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A SUPERCONDUCTING RADIOFREQUENCY e^+e^- LINEAR COLLIDER FOR BOTTOM QUARK AND NUCLEAR PHYSICS STUDIES

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ABSTRACT :

The design of an accelerator complex based on recirculated linacs is presented. It could be used as a $b\bar{b}$ hadron factory and simultaneously it could provide nearly continuous beams for Nuclear Physics studies. The expected performances of this accelerator are given. The main components and the associated developments are mentioned. The characteristics of the associated detector requested to perform an original $b\bar{b}$ physics program are also listed. Finally, possible extensions offered by the accelerator complex are presented.

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1. INTRODUCTION.

Two different ways can be considered today to improve our knowledge of fundamental particle physics : either go to higher energy to produce directly more massive particles or use machines with increased luminosity and improved detectors to perform more precise measurements in an energy domain already reached.

As ultimately the future e^+e^- TeV collider will have to use linear accelerators and will also need to have a high luminosity, $L \simeq 10^{33}\text{-}10^{34} \text{ cm}^{-2}\text{s}^{-1}$, U.Amaldi and myself [1-4] came to the conclusion that a moderate energy linear collider, with a luminosity in the quoted range, which would allow for an interesting physics program, could be considered as part of a reasonable strategy to prepare the next generation of machines.

Heavy quark factories, and in particular a $b\bar{b}$ quark factory promise to provide new insight into fundamental aspects of Physics. This includes [5,6] precise tests of the Standard Model, study of $B\bar{B}$ mixing, study of rare B-meson decays sensitive to new physics, and eventual discovery of CP violation in the B-system.

On the other hand, for Nuclear Physics research, a multi-GeV high current and high duty factor electron accelerator is needed [7,8] to better understand the structure of nuclei and the nuclear force in general.

The proposed design of an accelerator complex based on superconducting radiofrequency linacs with recirculators would satisfy the requests both for $B\bar{B}$ physics and Nuclear Physics studies. As we will see, it also offer the possibility of further extensions, e.g. as a Z factory or a Toponium factory.

2. ADVANTAGES OF A LINEAR $B\bar{B}$ FACTORY.

Fig.1 summarizes our knowledge of the $e^+e^- \rightarrow \text{hadron}$ cross section in the $9 < W < 11$ GeV center of mass region. Table 1 gives the measured and estimated masses of the bound $b\bar{b}$ and open b systems. The $Y(4S)$ state can decay into a pair of mesons $B_u^+ - B_u^-$ or $B_d^0 - \bar{B}_d^0$ produced nearly at rest. To also produce a $B_s^0 - \bar{B}_s^0$ pair one has to cross the $Y(5S)$ resonance.

When the center of mass energy increases, Fig.2, the total cross section decreases, and also the $b\bar{b}$ cross section, as W^{-2} . It reaches a minimal value at $W \simeq 60$ GeV, where the Z peak starts to appear. Since the Z decays in 15 % of the cases into a $b\bar{b}$ pair, with or without associated gluons, it is evident from Fig.2 and Table 2 that a Z factory with $L \simeq 10^{33}\text{cm}^{-2}\text{s}^{-1}$, if available, would be an ideal place to study $B\bar{B}$ physics.

Fig.1a) The cross section for $e^+e^- \rightarrow \text{hadrons}$ in the upsilon energy range.

Fig.1b) Corrected $R(\sigma_{\text{had}}/\sigma_{\mu\mu})$ versus center of mass energy as measured by the CLEO detector at CESR.

Table 1. Masses of the bound $b\bar{b}$ and open b systems [from "Review of Particle Properties", Phys. Lett. 107B, 1986]

	Mass (GeV)	Full Width (MeV)		Mass (GeV)
T(1S)	9460.0 ± 0.2	0.043 ± 0.003	B_u^+, B_u^-	5271.2 ± 3.0
T(2S)	10023.4 ± 0.3	0.030 ± 0.007	$B_d^0, \bar{B}_d^0$	5275.2 ± 2.8
T(3S)	10355.5 ± 0.05	0.012 ± 0.010 0.004	$B_s^0, \bar{B}_s^0$	≈ 5400
T(4S)	10577 ± 4	24 ± 2		
T(5S)	10865 ± 8	110 ± 12	B_c^+, B_c^-	≈ 6600 (estimate)
T(6S)	11019 ± 9	79 ± 16

Fig.2 The cross section for $e^+e^- \rightarrow \text{hadrons}$ in the 2 to 100 GeV center of mass energy domain (adapted from Ref.10).

In the absence of such a Z factory, the "near threshold" region, i.e. $W \simeq Y(4S), Y(5S)$ offers the largest cross-section for $B\bar{B}$ production. But what finally matters, for the physics measurements we are interested in, is the quantity :

$$Q = \frac{\sigma_{b\bar{b}}}{\text{BR}(b \rightarrow B \rightarrow f)} \frac{1}{A_{\text{sep}}} \frac{1}{\epsilon_{\text{rec}}^f} \frac{1}{\epsilon_{\text{tag}}}$$

with $\sigma_{b\bar{b}}$ $b\bar{b}$ production cross section;
 $\text{BR}(b \rightarrow B \rightarrow f)$ branching ratio of B meson into a particular final state f;
 A_{sep} particle-antiparticle separation;
 ϵ_{rec}^f reconstruction efficiency of final state f;
 ϵ_{tag} tagging efficiency of the associated $\bar{B}$.

