AN IMPROVED EXAMPLE OF A SUPERCONDUCTING ELECTRON LINAC SCHEME, UTILIZING IDEAS DISCUSSED IN THE 2nd ICFA WORKSHOP

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ABSTRACT

As an improved version of the superconducting electron collider system with energy recovery described earlier[4,5], an explorative design example is given that incorporates new schemes for space charge compensation and chromatic correction at the interaction point, and for positron regeneration.

SCOPE

Electron colliders of the "peloron" type, consisting of two superconducting linacs which, after collision, recover the energy of the accelerated bunches, have been discussed by several authors[1,2,3]. A particular system that also recovers the particles was described by H. Gerke and myself[4]. In this system, the acquired energy spread of the decelerated bunches is reduced in a debunching section, and the bunches are then captured and reconditioned in a special damping ring composed of strong alternating bending magnets. In this "wiggler storage ring" [5], the strong bending causes a short damping time and thus permits a high repetition frequency, while its alternating sign causes a very small dispersion and thus the very small beam emittance needed for high luminosity.

Among the ideas discussed in this workshop, the following appeared most interesting to be incorporated in the above system:

A) A regeneration of positrons by photons, emitted by the high energy bunch in a wiggler channel

B) A space charge compensation at the interaction point, avoiding the detrimental effects of "beam strahlung"

C) A local chromatic correction of quadrupoles in the interaction region, reducing the energy dependence of focal length and the corresponding growth in spot size.

This note gives an exploratory design example of the system thus improved; it only describes the added schemes B) and C) in some detail, followed by an updated listing of the main system and performance parameters. For a more complete description of the collider system, the reader is referred to references 4) and 5), and for positron generation to reference 6).

SPACE CHARGE COMPENSATION

It was suggested by A.N. Skrinsky in this workshop to avoid the problems due to "beam strahlung" during bunch interaction by using the Orsay-type space charge compensating scheme in which, in either direction, a positron bunch and an electron bunch are superimposed before collision; he pointed out that in linear schemes with single bunch passage the instabilities encountered at DCI are not to be expected.

As an explorative example, a scheme of this type has been designed and is shown in Fig. 1. This bunch phasing system has different path lengths for electrons and positrons entering in the same direction. Branch (II) is about 95 cm longer than branch (I) . A positron bunch travelling 19 half wave lengths behind the electrons in the S-band linac will then catch up with the electron bunch at the I.P. The radius of curvature is taken to be $\rho = 250$ m in this example which, at 100 GeV, leads to a synchrotron radiation loss of $\frac{\Delta E}{E} = 7 \cdot 10^{-3}$ in the (long) branch (II) of the half system shown in Fig. 1. The critical energy of the emitted quanta is 8.9 MeV, and their average number is 79 per electron. It is obvious from these

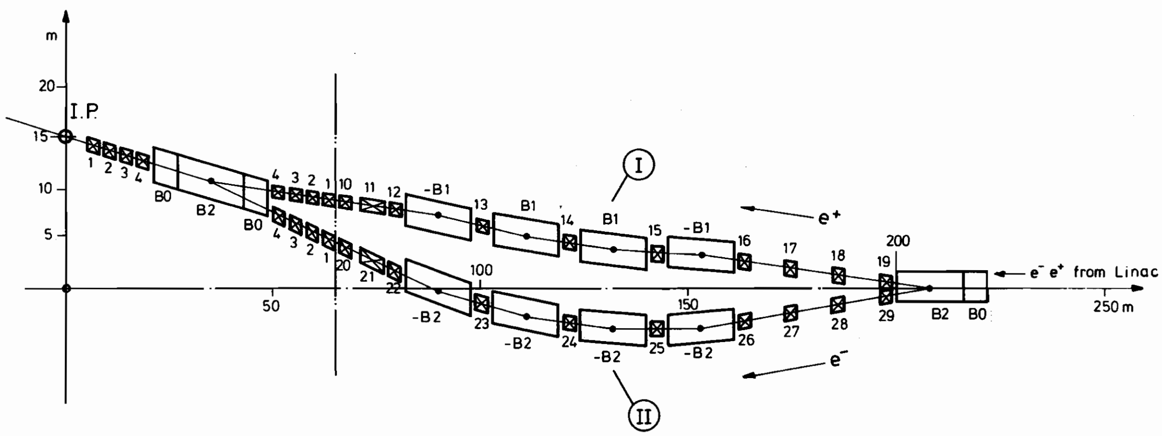

Fig. 1: Space charge compensated achromatic beam collision system, plan view.

