Application of cooling methods at NICA project

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Outline

1. NICA scheme, modes of operation, working cycles;

2. Booster scheme, parameters, beam requirements;

3. Status of the electron cooler for booster;

4. Collider scheme, parameters, beam requirements;

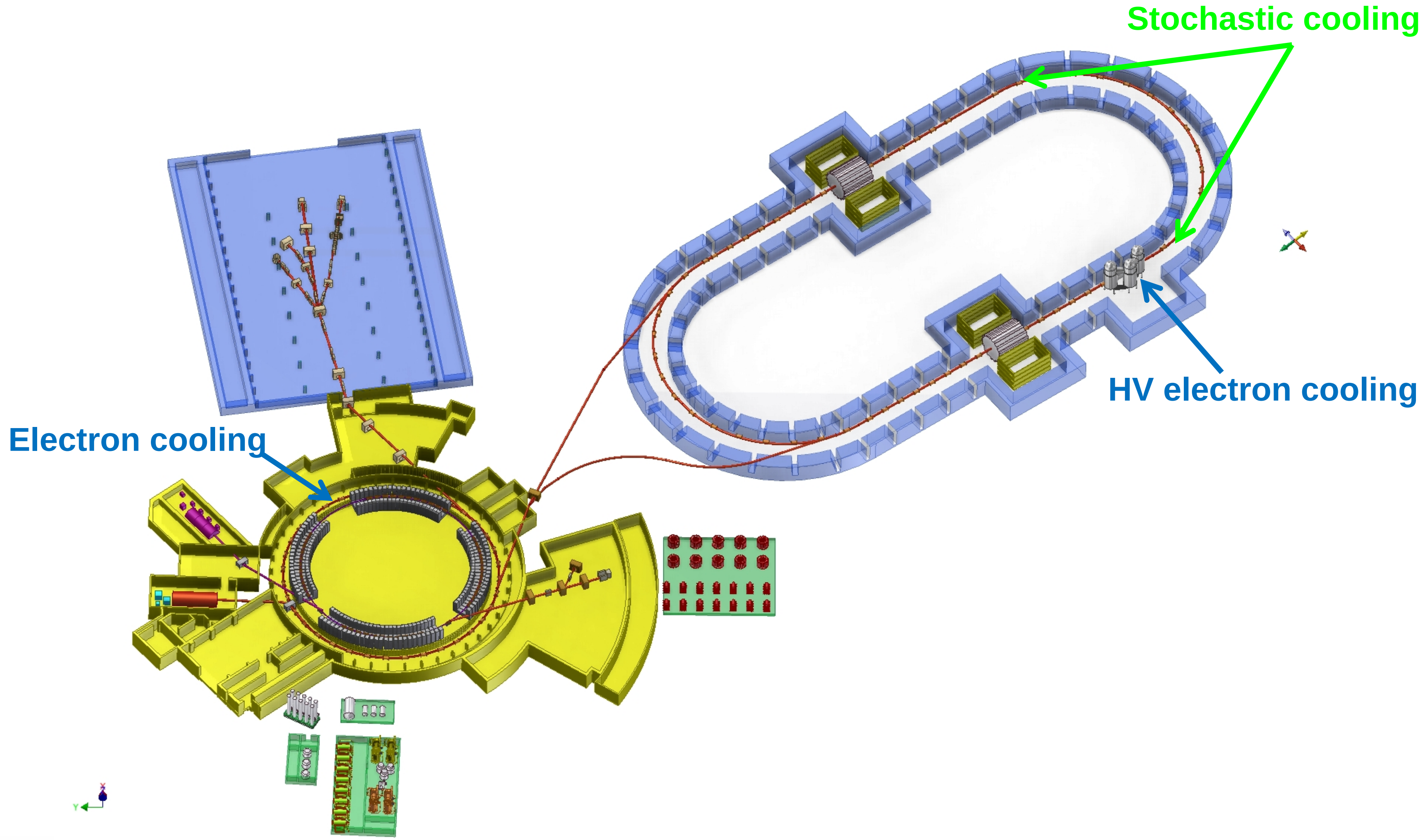
5. Beam cooling scenario at the collider: numerical simulations, choice of energy range for optimal operation of beam cooling systems to provide required luminosity life-time for the experiment;

6. Conceptual design of the stochastic cooling system for collider;

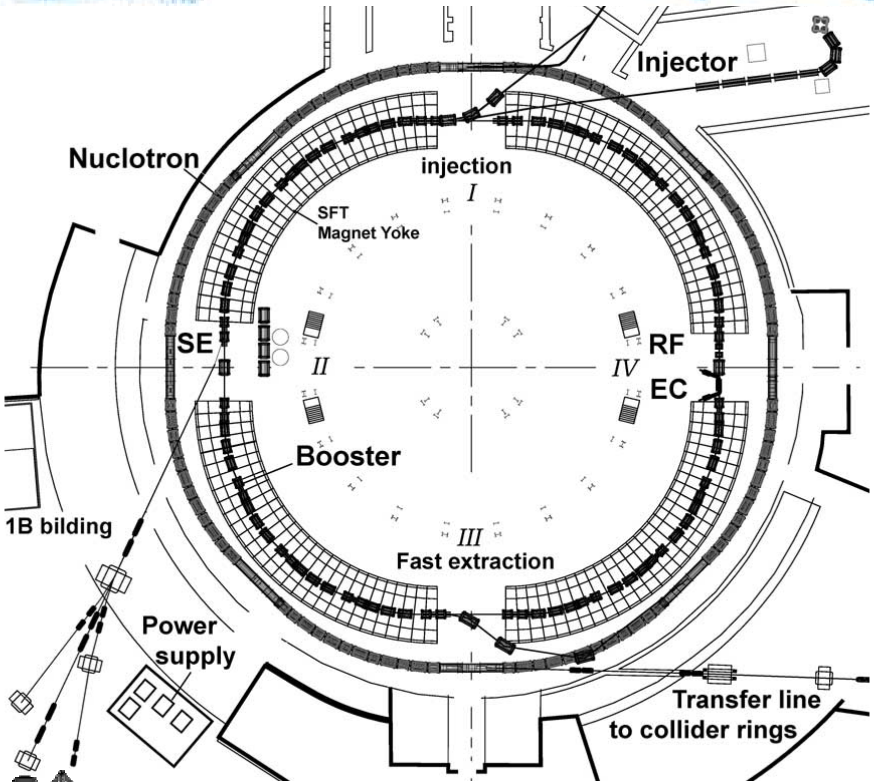
7. Conceptual design of the HV electron cooler for collider;

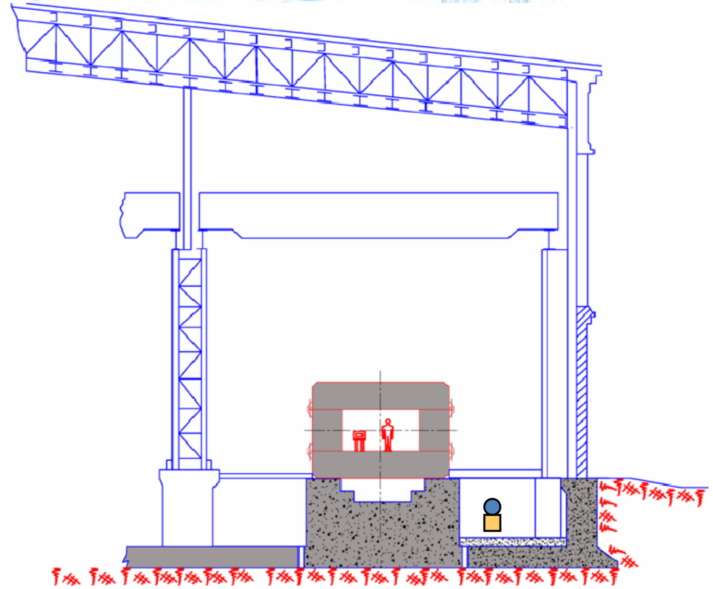
8. Experiment on stochastic cooling at Nuclotron in the NICA energies

