THE USES OF ELECTROSTATIC BENDING AND FOCUSSING ELEMENTS FOR AUXILIARY STORAGE RINGS IN LARGE PROTON COLLIDER TUNNELS

David R. Winn
Schlumberger Research
Ridgefield, CT 06877-4108

Summary

We discuss the possibility of using electrostatic elements, instead of magnets, for bending and focussing in auxiliary electron storage rings in the tunnels of large proton accelerators. For example, in the proposed SSC tunnel, electron beam energies of ~100 GeV appear to be possible. Benefits of electrostatic systems over conventional magnets in cost, aperture, beam dynamics, radiation hardness, and power are presented. Electrostatic element designs are discussed, as are applications to electron, anti-proton & heavy ion beams.

Introduction

We note the obvious: that the large SSC tunnel (82.9 km circumference) [1] is a significant opportunity to add an electron ring for e^-p or e^+e^- collisions. Taking the LEP RF [2] necessary for ~60 GeV operation as a typical limiting case implies a beam energy of ~60 GeV$\times(R_{SSC}/R_{LEP})^{0.25}$, or ~80 GeV/beam in the SSC tunnel. An 80 GeV beam implies a very modest bending magnetic field of about ~500 Gauss for a lattice with a dipole filling factor similar to LEP [2] on the scale of the SSC. The main purpose of this note is to point out the amusing possibility that such very modest bending in very large circular accelerators may be obtainable by electrostatic rather than by magnetic fields. Moreover, electrostatics may be obtainable more cheaply and compactly.

The electrostatic bending for a dipole field oriented horizontally and continuously along the bending radius direction [3] is:

$$p = eEr/\beta \qquad (1)$$

where r is the bending radius in cm, E is the electric field in kV/cm, β is the velocity and p is the momentum in KeV/c. The equivalent electric to magnetic field for small angle bending is [3]:

$$E(MV/m) = 300\ \beta\ B(T). \qquad (2)$$

This implies an electric dipole field of 150 kV/cm to maintain a LEP-like separated function lattice at 80 GeV on the SSC arcs (11.7 km radius) [1], or a continuous dipole field of about 70 kV/cm with combined function bending and focussing (for example by simply immersing the electric dipole in magnetic quads). Continuous bend fields smooth out the radiation losses over the whole beam pipe, and reduce the orbit distortions from field errors at interfaces. A continuous dipole field of 100 kV/cm would imply a momentum capability of about 120 GeV/c for low mass particle beams in the SSC tunnel, and higher momenta for beams of lower-velocity very heavy nuclei. Even a conservative ~40 kV/cm continuous field will be enough for a Z^0-factory or a very effective e-p collider (~45 GeV/beam). These fields appear to be possible with present technology, and may result in substantial cost-savings over building the large numbers of low-field magnets.

Dipole Field Issues

The electric fields feasible to bend the electron beam depend on both the gradient and the maximum standoff. Field strengths between 50-100 kV/cm are fairly routine in vacuum, but require care in design to avoid field-emission [4]. The maximum dipole voltage that might be feasible is ~600 kV [4], using ±300 kV [5] on 2 electrodes, with a horizontal aperture of 6 cm at 100 kV/cm, and 12 cm at 50 kV/cm. A 300 kV potential is still good for 45 GeV at 40 kV/cm in 3 inches. Vertical aperture can be made arbitrarily large simply by extending the plates in the vertical direction.

A large beam-pipe is required to avoid breakdown, but is still low-mass and compact. Coating surfaces with a vacuum-formed (semi-)insulator may help avoid breakdown; electrodes rely on very good finish (<10 μ-inch). The stored energy in the electric field is ~10 kJ and ramping during the slow acceleration in a storage-ring presents no problem.

For a separated function machine, the schematic of an electric dipole is shown in figure 1. Two high-precision bending plate

