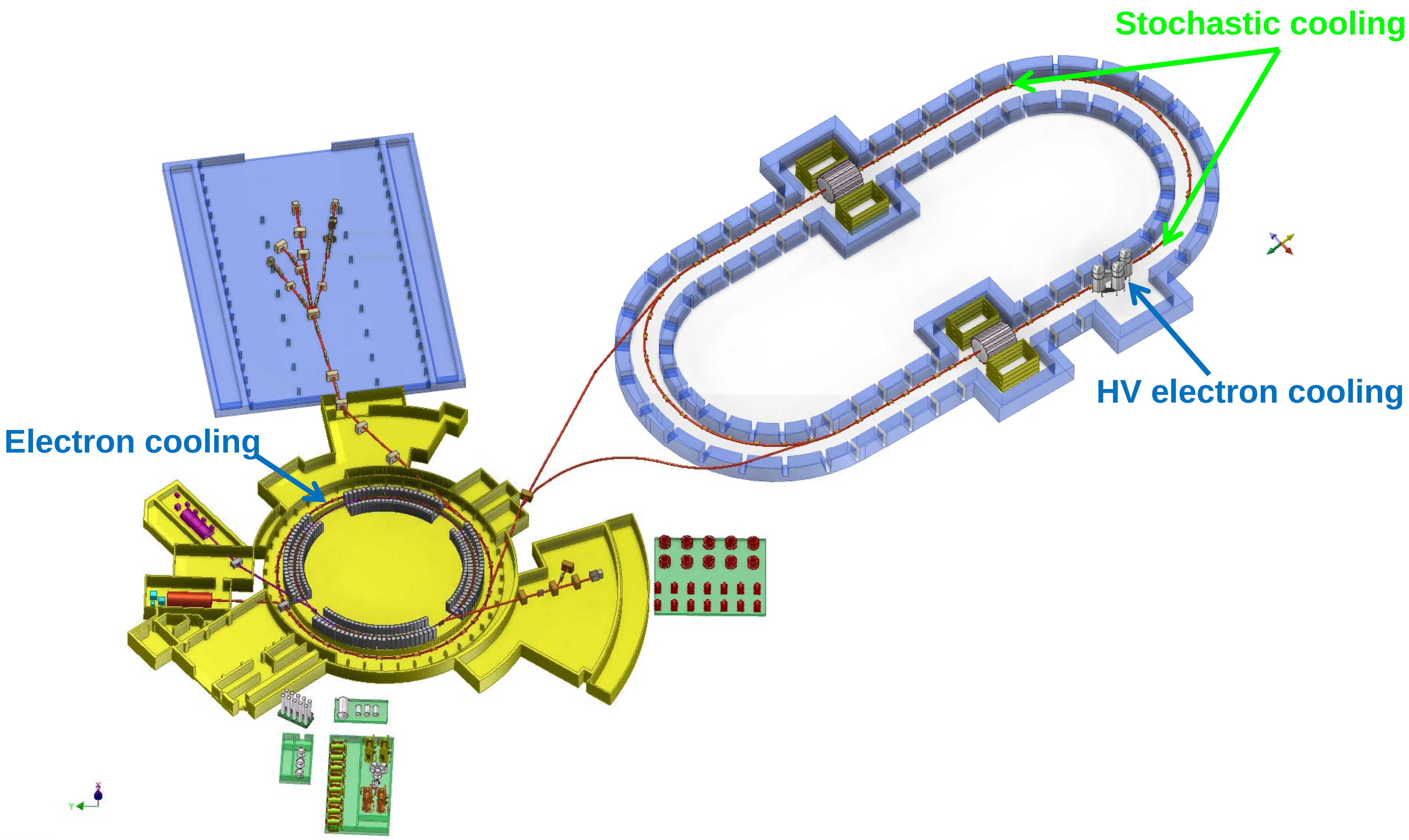
Application of cooling methods at NICA project

