VLHC Based on the Nuclotron-Type Cryomagnetic System

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***Abstract* - The Nuclotron-type low-cost technology of superconducting magnetic systems for future multi-TeV energy range synchrotrons and colliders is considered. The status of the Nuclotron is presented.**

I. INTRODUCTORY REMARKS

The Laboratory of High Energies (LHE) of JINR is a pioneer in designing and constructing the world first superconducting synchrotron based on iron dominated SC-magnets. This 6 A GeV accelerator named Nuclotron was being built for five years (1987-1992), its magnetic system was fabricated by the JINR and LHE workshops without having recourse to industry. The Nuclotron ring 251 m in perimeter is installed in the technological tunnel with a cross-section of 2.5m x 3 m (Fig.1). The project cost of the Nuclotron is 8.35 MRbls (in prices of 1986).

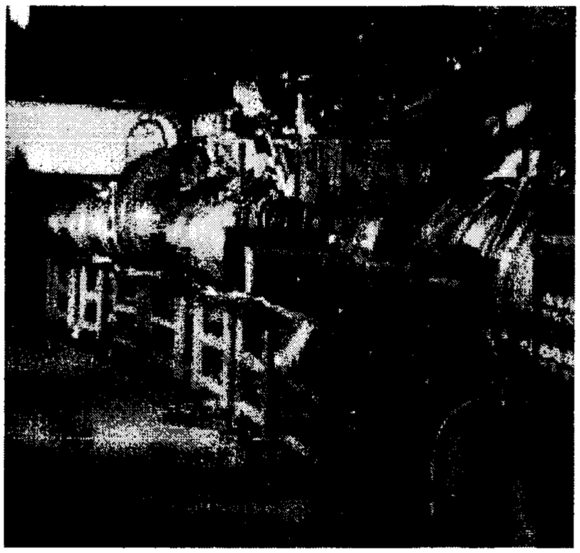

Fig 1. The Nuclotron in the tunnel.

The idea to construct a specialized superconducting accelerator of relativistic nuclei - Nuclotron at LHE was put forward by A.M.Baldin early in the 70th. Several options of pulsed superconducting SC-magnets and magnetic systems had been proposed and tested at the Laboratory during 1974-1980 before the choice of the Nuclotron system was made[1]. The technical proposal of the accelerator complex - Supernuclotron at LHE (2x60 A.GeV nuclear collider, 2x120 GeV pp-collider) based on the low-field, cold iron superconducting magnetic system was designed during 1987-89 after the building of the Nuclotron has been started. Further miniaturization of the SC-magnet and tunnel cross-section were the key features of that proposal.

The first our estimates of the parameters of a 100 TeV synchrotron/collider based on the Nuclotron-type cryomagnetic system were made in December 1995 and presented at Mini-Symposium in Indianapolis in May 1996 [2]. Since that time our activity in this direction is continuing in cooperation with the designers of the VLHC at FNAL [3].

II. THE NUCLOTRON:

The Nuclotron cryomagnetic system has no analogues. The key element of the system is a unique rapid cycling SC-magnet with a cold iron yoke and low inductance coil made of a specially designed hollow tube-type SC-cable.. The magnets (96 dipoles and 64 quadrupoles) are connected to supply and return helium headers in parallel (not electrically) and cooled by forced flow of two-phase helium. The main parameters of the Nuclotron ring and its cryomagnetic system are presented in Table 1.

TABLE 1

Parameter	Unit	Value	Remarks
Maximum energy	GeV	12.8	for protons
Peak magnetic field in SC-dipoles, B_m	T	2.0	at I = 6.3 kA
Stored energy	MJ	2.35	at B = B_m
Circumference	m	251.5	
Operating temperature	K	4.5	
Total cold mass	t	80	
Static heat leaks	kW	1.75	
Dynamic heat releases	kW	2.90	at dB/dt = 2 T/s
Capacity of the refrigerators	kW	3x1.6	at T = 4.5 K
Cool down time	hours	80	
Repetition rate	Hz	1.0	maximum
Vacuum:			
beam pipe	nTorr	0.1 - 1.0	
isolating volume	nTorr	100	
Cryostat diameter	m	0.7	

Thirteen runs of a total duration of 3100 hours were carried out since March 1993. The investigation of the superconducting magnetic system, different modes of its cooling and operation, as well as data taking for physics experiments with relativistic nuclei, was performed.