values that, in a final design, the magnet strength must be reduced. Then, the remaining energy loss in branch (II) can be replenished by a linac section near quadrupole 24. The weak magnets B0 ($\rho = 4000$ m) are installed for reducing the radiation background at the I.P. and in the linac.

CHROMATICITY COMPENSATION

D. Ritson explained in the ICFA workshop the design principles of a chromaticity compensating insertion that he and K. Brown are working on for the suggested 2 x 50 GeV SLAC collider[7]. One of these insertions is placed on each side of the interaction region; it consists of two quadrupole doublets which, in a symmetric optical arrangement, produce a beam waist between them. At this waist, a bending magnet produces a dispersion that is also symmetric with respect to this point. Chromaticity compensation, then, is provided by two symmetric pairs of sextupoles that have one of their members placed near each of the quadrupole doublets. Since the betatron phase advance between the sextupoles of each pair is thus very close to 180°, the geometric aberrations caused by one member of the pair are compensated again by the other member.

Incorporating the above principle, the system shown in Fig. 1 has the following features[8]:

(1) The high beta interaction region quadrupoles are incorporated in the corrective insertion and used as part of its symmetric arrangement.

(2) The horizontal bending magnet that is needed in the space charge compensating scheme for superimposing the e^+/e^- bunches onto each other is also incorporated in the corrective insertion where it produces, at the same time, the required symmetric dispersion.

Since, in the system described here, the interacting beams are "round", we want the same minimum beta in horizontal and vertical directions and therefore choose quadrupole quadruplets instead of doublets. The corrective insertion on either side of the I.P., then, requires two quadruplets (1,2,3,4) that are symmetric with respect to the center of the bending magnet (B2) between them.

The beam envelopes, for an emittance of $\varepsilon = 3.2 \cdot 10^{-10}$ radm, are given in Fig. 2; they correspond to $\beta_x^* = \beta_z^* = 2.5$ mm at the I.P. and to maximum beta values of 53 km and 86 km, respectively. Since particles of opposite charge travelling in the same direction see opposite signs of focusing and bending strengths in the magnets, their horizontal and vertical envelopes are exchanged and their dispersion functions D are different, as shown in Fig. 1. D_1 and D_2 cross the I.P. at a slope of 55 mrad and have maximum values of 60 - 80 cm in the quadruplets. In order to have them both symmetric with respect to the center of the corrective insertion, it is necessary that the quadruplet has equal focal lengths in horizontal and vertical directions.

The correcting sextupoles S_i, i = 1,4, are suggested to be placed in 180°-pairs as indicated in Fig. 2. There are four chromaticities to be compensated: the horizontal and the vertical one for electrons as well as for positrons. Compensation requires an equation of the type

$$2 \cdot \frac{1}{4\pi} \sum_{i=1}^{4} D_i \beta_i \cdot s_i = - \xi$$

to be satisfied for each of these chromaticities ξ, with s_i being the integrated strength of the i-th sextupole. In the quadrupoles, we have very nearly $D_k \propto E_k$, k = 1, 2, where E_k are the beam envelopes. With $\beta_k \propto E_k^2$, we then get a system of 4 linear equations for determining the sextupole strengths s_i:

