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JOINT INSTITUTE FOR NUCLEAR RESEARCH

Project of Nuclotron-based Ion Collider fAsility (NICA) at JINR

Anatoly Sidorin
on behalf of the NICA/MPD working group

LINC08, Protvino, 18 June 2008

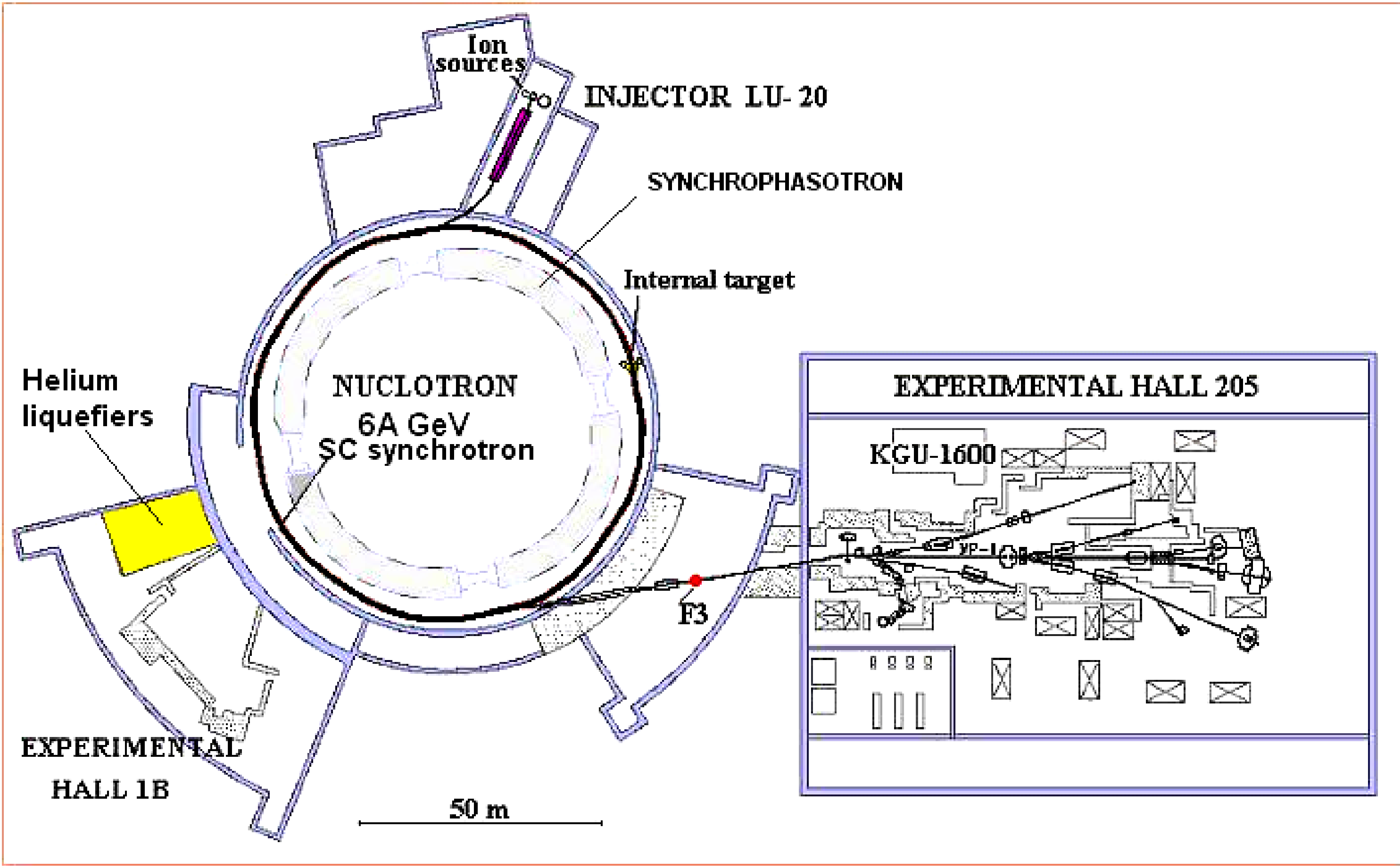
Nuclotron-based Ion Collider fAcility Multi-Purpose Detector

- Nuclotron –NICA
- Goals of the NICA/MPD project
- NICA scheme and layout
- Multi-Purpose Detector
- The project milestones

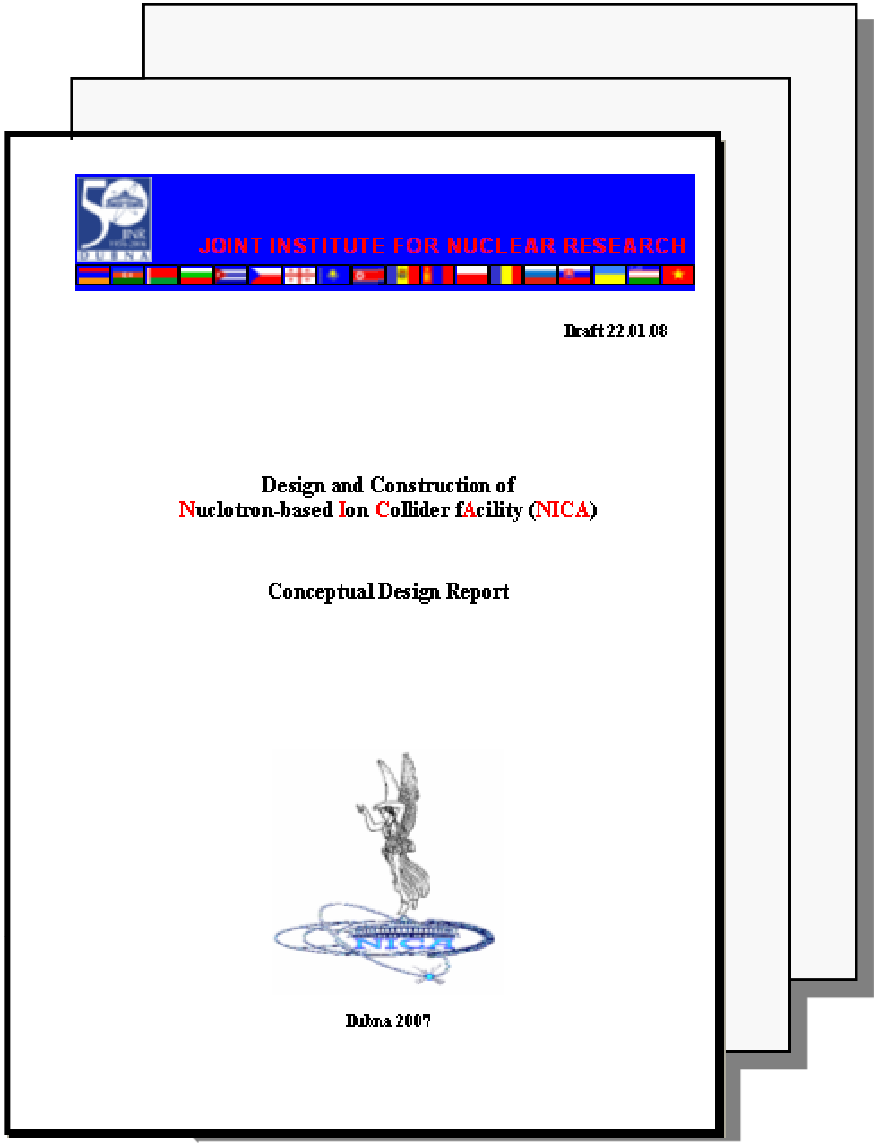
The Nuclotron

6 A·GeV 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. The annual running time of 2000 hours is provided during the last years.

Nuclotron upgrade program has been started in 2007



Ion sources
INJECTOR LU- 20
SYNCHROPHASOTRON
Internal target
Helium liquefiers
NUCLOTRON
6A GeV
SC synchrotron
EXPERIMENTAL HALL 205
KGU-1600
F3
EXPERIMENTAL HALL 1B
50 m



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Draft 22.01.08

Design and Construction of
Nuclotron-based Ion Collider fAcility (NICA)

Conceptual Design Report

Dubna 2007

Project leaders: A. Sissakian, A. Sorin

Accelerator group leaders: I. Meshkov, A. Kovalenko

JINR

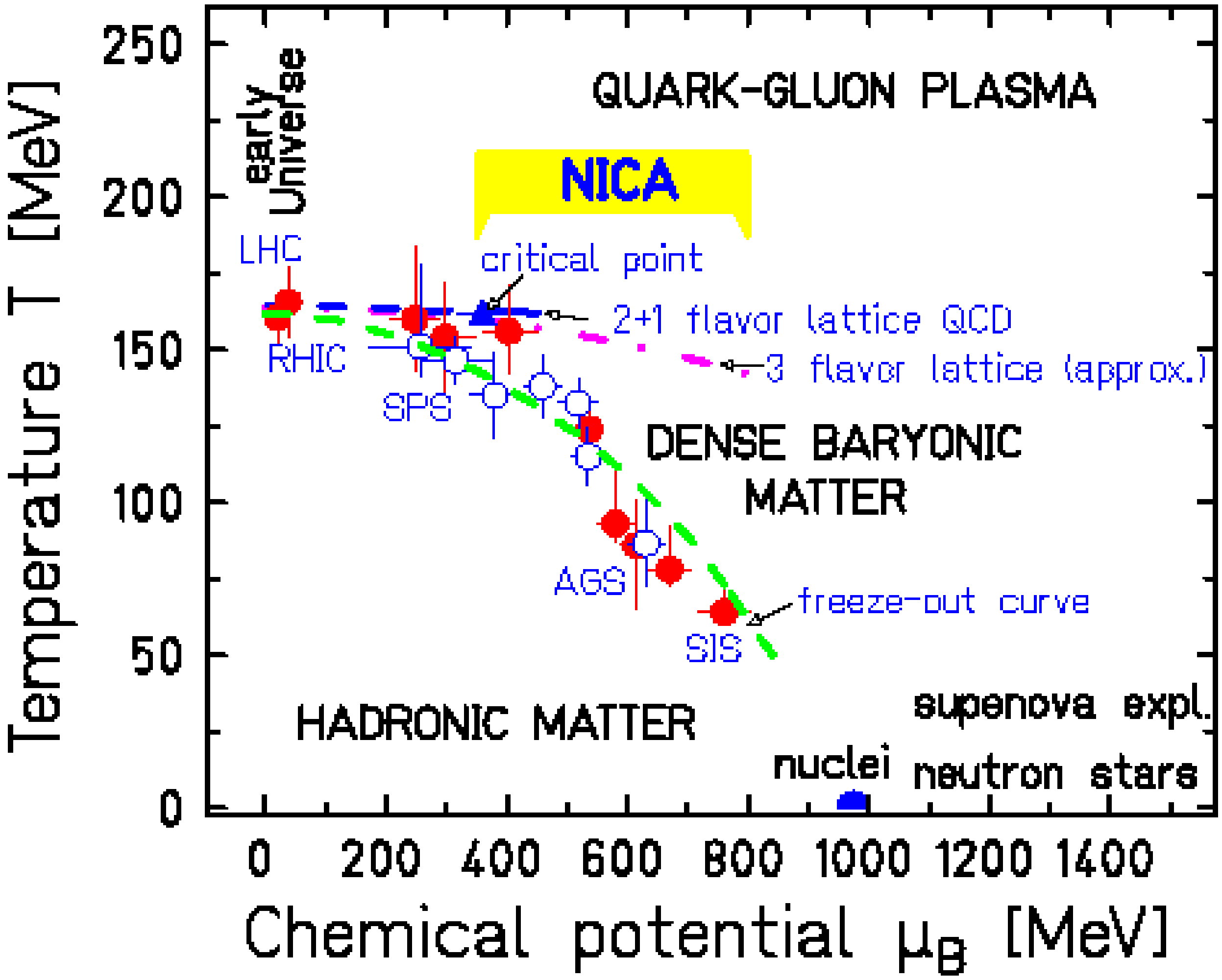
N.Agapov, V.Alexandrov, A.Alfeev, O.Brovko, A.Butenko, B.Vasilishin, V.Volkov, E.D.Donets, E.E.Donets, A.Eliseev, I.Issinsky, G.Khodzhibagiyan, V.Karpinsky, V.Kobets, O.Kozlov, A.Kuznetsov, V.Mikhaylov, V.Monchinsky, A.Sidorin, G.Sidorov, V.Shevtsov, A.A.Smirnov, A.V.Smirnov, V.Toneev, G.Trubnikov, V.Zhabitsky.

