

NICA Stochastic Cooling System: Designing and Modeling

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Introduction

Stochastic cooling

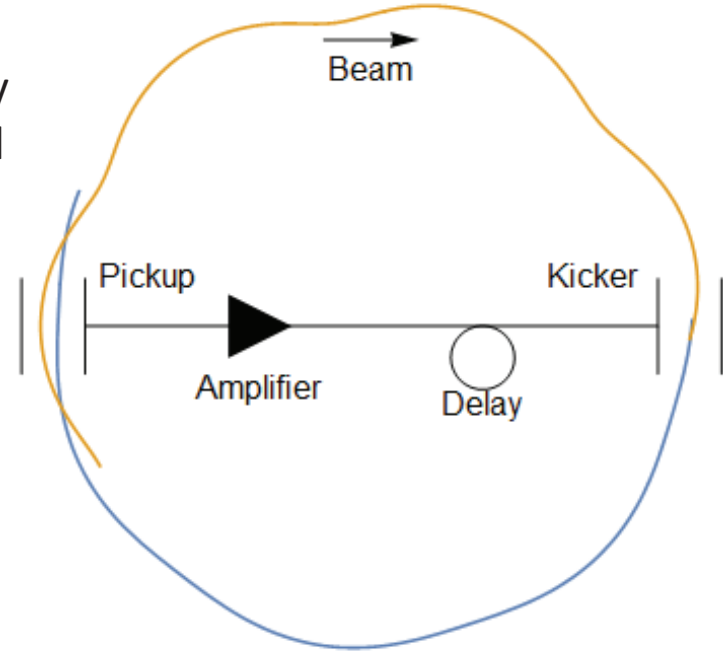
Physically: reduction of the beam phase space by feeding to the beam particles their own noisy signal

Technically: broadband feedback system

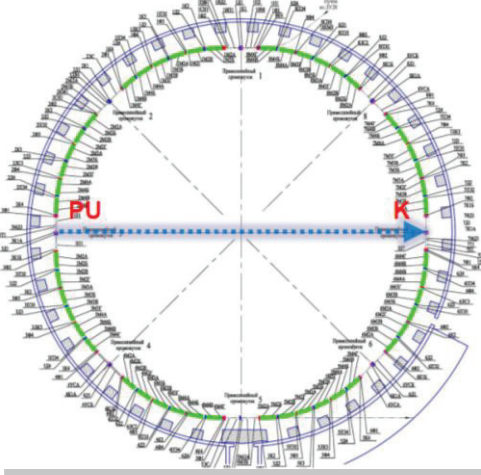
$$\text{Bandwidth } W \quad \text{Gain } g = g(P_{in}, P_{out})$$

$$\text{Mixing } M = M(W, Pu \leftrightarrow Kk) \quad U = \frac{\text{noise}}{\text{signal}}$$

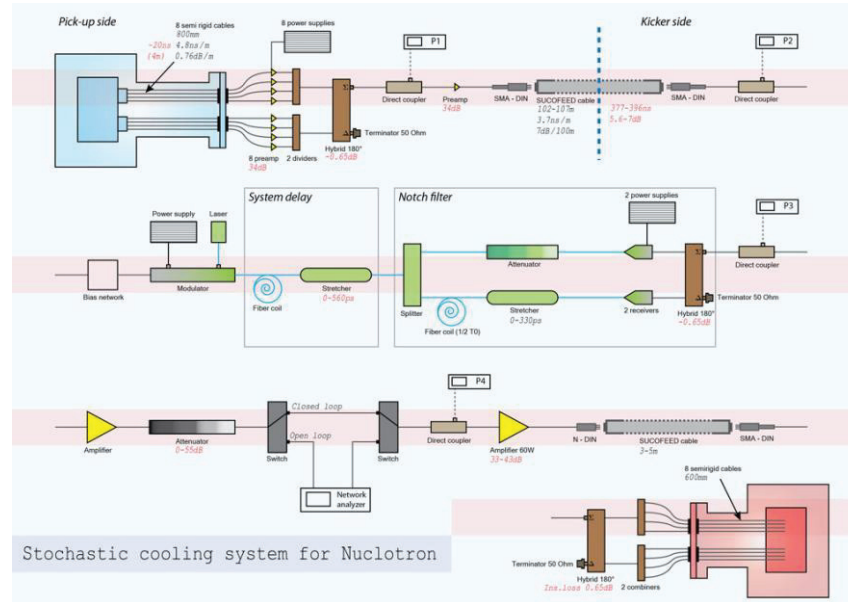
$$\frac{1}{\tau_{Cool}} = \frac{W}{N} (2g[1 - \tilde{M}^{-2}] - g^2[M + U])$$



Nuclotron as test facility for NICA



Circumference, m	251.52
Ions	p, d, C
Energy, GeV	3.0(d) 2.5(C)
Rev.frequency, MHz	1.15
Vacuum, Torr	10^{-9}
Intensity	$10^{10}(\text{d})$ - $10^9(\text{C})$
Ring slip-factor	0.0322
dp/p	10^{-4}