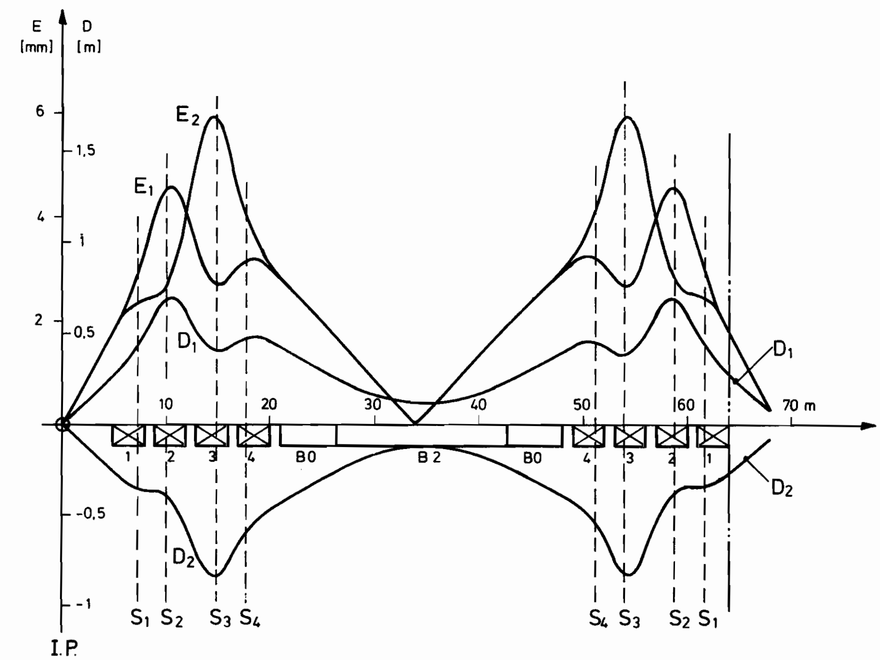

Fig. 2 : Envelopes and dispersions near the interaction point (I.P.)

$$\sum_{i=1}^{4} E_{1i}^{3} \cdot s_i = c_1$$
$$\sum_{i} E_{1i}^{2} E_{2i} \cdot s_i = c_2$$
$$\sum_{i} E_{1i} E_{2i}^{2} \cdot s_i = c_3$$
$$\sum_{i} E_{2i}^{3} \cdot s_i = c_4$$

It is apparent that the rows of coefficients in this system will, in general, be linearly independent if the ratio E_2/E_1 has sufficiently different values in the 4 sextupole positions. In our example, we have

sextupole position:	S_1	S_2	S_3	S_4
ratio E_2/E_1 :	0.76	0.59	2.1	1.23

and the system can therefore be solved for the sextupole strengths s_i.

It was noted by Ritson and Brown that, in their experience, the best chromaticity correction is obtained when, at the sextupoles, the beam width due to energy spread alone is of the same order as the betatron envelope E. In our example, this is the case for an energy spread of the order of 0.5 %.

In the linac, the dispersion function must be zero. Therefore, in the branches (I) and (II) of the bunch phasing system, the dispersions D_2 and D_1 must respectively be matched to vanish at the end of the system. In our

