УДК 539.1.076 621.384.6

A 100 TeV SYNCHROTRON/COLLIDER BASED ON THE NUCLOTRON-TYPE CRYOMAGNETIC SYSTEM

A.M.Baldin, A.D.Kovalenko

The approach to superhigh energy hadron synchrotron/collider of new generation is considered. Physics motivations post LHE collider as well as extrapolation of the Nuclotron-type cryomagnetic system parameters for very big accelerator are presented.

The investigation has been performed at the Laboratory of High Energies, JINR.

Синхротрон/коллайдер на энергию 100 ТэВ, основанный на криомагнитной системе типа нуклотрон

А.М.Балдин, А.Д.Коваленко

Рассмотрен подход к созданию адронного синхротрона/коллайдера сверхвысоких энергий нового поколения. Представлены соображения по физической проблематике коллайдера существенно выше 14 ТэВ и данные экстраполяции криомагнитной системы типа нуклотрон для очень большого ускорителя.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

Such a title was proposed to us for the talk at the Mini-Symposium organized by Ernest Malamud and G.William Foster in the frames of APS/AAPT Annual Meeting to be held in May 2—5, 1996.

The paper is only a brief description of our presentations and does not cover a set of very interesting ideas presented by other participants from the leading scientific centres and firms of the USA and also from Japan, connected with new superferric magnets and prototype work at Fermilab, microtunneling challenges and opportunities for the use of new types of superconductors as well as geological tests in the Fermilab region. We started from the usefulness of our point of view on the construction of superhigh energy accelerators of the next generation, taking into account the Dubna experience in the construction and operation of the Nuclotron cryomagnetic system [1]. Notice that the most sensitive economic estimates made by us were very close to the estimates by American physicists. But the main parameters of a new generation of colliders such as maximum energy and reasonable luminosity which determine the cost of construction need to be discussed in the context of future development of high energy physics.

1. Beam Energy and Luminosity

The idea to attain superhigh energies during many years was motivated by the search for new elementary particles with heavier and heavier masses, the existence of which was dictated by the principles of invariance and, respectively, by the most fundamental laws of nature. This strategy was justified by the discovery and investigation of μ, $\bar{p}$, K, J/ψ, Υ, τ, W, Z and t-particles. But the cross-sections for the heavy particle production in the processes of primary point-like particle collisions decrease as $\sigma \propto 1/m^2$ (m is the mass of the produced partice) and, due to this fact, extremely high luminosities and essentially new approaches to the particle registration are needed to observe its production. In this connection, without changing the main goal of high energy physics — discovery of basic laws of nature, we need pay more attention to the study of the regularities, dictated by infrared asymptotic of gauge fields and, first of all, to the investigation of multiboson processes in electroweak interactions.

The study of such processes is important due to the following:

At first, the multibosonic processes are connected with the violation of the sum of baryonic (B) and leptonic (L) numbers in the Standard Model. Hence, it could be responsible for baryosynthesis at high temperatures in the early Universe [2]. Next, the solution of the problem of multiparticle processes in the weak interaction theories will make it possible to discover new basic laws dictated by the nonperturbative field dynamics.

The cross-sections for the processes with $(B+L)$ violation and multiple production of electroweak bosons can substantially be larger than the cross-sections for the new heavy particle production. There is a lot of papers (see, for example, [7]) where the large cross-section of such processes (up to the unitary limit) was argued.

The cross-sections of multiple Higgs-particle production have also been predicted. Special attention is devoted to the instanton mechanism.

According to quite general scaling arguments [3,4] the total cross-section obtained from the collision of instantons is written as:

$$\sigma^{\text{tot}}_{\Delta(B+L)} \propto \exp\left[-\frac{4\pi}{\alpha_w} F\left(\frac{E}{E_0}\right)\right], \quad \text{where } E_0 = \frac{m_w}{\alpha_w}$$

The function $F(\varepsilon)$ is called «Holy grail» function. At $\varepsilon = 0$, $F(0) = 1$ and the cross-section is negligible, but due to multiboson channels $F(\varepsilon)$ [5,6]

$$F(\varepsilon) = 1 - 9/8\,\varepsilon^{4/3} + \ldots, \quad \text{where } \varepsilon = E/E_0 \text{ and } E_0 = \sqrt{6\pi}\, m_w/\alpha_w \approx 18 \text{ TeV}.$$

Unfortunatly the existing models give no predictions for $F(\varepsilon)$ at $\varepsilon \approx 1$. There exists a point of view that the multiparticle electroweak processes with many bosons in both the initial and final states with $(B+L)$ violation, are not suppressed at high temperature and thus they indeed determine the $(B+L)$ history of the Universe.

