THE CHALLENGE OF FUTURE ACCELERATORS

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Abstract

An overview of future particle accelerators is given including those which are still under construction and where procurement is still ongoing. Emphasis is on the large projects and the key technological challenges for industry are outlined.

1 INTRODUCTION

A number of charged particle accelerators is under construction or is being designed; for others either the feasibility or the concept have been studied. All of them offer a challenge for industry as they require very advanced technology and techniques. The accelerators under study are based on new ideas implying often a completely new technology which has to be developed and tested.

The paper provides an overview of the future accelerators for the Special Session for Industry without claiming to be exhaustive. Emphasis is given to large projects though smaller accelerators used for medical treatment and industrial applications are certainly also of interest for industry given their large numbers.

Examples are given how industry has been or could be involved in the development of advanced technology and the construction of leading-edge components for these accelerators. Obviously, most of the components of the accelerator are based on state-of-the-art technology and can be purchased from industry without requiring any further R&D. These components will not be mentioned though they dominate the construction budgets.

We deal first with proton and ion colliders and accelerators, then with electron-positron colliders and accelerators. At the end, neutrino factories are mentioned requiring acceleration of protons and of muons which are particles like electrons but 205 times heavier and with a short lifetime.

2 HADRON COLLIDERS

Hadron colliders are rings where either protons or ions are stored in two counter-rotating beams. These beams are brought into collision in a few points around the circumference where the detectors of these collisions are located.

The Large Hadron Collider (LHC) [1] will collide either protons with 7 TeV or lead ions with 2.76 TeV per nucleon dependent on the mode of operation chosen.It is under construction at CERN and the start of commissioning is forseen for the middle of 2005.

The particles will be kept on orbit by strong magnetic fields produced by superconducting coils [2]. The dipole magnets will be 15 m long and have a nominal field of 8.35 T. Their development is a good example of efficient collaboration between research institutes and industry stretching over many years.

The coils in these magnets are made from NbTi superconducting cable which has been developed originally in the Rutherford Laboratory in UK and which is now routinely produced by industry. The cable is made up from 5 µm diameter NbTi filaments embedded in a coppermatrix produced be repeated deep-drawing. Fig.1 shows the cross-section of such a magnet. Short models of these magnets have been developed at CERN but the 10 and 15 m long prototypes have already been made by four European firms in close collaboration with CERN. At present, three firms are producing the first 90 magnets, about 1200 will be required. In total, approximately 8000 superconducting magnets of different types will be purchased for LHC in industry.

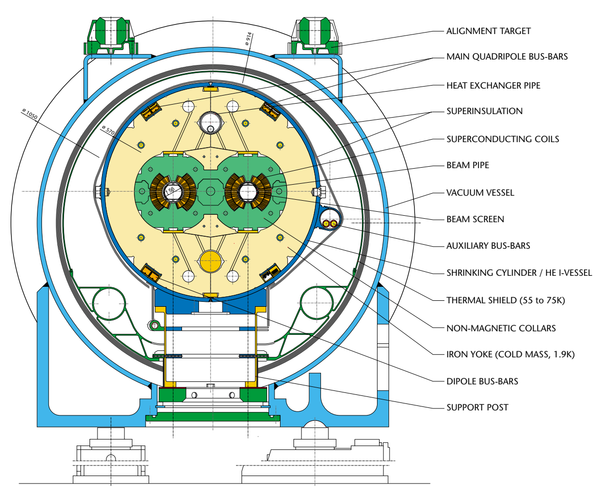

Fig.1: Cross-section of a 8.4 T two-beam channel LHC dipole magnet

In order to be in a superconducting state and, therefore, be able to conduct a current of 11.5 kA virtually without losses, the coil has to be immersed in superfluid Helium at 1.9 K. To reach this low temperature in the Helium,the eight 18 kW (4.5K equivalent) refrigerators will be equipped with hydrodynamic cold compressors, being able to compress He at 15 mbar up to atmospheric pressure. After initial development studies by CERN and CEA/France, based on experience obtained during the construction of CEBAF in the US, R&D was conducted with three industrial partners. Consequently, European and Japanese industry could supply such compressors featuring novel ideas in wheel design, as well as bearing and drive technology, and will participate in commissioning and testing.

A Very Large Hadron Collider for a proton energy of 50 TeV per beam in under study by a group of US laboratories [3]. Depending on the magnetic field (2 resp. 12 T) the ring would have an enormous circumference (600 resp.100 km). The ability to produce very cheap low-field magnets and the development of very efficient tunneling methods are imperative for the feasibility of the low-field version. For the second variant, high-field superconducting magnets based on LHC experience are being developed.