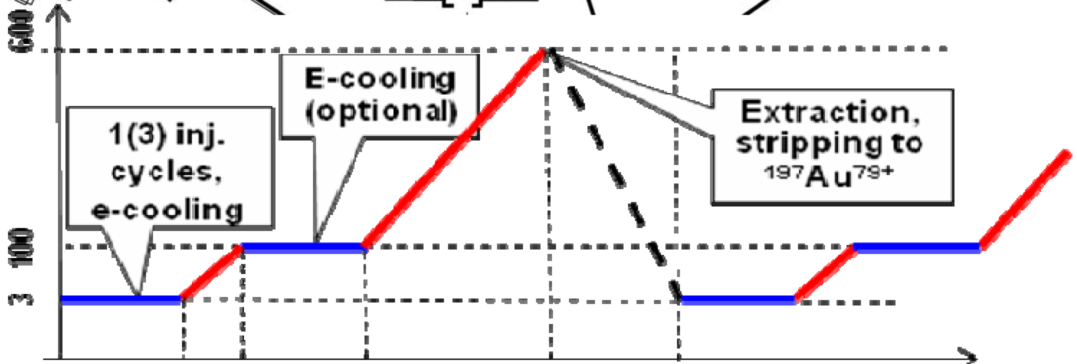
NICA complex

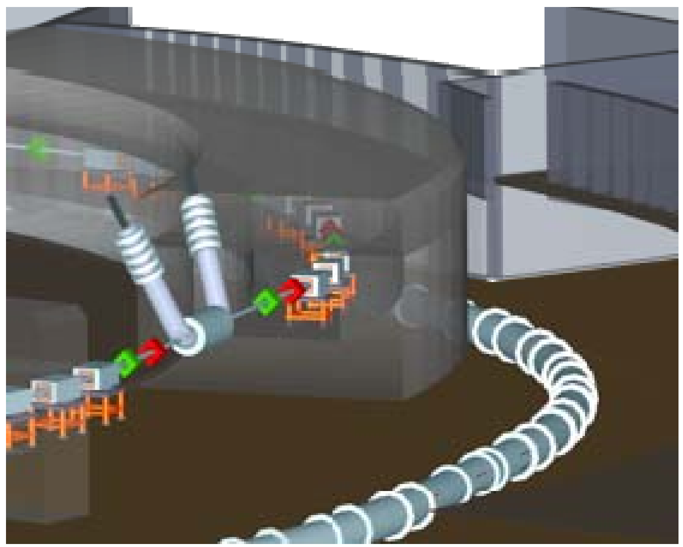


Booster synchrotron

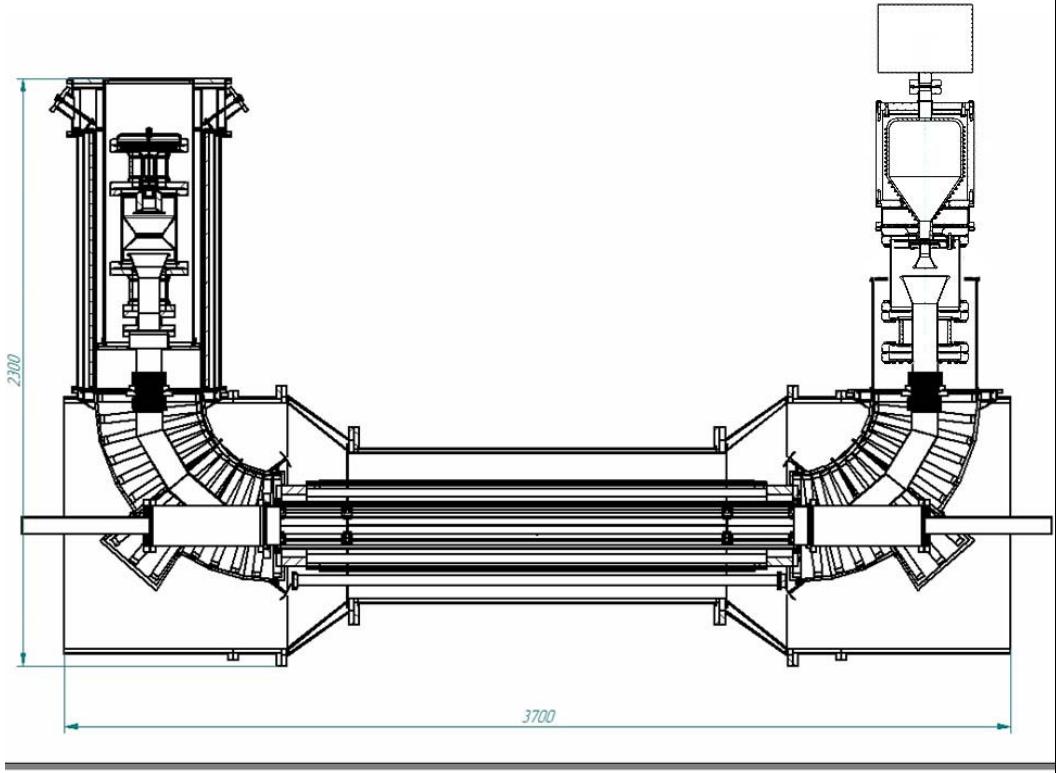








Booster electron cooling system

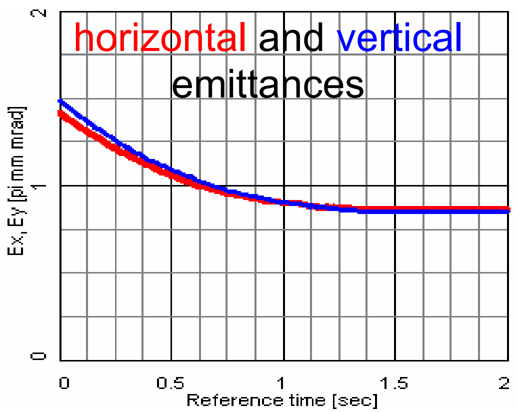


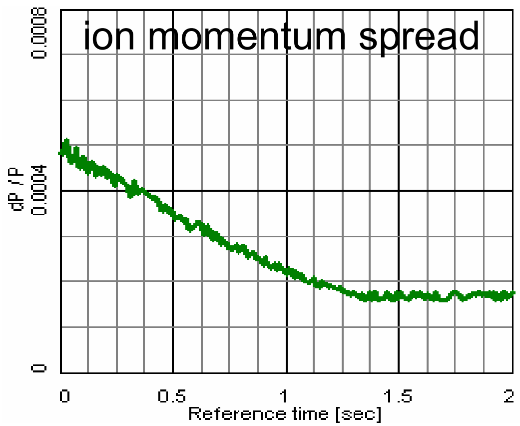
Ions	$197Au^{31+ (65+)}$
Booster circumference, m	211.2
Injection/extraction energy, MeV/u	3/600
Max. dipole field, T	1.8
Ion number	2×10^9
Beta functions in cooling section, m	8 / 8
Dispersion in cooling section, m	0.6
Maximum electron energy, keV	50.0
Electron beam current, A	0 ÷ 1.0
Cooler overall length, m	4.0
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, $\Delta B/B$	$1\cdot10^{-4}$
Electron beam radius, cm	2.5
Transverse electron temperature, meV	200
Longitudinal electron temperature, meV	0.5
Cooling time, s	1
Residual gas pressure, Torr	10^{-11}

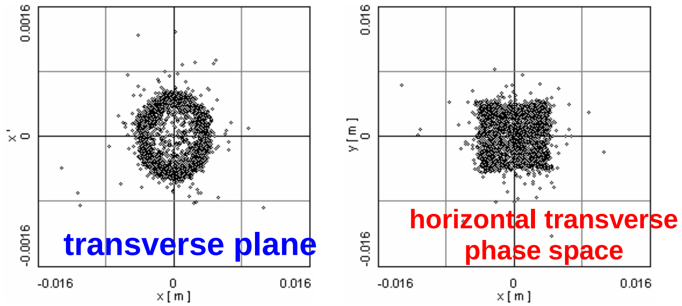
Poster session: A.Rudakov

Simulation of cooling process with BETACOOL

Evolution of the bunched ion beam parameters during the cooling process

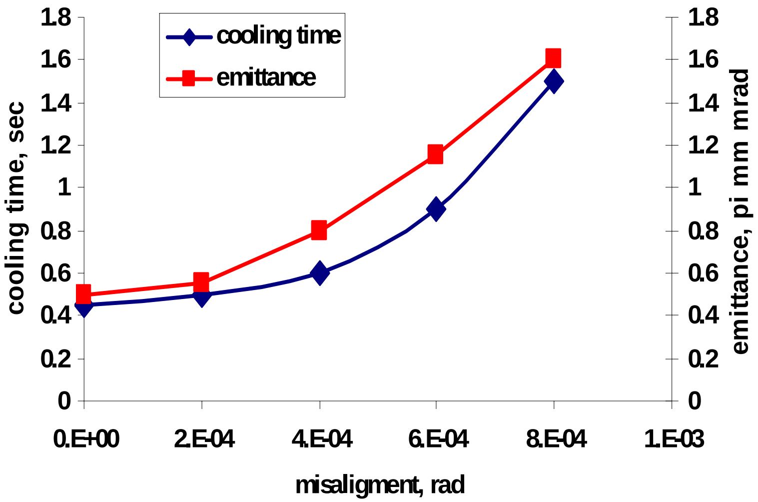






Ion beam density distribution after 2 seconds of the cooling

The dependence of the cooling time and transverse emittance after cooling process on misalignment angle between electron and ion beams axes