IHEP

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

INR

V. Matveev, L. Kravchuck



Temperature T [MeV]
250
200
150
100
50
0
early Universe
QUARK-GLUON PLASMA
NICA
critical point
LHC
2+1 flavor lattice QCD
RHIC
3 flavor lattice (approx.)
SPS
DENSE BARYONIC MATTER
AGS
freeze-out curve
SIS
HADRONIC MATTER
supenova expl.
nuclei
neutron stars
0 200 400 600 800 1000 1200 1400
Chemical potential μ_B [MeV]

Facility:	SPS	RHIC	NICA	SIS-300
Exp.:	NA61	STAR PHENIX	MPD	CBM
Start:	2009	2010	2013	2015
Pb Energy: (GeV/(N+N))	4.9-17.3	4.9-50	≤9	≤8.5
Event rate: (at 8 GeV)	100 Hz	1 Hz(?)	≤10 kHz	≤10 MHz
Physics:	CP&OD	CP&OD	OD&HDM	OD&HDM

CP – critical point
OD – onset of deconfinement, mixed phase, 1st order PT
HDM – hadrons in dense matter

25

NICA goals and physics problems

Study of in-medium properties of hadrons and nuclear matter equation of state, including a search for possible signs of deconfinement and/or chiral symmetry restoration phase transitions and QCD critical endpoint in the region of $\sqrt{s}_{NN}$=4-9 GeV

by means of careful scanning in beam energy and centrality of excitation functions for

the first stage

Multiplicity and global characteristics of identified hadrons including multi-strange particles

- ♣ Fluctuations in multiplicity and transverse momenta
- ♣ Directed and elliptic flows for various hadrons
- ♣ HBT and particle correlations

the second stage

- ♣ **Electromagnetic probes (photons and dileptons)**

Required mean luminosity is about 10^{27} $cm^{-2}s^{-1}$

The required luminosity level was estimated from the following basic initial parameters:

Ion kinetic energy	$1 \div 3.5$ GeV/u.
The detector covers solid angle close to	4π.
Total cross section of heavy ions interaction (U+U)	7 barn
Fraction of central collisions	5%.
Fraction of events with strange particles	6%
Fraction of events with lepton pairs in domain of ρ meson	10^{-4}.

The following interaction rate characterizes the detector capability at the luminosity equal to 10^{27} cm^{-2} s^{-1}:

Frequency of interactions	7×10^{3} Hz.
Total number of interactions per year assuming the statistics is being collected for 50% of the calendar time	1×10^{11}.
A number of central interactions per year	5×10^{9}.
A number of central interaction with strange particle generation per year	3×10^{8}.
A number of central interaction with lepton pairs in the domain of ρ meson per year	5×10^{5}.

An estimate of the **multi-strange hyperons** is quite model-dependent.

For example, the multiplicity of Ω^- baryons at the maximal colliding energy is approximately 0.6 and 0.1 in central and minimal-bias events, respectively. It results in the production rate 200/*s* and 700/*s* for 5% centrality and the minimal-bias collision.

Proceeding to the lowest colliding energy $\sqrt{s}$ = 4 GeV these numbers are changed by two orders of the magnitude. So, a decrease of luminosity at this energy more than by order of the magnitude may be quite crucial.

Energy dependence of **antiproton production** is more strong as compared to Ω^- hyperon. In central *U* + *U* collisions at $\sqrt{s}$ = 4 GeV the p-bar yield is in twice lower but at $\sqrt{s}$ = 9 GeV is by factor of 4 larger than that for Ω^- hyperons.

Luminosity of the collider

$$L = \frac{N_b^2}{4\pi\varepsilon\beta^*} F_{coll}\, f\left(\frac{\sigma_s}{\beta^*}\right)$$

$$F_{coll} = N_{bunches}\, F_{rev}$$

$$f\left(\frac{\sigma_s}{\beta^*}\right) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} \frac{\exp(-u^2)\,du}{\left[1 + \left(\frac{u\sigma_s}{\beta^*}\right)^2\right]}$$

Low beta function in the interaction point.

The beam emittance corresponding to the space charge limit.

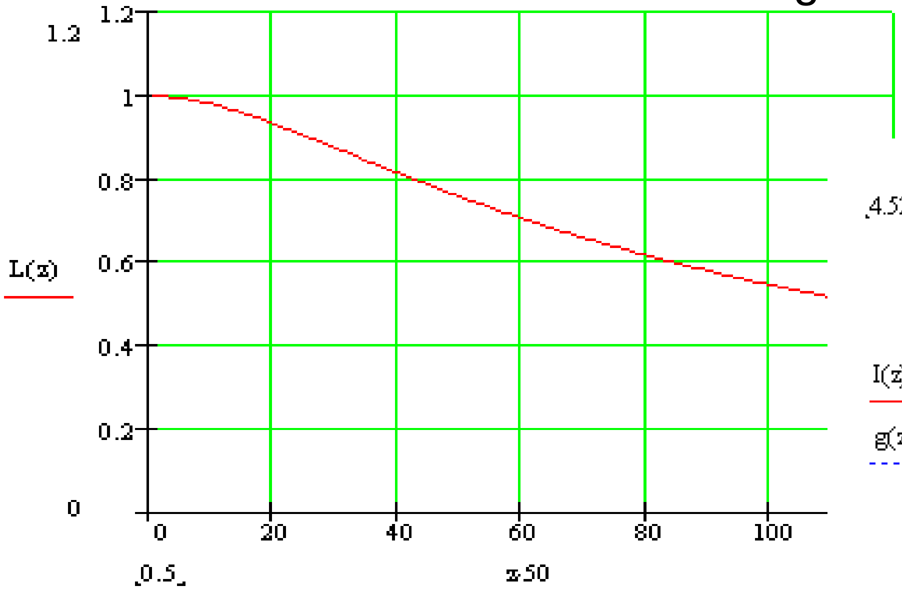
High collision repetition rate.

Long luminosity life-time.

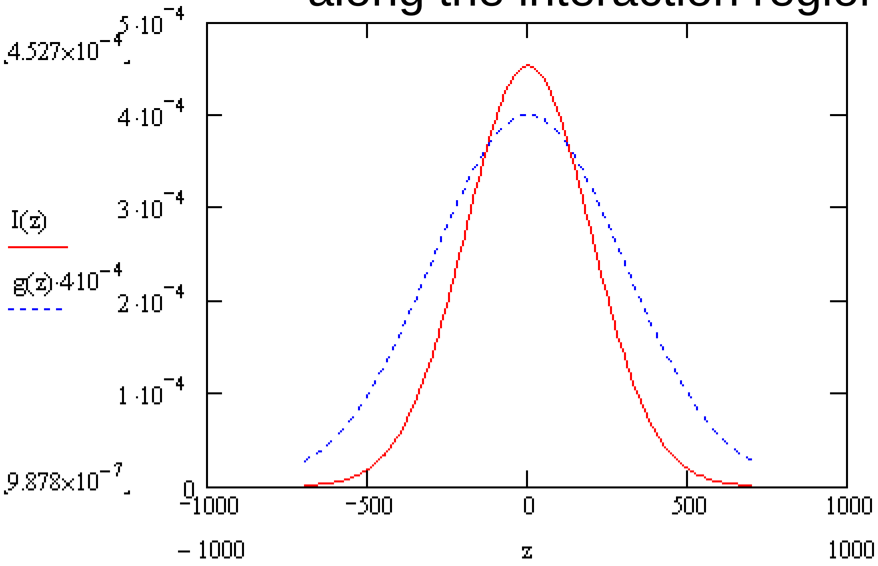
It is proposed to achieve the required luminosity level at the ion bunch intensity (10^9 ions per bunch) already used at RHIC in routine operation.

Bunch length

f-factor vs bunch length in cm



luminosity distribution along the interaction region



At β^* = 0.5 m, σ_s = 0.3 m:

***f* = 0.9 and 80% of the luminosity is distributed inside ±0.25 m**

Luminosity limitations

Beam-beam effect and tune shift

$$\xi = \frac{Z^2 r_p}{A} \frac{N_b}{4\pi\beta^2\gamma\varepsilon} \frac{1+\beta^2}{2}$$

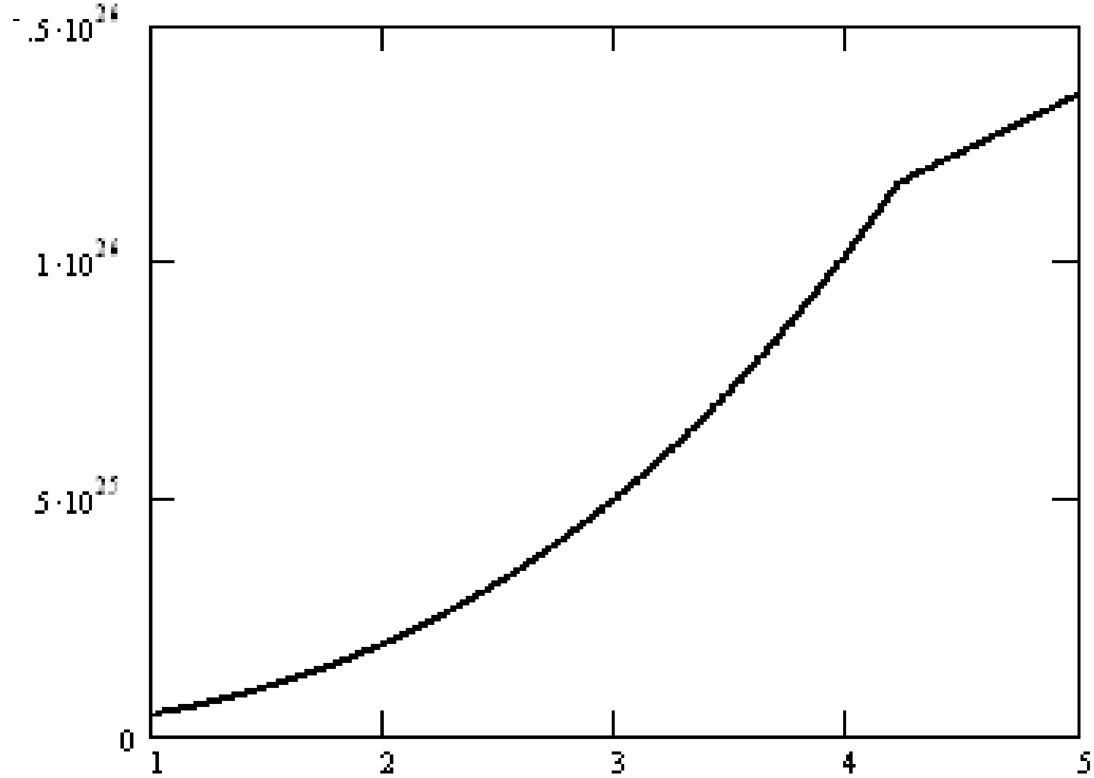
$$\Delta Q = -\frac{Z^2 r_p}{A} \frac{N_b}{4\pi\beta^2\gamma^3\varepsilon} F_{sc} F_b \qquad F_b = \frac{C}{\sqrt{2\pi}\sigma_s}$$

$$L \le \frac{A}{Z^2 r_p} \frac{N_b c}{\beta^* C} \frac{2\gamma\beta^3}{1+\beta^2} f\left(\frac{\sigma_s}{\beta^*}\right)\xi$$

$$L \le \frac{A}{Z^2 r_p} \frac{N_b c}{\beta^*} \frac{\sqrt{2\pi}\sigma_s}{C^2} \gamma^3 \beta^3 f\left(\frac{\sigma_s}{\beta^*}\right)\Delta Q$$