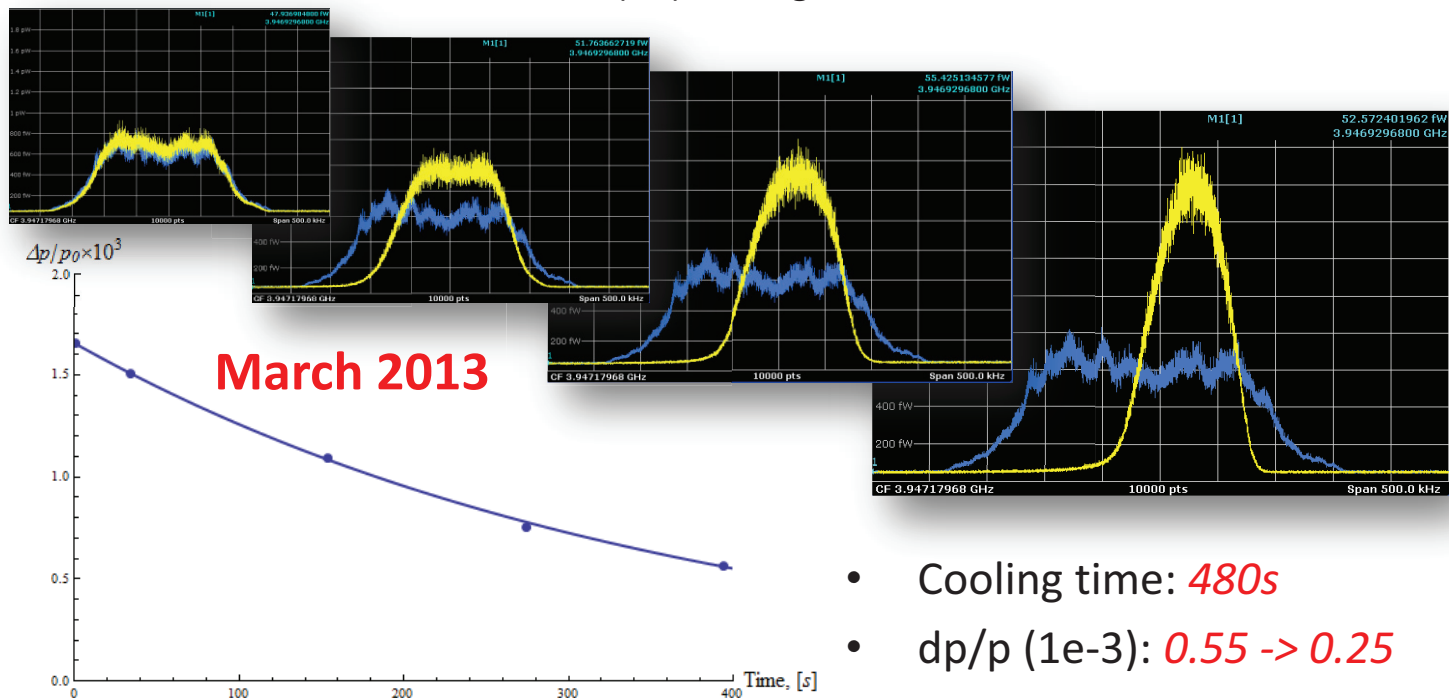
Band 2 – 4 GHz

Output power up to 60 W

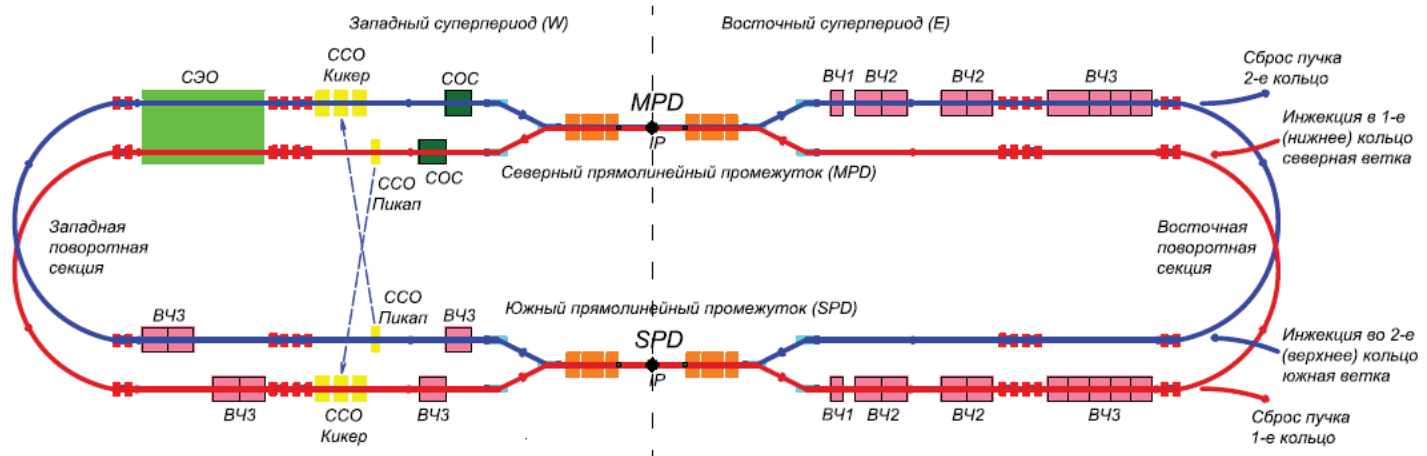
Goals: Investigation of different cooling methods
Equipment tests for the collider

Nuclotron as test facility for NICA

First beam (D+) cooling at Nuclotron



Tasks for NICA



- Beam accumulation(at low intensities)
- Longitudinal emittance reduction during the bunching
- Luminosity preservation (counteraction to intrabeam scattering (IBS))

Start-up mode	Project mode
RMS bunch length $\sigma_s=1,2$ m	RMS bunch length $\sigma_s=0,6$ m
RF Voltage $U_{RF} = 50$ kV	RF Voltage $U_{RF} < 1000$ kV
Harmonic number $h = 22$	Harmonic number $h = 66$
Ions $^{179}\text{Au}_{97+}$	
$\epsilon_{\perp\text{rms.max}} = 1,1 \pi \text{ mm.mrad.}$	
$\Delta p/p_{\text{max}} = 1\%$	
Energy range 3-4,5 GeV/u	
Only longitudinal cooling	3-D cooling

