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HERA, A NEW STAGE IN COLLIDING BEAM FACILITIES

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Summary

DESY has proposed to base its long range scientific future on a large electron-proton colliding beam facility to be constructed on a site ajoining the present site. The facility is designed to collide 820 GeV protons with 30 GeV electrons in four interaction regions. The design, the expected performance and the layout of the various components will be discussed.

1. Introduction

The possibility of reaching very high energies by using electron-proton colliding beams was recognized[1] a long time ago, but no such facility has been constructed despite its attractive features.

DESY has proposed to construct HERA, a large electron-proton colliding beam facility on a site ajoining the present site. HERA is designed to collide 820 GeV protons with 30 GeV electrons in 4 interaction regions yielding 314 GeV in the center-of-mass and a maximum momentum transfer squared of 98400 GeV^2.

The kinematical region liberated by HERA is shown in Fig. 1 and is equivalent to that of an 52 TeV electron impinging on a proton at rest. In the bottom left corner the region covered by a 1 TeV fixed target machine is shown. It is clear that HERA opens up a totally new kinematical region not accessible by other means, and in particular the region around 100 GeV in c.m., the presumed mass scale of the weak interaction, can be investigated in detail.

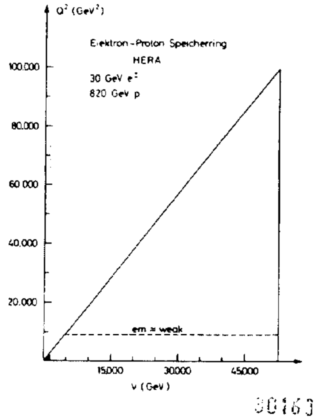

Fig. 1 - Kinematical region in momentum transfer squared (Q^2) and energy (ν) which can be explored with HERA.

A feasibility study[2] of this project done in collaboration with ECFA has been completed. The project has received strong support from the German high energy community and last year a project definition endorsed by ECFA was forwarded to a committee appointed by the German minister of Science and Technology to evaluate this and other large science projects. This committee is expected to issue a preliminary report shortly. A few months ago a new study group was formed to review the feasibility report and to prepare a proposal to be submitted to the German Government later this year. This group is rather broadly based with strong participation of physicists and engineers from other European Universities and Institutions who will - if HERA is approved - participate in the construction and the use of HERA.

In this talk I'll describe the HERA project based on the ECFA-DESY Report listed in reference 2.

2. General Description

2.1 Layout

The layout of HERA on a site ajoining DESY is shown in Fig. 2.

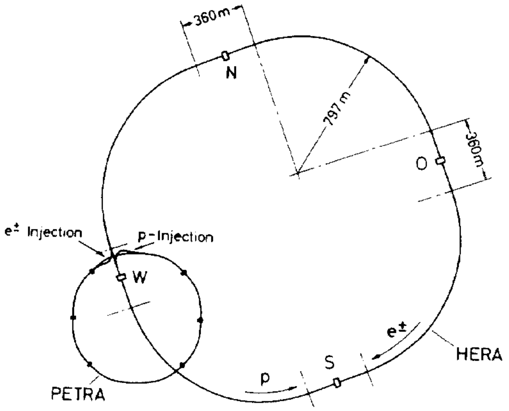

Fig. 2 - Layout of HERA

The machine has a fourfold symmetry; four 360 m long straight sections are joined by four arcs with a geometric radius of 797.6 m yielding a total circumference of 6451.2 m. HERA consists of two rings, one for electrons (positrons), the other for protons and the rings cross in the middle of the long straight sections. The machine and the four experimental areas will be buried some 10 - 20 m below the surface avoiding any disturbance to the urban surroundings. The tunnel traverses largely land belonging either to the Federal Government or to the City of Hamburg and it intersects the PETRA ring about 20 m below the surface. Thus the physical plant can be located on the present DESY site and only short injection paths are needed to connect PETRA and HERA.