The above-mentioned problems, in particular, those related to cosmology and astrophysics, were discussed in many papers presented at the XXVII International Conference on High Energy Physics in Glasgow [7]. The contribution of the many → many scattering at high temperature is described by expansion around nontrivial classical solutions of the field equations: sphalerons and, more generally, periodic instantons. However there are some doubts [7] that few → many scattering (inverse cumulative process) can fully be described by using classical configurations of the field. A manifestation of instantion induced weak coupling regime can be observed in hard processes in QCD at low energies. The same mechanism is reponsible for both the violation of $(B + L)$ number conservation in electroweak interactions and anomalous spin effects in QCD which are being under investigation at present, in Dubna [8].

Over more than twenty years, in quark-gluon nuclear physics one has studied cumulative processes [9] in which the energy of the particle group of the initial state is transferred to one particle.

These results show that the cross sections for many → many and few →many processes in gauge theories are not small and the study of them in the energy range 30 TeV will make it possible to restrict oneself to lumonisities available from existing colliders. At the same time, the potential of discovery of fundamental laws and phenomena in this energy and luminosuty range seems to be very essential. Thus, basing on the prognosis of development of high energy physics it is possible to find optimal values for the parameters of the colliders of a new generation and to make their construction feasible.

A 100 TeV Nuclotron

The first estimates of the Nuclotron-type cryomagnetic system for the case of a 100 TeV range synchrotron/collider were presented at the 79th Session of the JINR Scientific Council, January 18—19, 1996. The data are based on extrapolation of the Nuclotron operational parameters, and the results of R&D works on the miniature iron-shaped 2T field SC magnets have been obtained at the Laboratory of High Energies (LHE) since 1975.

The LHE JINR was a pioneer in designing and constructing the first, low cost accelerator named Nuclotron which is based on low-field iron dominated SC-magnets (Fig.1). The 6A · GeV Nuclotron was built during five years (1987—92), the main equipment of magnetic and many other systems of it were fabricated by JINR and LHE workshops without recourse to industry.

The Nuclotron ring of 251 m in perimeter is installed in a technological tunnel with a cross-section of 2.5x3 m^2. The pilot physics experiments were started at the Nuclotron internal target in 1993. By the present time nine runs of cooling and beam acceleration were carried out at this new basic facility of JINR. The total running time is 2200 hours.

The first conceptual proposal of the Nuclotron was formulated at the beginning of the '70s. Pulsed SC dipoles with a peak magnetic field of 6T were suggested to be used for the main ring. However, after the first tests of $\cos\theta$-type high-field SC-magnets had been performed, further R&D works were reoriented at the investigation of a miniature iron-shaped field SC-magnets. It was the only feasible way of constructing a new accelerator at LHE because of very limited funds allocated to the relativistic nuclear physics program.

Five different modifications of low-field iron dominated pulsed superconducting dipoles were constructed and tested at LHE up to 1978 [10]. A «window-frame» type magnet provides in this case minimization of both the SC-coils cross-section, the iron yoke

