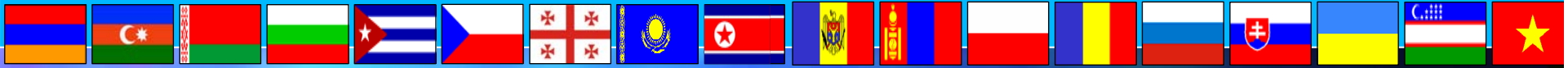


# Joint Institute for Nuclear Research



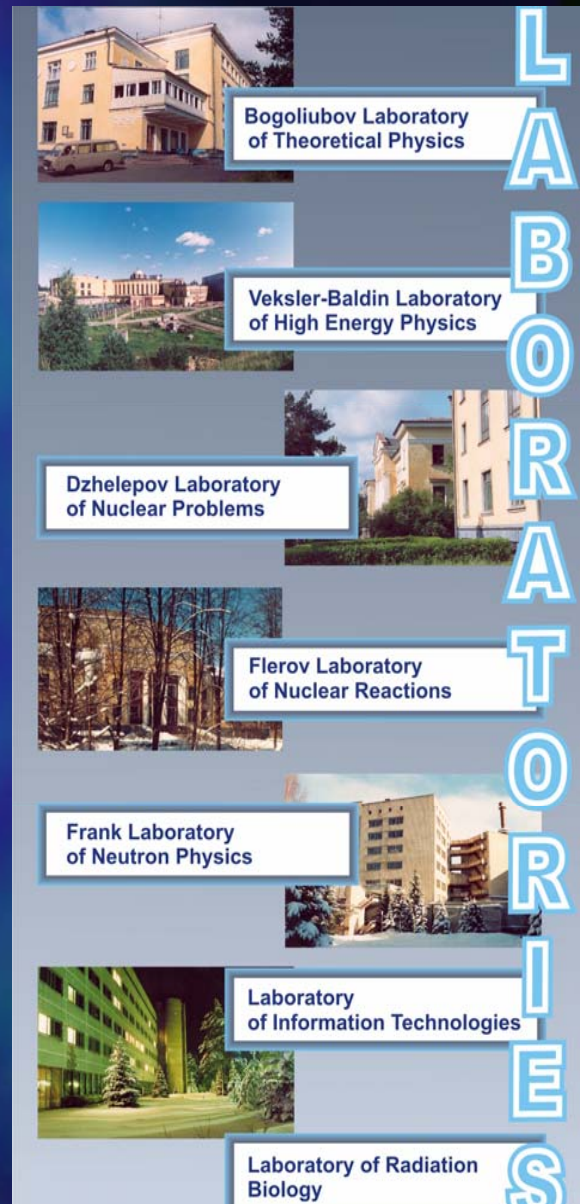
Development of the JINR basic facility for  
generation of intense relativistic heavy ion and  
polarized nuclear beams

Project "Nuclotron M" / NICA



# JINR's research niche offered by home facilities

- **Heavy-Ion Physics:**
  - at high energies (up to 5 GeV/n)  
(in future  $\sqrt{s_{NN}} = 9$  GeV, NICA facility)
  - at low and intermediate energies (5 – 100 MeV/n)
- **Condensed Matter Physics** using nuclear physics methods



# WORLD FACILITIES


Facility	SPS	RHIC	NICA	FAIR SIS-300
Detector	NA61	STAR PHENIX	MPD	CBM
Start (year)	2010	2010	2013-2014	2015-2016
Energy (for Pb-ions) c.m. GeV	4.9-17.3	4.9-50	$\leq 9$	$\leq 8.5$
Physics	CP,OD	CP,OD	CP,OD,HDM	CP,OD,HDM

**CP – critical endpoint**

**OD – onset of deconfinement**

**HDM – hadronic dense matter**

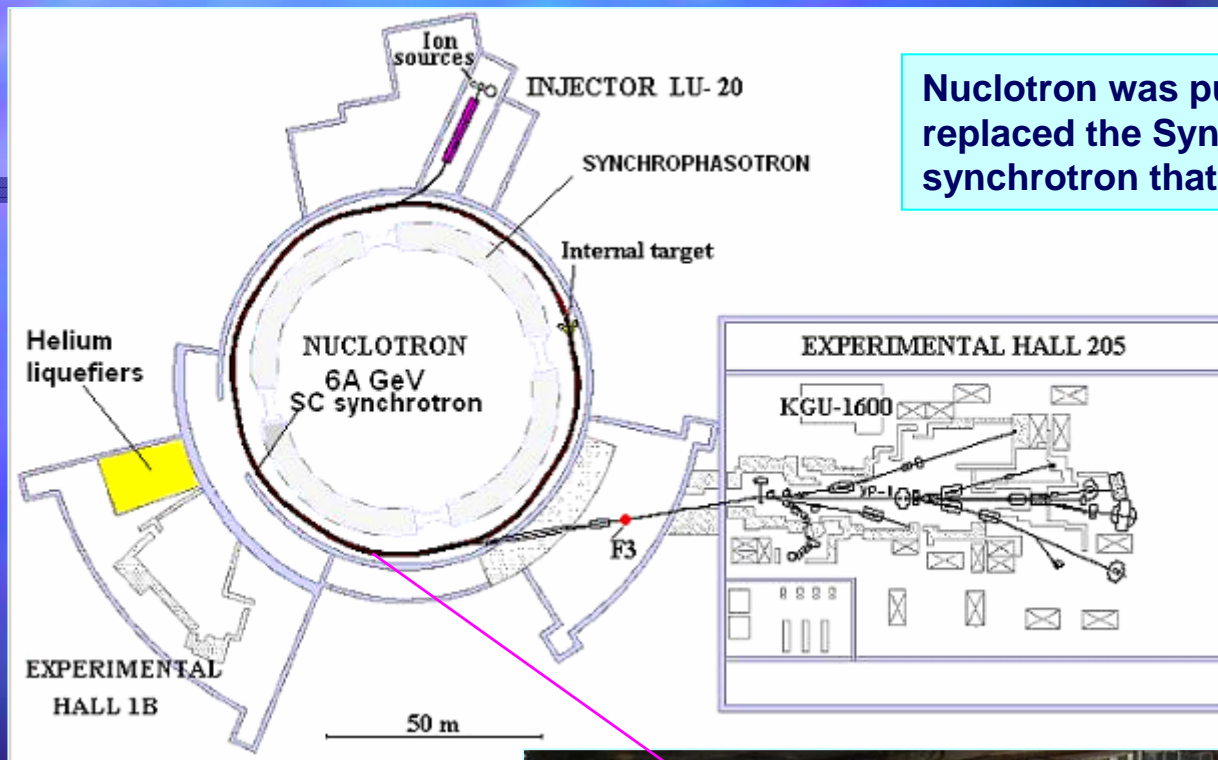
**A.Kovalenko, SYMMETRIES AND SPIN, Praha, July 20-26, 2008**



**JINR Veksler-Baldin Laboratory  
of High Energy Physics:**

**Accelerator buildings**

# Existing JINR facility: Nuclotron



Nuclotron was put into operation in 1993 and replaced the Synchrophasotron – 10 GeV proton synchrotron that was under operation since 1957



Nuclotron is based on the unique technology of fast-cycled superconducting magnets that was proposed and realized at the laboratory