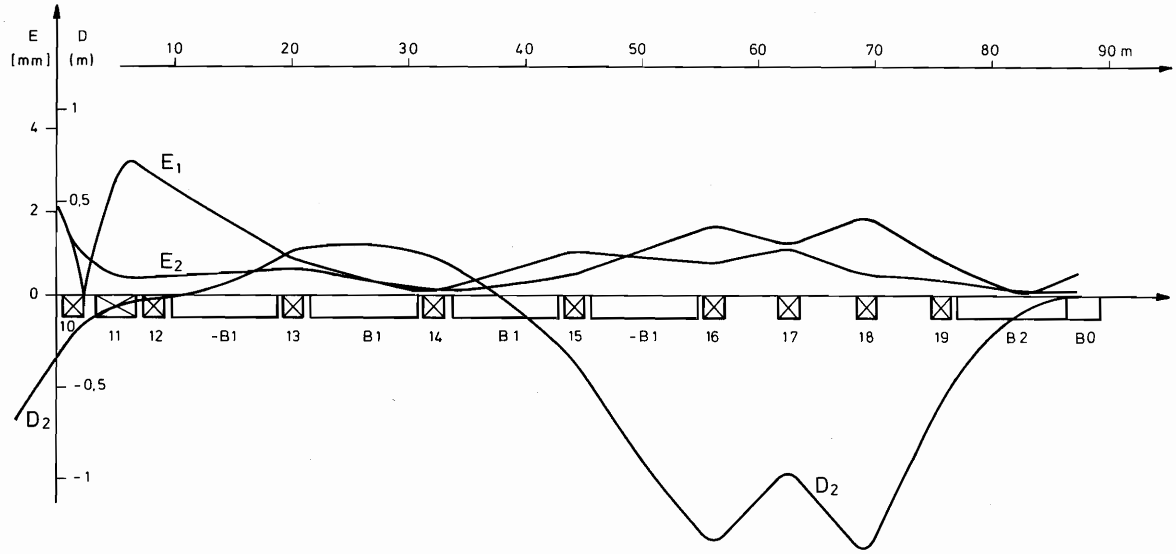

Fig. 3: Envelopes and dispersion in branch (I) (weak bending)

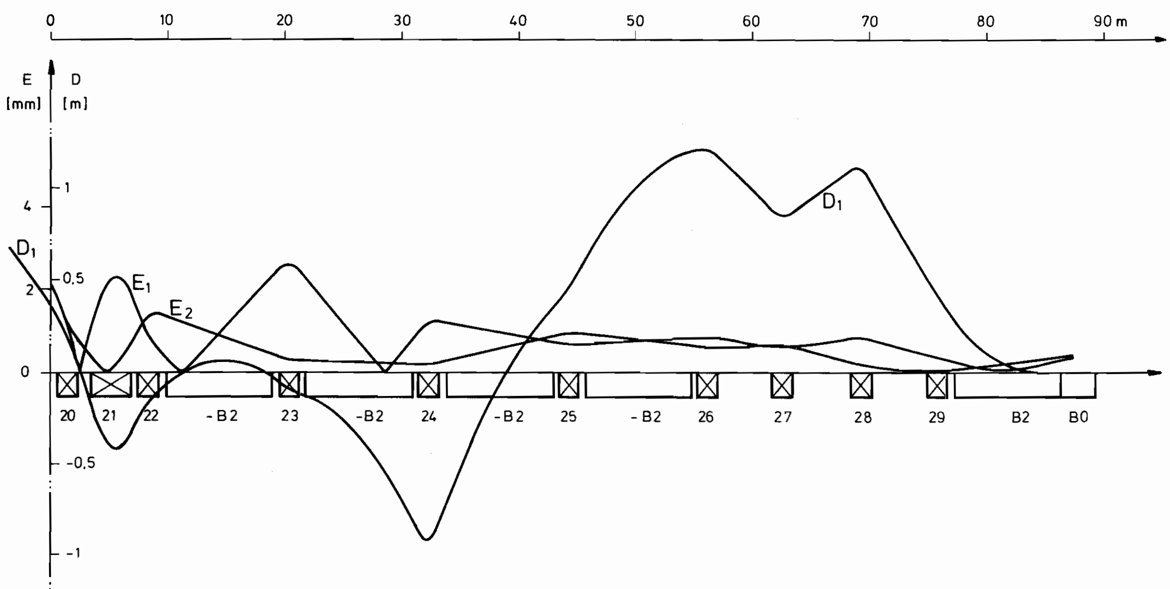

Fig. 4: Envelopes and dispersion in branch (II) (strong bending)

example, it was not quite easy to achieve this and led to introducing in the (short) branch (I) a series of weak bending magnets that affect the dispersion, but hardly the path length. The dispersion functions and beam envelopes in branch (I) and branch (II) are shown in Figs. 3 and 4. All magnet parameters of the system are given in Tab. 1.

