Научная сессия-конференция
секции ядерной физики ОФН РАН
«Физика фундаментальных взаимодействий»

Проект Ускорительного Комплекса NICA ОИЯИ

Nuclotron-based Ion Collider fAcility

И.Н.Мешков
от имени Группы NICA

ИФВЭ, Протвино, 22-25 декабря, 2008

Содержание

1. Поиск смешанной фазы сильновзаимодействующей материи

Precursors, Predecessors and Hints

1970 – Synchrophazotron (JINR): observation of

dd $\Rightarrow$ π-jet : $\Sigma E_{jet} > 2m_n c^2 \Rightarrow$ first cumulative effect!

(V.Sviridov, V.Stavinsky)

The 1980th: AGS (BNL),
NA49, NA50 and CERES at SPS (CERN),
STAR & PHENIX at RHIC (BNL)

Coming soon: ALICE at LHC (CERN)

(NA49) $\Rightarrow$ NA61 (2011?) at SPS (CERN)

STAR & PHENIX at RHIC (BNL) at $\sqrt{s} \Rightarrow$ 20(?) GeV/u

Precursors, Predecessors and Hints

NA49 & NA50 at SPS ⇒ $^{208}Pb^{82+}$ x $^{208}Pb^{82+}$, 2x158 GeV/u

↓

Hypothesis of quark–gluon plasma (QGP) –

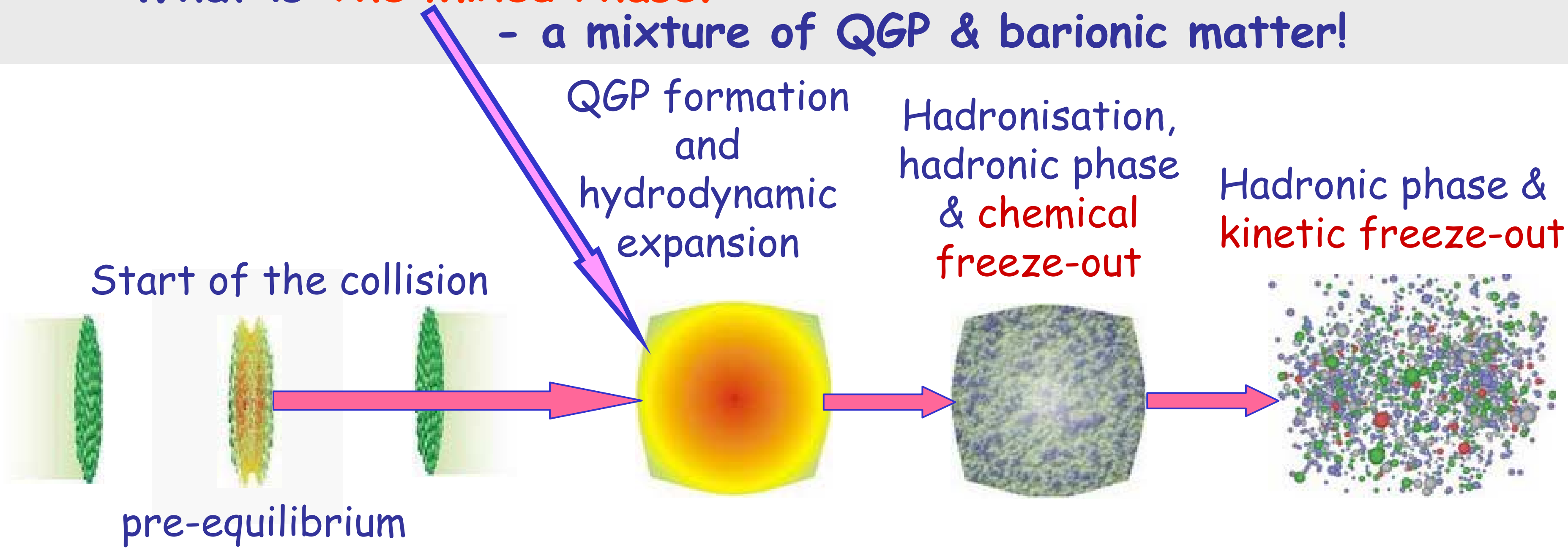
- a "mirage" never proved been observed

Nevertheless, there are all indications of a qualitatively new form of matter produced in central Au x Au collisions at RHIC!

(see further)

Evolution of collision region in NN Interaction

What is The Mixed Phase? –
– a mixture of QGP & barionic matter!



"Chemical freeze-out" – finish of inelastic interactions;
"Kinetic freeze-out" – finish of elastic interactions.

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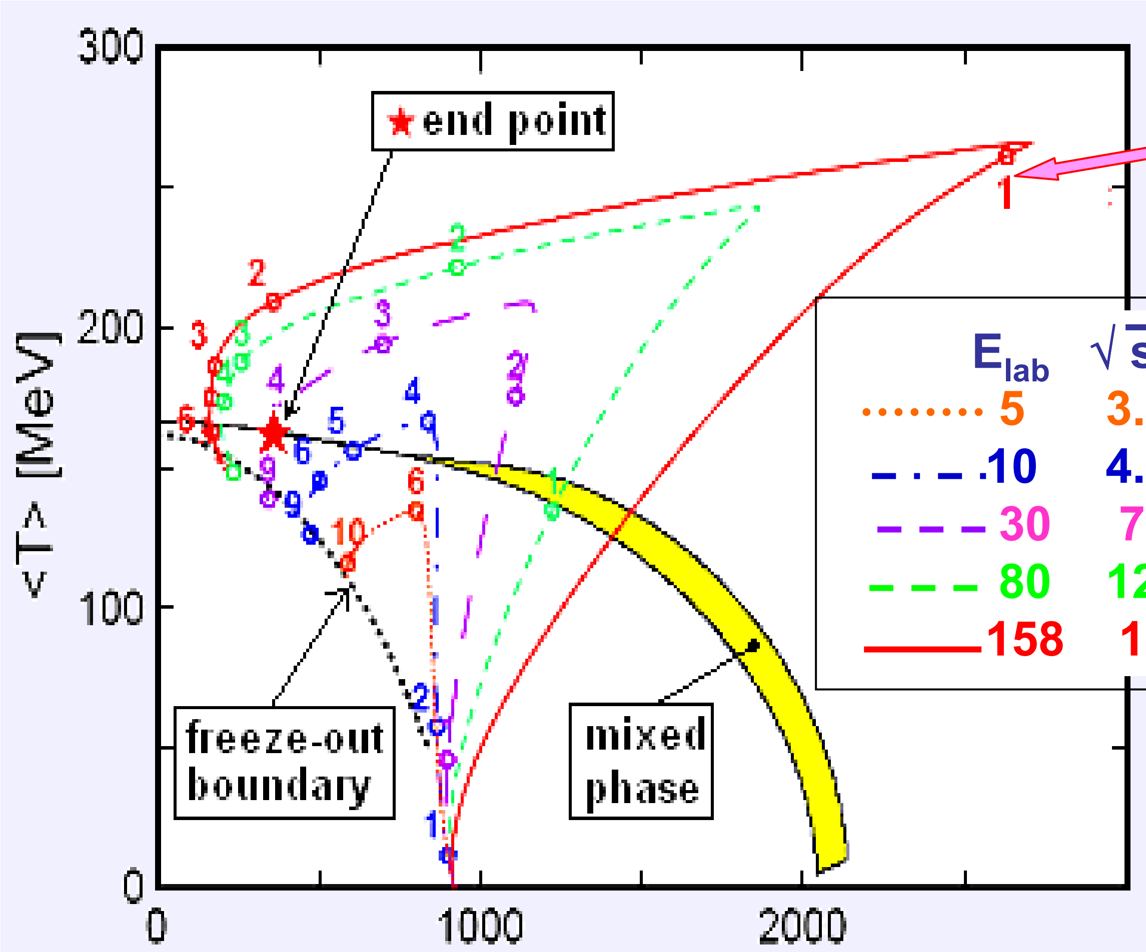
*) freeze-out – here means "to get rid"

1. Поиск смешанной фазы сильновзаимодействующей материи



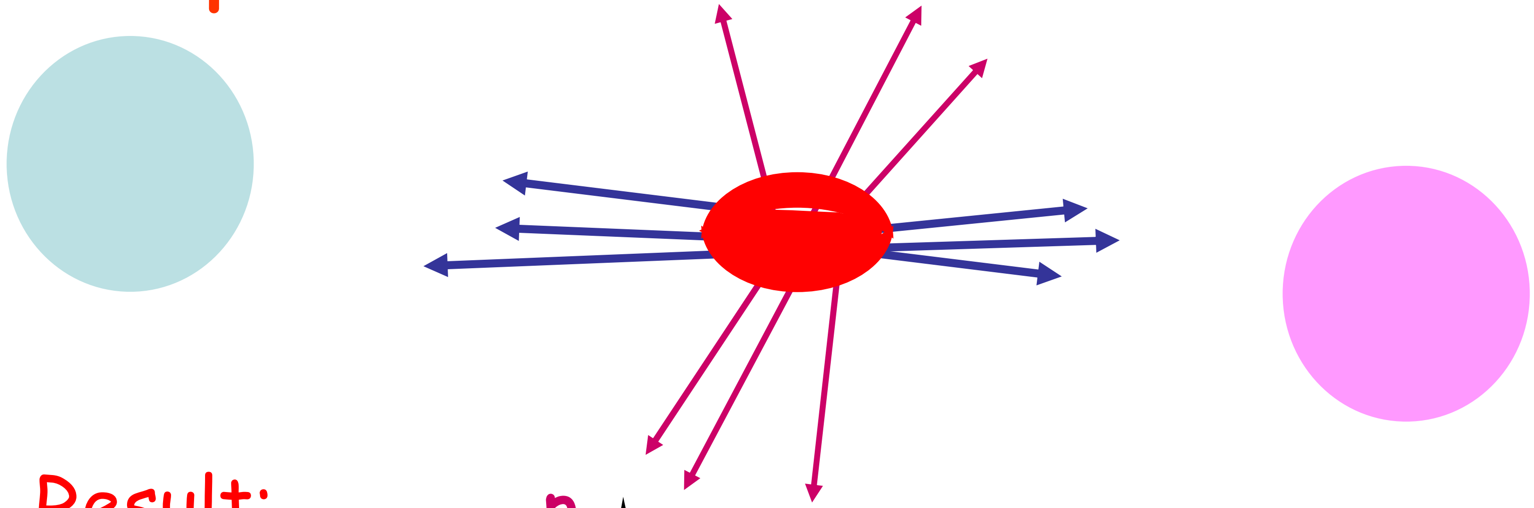
E_{lab}	$\sqrt{s}$ GeV/u	
5	3.60	NICA & CBM
10	4.73	NICA & CBM
30	7.75	NICA & CBM
80	12.42	RHIC (?)
158	17.36	NA49/61 (SPS)

What to look for ?

There are a few experimental characteristics to be measured

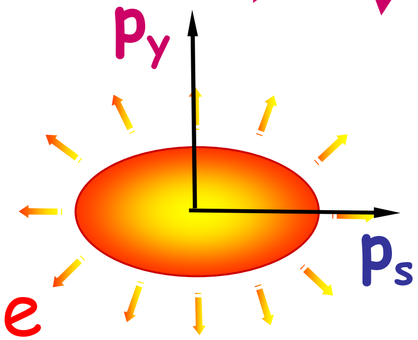
What to look for ?

Elliptic flow of central fireball matter



Result:

Anisotropy in momentum space



One has to measure the ellipticity parameter

$$\chi(E_{total}) = \langle p_s \rangle / \langle p_y \rangle$$

What to look for ?

Much more convincing:

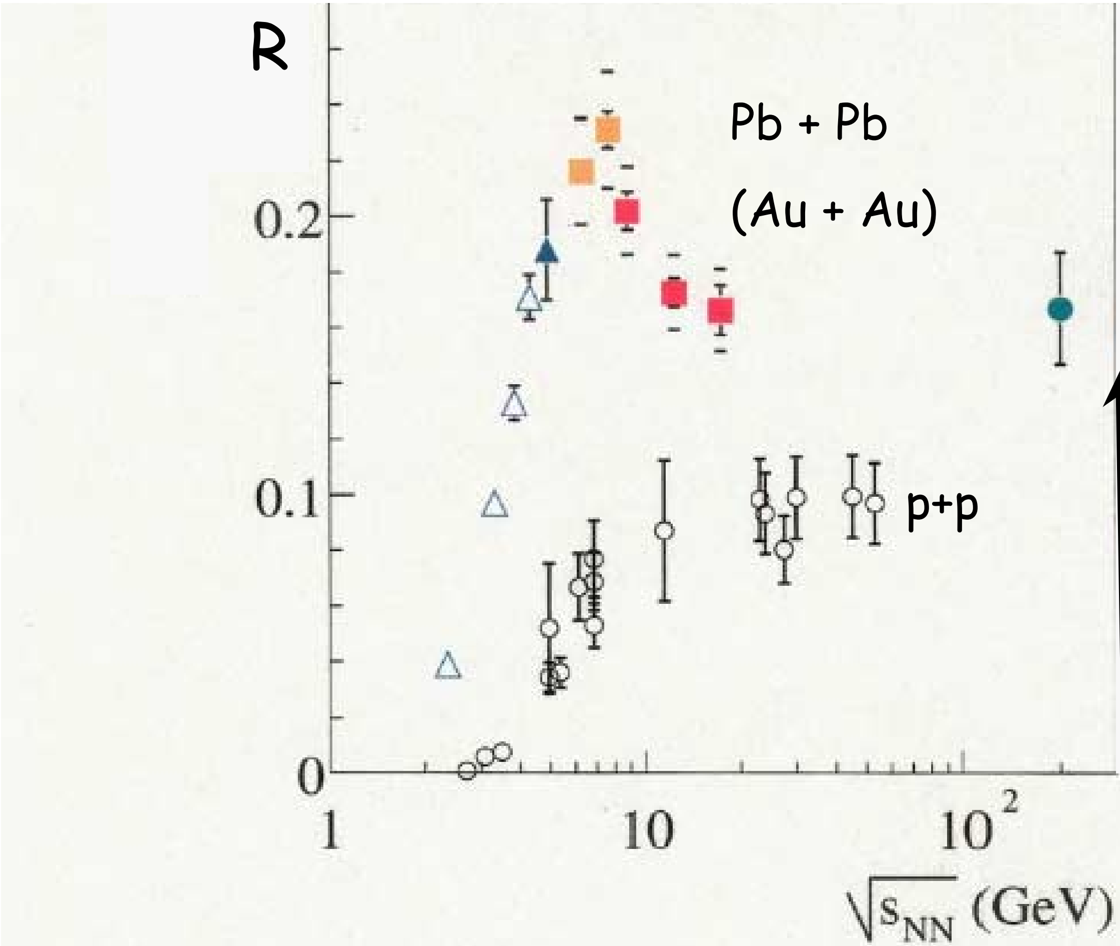
Fluctuations! They are “a sign” of the mixed phase: system becomes unstable at the two-phases stage!

