

NICA Stochastic Cooling System

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Introduction

Stochastic cooling

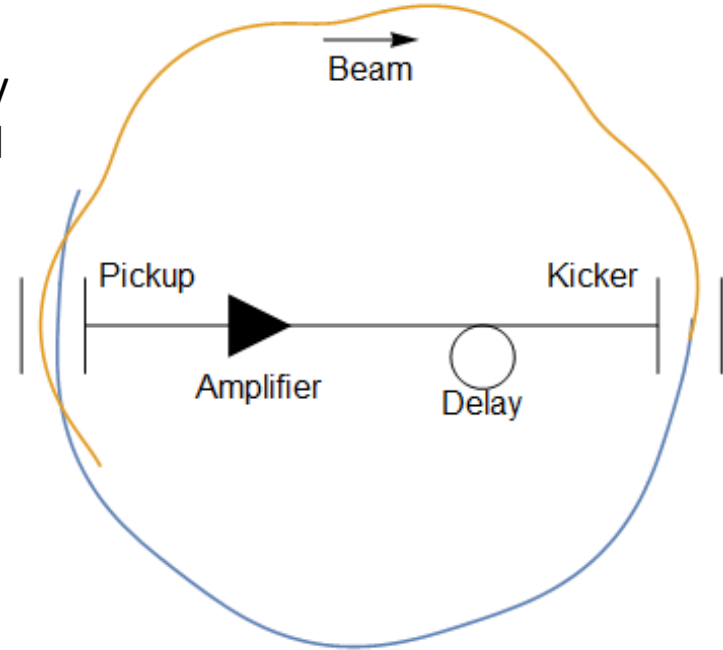
Physically: reduction of the beam phase space by feeding to the beam particles their own noisy signal

Technically: broadband feedback system

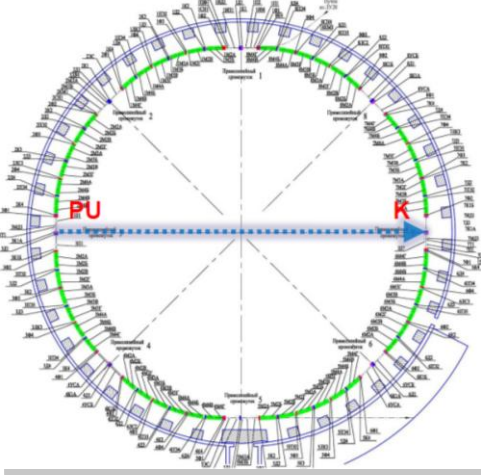
$$\text{Bandwidth } W \quad \text{Gain } g = g(P_{in}, P_{out})$$

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

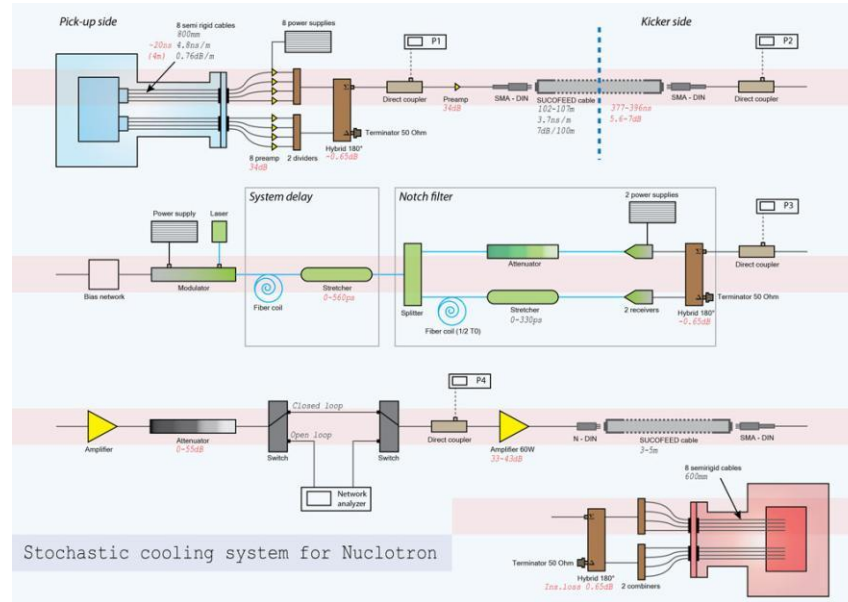
$$\frac{1}{\tau_{Cool}} = \frac{W}{N} (2g[1 - \tilde{M}^{-2}] - g^2[M + U])$$



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}



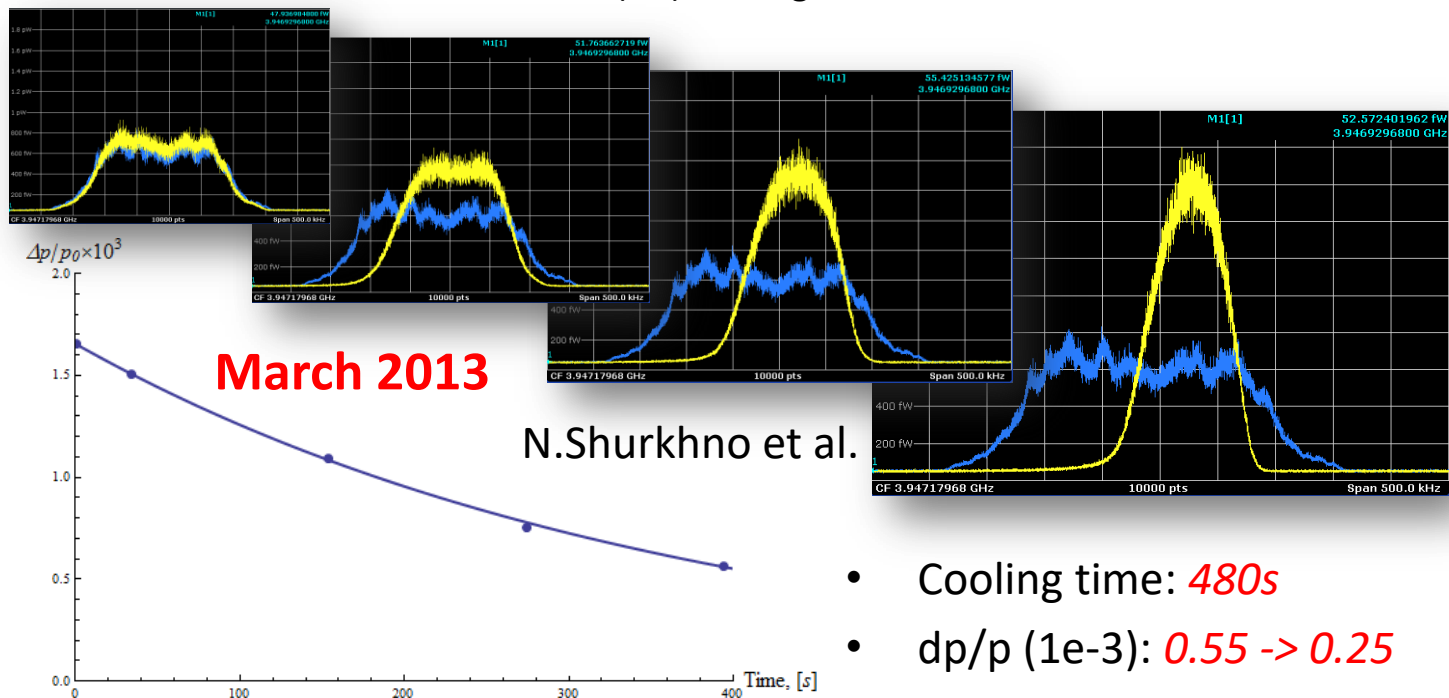
Band 2 – 4 GHz

Output power up to 60 W

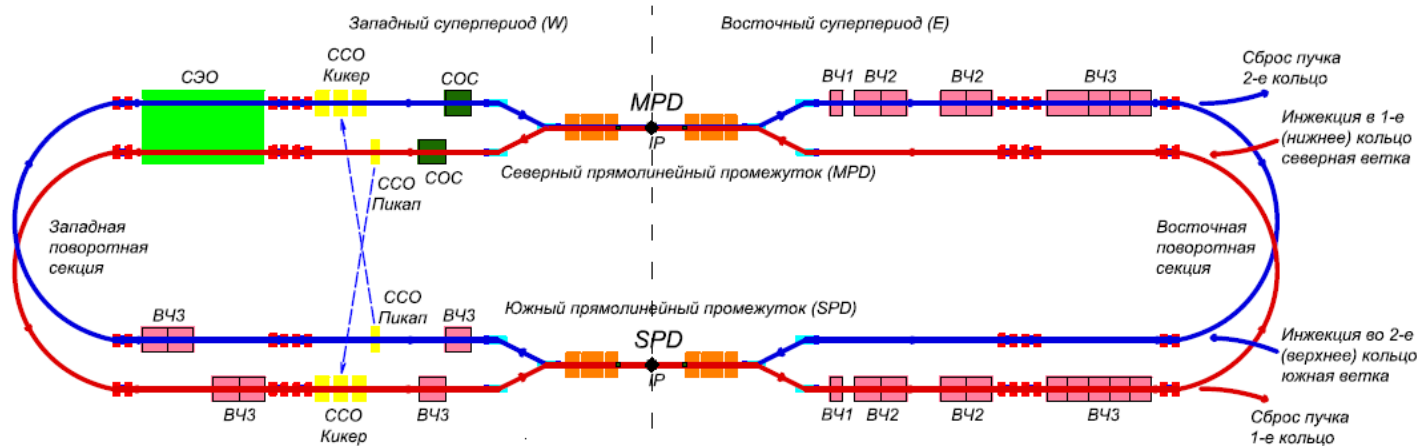
Goals: Investigation of different cooling methods
Equipment tests for the collider

