A Cold- Iron Low Field Magnets for the VLHC

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***Abstract* - The new concept of a cold-iron 2T SC-magnetic system for the VLHC is presented.**

INTRODUCTORY REMARKS

The Laboratory of High Energies (LHE) of JINR has 25 year experience in design and construction of a cold-iron 2T SC-magnets and magnetic systems. The world first superferric synchrotron - Nuclotron was being built at LHE 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). The Nuclotron cryomagnetic system has no analogues. 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.

Fourteen runs of a total duration of 3500 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 [1]-[4]. 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.

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. The proposal of 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 [5]. Since that time our activity in this direction is continuing in cooperation with the designers of the VLHC at FNAL [6].

Two options of a cold iron low field magnetic system for the VLHC conceptually designed at the LHE up to now. Both are presented below.

THE NUCLOTRON

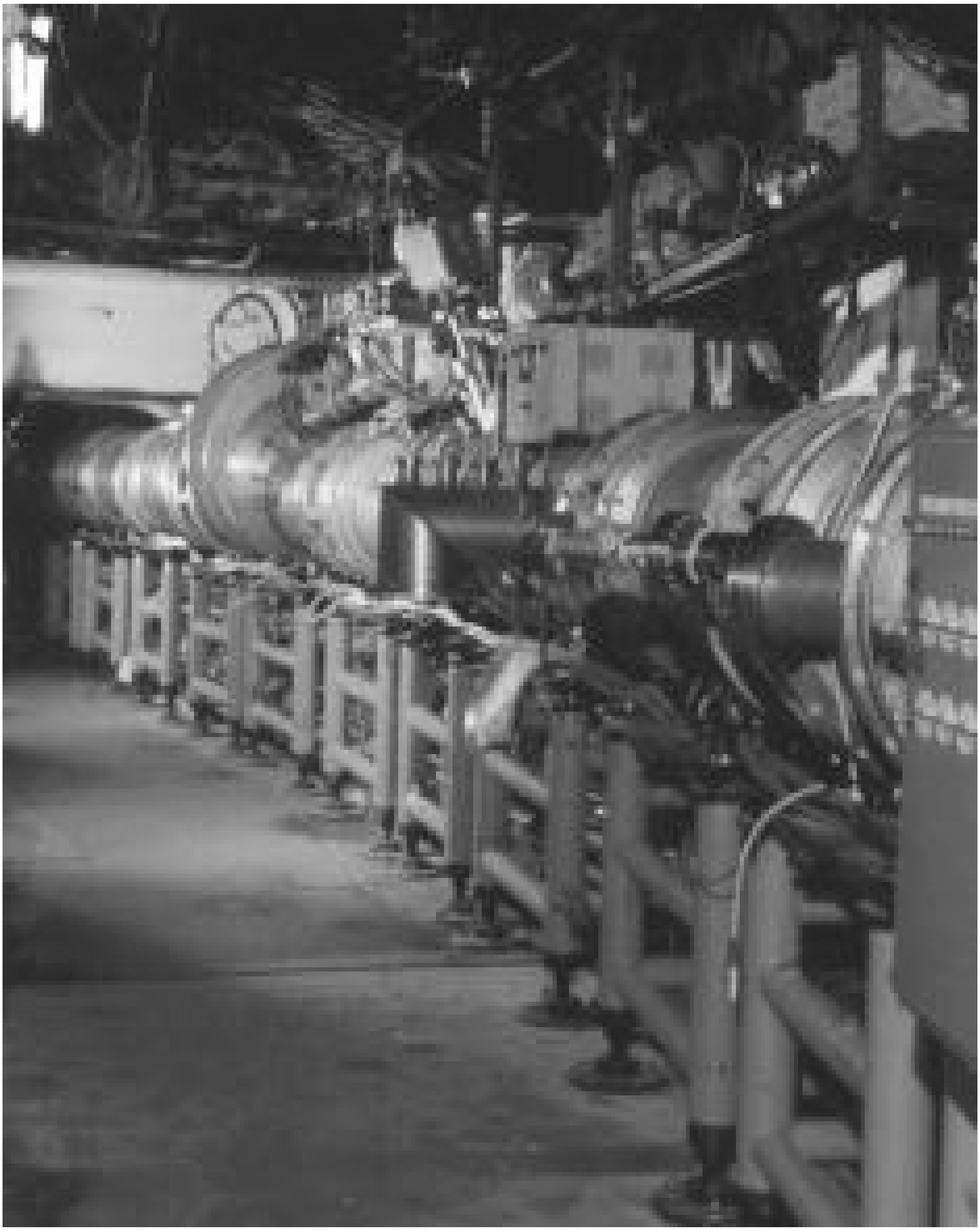


Fig 1. The Nuclotron in the tunnel.