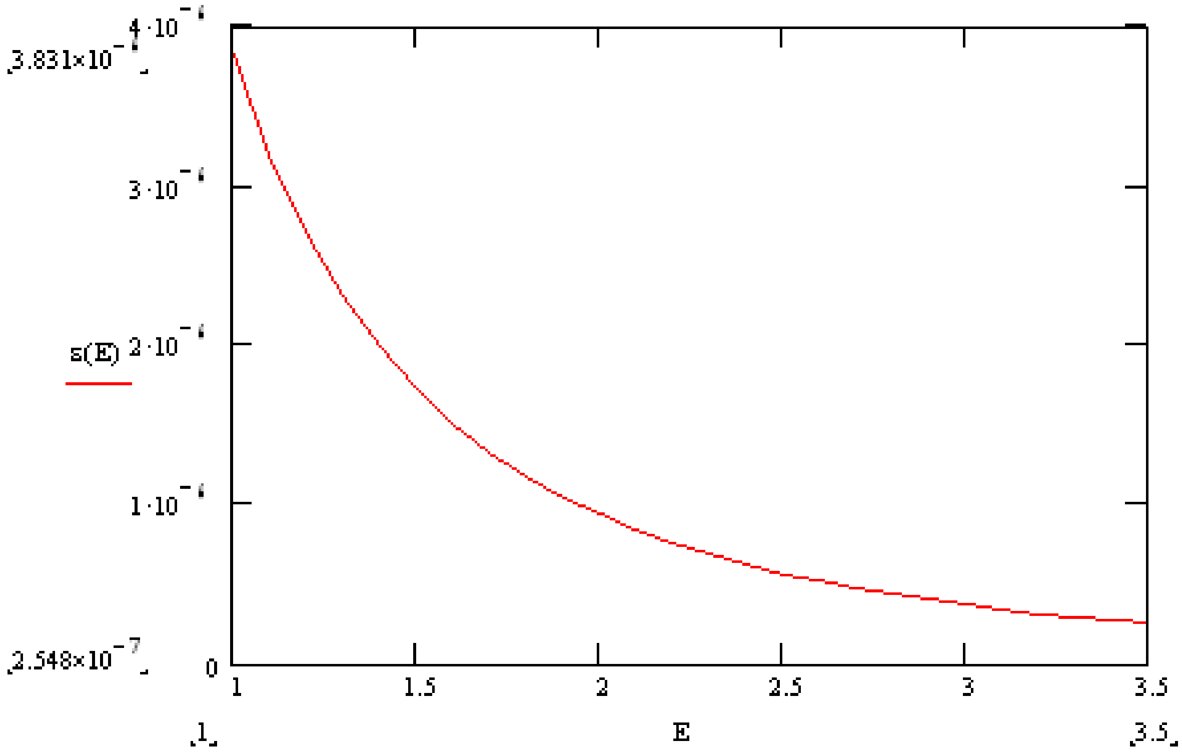
$\Delta Q = 0.05$ and $\xi = 0.005$.

Single-bunch luminosity
as the function of the beam energy,
for U ions. (C ~ 225 m)



Aperture limitation of the luminosity

Rms unnormolized emittance in π·m·rad corresponding to ΔQ = 0.05 as the function of the beam energy in GeV/u.



Short interaction region (of about 10 m) allows to have maximum beta functions in the triplets of about 90 m at the beta function of 0.5 m in the interaction point. → Triplet lenses aperture is about 8 cm

Collision repetition rate

Single bunch luminosity is about $7.3 \cdot 10^{25}$ $cm^{-2}s^{-1}$

The collider is operated at the bunch number of 10 ÷ 15 in each ring.

This is achieved at well established injection kicker parameters
(the kicker pulse duration is about 100 ns)
by means of injection into the collider of bunches of a short length.

The bunch of the required length is formed in the Nuclotron
after the acceleration.

Small longitudinal emittance value required for the bunch compression
is provided by the electron cooling of the ion beam in the Booster.

Electron cloud: the same distance between the bunches as in RHIC corresponds to $N_{bunches} = 7$.

NICA parameters for U-U collisions

Circumference	m	225
Number of collision points		2
Beta function in the collision point	m	0.5
Rms momentum spread		0.001
Rms bunch length	m	0.3
Number of ions in the bunch		10^9
Number of bunches		15
Incoherent tune shift		0.05
Rms unnormalized beam emittance at 1 GeV/u at 3.5 GeV/u	π mm mrad	 3.8 0.26
Luminosity per one interaction point at 1 GeV/u at 3.5 GeV/u	$cm^{-2}s^{-1}$	 $6.6 \cdot 10^{25}$ $1.1 \cdot 10^{27}$

$\varepsilon_{||,rms}$ = 3 eV·s = 0.013 eV·s/u

Luminosity life-time

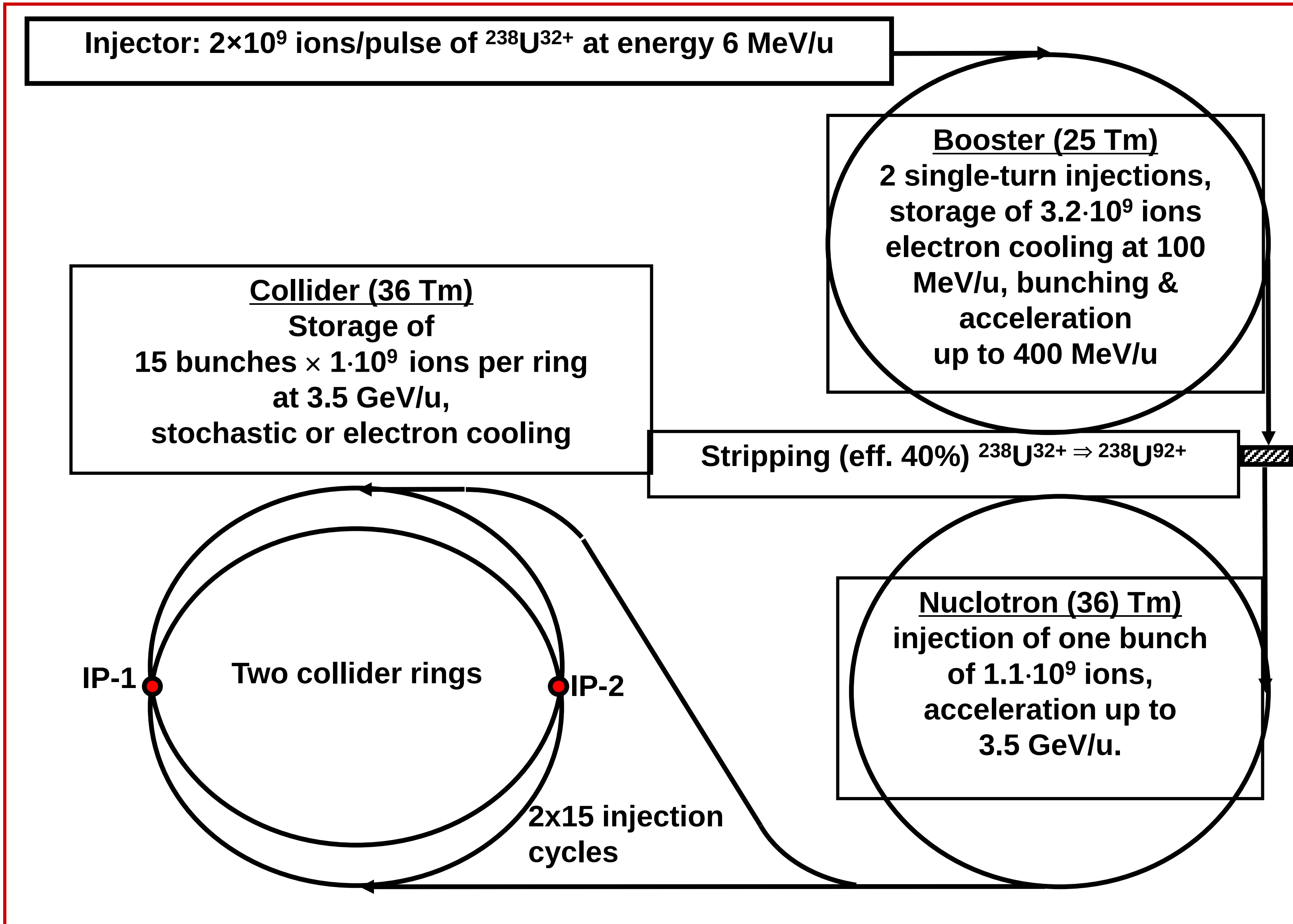
Without beam cooling during the experiment the beam emittance and the bunch length increase due to intrabeam scattering (IBS) process.
The IBS leads to the emittance growth approximately as the square root of time.
In this case the luminosity e-fold decrease time is equal to about $3\tau_{IBS}$.
The expected IBS growth time values in the collider are of about 50 s at 3.5 GeV/u ion energy.

Electron cooling:
Recombination in the cooling section + formation of a dense core in the distribution

Two solutions:
non-magnetized cooling + recombination suppression with undulator;
large electron transverse temperature + large magnetic field