# Nuclotron: status 2007

Parameter/System	Nuclotron (available) in 2007
<u>The heaviest accelerated ions:</u> <ul style="list-style-type: none"> <li>• Mass, A</li> <li>• Charged state, q</li> </ul>	56 (iron) 24
<u>Dipole magnetic field, T</u> <ul style="list-style-type: none"> <li>• Maximum tested in the ring</li> <li>• More frequently operation</li> </ul>	1.5 1.2 (up to)
Magnetic field ramp, T/s <ul style="list-style-type: none"> <li>• Nuclotron project</li> <li>• Maximum operating</li> </ul>	2.0 (up to) 1.0
Vacuum in the ring (averaged), Torr	$\sim 2 \cdot 10^{-8}$
<u>RF acceleration:</u> <ul style="list-style-type: none"> <li>• Number of the RF stations</li> <li>• Particle capture scheme</li> </ul>	2 non-adiabatic
Beam extraction: <ul style="list-style-type: none"> <li>• Max. beam energy, GeV/u</li> <li>• Electrostatic septa voltage, kV</li> <li>• Spill duration (minimum), mks</li> <li>• Spill duration (maximum), s</li> </ul>	2.2 120 100 10
<u>Beam intensities, (part. per cycle):</u> <ul style="list-style-type: none"> <li>• Protons, deuterons</li> <li>• Heavy ions (A ~ 200)</li> <li>• Polarized deuterons</li> </ul>	$\sim 3.5 \cdot 10^{10}$ not available $\sim 10^7 - 10^8$

annual operation time was  
at the level of 2000 hours

# “NUCLOTRON-M”

- The project “Nuclotron-M” is considered as the first subproject (SP1) of the JINR future project **NICA/MPD** ( **N**uclotron-based **I**on **C**ollider **f**acility and **M**ixed **P**hase **D**etector).
- The NICA/MPD facility is aimed at investigation of the mixed phase formation in strongly interacting nuclear matter at extremely high baryon densities and polarization phenomena in few-body nucleon systems.
- The extension of JINR research capabilities for generation of intense heavy ion and high intensity light polarized nuclear beams, including design and construction of heavy ion collider aimed at reaching the collision energies of  $\sqrt{s_{NN}} = 4\div 9$  GeV and average luminosity of  $1\cdot 10^{27} \text{ cm}^{-2}\text{s}^{-1}$ .
- Different schemes of the **NICA** were considered by the present time. It was shown, the NICA specified parameters (average luminosity, c.m. collision energy, atomic mass range) can be reached.
- The main parts of the project are the following:
  - *development, modernization and improvement of the Nuclotron systems,*
  - *design and construction of heavy ion injector,*
  - *design and construction of heavy ion booster synchrotron and*
  - *design and construction of the collider rings.*

# Nuclotron: status and future development

Parameter/System	Nuclotron (available) in 2007	"Nuclotron-M" (project goals) 2008-2010	Comments
<u>The heaviest accelerated ions:</u> <ul style="list-style-type: none"> <li>• Mass, A</li> <li>• Charged state, q</li> </ul>	56 (iron) 24	238 (uranium) <sup>*)</sup>	<sup>*)</sup> acceleration of gold ions (A=198, q = 65) will be realized first
<u>Dipole magnetic field, T</u> <ul style="list-style-type: none"> <li>• Maximum tested in the ring</li> <li>• More frequently operation</li> </ul>	1.5 1.2 (up to)	2.0 2.0	<b>2.12 T</b> at the test bench before installation in the ring
<u>Magnetic field ramp, T/s</u> <ul style="list-style-type: none"> <li>• Nuclotron project</li> <li>• Maximum operating</li> </ul>	2.0 (up to) 1.0	1.2 – 1.5 1.2 – 1.5	<b>4.0 T/s</b> at test bench before installation in the ring
Vacuum in the ring (averaged), Torr	$\sim 2 \cdot 10^{-8}$	$\sim 5 \cdot 10^{-10}$	N <sub>2</sub> concentration at T = 300 K equivalent
<u>RF acceleration:</u> <ul style="list-style-type: none"> <li>• Number of the RF stations</li> <li>• Particle capture scheme</li> </ul>	2 non-adiabatic	3 adiabatic <sup>*)</sup>	<sup>*)</sup> better efficiency of capture (by a factor of two)
<u>Beam extraction:</u> <ul style="list-style-type: none"> <li>• Max. beam energy, GeV/u</li> <li>• Electrostatic septa voltage, kV</li> <li>• Spill duration (minimum), mks</li> <li>• Spill duration (maximum), s</li> </ul>	2.2 120 100 10	6 200 - $\sim 2.5 \cdot 10^{-8}$	(q/A = 0.5)  single bunch
<u>Beam intensities, (part. per cycle):</u> <ul style="list-style-type: none"> <li>• Protons, deuterons</li> <li>• Heavy ions (A ~ 200)</li> <li>• Polarized deuterons</li> </ul>	$\sim 3.5 \cdot 10^{10}$ not available $\sim 10^7 - 10^8$	$\sim 1 \cdot 10^{11}$ $\sim 10^7$ $\sim 10^{10}$	minimization of the losses, development of the ion source KRION, new polarized ion source

The necessary set of R&D, construction and experimental work that should be done for the Nuclotron upgrade is covered by the project "Nuclotron-M".



# The main goal of the NICA project is an experimental study of hot and dense nuclear matter and spin physics problems

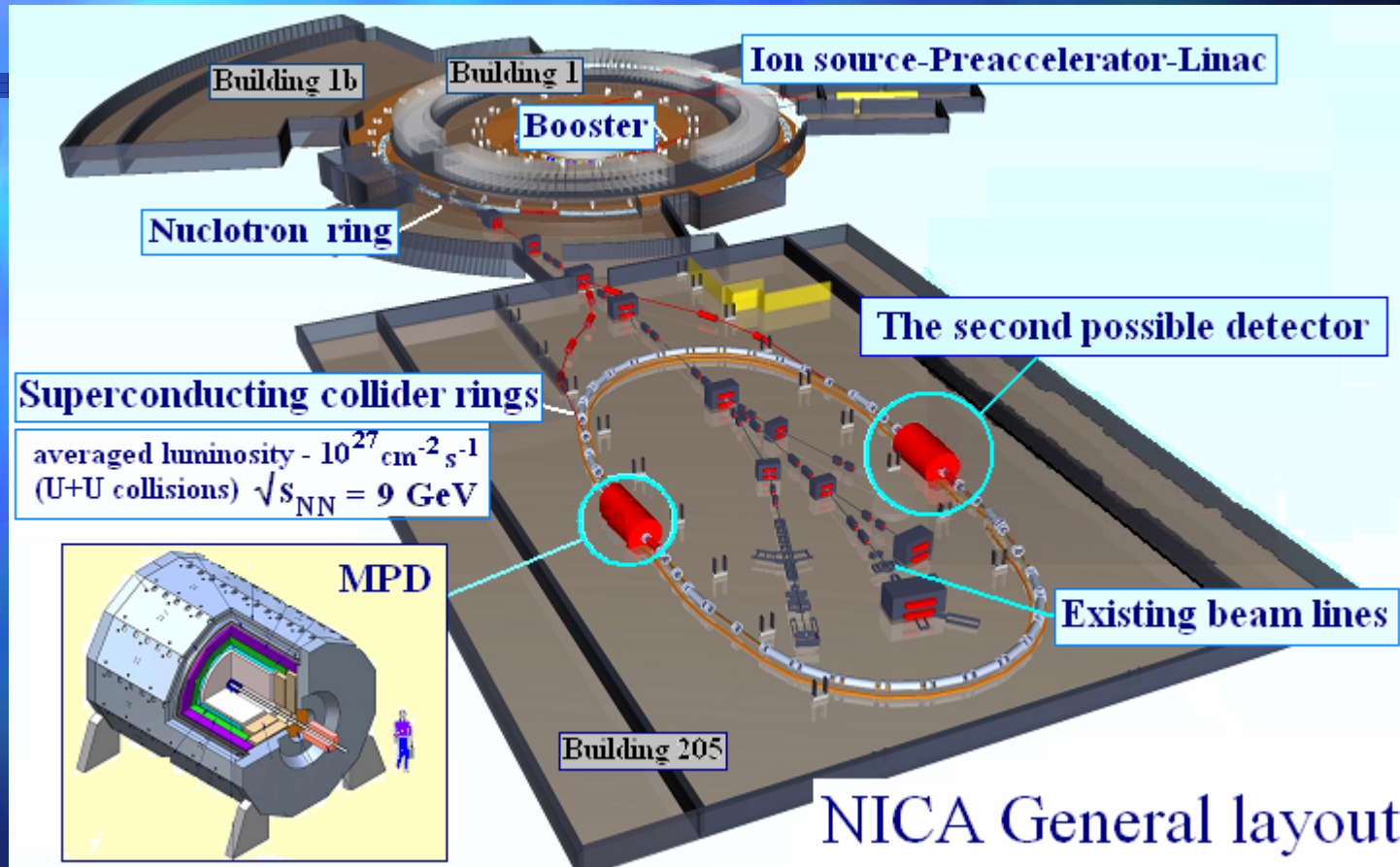
These goals are proposed to be reached by:

- development of the existing accelerator facility as a basis for generation of intense beams over atomic mass range from protons to uranium and light polarized ions; (1st stage of the NICA accelerator programme: Nuclotron-M)



- design and construction of heavy ion collider with maximum collision energy of  $\sqrt{s_{NN}} = 9 \text{ GeV}$  and average luminosity  $10^{27} \text{ cm}^{-2} \text{ s}^{-1}$  (for  $\text{U}^{92+}$ ), and polarized proton beams with energy  $\sqrt{s} \sim 27 \text{ GeV}$  and average luminosity  $> 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ ;
- design and construction of the MultiPurpose Detector (MPD).

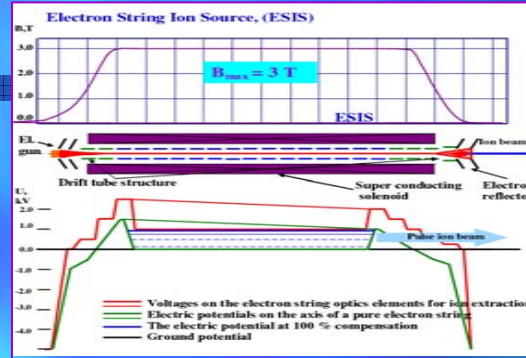
# Layout of the NICA/MPD (2007 )



**Subproject SP1.1 “Design and construction of highly charged state heavy ion source based on the “KRION” technology”**  
 ( leaders: E.E. Donets and E.D. Donets )



• **Development of heavy ion source KRION**



The first Au<sup>32+</sup> ion beams have been obtained in October 2006. Ionization time was 100 ms. The total intensity was of  $1.2 \cdot 10^9$  ions/pulse.

*General view of the ion source and basic operation scheme.*

**Construction and test of the new ion source with 6 T solenoid within the coming two years is the main goal of the SP1.1.**

The new important feature of the source is capability of operation at high pulse repetition rate in the case of production heavy ions at intermediate charged states, was considered.

U<sup>30+</sup> intensity of  $(4-8) \cdot 10^{10}$  ions/sec is reached in the case of the pulse repetition rate of 5-10 Hz.

The fundamental parameter of a KRION-type source is a factor  $j\tau$  - product of electron current density and ionization time. The  $j\tau$  value depends, in particular, on the applied external magnetic field. The maximum magnetic field in the existing ion source don't exceed 3 T. Ionization capability of the source and experimental results have been obtained at test bench are presented

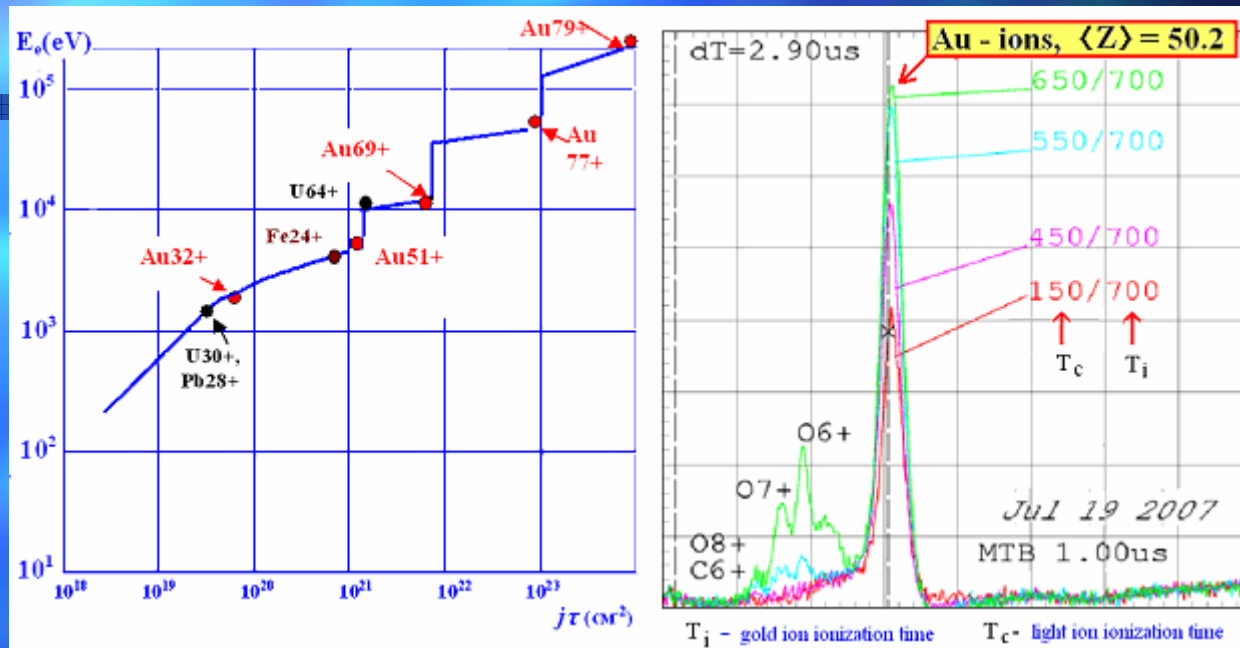


Fig. 2. Ionization capability (left plot) and experimental results from the ion source KRION-2 on generation of highly charged state gold ions.