THE FIRST SET OF 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. About half a year later, the first SC-dipole of option «c» was fabricated. Main parameters of these magnets are presented in Table 1.

TABLE 1

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

NUCLOTRON-TYPE SEGMENT OF THE VLHC

(option of June 1996)

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 2. 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 presented in Fig.2 [7]. Other architecture of the window-frame yoke, for example, twin aperture «bottom-on-top» can be even more preferable.

TABLE 2

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 3.

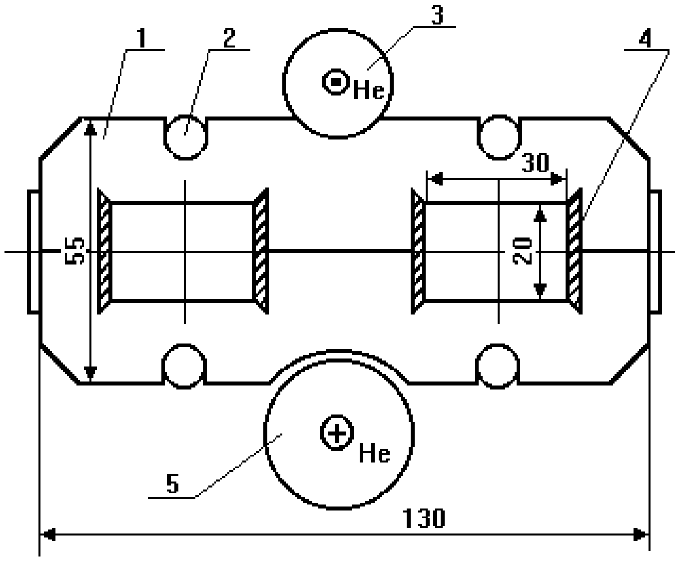


Fig 2. Cross-section of the Nuclotron-type dipole for the multi-TeV Hadron Collider. 1-iron yoke; 2-cooling channel; 3,5-supply and return headers, respectivily; 4-SC-winding.