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 $U_{RF} = 50-100$ kV	RF Voltage $U_{RF} < 1000$ kV
Harmonic number $h = 22$	Harmonic number $h = 66$
Ions $^{179}\text{Au}_{97+}$	
$\varepsilon_{\perp\text{rms.max}} = 1,1 \pi \text{ mm.mrad.}$	
$\Delta p/p_{\text{max}}=1\%$	
Energy range 3-4,5 GeV/u	
Only longitudinal cooling	3-D cooling

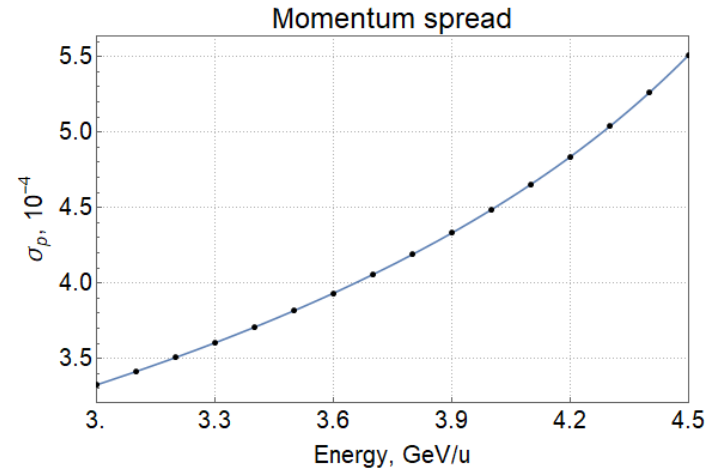
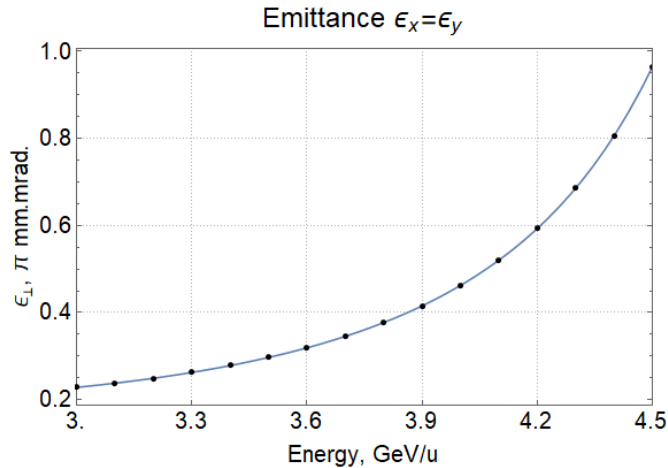
Start-up mode: Phase Volume

IBS calculations: BETACOOOL

Longitudinal cooling only

IBS simulation condition

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

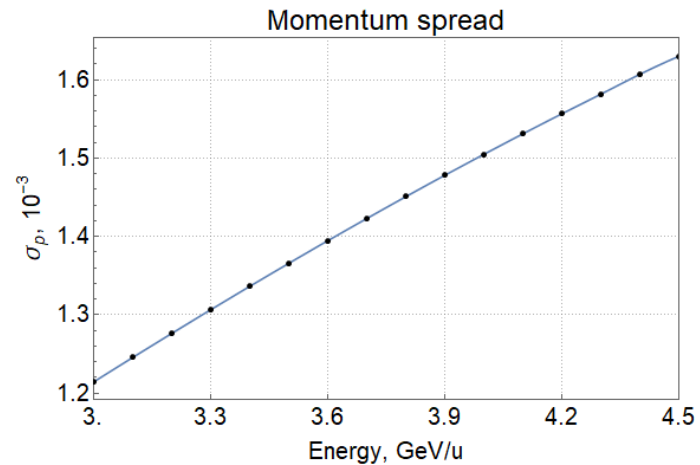
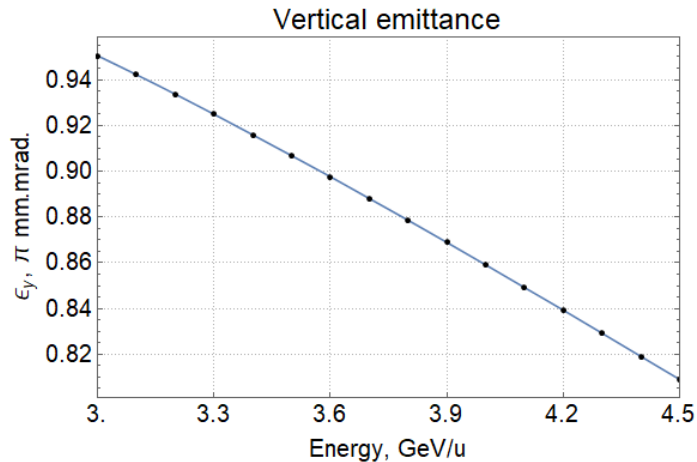


Project Mode: Phase Volume

3-D cooling

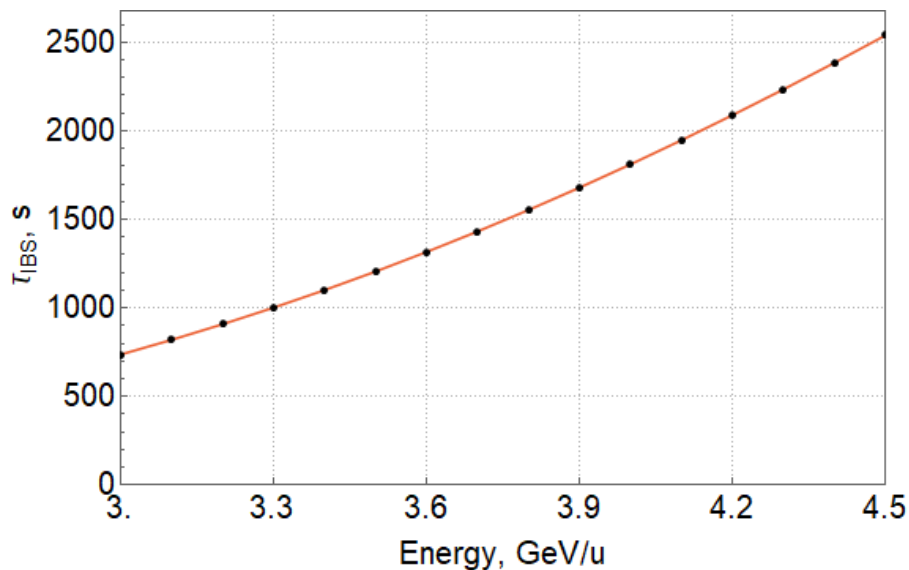
IBS simulation condition

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



Project Mode: IntraBeam Scattering

$$L_{max} = 10^{27} \text{cm}^{-2} \text{s}^{-1} \quad N_{b,max} = 2.75 \times 10^9$$