The site, according to records made available by the Geologisches Landesamt in Hamburg is well suited for tunneling. This has now been confirmed by a series of 60 drillings made along the circumference of the ring. The tunnel will be drilled using special boring machines equipped with driving shields. These machines, protected by the driving shield, can bore tunnels below the water table without the use of pressurized air. This method has been extensively used in Hamburg and is well adapted to the requirements posed by the HERA tunnel.

A total floorspace of 875 m^2 is available for experiments compared to the 650 m^2 available in a typical PETRA Hall. The beam traverses the hall some 5.5 m above the floor level. Machine components like klystrons, power supplies and compressors are located in a multistory structure built at the side of the hall and above the hall, providing a total area of some 3600 m^2. This structure including the hall will be completely covered after construction and only the access roads and a small one story building will be visible on the surface.

2.2 Parameters and Performance

The general parameters of HERA are listed in Table 1. The energy of the electron beam can be varied between 35 GeV and 10 GeV where the upper limit is determined by the available RF power and the lower limit by the damping time. At the nominal energy of 30 GeV the transverse polarisation builds up in 19.5 min compared to an expected lifetime of several hours.

The maximum field of the HERA magnets is chosen to be 4.725 Tesla compared to 4.3 Tesla for the FNAL Tevatron[3] or 5.0 Tesla, the design values for Isabelle[4]. With a dipole packing fraction of 0.727 in the arcs this yields a maximum proton energy of 820 GeV. The lower li-

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Table 1 - Machine parameters

	p-ring	e-ring
Nominal energy (GeV)	820	30
$s = Q^2_{max} (GeV^2)$	98400	
Luminosity ($cm^{-2}sec^{-1}$)	0.35×10^{32}	
Polarisation time (min)		19.5
Number of interaction points	4	
Length of straight sections (m)	360	
Free space for experiments (m)	10	
Circumference (m)	6451.2	
Bending radius (m)	579.436	550.0395
Magnetic field (Tesla)	4.725	0.1819
Total number of particles	$6.72 \cdot 10^{13}$	$0.78 \cdot 10^{13}$
Circulating current (mA)	500	58
Energy range (GeV)	100 → 820	10 → 33
Emittance (ϵ_x/ϵ_z) ($\times 10^{-8}$m)	0.47/0.23	3.2/0.8
Beta function β^*_x/β^*_z (m)	7/0.6	5/0.15
Dispersion function D^*_x/D^*_z (m)	0.5	0
Beam-beam tune shift $\Delta Q_x/\Delta Q_z$	0.0007/0.0007	0.014/0.01
Beam size at crossing σ^*_x(mm)	0.18(0.97)**	0.40
Beam size at crossing σ^*_z(mm)	0.038	0.035
Number of bunches	224	
Bunch length (cm)	9.5	1.1
RF frequency (Mhz)	208.189	499.665
Maximum circumferential voltage (MV)	100***	288
Total RF power (MWatt)	2	13.2
Filling time (min)	8.5	5
Injection energy (GeV)	40.0	14.0
Energy loss / turn (MeV)		140.2
Critical energy (keV)		109

* At the interaction point

** Including the bunch length

*** 25 MW is foreseen initially

mit on the proton energy for long term storage is determined by the effect of persistent currents in the superconducting coils. The relative importance of these currents decreases with energy as they cause constant higher multipole fields disturbing the dipole field. An estimate of these effects, based on the FNAL magnets, shows that it should be possible to inject protons at 40 GeV and store them down to energies of about 100 GeV.

In experiments[5] with a stored bunched beam in the SPS it has been found that the bunch length should be no more than about 30% of the bucket length. If this condition is violated, then RF noise will lead to a loss of beam. We have chosen 208 MHz as the RF frequency for the proton beam. At this frequency the bunch will be stable with an RF voltage of 25 MV, a voltage which can be provided with high Q cavities at a modest power consumption.