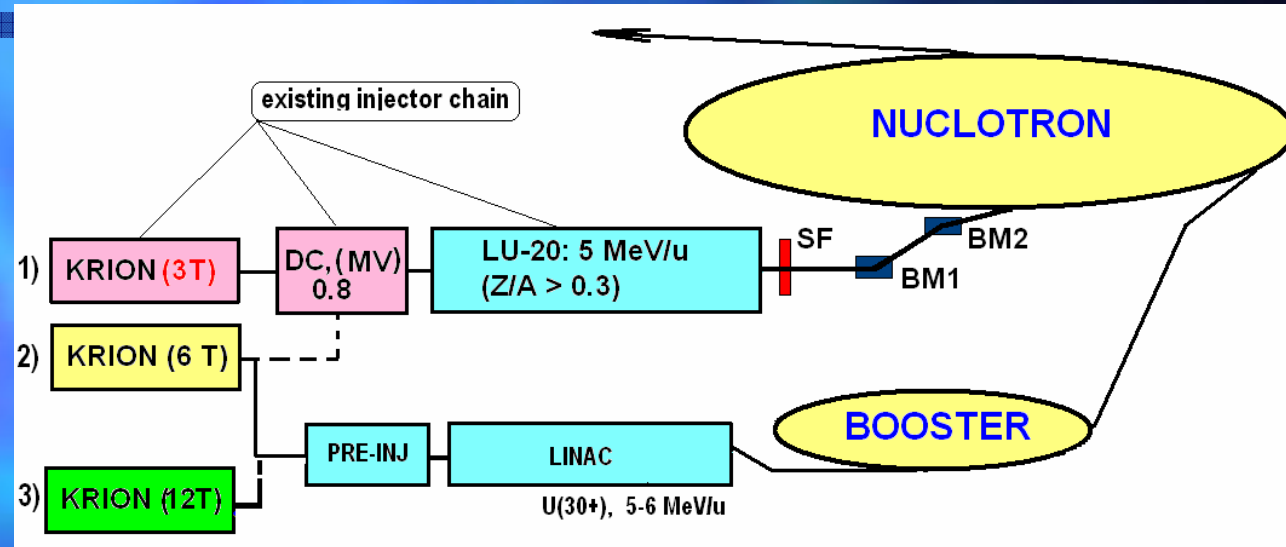
1. Design and construction of the new electron-string highly-charged state heavy ion source KRION-6T aimed at generation of heavy ion beams with  $q/A$  up to 0.33 (for example Au65+ ÷ Au69+).
2. Study of the electron string phenomenon at different conditions in the source working volume ( magnetic field range up to 6 T, energy of electron beam up to 25 keV). Development and optimization of heavy atoms injection into the string and ion-ion cooling process. The further investigation of tubular electron-string ion source
3. Preparation of the existing source KRION-2 to the next run at the Nuclotron aimed at acceleration of the ion beams over atomic mass range of  $A \sim 100$  ( the last decision is xenon Xe(44+).



**•Design and construction work on heavy ion pre-accelerator chain with injection and extraction beam lines**

The existing complex will be used for protons, deuterons, **polarized deuterons** and light ions ( $Z/A > 0.3$ ).

The new heavy ion source KRION-6T, upgrade of pre-accelerators and improvement of vacuum in LU-20 and injection line is supposed within the project “Nuclotron-M”.

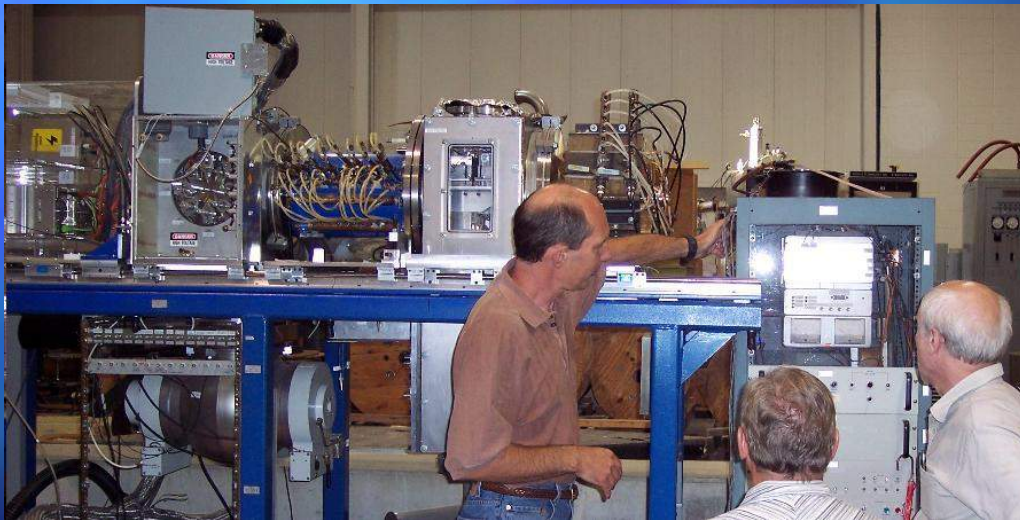


*The limiting charge-to-mass ratio of ion accelerated in the LU-20 is  $q/A \geq 0.3$ . As it follows from the SP1.1 sub-project description, the possibility of the KRION-type ion source with the magnetic field of 3 T and energy of the electron beam up to 6 keV (existing version of the source) can provide ion beam of  $^{130}\text{Xe}^{44+}$ , i.e. ions with  $q/A \approx 0.34$ . Thus, it is possible to perform a test acceleration of heavy ion beam with atomic mass of 130 at the Nuclotron after completion of the work on improvement of vacuum in the accelerator chamber. Acceleration of gold ions will be performed after construction of KRION-6T ion source.*

## Design and construction of high intensity polarized deuterons and protons ion source.”



The main direction of work aimed at increase of polarized beam intensity at the Nuclotron is connected with the design and construction of the new high current polarized ion source (IPSN) based on the equipment of CIPIOS polarized proton and deuteron ion source from Bloomington. The work is carried out in collaboration with INR (Troitsk). The ion source equipment (not completed) was transported to Dubna from IUCF (Indiana University, Bloomington, USA). Some parts of a suitable equipment for the new source were presented from DAPNIA (Saclay).



See presentation  
by V.Fimushkin at  
this workshop for  
more details

A.Kovalenko, SYMMETRIES AND SPIN, Praha, July 20-26, 2008

# Scheme of the NICA (CDR, January 2008)

**Injector:**  $2 \times 10^9$  ions/pulse of  $^{238}\text{U}^{32+}$   
at energy 6 MeV/u

## Collider (45 Tm)

Storage of  
15 bunches  $\times$   $1 \cdot 10^9$  ions per ring  
at 3.5 GeV/u,  
electron and/or stochastic cooling

## Booster (30 Tm)

2(3?) single-turn injections,  
storage of  $3.2 \times 10^9$ ,  
acceleration up to 50 MeV/u,  
electron cooling,  
acceleration  
up to 400 MeV/u