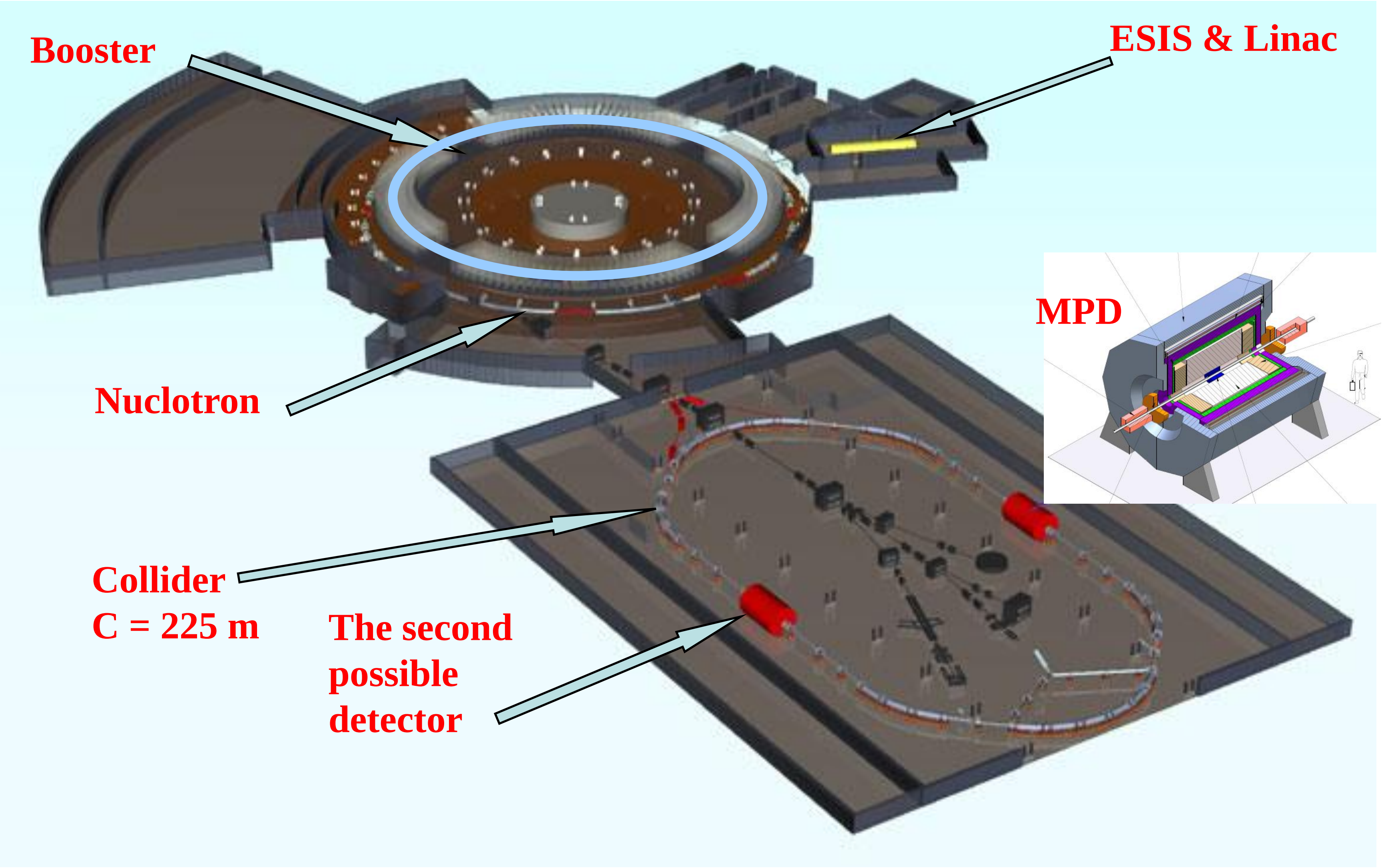
Stochastic cooling:
To provide ~100 s of the cooling time the bandwidth has to be ~ 4 GHz

NICA scheme



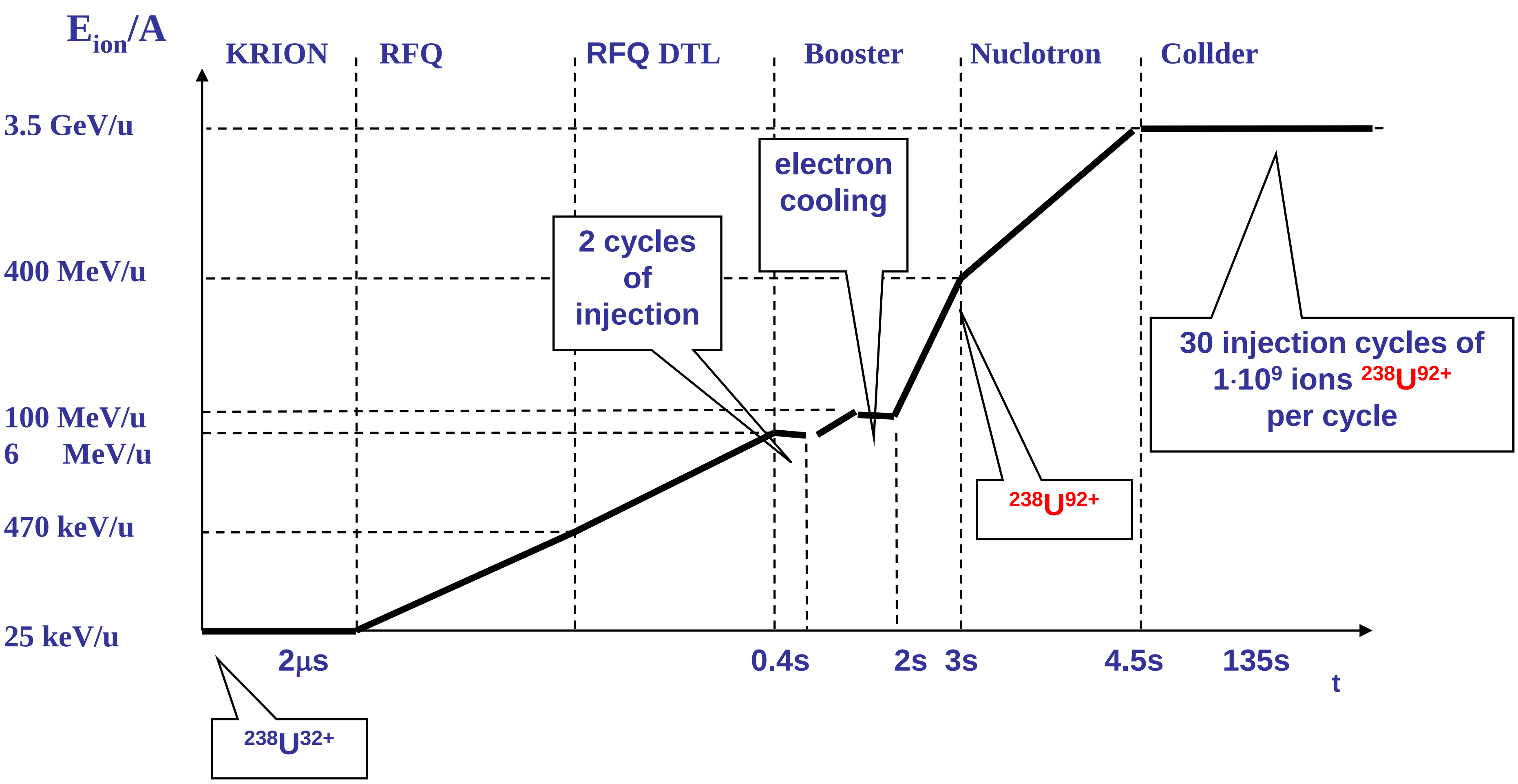
Injector: 2×10^9 ions/pulse of $^{238}U^{32+}$ at energy 6 MeV/u
Booster (25 Tm)
2 single-turn injections, storage of $3.2\cdot10^9$ ions electron cooling at 100 MeV/u, bunching & acceleration up to 400 MeV/u
Collider (36 Tm)
Storage of 15 bunches $\times$ $1\cdot10^9$ ions per ring at 3.5 GeV/u, stochastic or electron cooling
Stripping (eff. 40%) $^{238}U^{32+} \Rightarrow {}^{238}U^{92+}$
Nuclotron (36) Tm)
injection of one bunch of $1.1\cdot10^9$ ions, acceleration up to 3.5 GeV/u.
IP-1
Two collider rings
IP-2
2x15 injection cycles

NICA general layout

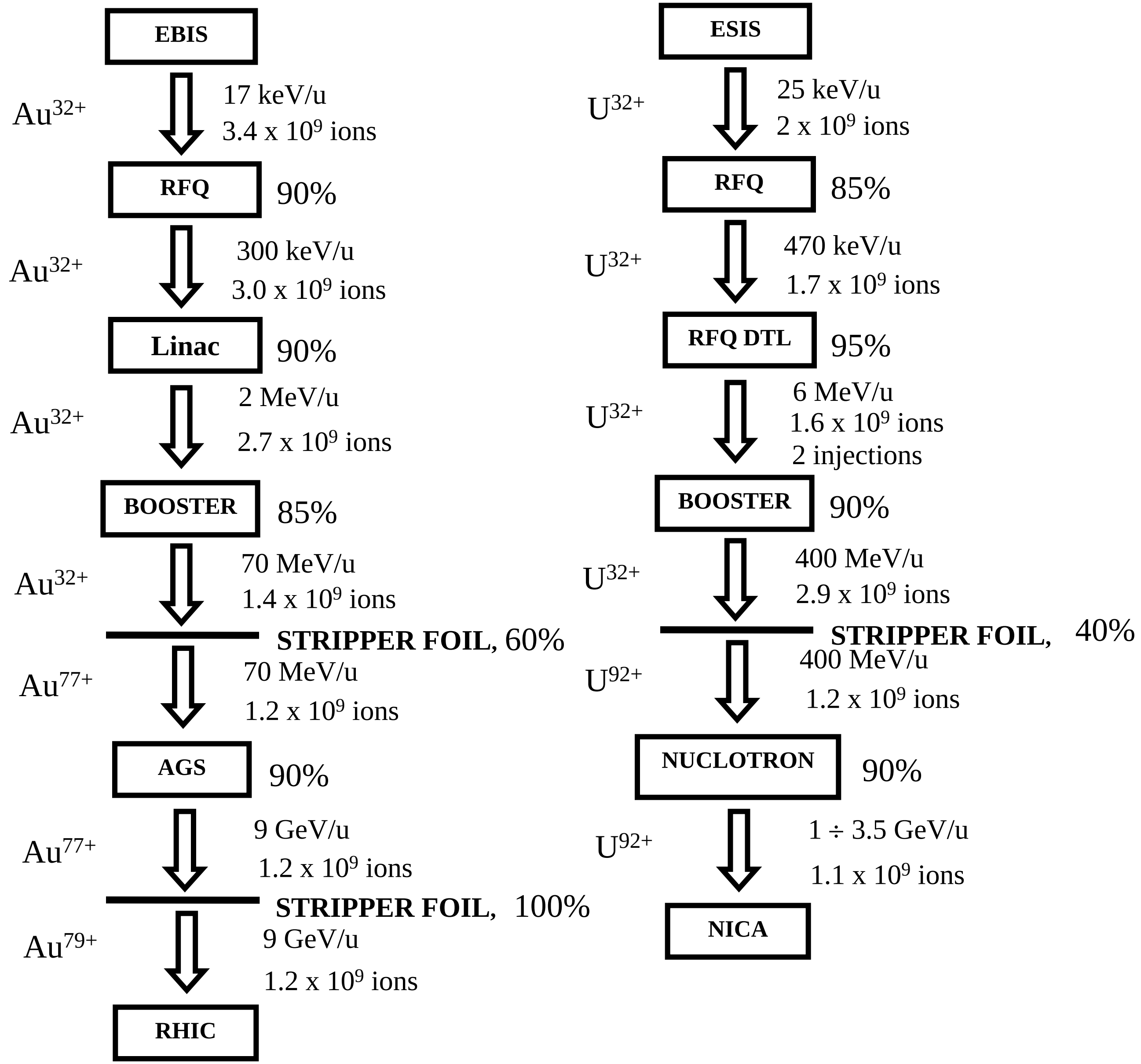


	Booster	Nuclotron	Collider
Ring circumference, m	215	251.52	225
Injection energy, MeV/u	6	400	1000 - 3500
Final kinetic energy, MeV/u	400	1000 - 3500	1000 -3500
Magnetic rigidity, Tm	2.4 - 25	8.2 - 36	14 - 36
Bending radius, m	14	22	9
Magnetic field, T	0.17 – 1.8	0.37 – 1.64	1.56 – 4
Number of dipole magnets	40	96	24
Number of quadrupoles	48	64	32
d*B*/d*t*, T/s	1	1	0
RF harmonics number	4 / 1	1	90
RF frequency range, MHz	0.6 – 1	0.857 – 1.17	105 – 117
RF voltage, kV	4	120	100
Residual gas pressure (equivalent for nitrogen atmosphere at room temperature), Torr	10^{-11}	10^{-8}	10^{-10}

