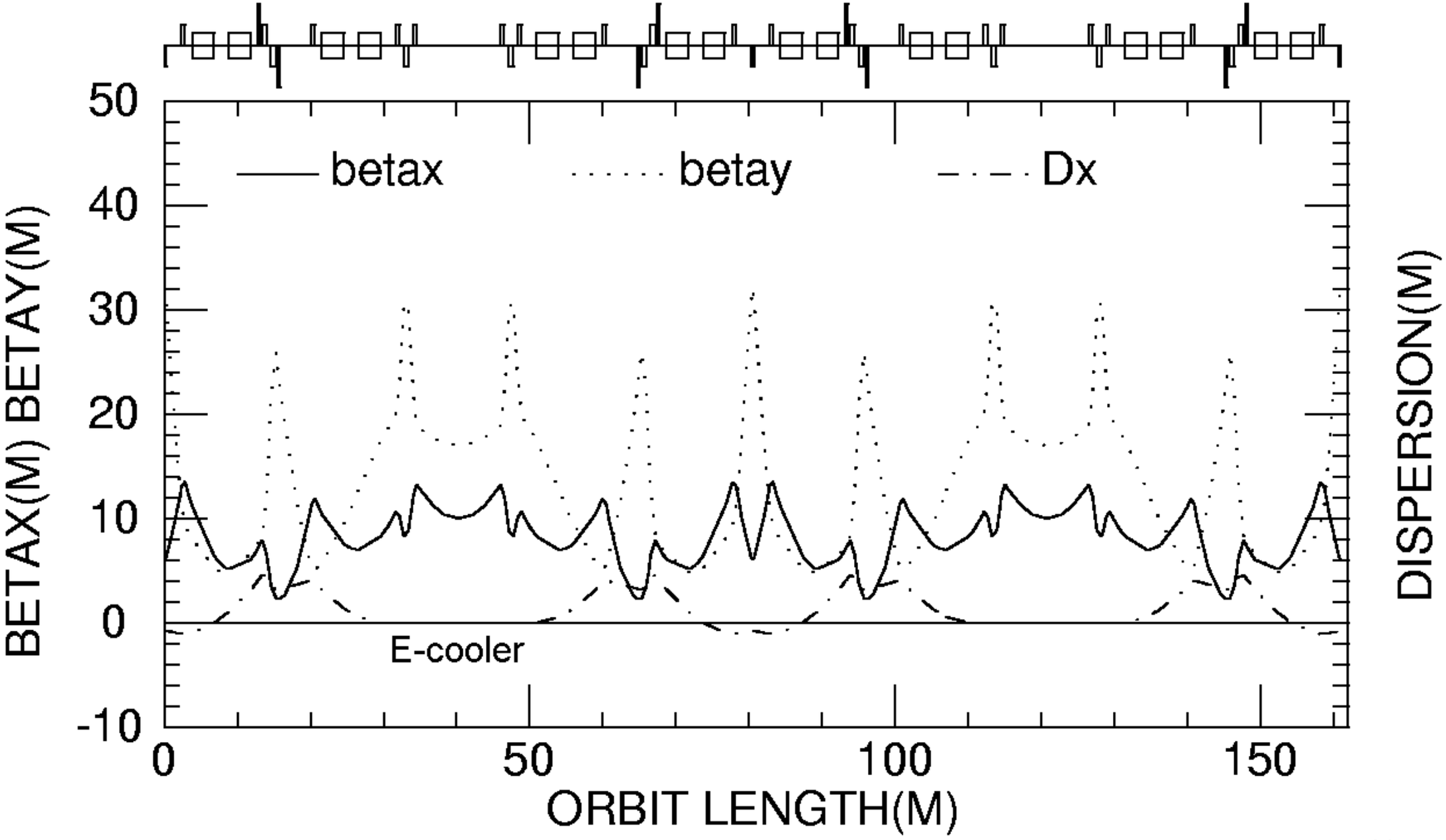
Synchrotron
Fast extraction
Slow extraction

External target
Internal target

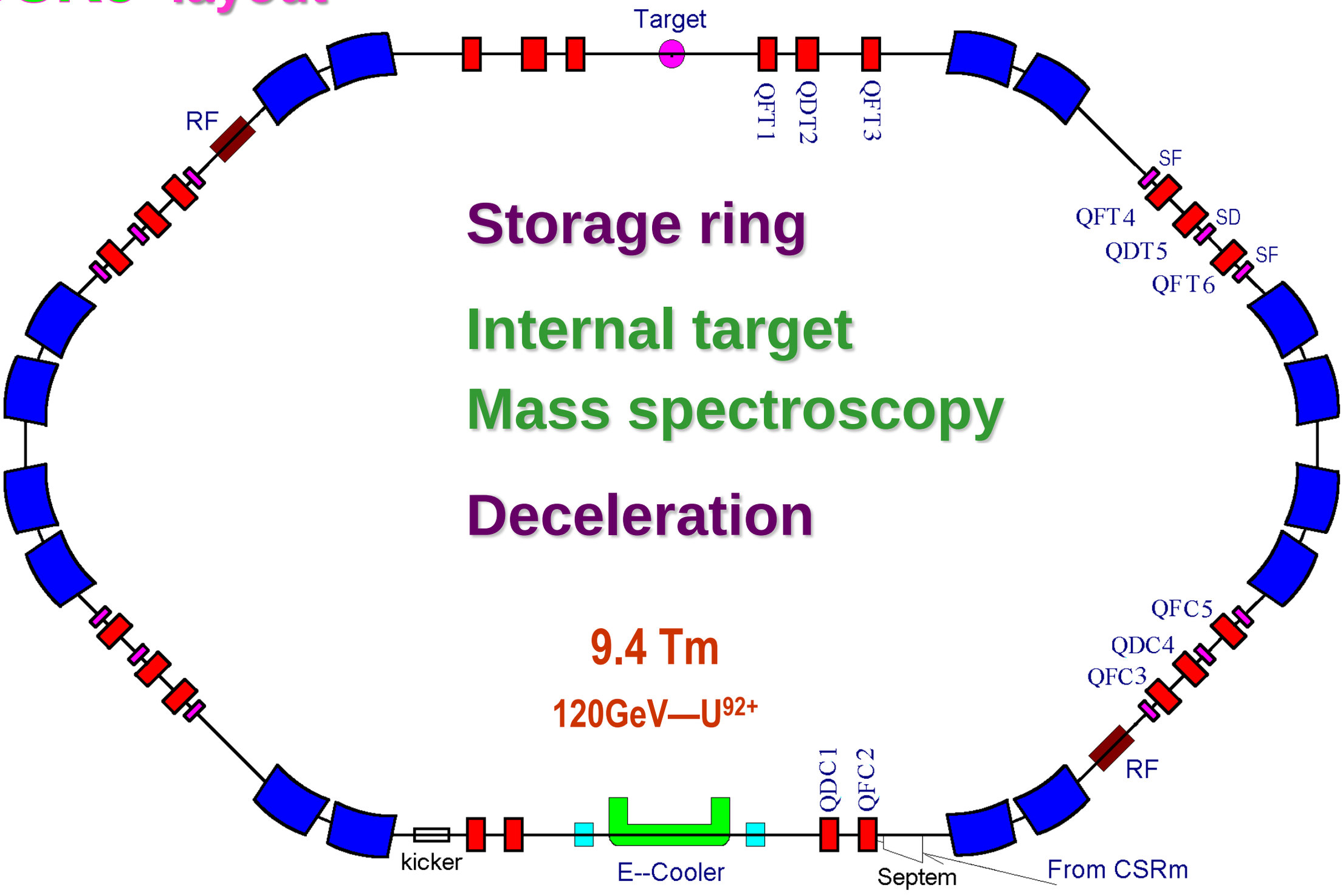
12 Tm

12GeV—C^{6+}, 120GeV—U^{72+}

Twiss Parameters of CSRm



CSRe layout



Storage ring

Internal target

Mass spectroscopy

Deceleration

9.4 Tm

120GeV—U^{92+}

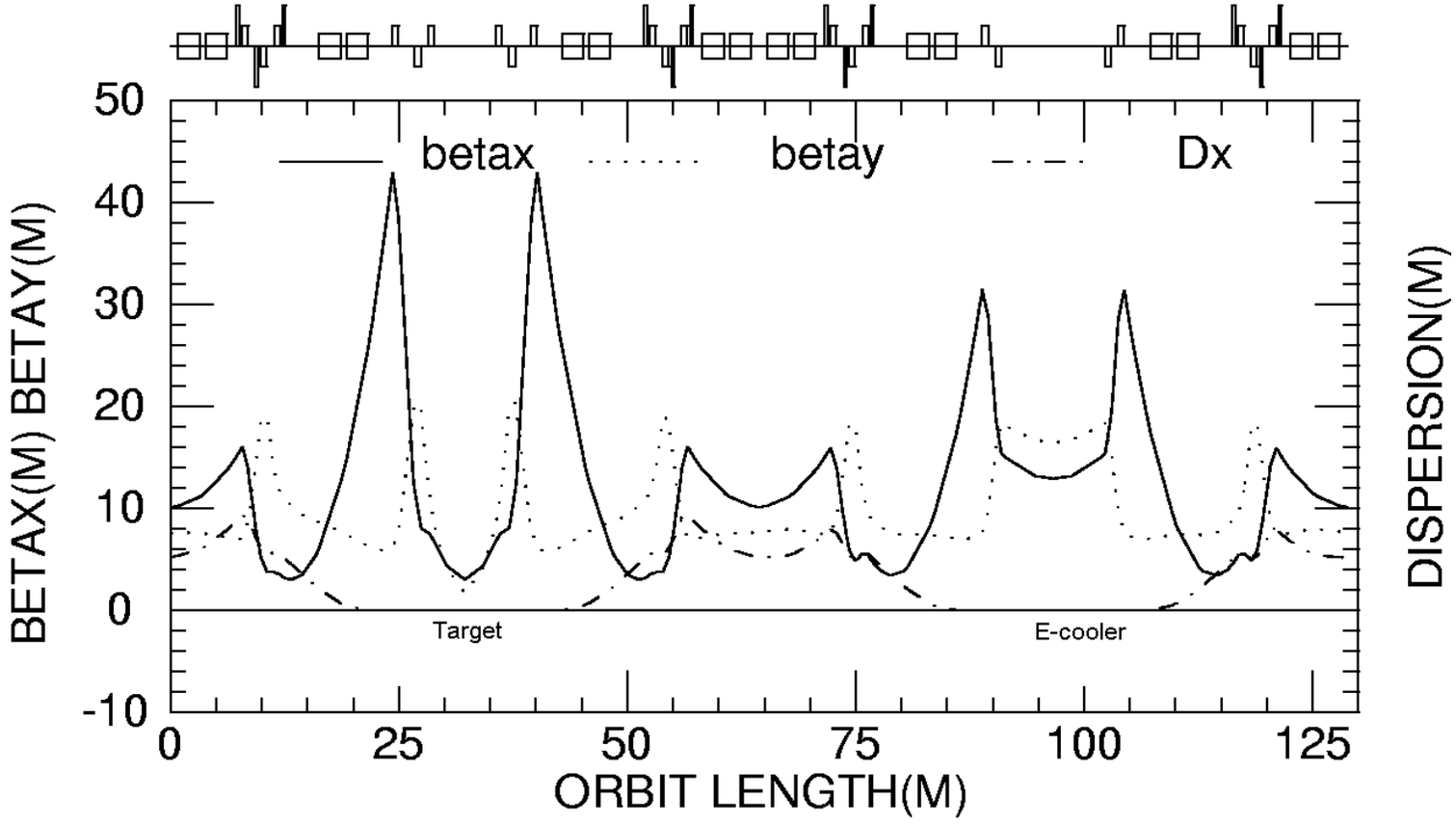
Three Lattice Mode of CSRe

Internal-Target Mode

Small β-amplitude in target point

Large transverse acceptance for internal-target experiments

Ah=150πmm mrad, Av=75πmm mrad

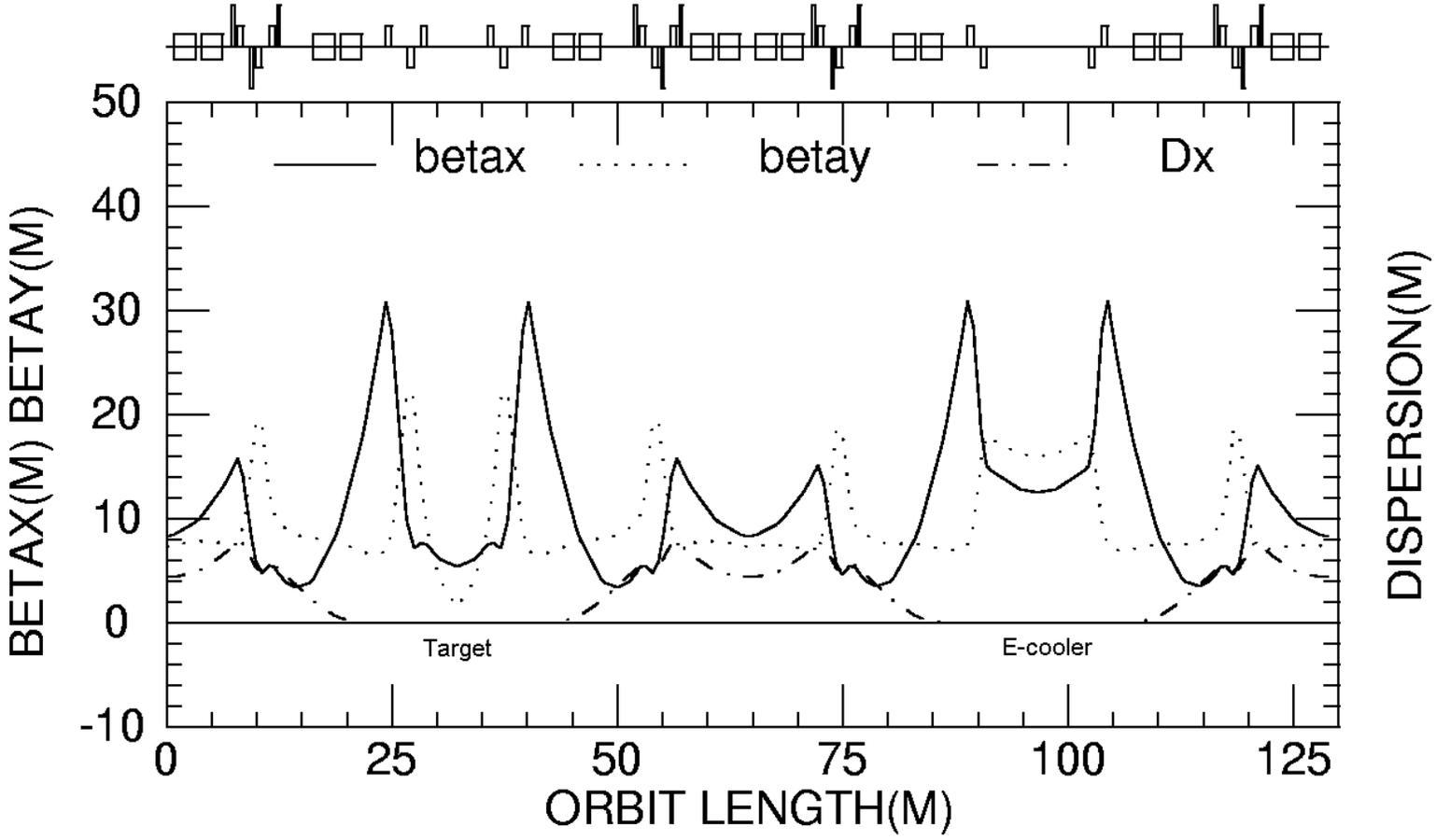


Three Lattice Mode of CSRe

Normal Mode

Large momentum acceptance, ΔP/P = 2.6%

For high-precision mass spectroscopy

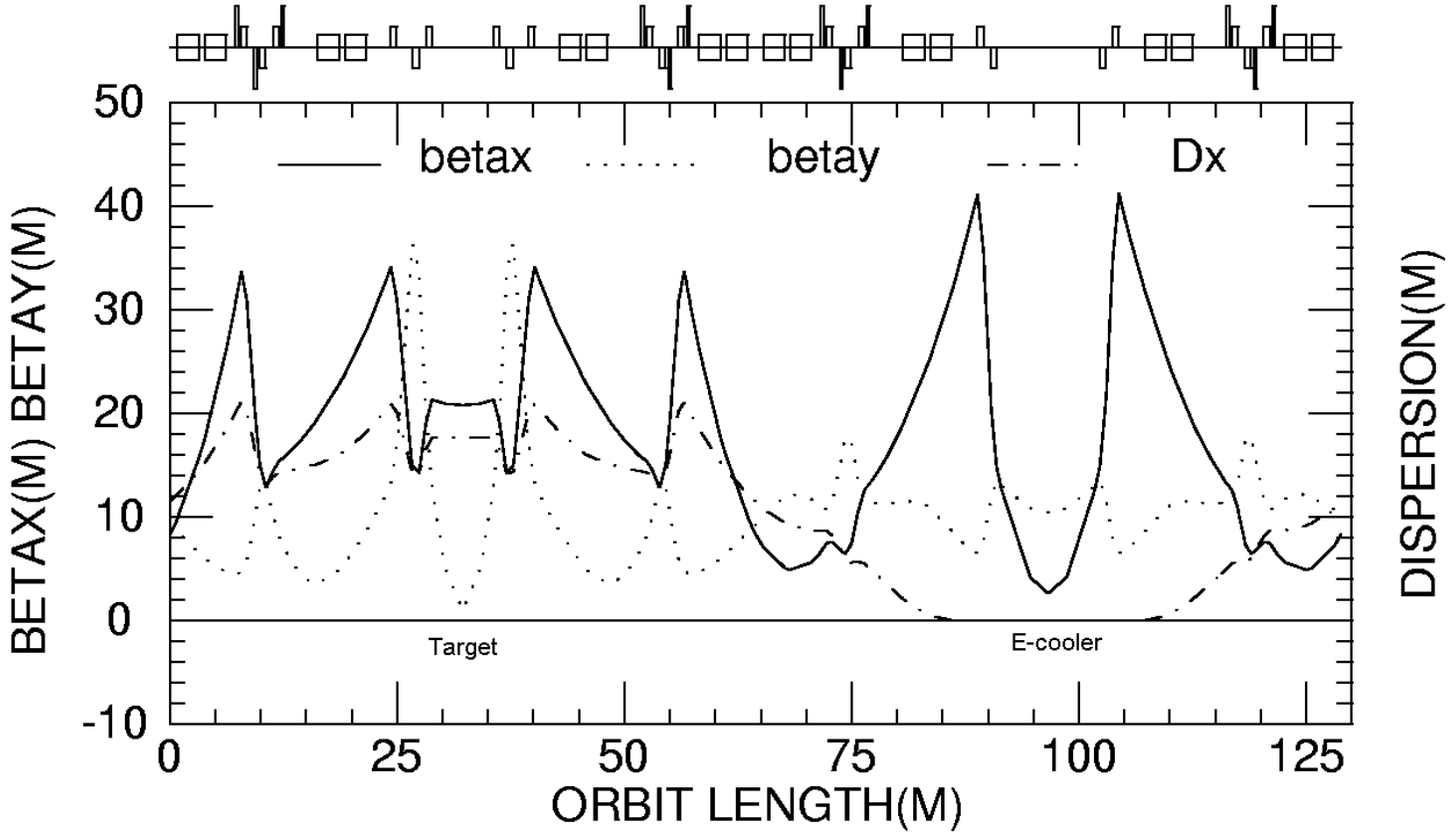


Three Lattice Mode of CSRe

Isochronous Mode

Small transition γtr = Beam energy γ of several hundred MeV/u

For the mass measurement of the short-life-time RIB



CSR major parameters (1)