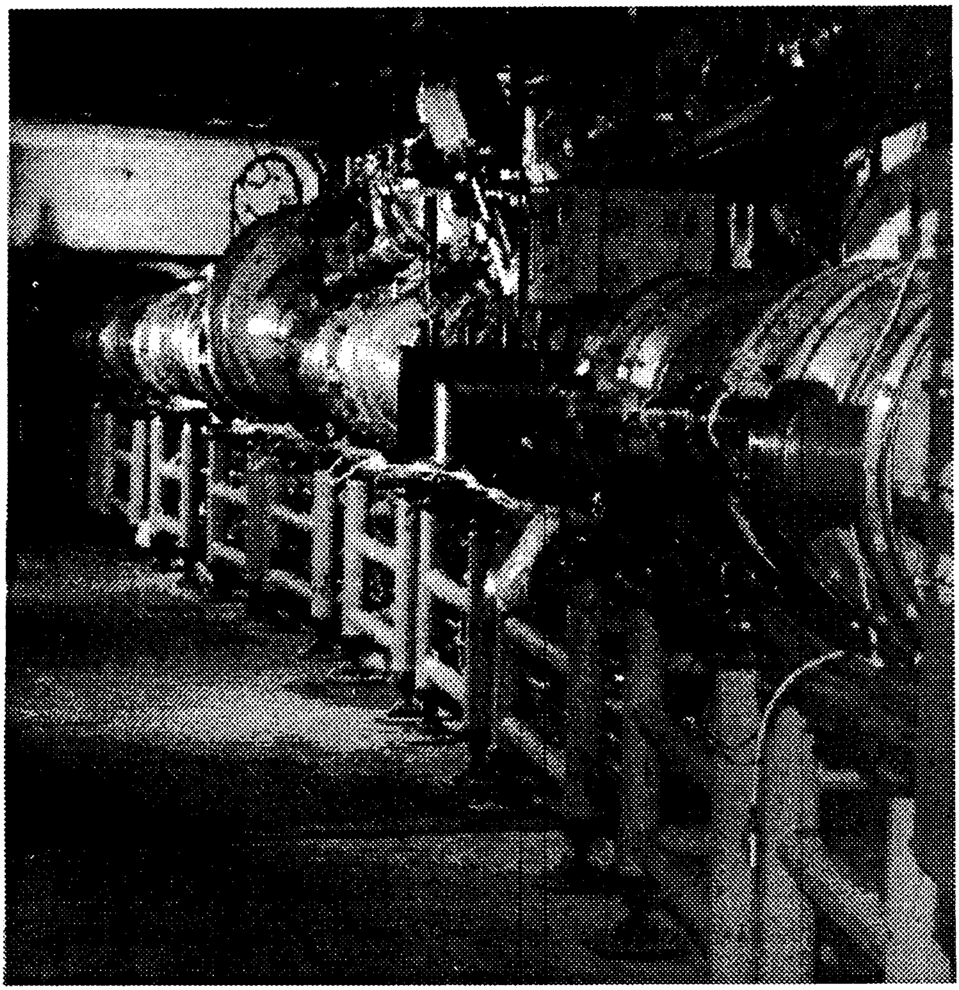

Fig.1. The Nuclotron in the tunnel

weight, and stored energy. High homogeneity of the magnetic field across the aperture is also achieved. The model superconducting system — 1.5 GeV Synchrotron (SPIN) based on such magnets had been fabricated and tested at LHE before the Nuclotron building was begun. The proposal of a Supernuclotron complex has also been worked out. A SC synchrotron of an energy of 60 A GeV, a stretcher ring and a nuclear collider of an energy of 2x60 A GeV were considered as components of the facility. Further progress in minimization of the magnetic system and the cross-section of the tunnel was suggested. Many years later, in 1991, the design of miniature SC magnets for accelerators carried out at LHE, JINR was awarded the first Russian Federation prize for the best scientific achievement in physics, mathematics and mechanics.

The SPIN-type magnets named «superferric» in western publications were also investigated at other laboratories [11]

A new version of the miniature iron-shaped field SC-magnet was built at LHE by 1978 [12]. The SC-winding was made of a specially designed tube-type superconductor cable to be manufactured of a 5 mm in diameter cupro-nickel tube with a wall thickness of 0.5 mm and 31 connected in parallel multifilament SC-strand of 0.5 mm in diameter covering the outer surface of the tube. Two-phase helium passing through the tube provides circulatory cooling of the coil down to 4.5 K while for the SPIN-type magnets immersible cooling was used. Due to lower average current density in the winding the SC-coils cross-section of the tube-type magnets is larger and, as a result, their weight and stored energy are higher than for the SPIN-type magnets. Nevertheless the tube-type magnets have a crucial advantage — a very simple and effective cooling system, which makes it possible to achieve a fast cycling mode of operation (up to 1 Hz). After successful tests of the «tube-type» magnets the final version of the Nuclotron concept was forlmulated [3].