3 PROTON AND ION ACCELERATORS

3.1 Spallation Neutron Sources [4]

Neutron scattering requires low-energy (< 0.01 eV) neutrons to obtain a De Broglie wavelengths commensurate with the size of the structures to be studied. The neutrons are generated by protons of 1 to 2 GeV impinging on Mercury or metal targets. These protons are generated either by linear accelerators (linacs) or fast-cycling synchrotrons. However, the neutrons are produced in the target in the MeV range and have to be slowed down in low-Z moderators to the < 0.01 eV range. Since the beam pulse has to be shorter than the time-distribution widths of neutrons emerging from the moderator for an instantaneous proton pulse, an accumulator ring is introduced between the proton accelerator and the targest where the beam pulse gets shortened to less than 1 μs.

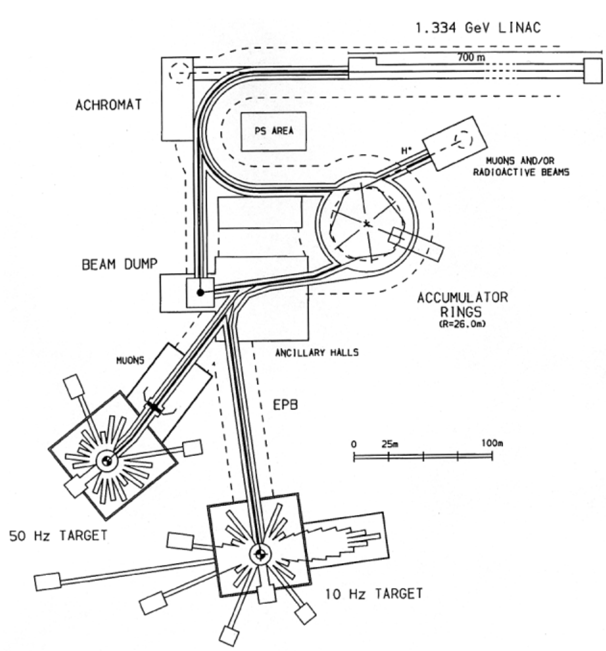

Fig. 2: Schematic layout of ESS

The Spallation Neutron Source (SNS) is under construction in the US and will become operational in 2006 [5]. A conceptual design report for a European Spallation Source (ESS) has been produced [6]. Fig.2 shows the schematic lauout of ESS which is likely to further evolve. The Japanese Joint Project [7,8] includes a spallation source and a conceptual design for a European regional spallation source (AUSTRON) is available [9].

The components requiring advanced technology which have to be produced in large numbers by industry are the accelerating structures for the linacs. For acceleration at low energy these structures are made from precision-machined Copper and frequencies 250 to 400 MHz are under study. If a linac is chosen for acceleration to highest energy, it could be based also on Copper structures in the 700 to 800 MHz range or on superconducting cavities operating between 350 to 700 MHz. Fig.3 shows a five-cell 352 MHz superconducting cavity for $\beta = 0.8$ providing 10 MV/m [10].

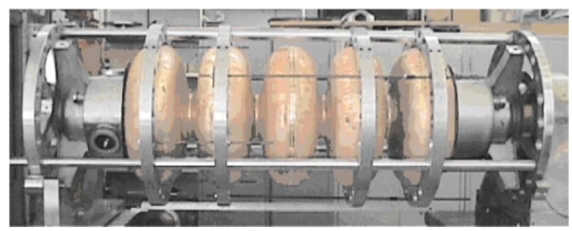

Fig. 3: Superconducting 352 MHz rf cavity for $\beta = 0.8$ providing 10 MV/m

Of great importance is the development of efficient rf power sources in industry for these linacs which could be tetrodes or klystrons operating with about 0.5 ms pulse-lengths and with 50 Hz repetition rates.

3.2 High-intensity proton accelerators

High-proton intensity linacs are also considered as drivers for spallation neutron production for accelerator-driven sub-critical assemblies in facilities transmuting nuclear waste as considered in the TRASCO study [11] and/or for generating energy with a minimum of radioactive waste [12]. They are based on the same technologies as the spallation neutron sources but have the additional requirement of extreme reliability (less than 10 trips per year of < 1s) in order to avoid thermal and hydrodynamic shocks in the target which is part of the assembly.

High-intensity 1 to 2 GeV proton linacs are also considered for facilities under study for the production of radio-active ion beams [13] but requiring only a low beam power of about 0.2 MW.

