STATUS OF CERN LINEAR COLLIDER STUDIES

G. Guignard
CERN, CH-1211 Geneva 23

Abstract

A description is given of the topics which have been the subject of studies and developments, and the status of the work on a CERN linear collider (CLIC) is summarized. Progress was made on the test facility, for investigating the critical question of generating the short and intense bunches required for the driving beam. In the drive linac, the wake fields associated with the transfer structure and the consequent stability issue are severe. Therefore, studies and calculations are carried on overmoded pipes, cylindrical with either symmetrical corrugations or combs asymmetrically placed on one side. In the main linac, the question was addressed of minimizing the energy spread by shifting the phase of the accelerating voltage, leading to requirements conflicting with those for beam stability. A prototype of high-gradient accelerating cells has been built and measured. In parallel with the design studies of the final focus system, a model of a small-aperture, high-gradient quadrupole, that could be part of the scheme, has been realized and measured.

Introduction

Research and development on a linear electron-positron collider aiming at a 2 TeV c.m. energy continue at CERN and the work done concerns hardware developments as well as fundamental problems. Prototypes of key elements and test facilities have been or are being constructed, and theoretical or conceptual studies on injection, beam optics and wake-field effects have progressed. Before reporting on these topics, let us briefly recall the main characteristics of the CLIC scheme and give a short list of the main linac parameters (Table I).

TABLE I
Main Linac Tentative Parameters

Parameters	Values	Units
Energy	1.0	TeV
Luminosity	$1.1 \cdot 10^{33}$	$cm^{-2}s^{-1}$
Gradient	80	$MV\ m^{-1}$
RF frequency	30	GHz
Repetition rate	1.7	kHz
Bunch population	$5 \cdot 10^{9}$	
V-emittance $(\gamma\varepsilon_y)$	$0.5 \cdot 10^{-6}$	rad m
H-emittance $(\gamma\varepsilon_x)$	$1.5 \cdot 10^{-6}$	rad m
FF aspect ratio	5	
FF beam height	12	nm
Bunch length	0.17	mm

There are two distinctive features of the CLIC scheme[1]. The first one is the 30 GHz chosen for the main linac operating frequency, because the average RF power is inversely proportional to its square. This was considered as the highest possible value when taking into account the manufacturing tolerances, beam-induced wake fields and alignment tolerances. The work done so far has now shown any impossibility even if feasibility limits are nearly reached. The success with the construction of a prototype accelerating structure and its positioning to better than 1 μm is encouraging. The second feature is the generation of the RF power by a two-beam scheme, in which the drive beam passes decelerating structures where the 30 GHz power is generated and fed to the main linac. The drive beam consists of a train of intense short bunches and receives energy from 350 MHz sc cavities. The difficult questions of generating this beam and designing transfer structures require considerable development. The test facility addressing the former is fairly advanced and concepts of travelling-wave structure are under study.

Power Generation and Test facility

The generation of a drive beam, consisting of bunches of 1 mm r.m.s. length, 1 cm spacing and 10^{12} particles requires development. It is proposed that trains of such bunches , separated by the drive linac wavelength of c/350 MHz, will be generated by a battery of complex pre-accelerators. In order to study the feasibility of these devices, an experimental CLIC test facility (CTF) is in preparation [2]. It includes an RF gun, a beam line acting as magnetic spectrometer, acceleration to ~ 60 MeV and RF power generation at 30 GHz. A pulse compressor may be added eventually. A key element of this facility is the laser-driven photocathode and a d.c. test bench has been built for testing its fabrication [3].