For the electron RF system we have chosen 500 MHz, the frequency adopted for the other DESY machines. This choice allows us to exploit fully both the expertise and the hardware available at DESY and makes it attractive to construct the RF system in stages. The final stage employs 192 cavities and a total RF power of 13.2 MW, sufficient to reach 35 GeV electron energy with zero current.

The luminosity of an electron-proton colliding ring is given by

$$L = \frac{f_o \cdot n_b \cdot N_e \cdot N_p}{2\pi(\sigma^2_{xp,eff} + \sigma^2_{xe})^{1/2} (\sigma^2_{zp} + \sigma^2_{ze})^{1/2}} \qquad (1)$$

In this formula f_o is the revolution frequency, n_b the number of bunches in each ring, N_e and N_p the number of electrons and protons per bunch respectively, $\sigma_{xp,eff} = (\sigma^2_{xp} + (\sigma_{sp} \cdot \phi)^2)^{1/2}$ with σ_{sp} denoting the proton bunch length and ϕ the crossing angle assumed to be ± 5 mrad, σ_{xe} is the width of the electron beam and σ_{zp} and σ_{ze} the height of the proton and the electron beam respectively.

The luminosity for a given value of the tune shift increases in proportion to the number of bunches. We have chosen 224 equidistant bunches for each ring corresponding to a distance of 96 nsec between adjacent bunches. With 3×10^{11} protons per bunch at 820 GeV and 0.35×10^{11} electrons per bunch at 30 GeV we obtain a luminosity of 3.5×10^{31} $cm^{-2}sec^{-1}$.

One potential limit to the luminosity is the maximum values of the beam-beam tune shifts. The tune shifts are 7×10^{-4} and 1.4×10^{-2} per crossing respectively for protons and electrons. These values for the Q shift are not as high as the limits assumed by proponents of other machines. In fact, HERA's luminosity is limited rather by the currents in the two rings. The electron current is fixed by available RF power while the proton current is limited by single particle instabilities in HERA and its injectors to 3×10^{11} protons per bunch or a circulating current of 500 mA.

The luminosity is plotted in Fig. 3 versus the proton energy for electron energies of 10, 20, 28 and 30 GeV.

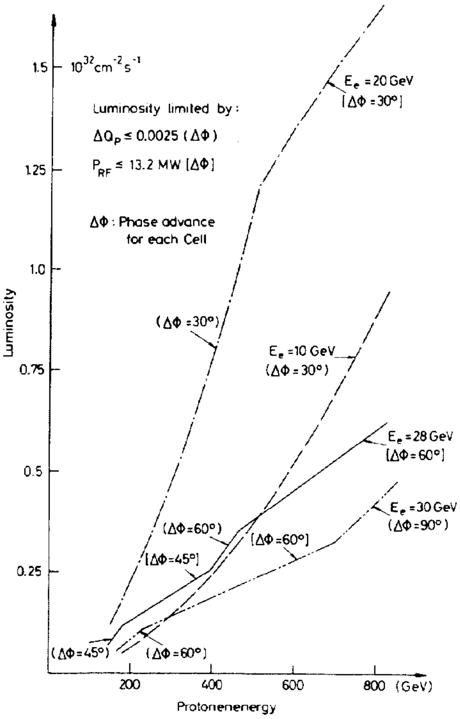

Fig. 3

Luminosity versus proton energy.

3. Injection

The injection system is capable of filling the electron ring of HERA with 224 bunches of 14 GeV electrons (positrons) with a maximum intensity of 1.3×10^{11} particles per bunch in 10 to 20 min. The proposed injection system is based on Linac II, the DESY synchrotron and PETRA for electrons and on Linac II, PIA, the DESY synchrotron and PETRA for positrons.

The proton injection scheme is also to a large extent based on existing accelerators. Protons from a new 50 MeV linear accelerator are injected into the DESY synchrotron, accelerated to 7.5 GeV and transfered to PETRA where they are accelerated to 40 GeV, the maximum possible energy, and injected into HERA.