Thermodynamics analog: boiling water –
- a flow of bubbles fluctuates tremendously.

Which fluctuations?

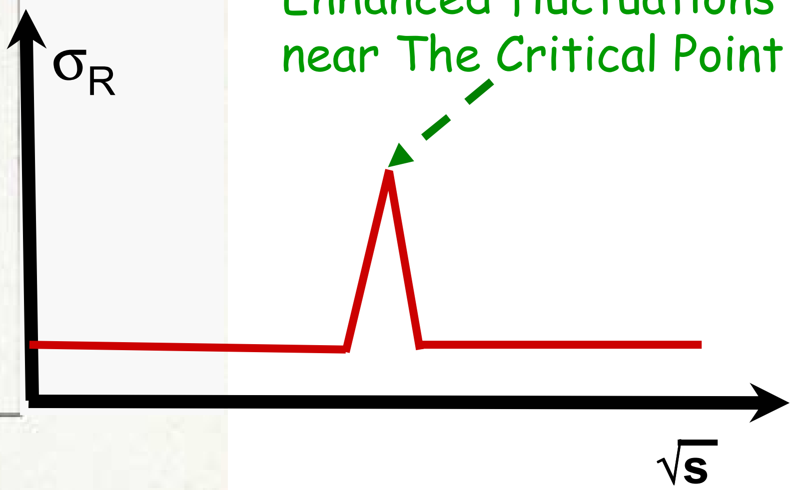
1. Поиск смешанной фазы сильновзаимодействующей материи

Main candidate: energy dependence of particle ratio and its fluctuations, for instance ⇒ $R = \langle N_{K+}\rangle / \langle N_{\pi+}\rangle$



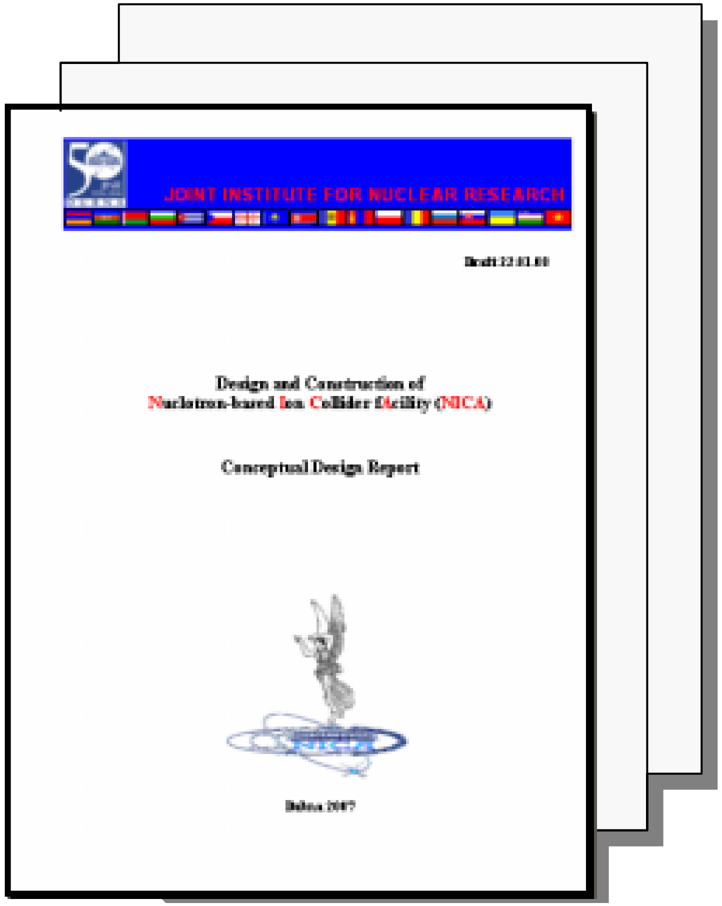
The task: to locate the critical point using correlation/fluctuation measurements:

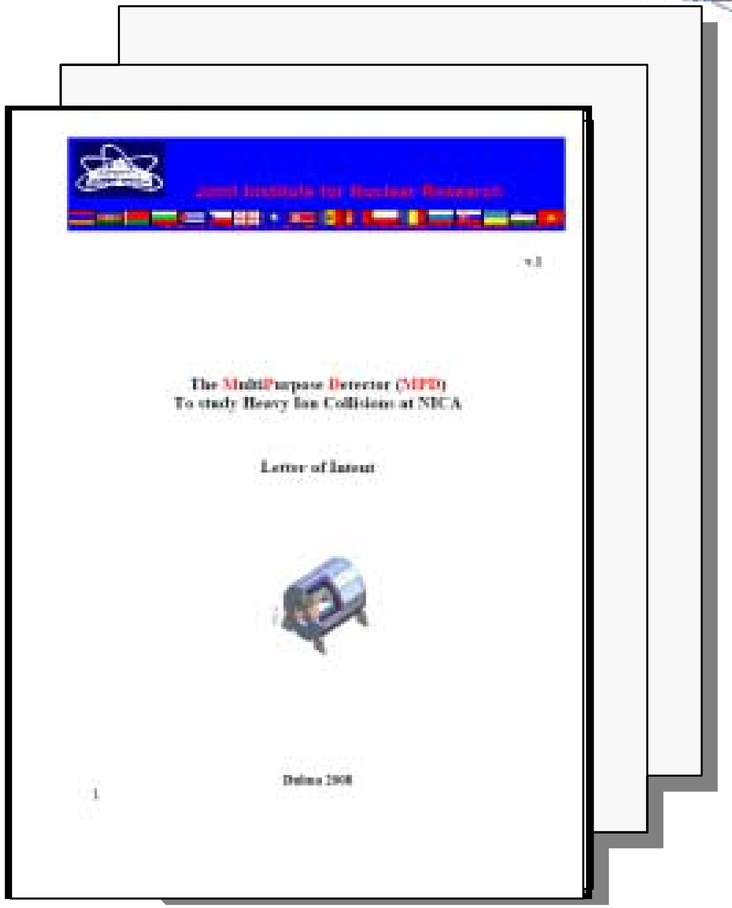
$$\sigma_R = \langle (R - \langle R\rangle)^2 \rangle$$



Rajagopal, Shuryak, Stephanov

2. NICA/MPD: Концепция-1





January 2008

The intention and the goal:

Development of the JINR basic facility for generation of intense heavy ion and polarized nuclear beams aimed at searching for the mixed phase of nuclear matter and investigation of polarization phenomena at the collision energies up to $\sqrt{s_{NN}}$ = 11 GeV/u,

i.e. $^{238}U \times {}^{238}U$ in the energy range of 1 ÷ 4.5 GeV/u

at average luminosity (at 3.5 GeV/u)

$$L_{average} = 1 \cdot 10^{27}\ cm^{-2} \cdot s^{-1}.$$

"The Basic Conditions" for the Project Development and Some Consequences

1. Minimum of R & D

2. Application of existing experience

3. Co-operation with experienced research centers

2. NICA/MPD: Концепция-1

"The Basic Conditions" for the Project Development and Some Consequences

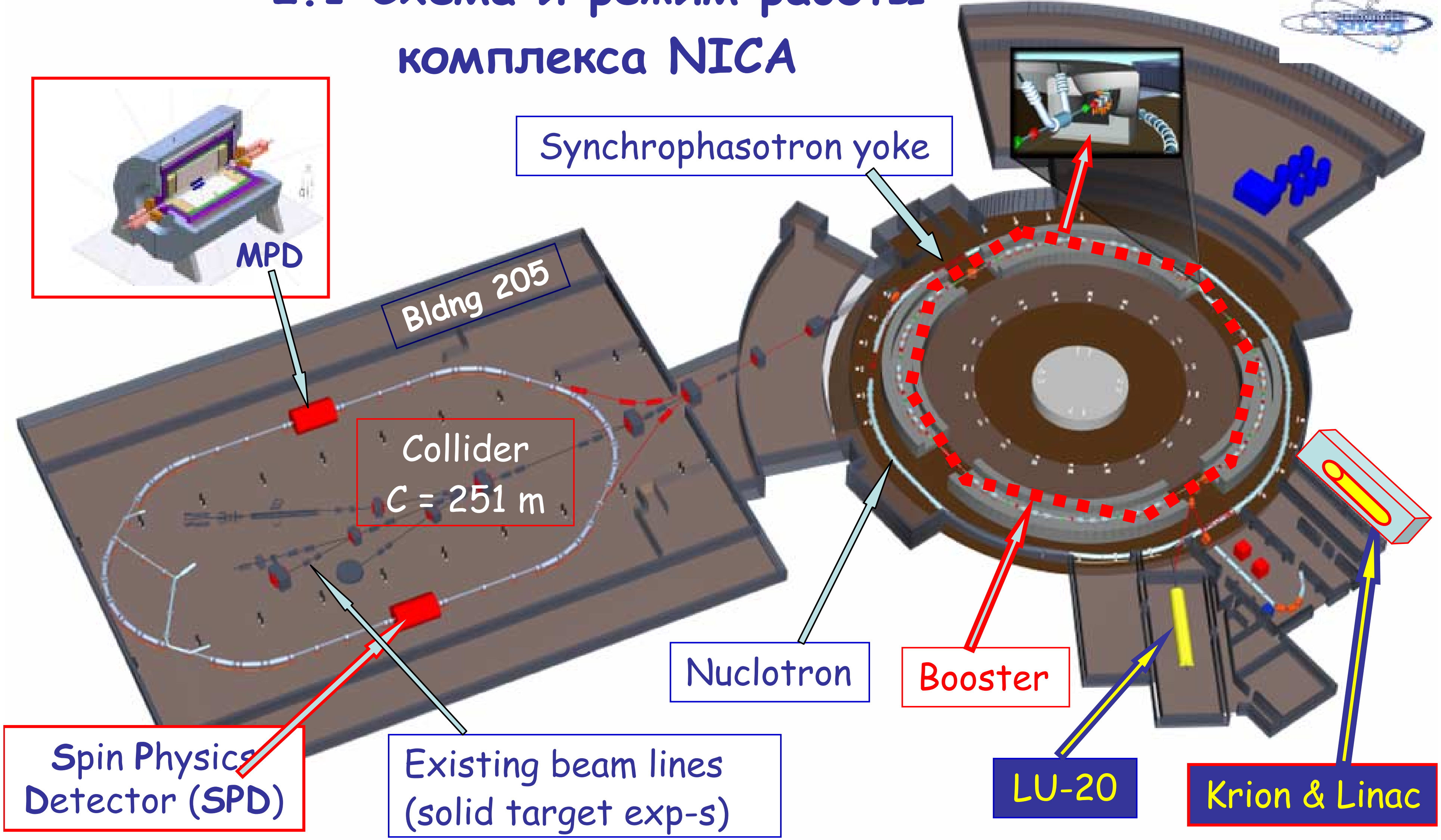
4. Cost – as low as possible
5. Realization time – 4 – 5 years

Choice of an existing building for dislocation of the collider

Collider circumference is limited by ~ 250 m

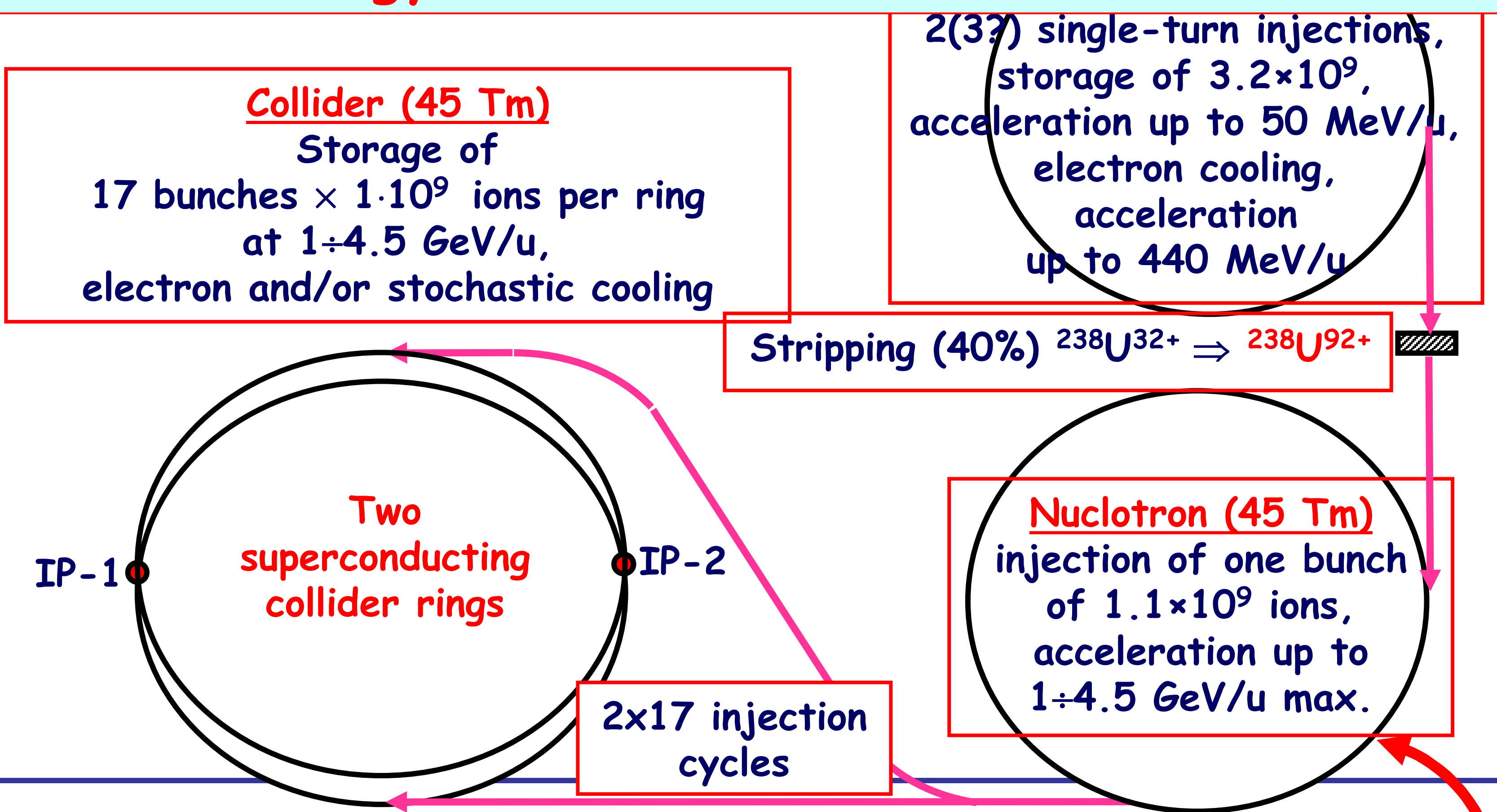
Luminosity → High beam intensity, multibunch regime, low beta-function in Interaction Point, ……………………………………………………