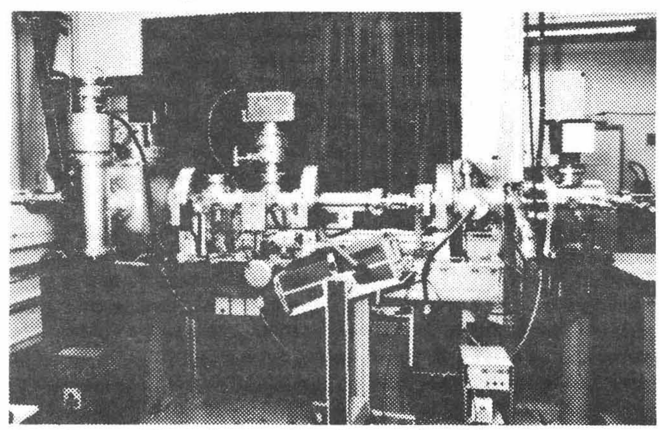

Fig. 1 The photocathode test bench

The photocathode test bench (Fig.1) is made up of a preparation chamber, a d.c. gun and an instrumentation beam line. The preparation chamber has three evaporators, an arm to transfer the cathode in the gun and a thickness monitor and has been upgraded recently with emission monitoring during evaporation and a new pumping system. The quantum efficiency is indeed a critical parameter (10^{-3} required for a few tenths of nC's) and the quality of the photocathodes depends strongly on the vacuum pressure. The d.c. gun field can reach 8 MV/m and the beam line contains four focusing coils, longitudinal profile monitor, luminescent screen for image analysis and Faraday cup for recording the charge. For a 4 mm spot size and 10 ns pulses, the gun space-charge limit is at ~12A. Best results ($7 \cdot 10^{11}$ e^-) have been achieved with Cs_3Sb and 266 nm laser.

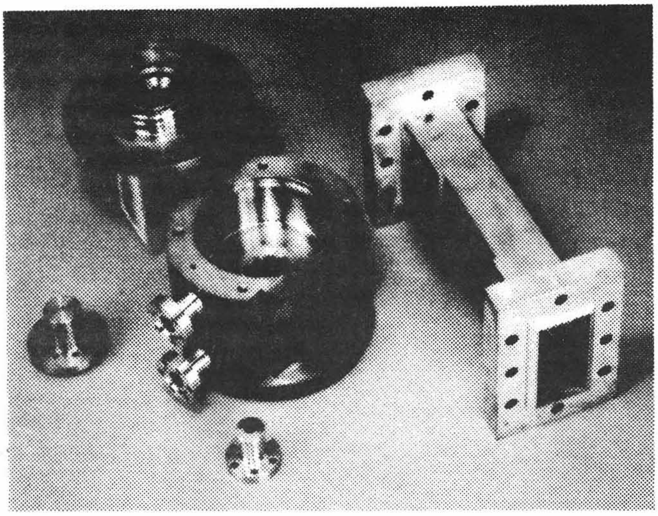

Fig. 2 The test facility RF gun

The aim of the CTF is to study the generation of very short (some ps), high-intensity (> 10 nC) bunches and of 30 GHz RF power by deceleration in a CLIC structure, whose prototype is described below. Main objectives are to learn about the guns, the bunch compressors, eventually to generate 24 MW peak power for 11 ns, to create an 80 MV/m gradient in a second structure and to test beam instrumentation. This planned performance requires an intensity of 40 nC or $2.5 \cdot 10^{11}$ particles. The adopted design is based on a one-and-a-half-cell S-band RF gun, with an operating frequency of 3 GHz. The RF gun (Fig. 2) is under test and generates up to 100 MV/m at the cathode. The transfer line, including spectrometer, instrumentation and steering or focusing elements, will be installed next. First beam will then be produced with a non-synchronized laser giving a long pulse (8 ns) and optics and instrumentation tests will be carried out. Later a laser with phase and amplitude stabilization becomes available, which can be synchronized to the RF. The RF phase at the laser pulse is an important parameter for obtaining the proper longitudinal phase space distribution for the compressor and a good survival rate of the initial charge. Numerical simulations [4] have shown that 30 nC/beam could be obtained (with optimistic cathode parameters), at the sacrifice of emittances and energy spread. To alleviate the task of the gun, trains of bunches distributed over two structure fill-times can be used. If the charge in the train per fill-time is equal to the single bunch charge (40 nC) about the same RF power is generated.

Drive Linac and Power Transfer

Energy requirements in the two-beam CLIC scheme imply an integrated gradient ratio equal to the frequency ratio. With the figures of Table 1 and a gradient in the sc cavities of the order of 10 MVm^{-1} say, the filling factor of the active part is around 10%. This gives the advantage of long distances between re-accelerating structures and the freedom of most of the tunnel from active high-power equipment other than copper structures. To induce the required 30 GHz power, the drive beam is made of four trains (distant by 2.8 ns) of ten bunches separated by 33 ps. The drain time of the transfer structure fills the gap between trains, whose number is conditioned by the fill-time of the main accelerating structure.