The last three parameters, A_{sep} , ϵ_{rec}^f and ϵ_{tag} are energy, machine and detector dependent. In particular it would be worthwhile (see Table 2 and Ref.[9]) to run at $W \simeq 15$ GeV to boost the produced $B\bar{B}$ mesons and detect their decay vertices with a sophisticated microvertex detector. In this respect linear colliders offer advantages over circular colliders such as the possibility of small beam pipe radius and of increasing the luminosity by increasing the center of mass energy resolution, outside the resonance region.

Table 2. $b\bar{b}$ production and hadronic cross sections, together with typical decay lengths of B meson for various e^+e^- center of mass energies.

W (GeV)	$\sigma_{b\bar{b}}$ (nb)	$\sigma_{b\bar{b}}/\sigma_{had}$	$\beta\gamma c\tau$ (mm)
$\Upsilon(4S)$	1.0	0.25	0.03
15	0.1	0.09	0.30
26	0.04	0.09	0.60
Z	5.0	0.22	3.00

3. MAIN PARAMETERS AND BASIC FORMULAE FOR LOW ENERGY LINEAR COLLIDERS.

With two gaussian bunches of particles colliding at the interaction point, one can define [11] :

3.1. The Energy and beam parameters.

- $E_0 = \gamma mc^2$: positron and electron beam energy
- $W = 2E_0$: center of mass energy of the collision.
- $N^+(N^-)$: number of positrons (electrons) per bunch.
- $\sigma_x = \sigma_y = \sigma_t$: transverse bunch dimension.
- σ_z : bunch length dimension.
- ϵ_n : $\gamma \sigma_t^2 / \beta^*$ normalized emittance.
- β^* : beta function at the collision point.

3.2. The beam power of each beam.

$$P_b = 16(N/10^{11})(f_r/\text{kHz})(E_o/\text{TeV})$$

where f_r is the pulse repetition frequency.

3.3. The disruption parameter and the pinch effect.

The focusing effect produced by one bunch acting on the particles in the other bunch depends on the disruption parameter defined as :

$$D = \frac{r_e N \sigma_z}{\gamma \sigma_t^2} \approx 28(N/10^{11})(10^{-5}\text{m}/\epsilon_n)(\sigma_z/\beta^*)$$

with r_e the electron radius.

For $D \ll 1$, each beam acts like a lens with focal length $F = \sigma_z/D$ for particle in the opposite beam.

For $D \geq 1$, the particle will make oscillations as it passes through the opposite bunch and the bunches will pinch. This pinch effect will cause luminosity enhancement, characterized by an enhancement factor H_D .

This enhancement factor has been recently computed [12] for beams with gaussian radial profiles, finite emittance, and different values of $A = \sigma_z/\beta^*$. The variation of H_D as a function of D is shown in Fig.3. This computation indicates that H_D increases with D , for any D value. A similar result has been obtained independently in Ref.13. These results do not show the saturation effect [$H_D = 6$ for $D \geq 5$] originally computed by Hollebeek [14] for beams with zero initial emittance.

Fig.3 Luminosity enhancement factor H_D as a function of D for different values of $A = \frac{\sigma_z}{\beta^*}$ (from Ref.12).

3.4. The Luminosity.

It can be expressed as:

$$L/10^{31} \text{ cm}^{-2} \text{ s}^{-1} = \left(\frac{N^+}{10^{11}}\right) \left(\frac{N^-}{10^{11}}\right) \left(\frac{f_r}{\text{kHz}}\right) \left(\frac{\mu\text{m}}{\sigma_t}\right)^2 \left(\frac{H_D}{4\pi}\right)$$

$$\approx \frac{D}{30} \frac{H_D}{\sigma_z} \left(\frac{\text{mm}}{\sigma_z}\right) \left(\frac{P}{\text{MW}}\right)$$

3.5. The beamstrahlung.

During crossing, particles will be bent and then emit synchrotron radiation, called beamstrahlung. It will cause an energy loss of the beam.

In the case considered here, with E_c the average photon critical energy, the relevant parameter Υ defined as :

$$\Upsilon = \frac{E_c}{E_0} \approx \frac{0.215 (E_0/\text{TeV}) (N/10^{11})}{(\sigma_z/\text{mm}) (\sigma_t/\mu\text{m})} \sqrt{H_D}$$

is much smaller than 1, and "classical" formulae can be applied to estimate :

N_γ	the average number of emitted photons.
$\langle \epsilon \rangle = \langle E - E_0 / E_0 \rangle$	the average fractional energy loss.
ΔW_b	the center of mass energy spread due to beamstrahlung.

In particular, ΔW_b is approximated by :

$$\Delta W_b / \text{MeV} \approx 1.2 (E_0 / \text{GeV})^2 (L / 10^{31} \text{ cm}^{-2} \text{ s}^{-1}) (\text{mm} / \sigma_z) (\text{kHz} / f_r)$$

but one has to remember that the center of mass energy W caused by the beamstrahlung radiation is not normal.