2.1 Схема и режим работы комплекса NICA



2.1 Схема и режим работы комплекса NICA

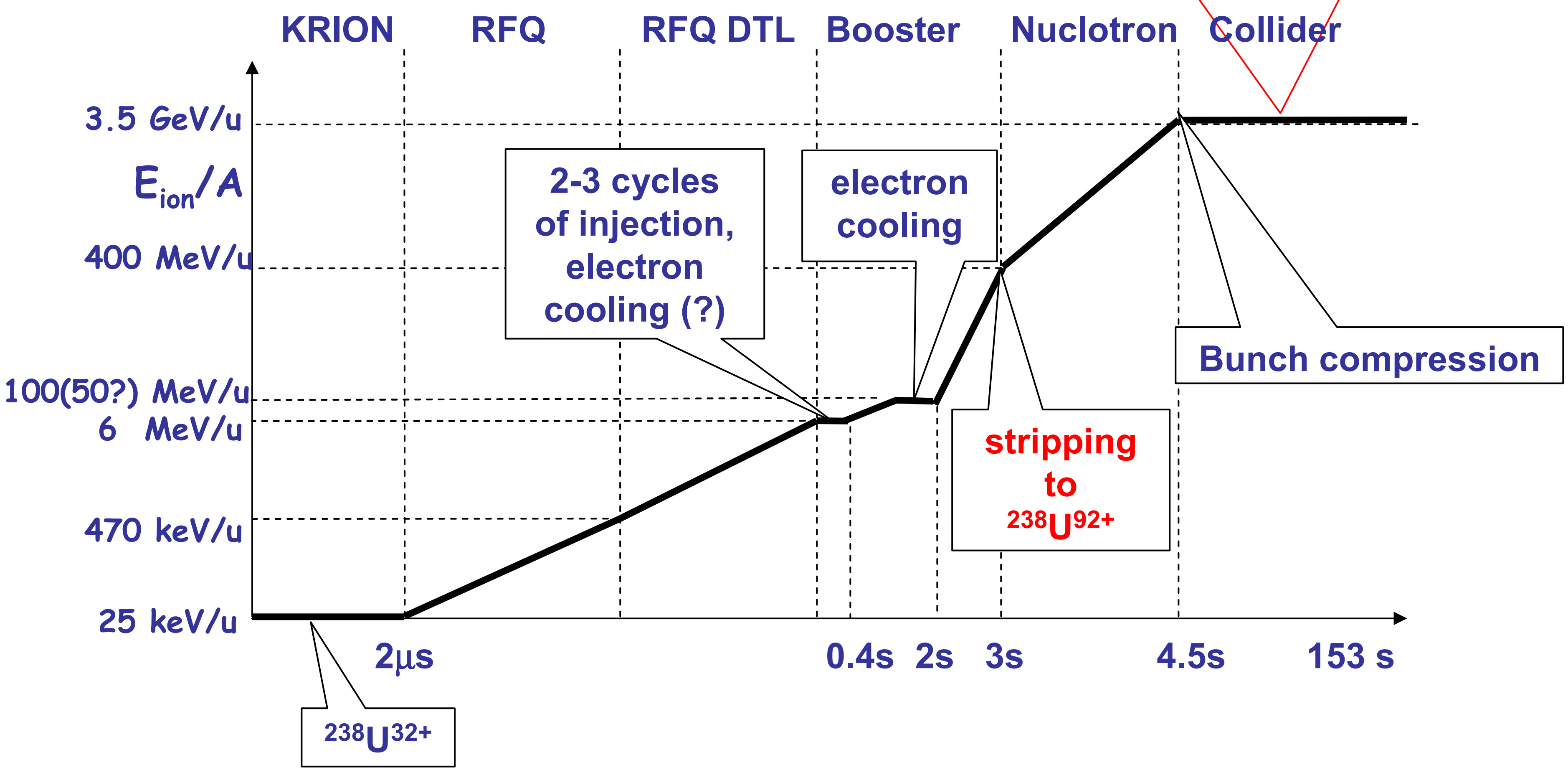
Why two boosters? ⇒ complete stripping to get max energy in Nuclotron!



Bunch compression ("overturn" in phase space)

34 injection cycles of $1 \cdot 10^9$ ions $^{238}U^{92+}$ per cycle
$1.7 \cdot 10^{10}$ ions/ring

Time Table of The Storage Process



O.Kozlov
I.Meshkov
A.Smirnov
A.Sidorin

2.2. Ионный коллайдер

General Parameters

Ring circumference, [m]	251.0
Bρ max [T·m]	44.0
Ion kinetic energy (U92+), [GeV/u]	1.0 ÷ 4.36
Dipole field (max), [T]	4.0
Quad gradient (max), [T/m]	29.0
Number of dipoles / length	24 / 2.8 m
Number of vertical dipoles per ring	2 x 4
Number of quads / length	32 / 0.4 m
Long straight sections: number / length	2 x 48.0 m
Short straight sections: number / length,	4 x 7.2 m

2.2. Ионный коллайдер

General parameters (Contnd)

βx_max / βy_max in FODO period, m	20 / 17
Dx_max / Dy_max in FODO period, m	6.1 / 0.1
βx_min / βy_min in IP, m	0.5 / 0.5
Dx / Dy in IP, m	0.0 / 0.0
Free space at IP (for detector)	8 m
Beam crossing angle at IP	0 !
Betatron tunes Qx / Qy	5.5 / 5.2
Chromaticity Q'x / Q'y	-12.4 / -12.2
Transition energy, γ_tr / E_tr	5.0 / 4 GeV/u
RF system harmonics amplitude, [kV]	70 100
Vacuum, [pTorr]	100 ÷ 10

2.2. Ионный коллайдер

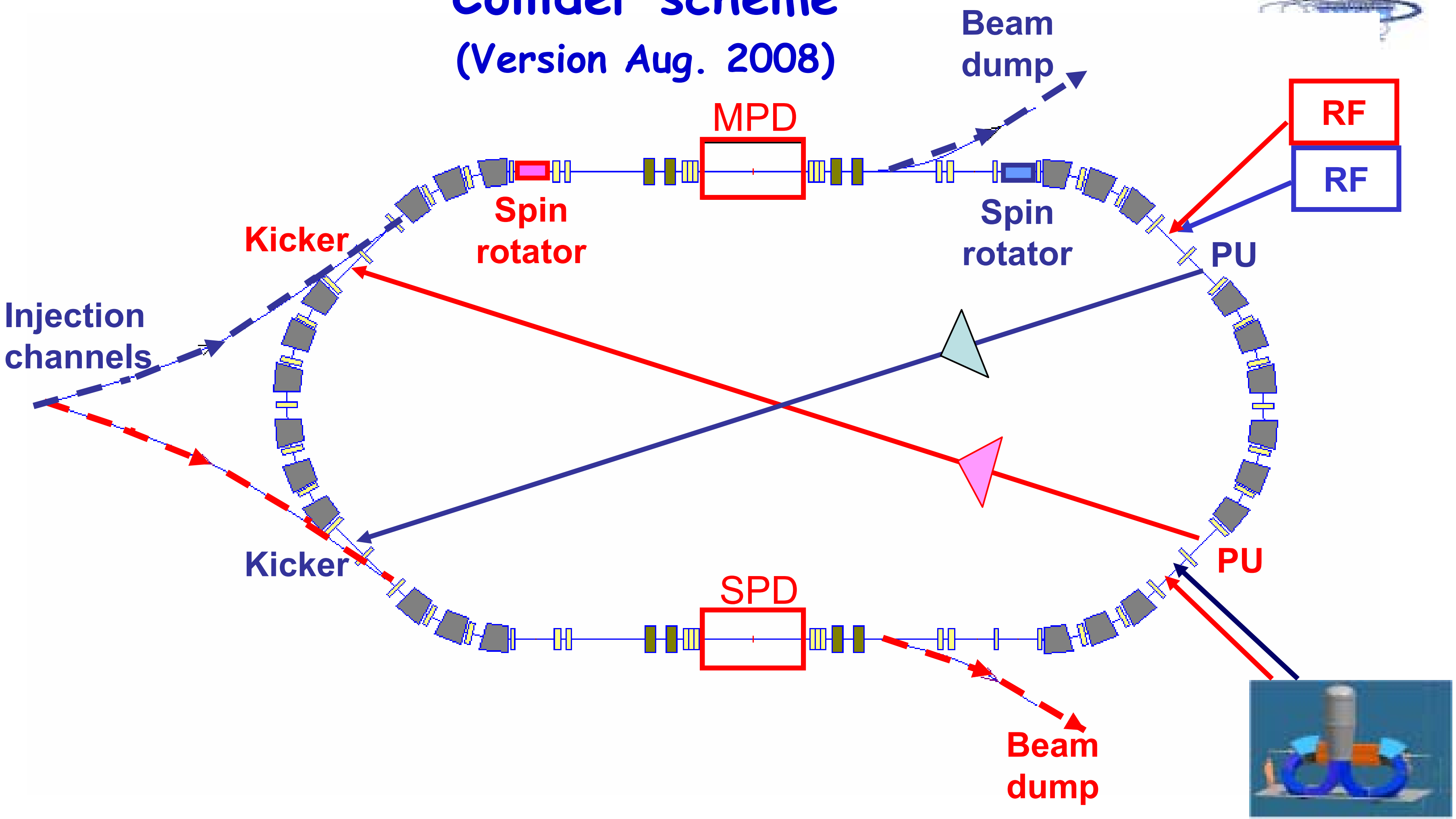
Collider beam parameters and luminosity

Energy, GeV/u	1.0	3.5
Ion number per bunch	1E9	1E9
Number of bunches per ring	17	17
Rms unnormolized beam emittance, π·mm mrad	3.8	0.3
Rms momentum spread	1E-3	1E-3
Rms bunch length, m	0.3	0.3
Luminosity per one IP, $cm^{-2}\cdot s^{-1}$	**0.75E26**	**1.1E27**
Incoherent tune shift ΔQ_{bet}	0.056	0.047
Beam-beam parameter ξ	0.0026	0.02
Luminosity "life time" limited by IBS, s	**650**	**50**

2.2. Ионный коллайдер

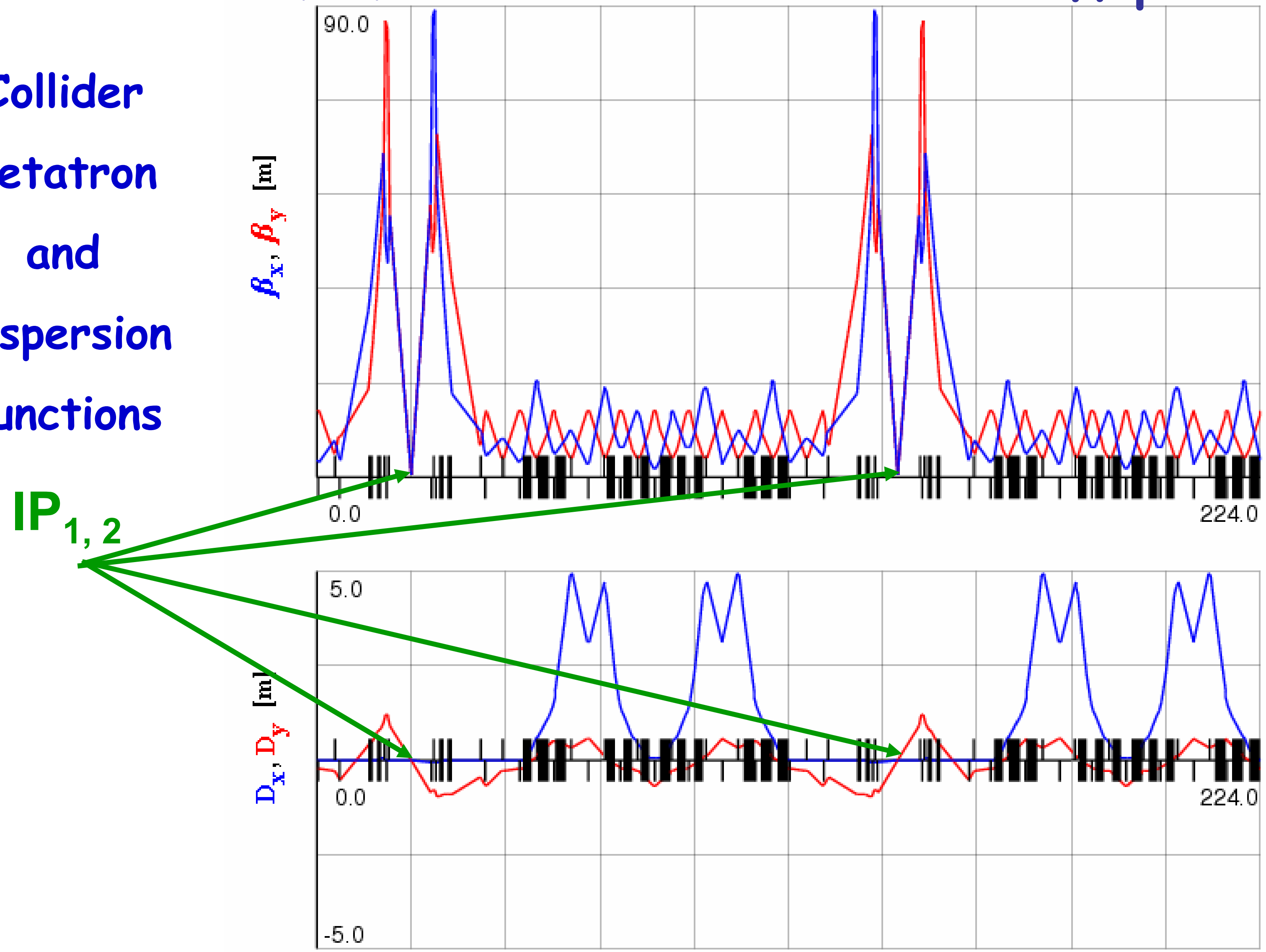
Collider scheme

(Version Aug. 2008)