Recently, it has been suggested to study a European Multi-Function Facility whose back-bone is a proton linac of 20 MW average beam power. By time-sharing the pulse a number of users could be served by this one and the same linac: spallation neutron source, irradiation tests, source of radio-active ions, accelerator-driven sub-critical assemblies, and possibly production of intense muon and neutrino beams [14].

An extension of the accelerator complex in GSI is under study since some time [15]. The key element would be a high-intensity, multi-purpose synchrotron using fast-cycling superconducting magnets providing 60 GeV protons (200T.m) and heavy ion beams (e.g. 23 GeV/u U 92+). The protons could be used to produce antiprotons which would be stored in a ring at 14 GeV from where they would be extracted to the experiments. A set of storage rings for ions would complete the complex which could later on improved by an upgraded linac.

4 ELECTRON-POSITRON ACCELERATORS

4.1 Linear Colliders

In order to avoid the strong synchrotron radiation of circular colliders, two linacs are used one accelerating electrons and the other positrons which would collide in the interaction point in the middle between the linacs.

Such schemes are under study and conceptual design reports have been presented for TESLA in Europe [16], for JLC in Japan [17] and for NLC in the US [18]. Their design is still evolving appreciably as R&D is progressing. The energy of the individual beams is between 250 to 400 GeV with extension to above 500 GeV under study. CERN is studying a more advanced but also more demanding scheme, a Compact Linear Collider (CLIC) in order to reach energies in the 1.5 TeV range per beam [19].

The TESLA electron beam can also drive a Free-Electron Laser (FEL) providing very powerful x-rays for a multitude of applications.

Vigorous R&D is performed in collaboration with Industry, particularly for the first three schemes, and test facilities have been built to test components developed together with Industry [20]. Klystrons, accelerating cavities and structures together with more conventional equipment will have to be built in large numbers in case one of these projects gets approved.

TESLA is based on superconducting cavities operating at 1.3 GHz cooled by liquid He at 2 K. Many cavities have been built in the ongoing R&D phase together with industry resulting in confidence that cavities with accelerating gradients of 25 MV/m can be built reliably in large series. Fig.4 shows the performance of these cavities.

