A FLAVOUR FACTORY AND NUCLEAR PHYSICS FACILITY BASED ON SUPERCONDUCTING LINACS

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1. Introduction

In December 1987 a Workshop was held in Courmayeur (Italy) on 'Heavy-Quark Factory and Nuclear-Physics Facility with Superconducting Linacs'. In this paper we summarise and update the main machine points discussed in detail in the Proceedings of the workshop [1].

The facility proposed by two of us [2] is schematically shown in Fig. 1 which is taken from Ref. [3]. The *'SC radiofrequency complex'* is a recirculated superconducting electron and positron linac which serves as a $b\bar{b}$ factory and a high-duty cycle nuclear physics facility. It can provide electron-positron collisions in the c.m. energy range $10 \leq W \leq 20$ GeV with luminosities $L \leq 10^{34}$ cm^{-2} s^{-1} and, at the same time, high intensity and large duty cycle electron beams for nuclear physics experiments up to about 10 GeV. The scheme of Fig. 1 consists of two racetrack linacs, each one being similar to the CEBAF design [4]. It offers also the possibility of producing $c\bar{c}$(quarks) for $3 \leq W \leq 4$ GeV with $L > 10^{32}$ cm^{-2} s^{-1} and of colliding 2.5 GeV positrons (extracted from the damping ring) with 11.2 GeV electrons, so as to produce moving Υ(4S) states and have an easier access to the study of CP violation. The main parameters for the $b\bar{b}$ factory are collected in Table 1. For nuclear physics the CW beam has a current ≤ 200 μA and a duty cycle $\geq 80\%$.

Table 1
Parameters for the SC complex of Fig. 1 [1].

Quantity (Unit)	High resolution mode	Low res. mode
Beam energy, E_0 (GeV)	$5-6$ a)	$6-11$ a)
Collision energy, W (GeV)	$10-12$	$12-22$
Positrons per bunch, N^+	3×10^{10}	6×10^{10}
Electrons per bunch, N^-	8×10^{10}	8×10^{10}
Invariant tr. emittance, ε_n (m)	2×10^{-6}	2×10^{-6}
Positron long. emittance, $\varepsilon_L{}^+$ (m)	4×10^{-2}	6×10^{-2}
Electron long. emittance, $\varepsilon_L{}^-$ (m)	1×10^{-2}	1×10^{-2}
Positron bunch length, σ_z (mm)	2.5	0.7
Electron bunch length, σ_z (mm)	1.0	0.5
β-value at crossing, β^* (mm)	5.0	2.0
Bunch r.m.s. radius, $\sigma_x=\sigma_y$ (μm)	1.0	0.65
Positron disruption parameter, D^+	21	23
Electron disruption parameter, D^-	21	23
Enhancement factor, H_D	5.5	6
Repetition rate, f_r (kHz)	12	12
Beamstrahlung spread, ΔW_b(MeV)	6.8	200
Spread due to long. emittance ε_L, ΔW_L (MeV)	9.6	50
Luminosity (cm^{-2}s^{-1}), L	1.2×10^{33}	1.2×10^{34}

