VLHC BASED ON COOLED IRON INTERMEDIATE FIELD SUPERCONDUCTING MAGNETS
A.D.Kovalenko, JINR, Dubna, Russia

Abstract
A new approach to the VLHC cryomagnetic system design is considered. The magnets are based on a superconducting one-layer winding at T=4.5 K and an iron yoke/shield at T=(50+80) K. The experimental results obtained in this direction at the Laboratory of High Energies, JINR are presented. Essential features of the redesigned Nuclotron-type and cosine θ-type magnets are analysed. Other key problems of the VLHC construction are also discussed.

1 INTRODUCTION
Works on a search for and an analysis of the most cost-effective cryomagnetic systems of proton and ion high energy synchrotrons/colliders over an energy range of much larger than the LHC started at the Laboratory of High Energies (LHE), JINR in 1995. Our first result, presented at the Mini-Symposium “New Low-Cost Approaches to High Energy Hadron Colliders at Fermilab” in Indianapolis, was based on the extrapolation of the operating parameters of the Nuclotron cryomagnetic system, as well as on the results of R&D works at miniature iron-dominated 2T field SC-magnets obtained at the LHE since 1975, for a 100 TeV synchrotron/collider [1]. A more detailed design of this concept was reported at EPAC’95 in Barcelona [2] and at HEACC’98 [3]. The option of a window-frame 20×30 mm² (v×h) twin aperture (side-by-side) magnet with a cold iron yoke and a one-turn NbTi superconducting bus driven by I=34 kA per each aperture was considered and discussed. By the time of HEACC’98, the steering committee for a future very large hadron collider was appointed to coordinate efforts in the United States to achieve a superconducting pp-collider with approximately 100 TeV cm and an approximately 10⁶³ cm² sec⁻¹ luminosity [4]. Three working groups, namely: magnet technology, accelerator technology and accelerator physics, were established. The progress achieved at our Laboratory and some new ideas were presented at both the Workshops 1 and 2 on the VLHC Magnet Technology in Port Jefferson (November 16-18, 1998) and in Batavia (May 24-26, 2000). The option presented in Port Jefferson[5] and called “8”-magnet was different from the previous one in its yoke configuration and cooling system. A window-frame twin aperture “bottom-on-top” yoke suitable for combined function magnet operation was proposed. The possibility to operate without a beam pipe and a high vacuum pumping system was also discussed. Nevertheless, all of the above-mentioned “Nuclotron-type” options of the VLHC were based on a cold iron/cold bore/LTS-coil approach. The next step towards a more effective cryomagnetic system can be made by applying a new concept- an intermediate temperature iron SC-magnet [6].

2 IRON YOKE AT INTERMEDIATE TEMPERATURE
The iron yoke is an important element of the magnet. It plays two major roles in superconducting accelerator magnets: a) it enhances the value and improves the quality of a magnetic field in the magnet bore, and b) it works as a magnetic screen confining a return magnetic flux and protecting the filed in the bore against the distortion caused by variations of the external magnetic environment. The greater part of SC-magnets designed for high energy proton/ion synchrotrons is based on a cold yoke (T=4.2÷4.5 K). These are the magnets developed for HERA, Nuclotron, UNK, SSC, RHIC, LHC and for the most of high field VLHC options. There are also three cases: a) a Tevatron, a Double-“C” Transmission line magnet [7] and a double aperture 11T Nb₃Sn dipole magnet at Fermilab [8], using an iron yoke at T=300 K. The main disadvantage of the magnet with an iron yoke at T ≥ 4.5 K is its huge cold mass. In the case of “warm iron” options, the cold mass has a minimum value. Nevertheless, the field enhancement due to magnetic flux concentration by the yoke is much smaller (for cosine theta magnets). Another problem is the complexity of a cryostat with a superconducting winding at T ≅ 4.2 K inside.

The advantages of the above cases can be realized if the temperature of the iron yoke (or its main part) has an intermediate level, say T=50÷80 K. Such an approach is easily applied to different types of yokes: window-frame, cosine theta for single and double apertures, as well.

The proposed layout of the cosine θ magnet is shown in Fig.1. The superconducting winding is pressed between two tubes a beam pipe and a cold mass shell. A coolant passes through the space between the tubes to provide an operating temperature. The beam screen is installed inside the beam pipe to absorb the synchrotron radiation power. Its temperature is much higher than that of the beam pipe. (20 ÷ 80 K). The cold mass shell outer diameter made 2-3 mm smaller than the internal diameter of the iron yoke. So, there is a gap of 1-1.5 mm between them after assembling. The needed fixation of the cold mass and the alignment of the SC-winding, inside the yoke can be
made in a different manner. Such a kind of the problem has been solved under the Tevatron design. Our case is much simpler because the support structure is completely inside the vacuum vessel. Due to a small weight and surface of the cold mass and not so high electromagnetic displacing forces, the heat flow through the support structure does not exceed 0.1 W/m. There is no separate liquid nitrogen or gaseous helium screen because the yoke plays this role. The support of the yoke is also much simpler.

In accordance with our basic vision, a magnetic field of 2-2.5 T is the most reasonable value for a very large hadron collider. The main limiting factor is synchrotron radiation from the beam. The radiated power is expressed as:

\[ P = 4.7 \cdot 10^{-21} \gamma^2 B^2 N_0 \text{ (W)}, \]

where \( \gamma = E/M_0 c^2 \) – Lorentz-factor, \( M_0 \) – proton rest mass, \( c \) - speed of light, \( B \) – bending magnetic field in [T], \( N_0 \) – the total number of accelerated protons.