Table 1

List of magnets in the space charge compensated achromatic beam collision system

Bending magnets:

type:	ℓ(m)	ρ(m)	$\phi=\ell/\rho$(mrad)
B2	15.6	250	62.4
B1	15.6	1000	15.6
B0	5.2	4000	1.3

Quadrupoles: ℓ = 3 m (6 m)

type:	1	2	3	4
k(m^{-2}):	.04697	-.10329	.10342	-.04703

branch (I) :

type:	10	11(6m)	12	13	14
k(m^{-2}):	-.07677	-.05166	.00421	.02195	.01856

type:	15	16	17	18	19
k(m^{-2}):	-.02065	.02040	-.02781	.02925	-.01256

branch (II) :

type:	20	21(6m)	22	23	24
k(m^{-2}):	.05870	-.08765	.08654	-.04844	-.06418

type:	25	26	27	28	29
k(m^{-2})·	.01887	-.01232	.02371	-.02810	.01255

POSITRON REGENERATION

It was suggested by A.N. Skrinsky and collaborators and independently by U. Amaldi and C. Pellegrini at this workshop[6)] to regenerate positrons by passing the high energy bunch through a magnetic wiggler channel and using the photons emitted in this wiggler for positron production in a target. In a 100 m long wiggler channel of 2.5 cm wavelength and a (permanent magnet) field of 0.37 T, each electron radiates about 50 photons while losing less than 1 % of its energy[3)]. Above about 150 GeV, these photons produce more than one positron in a conventional converter system working at a few MeV. In the 2 x 100 GeV design example studied in this note, this scheme does not permit a 100 % particle regeneration, but it may easily replenish a few percent of the particles. We therefore retain the particle recovery scheme but can now be much more relaxed about particle losses. A wiggler may, for example, be installed in branch (I) near quadrupole 14 (Fig. 1).

PERFORMANCE OF THE COLLIDER SYSTEM

Before listing the main system and performance parameters, a few particulars should be noted:

The space charge and chromaticity compensated interaction scheme greatly reduces the phase space deterioration of the bunches. In principle, therefore, it permits to increase the luminosity by either reducing the beam size at the I.P. or by colliding a sequence of bunches at consecutive interaction points (multiple collisions). The scheme of Fig. 1, for example, can be extended to 3 interaction points (served by 2 x 2 charge-compensated bunches) by inserting, at the I.P., a system of two quadruplets similar to the one shown in Fig. 2, but without bending magnets and sextupoles. The chromaticity of the added quadruplets must then be included in determining the strengths of sextupoles S_1 to S_4. In our example, however, we have not explicitly incorporated these possibilities, leaving them as further options.

When running the system without space charge compensation, it permits to study (e^+e^-), (e^+e^+), and (e^-e^-) collisions individually.

At the proposed bunch repetition frequency of 10 kHz, there will be no spurious collision points within the linacs. In principle, however, these would anyway not pose a problem since the bunches could rather easily be separated there in local bypass systems composed of static and rf magnets.

For operation at a reduced energy, only a correspondingly reduced linac length would be used for acceleration. The luminosity, then, would decrease linearly with energy since the beam cross section varies as 1/E. This compares quite favourably with storage rings, where the luminosity decreases at least quadratically with energy.

The higher order mode losses in the linac, when calculated for a single bunch and multiplied by the bunch rate, would be about 3 % of the energy gain; the corresponding energy spread could then be made smaller than 0.5 % by riding the bunch off the crest of the linac wave. It was, however, noted by A. Hutton and G. Saxon[9] that there may, in fact, be no HOM losses in the superconducting linac if no special damping is applied, since the bunch rate is higher than the decay rate of the modes and the wake field of each bunch will be counteracted by the HOM fields left behind by all previous bunches. But, as Saxon pointed out, there remains the question whether transverse beam break-up can be avoided if no damping is used.

