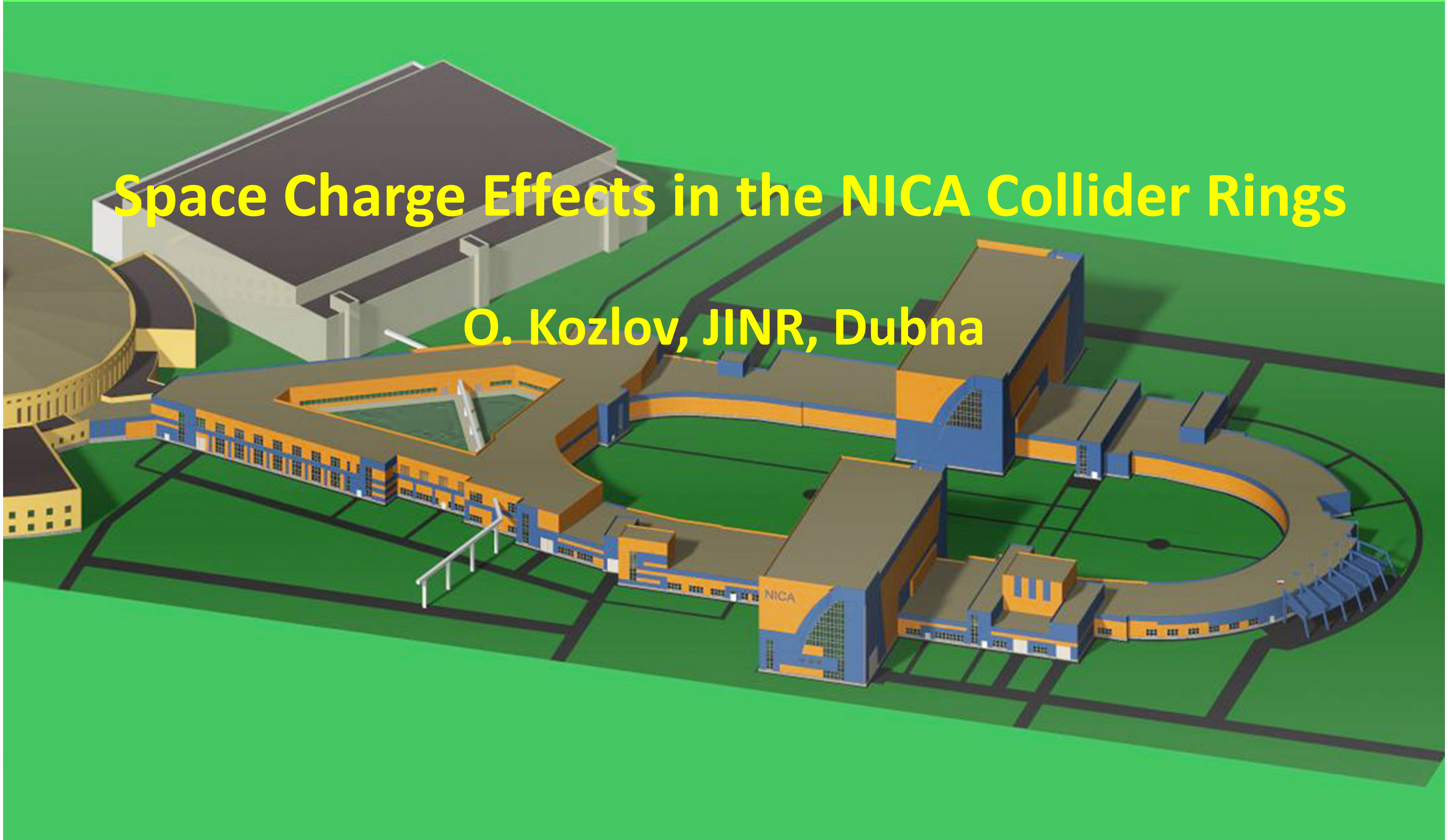
The 52nd ICFA Advanced Beam Dynamics Workshop
on High-Intensity and High-Brightness Hadron Beams,
Beijing, September 17 to 21, 2012.



Space Charge Effects in the NICA Collider Rings

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Contents

Introduction: The goal of the project

The goal of the project is

<u>construction at JINR of a new accelerator facility</u> that provides

1a) Heavy ion colliding beams 197Au79+ x 197Au79+ at

$\sqrt{s_{NN}}$ = 4 ÷ 11 GeV (1 ÷ 4.5 GeV/u ion kinetic energy)

at $L_{average}$= 1E27 cm-2·s-1 (at $\sqrt{s_{NN}}$ = 9 GeV)

1b) Light-Heavy ion colliding beams of the same energy range and luminosity

2) Polarized beams of protons and deuterons in collider mode:

p↑p↑ $\sqrt{s_{pp}}$ = 12 ÷ 27 GeV (5 ÷ 12.6 GeV kinetic energy)

d↑d↑ $\sqrt{s_{NN}}$ = 4 ÷ 13.8 GeV (2 ÷ 5.9 GeV/u ion kinetic energy)

$L_{average}$ ≥ 1E30 cm-2·s-1 (at $\sqrt{s_{pp}}$ = 27 GeV)

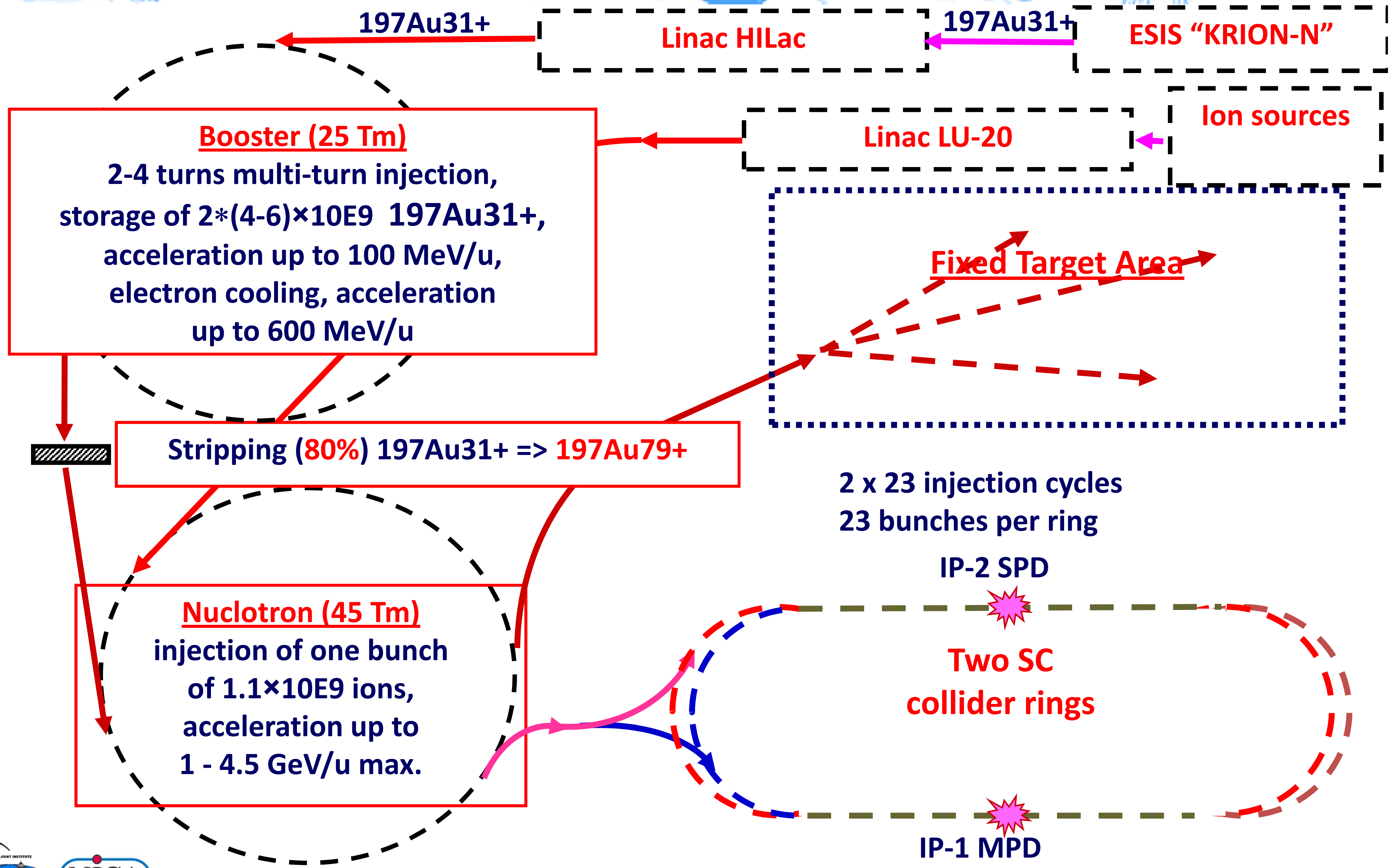
3) The beams of light ions and polarized protons and deuterons for fixed target experiments:

Li ÷ Au = 1 ÷ 4.5 GeV /u ion kinetic energy
p, p↑ = 5 ÷ 12.6 GeV kinetic energy
d, d↑ = 2 ÷ 5.9 GeV/u ion kinetic energy

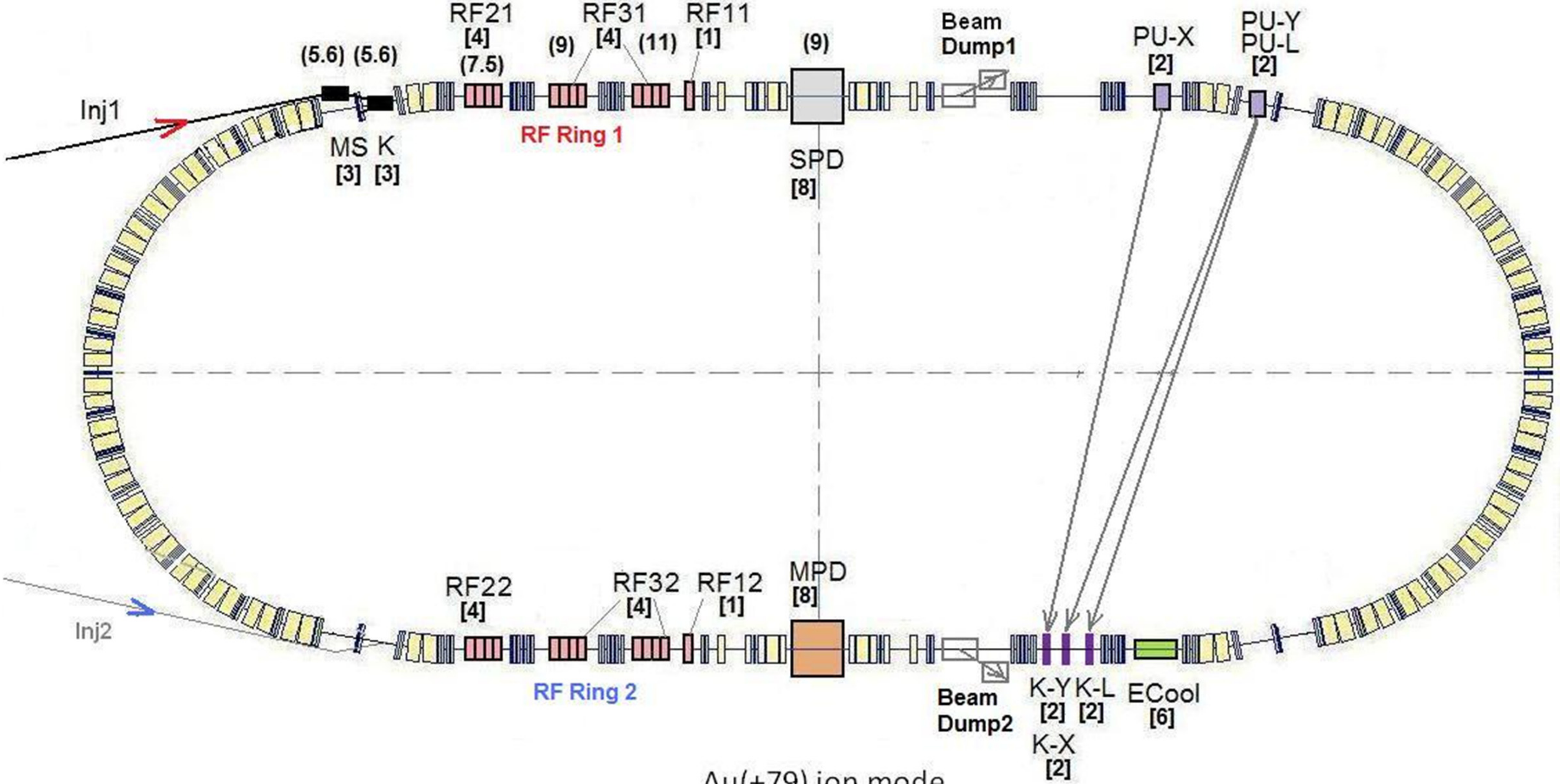
4) Applied research on ion beams at kinetic energy

from 0.5 GeV/u up to 12.6 GeV (p) and 4.5 GeV /u (Au)

Facility scheme and operation scenario



Collider Ring Composision. Ion Mode



Au(+79) ion mode

Collider Luminosity

NICA collider parameters and boundary conditions

Ring circumference, m	503,04		
Number of bunches	23		
Rms bunch length, m	0.6		
Beta-function in the IP, m	0.35		
Betatron tunes, Qx/Qy	9.44/9.44		
Ring acceptance	40 $\pi\cdot$mm$\cdot$mrad		
Long. acceptance, dp/p	±0.010		
Gamma-transition, γ_{tr}	7.091		
Ion energy, GeV/u	1.0	3.0	4.5
Ion number per bunch	$2.75\cdot10^{8}$	$2.4\cdot10^{9}$	$2.2\cdot10^{9}$
Rms dp/p, 10^{-3}	0.62	1.25	1.65
Rms beam emittance, h/v, (unnormalized), $\pi\cdot$mm$\cdot$mrad	1.1/ 1.01	1.1/ 0.89	1.1/ 0.76
Luminosity, $cm^{-2}s^{-1}$	1.1e25	1e27	1e27
IBS growthe time, sec	190	700	2500

1. ***Beam emittance (unnormalized) $\varepsilon_b \leq 1$ $\pi\cdot$mm$\cdot$mrad, limited by the ring acceptance***
2. ***$L(E_i) \geq$ 1E27 cm-2$\cdot$s-1 at 3.5 < E_i < 4.5 GeV/u – physics requirement***
3. ***Ion number per bunch is limited by injection chain and ion storage time duration: $N_b \leq$ 2E9 per bunch***

Collider Luminosity

For identical round colliding bunches the peak luminosity :

$$L = \frac{N_b^2}{4\pi\varepsilon\beta^*} F_C f_{HG}\left(\sigma_s, \beta^*\right),$$