The calculations made in [9] for both low (B=2.1 T) and high (B=12.5 T) field options of 2x50 TeV vlhc, give the value of losses 0.12 W/m and 2.2 W/m, respectively at a luminosity of \( 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \). For much higher energy, say 2 x 1000 TeV, the radiated power from the beam increases up to about 50 W/m for the low field case and to about 1000 W/m for the high field one. To compensate a heat flow of 50 W/m effectively the radiation screen at T=20-50 K can be used. It was made at a temperature difference of 1.9 K/4.7 K at the LHC. Assuming a beam radiation screen aperture of \( \Omega \approx 35 \text{ mm} \), we can determine the internal diameter of the SC-winding as 50 mm.

Notice that the separation of the SC-coil from the main part of the yoke allows an easy replacement of a low temperature superconductor by a high temperature one without the reconstruction of magnet “hardware”.

3 EXPERIMENTAL TEST OF THE 80 K OPTION

First tests of the modified Nuclotron dipole were performed at the LHE in December 2000. The standard elements of the Nuclotron cryomagnetic unit are used, namely: a window-frame iron yoke 1400 mm in length, the sizes of the window are \( 146 \times 56.2 \text{ mm} \); a saddle-shape superconducting two-layer winding made of a hollow-tube NbTi superconducting cable. A more detailed description of the Nuclotron magnets was published earlier [10]. A general view of the modified magnet inside the cryostat is shown in Fig.2. The SC-coil is reinforced by a fiberglass epoxy bandage 0.5 mm in thickness. The sizes of the window increased up to 59 mm – vertical and 151 mm – horizontal. The adjustable support/alignment shifits passing through the holes in the yoke were used to fix the coil. As a result, the direct thermal contact between the SC-coil cooled by two-phase He at T=4.5 K and the yoke cooled by liquid N\(_2\) at T=80 K was decreased. The magnet was ramped by current pulses up to \( I \approx 5.9 \text{ kA} \), with a repetition rate up to \( f \approx 1 \text{ Hz} \). The maximum magnetic field in the aperture was \( B \approx 1.87 \text{ T} \) and \( dB/dt \approx 4 \text{ T/s} \). The measured static heat flow (~1.8 W/m) was close to the calculated one.

4 SUPERCOLLIDERS OR COSMIC RAYS?

The only tools for the physics quest into an energy range of tens and hundreds TeV’s are hadron
supercolliders. There is no even idea how to construct an $e^+e^-$ or $\mu^+\mu^-$ collider of comparable energies. On the other hand, it is interesting to imagine a reasonable or natural limit for a possible future hadron collider.

Cosmic rays are the “Alma mater” of elementary particle physics. Many discoveries of new elementary particles were made at the accelerator given to us by the Nature – cosmic rays. The highest energy of a proton, whenever observed in cosmic rays, is $E = (3,0 \pm 0.3) \times 10^{20}\text{ eV}$ [11]. Is it possible to attain higher energies at a “hand made” hadron collider? If we assume the collider of $2 \times 1000\text{ TeV}$, the equivalent energy: $E = 2E_{\text{cm}}/M_0c^2$ will be about $2 \times 10^{21}\text{ eV}$! The natural limit for such collider is the length of the accelerator/collider ring. Let’s take the magnetic field value of about 2T. In this case, the circumference of the accelerator ring should be about $10^7\text{ km}$. Is there a place on the Earth where such a ring can be built? The answer is shown in Fig.3. The imagine ring surrounding the Sahara desert has just the same length.

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**Fig.3. Main parameter of a 2 \times 1000\text{ TeV} hadron collider.**

CIRCUMFERENCE 10 000 km
MAGNETIC FIELD 2.22 T
COLLISION ENERGY 2 x 1000 TeV
PARTICLES $p, \bar{p}, \text{nuclei}$
LUMINOSITY $10^{34} - 10^{36}\text{cm}^{-2}\text{s}^{-1}$
COLD MASS (T= 4.7 K) $10^6\text{ t}$
IRON YOKE (T=80 K) $10^6\text{ T}$
BEAM PIPE (T=47K) $\varnothing 50\text{ mm}$
HEAT FLOW AT 4.7 K 2 MW
BEAM SCREEN (T=80 K) $\varnothing 35\text{ mm}$
ELECTRIC POWER 5 000 MW

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5 CONCLUSION

The first probe of the idea of a $2 \times 1000\text{ TeV}$ collider was made by the author at International Seminar on High Energy Physics Problems (Dubna, September 16-18, 2000).

It may looks as a fantastic idea to construct the accelerator with a circumference of ten thousand kilometers in the Earth region where the people’s life is hard enough and the level of technical development is insufficient at present. The author’s understanding of this problems is very clear. Nevertheless, I would say, there is even a wonderfull coincidence of such different circumstances as:

- the needed dimensions of the accelerator ring and the envelope of the area;
- excellent stable geology, the absence of industrial ground motion
- a long underground tunnel passing around the area can be designed not only for the accelerator but also for interstate connections,
- much Sun energy, much gaseous helium, much ocean water not far from the main part of the ring.

So, it looks very attractive. The efforts of the world community in designing such a project can lead to general progress of at the continent as well as to the progress of a high energy accelerators for a long future.

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