The total energy spread is finally given by :

$$\Delta W \simeq (\Delta W_b^2 + \Delta W_L^2)^{1/2}$$

with ΔW_L the longitudinal energy spread due to the longitudinal emittance.

Finally, the disruption angle, i.e. the angle of photon emission relative to the original beamline, can be approximated by :

$$\theta_D \simeq 1.84 N r_e / \sqrt{D} \gamma \sigma_t$$

for large D values.

From these formulae one sees that when for instance E_0 , P , ϵ_n , $\langle \epsilon \rangle$ and D are chosen, all the other quantities defining the collider are fixed.

4. THE FIRST DESIGNS OF THE ACCELERATOR COMPLEX.

The main idea of a beauty factory based on superconducting linacs with recirculators was proposed in 1986 by U.Amaldi and myself [1]. Initially, it was planned to reach $W = 2 E_0 \approx 10 \text{ GeV}$ and to work near the $Y(4S)$ resonance.

It then evolved into the conceptual design of a multipurpose beauty factory [2], shown schematically in Fig.4, and briefly described below.

Fig.4 Scheme of the SC complex proposed in Ref.2.

The electrons and positrons are injected into two 100 m long linear accelerators equipped with superconducting RF cavities. Assuming an accelerating gradient $G = 7 \text{ MV/m}$, and a filling factor of 0.5, they gain 350 MeV per linac crossing. After three recirculations in the first stage, the positrons and electrons are then injected at 2.4 GeV into their respective damping rings. After some 10 ms, when the particles have reached the required invariant emittance ($\epsilon_n \simeq 2 \times 10^{-6} \text{ m}$), they are injected into the 300 m long linacs of the second stage in which they acquire some 1000 MeV per crossing. They make a 180° turn into dedicated arcs before being accelerated into the second linac.

After one, two or three recirculations, the electrons and positrons could collide at $W \simeq 10, 15$ or 20 GeV respectively. Two main working conditions were considered :

- Near threshold, i.e. at $W \simeq Y(4S) = 10.58$ GeV in high energy resolution mode.
- In the continuum, i.e. at $W \simeq 15-20$ GeV, in low energy resolution mode.

The main parameters and the expected performances for both modes are presented in Table 3.

Table 3. Parameters for the high resolution and low resolution modes of the beauty factory [Ref.2].

Quantity	Symbol/unit	High resolution mode	Low resolution mode
Bunch energy	E/GeV	$5-6^{\text{a)}}$	$6-10^{\text{a)}}$
Luminosity	$L/\text{cm}^{-2} \text{s}^{-1}$	10^{33}	10^{34}
Power/Beam	P/MW	0.5	1.5
Bunch frequency	f_r/kHz	12	12
Invariant emittance	ϵ_n/m	2×10^{-6}	2×10^{-6}
Disruption parameter	D	16	13
Pinch factor	H_D	6	6
Particles/bunch	N	5×10^{10}	8×10^{10}
Bunch rms length	σ_z/mm	1.3	0.4
β -value at IP	β^*/mm	6.0	4.0
Bunch rms radius	$\sigma_t/\mu\text{m}$	1.1	0.60
Av. critical energy	E_c/MeV	2.3	85
E_c/E	T	4.5×10^{-4}	8.5×10^{-3}
Fractional energy loss	$\langle \epsilon \rangle$	4.5×10^{-4}	2.5×10^{-2}
Av.number of photons	N_γ	2.5	7.5
Collision energy	W/GeV	10-12	12-20
Fract. rms of W	σ_w	3.5×10^{-4}	1.3×10^{-2}
Rms of $W = \sigma_w W$	W/MeV	3.4	250

a) The other parameters are given for $E = 5$ GeV and $E = 10$ GeV respectively.

One notices that, on purpose, the parameters σ_z , β^* and $\sigma_t = \sigma_x = \sigma_y$ of the high resolution mode are similar to the designed SLC ones. The invariant emittance is ten times smaller, that the SLC one, but is equal to the one achieved in modern synchrotron light sources. The gain in luminosity comes mainly from the bunch frequency, (as allowed by the use of SC cavities), which is one hundred times larger than in the SLC case, and from the large value of the disruption parameter D and then H_D .

In the high luminosity low resolution mode the emittance and the frequency are equal to the ones needed in the high resolution mode while the other parameters are somewhat more demanding.

This version presented two major difficulties :

- The necessary positron flux was assumed to be produced with a ~ 150 MeV-30 mA electron beam corresponding to 5 MW power on the conversion target.
- The required invariant emittance was assumed to be achieved by putting trains of five bunches in four e^- rings and four e^+ rings, each ring having a $\simeq 100$ m circumference.

Recently, new ideas have been proposed for the production of electron bunches with small emittance and encouraging tests have been performed [15-16]. We then assumed that, after some R and D work, it would be possible to achieve the required value ($\epsilon_n \simeq 2 \times 10^{-6}$ m) without the need of expensive damping rings. The design developed then into the scheme [3] shown in Fig.5. One notices that experimental areas for Nuclear Physics studies are also indicated. They could be provided with nearly continuous electron beams at an energy reaching up to 2.5 GeV in stage 1 and 10 GeV in stage 2.