2.2. Ионный коллайдер

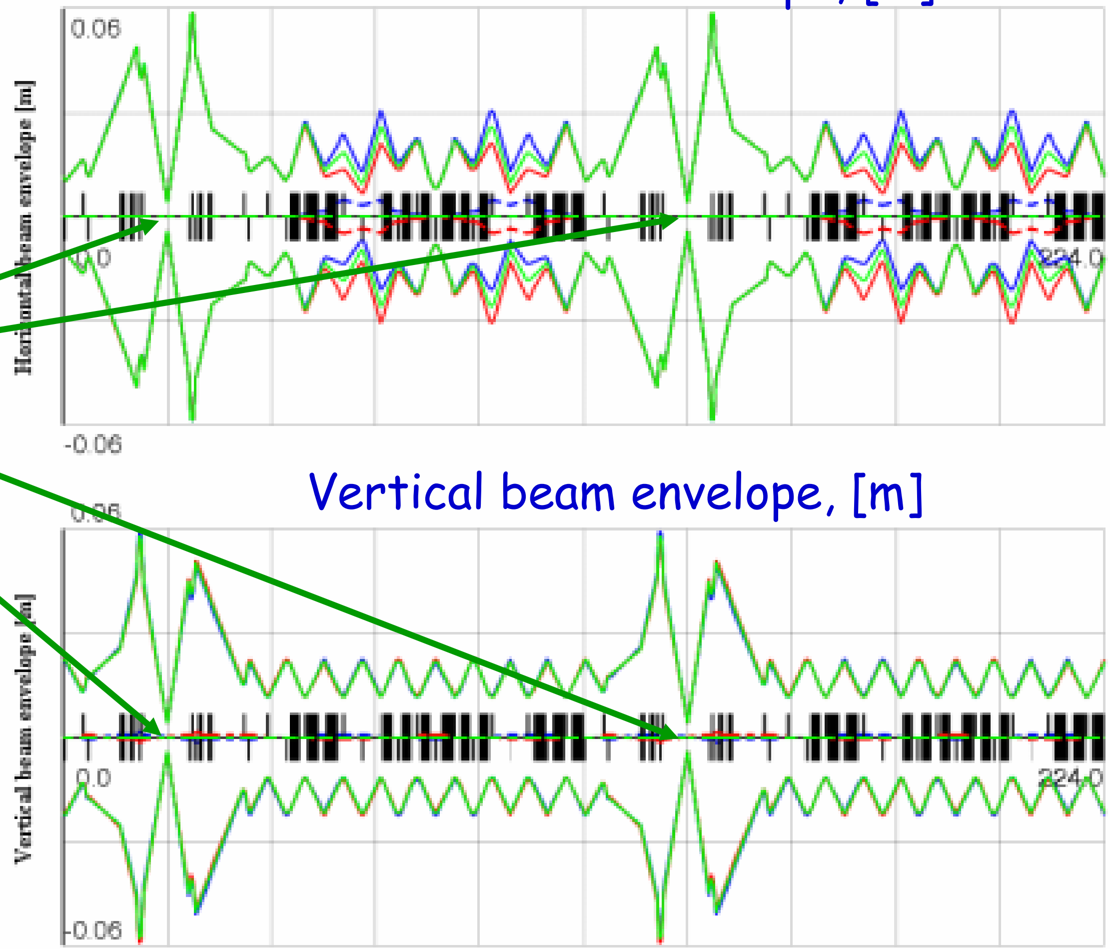
Collider Betatron and Dispersion Functions



2.2. Ионный коллайдер

Beam envelopes

IP$_{1,2}$



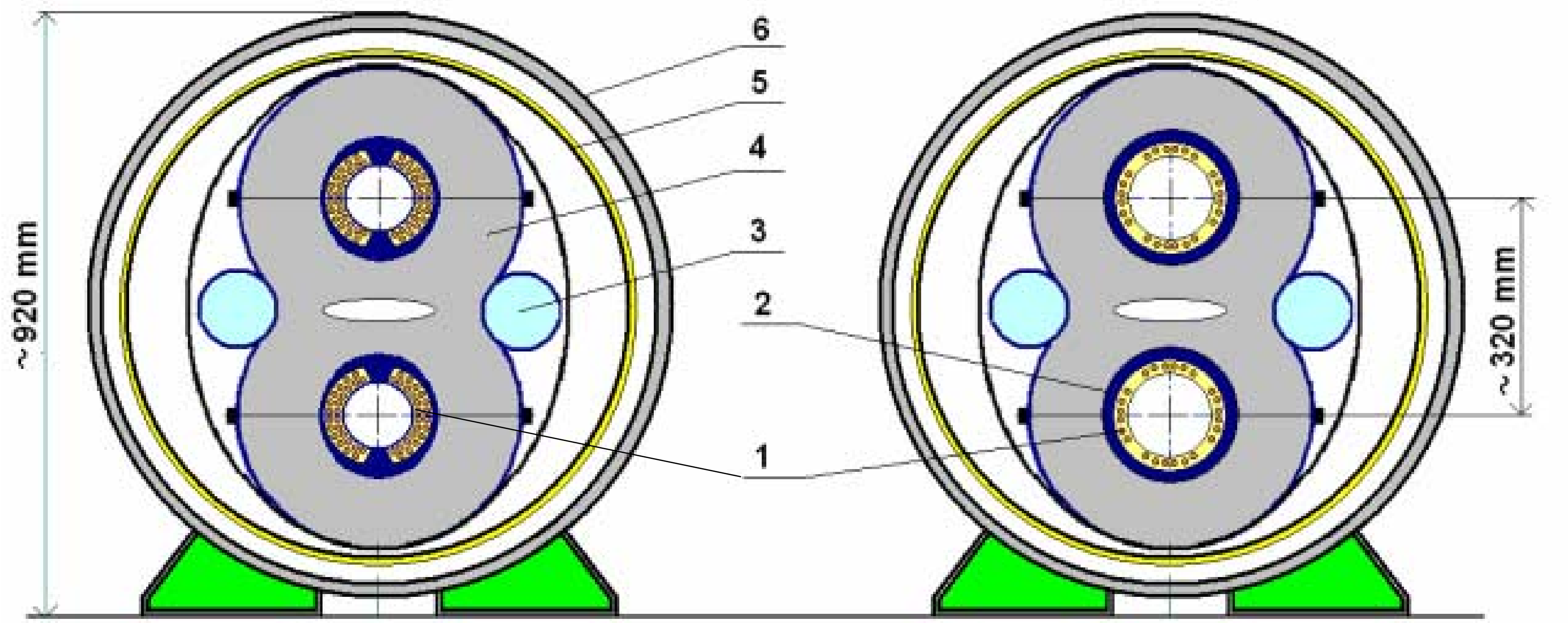
The momentum deviation $\Delta p/p = 0$ (green), 0.001(red), +0.001 (blue)

2.2. Ионный коллайдер

A.Kovalenko
G.Khodjibagiyan

“Twin magnets for NICA collider rings

“Twin” dipoles   “Twin” quadrupoles



1 – Cosθ coils, 2 – “collars”, 3 – He header, 4 – iron yoke,

5 – thermoshield, 6 – outer jacket

2.2. Ионный коллайдер

A.Eliseev
I.Meshkov
A.Smirnov
A.Sidorin

Collider Luminosity

Collider beam bunch length

σ_{bunch} = 33 cm

How to get it?

2.2. Ионный коллайдер

Collider beam bunch length

The scenario of the short bunch formation:

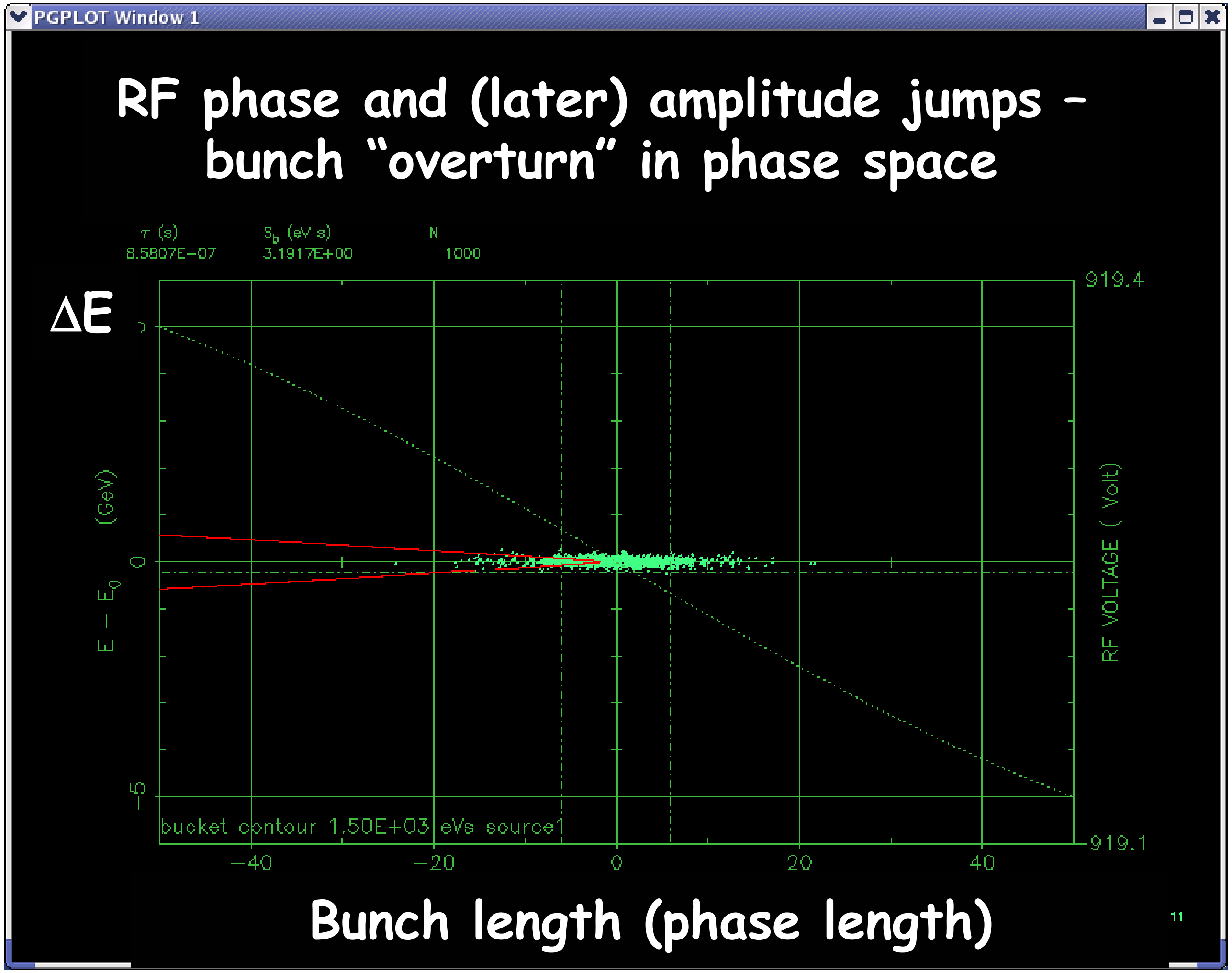
1) from injector ⇒ to booster, electron cooling, adiabatic capture at acceleration,

2) from booster ⇒ to Nuclotron, adiabatic capture at acceleration,

3) RF phase jump and "overtun" in phase space by "fast" increase of RF voltage,

4) short bunch from Nuclotron ⇒ to collider.

2.2. Ионный коллайдер



Collider Luminosity

How to keep it?

IBS Heating & electron/stochastic cooling

Intrabeam scattering (IBS) characteristic time:

$$\tau_{IBS} \propto \frac{A^2}{Z^4} \cdot \beta^4 \cdot \gamma^5 \cdot \varepsilon_x \cdot \varepsilon_y \cdot (\Delta p / p) \cdot \left(\frac{\sigma_s}{N_{bunch}} \right) \cdot f(\sigma_x, \sigma_y, \sigma_s, lattice\ \ functions)$$

For NICA: 17 bunches x 10E9 $^{238}U^{92+}$ ions at σ_s = 0.3 m, etc.,…

τ_{IBS} ~ 20 – 50 s

Electron cooling: 2.4 MeV x 1.0 A $\Rightarrow \tau_{ecool} \approx$ 25 s $\Rightarrow$ complicated!

Stochastic cooling: ΔW = 3 GHz $\Rightarrow \tau_{scool} \approx$ 1000 s $\Rightarrow$ not sufficient!