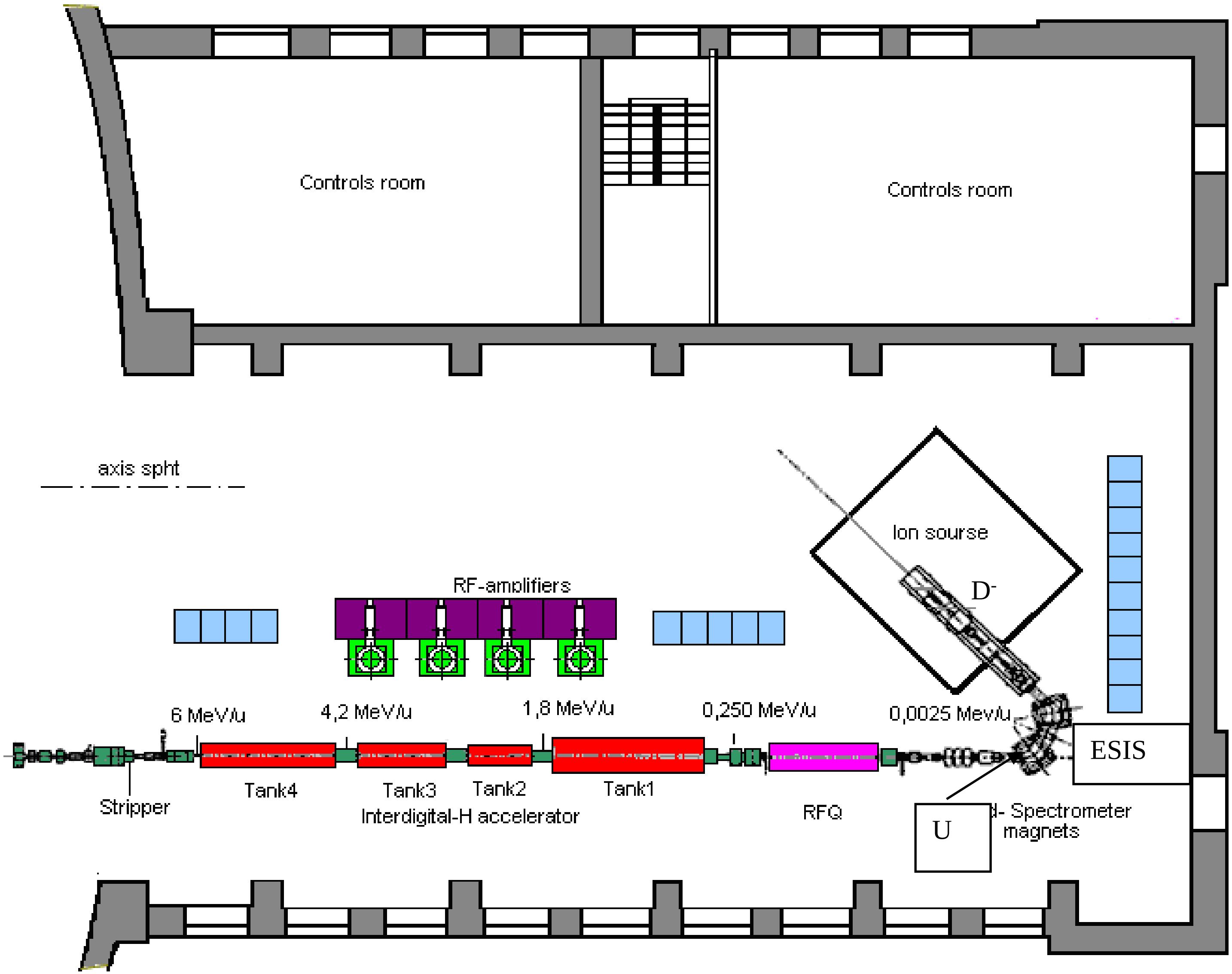
Time table of the storage process



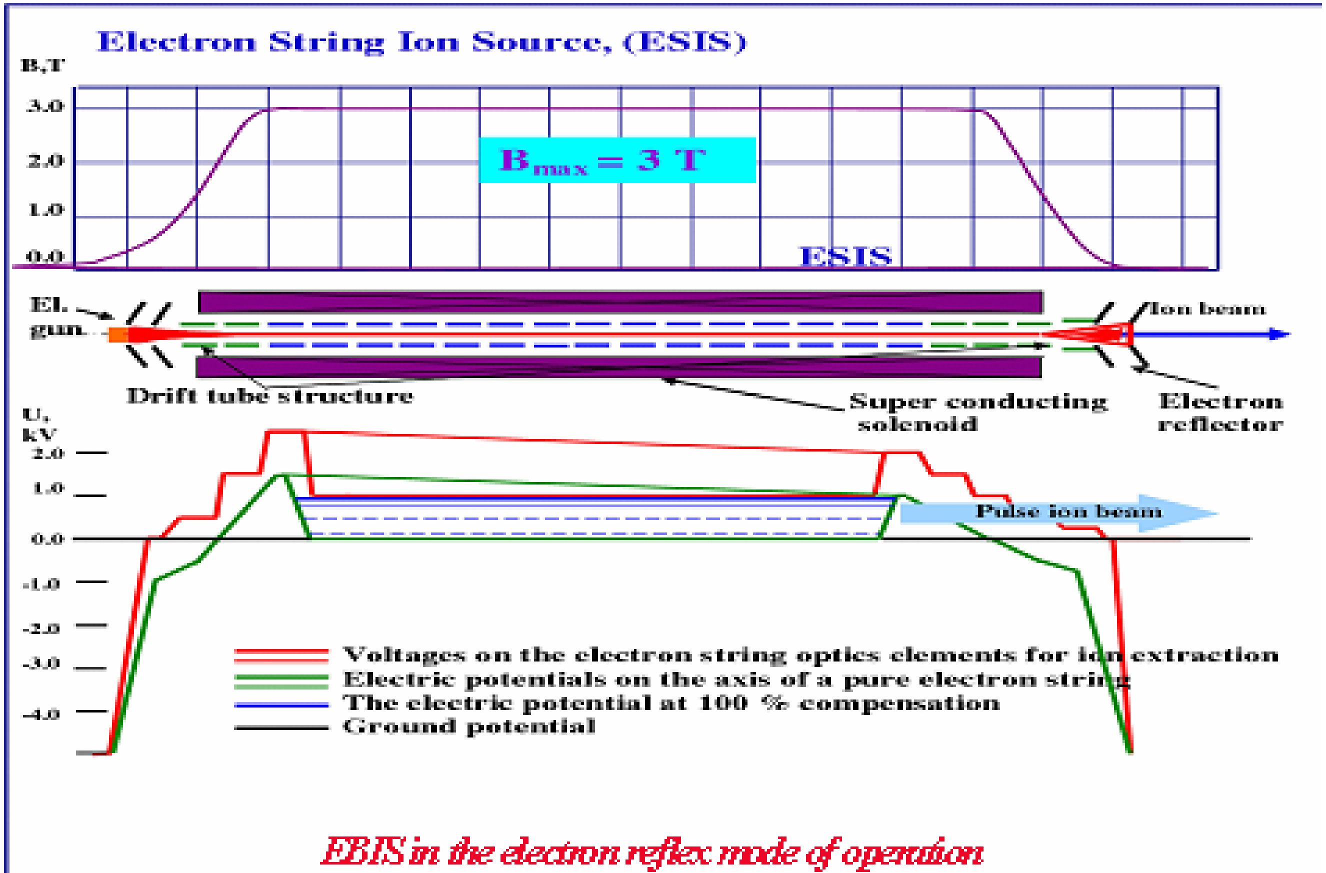
Injection chain



Injector: Ion Sources + Linac



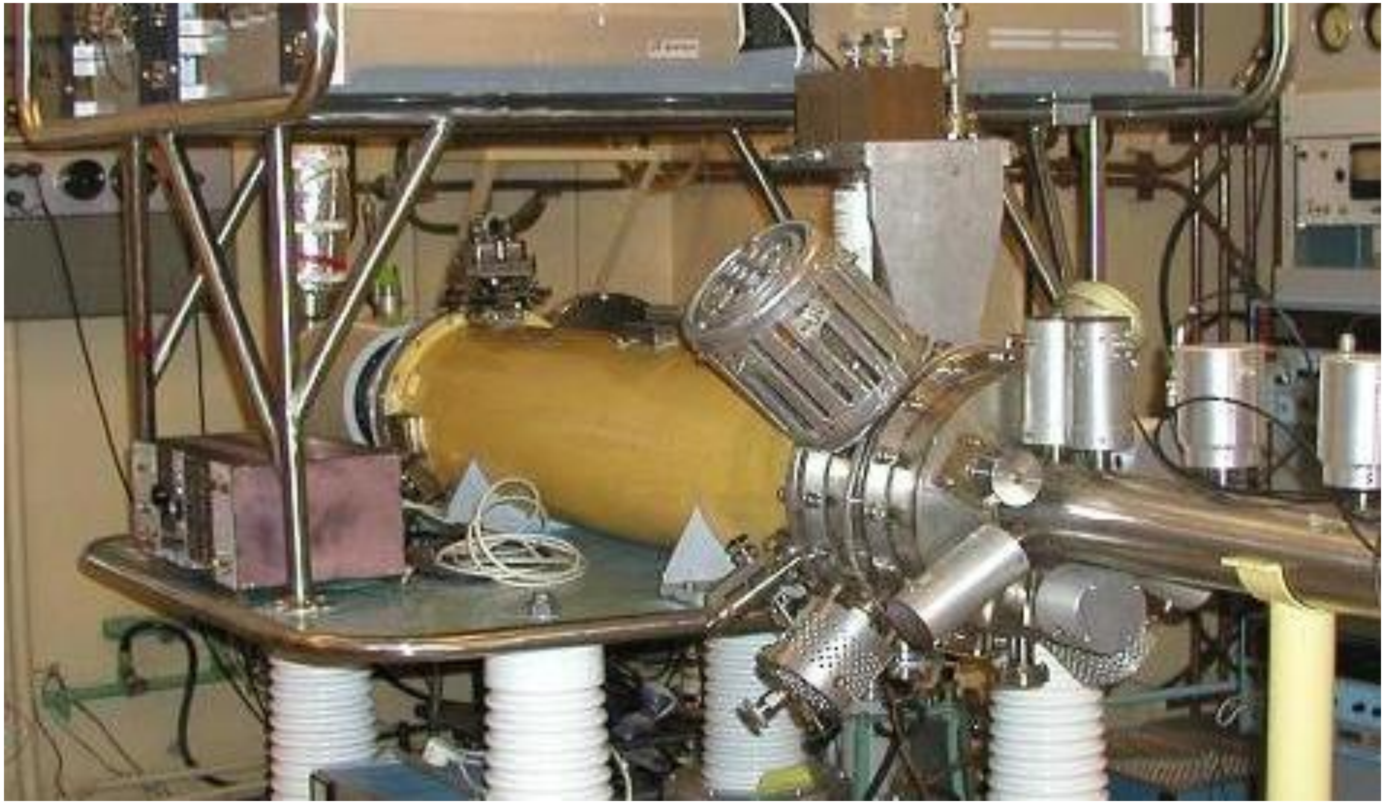
Electron String Ion Source



EBIS: 300 kW DC electron beam power

ESIS: 200 W

General view of the KRION ion source with 3 T solenoid

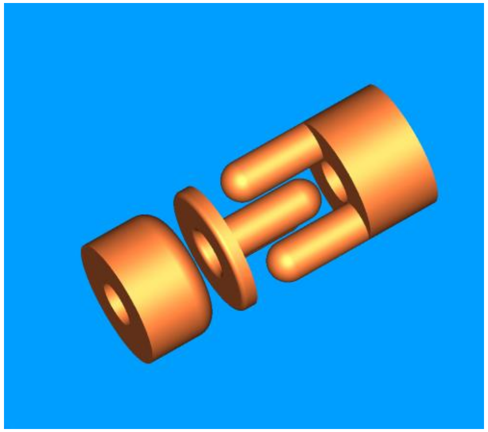


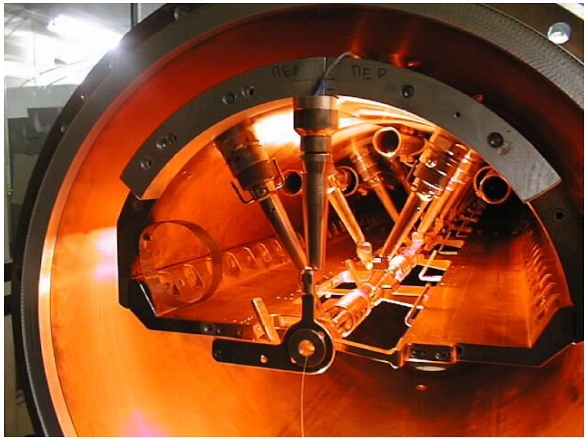
Experimental result — 3 T solenoid: $5 \cdot 10^{8}$ Au^{30+} — E. Donets

