12th International Workshop COOL'19

Budker Institute of Nuclear Physics SB RAS

September 23 - 27, 2019

Electron Cooling in the NICA Project: Status and Problems

I.Meshkov[1], N.Mityanina[2], A.Philippov[1], and E.Syresin[1] for NICA Team

[1] JINR Dubna, [2] Budker INP SB RAS

Outline

Introduction: NICA project goals and three stages of the NICA project

1. Stage I: Experiment “The Baryonic Matter at Nuclotron”

2. Stage II : Search for The Mixed Phase and New Physics In Heavy Ions’ Collisions at NICA Collider

3. Stage II-a: The basic configuration of the NICA complex

    3.1. Status of The NICA civil construction (11.05.2017)

4. Stage II-b: The project (full) configuration of the NICA complex

5. Stage III: Polarized Beams’ Mode of The Collider

Introduction: Goals and Three Stages of the NICA Project

- We intend to study the Universe

as it was 13.799 ± 0.021 billion years ago (Planck Mission data, 2015)

and ~ 10-100 μs after Big Bang;

- We wish to try to understand the nature of particle spin.

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Stage II : Search for The Mixed Phase and New Physics In Heavy Ion Collisions

at NICA Collider 2022 => ...

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Stage I & II – NICA White Paper: EPJ A. V 52, N8, 2016. 267 p. and http://theor0.jinr.ru/twiki/pub/NICA/WebHome/WhitePaper_10.01.pdf

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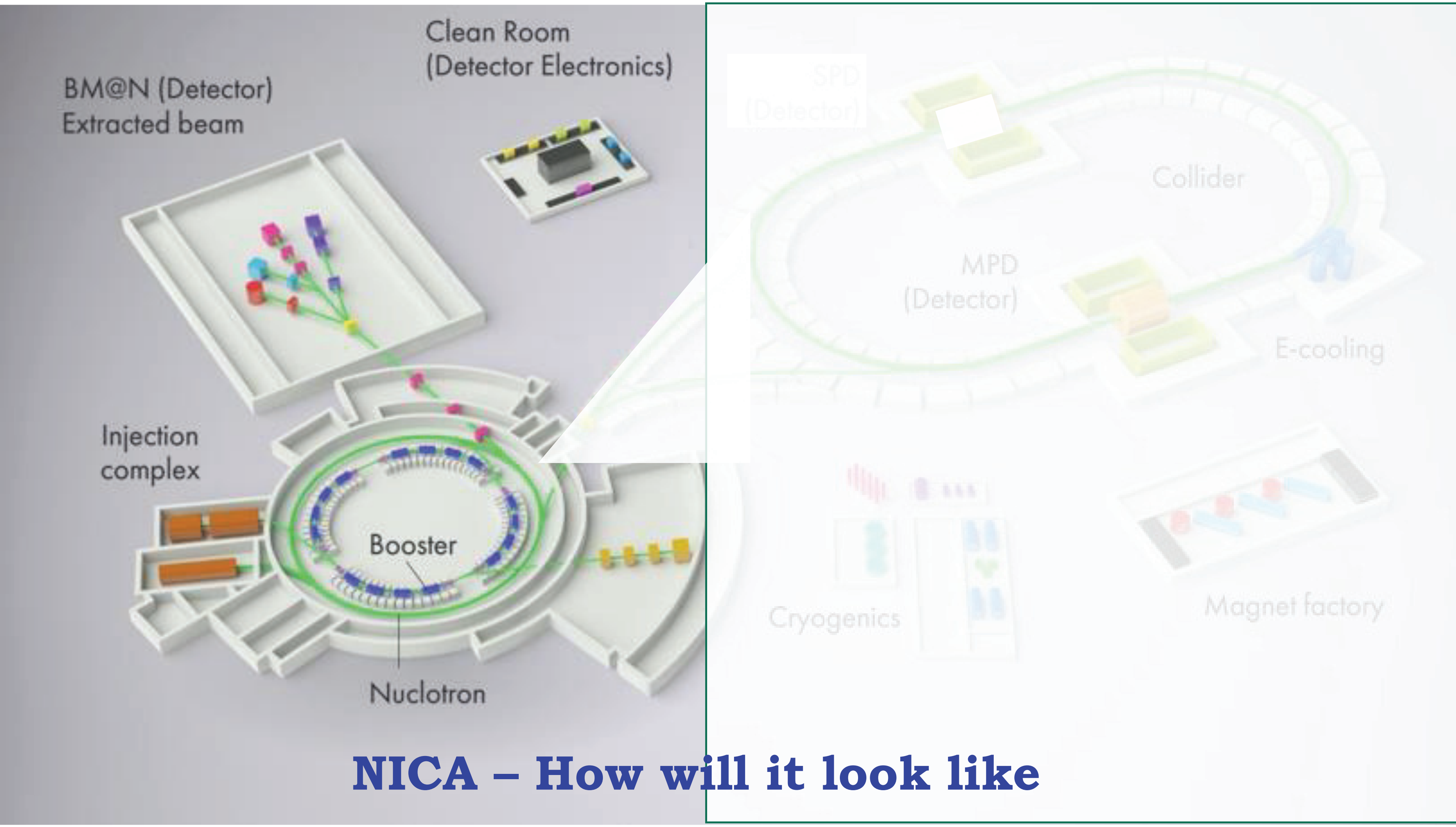

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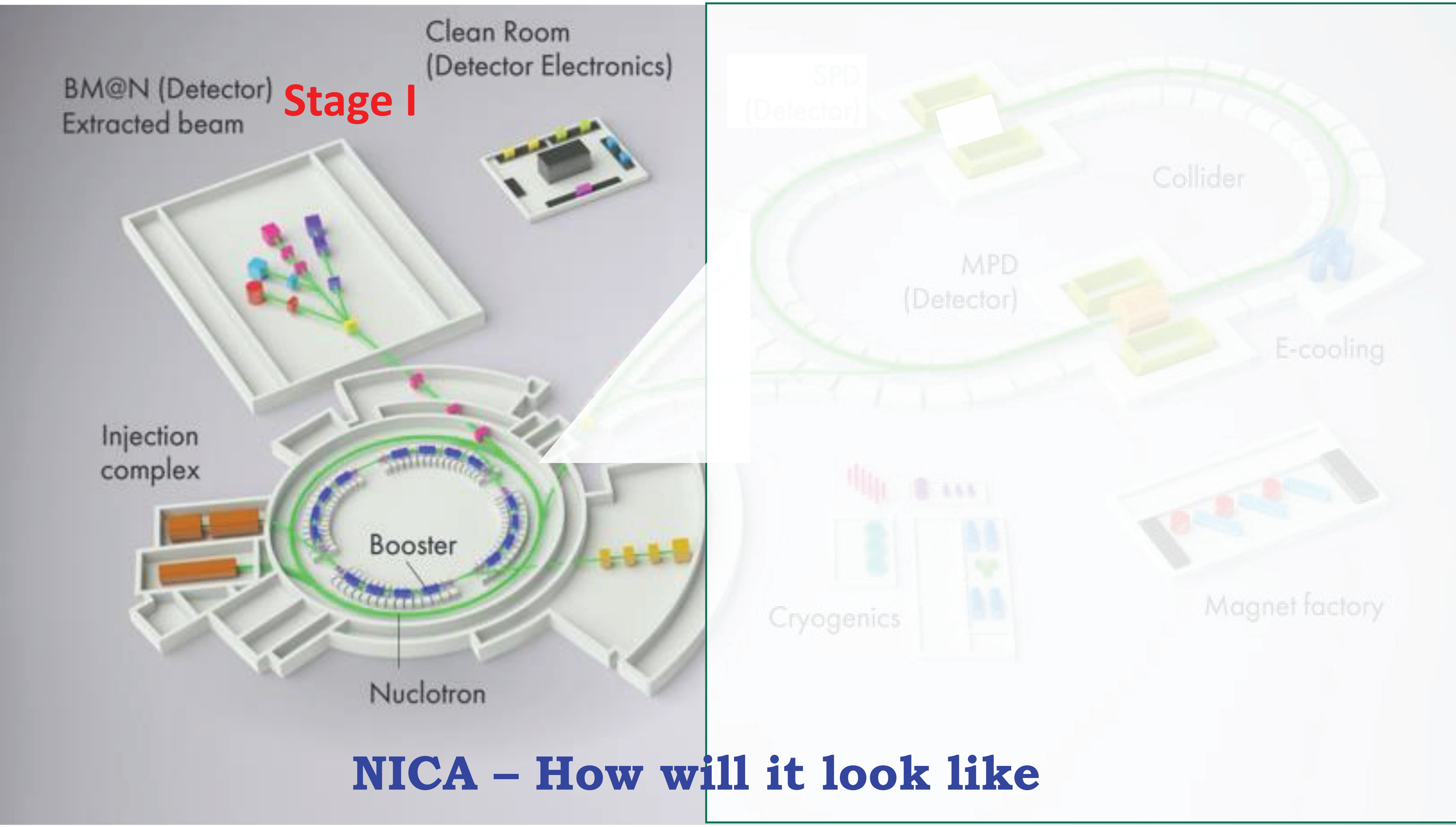

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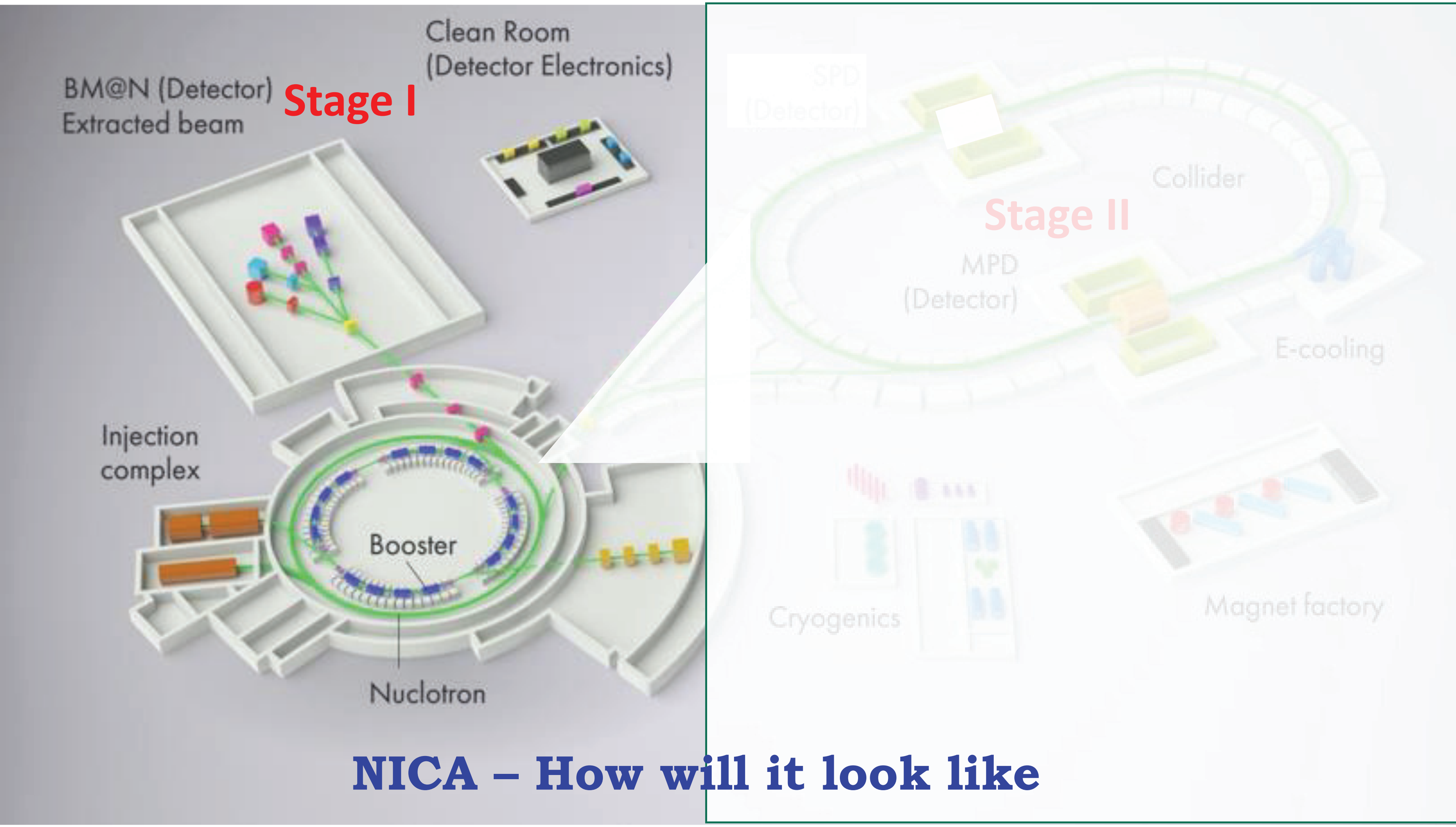

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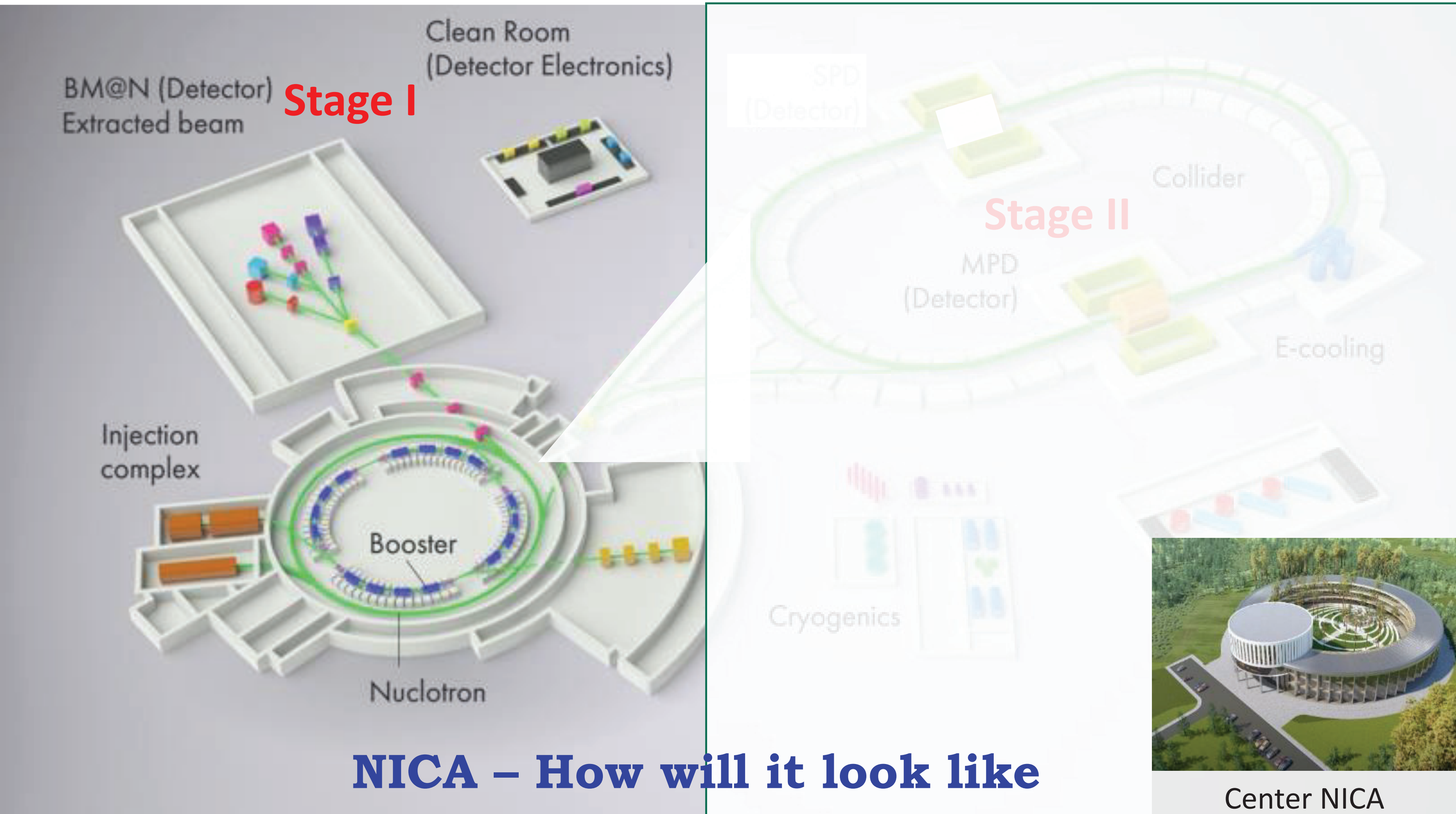

Center NICA

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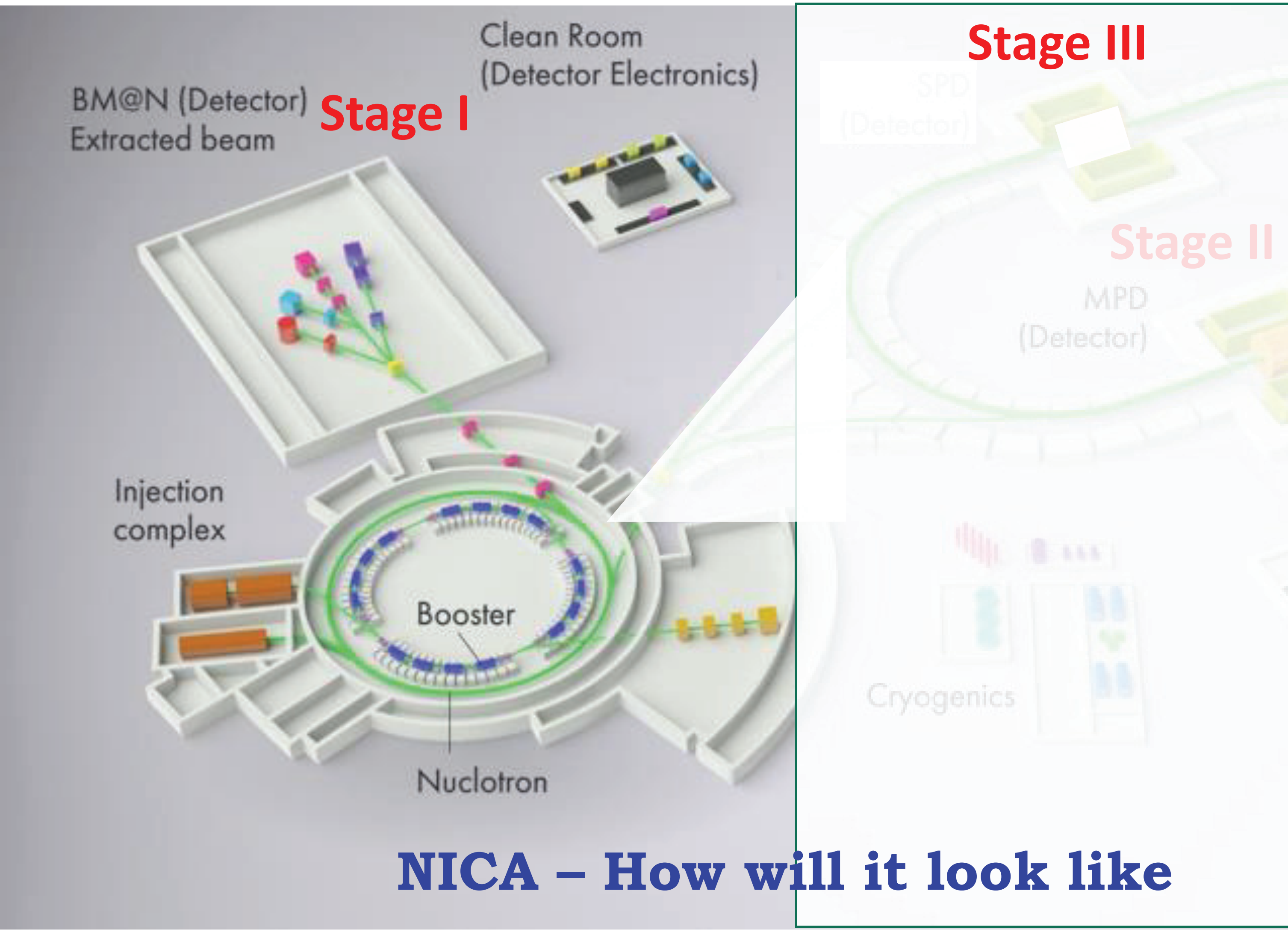