2.2. Ионный коллайдер

Collider Luminosity: How to keep it

Electron cooling: 2.4 MeV x 1.0 A ⇒ $\tau_{ecool} \approx$ 25 s

Electron cooling ⇒ parameters and problems:

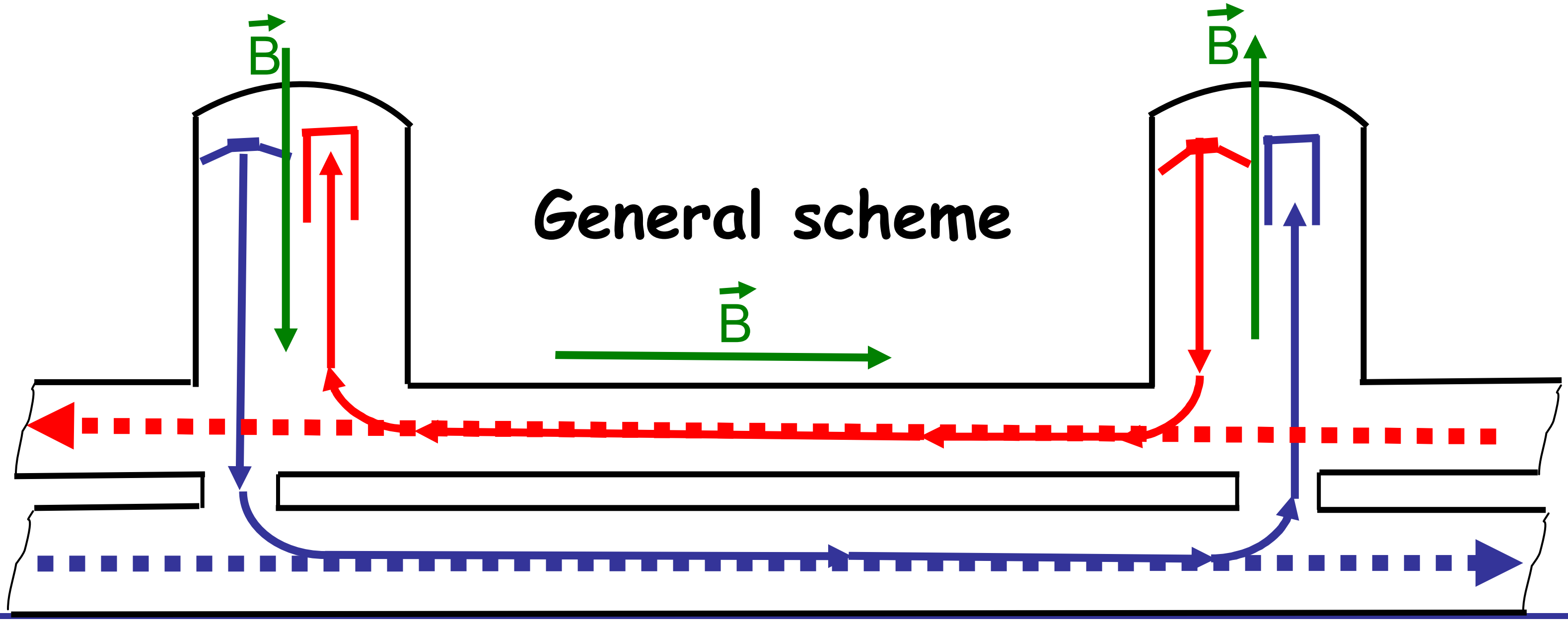
Electron beam 2.4 MeV x 1 A

ion recombination ⇒ hollow electron beam?

HV power supply

SC solenoid + “hot” electron collector

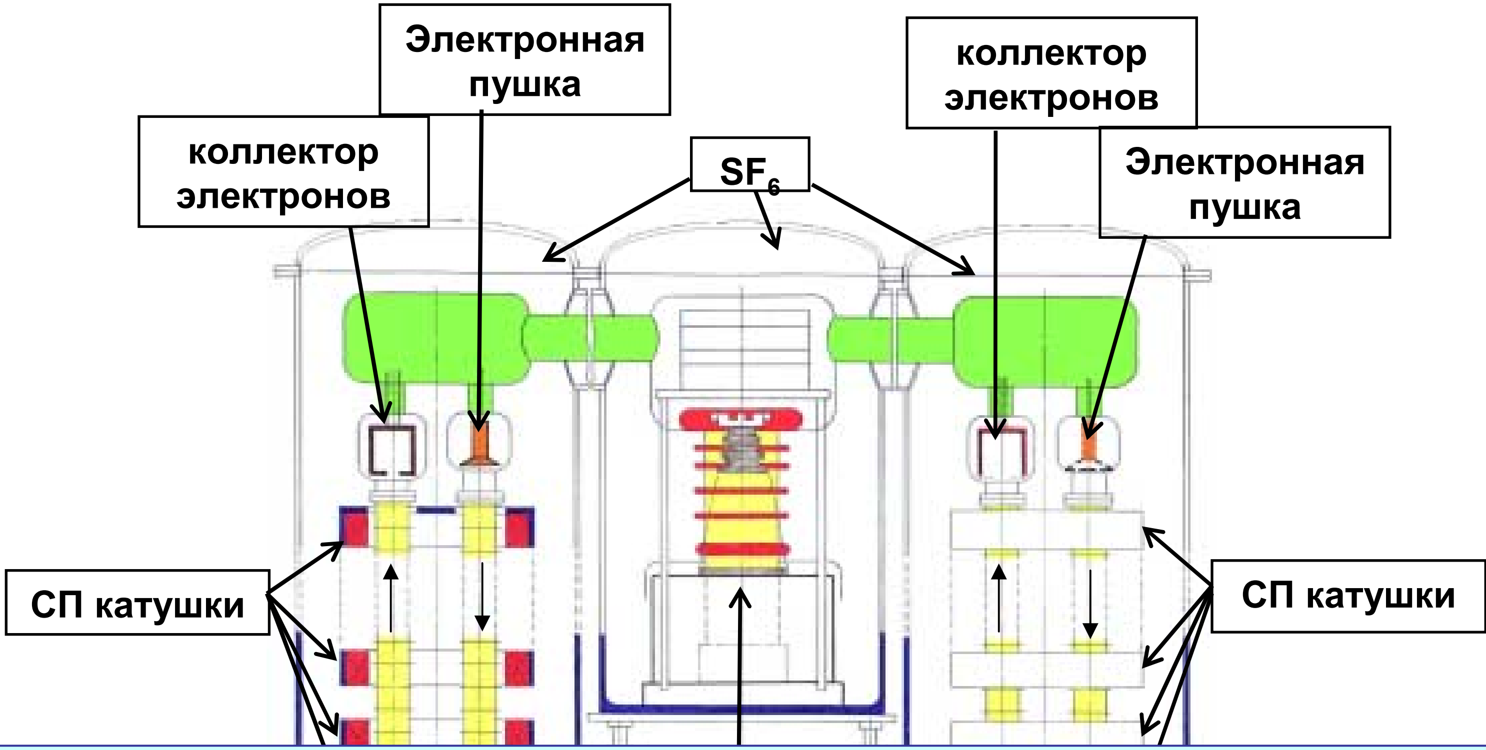
V.Bykovsky
I.Meshkov
A.Smirnov



2.2. Ионный коллайдер

Collider Luminosity: How to keep it

Electron cooling: 2.4 MeV x 1.0 A $\Rightarrow \tau_{ecool} \approx 25$ s



Collaboraton with All-Russian Institute
for Electrotechnique (ВЭИ) has been started

1

2. NICA/MPD: Концепция-1

2.3. Элементы комплекса: инжектор

Injector concept

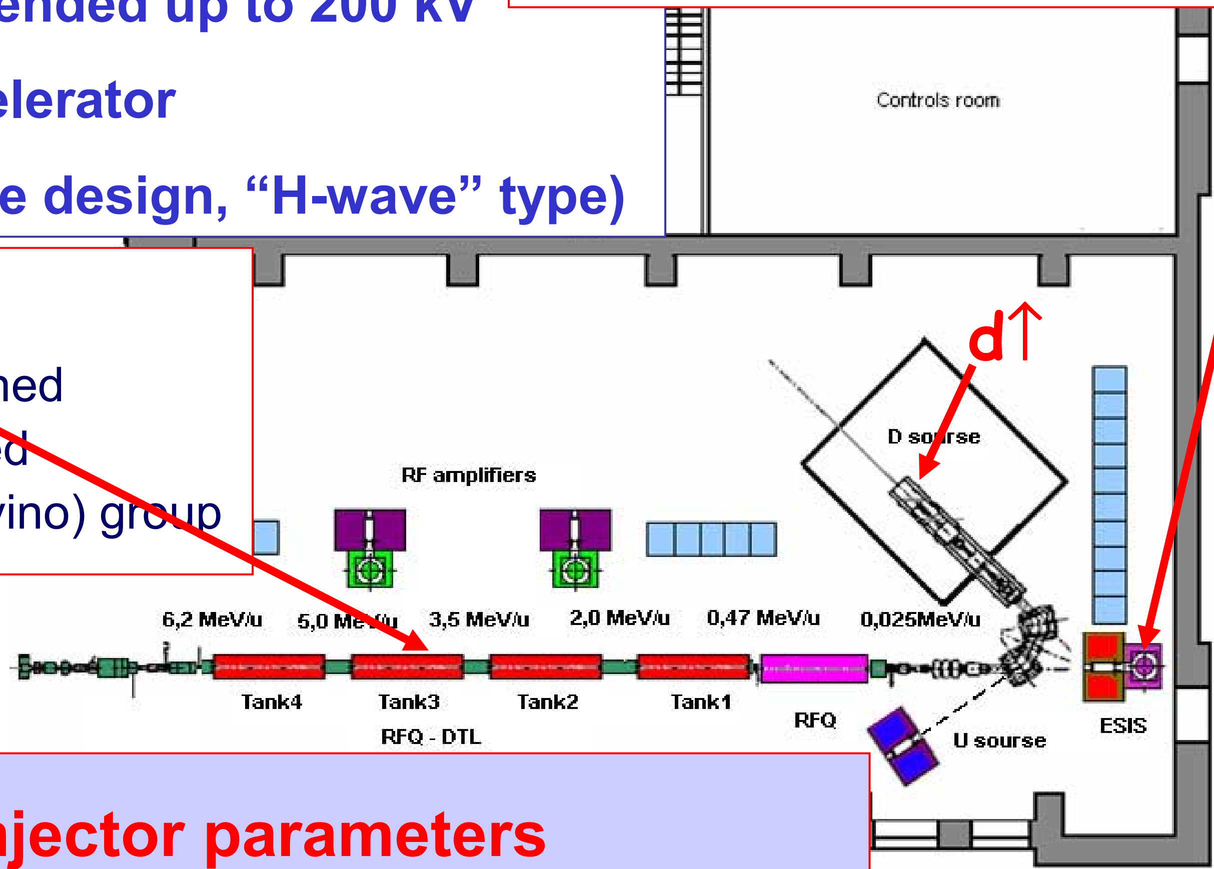
KRION suspended up to 200 kV

RFQ preaccelerator

Linac (unique design, “H-wave” type)

EBIS ⇒ ESIS ⇒ KRION

Linac
Is being designed
and constructed
by IHEP (Protvino) group



Injector parameters

Ions	d↑ ÷ $^{238}U^{32+}$ (2.5·10E8/pulse)
Energy at exit	6.2 MeV/amu
Length	25 m

2. NICA/MPD: Концепция-1

2.3. Элементы комплекса: инжектор

E.D.Donets
E.E.Donets

Ion Sources comparison

Ion source	KRION, Au^{30+}	ECR, Pb^{27+}
Peak ion current, mA	1.2	0.2
Pulse duration, μs	8	200
Ions per pulse	2×10^{9}	1×10^{10}
Ions per μsec	$2.5\text{x}10^{8}$	$5\text{x}10^{7}$
Norm. rms emittance	0.15÷0.3	0.15÷0.3
Repetition rate, Hz	60	30

Multiturn injection?

Crucial parameter: Ions per μsec!
Thus, KRION has very significant advantage!

IHEP O.Belyaev, Yu.Budanov, I.Zvonarev, A.Maltsev

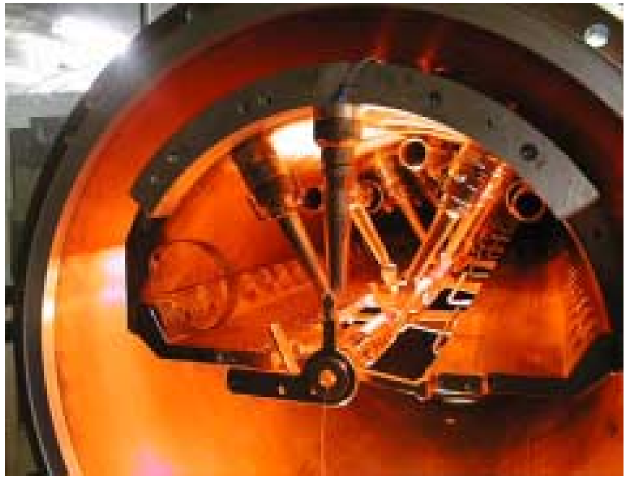
2.3. Элементы комплекса: инжектор

Heavy Ion Linac RFQ + RFQ DTL (IHEP, Protvino)

- ✓ Technical design – in progress in accordance with the schedule;
- ✓ Interim technical design report of the 1st section (RFQ) is completed;

RFQ Electrodes

2H cavities of "Ural" RFQ (prototype)



Sector H-cavity of "Ural" RFQ DTL (prototype)