Stripping (40%)  $^{238}\text{U}^{32+} \Rightarrow ^{238}\text{U}^{92+}$

IP-1

Two  
superconducting  
collider rings

IP-2

2x15 injection  
cycles

## Nuclotron (45 Tm)

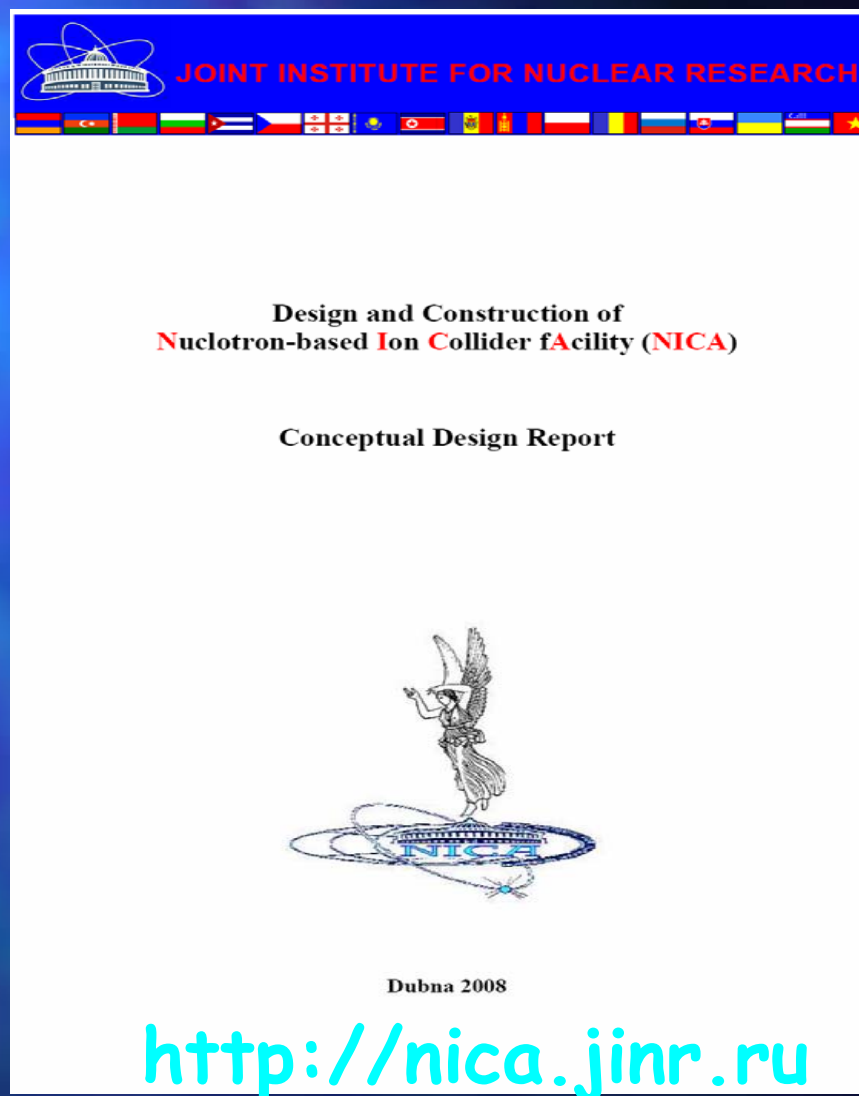
injection of one bunch  
of  $1.1 \times 10^9$  ions,  
acceleration up to  
3.5 GeV/u max.

1. Circumference, m	224
2. $\beta^*$ , m	0.5
3. $\Delta p/p$ ( $1\sigma$ )	$1 \cdot 10^{-3}$
4. Bunch length ( $\sigma$ ), m	0.3
5. Beam emittance ( $\sigma$ ), $\pi \cdot \text{mm} \cdot \text{mrad}$	0.26
6. Bunch intensity	$(1-2) \cdot 10^9$
7. Bunches per ring	15
<b>8. Average luminosity, <math>\text{cm}^{-2} \cdot \text{s}^{-1}</math></b>	
for UU: at 3.5 GeV/u	$1.1 \cdot 10^{27}$
at 1.0 GeV/u	$6.6 \cdot 10^{25}$
for pp: at 12.5 GeV	$3 \cdot 10^{31}$
dd: at 6 GeV/u	$1 \cdot 10^{31}$



# NICA – Collaboration

- Joint Institute for Nuclear Research
- Institute for Nuclear Research  
Russian Academy of Science
- Institute for High Energy Physics,  
Protvino
- Budker Institute of Nuclear  
Physics, Novosibirsk
- MoU with FAIR is under preparation
- *Open for extension ...*



# The NICA Project Milestones

*Proposal 2006*

- Stage 1: years 2007 – 2009

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

- Stage 2: years 2008 – 2012

- **Design and Construction of NICA and MPD**

- Stage 3: years 2010 – 2013

- Assembling

- Stage 4: year 2013 - 2014

- Commissioning

# The NICA/MPD (2008 )

## • NEW REALITY:

- request for 4 collision points (2 for the Mixed Phase Detector (hadron observables and lepton observables) and 2 for spin physics research – more space is needed

# The NICA/MPD (2008 )

- **NEW REALITY:**

- request for 4 collision points (2 for the Mixed Phase Detector (hadron observables and lepton observables) and 2 for spin physics research – more space is needed

- **SOLUTION?:**

# The NICA/MPD (2008 )

## • NEW REALITY:

- request for 4 collision points (2 for the Mixed Phase Detector (hadron observables and lepton observables) and 2 for spin physics research – more space is needed

## • SOLUTION?:

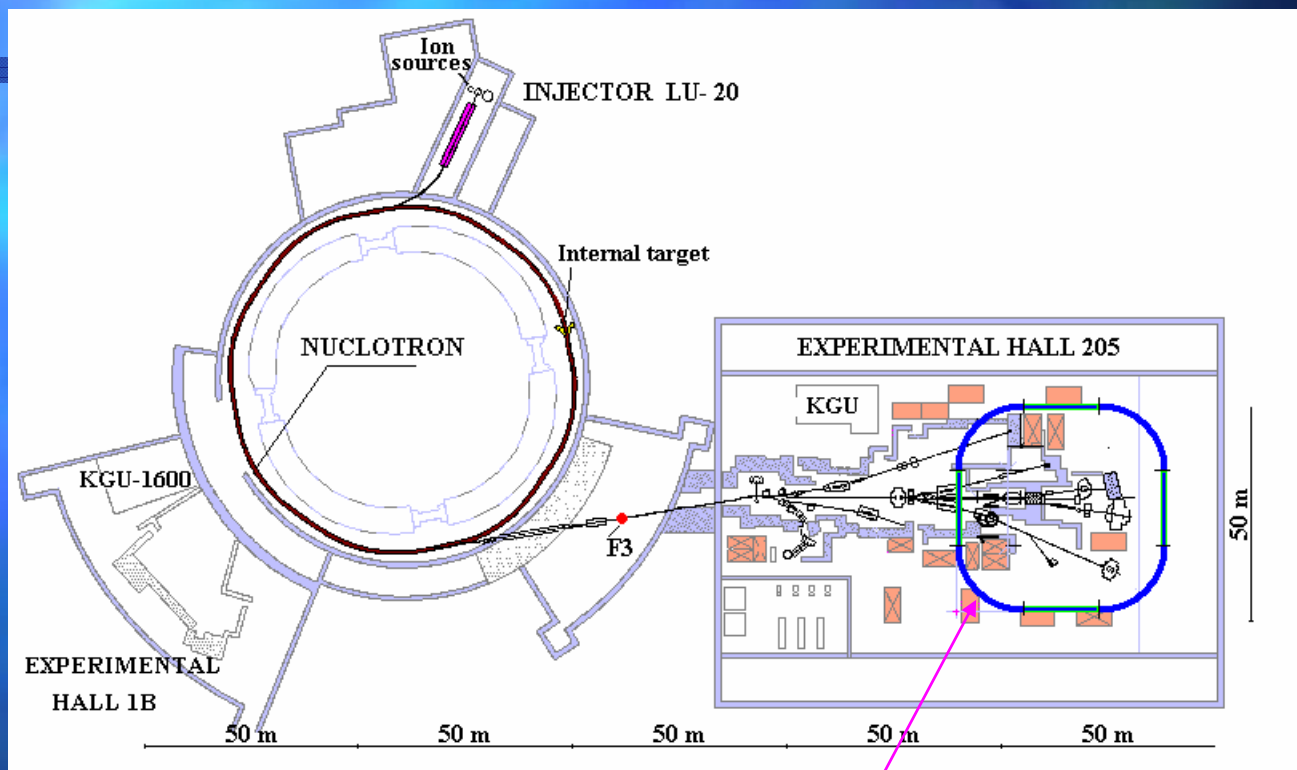
build the  
collider facility  
in the new  
tunnel?

to find feasible  
option of the collider  
rings for the existing  
building?

