Simulation of Two-Plane Painting Multiturn Injection into BRing with Space Charge Effect

Alexander Smirnov **(JINR, Dubna, Russia)**
Weiping Chai, Guo Feng Qu, Liping Yao (IMP, Lanzhou, China)

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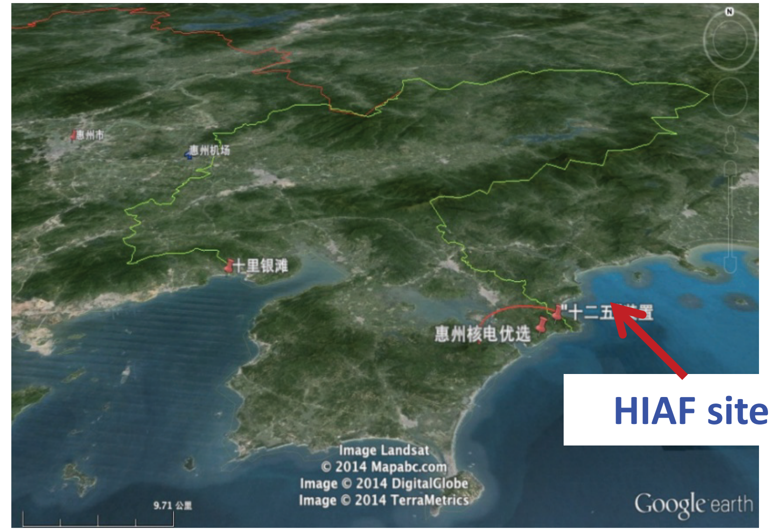
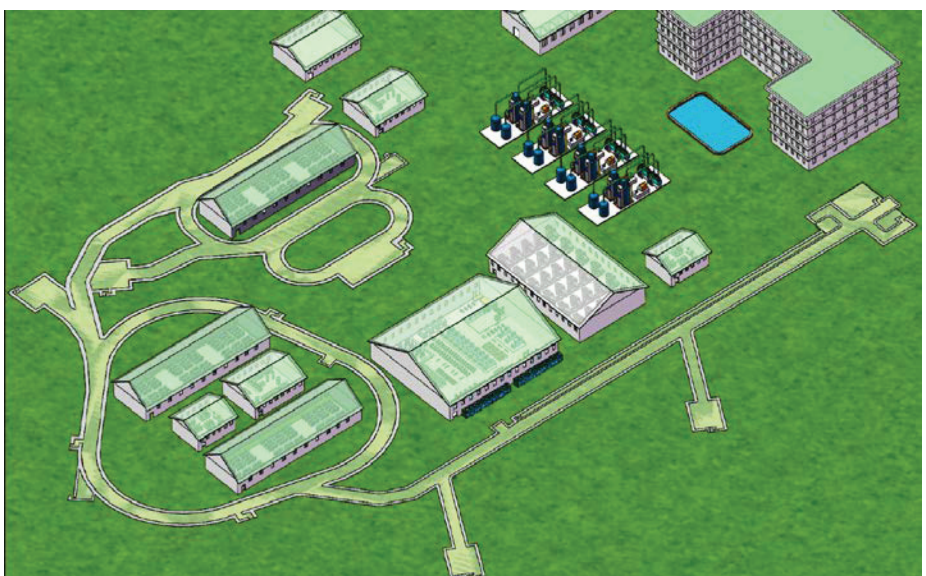
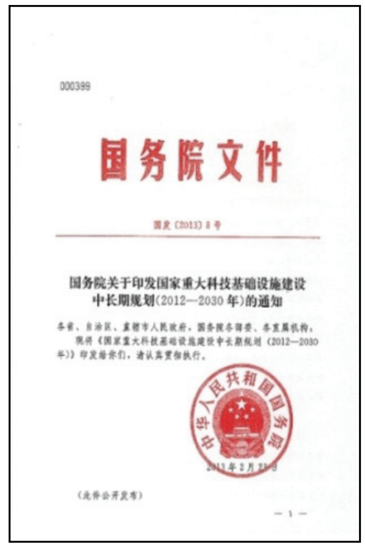
High-Intensity Heavy Ion Accelerator Facility





Background and science motivation

HIAF: One of 16 large-scale research facilities proposed in China in order to boost basic science. Next-generation high intensity facilities for advances in nuclear physics and related research fields.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国务院文件

国发〔2013〕8号

国务院关于印发国家重大科技基础设施建设中长期规划（2012—2030年）的通知

各省、自治区、直辖市人民政府，国务院各部委、各直属机构：
现将《国家重大科技基础设施建设中长期规划（2012—2030年）》印发给你们，请认真贯彻执行。

中华人民共和国国务院

（此件公开发布）

— 1 —

（一）海底科学观测网
（二）高能同步辐射光源验证装置
（三）加速器驱动嬗变研究装置
（四）综合极端条件实验装置
（五）强流重离子加速器
（六）高效低碳燃气轮机试验装置
（七）高海拔宇宙线观测站
（八）未来网络试验设施
（九）空间环境地面模拟装置
（十）转化医学研究设施
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Milestones of HIAF

- Proposed by IMP in 2009.
- Approved in principle by the central government in the end of the 2012.
- Design Report(v1.0) was published in July 2014
- The final approval was in the December of 2015
- Start of operation 2024

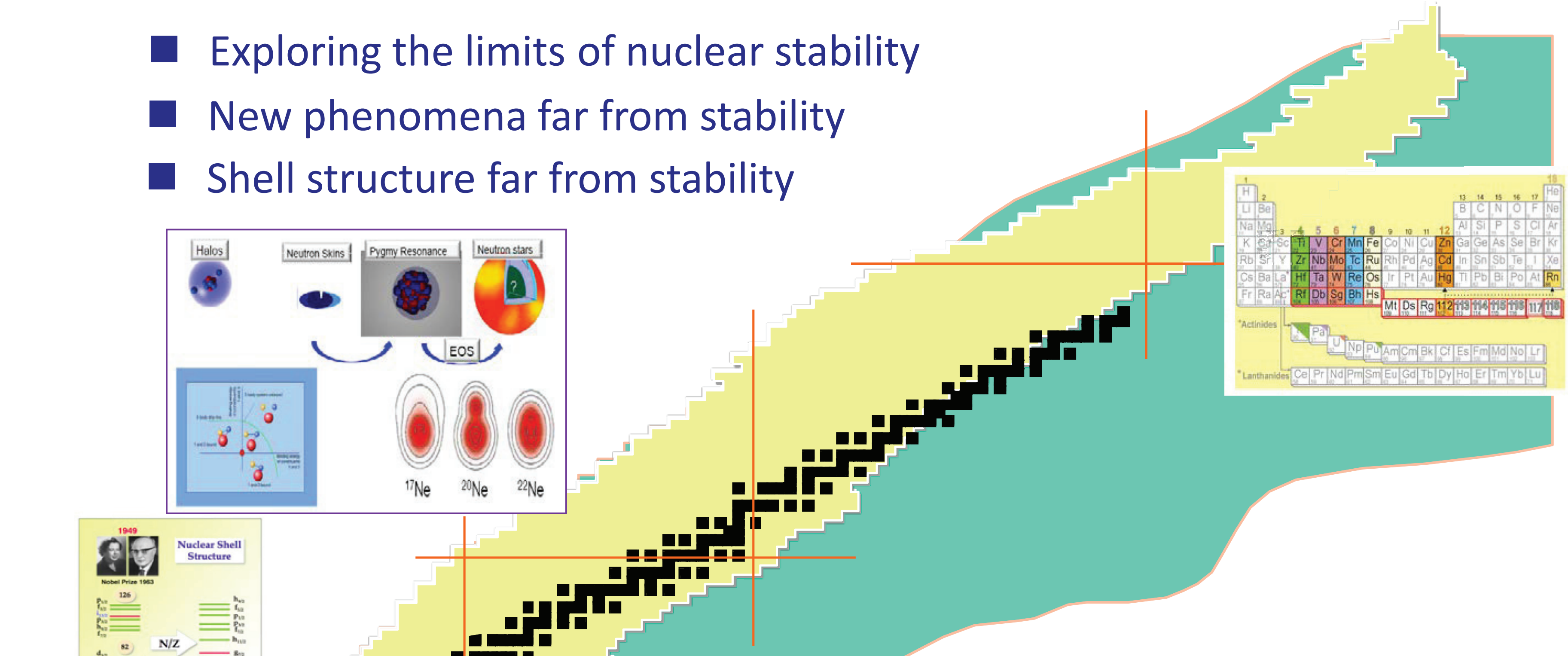
Science motivations

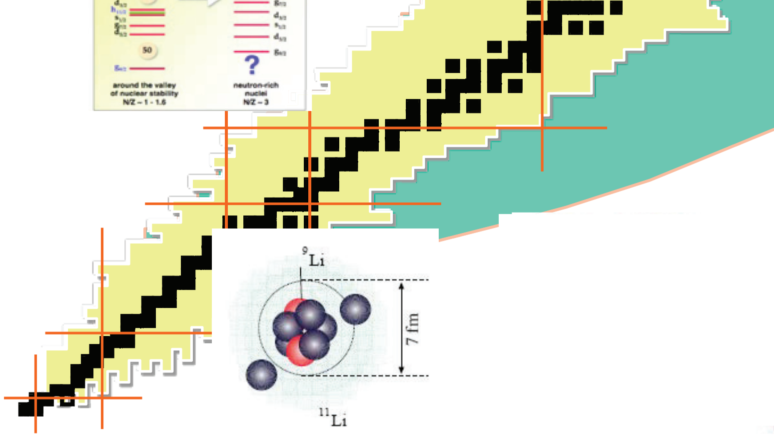
- Nuclear physics
- Nuclear astrophysics
- High energy and density physics
- Atomic physics
- Spontaneous electron–positron pair production

HIAF Science-1

Nuclear Physics

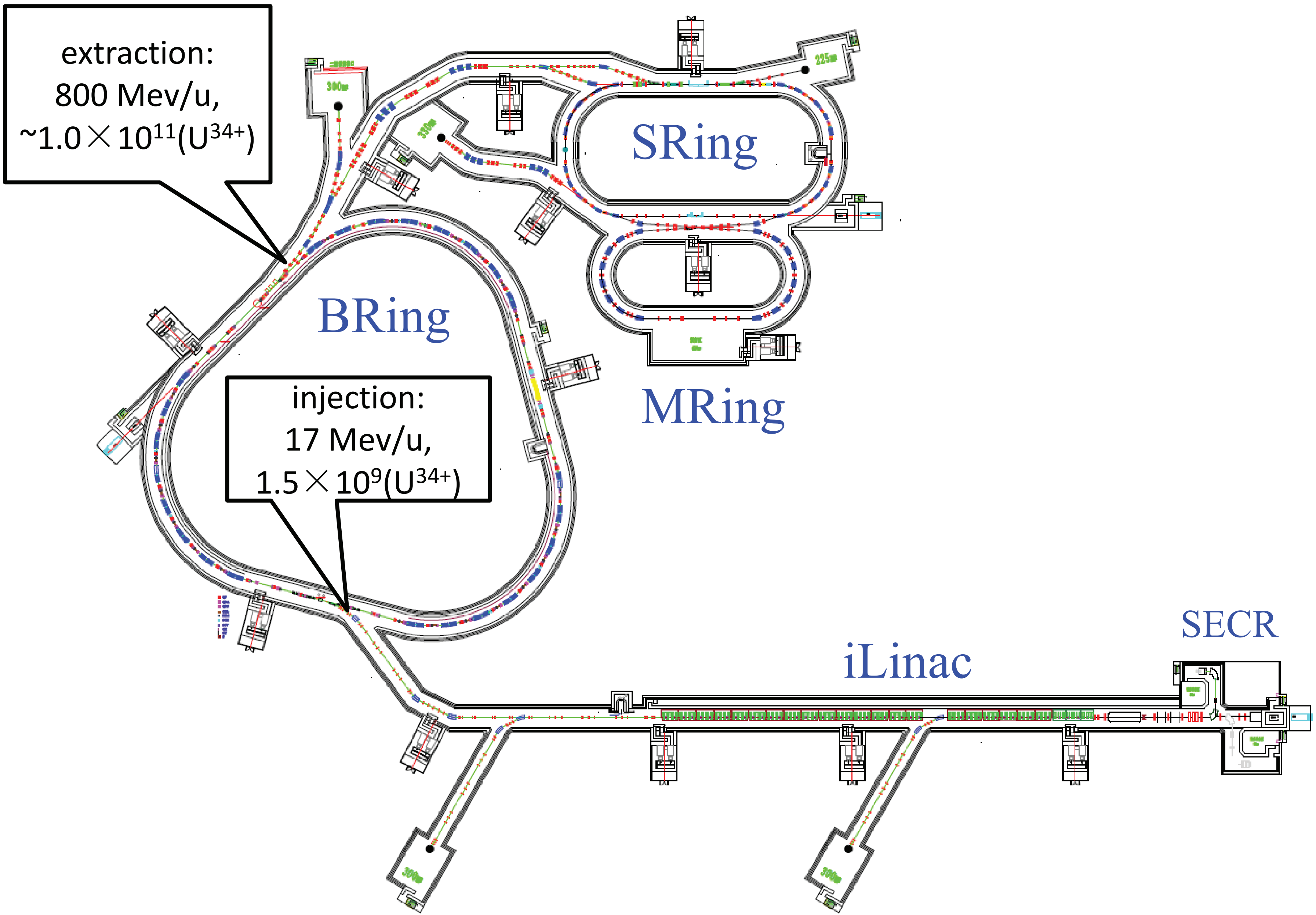
- Exploring the limits of nuclear stability
- New phenomena far from stability
- Shell structure far from stability