Expectation — 6 T solenoid: $2 \cdot 10^{9}$ U^{32+}

RFQ + RFQ-DTL

Designed in IHEP (Protvino)





Large peak current: 10 mA

It is required due to short pulse – 7 μs

Booster

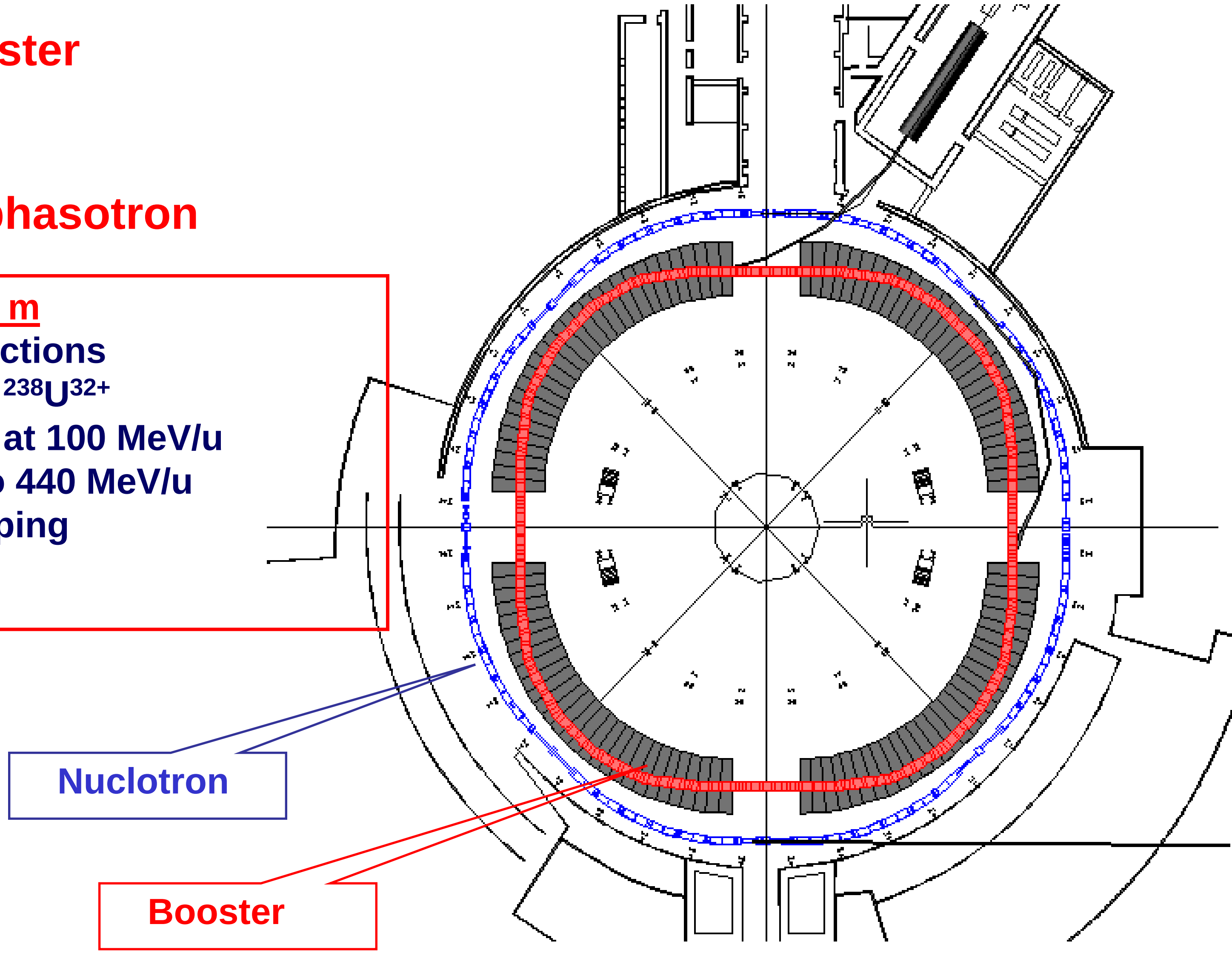
Superferric booster

on base

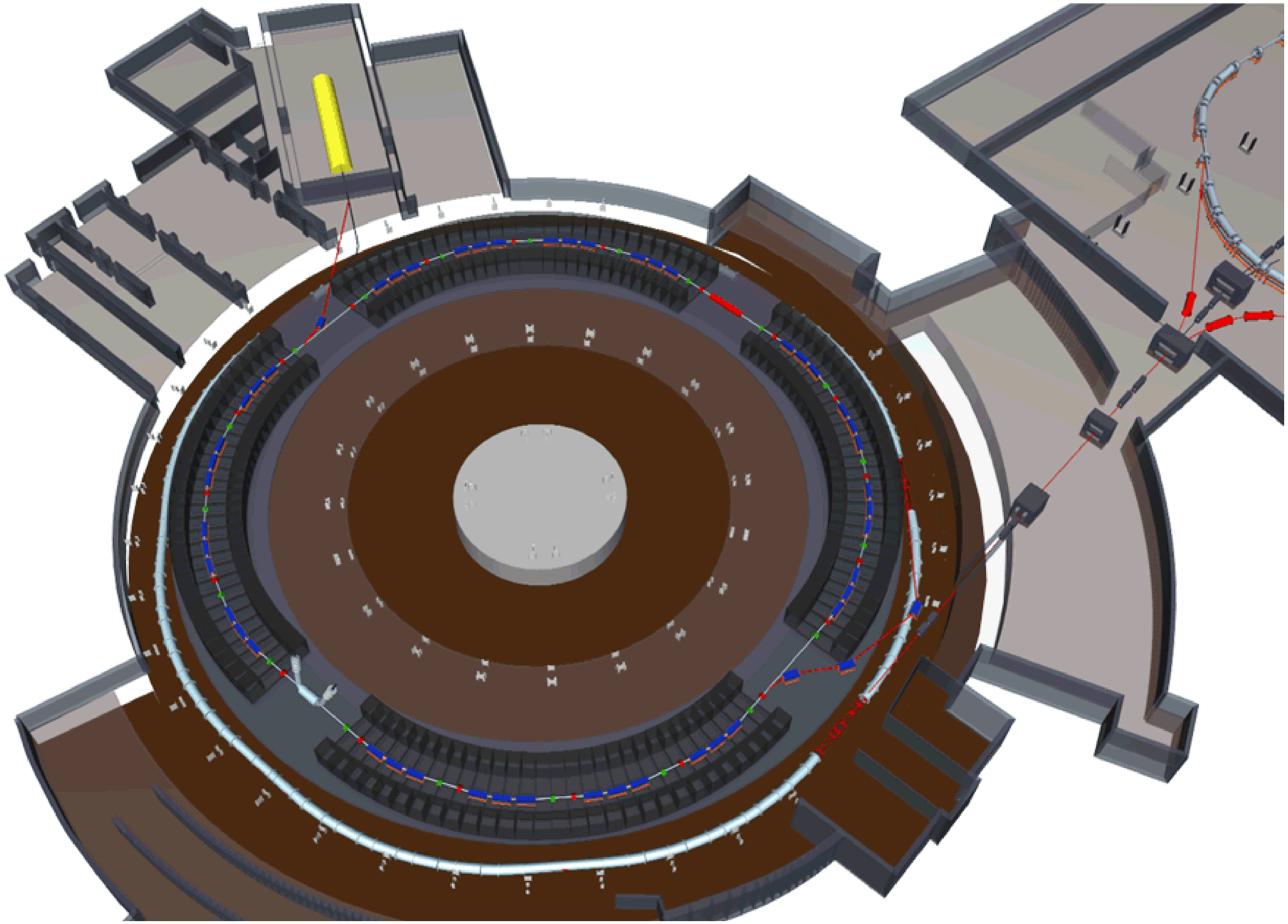
of the Synchrophasotron

$B\rho$ = 25 T·m, C = 210 m

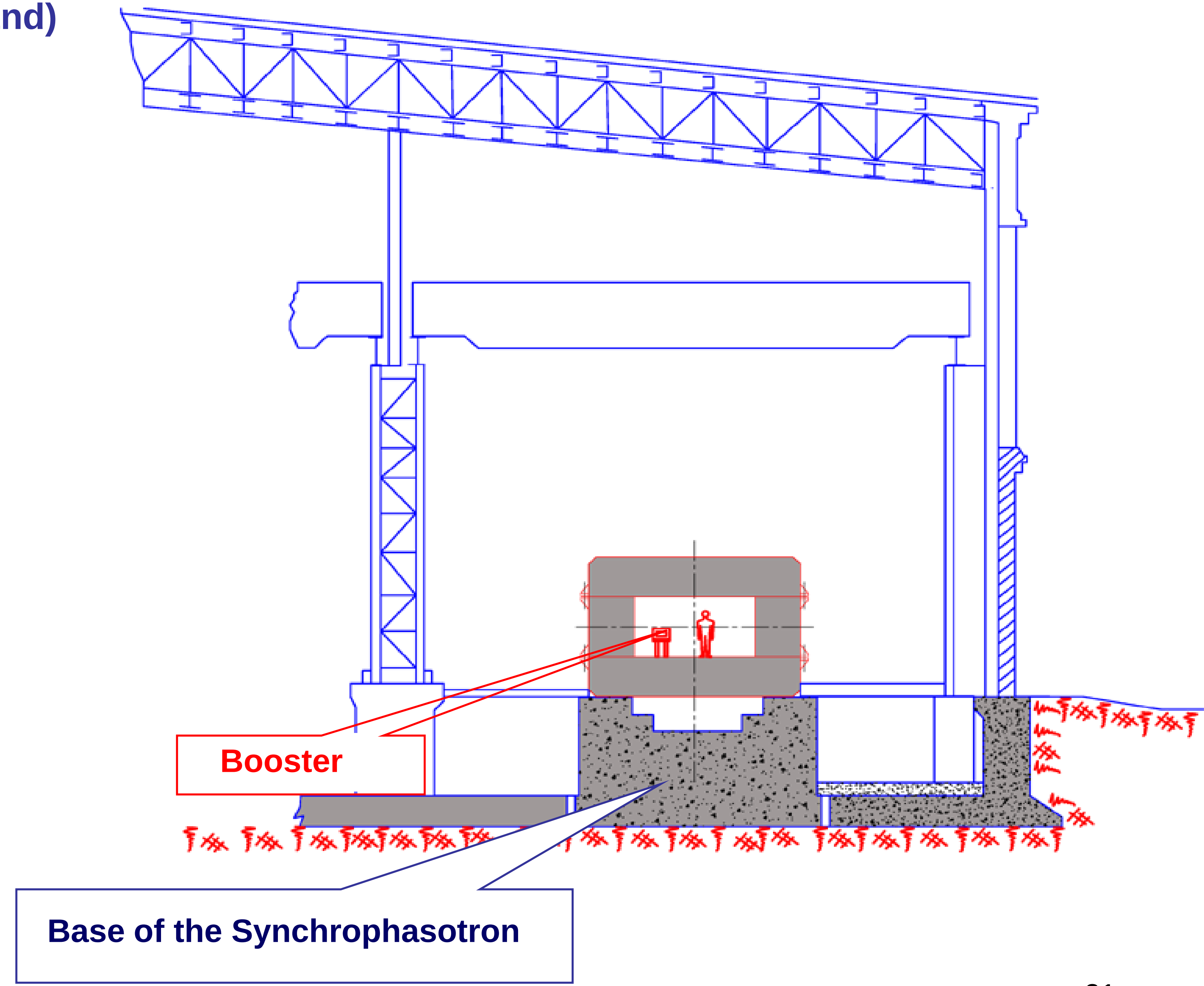
1) 2 single-turn injections
2) Storage of 3×10^{9} $^{238}U^{32+}$
3) Electron cooling at 100 MeV/u
4) Acceleration up to 440 MeV/u
5) Extraction & stripping