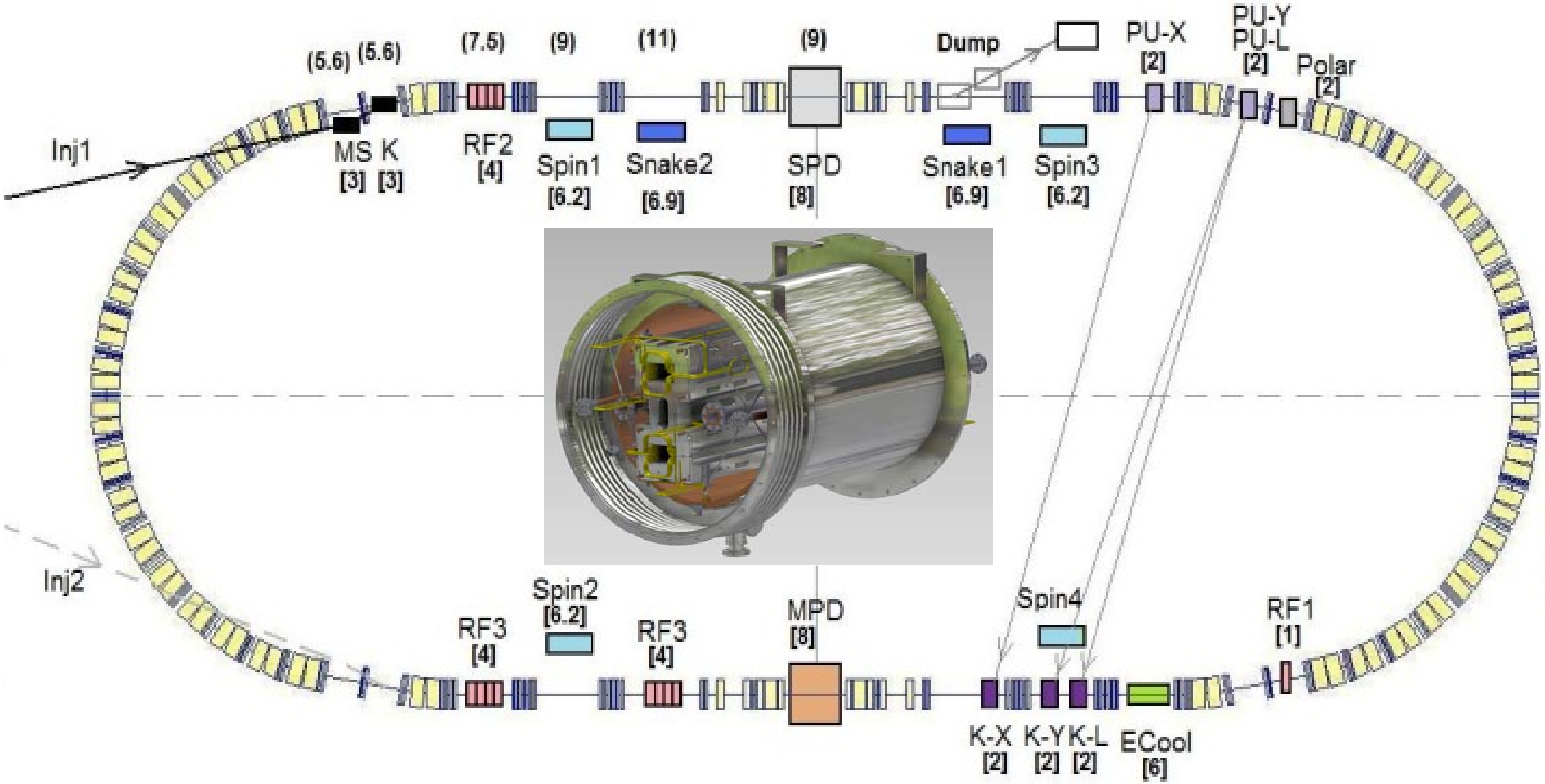


Initial parameters of the cooling

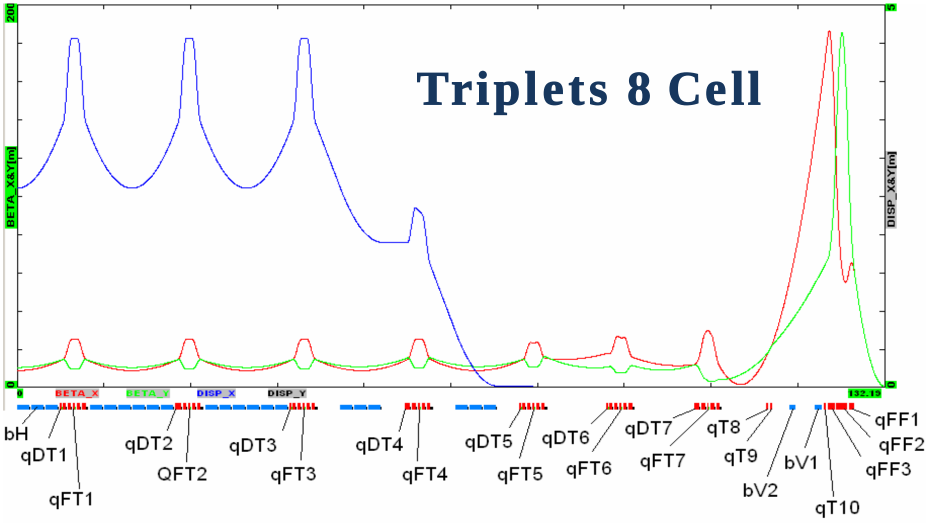
Ion energy, MeV	100
Ion kind	$^{197}Au^{31+}$
Particle number	2×10^9
Initial Tr_emittance, π mm mrad	1.5
Initial momentum spread	5×10^{-4}
RF voltage, kV	10
Initial bunch length, m	14
Electron beam current, A	1.0
Electron beam temp. long/trans, meV	200 / 0.5
Misalignment of ion and electron beams axes	5×10^{-4}

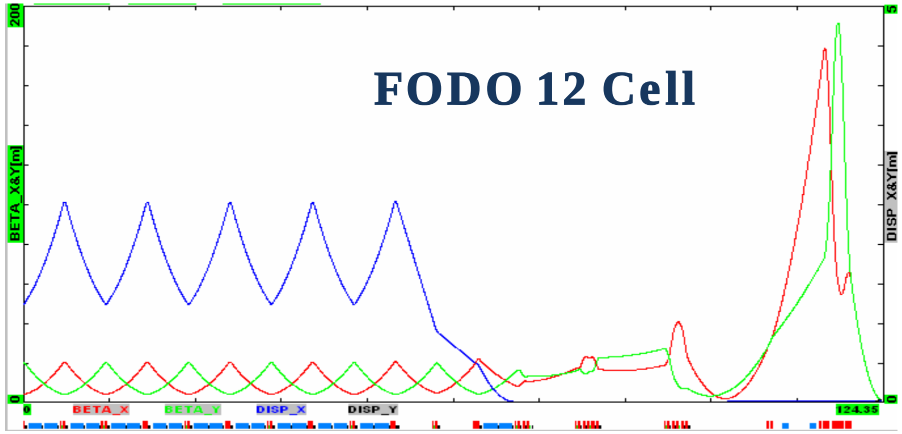
Poster session: A.Rudakov

NICA collider



Lattice choice





Optics	Ring circumference, m	E_{tr}, GeV/u (γ_{tr})	Slip-factor, η at 4.5 GeV/u	VRF-max, kV	Number of the dipoles in the ring	Length of the dipole magnet, m	T_{IBS},s
FODO-12 cells	497	5.68 (7.05)	0.010	804	80	1.94	1240
FODO-11 cells	489	5.10 (6.43)	0.006	702	72	2.16	1110
FODO-10 cells	503	4.54 (5.89)	0.0006	666	96	1.62	980
Triplets 8 cells	529	4.66 (5.96)	0.002	720	84	1.85	1200
Triplets 10 cells	576	6.16 (7.56)	0.012	995	108	1.44	1610

Key issue:

injection

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 $\sigma_s << \beta^*$):

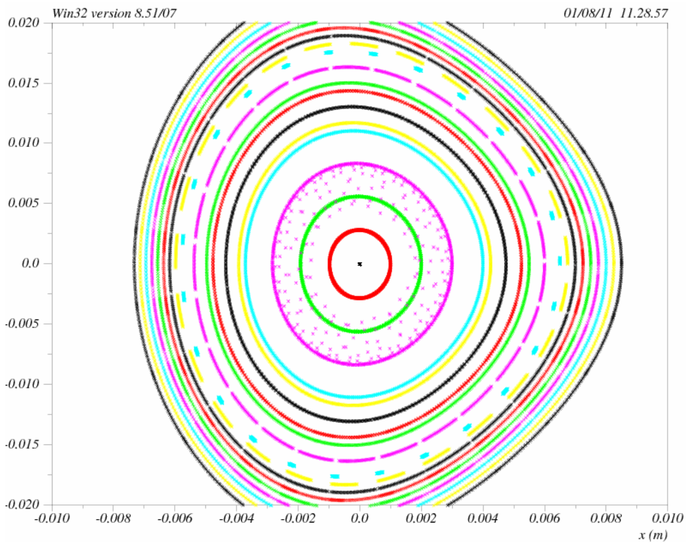
$$f_{HG}\left(\frac{\sigma_s}{\beta^*}\right) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} \frac{\exp(-u^2)du}{\left[1+\left(\frac{u\sigma_s}{\beta^*}\right)^2\right]}$$

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

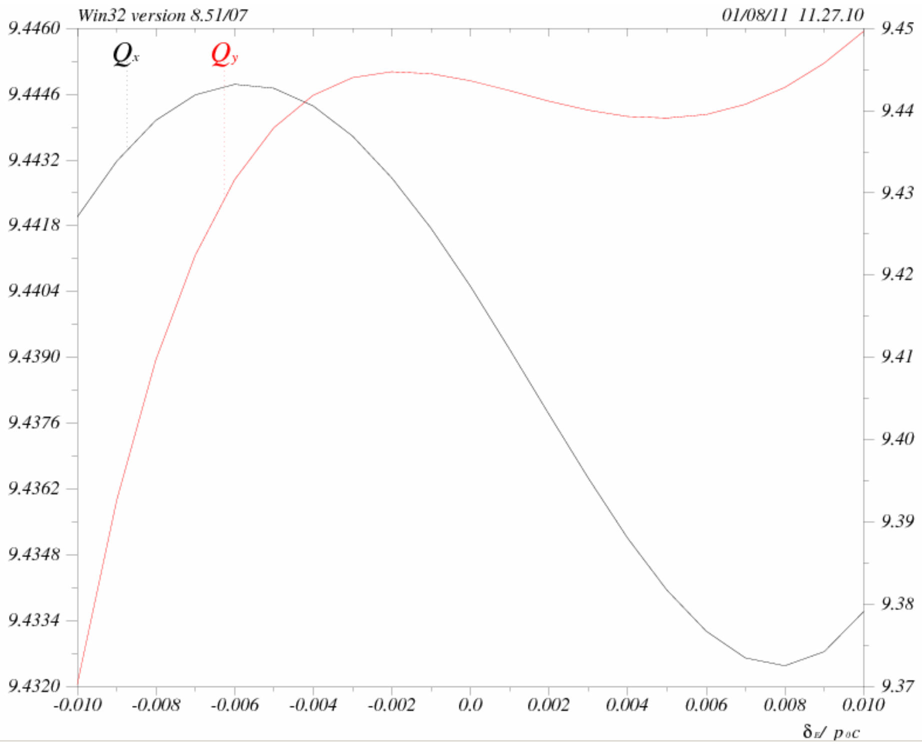
Lattice requirements and limitations

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.