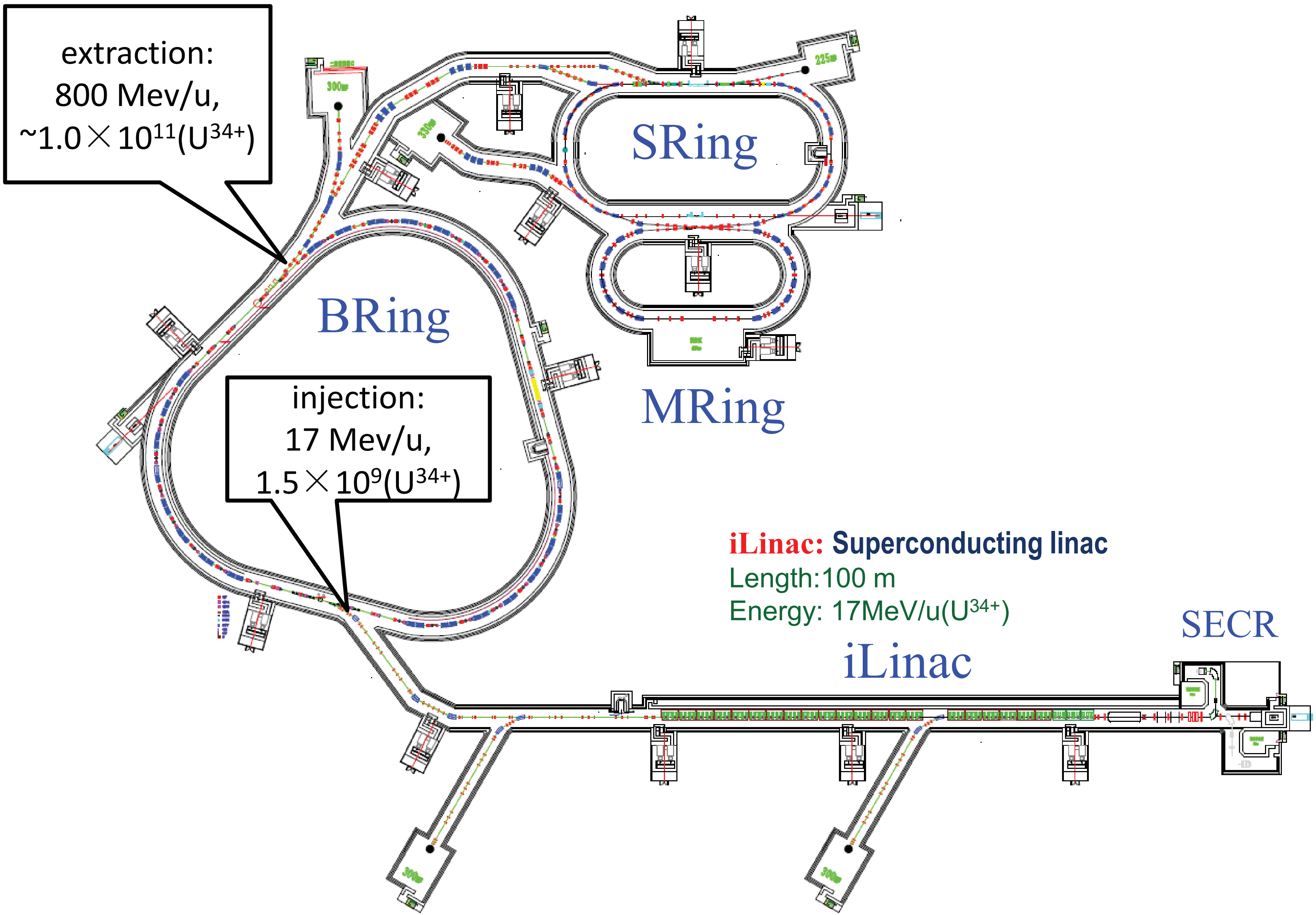


- Precise mass measurements for short-lived nuclei
- Synthesis of new isotopes near the proton-drip line
- Structure and reaction mechanism with exotic beams
- Properties of asym. nuclear matter at high density
- Decay and chemical properties of super-heavy nuclei
- Evolution of collective motion in complex nuclei

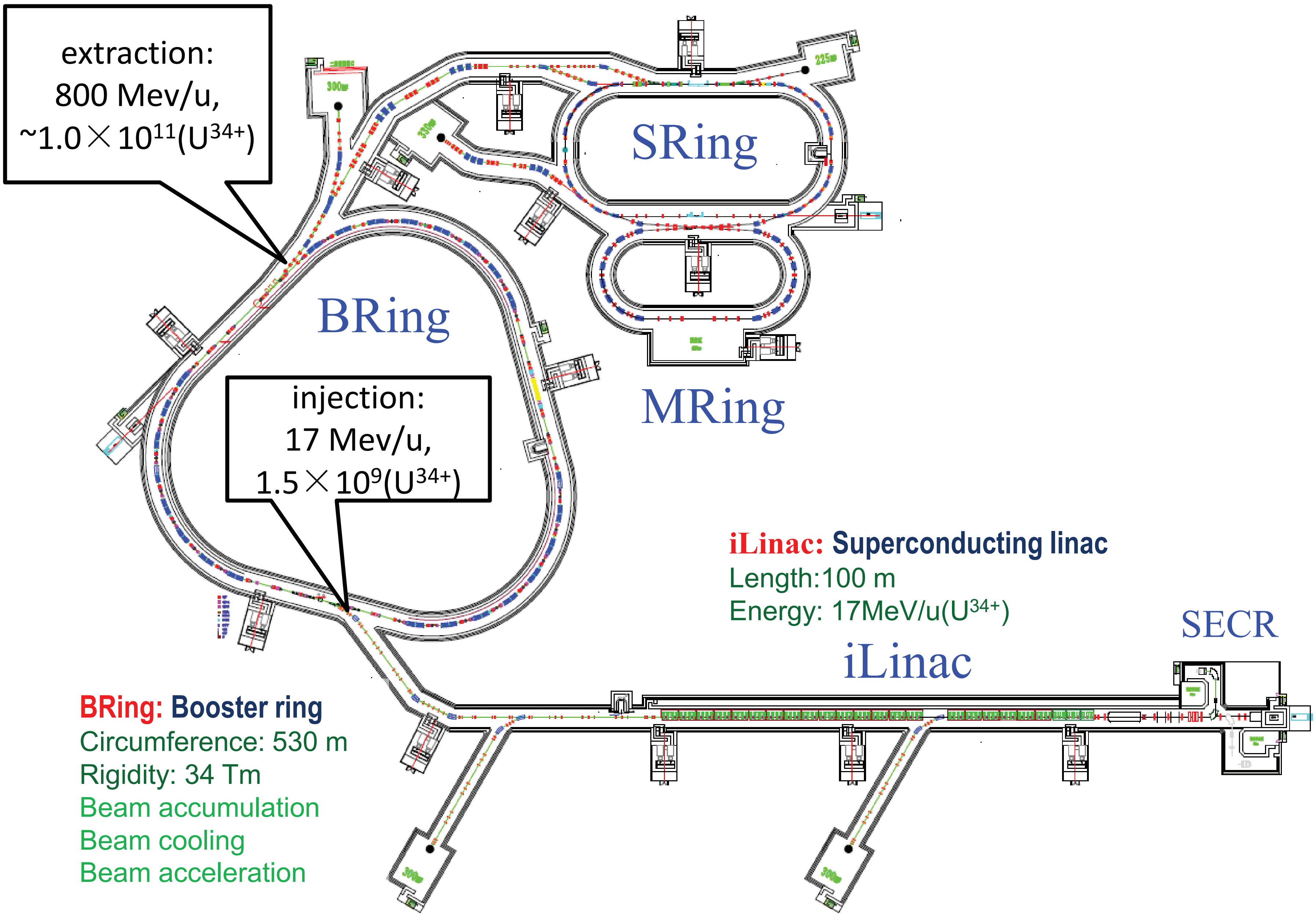
Main components



Main components



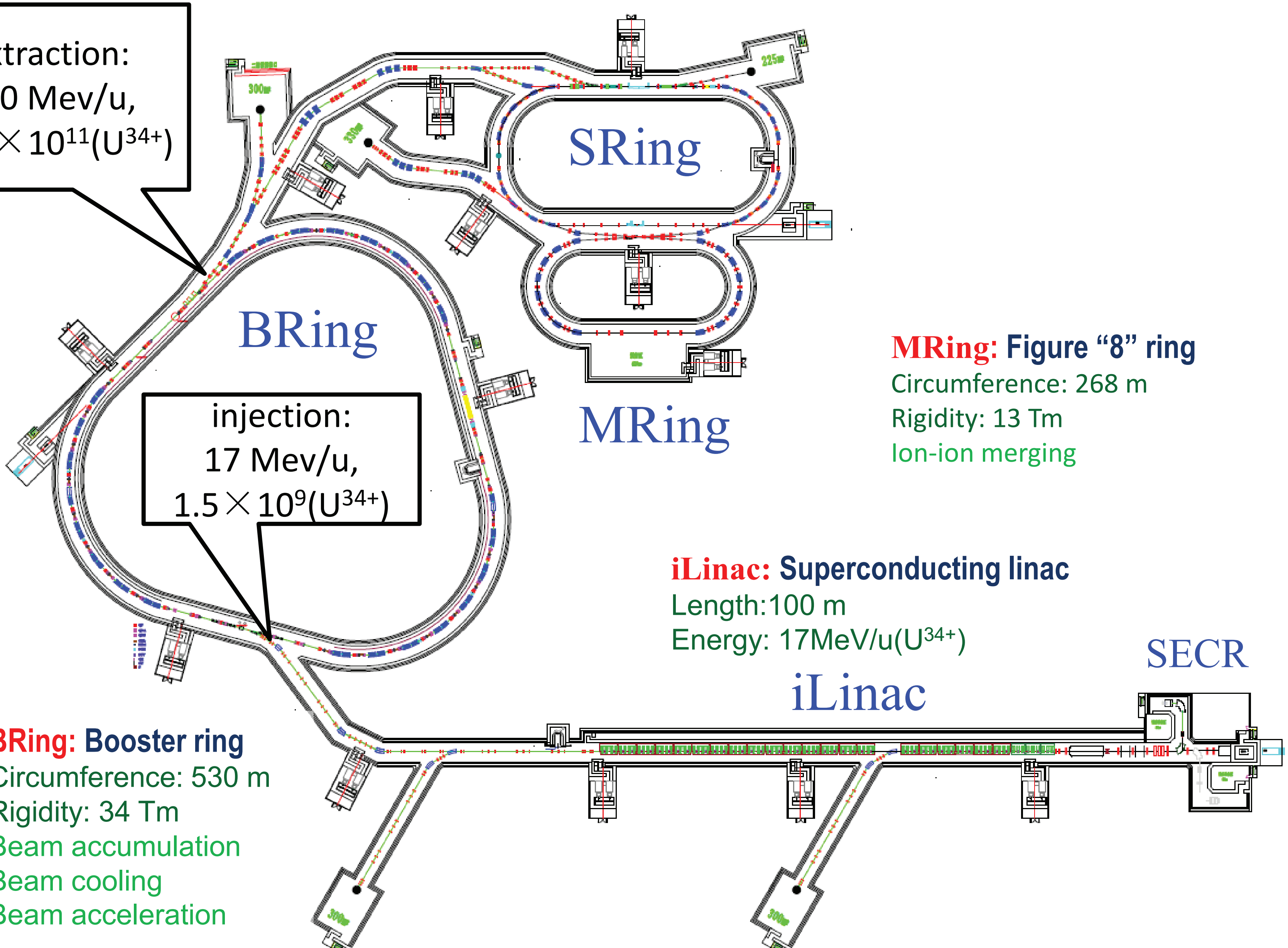
Main components



iLinac: Superconducting linac
Length: 100 m
Energy: 17MeV/u(U^{34+})