Fig.5 Scheme of the SC accelerator complex presented in Ref.3.

This scheme was used as a basis of discussion and work preparation for the Courmayeur Workshop held in December 1987. This workshop was called by physicists from the Italian Institute for Nuclear Physics (INFN) with the aim of examining the design problems and discussing the possible solutions, together with the Physics issue and the detector considerations. During the Workshop a number of important ideas and alternatives were put forward (see Ref. [6]). In particular, during the final discussion, the idea of a single racetrack collider was mentioned.

5. THE PRESENT DESIGN OF THE ACCELERATOR COMPLEX.

Immediately afterwards, U. Amaldi and myself worked out the one racetrack scheme [4] shown in Fig.6.

Fig.6 Scheme of the single racetrack superconduction accelerator (Ref.4).

In this scheme, now considered as the reference scheme for the designed accelerator, four types of bunches are accelerated :

The first three bunches, accelerated with a repetition rate $f_r = 10$ kHz, are used for quark physics. The low intensity bunches, accelerated at 500 MHz, are used for nuclear physics. The timing sequence is described following Fig.7.

Fig. 7 a. Timing sequence of the bunches in the point, A, B, C, D, E of Fig. 6.
b. Timing of the bunches in point E.

By irradiation of a photocathode with a laser burst, an intense bunch of $8 \times 10^{10} e^-$ and of small transverse emittance ($\epsilon_n \simeq 2 \times 10^{-6}$ m) is produced [15,16]. This bunch is preaccelerated in two stages up to $\simeq 100$ MeV. The bunch is then injected in point A of Fig.6

into an ~ 500 m long linac made of 500 MHz superconducting (SC) cavities. Assuming an accelerating gradient $G = 5$ MV/m and a filling factor 0.4, the bunch will take roughly $1.5 \mu\text{s}$ to reach point B with the nominal energy of 1.15 GeV (see Fig.7a). It spends roughly $1 \mu\text{s}$ to make a 180° turn in the recirculator arc BCD (whose radius is ~ 100 m) before entering the second linac section DE, in which the electrons gain 1.05 GeV. After recirculation in the arc EFA, the bunch is back in point A, with $E_0 \simeq 2.2$ GeV, $5 \mu\text{s}$ after injection, ready to start a new circulation.

A very intense electron bunch (whose intensity is in the range $2.5\text{-}5 \times 10^{11} e^-$), delayed with respect to the intense electron bunch ($8 \times 10^{10} e^-$) by some $0.5 \mu\text{s}$ (Fig.7a and 7b), is also accelerated up to 2.2 GeV. This very intense electron bunch is ejected in E to produce positrons in a rotating target as described in Ref. [17]. The positron bunch ($2.5\text{-}5 \times 10^{10} e^+$) is preaccelerated in two steps up to 0.1 GeV before injection in A and acceleration up to 1.15 GeV. The bunch finds in B a dedicated 1.15 GeV recirculator which guides it to point D. After a second acceleration in the linac DE, the positron bunch reaches E with 2.2 GeV. From E it is extracted and injected in the single damping ring DR which in Fig.6 is drawn as considered by Bassetti and collaborators [18]. After a waiting time $T \simeq 5\tau \simeq 5$ ms, the required normalized emittance is achieved and the 2.2 GeV positron bunch is extracted with fast kickers [19,20] and injected in the linac at point E. The positron bunch produced in a previous accelerating cycle and the intense ($8 \times 10^{10} e^-$) electron bunch, which will ultimately be used for e^+e^- collisions reach in synchronism points E and A respectively. From then on, the e^+ and e^- bunches are rotating in opposite directions and have to be electrostatically separated at 3.25, 4.30, 5.35 and 6.40 GeV, in the centre of the arcs (points C and F) to avoid unwanted collisions. When they reach 5.35 GeV, in B for the electrons and in D for the positrons, the two bunches are extracted into special channels and made to collide at the Interaction Region (IR). With one more recirculation the ejection will be at the energy $E_0 = 7.45$ GeV and the collision will take place at $W \simeq 15$ GeV.

In addition to the intense electron and positron bunches, the linacs accelerate low intensity (2.5×10^6) electron bunches moving at a distance equal to the RF wavelength (60 cm corresponding to 2 ns). These very high frequency (500 MHz) and low intensity electron bunches can be ejected in point E at the nominal energies of 2.2, 4.3, 6.4 and 8.5 GeV, depending on the number of recirculations, giving a current $\leq 200 \mu\text{A}$. The energies 1.15, 3.25, 5.35 and 7.45 GeV will also be available through a magnetic channel which bypasses the acceleration in the second linac between points D and E. As shown in Fig.1 these electrons are then sent into a channel followed by a deflection system providing beams to the high-luminosity hall and to the low-luminosity hall for nuclear physics experiments. As proposed by Ritson [21], the channel could be equipped with a 'trimming linac' to adjust the energy by roughly

± 0.2 GeV, if needed. In principle, it would also be possible to eject electron bunches in point B at nominal energies 1.15, 3.25, 5.35 and 7.45 GeV to provide another hall with electrons.