Requirements for the system: cooling times less than 700-2600 s

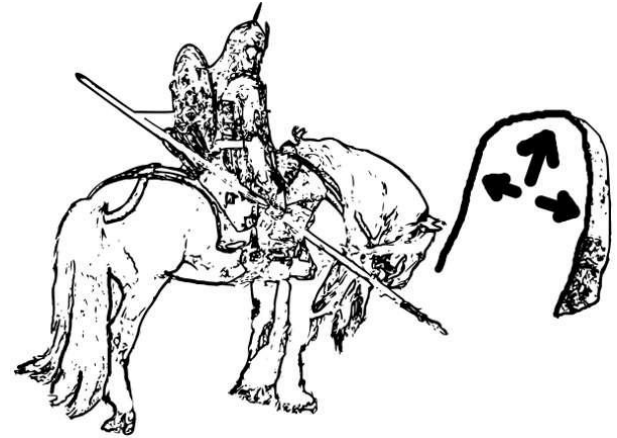
Design Steps

- 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

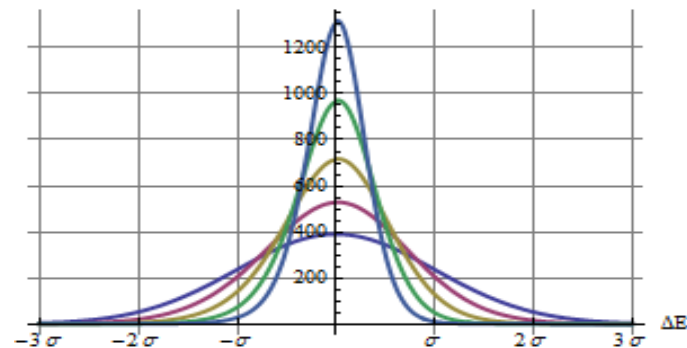
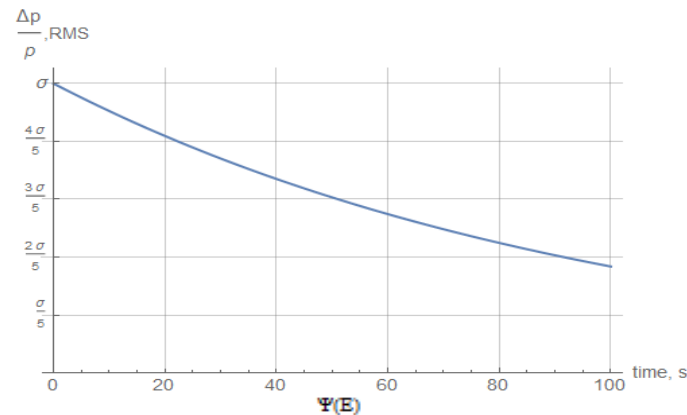
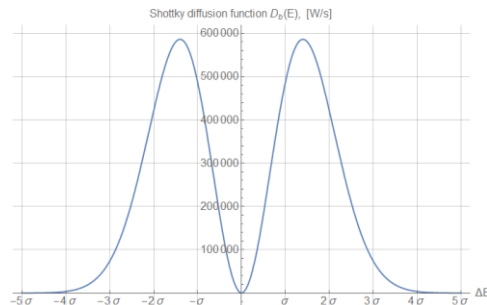
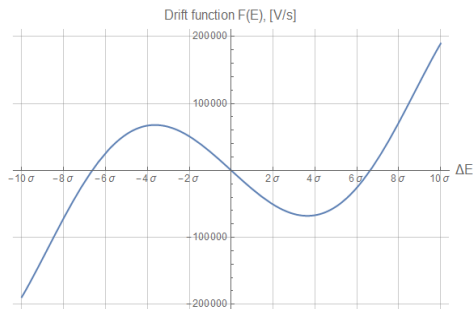
$$\frac{\partial \Psi(E, t)}{\partial t} + \frac{\partial}{\partial E} \left(F(E) \Psi(E, t) - D(E, t) \frac{\partial \Psi(E, t)}{\partial E} \right) = 0$$

Drift term

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

Diffusion term

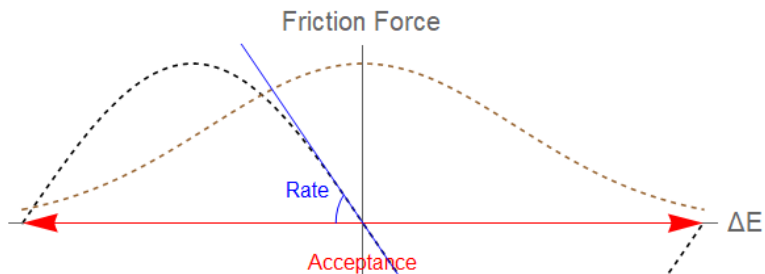
$$D(E, t) = \frac{1}{2} f_0 \langle \Delta E_{ic}^2 \rangle \sim \prod_j TF_j^2$$



Bandwidth and Cooling Rate vs Acceptance

Cooling rate

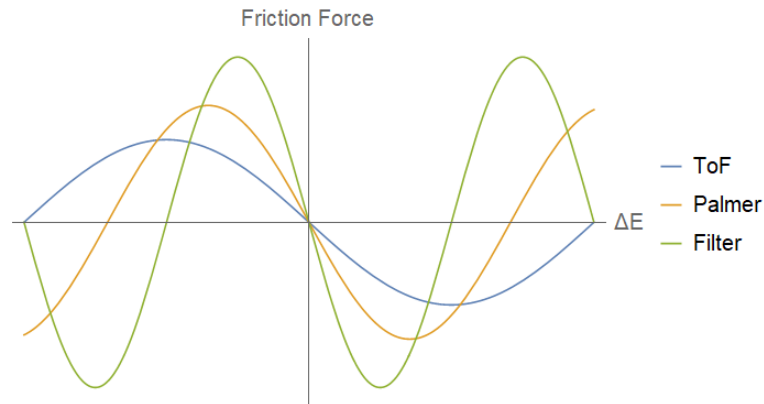
$$\frac{1}{\sigma^2} \frac{d\sigma^2}{dt} = \frac{4}{N\sigma} \int E \left[F(E)\psi(E,t) - D(E,t) \frac{\partial \psi(E,t)}{\partial E} \right] dE$$



$$F(f) = -\sum_{n=n_1}^{n_2} A(nf) \sin[k(\eta_{pk}, \eta_0, meth.)nf]$$

$$\Delta A \updownarrow \leq \pm 2dB$$

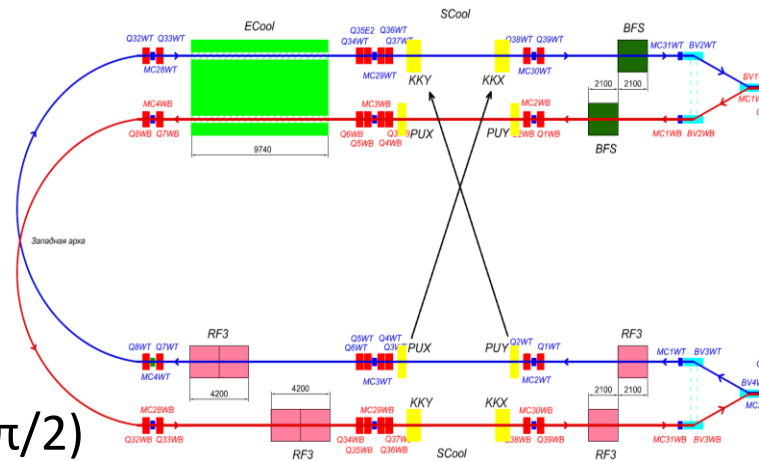
$$\Delta \phi \updownarrow \leq \pm 15^\circ$$



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

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 ($D_p \uparrow, \beta_p \downarrow, D_k \rightarrow 0$)~~
 - ~~...~~

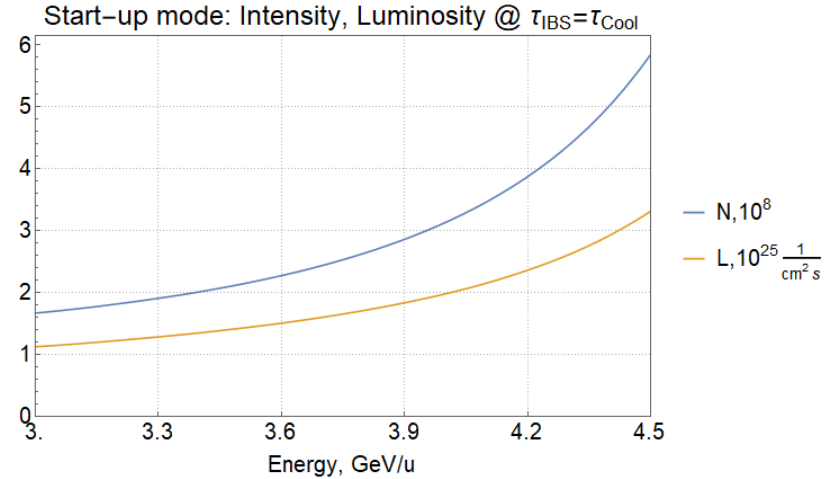
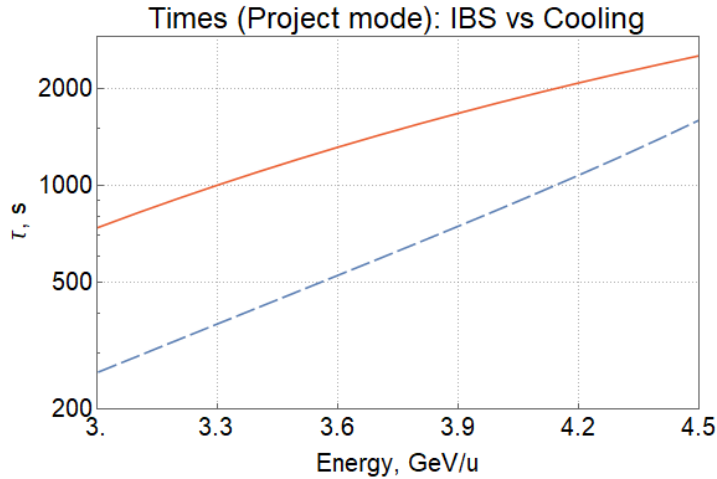


System parameters

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	
Gain variation, dB	$\leq \pm 2$	
Deviation from linear phase, deg	$\leq \pm 15$	
Peak power at kicker, W	120	
Pickup/noise temperature, K	300/40	