The design of the travelling-wave transfer structures then becomes difficult. The equilibrium between the energy loss in the structures and gain in the drive cavities implies a very low characteristic impedance (several Ω/m) and subsequently the parasitic impedances must be held to very low values also. Studies have shown that fractional wake loss per transition from structures to cavities can be kept low (10^{-4}) and the higher-mode energy loss in cavities reaches a tolerable value of ~6%. Major problems arose when computing longitudinal and transverse wake fields due to the resistive walls of transverse structures made of two parallel plates with combs. Longitudinal wakes could generate a decelerating field up to 18% of the average voltage gain and transverse wakes were so strong that stabilizing the drive beam with BNS damping would require very strong external focusing and large energy spread (~10%). To alleviate these constraints, work started on structures with increased beam-to-wall distance and reduced resistive wall effects [5]. Further developments are certainly required.

The first improved concept starts from a large circular pipe of 12 mm diameter (transverse wakes reduced by a factor 27), with a smooth inner wall. A power collecting rectangular waveguide runs along the outside of the pipe and is coupled to the inside via periodic holes. In order to fill the gap between the trains with the pulse produced, the group velocity of the wave travelling in the guide must be < c (say ~c/2) and the phase velocity then reaches ~2c. Hence, the coupling holes must be separated by two 30 GHz wavelengths (20 mm) and their dimensions adjusted to give the requisite impedance. Since a TEM field is easy to simulate, a model has been built (Fig. 3) and has shown that obtaining the 11.4 ns pulse with the right phase and amplitude might require working at lower phase velocity (~1.2 c) and coupling to a backward wave. The pipe being large, it is also overmoded and there is one accelerating mode with a cut-off below 30 GHz. It can be cancelled if its phase slip with respect to the wave in the guide is equal to π between two consecutive holes.

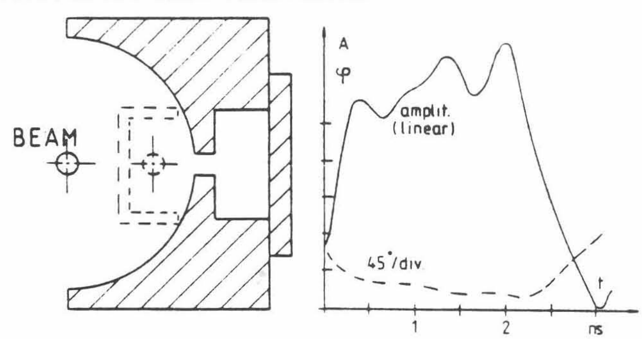

Fig. 3 Possible concept of transfer structure

Another concept of similar nature is studied numerically. It is based on an even larger pipe (22 mm diameter) with very shallow and 6 mm periodic corrugations and a rectangular waveguide on one side. In principle, the discontinuities created by the corrugations make it possible to generate in the guide a backward wave with phase velocity equal to c and group velocity below c. Coupling is again achieved via periodic holes between the cylinder and the guide.

Energy Spread and Beam Stability

An important problem is making the final focus (FF) system accept the unavoidable energy spread of the beam, due to high single-bunch extraction and stabilization of the wake field's deflecting effects by strong BNS damping [8]. The required focusing gradient over the bunch length can be generated by a deliberate energy spread from head to tail adding to external quadrupole fields and/or actual RF quadrupoles created with asymmetric slots in a fraction (~10%) of the structure. Without RF quadrupoles, stabilization implies a 4 to 6% energy spread that is obviously in conflict with the energy acceptance of the FF, limited by chromaticity compensation to a value ten times smaller.

It now seems possible to match the beam's energy spread to FF acceptance by cancelling to higher orders the longitudinal wake with the RF voltage [6]. The resulting accelerating-gradient variation over the bunch can be flattened by adjusting the RF phase, for given bunch length and population. In this way very flat curves near the centre of the bunch have been obtained, with two maxima of about the same amplitude and one minimum. The energy distribution is deduced from such curves via the inverse of their derivatives [7] and has therefore sharp peaks related to the points with zero derivatives. In the presence of these peaks, the distribution can be centred with respect to the average value of the energy and the tail population reduced. On top of this, it is reasonable to assume that a small fraction of particles with an energy below a certain limit does not contribute to luminosity.