## NICA collider facility in the new tunnel



**feasible option of the collider rings for the existing building?**



**Superconducting 4.2 T dipoles are necessary for the collider rings, i.e. R&D.**

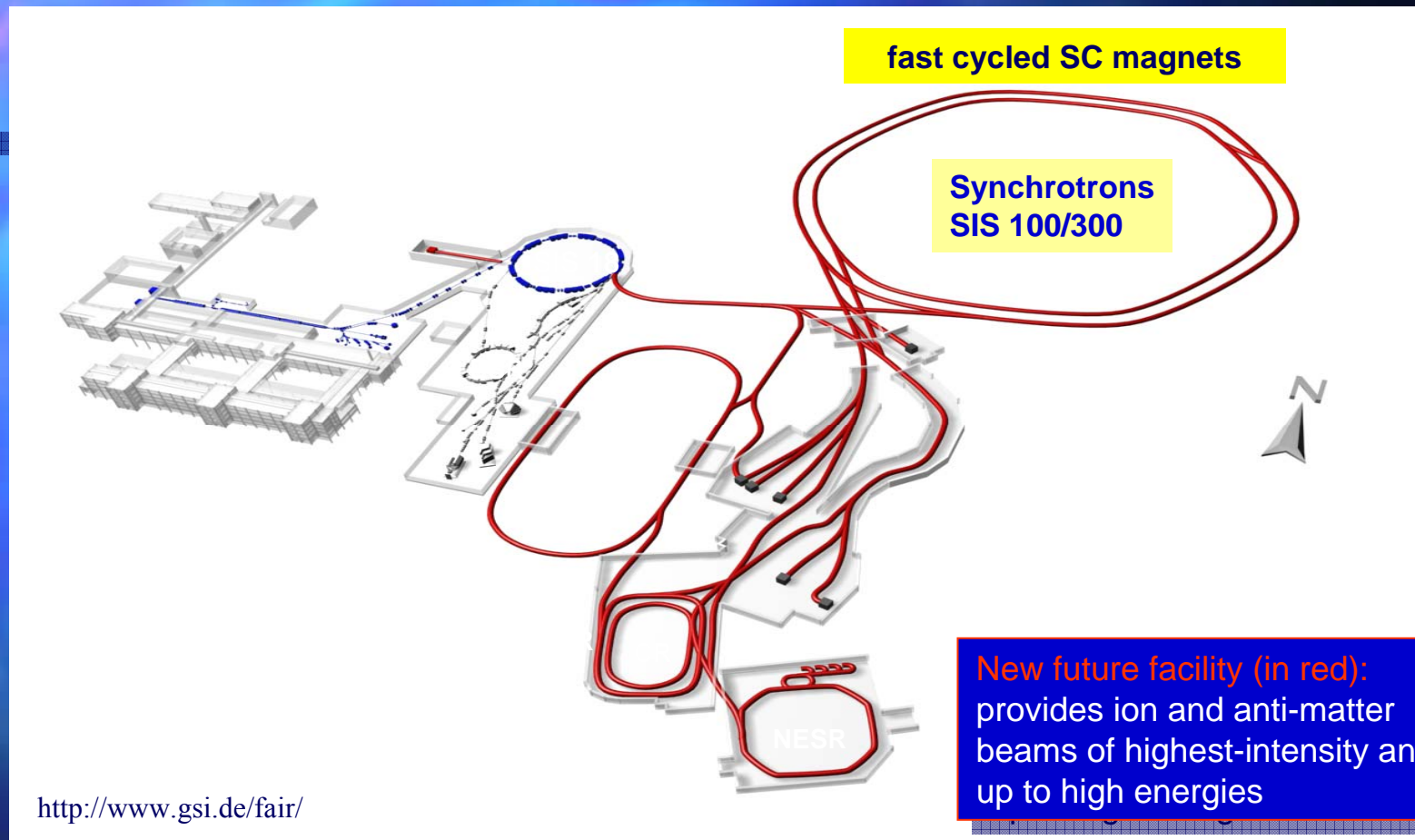


**Our Laboratory has a long term  
experience in a superferric 2 T  
magnets design and operation**

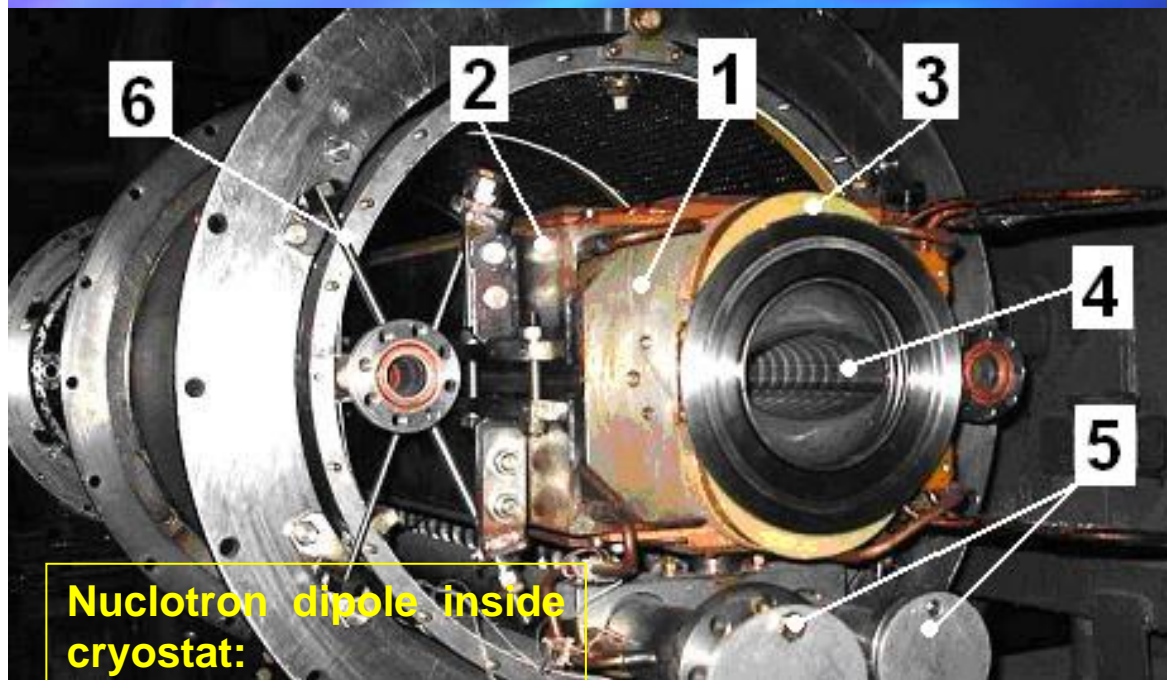
**A.Kovalenko, SYMMETRIES AND SPIN, Praha, July 20-26, 2008**



