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A CONCEPTUAL DESIGN OF A LINAC-STRETCHER RING TO OBTAIN A 2-GeV CONTINUOUS ELECTRON BEAM*

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Summary

In order to obtain a high duty factor, > 100 μA 2-GeV electron beam, we have designed a linac-stretcher ring system. The system is an attractive option because it draws heavily on the existing accelerator technology. The linac-stretcher ring consists of a 2-GeV SLAC-type pulsed linac which injects into a storage ring. In between linac pulses, the stored electron beam is to extract resonantly. This design differs from those discussed recently[1] in several important respects. The storage ring includes an RF system whose purpose is to control the beam orbit and rate of extraction from the ring. With an RF system in the ring, the injection scheme consists of a few turns of synchronous transfers of beam between the linac and storage ring.

Introduction

The use of a pulse stretcher storage ring to convert a pulsed beam of electrons to continuous beam is an attractive option because it draws heavily on technologies developed in high-energy physics colliding beam facilities, and it utilizes the short pulse linac injectors of well-established design. The linac-stretcher ring design presented here consists of a 2-GeV SLAC-type linac that injects into a storage ring of 251 m in circumference.

The design developed here differs from those discussed recently[1] in several important respects. The storage ring includes an RF cavity system whose purpose is to control the beam orbit and rate of extraction from the ring. A constant rate of extraction can be maintained for all energies. Such controlled extraction would be difficult in a storage ring system that relies on synchrotron radiation to translate the beam orbit. With an RF system in the ring, a synchronous injection method has to be employed in order to achieve the maximum efficiency. Consideration of the synchrotron frequency in the storage ring precludes the use of the same frequencies in the linac and ring RF systems. However, synchronous injection is possible when the frequency of the storage ring is a subharmonic of the linac RF, and the micropulses of the linac are chopped so that the spacing of the beam bunches is the same as the ring bucket system. To achieve this, a chopper system used elsewhere[2] or a subharmonic buncher at the electron source would be used. The storage ring RF system can be, then, similar to that of existing e^+-e^- colliders. Electron beams of 900 mA have been stored in the e^- ring of DORIS-I[3] at DESY. With that performance established, our design objective, storage of 500 mA by synchronous injection, appeared sound.

Beam extraction would be accomplished by inducing a third integer resonance in the horizontal phase space. Extraction sextupole magnets would be placed at appropriate places to induce a third integer resonance separatrix at the extraction septum magnets. In order to facilitate smooth, efficient extraction during the entire extraction period, a "hollow" phase space technique would be used. The technique has been employed extensively in the ZGS extraction system[4] at ANL. A third integer resonance extraction also offers the possibility of extracting up to three beams simultaneously. (At the ZGS, two-beam simultaneous extraction had been a routine operation.) The use of horizontal extraction would enhance the quality of the extracted beam, particularly the energy spread.

Linac Design

The characteristics of the injector linac will be determined by the radius of the stretcher ring, the magnitude of the circulating current, and the peak current in the linac itself. Operation at the highest acceptable peak current is desirable because the cost of linac RF components is directly proportional to the RF duty factor. Limits on peak currents of ∿100 mA have been established on the basis of operational experience with SLAC structures of much longer lengths than contemplated in this study. Earlier conceptual designs of 2-GeV systems based on such limits have resulted in design values for klystron duty factors that are typically twice that of SLAC design and operational experience. Upgrading the existing SLAC klystrons to the performance required would be a formidable task necessitating the redesign of the klystron collector and cooling, as well as development of RF windows of new materials. All of these problems can be avoided if the peak current in the linac can be raised to ∿400 mA. Thus, the resulting klystron duty factor would be within present operating range. This, in turn, enables us to inject into the stretcher ring in a more efficient single turn.

Because beam breakup threshold currents are a strong function of linac length and focusing lattice, it is important to study breakup thresholds in systems appropriate to the pulse stretcher injector linac. R. Helm[5] has carried out a series of calculations of current thresholds for beam breakup for a SLAC-type linac with the specifications given in Table 1. The linac in-line system used consists of 3-meter sections grouped into four sectors, each containing 14 sections with a 3-meter drift for extraction at the end of each sector. Nine quadrupoles scaled with energy to maintain a phase advance of about 90 degrees per cell. The four quadrupoles in matching cells at the end of each sector are adjusted to match the beam envelope from one sector to the next. The cumulative beam breakup arises from a few resonant modes in the HEM_{11} passband, which occur in the first few cells of each 3-meter section. The values for the frequencies and transverse shunt impedances were chosen on the basis of experience with the SLAC system. The beam breakup was assumed to be driven by an initial betatron oscillation of about 1 mm,

Table 1. Linac Parameters Used in Beam Breakup Calculations

Structure	SLAC $2\pi/3$
Section Length	3 m
Filling Time	0.44 μs
Gradient	12 MeV/m
Number of Sections	56
Extraction Points	0.5, 1.0, 1.5, 2.0 GeV
Beam Pulse Length	2.5 μs
Bunching Frequency	476 MHz

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and the threshold was defined arbitrarily as the current at which the beam displacement grows to 1 cm.

