

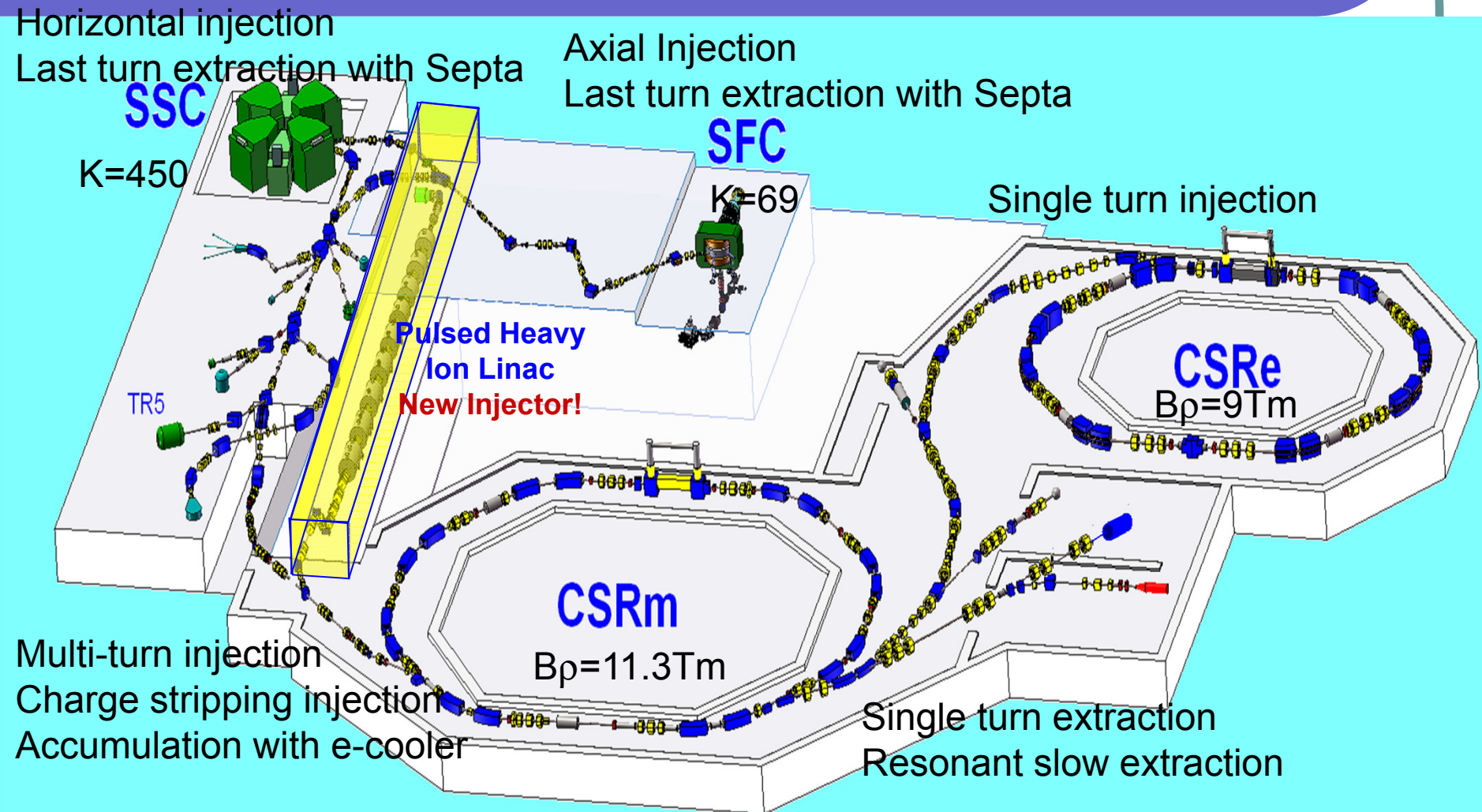
Study of Intense Beam Injection and Extraction of Heavy Ion Synchrotron

Youjin Yuan

Institute of Modern Physics, CAS

September 1, 2012

Introduction to HIRFL-CSR



The Cyclotron Injectors

- SFC (Spiral Sector Focusing Cyclotron)
 - $K=69$, $\epsilon_{x,y} \sim 24\pi \mu\text{m.rad}$, $\Delta p/p \sim 1\%$, $\Delta\psi \sim 30^\circ$.
 - provided H_2^+ , $^{12}\text{C}^{4+}$, $^{18}\text{O}^{6+}$, $^{22}\text{Ne}^{7+}$, $^{58}\text{Ni}^{19+}$, $^{78}\text{Kr}^{19+}$, $^{129}\text{Xe}^{27+}$, $^{209}\text{Bi}^{36+}$, $^{238}\text{U}^{32+}$ for CSRm
- SSC (Separator Sectors Cyclotron)
 - $K=450$, $\epsilon_{x,y} \sim 10\pi \mu\text{m.rad}$, $\Delta p/p \sim 0.4\%$, $\Delta\psi \sim 15^\circ$.
 - provided $^{36}\text{Ar}^{8+} || 18\text{MeV/u} || 3\text{e}\mu\text{A}$ for CSRm.

Injection and accumulation methods of HIRFL-CSR synchrotron CSRm

- **Multi-turn injection** (Horizontal phase space painting) is the fundamental method. →to make maximum use of the ring acceptance
- **Charge stripping injection** for light heavy ion beam. →to overcome Lowville theorem limit, condense the phase space.
- Accumulation with **electron cooling** for both of above. →to overcome Lowville theorem limit, condense the phase space.

Injection and Accumulation Schemes

For heavy ions: $\tau_{\text{cool}} < 1\text{s}$

- Multi-turn injection $\rightarrow$ **MI** is base of inj.
- MI + e-cooler $\rightarrow$ **MMI**

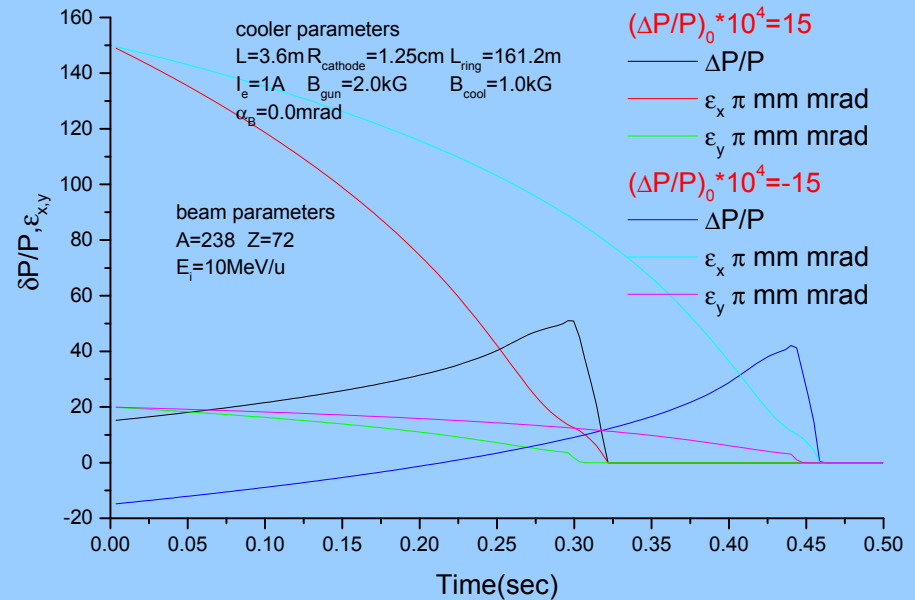
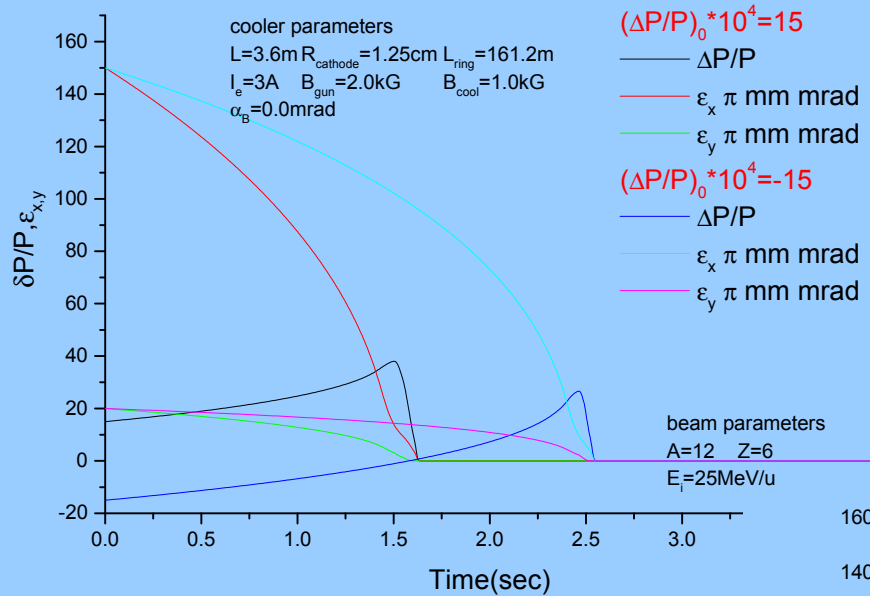
For Light ions: $\tau_{\text{cool}} > 1\text{s}$, $\eta_{\text{str.}} > 50\%$

- Charge stripping injection $\rightarrow$ **CI**
- **CEI + e-cooler $\rightarrow$ MCI**
- **RF Bucket-on Single CI $\rightarrow$ SCI** for
Cancer Therapy Facility

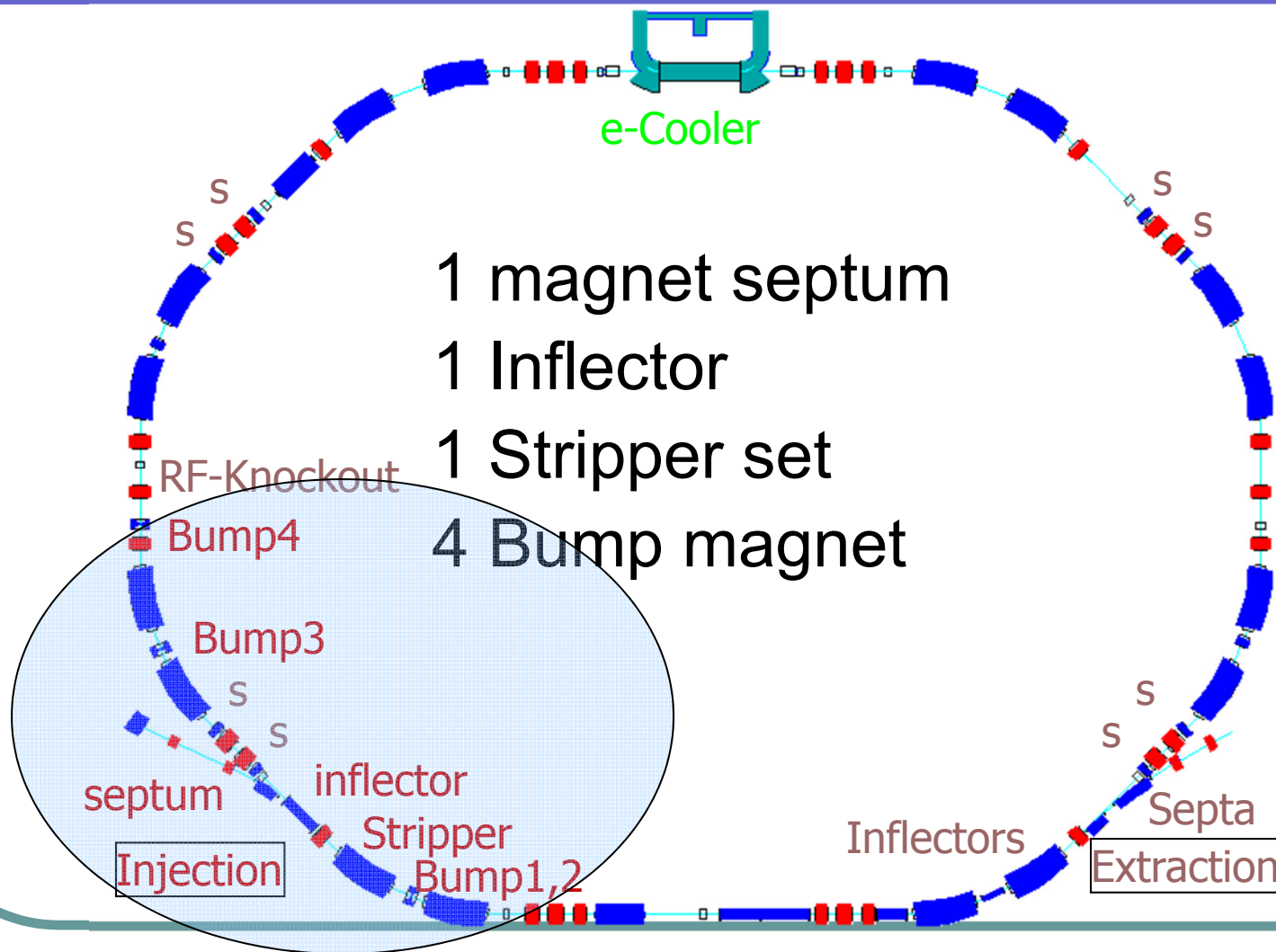
Electron Cooler for Accumulation

- First electron cooler with modifiable cross-section electron beam
- Parameters
 - $V_{\max}=35\text{kV}$, $I_e<1\text{A}$, $T_e\sim 0.1\text{eV}$
 - Diameter of electron beam : 60mm