Bunch length has to be small enough to decrease "hour-glass" effect and to provide luminosity concentration in the detector center, but very small length increases tune shift and coherent instability:

$$f_{HG}\left(\sigma_s / \beta^*\right) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{+\infty} \frac{\exp(-u^2)du}{1+\left(u\sigma_s / \beta^*\right)^2}$$

Beam intensity is limited by space charge effects – "Tune shift criteria":

1. **The Laslett tune shift – most strong:**

$$\Delta Q = \frac{Z^2 r_p}{A} \frac{N_b}{4\pi\beta^2\gamma^3\varepsilon} F_{SC} F_b, \quad F_b = \frac{C_{Ring}}{\sqrt{2\pi}\sigma_s}$$

2. **Beam-beam parameter:**

$$\xi = \frac{Z^2}{A} \frac{r_p N_b (1+\beta^2)}{4\pi\beta^2\gamma\varepsilon}$$

For practical estimates the numerical criterion for beam stability is used:

$$\Delta Q_{total} = \Delta Q + n_\xi \xi \le 0.05,$$
$$n_\xi = 2 - number\ of\ IPs$$

Collider Luminosity

From the Formulae above one can derive the simple relations between parameters:

$$\left.\begin{array}{l} L \propto \dfrac{N_b^2}{\varepsilon} \cdot f_1(E_i) \cdot f_{HG} \\ \Delta Q \propto \dfrac{N_b}{\varepsilon} \cdot f_2(E_i) \end{array}\right\} \Rightarrow L \propto \Delta Q^2 \cdot \varepsilon \cdot f_3(E_i) \cdot f_{HG}, \quad N_b \propto \Delta Q \cdot \varepsilon \cdot f_4(E_i)$$

At fixed $\Delta Q = \Delta Q_{max} \approx 0.05$ maximum luminosity is achieved when all acceptance is filled with ions!

"Space Charge Dominated Regime" (SCD Regime)

$$\tau_{cool} < \tau_{IBS}$$

Collider Luminosity

Then at fixed Luminosity:

$$\left.\begin{array}{l} L \propto \dfrac{N_b^2}{\varepsilon} \cdot f_1(E_i) \cdot f_{HG} \\ \Delta Q \propto \dfrac{N_b}{\varepsilon} \cdot f_2(E_i) \end{array}\right\} \Rightarrow \quad if\ L = const = 10^{27} \Rightarrow$$

$$N_{ion} \propto \sqrt{L \cdot \varepsilon} \cdot f_4(E_i, \beta^*, \sigma_s), \quad \Delta Q \propto \sqrt{\frac{L}{\varepsilon}} \cdot f_5(E_i, \beta^*, \sigma_s) < \Delta Q_{max} = 0.05$$

If luminosity can be limited (for some "not beam related" reasons – e.g., detector performance) one can have

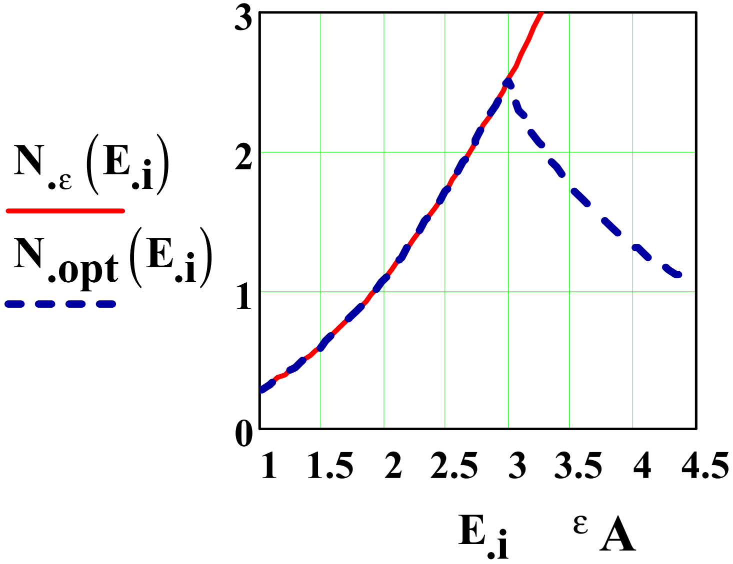
IBS Dominated Regime:

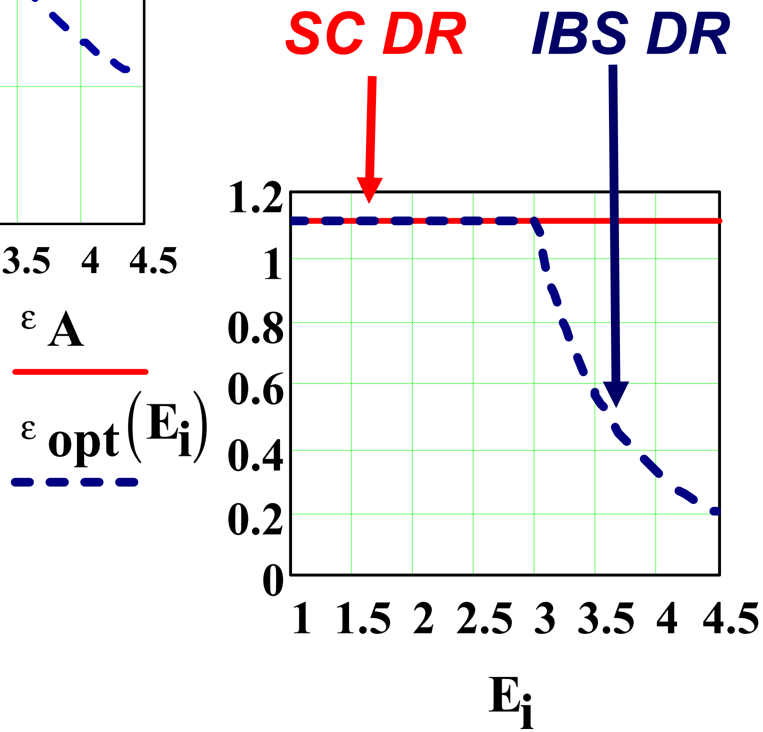
$$\tau_{IBS} = \tau_{cooling}$$

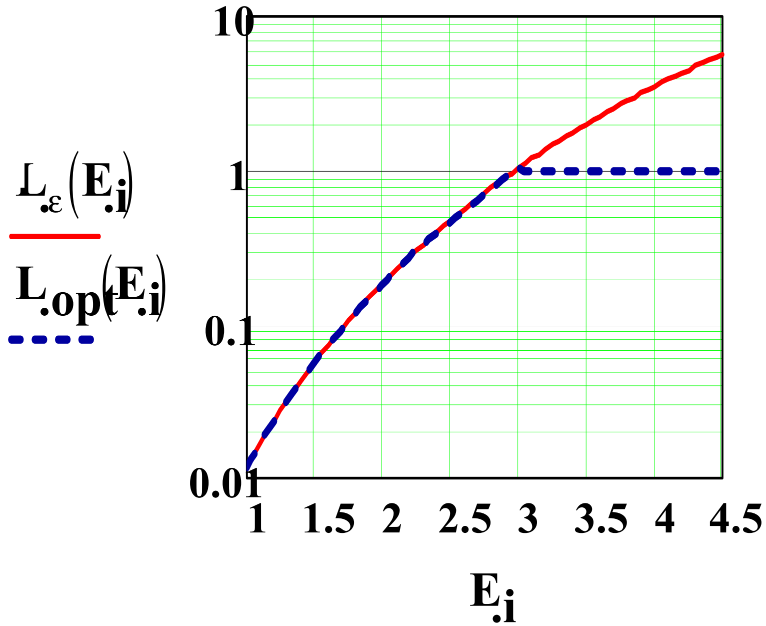
Energy Ranges of Two Regimes

A) *Acceptance is filled with ions up to* $\Delta Q = \Delta Q_{max} = 0.05$, $L = L_{max}$