BRing: Booster ring
Circumference: 530 m
Rigidity: 34 Tm
Beam accumulation
Beam cooling
Beam acceleration

Main components

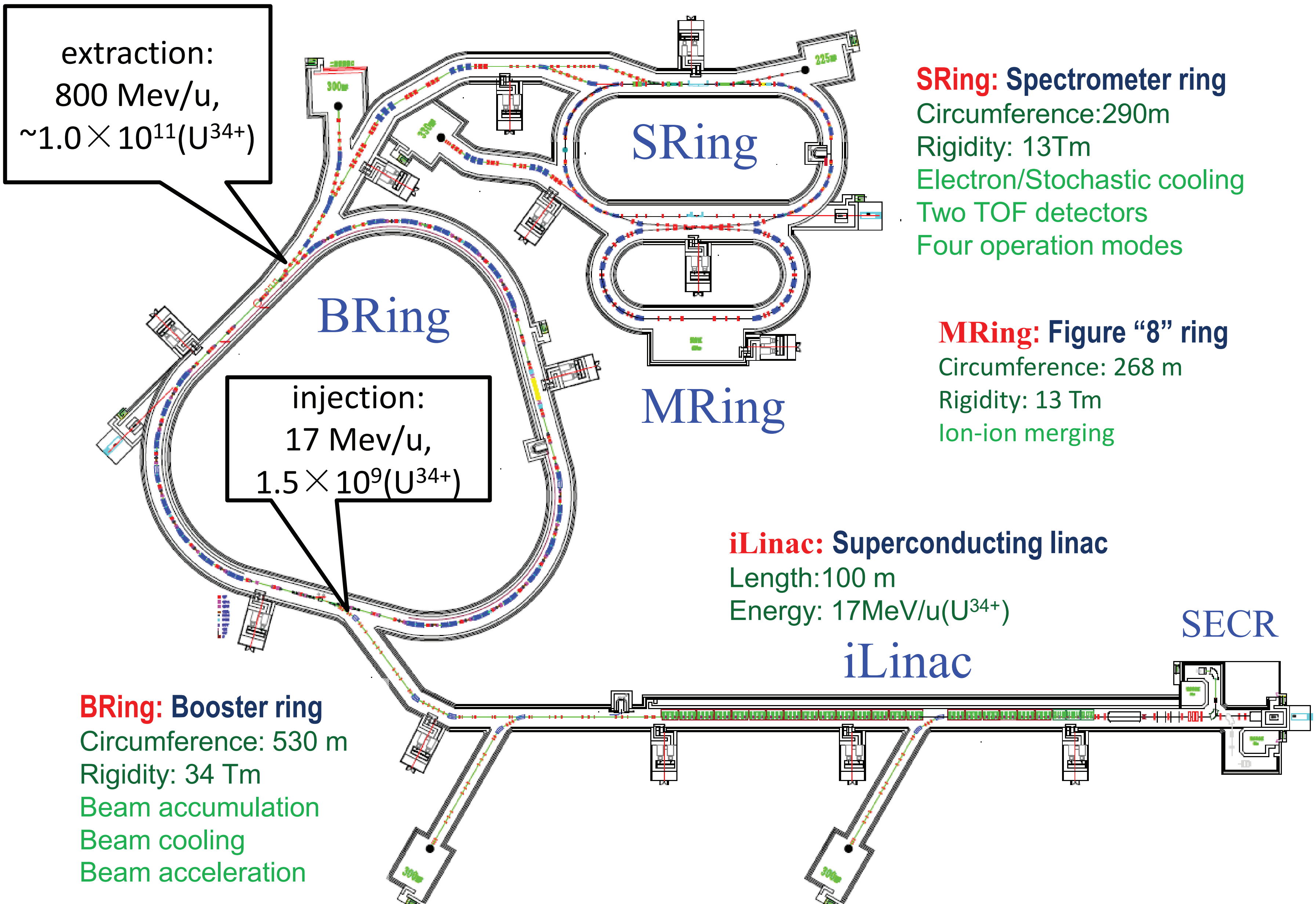


MRing: Figure "8" ring
Circumference: 268 m
Rigidity: 13 Tm
Ion-ion merging

iLinac: Superconducting linac
Length:100 m
Energy: 17MeV/u(U^{34+})

BRing: Booster ring
Circumference: 530 m
Rigidity: 34 Tm
Beam accumulation
Beam cooling
Beam acceleration

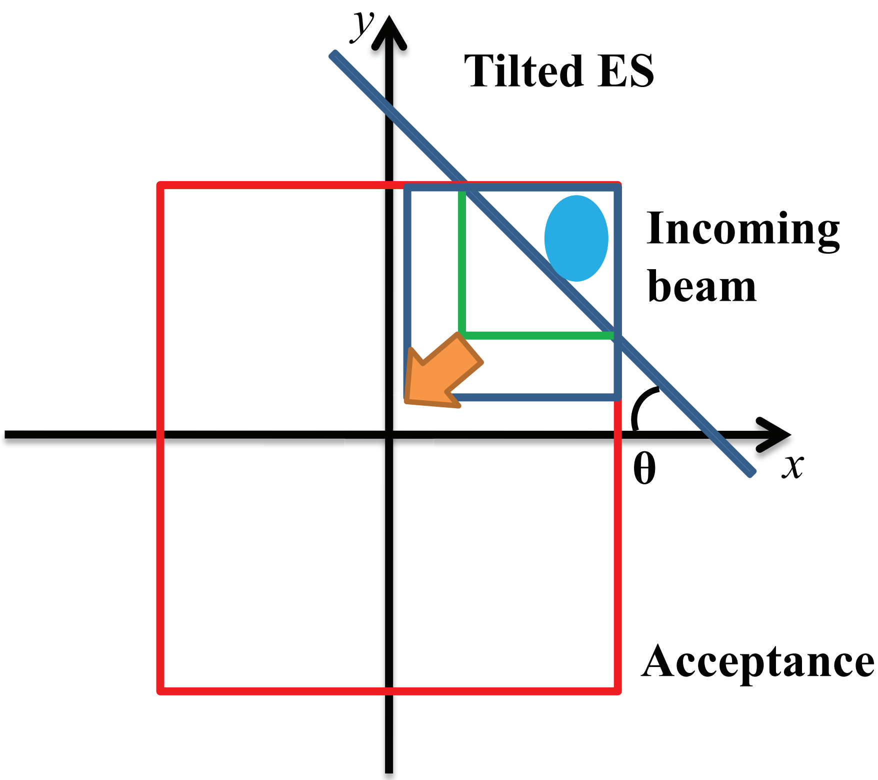
Main components

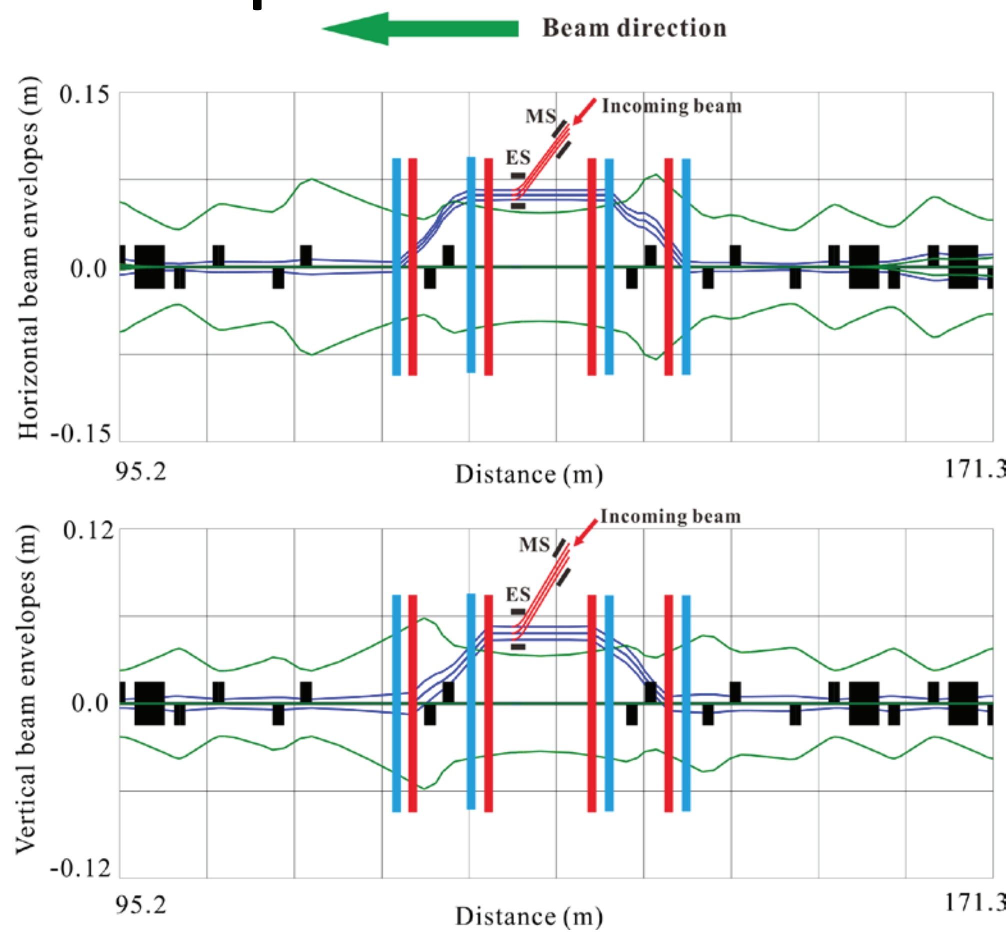


General description – Basic beam parameters

	Ions	Energy	Intensity
SECR	$^{238}U^{34+}$	14 keV/u	0.05 pmA
iLinac	$^{238}U^{34+}$	17 MeV/u	0.028 pmA
BRing	$^{238}U^{34+}$	0.8 GeV/u	$\sim 1.4 \times 10^{11}$ ppp
SRing	RIBs: neutron-rich, proton-rich	0.84 GeV/u(A/q=3)	$\sim 10^{9\text{-}10}$ ppp
	Fully stripped heavy ions H-like, He-like heavy ions	0.8 GeV/u($^{238}U^{92+}$)	$\sim 10^{11\text{-}12}$ ppp
MRing	$^{238}U^{92+}$	0.8 GeV/u	$\sim 1.0 \times 10^{11}$ ppp

