NICA Stochastic Cooling System: Designing and Modeling

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Introduction

Stochastic cooling

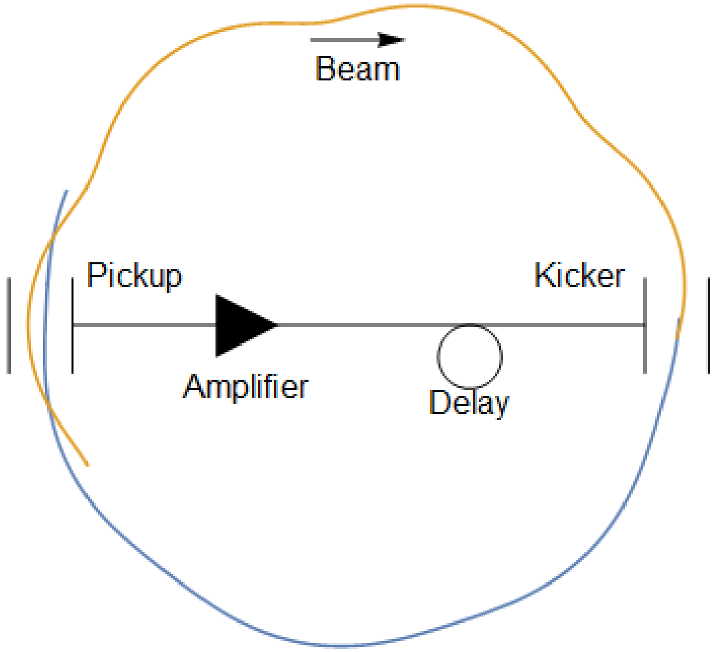
Physically: reduction of the beam phase space by feeding to the beam particles their own noisy signal

Technically: broadband feedback system

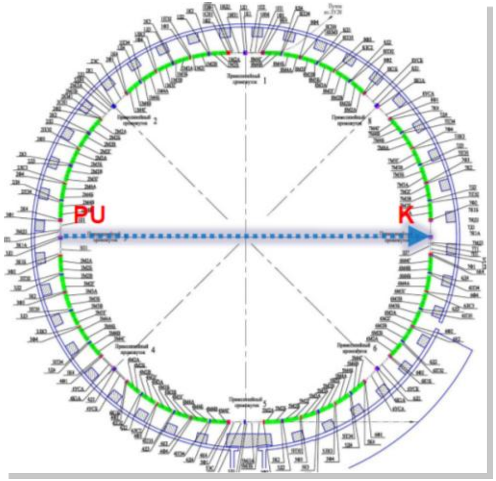
$$Bandwidth\, W \qquad Gain\; g = g(P_{in}, P_{out})$$

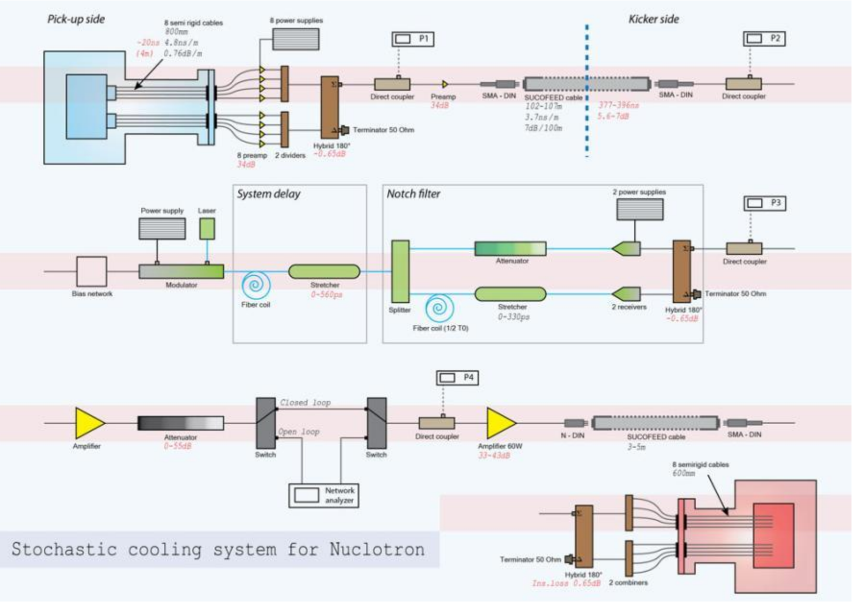
$$Mixing\; M = M(W, Pu \leftrightarrow Kk) \qquad U = \frac{noise}{signal}$$

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



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}(d)-10^{9}(C)
Ring slip-factor	0.0322
dp/p	10^{-4}