Electrostatic Dipole Schematic

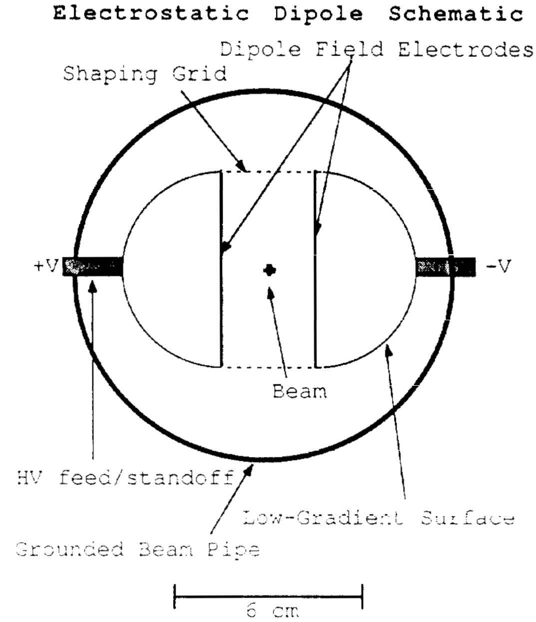

Fig.1.Schematic of an Electrostatic dipole bending system

CH2387-9/87/0000-1152 $1.00 © IEEE

electrodes are inserted into the beam pipe on high voltage feed-thrus and ceramic insulators. (Note:the normal vacuum, cooling and shielding channels for electron machines to the side of the beam pipe are not shown in this simple schematic representation.) The bend plates are shaped to lower the extreme gradients at edges (D-shapes in figure 1). A graded field grid at the proper equipotentials across the dipole gap will help to ensure high quality field (multipole correction) over the entire aperture, as will electrode shaping.The electrode shape must be accurate to ~0.1mm. Many variations are possible, including "cos-θ" biased electrodes on a circle. Composite vacuum-formed insulator/conductor materials can develop high quality shaped fields at the expense of high voltage power [6]. Designs based on continuous extrusions or other mass-production are essential.

The leakage currents in the insulators constitute one of the major power losses in such a machine, assuming that the work to bend the beam is not irreversibly lost in the power supplies. Leakage currents in the ceramics are ~μA/m, implying a power loss of less than 50 kW for an SSC ring.Supply ripple must be < 0.01% for stable beam.

Non-DC HV schemes are by far too lossy unless a highly efficient energy recovery or high-Q system can be designed. Considering the proximity of the LHe (or will it be LN_2 now?) system in the SSC, it is amusing to consider a superconducting whole ring RF system for continuous e-m bending and low gradient acceleration, until one tries to accomodate the synchrotron radiation load.

Focussing Quads

Typical quadrupole gradients are of the order of 10 T/m [7] in a machine of this size and magnetic quads may be incorporated around the (non-magnetic) vacuum pipe with no loss of bend gradient, superimposing the magnetic quad field directly on the electric dipole field. In the electrostatic case, these gradients correspond to an ~impossible 300 kV/cm/cm. However, the total length of quads is ~10-20% of the total length, and a continuous quadrupole electrostatic gradient of 30-60 kV/cm/cm superimposed on the dipole field may be a feasible but difficult possibility in order to achieve continuous AG or weak focussing or to supplement magnetic focussing (like RFQ technology). Some electrostatic quad designs include four hyperbolic equipotential surfaces (Figure 2) [8],[9], or double helix sections of electrodes [10]. The hyperbolic quad produces a harmonic potential (constant gradient); more extreme electrode shapes are as found in RFQ machines. As an example for simultaneously producing dipole and quadrupole components with a hyperbolic section, the 2 negative potentials (-V,-V) in the horizontal plane of Figure 2 could be replaced by (-2V,-V), or (-V,0), etc. This requires alternating positive and negative biases periodically around the ring to maintain equal focussing in all coordinates, for example by replacing (-V,-V) in Figure 2 by (+V,-2V), etc. Note that this is similar to the destructive dipole mode in an RFQ which normally is to be avoided, but which is helpful in this case [12]. Note that many electrostatic elements focus achromatically in both coordinates, a big plus.

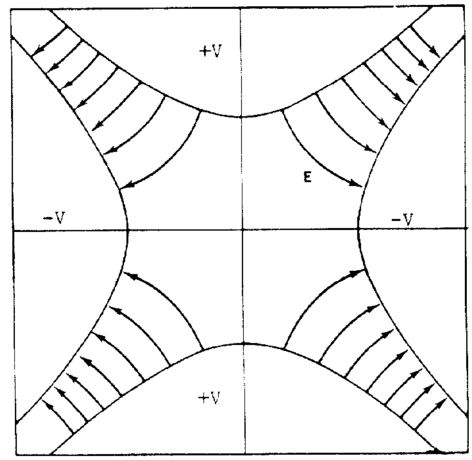

Fig. 2. Schematic of an electrostatic quadrupole

Synchrotron Radiation and Vacuum

A primary difficulty is synchrotron radiation in conjunction with high transverse accelerating electric fields. A large electron and ion flux pumped by the radiation power [13] of about 25 MW in the case of an 80 GeV 2 mA machine could cause not only breakdown from secondary emission, but a large power loss from electron currents as well. Note, however, that the radiated power is spread over a considerably larger beam pipe than is normal in a magnetic machine.