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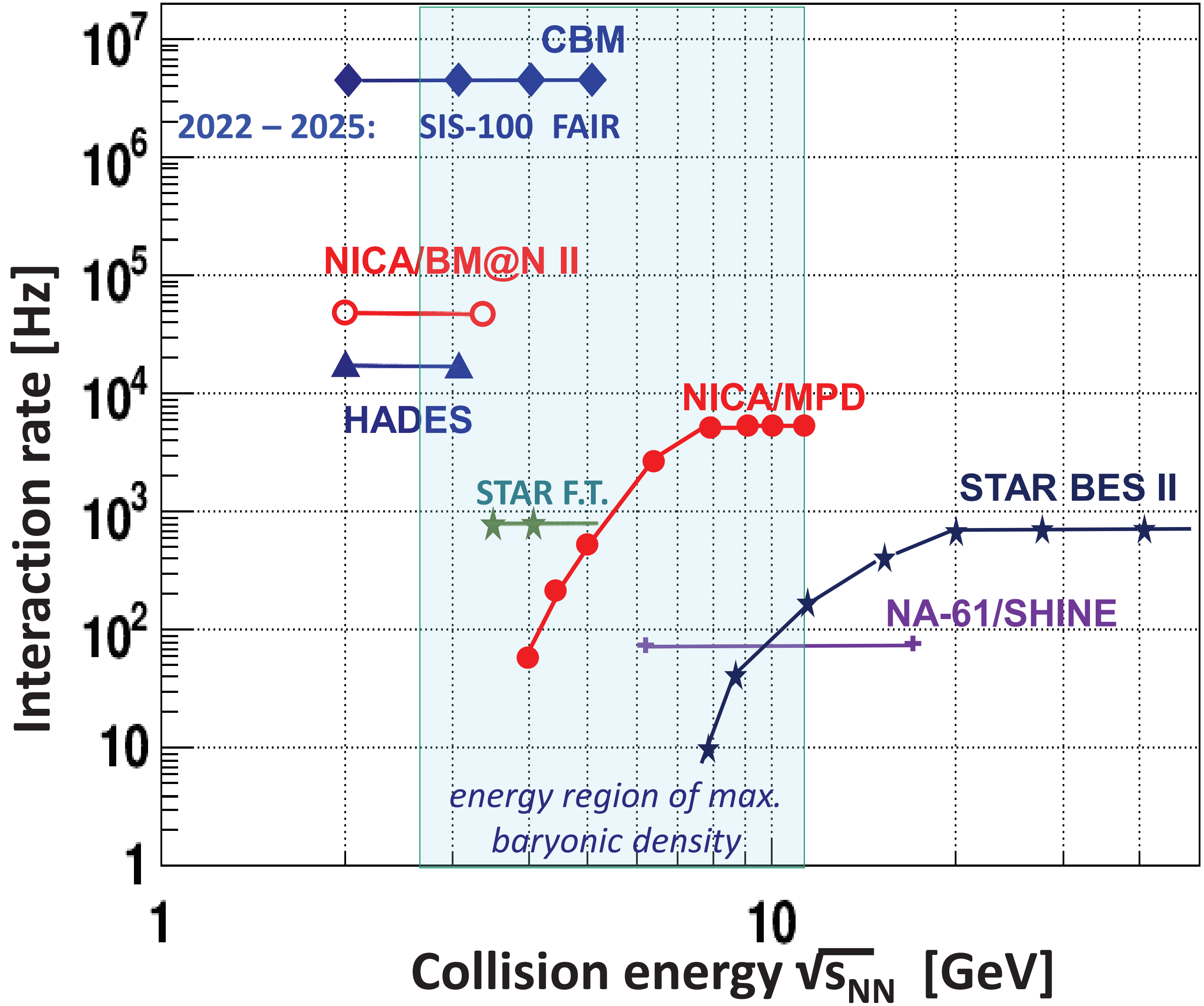
Present and Future Heavy Ion Experiments



1. Stage I: Experiment "The Baryonic Matter at Nuclotron"

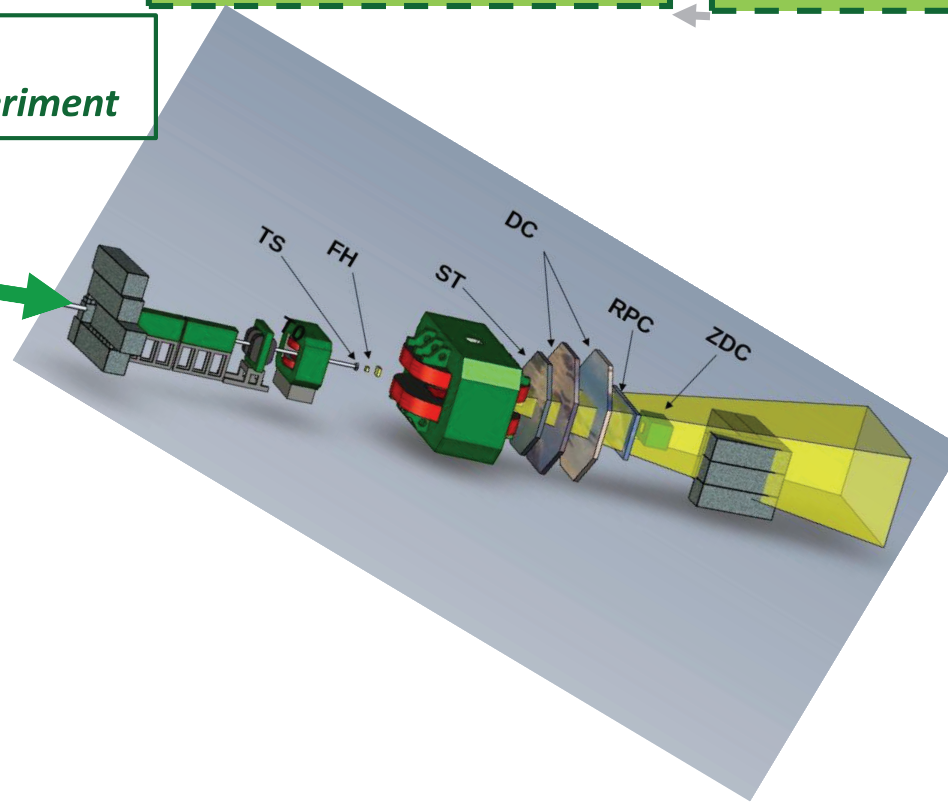
BM@N will study the same physics in heavy ion collisions as NICA/MPD and CBM/FAIR, but in fixed target experiment at lower energy $\sqrt{s}$ = 2.3 ÷ 3.47 GeV/u .

ЛУ-20

KRION

Nuclotron
(42 Tm)
$^{79+}Au^{197}$
5.0 ≤ E_{ion} ≤ 3800 MeV/u

26.02.2018 – 03.04.2018
First run for physics experiment



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$^{26+}Kr^{84}$ 2.4 GeV/u	Al, Cu, Sn, Pb

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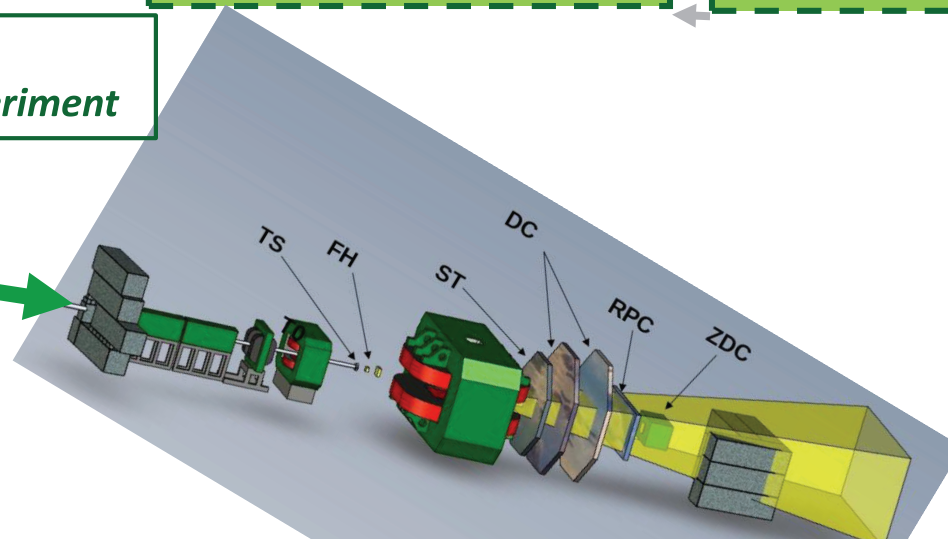

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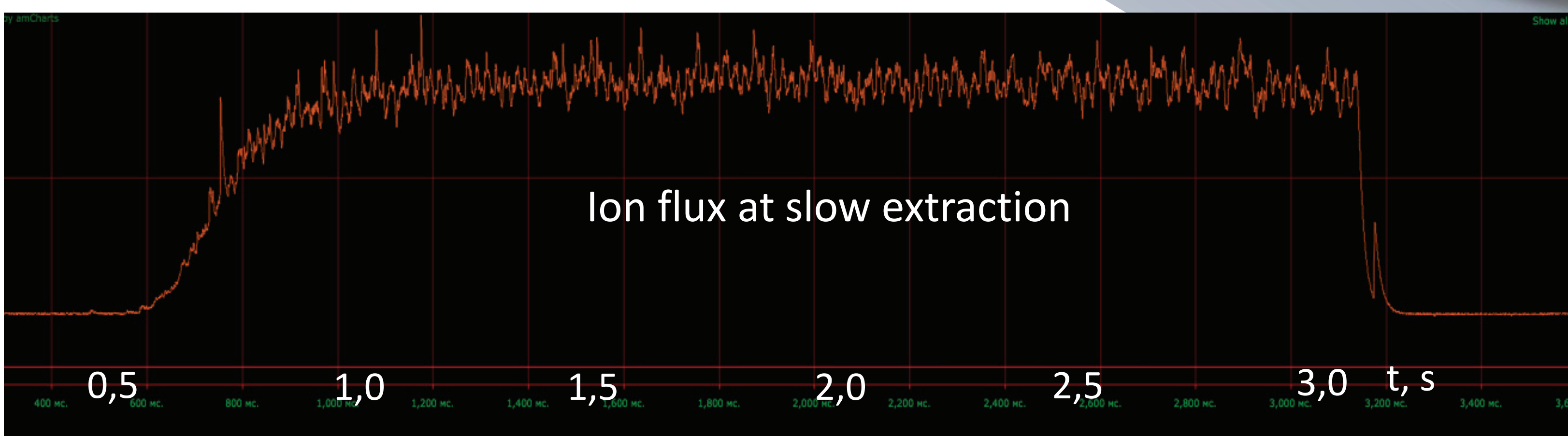

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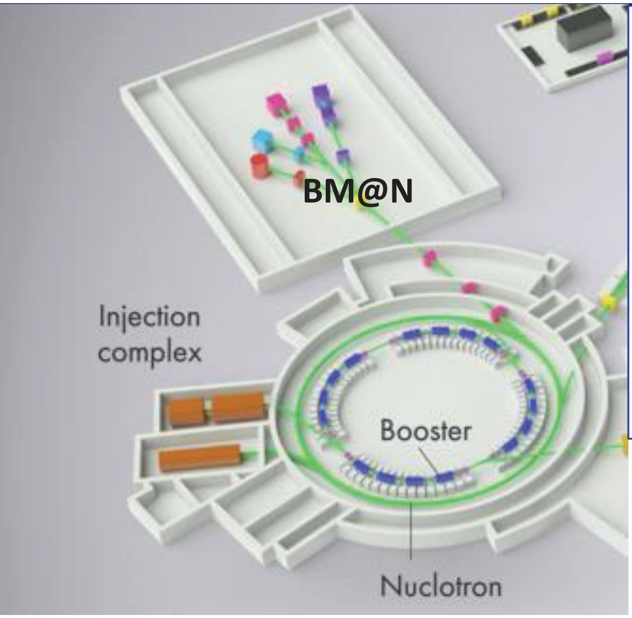

For the full configuration of the Stage I we need:

- **Injector – KRION + HILAc + Beam transfer line (BTL) from injector to the Booster**
- **Booster** (under mounting and commissioning)
- **BTL Booster - Nuclotron** (under manufacturing at BINP, to be delivered to JINR in March 2020, commissioning – May 2020)
- **Upgrade of BTL Nuclotron – BM@N** (slow extraction)

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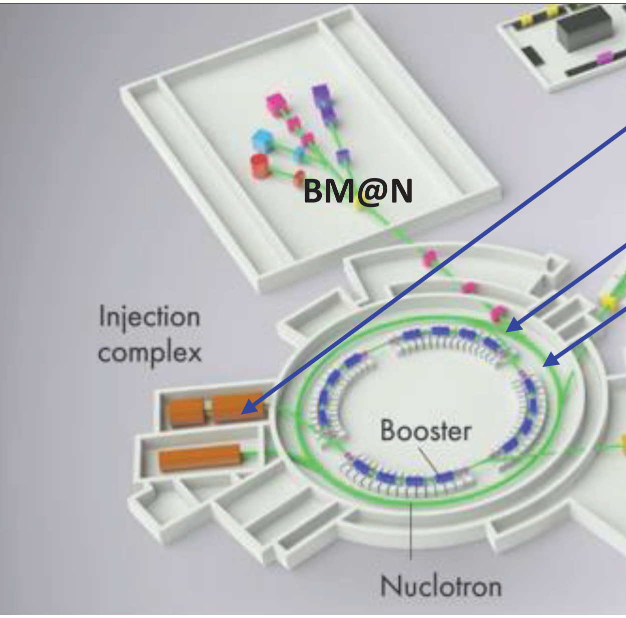

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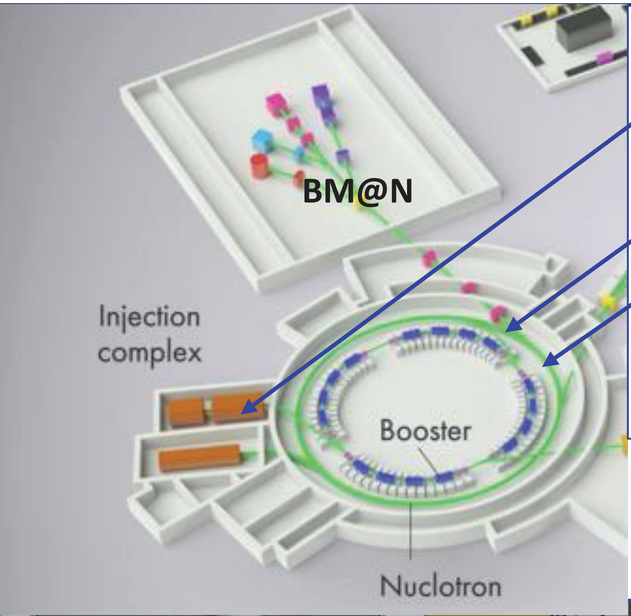

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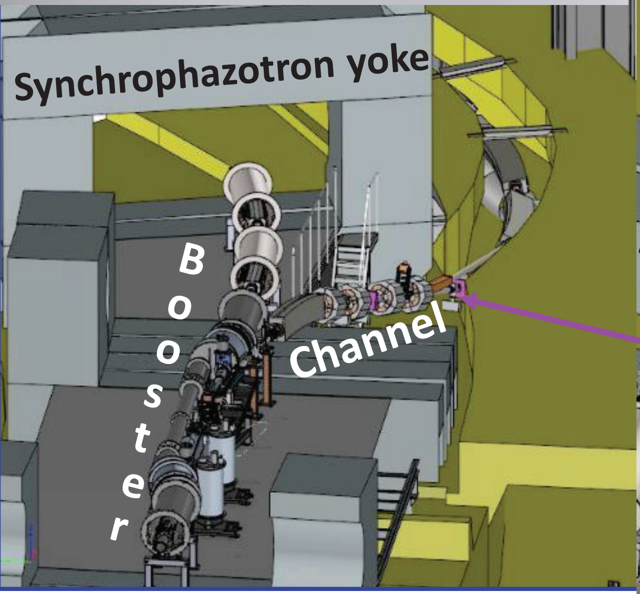

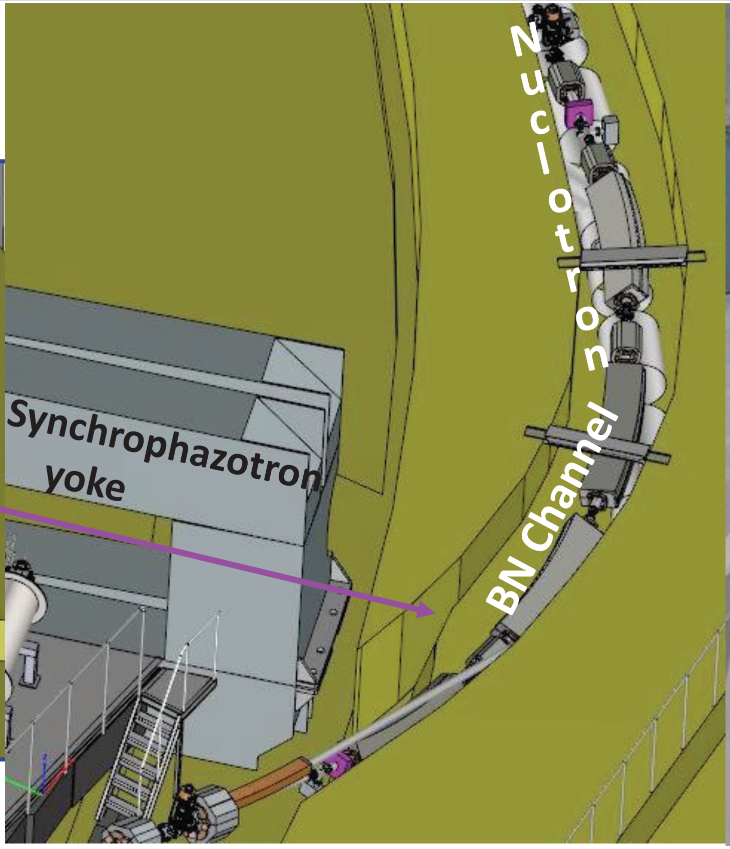

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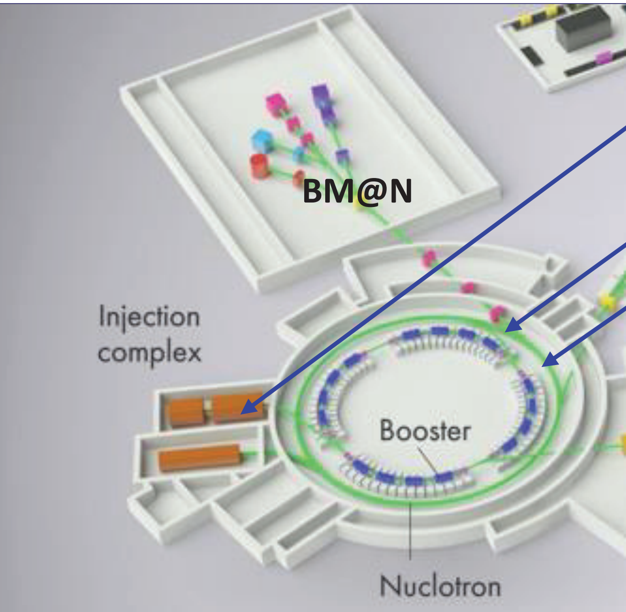

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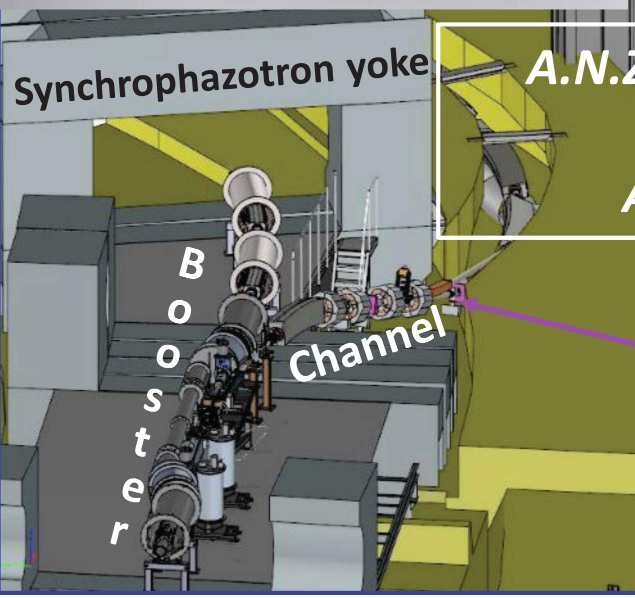

A.N.Zhuravlev & the Team (BINP)

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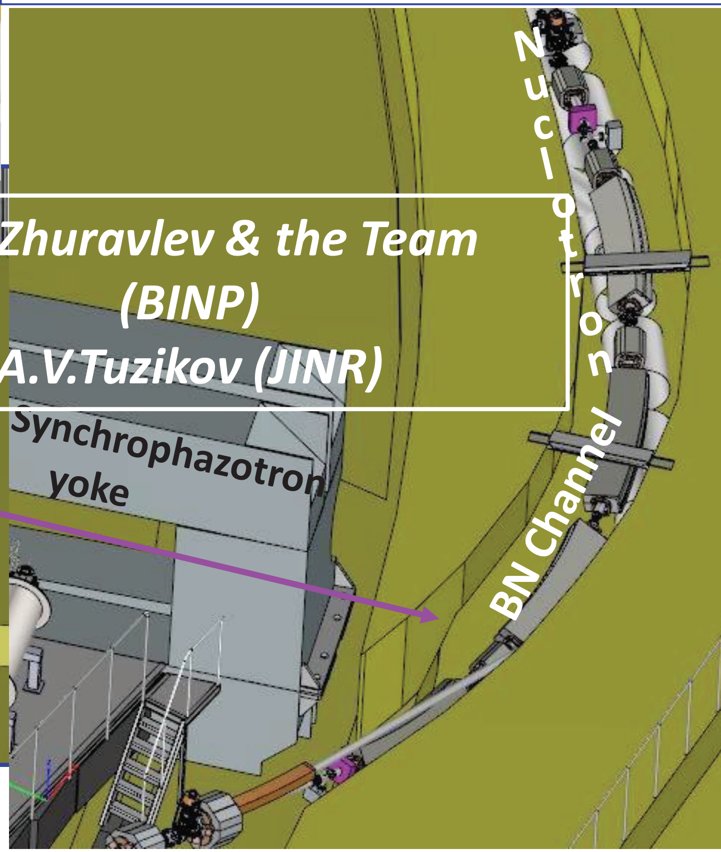