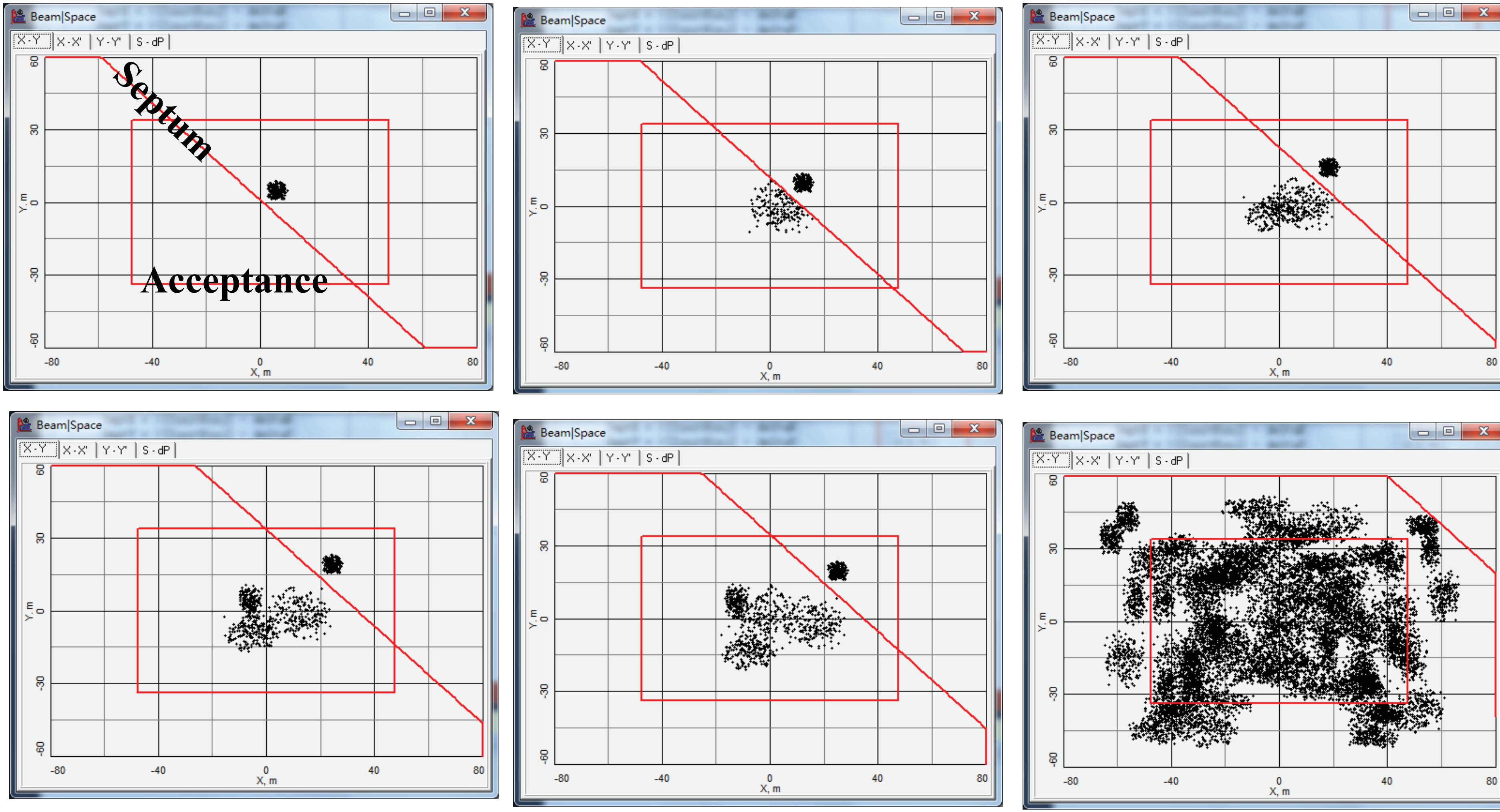
Two-plane painting during multi turn injection procedure





Large space charge leads to the shift and spread of the tune that can bring additional losses on the septum and acceptance

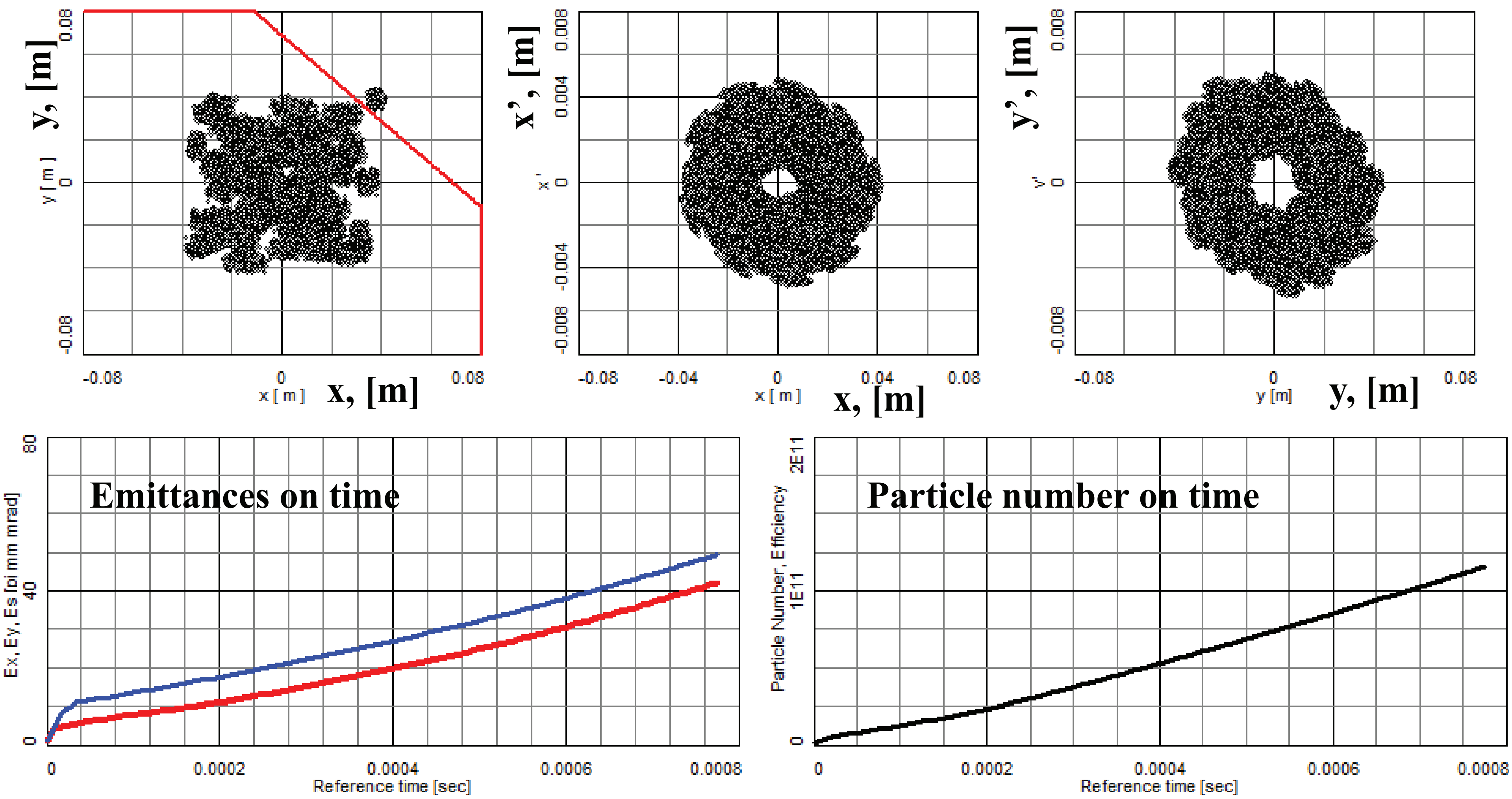
Transverse plane during injection



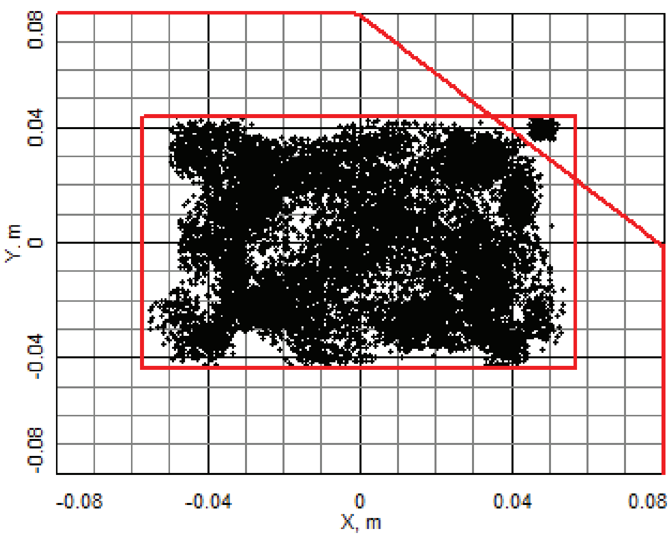
http://betacool.jinr.ru

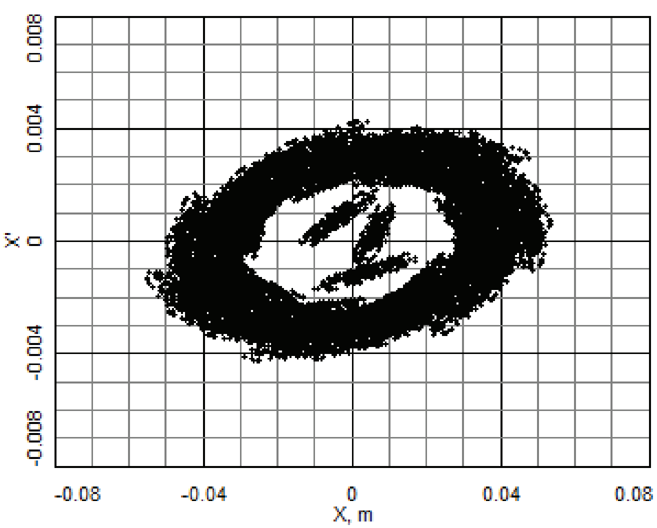
1.5e9 x 90 injections = 1.15e11 (85%)

(no space charge effect)