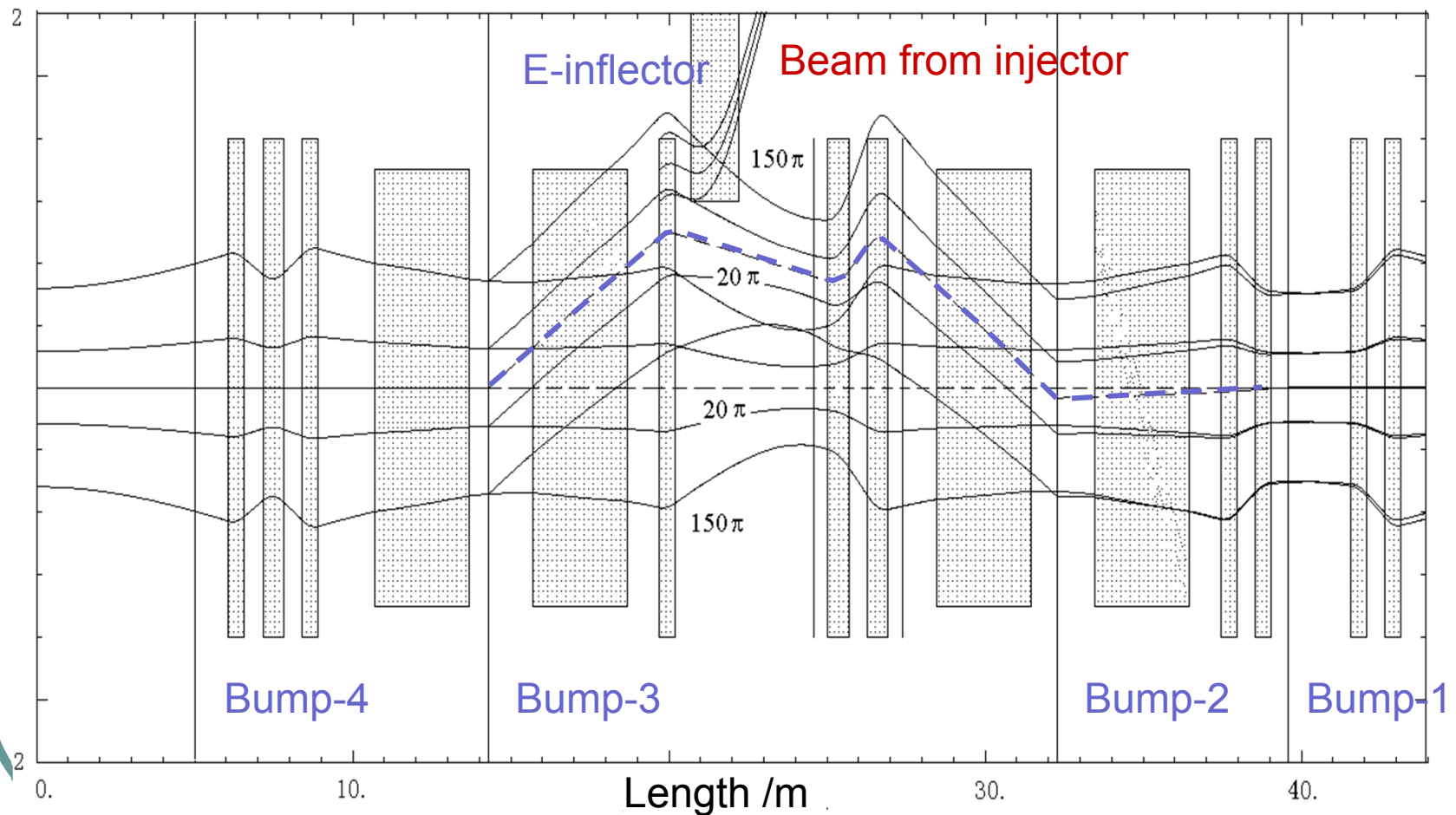
Electron-Cooling Calculation



Layout of CSRm Injection

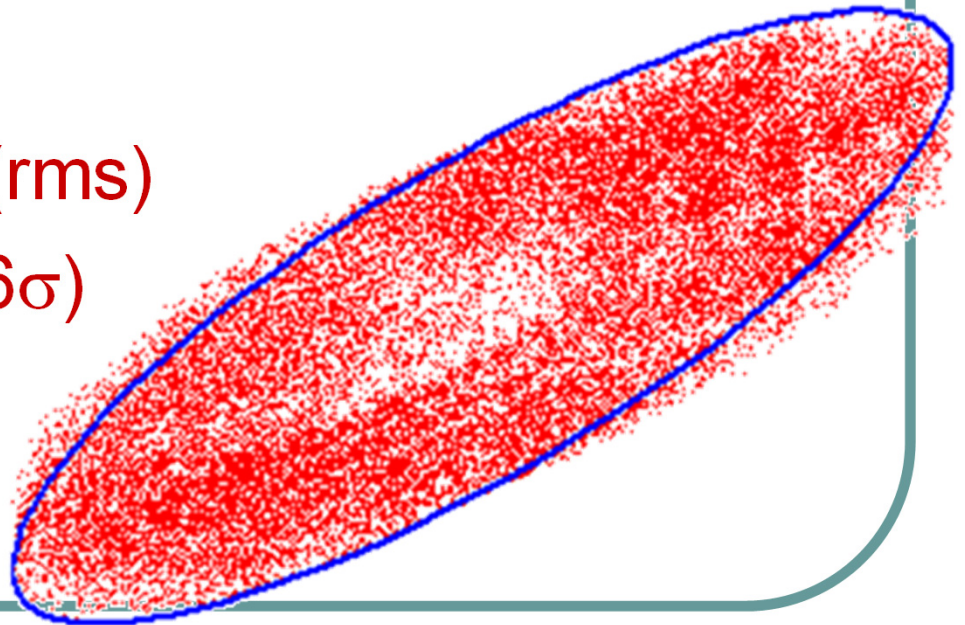


Injection Orbit And Beam Envelope of MI

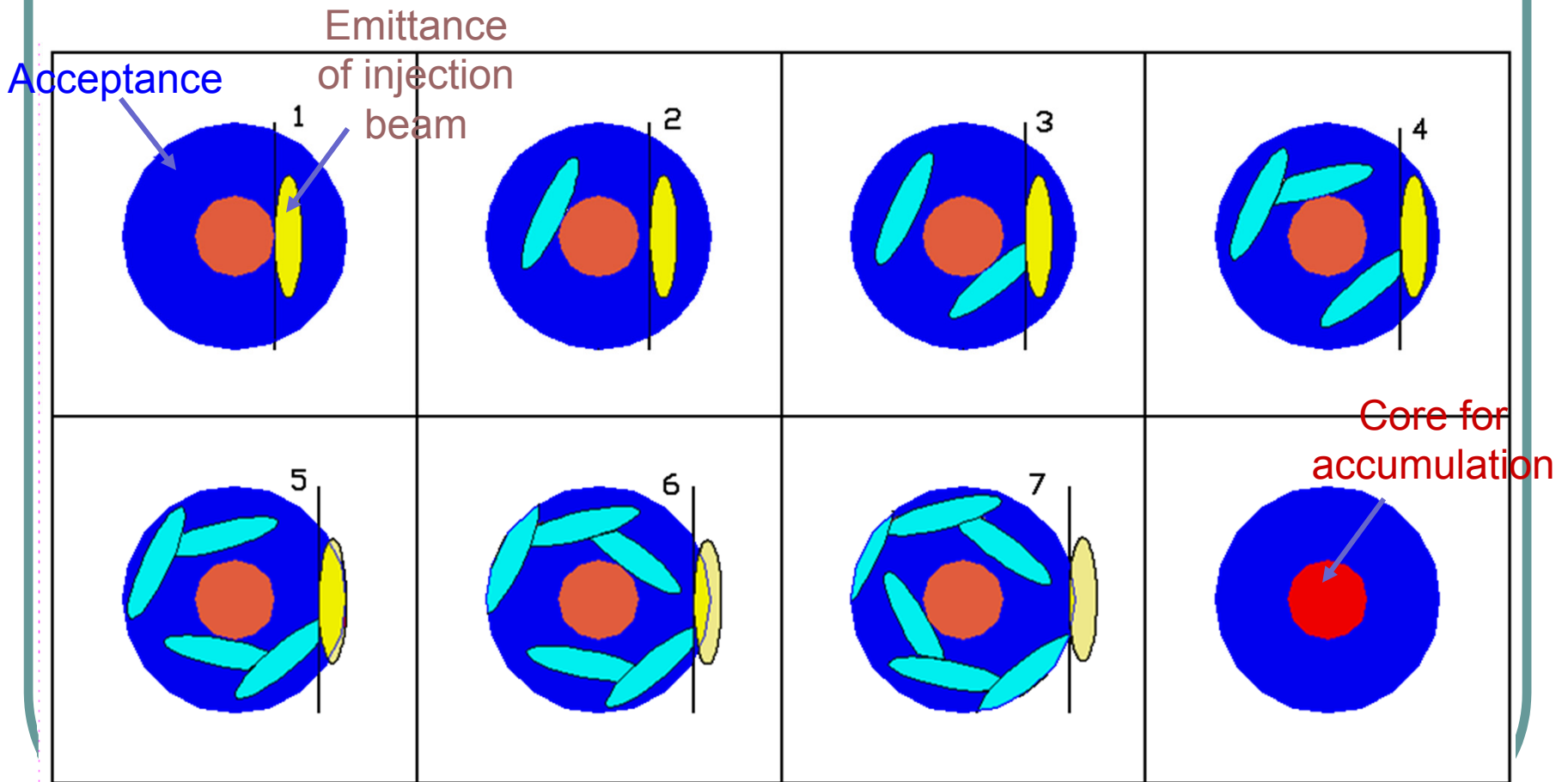


Phase Space of MI

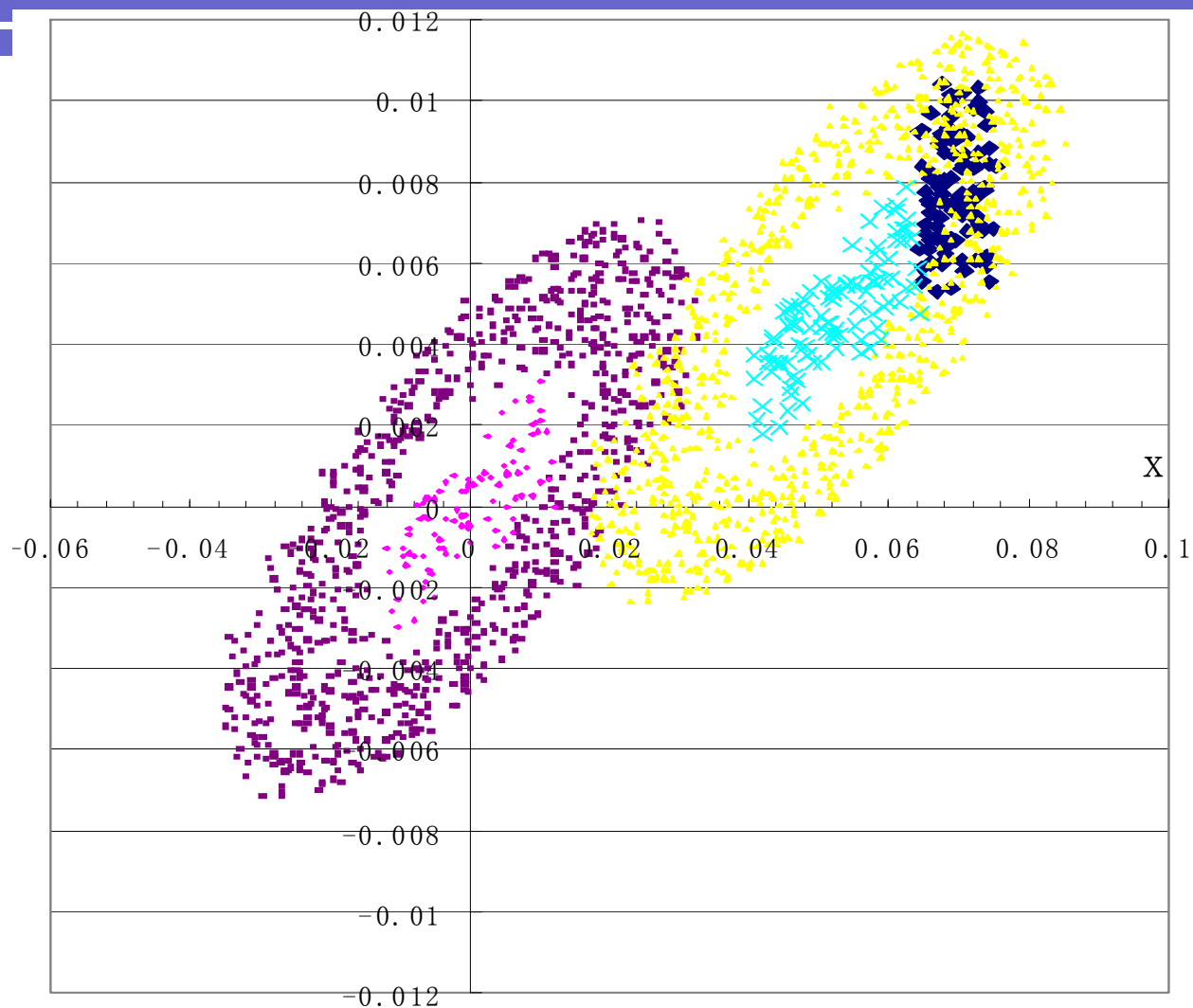
- $X_{ES}=60\text{mm}$ Thickness $d=0.1\text{mm}$
- Gain Factor=8.7
- Beam from injector
 - $Ax=150 \pi\text{mmrad}$
 - $\varepsilon_{x,y}=2.5\pi\text{mmrad(rms)}$
 - $\delta p/p=\pm 0.5\%(2.236\sigma)$