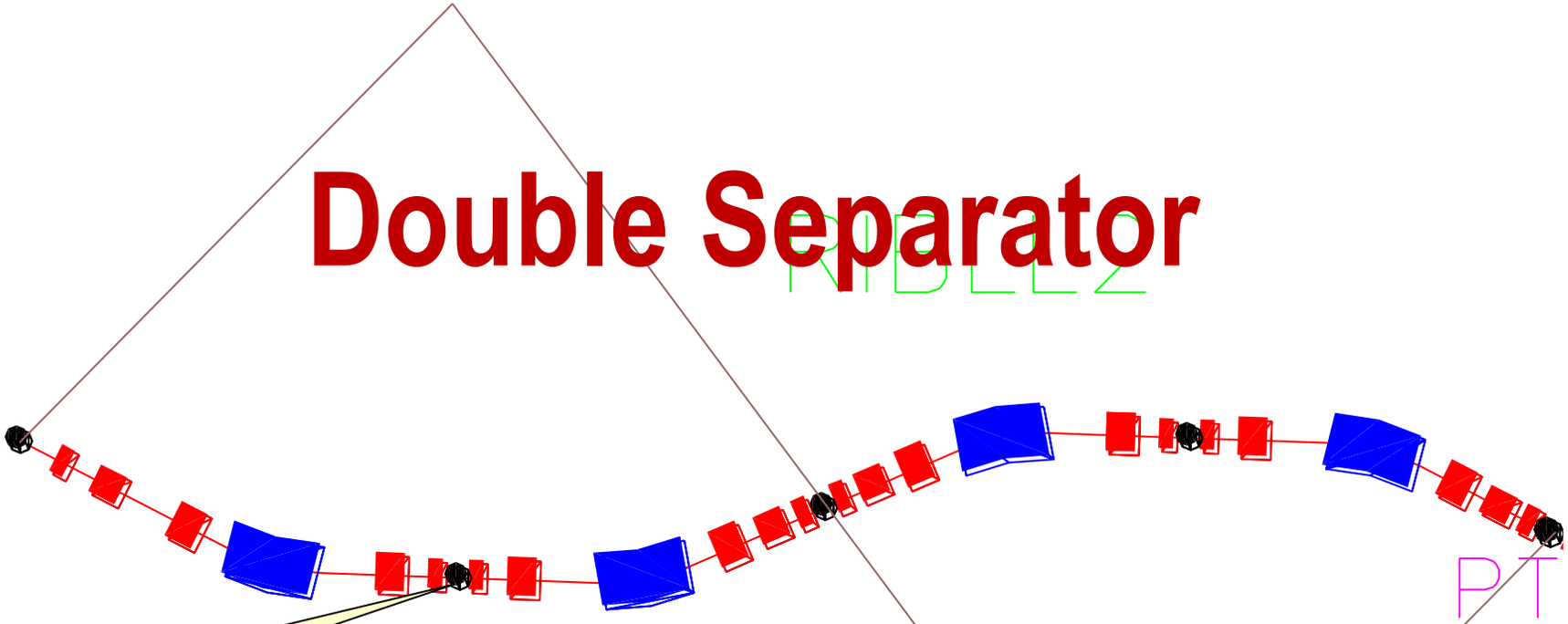
	CSRm	CSRe
Circumference (m)	161.0014	128.8011
Average radius (m)	$8R_{SSC}=34R_{SFC}=25.62416$	$4/5R_{CSRm}=20.499328$
Geometry	Race-track	Race-track
Max. energy (MeV/u)	2800 (p) 1100 (C^{6+}) 500 (U^{72+})	2000 (p) 750 (C^{6+}) 500 (U^{92+})
Bρ (Tm)	0.81/12.05	0.50/9.40
B(T)	0.10/1.60	0.08/1.60
Ramping rate (T/s)	0.05 ~ 0.4	-0.1 ~ -0.2
Repeating circle (s)	~17 (~10s for Accumulation)	
Acceptance	Fast-extraction mode	Normal mode
A_h (π mm-mrad)	200 (Δp/p = ±0.3 %)	**150** (Δp/p =±0.5%)
A_v (π mm-mrad)	40	**75**
Δp/p (%)	1.4 (ε_h= 50 π mm-mrad)	**2.6** (ε_h= 10 π mm-mrad)

CSR major parameters (2)

	CSRm		CSRe
E-cooler			
Electron energy (KeV)	35		300
Eff. cooling length (m)	3.4		3.4
RF system	Accel.	Accum.	Deceleration
Harmonic number	1	16, 32,64	1
f_{min}/f_{max} (MHz)	0.24/1.81	6.0 / 14.0	0.4 / 2.0
Voltages (n × kV)	1 × 7.0	1 × 20.0	2 × 10.0
Vacuum (mbar)	(3.0×10^{-11})		

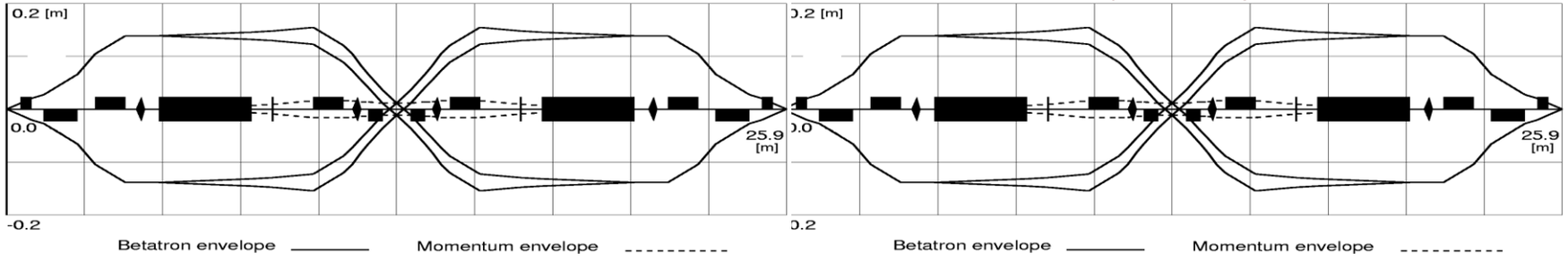
Radioactive Ion Beam Line between CSRm and CSRe

Double Separator



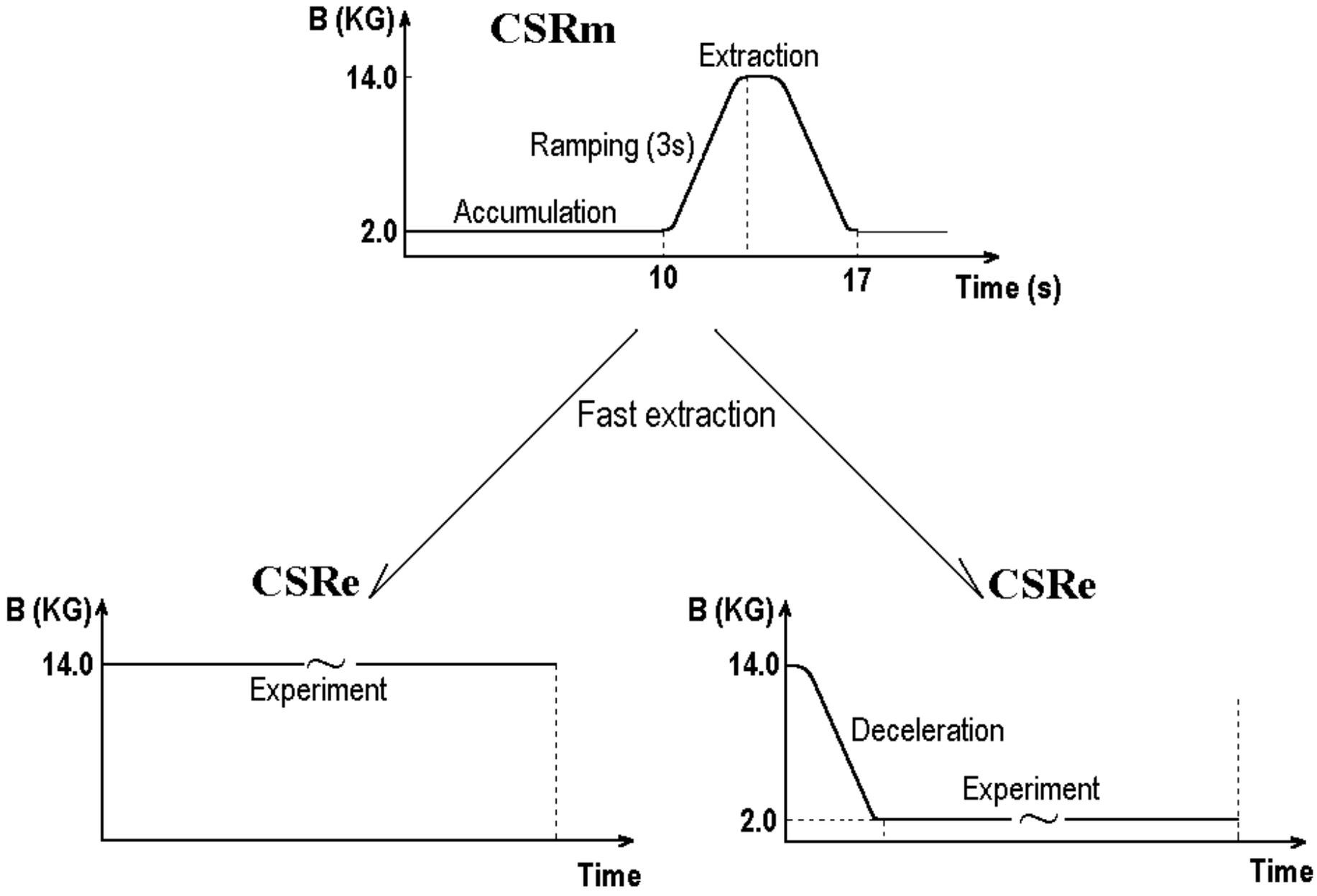
PF mothod

Projectile Fragmentation



$\Delta P/P = \pm 1\%$, Emittance = 25π mm-mrad

CSR Operation Scheme



CSRm Injection Scheme

C, N, O, F, Ne, Ar, Ca, A<40, E = 7---10 MeV/u

SFC + CSRm

Stripping Injection + E-cooling $\longrightarrow$ I=$10^{8\sim9}$

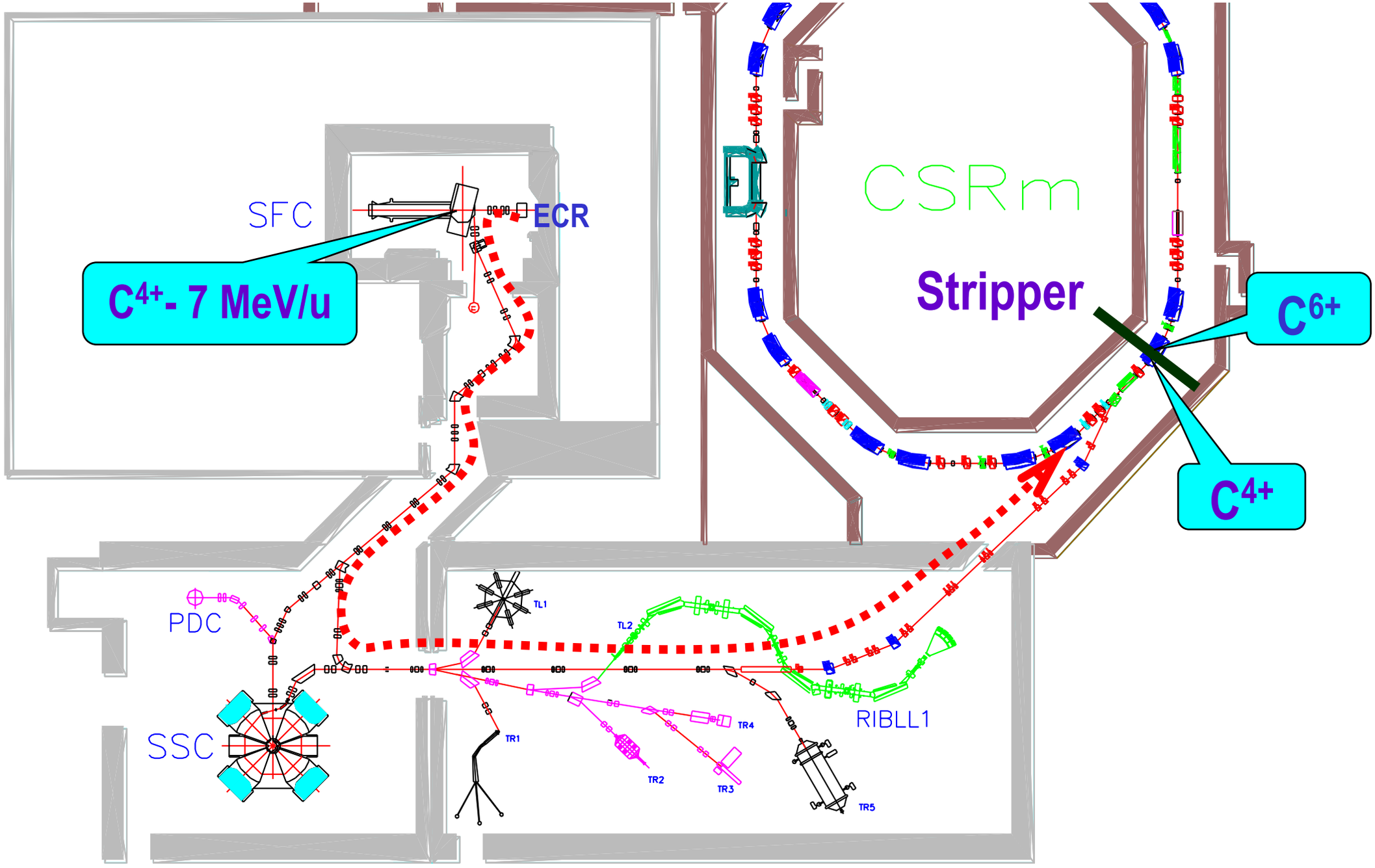
Ar, Kr, Xe, Ta, Au, Pu, U, A ≥ 40, E = 10---25 MeV/u

SFC + SSC + CSRm

Multiple Multi-turn Injection + E-cooling $\longrightarrow$ I=$10^{7\sim8}$

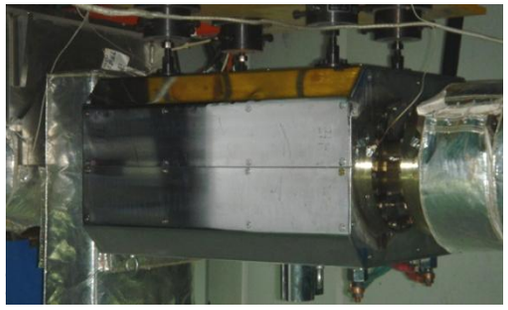
Scheme of the stripping injection in CSRm

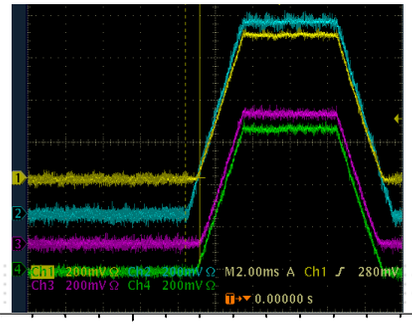
2006.01



Bump section for CSRm stripping injection

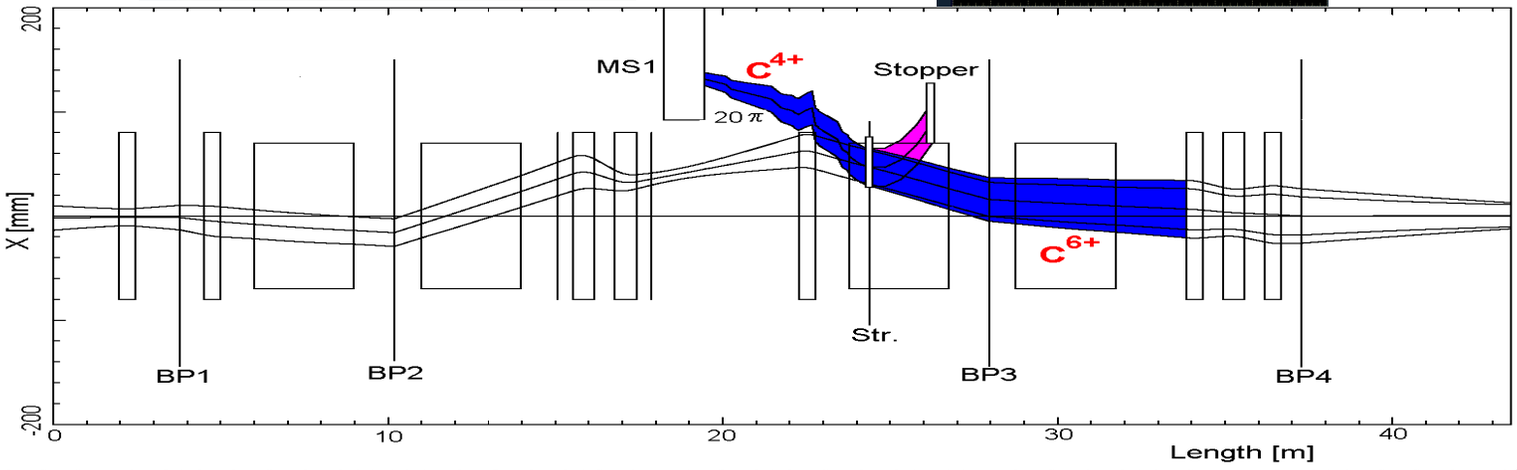
2006.01





Bump-PS

20μs
3200A
1600V



BP1

BP2

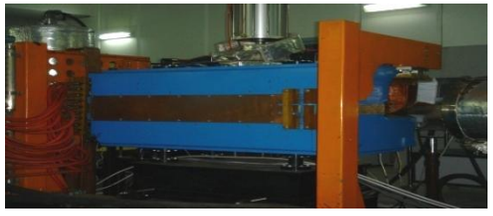
PB3

BP4

MS

Str.

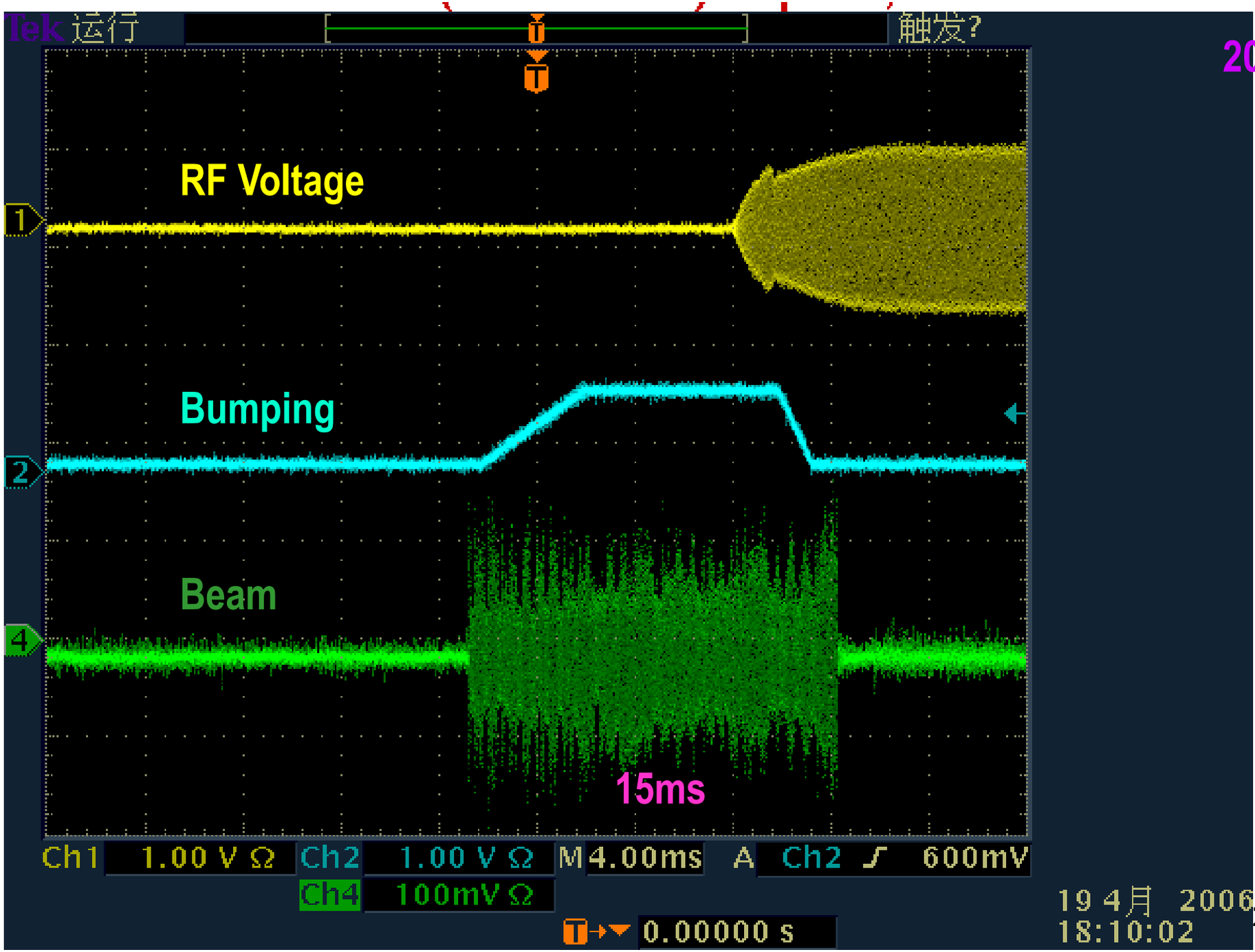
Beam



2900A, 8600G

Signals of beam + bump + RF for stripping injection

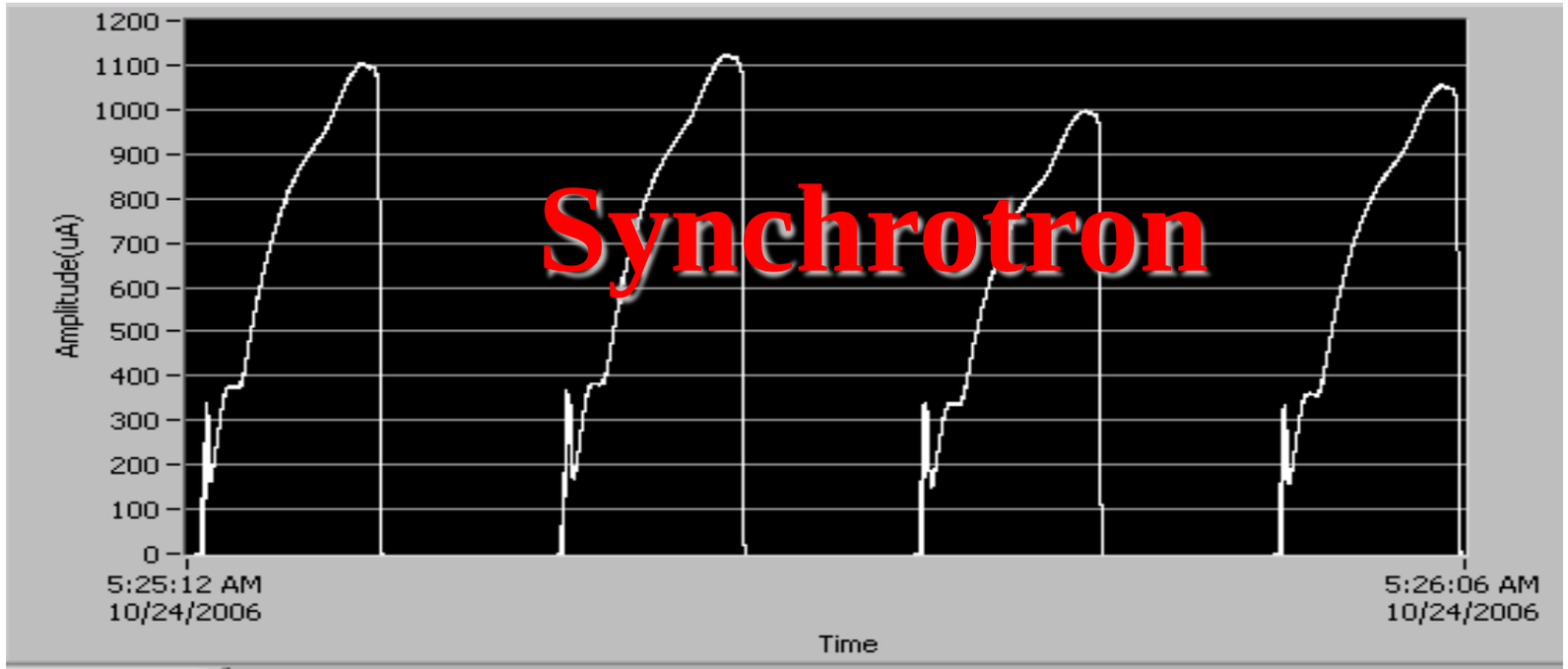
PS of bumps, dipoles and quadruples were controlled by the new DSP