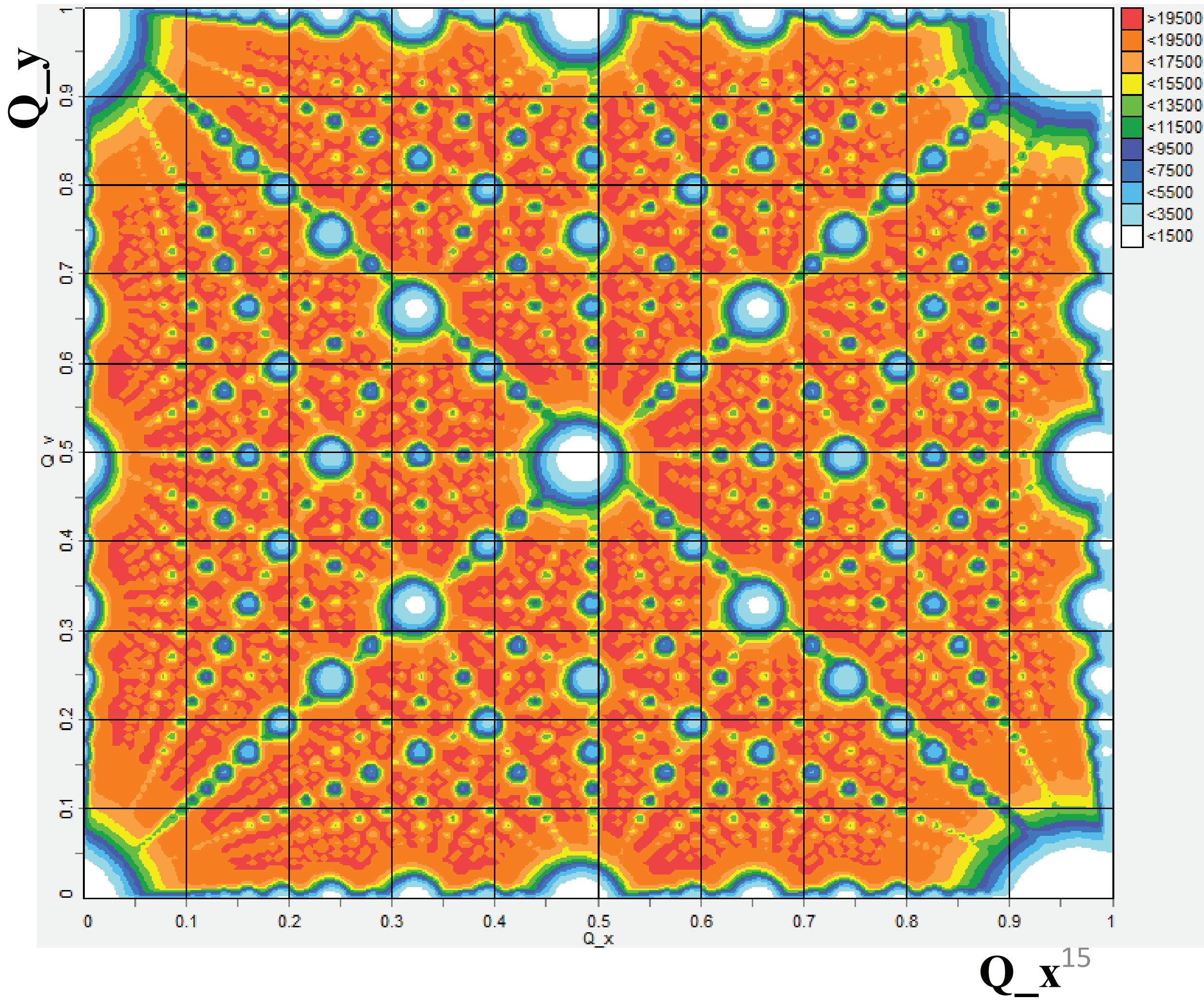


Multi turn injection into BRing with particle losses on septum and acceptance

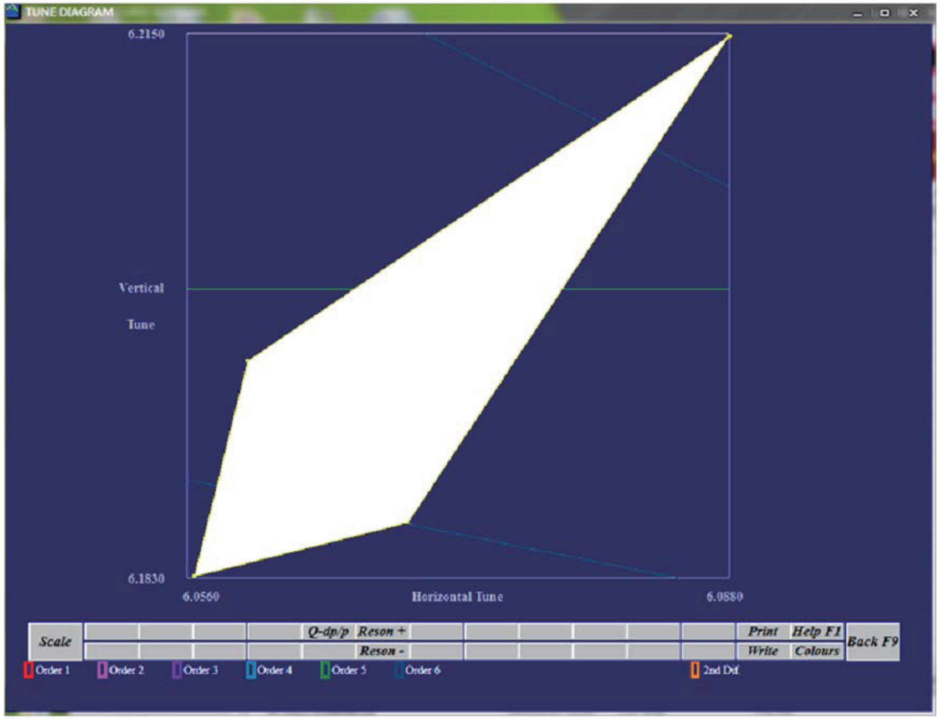




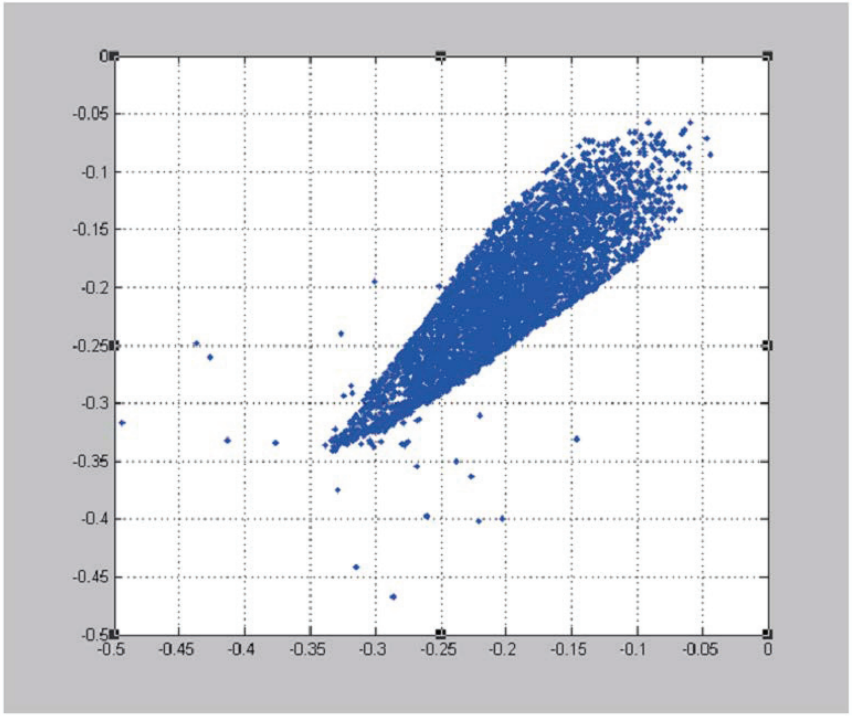
Injection efficiency on tune diagram



Tune shift diagram



Tune shift diagram is calculated with Winagile program



Tune shift diagram is calculated with averaging over betatron oscillation for 2D space (coasting beam)

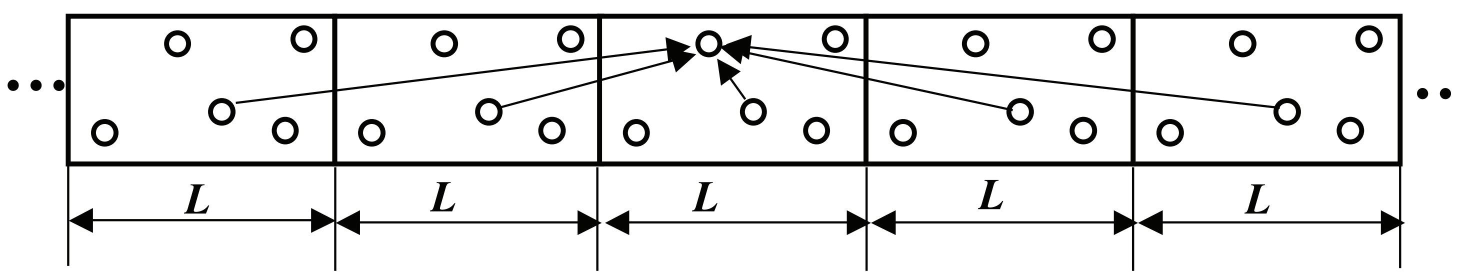
Tune shift diagram is very important for long beam dynamics when particles cross the structure resonances and can be lost.

Method of Molecular Dynamics

$$H = -\frac{xp_z}{\rho} + \frac{p_z^2}{2\gamma_0^2} + \frac{{p_x}^2 + {p_y}^2}{2} + \frac{1}{2}\left(\frac{1}{\rho^2} + K\right)x^2 - \frac{K}{2}y^2 +$$

$$\frac{\lambda}{6}\left(x^3 - 3xy^2\right) + \frac{r_{ion}}{\gamma_0^2\beta_0^2}\sum_i \frac{1}{\sqrt{(x-x_i)^2 + (y-y_i)^2 + \gamma_0^2(z-z_i)^2}},$$

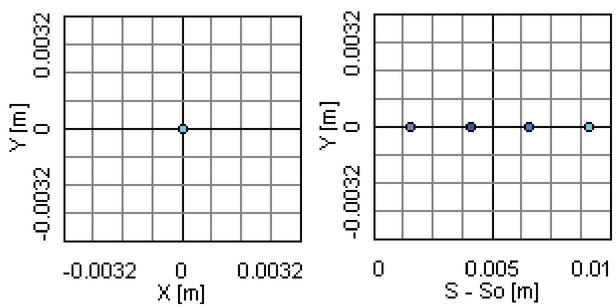
$$U_{sc}(s,r) = \frac{1}{4\pi\varepsilon_0}\left(\frac{q}{a} + \frac{2q}{L}\int_0^\infty \frac{J_0(kr/L)\cosh(ks/L) - 1}{\exp(k) - 1}dk\right)$$



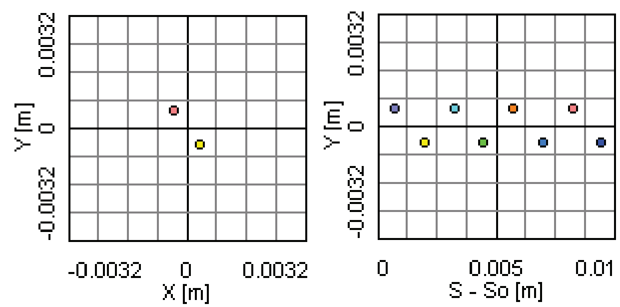
Crystalline beams for infinity channel

$$\lambda_{ion} \equiv \frac{N}{C}\left(\frac{3\, r_{ion}}{2k\gamma_0^5\beta_0^2}\right)^{1/3} = \left(\frac{3N^3 r_{ion}}{8\pi^2 Q^2 C\gamma_0^5\beta_0^2}\right)^{1/3}$$

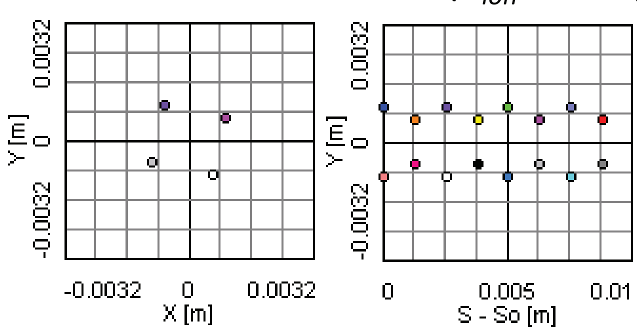
String ($\lambda_{ion} < 0.709$)



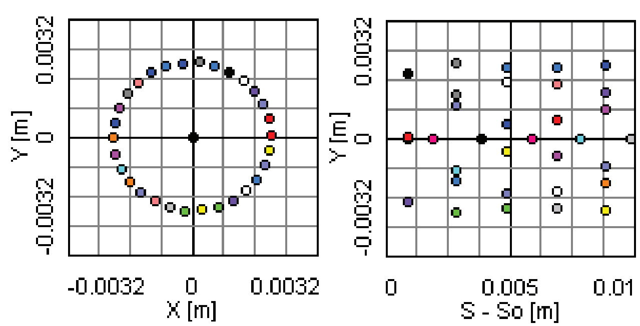
Zigzag ($\lambda_{ion} < 0.964$)



Helix or Tetrahedron ($\lambda_{ion} < 3.10$)



Shell + String ($\lambda_{ion} < 5.7$)



Betatron tune shift

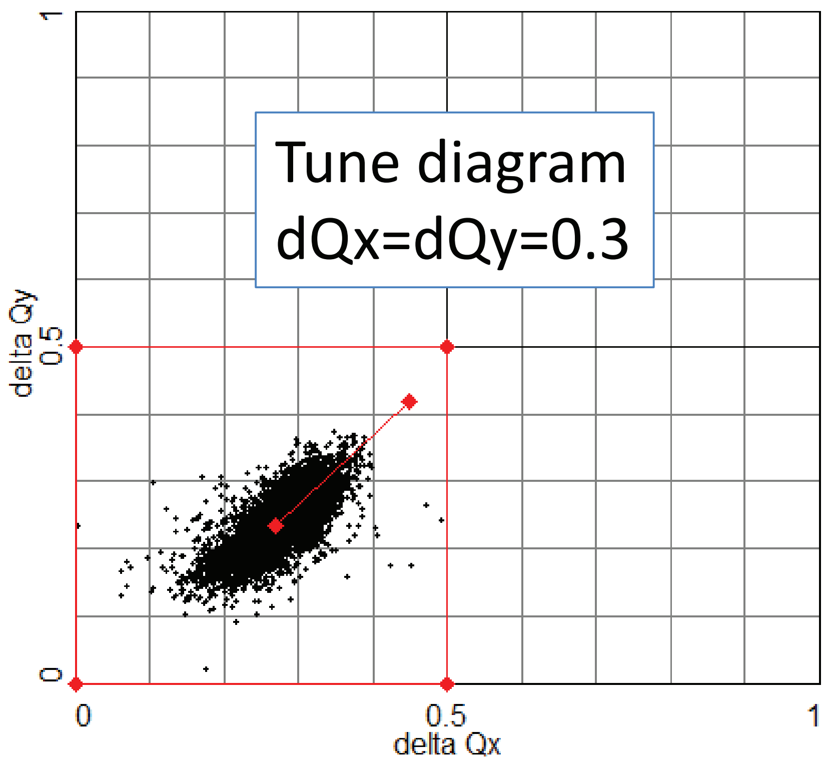
Particle coordinates are changed after (i+1) turn with phase advance μ of transformation matrix as [MAD program]:

$$\begin{bmatrix} x \\ x' \end{bmatrix}_{i+1} = \begin{bmatrix} \cos\mu + \alpha\sin\mu & \beta\sin\mu \\ -\gamma\sin\mu & \cos\mu - \alpha\sin\mu \end{bmatrix} \times \begin{bmatrix} x \\ x' \end{bmatrix}_{i}$$