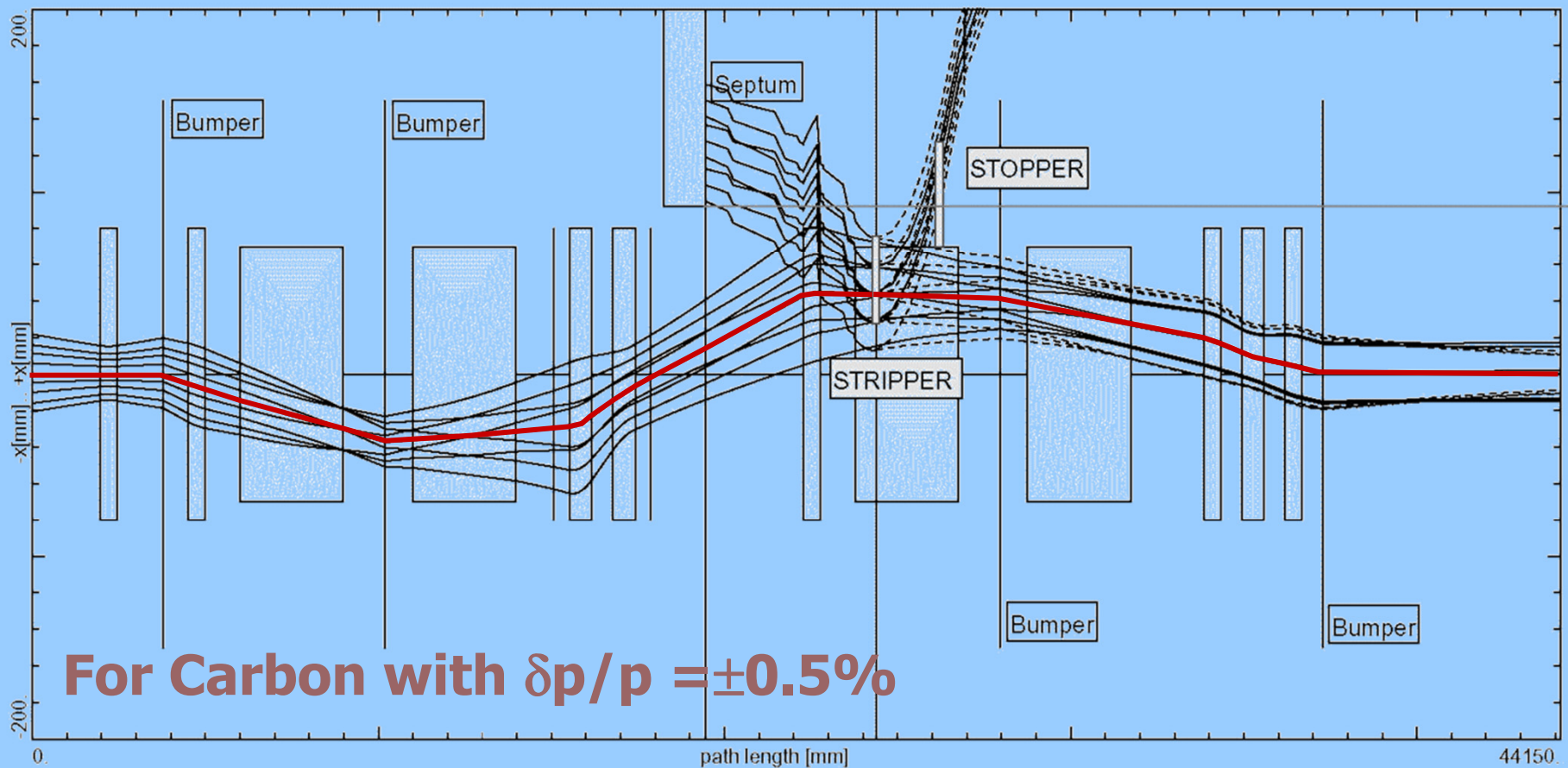
MI and Accumulation with e-Cooler



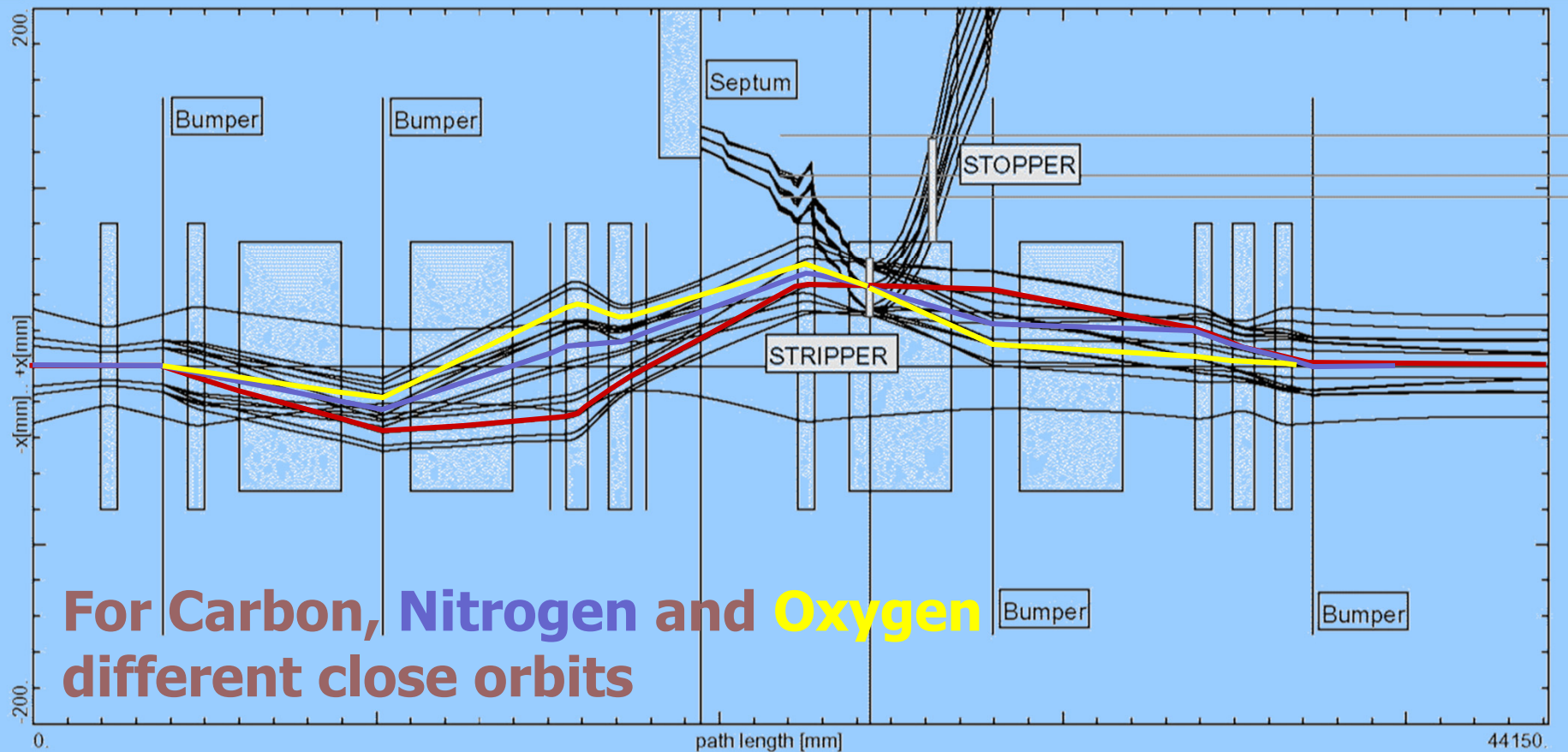
Phase Space of MI



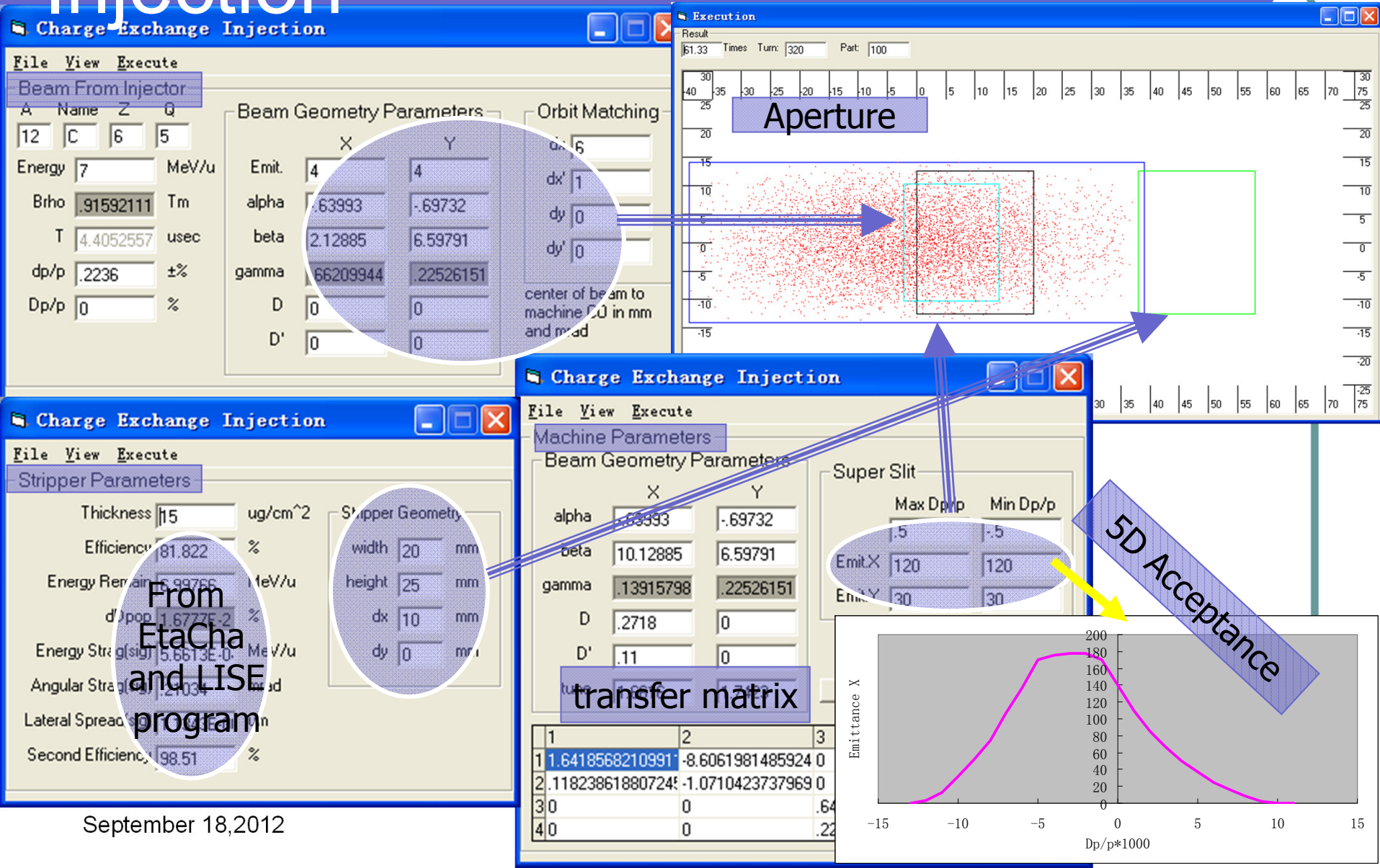
Injection Orbit and Beam Envelope of CI



Injection Orbit And Beam Envelope of CI



Simulation Program for Stripping Injection



Simulation Program for Stripping Injection

Injection procedure control

Charge Exc...

File View Execute

Execution Parameters

No. of Particles: 100

Sigmas of Inj. Beam Dist.: 2

Sigmas of Stripping: 2.236

Seed: 23423.42

No. of Turns Injected: 200

Turns Stripper Shift: 120

Tau Shift in Turns: 35

Tau in us: 154.18395

Stripper Shift in mm: 38

☐ Write Particles

Parameters
are stored
in database
or in files.

Charge Exchange Injection

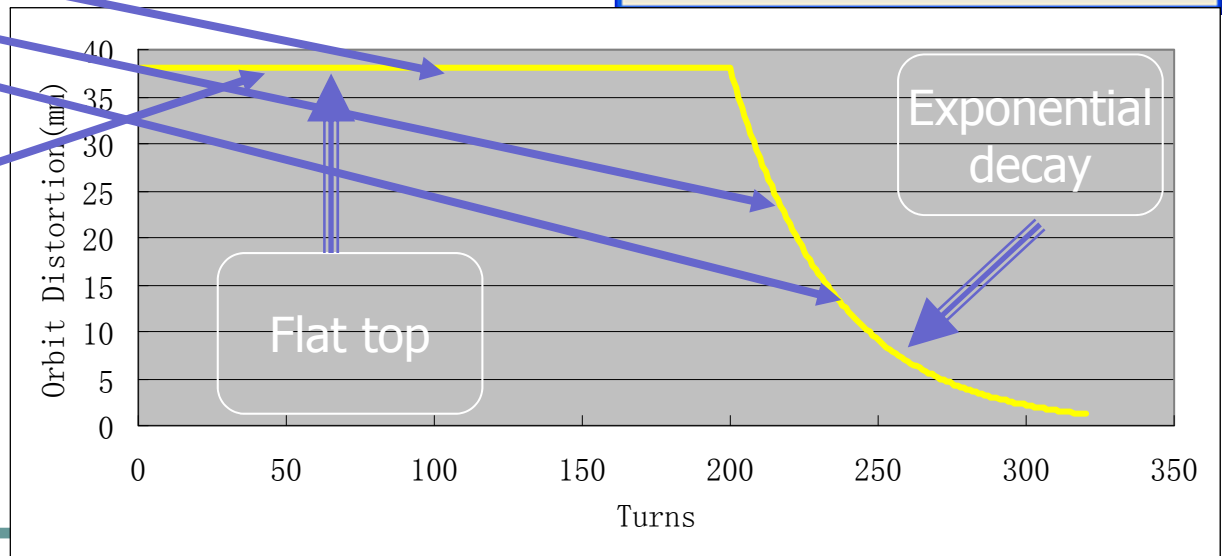
File View Execute

DataBase

Record No. 1 Gain 54

Load Save

Execute From: 1 To: 1



Injection Particles

Charge Exchange Injection

File View Execute

Beam From Injector

A	Name	Z	Q
12	C	6	5

Energy 7 MeV/u

Brho .91592111 Tm

T 4.4052557 usec

dp/p 2236 ±%

Dp/p 0 %

Beam Geometry Parameters

	X	Y
Emit.	4	4
alpha	.63993	.69732
beta	2.12885	6.59791
gamma	66209944	.22526151
D	0	0
D'	0	0

Orbit Matching

dx 6

dx' 1

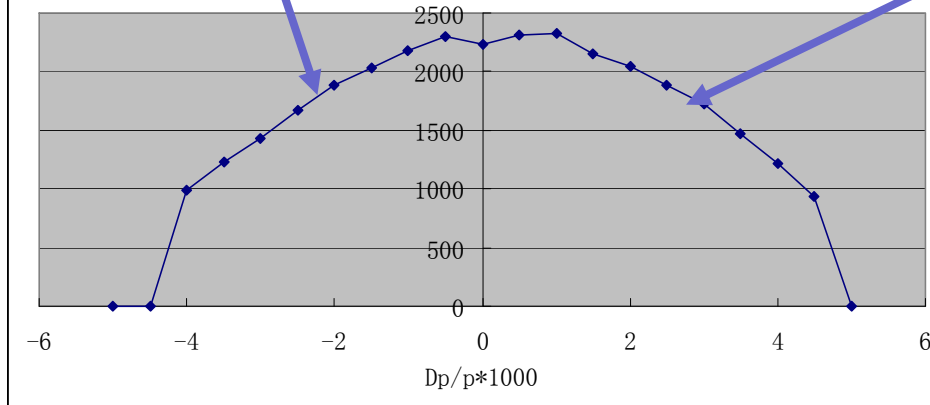
dy 0

dy' 0

center of beam to machine CO in mm and mrad

5D phase space of injection beam

Gaussian Distribution and cut



Charge Exc...