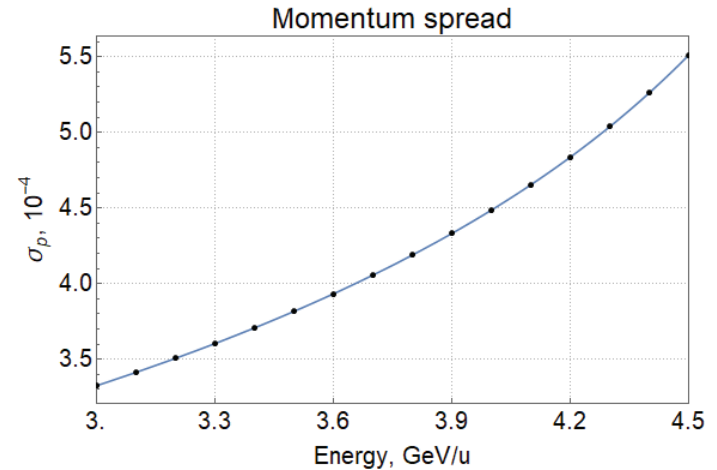
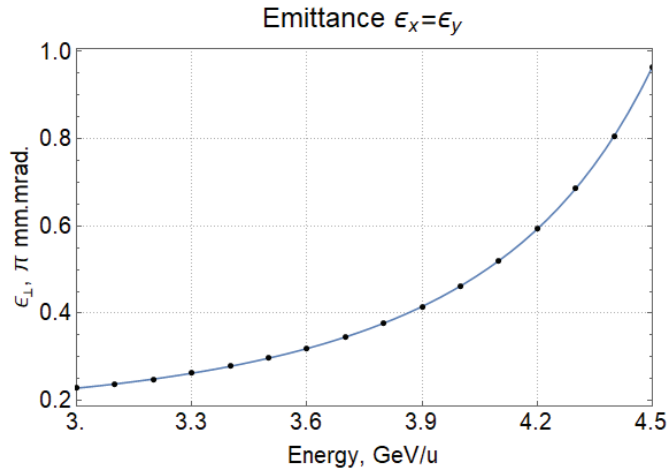
Start-up mode: Phase Volume

IBS calculations: BETACOOOL

Longitudinal cooling only

IBS simulation condition

$$\tau_{IBS}^x \cong \tau_{IBS}^y \rightarrow \infty$$

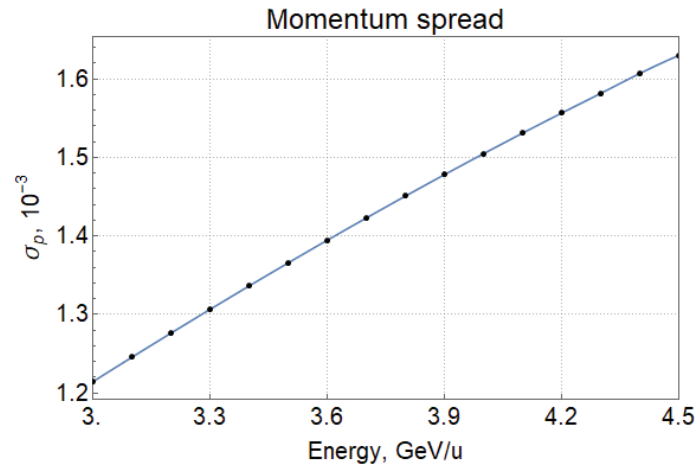
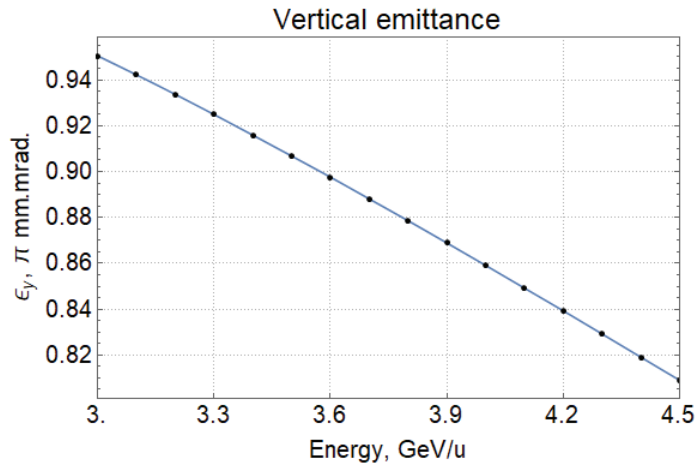


Project Mode: Phase Volume

3-D cooling

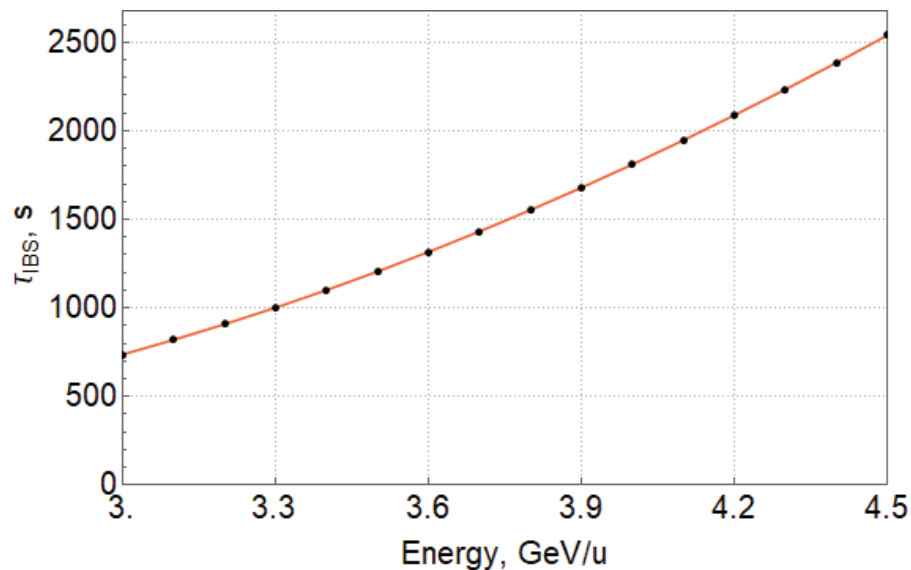
IBS simulation condition

$$\tau_{IBS}^x = \tau_{IBS}^y = \tau_{IBS}^s$$



Project Mode: IntraBeam Scattering

$$L_{max} = 10^{27} \text{cm}^{-2} \text{s}^{-1} \quad N_{max} = 2.75 \times 10^8$$