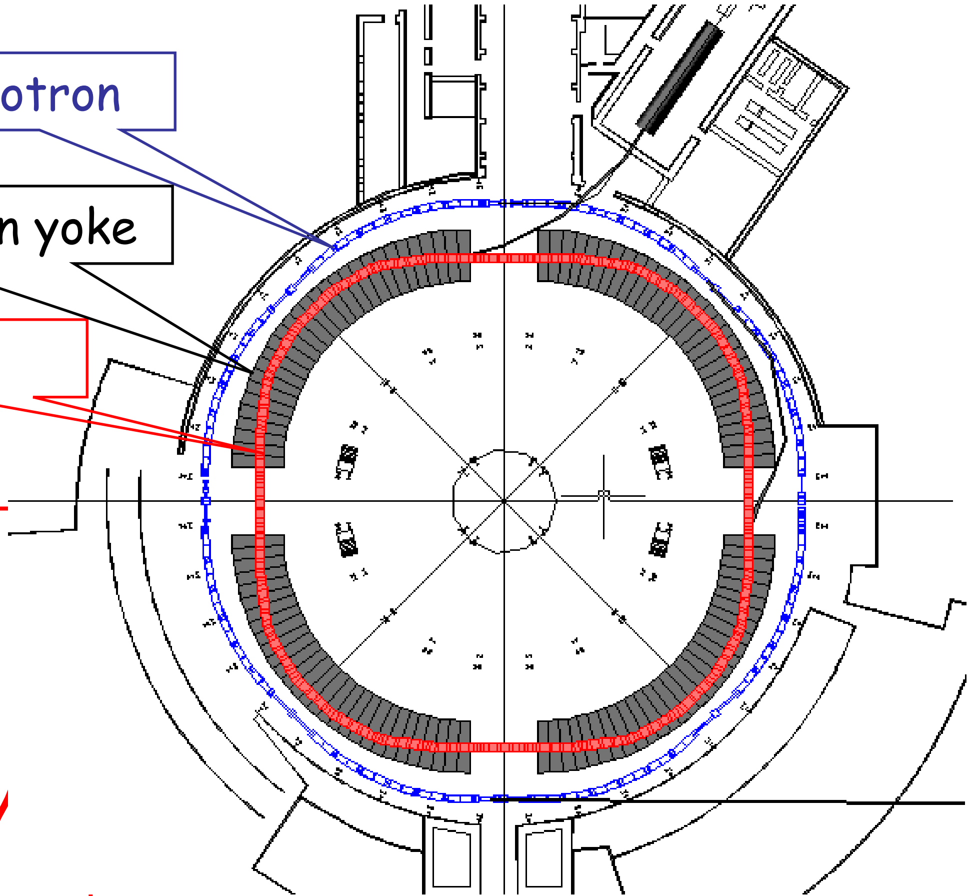
The goal – TDR of the linac & working drawings ⇒
⇒ December 2009

2. NICA/MPD: Концепция-1

2.3. Элементы комплекса: Бустер

Superconducting Booster in the magnet yoke of The Synchrophasotron

A.Butenko
O.Kozlov
V.Mikhailov



$B\rho$ = 25 T·m, B_{max} = 1.8 T

1) 3 single-turn injections
2) Storage and electron cooling of 8×10^9 $^{238}U^{32+}$
3) Acceleration up to 440 MeV/
4) Extraction & stripping

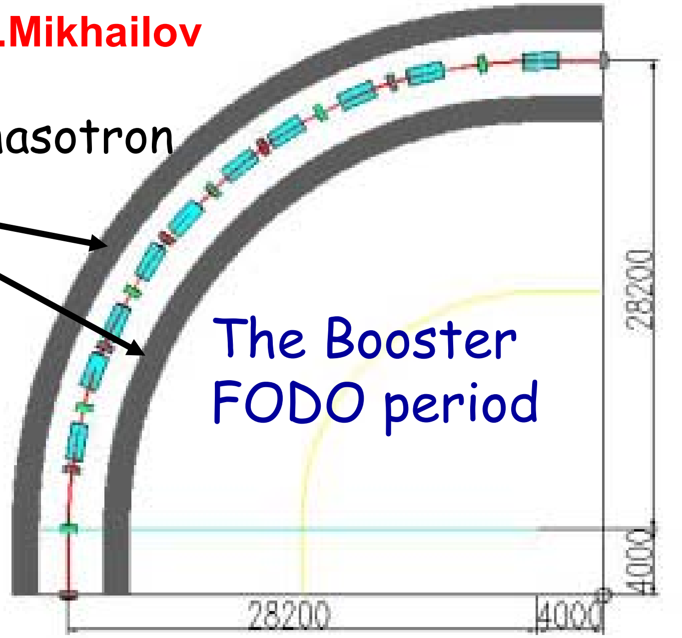
2.3. Элементы комплекса: Бустер

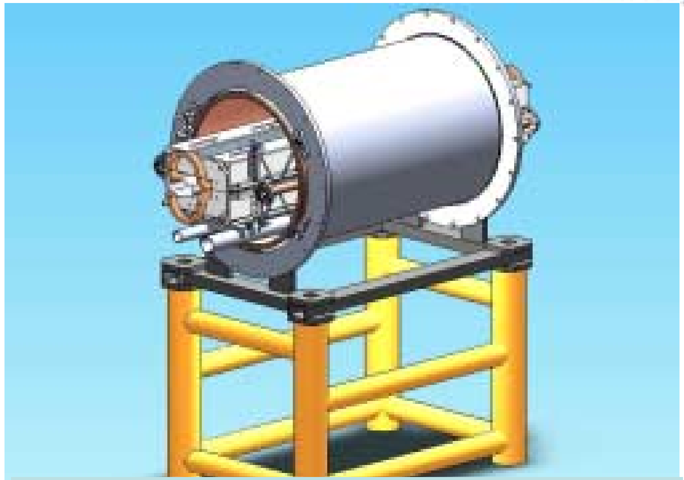
The Booster Location in “The Belly” of The Synchrophasotron

2.3. Элементы комплекса: Бустер

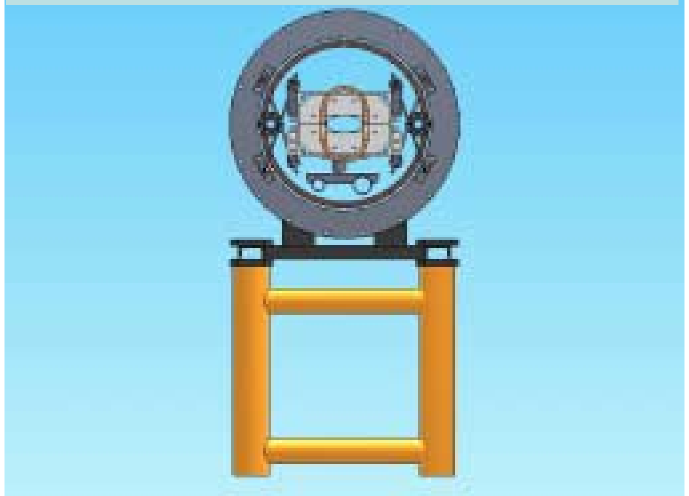
SC dipoles – “Nuclotron/SIS-100 type”

A.Butenko
O.Kozlov
V.Mikhailov





A.Kovalenko, G.Khodjibagiyan



Status: technical project in progress

Working drawings ⇒ during 2009÷2010

Beginning of manufacturing ⇒ 2010

2.3. Элементы комплекса: Бустер

Budker INP G.Kurkin et al.
JINR V.Kobets, A.Sidorin

RF System

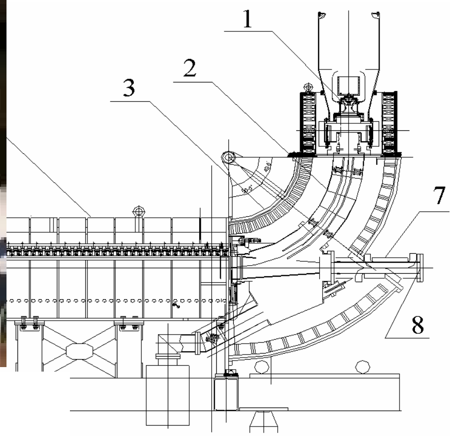
RF system of Cooler Storage Ring of Heavy Ion Research Facility in Lanzhou (HIRFL) – analog of The RF system for The Booster of NICA.

Technical Report of RF System has been completed by the group of Budker INP in September 2008:
2 RF stations by Rubles 12.5 M each one,
1.5 years for manufacturing

V.Bykovsky, A.Kobets, I.Meshkov, A.Rudakov, A.Smirnov

Booster Electron Cooler

Reconstruction of The El_Cooler Test Bench was started at DLNP.



The prototype: Electron Cooler EC-35 (Budker INP)
1 – electron gun, 2 – electrostatic plates for compensation of centrifugal drift, 3 – toroidal solenoid, 4 – straight solenoids, 5 – magnetic shield, 6 – collector, 7 – ion beam orbit magnetic correctors, 8 – ion beam channel

The JINR concept: the electron cooler with superconducting magnetic system

Status: technical project in progress

Working drawings ⇒ end of 2009

Beginning of manufacturing ⇒ 2010

2. NICA/MPD: Концепция-1

2.3. Элементы комплекса: Нуклотрон (бустер-2)

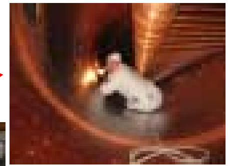
6 GeV/u SC synchrotron based on unique fast-cycling superferric magnets, was designed and constructed at JINR for five years (1987-1992) and put into operation in March 1993.

Alexander M.Baldin

Nuclotron Parameters

Parameter	3.0 GeV/u for 238U92+	Status (March 2008)
1. Circumference, m	251.5	
2. Maximum B-field, T	2.05	1.5
3. Max. magn. rigidity, T·m	45	33
4. Cycle duration, s	2.0	5.0
5. B-field ramp, T/s	2.0	1.0
6. Accelerated particles	p–U, p↑, d↑	p-Fe, d↑
7. Max. energy, GeV/u	12.6(p), 4.36($^{238}U^{92+}$)	4.1(d),
6. Intensity, ions/cycle	$1\cdot10^{11}$(p), $1\cdot10^{9}$(A/Z = 2)	$1\cdot10^{11}$(p), $1\cdot10^{6}$(Fe^{24+}) $2\cdot10^{8}$(d↑)

Нуклотрон: программа реанимации



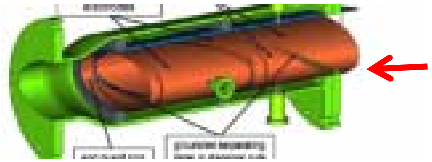
Ведётся модернизация

✓комплекса ЛУ-20

✓вакуумной системы

✓ВЧ системы

✓Система медленного вывода пучка



✓систем контроля и управления, диагностики

✓систем питания ускорительного комплекса

✓системы криогенного обеспечения

✓Каналы вывода, рад.безопасность

✓восстановление геодезической сети Нуклотрона

2.3. Элементы комплекса: Нуклотрон (бустер-2)

Начальник УО ЛФВЭ
Г.В.Трубников

Нуклотрон:

Программа Реанимации

Гл. инженер
Нуклотрона
А.В.Бутенко

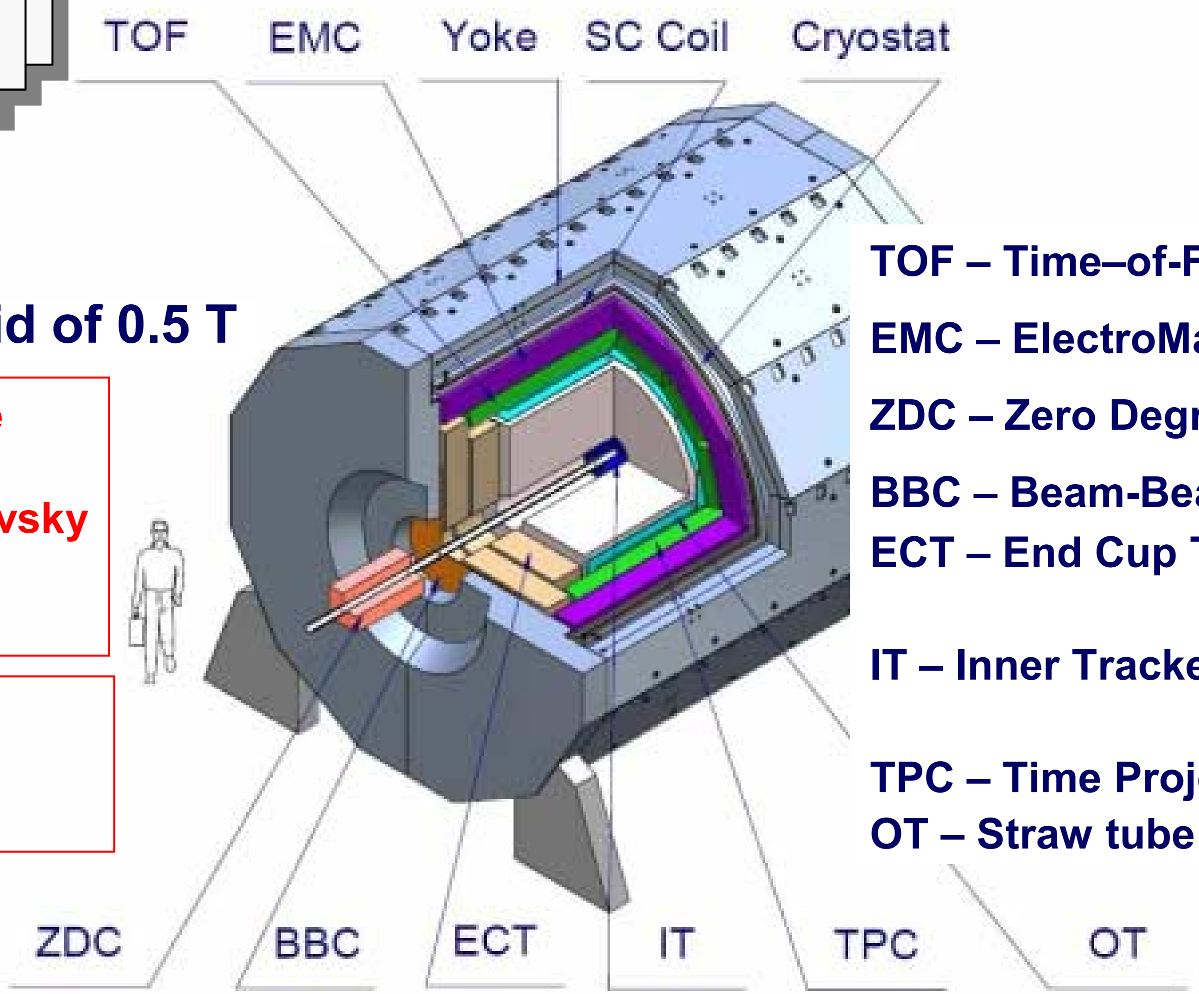
Начаты, совместно с ИЯИ РАН, работы по созданию нового источника поляризованных частиц