As shown in Fig.7a, the time needed for the acceleration of the bunches used for the beauty factory is $\sim 12 \mu\text{s}$ at 5.35 GeV per beam and $\sim 17 \mu\text{s}$ at 7.45 GeV per beam. The timing of the various bunches in point E is shown in Fig.7b. It is seen that the electron bunches for nuclear physics must leave about $20 \mu\text{s}$ for the particle bunches, so that the duty cycle for nuclear physics is $\simeq 80\%$ with a beauty factory repetition rate $f_r = 10$ kHz. This implies that, while the collider runs, the nuclear physics halls can be provided with the following choices of energies : 1.15, 2.2, 3.25, 4.3, 5.35, 6.4, 7.45 and 8.5 GeV. If necessary, the nuclear physics experiments could be prime users and could choose the energy for some part of the time.

Table 4 gives the main parameters of the accelerator complex for different energies with different resolution modes justified by physics arguments, i.e. resonance width when running on a resonance or maximal luminosity when working in the continuum.

Table 4

Mode:	cc-factory	High-resolution Y(4S)	Medium-resolution Y(5S)	Low-resolution 'continuum'
E_0 (GeV)	2.0	5.29	5.43	7.5
W (GeV)	4.0	10.58	10.86	15.
N^+ (10^{10})	2.5	2.5	2.5	5.0
N^- (10^{10})	8.0	8.0	8.0	8.0
ϵ_n (10^{-6} m)	2.0	2.0	2.0	2.0
ϵ_L^+ (10^{-2} m)	4.0	4.0	4.0	6.0
ϵ_L^- (10^{-2} m)	1.0	1.0	1.0	1.0
σ_z^+ (mm)	3.0	3.0	1.5	0.7
σ_z^- (mm)	1.0	1.0	0.5	0.5
β^* (mm)	5.0	5.0	2.0	2.0
$\sigma_x = \sigma_y$ (μm)	1.6	1.0	0.6	0.52
D^+	21	21	27	25
D^-	22	22	28	28
II_D a)	7.7	7.7	7.3	9.5
f_r (kHz)	7.5	10.	10.	10.
ΔW_b (MeV)	1	4	15	75
ΔW_L (MeV)	9	9	17	45
P^+ (MW)	0.06	0.2	0.2	0.6
P^- (MW)	0.2	0.7	0.7	1.0
P_{Γ^-} (MW)	0.7	0.9	0.9	1.8
P_{main} (MW)	16	18	18	20
L ($10^{33} \text{cm}^{-2}\text{s}^{-1}$)	0.35	1.3	3.0	11

The values of most of the parameters are very similar to the ones of Refs. [2,3]. The main differences are the following :

- .The number of positrons N^+ and electrons N^- per bunch are different, as in Ref. [22]. Since intense positron bunches are difficult to produce and dump,, the number of positrons per bunch has been decreased while the number of electrons increased.
- .The positron bunches are longer than the electron bunches, so that $N^+\sigma_z^+ \simeq N^-\sigma_z^-$ [22,23]. This implies that the disruption parameters $D \propto N\sigma_z$ of the two bunches are approximately equal.
- .The disruption parameter D has been somewhat increased and the corresponding enhancement factor H_D has been computed using the expression given in Ref. [12], and shown in Fig.3, which assumes equal lengths and populations of the e^+ and e^- bunches. To adapt it to our asymmetric conditions, the average values of the disruption parameters and of the bunch lengths have been used.

6. MAIN COMPONENTS AND ASSOCIATED DEVELOPMENTS.

At the Courmayeur Workshop, the Machine Group* has examined in details the various components of the accelerator complex and pointed out the topics which need Research and Developments.

The work was mainly done in the framework of the machine design presented in Ref. [2,3], but most of the conclusions apply to the single racetrack version of Ref. [4].

The different topics [24] can be separated in the following way :

6.1. Superconducting RF cavities.

Among the advantages offered by the Superconducting (SC) cavities for linear collider one can list :

- The relatively low RF frequency ($f_{RF} \simeq 500$ MHz) is especially important to get good beams, and small $\Delta E_0/E_0$ since during acceleration
 - the longitudinal wake field E_L is proportional to f^2_{RF} .
 - the transverse wake field E_T is proportional to f^3_{RF} .

* The Contributors to the Machine Group were :

U.Amaldi, M.Bassetti, C.Benvenuti, P.Bernard, C.Biscari, J.Bisognano, R.Boni, K.Brown, I.Campisi, M.Castellano, N.Cavallo, B.Chehab, E.Chiaveri, G.Coignet, S.De Simone, D.C.Fiander, K.Gabathuler, U.Gambardella, E.Gianfelice, S.Guiducci, J.Haissinski, H.Henke, J.Kewisch, S.Kulinski, C.H.Leeman, H.Lengeler, A.Massarotti, M.Minestrini, G.Modestino, A.Odian, C.Pagani, L.Palumbo, R.Paroli, P.Patteri, H.Piel, M.Placidi, M.A.Preger, D.Proch, M.Promé, J.Rees, D.M.Ritson, R.Rossmannith, A.Schwettman, M.Serio, P.Sievers, B.Spataro, S.Tazzari (convener), F.Tazzioli, M.Vescovi, R.C.York.