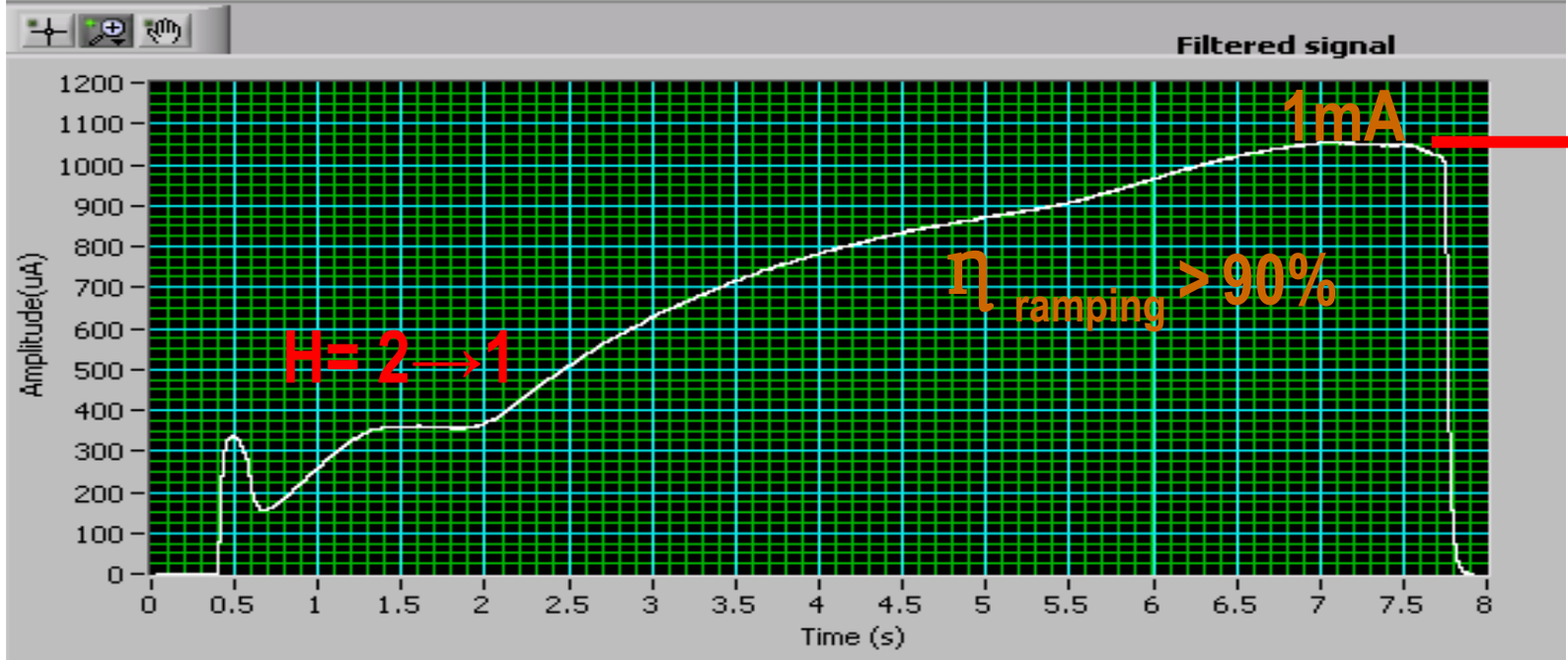


7MeV/u→12GeV (C^{6+}) STI + Ramping in CSRm

06/10/24 05:19

Mode: SFC+CSRm, STI, H = 2→1, f_{rf} = 0.45→1.63MHz, G = 11.3Tm



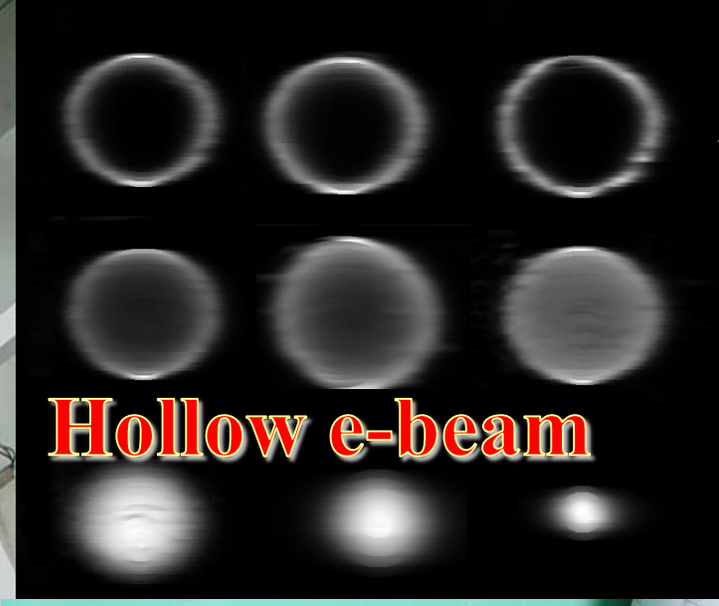


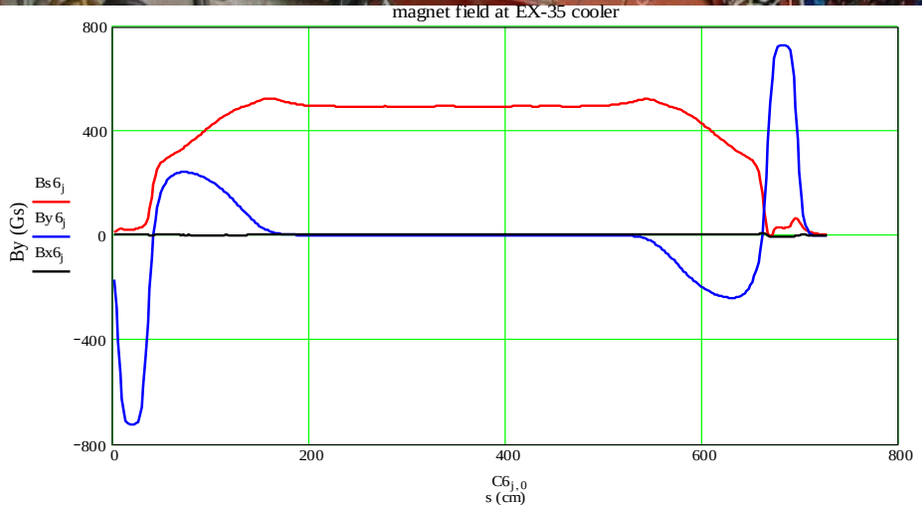
→ $6x10^8$

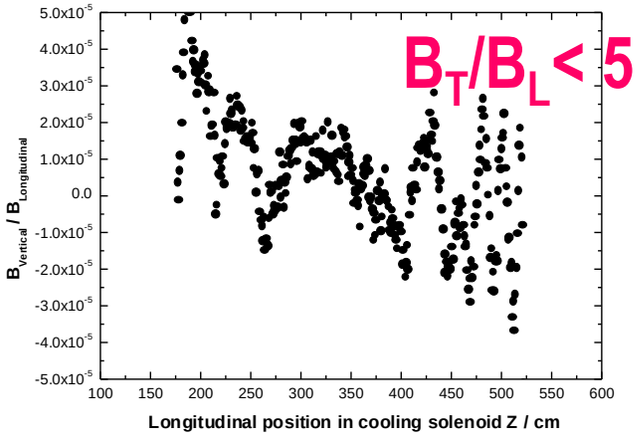
2006.12

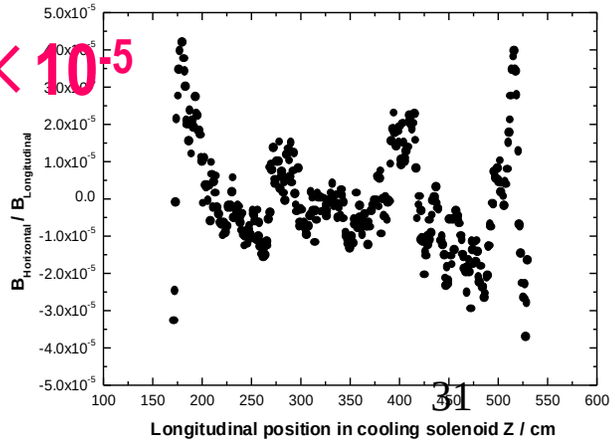
e-cooler

for ion cooling



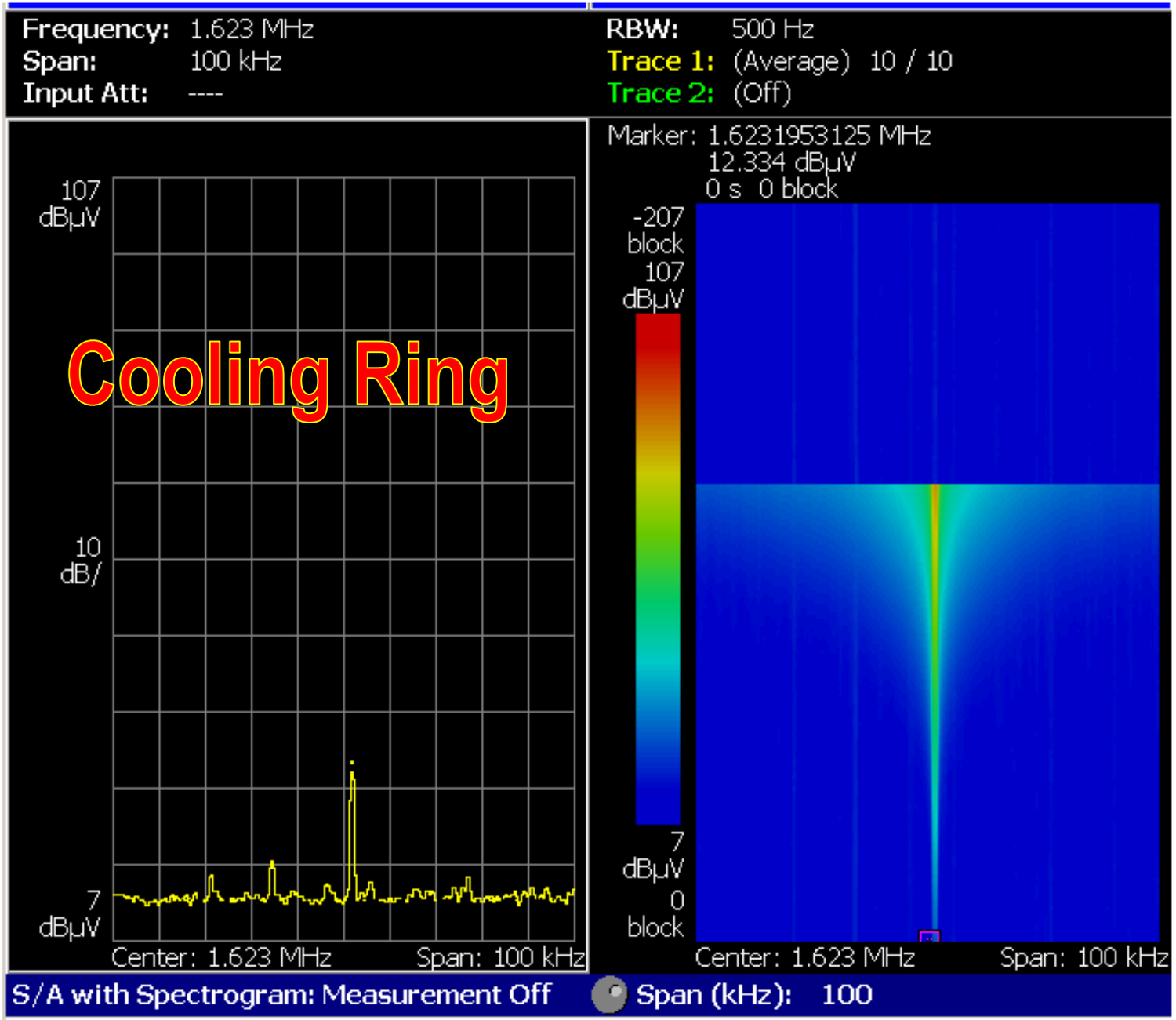






e-cooling effect

C^{6+}-7MeV/u , observed the longitudinal schottky signal from spectrum analyzer



ΔP/P

4×10^{-3}

↓

↓

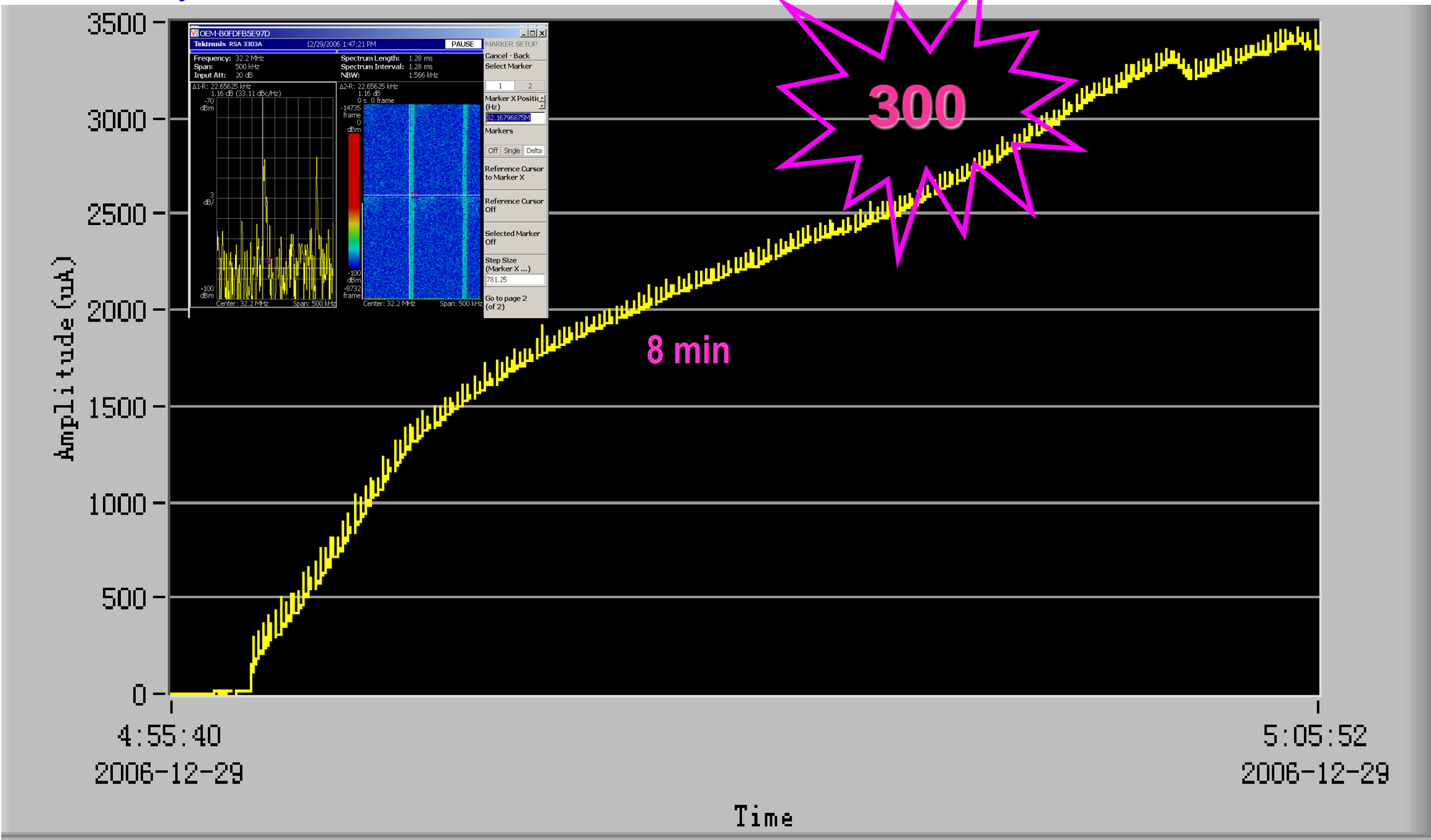
↓

2×10^{-4}

Beam Accumulation with e-cooing in CSRm

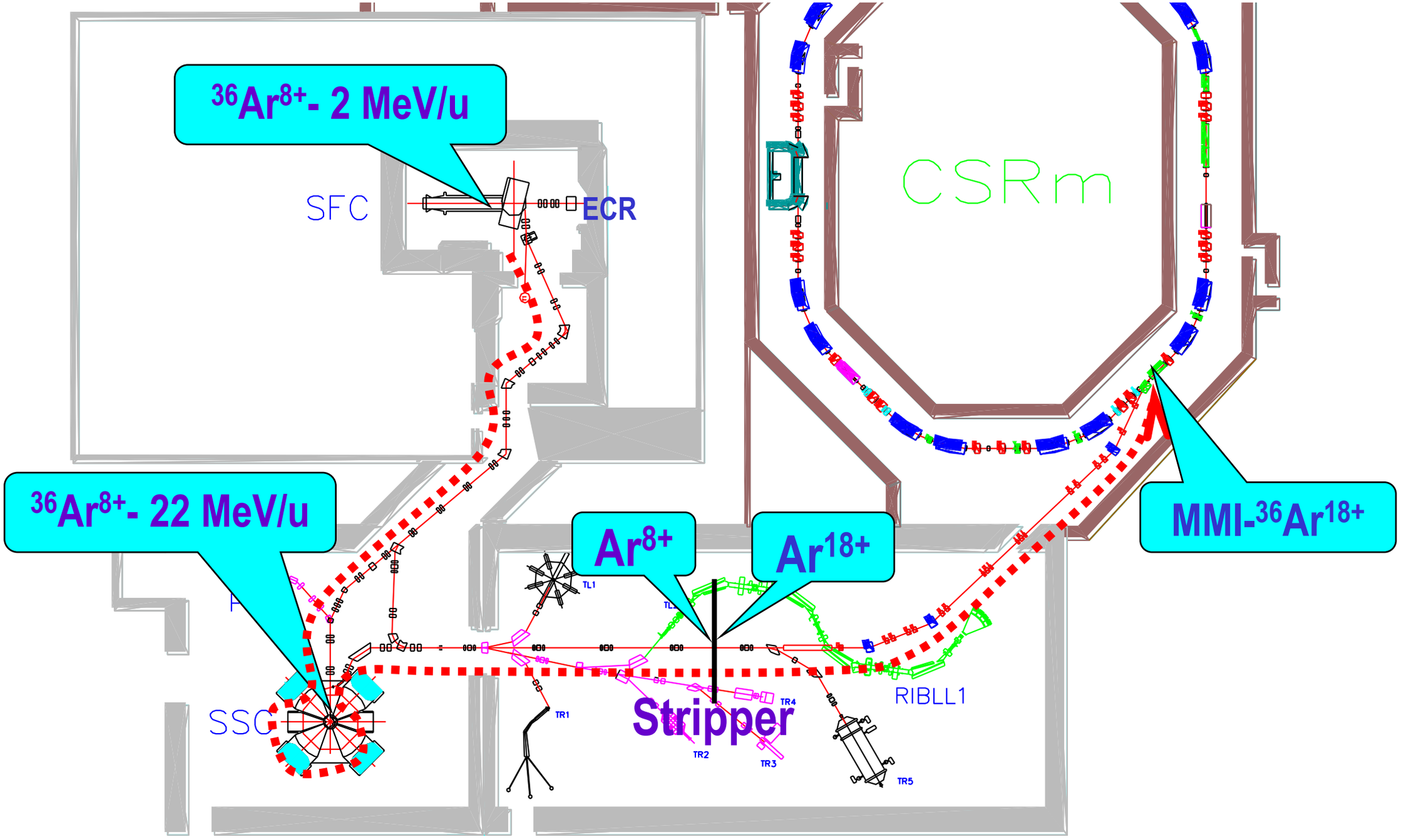
I_{inj}=10.2μA, Beam current: 3.2mA, 1.6×10^{10}, 8min., Gain=300