The collider dynamic aperture in the horizontal phase space.

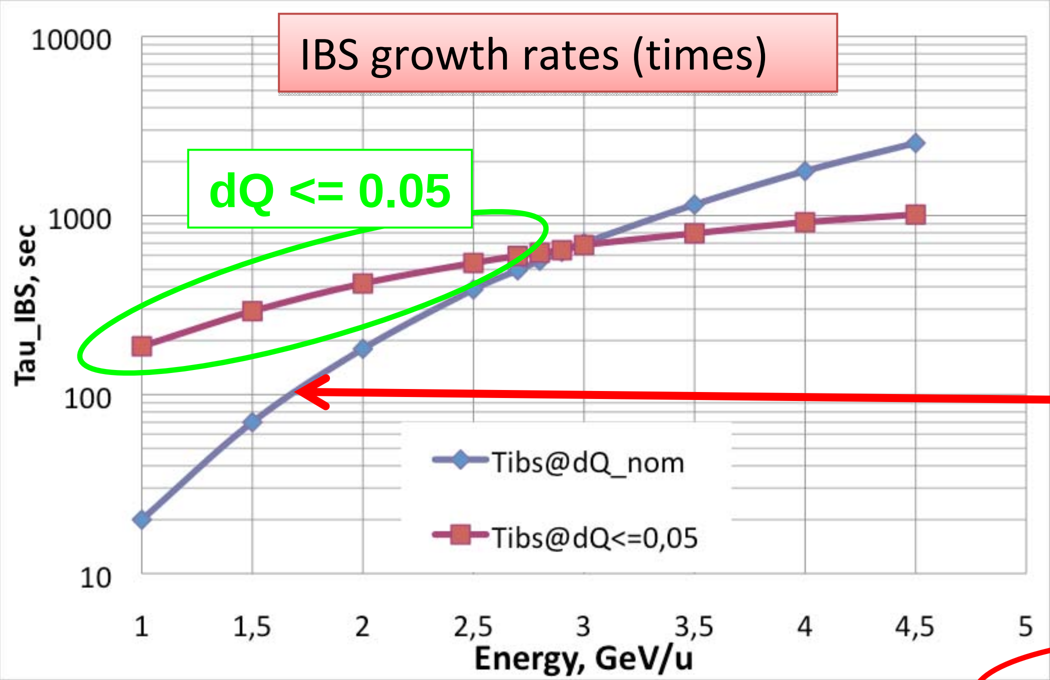


Dependence of the betatron tunes on the dP/P.

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%

IBS calculations



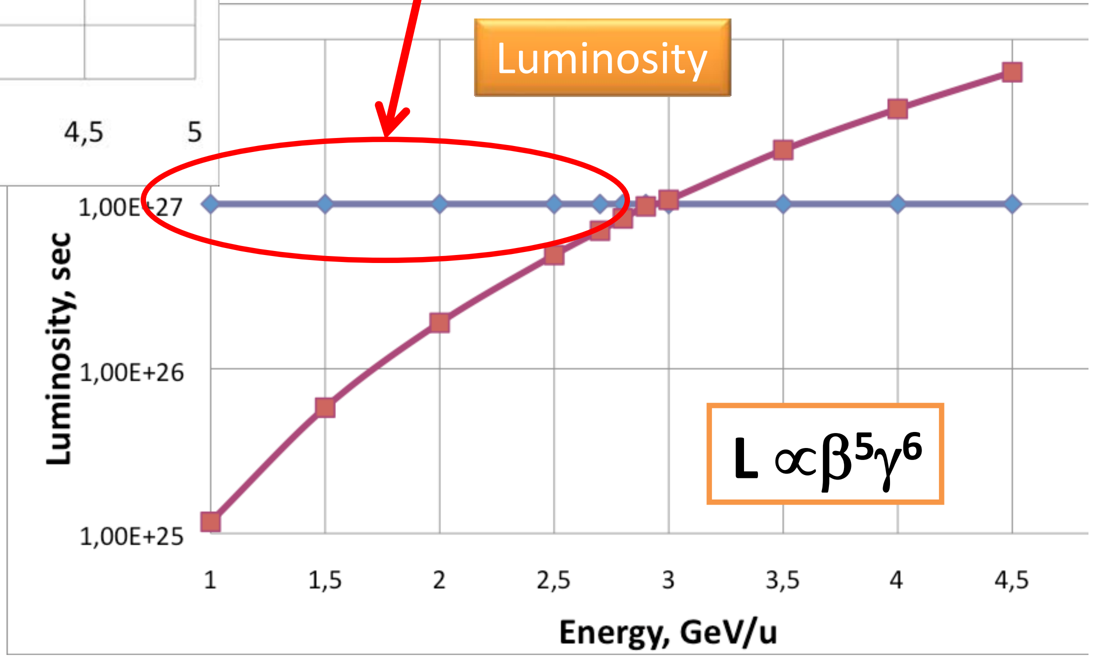
Strategy:

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)

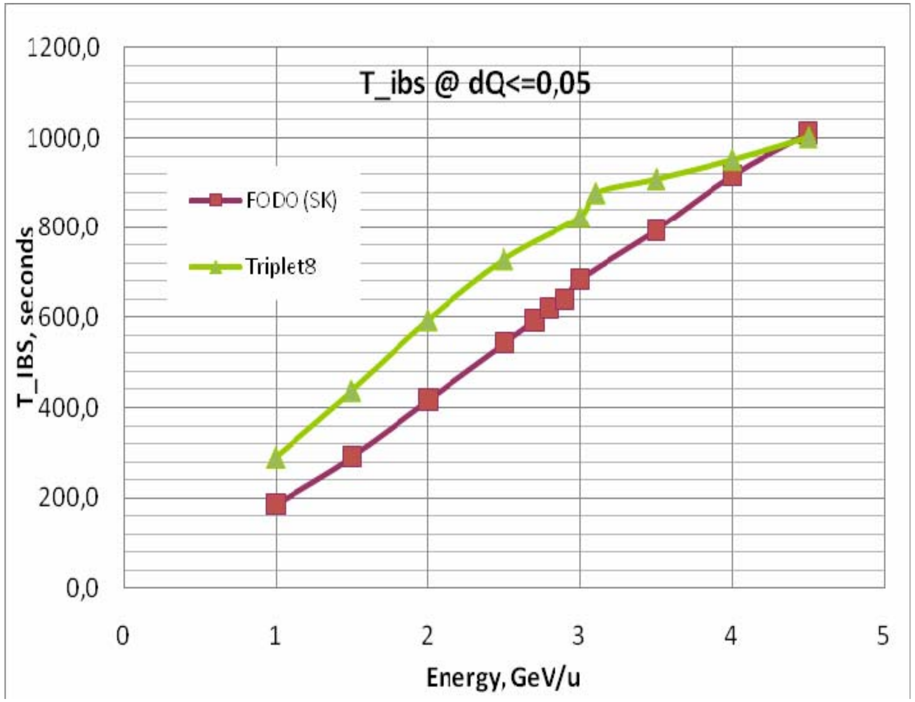
"IBS dominated regime": bunch parameters are determined by equillibrium between IBS and beam cooling.

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



Different regimes of operation

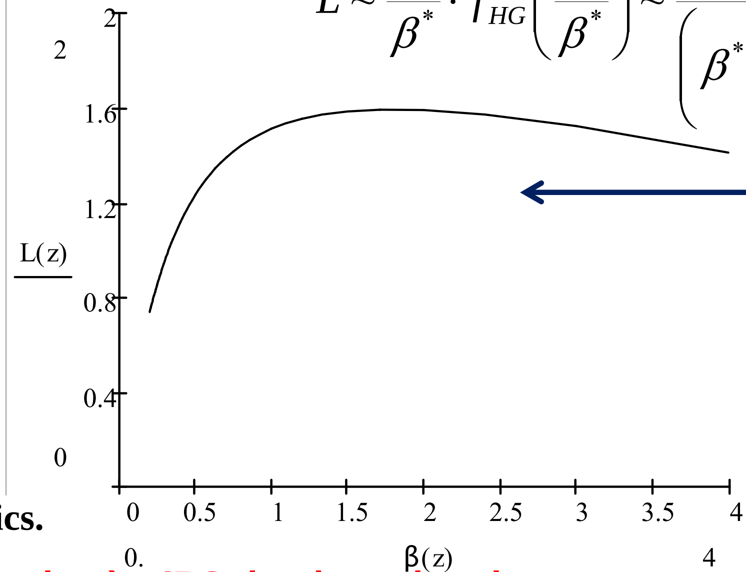
Conclusions: when Energy > 3 GeV/u we can allow T_cool = T_ibs.
when E < 3 GeV/u we need T_cool << T_ibs (at least by one order)



IBS heating times at maximal luminosity for two arc optics.