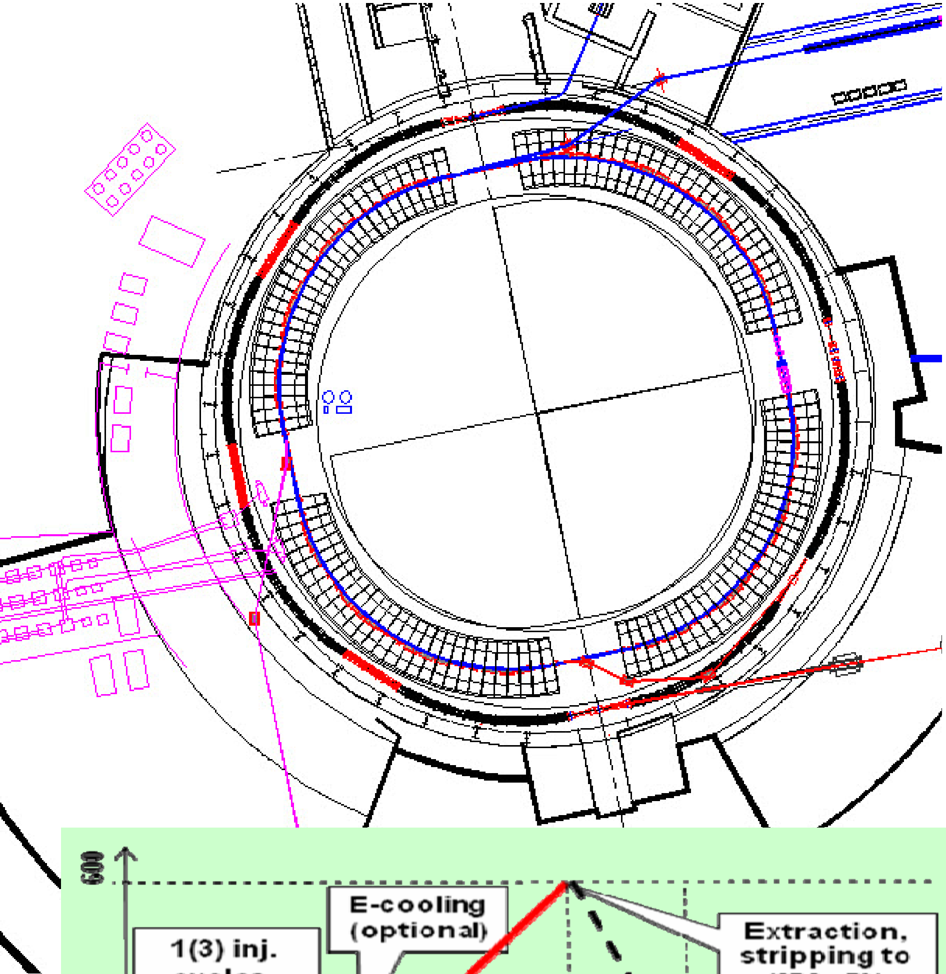
G.Trubnikov on behalf of team

RUPAC-12 conference
St.Petersburg, 25 September 2012

NICA complex

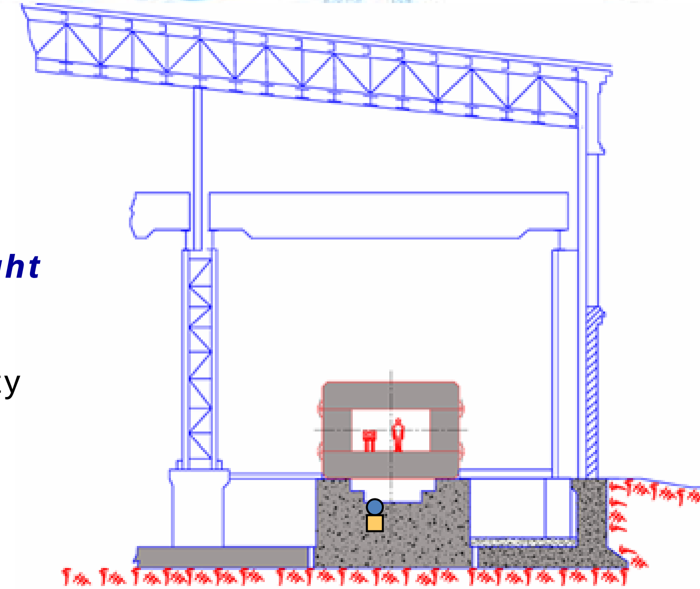


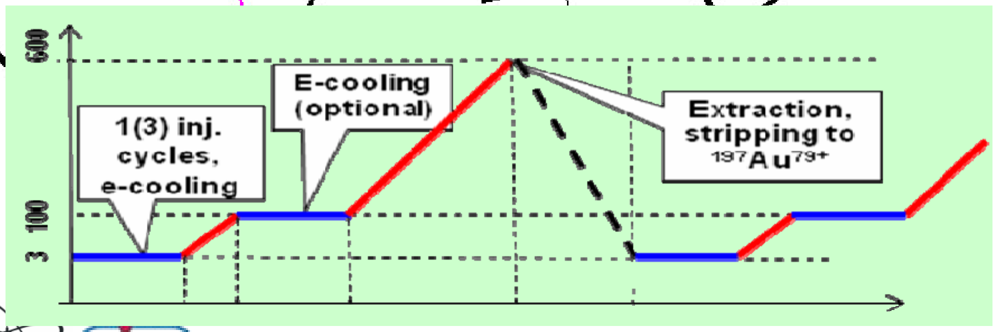
Booster synchrotron

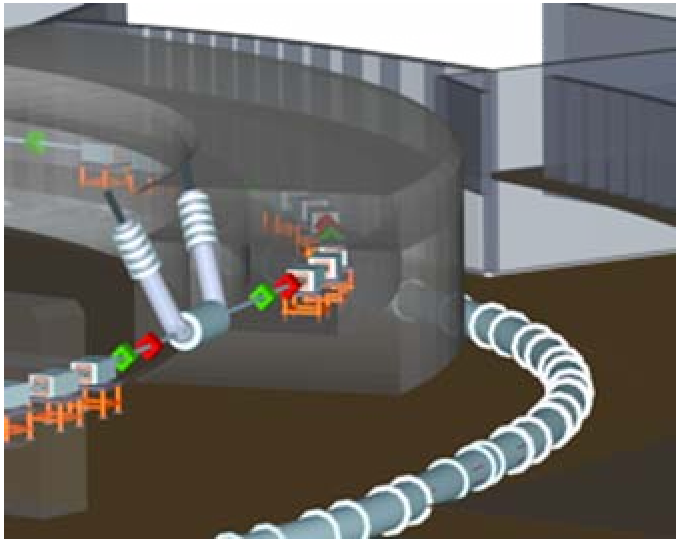


Injector
3MeV/nucleon
Au31+ RFQ

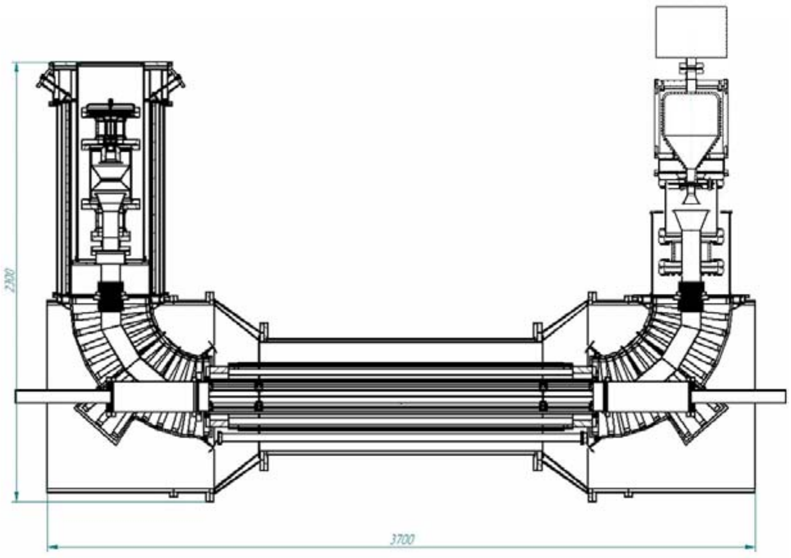
4 large straight sections
1.Injection
2.Two RF-cavity
3.One turn extraction
4.E-cooler

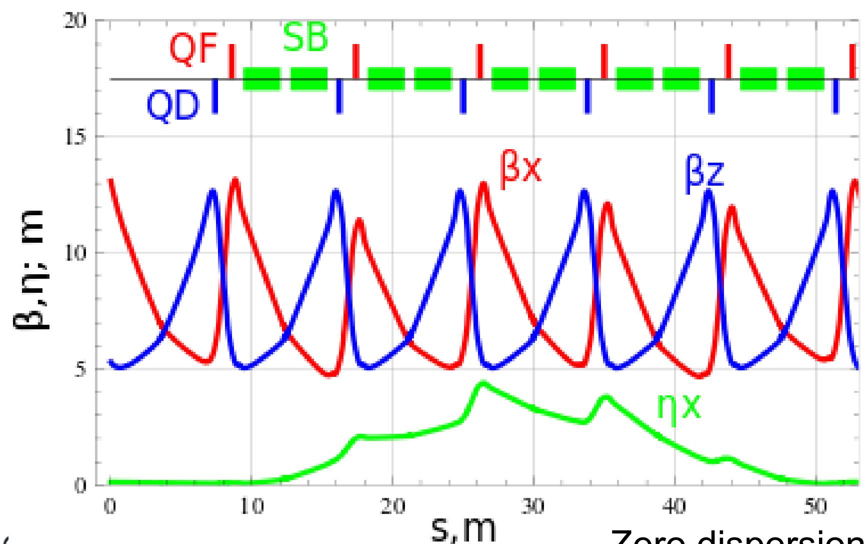






Booster electron cooling system





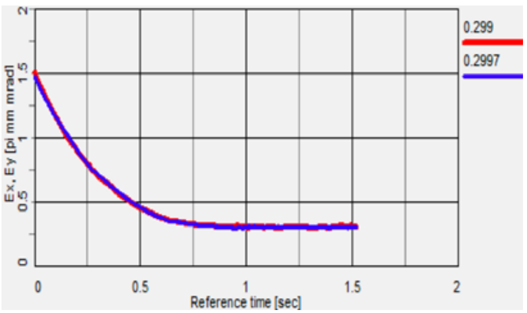
Ions	$197Au^{31+ (65+)}$
Booster circumference, m	211.2
Injection/extraction energy, MeV/u	3/600
Max. dipole field, T	1.8
Ion number	2×10^{9}
Beta functions in cooling section, m	10-6 / 6-10
Dispersion in cooling section, m	0.6
Maximum electron energy, keV	50.0
Electron beam current, A	0 ÷ 1.0
Cooler overall length, m	5.7
Eff. length of the cooling section, m	2.5
Magnetic field in the e-cooler, kG	1.5
Magnetic field inhomogeneity in the cooling section, ΔB/B	$1\cdot10^{-4}$
Electron beam radius, cm	2.5
Trans.electron temperature, meV (min)	200
Long. electron temperature, meV	0.5
Cooling time, s (I_e=0.05A)	0.4
Residual gas pressure, Torr	10^{-11}

Zero dispersion in the large stright section

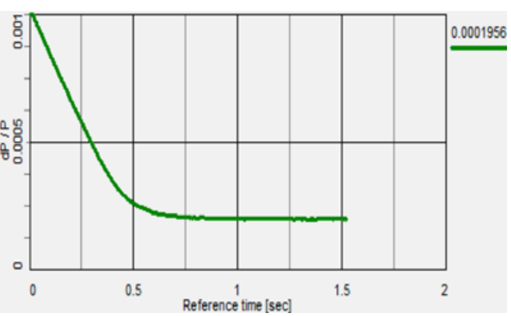
Simulation of cooling process with BETACOOL

Evolution of the bunched ion beam parameters during the cooling process (Ion energy = 3 MeV/u).

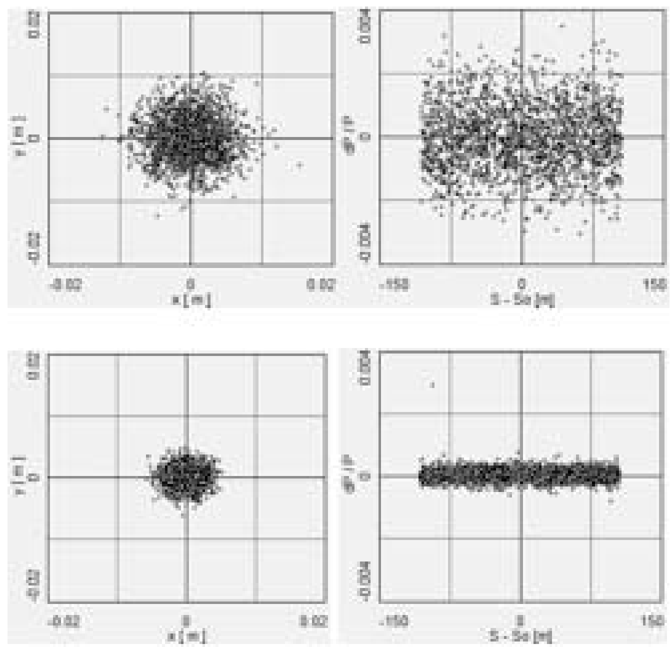
Horizontal and vertical emittances



ion momentum spread



Phase space diagrams



Initial parameters of the cooling

Ion energy, MeV	3
Ion kind	$^{197}Au^{31+}$
Particle number	2×10^{9}
Initial Tr_emittance, π mm mrad (rms)	1.5
Initial momentum spread	1×10^{-3}
RF voltage, kV	10
Electron beam current, A	0.05
Electron beam temp. long/trans, meV	200 / 0.5

Transverse emittance evolution in the collider injection chain

From HILac $6\sigma \leq 10\ \pi\cdot$mm$\cdot$mrad (upper limit for vertical emittance)

Horizontal Booster acceptance ~ 120 $\pi\cdot$mm$\cdot$mrad
(upper limit for the horizontal 6σ emittance in the case of multiturn injection)

In Booster: Kinematic decrease + Electron cooling (if necessary)

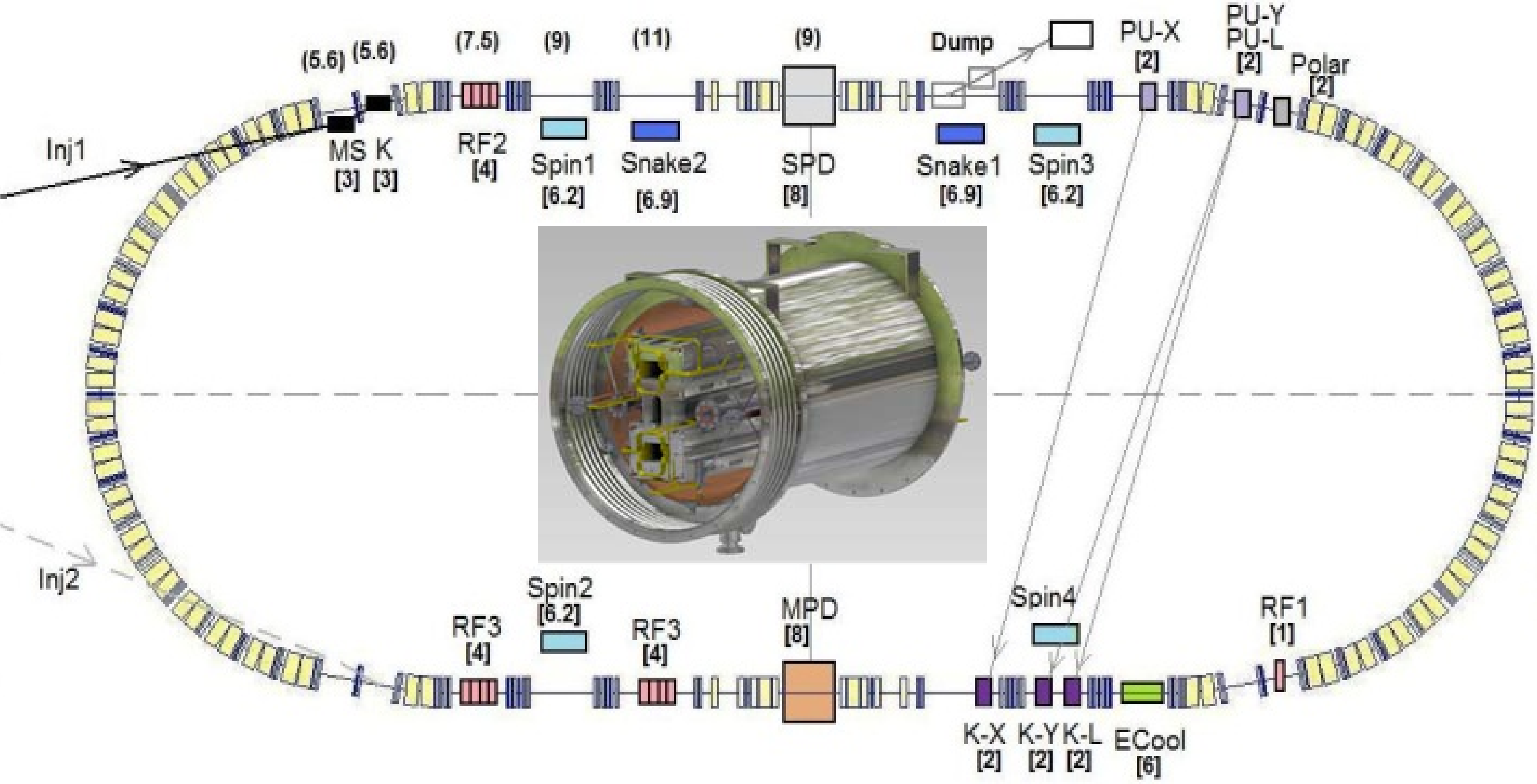
At 65 MeV/u rms $\varepsilon_h \leq 4.21\ \pi\cdot$mm$\cdot$mrad $\varepsilon_v \leq 0.35\ \pi\cdot$mm$\cdot$mrad