Main parameters for NICA Stochastic cooling system has been defined

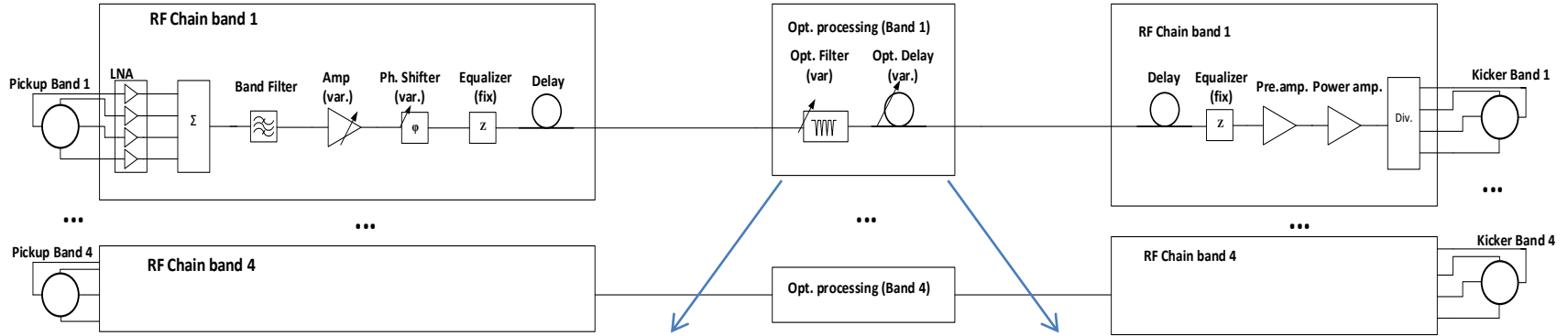
Cooling rates



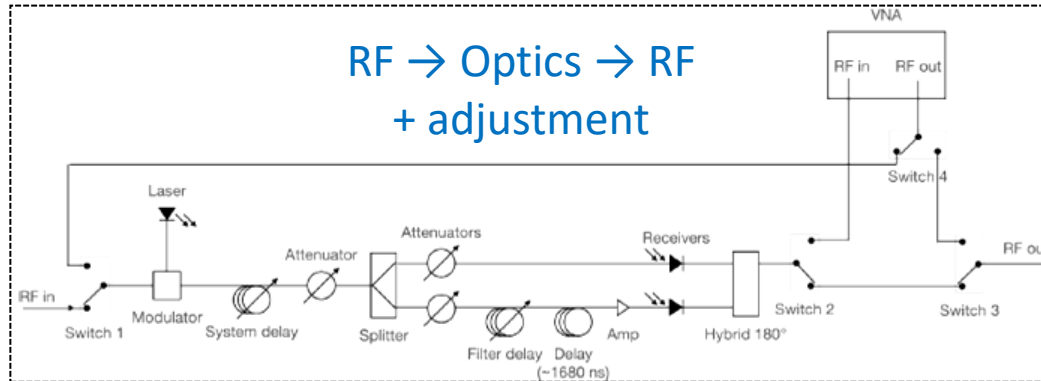
- Filter method is chosen for longitudinal cooling, betatron method – for transverse cooling. Main parameters are defined.
- Given stochastic cooling system provides the required cooling rates.

General scheme

Low level

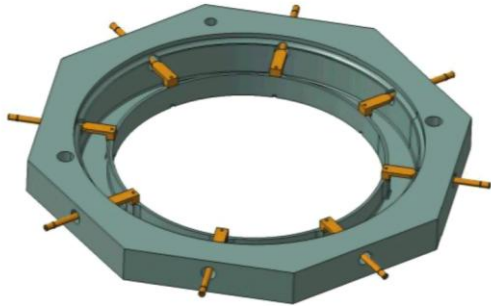


RF \rightarrow Optics \rightarrow RF
+ adjustment

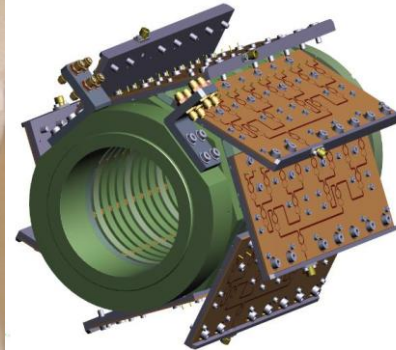
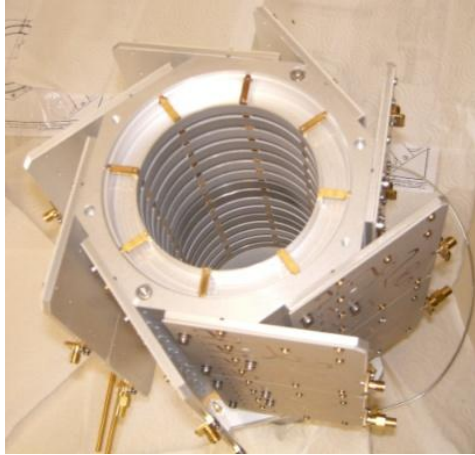


Ring-Slot Coupler Pickup/Kicker

Proposed by L.Thorndahl Developed by R.Stassen



Pickup ring



16 rings stack

Advantages:

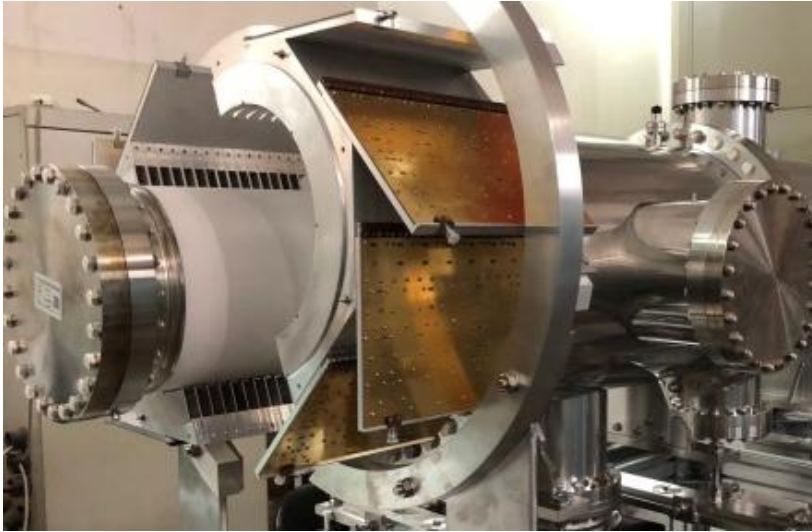
High Coupling Impedance (sensitivity)
Applicable for both long./trans. cooling

Problem:

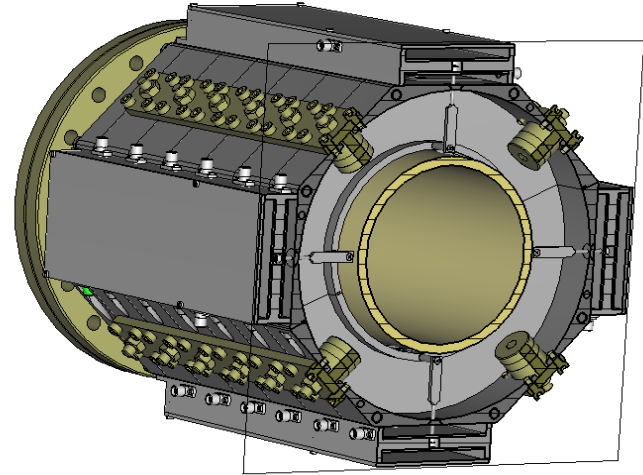
Extremely hard to achieve ultra-high vacuum