- The number of particles per bunch being limited by the wake fields in the accelerating structure, one can put more particles per bunch.
- The accelerating field is present nearly continuously, i.e. the system has a very high efficiency, and allows to run with high repetition frequency ($f_r \simeq 10$ KHz).

The present disadvantages of the SC cavities reside in their cost and their low accelerating gradient. This last point matters essentially to achieve high beam energy.

Following the advices of the SC RF system and cryogenics group [25], conservative four-cell cavities (DESY-type) have been considered : $G = 5$ MV/m, $Q = 2 \times 10^9$, $f_{RF} = 500$ MHz, $T = 4.3^\circ\text{K}$. The possibility to operate at $G = 7$ MV/m has also been investigated. It was also estimated that the overall cost of the RF and cryogenics systems could be reduced by a large amount (30 % to 40 %) when going from a double stage scheme to a single racetrack scheme.

It was concluded that, even if the system was possible with the present technology, to become economically more attractive an R & D program should be adequately supported to achieve higher gradients, higher quality factors and to reduce the production prices.

6.2. Electron Source.

As previously mentioned, it was assumed that the electron source was able to directly produce electrons with a very small normalized transverse emittance, $\epsilon_n \simeq 2 \times 10^{-6}$ m, and also a small longitudinal emittance $\epsilon_L \simeq 10^{-2}$ m.

At Stanford, a scheme based on magnetic bunching and harmonic compensation has been developed which should soon provide the necessary number of electrons with the required normalized emittance [15]. At Los Alamos, an RF source with a photocathode illuminated by a laser has produced more than 100 A of peak current with an emittance $\epsilon_n = 10^{-5}$ m [16]. Further tests are going on and one expects that $\epsilon_n = 2 \times 10^{-6}$ m could be achieved for $N \simeq 10^{10}$ electrons per bunch.

Any progress coming from the R & D programs already launched in various laboratories have to be watched with interest and further stimulated since the elimination of damping rings would allow a considerable saving in the construction of colliding linacs.

6.3. Positron source.

The production of very high average and peak positron currents is a critical item, especially for low energy linear colliders. To produce the required $(2.5-5)10^{10}$ positrons per bunch one needs an electron beam with $P_T \simeq 1$ MW or more (see Table 4).

A conceptual design of an electron positron conversion target which could produce $N^+ \sim 5 \times 10^{10}$ positrons at a rate $f_r = 12$ KHz has been worked out by P.Sievers [17]. Fig.8 shows a scheme of the proposed 1 m diameter wheel rotating at 1150 turns per minute. It

Fig.8 Proposed layout of the positron target station (from Ref.17).

Fig.9 W and Cu targets (lateral cuts and front view) encapsuled in graphite containers and mounted between Cu-coolers (from Ref.17).

is made of 628 individual 2 mm diameter targets with 5 mm distance between them. Fig.9 represents the detailed geometry and the cooling system around individual targets of Cu or W.

In view of the beam induced shock effects and radiation damage which are difficult to predict it would be highly desirable to make prototype tests under conditions which are similar to those anticipated. Such tests would be feasible at the SLC with beam intensities and dimensions of the target wheel scaled correspondingly.

Important aspects connected with the need for collecting positrons with high efficiency and transporting them to the superconducting linac have been looked at [26] but need further studies.

6.4. Damping Ring.

Another important topic which has deserved particular attention is the damping ring (DR) for positrons.

Table 5

Damping Ring	Parameter list	
Energy	2.2	Gev
Circumference	646	m
Number of bunches	92	
Bunch separation	7	m
Repetition frequency	12	KHz
Betatron damping time	1.5	ms
Normalized transverse emittance	2	μm
Total transverse emittance	.93	nm
<u>Arcs :</u>		
Emittance	1.47	nm
Length	221	m
Radius of curvature	21.5	m
Filing factor	.65	
<u>Wigglers :</u>		
Emittance	.708	nm
Length	425	m
Radius of curvante	4.3	m
Magnetic field	1.7	T
Filing factor	.8	
η	12.6	
Momentum compaction	.0027	
Energy radiated per turn	6.2	MeV
Natural relative energy spread	.0009	
Radiofrequency voltage	20	MV
Natural bunch length	4.1	mm
Natural longitudinal emittance	.016	
Number of particles per bunch	2×10^{10}	
If $ Z/n = 1\Omega$:		
Relative energy spread	.0013	
Bunch length	5.9	mm
Longitudinal emittance	.033	

M.Bassetti and collaborators [18] have designed a scheme which at $E_0 = 2.2$ GeV could provide the required $\epsilon_n \simeq 3 \times 10^{-6}$ m for $N^+ \simeq 10^{10}$ positrons in a damping time $\tau \simeq 1$ ms.