More detailed description of the Nuclotron cryomagnetic system and the parameters of the SC-magnets, were presented earlier [4]-[6]. Even in the case of rather large aperture (55mmx110mm), the weight of the Nuclotron magnetic system normalized per unit of length (about 300 kg/m) is the smallest one among circular accelerators. Other advantages such as a minimum amount of helium inside the cryostat, safety, good mechanical stability, and a high electric strength are also provided with the Nuclotron-type magnetic system. The ring is divided into two (cryostats) 125 m long. Each one is connected to the refrigerator of a nominal capacity of 1.6 kW at 4.5 K. Dynamic heat releases are a main heat load to the fast cycling mode of the Nuclotron operation. The mass vapour content of helium varies from 0 at the inlet of the magnet to 0.35 at its outlet. The length of SC-cable which the dipole magnet SC-coil made of is 62 m. Inner diameter of copper-nickel tube (cooling channel) is 4 mm. Helium in the supply header of each half-ring is kept in a liquid state by means of a phase separator and subcoolers. During all the runs, cooling the magnets was stable. No flow oscillations in the parallel cooling channels were observed under a pressure difference of above 20 kPa between the supply and return headers.

III. LOW COST LOW FIELD SC-MAGNETS AT LHE

The options of SC-magnets constructed and tested at LHE were the following:

a) cos θ - type model magnet with a peak field of 6T;

b) 2 T magnets with a window-frame type iron yoke and SC-coils made of the Rutherford-type SC-cable and refrigerated at 4.5K by immersion in liquid He;

c) 2T magnets with a window-frame type iron yoke and SC-coils made of the tube NbTi superconductor, cooled with a two-phase helium flow.

Option "a" was rejected after the first tests of the 6T prototype had been performed. It was clear that the high cost and complexity of a magnetic system of such a type led to the unfeasibility of the Nuclotron construction. So, since 1975 R&D work at LHE have been focused on the investigation of low-field iron dominated SC-magnets. This program resulted in the construction of two new accelerators: a 1.5 GeV synchrotron (named SPIN) and a 6 GeV/u synchrotron-Nuclotron based on options "b" and "c", respectively.

Five different modifications of 2-2.5T SC-dipoles (option "b") were constructed and tested by 1978. A general view of the magnets is shown in Fig.2. About half a year later, the first SC-dipole of option "c" was fabricated. Main parameters of these magnets are presented in Table 2.

TABLE 2

PARAMETERS OF THE FIRST LOW-COST SC-DIPOLES AT LHE , JINR

Parameter		Option "b"	Option "c"
Peak magnetic field	T	2.5	2.37
Aperture (hxv)	mm^2	55x55	55x55
Critical current	A	2600	7380
Stored energy	kJ/m	10.0	12.5
Iron yoke:			
type		"window-frame"	"window-frame"
cross-section	mm^2	140 x 130	180x150
window sizes (hxv)	mm^2	67x55	91x55
weight	kg/m	91	167
SC-coil:			
Superconductor		50%Nb-50%Ti	50%Nb-50%Ti
winding cross-section		rectangular	tube ∅6.5 mm
number of turns		48	16
inductance	mH/m	3.5	0.45
current density	kA/cm^2	60	12.4
Cooling:			
operating temperature	K	4.7	4.7
coolant		LqHe	two-phase He
method of cooling		immerse	forced flow

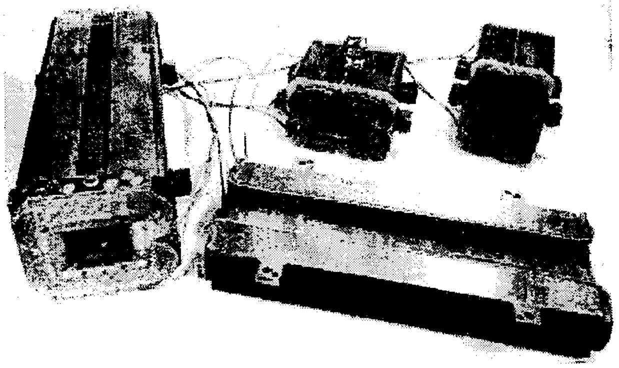

Fig.2. View of the magnets, option "b".

The magnets of option "b" are the most miniature accelerator magnets to date. The highest current density, as well as the best ratio between the total and "useful" area of the magnetic field, is realized in such design. Nevertheless, the magnets of option "c" have a convincing advantage: a very simple and effective cooling system. Stand tests of these magnets were performed at a magnetic field ramp rate of up to 8 T/s. Finally, option "c" was chosen for the Nuclotron magnetic system.