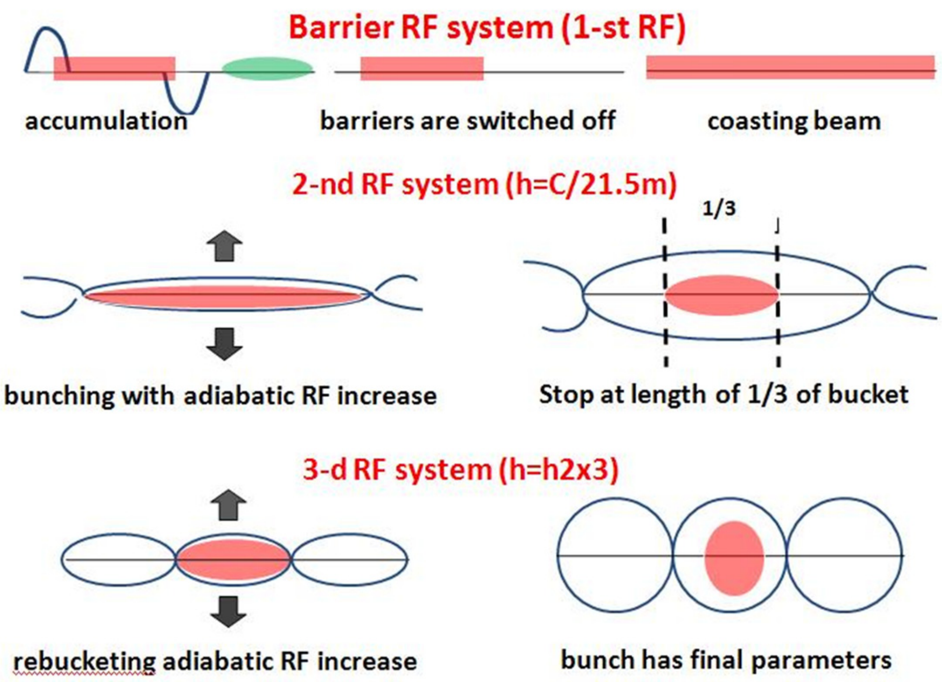
B) *Optimal regime*: $L = \begin{cases} L_{max} & \text{at } 1 \le E_i \le 3 \text{ GeV/u}, \\ 1E27 = const & \text{at } 3 \le E_i \le 4.5 \text{ GeV/u}. \end{cases}$







Beam preparation scheme



Beam storage at the experiment energy :

1. **RF barrier bucket system (RF1)**
   allowing storage of the required beam intensity

2. **1st narrow-band RF system (RF2)**
   operating at harmonics of revolution frequency corresponding to the bunch number; it provides the beam bunching.

3. **2nd narrow-band RF system (RF3)**
   operating at harmonics number larger than the 1st one, that provides the bunch length necessary for collision experiments.

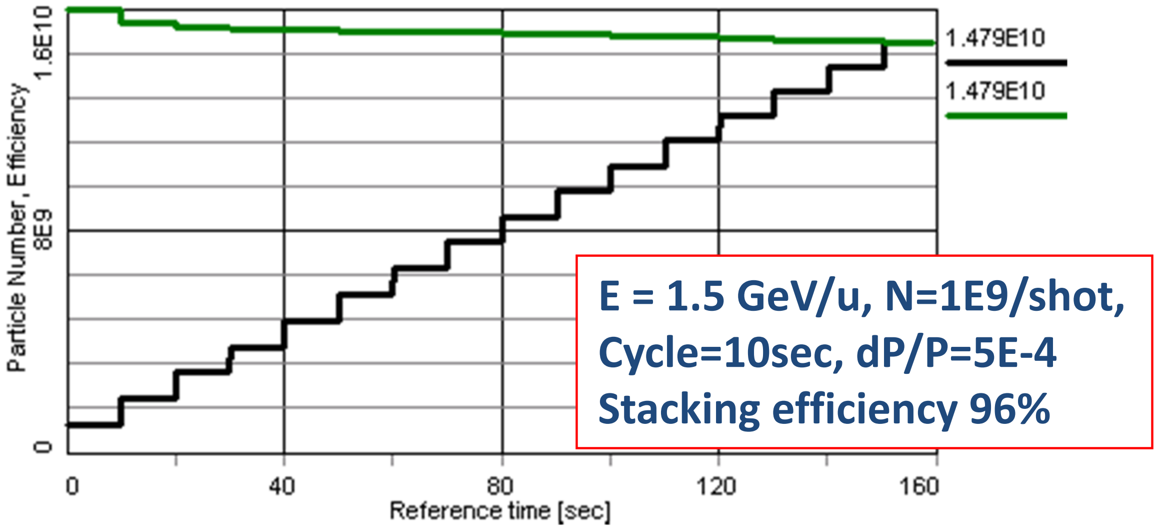
All stages are provided with cooling

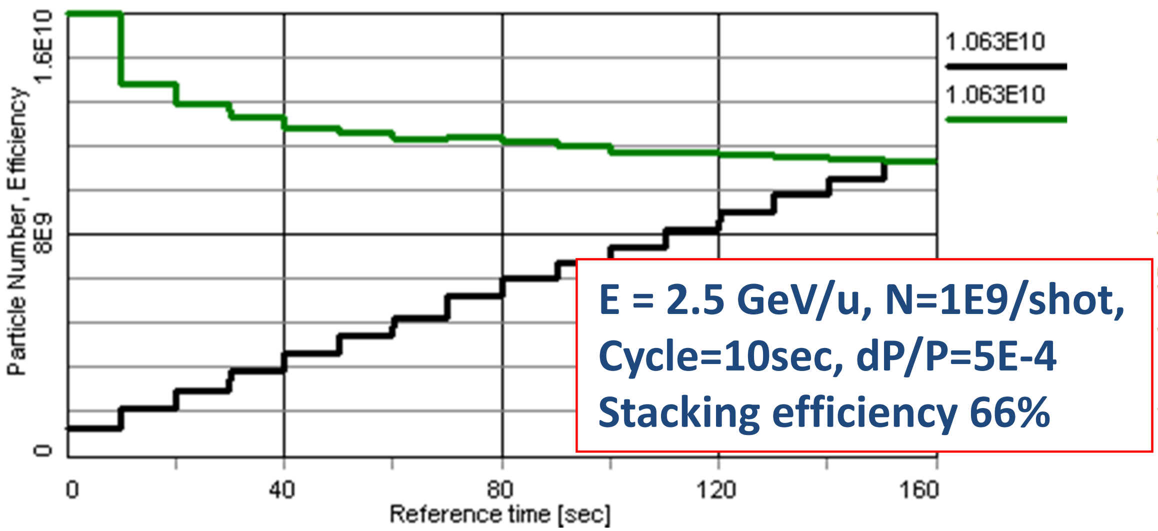
Main parameters of RF systems

	RF1	RF2	RF3
Frequency, MHz	BB	11.4-12.8	34.2-38.4
Total voltage ampl., kV	5	100(50)	1000
Voltage/resonator, kV	5	25	125
Number of resonators	1	4	8
Resonator length, m	0.8	1.1	1.1
Total length, m	0.8	4.4	8.8