Band 2 – 4 GHz

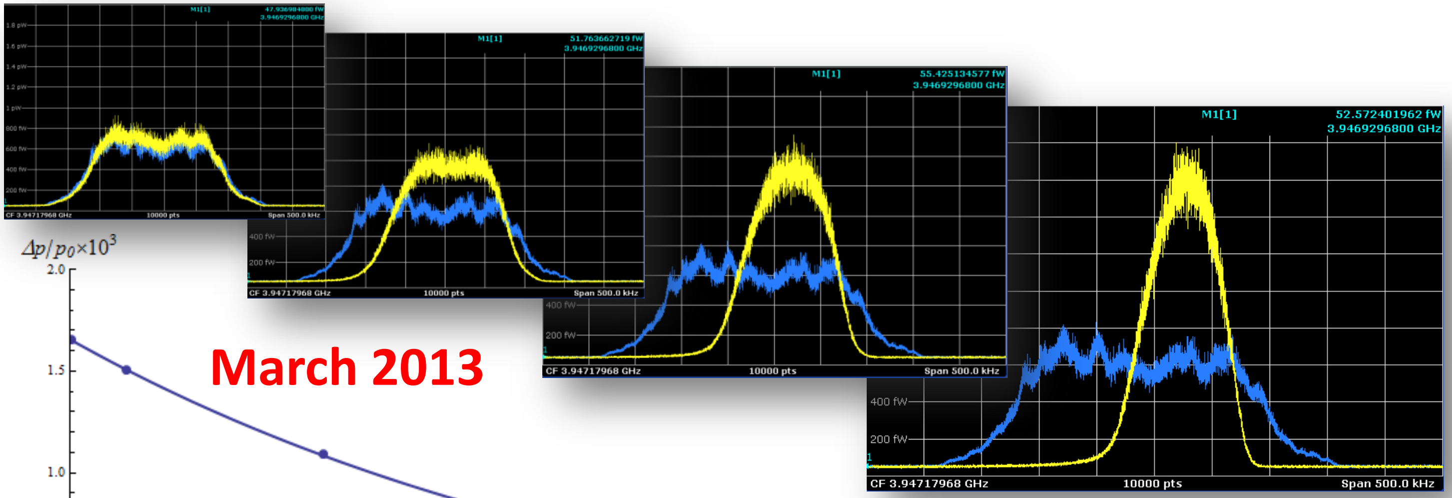
Output power up to 60 W

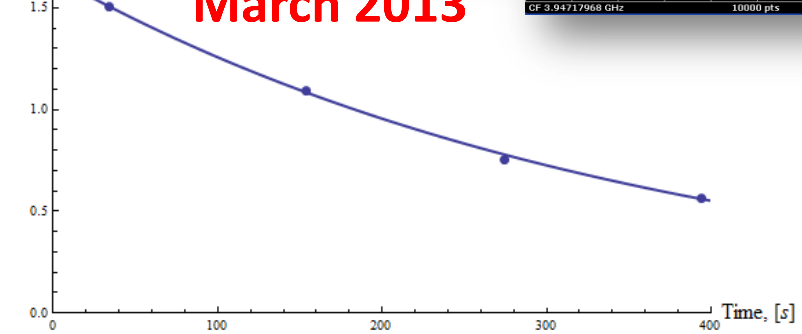
Goals: Investigation of different cooling methods

Equipment tests for the collider

Nuclotron as test facility for NICA

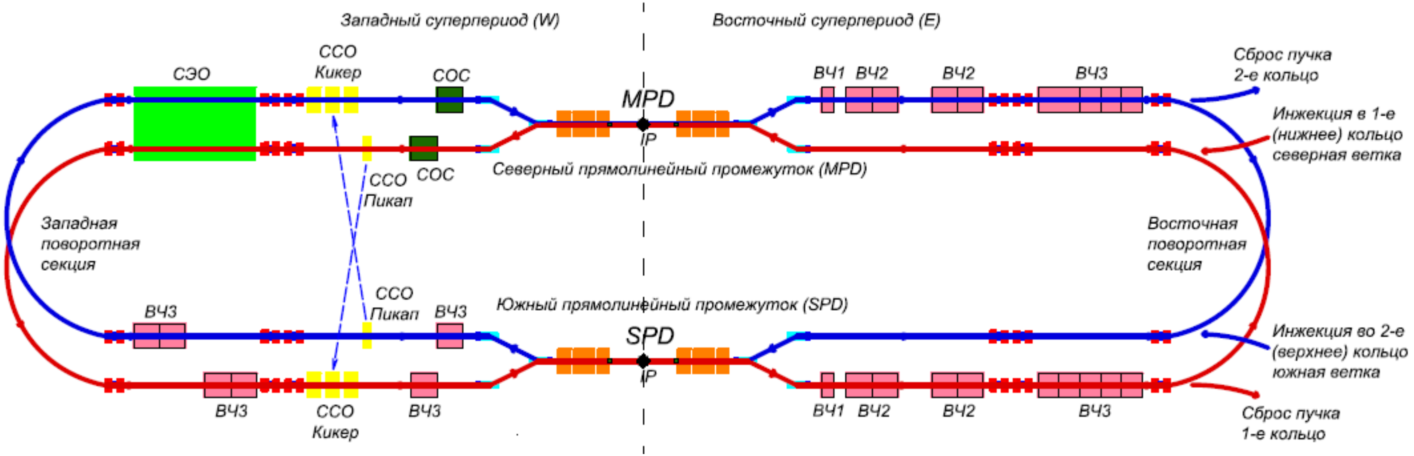
First beam (D+) cooling at Nuclotron





- Cooling time: *480s*
- dp/p (1e-3): *0.55 -> 0.25*

Tasks for NICA



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

Start-up mode	Project mode
RMS bunch length σ_s=1,2 m	RMS bunch length σ_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 $^{179}Au_{97+}$	
$\varepsilon_{\perp rms.max}$= 1,1 π mm.mrad.	
$\Delta p/p_{max}$=1%	
Energy range 3-4,5 GeV/u	
Only longitudinal cooling	3-D cooling