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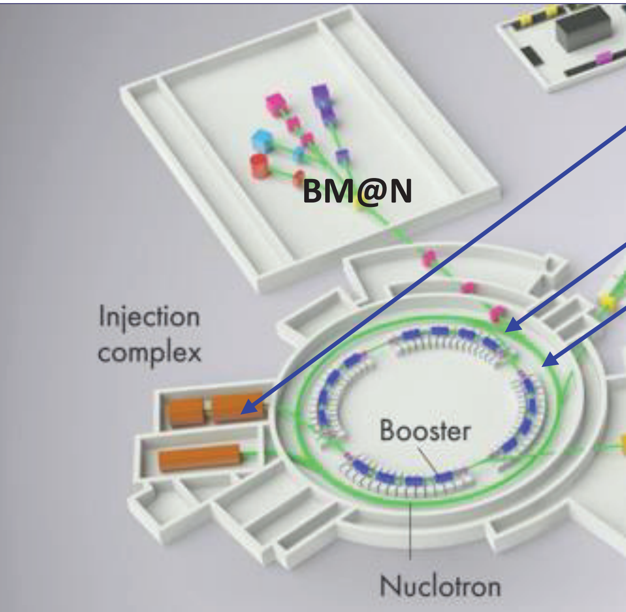

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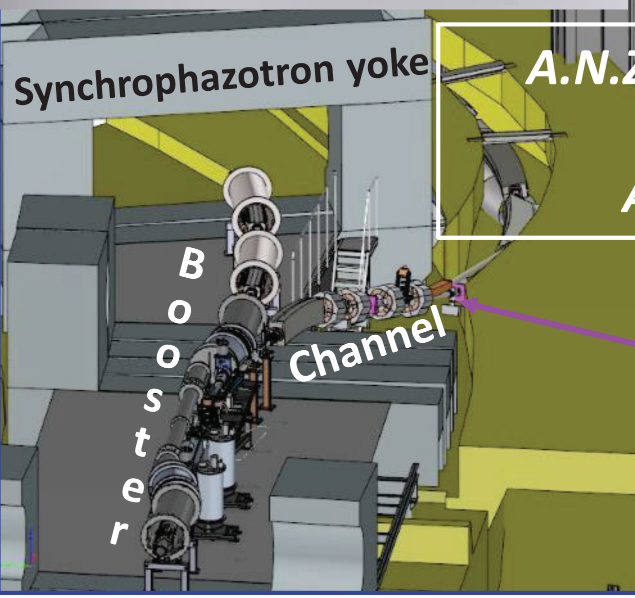

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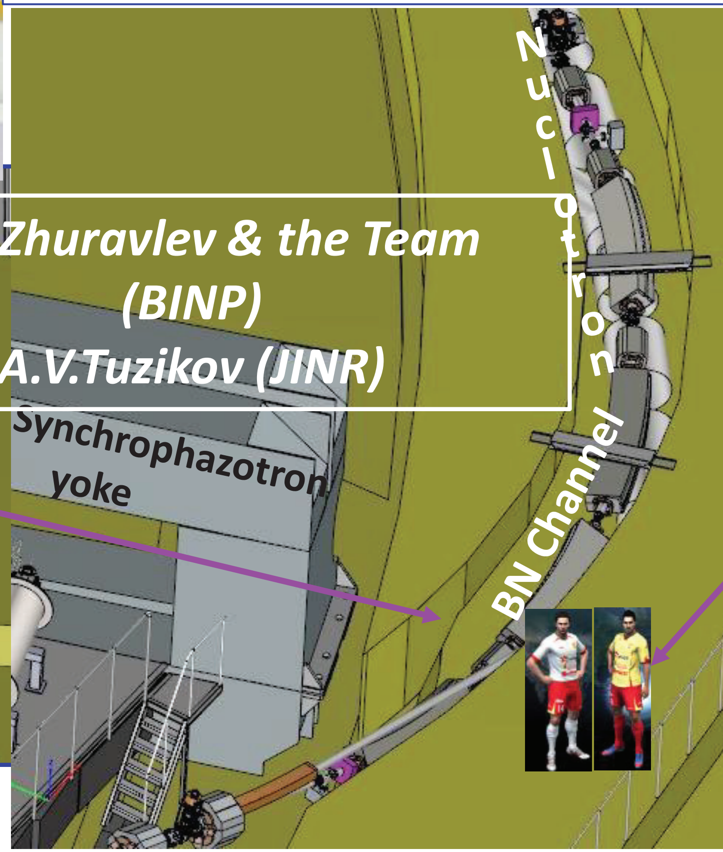

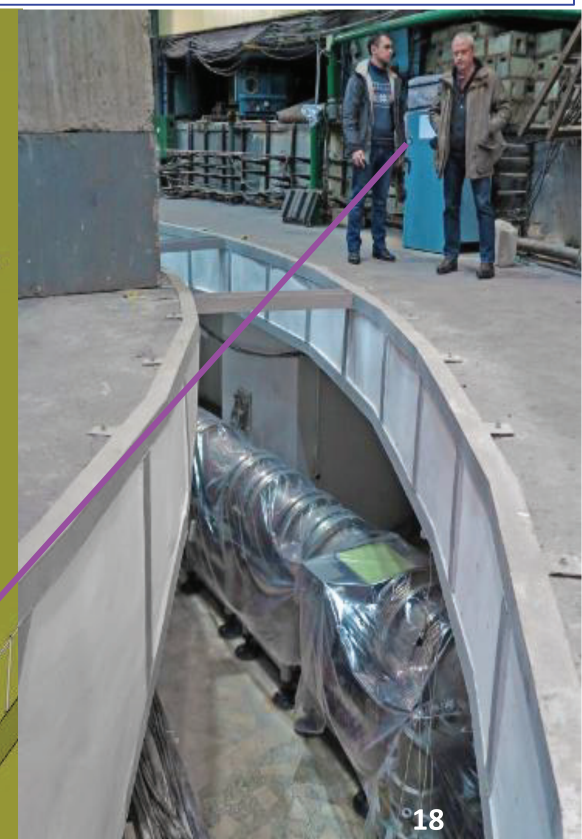

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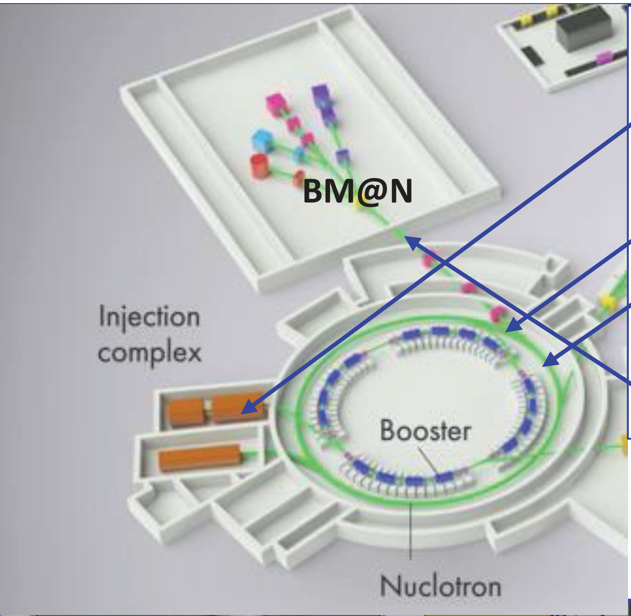

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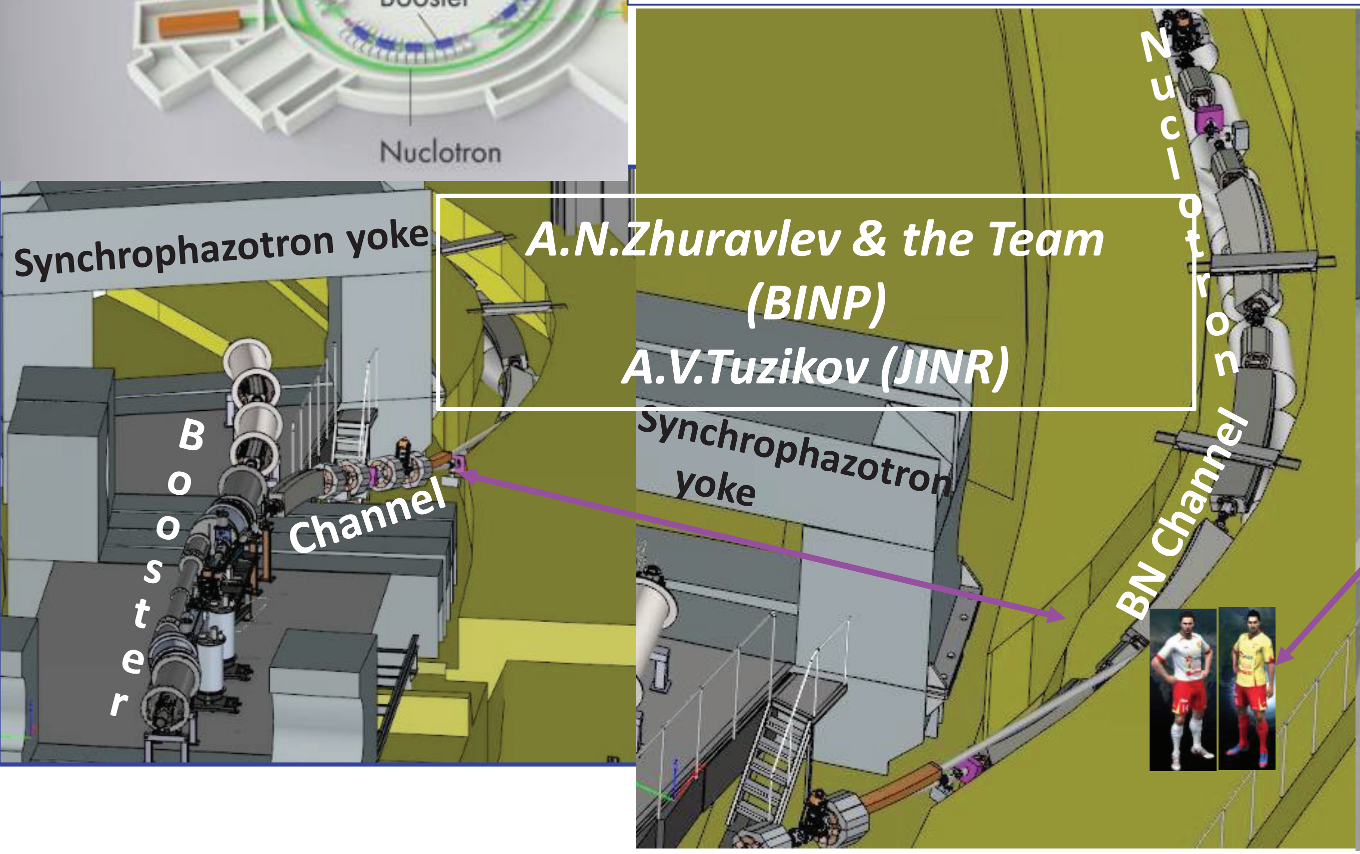

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Booster Mounting and Nearest Plans

100% of dipoles have been mounted
Quads tests and mounting is in progress

Superconducting connections and cables

Booster PSs installed on the top of Synchrophasotron yoke

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Nearest Plans

1. November 2019 – mounting completion, technological run;
2. December 2019 - January 2020 – ion injection and acceleration in Booster;
3. May - June 2020 – ion acceleration and extraction, injection into BTL and transportation to Nuclotorn

2020 – first run with heavy ions at maximum energy of Nuclotron.

Electron Cooling Application to The NICA Booster

The goals of e-cooling application:

1) storage of ions at injection,
2) formation of a dense bunched ion beam.

1. Injection – three schemes of injection into the Booster:

$^{197}Au^{31+}$

1-1. Single turn injection
1-2. Multiturn injection
1-3. Multicycle injection

Ion energy 3.24 MeV/u, E_e = 1.765 keV

2. Electron cooling on energy plateau at acceleration

E_{ion} = 50 – 80 MeV/u , E_e = 27.233 – 43.573 keV

Characteristic cooling time $\lesssim$ 1 sec

Why *such an energy choice*: to avoid space charge limitation at the cooled beam shrinking.

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Electron cooling will be used in all three schemes.
Characteristic cooling time ~ 0.1 sec.

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Stage I: Experiment "The Baryonic Matter at Nuclotron"

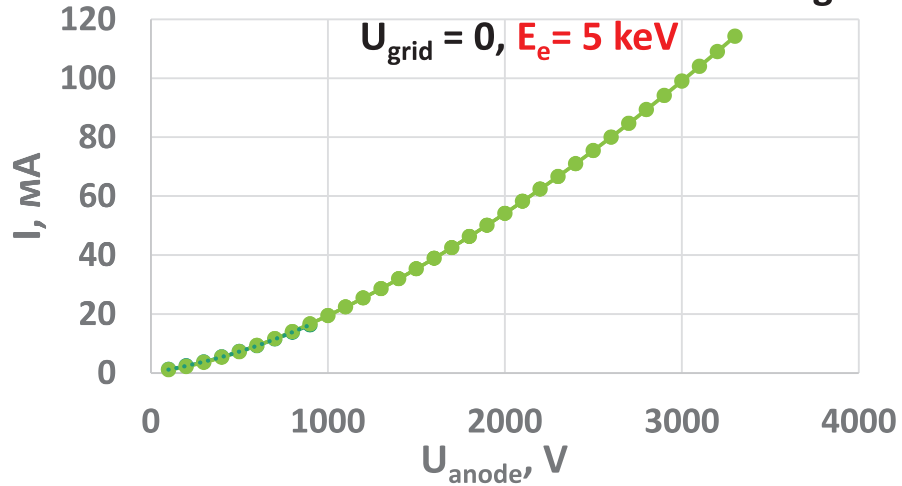
Electron Cooling Application to The NICA Booster

Booster Electron Cooler Commissioning

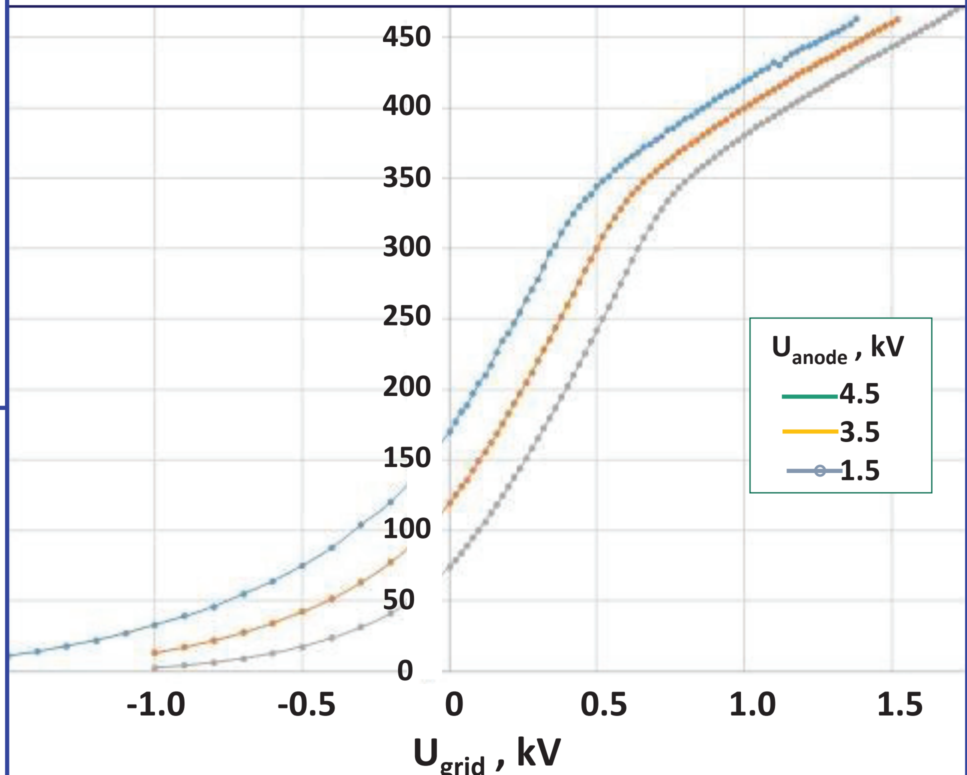
A.Kobets, S.Melnikov, O.Orlov, S.Semenov, A.Sergeev, Al. Sidorin

July 09-24, 2019

Electron beam current vs anode voltage



Electron beam current vs grid voltage, E_e = 15



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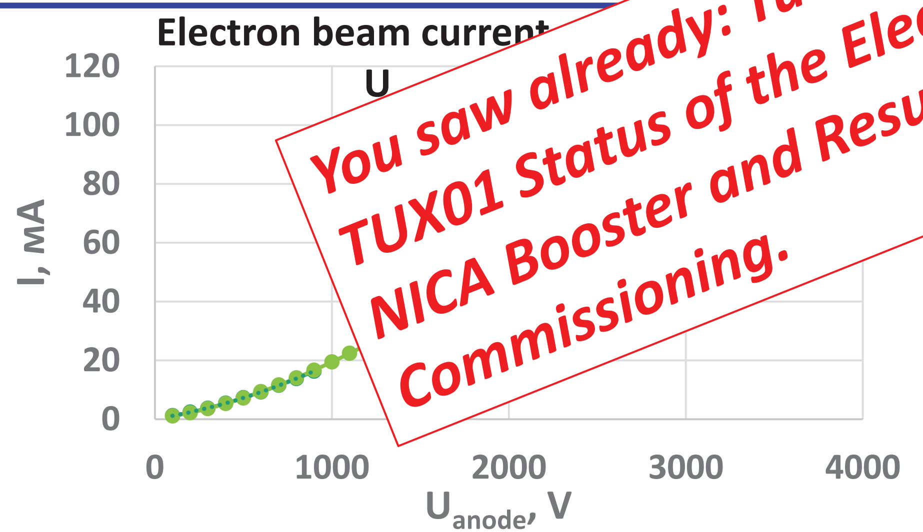
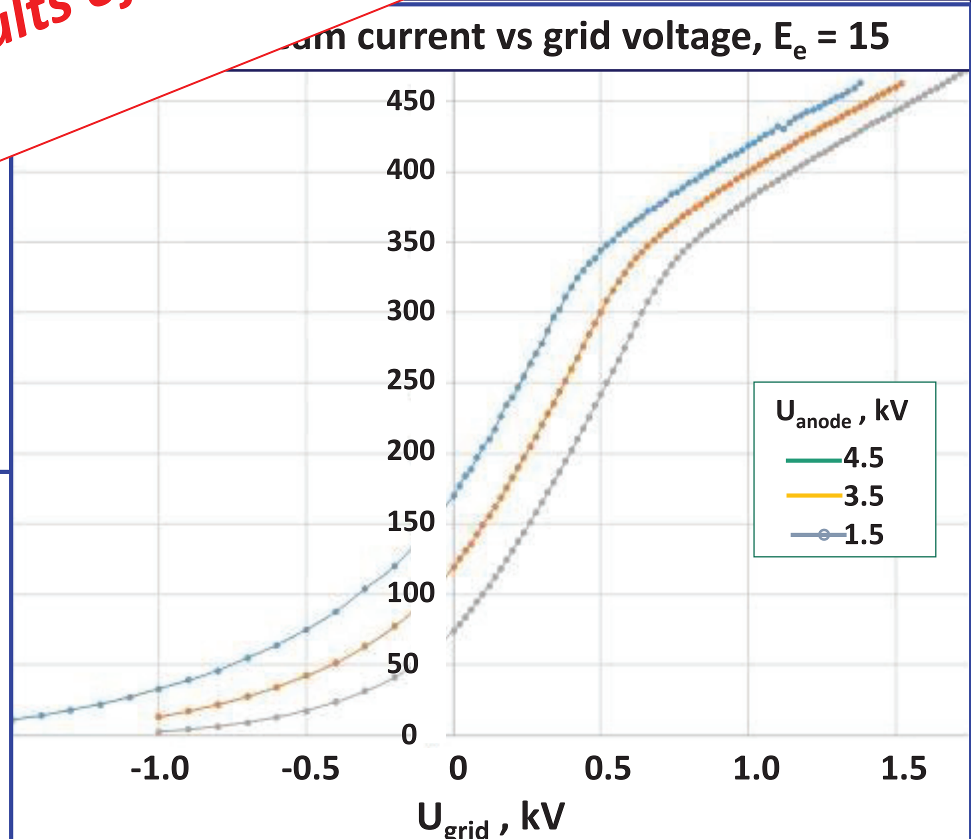
Electron Cooling Application to The NICA Booster

Booster Electron Cooler ... ning

A.Kobets, S.Melnikov, O.Orl... Al. Sidorin

You saw already: Tue 9:00 M.Bryzgunov TUX01 Status of the Electron Cooler for NICA Booster and Results of Its Commissioning.