Betatron tune shift for each particle can be calculated as:

$$\Delta Q = \frac{1}{2\pi}\arctan\frac{\sin\mu}{\cos\mu}$$

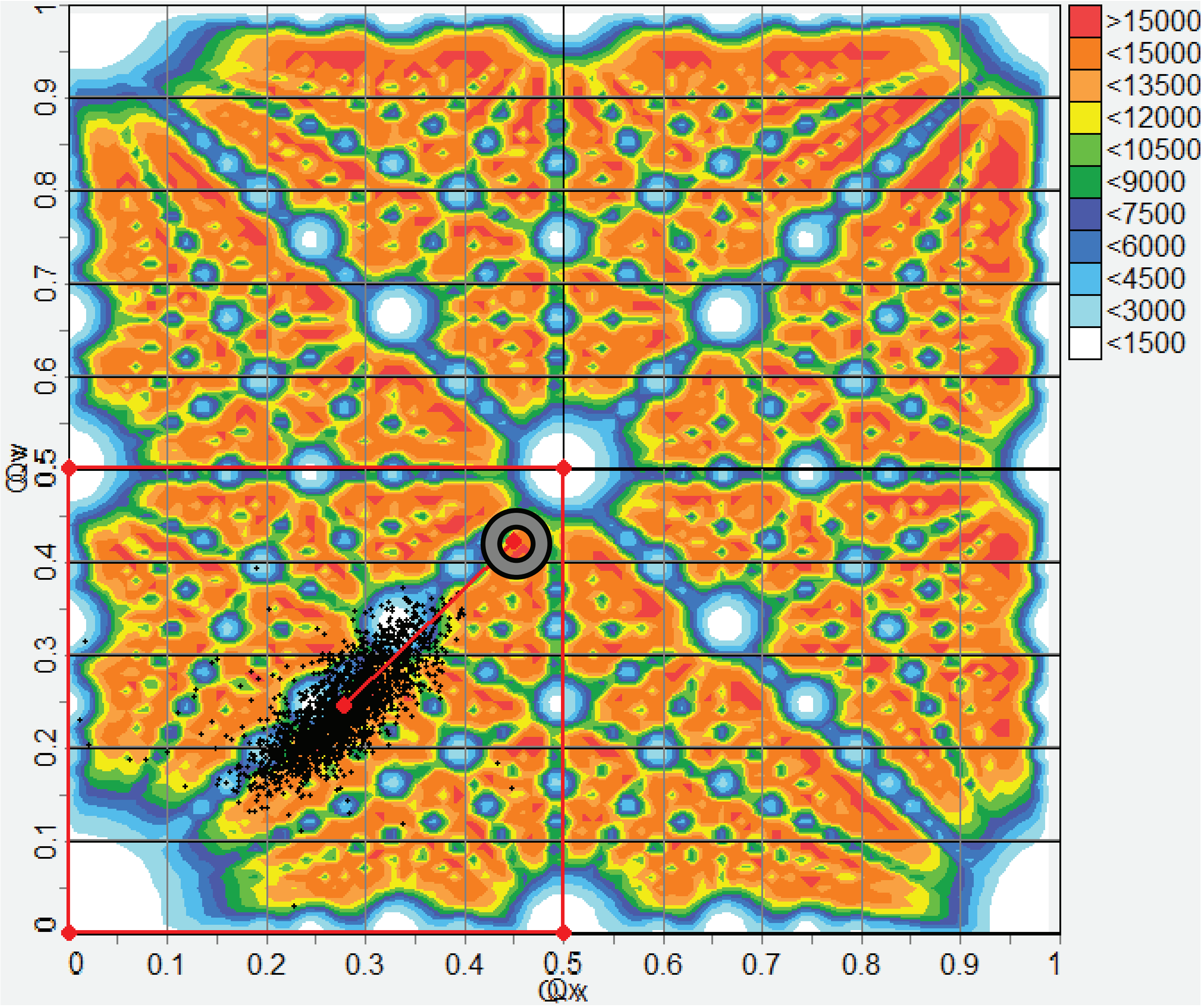
ΔQ = [-0.25…+0.25]



Injection efficiency and tune diagram

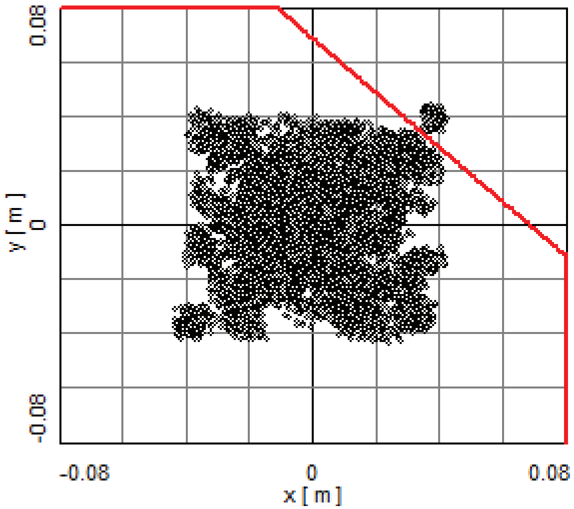
Working point:
Qx = 0.45
Qy = 0.42

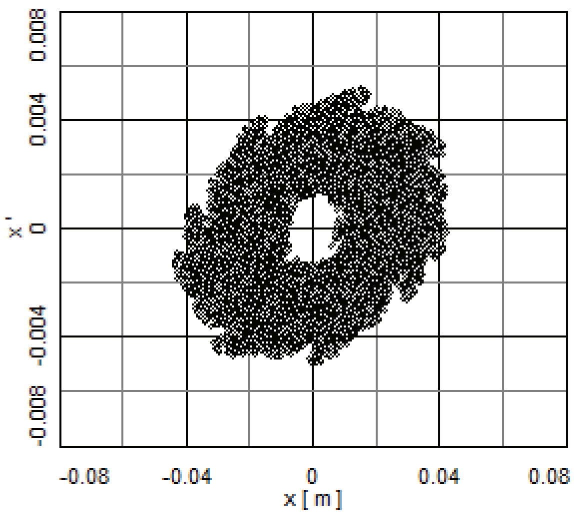
N=1.5e10
E~1 pi mm mrad
dQx=dQy=0.28

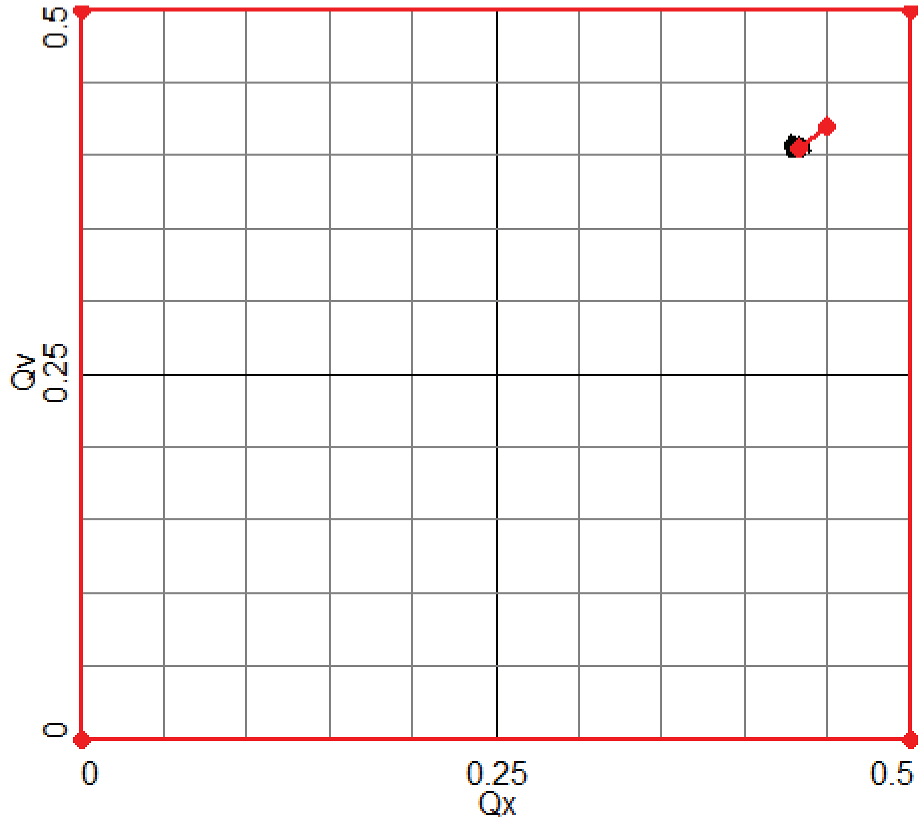


1.5e9 x 90 injections = 9.6e10 (71%)

(space charge effect on)

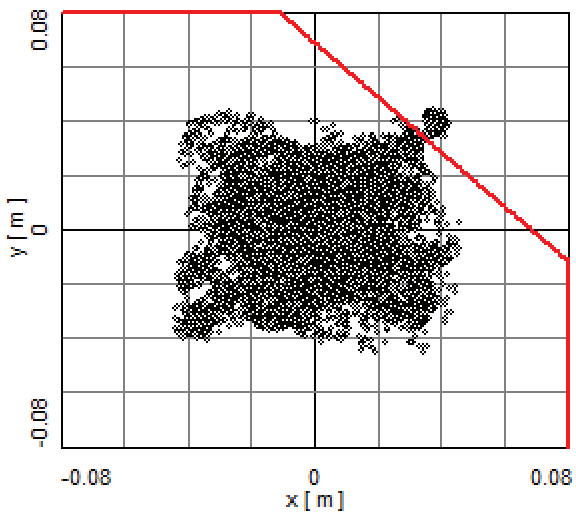


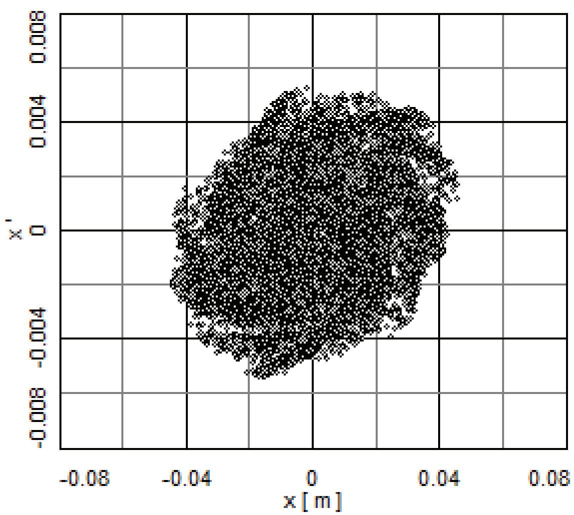


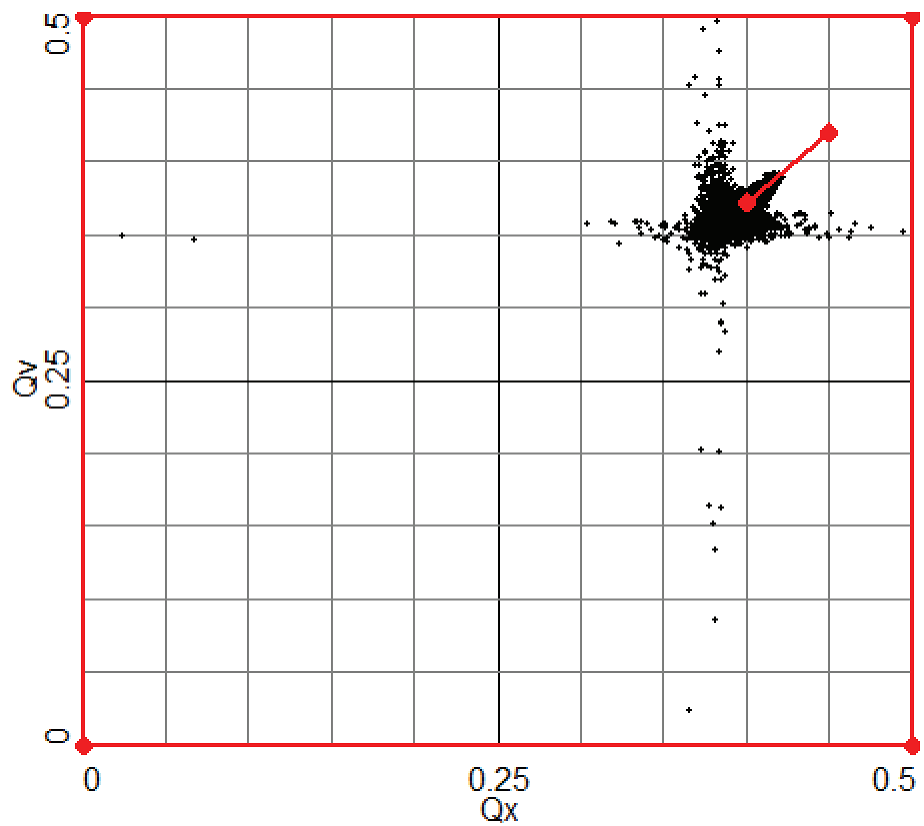


dQx ~ 0.02 for 1st injection and
dQx ~ 0.08 after 90th injections !