Pickup/Kicker Modification

Separated structure with ceramic vacuum chamber inside rings



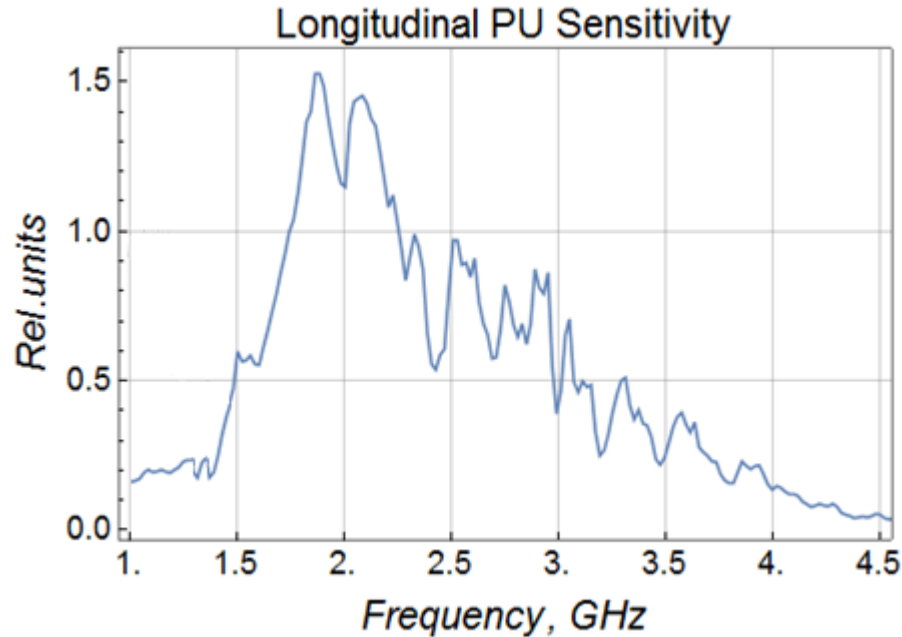
G.Zhu et al., HIAF, IMP, Lanzhou, China



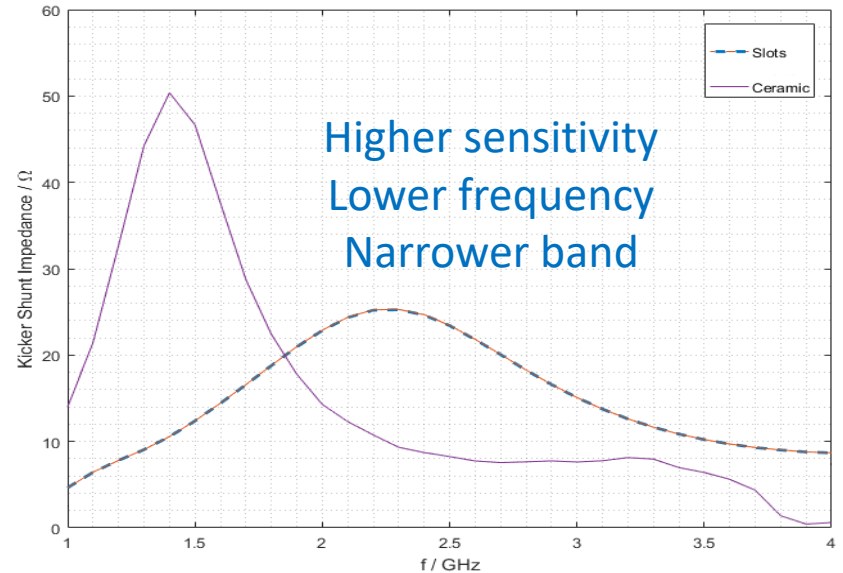
Design by Konstantin Osipov, JINR

Sensitivity

Nuclotron measurements: original structure

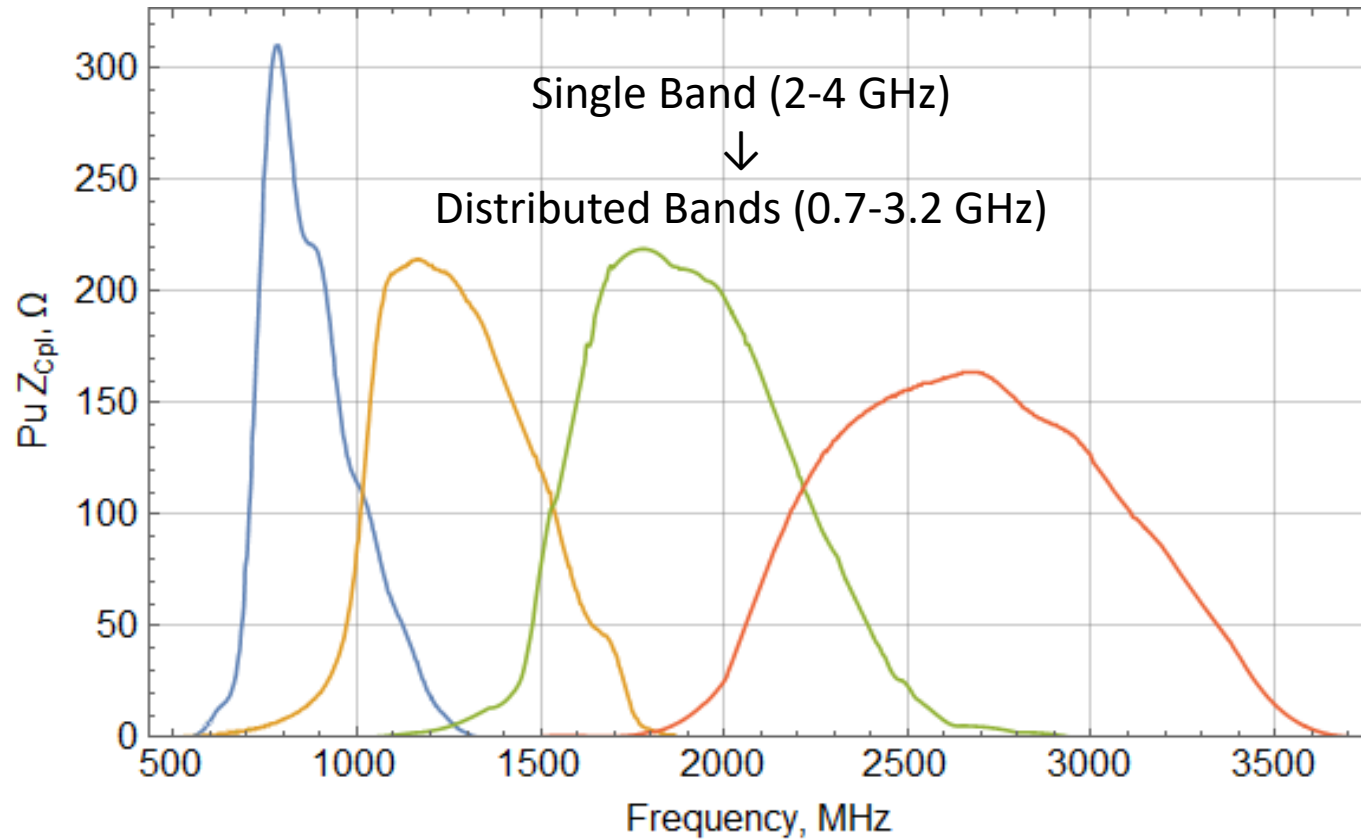


Comparison with modifications

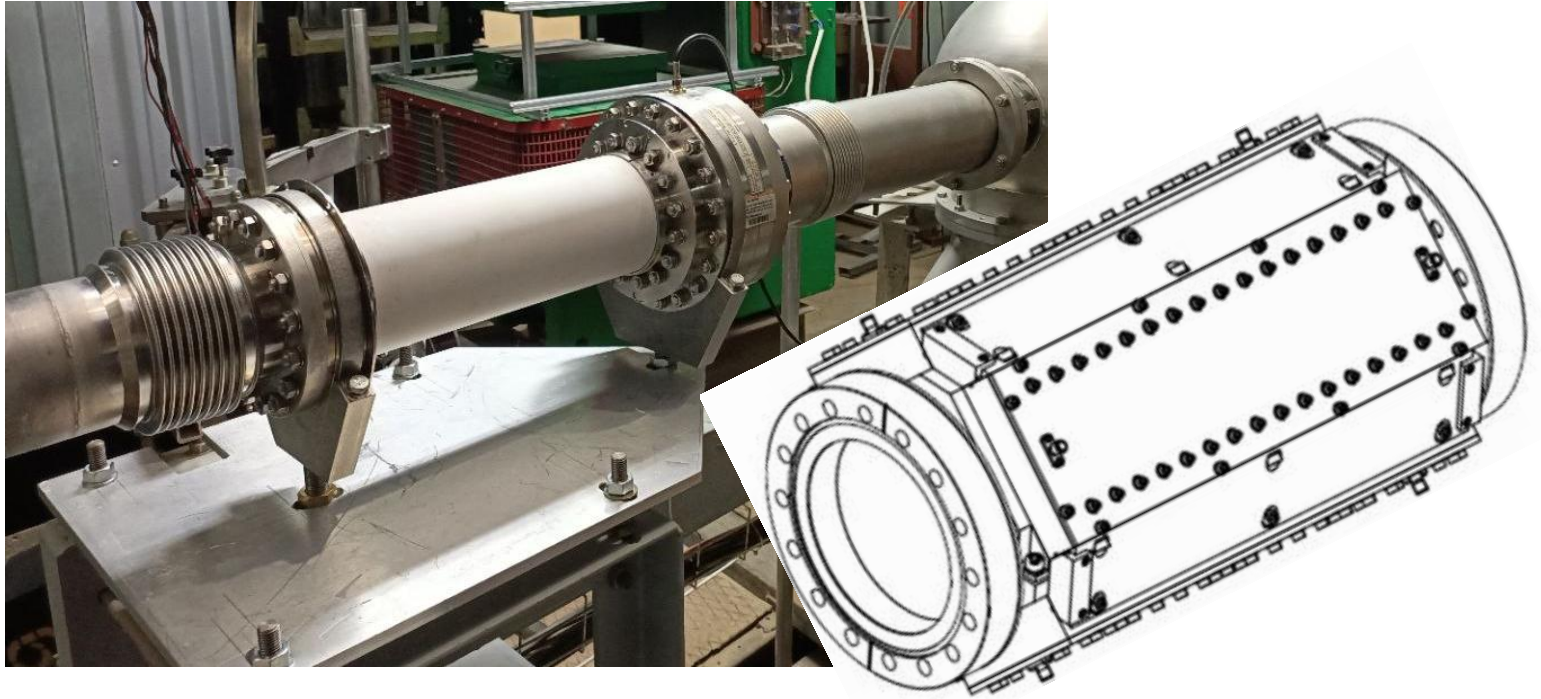


Pickups do not need to be inside cryostat due to higher sensitivity and heavy ions