$$A \approx \frac{a^2}{\beta_{\max}} \qquad \beta_{\max} \approx \beta^* + \frac{l_{tr}^2}{\beta^*}$$

$$L \sim \frac{\varepsilon}{\beta^*} \cdot f_{HG}\left(\frac{\sigma_s}{\beta^*}\right) \sim \frac{a^2}{\left(\beta^* + \frac{l_{tr}^2}{\beta^*}\right)\beta^*} f_{HG}$$



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

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

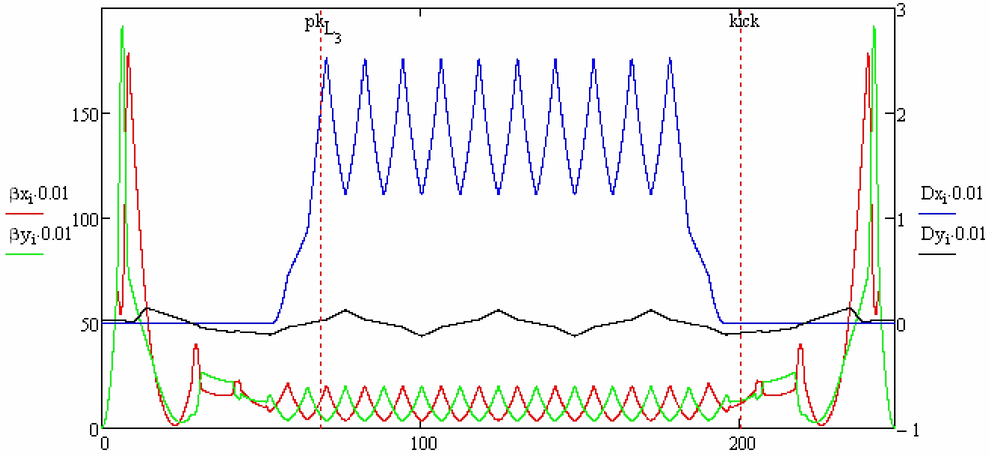
At low energy range IBS DR we can increase Luminosity increasing emittance.

But as soon as ε_x is limited by aperture FF lenses, we should increase beta-function at IP.

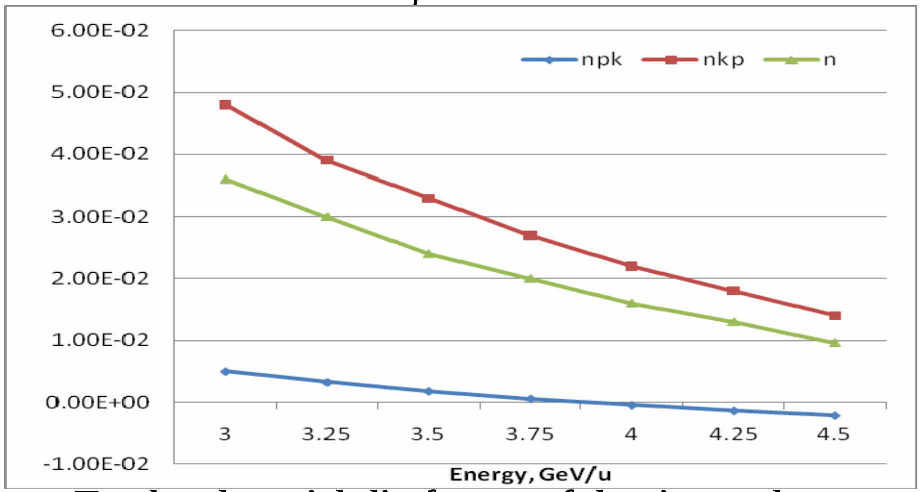
It can give additional 50% for Luminosity

Stochastic cooling

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

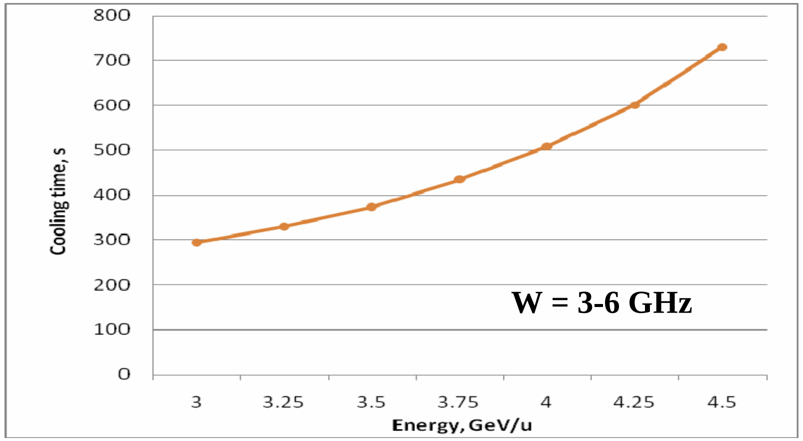


Kicker - 48 meters upstream the IP-point
PU - 132 meters upstream the Kicker



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

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

$$L_P = \ln\left(\frac{\rho_{\max}+\rho_{\min}+\rho_\perp}{\rho_{\min}+\rho_\perp}\right)$$

$$\rho_{\min} = \frac{Ze^2}{m}\frac{1}{V^2+\Delta^2_{e,eff}}$$

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

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

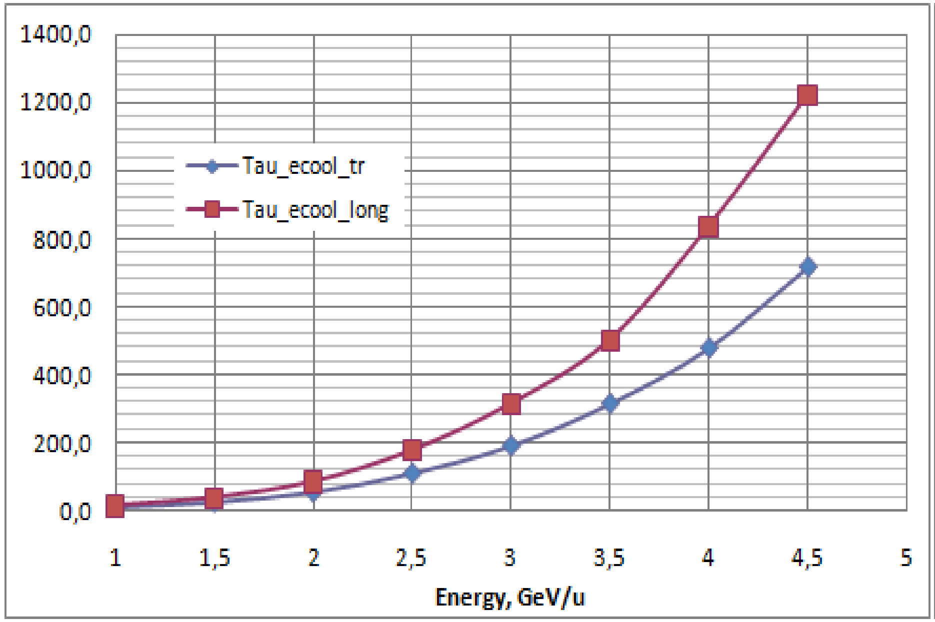
Angular spread [rad] = 2e-5

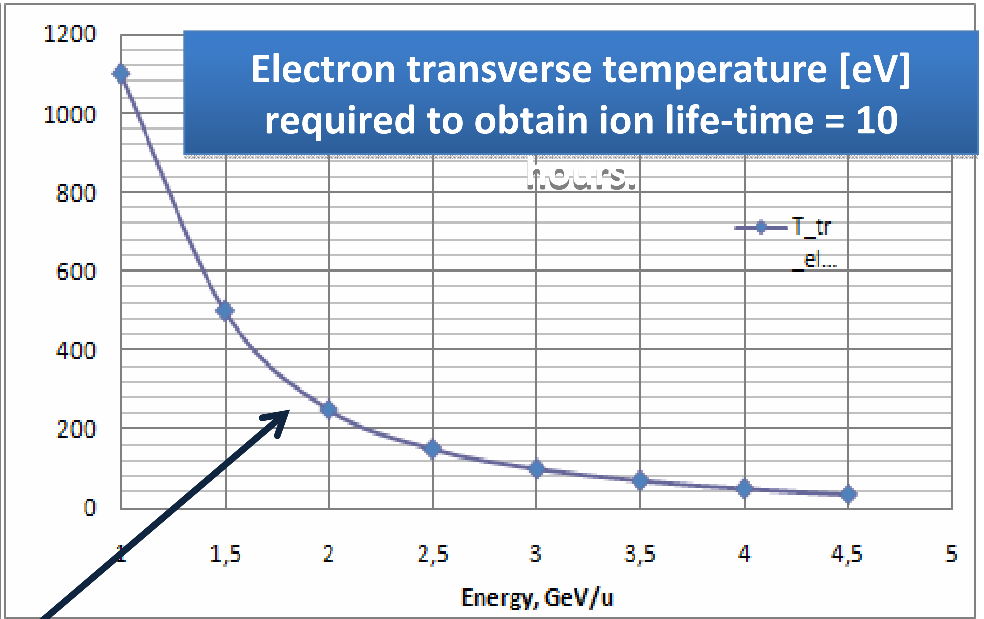
Parkhomchuk model. $\beta_x = \beta_y \approx$ 20m @ cooling section, L = 6m, B=1T (required mainly to provide adiabatic transport of the electron beam from HV source to the cooling section), I_electron = 0,5A. T_tr_e - chosen at all energies to the value in order to have τ_{life} (due_to_recombination)>=10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