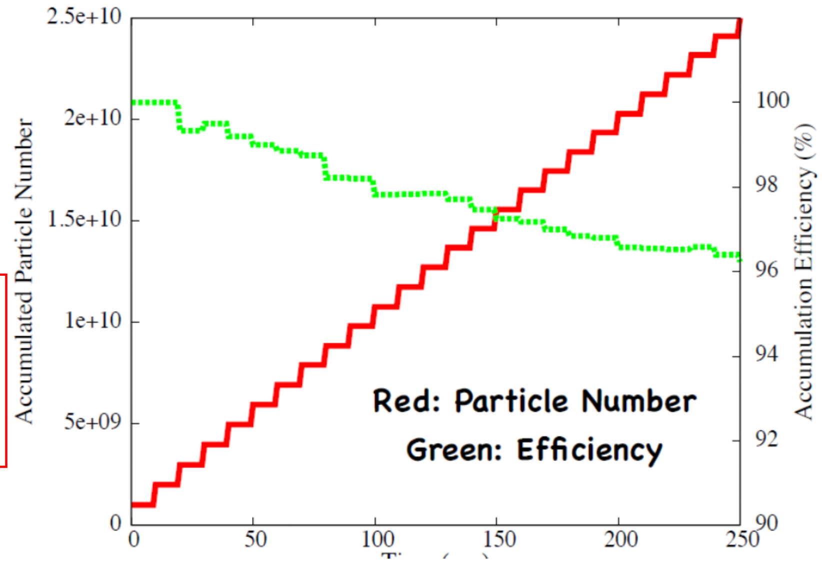
Beam stacking with electron cooling

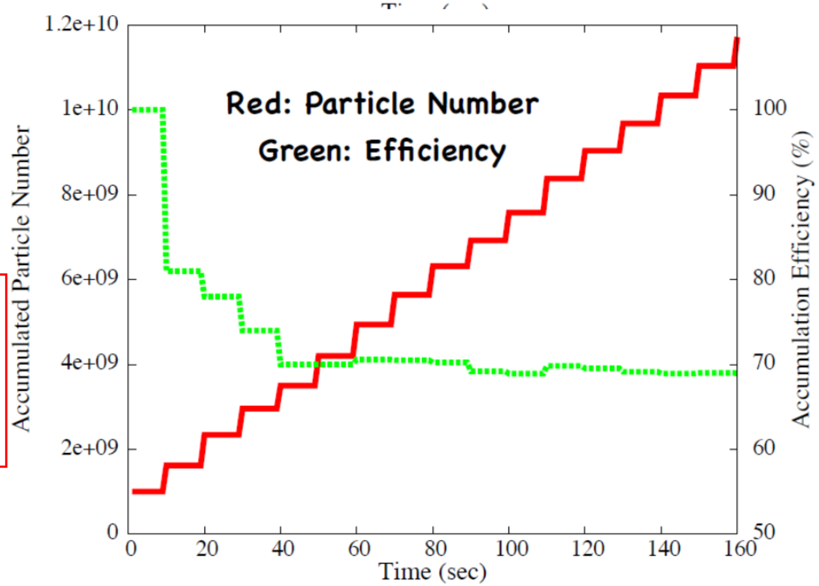
A.Smirnov (Betacool)





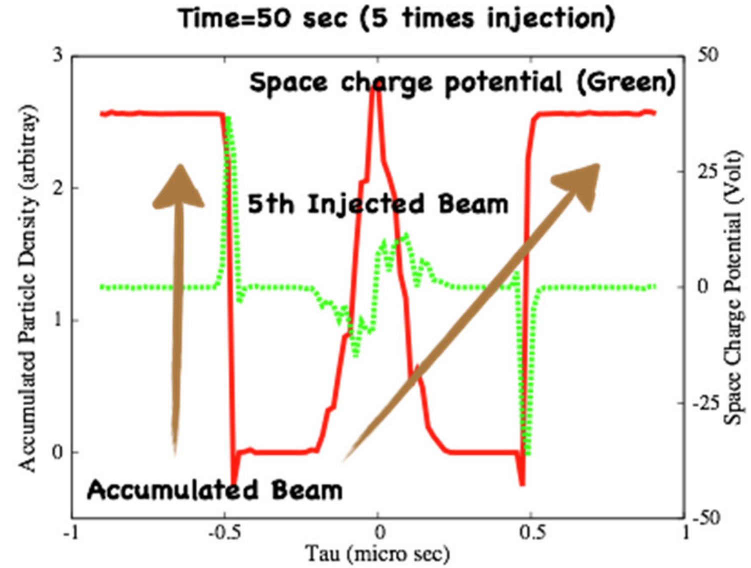
T.Katayama

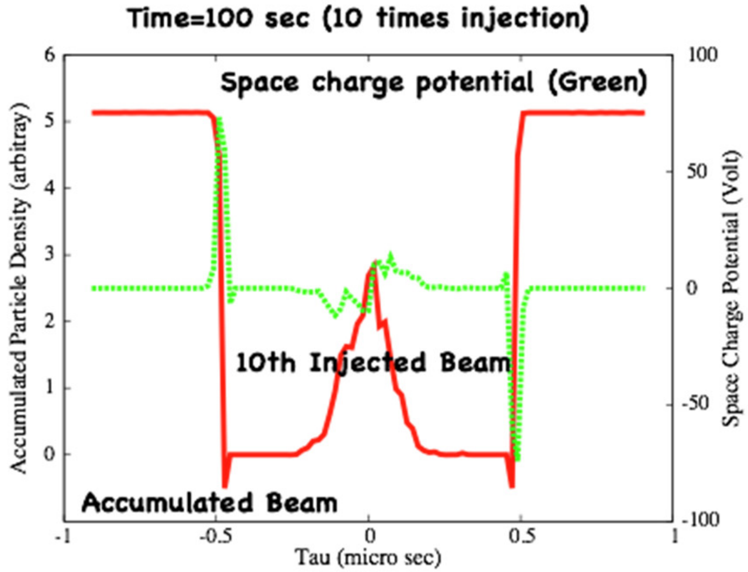




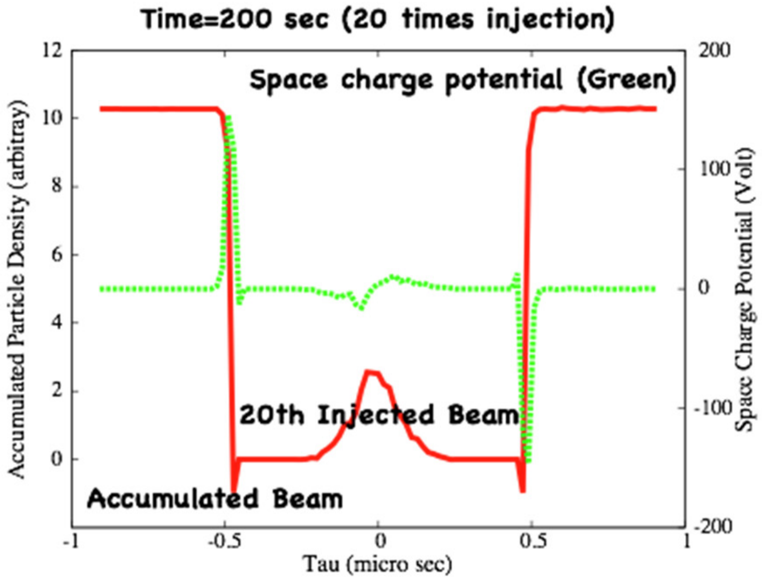
Space charge effect during stacking and bunching