It would have two $\simeq 115$ m long straight sections equipped with wigglers and two $\simeq 110$ m long arcs, i.e. $\simeq 450$ m in total. At any time, about 60 bunches would be present in this single ring. Its main characteristics are given in Table 5.

Special attention has been given to the longitudinal invariant emittance lengthening, which is of a main importance when working in high resolution mode. It was estimated that $\epsilon_L \simeq 4-6 \times 10^{-2}$ m could be reached but that more theoretical and experimental work should be carried out to cast further light on the dynamics of short bunches.

6.5. Fast kickers.

Fast kickers are needed to inject and extract the positron bunches from the DR at a distance $l_b = 8$ m (26 ns). Solutions based on magnets with fast enough rise and fall times and with the required stability have been proposed [19,20]. A novel idea, based on the use of RF separators operating at slightly different frequencies in order to separate individual bunches one from another has also been proposed [27].

The injection-extraction problem, even if considered solvable, also needs R & D work.

6.6. Optics for linacs and arcs.

Number of recirculations, beam break up design and momentum acceptance of the arcs, and variable energy operation have been considered. No principle difficulties were identified and a viable scheme based on FODO scheme was worked out. The optimization of each subcomponents would still have to be done.

6.7. Final Focus.

A final focus system was first worked out by D.Ritson [29] for the two-stage scheme with a beam energy $E_0 = 10$ GeV. It is based on the experience gained at SLC and it fulfills the beam requirements at the interaction point. The setup is shown schematically in Fig.10.

Fig.10 Final focus : Physical layout of components on the beam line (from Ref.29).

D.Ritson has also designed a final focus system for the single racetrack version. Using a total length of some 150 m on each side of the Interaction Point, with successive matching masking, achromatic bend, chromatic correction and masking, and final demagnification he achieves, with the program Turtle, the required beam dimensions and $\Delta E_0/E_0 \leq 2 \times 10^{-3}$ with $\beta^* \geq 1$ mm.

7. B PHYSICS DETECTOR CONSIDERATIONS.

The characteristics required for the experimental apparatus to carry out the physics program briefly outlined in Chapter 2 were examined previously in Ref.[31] and more recently by the Experimental Physics Group** at the Courmayeur Workshop [32].

In designing such an apparatus the main features of B decays at the Y(4S) were kept in mind :

- the average charged tracks multiplicity is 5.5.
- the average number of produced photons is 5.
- the average charged momentum is $\simeq .5$ GeV/c.
- the average photon energy is 200 MeV (most probable value 75 MeV).

** The contributors to the Experimental Physics Group were :

A.Antonelli, N.Bacchetta, C.Bacci, R.Baldini-Ferroli, G.Barbiellini, G.Battiston, A.Beatrici, A.Benvenuti, M.E.Biagini, D.DBisello, B.Borgia, A.Calcatera, G.Capon, A.Castro, M.Cavalli-Sforza, F.Cavanna, L.Cerrito, G.Ciapetti, G.Coignet, F.de Notaristefani, R.De Sangro, P.De Simone, B.Dulach, F.Ferroni, P.Franzini, A.Fridman, F.Grancagnolo, G.Gratta, P.Laurelli, J.Lee Franzini, P.Lipari, E.Longo, V.Lüth, A.Marini, L.Maritato, G.P.Murtas, L.Nisati, A.Odian, I.Peruzzi, L.Pescara, M.Piccolo (convener), F.Pierre, F.Ronga, P.G.Rancoita, G.Salvini, C.Sanelli, R.Santacesaria, C.Santoni, M.Schioppa, A.S.Schwarz, J.Wyss, C.Zaccardelli.

Since the average momentum of both charged and neutral particles is so low, the precision in the measurement of momenta and angles is determined by the multiple scattering and the material in front of the calorimeter should be reduced as much as possible.

The detector discussed at the Workshop is shown schematically in Fig. 11 and its main parameters and performances are listed in Table 6.

Fi.11 Section of one detector's quadrant in a plane containing the beam axis (from Ref.32).

In this set up the charged particles are tracked and momentum analyzed with a solid state vertex detector [33,34] (note shown on Fig.11), and by a low mass drift chamber [35] installed inside a superconducting coil producing a 1 T field. The particle identification of charged particles is done by dE/dx in the drift chamber and by ring imaging Cerenkov detector [36]. Special attention was devoted to the electromagnetic calorimeter which has to achieve the best resolution at an energy as small as possible. Two solutions were considered : a "standard" one using BGO [37] and an "exotic" one using liquid Xenon [38]. Muon identification is done with plastic tubes operated in the limited steamer mode installed in the return yoke. The trigger and the data

acquisition system [39] were also studied as well as the shielding of the inner detectors from the synchrotron radiation background [40].