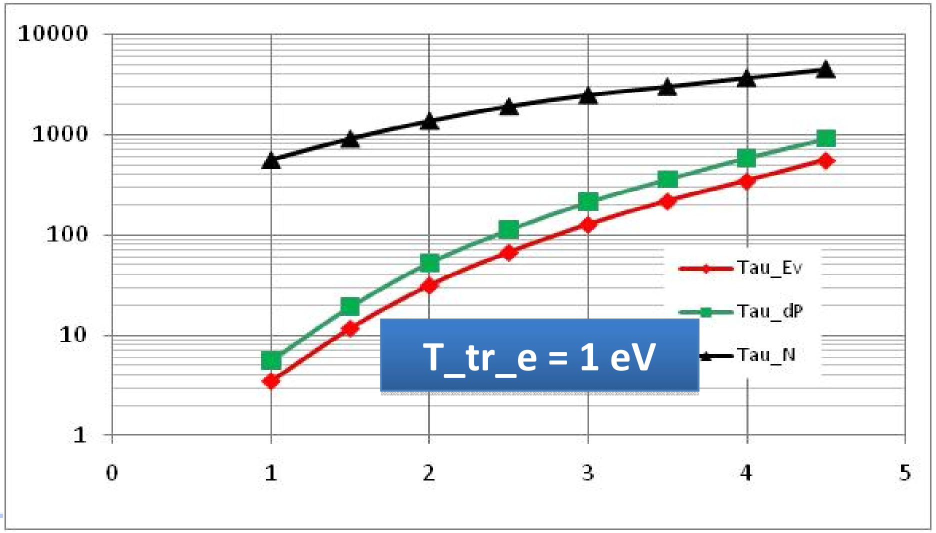


Dependence of the cooling times for transverse and longitudinal degrees of freedom

Recombination supression:

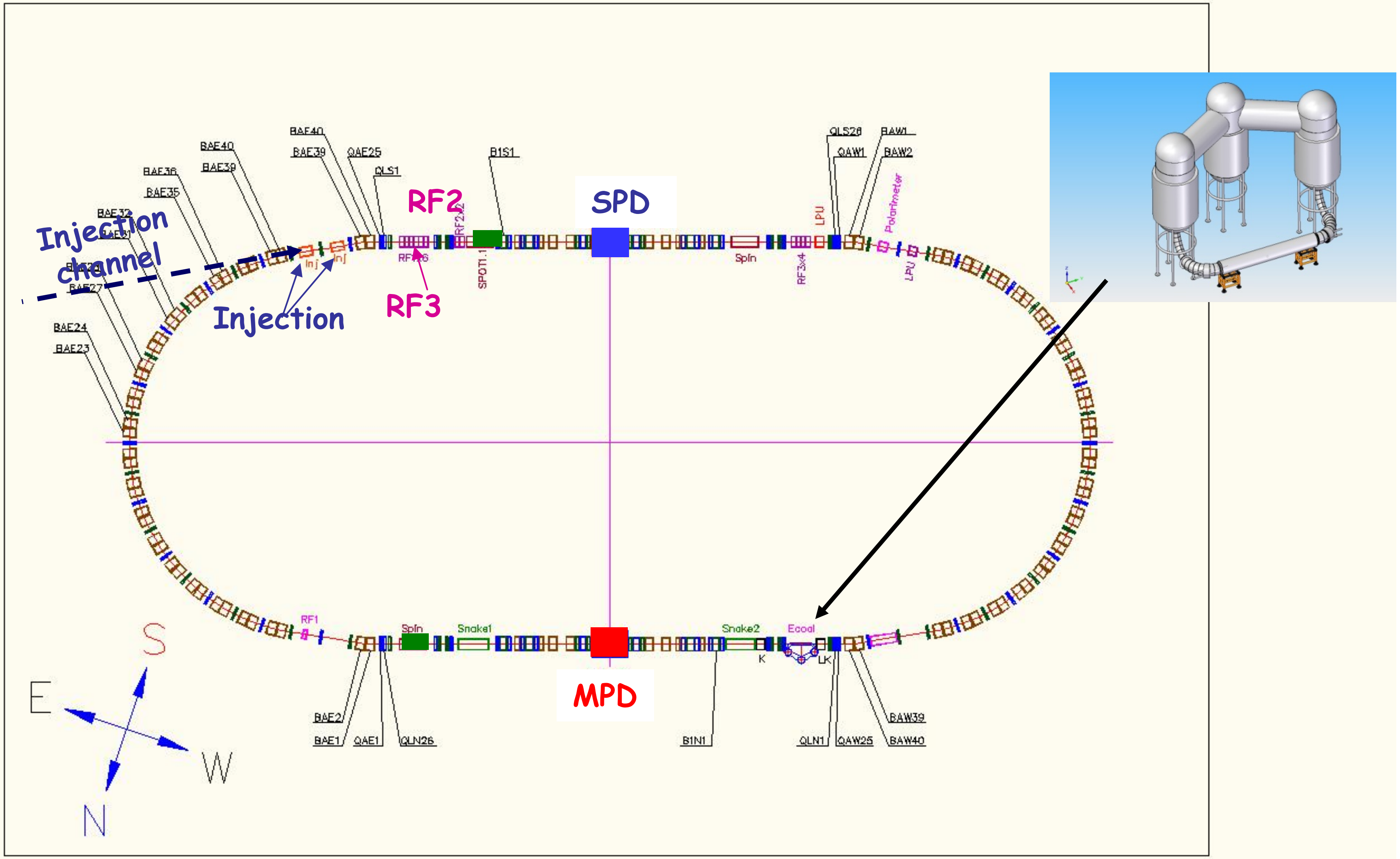
a) Increasing T_tr_e

b) "Shift" of electron energy (Talk A.Philippov)

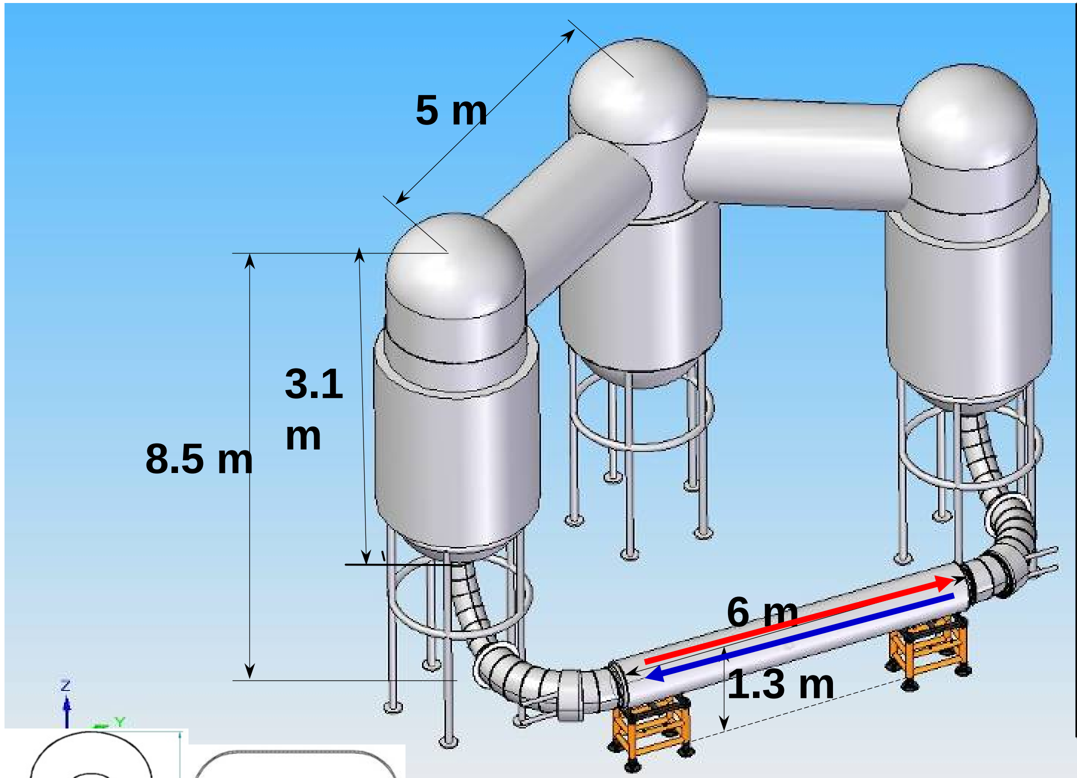


Conclusions: T_ecool ~ 0,05 Tibs at 1 GeV/u

HV electron cooling system

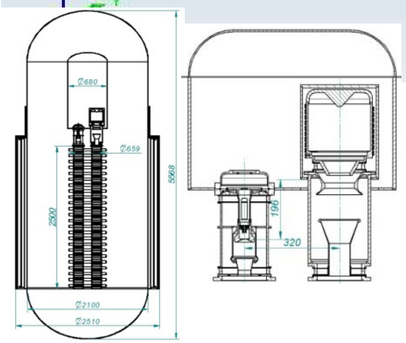


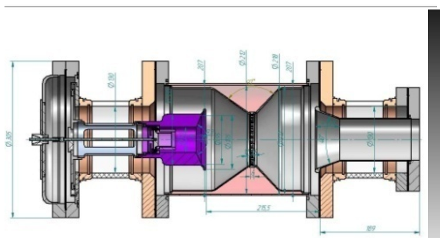
HV electron cooling system

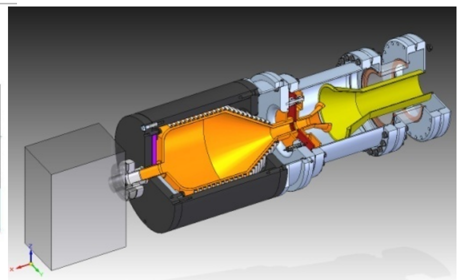


Electron beam energy, MeV	0,5 ÷ 2,5
Collector potential vs to cathode, kV	0,5 ÷ 2,0
Electron beam current	0.1 ÷ 1,0
Electron beam current losses, μA	< 0.1
Radiated power from cathodes,, W	2×100
Max. radiated power at collectors, kW	2×2
Electron cathode diameter, cm	3,0
Long. Magnetic field, T	0,1 ÷ 2,0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