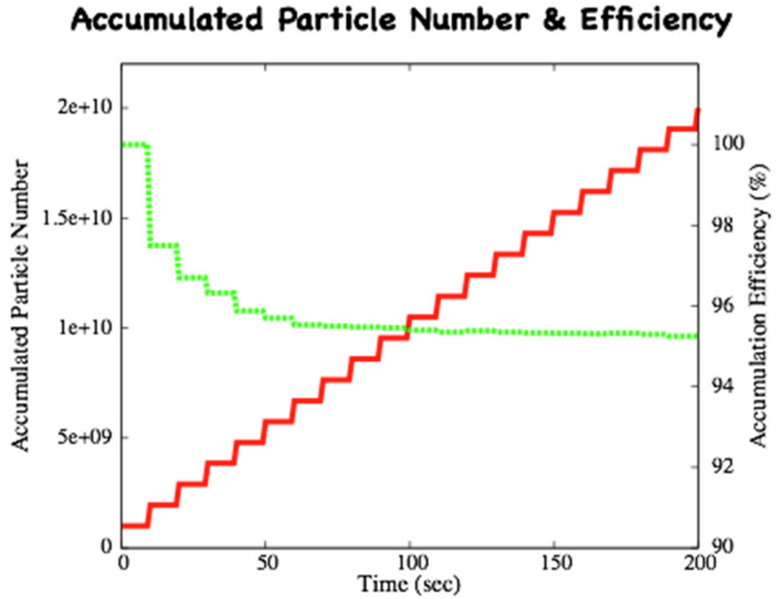
(T.Katayama)





1.5 GeV/u

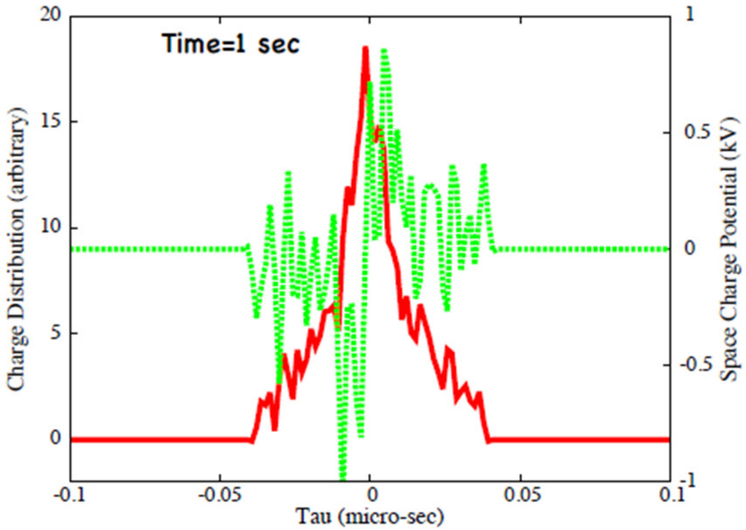


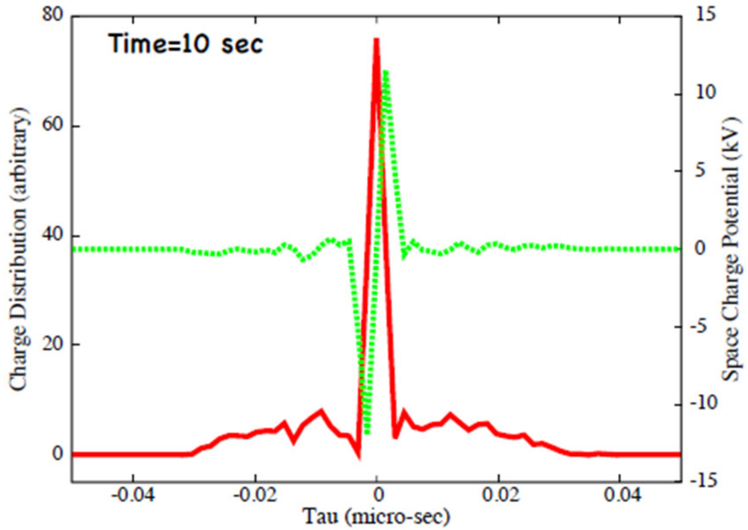


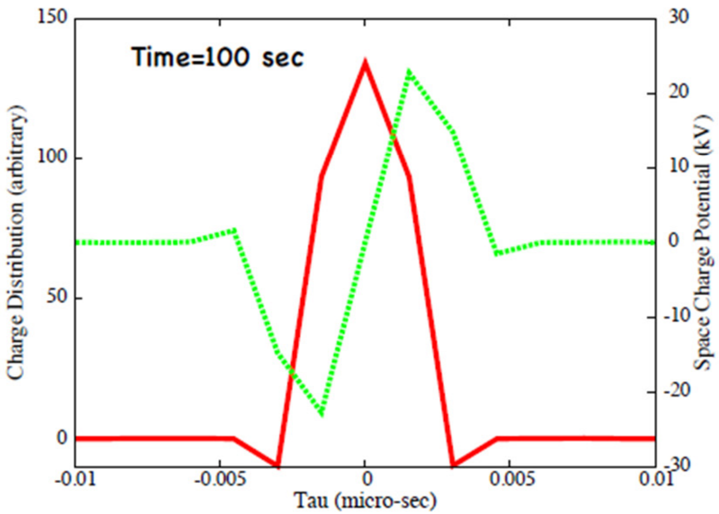
Formation of the bunch shape

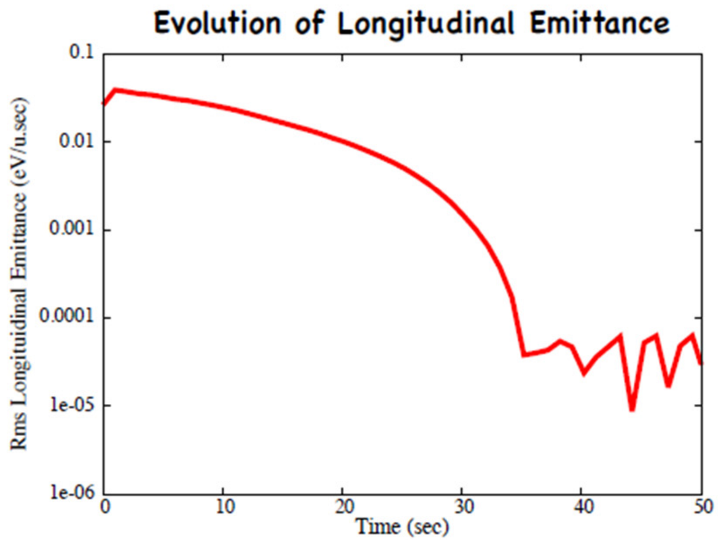
T.Katayama

Ek=1.5 GeV/u, N=1e9, RF voltage=200kV, eta=0.1268, dp/p(initial)=5e-4(rms) (Gaussian)