At 600 MeV/u (without cooling) rms $\varepsilon h \leq 1.23\ \pi\cdot$mm$\cdot$mrad $\varepsilon v \leq 0.102\ \pi\cdot$mm$\cdot$mrad

Increase in transfer line from Booster to Nuclotron:
-Stripper
-Coupling
-Mismatch
If $\varepsilon_h >> \varepsilon_v$, ε_h ~ constant, ε_v increases by about 3 times

At injection into Nuclotron rms $\varepsilon_h \leq 1.23\ \pi\cdot$mm$\cdot$mrad $\varepsilon_v \leq 0.3\ \pi\cdot$mm$\cdot$mrad

NICA collider



Collider parameters

Ring circumference, m	503,04		
Number of bunches	23		
Rms bunch length, m	0.6		
Beta-function in the IP, m	0.35		
Ring acceptance (FF lenses)	40 π mm 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	$2.75 \cdot 10^8$	$2.4 \cdot 10^9$	$2.2 \cdot 10^9$
Rms momentum spread, 10^{-3}	0.62	1.25	1.65
Rms beam emittance, h/v, (unnormalized), π·mm·mrad	1.1/ 1.01	1.1/ 0.89	1.1/ 0.76
Luminosity, $cm^{-2}s^{-1}$	1.1e25	1e27	1e27
IBS growth time,sec	186	702	2540

Peak luminosity can be estimated as:

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

The collision repetition rate:

$$F_{coll} = \frac{\beta c}{l_{bb}}, \quad l_{bb} = \frac{C_{Ring}}{n_{bunch}}$$

Hour-glass effect ~ 1 (because in our case $\sigma_s << \beta^*$):

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

Maximum luminosity is reached when the bunch phase volume corresponds to the ring acceptance

NICA

Collider parameters

To reach maximum peak luminosity one needs to meet the following evident requirements:

- minimum beta function in the IP;
- maximum collision repetition rate (that corresponds to bunch number in rings as maximum as possible);
- maximum bunch intensity;
- minimum beam emittance;
- minimum bunch length.

Peak luminosity can be estimated as:

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

The collision repetition rate:

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FF lenses aperture (radius) : 40mm

Proposed chromaticity correction scheme provides the transverse dynamic aperture of about 120 pi·mm·mrad and dynamic aperture on the relative momentum deviation of about ±1%

Maximum luminosity is reached when the bunch phase volume corresponds to the ring acceptance

The problems we have met and the solutions

The problems:

- ✓ Beam space charge effects
- ✓ Beam-beam effects
- ✓ IntraBeam scattering (IBS) ⇒ ⇒ luminosity degradation
- ✓ Recombination in e-cooler
- ✓ Bunch halo formation ⇒ ⇒ parasitic collisions, background growth

The solutions:

- ➢ Electron cooling application
- ➢ Stochastic cooling application
- ➢ Beam parameters choice
- ➢ Operation scenario optimisation
- ➢ Scrappers and collimators

Role of beam cooling

1. Beam stacking using BB system:

   Injection repetition is 10 sec, the cooling times has to be short enough

2. Longitudinal cooling during beam bunching

3. During experiment:

   - in IBS dominated mode - Suppression of IBS;

   - in SC dominated mode – providing optimum phase volume

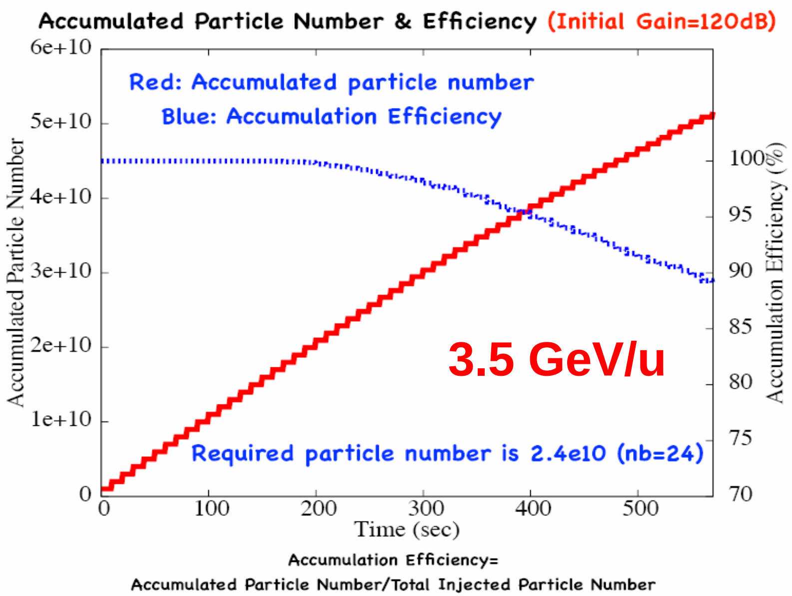
Beam stacking with BB system and cooling

E > 3 GeV/u:
stacking with Stochastic cooling
The cooling time is proportional to the bunching factor
for “almost” coasting beam in BB the cooling times ~ 10 sec
(T.Katayama previous MAC)

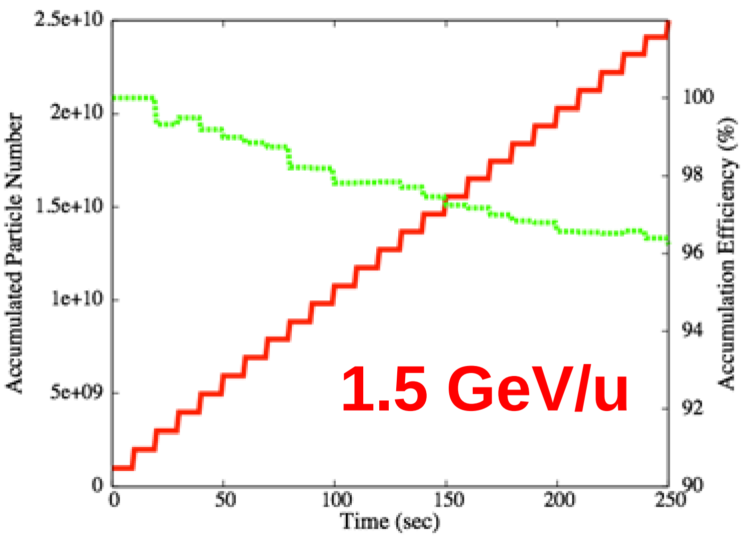
E < 3 GeV/u:
Stacking with Electron cooling
Problem – cooling time strongly depends on energy
and does not depend on bunching factor

The cooling power sufficient for experiment can be
insufficient for effective stacking

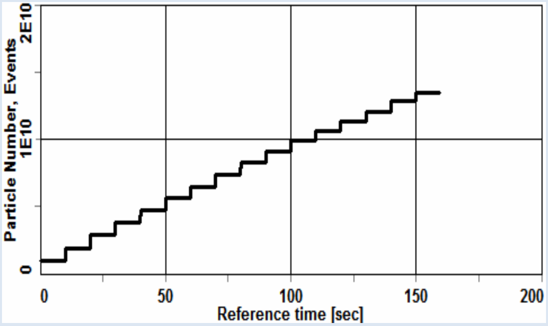
T.Katayama, October 2011, 3.5 GeV/u



Beam stacking with electron cooling

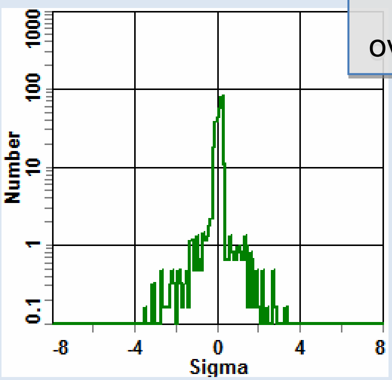


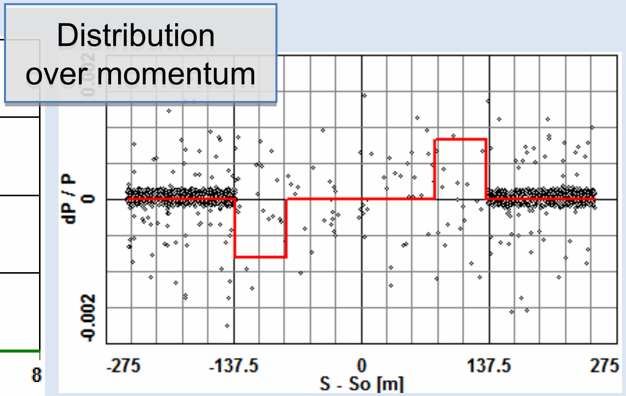
Stacking efficiency (A.Smirnov)