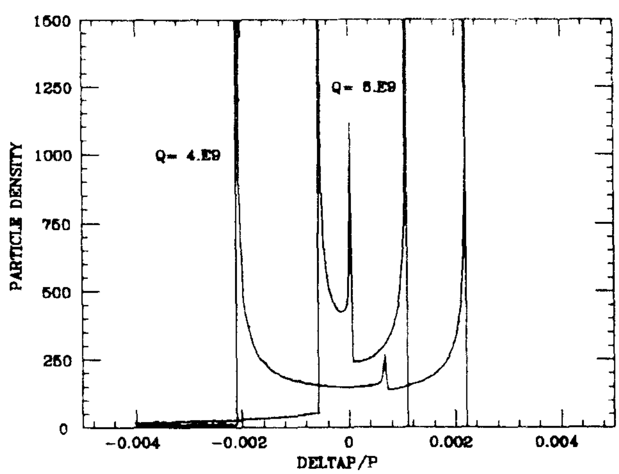

Fig. 4 Distributions reducing energy spread

With such energy distributions and "tail cuts", a minimum r.m.s. energy spread of 0.9‰ was achieved for a bunch length of 0.17 mm and $6 \cdot 10^9$ particles (14% being discarded from the tail). This optimum corresponds to the nominal parameters of Table 1, an RF phase of 8° and a total relative energy range of from +1.2 to -4‰, so as to fit the FF acceptance. Figure 4 shows the corresponding energy distribution together with that obtained with another set of parameters (0.11 mm bunch length, $4 \cdot 10^9$ particles, 7° RF phase and only 4% discarded) to indicate the range in which they can be varied. In the last case, the r.m.s. energy spread is 1.6‰ and the total range from +2.2 to -4‰ is accepted by the FF system.

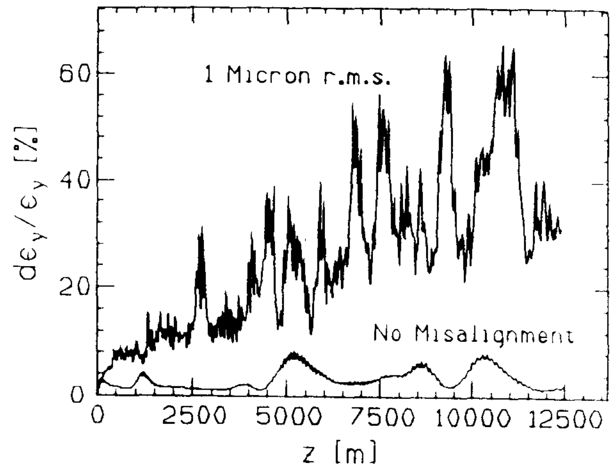

Fig. 5 Vertical blow-up with autophasing

Recently, numerical simulations were carried on with the main linac parameters about a possible higher order BNS scheme [8], called autophasing and using the wake to create coherence within a bunch. Preliminary results have shown that for a perfect linac, with only magnetic focusing of 90° phase advance and 20 m wavelength, and injection errors of 4.2 and 1 μm per plane (H and V), the emittance blow-up could be kept below 6% (Fig. 5) using four linac sections with RF phases between -35° and -10°, and an energy spread of 4.5%. In the presence of random errors in quadrupole alignment (e.g. 1 μm, r.m.s.), autophasing is more difficult. After RF phase adjustment to larger values between -40° and -16.5° (5.4% energy spread) and simple trajectory corrections, the emittance growth was about 50% (horizontal) and 30% (vertical), as is also shown in Fig. 5. Further investigations are necessary, since the tolerances are a critical question.

Structure Fabrication and Alignment

Each main linac proposed is composed of 45'750 27.32 cm long accelerator sections, with gradients of 80 MV/m, quality factor of 4224, shunt impedance of 110.6 MΩ/m and fill time of 11.1 ns. The total peak input power is 1.848 TW/linac and there would be 82 cells per section. The outer diameter of the accelerating structure, machined to ±1 μm, serves as reference for alignment. The structure is pumped by four vacuum manifolds through a series of radial holes or damping slots if incorporated. There are four 5 mm diameter holes for cooling and two 1.6 mm diameter recessed holes for dimple tuning. The cell dimensions give a measured $2\pi/3$ mode frequency of 29.985 GHz.