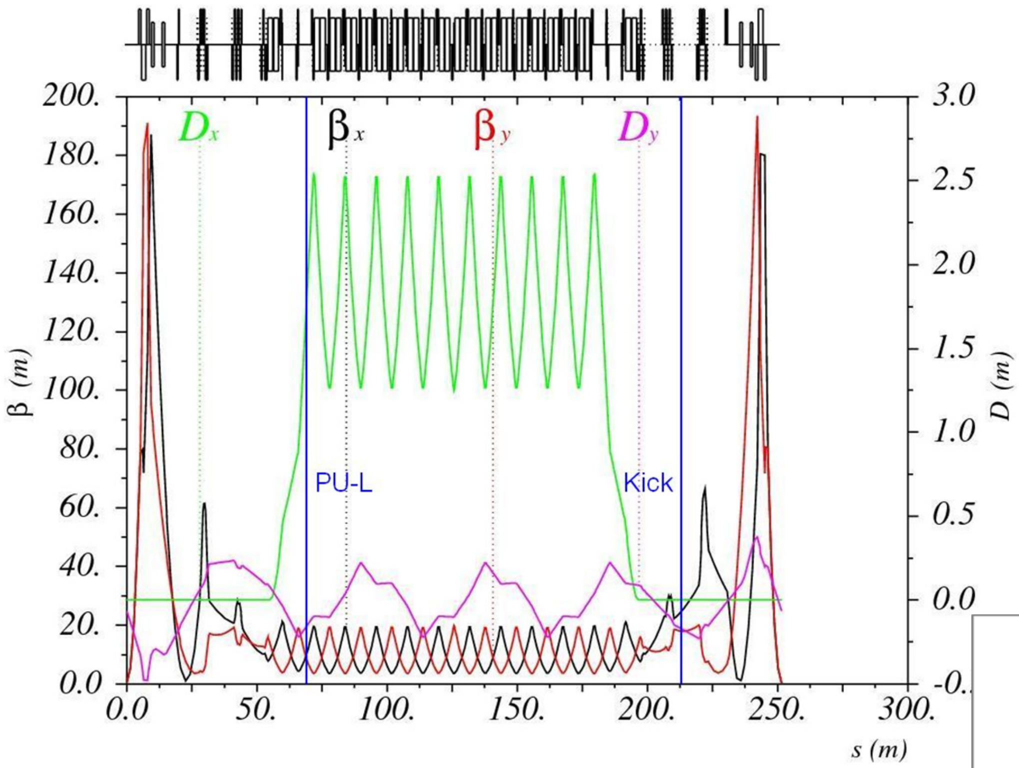


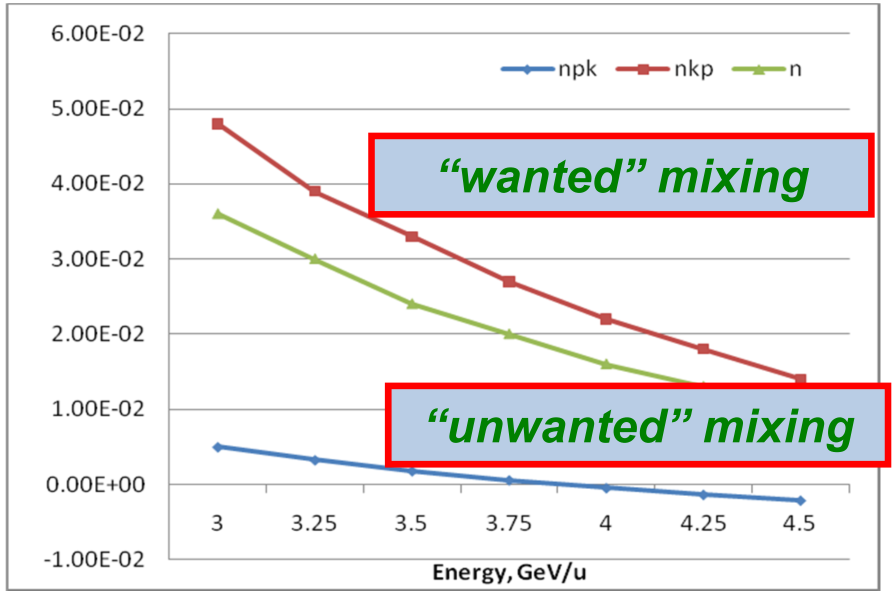




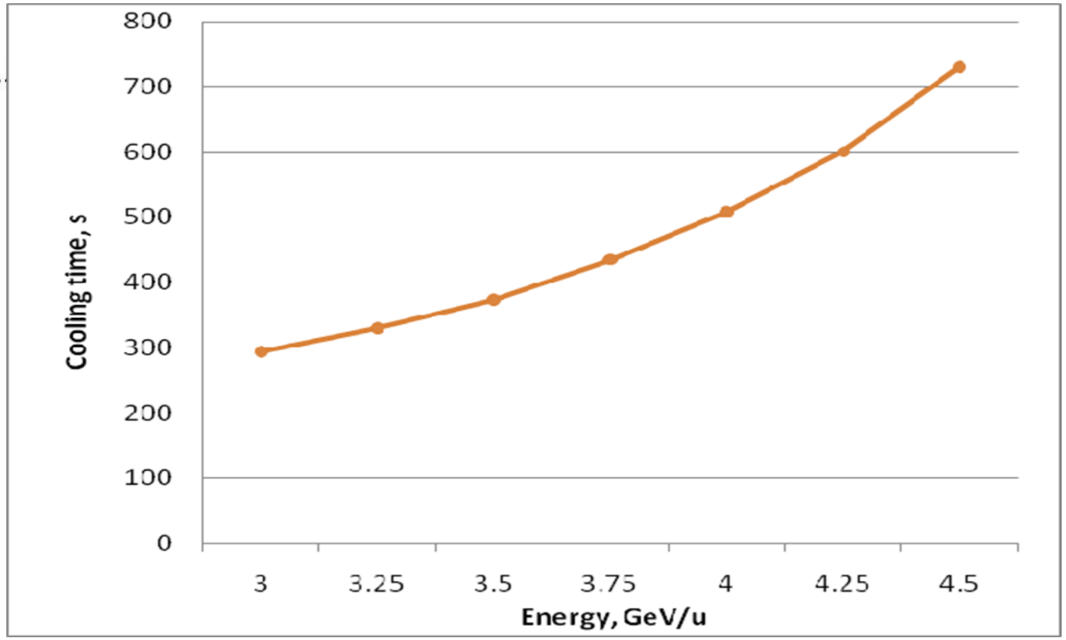


Stochastic cooling (3-4.5 GeV/u)



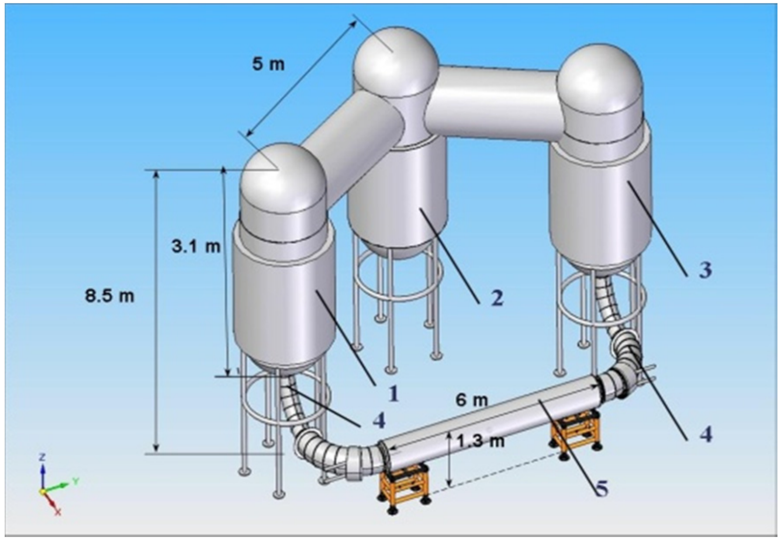


Bandwidth from 3 to 6 GHz
Cooling times varies by about 2 times
In the energy range from 3 to 4.5 GeV/u