2009

Сеанс № 39 - февраль, 400-900 часов

Сеанс № 40 - октябрь-ноябрь, 400-900 часов

3. Многоцелевой детектор
MultiPurpose Detector (MPD)



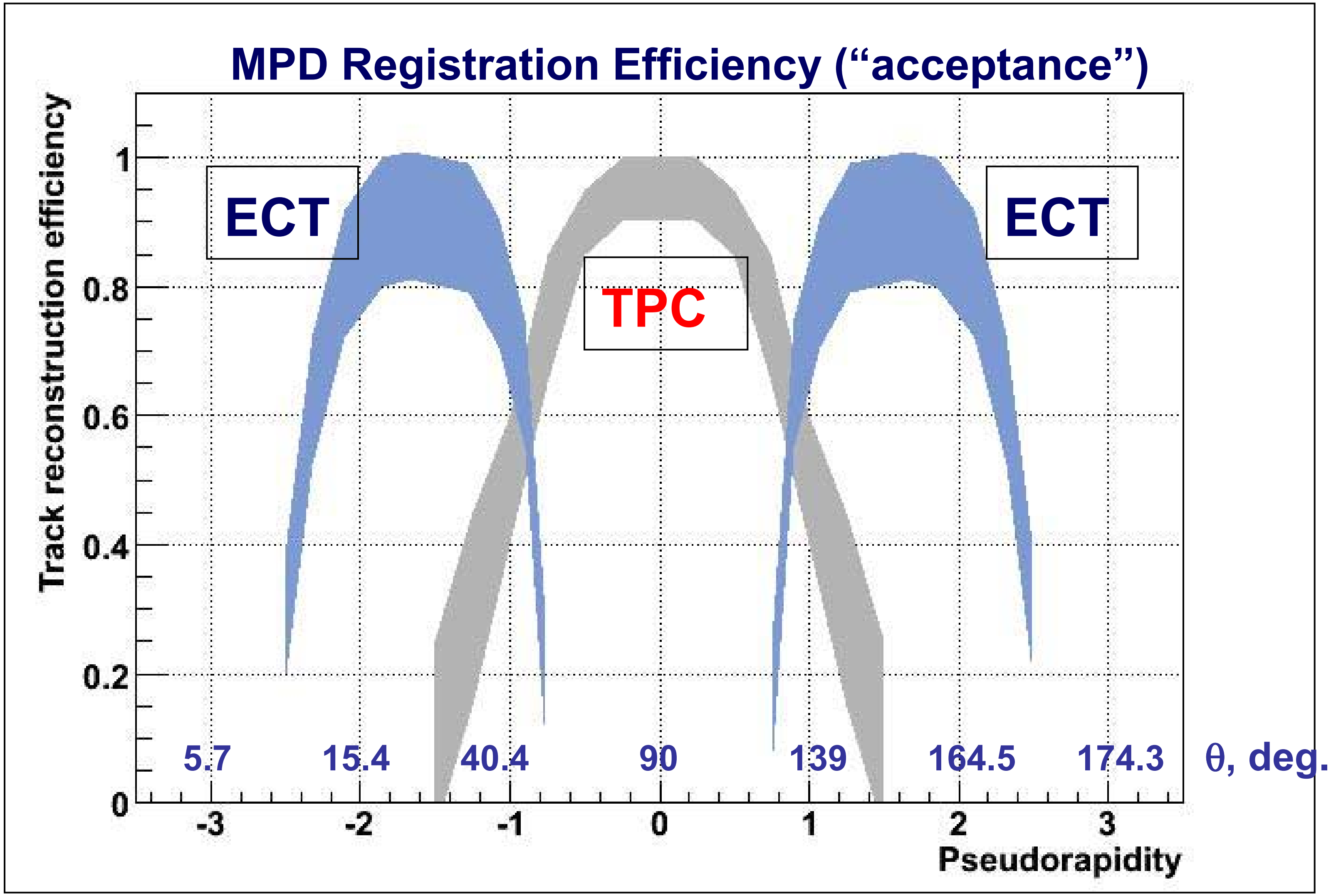
SC solenoid of 0.5 T

V.Kekelidze
V.Nikitin
O.Rogochevsky
A.Sorin
et al.

A.Kurepin
et al.,
INR RAS

TOF – Time–of-Flight detector
EMC – ElectroMagnetic Calorimeter
ZDC – Zero Degree Calorimeter
BBC – Beam-Beam Counter
ECT – End Cup Tracker (“straw tubes”)
IT – Inner Tracker (silicon strip detector)
TPC – Time Projection Chambers
OT – Straw tube Overlap Tracker

3. Многоцелевой детектор (MPD)



MPD characteristics

For the transversal momentum measurements by TPC **the solenoid magnetic field** has to have **the homogeneity $B_r/B_z < 10^{-4}$.**

The proposed design provides a field for the charged particles momentum measurements in the region of

$|\eta| \geq 1.0$ ($\theta = 90^0 \pm 40^0$) in homogeneous solenoidal field.

The field is to be formed by a yoke with a small holes in endcaps. The size of the holes is defined by ZDC acceptance.

4. Концепция-2

4.1. Коллайдер со стохастическим охлаждением

IBS characteristic time

$$\tau_{IBS} \propto \frac{A^2}{Z^4} \cdot \beta^4 \cdot \gamma^5 \cdot \varepsilon_x \cdot \varepsilon_y \cdot (\Delta p / p) \cdot \left(\frac{\sigma_s}{N_{bunch}} \right) \cdot f(\sigma_x, \sigma_y, \sigma_s, lattice\ \ functions)$$

$$\tau_{IBS} \propto \frac{\sigma_s}{N_{bunch}}$$

Characteristic time of bunched beam stochastic cooling

$$\tau_{SCBB} \approx \frac{20 \cdot N_{bunch}}{W} \cdot \frac{C_{Ring}}{3\sigma_s} \longrightarrow \tau_{SCBB} \propto \frac{N_{bunch}}{\sigma_s}$$

Thus, a decrease of N_{bunch}/σ_s both increase τ_{IBS} and decrease τ_{SCBB}

How to decrease keeping luminosity at the same level?

4. Концепция-2

4.1. Коллайдер со стохастическим охлаждением

The idea (T.Katayama, A.Sidorin, 2008):

How to decrease N_{bunch}/σ_s keeping luminosity at the same level?

$$L = \frac{n_{bunch} N_{bunch}^2}{4\pi\sqrt{\varepsilon_x \varepsilon_y} \cdot \beta_{min}} \cdot \frac{\ell_{coll}}{\sigma_s} \cdot f_{rev}$$

"The remedy" ⇒ an increase of σ_s and n_{bunch} that decreases N_{bunch}/σ_s .

It leads to decrease of intrabunch space ⇒

⇒ an increase of beam-beam effect!

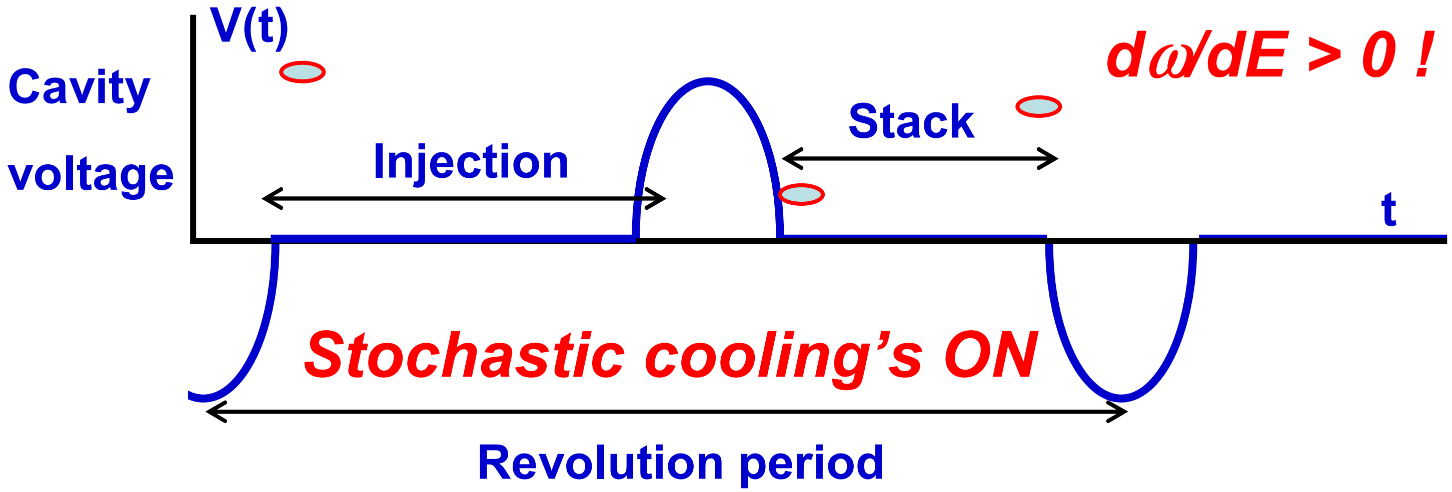
To avoid it one needs to have beam crossing angle at IP !

4. Концепция-2

4.1. Коллайдер со стохастическим охлаждением

A decrease of intrabunch space ⇒ injection (ion storage) problem !

The next "remedy" ⇒ *"barrier bucket"* method



The method was tested experimentally at ESR (GSI) with electron cooling (2008).

4. Концепция-2

4.2. Схема накопления ионов в коллайдере

The concept scenario:

1) From KRION up to Nuclotron exit – the same procedure,

no bunch compression in Nuclotron is necessary now!

2) Stacking in collider rings;

3) Adiabatic bunching, collision synchronization, beginning of experiment;

4) **After luminosity decrease:** RF OFF ⇒ debunching ⇒

⇒ Barrier Bucket RF ON ⇒ stacking by the procedure 1-3.

4. Концепция-2

4.3. Достоинства и недостатки схемы

The advantages:

1) Stochastic cooling is sufficient to keep luminosity ⇒

⇒ electron cooling in collider is not necessary anymore (**?**);

2) *No bunch compression in Nuclotron is necessary;*

3) One can "utilize" the beam "remnants" after luminosity decrease ⇒

⇒ increase of the average luminosity (!).

The disadvantages and problems:

1) Beam crossing angle in detector ⇒ loosing of axial symmetry of "the secondary particles", complicated track analyses

2) Some problems for detector design (solenoid shield, …)

3) High repetition fequency of the bunch collisions – detector trigger loading;

4) "Electron clouds" problem

…………………………………………………………………………………………

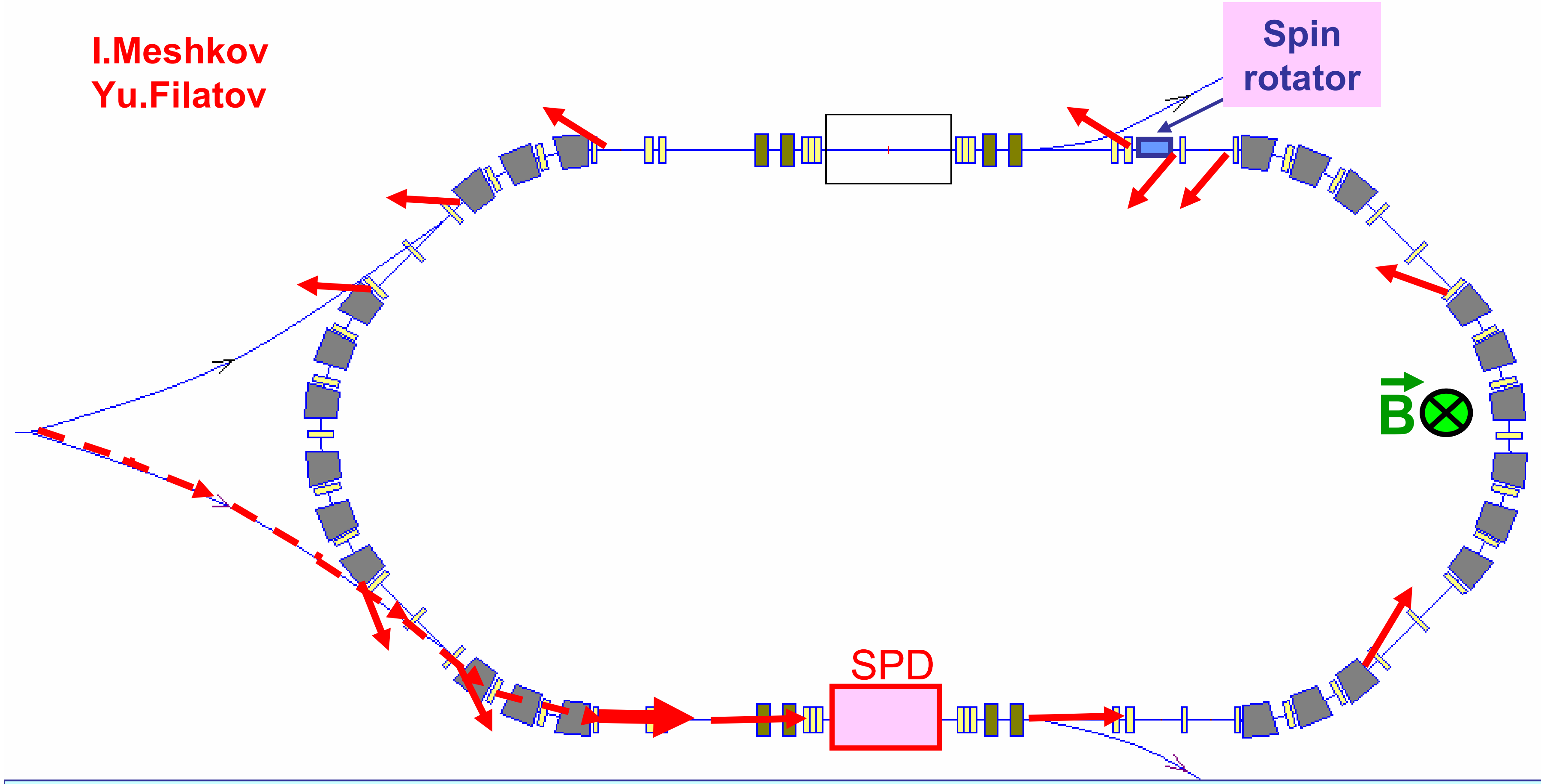
5. Поляризованные пучки в NICA

Polarized proton beams parameters

Energy, GeV	5	12
Proton number per bunch	6E10	1.5E10
Rms relative momentum spread	10E-3	10E-3
Rms bunch length, m	1.7	0.8
Rms (unnormalized) emittance, π·mm·mrad	0.24	0.027
Beta-function in the IP, m	0.5	0.5
Lasslet tune shift	0.0074	0.0033
Beam-beam parameter	0.005	0.005
Number of bunches	10	10
Luminosity, $cm^{-2} \cdot s^{-1}$	1.1E30	1.1E30