Table 6 Summary of the performances of the proposed apparatus

Vertex detector	Segmentation	$22\mu m \times 22\mu m$
	Spatial resolution	$5\mu m$
	Two tracks separation	$50\mu m$
	Thickness (per layer)	$1.5 \times 10^{-3} X_0$
Drift chamber system	Spatial resolution	$\sim 150\mu m$
	Magnetic Field	1 Tesla
	$\sigma(\frac{1}{p})$ meas. limit	$4 \times 10^{-3} (\text{GeV}/c)^{-1}$
	$\frac{\sigma(p)}{p}$ multiple scattering limit	3×10^{-3}
	Two tracks separation	2 mm
Particle identification	e/π	1×10^{-3}
	μ/π (above $1\text{ GeV}/c$)	5×10^{-3}
	π/K (up to $2.5\text{ GeV}/c$)	1×10^{-3}
	K/p (up to $5\text{ GeV}/c$)	1×10^{-3}
E. M. calorimeter	Energy res. $\frac{\Delta E}{E}$	$\frac{\sim 1\%}{\sqrt{E}}$
	Segmentation	$23\text{ mrad} \times 23\text{ mrad}$
	Angular resolution	$\sim 2\text{ mrad}$
Solid angles	Tracking	98%
	Particle identification	80%
	Calorimetry	99%

The conclusions of the Experimental Physics Working Group was that such a detector, able to reconstruct B mesons with good efficiency, could be build with the present techniques. However an R & D program should lead to the design of an improved detector, able to reconstruct B mesons with good efficiency.

8. OPTIONS AND EXTENSIONS.

The proposed accelerator complex offers various other options.

- By reducing the linac and DR energies by a factor $s = 0.6$, the damping time τ increases by a factor 5 so that one can collide in the I.R. electron and positron bunches at $W \simeq J/\psi = 3.1$ GeV with a repetition rate $f_r = 3$ kHz. The expected luminosity is $L \simeq 2 \times 10^{32} \text{ s}^{-1}$ for $\Delta W \simeq 10$ MeV. Parameters for $W = 4$ GeV are given in Table 4. This would allow to study charm (and τ) physics with very high statistics.
- Following the idea described in Ref.[41] and as proposed in Ref.[42], by adding a SC linac to accelerate electrons to 130 MeV and by making them to collide with the 2.2 GeV positrons in one of the straight sections of the DR, it would be possible to produce ϕ -mesons with $L \simeq 3 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ and obtain high fluxes of charged and neutral kaons. This is shown in Fig.6. In these conditions the positron bunches have their nominal population and each electron bunch contains about 10^9 particles. The repetition rate is 35 MHz and the power of the electron beam about 1 MW, which can certainly be obtained with a short superconducting linac. A similar proposal was made by C. Rubbia for the Trieste Synchrotron light source Elettra [43].
- The complex of Fig.6 allows also the production, in the normal IR of the collider, of standing Φ -states. The linac AB would run at a lower gradient and accelerate particles to 0.5 GeV, while the linac DE would boost positron bunches up to 1.5 GeV. The DR can produce low emittance positron bunches at 1.5 GeV with a repetition rate $f_r = 3$ kHz. After extraction, the positron bunches would be slowed down from 1.5 GeV to 0.5 GeV by the second linac. The luminosity turns out to be $10^{32} \text{ cm}^{-2}\text{s}^{-1}$.
- If accelerating cavities with high average gradient ($G \simeq 50$ MV/m) become available and are installed in each of the 500 m long linac sections, the accelerator complex will transform into a Z-factory ($L \geq 10^{33} \text{ cm}^{-2}\text{s}^{-1}$) and eventually a Toponium factory ($L \geq 10^{32} \text{ cm}^{-2}\text{s}^{-1}$), as described in Ref. [2,3].
- Finally, the accelerator complex can also be used as an injector for a TeV linear collider since the electron and positron bunches have, for instance, all the characteristics required for the injection into the CERN Linear Collider (CLIC) [44].

9. CONCLUSIONS.

In this contribution I have tried to show that the designed accelerator complex based on superconducting linacs with recirculators offers various advantages :

1) As a $b\bar{b}$ factory, it could be operated in various modes :

- High or medium resolution mode, near threshold, i.e. at $W = Y(4S)$ or $Y(5S)$, with a luminosity $L \simeq 10^{33} \text{ cm}^{-2}\text{s}^{-1}$.
- Low energy resolution mode in the continuum, i.e. at $W \simeq 15 \text{ GeV}$, with $L = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

In both cases, the small beam transverse dimensions would allow to install a microvertex detector very close to the interaction point. It would be part of a high performance apparatus based on the most recent developments in detector technology.

2) Simultaneously, it would provide nearly continuous electron beams with an energy ranging from 1 to 8 GeV. These beams which are requested for Nuclear Physics studies could be longitudinally polarized.

3) It could also be modified as an $s\bar{s}$, $\tau\bar{\tau}$ or $c\bar{c}$ factory. Later on, assuming that higher accelerating gradients would be achieved, it could be transformed into a Z factory (low resolution mode) or a Toponium factory (high resolution mode).

4) It could help to prepare the future high luminosity TeV colliders for which more demanding performances are requested.

5) It could be used as an injector for a TeV linear collider.

A preliminary feasibility study of the proposed design has been made by experts in various fields. In principle no impossibility has been encountered and possible technical solutions have been proposed for each main components. Some of the proposed solutions are new and require an intense R & D work, most of which would be useful for future high luminosity TeV colliders. Once the R & D work has proven its technical feasibility, a final proposal for this accelerator complex could then be made.

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