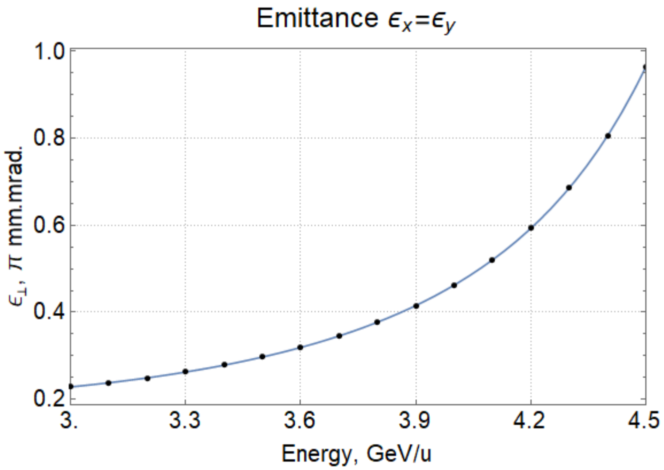
Start-up mode: Phase Volume

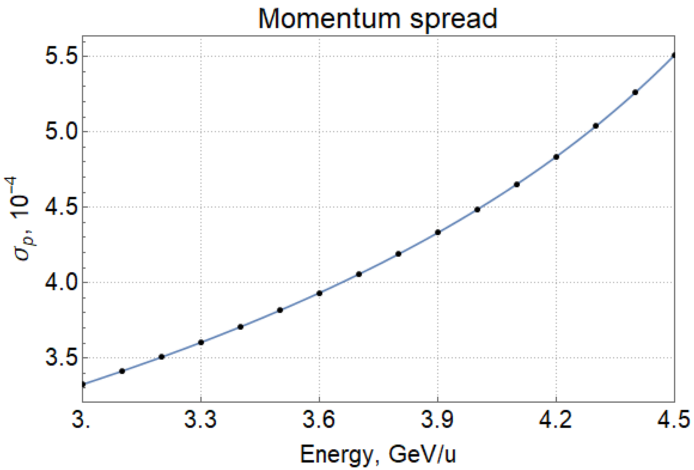
IBS calculations: BETACOOL

Longitudinal cooling only

IBS simulation condition

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



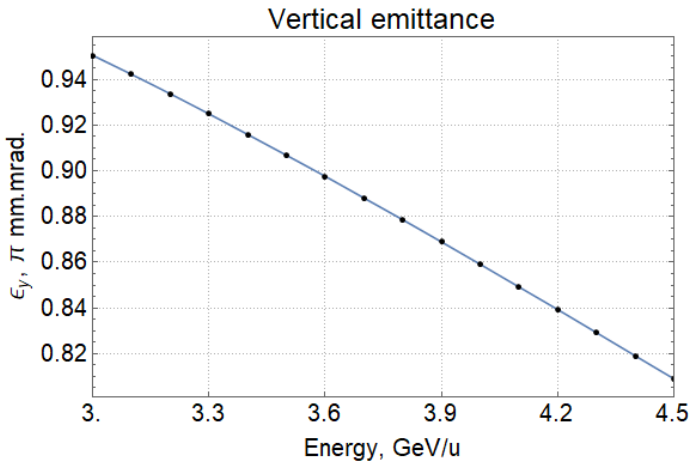


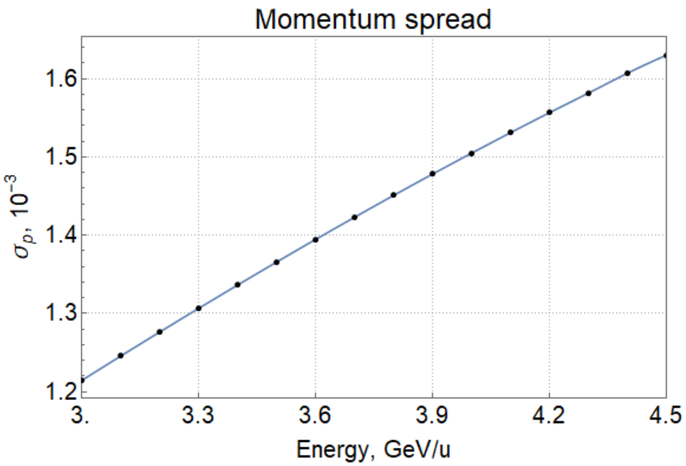
Project Mode: Phase Volume

3-D cooling

IBS simulation condition

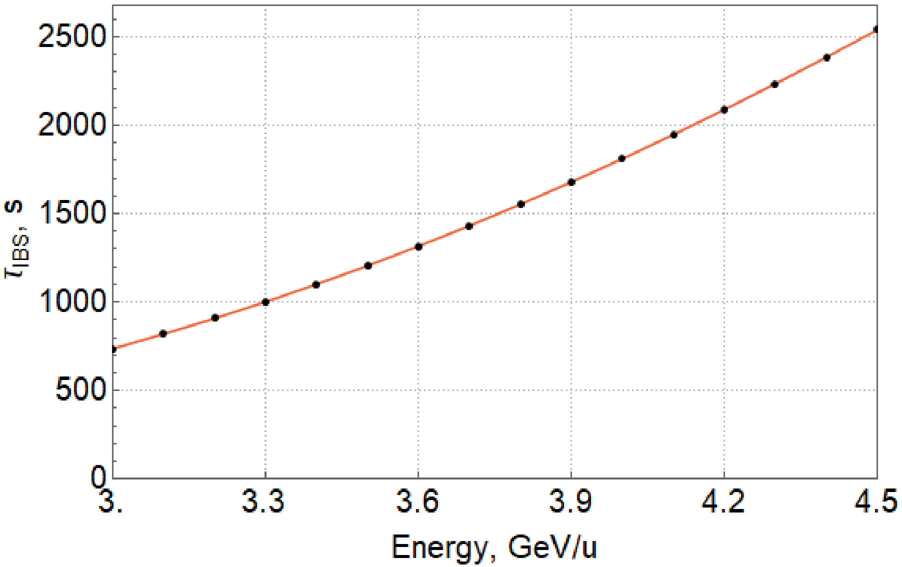
$$\tau_{IBS}^{x} = \tau_{IBS}^{y} = \tau_{IBS}^{s}$$