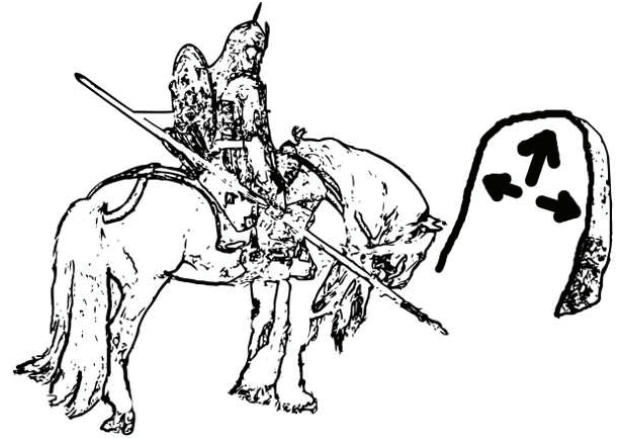
Conceptual Design Steps

- Choose cooling method
- Define main parameters
 - Pickup, Kicker locations
 - Bandwidth
 - Sensitivity
 - Thermal noises (Pickup inside cryo?)
 - Preamplifier Noise Figure
 - Pickup/Kicker Impedance
 - Output power



Choice of cooling method

- Uncoupled motion
 - Momentum cooling
 - Transit Time method ($\eta_{p \leftrightarrow k} \uparrow$)
 - Filter method ($\eta_{p \leftrightarrow k} \rightarrow 0, \eta_{p,k,k} \uparrow$)
 - Transverse cooling
 - Betatron method ($\phi_{p \leftrightarrow k} \rightarrow (2k-1) \cdot \pi/4$)
- Coupled motion
 - Palmer method ($D_p \uparrow, \beta_p \downarrow, D_k \rightarrow 0$)
 - Palmer-Hereward method ($D_p \uparrow, \beta_p \downarrow, D_k \rightarrow 0$)
 - ...



Design on the basis of simulation

Fokker-Planck approach

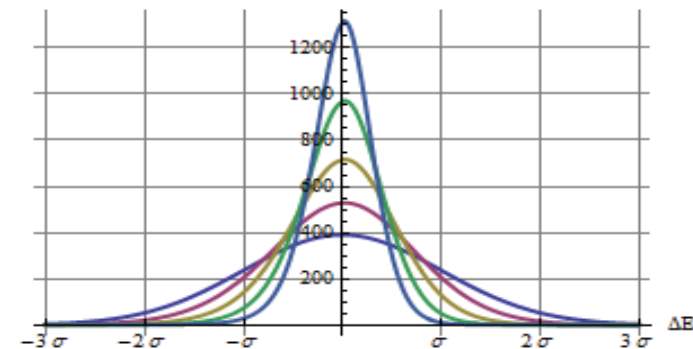
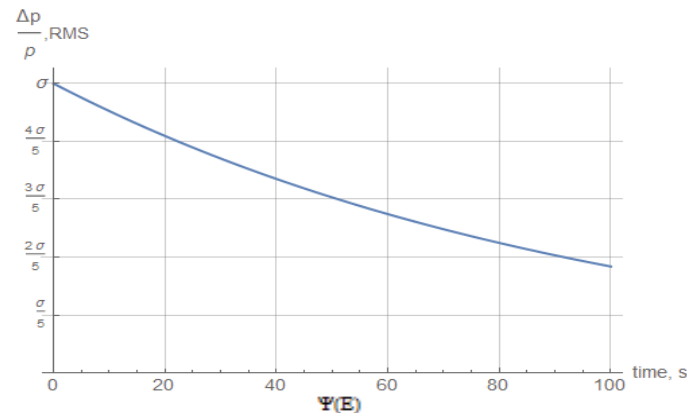
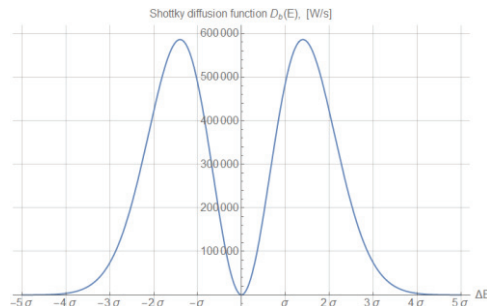
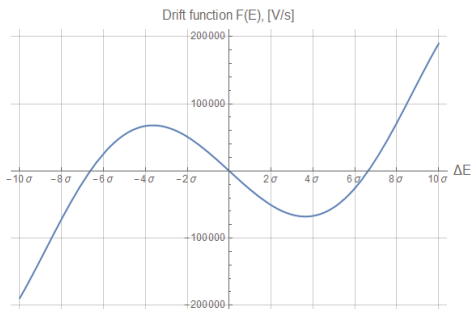
$$\frac{\partial \Psi(E, t)}{\partial t} + \frac{\partial}{\partial E} \left(F(E) \Psi(E, t) - D(E, t) \frac{\partial \Psi(E, t)}{\partial E} \right) = 0$$

Drift term

$$F(E) = f_0 \Delta E_c \sim \prod_j TF_j$$

Diffusion term

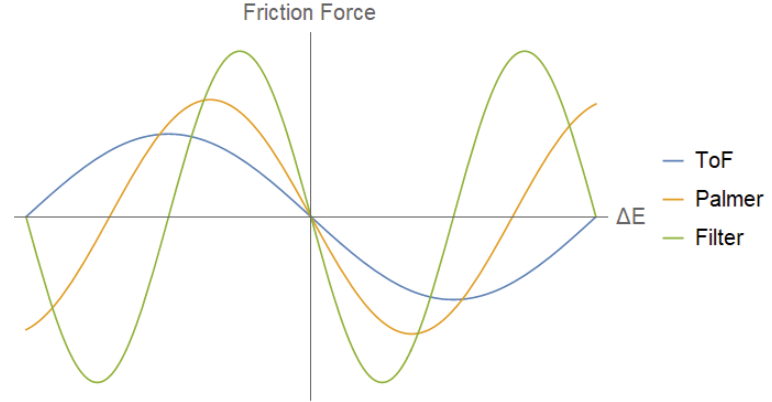
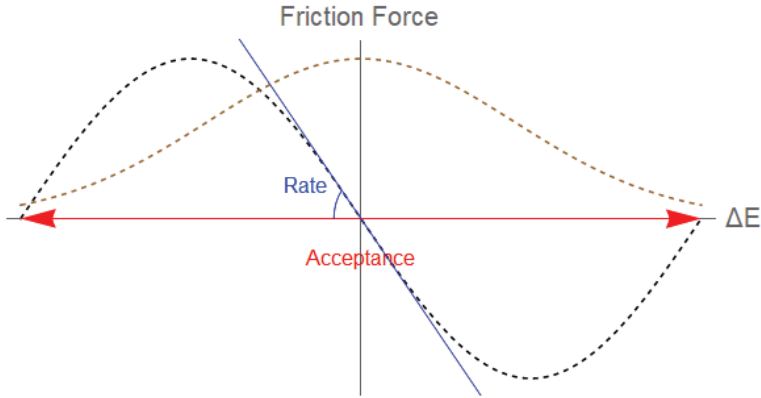
$$D(E, t) = \frac{1}{2} f_0 \langle \Delta E_{ic}^2 \rangle \sim \prod_j TF_j^2$$