A prototype section [9], with only 30 cells, but otherwise complete, with reference surfaces, input and output couplers and vacuum and cooling connections has been made at CERN with the help of industry (Figs. 6 and 7). Brazing of machined copper cups was the fabrication method used. Machining tolerances of ±2 μm (except for reference surfaces) and a surface finish to 15 nm r.m.s. roughness enabled cell-to-cell phase shift errors to be kept below 0.5° on unbrazed damped stacks of 15 cells and the Q-factor to reach 95% of the theoretical value. Since non-reproducible frequency changes could be produced by subsequent brazing operations, the 30-cell structure has been designed to require a 3° phase shift change per cell in the finished prototype section. Therefore, four dimple tuners per cell were foreseen and two actually used for final tuning. High-quality brazing of the discs is necessary to prevent excess flow of braze either on the external surface (reference) or into the cell (frequency changes). This was achieved by creating 1 mm annular copper-to-copper diffusion bond (mirror finish) at the inside and outside edges of the cup. These bonds stop braze leakage and provide electrical contact. Brazing of water and vacuum pipes was made in a second stage, after drilling out the cooling channels and milling the vacuum manifold recesses. Matching the impedance of the brazed structure with couplers is finished with phase shifts in the range +5°/-2.5°. Given the success of the prototype construction, it is now planned that two full-length sections will be fabricated for CTF.

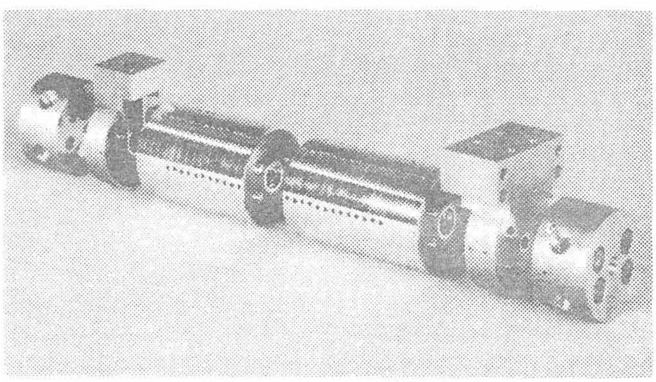

Fig. 6 Prototype section before brazing

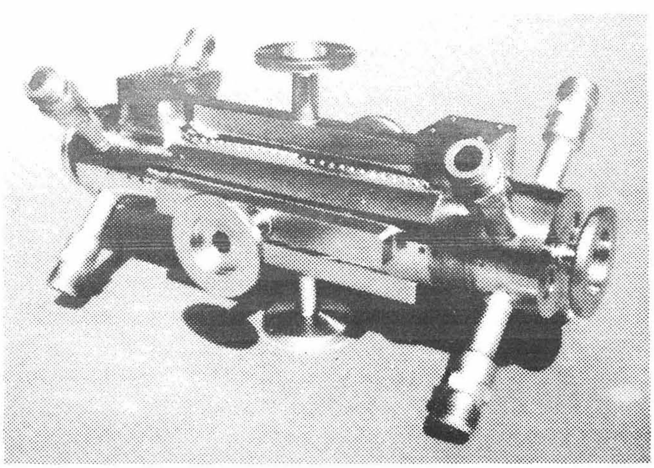

Fig. 7 Finished 30-cell prototype section

Accelerating structures with quadrupoles must be aligned within microns and an automatic alignment is mandatory. To study the question of precise positioning, a micro-movement test facility [10] has been constructed (Fig. 8) and installed on a reference granite block. It consists of two ceramic girders supported by three platforms which are each activated by three precision jacks that allow rotations in the three planes via swivel-joint link rods. Dummy accelerating sections were clamped to the ~1 m long girders via supports which have been fixed with a 3 μm precision. Commercial micromovers and capacitive-vernier transducers (0.1 μm resolution over ±4 and 5 mm) have been used. With this system, the structure could actually be displaced micron by micron, and the measured coupling between the three motions corresponds to the theoretical one. Automatic alignment also requires the beam position to be measured with micron resolution. Concept of position pick-up is based on an E_{110} mode cylindrical cavity, mounted coaxially to the main structure and working at 33 GHz to avoid interference with the RF pulse. The narrow band signal selection under development is carried out by filtering and mixing down signals in several stages.