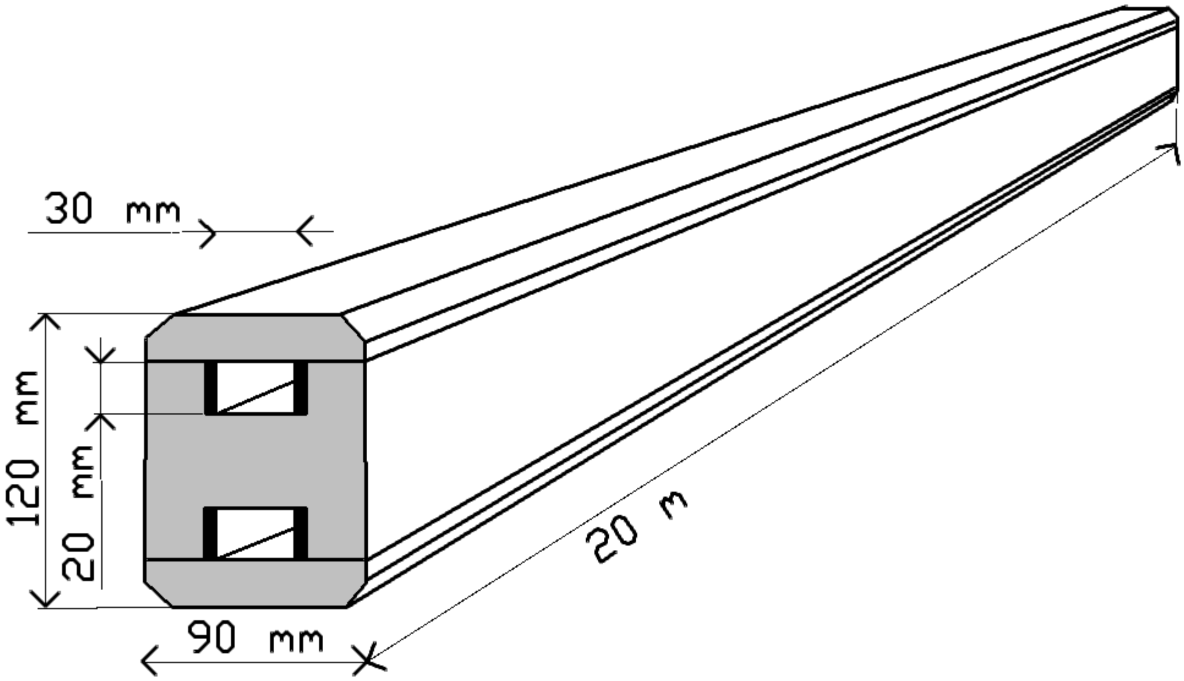
TABLE 3

NORMALIZED PARAMETERS OF THE NUCLOTRON-TYPE VLHC AND LHC SYSTEMS

Cost driver		VLHC [7]	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 at 1.9 K	 kW/TeV kW/TeV	 5 0	 343 1.8
Length of the ring	km/TeV	10	3.8
Cryostat diameter	m	0.28	0.98

Cold-Iron Low-Field SC-Magnet

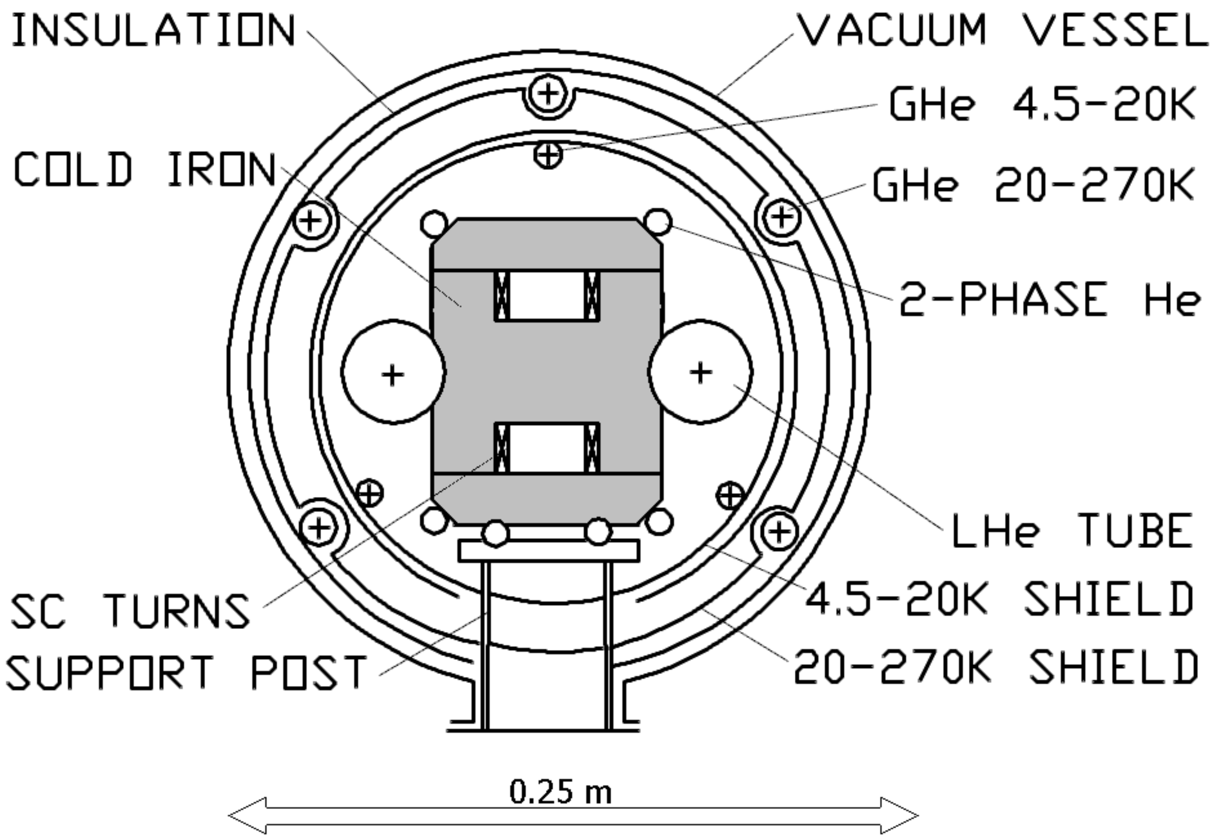
- «8-type» (option 2/98, Nov.1998)



peak field	2.2	T
length	20	m
aperture (horizontal/vertical)	30/20	mm
stored energy (per aperture)	1.35	kJ/m
yoke sizes (horizontal/vertical)	90/120	mm
cold mass	70	kg/m
number of turns	1	
cross-section of the turn	~ 1	cm^2
inductance (per aperture)	~ 3	μH/m
weight of NbTi	2x0.2	kg/m
drive current	34	kA
operating temperature	4.7	K