5. Поляризованные пучки в NICA

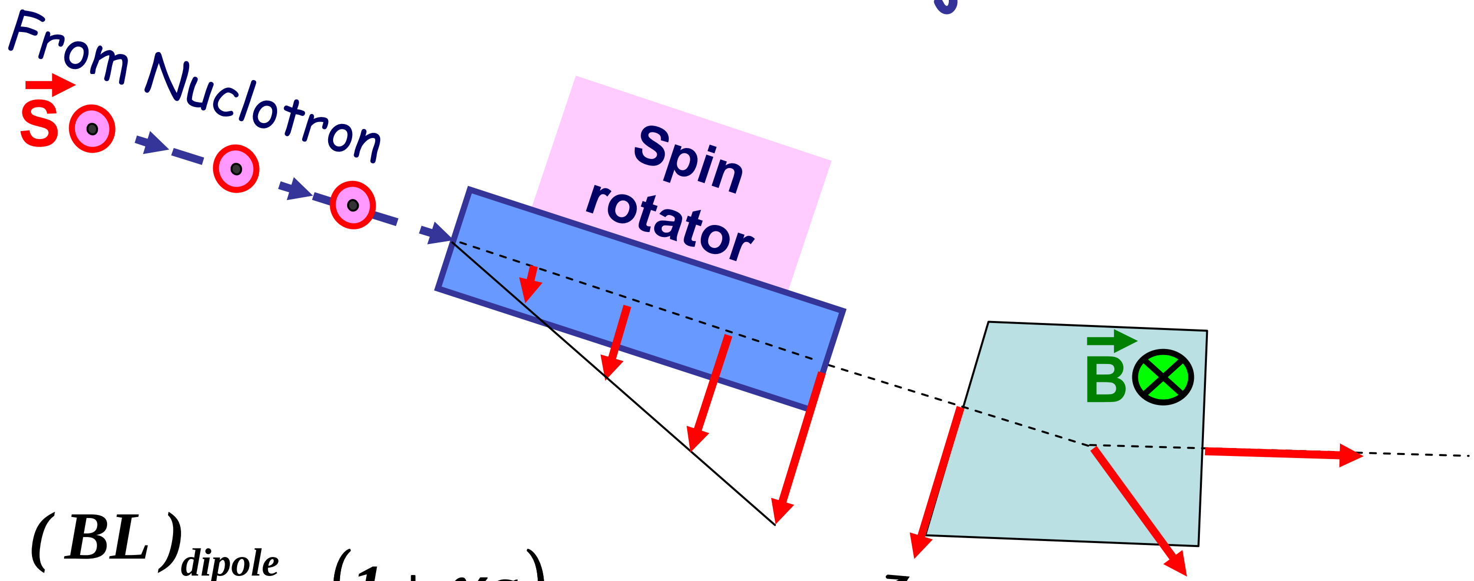
I.Meshkov
Yu.Filatov



Protons, $1 \le E \le 12$ GeV $\Rightarrow$ $(BL)_{solenoid} \le 50$ T·m

Deuterons, $1 \le E \le 5$ GeV/u $\Rightarrow$ $(BL)_{solenoid} \le 140$ T·m

Polarized beams ⇒ injection



$$\alpha_\perp = \frac{(BL)_{dipole}}{(B\rho)_{ion}} \cdot (1+\gamma a)$$

$\alpha_\perp \sim 90^0$

Protons, $1 \le E \le 12$ GeV ⇒ $(BL)_{dipole} \le 3$ T·m

Deuterons, $1 \le E \le 5$ GeV/u ⇒ $(BL)_{dipole} \le 5.8$ T·m

6. Этапы проекта

- **Stage I** *(2008-2010)* — ***Nuclotron-M subproject** and infrastructure development*
  - ***R&D programs***
  - ***Technical Design Reports on NICA and MPD***

Beginning of The Experiments –

2013 - 2014 г.

- **Stage III** *(2010-2012)* — ***Construction and assembling of NICA & MPD***

- **Stage IV** *(2013-2014)* — ***NICA commissioning, MPD start-up***

7. Коллаборация NICA & MPD

Budker INP

- ✓ Booster RF system
- ✓ Booster electron cooling
- ✓ Collider RF system
- ✓ Collider SC magnets (expertise)
- ✓ HV electron cooler for collider
- ✓ Electronics (?)

IHEP (Protvino)

Injector Linac

FZ Jűlich (IKP)

HV Electron cooler

Stoch. cooling

Fermilab

HV Electron cooler

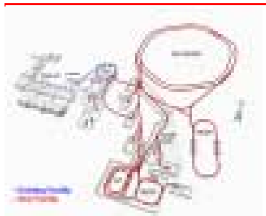
Stoch. cooling

All-Russian Institute for Electrotechnique

HV Electron cooler

BNL (RHIC)

Stoch. Cooling



GSI/FAIR

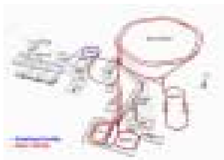
SC dipoles for Booster/SIS-100

SC dipoles for Collider/SIS-300

7. Коллаборация NICA & MPD

MPD collaboration – beginning of formation

- INR Rus. Academy of Sci.(Troitsk)
  - Nuclear Physics Institute of Lomonosov MSU (Moscow)
  - Bogolyubov Institute for Theoretical Physics of NAS (Kiev, Ukraine)
  - Institute of Appl. Phys. of Moldova Ac. of Sci.



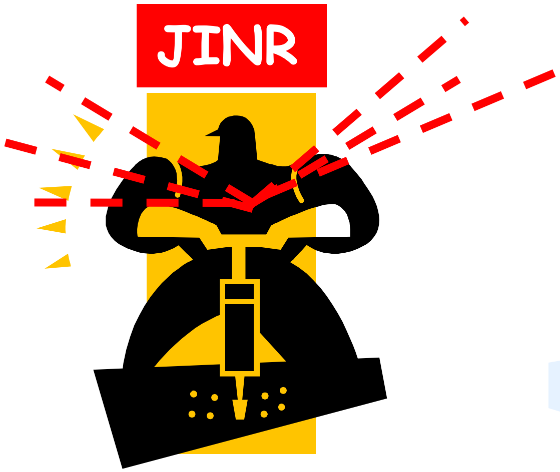
GSI/FAIR –CBM Collaboration

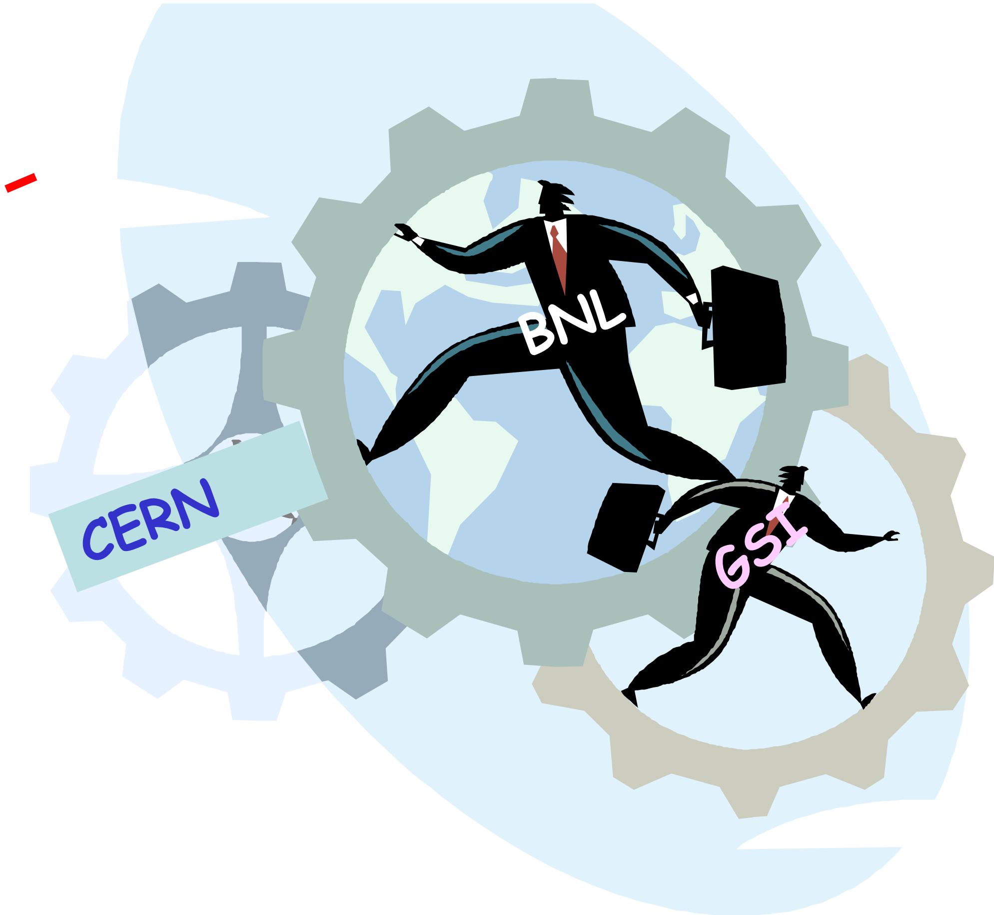
BNL (RHIC)

PHENIX

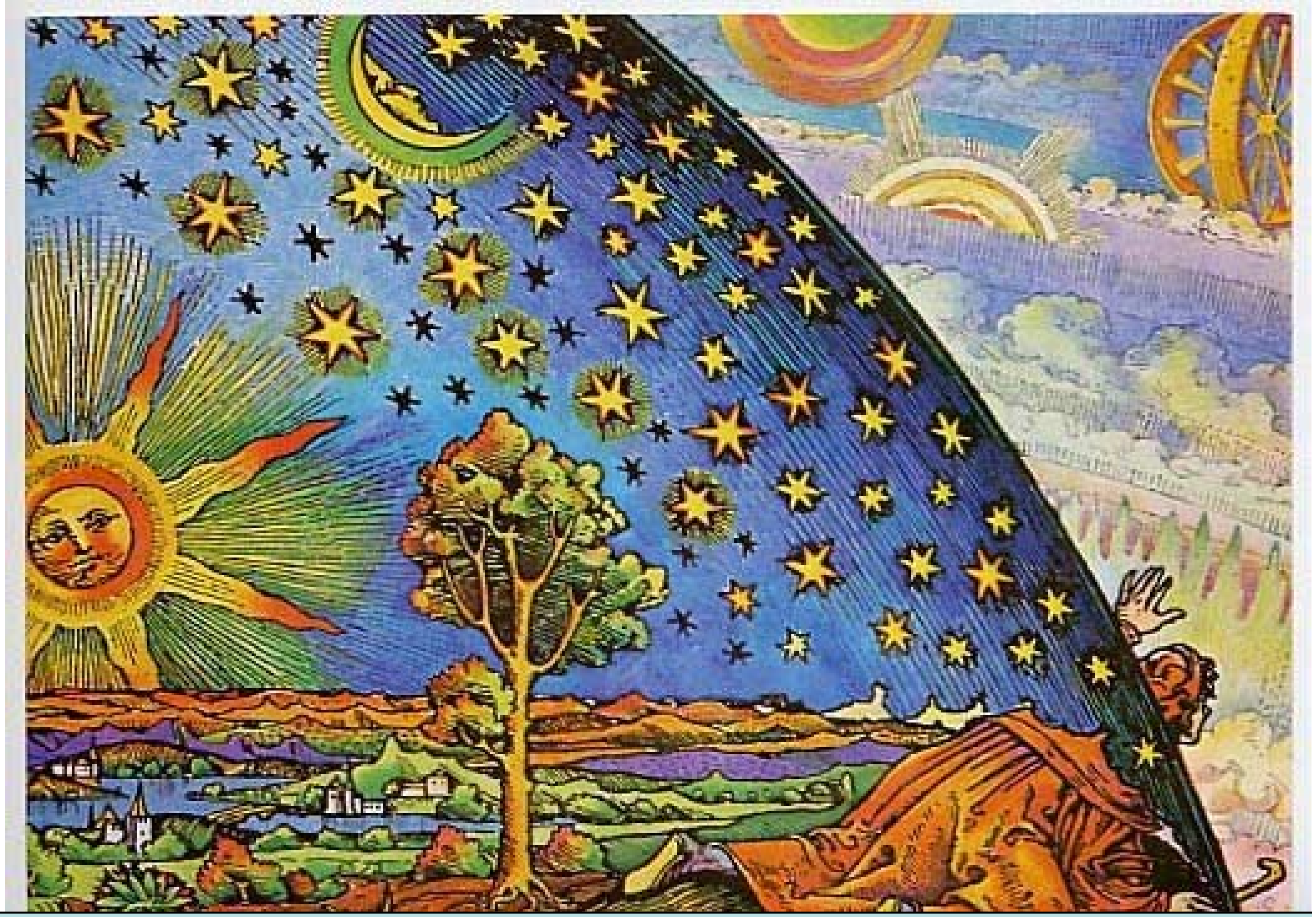
Заключение

“CBM Community” and “home experiments”





Заключение



Спасибо за внимание!