a) *The other parameters are given for E_0 = 5 GeV and 11 GeV respectively.*

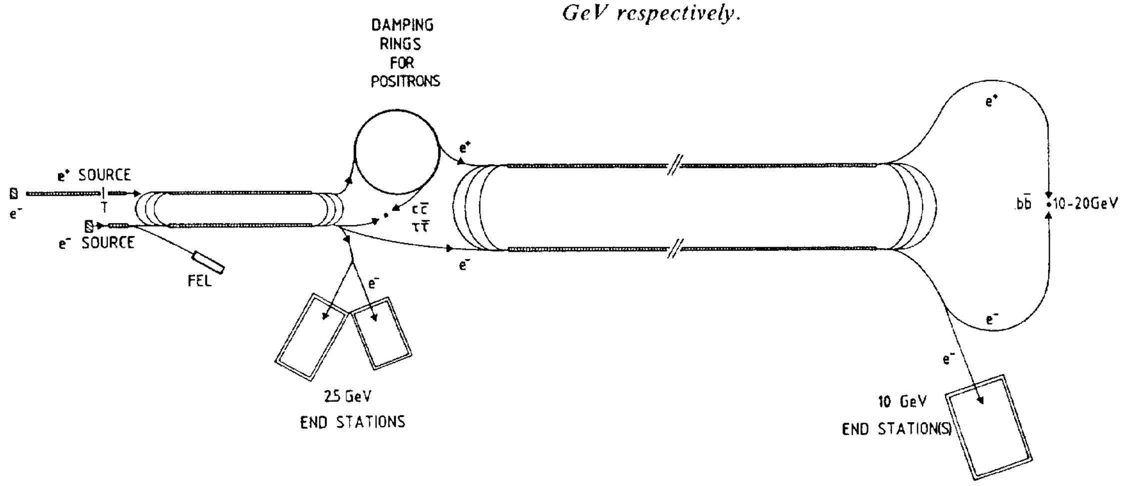

Fig.1 Scheme of the SC accelerator complex with two racetrack linacs [3]. The experimental areas for nuclear physics are indicated. The electron bunches are assumed to be directly produced by a source without the need of damping rings.

At the workshop the single-racetrack scheme of Fig. 2 was proposed [5], which is simpler and less costly but does not provide moving Υ(4S) states and reaches 8.5 GeV for Nuclear Physics for a gradient of 5 MV/m. In the energy range $10 \leq W \leq 15$ GeV the collider parameters are similar to the ones reported in Table 1.

Most of the components of the two schemes have by now been studied in detail; the present status is discussed in the following Sections.

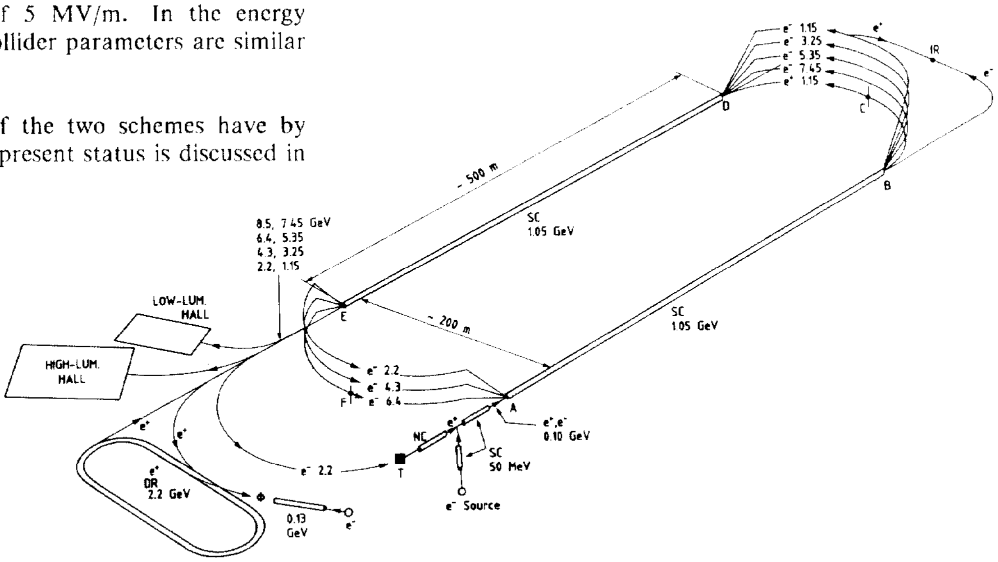

Fig.2 Scheme with a single racetrack [5].