The field at injection has a strong sextupole component resulting from persistent currents with a small contribution from winding errors. Using the measured[3] values of the sextupole field we find that the resulting chromaticity at 40 GeV is nearly an order of magnitude larger than the natural chromaticity. The average sextupolfield will be corrected by trim coils in the dipoles. The remaining effects caused by the fluctuations have been investigated[6] using a fast tracking program. The program includes multipoles up to order 16 as thin lenses in the middle of the dipole magnet. The strength of the multipoles is gaussian distributed with an rms width taken to be 1/3 of the maximum tolerable value required for the FNAL magnets. The persistent currents are assumed to fluctuate by ± 10% or less.

In Fig. 4 the maximum stable initial betatron amplitude is plotted versus the momentum deviation with the half aperture of the vacuum chamber as a parameter.

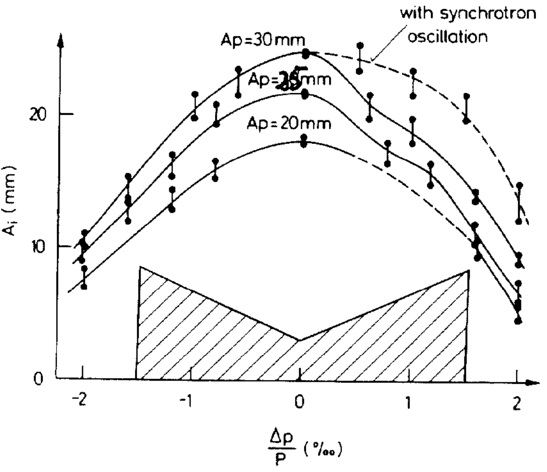

Fig. 4 - Maximum stable initial betatron amplitude versus momentum deviation at 40 GeV with the radius of the beam tube as a parameter.

For HERA we expect Ap to be between 25 mm and 30 mm. Each run consisted of 16 particles which were tracked for 100 revolutions. The "error bars" show A_i for the last run in which no particles were lost and for the first run in which the first particle was lost. The aperture occupied by the beam is indicated. A 25 mm half-aperture seems to be sufficient, however, note that closed orbit errors are not yet included in this computation.

4. Optics

4.1 The lattice

Both rings have a periodic FODO cell structure consisting of equidistant focusing and defocusing quadrupoles which alternate in sign. The magnet structure of the standard cells is depicted in Fig. 5. As much of the intervening space as possible is filled with bending magnets in order to reach the highest proton energy and in case of the electron machine, to minimize synchrotron radiation. A short straight section placed to one side of each quadrupole provides space for sextupole magnets, orbit detecting pickups, correction dipoles and vacuum equipment together with other beam detection equipment and correction windings.

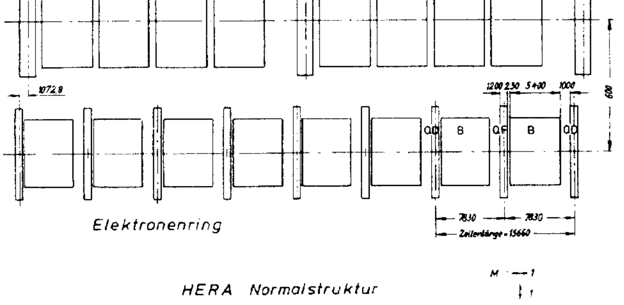

Fig. 5 - Magnet structure in the arcs.

The HERA lattice parameters are listed in Table 2.