06/12/29 5:00



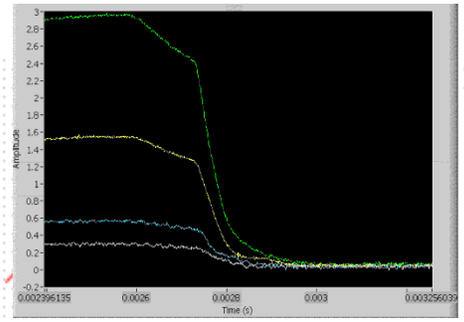
Scheme of the MMI for Ar-beam in CSRm

07/04/24

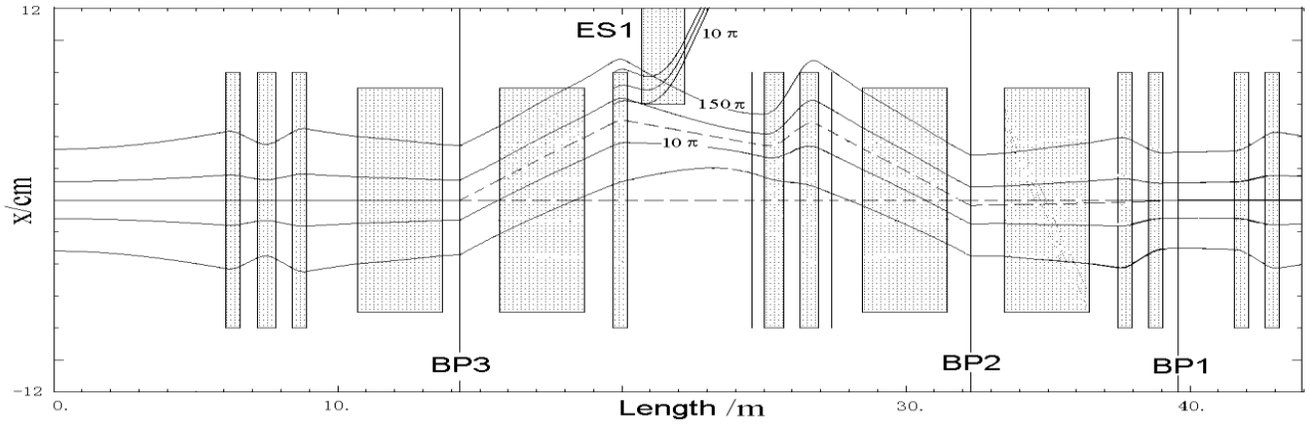


Bump section for CSRm Multi-turn injection

20007.03



Bump-PS



BP1

BP2

PB3

BP4

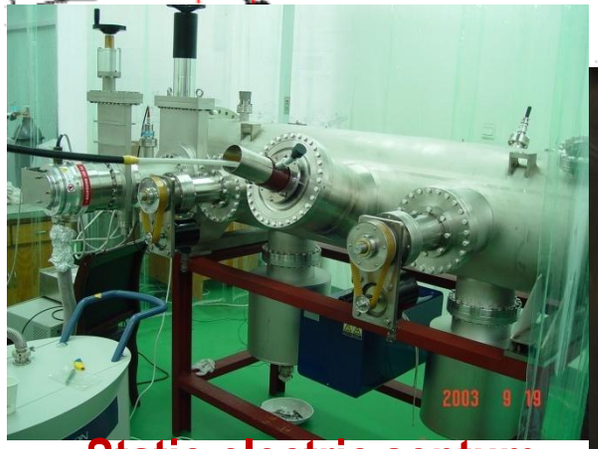
Orbits of the Multiple Multi-turn Injection

Beam

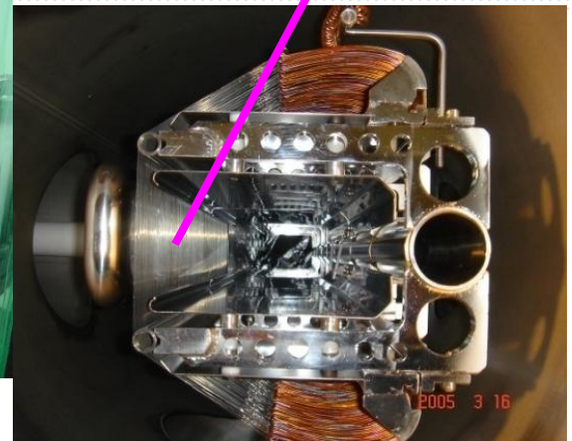
L = 2 m

$V_{max.}$ = 160 kV

Gap=23mm



Static-electric septum



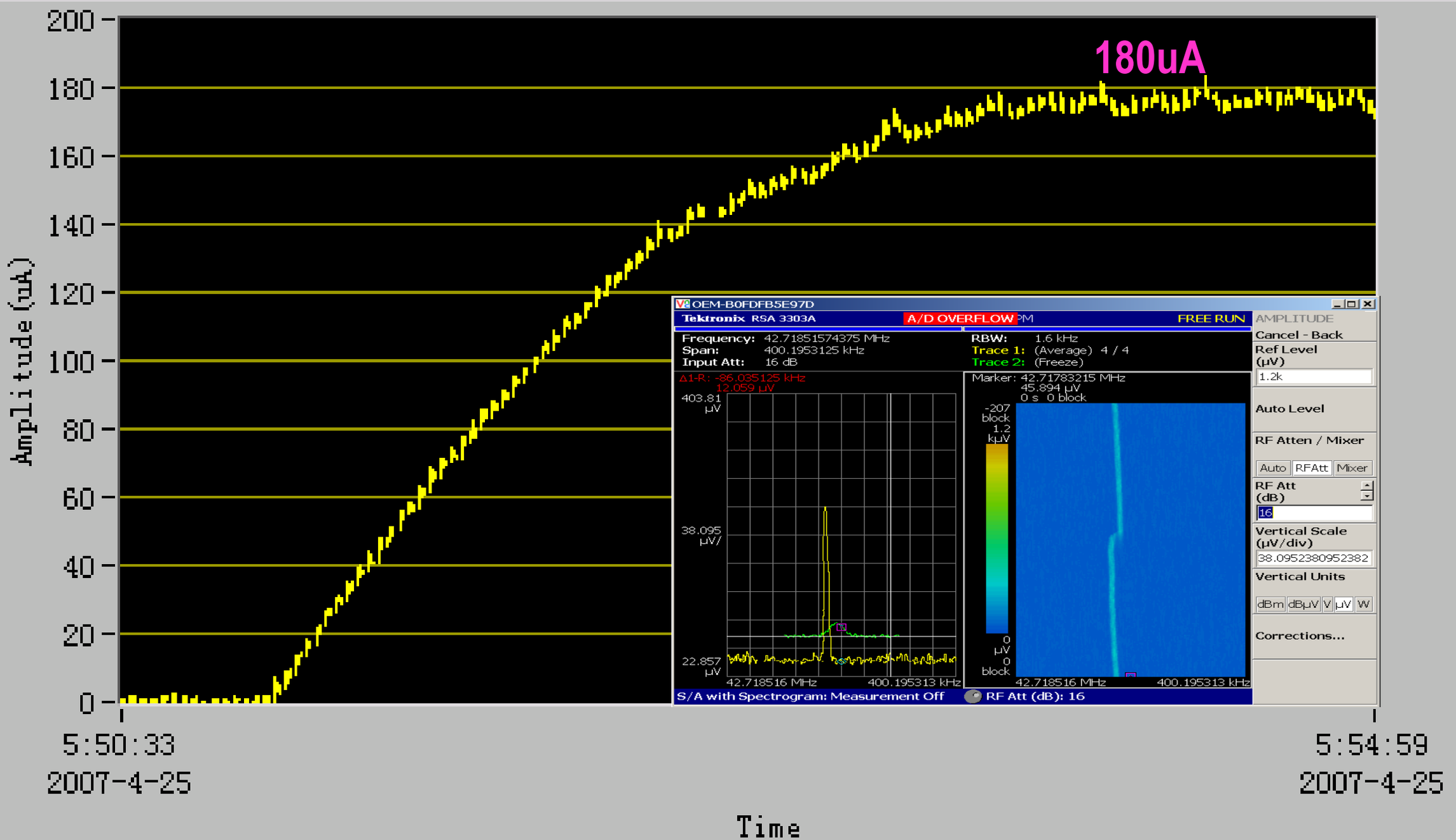
0.1mm

Septum (Wolfram silk)