Bandwidth and Cooling Rate vs Acceptance

Cooling rate

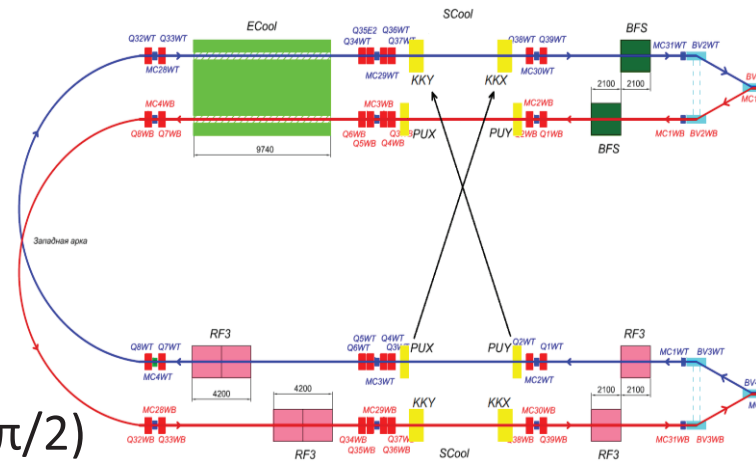
$$\frac{1}{\sigma^2} \frac{d\sigma^2}{dt} = \frac{4}{N\sigma} \int E \left[F(E)\psi(E,t) - D(E,t) \frac{\partial \psi(E,t)}{\partial E} \right] dE$$



Rate $\sim$ Bandwidth W
 Acceptance $\sim 1/\text{Band Center } (1/W_c)$

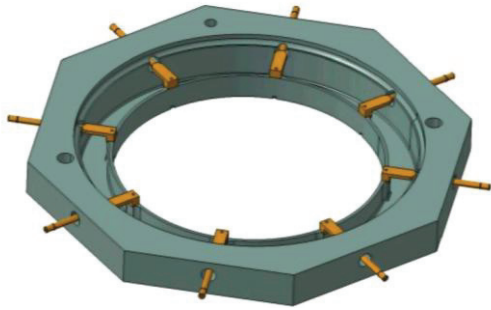
Pickup/Kicker Locations

- Uncoupled motion
 - Momentum cooling
 - Transit Time method ($\eta_{p \leftrightarrow k} \uparrow$)
 - ✓ • Filter method ($\eta_{p \leftrightarrow k} \rightarrow 0, \eta_{p,k,k} \uparrow$)
 - Transverse cooling
 - ✓ • Betatron method ($\phi_{p \leftrightarrow k} \rightarrow (2k-1) \cdot \pi/2$)
- ~~Coupled motion~~
 - Palmer method ($D_p \uparrow, \beta_p \downarrow, D_k \rightarrow 0$)
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 - ...

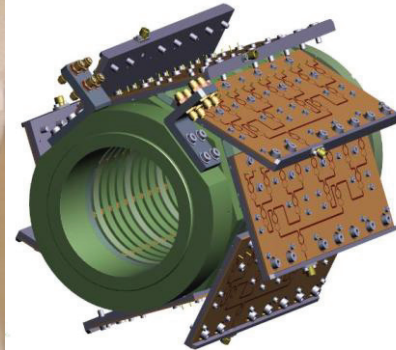
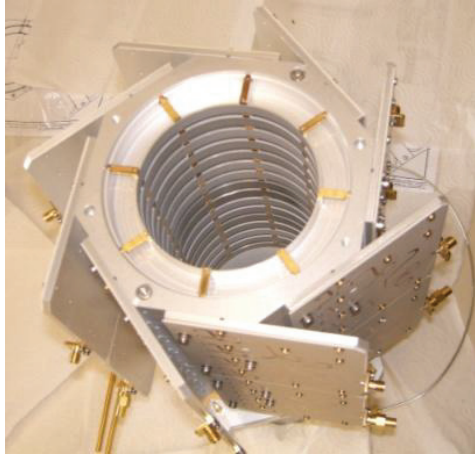


Ring-Slot Coupler Pickup/Kicker

Proposed by L.Thorndahl Developed by R.Stassen



Pickup ring



16 rings stack

Advantages:

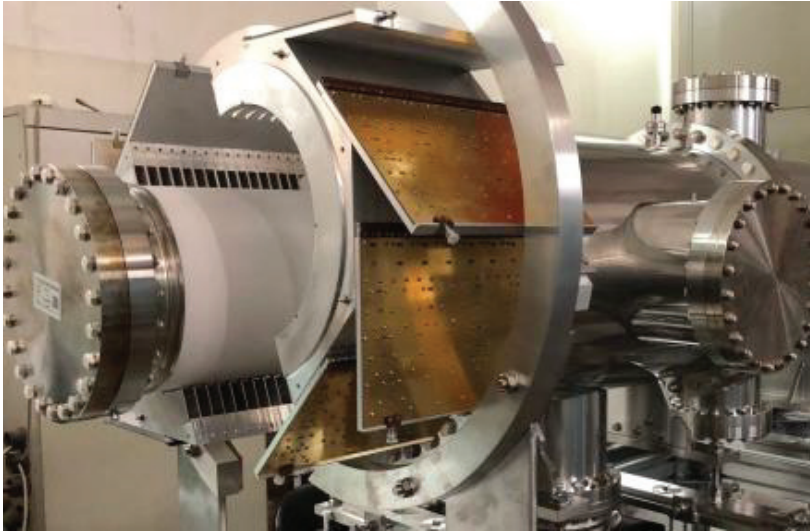
High Coupling Impedance (sensitivity)
Applicable for both long./trans. cooling