# FAIR: Facility for Antiproton and Ion Research

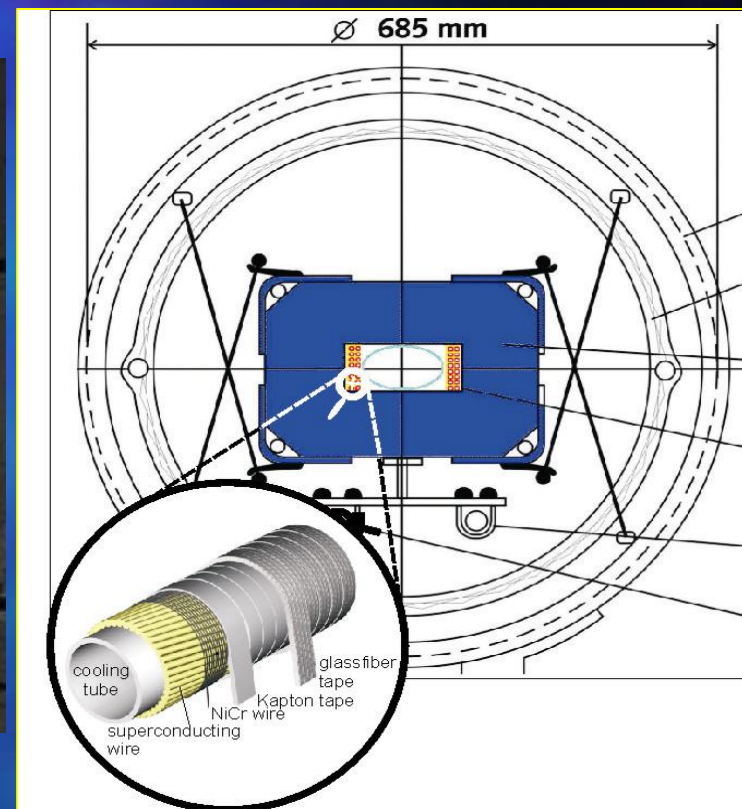


## Nuclotron Dipole – prototype of the FAIR SIS100 magnet



### Nuclotron dipole inside cryostat:

- 1 - yoke end plate
- 2 - brackets
- 3 - coil end loop
- 4 - beam pipe
- 5 - helium headers
- 6 - suspension
- 7 - laminated yoke



- Superferric design (window frame type)
- Maximum magnetic field: 2 T, Ramp rate: 4 T/s
- Hollow superconducting cable
- Two-phase helium cooling

# FAIR SIS100

1st Full Size Dipole made by industry,  
*BNG Company, Wirtsburg, Germany*



A.Kovalenko, SYMMETRIES AND SPIN, Praha, July 20-26, 2008

# Progress in the Design of a Fast-Cycling Cos $\theta$ -style Dipole Based on High Current Hollow Superconducting Cable

H. Khodzhabagyan\*, P. Akishin\*, A. Aifseev\*, V. Bartenev\*, A. Butenko\*, E. Fischer\*\*, A. Kovalenko\*, G. Kuznetsov\*, V. Mikhaylov\*, P. Nikitaev

\*Laboratory of High Energies, Joint Institute for Nuclear Research, Dubna, Russia; \*\*Gesellschaft fuer Schwerionenforschung mbH, Darmstadt, Germany

## INTRODUCTION

The concept of a fast-cycling Cos $\theta$ -style dipole based on a single-layer coil made from hollow NbTi cable was first presented at EUCAS2011. The main advantages of the new concept are much higher cooling efficiency of the superconductor and much less inductance of the magnet winding in comparison with traditional dipole based on classical Rebarford cable. The R&D and prototyping work in this direction is continuing at the LHE JINR since that time. One of the key issues is design and fabrication of a superconducting cable operating at 4.5 K, 30 kA and a gap magnetic field of 4 T and higher. Moreover, it is extremely important to reach the highest current density in the cable without losing its good cooling conditions. We continue to explore the concept of NbTi multi-wire hollow cable cooled with two-phase helium flow similar to the one which was proposed and used for the NIKKOLOV 2 T, 4 T and 6 T superconducting magnets. The proposed new design opens the possibility to improve substantially the cable performance substantially. The first results in optimization of the magnetic field in the magnet aperture were presented at EUCAS13. There was an attempt to suppress higher harmonics of the magnetic field in the aperture by means of a proper angular distribution of the coil turns. The best obtained result was a relative nonlinearity of the field  $\Delta B/B \approx 2 \cdot 10^{-3}$  with 75% of the magnet aperture at  $B = 4$  T. A new optimization step was made with the development of a mathematical model and a new computer code to perform the optimization of the linear shape of the ferromagnetic boundary.

## CROSS SECTION AND FIELD OPTIMIZATION

The optimized cross section of the dipole including the coil turns positions and the ferromagnetic yoke is presented in figure 1. The initial conditions were the following: the cable outer diameter is 9 mm, the aperture diameter of 104 mm, a radial position of the centers of the coil turns of 57 mm, BH curve of the ferromagnetic is the same as for the NIKKOLOV. The optimization process is based on a computer search for optimal angular positions of the turns and for an internal shape of the yoke inner profile which provide the minimum difference of the field vertical component at a circle of  $R = 40$  mm compared  $R = 0$ . Additional notches or current coils were introduced for limitation of the yoke. The optimization results are shown in figure 2. The sextupole nonlinearity was suppressed to about  $\pm 1 \cdot 10^{-4}$  of the main field with a 75% of the magnet aperture over dynamic range from 0.5 T to 4 T. Direct field calculations of the optimized dipole were performed using the ANSYS computer code. The obtained results confirm the excellent quality of the aperture field after the optimization of the dipole structure.

## OPTIMIZATION OF THE HOLLOW CABLE

The calculations show clearly, that the operating current of the cable should be about 35 kA for a magnetic field of 4 T (see figure 2). The space available for the optimal distribution of the coil turns (fig. 1) leads to the needed cable engineering current density of about 440 A/mm<sup>2</sup>. For the original NIKKOLOV cable the same parameter extrapolated to a value of  $B = 4$  T at 4.5 K would be exceeded 75 A/mm<sup>2</sup>, i.e. the difference reaches a factor of 6. Several possibilities to solve this problem were considered and partially have been tested experimentally: 1) increase of the outer cable diameter; 2) reduce the cooling channel diameter; 3) increase the percentage of the superconductor in the total cross section of the cable; 4) decrease the operating temperature of the coil; 5) optimize the magnet design to maximum B/I ratio; 6) use a wire made from other superconducting material (Nb<sub>3</sub>Sn, MgB<sub>2</sub>). A comparison of three new hollow cable versions (KNAW1, KNAW2 and KNAW3) designed in accordance with the mentioned above possibilities 1 - 4 is presented in Table 1.

It is obvious, that the calculated parameters of the KNAW2 and KNAW1 versions satisfy our design goal. The new cable's cross section is shown in figure 3. Note, the further increase of the KNAW2 critical current up to 53 kA is possible for example by means of decreasing the operating temperature to 4.3 K. The optimization of the dipole to a maximum B/I ratio can reduce the needed operating current. Nevertheless, additional sextupole correction windings should be added to the main dipole coil.

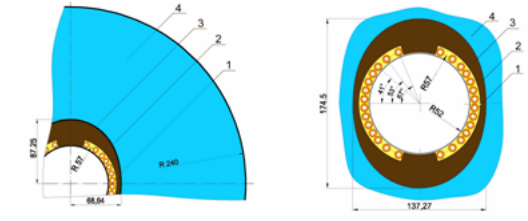


Figure 1. Optimized cross section of 4 T dipole: 1 - coil made from hollow superconducting cable, 2 - non-magnetic inner boundary, 3 - ferromagnetic inner boundary, 4 - laminated ferromagnetic yoke.