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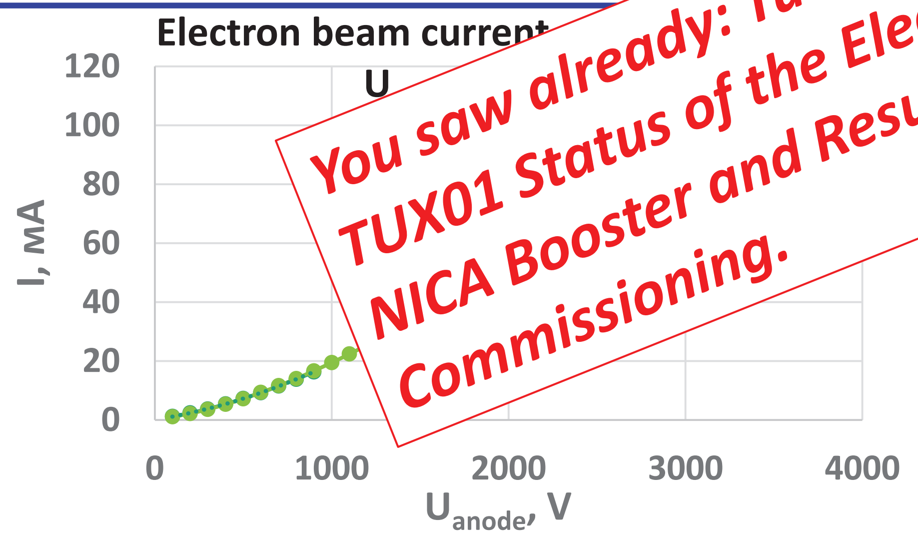
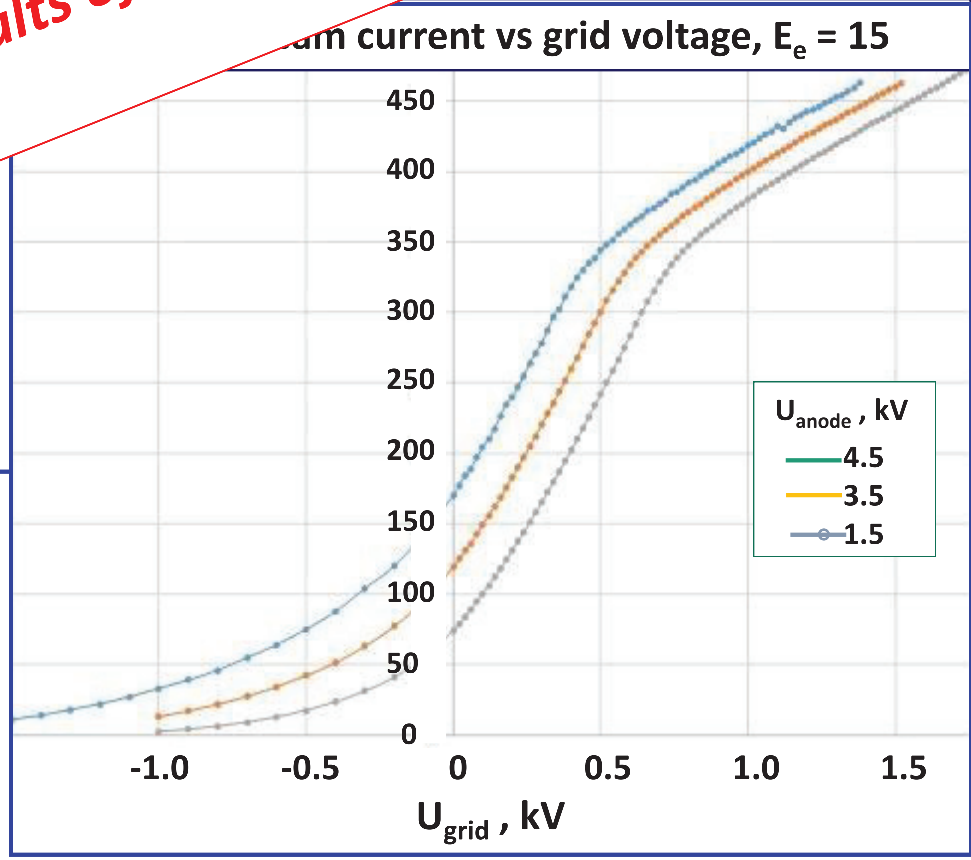




Stage I: Experiment "The Baryonic Matter at Nuclotron"

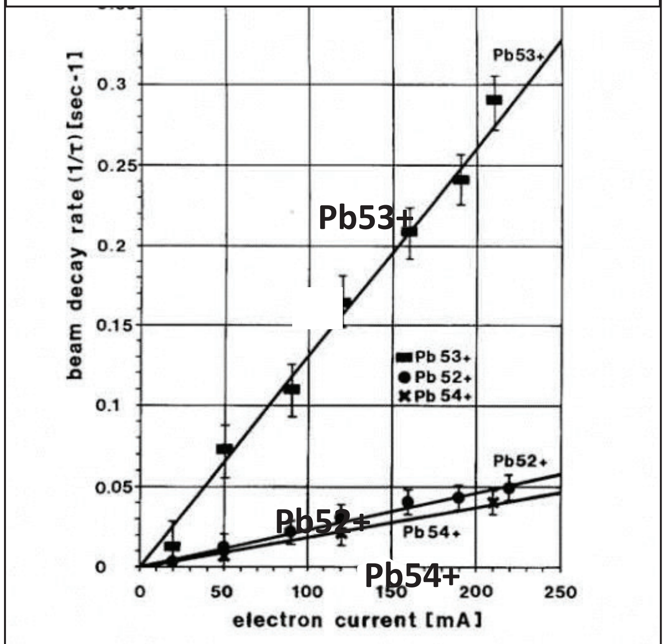
Electron Cooling Application to The NICA Booster

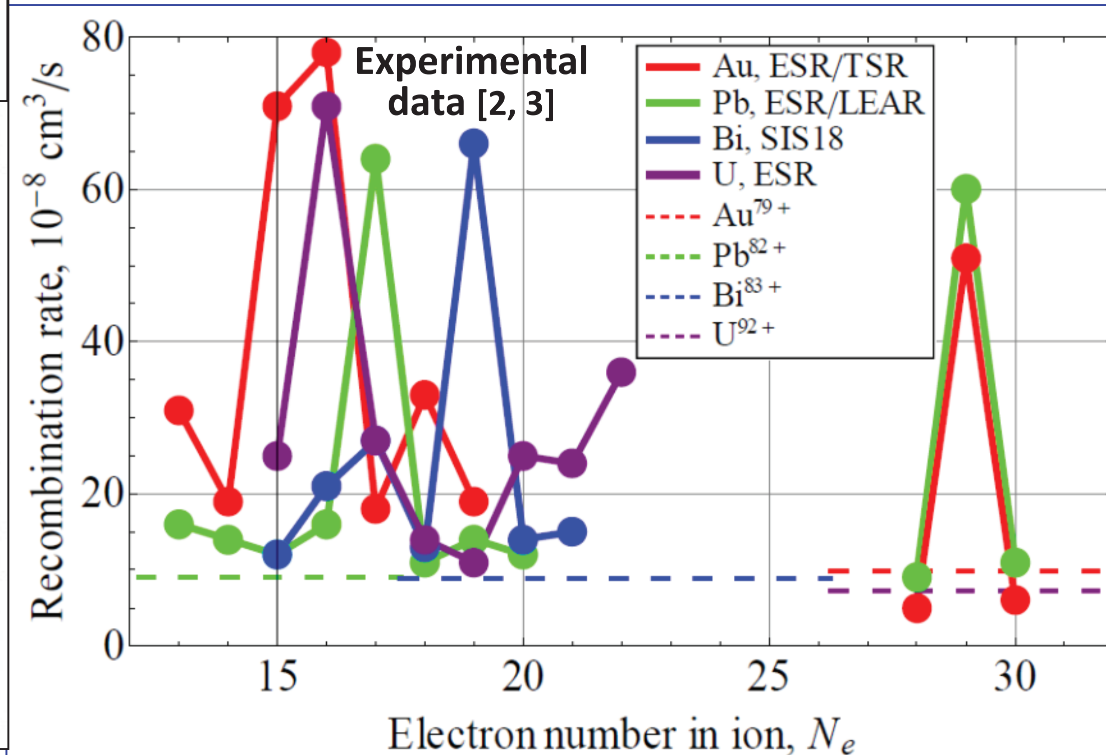
Why do we need to use $^{197}Au^{31+}$:

– because of limited capability of KRION ion source (ionization time, intensity, etc.),

– to avoid ion loss due to electron-ion recombination in electron cooler.

[1] Beam decay rate [1/sec] vs e-beam current [mA]





1. S.Baird, I.Meshkov, D.Moehl, et al., Phys. Lett. B, 361, 1995, pp.184–186.
2. I. Meshkov, Report at working seminar at CERN 14.03.2011
3. O. Uwira, A. Mueller, A. Wolf, et al., Hyperfine Interactions 108 (1997) 149–154 (Au49+, 50+, 51+)
4. A.V. Philippov, A.B. Kuznetsov, I.N. Meshkov, in Proc. COOL'11, https://www.jacow.org , THCOB01

Electron Cooling Application to The NICA Booster

Dependence of recombination rate $1/\tau_{rec}$ on electron shell structure has resonance character: $1/\tau_{rec}$ is

- **minimal** if outer (sub)shells are **completely filled**, either contain **even number** of electrons;
- **maximal** if outer (sub)shells have **one vacancy** or **odd number** of electrons.

$^{197}Au^{31+}$ ion contains 79 – 31 = 48 electrons in the outer subshell of this ion.

Ion	Electron number in the ion	Atomic shell structure											Measured rate [10^{-8} cm^3s^{-1}]
Pb^{52+}	30	$1s^2$	$2s^2$	$2p^6$	$3s^2$	$3p^6$	$4s^2$	$3d^{10}$					11 (full subshell)
Pb^{53+}	29	$1s^2$	$2s^2$	$2p^6$	$3s^2$	$3p^6$	$4s^2$	$3d^{10}$	$4p^1$				60 (1 in subshell)
Pb^{54+}	28	$1s^2$	$2s^2$	$2p^6$	$3s^2$	$3p^6$	$4s^2$	$3d^8$					9 (2 vacancies)
Au^{29+}	50	$1s^2$	$2s^2$	$2p^6$	$3s^2$	$3p^6$	$4s^2$	$3d^{10}$	$4p^6$	$5s^2$	$4d^{10}$	$5p^2$	
Au^{30+}	49	$1s^2$	$2s^2$	$2p^6$	$3s^2$	$3p^6$	$4s^2$	$3d^{10}$	$4p^6$	$5s^2$	$4d^{10}$	$5p^1$	
Au^{31+}	48	$1s^2$	$2s^2$	$2p^6$	$3s^2$	$3p^6$	$4s^2$	$3d^{10}$	$4p^6$	$5s^2$	$4d^{10}$		
Au^{49+}	30	$1s^2$	$2s^2$	$2p^6$	$3s^2$	$3p^6$	$4s^2$	$3d^{10}$					6 (full subshell)
Au^{50+}	29	$1s^2$	$2s^2$	$2p^6$	$3s^2$	$3p^6$	$4s^2$	$3d^9$					50 (1 vacancy)
Au^{51+}	28	$1s^2$	$2s^2$	$2p^6$	$3s^2$	$3p^6$	$4s^2$	$3d^8$					5 (2 vacancies)
Max. number of electrons in the shell of Au atom		2	4	10	12	18	20	30	36	38	48	54	

Estimates of recombination rate in Electron cooler of NICA Booster

$$\tau_{rec}^{-1} = \frac{\alpha}{\beta\gamma^2} \cdot \frac{J_e}{ce} \cdot \eta_{cool},$$

α is recombination coefficient, β, γ are relativistic factors,
J_e is electron current density, c is the speed of light, e is electron charge,
η is ratio of the cooling section length l_{cool} to the ring circumference C_{ring}.

Choosing the ion Au^{31+} and the parameter values

$\alpha = 10\times10^{-8}$ $cm^3 \cdot s^{-1}$, $l_{cool} = 1.5$ m, $C_{ring} = 210.96$ m, $\phi_{cathode} = 30$ mm

we find for the NICA Booster:

at injection: $E_{ion} = 3.2$ MeV/u $E_e = 1.76$ keV, $I_e = 0.2$ A => $\tau_{rec} = 13.3$ sec;
lifetime on vacuum 4.4 sec.

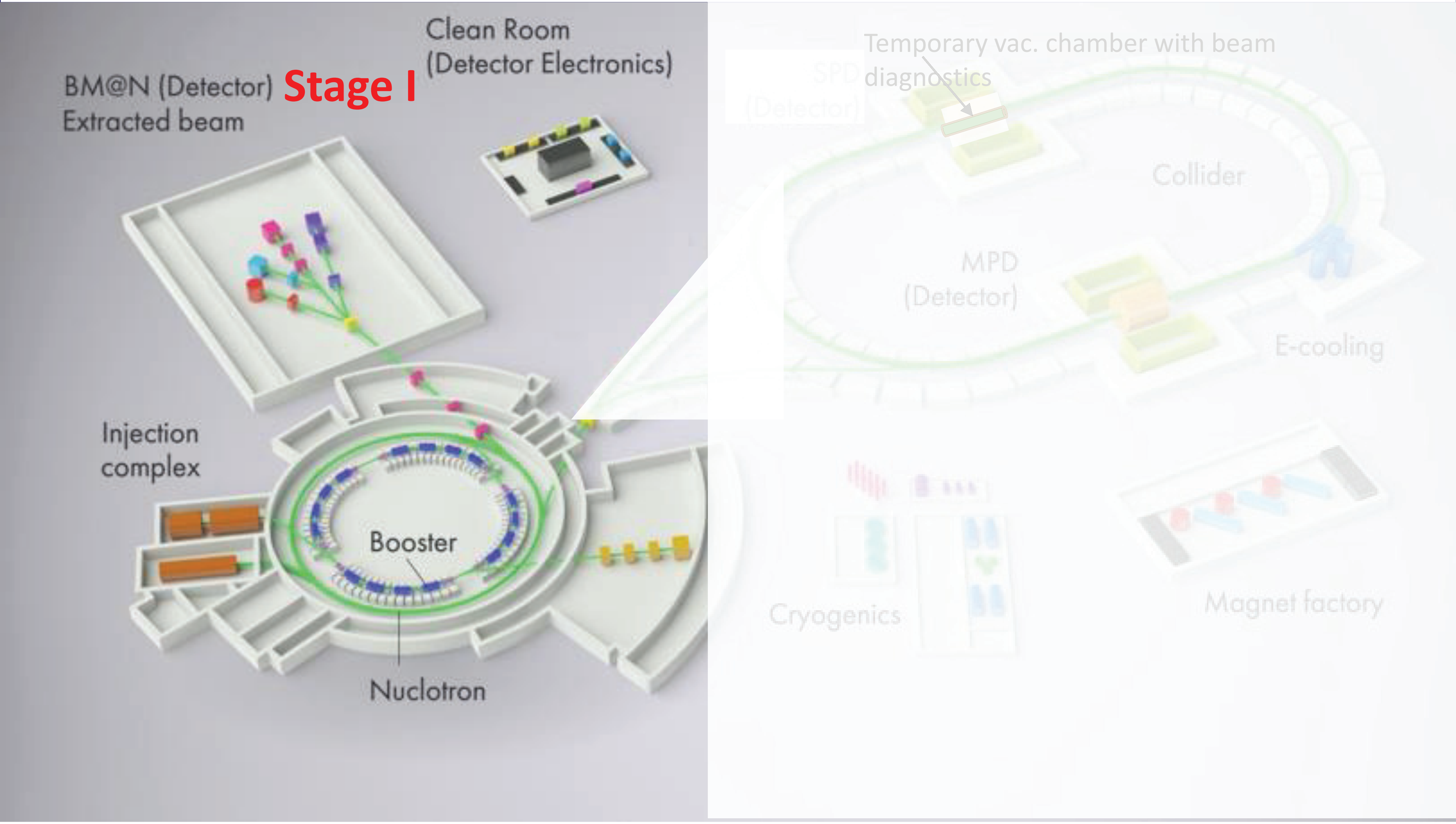
on "plateau": $E_{ion} = 80$ MeV/u: $E_e = 27.2$ keV, $I_e = 1.0$ A => $\tau_{rec} = 14.6$ sec.

These values of the ion beam life time limited by ion recombination in electron cooler

are sufficient for NICA operation.

Note that application of Au^{30+} will reduce recombination time by 5 – 10 times.

2. Stage II : Search for The Mixed Phase and New Physics in Heavy Ions' Collisions at NICA Collider



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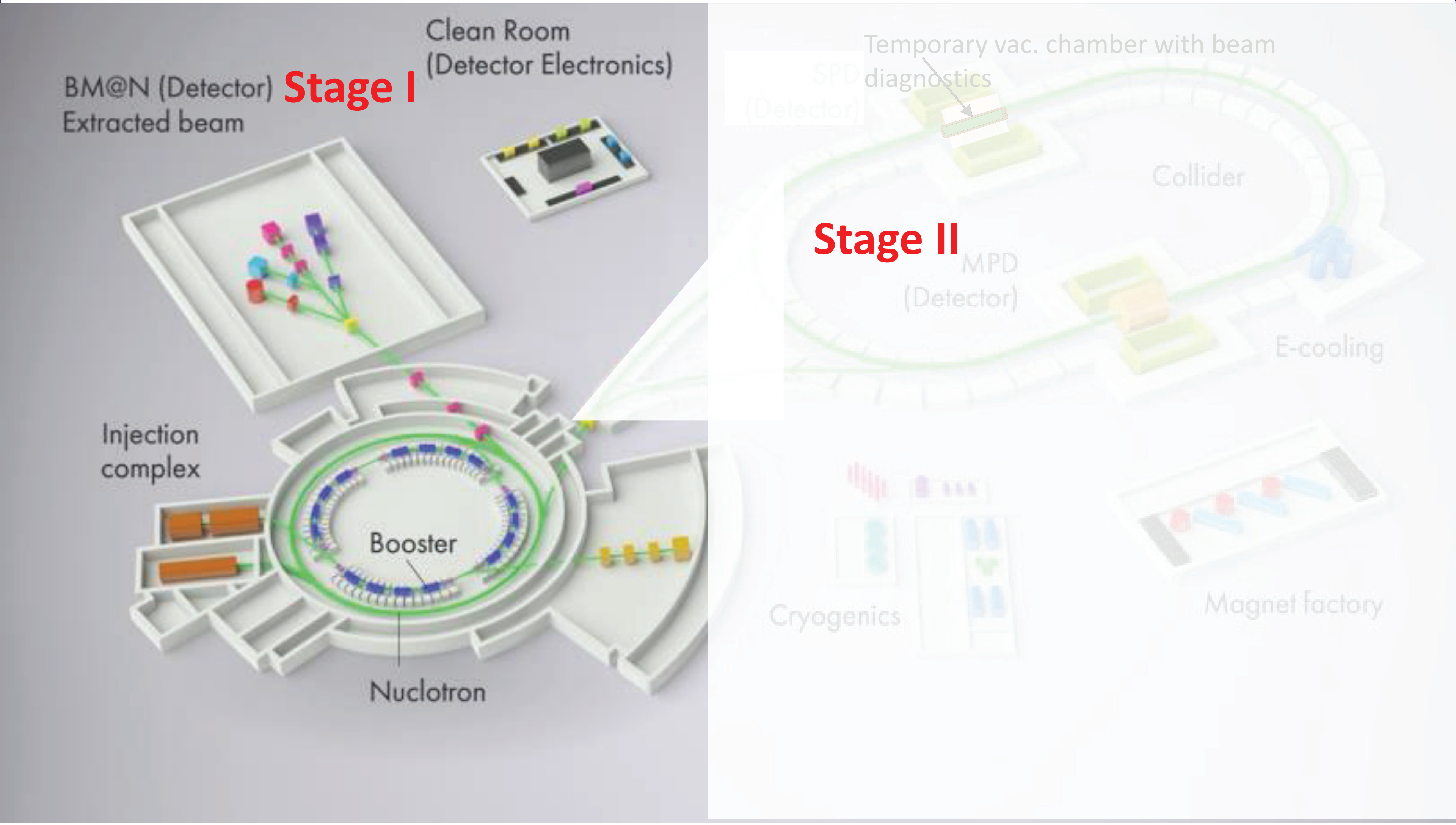