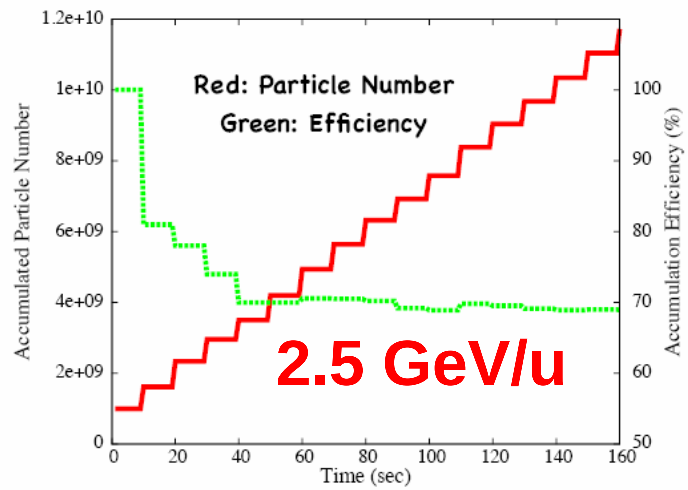


E = 1.5 GeV/u
Stacking efficiency 86%

E_Init = 1π·mm·mrad







Stacking with electron cooling and beam bunching

Effective stacking can be realized below ~ 2 GeV/u
Possible solution:
- Stacking at 1 GeV/u with efficiency closed to 100%
- Slow acceleration to the experiment energy

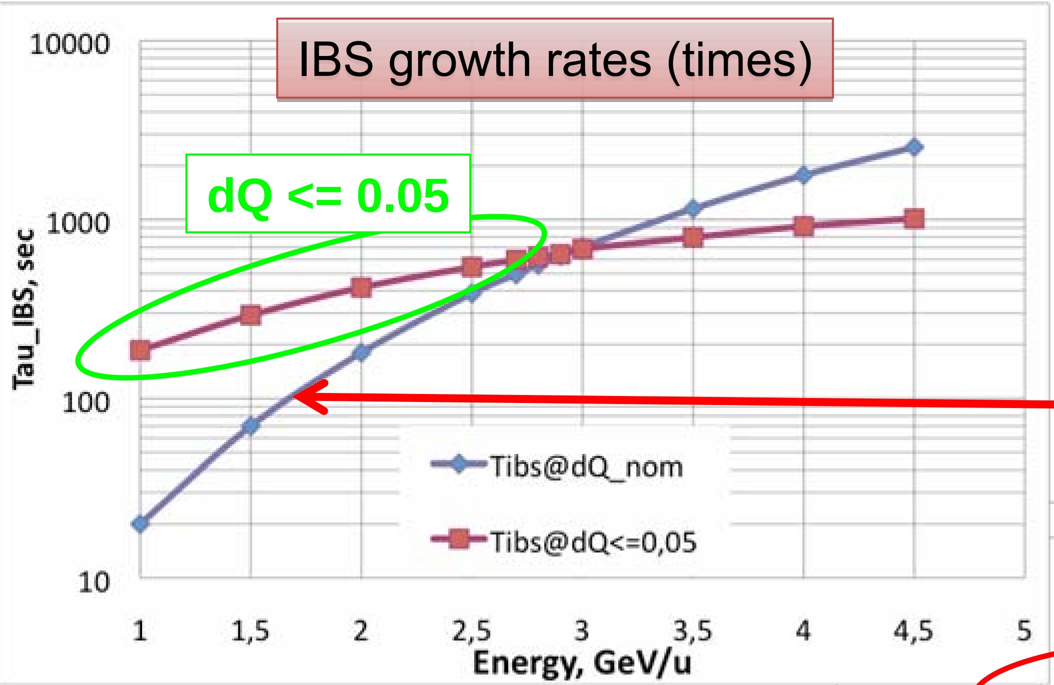
At constant longitudinal emittance ($\sigma_p \times \sigma_s$ = const) minimum threshold current of microwave instability corresponds to coasting beam
$I_{th} \sim \sigma_p^2$ the momentum spread is inversely proportional to bunching factor

Formation of required long emittance by a few steps:
- At storage of coasting beam formation σ_p required for the stability
(long emit. is larger than required at collisions by about bunching factor ~ 13)

- Bunching at 24 harmonics + cooling of long emittance by about 6 times,
Formation of the bunch of about 1.2 m, required to recapture in h=72

- Bunching + cooling at h = 72,
formation of required bunch length and momentum spread

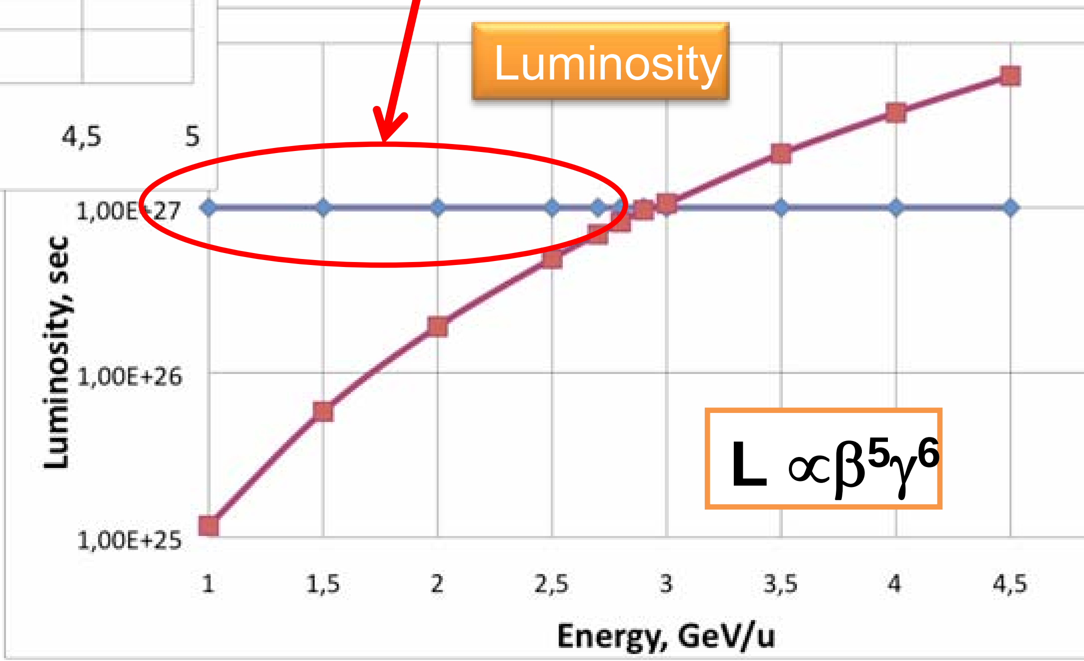
IBS calculations



Strategy:

1. ε_x= 1.1 pi mm mrad (due to $6\sigma_x$ = 40)
2. Equal heating rates of all degrees
3. dP/P~(1-1.5)e-3 is acceptable (from bunch coherent stability condition)
4. L <= 1e27

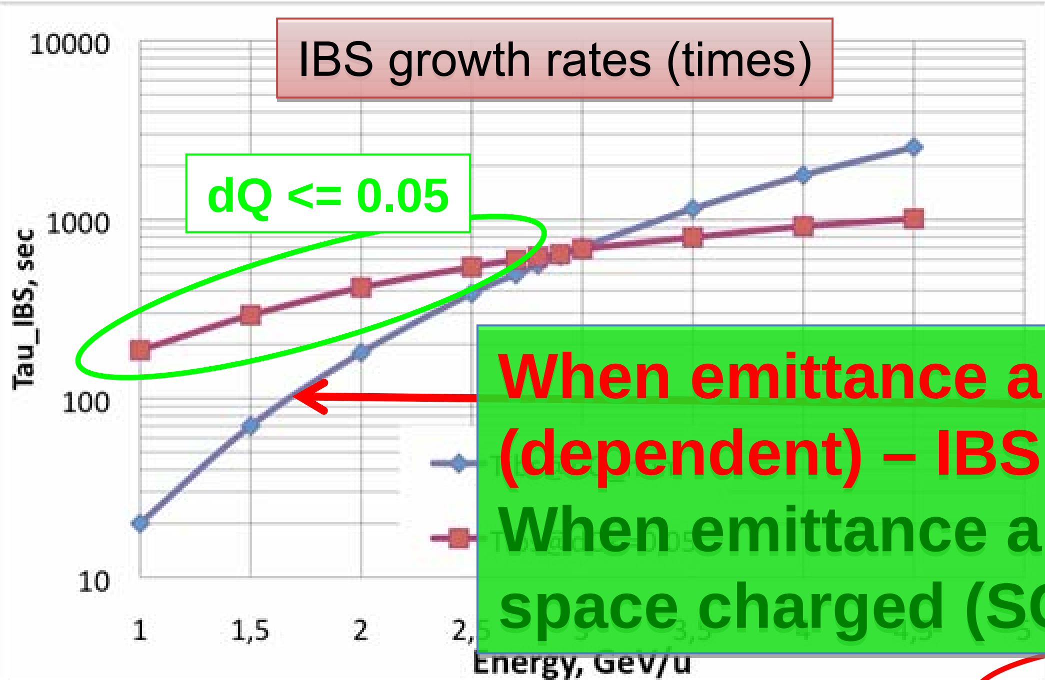
dQ > 0.05 (max @ 1 GeV/u: 0.471)



"IBS dominated regime":
bunch parameters are determined by equillibrium between IBS and beam cooling.

$$L = 8\pi^2 \beta^5 \gamma^6 \Delta Q^2 \frac{A^2}{Z^4} \cdot \frac{\varepsilon c}{r_p^2 \beta^* l_{bb}} \cdot \left(\frac{\sigma_s}{C_{Ring}} \right)^2 \cdot f_{HG}$$