The parameters of the Nuclotron SC-magnets and its cryomagnetic system were described in more detail in [14,15].

Even in the case of a rather large aperture, 55x110 mm^2, the weight of the Nuclotron magnetic system normalized per unit of length (about 300 kg/m) is the smallest one as compared with the circular accelerators. Other advantages, such as a minimal amount of helium inside the cryostat, safety, good mechanical stability, minimization of connections are also provided by the Nuclotron-type magnetic system.

The Nuclotron magnetic system comprises 96 dipole magnets 1.5 m long, 64 quadrupole lenses 0.45 m long, 28 multipole correctors 0.31 m long, twelve 6 kA helium-cooled current leads, 234 leads of 100 A current for correcting coils and 32 special purpose equipment (injection, 2 f station, monitoring, beam extraction). A general scheme of the Nuclotron cryogenics is shown in Fig.2. The magnetic elements are connected in parallel with the input and output helium headers. The ring is devided into two cryostast 125 m long supplied by helium refrigerator of a nominal capacity of 1.6 kW at 4.5 K each. A two-phase helium flow is used as a coolant. Total «cold mass» of the magnetic system is about 80 tons. Cooling of the system down to 4.5 K takes about 90 hours. The cooling system was designed taking into account the fast cycling mode of the Nuclotron operation (up to 0.5—1.0 Hz). In this case dynamic heat load are about 20 W per dipole and 12 W per quadrupole. Static heat losses are about 3.5 W/m. A long term experience of the Nuclotron operation showed a stable cooling of the magnets if helium pressure difference between headers is kept at a definite level.

To make desired extrapolation of the Nuclotron magnetic system for a 1000 km synchrotron/collider we assume for the first «clean» aperture in the dipoles of 27 mm — (vertical), and 35 mm — (horizontal), the peak field $B = 2.5$ T and heat load — 0.5 W/m. The result of such an extrapolation is presented in the Table.

It is clear that even in this case the basic parameters of 1000 km cryomagnetic system are not so unrealistic. Further progress can be provided by decreasing of the aperture. For