Booster position in the Synchrophasotron yoke



Booster (Contnd)



Electron cooling in the Booster

Transverse emittance has to be constant

Longitudinal emittance has to be decreased to the level of 2.5 eV·s

Methods for stabilization of the transverse emittance:

- application of white noise in transverse degree of freedom in order to displace equilibrium between cooling and heating into region of larger emittances,

- misalignment of the electron beam (introduction of some angle between electron beam and ion equilibrium orbit in the cooling section).

Expected cooling time is about 1 s.

Emittance growth at the stripping foil

	carbon	silica
Thickness, μm	125	100
Rms non-uniformity δ_t , %	5	0.5
Ionization energy loss ΔE_{BB}, MeV	320	397
$\delta_t \cdot E_{BB}$, MeV	16	1.99
Rms energy straggling E_{str}, MeV	3.76	4.38
δE, MeV	16.4	4.81
Rms scattering angle	$1.22 \cdot 10^{-4}$	$2.02 \cdot 10^{-4}$
Longitudinal emittance growth at $\sigma_s = 7\ m$, $eV \cdot s$	1.69	0.493
Normalized transverse emittance growth at $\beta_t = 1\ m$, $\pi \cdot mm \cdot mrad$	$7.76 \cdot 10^{-3}$	$2.13 \cdot 10^{-2}$

Nuclotron upgrade program

Development of the ESIS-type ion source, presuming increase of the source magnetic field up to 6 Tesla and electron injection energy up to 25 keV;

Sufficient improvement of the vacuum conditions in the Nuclotron ring and linear injector.

Development of the Nuclotron power supply system in order to reach magnetic field in dipole magnets of 1.8 - 2 T.

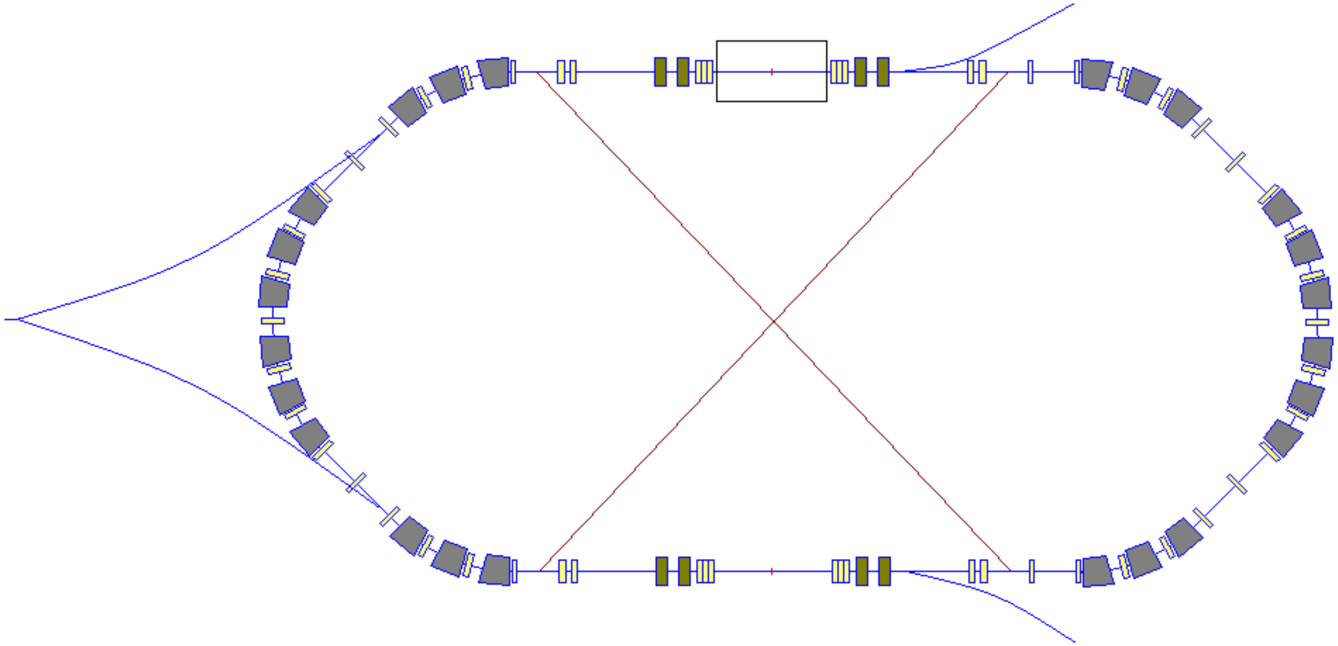
Upgrade of the Nuclotron RF system.

Beam dynamics studies,
minimizations of the particle loss at all stages of the acceleration.

Design of new injector (existing injector accelerates the ions at $q/A \geq 0.33$).