IBS calculations



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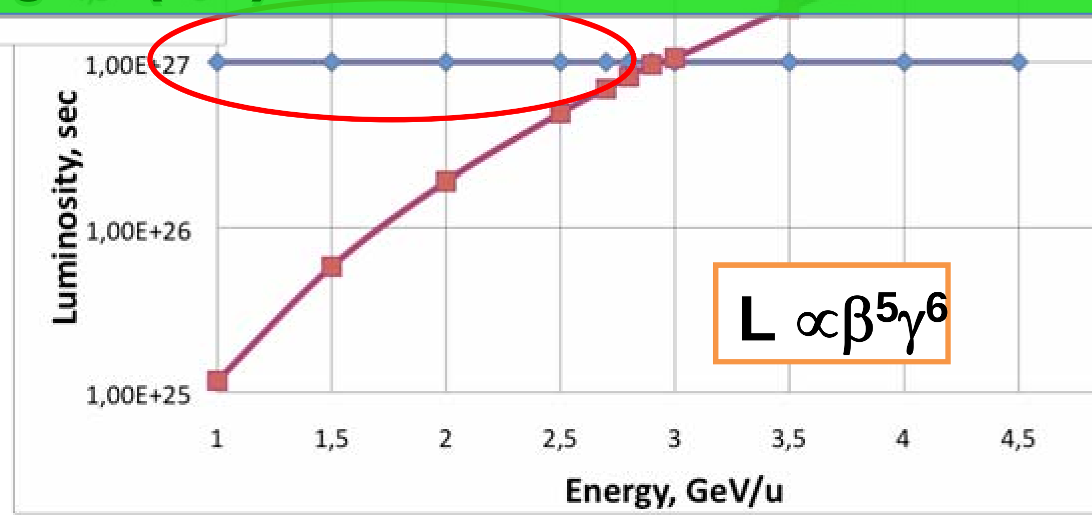
When emittance and dP/P are strongly bound (dependent) – IBS dominated regime

When emittance and dP/P are independent – space charged (SC) dominated

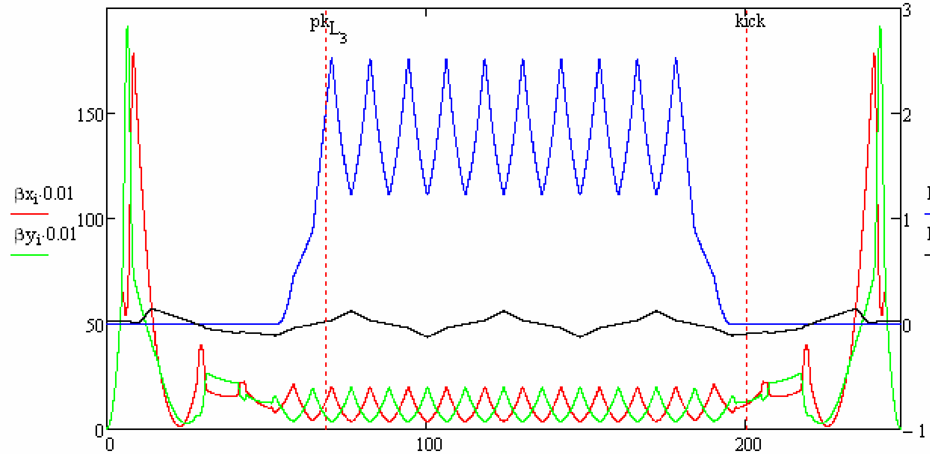
"IBS dominated regime":
bunch parameters are determined by equillibrium between IBS and beam cooling.

$$L = 8\pi^2 \beta^5 \gamma^6 \Delta Q^2 \frac{A^2}{Z^4} \cdot \frac{\varepsilon c}{r_p^2 \beta^* l_{bb}} \cdot \left(\frac{\sigma_s}{C_{Ring}} \right)^2 \cdot f_{HG}$$

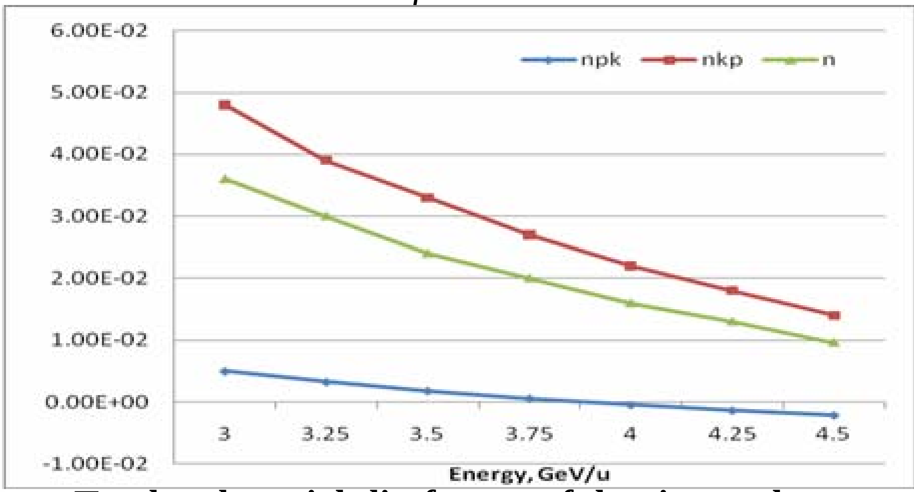


Stochastic cooling

$$\frac{1}{\tau}=\frac{W}{N}\frac{(1-1/M_{pk}^{2})^{2}}{M_{kp}} \qquad N_{eq}=N\frac{C}{\sqrt{2\pi}\sigma_s} \qquad M_{pk}=\frac{1}{2(f_{max}+f_{min})\eta_{pk}T_{pk}\frac{\Delta p}{p}} \qquad f_{max}\le\frac{1}{2\eta_{pk}T_{pk}\frac{\Delta p}{p}} \qquad M_{kp}=\frac{1}{2(f_{max}-f_{min})\eta_{kp}T_{kp}\frac{\Delta p}{p}}$$

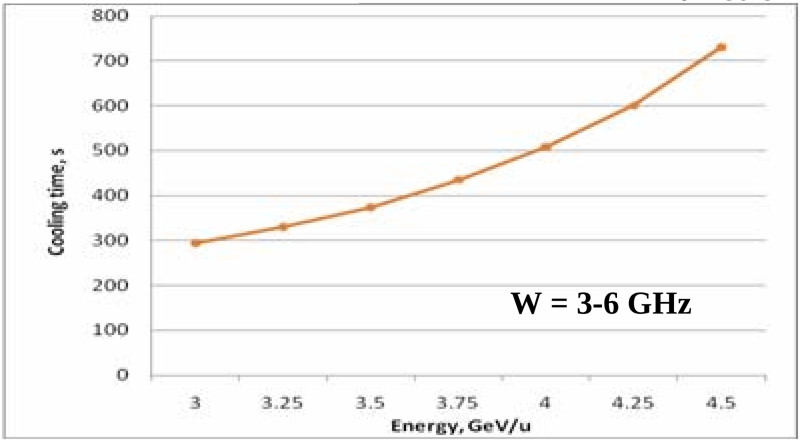


Kicker - 48 meters upstream the IP-point
PU - 132 meters upstream the Kicker



Total and partial slip-factors of the ring as the function of ion energy.

At such position of the kicker the condition gives for the acceptable upper frequency of the band the value of about 20 GHz (at the momentum spread equal to the ring dynamic aperture ±0.01). The luminosity of $1\cdot10^{27}$ cm^{-2}s^{-1} corresponds to about $2.3\cdot10^{9}$ ions per bunch, the effective ion number is about $8\cdot10^{11}$. To provide required cooling time the cooling bandwidth can be chosen from 3 to 6 GHz



"Slice" overlapping (by D.Moehl)

3..6GHz: Tsc ~ 0,5Tibs
2..4 GHz: Tsc ~ Tibs

Electron cooling

Beam emittances @ equillibrium state. Rates ($\tau\_\varepsilon_x = \tau\_\varepsilon_y = \tau\_\sigma_P$) - from IBS calculations for lattice.

Luminosity is fitted to 1e27, ε_x is fitted to 1.1 π mm mrad

$$\vec{F} = -\vec{V}\frac{4Z^2e^4n_eL_P}{m}\frac{1}{\left(V^2+\Delta_{e,eff}^2\right)^{3/2}}$$

$$L_P = \ln\left(\frac{\rho_{\max}+\rho_{\min}+\rho_{\perp}}{\rho_{\min}+\rho_{\perp}}\right) \qquad \rho_{\min} = \frac{Ze^2}{m}\frac{1}{V^2+\Delta_{e,eff}^2}$$

$$\rho_{\max} = \frac{v_i}{1/\tau_{flight}+\omega_p}$$

$\Delta_{e\ eff}$ = 0,0046 eV

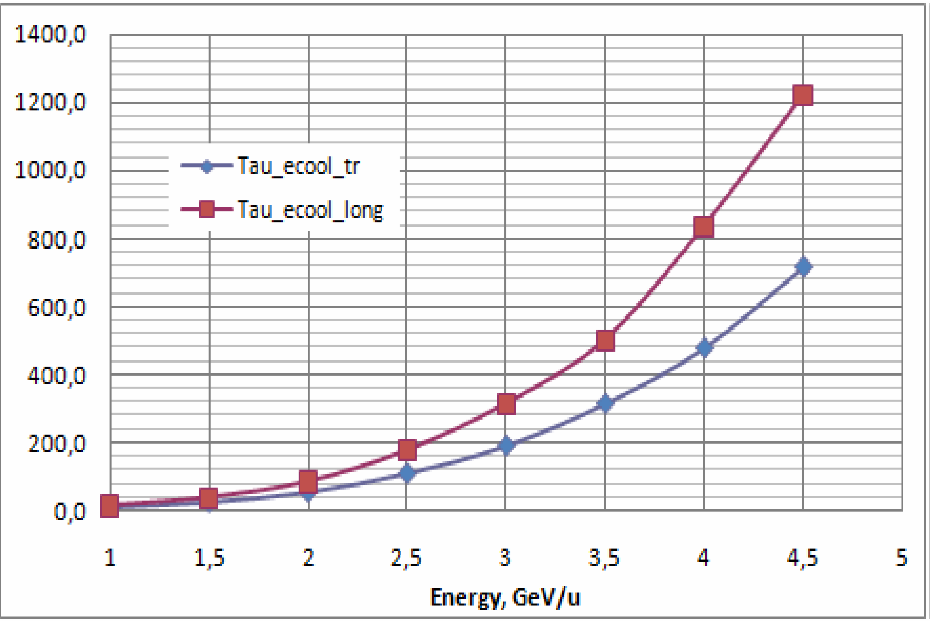
Angular spread [rad] = 2e-5

Parkhomchuk model. $\beta_x = \beta_y \approx$ 20m @ cooling section, L = 6m, B=1T (required mainly to provide adiabatic transport of the electron beam from HV source to the cooling section), I_electron = 0,5A. T_tr_e - chosen at all energies to the value in order to have τ_{life} (due_to_recombination)>=10 hours (36000 seconds: recombination rate limit = 2,7E-5.