Project Mode: IntraBeam Scattering

L_{max} = 10^{27} cm^{-2}s^{-1} $N_{max} = 2.75\times10^{8}$

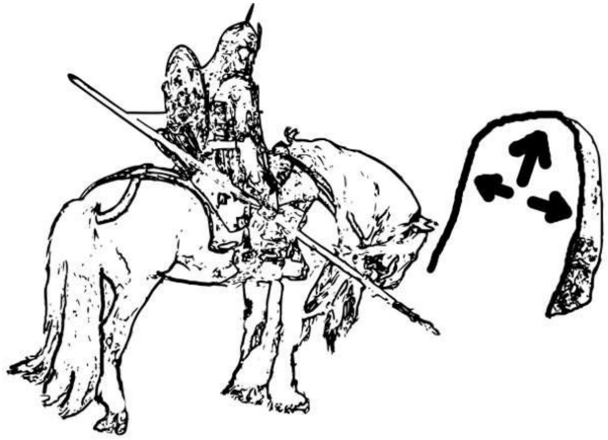


Conceptual Design Steps

- 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

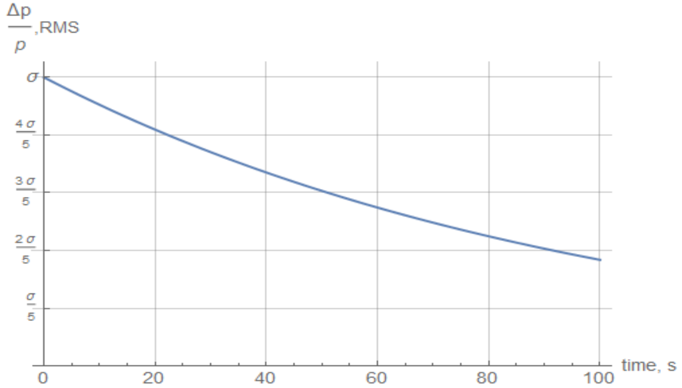
- Uncoupled motion
  - Momentum cooling
    - Transit Time method ($\eta_{p\leftrightarrow k}\uparrow$)
    - Filter method ($\eta_{p\leftrightarrow k}\rightarrow 0$, $\eta_{p,k,k}\uparrow$)
  - Transverse cooling
    - Betatron method ($\phi_{p\leftrightarrow k}\rightarrow(2k\text{-}1)\cdot\pi/4$)
-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