Pickup/Kicker Modification

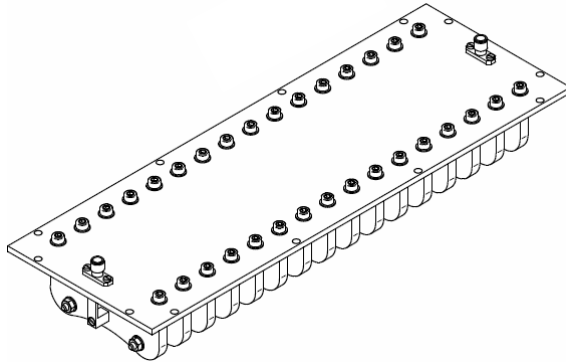
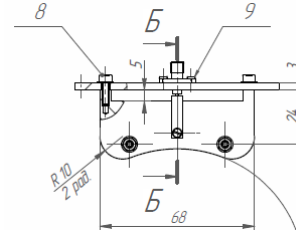
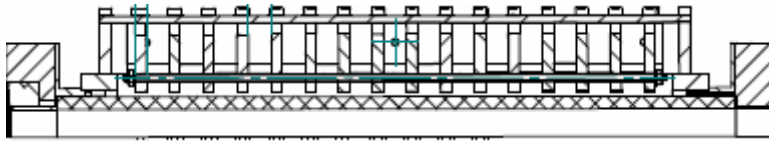


Pickup/Kicker



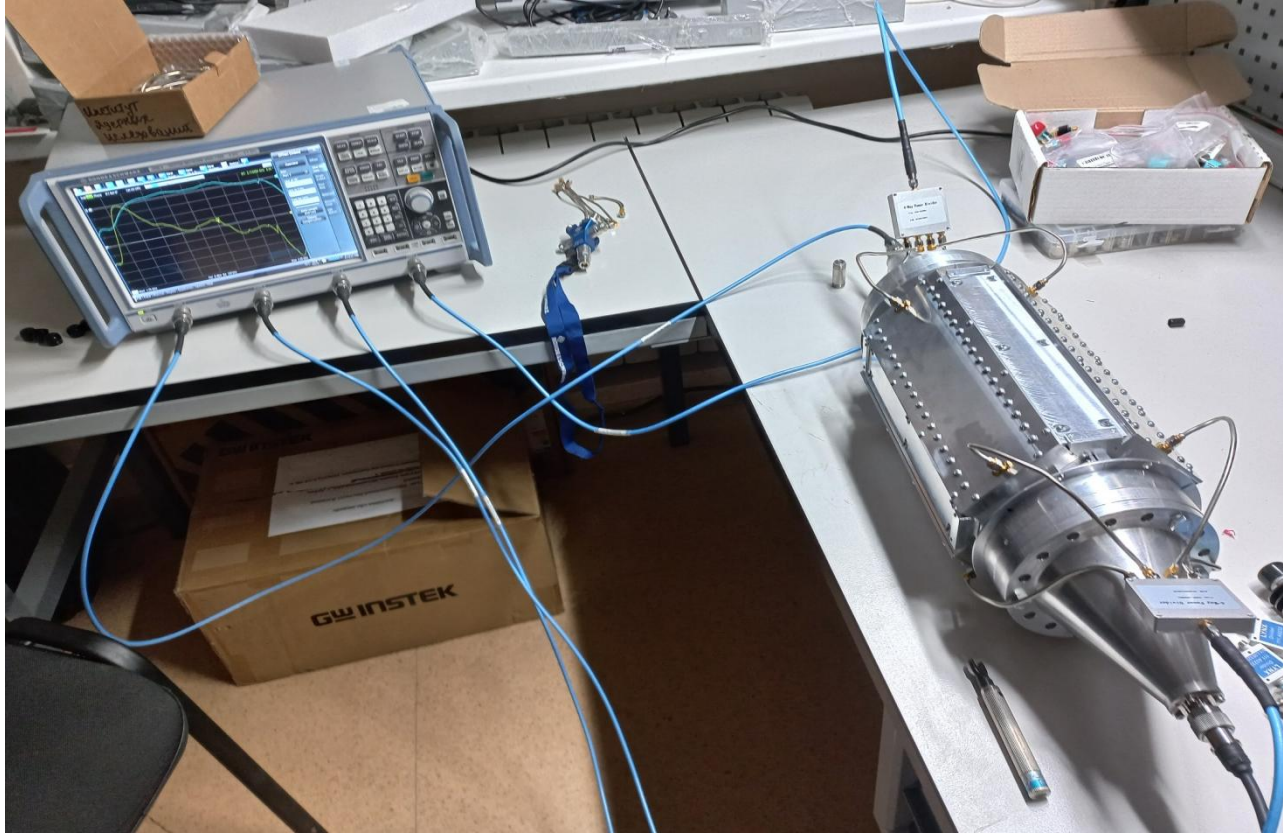
The base for prototype testing is installed at Nuclotron

Pickup/Kicker



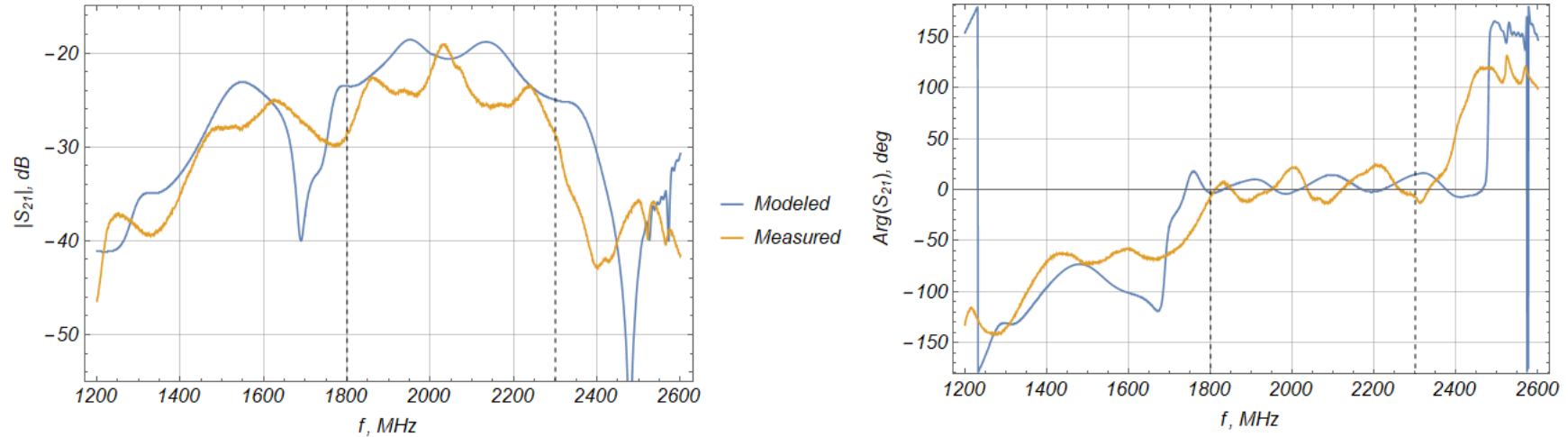
Test prototype of corrugated pickup has been produced

Pickup/Kicker



Pickup/Kicker

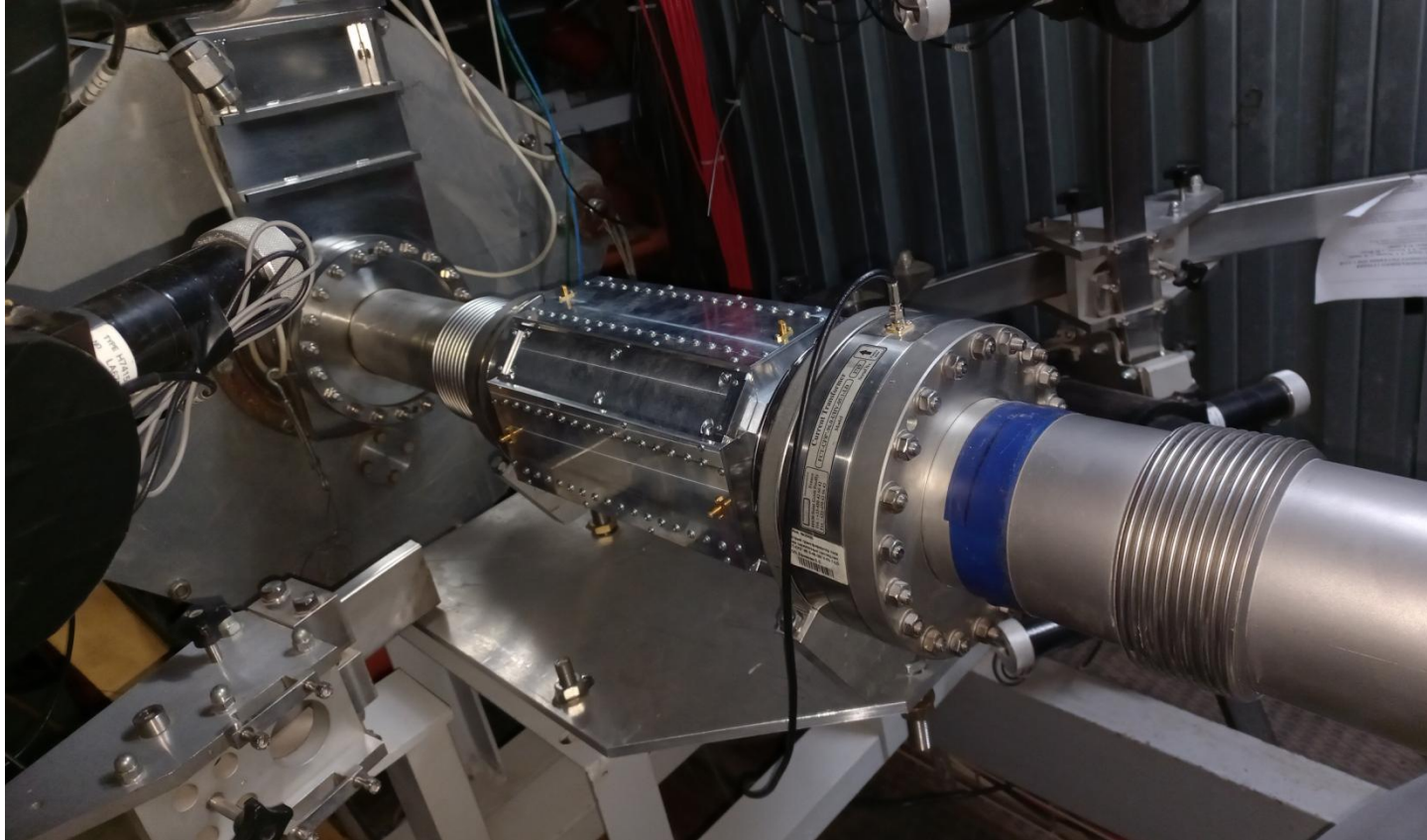
Coupling Axial \leftrightarrow Loop ports