Problem:

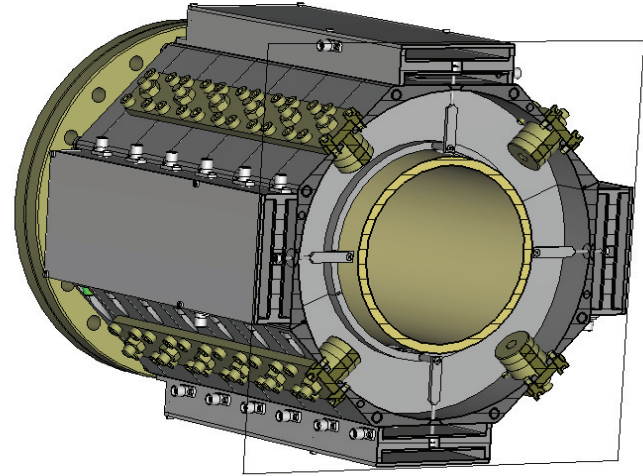
Extremely hard to achieve ultra-high vacuum

Pickup/Kicker Modification

Separated structure with ceramic vacuum chamber inside rings



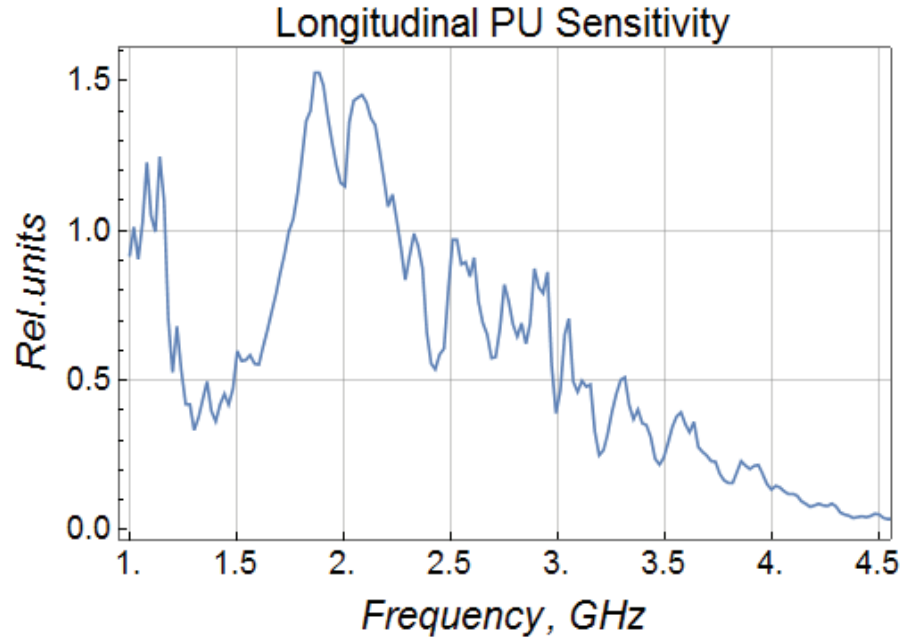
G.Zhu et al., HIAF, IMP, Lanzhou, China



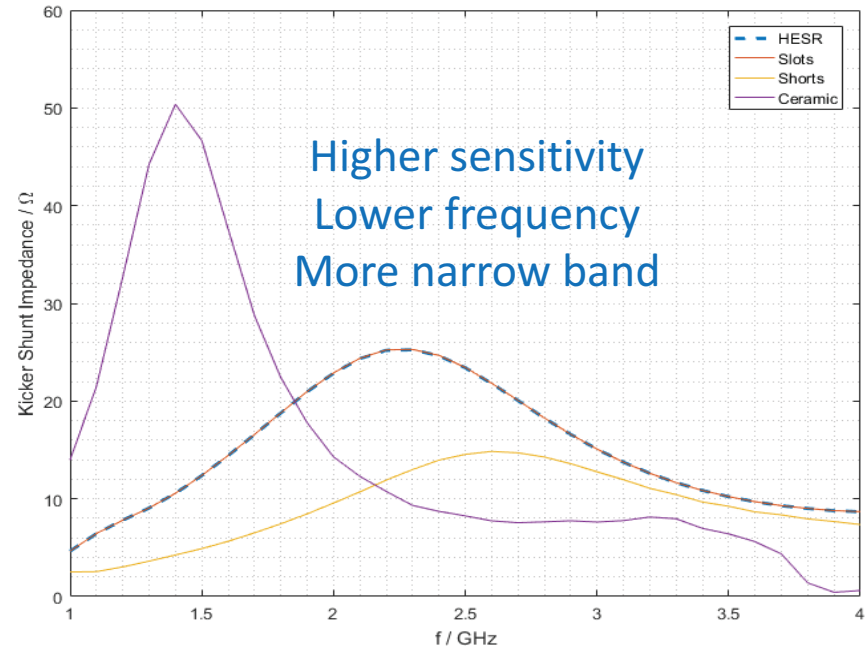
Poster by Konstantin Osipov for details