Table 2 - HERA lattice parameters

	p	e
Number of cells	80	320
Cell length (m)	62.64	15.66
Number of cell dipoles	640	640
Number of cell quadrupoles	164	644
Magnetic length of dipole (m)	5.69	5.40
Bending field (Tesla)	4.72	0.1819
Bending angle (mrad)	9.8175	9.8175
Bending radius (m)	579.4360	550.0395
Magnetic length of quadrupole (m)	1.8	1.2
magnet aperture dipole (mm)	63 ⌀	50 x 100
magnet aperture quadrupole (mm)	63 ⌀	70
Momentum compaction		5×10^{-4}
Transition γ_T	18.5	
Working point Q_x/Q_z	26.55/26.60	46.15/53.15
Nominal phase advance per cell (degr.)	90	45
Cell quadrupole strength K (m^{-2})	0.025	0.082
Cell quadrupole gradient (Tesla/m)	70	8.6
Cell beta function β^{max}/β^{min} (m)	106/19	31/14
Cell dispersion D^{max}/D^{min}	3.3/1.6	0.64/0.43

4.2 The interaction region

The interaction region in an electron-proton colliding ring is rather complex. Firstly it must bring the two beams with rather different properties into collision. The arcs must be matched into the long straight sections such that the dispersion is suppressed. Furthermore the spin of the electron which is transverse in the arcs must be turned by ±π/2 to become parallel or antiparallel to the beam direction in the interaction point and be restored to the transverse direction upon reentering the arcs. Minimizing the depolarization caused by the spin rotator introduce further constraints. Sufficient space for the RF cavities and the injector and the ejector must also be found.

In the insertion proposed in reference 2 the rings made an S bend in the vertical plane antisymmetric to the interaction point and cross in the horizontal plane at an angle of ± 5 mrad. This rotator produces only a single helicity, the vertical bends are rather strong and are a source of synchrotron radiation near to the interaction region.

An alternate design is shown schematically in Fig.6. In this design the spin is turned into the longitudinal direction by a 70 m long rotator installed at the end of the arc and restored to the transverse direction by a similar rotator positioned at the entrance to the next arc. The rotator and direction of the spin at the exit of each bending element is shown in Fig. 7.

The horizontal magnet in the rotator is a part of the lattice and must bend the particles by a fixed angle of 50.26 mrad in addition to precess the spin by π. The rotator is therefore optimized only for a fixed energy of 27.5 GeV. Both helicities can be obtained by reversing the sign of the vertical bending magnets in the rotators and reposition the magnets vertically

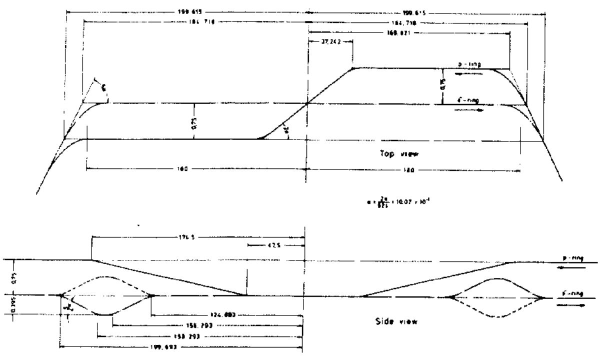

Fig. 6 - Geometry of the interaction region

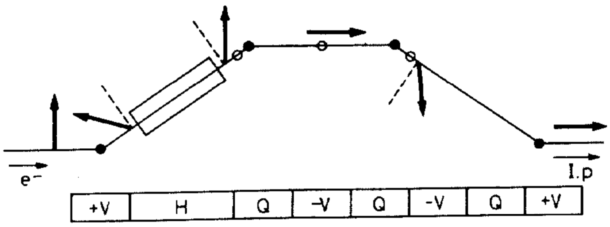

Fig. 7 - Principle of the spin rotator

by 80 cm.

The large distance between the interaction point and the last bend in the rotator minimizes the amount of synchrotron radiation which reaches the detector. A free space of ± 7.5 m around the interaction point is available for experiments. The horizontal crossing angle is a free variable. In the design shown here the beams cross at $\phi = \pm 10$ mrad. The larger crossing angle makes it possible to design the machines without common elements. The luminosity remains the same as in the earlier design since the increase in horizontal beamsize can be compensated by bringing the proton quadrupoles closer and reducing the vertical beam size.