File View Execute

Execution Parameters

No. of Particles: 100

Sigmas of Inj. Beam Dist.: 2

Sigmas of Stripping: 2.236

Seed: 23423.42

No. of Turns Injected: 200

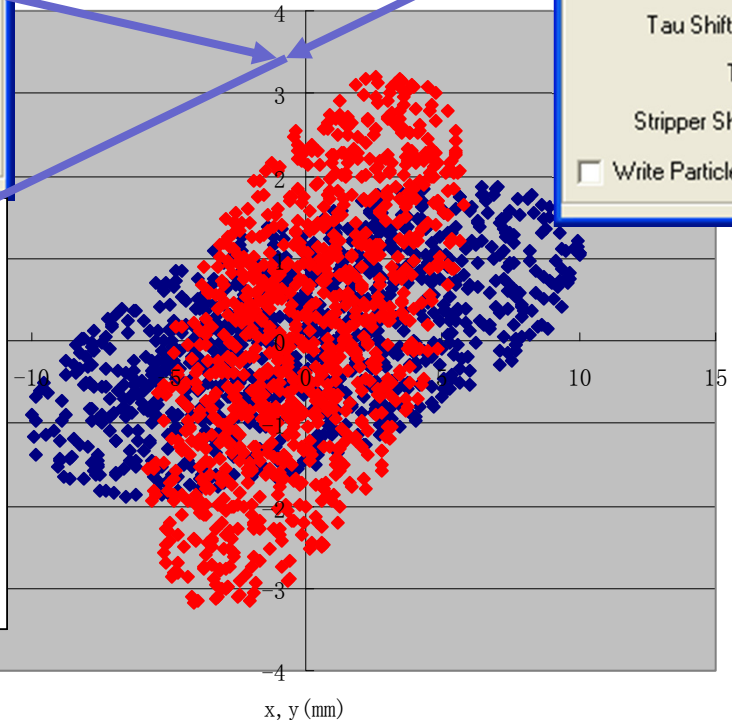
Turns Stripper Shift: 120

Tau Shift in Turns: 35

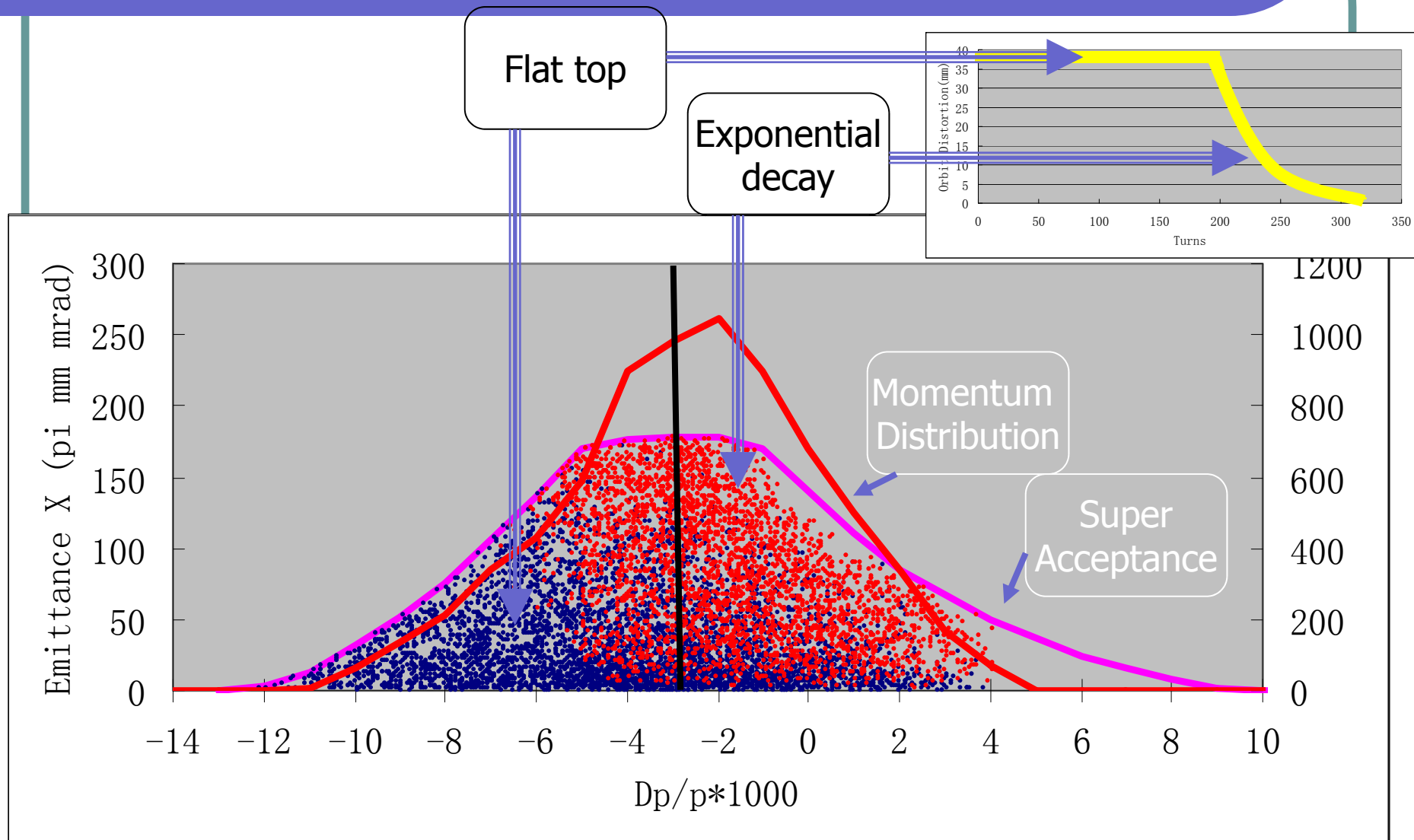
Tau in us: 154.18395

Stripper Shift in mm: 38

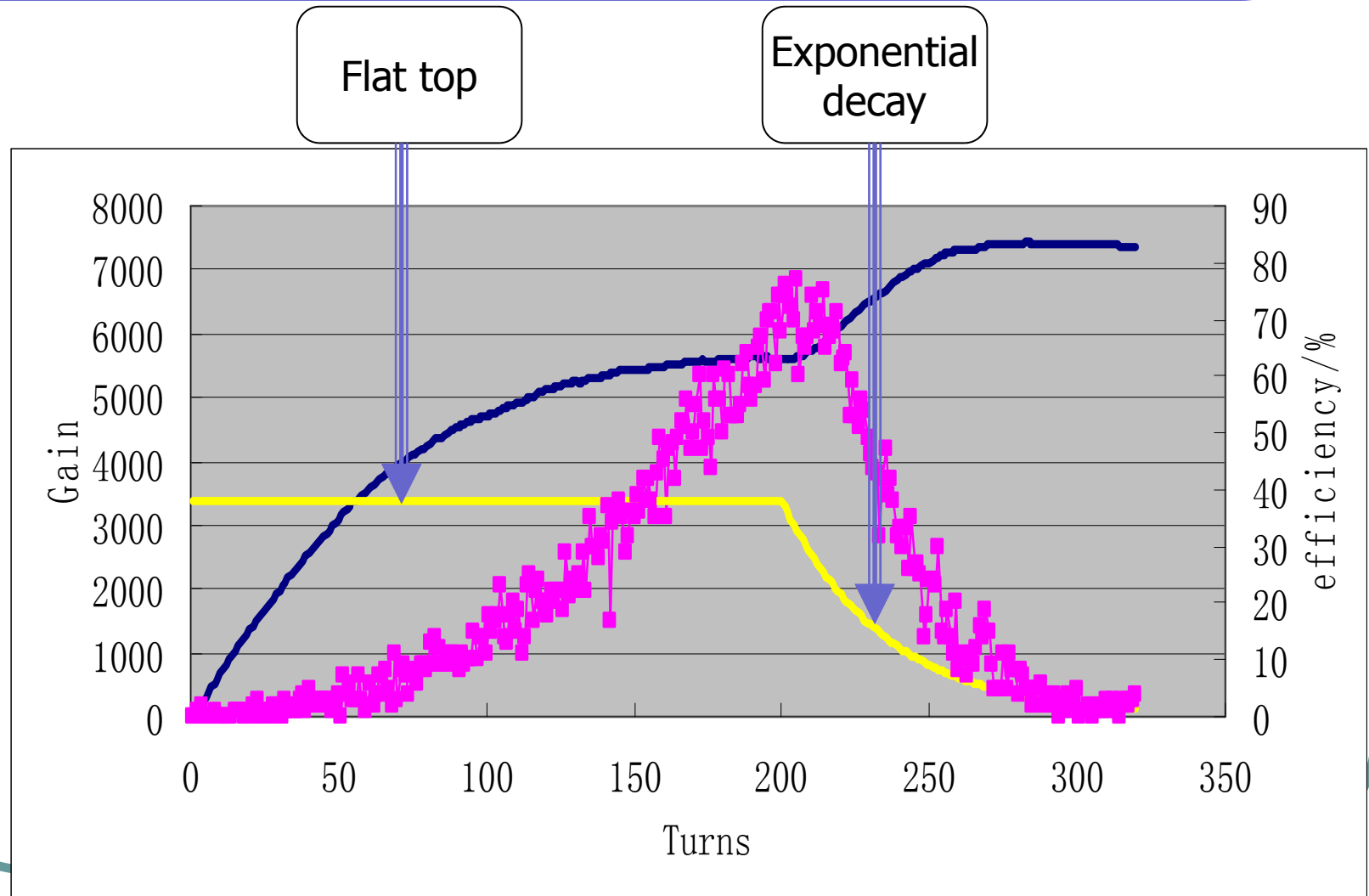
☐ Write Particles



Injected Beam Distribution

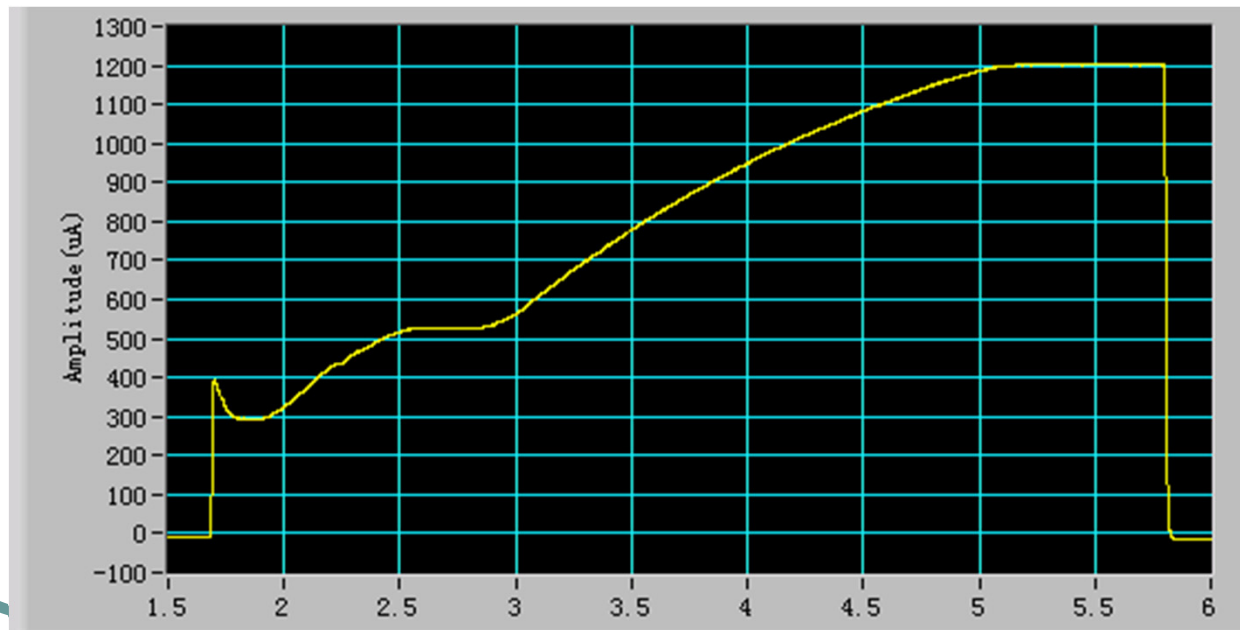


Gain and Efficiency



Carbon injection results

- MCI/10s $\rightarrow 1.2 \times 10^{10}$
- MCI/1.5s $\rightarrow 1 \times 10^8$
- RF Bucket-on single CI, no e-cooler $\rightarrow 1.3 \times 10^9$

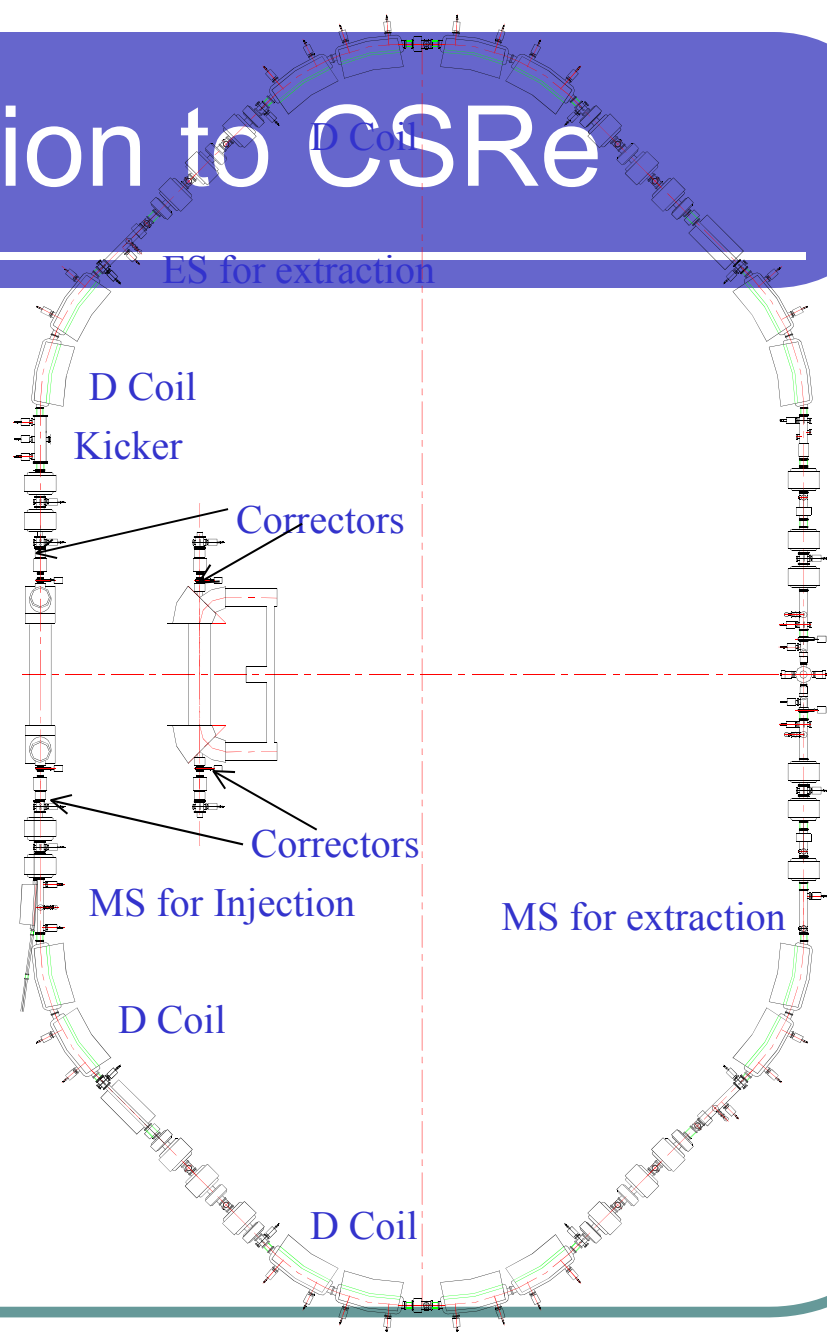


List of the provided beam from cyclotron injectors

Ion	E (MeV/u)	Injector Intensity (eμA)	Injection method	N ions stored in CSRm
H ₂ ¹⁺	10	7	MMI+eC	4.9E+08
¹² C ⁴⁺	8	5	CSI+eC	9.7E+09
¹² C ⁴⁺	8	5	CSI	2.2E+09
¹⁸ O ⁶⁺	7	3	CSI+eC	1.59E+09
²² Ne ^{7+/10+}	6.17	9	CSI+eC	7.03E+09
³⁶ Ar ^{8+/18+}	22	3	MMI+eC	2.33E+08
⁵⁸ Ni ¹⁹⁺	6.3	1.8	MMI+eC	1.51E+08
⁷⁸ Kr ^{19+/28+}	4	7	MMI+eC	1.83E+08
⁸⁶ Kr ^{20+/28+}	3.63	4.5/1.1	MMI+eC	1.92E+08
¹²⁹ Xe ²⁷⁺	3	4	MMI+eC	2.19E+08
²⁰⁹ Bi ³⁶⁺	2	2	MMI+eC	4.03E+07
²³⁸ U ³²⁺	1.22	1	MMI+eC	1.59E+08