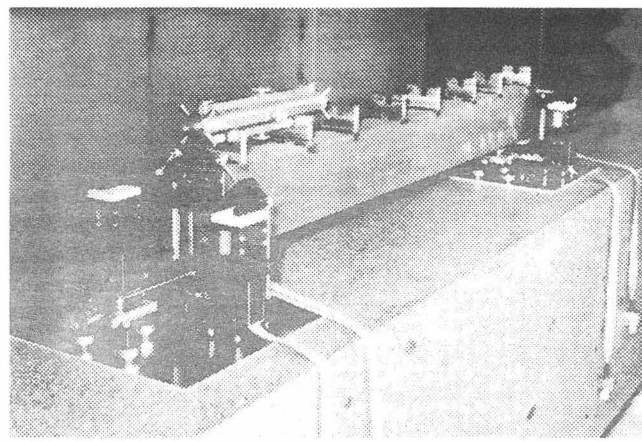

Fig.8 Micro-movement full-size model

Collision Point Requirements

The beam's transverse dimensions at the collision point must be small (nm) in order to reach the adequate luminosity. So as to avoid a centre-of-mass energy spread due to beam-beam radiation larger than 0.1 and too high a repetition rate, i.e. a beam power, the beam height is further reduced to a value corresponding to a large aspect ratio σ_x/σ_y (Table 1). Compression of the beam is provided by a four-lens telescope, with 25 × 75 de-magnification, that is 128.4 m long and optimizes the product of drifts and strengths. Large chromatic aberrations blowing up the beam are compensated in a chromatic correction section 320 m long and made of two lattices, one for horizontal and one for vertical compensation. Each lattice contains four pairs of quadrupoles for a total phase shift of 2π as well as a pair of equal-strength sextupoles, placed at the maximum of the corresponding β value and at equal dispersion. In addition, the two sextupoles of a pair are separated in phase by π and lie in both planes at a multiple of $\pi/2$ from the crossing point. With all these conditions, 2nd order geometric and chromatic aberrations created by the sextupoles themselves are cancelled, except for the two terms that correspond to the blow-up generated by the telescope and have to be compensated. The requisite dispersion is generated by weak 19 m long dipoles. The energy acceptance of this system [11]

(FF), defined as doubling the beta functions, is about ±4‰ (Fig. 9).

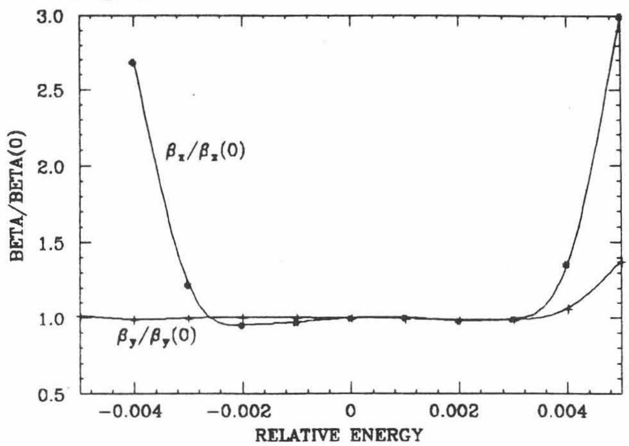

Fig. 9 Energy acceptance of Final Focus

The emittance blow-up by quantized radiation is critically dependent on the emittances (Fig. 10) for a given gradient in the last quadrupole. The effect nearly vanishes for small enough normalized emittances and this explains the revised values quoted in Table 1. The conceptual design of the damping rings has been examined again in view of these values. It is still based on the simplest lattice for small emittance, made of a FODO structure with a combined function magnet in the D-quadrupole [12]. However, to obtain these emittances with low damping times, the dipole length and the number of cells (hence the circumference) have been increased (340 cells), and the energy raised up to 3.35 GeV, which has implications on the injector complex. Luminosity not only depends on the emittances of the head-on colliding bunches, but also on the constriction of the orbits due to the bunch penetration. This important effect has been simulated numerically using non-Gaussian particle distribution as obtained by tracking and including aberrations and synchrotron radiation. It was found with the most recent parameters that the luminosity is enhanced by about 2.5 so as to reach the value of Table 1 with the beam sizes given.