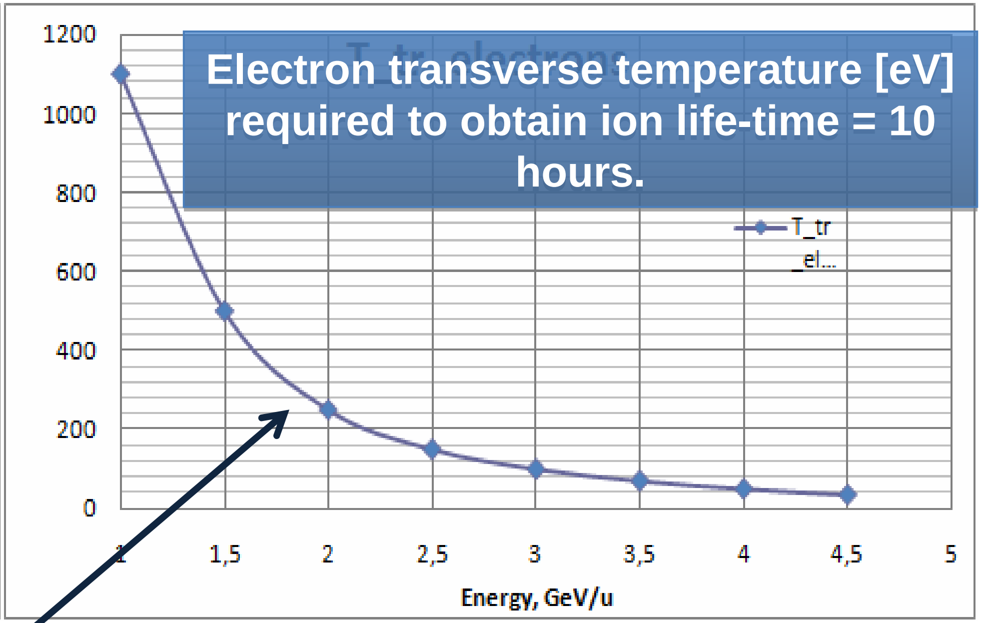
Radius_electron_beam chosen to have T_ecool = min (same at all energies)

The cooling rate is determined mainly by longitudinal electron temperature (that is dominated by HV generator stability) and logarithmically depends on the transverse one

Electron cooling

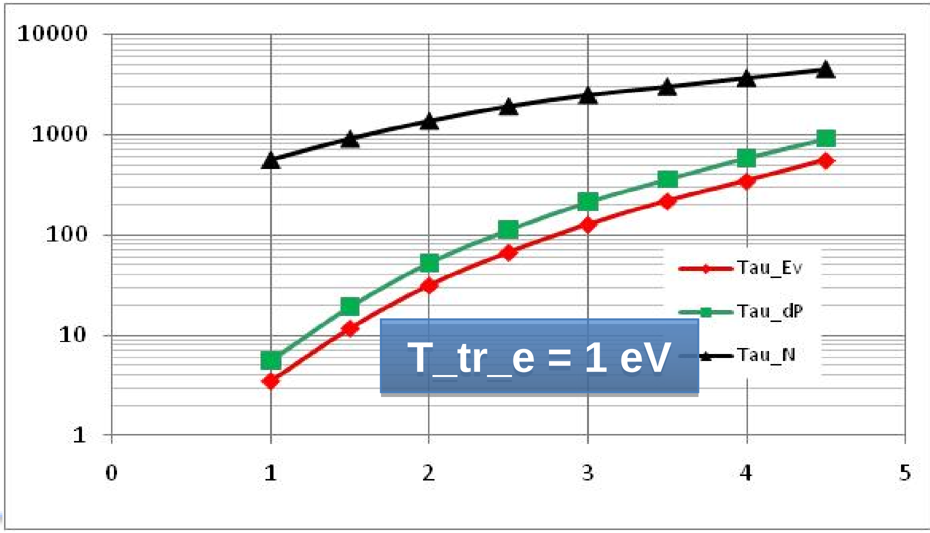


Dependence of the cooling times for transverse and longitudinal degrees of freedom



Electron transverse temperature [eV] required to obtain ion life-time = 10 hours.

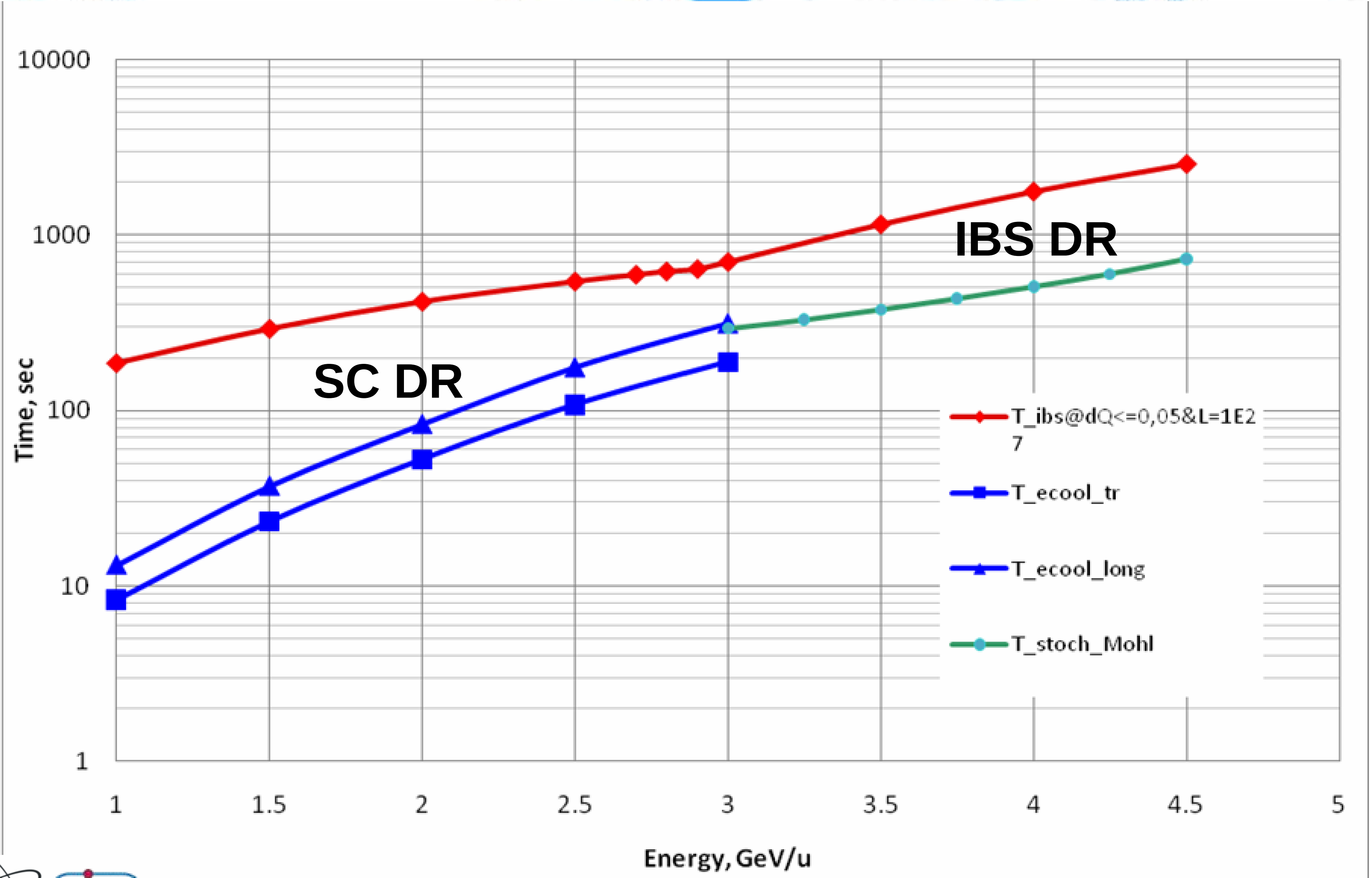
Recombination supression:
a) Increasing T_tr_e
b) "Shift" of electron energy