Single turn injection to CSRe

- 4 cells kicker with 150ns fall time and 700ns flat top
- D-coils for local orbit
- Fit all high resolution mode and isochronous operation modes
- 1 magnet septum



Injection Orbit: high resolution mode

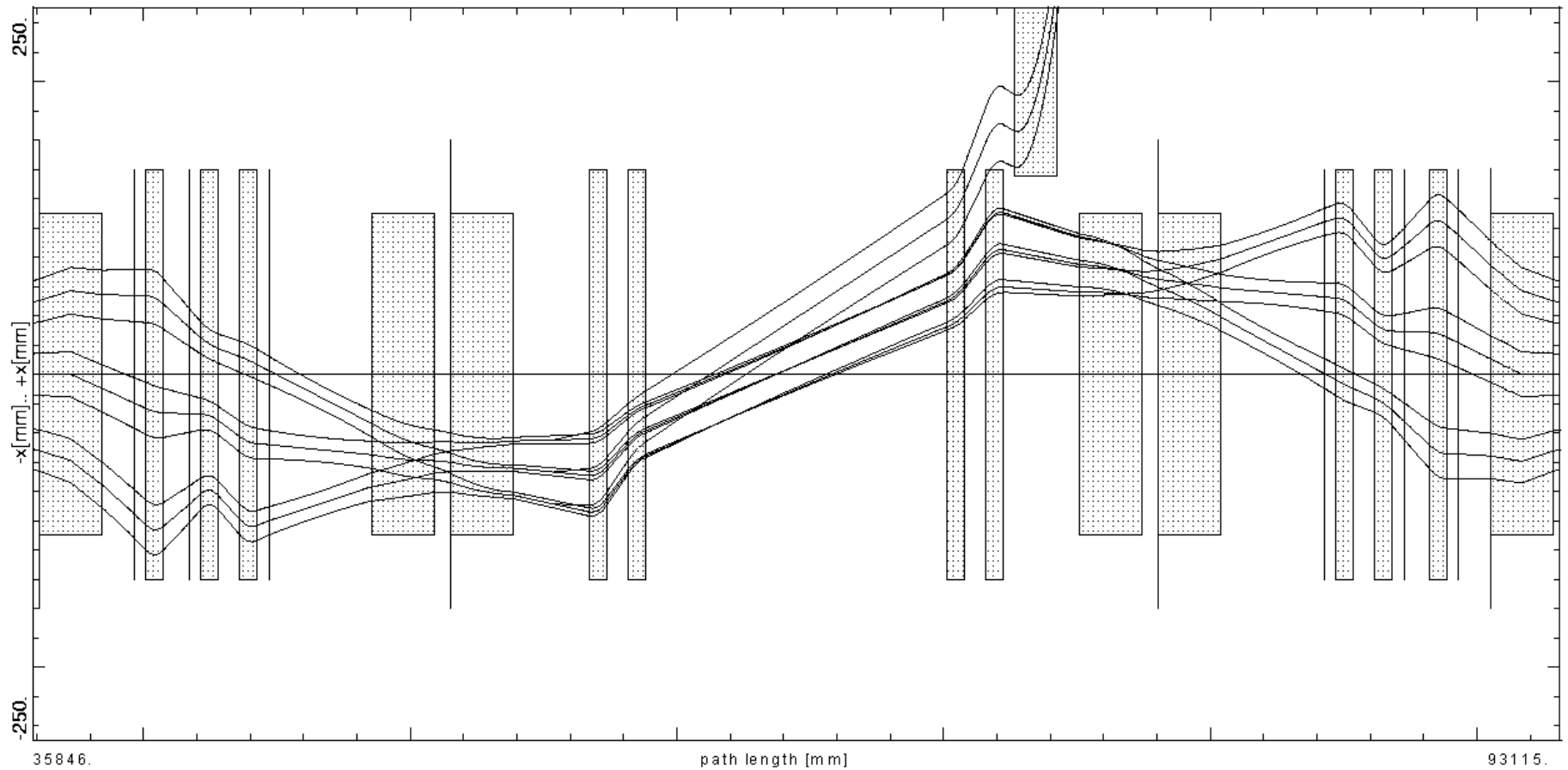


Figure 3-23 CSRe Single Turn Injection (High Resolution Mode)

Injection Orbit: Isochronous mode

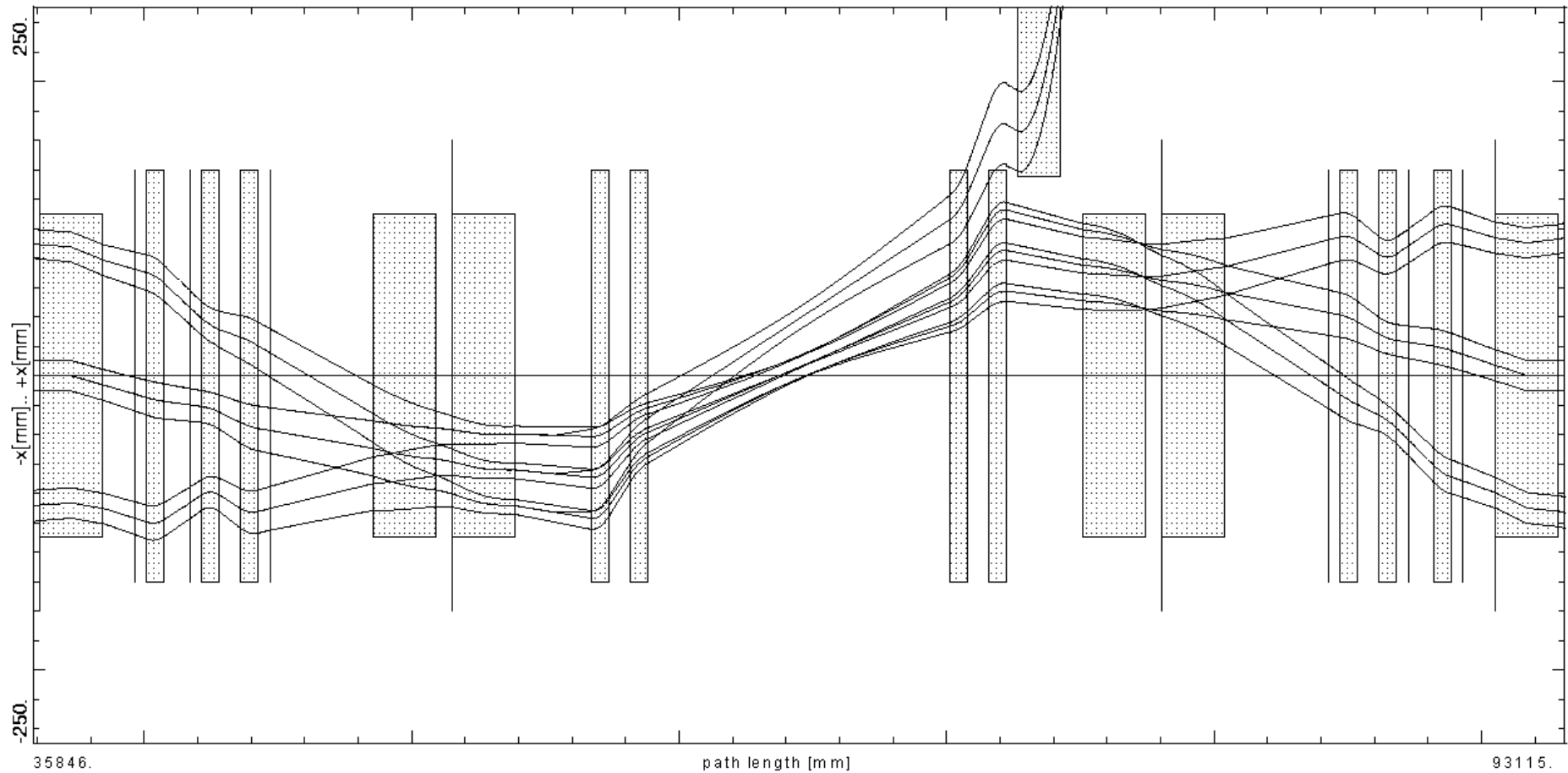


Figure 3-24 CSRe Single Turn Injection (Isochronous Mode)

Injection Orbit: high resolution mode

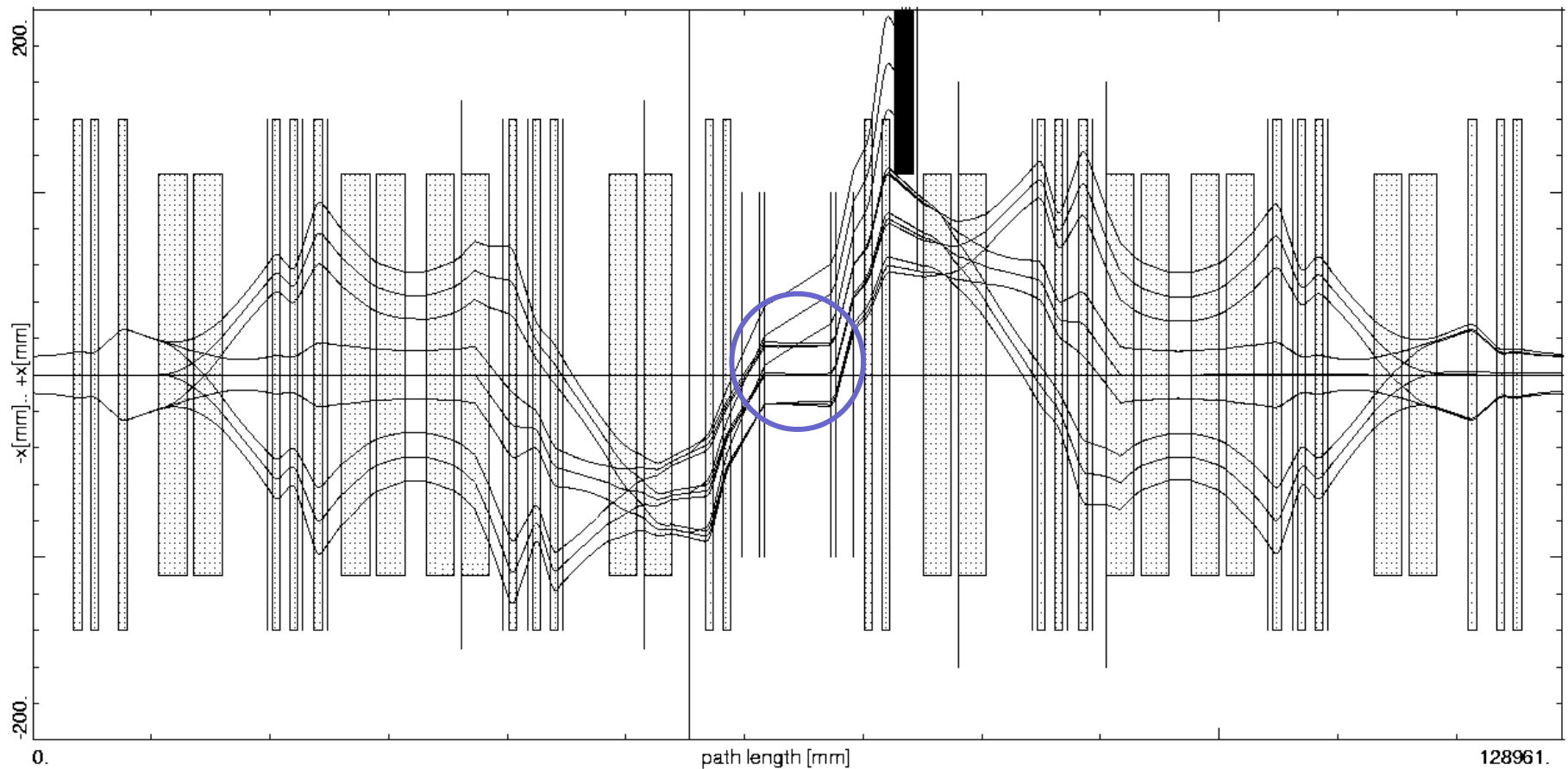


Figure 3-25 CSRe Injection Orbit with Cooling Section Correction(High Resolution Mode, 8.4T.M)