Sensitivity

Nuclotron measurements: original structure

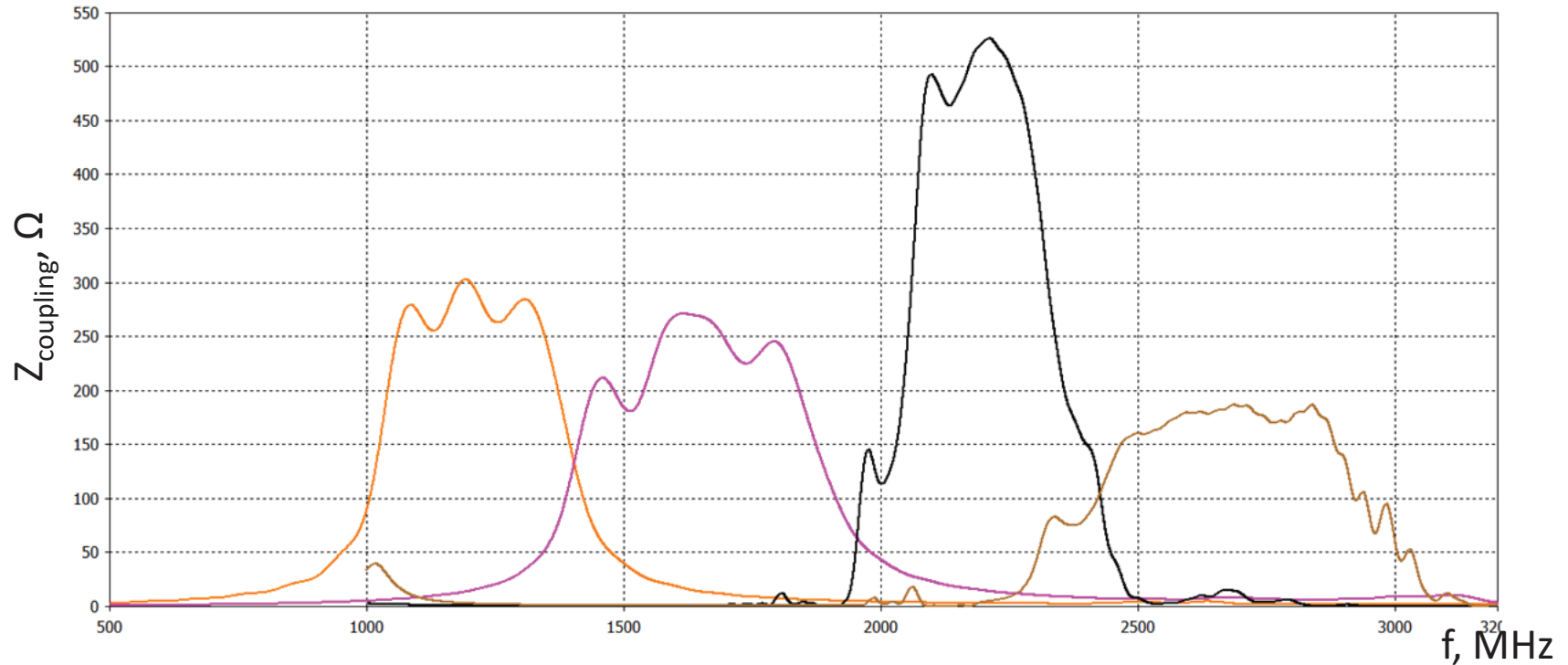


Comparison with modifications



Pickups do not need to be inside cryostat due to higher sensitivity and heavy ions

Single Band (2-4 GHz) ->
-> Distributed Bands (1-3 GHz)

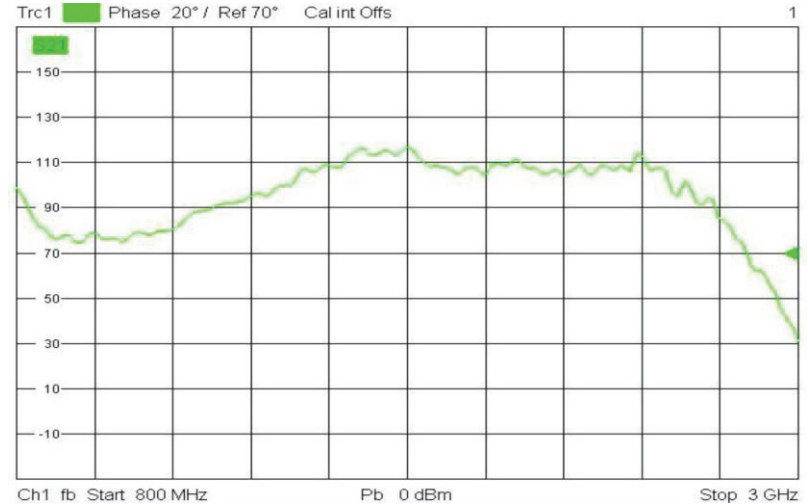
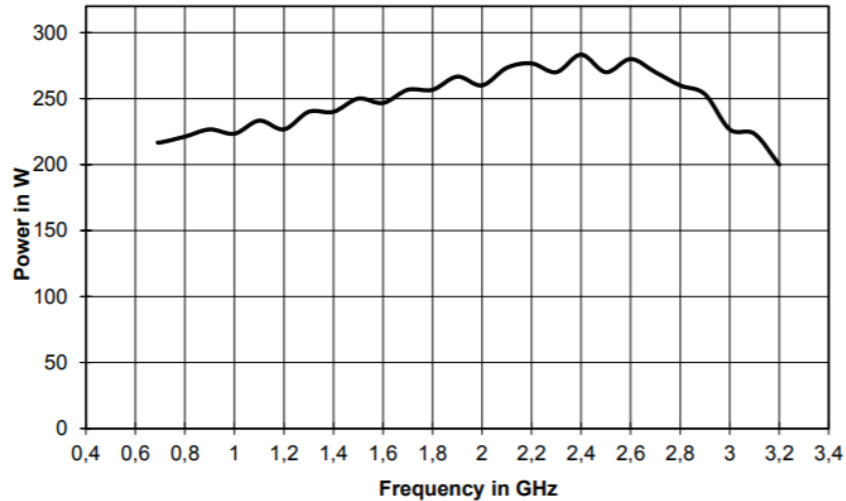