MMI for Ar-beam in CSRm with e-cooling

SSC-Ar-22MeV/u, $I_{inj.}$~ 2uA, DCCT~180uA, Period=2min., Gain ~90

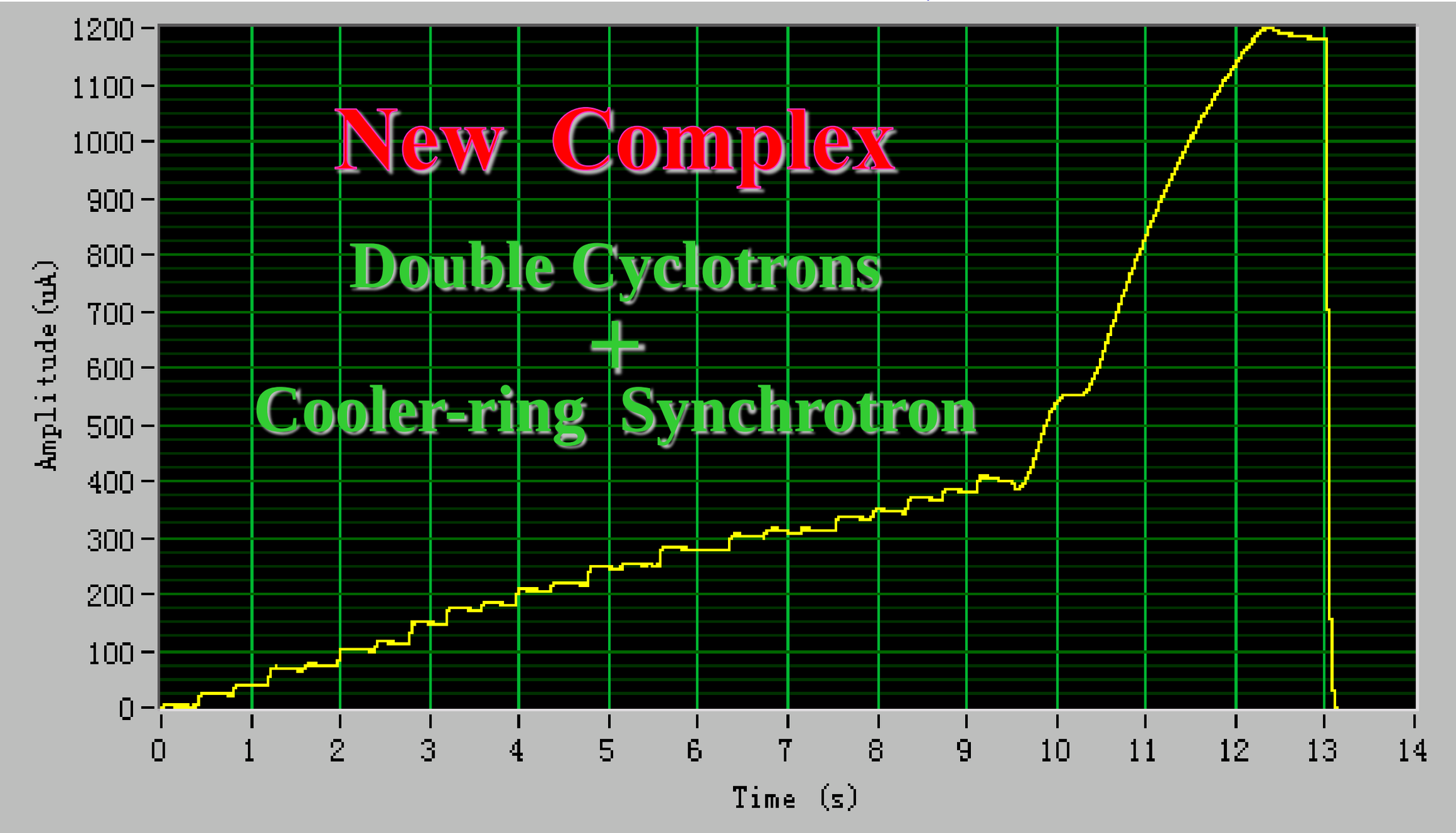
07/04/25 06:00



MMI + Ramping ($^{36}Ar^{18+}$--22~368MeV/u) in CSRm

Final record: 1.2mA, 4×10^8

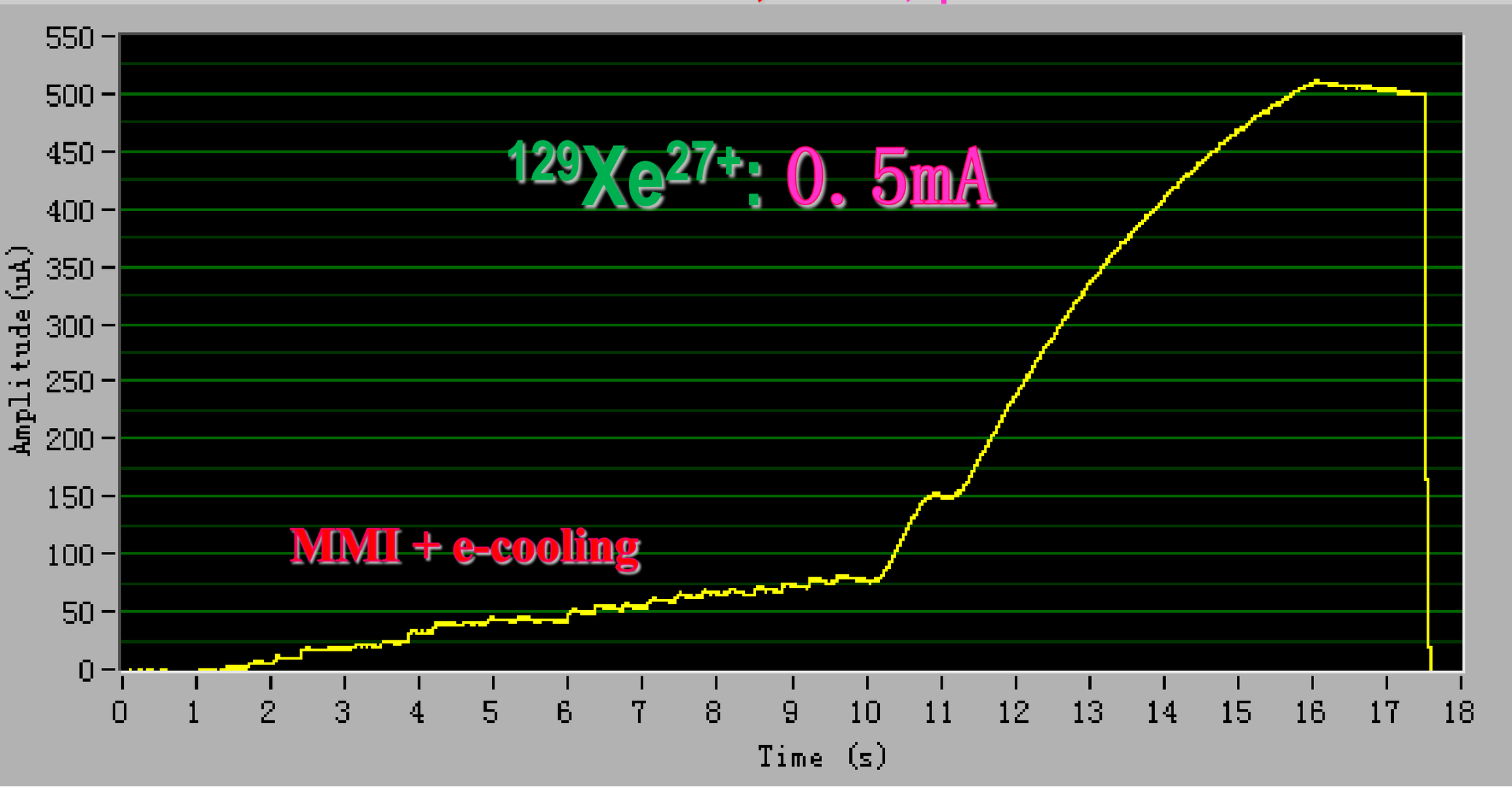
07/12/10 00:08



MMI + Ramping ($^{129}Xe^{27+}$-30GeV) in CSRm

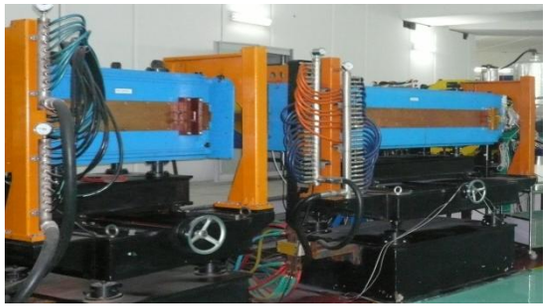
Mode: SFC+CSRm, 1×10^8, η=83%

07/06/25 07:20



Fast extraction section of CSRm

07/08



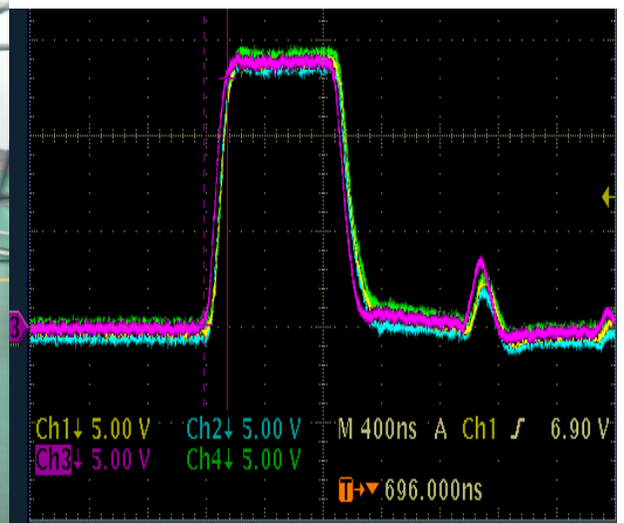
MS2: 2900A, 4300Gs

MS2: 2900A, 12800

$I_{max.}$ = 2700A

$V_{max.}$ = 60 kV

Rising time: 150ns



07.8.4

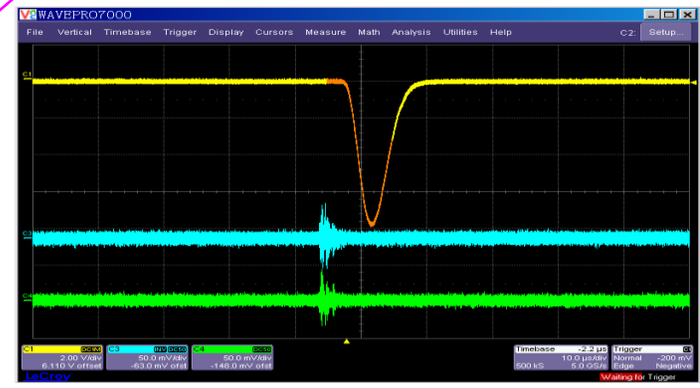
Fast-extraction from CSRm

Success

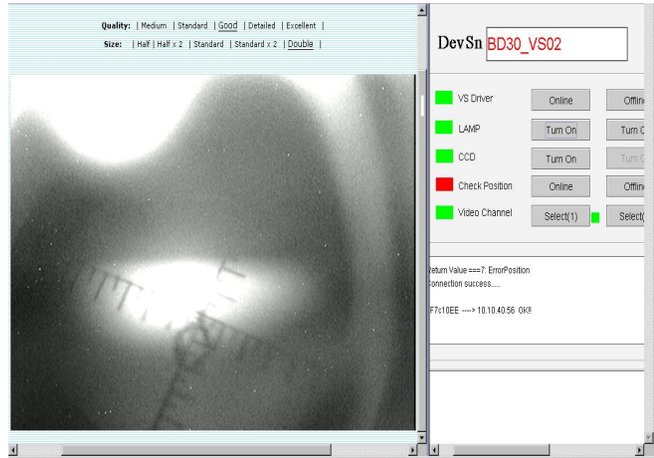
Rm

PT

30FC1



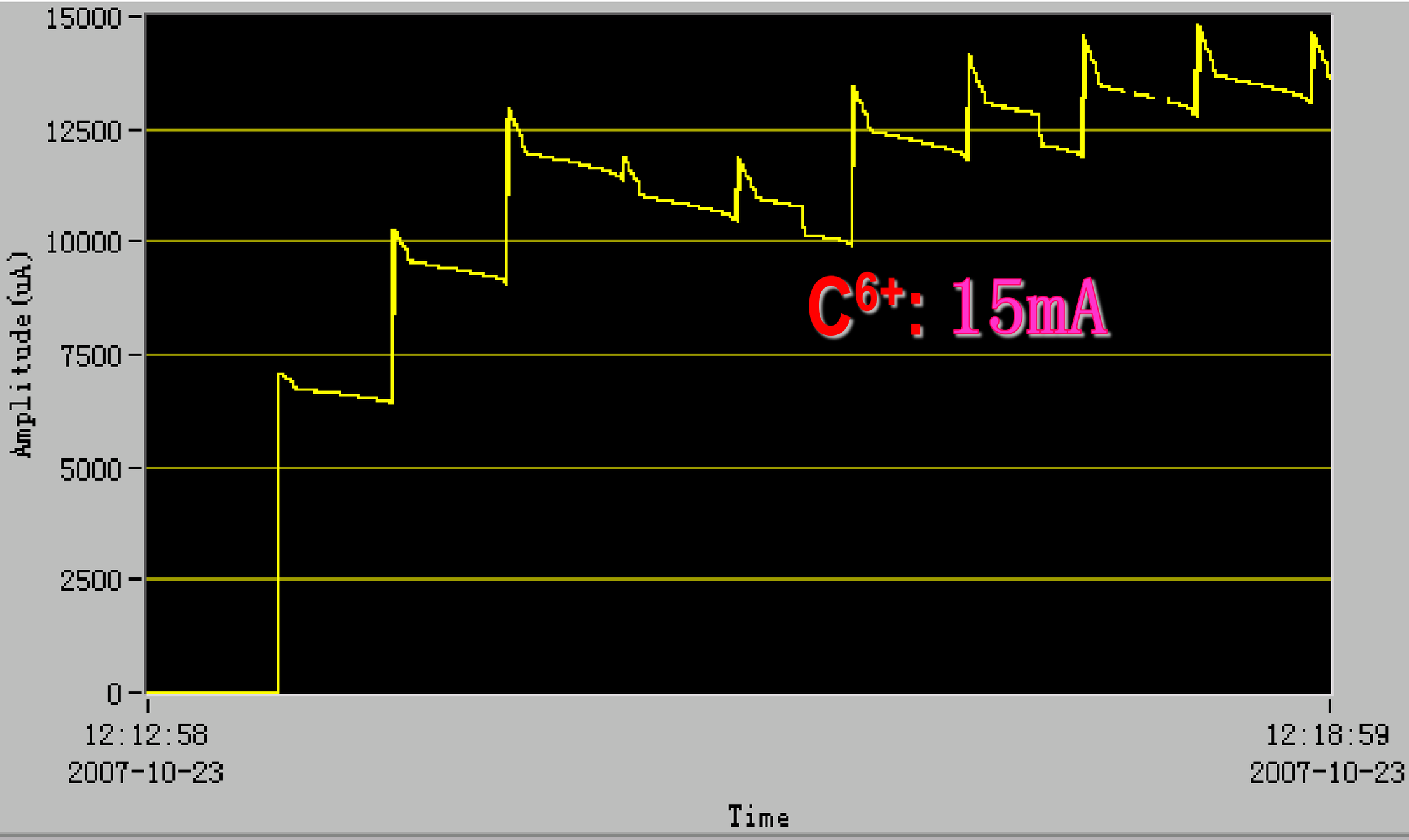
30VS2



Multi-time Injection for CSRe 1st Commissioning

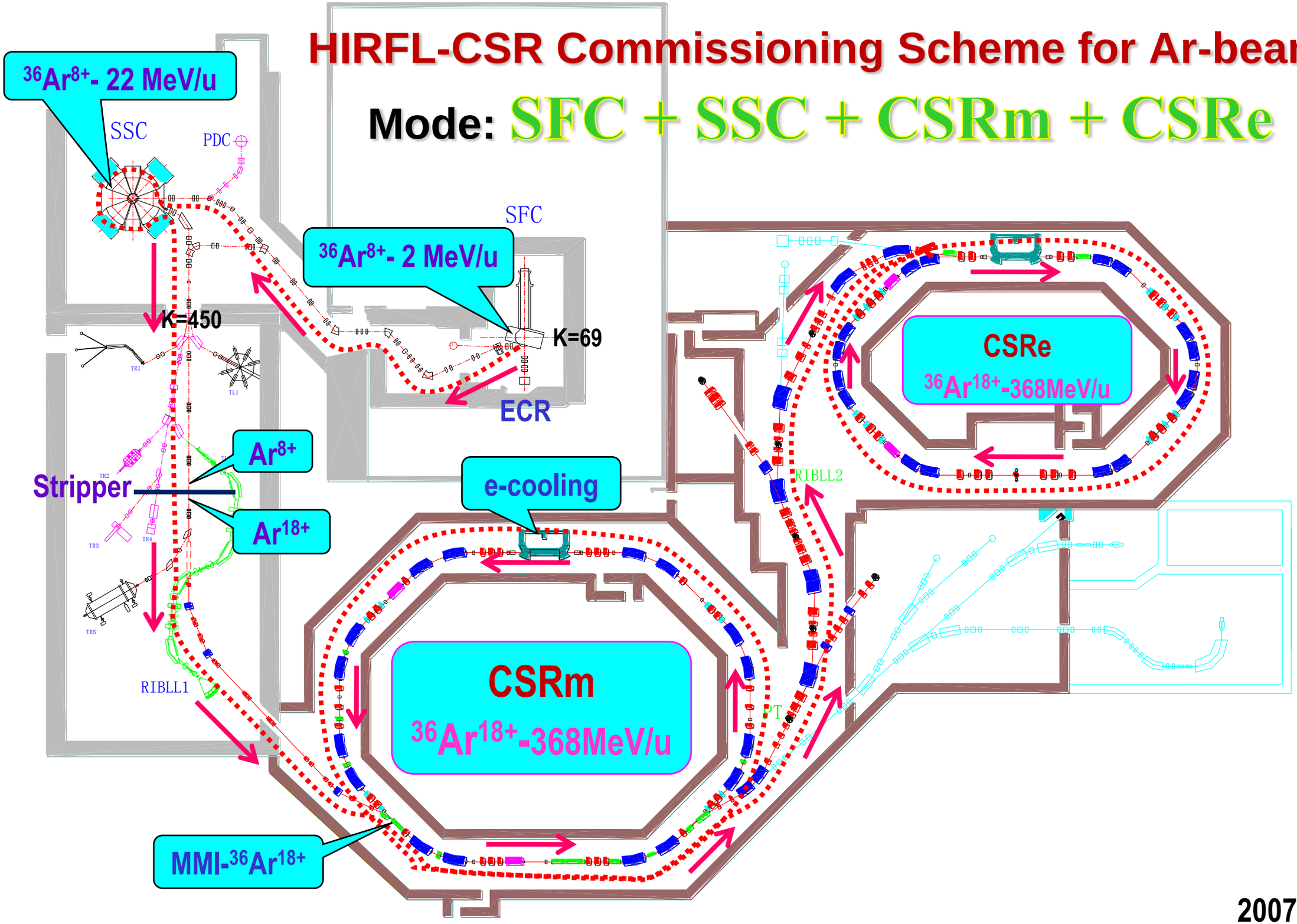
Mode: SFC+CSRm+CSRe, STI, $^{12}C^{6+}$-8GeV

07/10/23 12:18

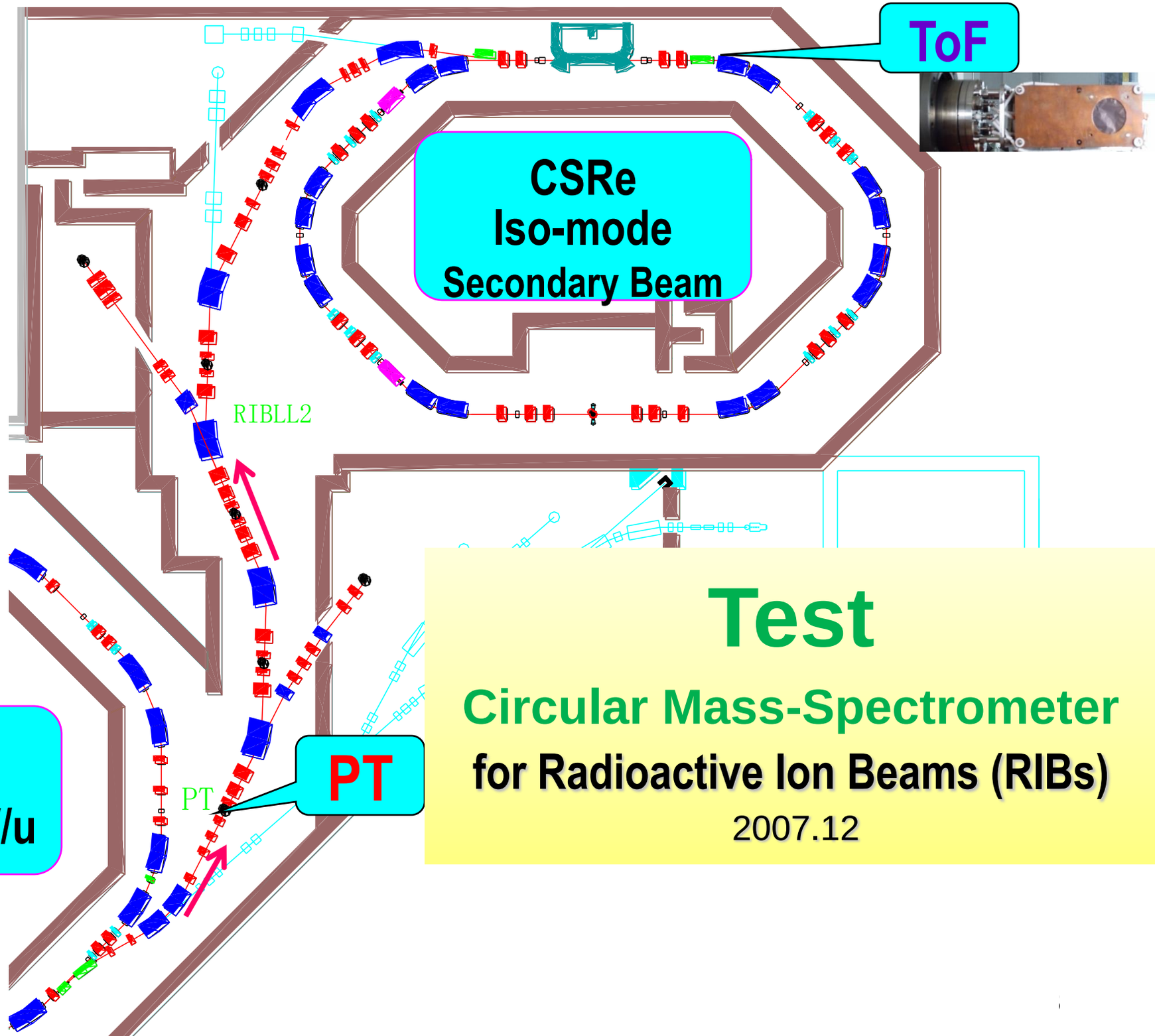


HIRFL-CSR Commissioning Scheme for Ar-beam

Mode: SFC + SSC + CSRm + CSRe



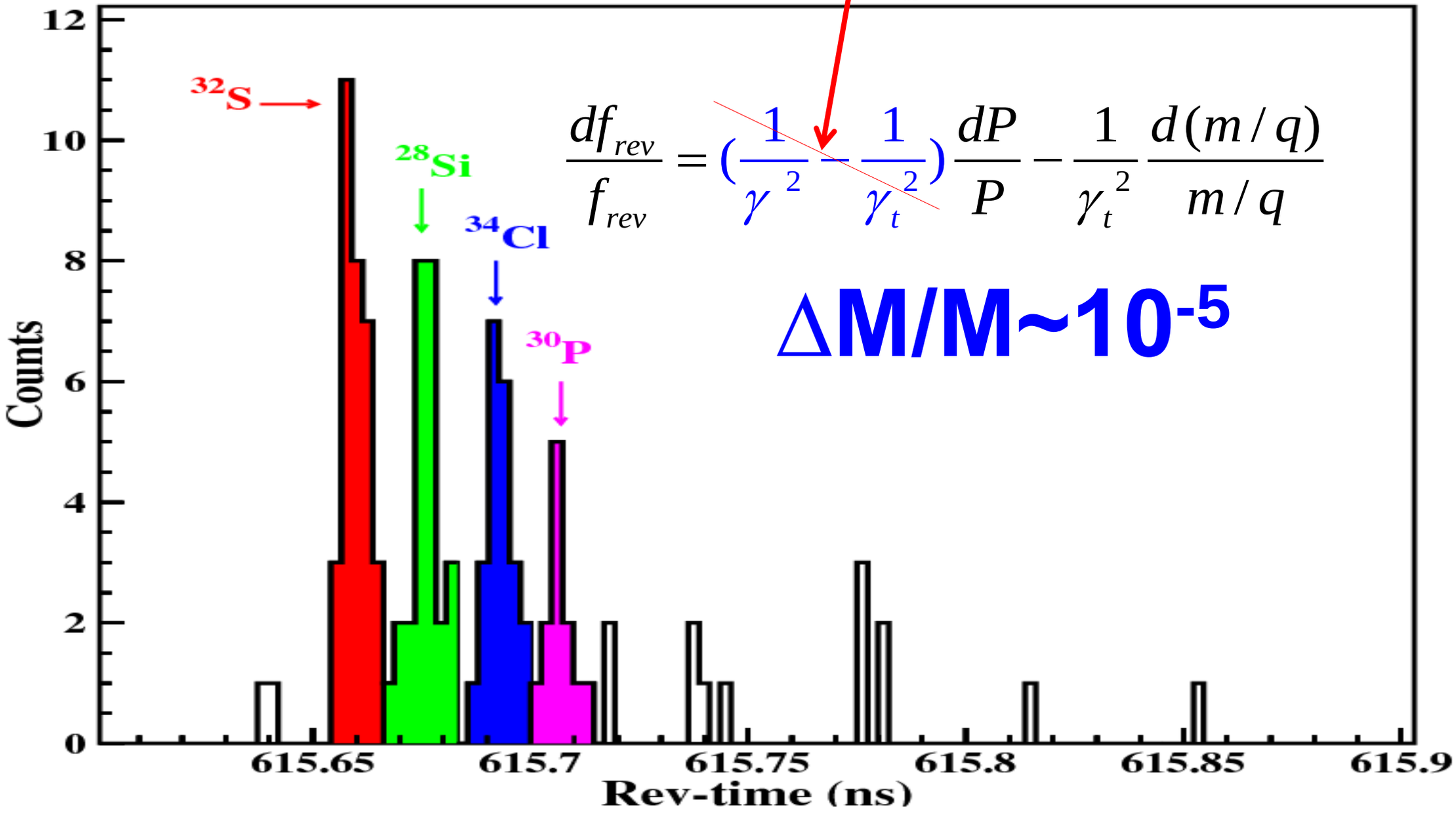
2007/12


ToF
CSRe
Iso-mode
Secondary Beam
RIBLL2
PT
PT
CSRm
$^{36}Ar^{18+}$-368MeV/u
Test
Circular Mass-Spectrometer
for Radioactive Ion Beams (RIBs)
2007.12

2007.12.07

Mass Measurement of RIBs in CSRe

Isochronous Mode: $\gamma = \gamma_{tr} = 1.395$, ToF



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

$\Delta M/M \sim 10^{-5}$

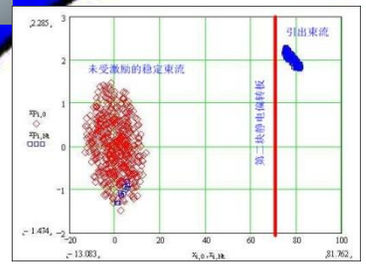
Slow extraction of 1/3 Resonance in CSRm