Injection Orbit: Isochronous mode

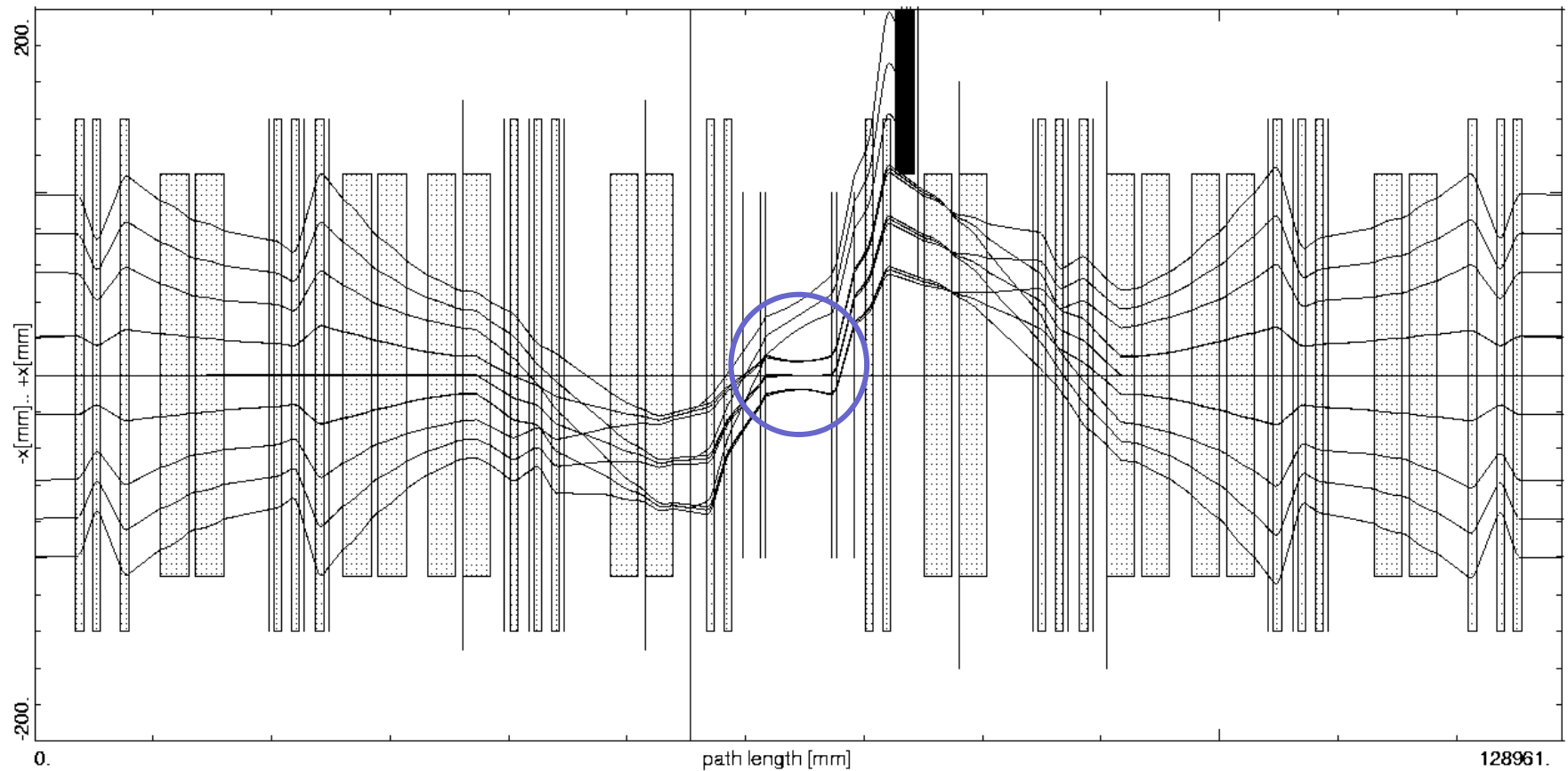
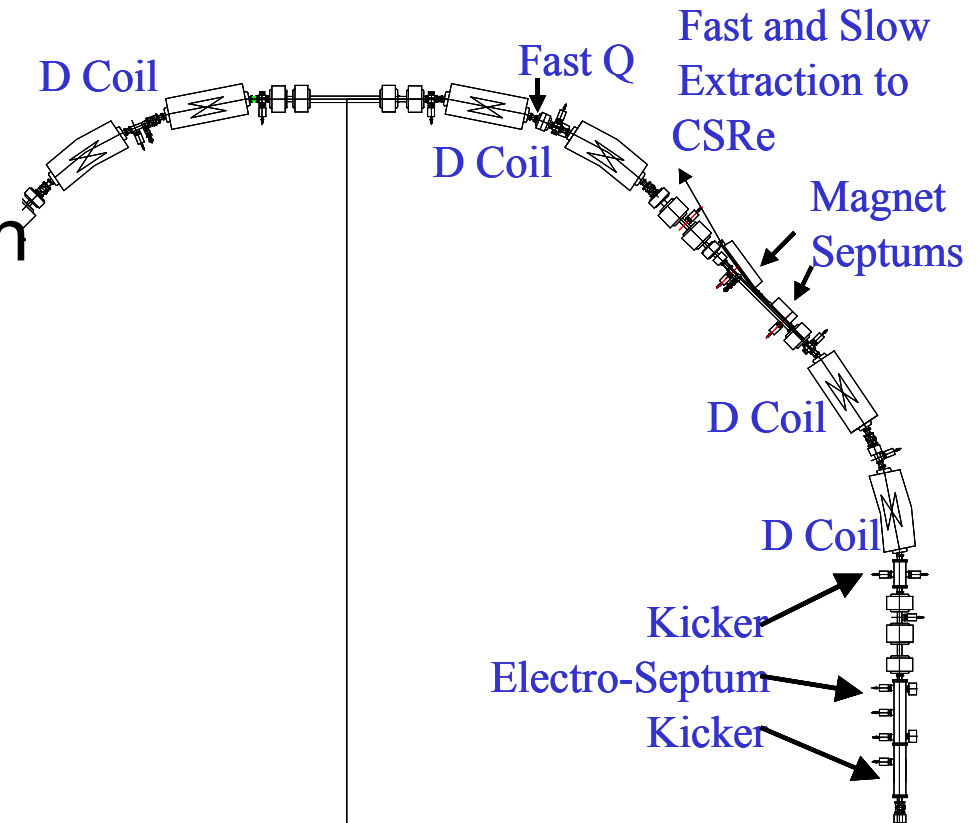


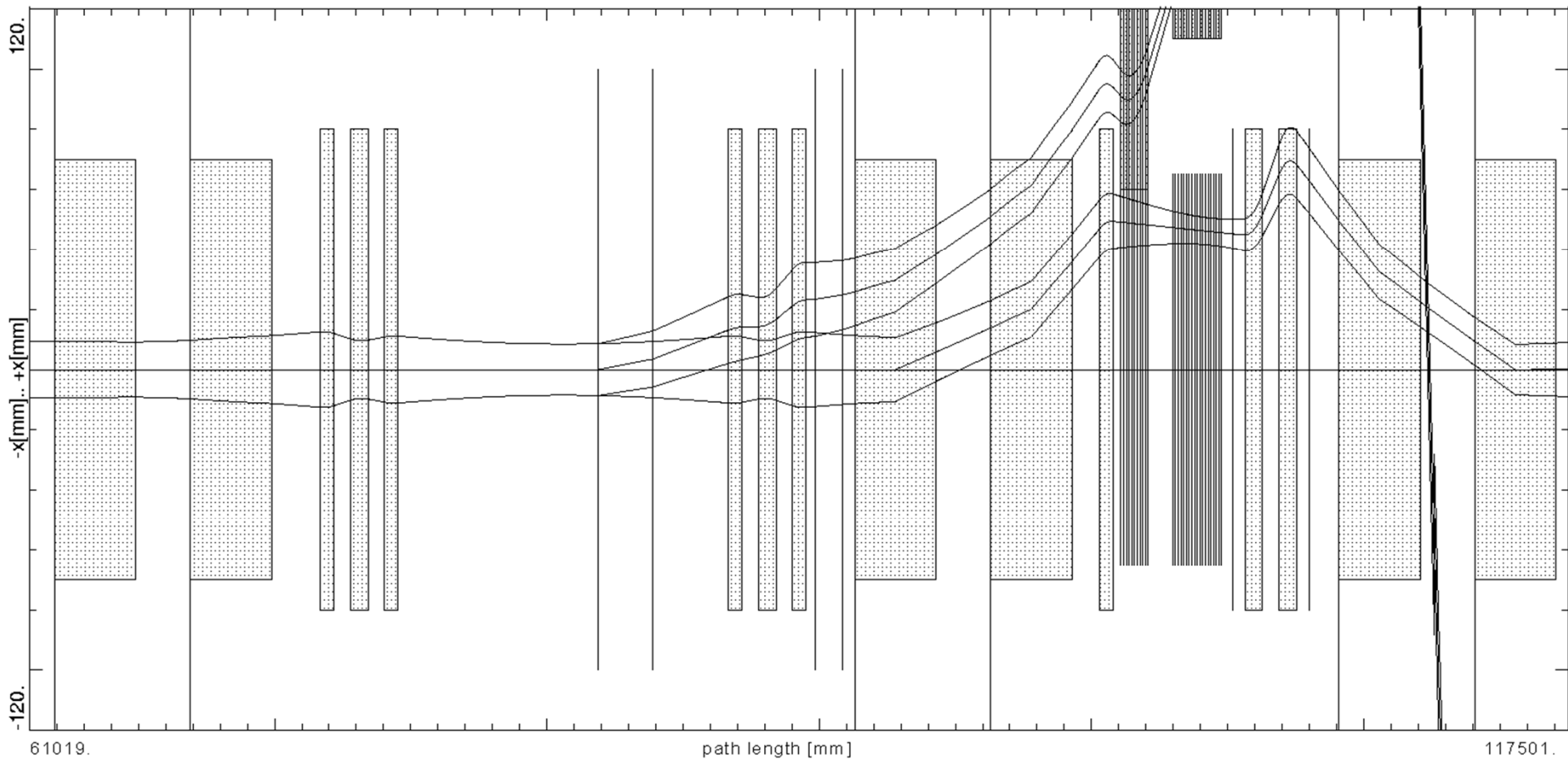
Figure 3-27 CSRe Injection Orbit with Cooling Section Correction(Isochronous Mode, 8.4T.M)

Fast extraction from CSRm

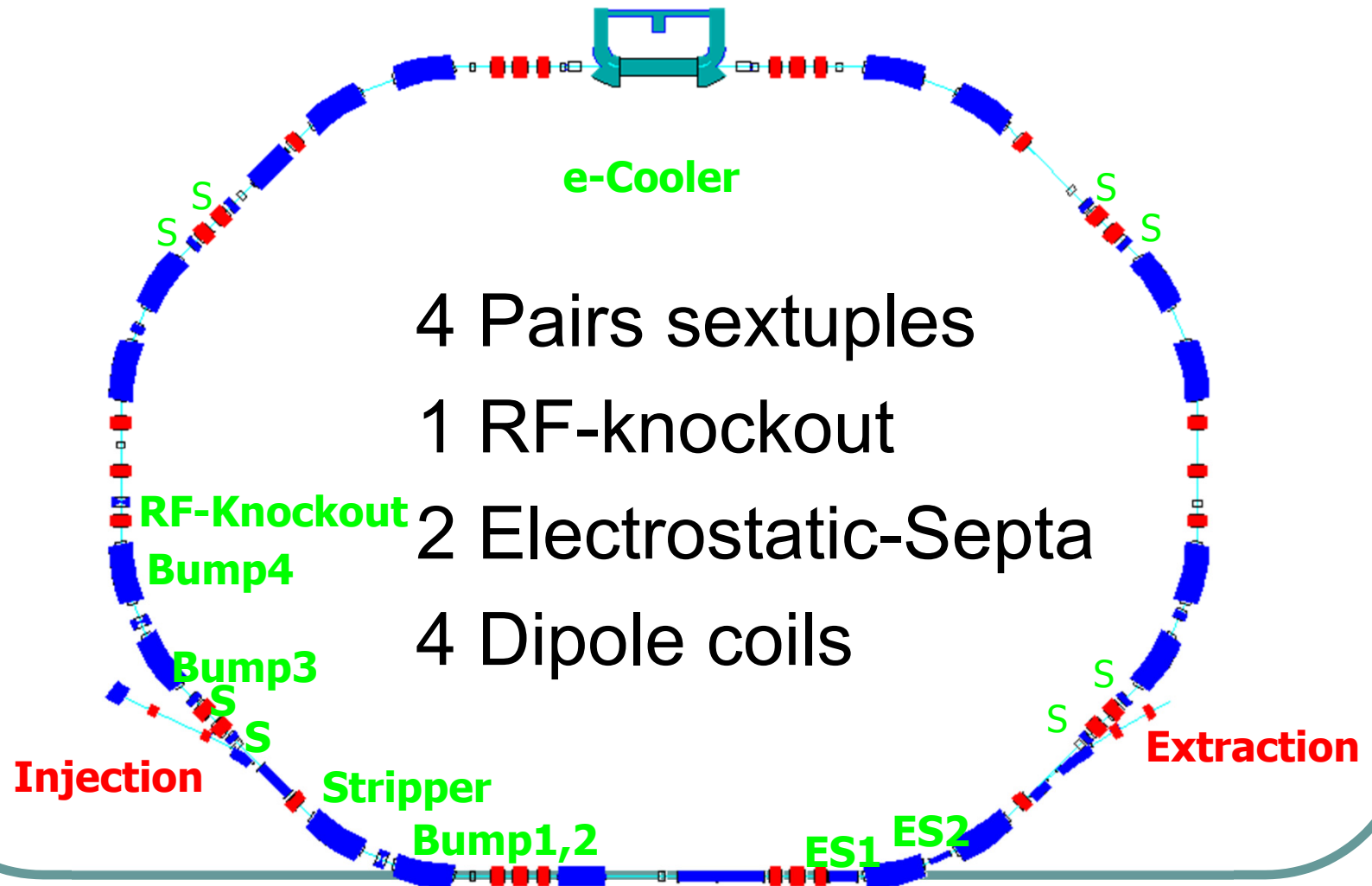
- Use the same extraction tunnel with slow extraction
- 6 cell kicker with 150ns raise time and 700ns flattop
- D-coils or global orbit shift
- 2 septum magnets