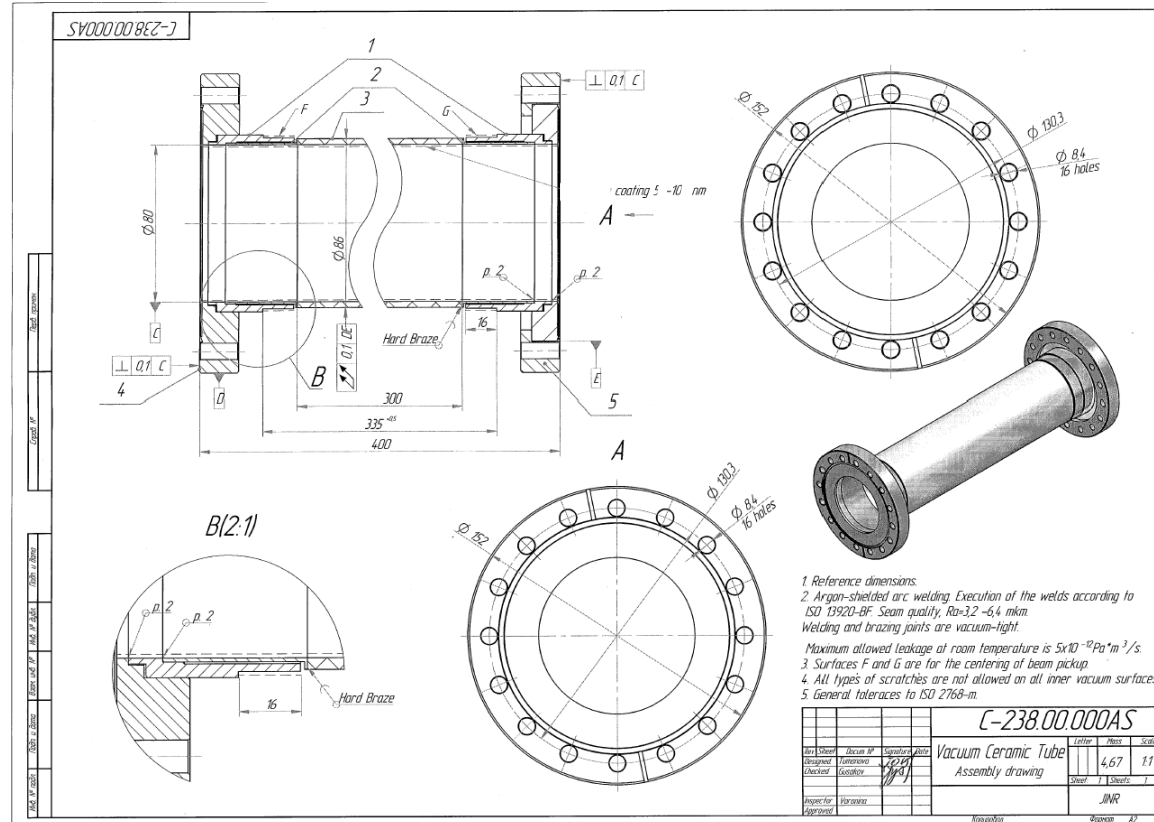
Band: 1800 – 2300 MHz

Simulated and measured S-parameters are in agreement with each other

Pickup/Kicker

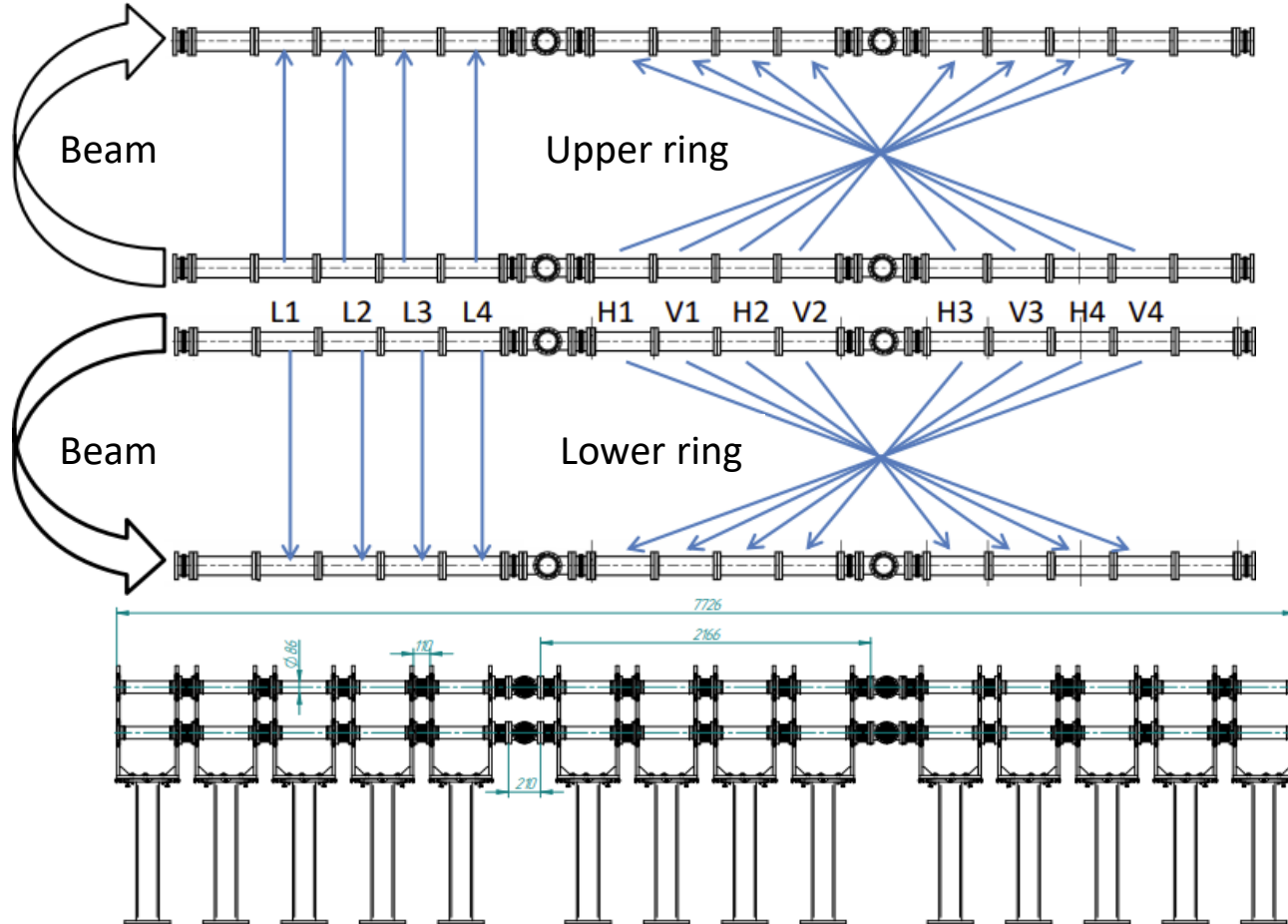


Pickup/Kicker Modification

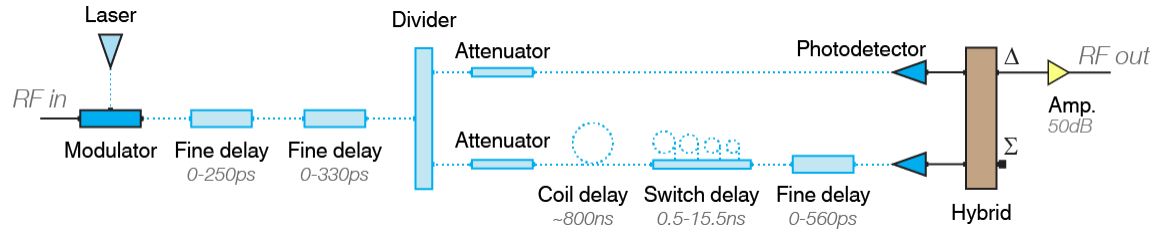


Design documentation for the base is ready. Tender procedure is in progress

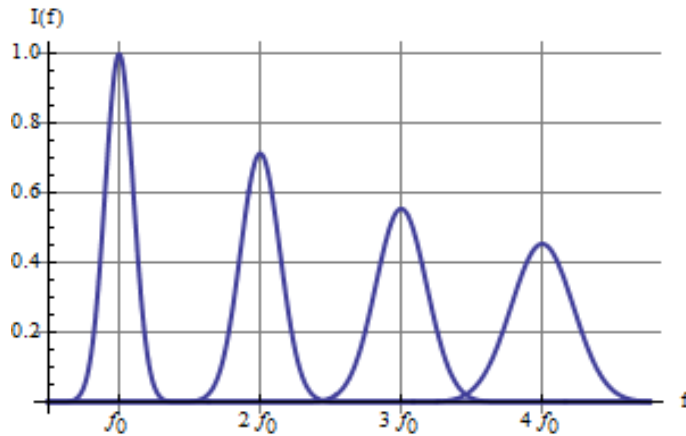
Channels distribution



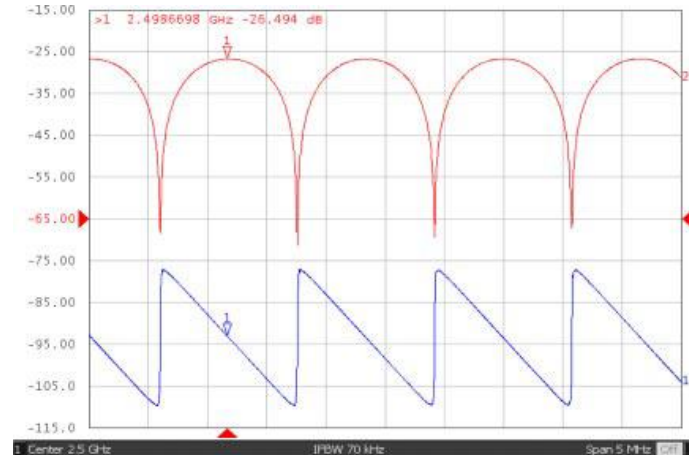
Comb Filter



$$f_{notch} = \frac{1}{T_{LongLeg} - T_{ShortLeg}}$$



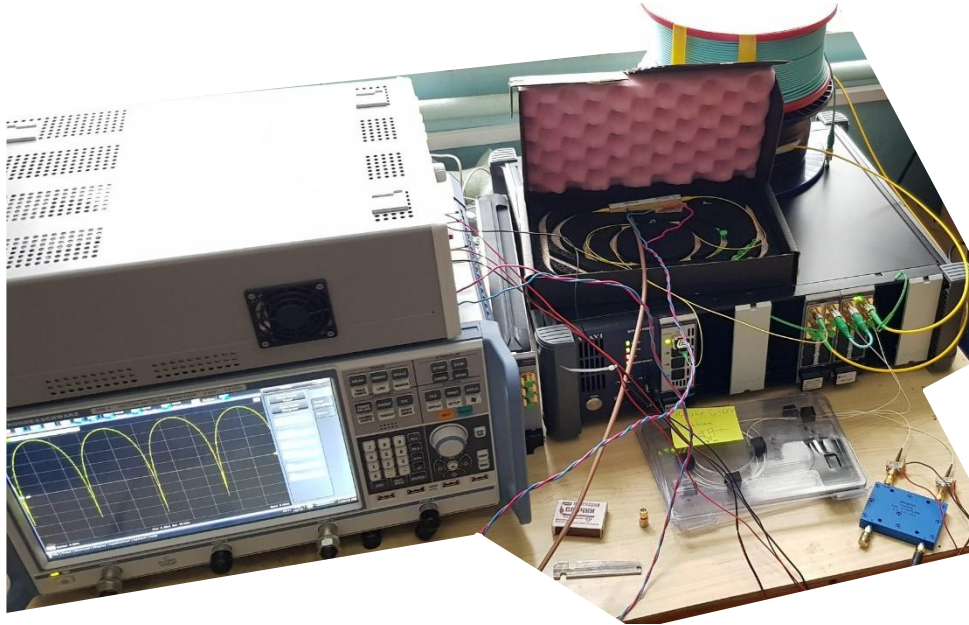
$$f_{notch} = f_{rev}$$



Comb Filter Specifications

RF:	
Frequency	see order description
<u>Latency (own delay)</u>	< 20 ns
Phase variation	$\pm 10^\circ$
Insertion loss variation	± 2 dB
Notch-frequency range	520.833 to 595.238 kHz ¹
<u>Average notch depths</u>	> 30 dB ²
Maximum input power	24 dBm
Optical delays:	
System delay range	0 to 88 ns
<u>Filter delay range</u>	0 to 240 ns
<u>Resolution</u>	< 0.75 ps
Accuracy	< 0.15 ps ³
Repeatability	< 0.15 ps ³
Other:	
System and filter optical attenuators ranges	0 to 30 dB