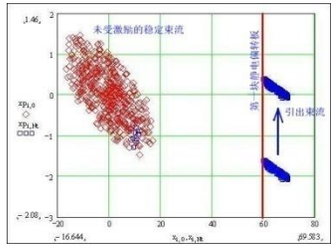
2008.01.10

ES2

ES3

Coil 1





MS2

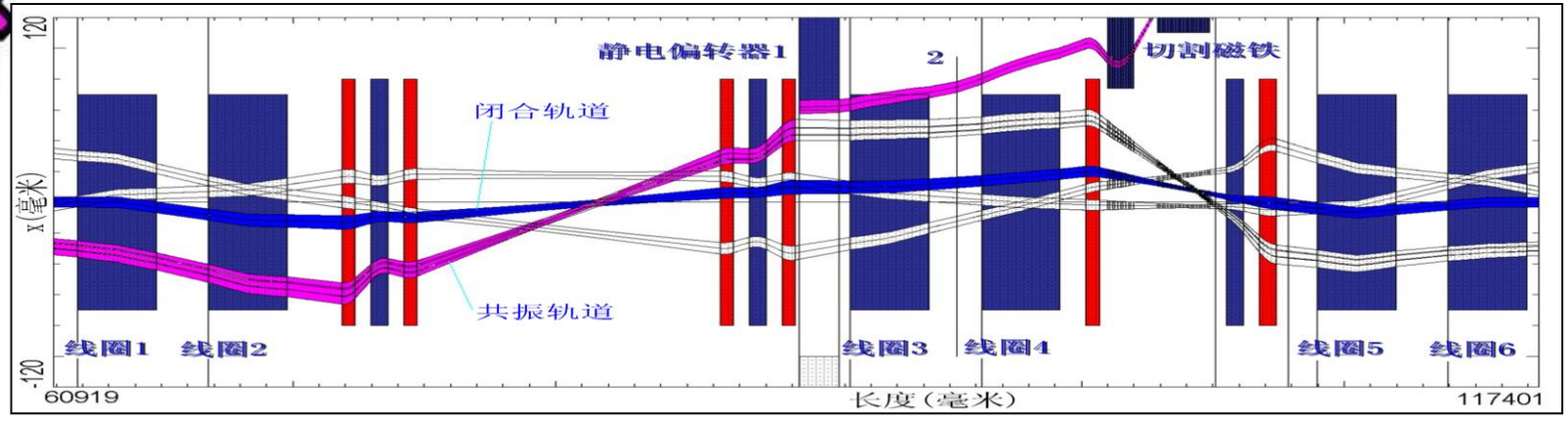
MS3

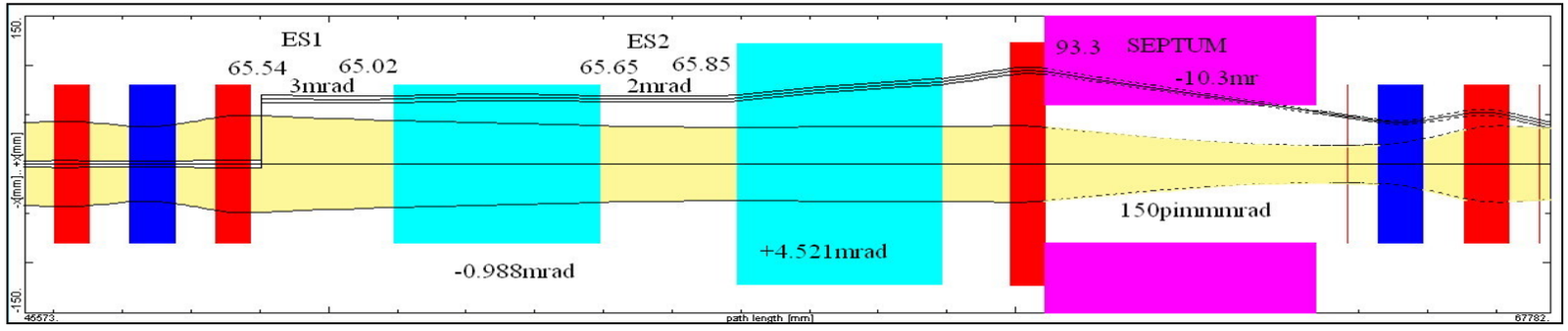
MS2: 2900A, 4300Gs

MS2: 2900A, 12800

Coil3

Coil 4

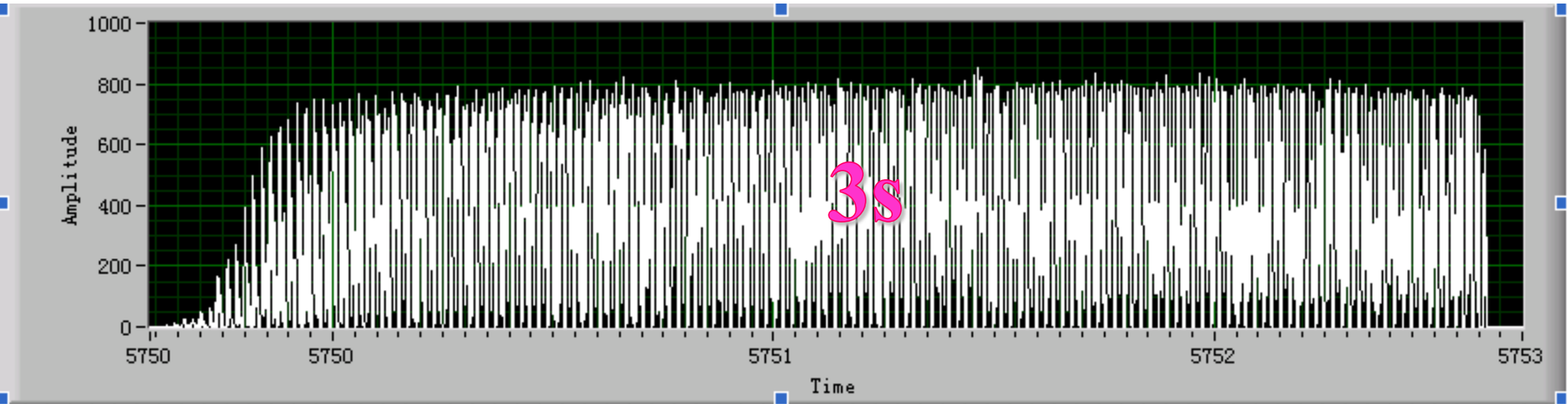


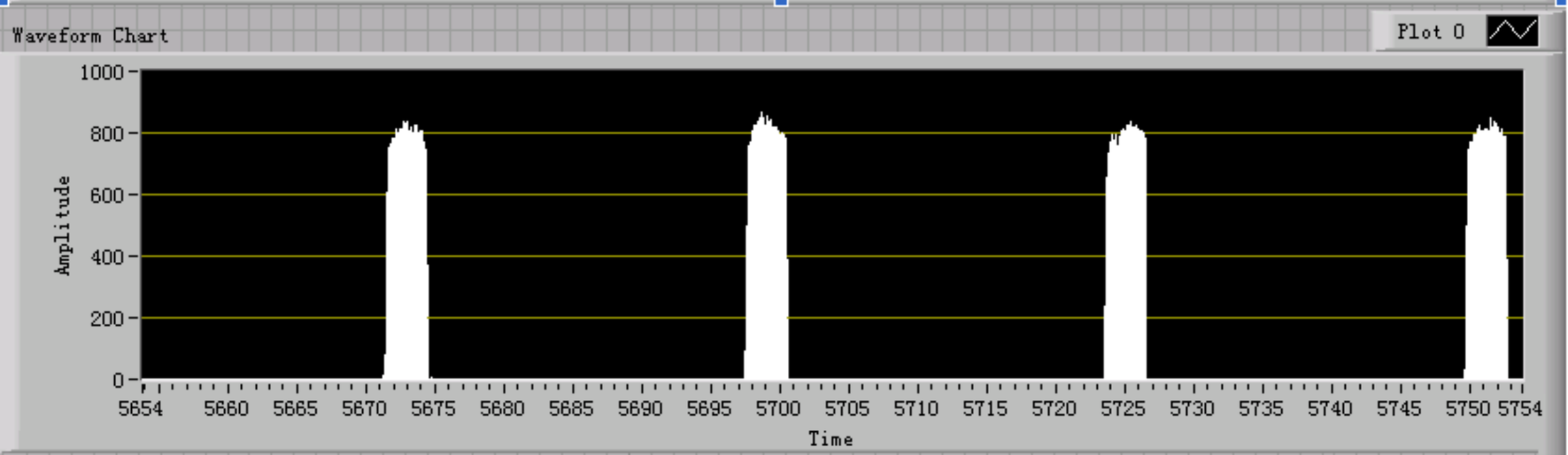


Slow extraction for $^{12}C^{4+}$-300MeV/u in CSRm

From Scintillation Crystal Monitor

2008.05.21 03:31

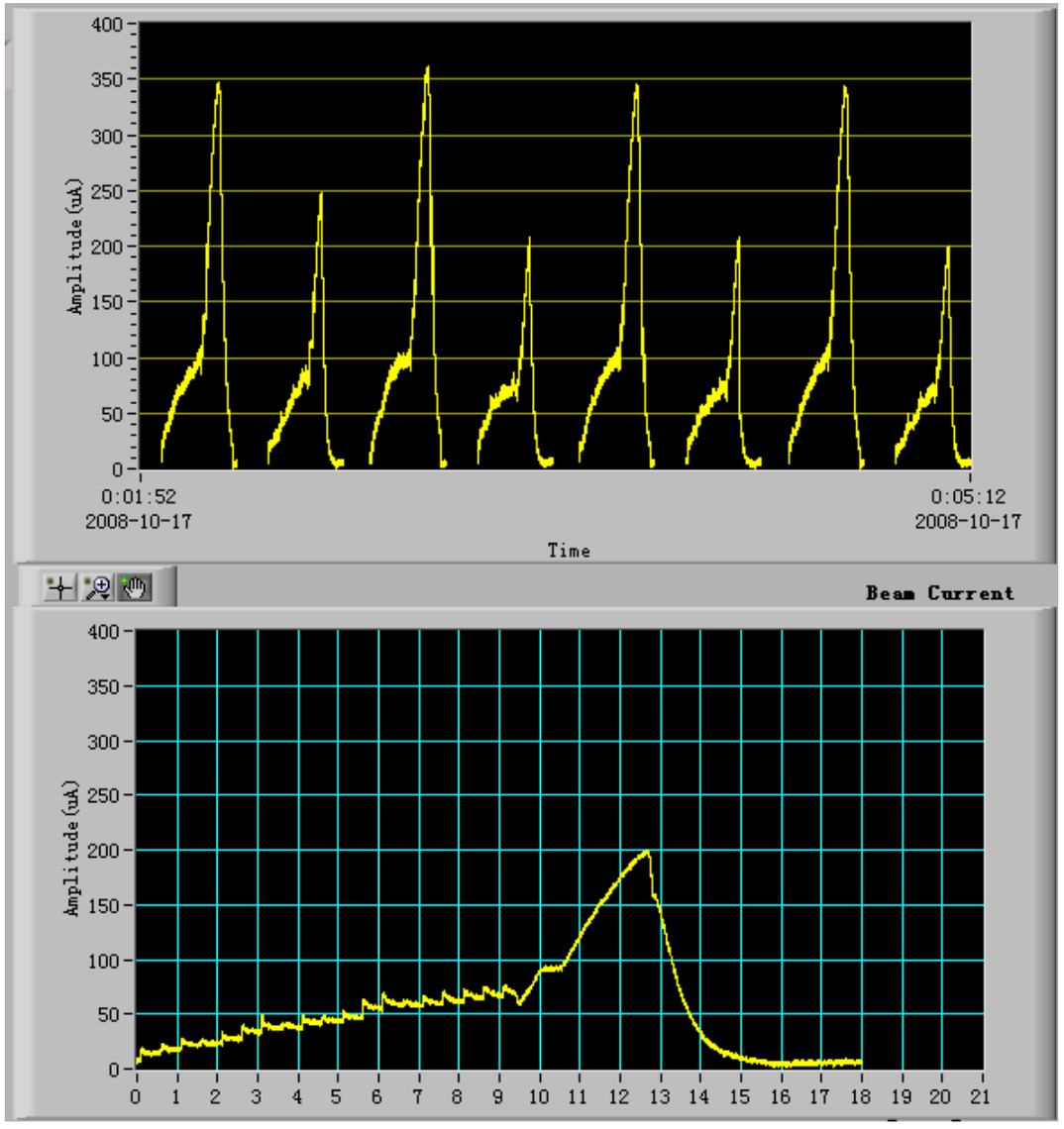


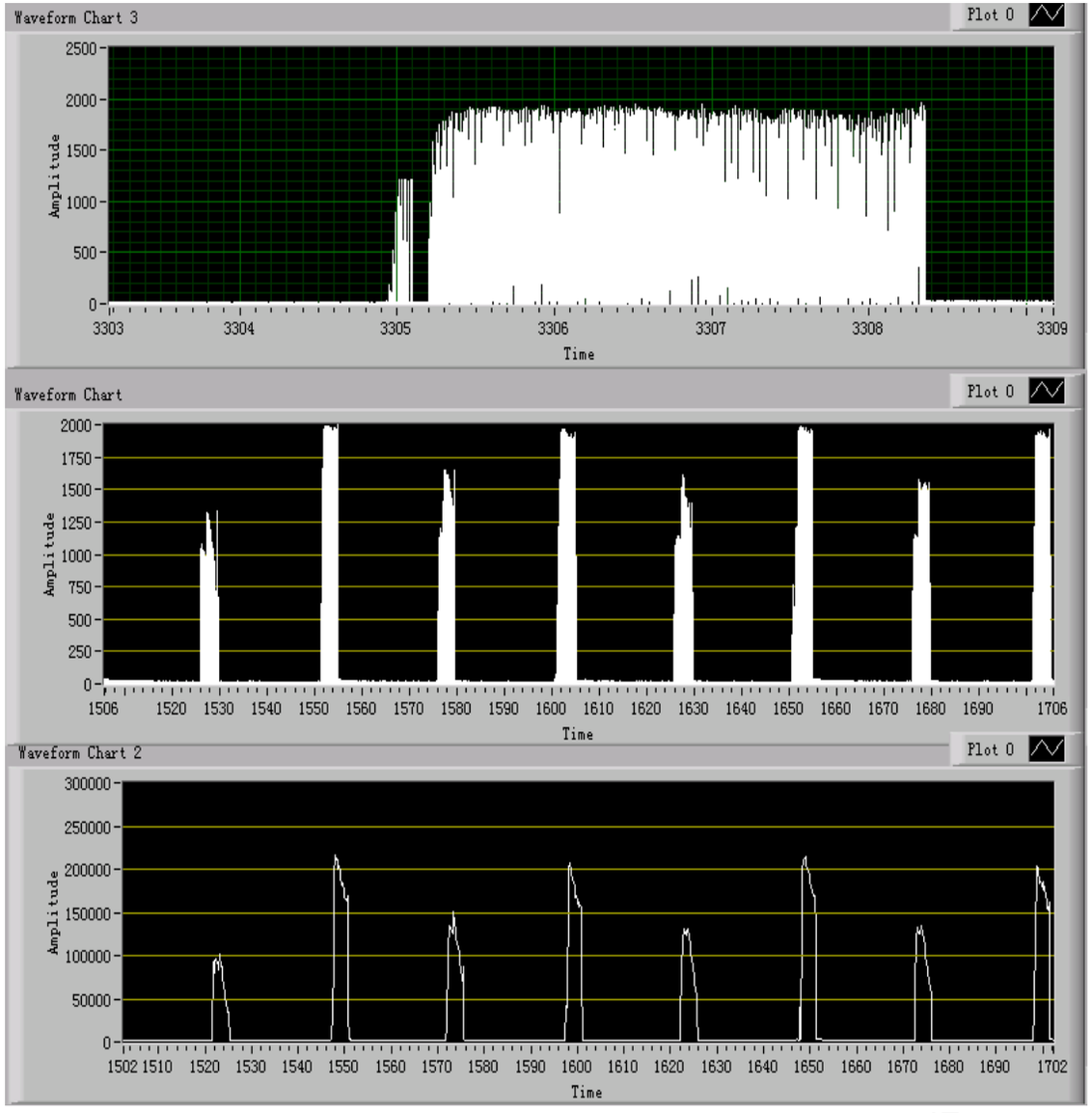


Energy conversion between cycles in slow extraction of CSRm

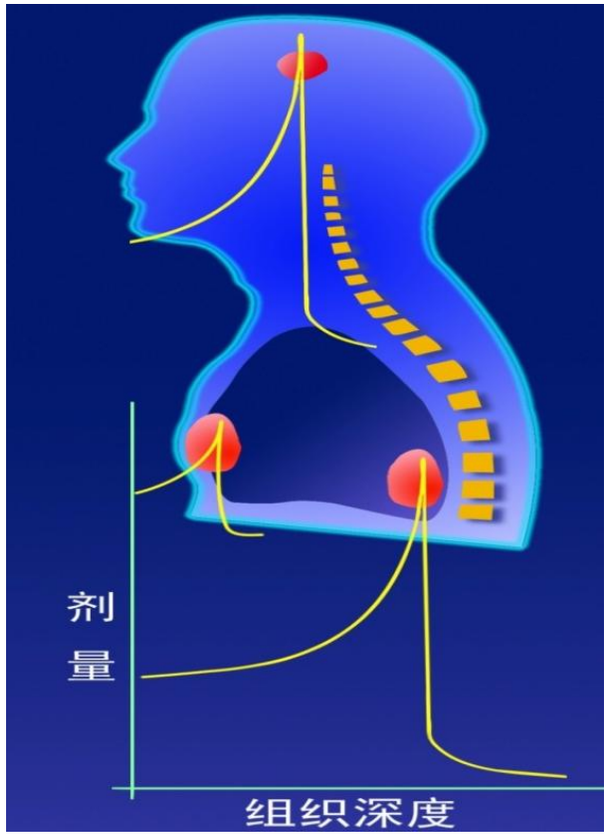
2008.10.15 03:31

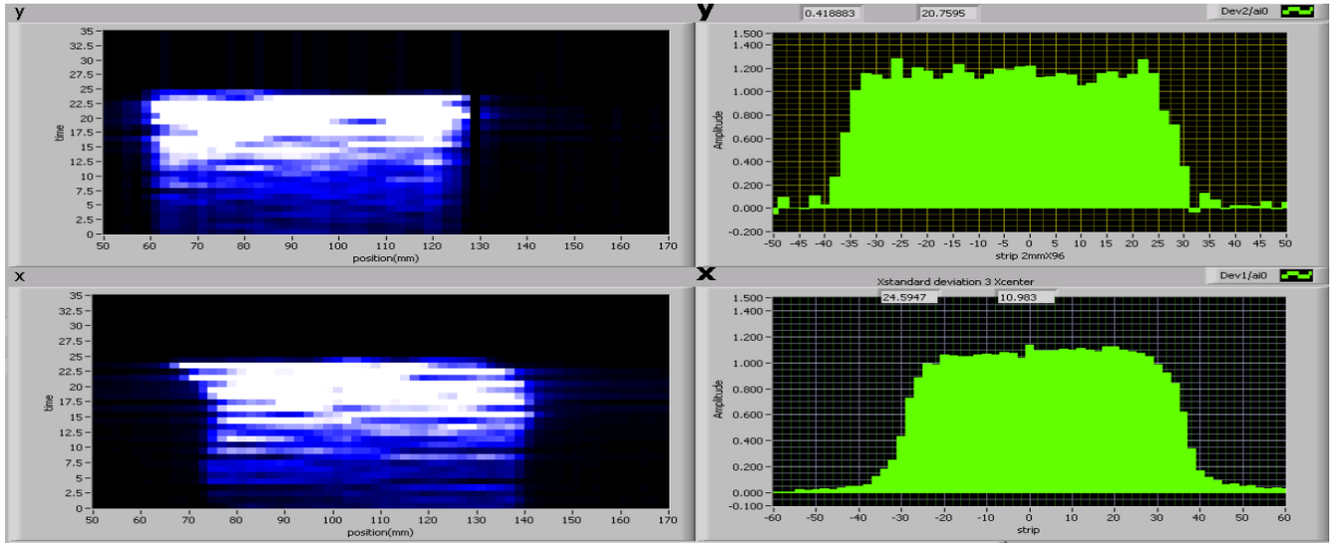
From Scintillation Crystal Monitor

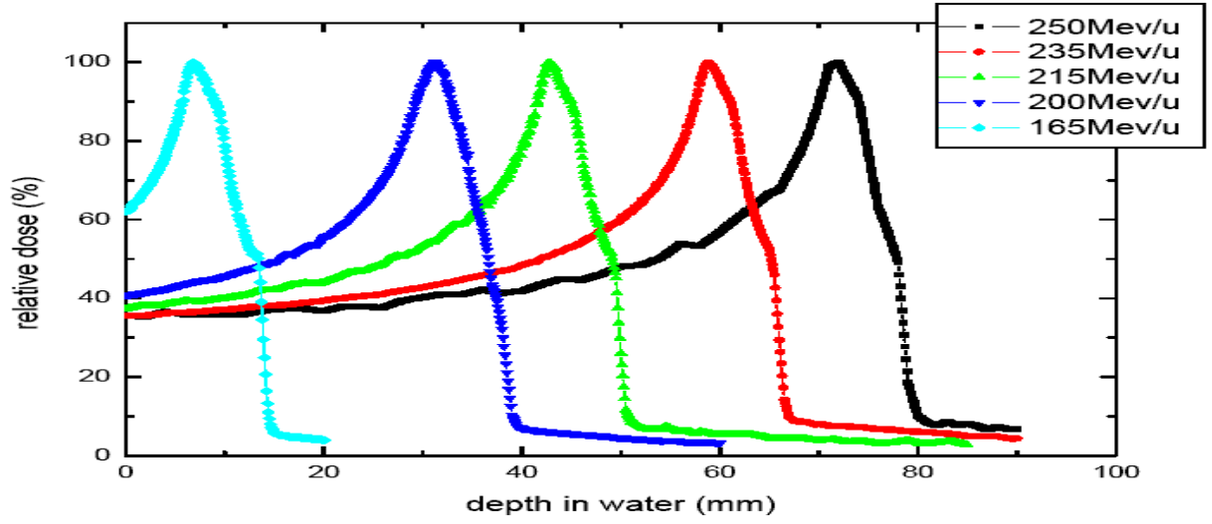


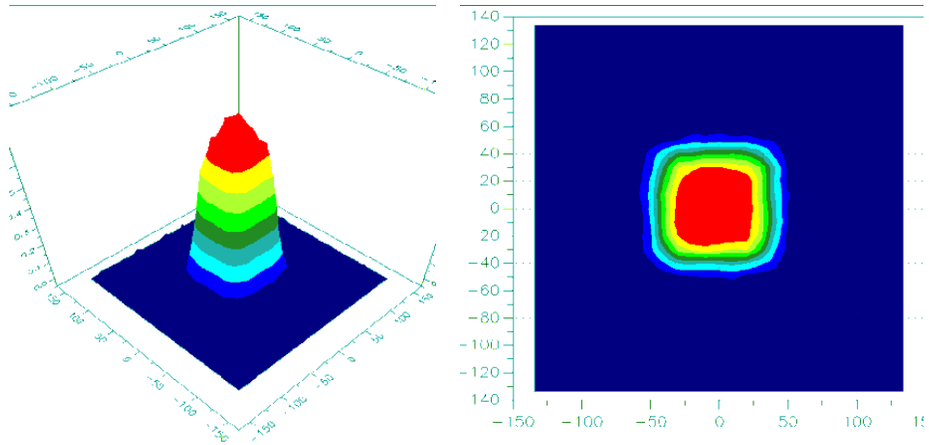


Deep site cancer therapy measurement

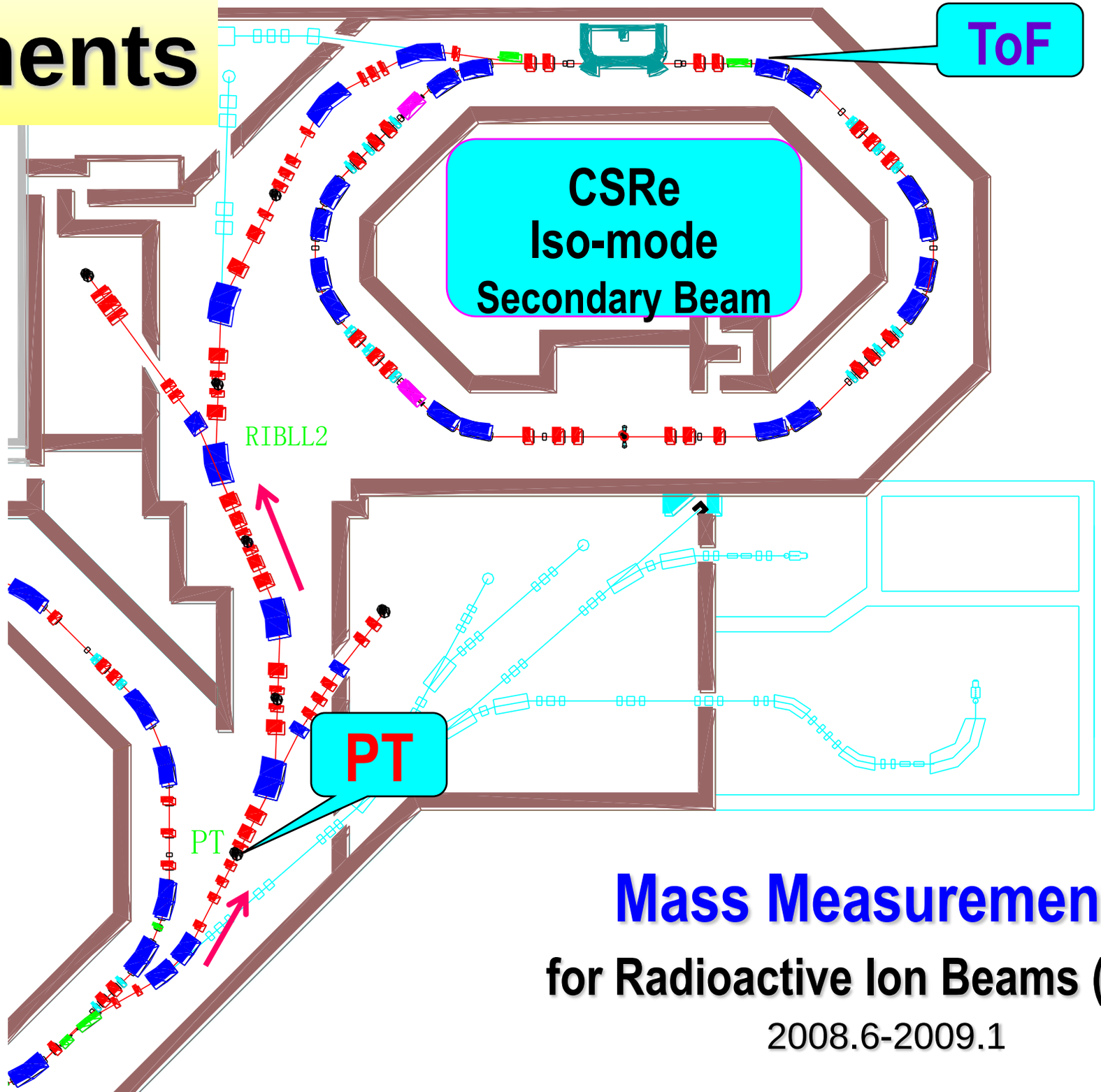








Experiments



CSRm

$^{78}Kr^{28+}$

447.8MeV/u

451.1MeV/u

458.4MeV/u

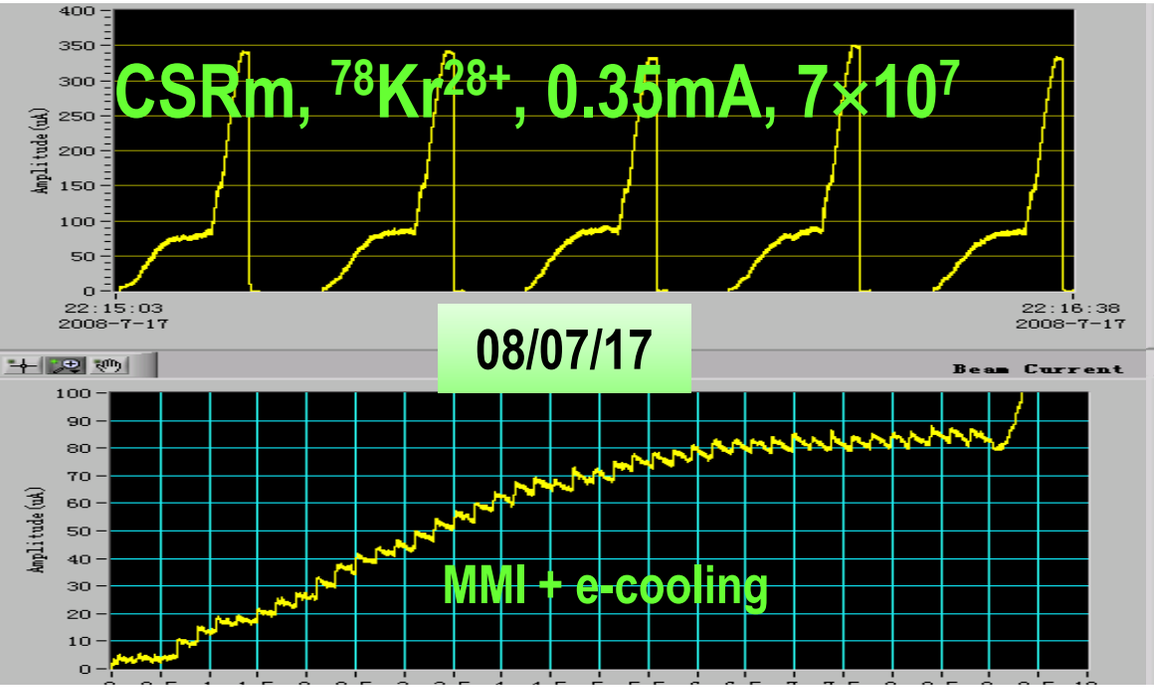
481.9MeV/u

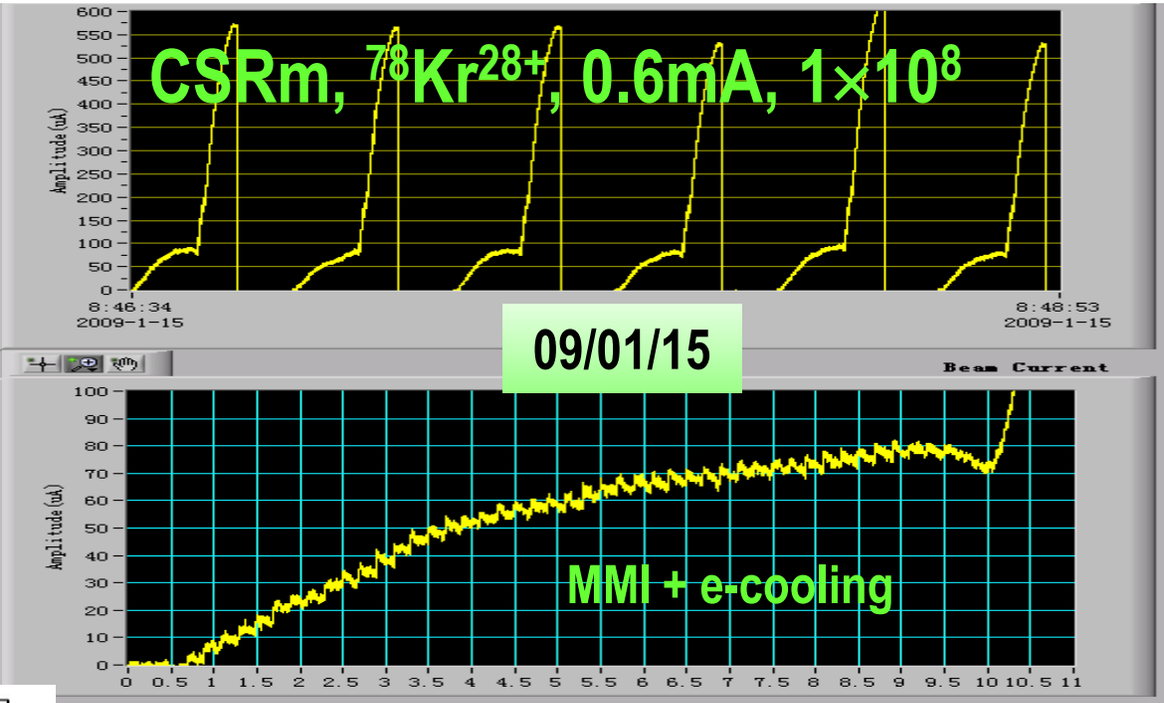
Mass Measurements

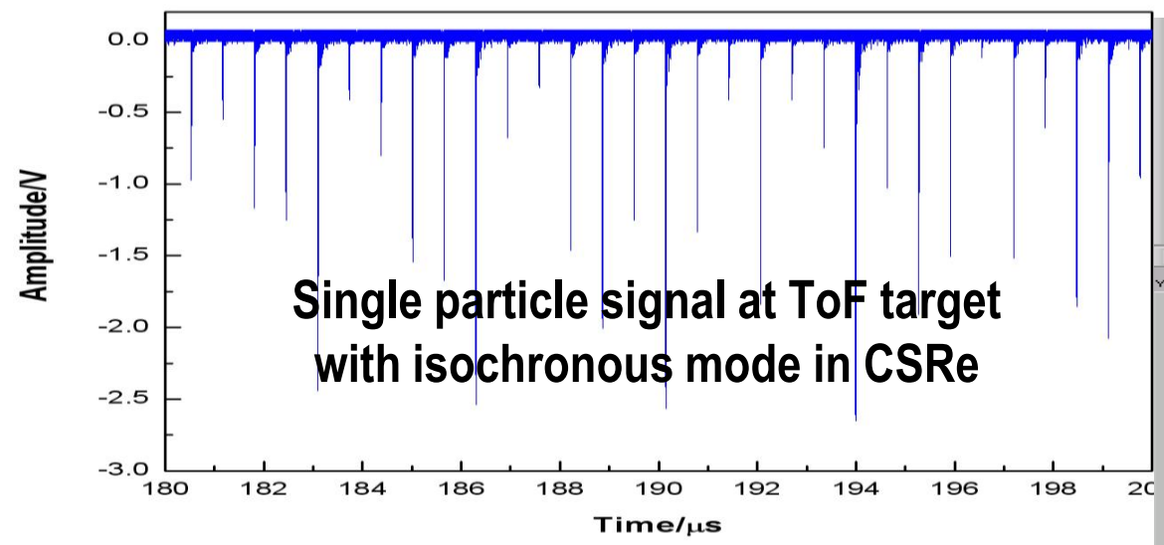
for Radioactive Ion Beams (RIBs)

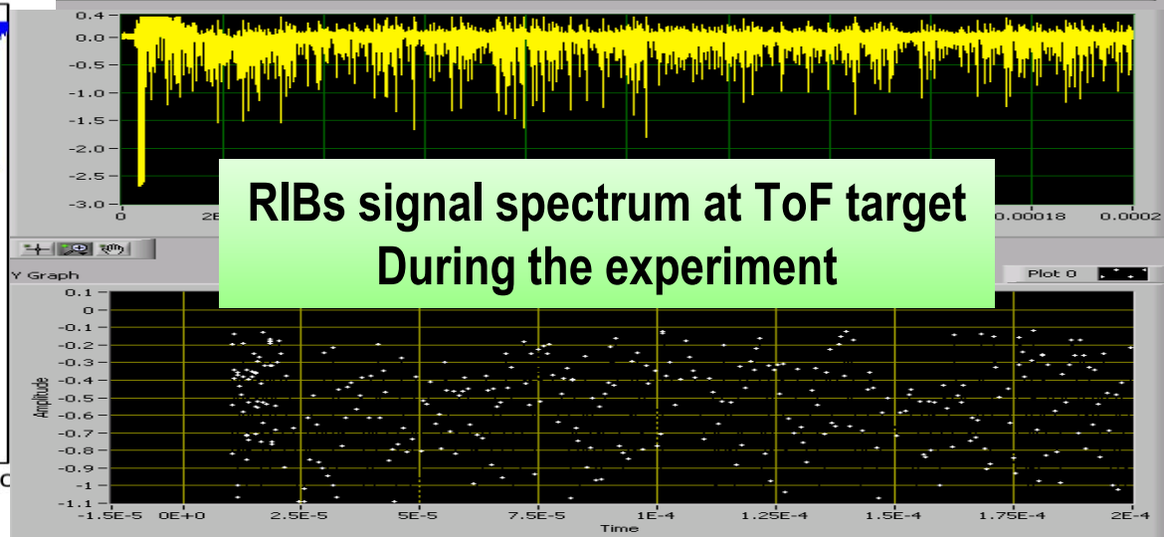
2008.6-2009.1

Experiments for RIBs spectroscopy