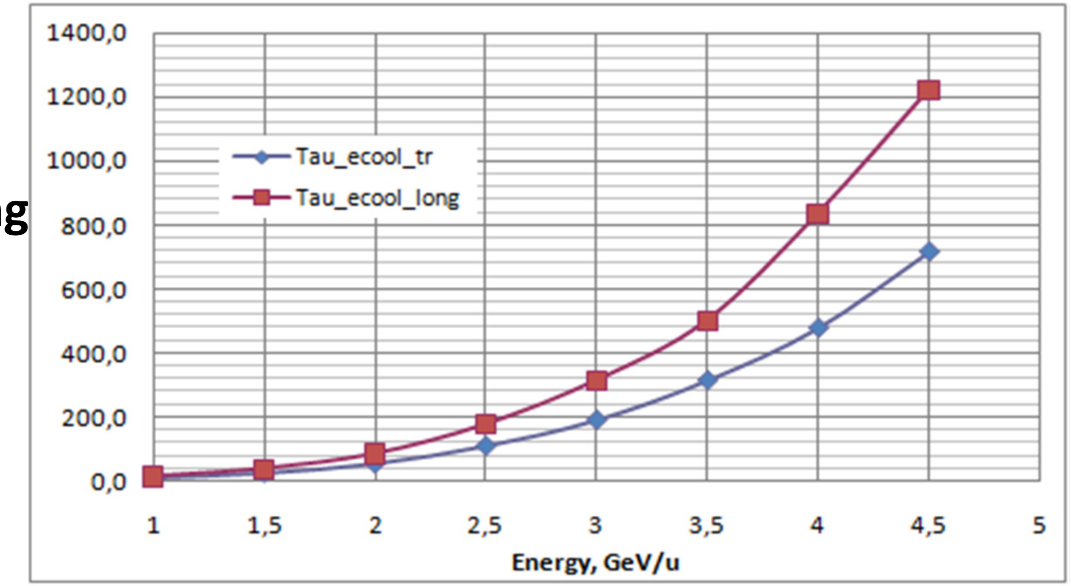


Electron cooling

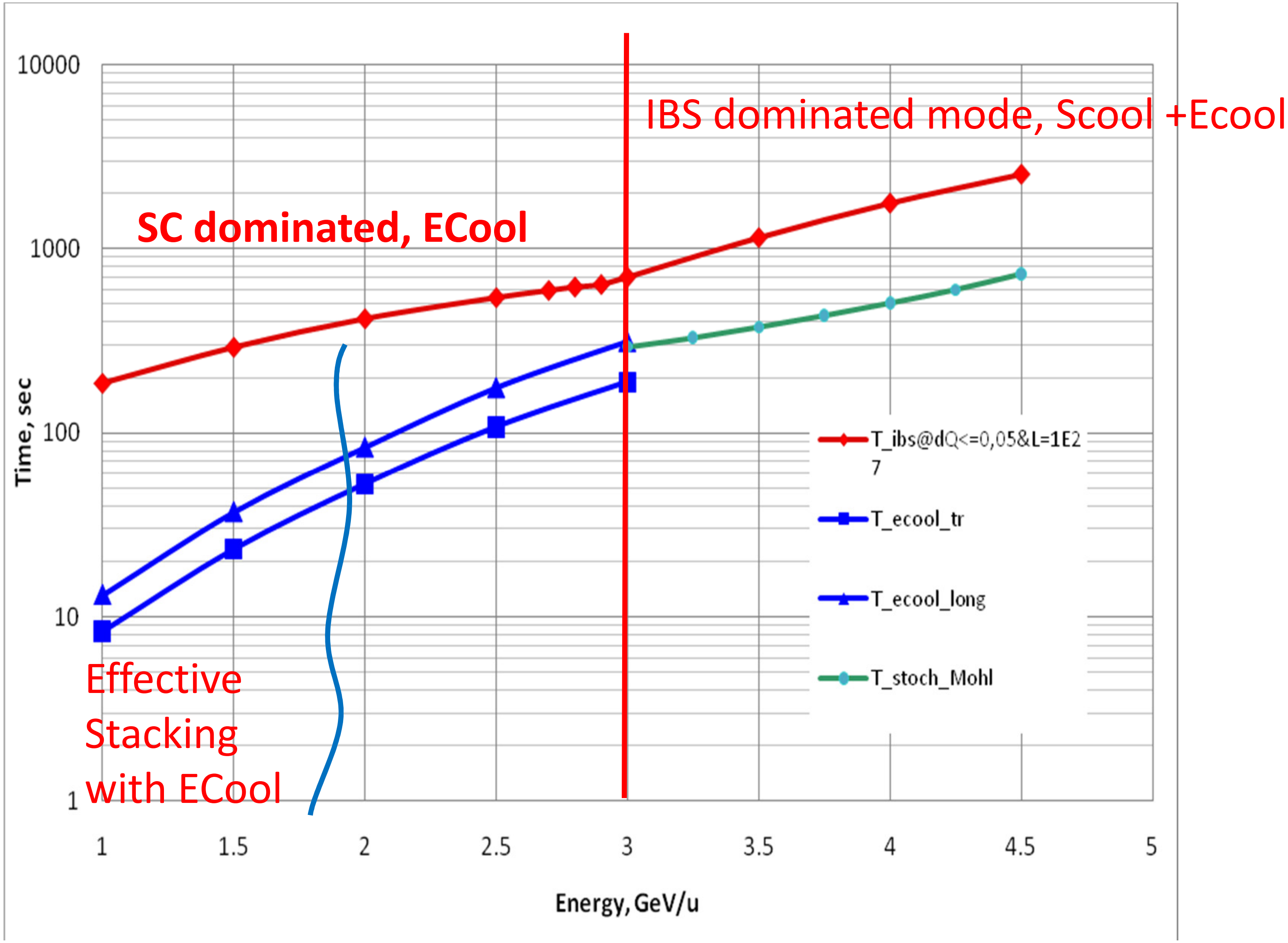
Maximum electron energy, MeV	2.5
Cooling section length, m	6.0
Electron beam current, A	1
Electron beam radius, cm	1
Magnetic field in cooling section, T	0.2
Magnetic field imperfection in cooling section	2×10^{-5}
Beta functions in cooling section, m	16
Longitudinal electron temperature meV	5.0



At higher energies 3-4.5 GeV/u:
ECooling times comparable with IBS heating times and SCooling times;
At lower energies 1-3 GeV/u:
ECooling times ~20 times shorter than IBS heating times



Strategy of the cooling at experiment



IBS is calculated for equal rates in 3 degrees of freedom

Conclusion

1. Collider has 2 modes of operation: Space Charge Dominated Regime (1-3 GeV/u) and IBS Dominated Regime (3-4.5 GeV/u)
2. Beam Cooling techniques are used for formation of high intensity and low emittance ion beams, and for providing the required luminisity life time
3. Stochastic cooling sufficient for IBS suppression is sufficient for beam stacking also
4. Electron cooling can be used for cooling at experiment in the total energy range
5. Electron cooling can provide effective stacking at small energy only
6. At energy larger than 3 GeV/u the experiment can be provided using electron cooling as well as stochastic, or combination of both methods
7. At energy below 3 GeV/u the experiment is provided using electron cooling. Possibility to increase of luminosity at minimum energy is related with space charge dominated mode

Tnank you for your attention!