The properties of the rotator have been investigated using the SLIM program[7], a computer code which traces the spin through the magnetic elements and evaluates the various depolarization mechanismn. Preliminary calculations with this program showed that it should be possible with four rotators to retain more than 50% of the polarisation obtained in a flat machine. This was obtained by minimizing the vertical dispersion emittance introduced by the rotator and by spacing the two rotators with a phase advance of $(2k + 1)\pi$.

5. Components

5.1 Electron ring

The electron ring of HERA is similar to the PETRA machine except that the circumference is larger by a factor of 2.8. Although the PETRA components in principle could be used directly, some changes, based on PETRA experience, are made to simplify the design and to reduce the cost.

The RF system is similar to the one used at PETRA except that the cavity will be designed with seven cells instead of five and a reduced hole size between adjacent cells. These design changes should increase the shunt impedance per meter by 50% to R = 18 MΩ/m and reduce power consumption.

The cross section of a dipole magnet with vacuum chamber and a pump is shown in Fig. 8. The dipole is excited by a single turn conductor traversing the entire ring. The stray field is cancelled by a second conductor mounted at the wall of the tunnel with the current flowing in the opposite direction.

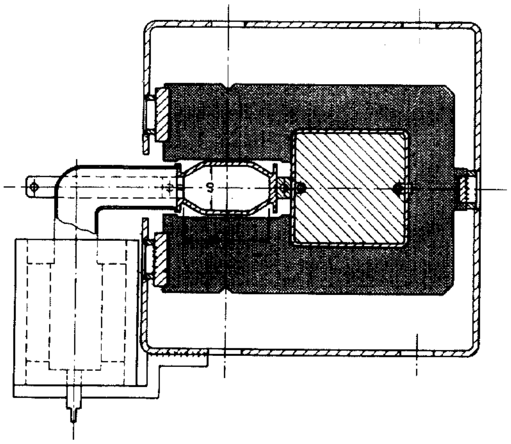

Fig. 8 - Cross section of a dipole magnet for the electron ring with vacuum chamber and pump

The vacuum chamber, 40 mm high and 80 mm wide, will be made of a copper pipe 4 mm thick. The pumping speed will be made independent of energy by using discrete pumps spaced 2 m apart.

At 30 GeV about 90% of the synchrotron intensity is contained in the beam pipe and the remaining 10% ($\sim$ 200 Watt/m) is absorbed in the magnets. During the anticipated lifetime of HERA this is equivalent to some 10^{10} rad deposited in the magnet coils. For the simple coil design shown in Fig. 8 it is possible to insulate the coil using radiation resistant material.

5.2 The Proton Ring

The proton ring of HERA will be constructed using superconducting magnets.

The conductor will be a niobium titanium superconductor imbedded in a copper matrix as used in the FNAL and BNL design. We have decided not to cool down the magnet yoke but rather leave it at room temperature as done in the FNAL design. In the early design we proposed to use a warm bore, to avoid any excessive load on the refrigerator system from higher order mode losses.

A vertical cut through a dipole magnet is shown in Fig. 9. The cryostat is mounted inside a 550 mm wide