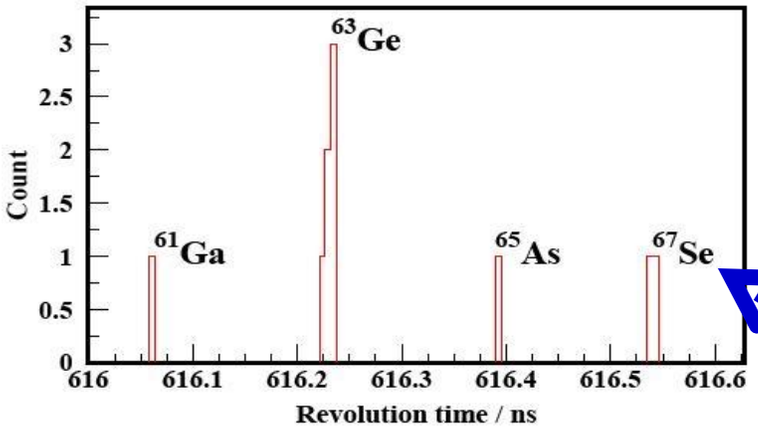


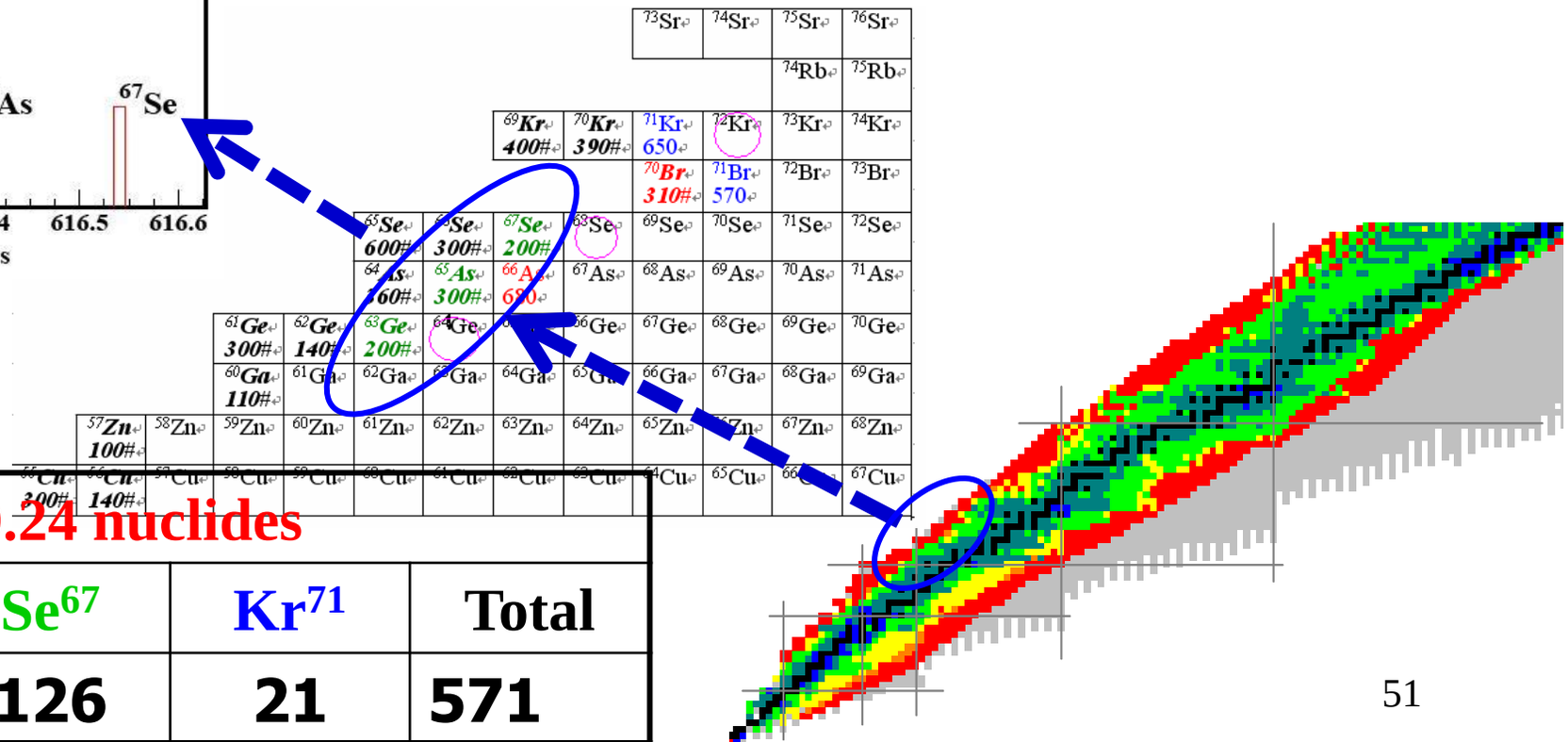






The first instance of measuring the mass of short-life nuclides near the proton drip line at the level of 100ms. The aimed target nuclei are ^{63}Ge(Germanium)、^{65}As(Arsenic)、^{67}Se(Selenium). It is important for scientists to understand the mass of these nuclides, as it will help scientists to estimate the nuclear reactions of celestial bodies'rp ,and richness distribution of the elements in the cosmos.

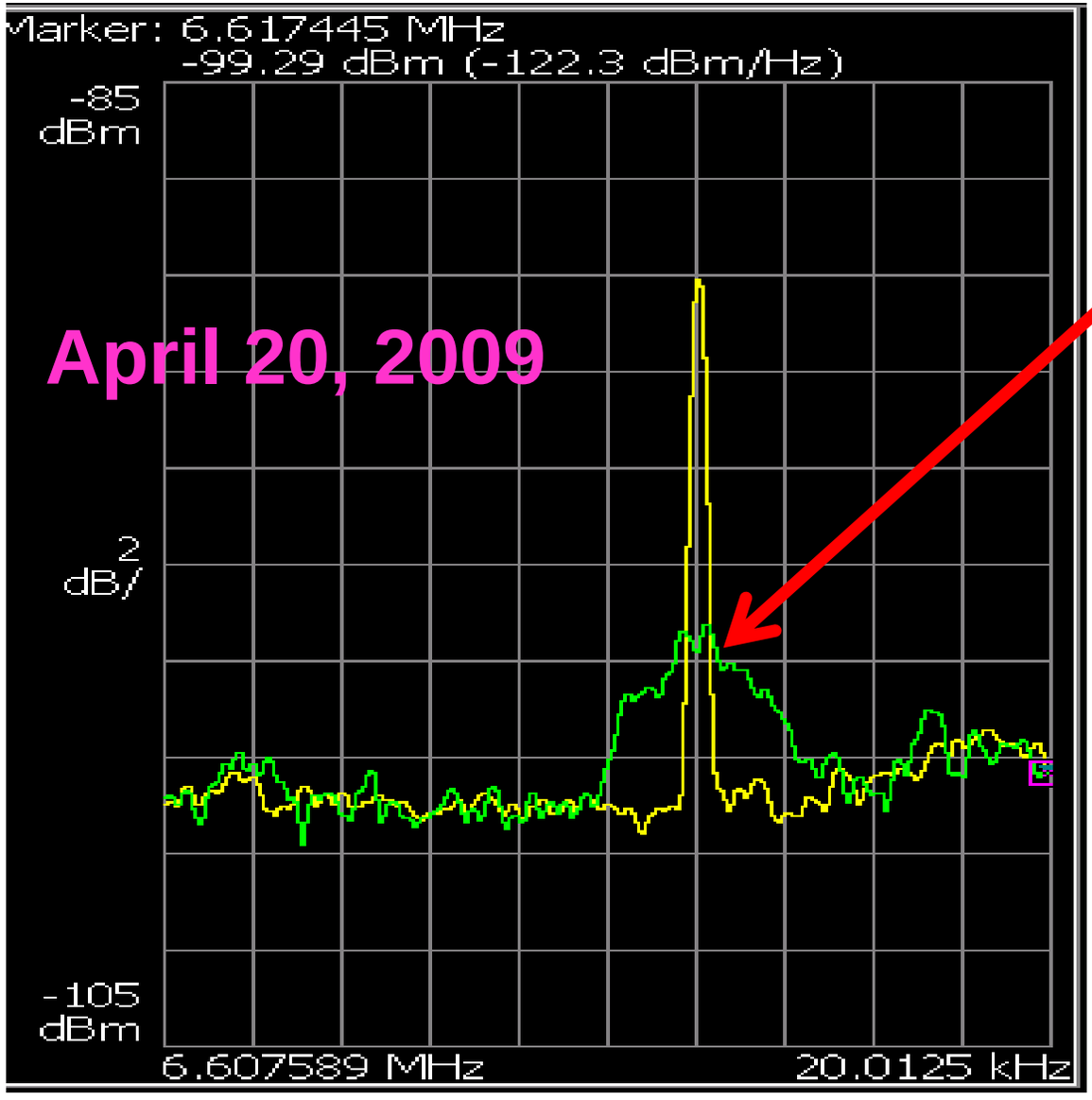




10.07–10.24 nuclides

Ge^{63}	As^{65}	Se^{67}	Kr^{71}	Total
372	52	126	21	571

Commissioning of CSRe E-cooler



C^{6+}-200MeV/u , 100uA

ΔP/P: $9\times10^{-4} \rightarrow 7.5\times10^{-5}$

Summarize: CSR Beam Status

Ion: $^{12}C^{6+}$, $^{36}Ar^{18+}$, $^{78}Kr^{28+}$, $^{129}Xe^{27+}$

Energy: 1GeV/u for C & Ar in CSRm

Intensity: 10mA (7×10^9) for C-600MeV/u in CSRm

1.2mA (4×10^8) for Ar-368MeV/u in CSRm

0.35mA (7×10^7) for Kr-205MeV/u in CSRm

0.5mA (1×10^8) for Xe-235MeV/u in CSRm

15mA (8×10^9) for C-660MeV/u in CSRe

Slow-extraction: 1.2s for Ar-368MeV/u, 3s for C-300MeV/u

For external-target experiments & cancer therapy.