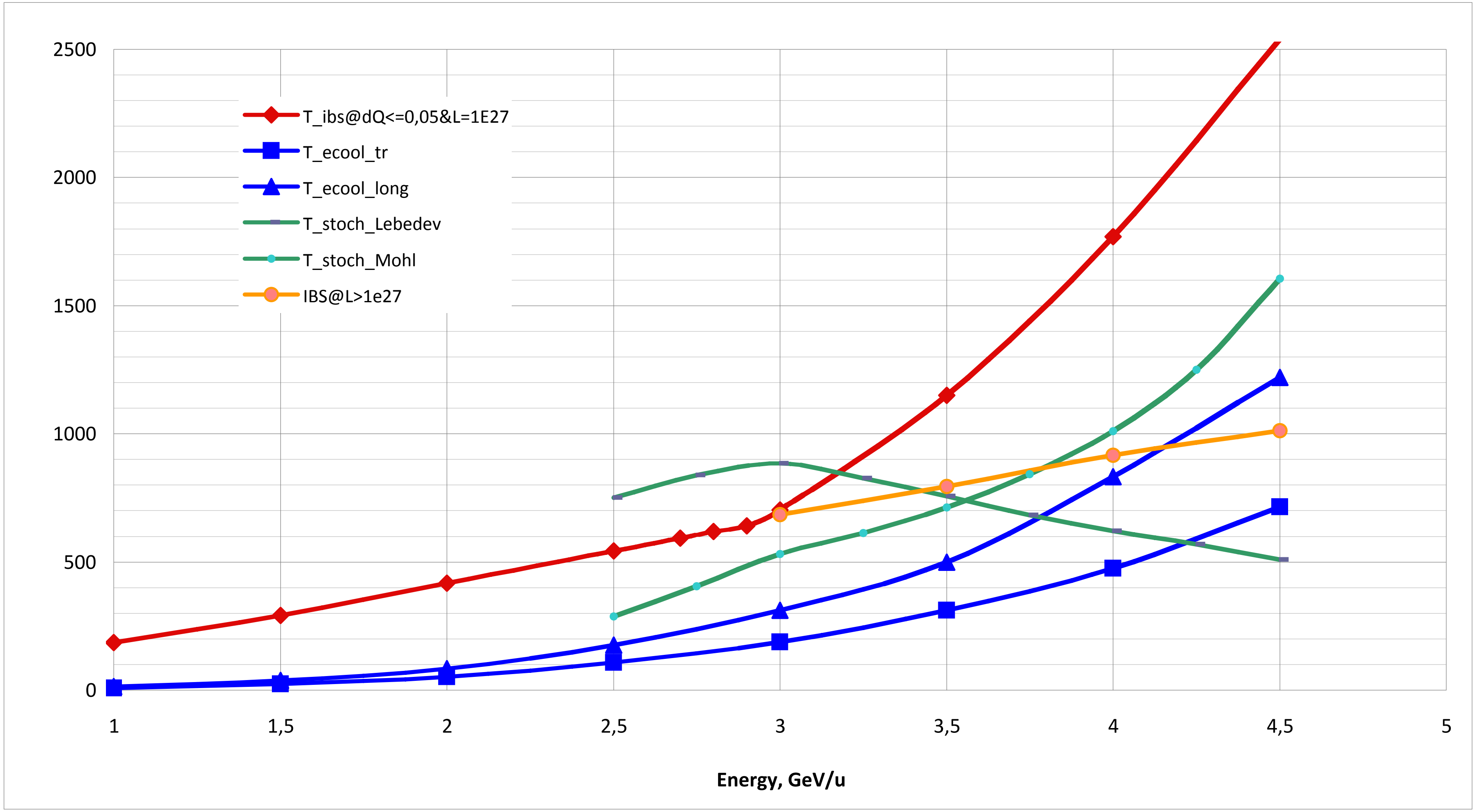
Poster session: S.Yakovenko



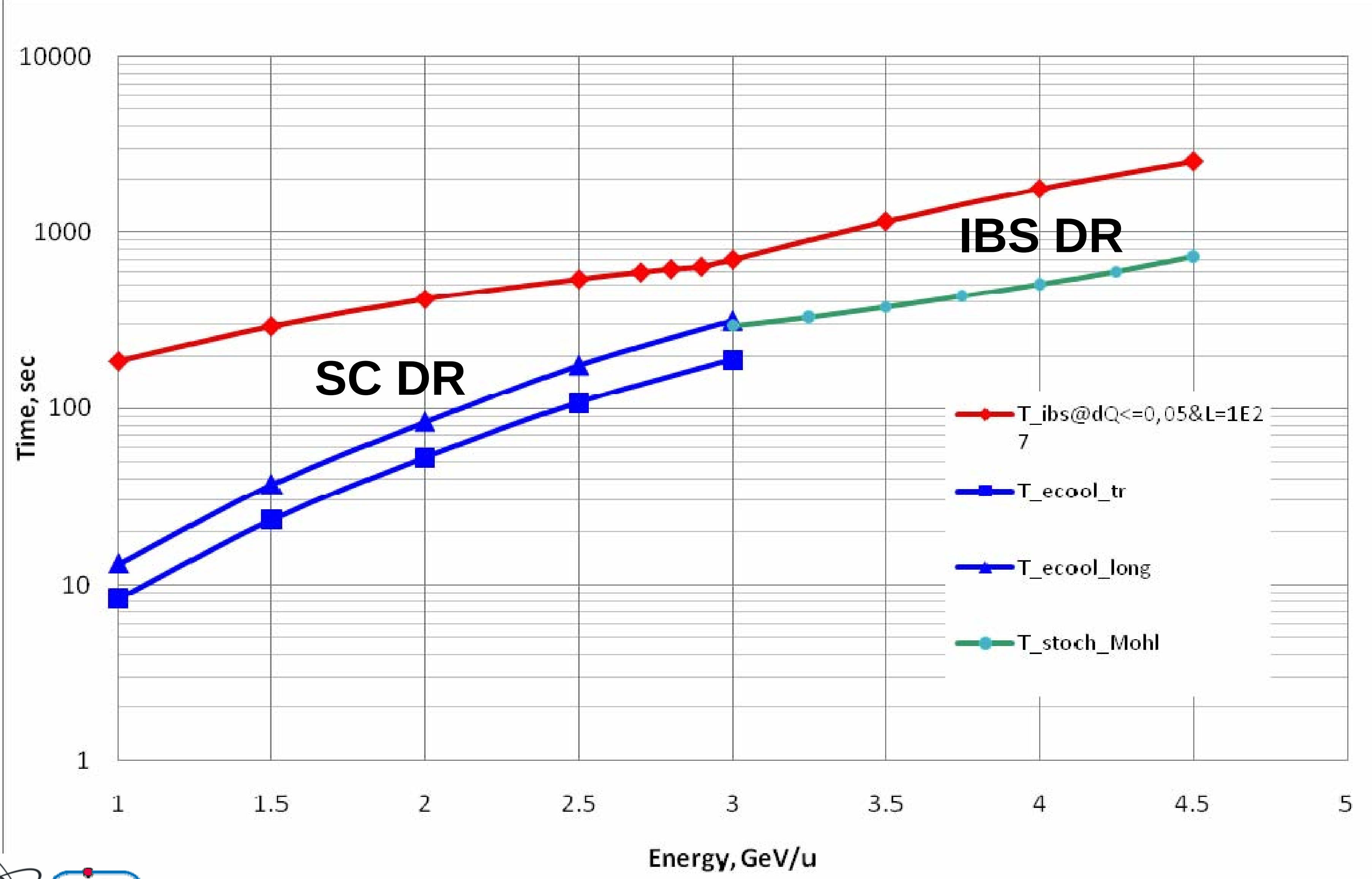




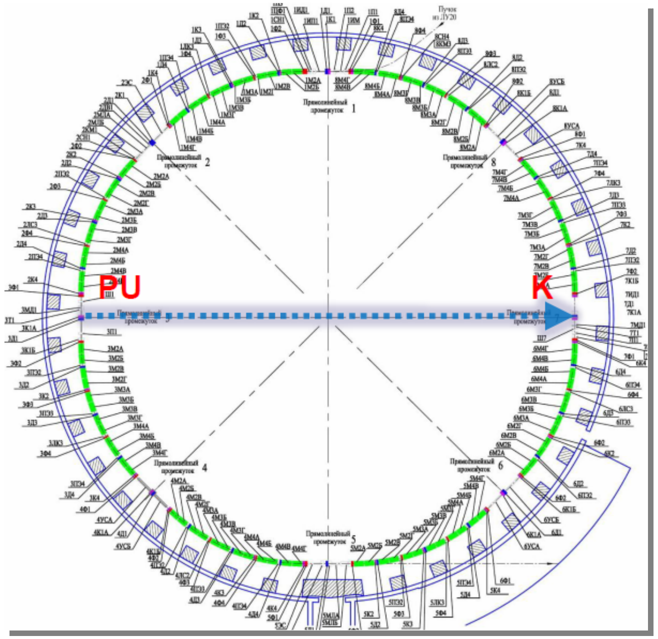
Summary v.1

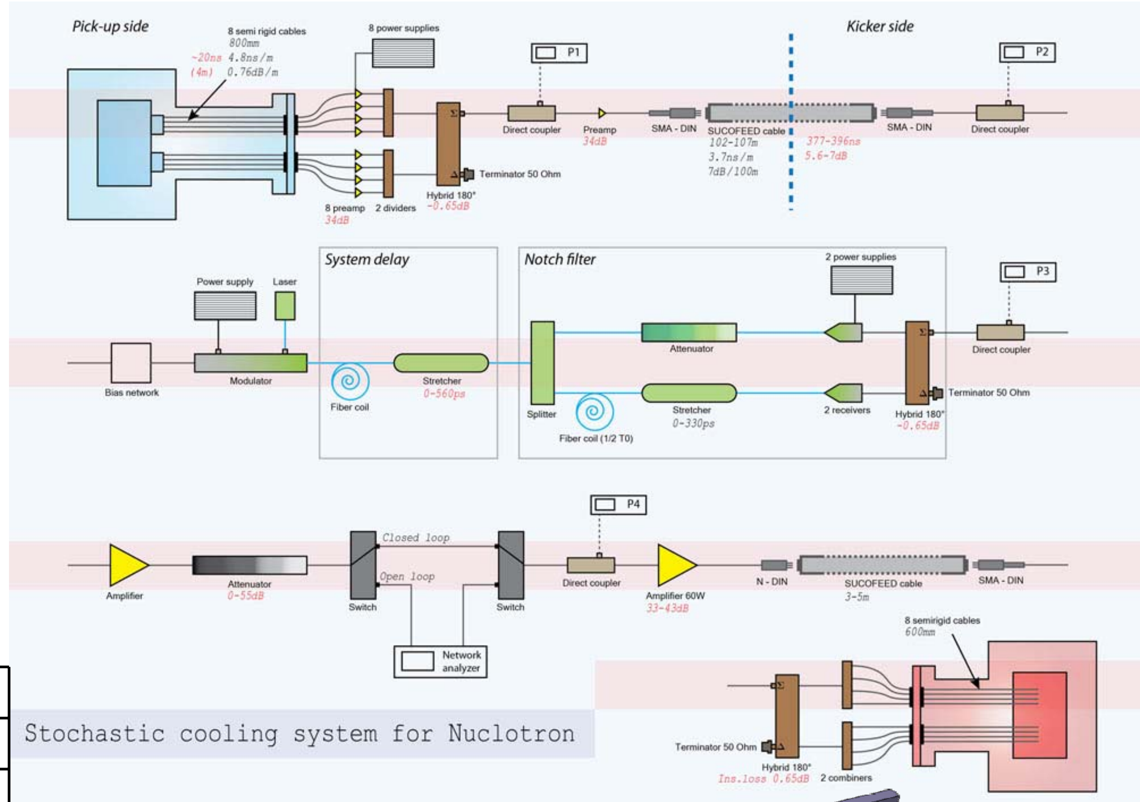

2500
2000
1500
1000
500
0
1
1,5
2
2,5
3
3,5
4
4,5
5
T_ibs@dQ<=0,05&L=1E27
T_ecool_tr
T_ecool_long
T_stoch_Lebedev
T_stoch_Mohl
IBS@L>1e27
Energy, GeV/u

Summary final

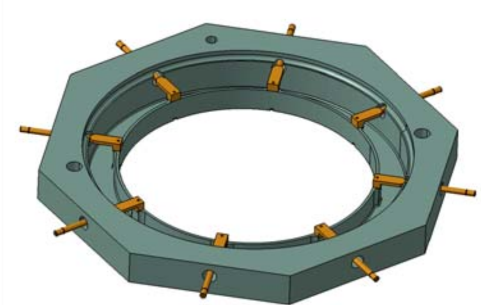


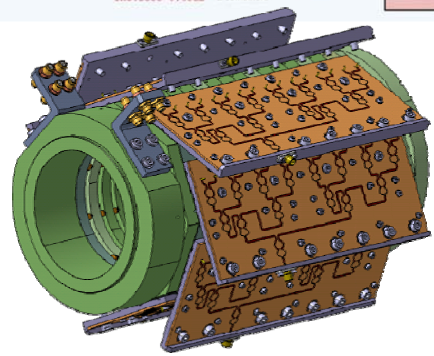
SC experiment at Nuclotron





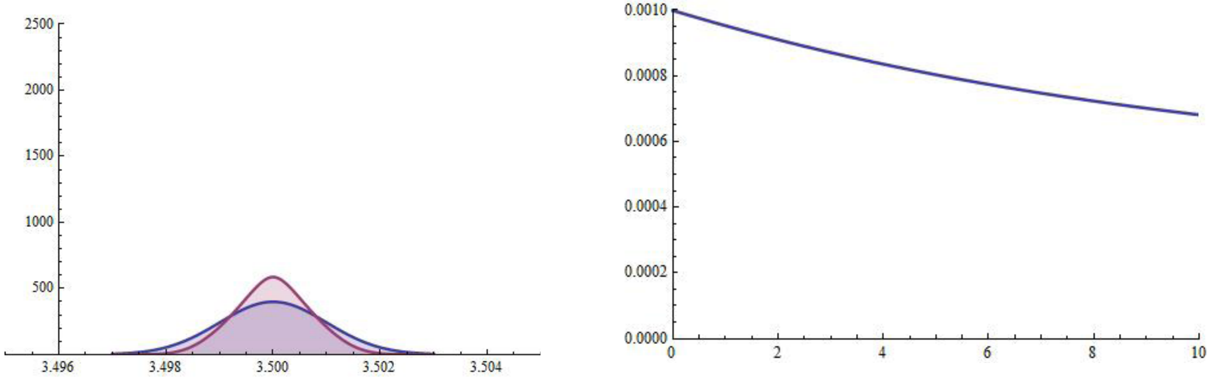
Stochastic cooling system for Nuclotron



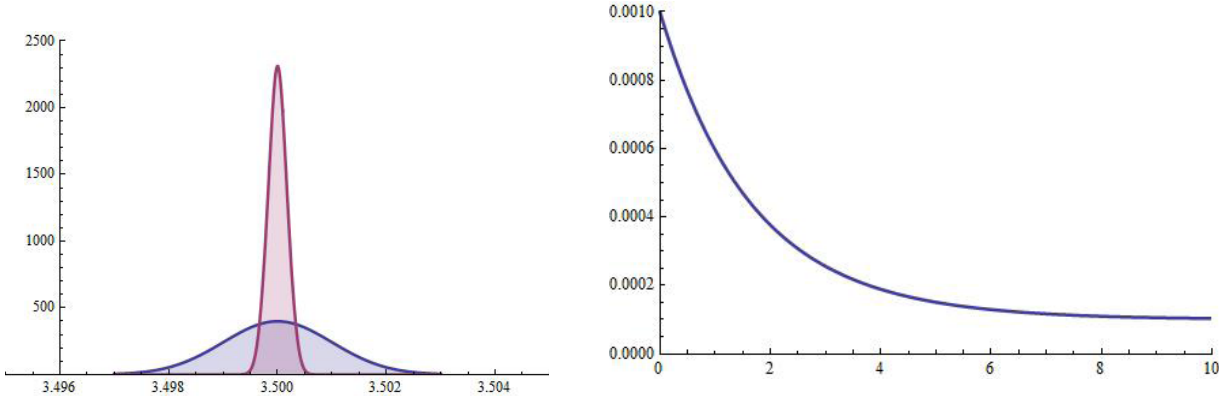


Circumference, m	251.5
Ions	up to A=56
Energy, GeV	3.5
Rev.frequency, MHz	1.2
Vacuum, Torr	10^-10
Intensity	10^11(p)-10^9(C12)
Ring slippage factor	0,0322
dp/p	10^-3