Design on the basis of simulation

Fokker-Planck approach

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

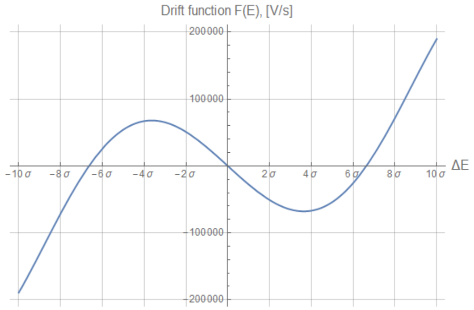


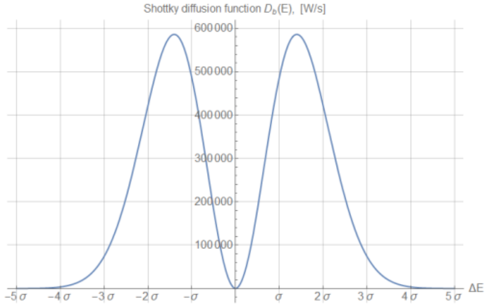
Drift term

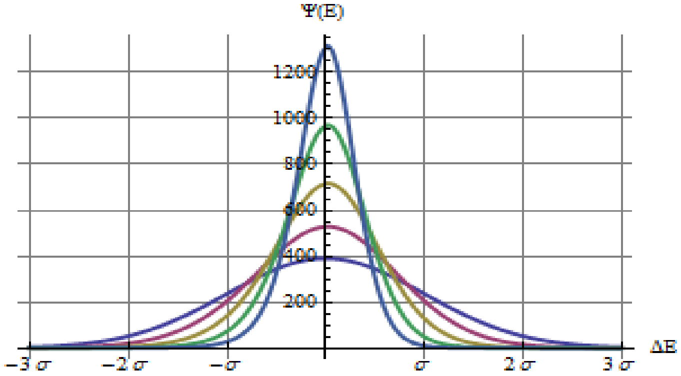
$$F(E)=f_0\Delta E_c\sim\prod_j TF_j$$

Diffusion term

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



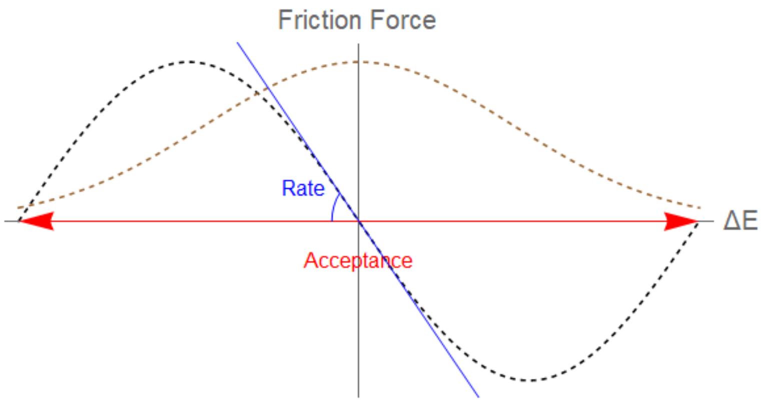


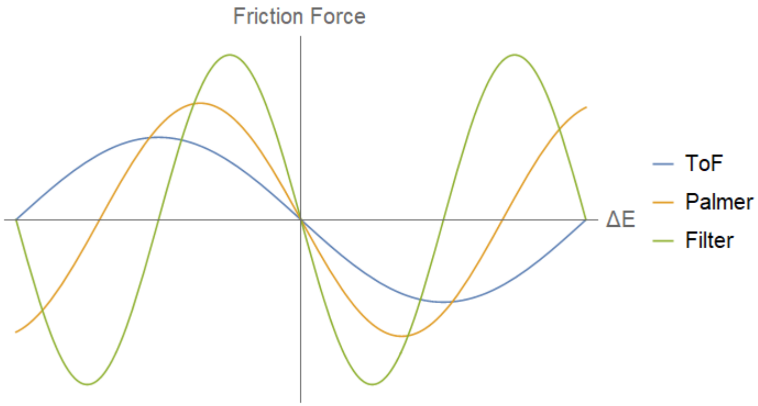


Bandwidth and Cooling Rate vs Acceptance

Cooling rate

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



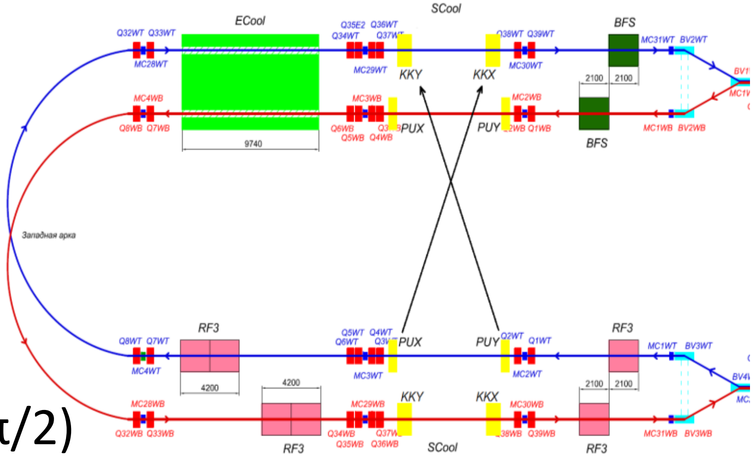


Rate ~ Bandwidth W

Acceptance ~ 1/Band Center ($1/W_c$)

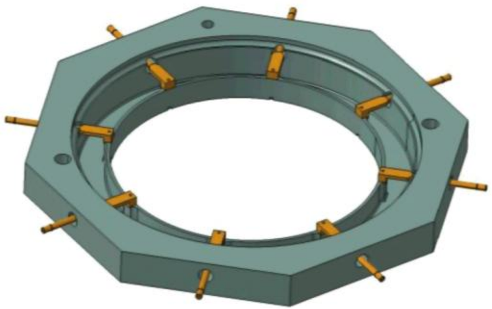
Pickup/Kicker Locations

- 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 ($D_p\uparrow,\beta_p\downarrow,D_k\rightarrow 0$)~~
    - ~~Palmer-Hereward method ($D_p\uparrow,\beta_p\downarrow,D_k\rightarrow 0$)~~
    - …

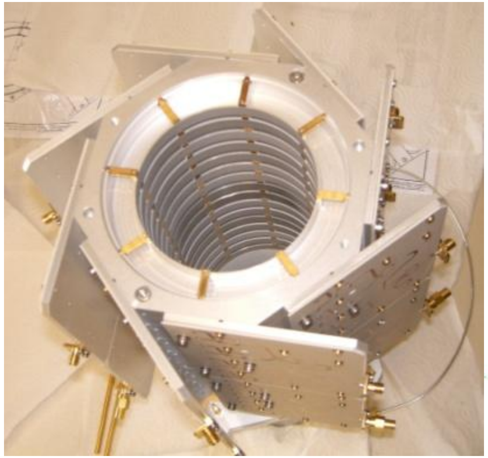


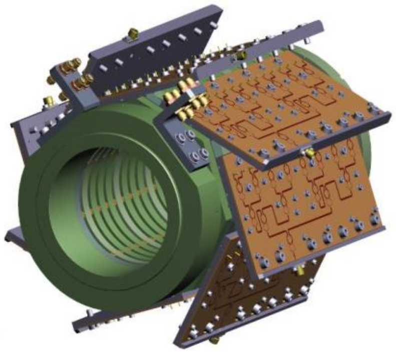
Ring-Slot Coupler Pickup/Kicker

Proposed by L.Thorndahl Developed by R.Stassen



Pickup ring





16 rings stack

Advantages:

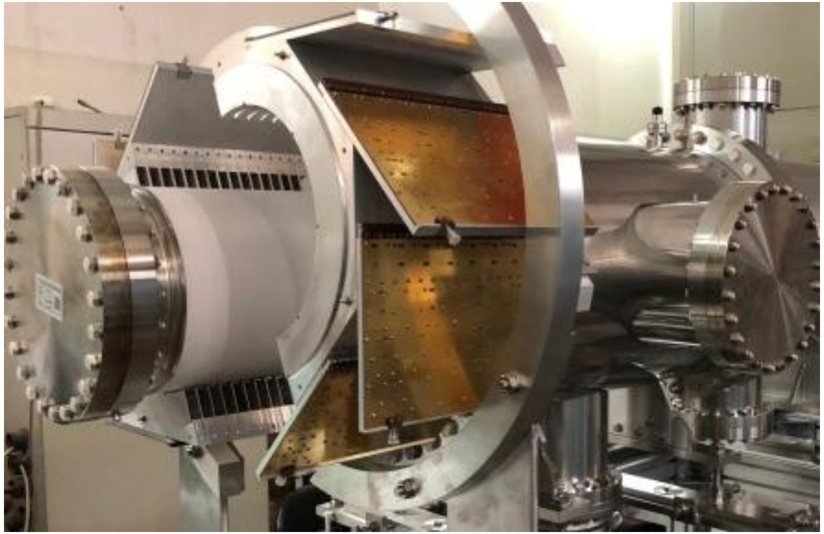
High Coupling Impedance (sensitivity)
Applicable for both long./trans. cooling