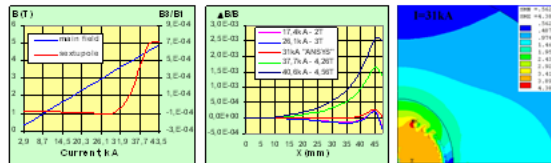


Figure 2. The results of 4 T dipole optimization (left plot) - dependence of the gap magnetic field and the field sextupole component (right plot) - relative (non-linear) field along horizontal axis; right plot - the field map, obtained with the ANSYS.

Table 1. Comparison of hollow cables

Parameter	Units	KNAW1	KNAW2	KNAW3
Cable diameter with insulation	mm	1.26	0.52	0.52
Cooling channel diameter	mm	4	3	3
Number of the strands		16	40	40
Strands cross-section	mm <sup>2</sup>	120	29	26.3
NbTi cross-section area	mm <sup>2</sup>	4.28	16.8	15.9
Percentage of NbTi in cable cross-section	%	10.1	26.9	25.4
Critical current density @ 4.5 T, 4.5 K	A/mm <sup>2</sup>	239.1	280	250.8
Operating current at 4.5 T	kA	12	27	40.1
Magnetic field in the aperture @ 4.5 K	A/mm <sup>2</sup>	2250	27	500
Critical current density @ 4.5 K	kA	11.46	48.8	43.1
Critical field operating current ratio		1.6	1.2	1.3

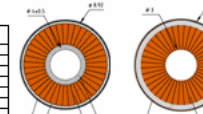


Figure 3. Cross section of the KNAW2 (left) and KNAW1 (right) cables: 1 - copper-clad NbTi, 2 - copper-clad NbTi strand, 3 - strand landing by wire, 4 - electrical insulation.

## MODEL CABLE TEST RESULTS

The KNAW1 version has been manufactured and tested as real dipole coil in the NIKKOLOV-type dipole. The R&D stages from keyhole wire fabrication at the Bocharov Research Institute (Moscow) to the first 50 m of the cable production at LHE JINR as well as the first coil from KNAW1 and its tests were described earlier. The maximum cycle operating current of 11.4 kA obtained in the July 2005 tests was limited not by the cable but by the test coil capabilities. The standard operation limits of the LHE test facility were: supply current of 6 kA, current ramp rate of 12 kA/s at a distance of 1 mH. The power supply upgrade performed in 2004-2005 made it possible to increase the current by a factor of two. The geometry of a single-layer turns winding made from KNAW1 corresponds to the 1.4 m long NIKKOLOV window frame yoke. The sizes of a window are 126 mm x 59 mm. The coil was separated from the yoke window by a gap of 2 mm. As stable operation of the magnet at  $B = 4$  T,  $I = 0.5$  Hz was obtained up to the 4 supply current of about 12 kA. The first quench occurred at a current of 14 kA after more than 10 cycles. The quench was initiated by the current lead. No normal zone was detected in the coil.

## SUMMARY & OUTLOOK

The optimized version of a 4 T "Cos $\theta$ -style" dipole with the aperture of 104 mm was developed based on a new mathematical model for the magnetic field calculations and a new approach to high current hollow NbTi composite multistrand cable manufacturing. The experimental tests of the KNAW1 cable version have verified the possibility to increase the operating current to about 12 kA, i.e. by a factor of 2 compared to the original one. Thus, the constraining capability of a single-layer 2 T, 4 T, 6 T Hz superconducting window-frame dipole magnet was confirmed as a by-product of the R&D. Preliminary calculations lead to the technical possibility to reach peak magnetic fields up to 4.4-4.5 T at field ramp rates of 3 - 4 T/s, based on a single-layer dipole with the coil made from high current hollow cable. These topics will be analyzed in further in more detail in the future.

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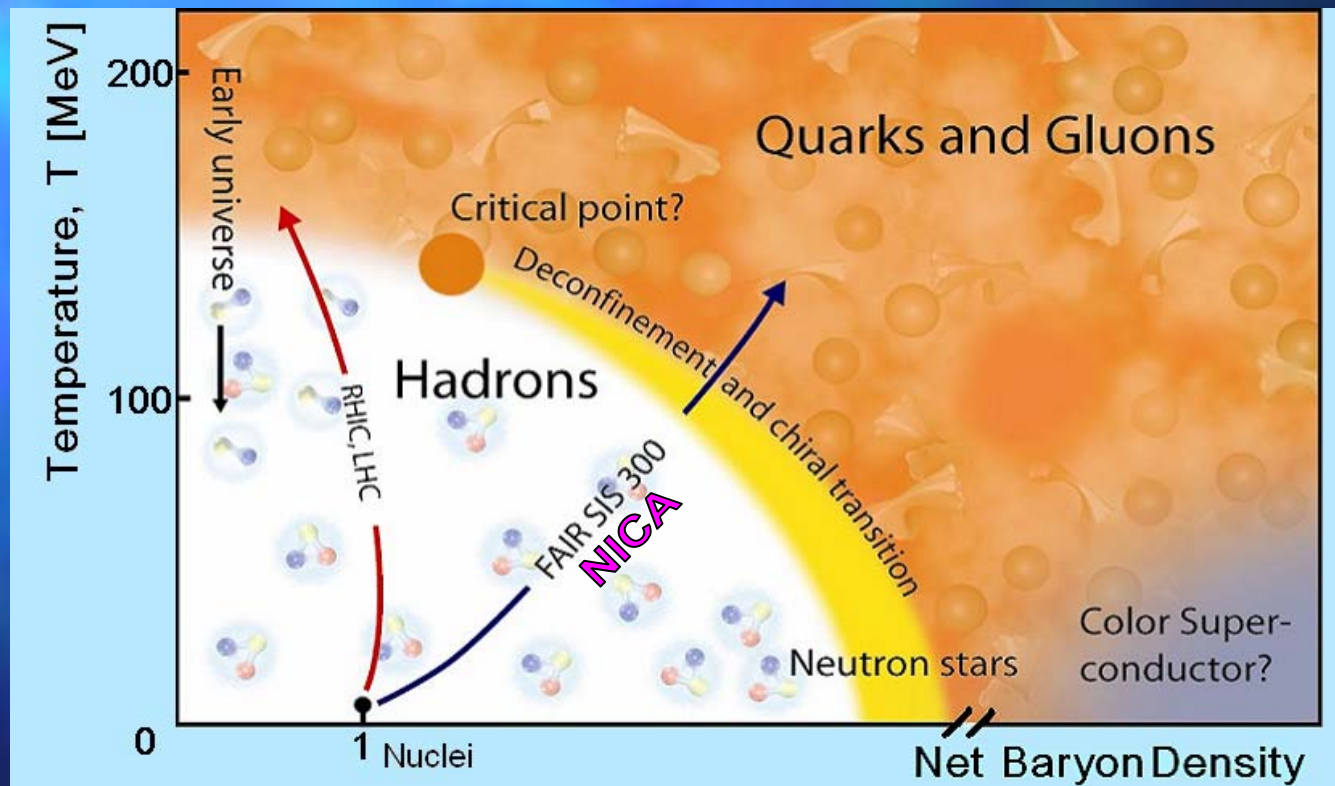
\*H. Khodzhabagyan, e-mail: hamie@yandex.ru

The work is supported in part by the Russian Foundation for Basic Research grant 09-02-00020.



A.Kovalenko, SYMMETRIES AND SPIN, Praha, July 20-26, 2008

Realization of the NICA project at JINR will make it possible to obtain the unique data on the interaction of both as heavy ion and light polarized nuclear beams. The FAIR CBM at SIS300 and MPD at NICA are complementary facilities.



A.Kovalenko, SYMMETRIES AND SPIN, Praha, July 20-26, 2008