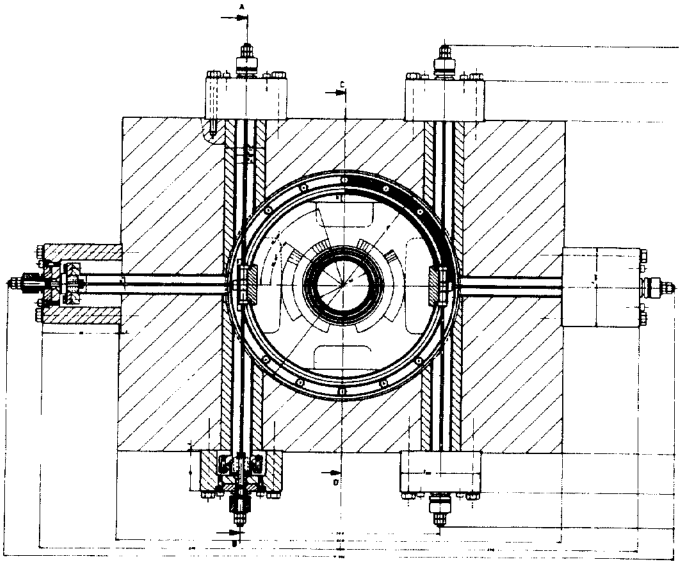

Fig. 9 - Cross section of a superconducting dipole magnet

and 420 mm high iron yoke using four sets of six tie rods each. The heat loss through the tie rods is small and this system allows us to adjust the coil within the iron following magnetic measurement without warming up the magnet. In the present design the dipole field is approximated by a two shell conductor arrangement fixed by precision stamped stainless steel collars as in the FNAL design.

The coil is immersed in a liquid helium bath at 4K. The heat shield is maintained at 50K by passing cold Helium gas through the outer cryostat.

The parameters of the dipole and quadrupole magnets are listed in Table 3.

Table 3 - Superconducting magnet parameters

Parameter	dipole	quadrupole
Magnetic length (m)	5.686	1.80
Induction (T)	4.725	-
Gradient (T/m)		74.4
Bore (cm)	6.3	6.3
Current (A)	6348	6348
Critical short sample current in cable at B = 5.5 T and the maximum tolerable operating temperature of t = 4.6 K	$I_{cr.s}$(4.6K) $\geq$ 8250 A	
Stored energy (kJ)	914	126
Mass (kg)	8514	934

Rather than one central plant, the refrigeration system is subdivided into 4 units each cooling two octants consisting of 99 dipoles and 38 quadrupoles plus one experiment. The total heat load is 16.3 kW at 4K plus 52 g liquid He/s. The load can be handled by 3 of the 4 units. The cryogenic system can thus be maintained and repaired without interrupting operations. The compressors, located on the DESY site, are feeding compressed helium in a warm circuit in the tunnel to the refrigerators which work with expansion turbines and Joule-Thomson effect.

For the proton RF we propose to use the 200 MHz system now being developed at CERN for the SPS. This system is modular with each RF cavity having its own small amplifier on top and vacuum pump underneath. We propose to install 48 groups of 3 single cell modules. The total cell length will amount to 104 m and the maximum voltage is 100 MV with an RF power between 4-6 MW. As the final power amplifier we propose to use the long-life tetrode currently being developed by European Industry.

6. Possible Design Changes

The new study group is now reviewing the feasibility study and some possible changes to this design have emmerged.

The layout of the insertions with the new spin rotators were discussed above. Possible changes may also occur in the proton ring. The superconducting magnets are not only the most costly but also the most difficult component of the ring to be constructed. Both the cost and the technical complexities can be reduced by decreasing the present coil diameter. This large diameter was chosen to provide sufficient aperture with a warm bore at injection. A warm bore seemed to be required by the heat losses due to image currents and higher order heat losses. The heat produced due to image currents can be reduced to some 0.25 W/m by a plating the inner wall of the vacuum chamber. If we give up the option of storing intense DC beams which require cleaning electrodes,then the vacuum chamber can be made very smooth such that higher order mode losses are reduced to a tolerable level. We therefore now favour a cold bore and this makes it possible to move the coils closer to the beam pipe without reducing the mechanical aperture. By reducing the coil diameter from 100 to 75 mm the cost is reduced by 20% and the forces acting on the coil and the stored energy is reduced by nearly a factor of two. A cold bore will also greatly simplify the design of the vacuum system.

The new design is expected to be completed in the next month and will then be forwarded to the government with a request for funding. If we are lucky we could then observe ep collisions before the thirtieth niversary of the first proposal to collide electrons and protons.

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