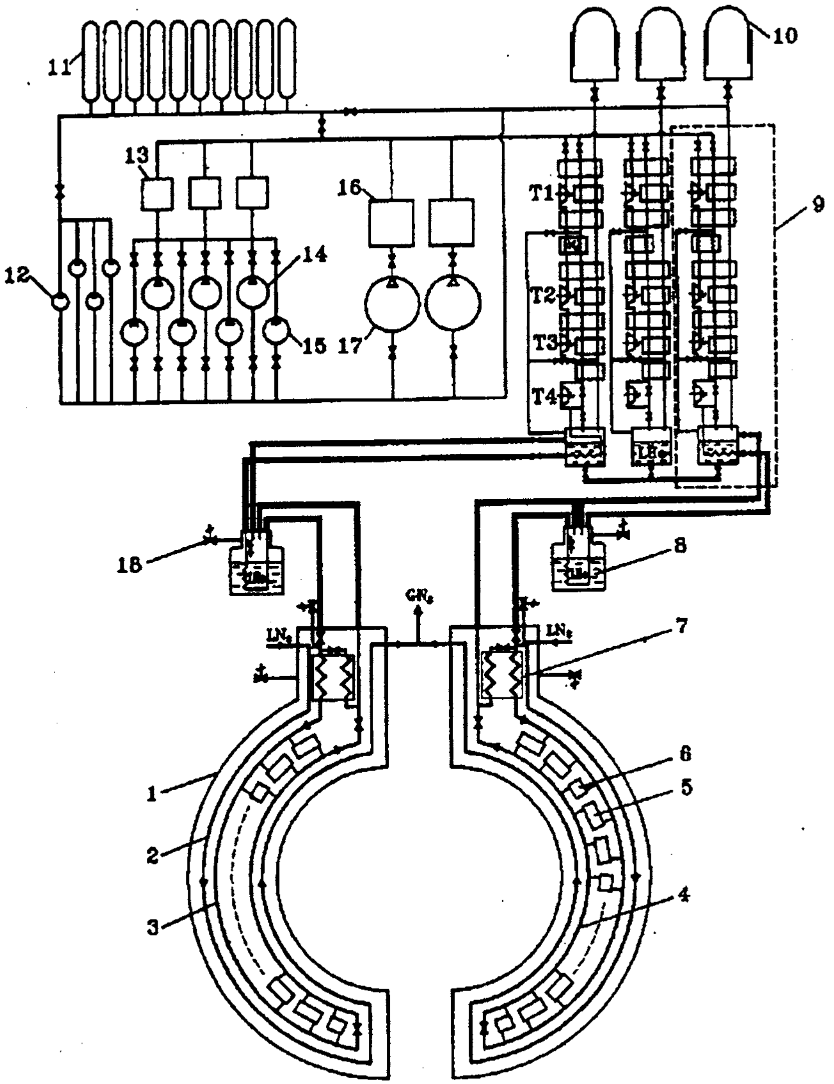

Fig.2. General scheme of the Nuclotron cryogenics. 1 — vacuum shell; 2 — heat shield; 3 — supply header; 4 — return header; 5 — dipole magnet; 6 — quadrupole magnet; 7 — main subcooler; 8 — phase separator; 9 — refrigerator; 10 — gas bag; 11 — storage vessel; 12,14,15,17 — compressors; 13,16 — purifiers; 18 — safety valve

the case of the aperture sizes: 15 mm (vertical) and 30 mm (horizontal) specific weight of cold iron 2-in-1 window-frame type SC-dipole will be about 60 kg/m.

It should be noticed that for optimization of the miniature superconducting magnet parameters at the field level higher 2T, magnetically oriented dysprosium can be used. The

Table. Cryomagnetic Parameter Estimates

• Weight of cold iron	kton	170
• Circumference	km	1000
• Heat losses	W/m	0.5
• Refrigerator capacity	kW	500 at 4.5 K
• Number of refrigerator units		100
• Length of helium headers for the refrigerator unit	km	2x5
• Magnetic field	T	2—2.2
• Length of magnet	m	~ 50
• Number of magnets connected in cryogenic unit		100
• Helium headers cross section, input/output	cm^2	55/108

first measurement and simulations have been performed at LHE. Saturation of the sample was occured at $B \simeq 3.3$—3.5 T. Of course, more detailed investigations are needed.

Conclusion

We consider low-cost low-field iron dominated superconducting miniature magnets as the only feasible concept for a superhigh energy accelerator of the next generation.

References

1. Baldin A.M. et al. — JINR, E8-95-65, Dubna, 1995; Kovalenko A.D. — Status of the Nuclotron, In: Proc. EPAC-94, v.1, p.161—64.
2. Kuzmin V.A., Rubakov V.A., Tinyakov P.G. — Nucl. Phys., 1991, v.B367, p.334.
3. Arnold P.B., Mattis M.P. — Phys. Rev., 1990, v.D42, p.1738.
4. Khlebnokov S.Yu., Rubakov V.A., Tinyakov P.G. — Nucl. Phys., 1991, v.B350, p.441.
5. Zakharov V.I. — Nucl. Phys., 1992, v.371, p.637.
6. Porrati M. — Nucl. Phys., 1990, v.B347, p.371.
7. Proc. XXVII Int. Conf. on High Energy Physics, Glasgow VK, 20—27 July 1994.
8. Adiasevich B.P. et al.: DAPNIA/SPP 96-03, SaCLAY, 1996.
9. Proc. XI International Seminar on High Energy Phys. Relativistic Nuclear Phys. & QCD, Dubna, JINR (1994) Ed. A.M.Baldin and W.Burov.

10. Averichev S.A. et al. — JINR, P8-11700, Dubna, 1978. (in Russian).
11. Heim J.R. et al. — Fermilab TM-1122, Batavia, 1982.
12. Agapov N.N. et al. — Cryogenics, June 1980, p.345—348.
13. Baldin A.M. et al. — IEEE Trans. Nucl., Sci., 1983, v.NS-30, No.4, p.3247—3249.
14. Baldin A.M. et al. — IEEE Trans. Appl. Superconductivity, 1995, v.5, No.2, p.875—877.
15. Baldin A.M. et al. — Adv. Cryog. Eng., 1995, v.39, p.501—508.

Received on June 11, 1996.