2. Positron Source

For the positron source it is proposed to use a 'multi-target' system where 628 targets, spaced by 5 mm from each other, are arranged around the rim of a rotating, water-cooled wheel which has a diameter of 1 m [6]. The target is illuminated with ~2 GeV electrons. To synchronise the rotation of the wheel with the train of bunches incident at 10 − 12 kHz, a circumferential velocity of 60 m/s i.e. a rotational frequency of 1150 r.p.m. is required. For further details, the reader is referred to Ref. [7]. The principal parameters of the e^+ source considered for Fig. 2 are given below:

No. of e^-/bunch	4×10^{11}
Beam diameter (FWHM)	1.2 mm
Average e^- beam current	~700 μA
Average e^- beam power	~1.5 MW
Tungsten target rods	Φ = 2 mm, l = 20 mm
Average power absorbed in targets plus target support.	~0.8 MW

Fig. 3 shows various possibilities to contain the tungsten target proper within the water cooled copper of the wheel.

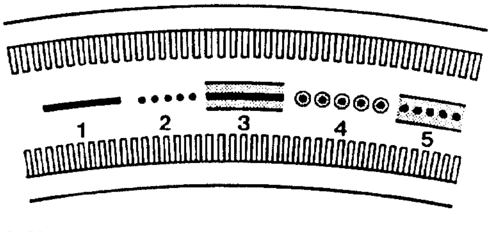

Fig.3 Various possibilities to mount the target material (solid parts) around the periphery of the water cooled target wheel. The target ribbons (rods) are inserted either directly into the copper (1,2) or into intermediate graphite jackets (3,4,5).

The layout of the target station was set up in the program EGS4 in order to calculate the energy deposition in the components, the shielding, the cooling water and the air of the cave. The energy depositions where related to induced radioactivity, so as define the needed shielding around the target station and to compute the production of noxious gases and corrosive chemicals. All these questions are extensively discussed in Ref. [7], which concludes that the problems are handleable.

3. Superconducting linacs and recirculators

For a conservative approach to a first cost estimate we have adopted in Ref. [8] presently available cavity parameters and operating conditions: these are essentially the design and operating parameters of the DESY cavities.

The choice of frequency is dictated by beam quality and machine physics considerations and the choice of 500 MHz provides immediate design and operating experience of other laboratories, notably DESY and CERN. In Refs. [2,5] the gradient of 7 MV/m was envisaged. At the Workshop operation at a gradient of 5 MV/m was considered to be safer, although indications exist that in a not too distant future gradients even larger than 7 MV/m could be reached. At the design gradient, typical unloaded Q values of $2\ 10^9$ are achieved at 4.3 K.

The cryostat design has also been taken from DESY's experience: it has a length of about 4.3 m and a liquid Helium capacity of slightly under 200 liters. Under the present design the filling factor was taken to be 0.40. This value has been used in determining the physical length of the linacs.

The lattices of the arcs and the focusing along the linacs have been designed [9] following CEBAF experience.

4. Damping Ring and Kickers

Low emittances are usually produced in high periodicity storage rings, with low field bending magnets, characterised by long damping times and therefore low extraction frequencies. In order to reduce both damping time and the transverse emittance, the insertion of wiggler magnets in the damping ring has been studied [10]. It has been shown that it is possible to express the radiated energy U per turn, the damping time τ, and the repetition frequency f_r in terms of an equivalent radius as follows:

$$U = 88.5 \times 10^{-6}\, E^4/\rho_{eq}\ [\mathrm{GeV}]$$
$$\tau = 7.53 \times 10^{-2}\, L\, E^{-3}\, \rho_{eq}\ [\mathrm{ms}]$$
$$f_r = 2.66\, E^3/(\rho_{eq} d)\ [\mathrm{kHz}]$$

with E expressed in GeV, L (circumference) in m, and

$$\rho_{eq} = \rho_W/(\eta + \rho_W/\rho),$$

where ρ(m) is the bending radius in the arc, ρ_W (m) is the wiggler bending radius, $\eta = L_W F_W/(2\pi\, \rho_W)$ with L_W (m) being the wiggler length, and F and F_W the arcs and wiggler filling factors. The intrabunch distance d (m) is determined only by the duration of the injection/extraction kicker pulse. A design of a magnetic kicker system which would allow d $\simeq$ 7 m is given in Ref. [11].