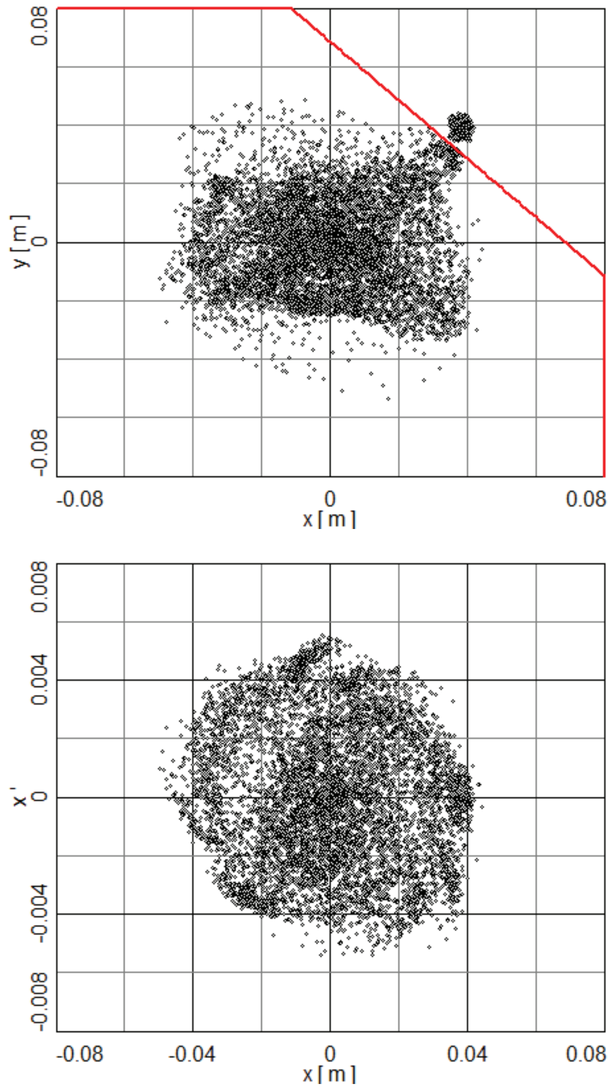
5e9 x 90 injections = 2.5e11 (55%)

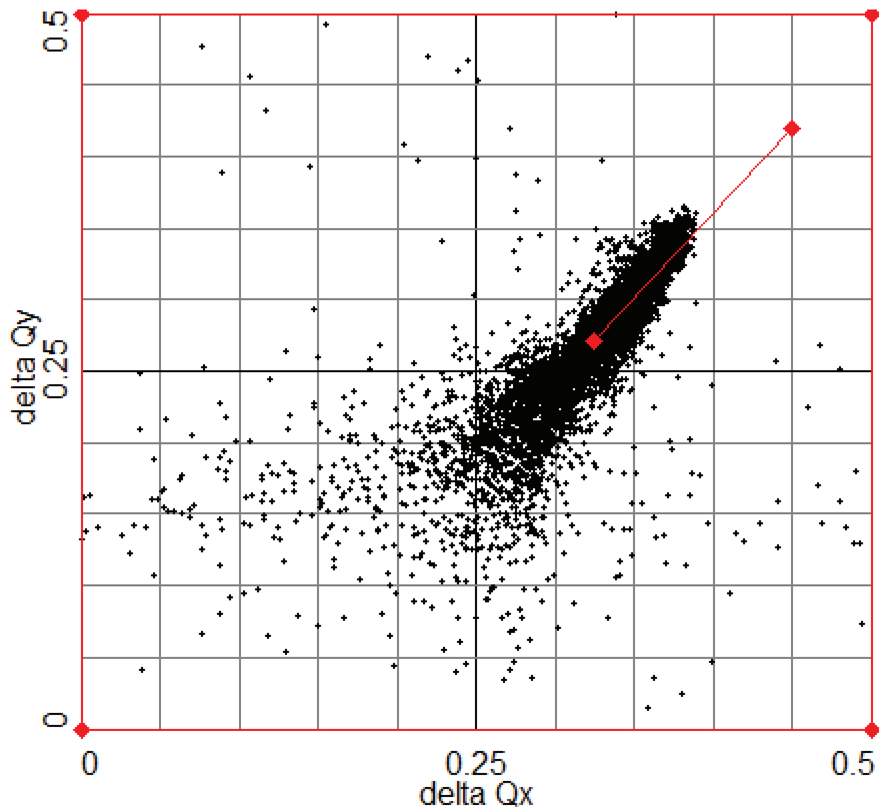






1.5e10 x 90 injections = 5.61e11 (42%)

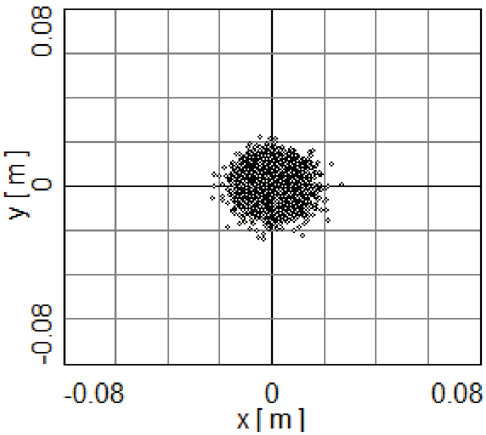


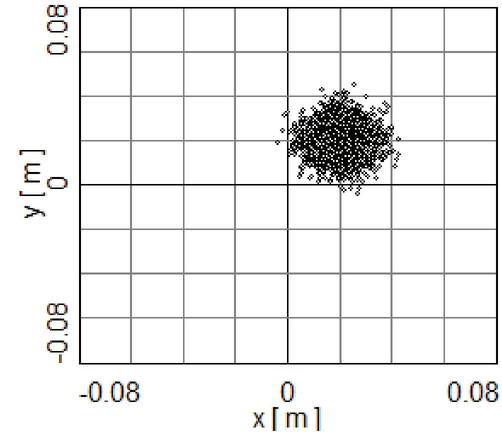


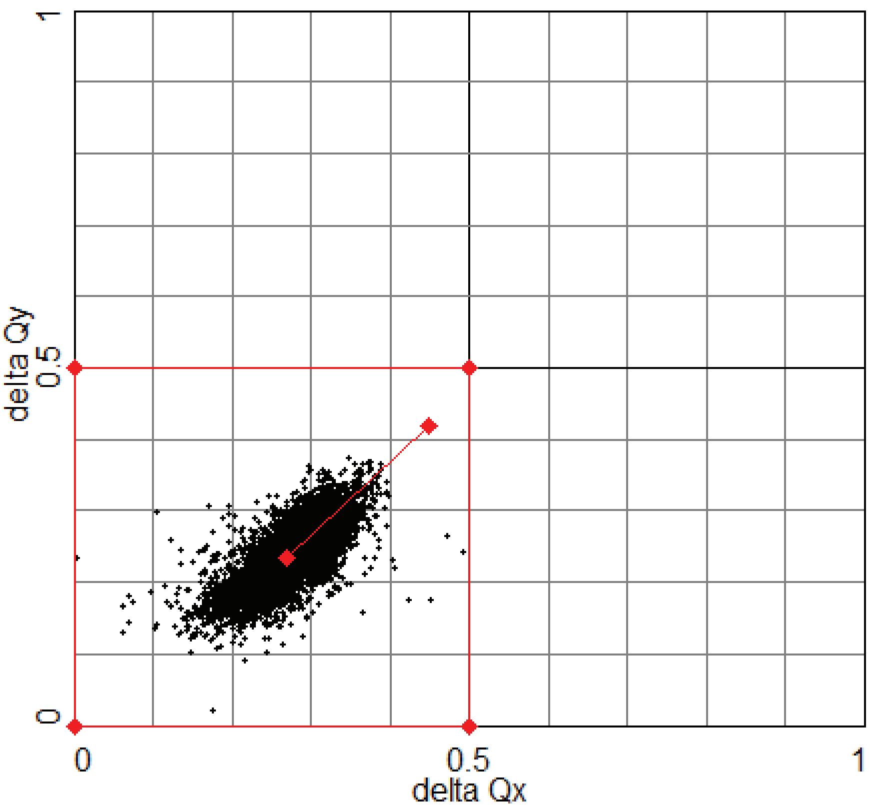
Transverse shift of ion beam

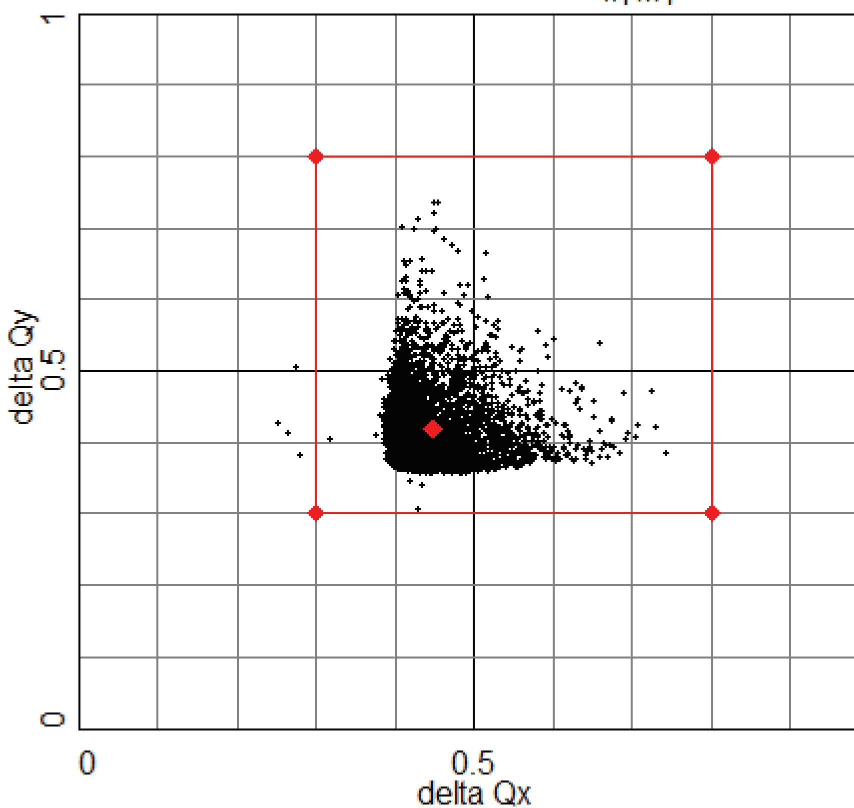
Ex = Ex = 5 pi mm mrad

dQx = dQy = 0.316





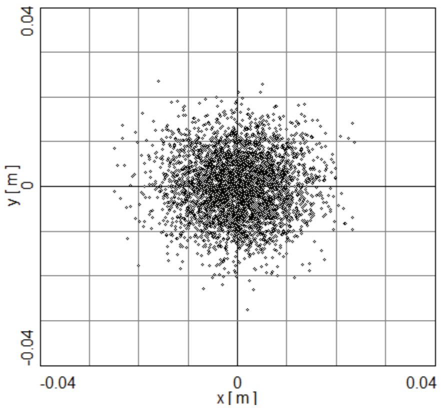


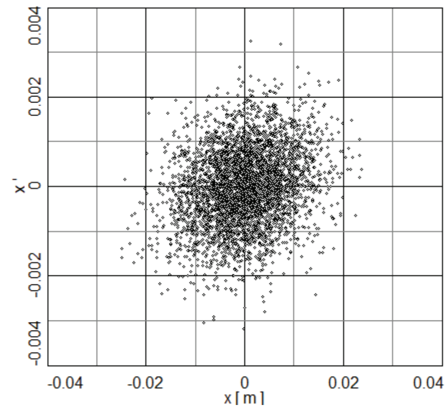


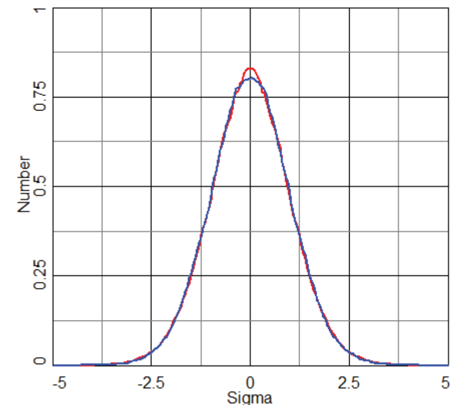
Electron cooling with angle misalignment