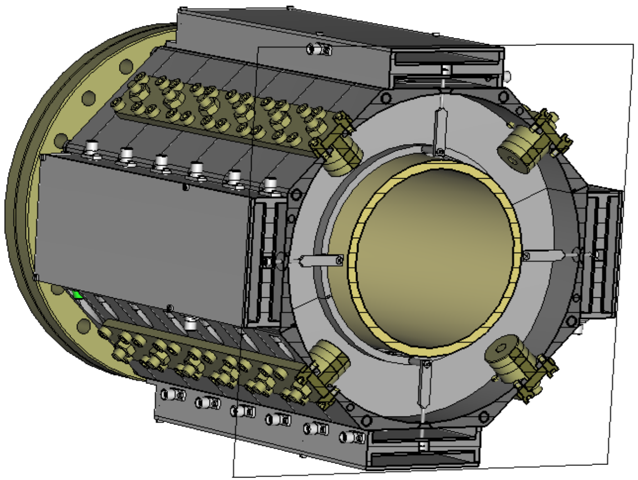
Problem:

Extremely hard to achieve ultra-high vacuum

Pickup/Kicker Modification

Separated structure with ceramic vacuum chamber inside rings



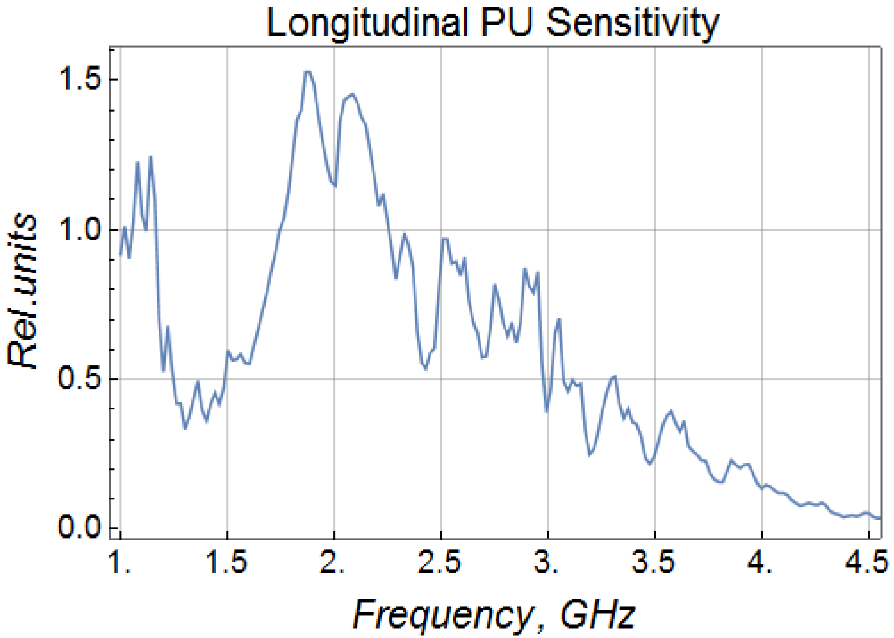


G.Zhu et al., HIAF, IMP, Lanzhou,China

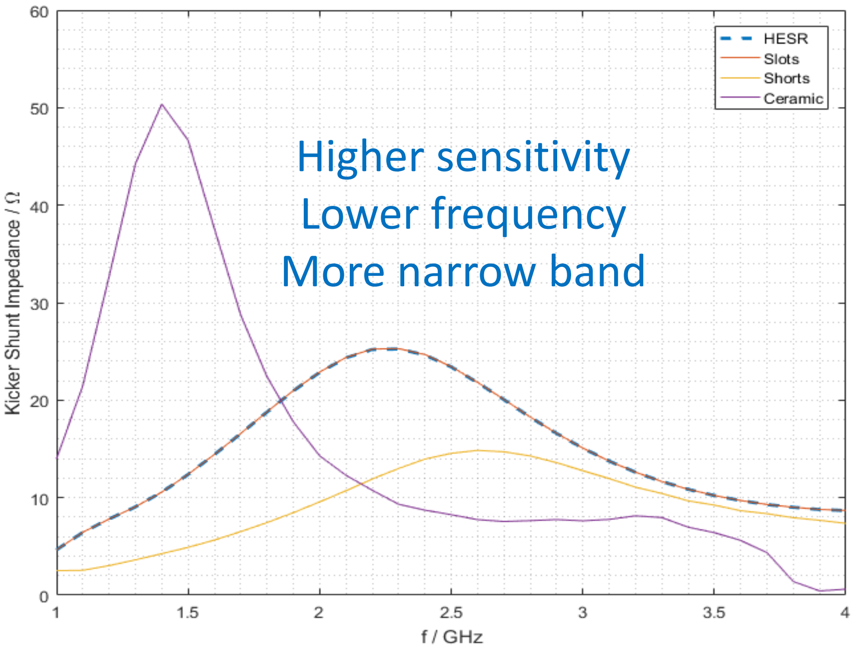