Control modes	Front panel controls, USB, Ethernet
Operating temperature	10°C - 40°C
Storage temperature	0°C - 60°C

Comb Filter



Filter is conceptually working. Reassembly is in progress

Power Amplifiers Specifications

Band №	I	II	III	IV
Band, GHz	0.7 – 1.0	1.0 – 1.5	1.5 – 2.2	2.2 – 3.2
Operating power, Watt	4	12	32	72
Quantity	8	8	8	8
Input/Output Impedance	50 Ω			
Max Input/Output VSWR	1.5			
Gain ripple	± 1.5 dB			
Phase deviation from linear	$\pm 10^\circ$			
1 dB compression point (P1dB)	> 6 dB above operating power			
Odd-order Intermodulation Intercept Point	> 6 dB above P1dB			

Power Amplifiers

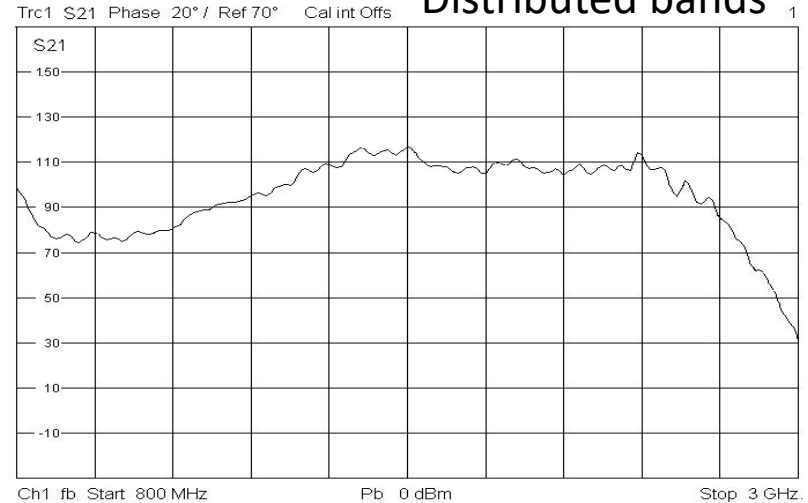
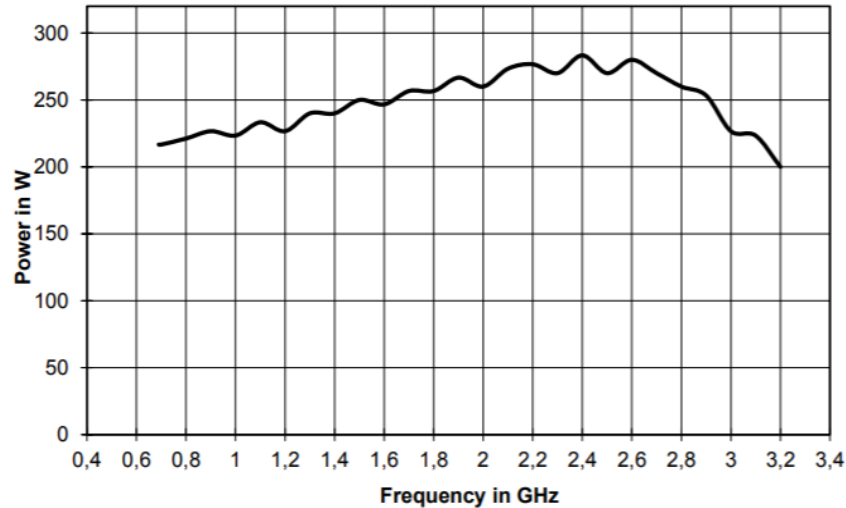
Commercially available



Single band



Distributed bands



Conclusion

- System parameters are defined and are in agreement with NICA tasks
- Requirements for the main components (Pu/Kk, Filter, Power Amps) has been specified
- Pu/Kk & Filter prototypes are under tests
- Ceramic tubes and Amplifiers are to be purchased

Thank you for attention