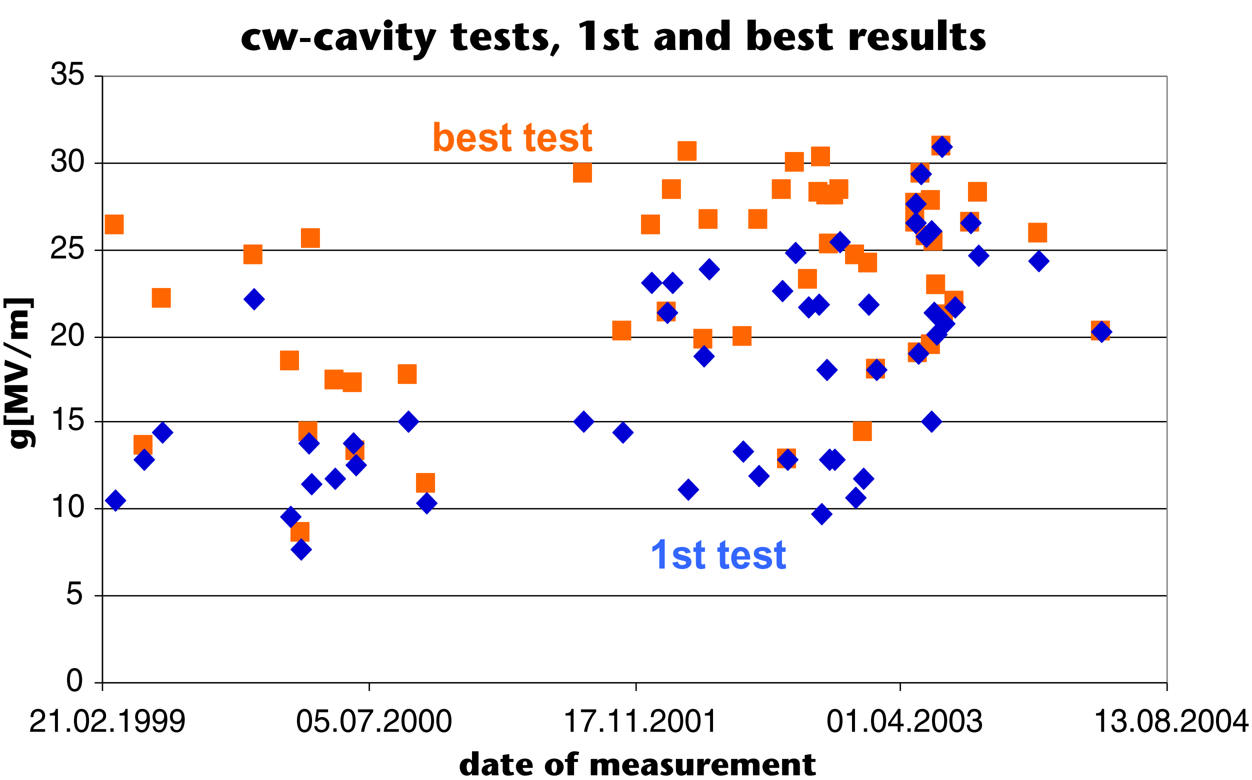

Fig.4: Quality factor as a function of the accelerating gradient of bulk Niobium 1.3 GHz superconducting cavities developed for TESLA.

The other schemes are based on classical 11.4 GHz about 2 m long accelerating structures made from precision-machined copper cells which are then either brazed and bonded. Of particular concern are there the klystrons. The small rf wavelength requires small components which consequently have to cope with heat deposited over relatively small surfaces. The klystrons have to deliver a peak power of 75 MW for about 2 micros at a repetition rate of 120 Hz.

For example, for 250 GeV per beam, TESLA requires 620 klystrons plus modulators and accelerating cavities of a total length of 23 km; for JLC/NLC the corresponding numbers are 3300 klystrons, 1700 klystron modulators and active structures of total length of 9 km.

4.2 Circular Accelerators

The powerful synchrotron light emitted from electrons following a curved orbit is used in synchrotron light sources for life sciences, condensed matter research and for atomic physics.

The Swiss Light Source (SLS), approved in 1997 and expected to start operation in mid-2001, is under construction The SLS ring has a 288 m circumference and the electron energy is 2.4 GeV [21]. The DIAMOND light source in the UK has been approved; its construction will start soon and it is expected to be commissioned in 2006. The ring has a circumference of 341 m and the beam energy is 3 GeV [22,23].

The principal technological challenges are the insertion devices as undulators or wigglers which are special magnets to enhance the synchrotron radiation. They require high-precision alignment and special supports. The magnetic field is often generated by permanent magnets which are supplied also by industry. The high thermal load of the vacuum chambers makes the cooling a challenge and the pumping of these long vacuum chambers requires novel getter pumping techniques [24] which will certainly find other applications in industry.

5 NEUTRINO SOURCES USING A MUON STORAGE RING

Conventional neutrino sources use the neutrinos produced by the decay of unstable mesons which in turn are generated by a proton beam hitting either a metal, Mercury or a Carbon target. This new more powerful but also more complex method uses the muons which are generated during the meson decay and stores them in a storage ring. The muons being not stable decay rapidly in electrons and two types of neutrinos. The advantage is the higher well-directed neutrino flux and the availability of two neutrino types without any contamination by other particles.

The facility would comprise a high-intensity proton driver, either a linac of about 2 GeV or fast-cycling synchrotrons of much higher energy, a target withstanding a large beam power (about 4 MW), and an efficient muon collection system. The muons would then be accelerated quickly to the highest energy and injected into the storage ring where they decay.

A feasibility study has recently been completed in the US [25]. A European Group is studying a variant of such a facility [26].

There are many technological challenges in these schemes, some of them in common with the high-intensity proton accelerators sketched above. A particular challenge is the high-power target, the proton beam dump, the muon collection system requiring high-gradient cavities and strong solenoids to work in high radiation fields. High-gradient cavities are also required for muon acceleration (total voltage required of the order of 10 GeV) and superconducting magnets for the muon storage ring which would operate with an energy between 20 to 50 GeV. A very appreciable R&D effort in the research laboratories in collaboration with industry will be required over years to establish the feasibility of the scheme and to prepare a well-founded proposal.

6 CONCLUSIONS

An overview of major accelerators under construction and under design has been given. Many components are still under development. In most cases, the first R&D steps are done in the research laboratories but industry gets associated relatively soon with the development once the concept has taken shape. The production of models or prototypes in industry takes advantage of the valuable know-how of industry, and that the cost can be better understood at an early stage and cost drivers eliminated by changes in the design. Usually, the prototyping requires a number of cycles and iterations between research institutes and industry.

New ideas for future accelerators have been outlined so that industry is aware of possible future opportunities and challenges though some of them may be quite far in the future.

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