Poster by Konstantin Osipov for details

Sensitivity

Nuclotron measurements: original structure

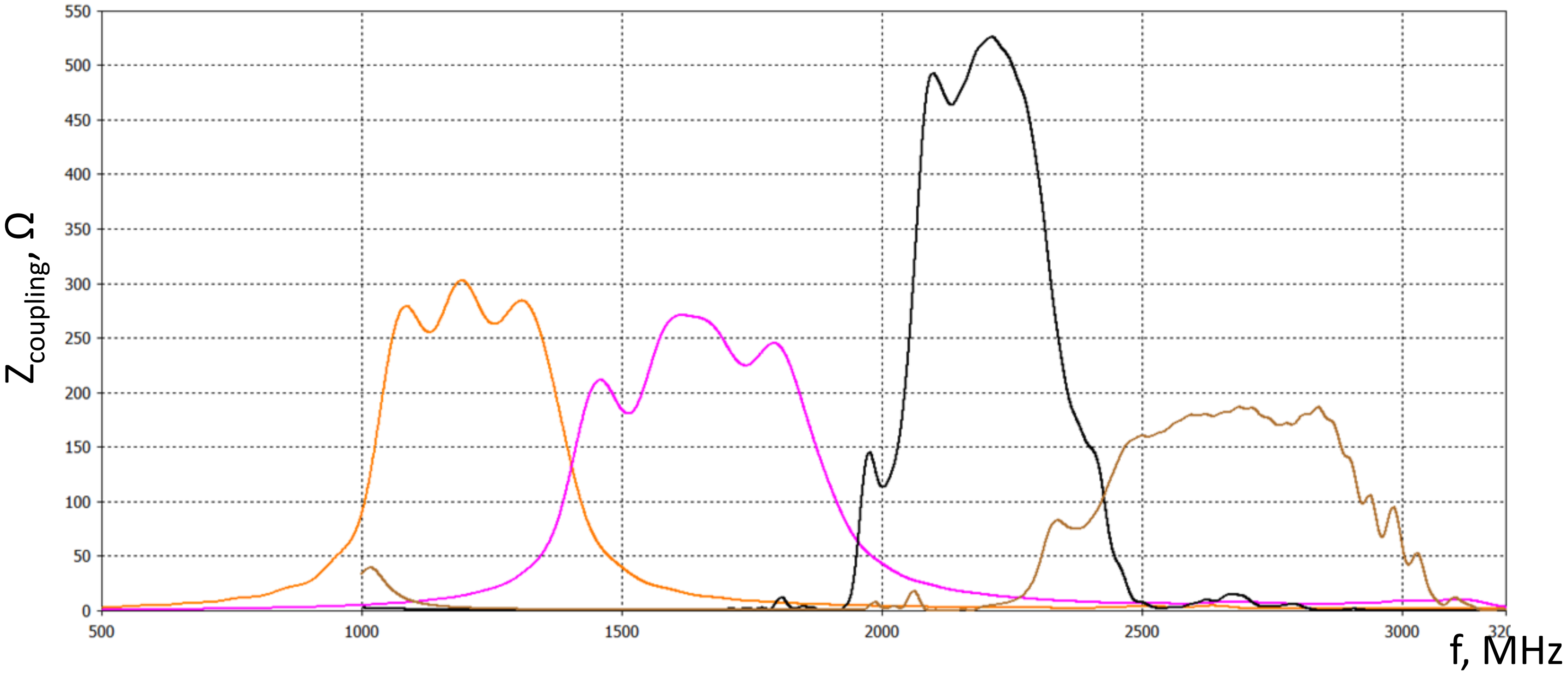


Comparison with modifications



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

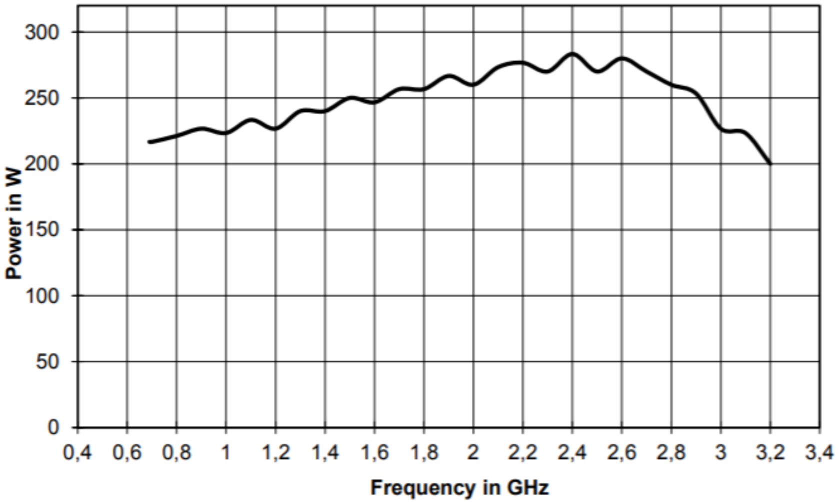
Single Band (2-4 GHz) ->
-> Distributed Bands (1-3 GHz)