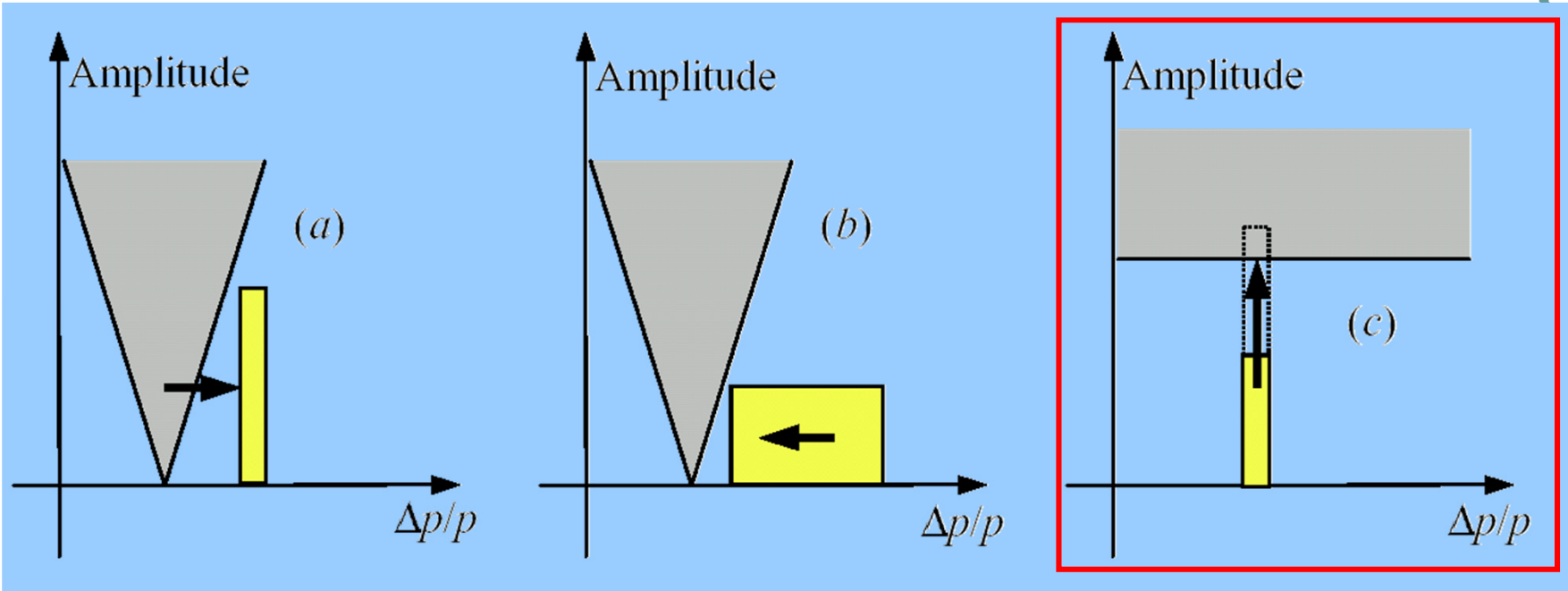
CSRm Extraction Orbit



Layout of CSRm Slow Extraction

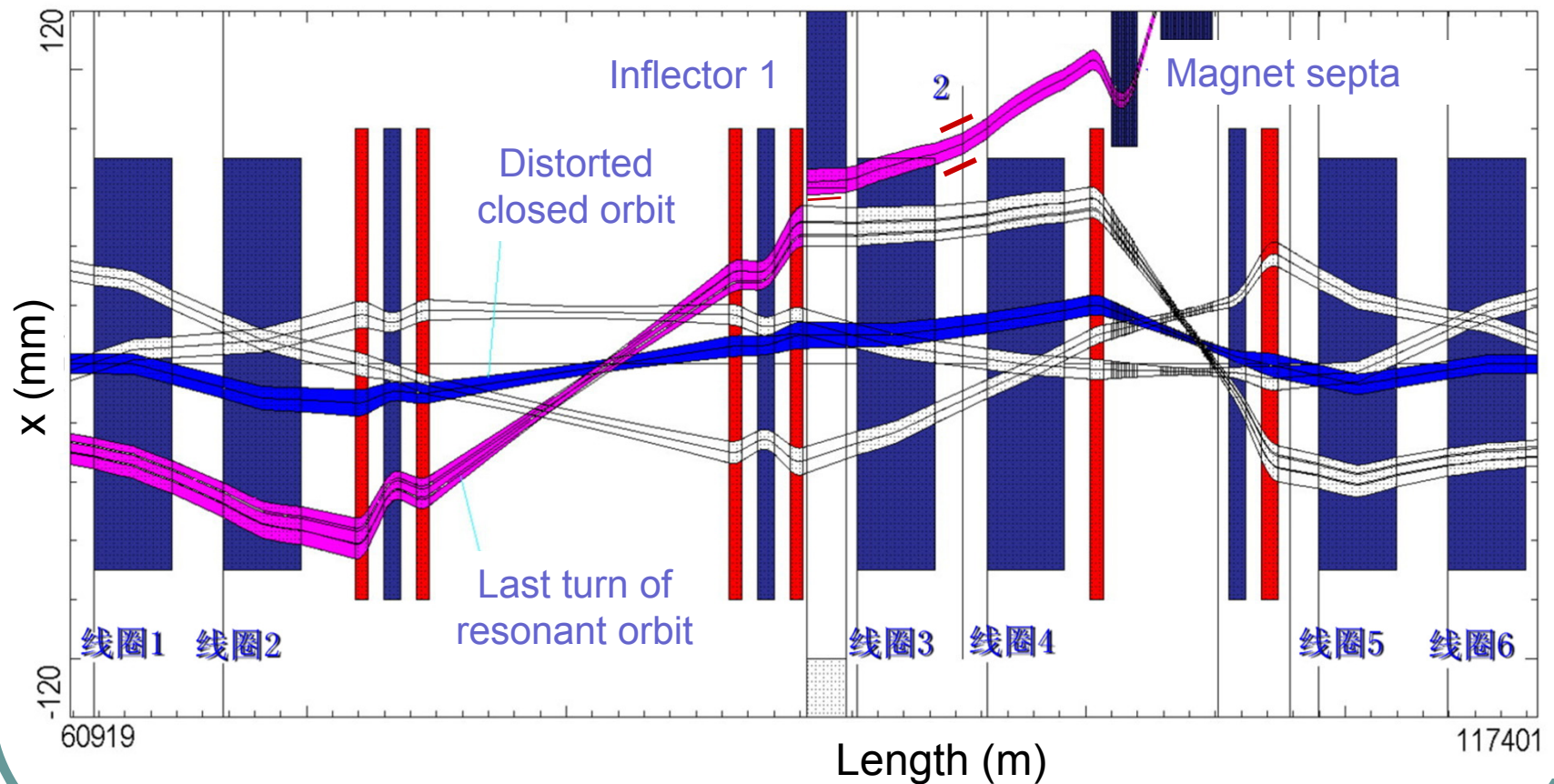


Slow Extraction Scheme

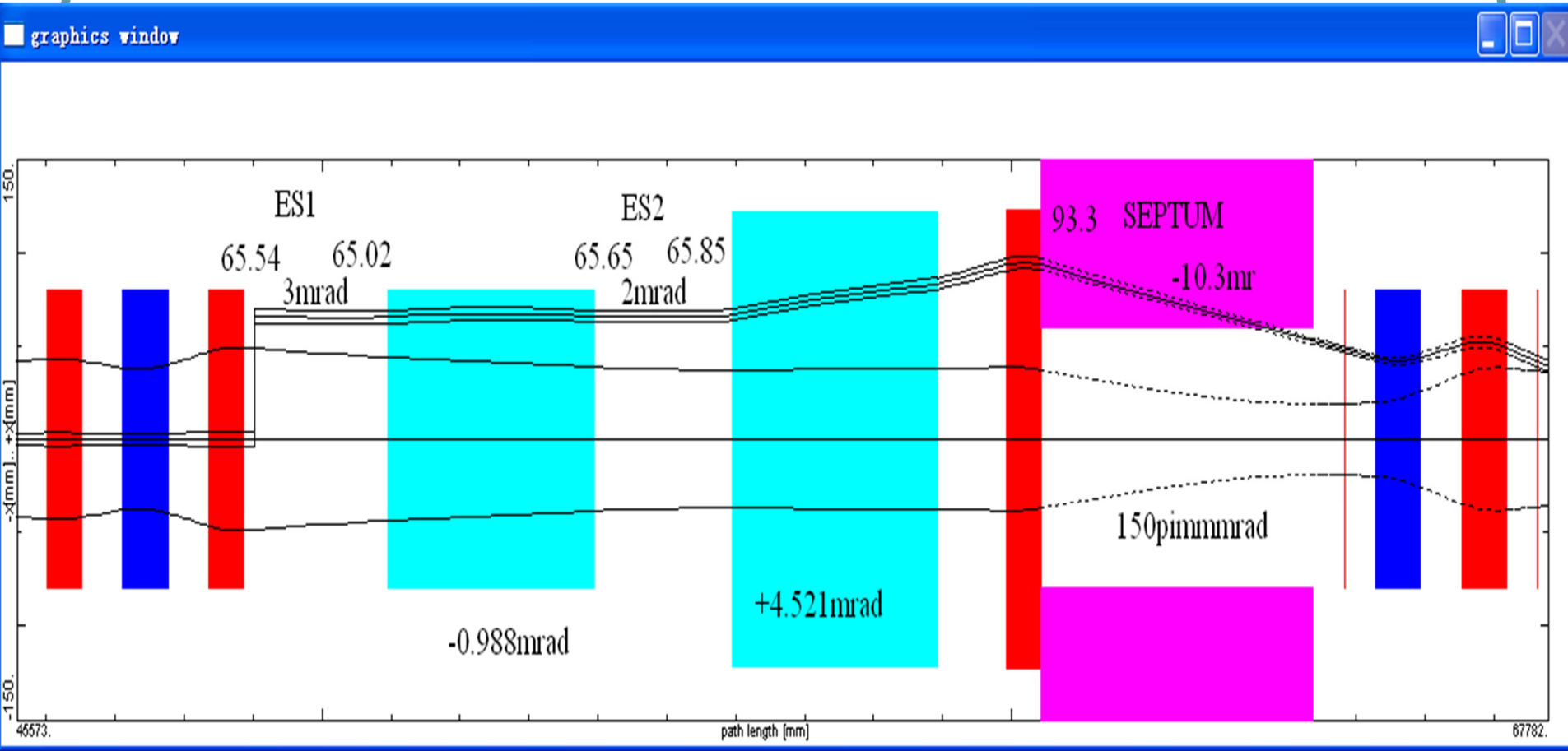


- (a) Amplitude selection + tune moving $\delta p \downarrow \xi \uparrow$
- (b) Momentum + Amplitude selection $\delta p \uparrow \xi \uparrow$
- (c) RF Knock-out —Zero Chromaticity $\delta p \downarrow \xi \downarrow = 0(\text{CSRm})$