angle x/y = 0.001/0.001, Ex = Ey = 5 pi mm mrad

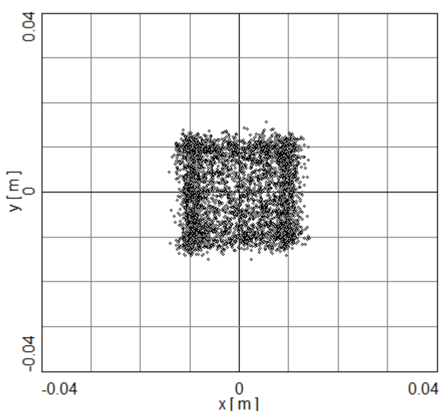
Ion beam distribution with normal electron beam position

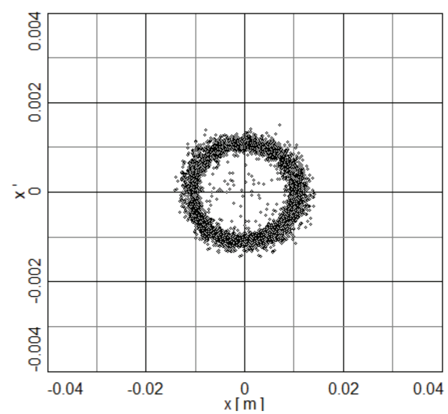


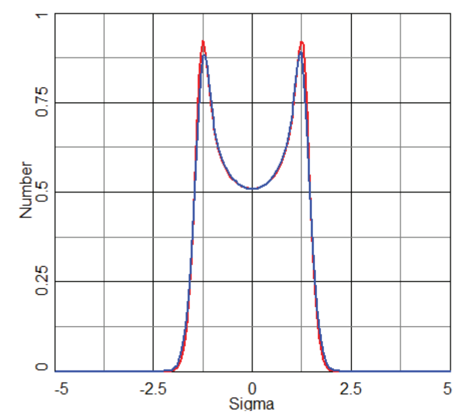




Ion beam distribution with transverse angle of electron beam

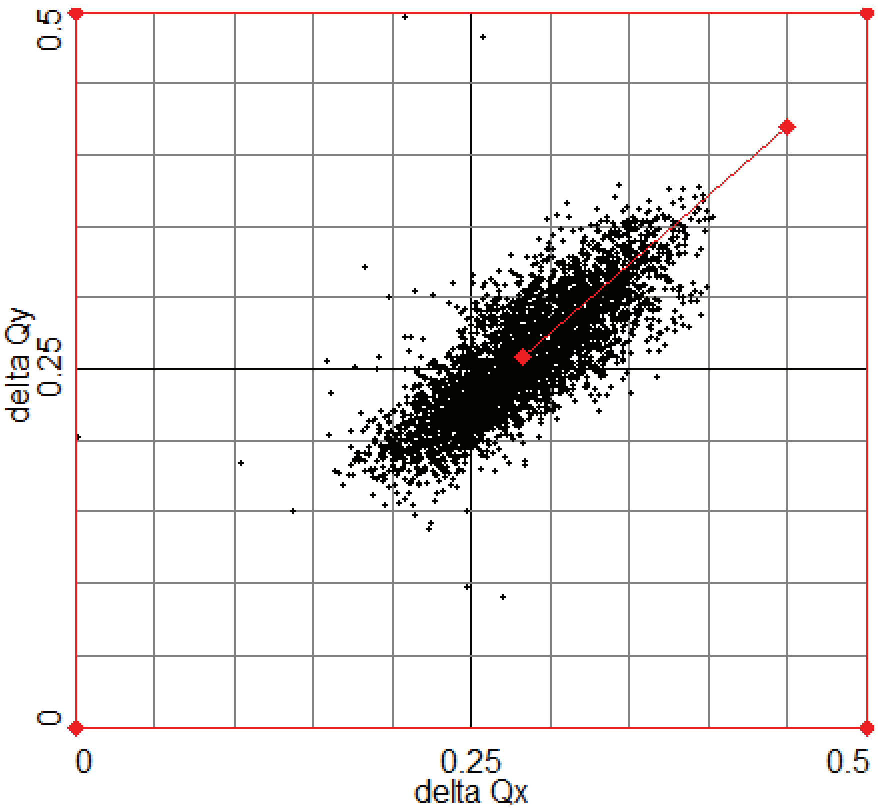




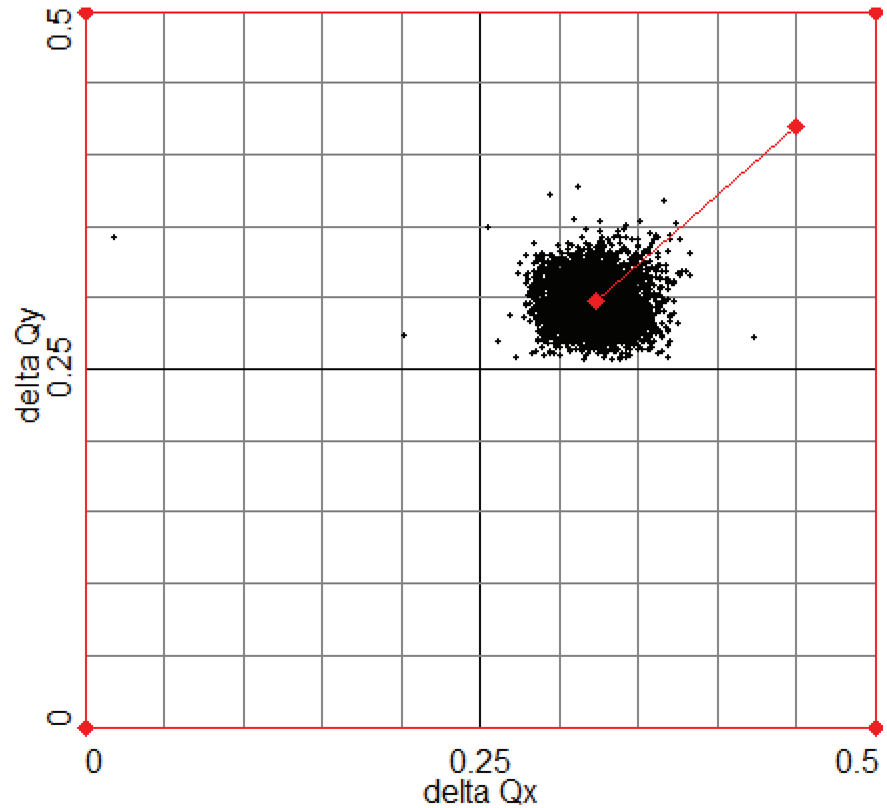


transverse plan | horizontal phase space | transverse profile

Tune diagram (dQx=dQy=0.262) after one turn

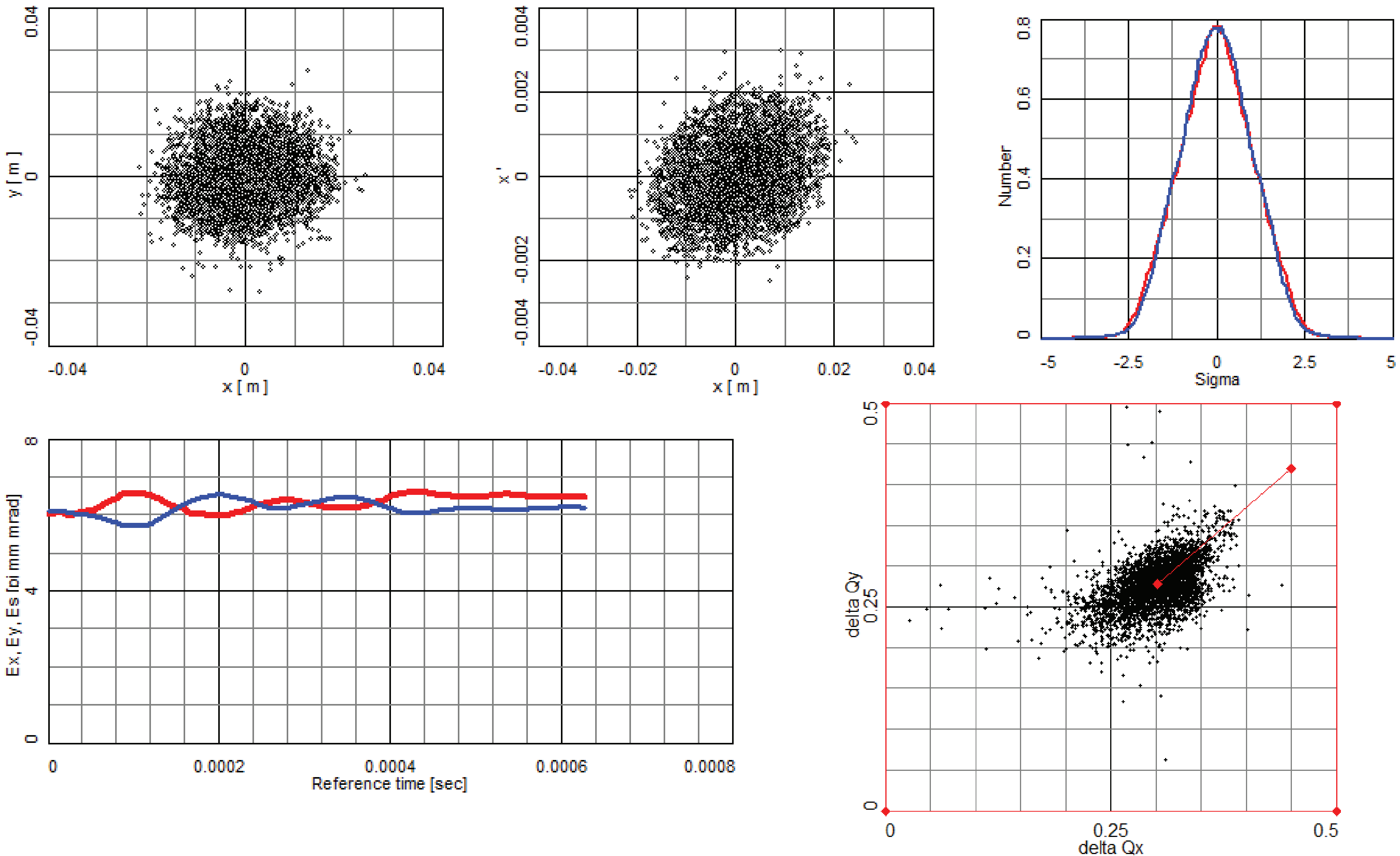


normal electron beam



angle misalignment

Particle distribution after 70 turns



Conclusions

- Space charge has not large effect on injection procedure in BRing (1.5e11, 17 MeV/u, U34+)

- Electron cooling during injection procedure in Bring leads to very large influence of space charge effect

- Influence of space effect is significantly decreasing for non-uniform ion beam distribution

- But space charge leads to fast mixing (relax) of particles distribution and beam becomes uniform