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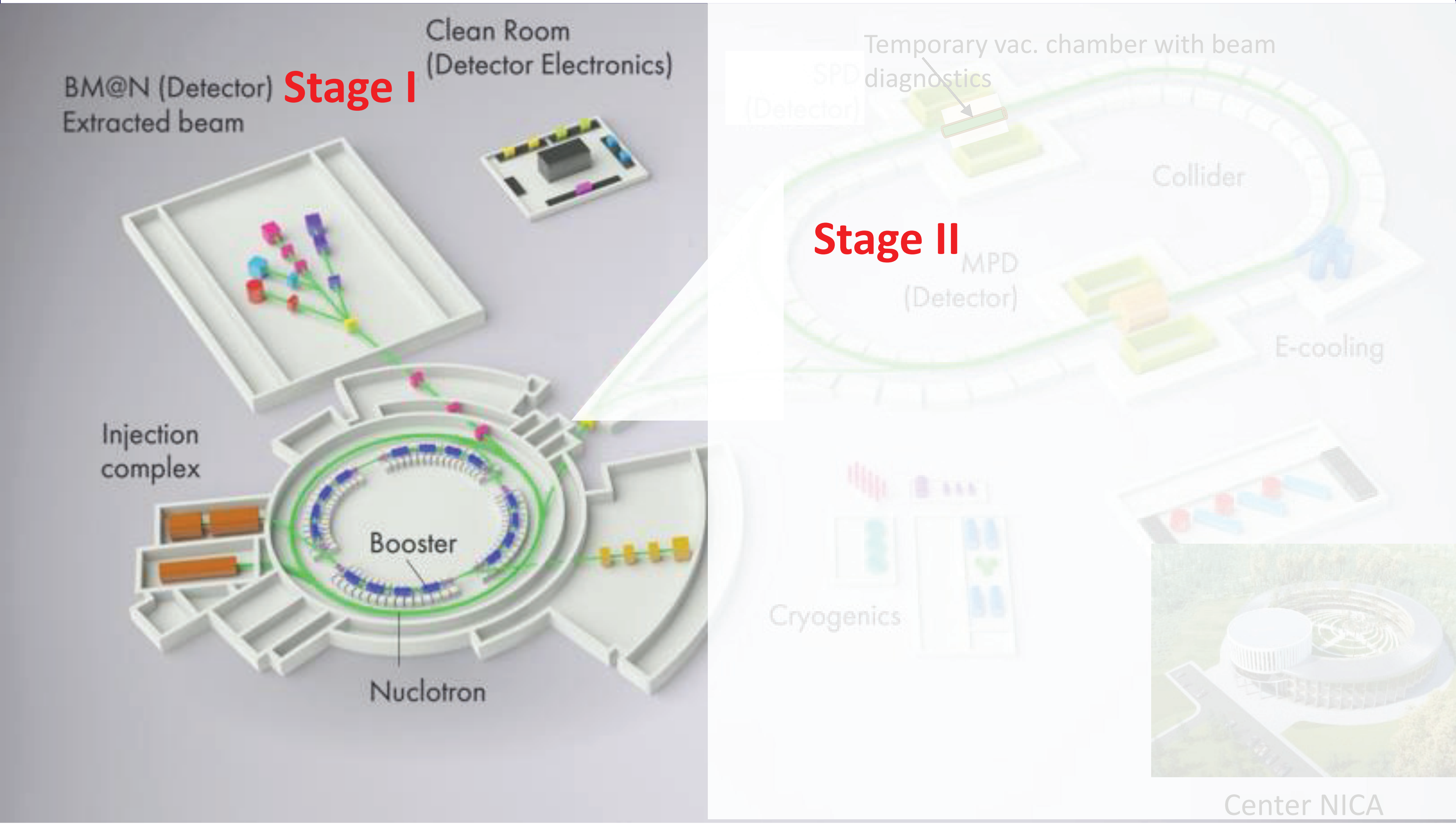
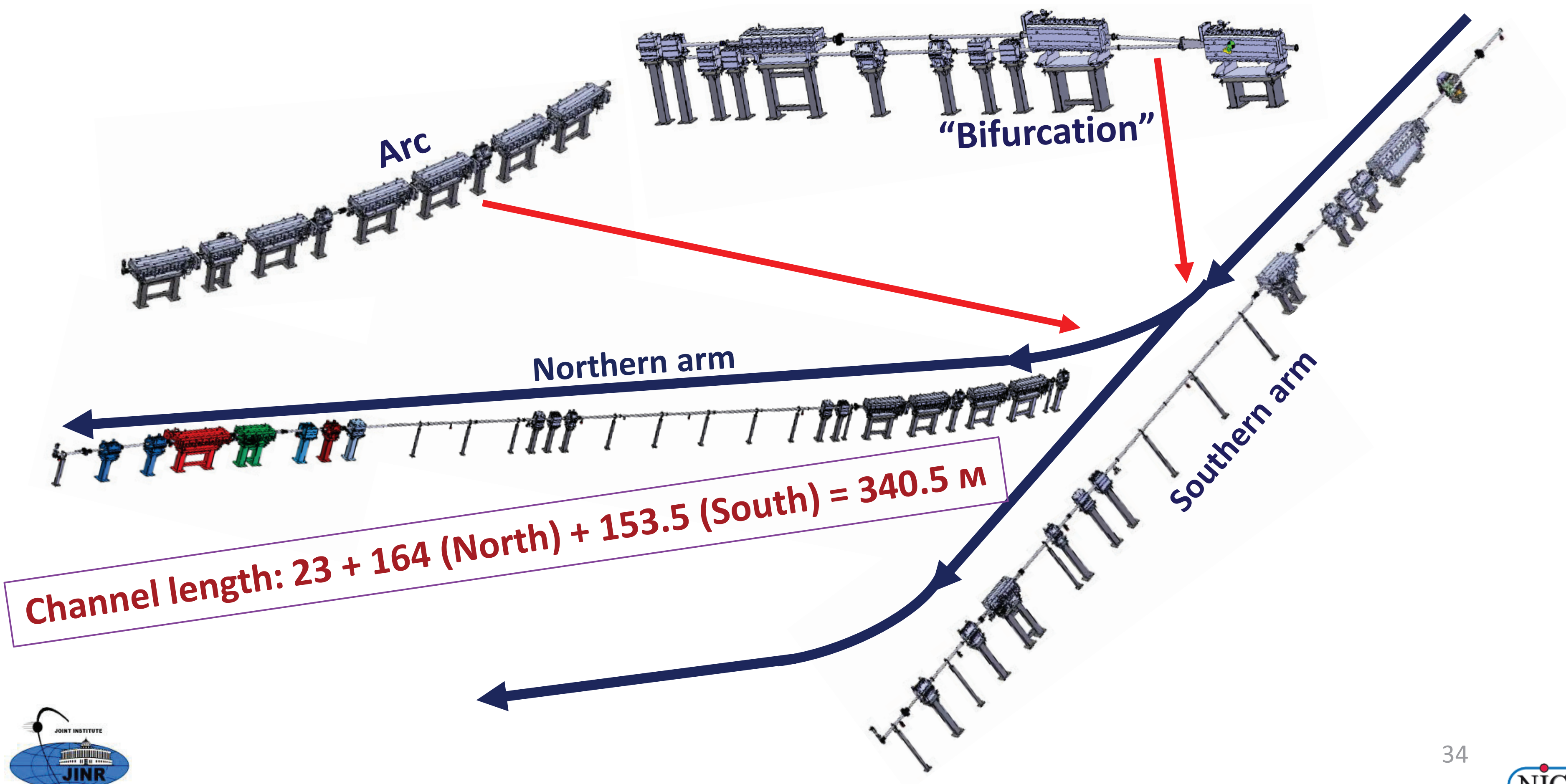


2. Stage II : Search for The Mixed Phase and New Physics in Heavy Ions' Collisions at NICA Collider

Beam Transfer Channel Nuclotron - Collider

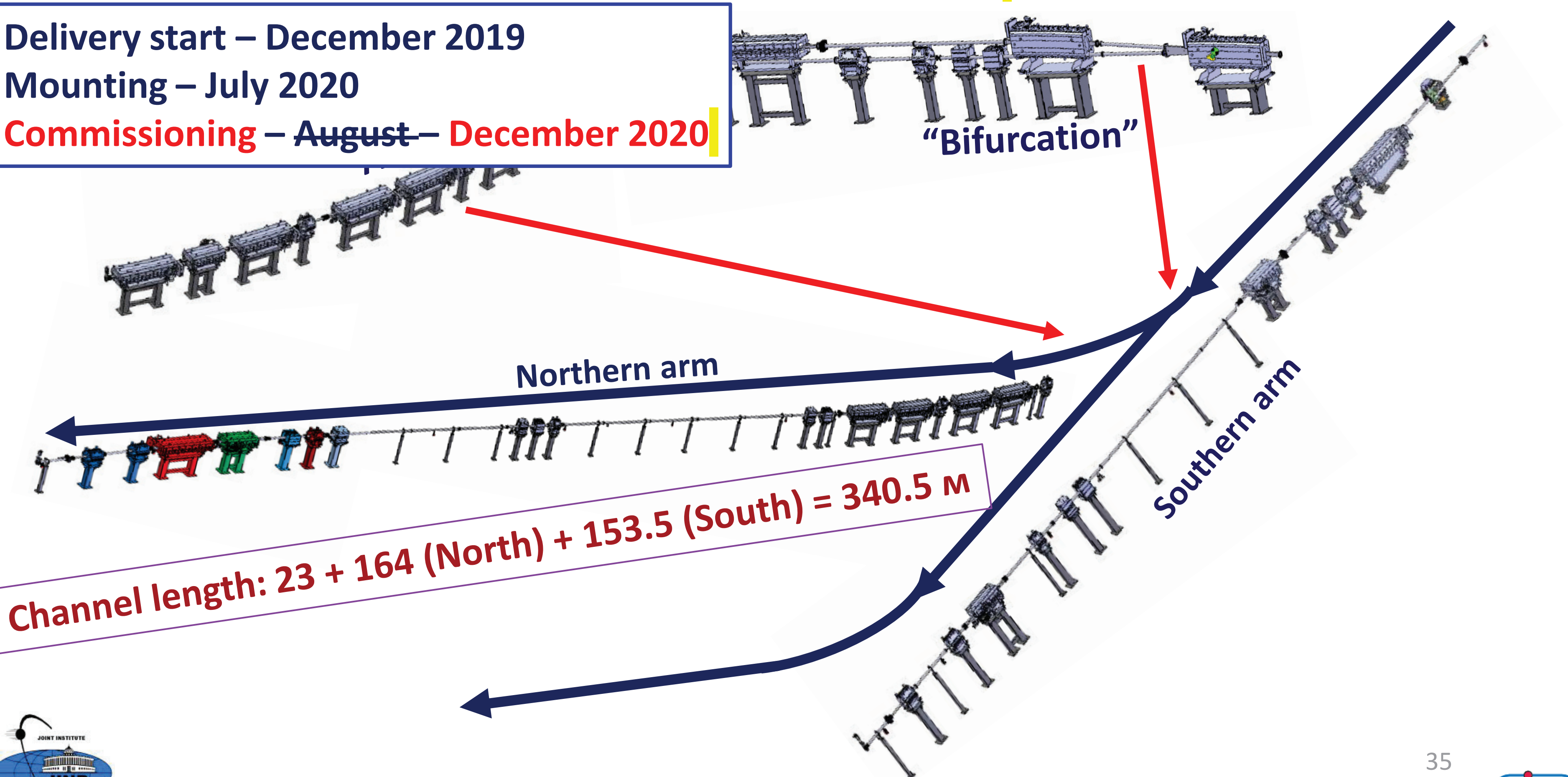
Physics project and coordination – A.Tuzikov (JINR)
Working project, fabrication – SigmaPhi C° (France)
Mounting and commissioning – common work



Beam Transfer Channel Nuclotron - Collider

Physics project and coordination – A.Tuzikov (JINR)
Working project, fabrication – SigmaPhi C° (France)
Mounting and commissioning – common work

Delivery start – December 2019
Mounting – July 2020
Commissioning – ~~August~~ – December 2020



Channel length: 23 + 164 (North) + 153.5 (South) = 340.5 м

The Collider: Focusing System

September 2019

SC magnets	Booster	Collider
Dipoles	40	88 (18)
Quads	24 (8)	82 (1)

The Collider: Focusing System

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Collider:

Mounting start – September 2021

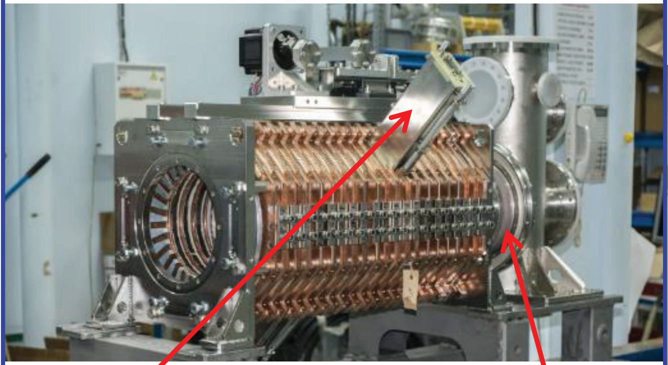
Commissioning – February 2022

2. Stage II : Search for the Mixed Phase and New Physics in Heavy Ions' Collisions at NICA Collider

The Collider: RF System (BINP, A.Tribendis and the team)

Photos of May 2019

Barrier bucket system RF1
(Rectangular periodic pulses)



Pulse generator — Ceramic gap

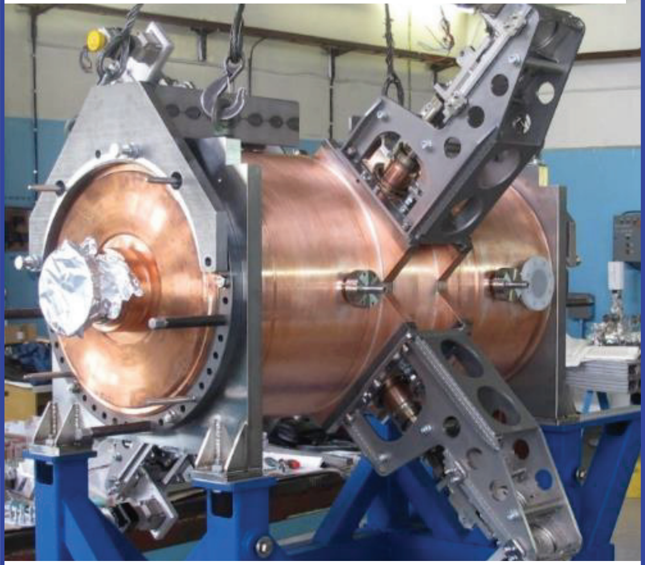
Test assembly at BINP
(Vac. chamber is not installed yet)

Harmonic systems RF2 and RF3

RF2 cavity prototype

f_0 = 11.1÷13.6MHz
Q_0 = 3 600 (@ 12.2MHz)
Ready for high power tests.

RF3 cavity prototype



f_0 = 34.1÷39.4MHz
Q_0 = 6 900 (@ 39.0MHz)
Test assembly at the BINP Workshop

2. Stage II : Search for the Mixed Phase and New Physics in Heavy Ions' Collisions at NICA Collider

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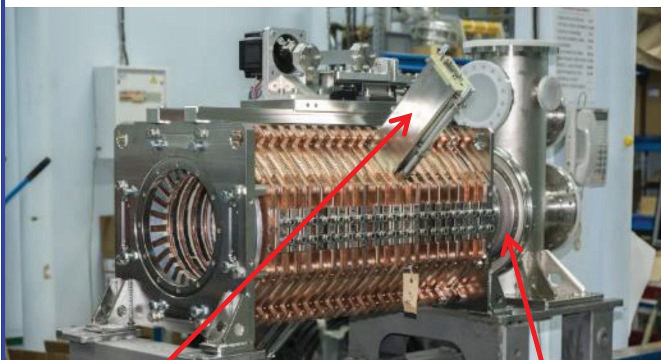

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Friendly inspection
21.03.2019

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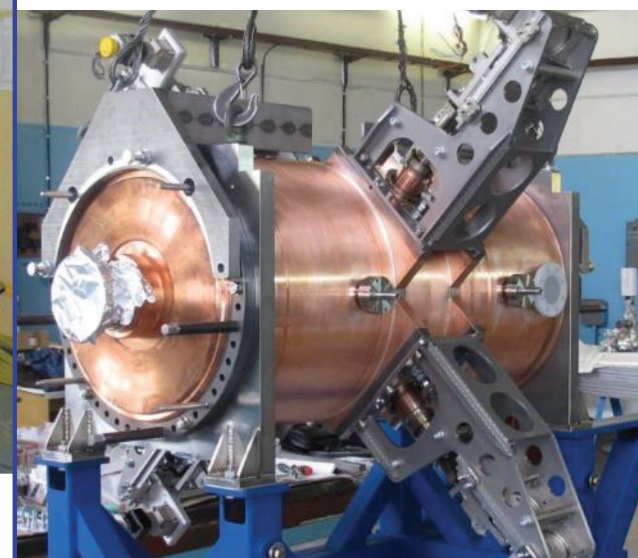

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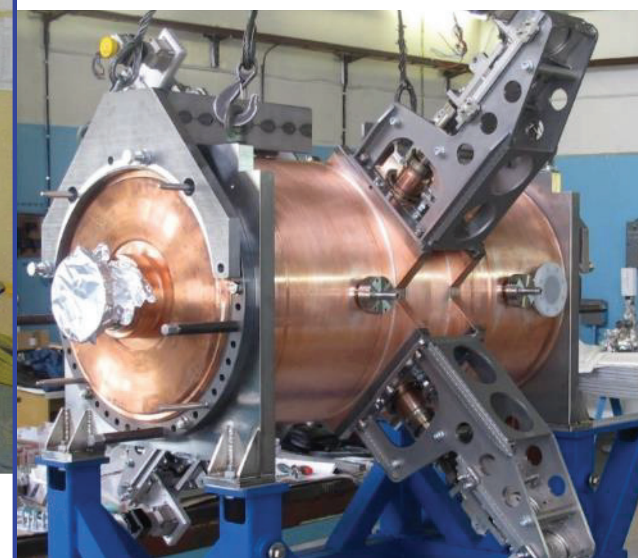

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23.09.2019 RF-2 and All The Team

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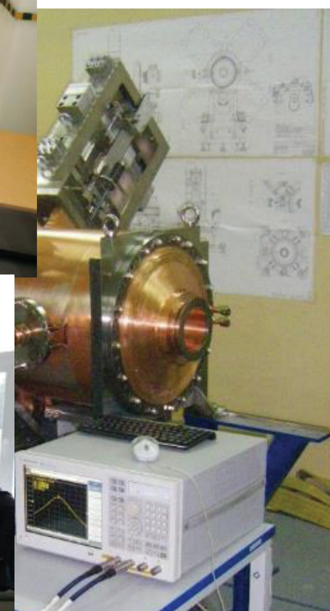

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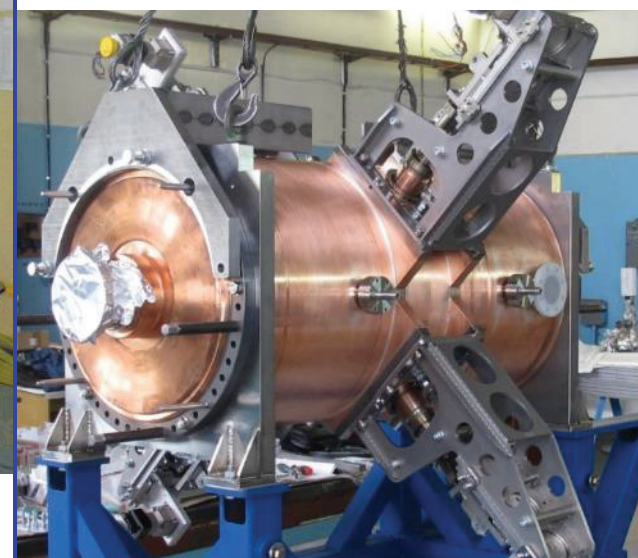

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24.09.2019 RF-2 Visit of the NICA MAC

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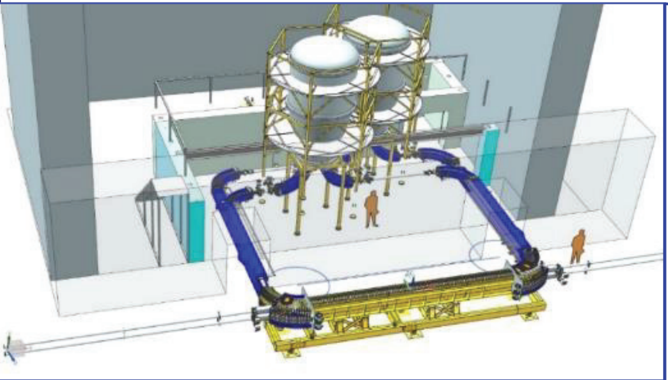
2. Stage II : Search for the Mixed Phase and New Physics in Heavy Ions' Collisions at NICA Collider

The Collider: HV Electron Cooler (BINP, V.Parkhomchuk and the team)



Peculiarity of Application of the HV Electron Cooler at NICA Collider

1. Energy range 1 – 4.5 GeV/u $^{197}Au^{79+}$ ions
   2 – 4.5 GeV protons
   0.55 – 2.45*) MeV electrons
2. Electron beam current 0.1 – 1.0*) A
3. Solenoid magnetic field 0.05 – 0.2 *) T
4. Two electron beams operated simultaneously *)
5. Suppression of ion beam space charge and IBS
6. Suppression of ion recombination with cooling electrons *)

*) Never reached before in electron coolers

Suppression of Ion Beam Space Charge and IBS. Luminosity Optimization

Optimum luminosity of an ion collider can be obtained if sum of the betatron tune shifts caused by both bunch space charge (Δq) and beam-beam effect (ξ) for both colliding beams does not exceed certain critical value (a shift to nearest betatron resonances):

$$\Delta q + \xi \leq \Delta Q_{max}$$

This criterion allows one to find optimum value of the intensity of both colliding beams (see next slide)*).