The last turns of 1/3 integer resonant / RF knock-out slow extraction at CSRm

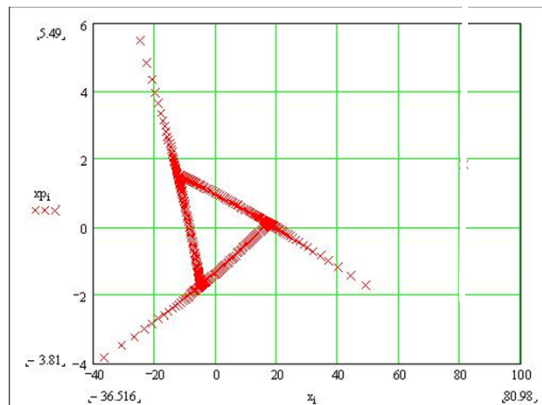


The slow extraction orbit



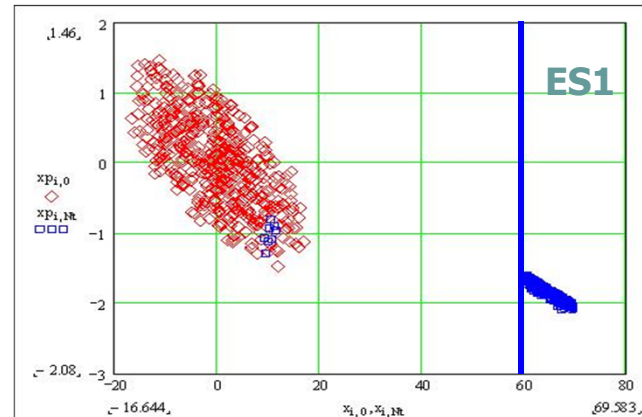
Basic Tracking Study

Stable 1/3 integer resonance phase space area



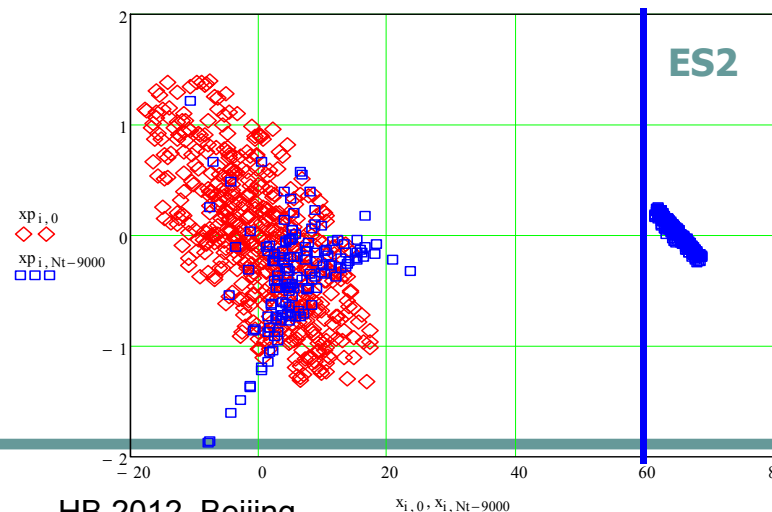
$A_s = 13\pi$ mm mrad

Extracted beam at 1st ES



$k_{ES1} = 3$ mrad

Extracted beam at 2nd ES

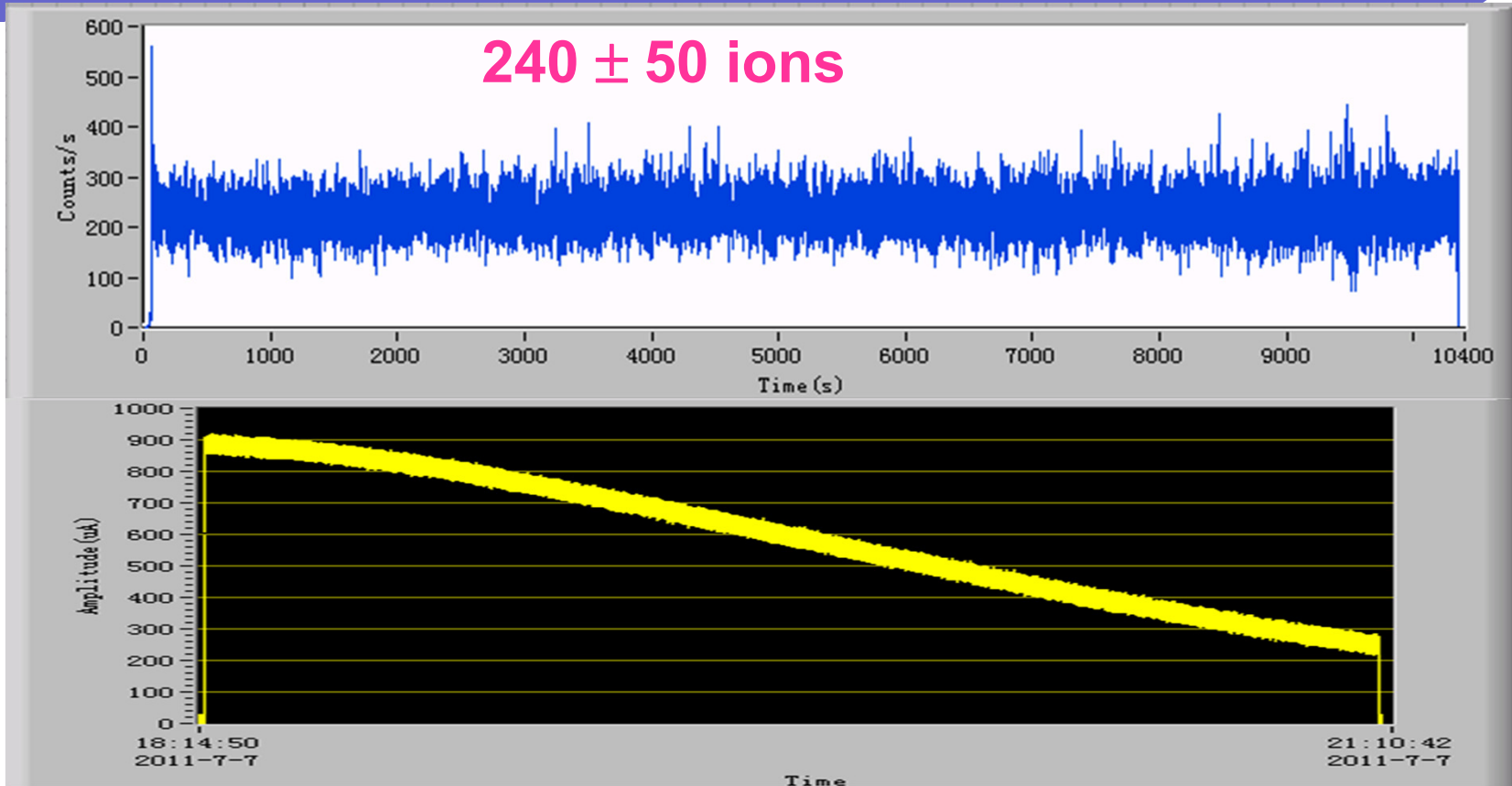


$k_{ES1} = 2$ mrad

Commissioning strategy for slow extraction

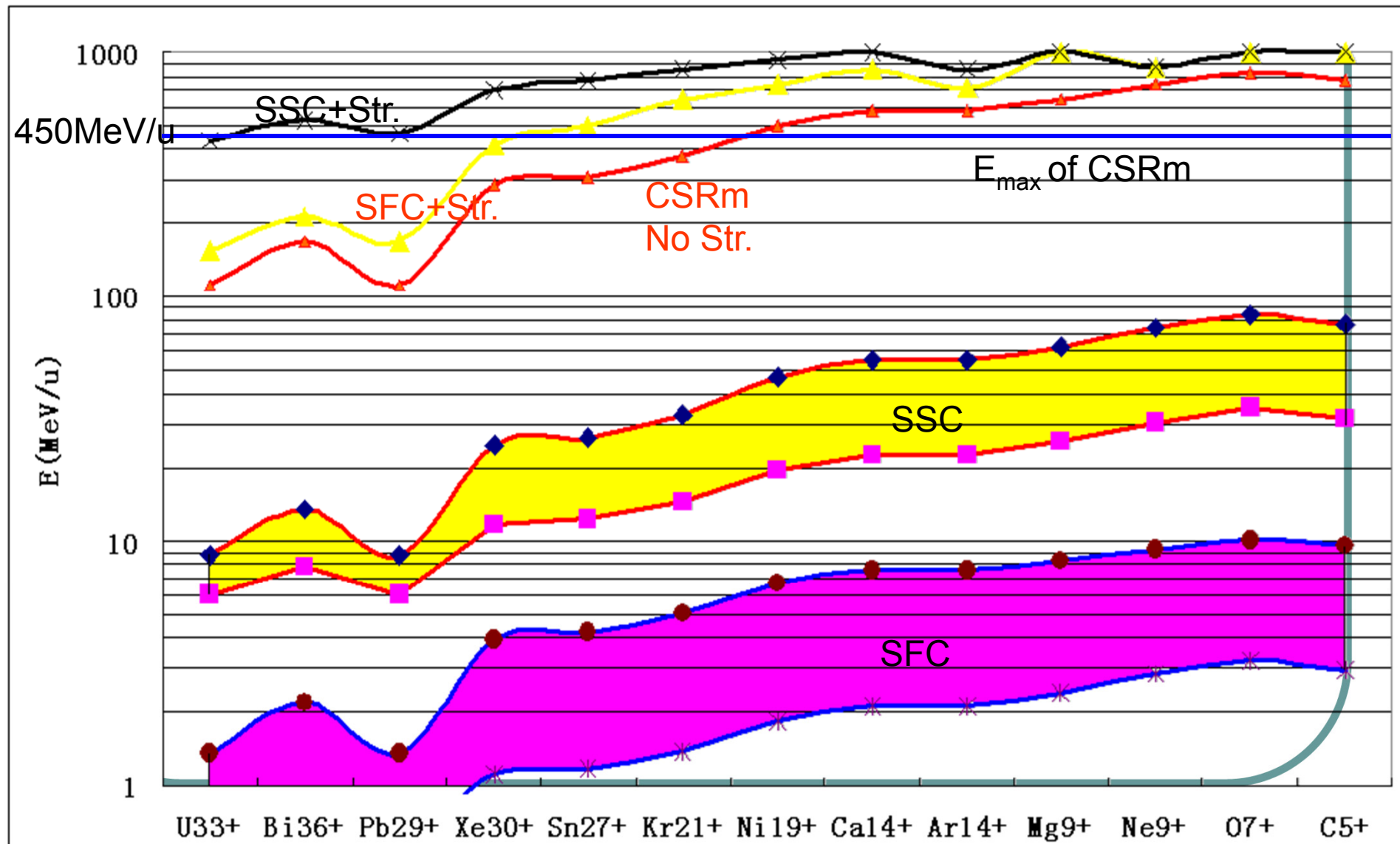
- Hardware: 8 sextuples, RF Knock-out, 2 ES, 4 orbit distortion coils
- From 2nd ramping section,
 - Starts the sextuples from 0.
 - Ramping the $Q_x \rightarrow 3.664$, keep Q_y
 - Keep the beam intensity
- → extraction section (top energy)
 - Resonance exciting strength $S=12$
 - Stable area $A_s = 13\pi$ mm mrad
- The parameters for $k''L$
 - $20S1=0.9745, 21S2=-0.6700, 22S2=-2.03, 23S2=-1.0527, 24S2=0.2939$
 - ✓ Exciting: $20S2=0.240559, -1.11941, -0.142105, 1.204465$
 - ✓ Cancel natural chromaticity: $20S2=-0.91060673033$
- Orbit corrections for slow extracted beam

Time structure of **long period** slow extraction at CSRm

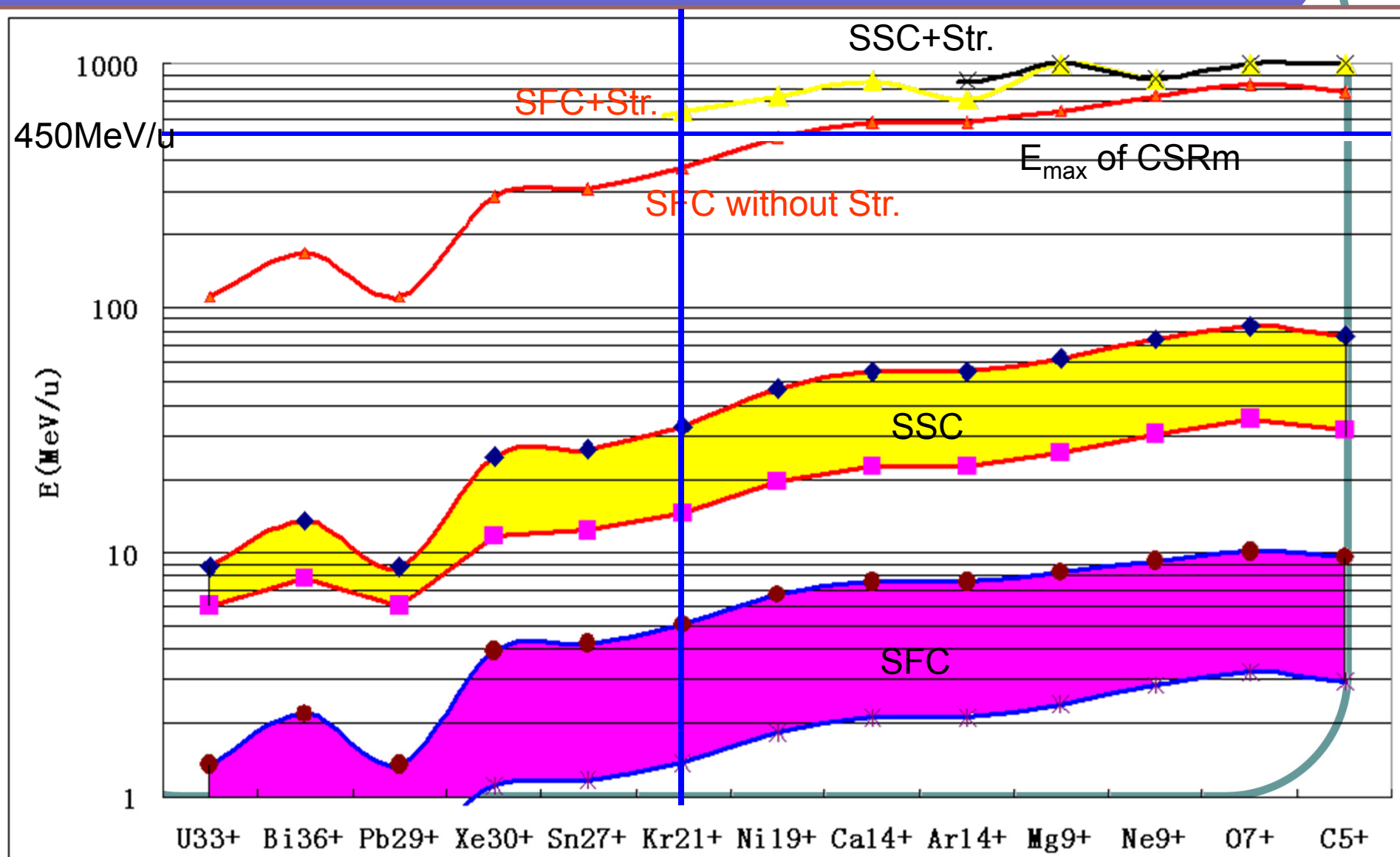


- 1/3 resonance slow extraction
- RF-Knockout exciting
- Feedback of extraction rates with fast servo Qs

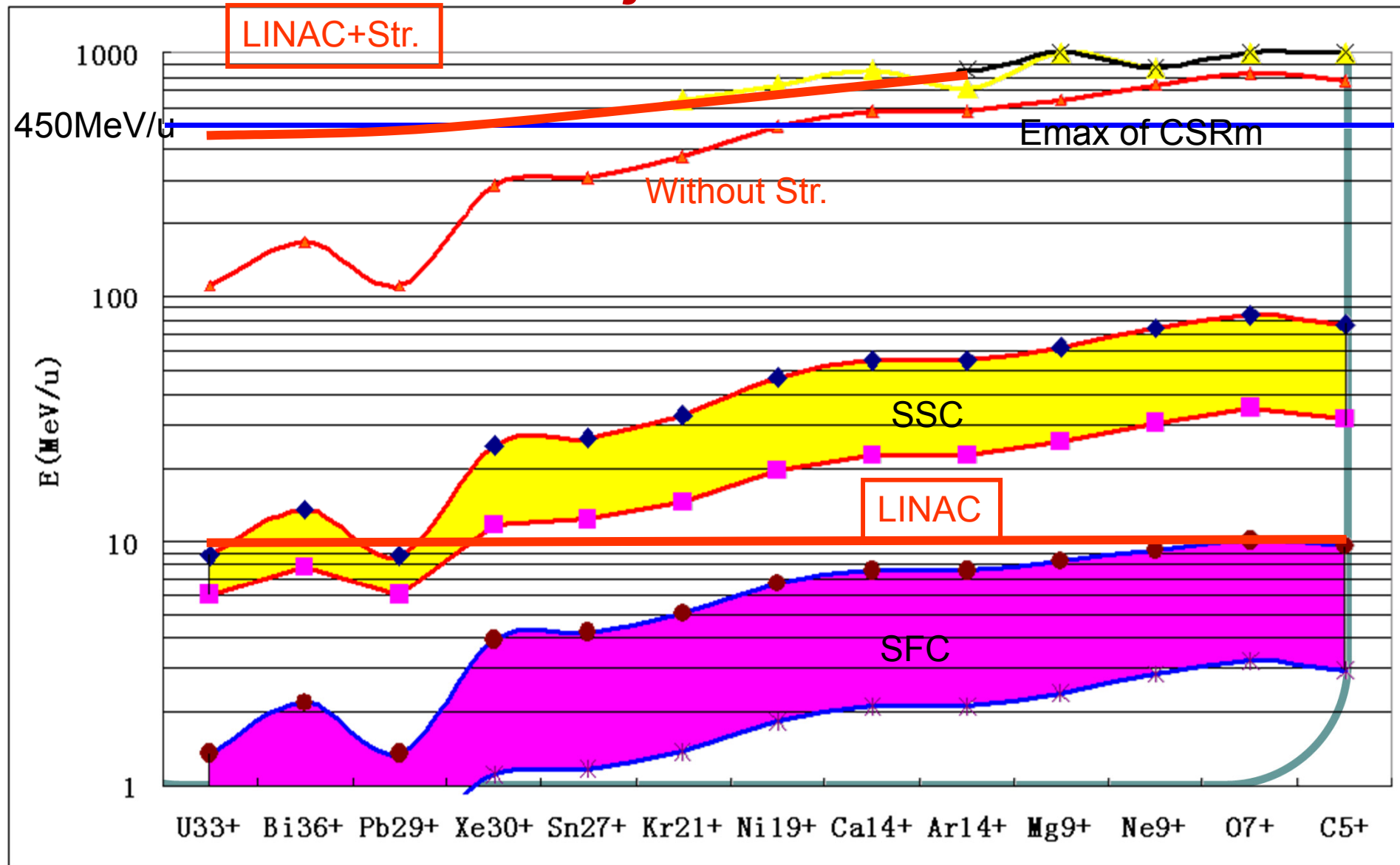
Energy range of HIRFL at design



Energy range of HIRFL if $I_{inj} > 1 \text{ e}\mu\text{A}$

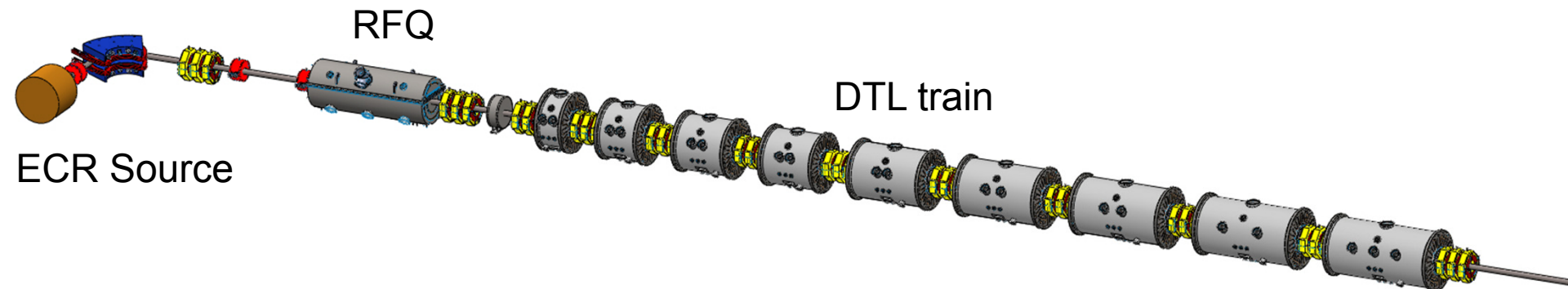


Energy range of HIRFL with new LINAC injector



The New LINAC Injector

- Accelerate ion beam C-U with $Q/A=1/3$ ~ $1/7$ up to 10MeV/u
- Pulsed operation $<10\text{Hz}$, $<5\text{ms}$ duration.
- Up to 150 e μA , 10~1000 times of cyclotron injector.



An aerial architectural rendering of a modern campus. The central feature is a large, white, multi-winged building with a flat roof. To its right is a large, white, oval-shaped sports field. Further right is a smaller, white, dome-shaped structure. The campus is surrounded by lush green lawns, numerous trees, and winding paths. In the background, there are residential-style buildings and a small pond. The overall scene is bright and sunny, with long shadows cast by the buildings and trees.

Thank you very much
for your attention!