Simulations of stochastic cooling



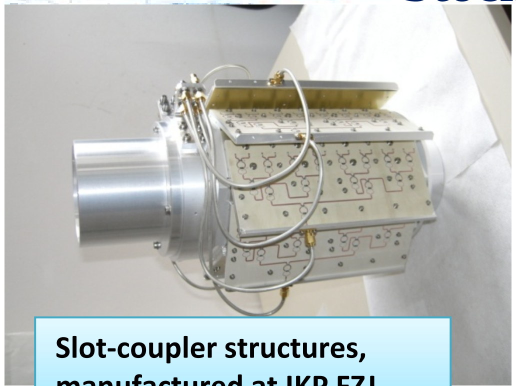
Expected evolution of particle distribution function and rms value of dP/P for <u>protons</u>.



Expected evolution of particle distribution function and rms value of dP/P for <u>carbon ions (C6+)</u>

Nuclotron-NICA

Stochastic cooling system prototype at Nuclotron


Slot-coupler structures, manufactured at IKP FZJ


Vacuum chamber for pick-up


Vacuum chamber for kicker

We plan to assemble and TEST stochastic cooling system prototype at Nuclotron in the end of 2011
(depends on electronics delivery)

2017

Thank you for your attention !

Many thanks to my colleagues for fruitful discussions and unvaluable help:

A.Sidorin, I.Meshkov, S.Kostromin, T.Katayama, R.Stassen, D.Moehl

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