*) I.Meshkov, Luminosity of an Ion Collider, Phys. Part. Nucl. (2019) v. 6

The Colli … ctron Cooler (BINP, V.Parkhomchuk and the team)

See details in V.Parkhomchuk report, THX02

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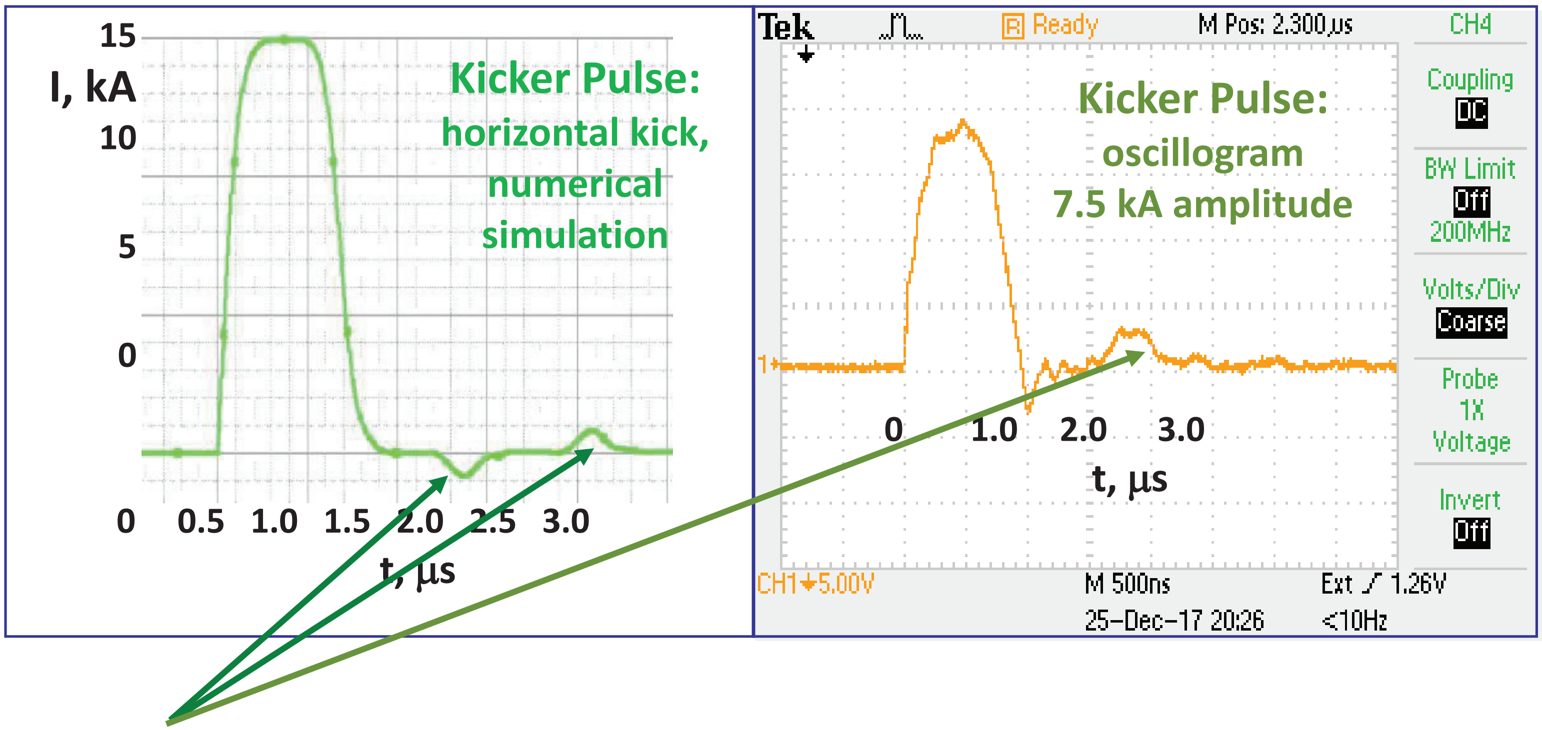
The Collider: Injection and Stacking with RF Barrier Voltage at Electron Cooling Application

Kicker Pulse



Ripples of the kicker pulse, which "heat" the ion stack

The Collider: Injection and Stacking with RF Barrier Voltage at Electron Cooling Application

Why do we need HV e-cooling…

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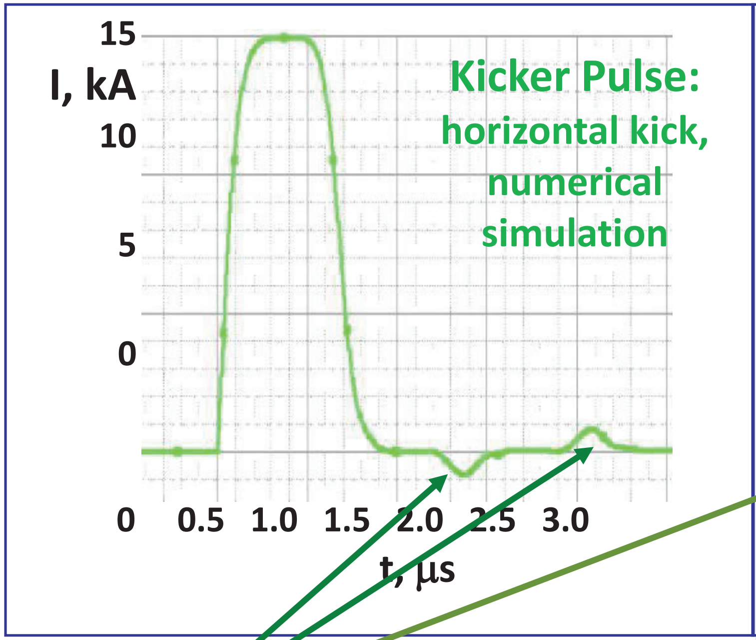

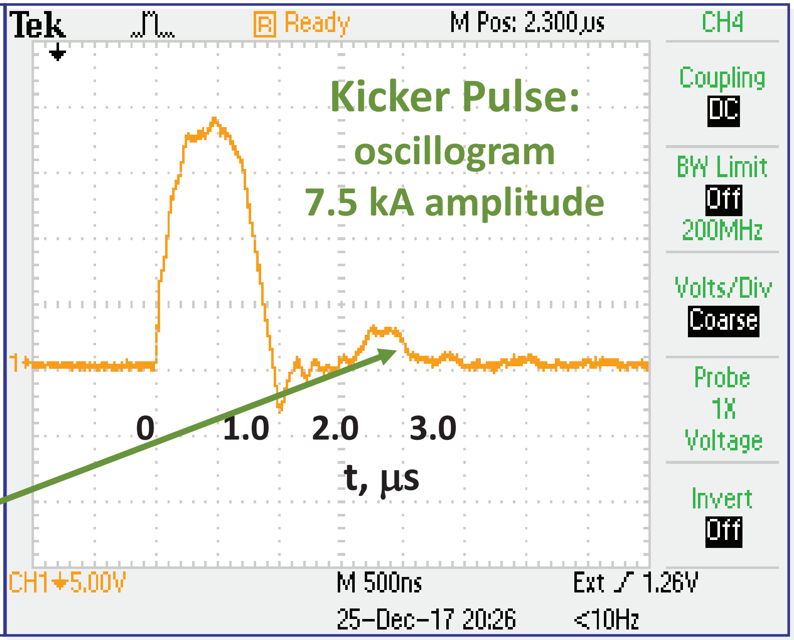

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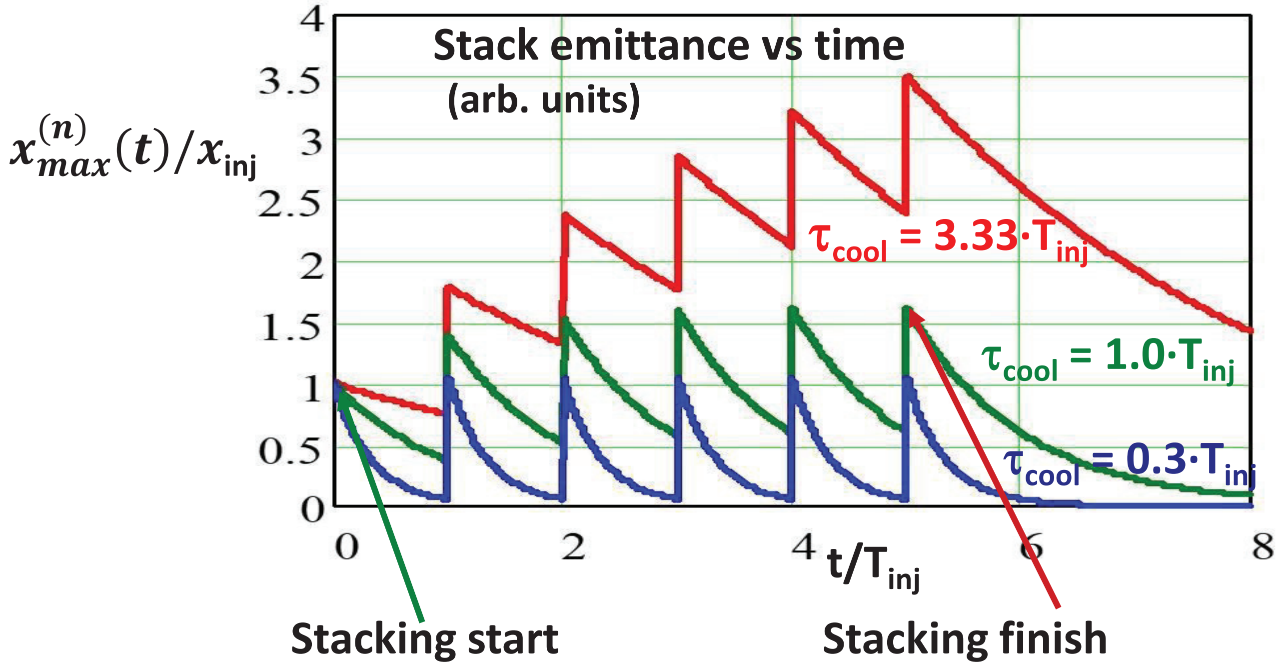
The Collider: Injection and Stacking with RF Barrier Voltage at Electron Cooling Application

Stack Transverse size vs Time (recurrent formula)

$$x_{max}^{(n)}(t) = x_{inj} \cdot \left(\sum_{m=1}^{n} e^{-(m-1)\alpha} (1+r)^{m-1} \right) \cdot e^{-\alpha(t-n)}, \qquad (n-1) \le t \le n$$

$\alpha = T_{inj}/\tau_{cool}$ is cooling decrement, T_{inj} *is injection period,* t is time in T_{inj} units,
$r = \Delta x / x_{max}$ is increase of the stack x-size under action of the kicker pulse ripples.



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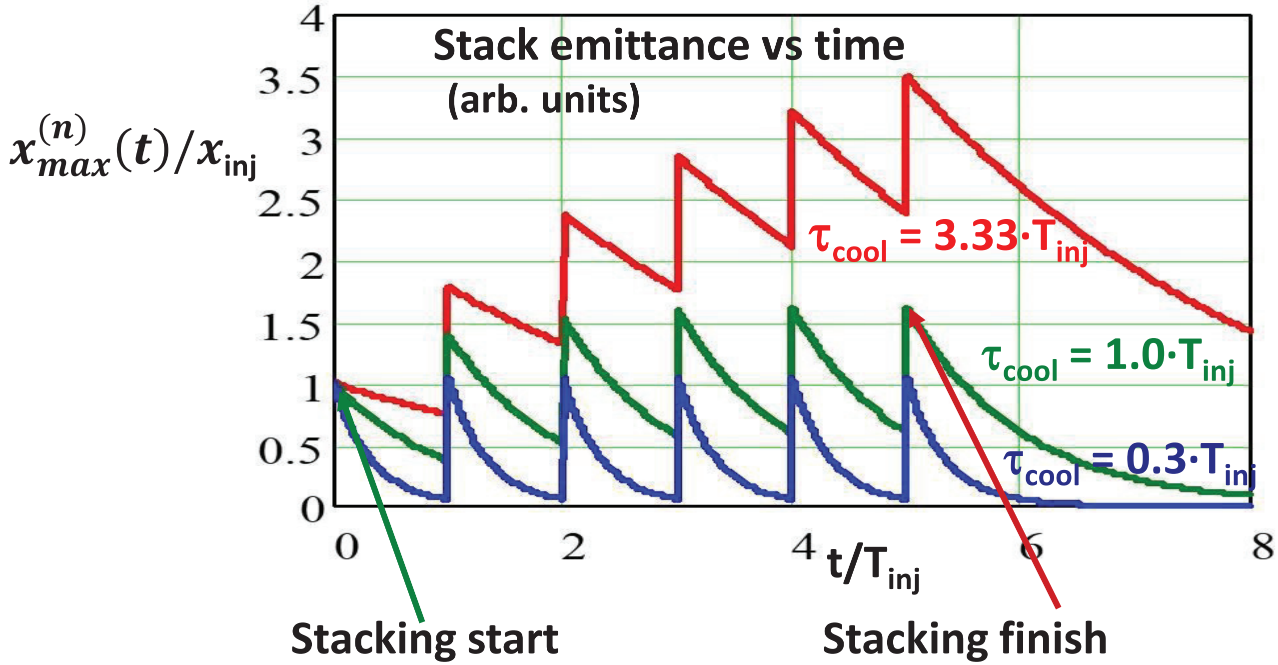

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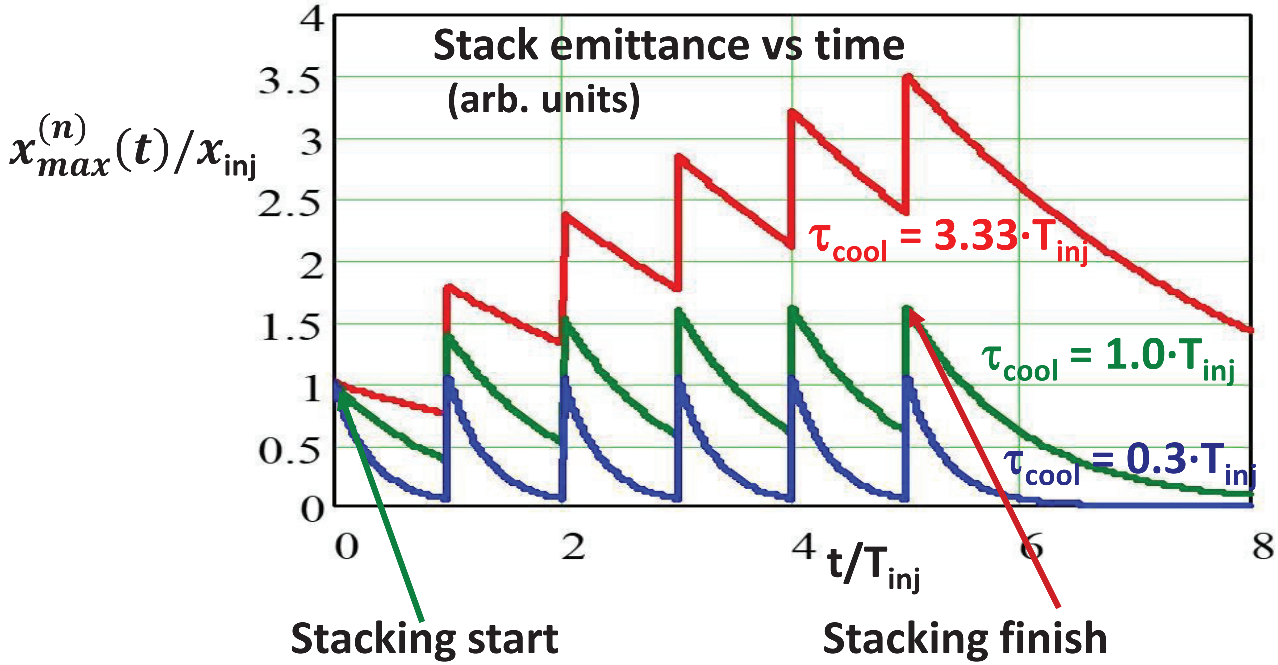
T_{inj} = 9 sec.



The Collider: Injection and Stacking with RF Barrier Voltage at Electron Cooling Application

Equilibrium of electron cooling and heating by the kicker pulses

Just after (n + 1)-st injection we have the beam x-size value $x^{(n+1)}$:

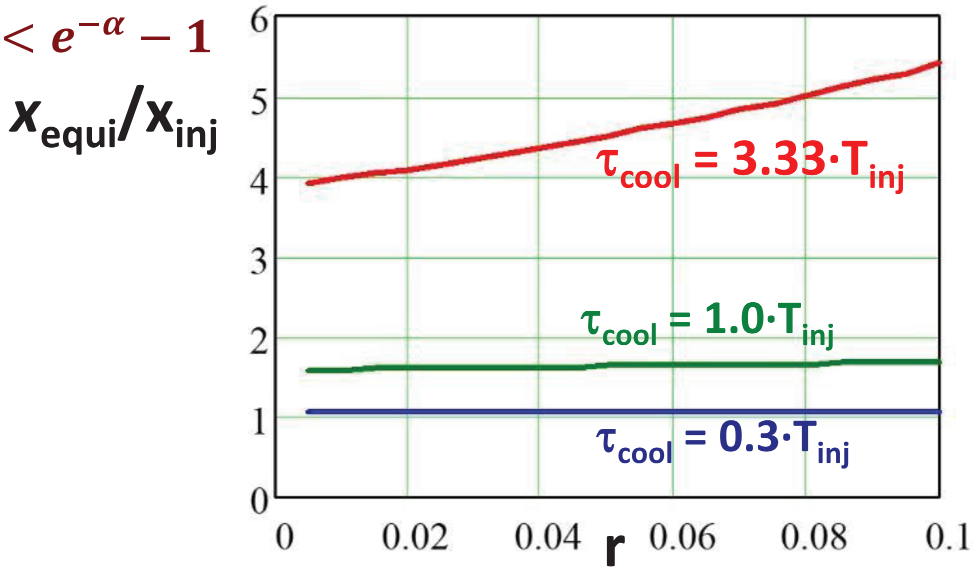
$$x_{max}^{(n+1)} = x_{max}^{(n)} \cdot e^{-\alpha} \cdot (1 + r) + x_{inj} \qquad (1)$$

The cooled n-th stack interrupted by ripples new injected bunch

Equilibrium condition: $$x_{equi} = x_{max}^{(n+1)} = x_{max}^{(n)} \qquad (2)$$

Inserting (2) in (1) we find: $$x_{equi} = \frac{x_{inj}}{1 - (1 + r) \cdot e^{-\alpha}} \qquad (3)$$

It follows from (3): $$r < e^{-\alpha} - 1 \qquad (4)$$



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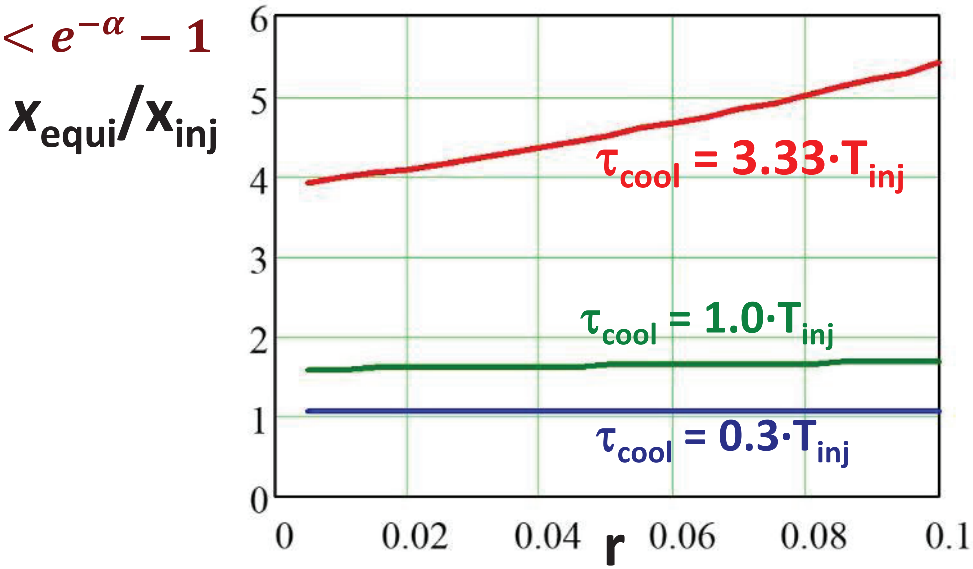


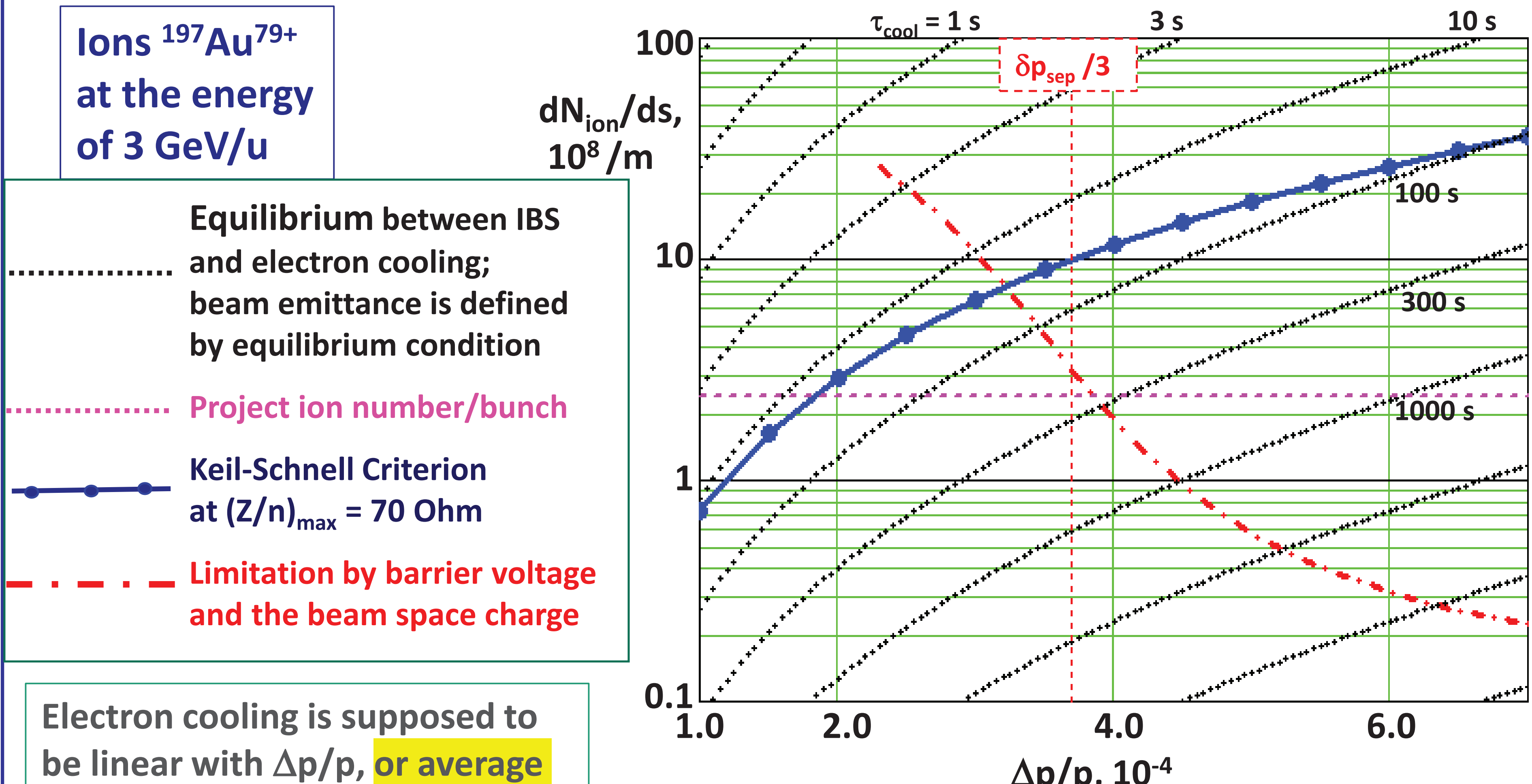
2. Stage II : Search for the Mixed Phase and New Physics in Heavy Ions' Collisions at NICA Collider

The Collider: Injection and Stacking with RF Barrier Voltage at Electron Cooling Application

Electron Cooling, IBS and Other Limitations

N.V.Mityanina

Ions $^{197}Au^{79+}$ at the energy of 3 GeV/u



Electron cooling is supposed to be linear with $\Delta p/p$, or average decrement over the beam.