Cross-section of the Cryo-magnet Assembly

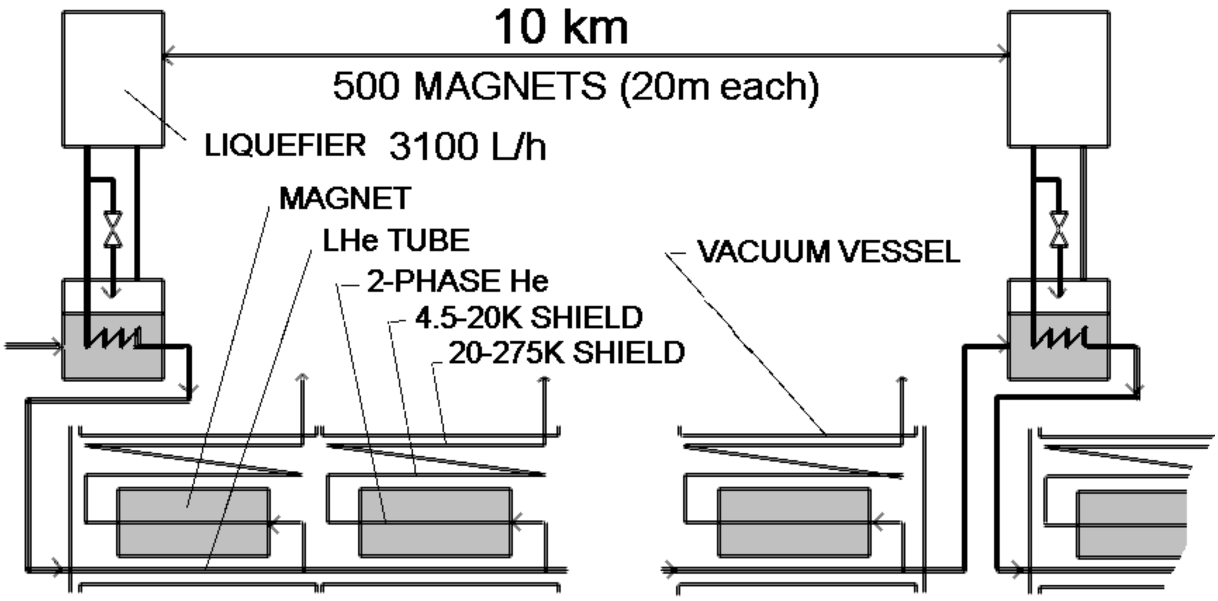
- **«8-type» (option 2/98, Nov.1998)**



- no vacuum chamber (p ≤ 1 nTorr)
- minimal number of elements and interconnections
- best ratio: good field/total field area
- possibility to change field direction
- high quality of the magnetic field:
  - sextupole & decapole correction;
  - normal quadrupole adjustment;
  - skew dipole & quadrupole suppression.

Flow Diagram of a VLHC Segment

- «8-type» (option 2/98, Nov.1998)



Length of the segment	10	km
Energy (per beam)	1	TeV
Cold mass	700	ton
Helium liquefaction capacity	3.1	m^3/hour
Heat load to 4.5 K	2.0	kW
Heat load to 4.5-20 K shield	9.1	kW
Heat load to 20-270 K shield	135.5	kW
Cross-section of LHE tubes	18	cm^2
Electric power	4.0	MW

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 ≡ 14 ÷ 20 T) SC-magnets are very important nevertheless application of such magnets for the VLHC looks very problematic due to many reasons.

The future works at LHE JINR in the frames of R&D on the VLHC could be the following:

- technical design of the «8-type» magnet prototype;
- design, fabrication & tests of SC-cable and SC-buses;
- fabrication and stand tests of the cryomagnet assembly prototype.
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