The bunch size depends on the beam parameters in the wiggler storage ring which are given in Tab. 2. The bunches are called off individually after staying in the ring for 3.4 longitudinal damping times. Before they enter the linac, their half bunch length is reduced to σ_s = 1.5 mm in a buncher. During acceleration, their transverse emittance shrinks as 1/E and is $3.2 \cdot 10^{-10}$ rad·m at 100 GeV. With $6 \cdot 10^{10}$ particles in the composite, space charge compensated bunch, a beta function of 2.5 mm and a bunch repetition frequency of 10 kHz, the instantaneous luminosity is $3.6 \cdot 10^{32} cm^{-2} s^{-1}$. Multiplied by the linac duty cycle of 10 % (e.g. 10 s "on" and 90 s "off"), there still remains a good average luminosity, which must be compared to the long term average of a storage ring, where the luminosity decays during the several hours between refills.
The luminosity and beam interaction parameters are composed in Tab. 3.

For the 3000 MHz superconducting linac structure, an acceleration of 20 MeV/m and a Q-value of $6 \cdot 10^{9}$ are assumed. Looking very optimistic today, these values may hopefully be reached after some more years of intense development. A list of basic linac parameters, including power figures, is given in Tab. 4. The total power consumption of the 2 x 100 GeV collider system is estimated to be 20-30 MW.

Table 2

Beam parameters of "wiggler storage ring"
(Double ring with separate e^+ and e^- beams)

energy	E =	1 GeV
damping time	τ =	1.8(0.9) msec
beam emittance	ε =	$3.2 \cdot 10^{-8}$ rad·m
r.m.s. half bunch length	σ_s =	1.4 cm
phase stable region	$\frac{(\Delta E)_{max}}{E}$ =	$\pm$ 4.2 %
no. of particles per bunch		$3 \cdot 10^{10}$
no. of bunches per beam		31

Tab. 5 displays the main features of the buncher that reduces the bunch length before acceleration, and of the two sequential debunchers that reduce the energy spread for particle recovery after deceleration.

Table 3

Beam interaction parameters and luminosity

energy	E	=	2×100 GeV
no. of particles per bunch	N	=	$6 \cdot 10^{10}$ $\begin{cases}(3 \cdot 10^{10} e^{+}) \\ +(3 \cdot 10^{10} e^{-})\end{cases}$
instant. bunch rep. rate	ν	=	10^{4} s^{-1}
beam emittance (adiab.reduced)	ε	=	$3.2 \cdot 10^{10}$ rad·m
r.m.s. beam radius			0.9 μ
" beam divergence			0.36 mrad
" half bunch length			1.5 mm
instant. luminosity	$L = \frac{N^2}{4\pi\varepsilon\beta}$	=	$3.6 \cdot 10^{32} cm^{-2} s^{-1}$
linac duty cycle			10 %
average luminosity	$\bar{L}$	=	$0.36 \cdot 10^{32} cm^{-2} s^{-1}$

Table 4

Superconducting cw linac (one of two)

energy	100 GeV
frequency	3000 MHz
waveguide structure	π-mode
length	5 km
assumed properties of supercond. rf: acceleration	20 MeV/m
assumed properties of supercond. rf: Q-value	$6 \cdot 10^{9}$
waveguide filling time	160 msec
no. of particles per e^{+}/e^{-} double bunch	$2 \times 3 \cdot 10^{10}$
reduction of stored energy by the double bunch	3 %
instant. bunch rep. rate	10^{4} s^{-1}
linac duty cycle	10 %
instant. power dissipation per m	20 W/m
mean power dissipation (at He-temp.)	100 kW
He-refrigerator efficiency	(1-2) ‰
power for refrigeration	5 - 10 MW
linac input power	< 0.1 MW
total power for 2 x 100 GeV collider system	20 - 30 MW

Table 5

Matching between linac and storage ring

			energy spread (MeV)	bunch length (mm)	f_{rf}	equiv."energy" of buncher
for reduction of energy spread after decelerating (particle recovery)	1^{st} debuncher at 4.5 GeV	in	$\pm$ 1000	1.5	3000 MHz	1900 MeV
		out	$\pm$ 250	6		
	2^{nd} debuncher at 1 GeV	in	$\pm$ 400	6	500 MHz	500 MeV
		out	$\pm$ 27	90		
for bunch length reduction before acceleration	buncher at 1 GeV	in	$\pm$ 1	15	3000 MHz	20 MeV
		out	$\pm$ 10	1.5		

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