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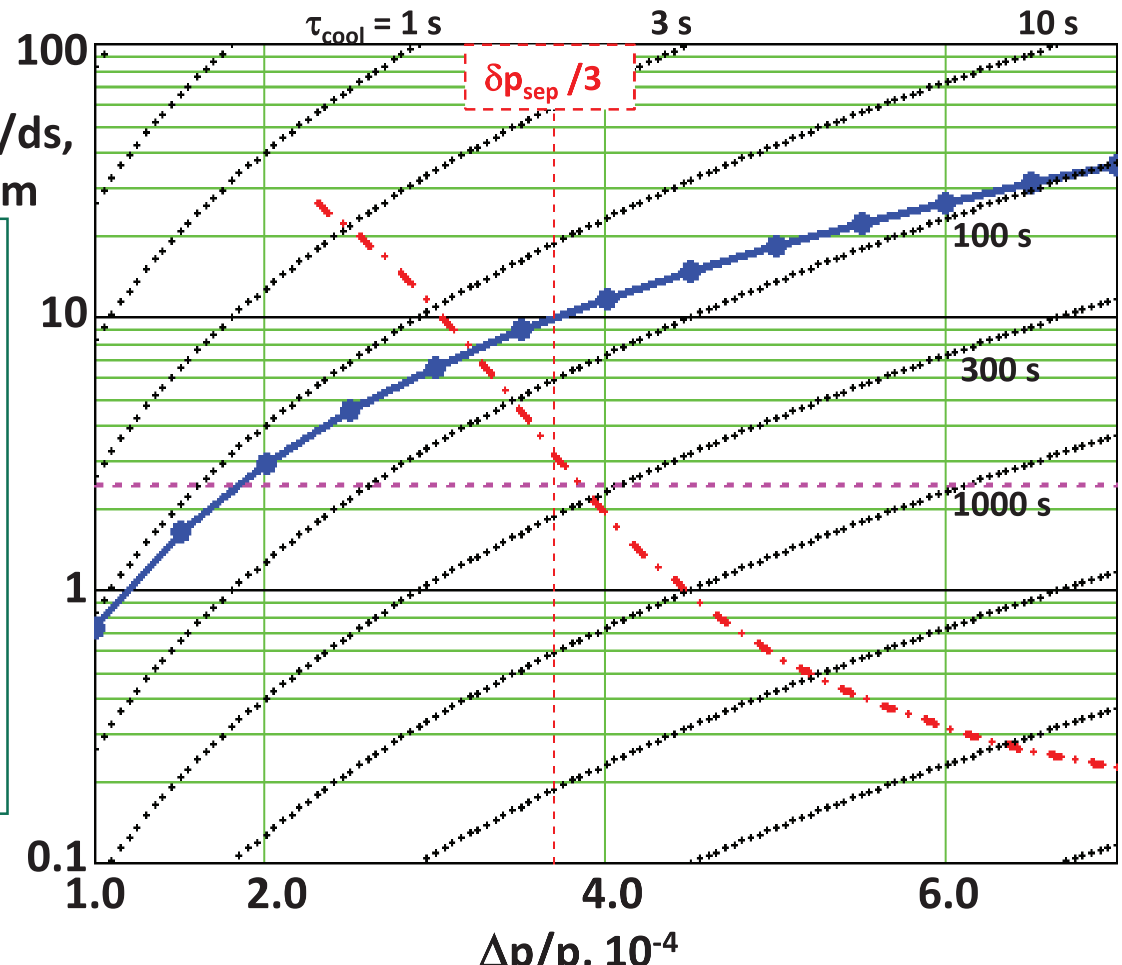

Equilibrium between IBS and electron cooling; beam emittance is defined by equilibrium condition

Project ion number/bunch

Keil-Schnell Criterion at $(Z/n)_{max}$ = 70 Ohm

Limitation by barrier voltage and the beam space charge

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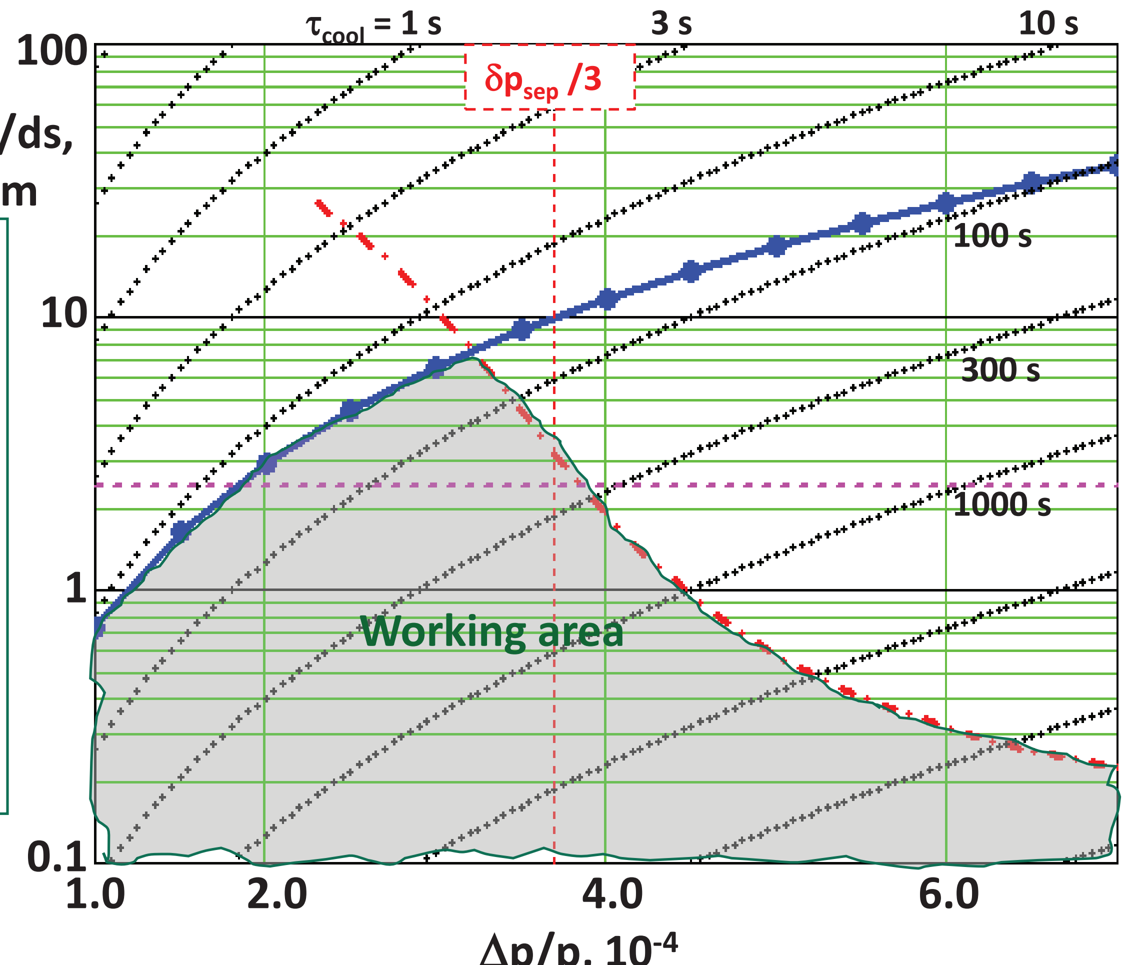

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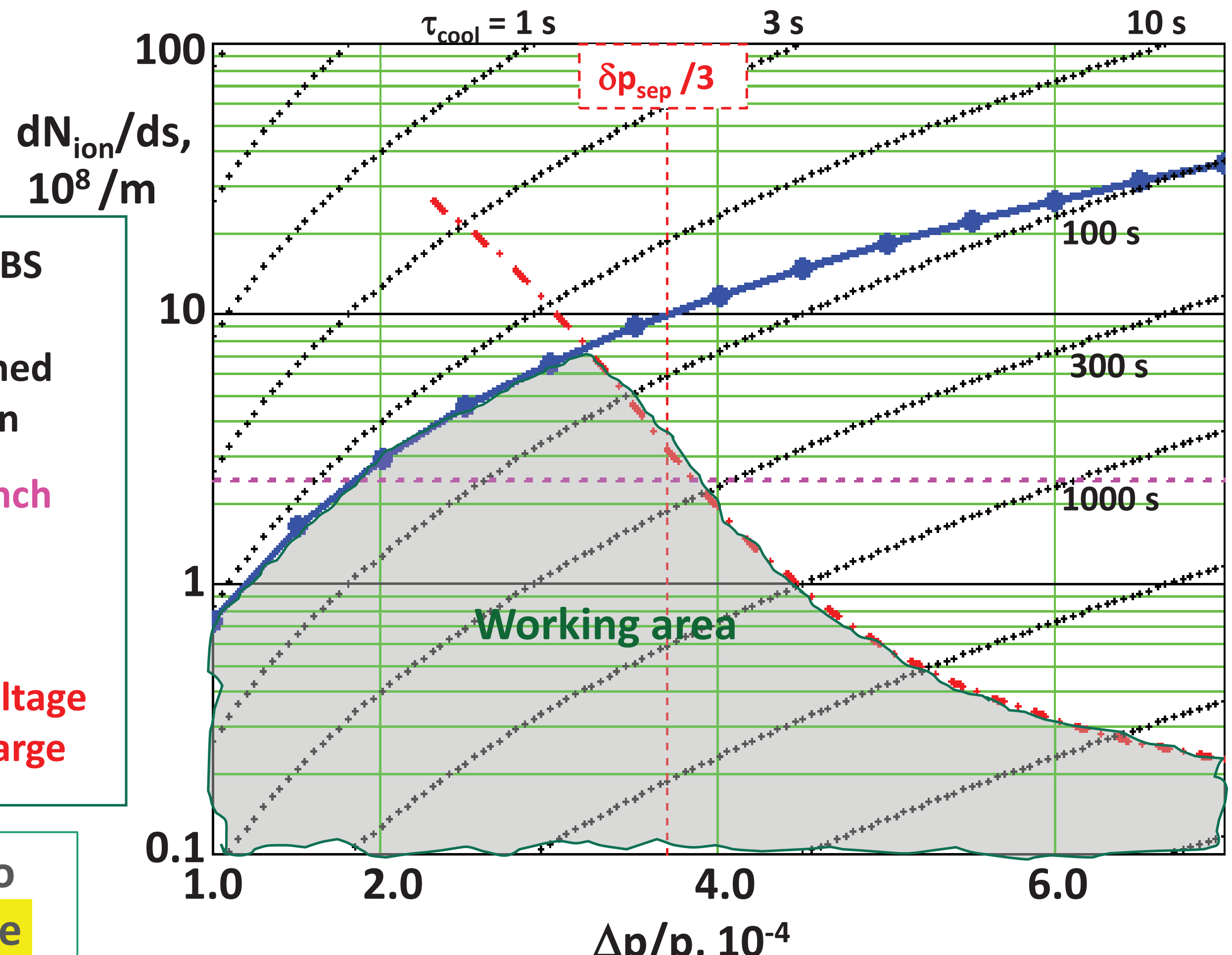

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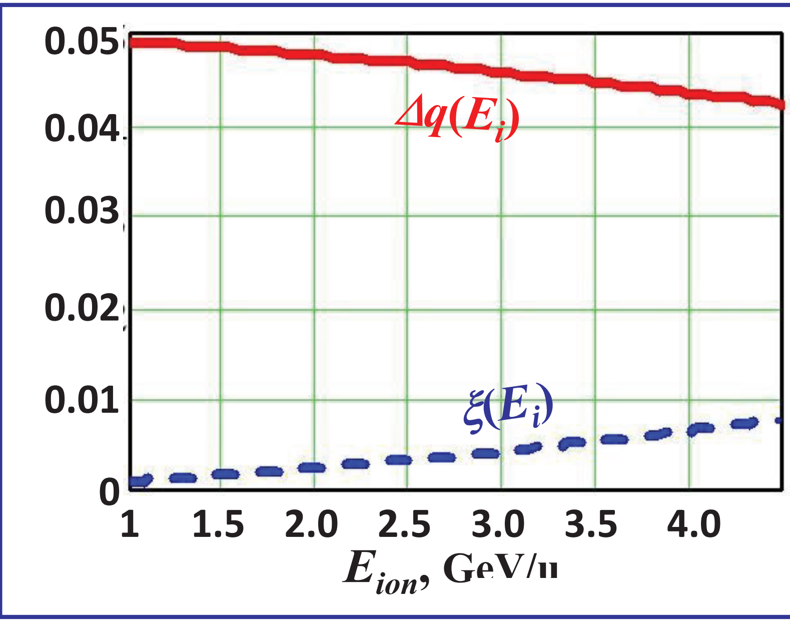
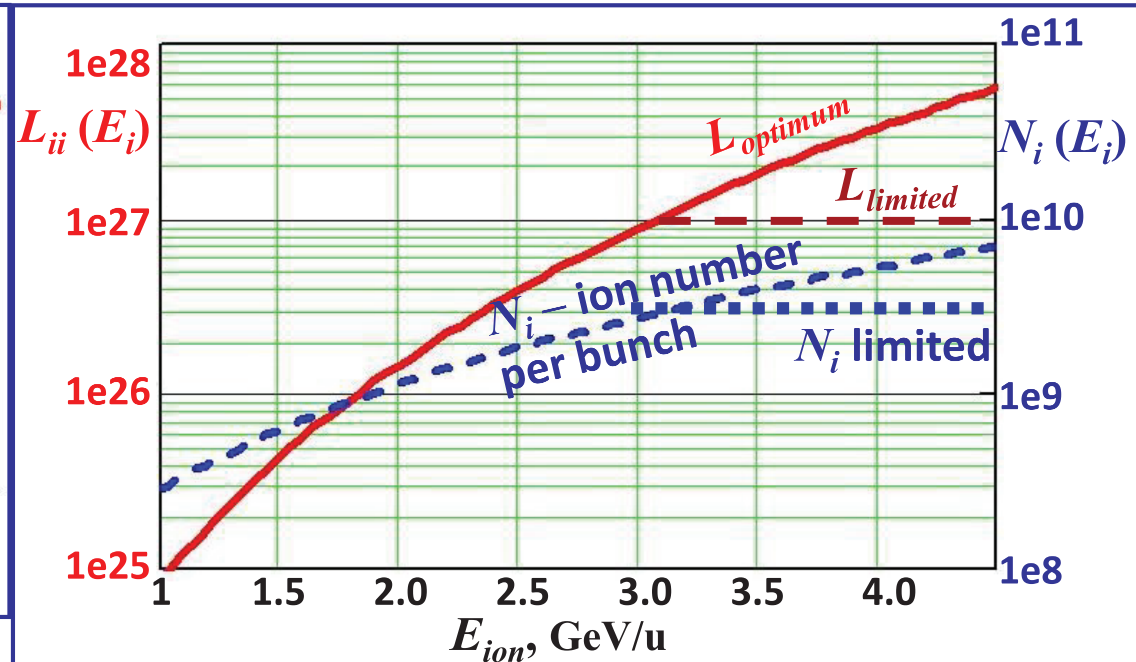
The Collider: HV Electron Cooler (BINP, V.Parkhomchuk and the team)

Suppression of Ion Beam Space Charge and IBS. Luminosity Optimization

An example: Optimum luminosity for the NICA Collider: $\Delta Q_{max} = \Delta q(E_i) + \xi(E_i) = 0.05$





Using an effective electron cooling one can hope to obtain $\Delta Q_{max} = 0.1$!

However, luminosity of NICA Collider will be limited, first of all, by intensity of injection chain… …and MPD capability.