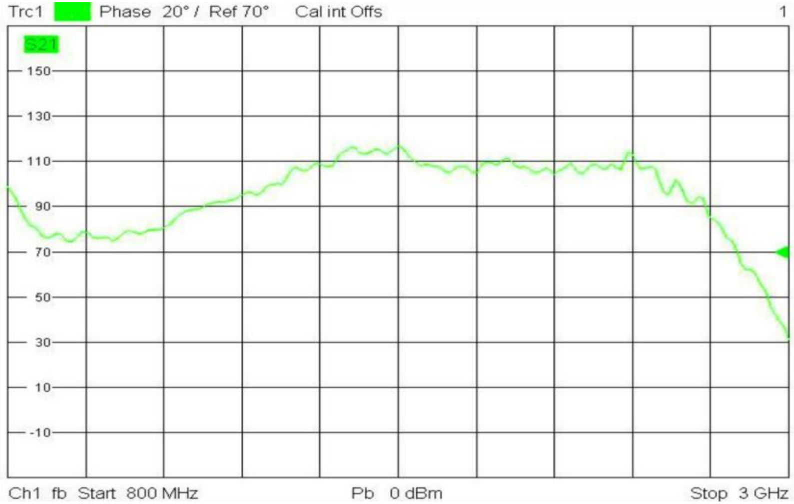


Power Amplifiers

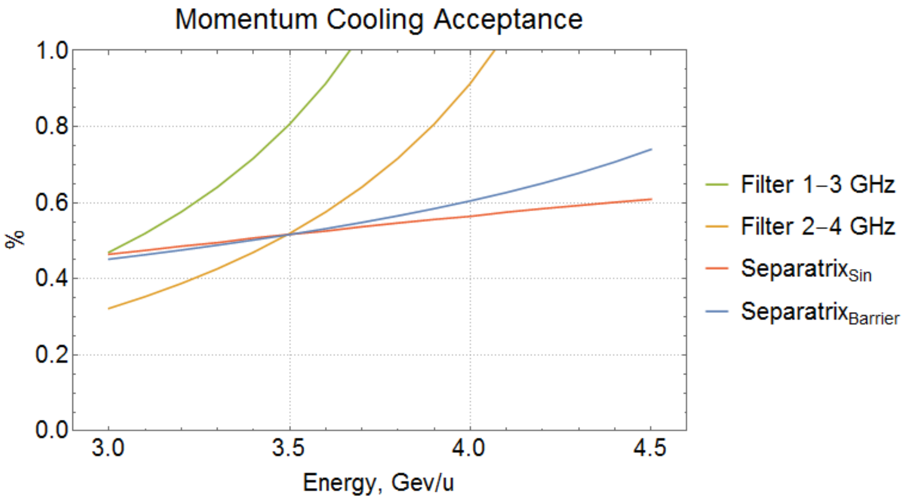
R&S®BBA150-D200, 200 W power class

Frequency response at 1 dB compression

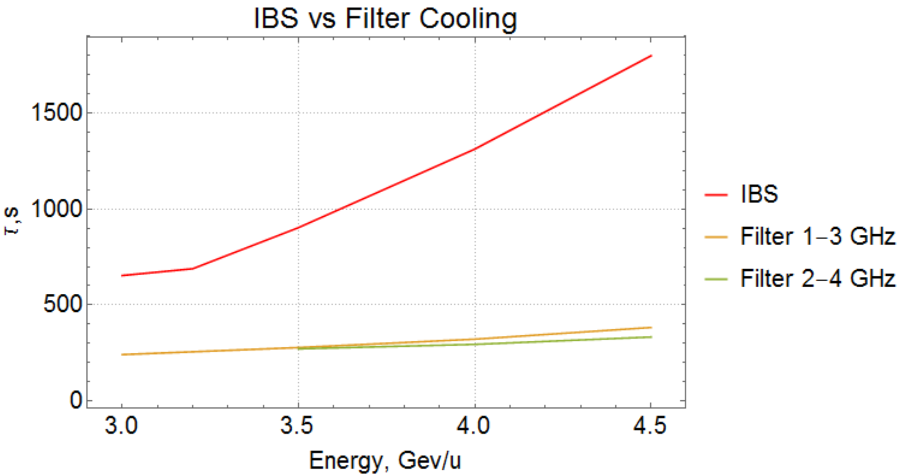




Band shift from 2 – 4 GHz to 1 – 3 GHz



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



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

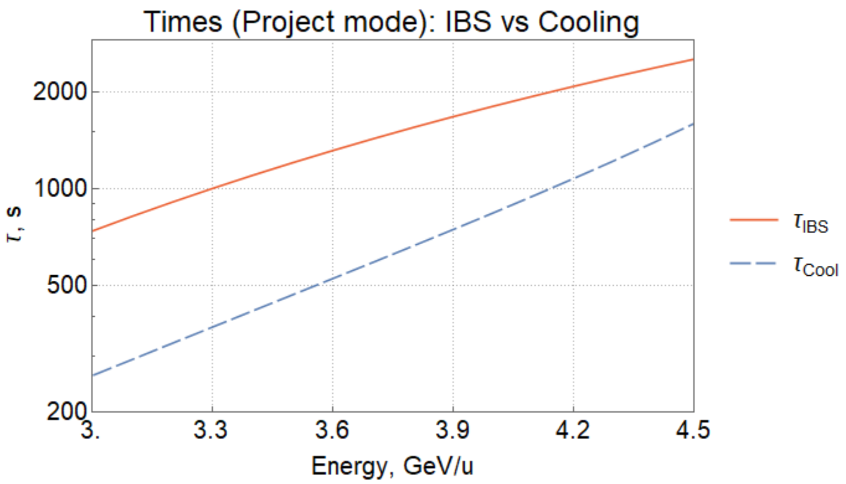
Filter method with band 1-3GHz can provide necessary momentum acceptance for energies above 3 GeV/u

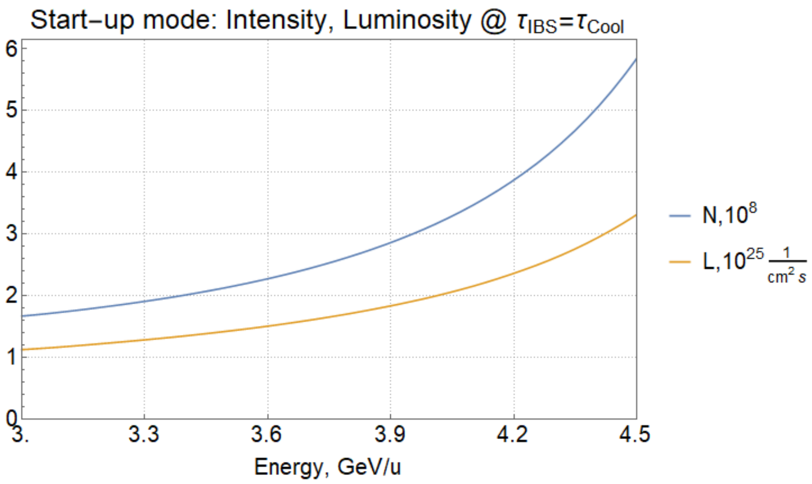
Conclusion

Longitudinal cooling method	Filter	
Passband, GHz	0,7 – 3,2	
Beam distance from pickup to kicker, m	179,8	
Ion Energy $^{197}Au^{79+}$, 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