With a conventional magnetic field $B_{max} = 1.7$ T, at $E = 2.2$ GeV, and assuming reasonable lattice filling factors, one obtains the following values of the relevant parameters: $\rho_{eq} \simeq 0.34$ m, $\eta \simeq 12$, $L_W \simeq 400$ m, $L \simeq 700$ m. There are 100 bunches in the ring, $\tau \simeq 1.7$ ms and one obtains $\varepsilon_n = 1.9 \times 10^{-6}$m, as required in Table 1.

Two kinds of achromat blocks have been analysed in some detail: a DBA and a FODO. The momentum compaction α_c of the FODO lattice turns out to be about four times larger making easier to satisfy the constraints on the longitudinal emittance. In the natural regime the longitudinal emittance ε_L, which has to be small to have an acceptable value of the quantity ΔW_L defined in Table 1, is proportional to the square root of the momentum compaction (in our case $\varepsilon_L = 0.31\sqrt{\alpha_c}$). However, when the peak current is higher than a threshold value given by $I_{pth} \simeq 2\pi\, \sigma_p^2\, E\, \alpha_c/(Z/n)$, where 'n' is the ratio between the frequency at which $Z(\omega)$ is computed and the revolution frequency ω_0, the bunch experiences the so called "turbulent" regime characterised by an increase of the momentum spread σ_p and a consequent degradation of the longitudinal emittance. In order to keep the longitudinal emittance small, i.e. to obtain $\varepsilon_L = 3.7\ 10^{-2}$ m, for RF peak voltages of $\sim$ 20 MV, an effective impedance of 1Ω is required. This value does not seem too far away from the impedance achievable in storage rings when enough care is taken in the construction of all parts.

5. Collective phenomena

The longitudinal and transverse wakefields have been estimated by scaling with the frequency the SLAC and CEBAF data. The longitudinal loss factor at 500 MHz was computed to be 2.4 V/pC/m for an rms bunch length of 1 mm; this yields a head-tail (4σ) energy spread of 1.2% for the 8 10^{10} electron bunches. This energy spread can be substantially reduced (to 0.2 – 0.3%) by accelerating the bunch off-crest without degrading the effective accelerating gradient. The scaled transverse wake results to be $W'_\perp = 2.5$ KV/pC/m^3; the above result is conservative since we did not account for the further reduction (almost a factor 2) due to the larger scaled size of the cavity iris.

Simulations of both single and multiple beam breakup (BBU) have been performed using the CEBAF optics; results have been compared with analytic estimates. A linac optics consisting of constant gradient 120^0 FODO cells, like at CEBAF, is suitable for our racetrack inasmuch as it optimises the focusing of the low energy electron bunches against the wakefields effects. For a 1 mm injection misalignment, the electron emittance degradation is of the same order of the unperturbed emittance. The positron bunches, less populated and injected at higher energy, experience much weaker transverse forces. A full width 1 mm random displacement of the cavities induces an emittance degradation of the order of 10%. The cumulative multipass BBU threshold is about 400 mA, and is not of any concern.

6. Design of the Final Focus System

The proposed final focus system was studied in Ref. [12] for the scheme of Fig. 1 and has been reconsidered for the scheme of Fig. 2. It utilises a 57 metre section subsequent to the linac with adjustable beta matching and a dedicated section for beam collimators and masking. This section is followed by 90 degree achromat bend with an average bend radius of 32 meters and a 70 meter section containing chromatic correction, final demagnification and space for masking. The system is designed to provide a final adjustable β down to 1 mm. TURTLE runs show that there is no appreciable degradation of the final spot sizes for beams with up to 0.2% momentum spread. The design incorporates lessons learned from SLC experience, it should be easier to adjust than the corresponding SLC design and makes provision for substantial experimental masking both prior and subsequent to the 90^0 bend.

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