The outer (away from machine center) electrode incorporates a center section of a fine grid to reduce the effect of x-ray pumping by intercepting only small fraction of the x-rays, transmitting the rest directly to a trapping channel. The inner wall, subject to the transverse electron current, may be made transparent to electrons by means of a secondary electrode to pull the electrons through the mesh.

It is important to note that although the electrons are strongly accelerated in the electrostatic case, they are not trapped as in the magnetic case. The natural "clearing field" and separation of the ion species in this type of bend may actually reduce the total effect of synchrotron radiation, despite enhanced field-emission processes. Lastly, synchrotron x-rays cannot damage magnets in a design without them.

Engineering and Costs

It is essential to prove that simple and cheap designs are feasible using a short model, inserted into an elctron storage ring. Experience with electrostatic beam separators may be a useful guide.If complex structures and exotic materials are necessary to avoid breakdown or synchrotron radiation effects, then the device is useless as an inexpensive alternative to low-field magnets.Less than 1000 T of stainless steel are expected to be required for the vacuum pipe/electrode structure, and could be a modest cost. The RF system required for 80 GeV operation is of the order of $100M using the plans for the LEP 7 MeV/m superconducting RF as a guide [11]. The vacuum system will also be costly, and can be estimated from LEP, although modification for use with the electrostatics mustbe studied. The HV is less than ~$20M.

Other Applications

Several other interesting applications of electrostatic elements are possible:

High Energy Electron Cooling

An auxiliary electron ring in for high energy electron cooling may be easily obtainable because an electric field of less than ~10 kV/cm is sufficient to produce a co-moving electron beam in any proton ring tunnel (by virtue of m_p/m_e and equation 2), and could be brought to bear on the protons in every available straight-section of the machine. Since the luminosity is already very high in the SSC design, this may not be interesting. However, this may generally be useful for improving space-charge and aperture limitations

Heavy Ions and Anti-Protons

Heavy ion beams may be accelerated in these devices effectively because of the 1/velocity dependence of the bending force. A ring capable of 80 GeV electrons is capable of accelerating singly ionized Uranium ions to about 150 GeV/c. For highly cooled anti-protons, which are being brought to rest, electrostatic technology is interesting for momenta below ~100 MeV/c.

Space Applications

Electrostatic bending may be an interesting method of obtaining high energies in outer space, because of the low mass and power of the bending components in weightless, high vacuum conditions. Niobium magnet technology typically has masses ~500 kg/m. To obtain the same bending electrostatically typically requires ~500 m/m of magnet. Therefore, if an electrostatic structure can be fabricated for zero-g and space vacuum in the hugh areas available in space for substantially less than 1 kg/m, then electrostatic structures become very competitive in space. An ultra-large combined dipole-quad aerospace structure may be feasible at ~10 km/ton of material boosted to orbit.

Conclusion

The use of electrostatic bending and focussing may have uses in high energy accelerators of enormous sizes, particularly in the case of electrons in the SSC tunnel.

References

[1] SSC CDG, Superconducting Super Collider Conceptual Design Report.Berkeley: SSC CDG,LBL,1986, ch. 4. pp. 93-100

[2] Particle Data Group, "Review of Particle Properties," Physics Letters, vol. 170B, pp.39,April 1986

[3] C. Bovet et. al., "A Selection of Formulae and Data Useful for the Design of A.G. Synchrotrons," CERN/MPS-SI/Int. DL/70/4, pp.7-8, April,1970

[4] F.Gamet & G.Thomer, Flash Radiography. NY:Elsevier,1976,ch.2, pp. 15-24

[5] Cables hold off ~300 kV maximum.

[6] Stesalit AG Kunststofwerk,Zullwill/SO

[7] G. Plass, "The LEP Project - Status and Plans," IEEE Trans. Nuc. Sci.,Vol. NS-30, No. 4, pp.1978-82, August, 1983

[8] J. J. Livingood, Principles of Cyclic Particle Accelerators. Princeton: Van Nostrand, 1961,ch.15, pp. 311

[9] P. S. Farago, Free Electron Physics. Middlesex,UK:Penguin,1970,ch.2,pp.35-70

[10] A. Zhigarev, Electron Optics and Electron Beam Devices. Moscow: Mir, 1972, ch. 2, pp.133-185,207-233

[11] S. Humphries, Principles of Charged Particle Acceleration, New York: Wiley, 1986, ch. 4, pp.45-67

[12] ibid., ch.14, pp. 482-92

[13] SSC CDG, Superconducting Super Collider Conceptual Design Report. Berkeley: SSC CDG,LBL, 1986, ch. 4. pp. 216-218