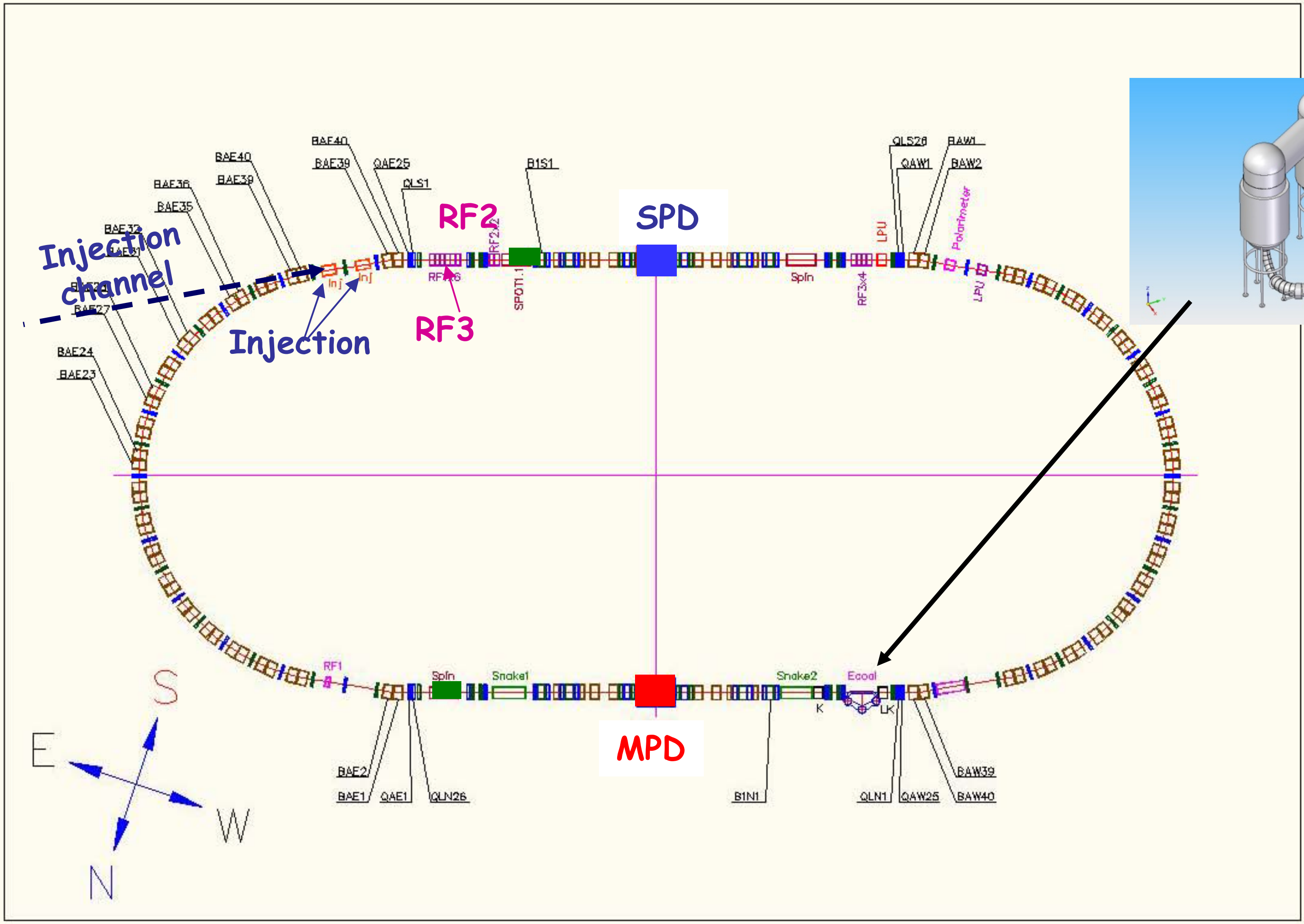
T_tr_e = 1 eV

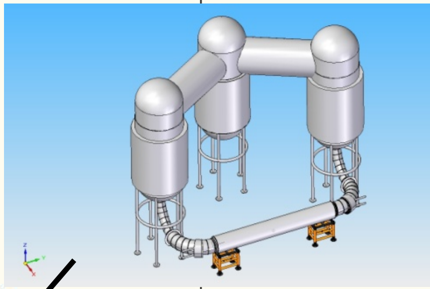
Conclusions: T_ecool ~ 0,05 Tibs at 1 GeV/u

Summary final



HV electron cooling system





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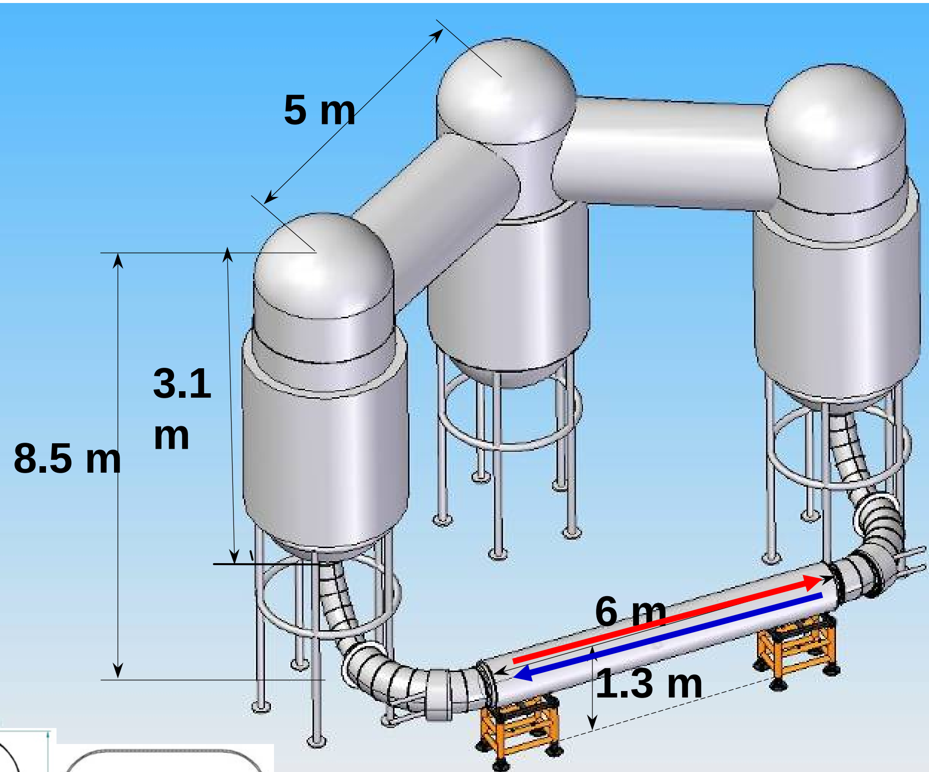
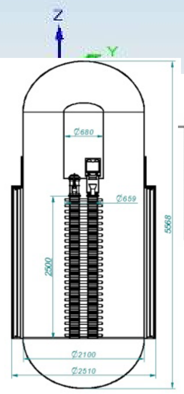
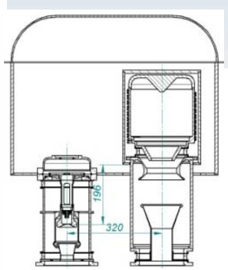
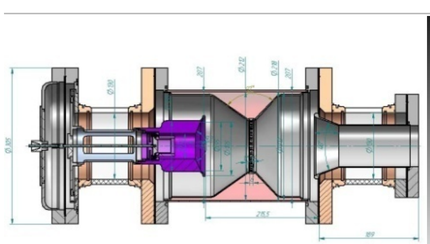
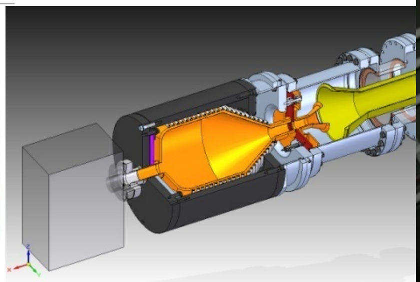


Electron beam energy, MeV	0,5 ÷ 2,5
Collector potential vs cathode, kV	0,5 ÷ 2,0
Electron beam current	0.1 ÷ 1,0
Electron beam current losses, мA	< 0.1
Radiated power from cathodes,, W	2×100
Max. rad. power at collectors, kW	2×2
Electron cathode diameter, cm	3,0
Long. Magnetic field, T	0,1 ÷ 2,0
Electron energy stability	1×10^{-4}