Modernization of the Nuclotron is one of the key points of the NICA project

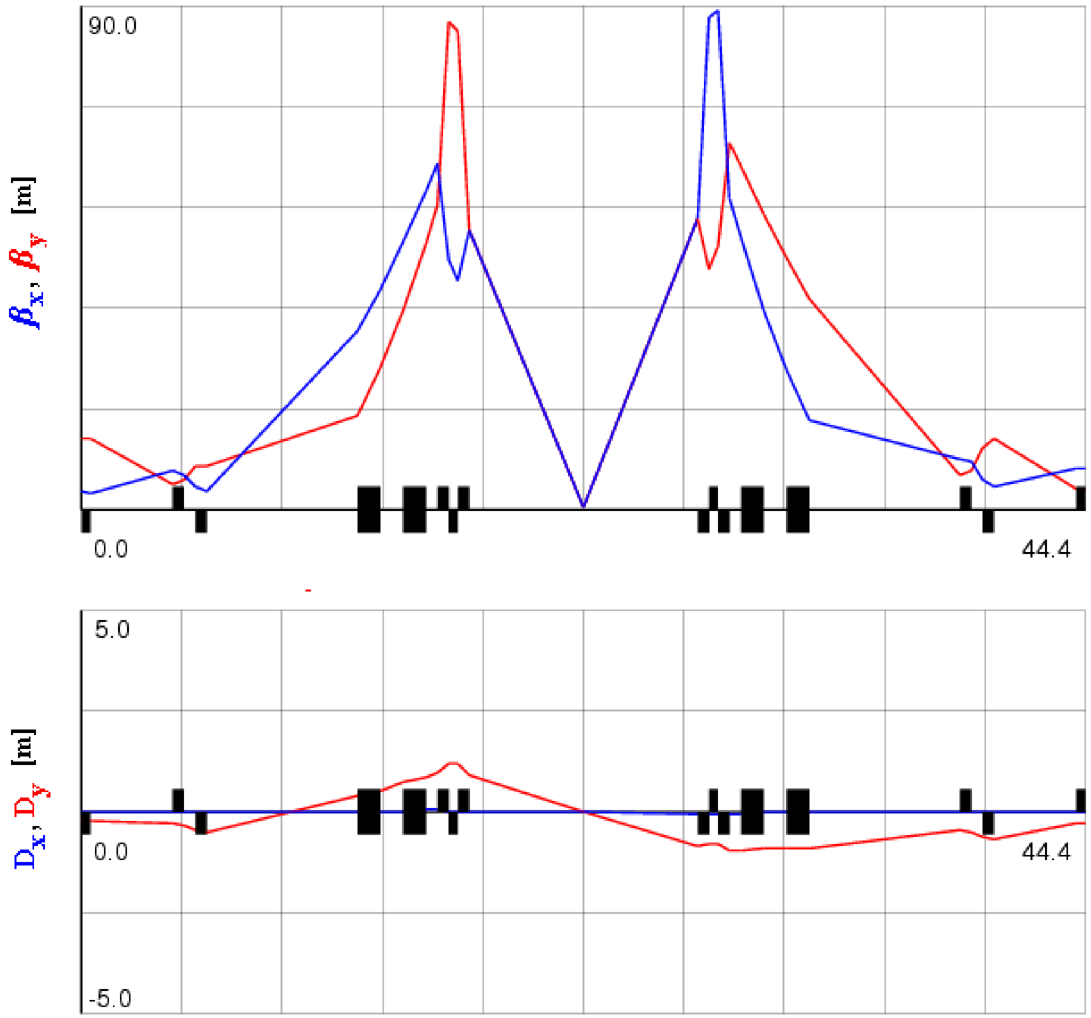
Collider rings



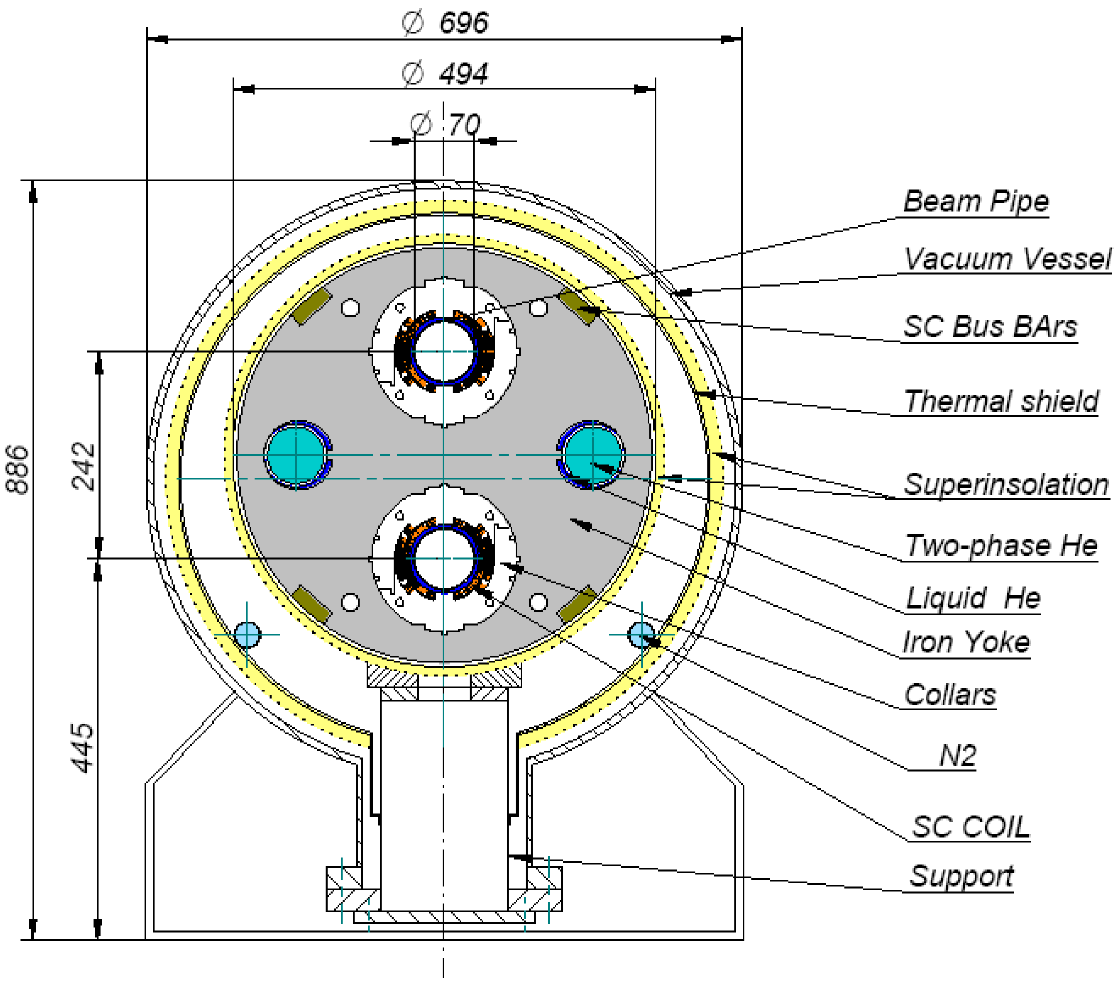
Two rings are located as one upon other that supposes two possible schemes:
bending and quadrupole magnets have two apertures in one yoke,
or rings are separate.
Here I discuss a preliminary design of twin bore magnets.
Magnetic rigidity of the rings is equal to maximum magnetic rigidity of the Nuclotron,
that corresponds to 45 Tm.
Maximum value of the bending field in superconducting dipole magnets
is chosen to be 5.5 T.
To provide a round beams in the collision point the collider will be operated
at equal tunes in horizontal and vertical directions.

Ion species		from d to U
Magnetic rigidity	Tm	45
Maximum heavy ion energy U Au Pb	GeV/u	 4.37 4.56 4.5
Maximum deuteron energy	GeV	12.6
Circumference	m	225
Number of collision points		2
Rms unnormalized emittance	π mm mrad	0.3
Rms momentum spread		0.001
Rms bunch length	m	0.3
Number of ions in the bunch		$(1 - 2)\cdot 10^9$
Number of bunches		10 - 15
RF harmonics number		90
RF voltage amplitude	kV	100
Beta function in the collision point	m	0.5

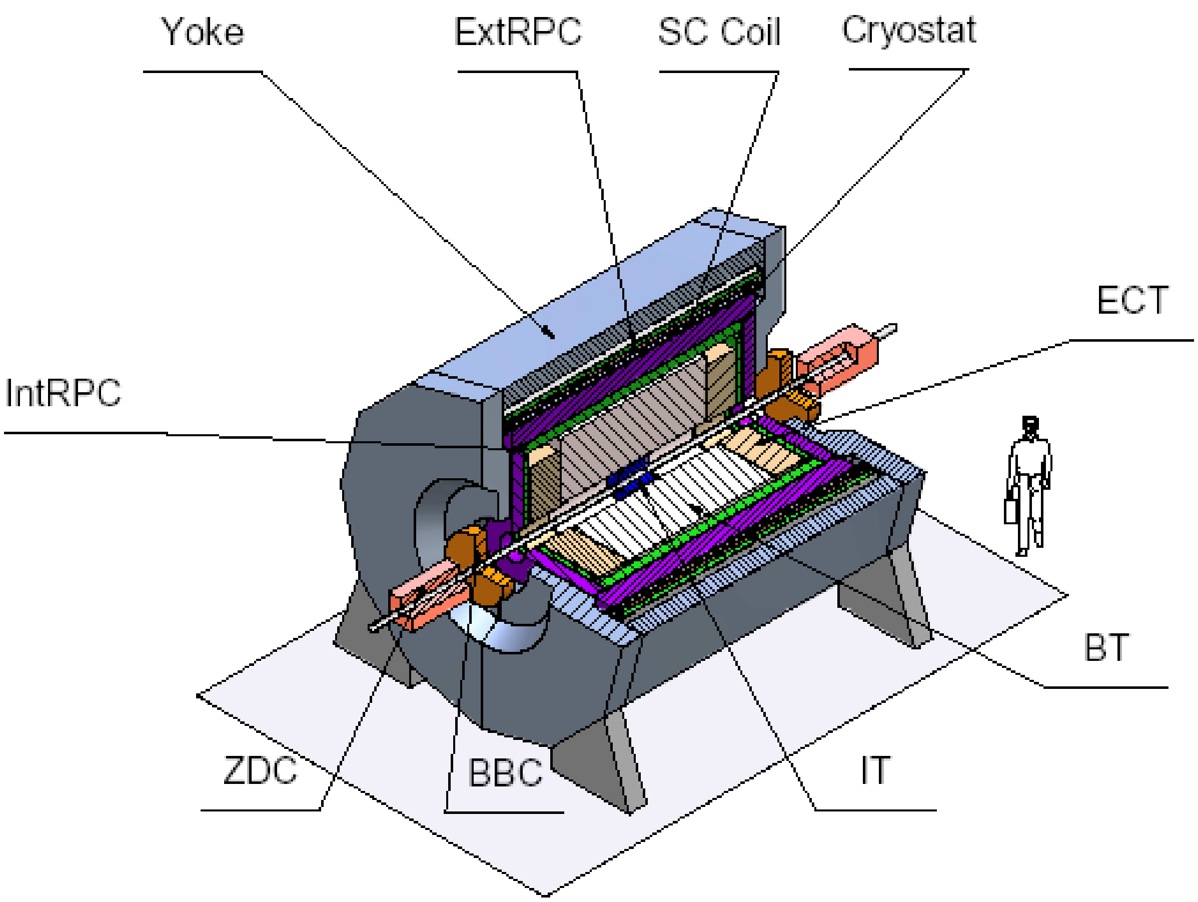
Amplitude and dispersion functions in the long straight section

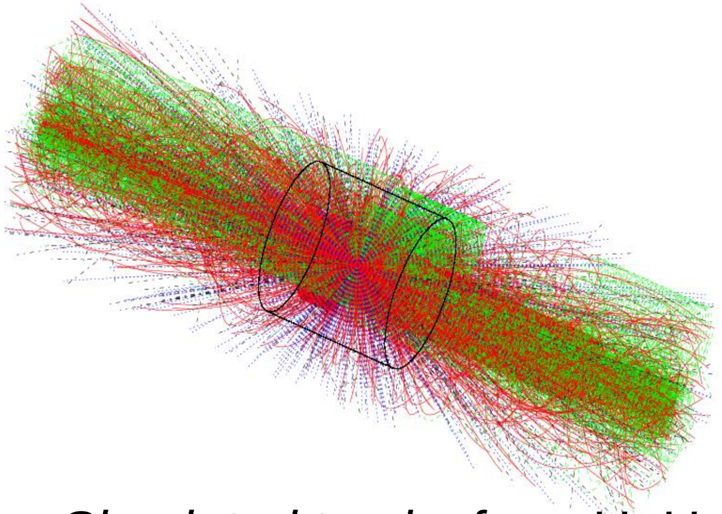


Twin bore structural dipoles with *Cos θ* - style superconducting coils proposed for the NICA collider. B = 5.5 T.



MPD general layout





Simulated tracks from U+U collision with $\sqrt{s_{NN}}$= 9 GeV energy with UrQMD model.

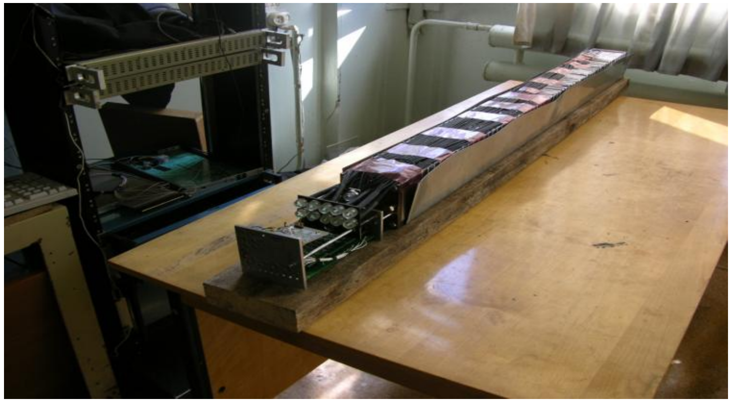
MPD dimension:

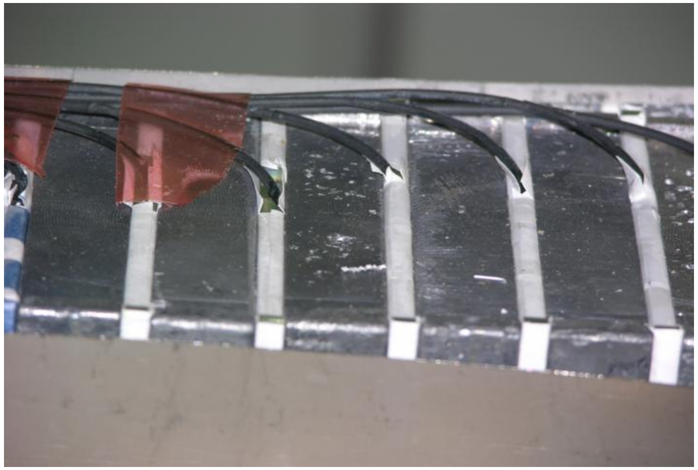
Along the beam – 8 m.

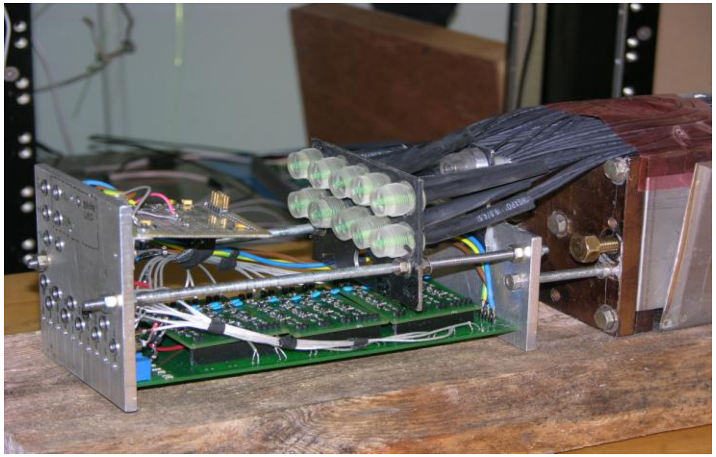
Diameter – 5 m.

Tracking detectors are situated in the magnetic field of ~0.5 T .

Assembling of the ZDC at INR (Troitsk)







The Project Milestones

- **Stage 1: years 2007 – 2009**

- Upgrate and Development of the Nuclotron facility
- Preparation of Technical Design Report
- Start for prototyping of the MPD and NICA elements

- **Stage 2: years 2008 – 2012**

- Design and Construction of NICA and MPD detector

- **Stage 3: years 2011 – 2013**

- Assembling

- **Stage 4: year 2014**

- Commissioning

THANK YOU FOR ATTENTION !