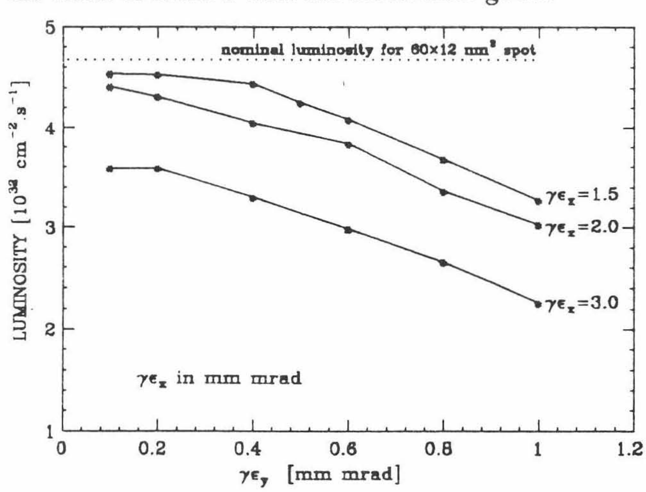

Fig. 10 Luminosity dependence on emittances

Quantized radiation also puts a limit on the useful quadrupole strength and on the interest for ultrahigh gradients. Therefore focusing in the FF system should be achieved by ferromagnetic, electromagnetic or pulsed quadrupoles with 1 mm apertures. Studies are being pursued of a quadrupole made of soft ferromagnetic poles with simple geometry for sub-micron tolerances as well as good field quality and excited by blocks of commercial permanent magnet material [13]. Pole prototypes of 25 mm long module with up to 1.4 T tip field have been built (Fig. 11) together with a precision measuring bench. In parallel, lenses made of four single, axial conductors (Fig. 12) and powered oppositely in pairs are considered and field quality was studied for different geometries [14]. To minimize the average power, these quadrupoles would be pulsed, with up to 7T on the surface, ~10 kA per conductor and 4 μs pulse length. An enlarged model has been built for low current tests .

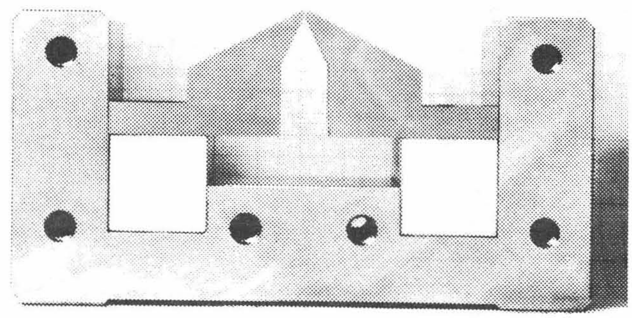

Fig. 11 Permanent half-quadrupole model

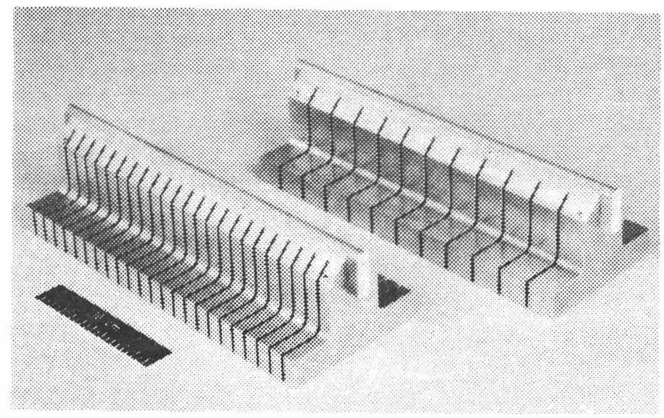

Fig. 12 Model of pulsed quadrupole conductors

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