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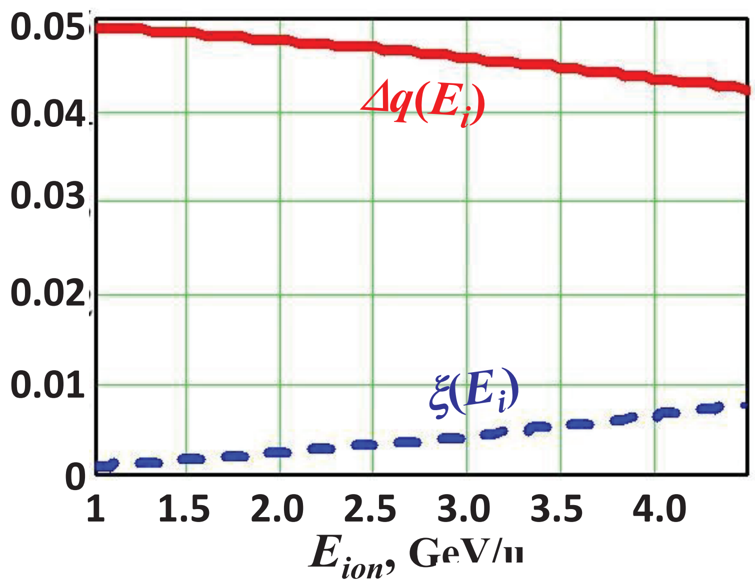

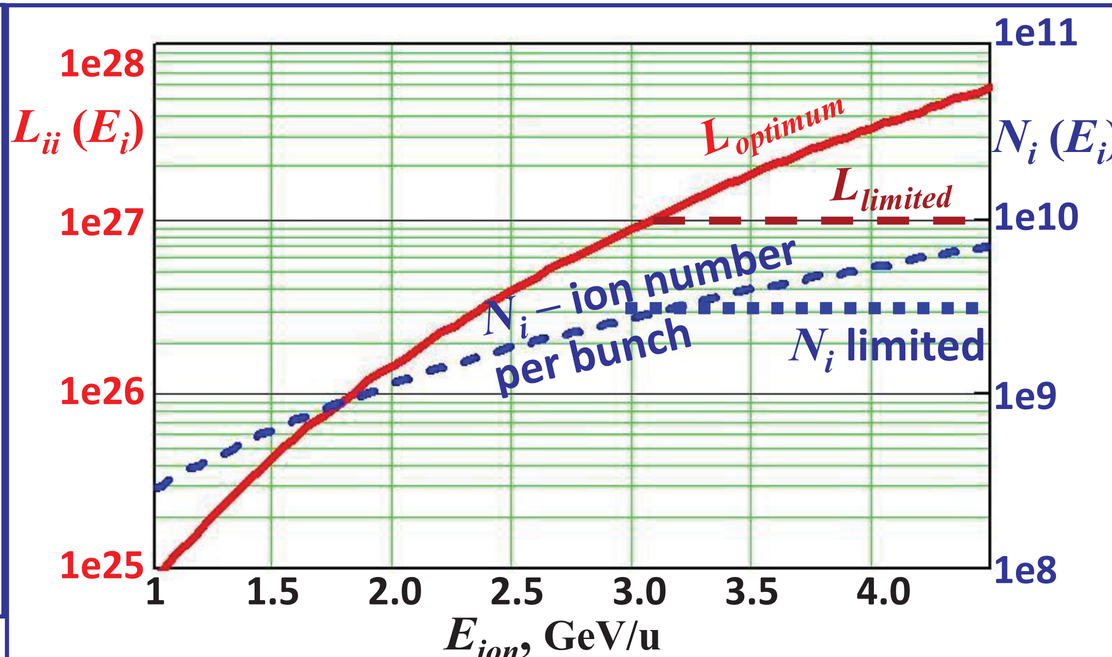

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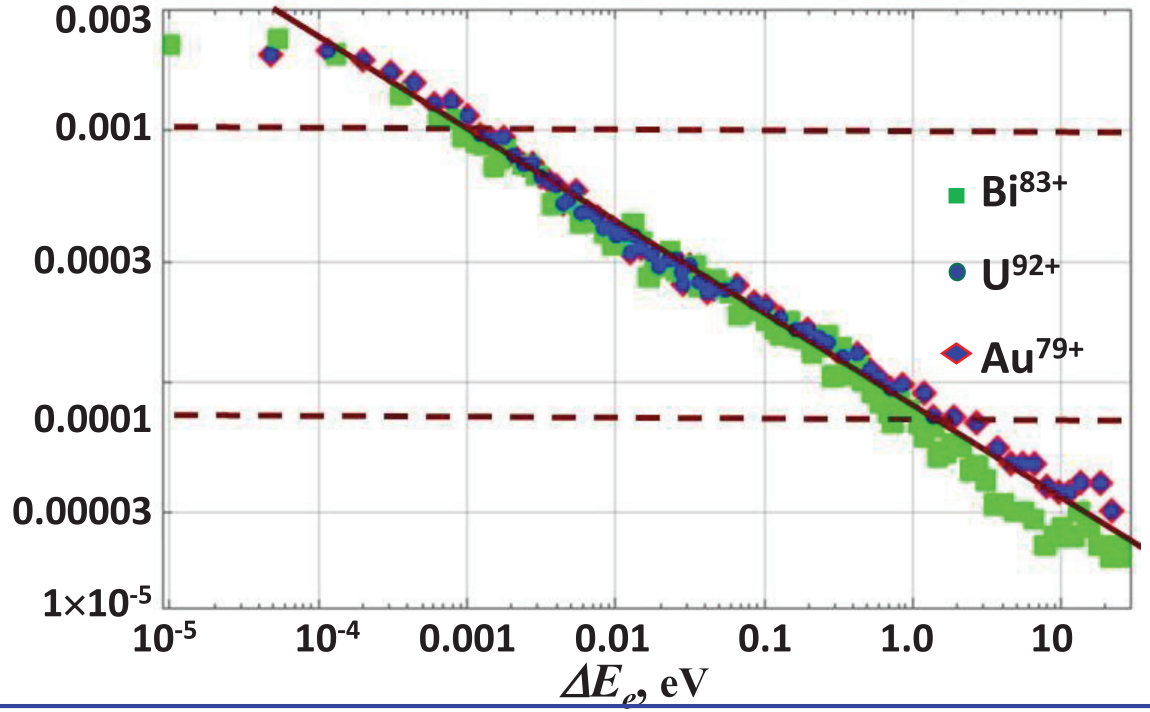
The Collider:

Recombination in E-Cooler of Collider and its suppression



Bi^{83+} A.Hoffknecht et al. Phys. Rev. A.mV.63 (2000) 012702

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Au^{79+} Recalculated from U^{92+} data

Fit equation:

$\alpha_z(\Delta E_e) = 7 \cdot 10^{-13} \cdot Z^2 T^k$, k = - 0.3849673 cm³/s

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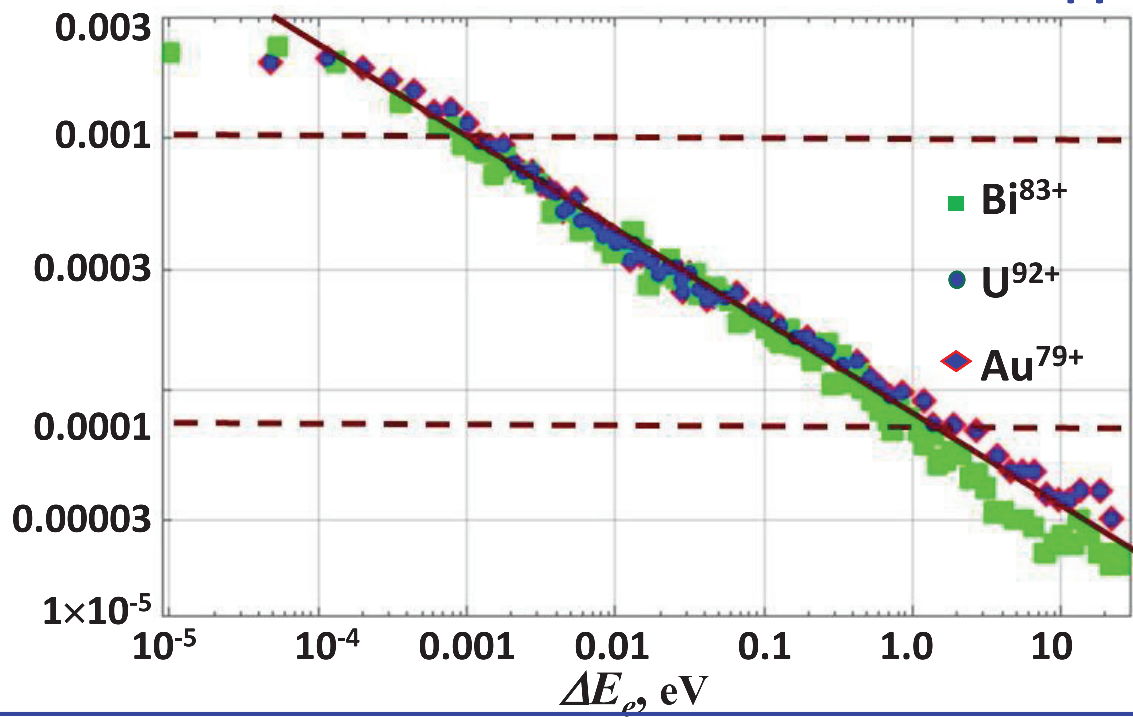

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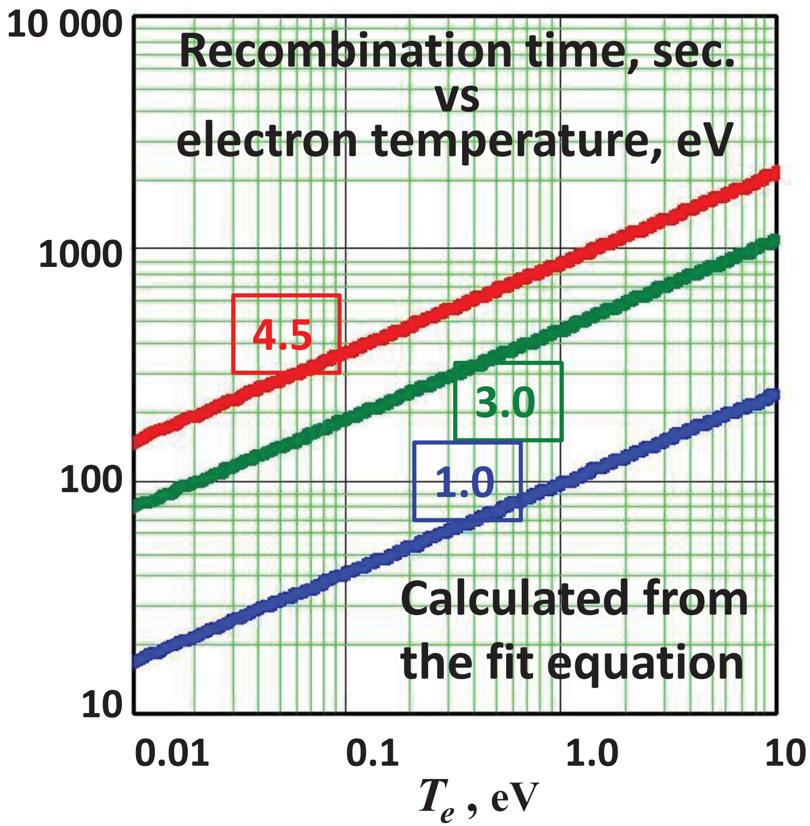
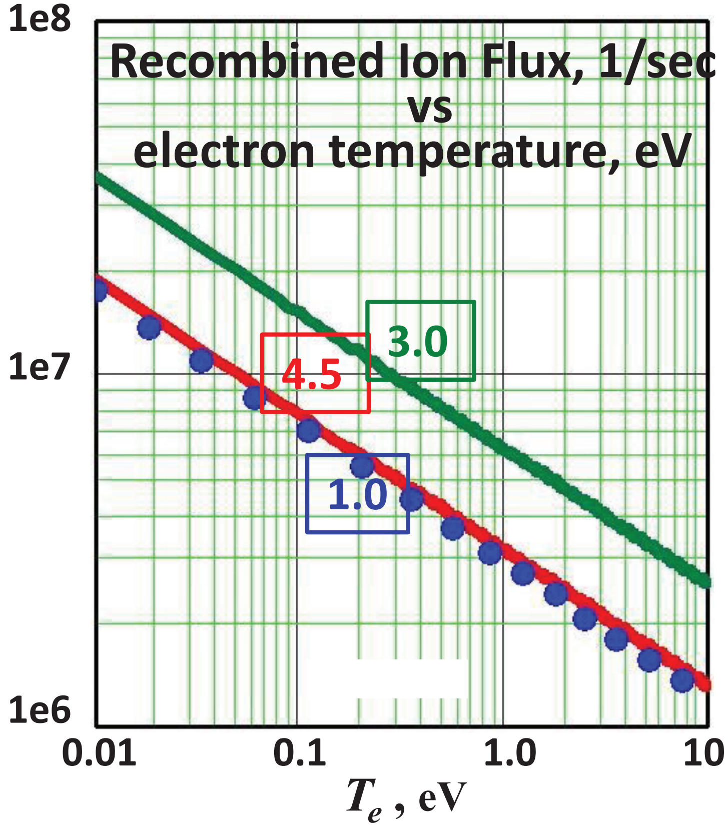
Flux of The Recombined Ions and Its Suppression





$^{197}Au^{79+}$, E_{ion} = 1 – 4.5 GeV/u (*shown in squares in diagrams*)

Electron cooler: I_e = 1 A, r_e = 3 mm, n_e = 1.41×10^8 cm^{-3}

cooling section: length = 6 m, solenoid field = 0.2 T

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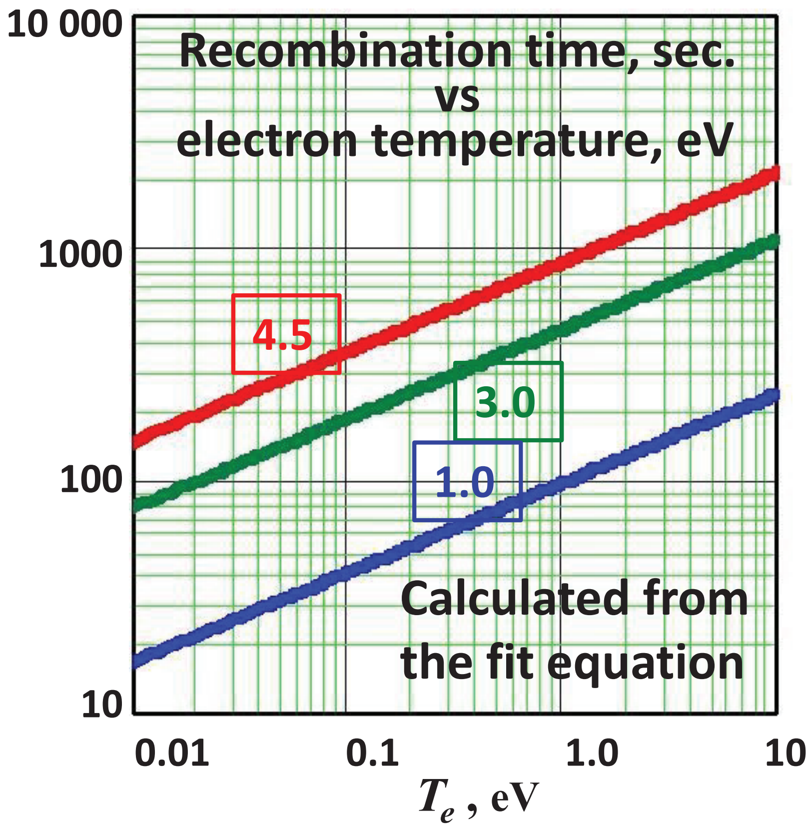

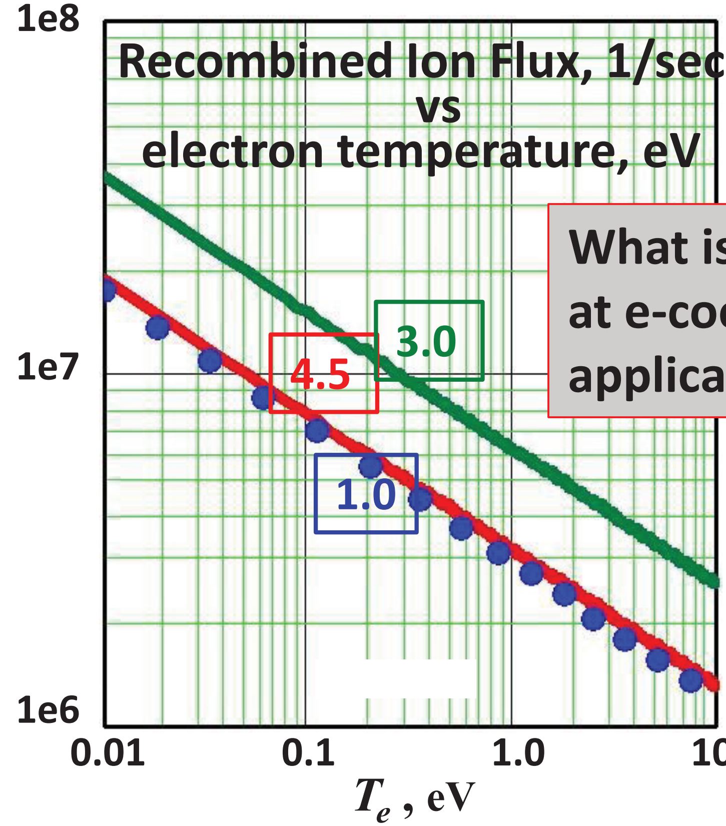

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The flux of recombined ions
1) shortens beam lifetime
2) generates parasitic signal in the detector – *collimation* (!),
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The flux of recombined ions can be suppressed by excitation of transverse temperature of electrons:

P.Beller, K.Beckert, B.Franzke, C.Kozhukharov, F.Nolden, M.Steck, NIM A V. 532 (2004) P. 427 - 432

The Collider: HV Electron Cooler (BINP, V.Parkhomchuk and the team)

Flux of The Recombined Ions and Its Suppression

What is bad at e-cooling application...

The flux of recombined ions
1) shortens beam lifetime
2) generates parasitic signal in the detector – *collimation* (!),
3) increases radiation level in vicinity of the NICA facility.

The flux of recombined ions can be suppressed by excitation of transverse temperature of electrons:

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Strong magnet field at cooling section is necessary for reduction of recombination without decreasing cooling rate.
In the electron cooler of the NICA Collider solenoid magnetic field is

$$B_{sol} \leq 0.2 \text{ T.}$$

The Collider: HV Electron Cooler (BINP, V.Parkhomchuk and the team)

Flux of The Recombined Ions and Its Suppression in NICA Collider

$^{197}Au^{79+}$, E_{ion} = 4 GeV/u,

C_{ring} = 503,04 m (not 580 m!)

Electron cooler: I_e = 1 A, r_e = 3 mm, $n_e = 1.41\times10^8$ cm^{-3}
cooling section: length = 6 m, solenoid field = 0.2 T

T_e , eV	τ_{cool} , sec	τ_{rec1} , sec	τ_{rec2} , sec
0.1	18.45	87.6	295
1.0	21.91	209.9	717
10	28.8	1153	1740
100	40.35	4843	2800

V.V.P. Formula

Fit of experimental data (slide 24)

M. Bell and J.S. Bell. Particle Accelerators. 1982. V. 12. P. 49-52

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What about stochastic cooling?

Both methods are complimentary and will be applied to *ion beams* of the NICA Collider (Poster reports of Konstantin Osipov TUPS17 and Ivan Gorelyshev TUPS18, both JINR, dedicated to stochastic cooling application to NICA have been presented on Tuesday).

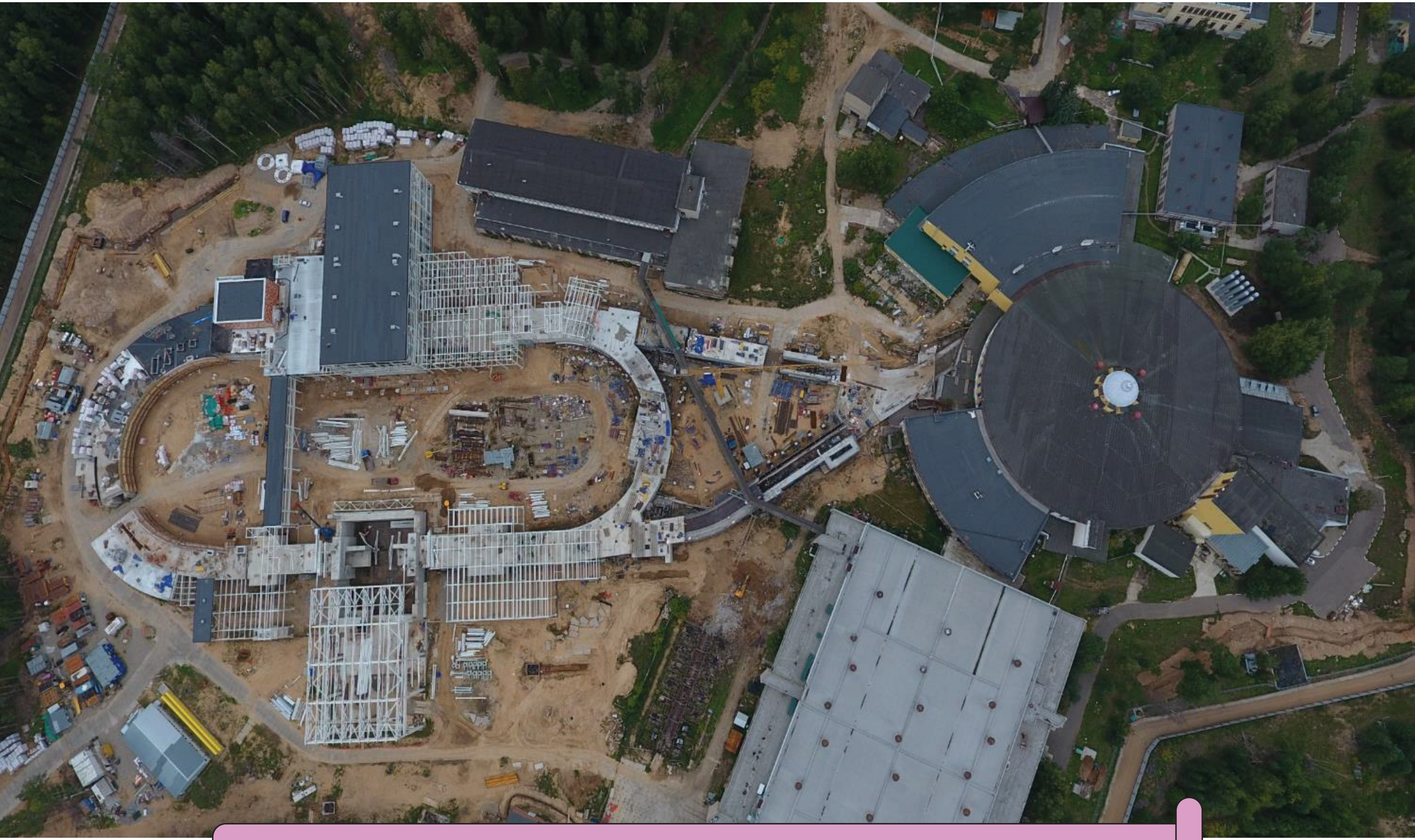
Concerning the proton mode it is much more complicated problem. We loose stochastic signal level by factor Z = 79 and get increasing of cooling time by factor N_{proton}/N_{ion} . This problem is under investigation by NICA group.

Conclusion

The presented talk describes the present status of the NICA project with focus on the problems related to application of electron cooling at the steps of ion injection and acceleration in the NICA Booster and ion storage in the NICA Collider.

More detailed analysis of ion storage with barrier RF voltage application (including “moving” barriers) and bunched beam formation in the Collider is decribed in the next talk of Natalya Mityanina.

Both talks demonstrate that electron cooling is a key issue of the NICA project.

Thank you for your attention!
Спасибо за внимание!