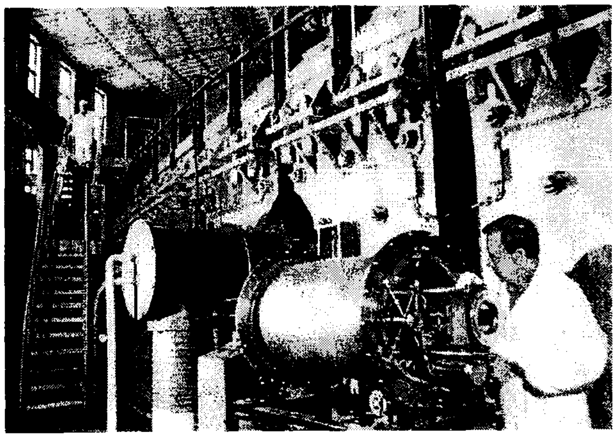

Fig.3. The Nuclotron cryomagnetic unit near the Synchrophasotron.

IV. NUCLOTRON-TYPE SEGMENT OF THE VLHC

To make desired extrapolation we assume: "good field" aperture in the dipoles of 18 mm x 25 mm (vxh); peak magnetic field $B_m = 2.2$ T;total heat load, including synchrotron radiation at E=50 TeV, not exceed 0.5 W/m. The results of such an extrapolation are presented in Table 3. The unit capacity of helium refrigerators was chosen to be 5 kW at 4.5 K, corresponds to the refrigerator capacity of the Nuclotron. Taking into account real possibility to use a combined function lattice for low-field VLHC the filling factor can be of 95%. In this case the segment 10 km long of the VLHC ring is needed to provide 1 TeV proton energy. So, the number of such segments is equal to desired VLHC energy per beam in TeV's. The option of "side-by-side" two-in-one SC-dipole was considered, like that has been presented in [7]. Other architecture of the window-frame yoke, for example, twin aperture "bottom-on-top" can be even more preferable.

TABLE 3
THE NUCLOTRON - TYPE CRYOMAGNETIC SEGMENT OF VLHC

Magnetic length	10	km
Peak field	2.2	T
Total cold mass	600	ton
Vacuum vessel outer diameter	0.28	m
Cooldown time	140	hrs
Ring segmentation		
unit capacity at 4.5 K	5	kW
number of strings in unit	2	
number of magnets in string	100	
helium headers (supply/return)	55/108	cm
Magnet		
window frame yoke	2-in-1	
length	50	m
aperture (horizontal/vertical)	30/20	mm
stored energy	~3	kJ/m
yoke sizes (horizontal/vertical)	130/55	mm
inductance (per beam)	~3	μH/m
winding	single turn	
weight of NbTi	2x10	kg
drive current	34	kA
coolant	two-phase helium	
operating temperature	4.7-4.4	K

So, the Nuclotron-type VLHC is based on the twin-aperture window-frame cold iron yoke, single turn SC-coil made of a plane superconducting cable and forced cooling the yoke with two-phase helium flow. The advantages of the above mentioned options "b" and "c" are combined in this approach. Notice that the magnetic field direction can be changed independently in each aperture. So, it is possible to use such a system both as for pp- and ppbar-collisions.

The comparison of the Nuclotron-type VLHC and the LHC presented in Table 4.

TABLE 4
NORMALIZED PARAMETERS OF THE NUCLOTRON-TYPE VLHC AND LHC SYSTEMS

Cost driver		VLHC	LHC [8]
Iron weight	ton/TeV	600	4300
Superconductor weight	ton/TeV	2	57
Stored energy	kJ/m (MJ/TeV)	6 (60)	493 (1900)
Inductance	mH/m	0.006	7.3
Refrigerating capacity			
at 4.5 K	kW/TeV	5	343
at 1.9 K	kW/TeV	0	1.8
Length of the ring	km/TeV	10	3.8
Cryostat diameter	m	0.28	0.98

V. SUMMARY & OUTLOOK

A low-field option of the VLHC provides much lower cost of SC-magnetic system, power supply, quench protection, cryogenics etc. High safety and reliability as well as flexibility of control and operation are also important advantages of a low-field VLHC. Long underground tunnel of 2÷2.5 m in diameter can be used not only for the accelerator ring, but also for interregional power lines, communication cables, etc. In this case the expenses on the construction and technical support of the tunnel infrastructure directly connected with the VLHC project could be substantially decreased.

The R & D on high - field (B ≅ 10 ÷ 15 T) SC-magnets is important but the usefulness for the VLHC is very problematic due to many reasons.

We consider cold-iron low-field concept as the most feasible way to construct the VLHC. Nevertheless, at the present stage different approaches should be carefully studied [9].

VI. ACKNOWLEDGEMENTS

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