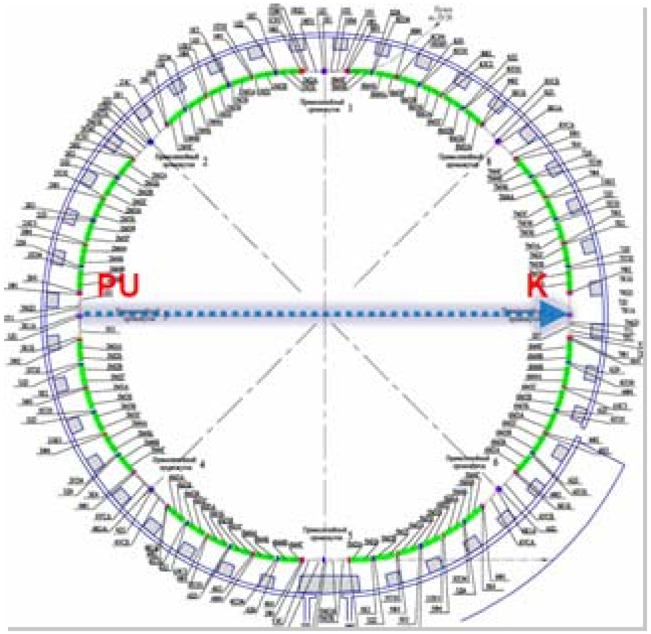


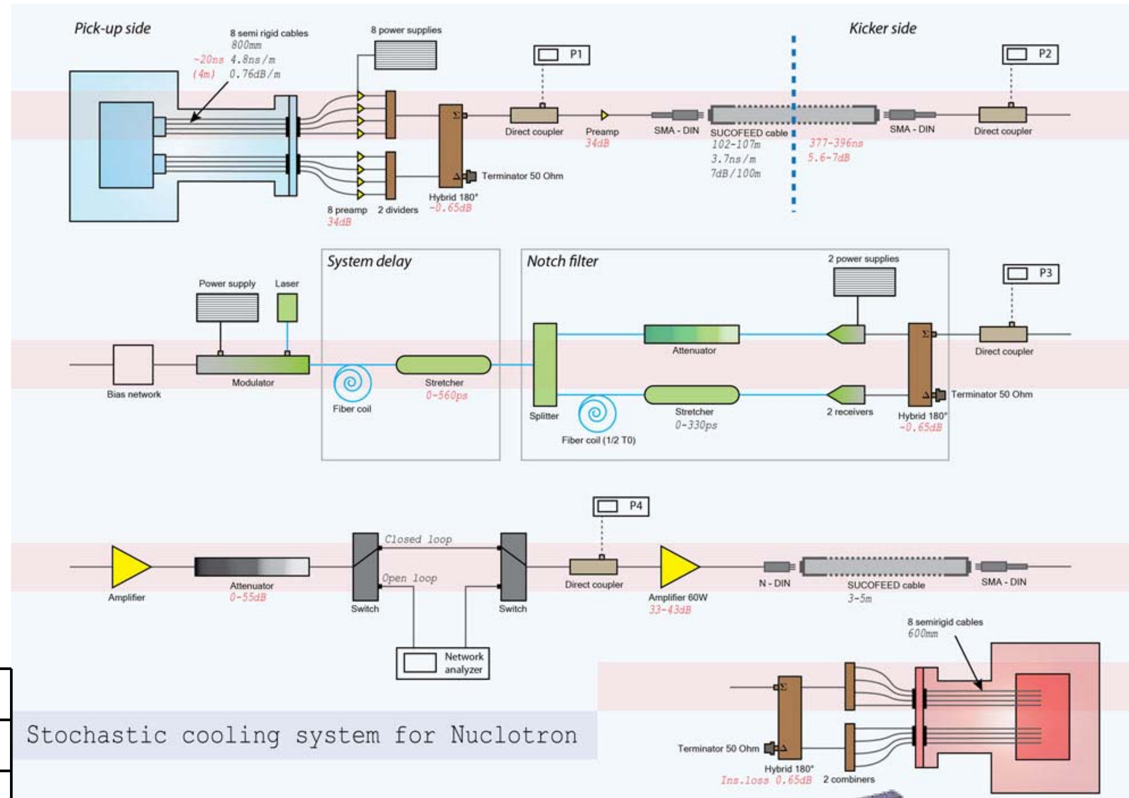


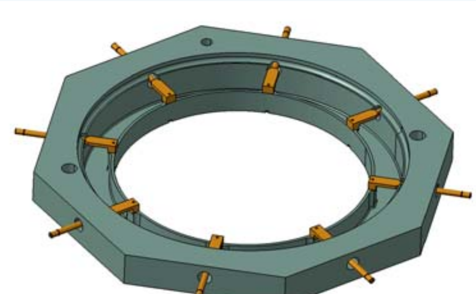


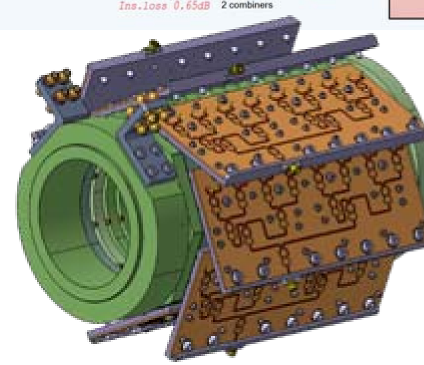
HV Generator prototype U=250 kV, I=1mA

SC experiment at Nuclotron





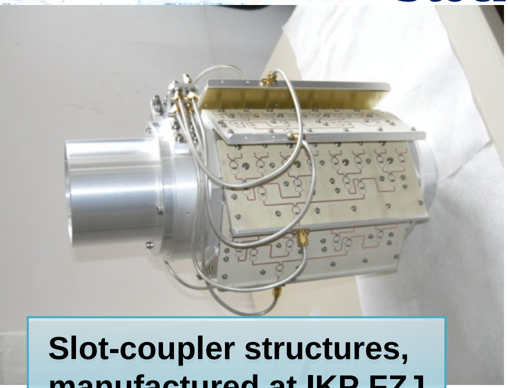




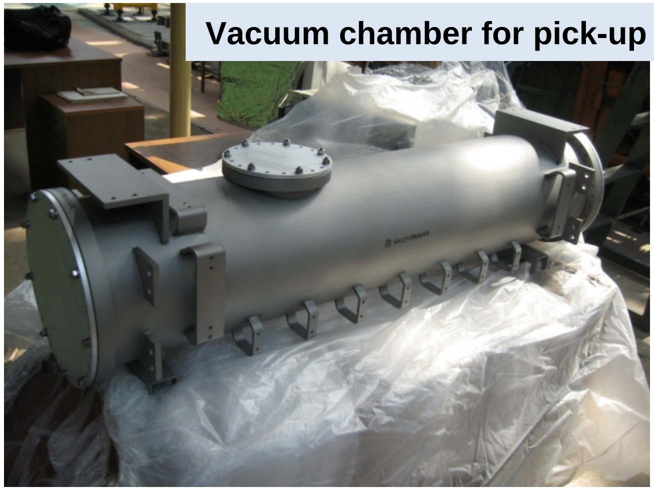
Circumference, m	251.5
Ions	up to A=56
Energy, GeV	3.5
Rev.frequency, MHz	1.2
Vacuum, Torr	10^-10
Intensity	10^11(p)- 10^9(C12)
Ring slippage factor	0,0322
dp/p	10^-3

Nuclotron-NICA

Stochastic cooling system prototype at Nuclotron

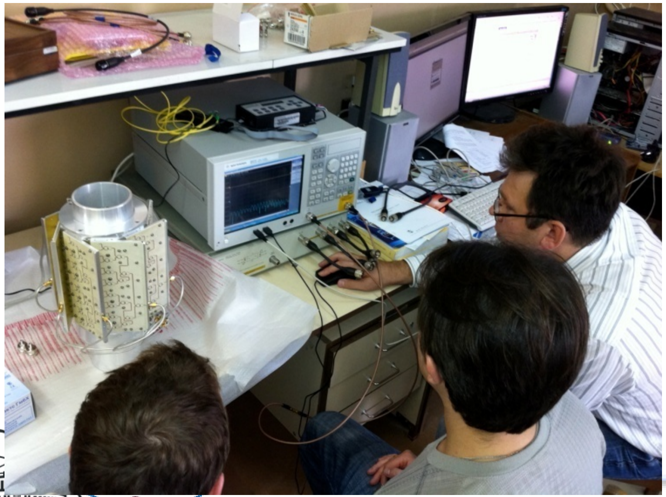


Slot-coupler structures, manufactured at IKP FZJ



Vacuum chamber for pick-up

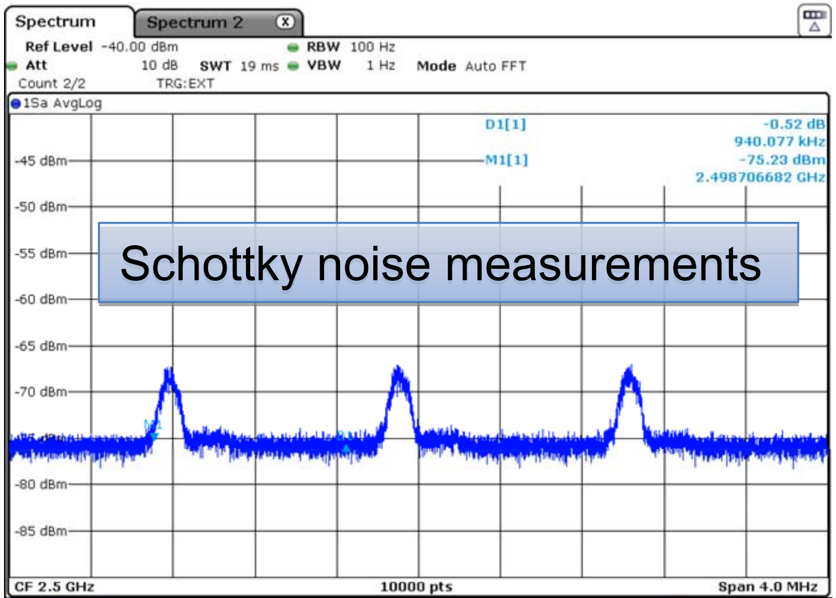
Vacuum chamber for kicker



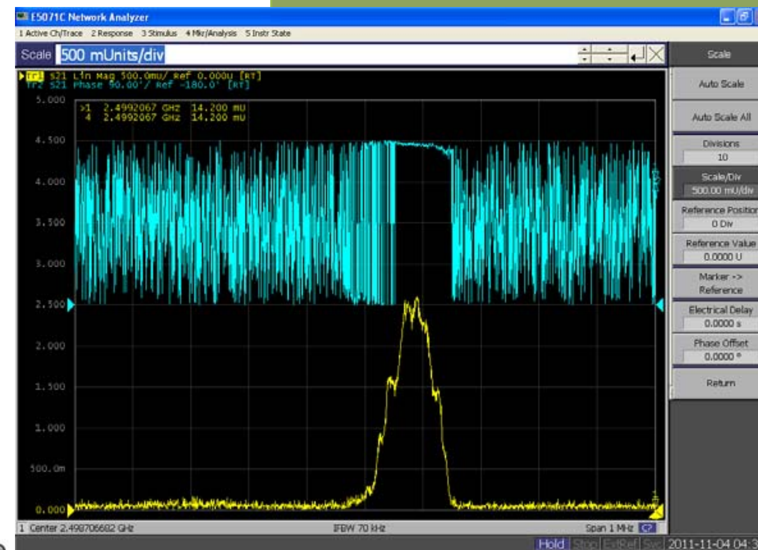
Experimental set-up:

Experimental results:

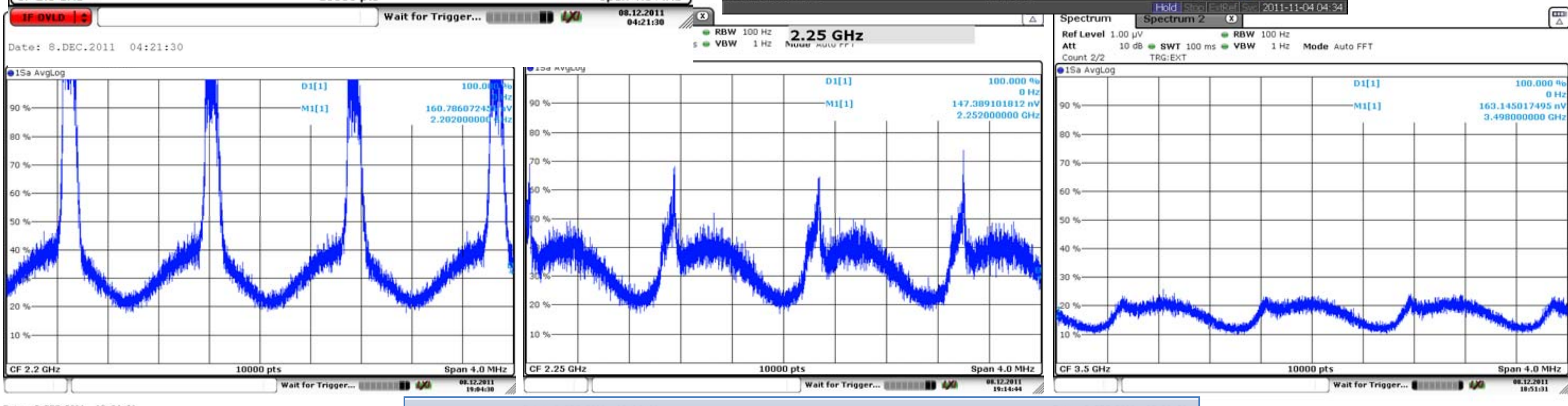
Energy range 0.5-4.0 GeV/u
Deutrons, C6+
During 2 runs in 2011 and 2012



Schottky noise measurements



Beam BTF
d, 2 GeV/u



Notch filter rejects revolution frequencies

Conclusions

1. Electron cooling at Booster is required to have wide machine possibilities at beam injection from HILAC and to perform applied research

2. Stochastic cooling at NICA collider is sufficient for IBS suppression and for beam stacking also

2. Electron cooling can be used for cooling at experiment in the total energy range

3. Electron cooling can provide effective stacking at small energy only

4. At energy larger than 3 GeV/u the experiment can be provided using electron cooling as well as stochastic, or combination of both methods

5. 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

6. Slow acceleration of the beam is presumed for the case when effective stacking (or injection) is complicated at the experiment energy

Thank you for your attention !

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