Experiment: RIBs from RIBLL2, isochronous mode in CSRe , $\Delta M/M\sim10^{-5}$

3.Near-future Development of HIRFL

- **What is the most important for HIRFL near future:**
  - Increase beam intensity from SSC
  - Increase injected beam intensity for CSR.

- **Three options depending on financial support**
  - Upgrade existing cyclotron system;
  - Build a low energy fixed frequency linac as a new SSC injector instead of SFC;
  - Build an intense heavy ion linac as a new injector for CSR

Upgrade Existing Cyclotrons

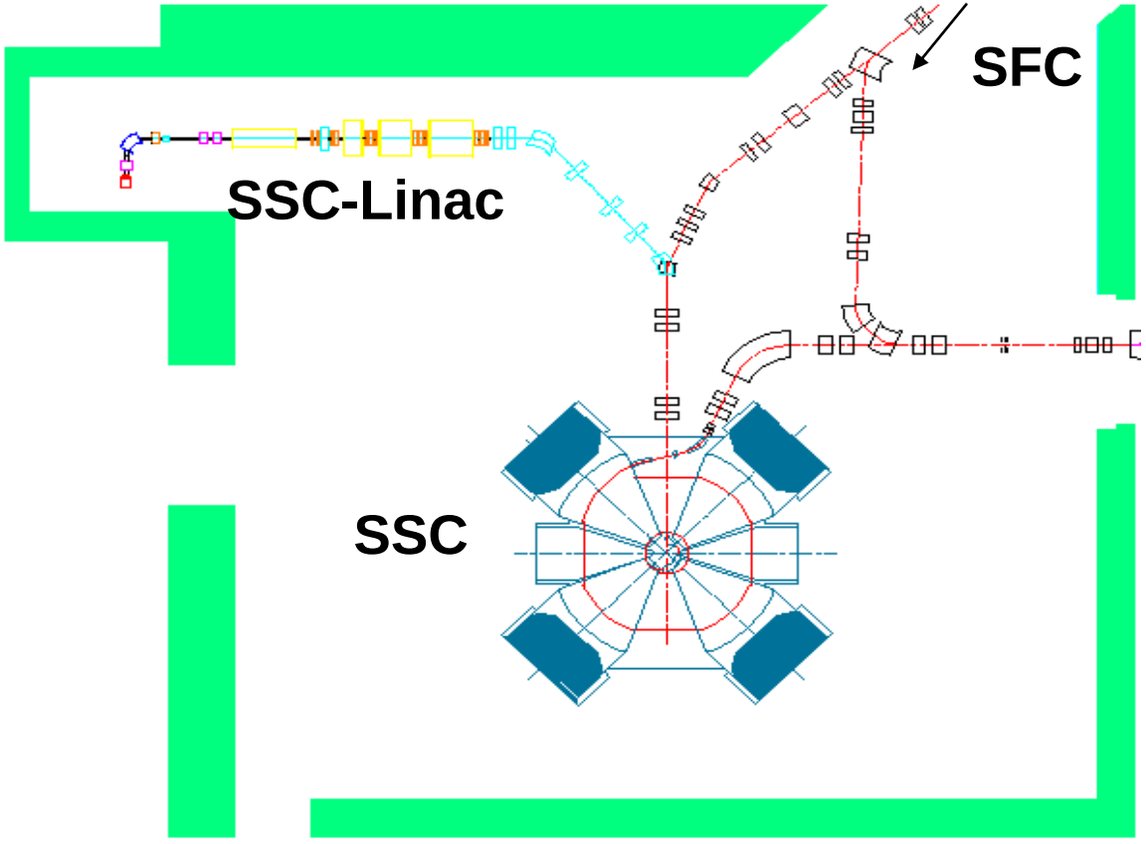
SFC

- New buncher to improve bunching voltage;
- 50-60 kV high voltage platform to increase injection energy;
- SFC isochronous field optimization;
- A new electrostatic deflector.

SSC

- Detailed studies about injection and extraction
- Modify the beam line between SFC and SSC;
- A new amplifier and control system for SSC rf;
- Solve problems related to 50% match and over-triming field.

Build a low energy fixed frequency linac as a new SSC injector

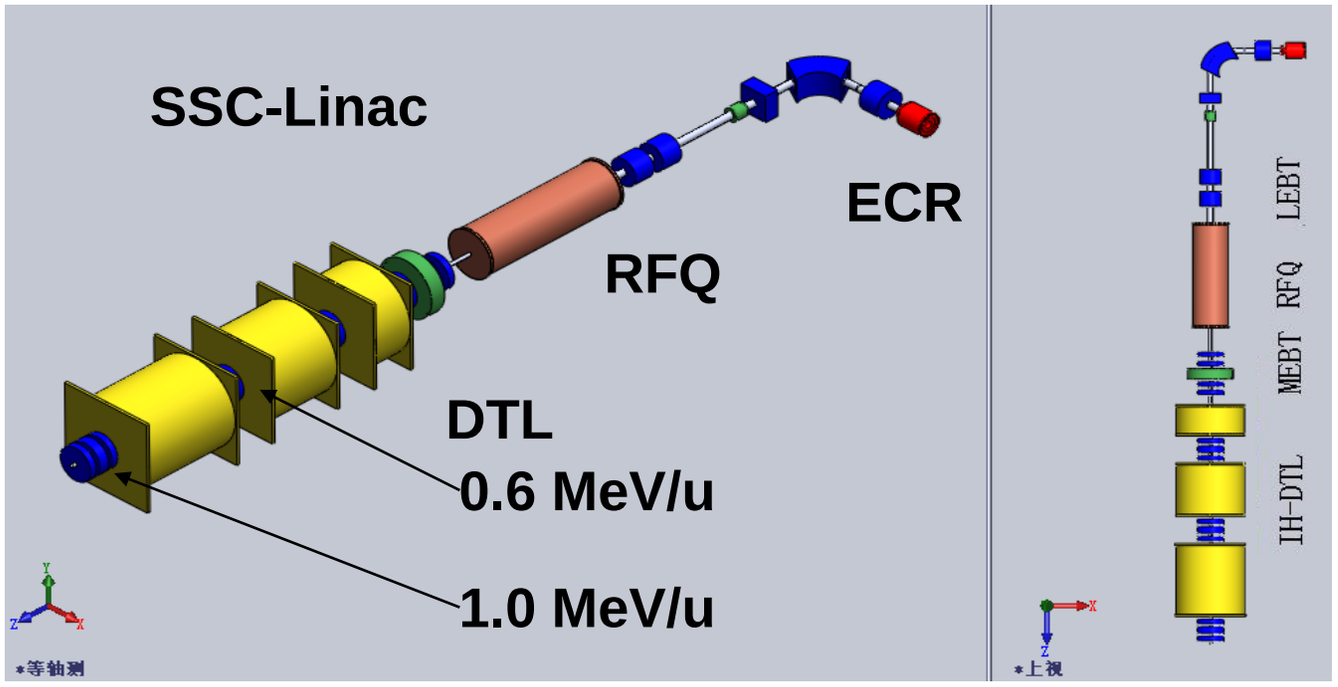


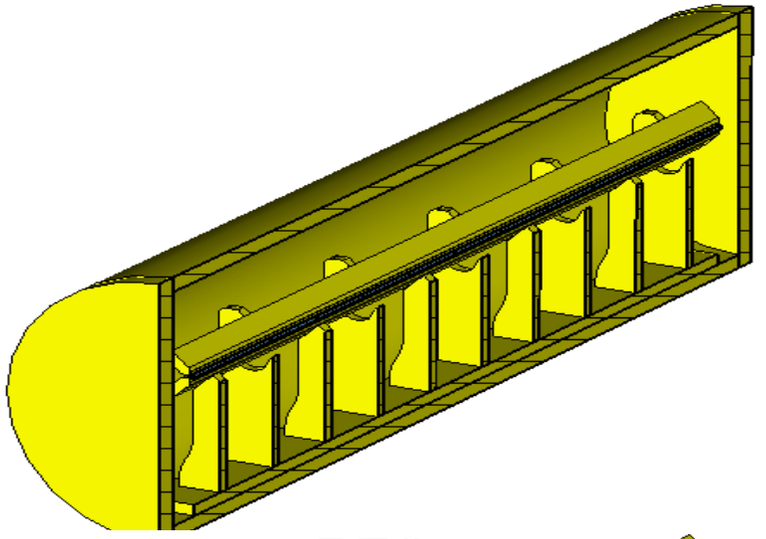
Items	value
Frequency	51.2 MHz
Mass to charge ratio	≦7
ECRIS extraction voltage	50 kV
ECRIS extraction emitance (nomalized)	0.6
RFQ type	4-rod
DTL type	IH
Extraction energy of stage1	0.6 MeV
Extraction energy of stage2	1.0 MeV
Operation mode	cw

Expected Beam Intensity from Linc+SSC:

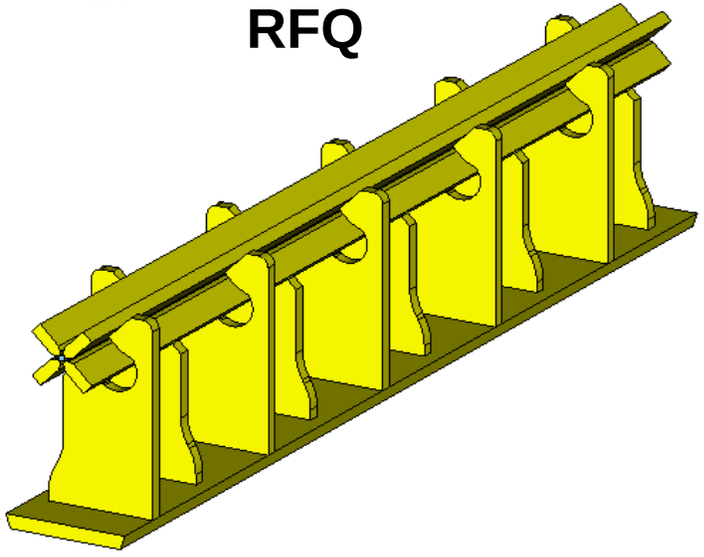
For Ca,Ni,Zn, 6MeV/u, 1-1.5 pμA, increased by a factor 2-3 compared to SFC;

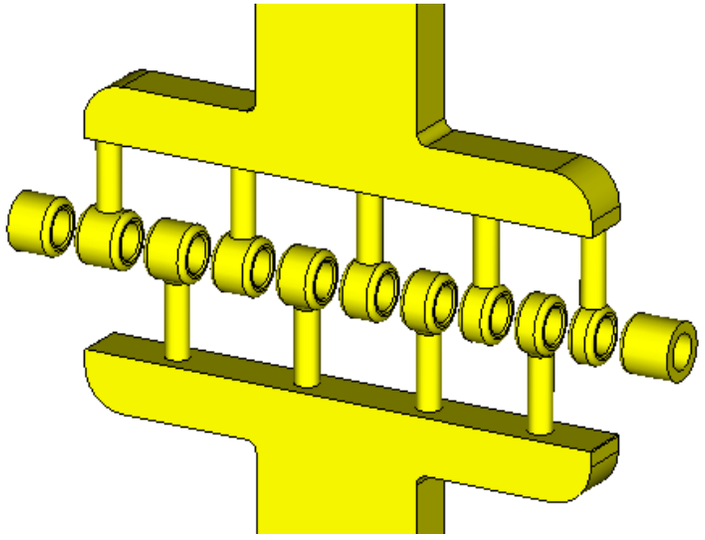
For Kr, Xe, Pb, U, 10MeV/u, 0.5-1pμA, increased by a factor 10 compared to SFC+SSC

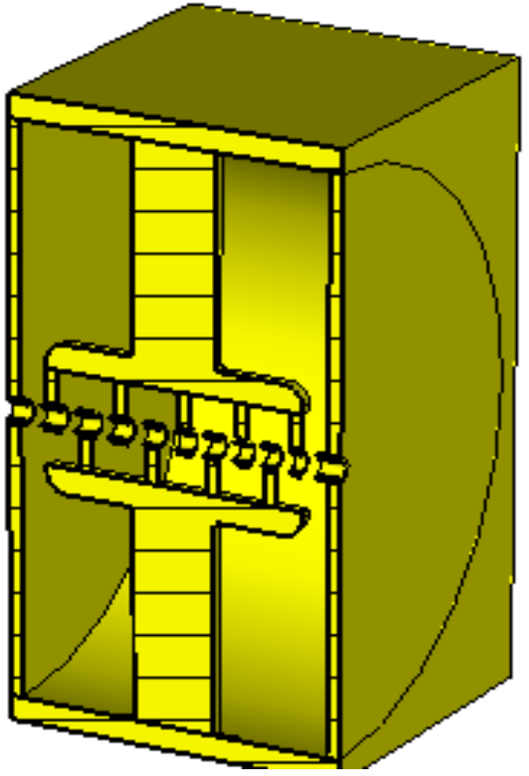

SSC-Linac
ECR
RFQ
DTL
0.6 MeV/u
1.0 MeV/u
*等轴测
LEBT
MEBT
RFQ
IH-DTL
*上视



RFQ

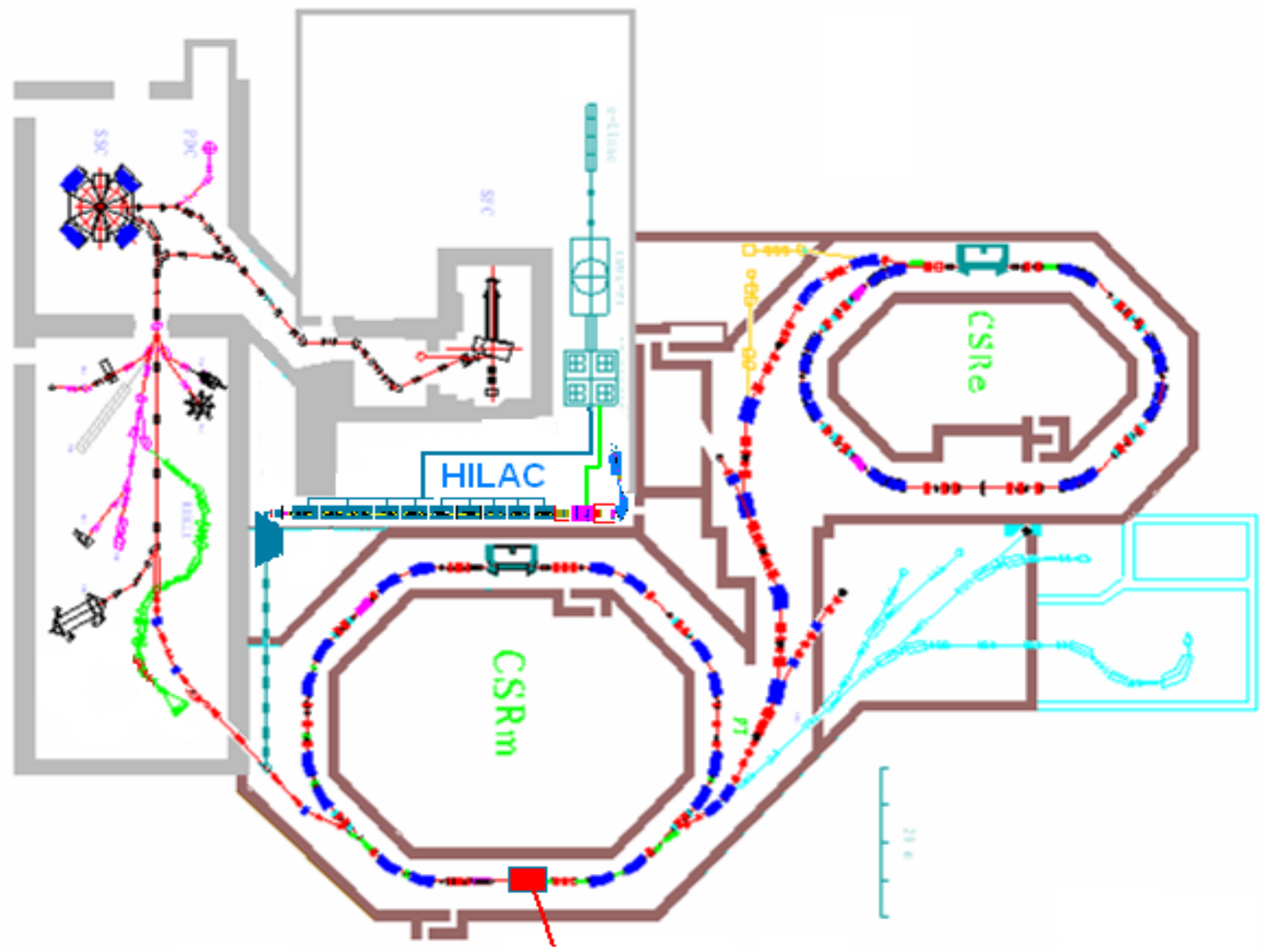




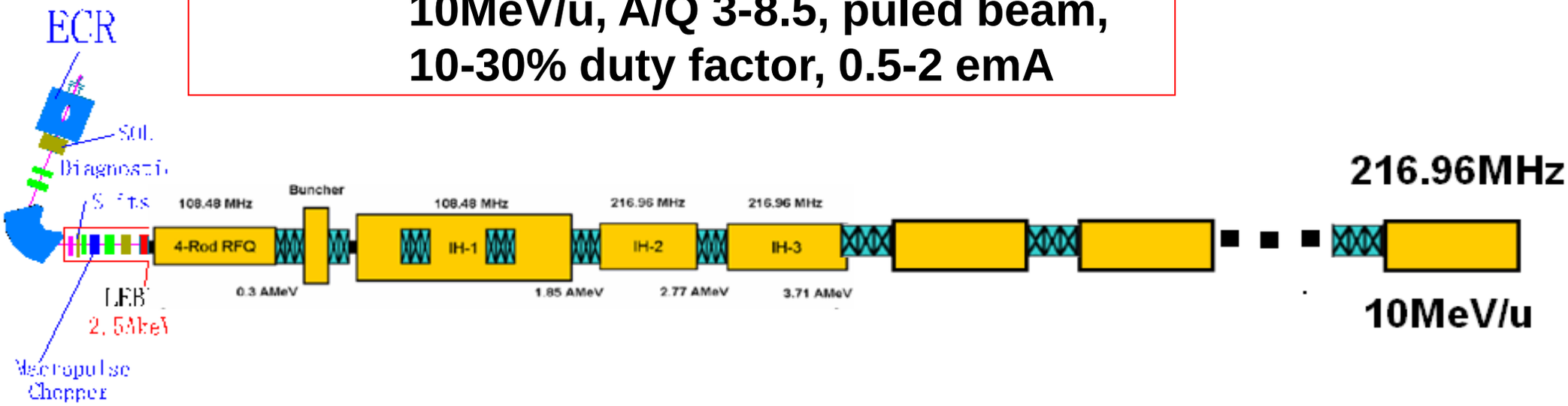


DTL

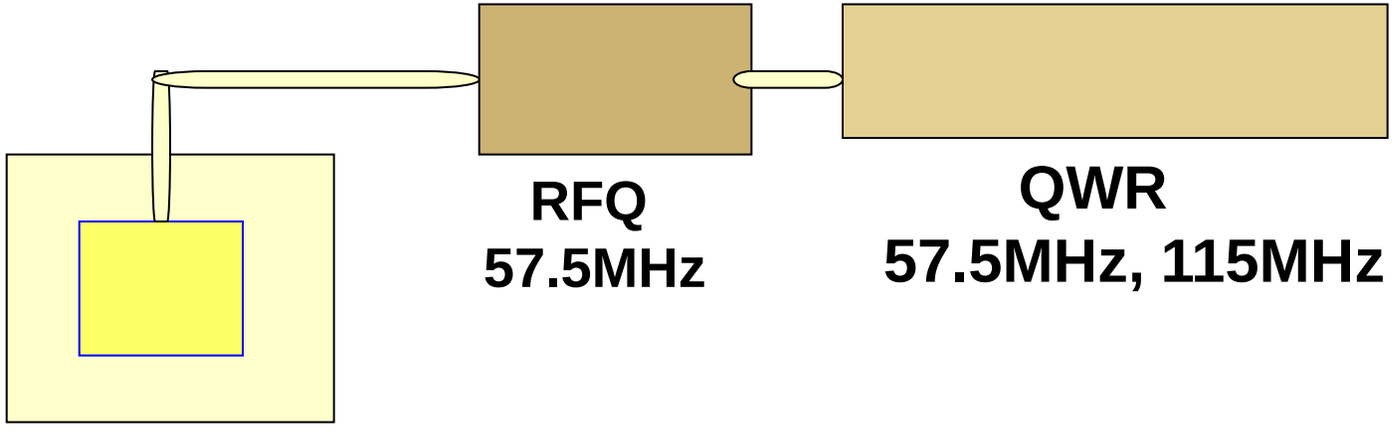
Build an intense heavy ion linac as a new injector for CSR



Option 1: Normal Conductor Linac
10MeV/u, A/Q 3-8.5, puled beam,
10-30% duty factor, 0.5-2 emA



Option 2: Superconducting Linac
10MeV/u, A/Q 8.5,



ECR Ion Source $^{238}U^{28+}$


Thanks !