Power Amplifiers



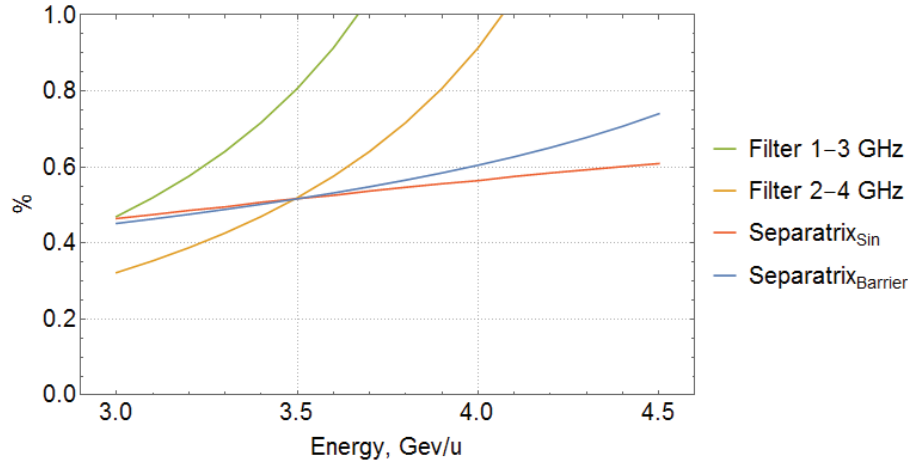
R&S® BBA150-D200, 200 W power class

Frequency response at 1 dB compression



Band shift from 2 – 4 GHz to 1 – 3 GHz

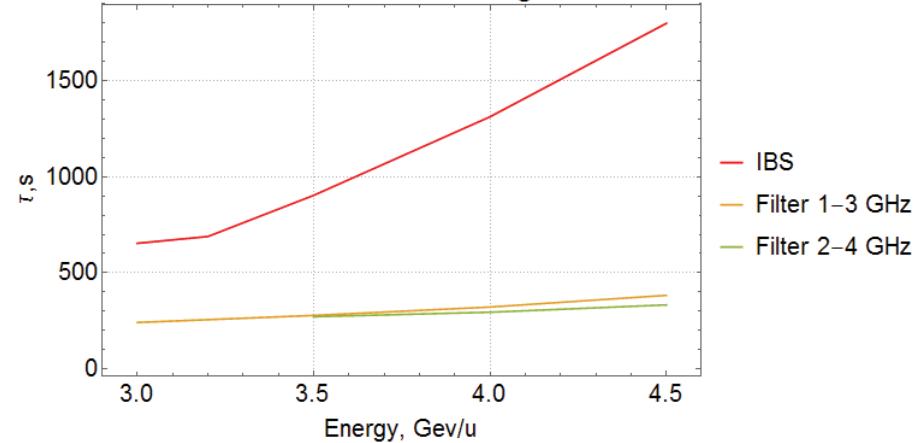
Momentum Cooling Acceptance



Cooling acceptance with 1 – 3 GHz filter covers both separatrices (sine and barrier) for energies over 3 GeV/u

Filter method with band 1-3GHz can provide necessary momentum acceptance for energies above 3 GeV/u

IBS vs Filter Cooling



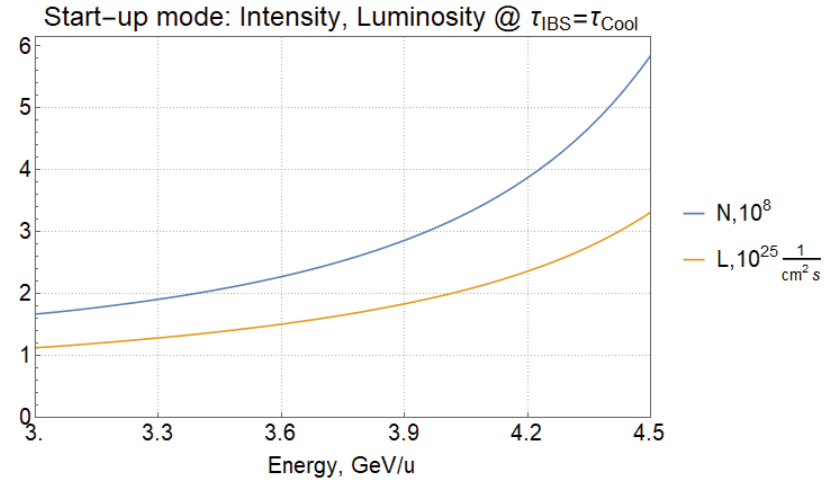
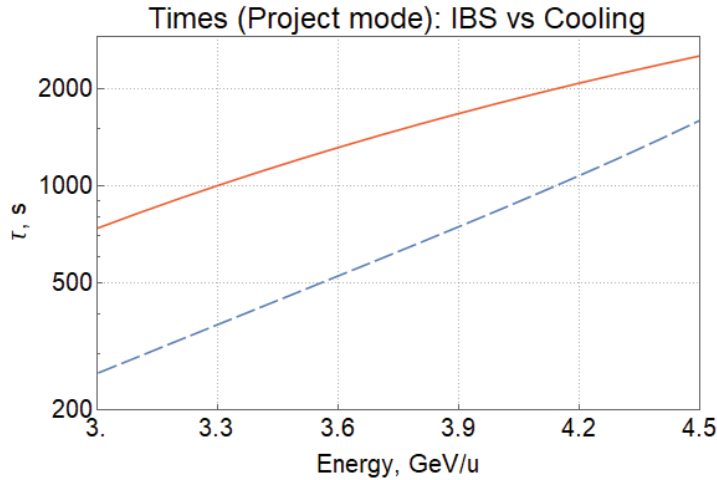
Cooling rate with 1 – 3 GHz filter decreases at most 15% (at higher energies)

Conclusion

Longitudinal cooling method	Filter	
Passband, GHz	0,7 – 3,2	
Beam distance from pickup to kicker, m	179,8	
Ion Energy $^{197}\text{Au}^{79+}$, GeV/u	3,0	4,5
Slip-factor from pickup to kicker	0.0294	0.0027
Collider slip-factor	0.0362	0.0095
Pickup/kicker coupling impedance, Ω	200/800	
Gain, dB	75 – 79	
Peak power at kicker, W	3×200	
Pickup/noise temperature, K	300/40	

Main parameters for NICA Stochastic cooling system has been defined

Conclusion



- Filter method is chosen for longitudinal cooling, betatron method – for transverse cooling. Main parameters are defined.
- For the project mode the stochastic cooling system provides the required cooling rates.

Thank you for attention