Calculations were made for three cases of linac structure design. Case A consisted of a linac of identical sections; Case B consisted of a structure in which the frequency of the blowup mode in the first 11 sections was 2 MHz below that of the remaining sections. In Case C, the frequency of sections 8-21 were 2 MHz above the initial sections, and the remainder were 4 MHz above the initial sections. These frequency shifts for transverse blowup modes can be realized in realistic designs with negligible effect on the accelerating properties of the structure. The computed breakup thresholds for these three cases were: Case A, 320 mA; Case B, 680 mA; and Case C, 1060 mA. While these calculations were not exhaustive, they did establish the feasibility of design objectives for peak linac currents in the range of 500 mA.

Using the operating experience in the DORIS-I e^- ring as a guide, we have chosen a maximum stored current of 400 mA, and the injection into the ring can be accomplished in a single turn with a peak linac current of 400 mA. The ratio of the stored current to external beam currents is the number of turns needed to extract, and this number, together with revolution frequency of the storage ring, fixes the linac repetition rate.

With these parameters, one can optimize the design in terms of the stretcher ring radius using overall construction cost as the criterion. We have used SLAC wave-guide structures modified to decrease the effect of beam loading by increasing the group velocity and reducing the attenuation. In Table 2, we show the wave-guide parameters and the linac parameters that resulted from this optimization. A total external beam current corresponding to three external 100 μA beams is assumed. Although the minimum cost occurs at a radius of about 8 m, we have chosen a somewhat larger radius of 15 m in order to permit operation at higher energies should such a need develop.

Table 2. Wave-Guide and Linac Parameters

Wave-Guide Type	Constant Gradient, Disc-Loaded
Section Length, ℓ	3 m
Operating Mode	$2\pi/3$
Attenuation/Section, τ	0.3 nep.
Shunt Impedance, r	53 MΩ/m
Q	13,000
Filling Time, T_F	0.44 μs
RF Power Input/Section, P	40 MW
Maximum Energy	2 GeV
Beam Loading	415 MeV
Linac Peak Current	440 mA
Linac Total Length	175 m
Number of Sections	46
Linac Frequency	2856 MHz
Linac Repetition Rate	894 pps
Linac Duty Factor	1.1×10^{-3}
Linac ac Power	4.0 MW
Pulse Length	1.27 μs

Stretcher Ring Design

The design of the stretcher ring lattice structure has to fulfill the following requirements: (a) At the locations of the injection and extraction septum magnets and RF straight section, the dispersion function must be zero; (b) At the location of the resonance extraction magnet, the dispersion function must be as large as possible; and (c) For two or more simultaneous extractions, the betatron phase advance between the extraction straight sections must be a multiple of 120°. These requirements may be satisfied by a FODO cell with a phase advance per cell of approximately 60°. Figure 1 shows the lattice layout of one of four straight sections. The dispersion function is made to zero by leaving out bending magnets. In Table 3, we have listed the main parameters of the ring.

Table 3. Ring Parameters

Maximum Energy	2 GeV
Current	400 mA
Machine Circumference ($2\pi R$)	251.3 m
Bending Radius	15 m
Maximum Bending Field	0.445 T
Length of Bending Magnet	1.473 m
Bending Magnet Gap	0.031 m
Power Loss/Bending Magnet	5 kW
Number of Bending Magnets	64
Maximum Quadrupole Gradient	4.68 T/m
Length of Quadrupole Magnet	0.5 m
Diameter of Quadrupole Magnet	0.3 m
Power Loss/Quadrupole Magnet	1 kW
Number of Quadrupole Magnets	88
Radial Betatron Frequency (ν_x)	7.25
Vertical Betatron Frequency (ν_y)	6.25
Number of Cells (Total)	44
Number of Normal Cells	32
Super Period	4
Synchrotron Rad. Loss/Turn	94 kV
RF Voltage/Turn	800 kV
Harmonic Number	399
RF Frequency	476 MHz
Rotation Frequency	1.193 MHz
Synchrotron Frequency/Turn (ν_s)	0.02
β_x Max	9.93 m
β_x Min	3.35 m
β_y Max	10.50 m
β_y Min	4.17 m
Normal Cell η_{max}	1.25 m
Normal Cell η_{min}	0.75 m

The bending radius of the magnets is chosen to be 15 m. This corresponds to a field of 0.445 T at 2-GeV and 0.0445 at 200-MeV. This field is high enough that the effects of coercive force and permeability of the magnet iron will be negligible. There are 64 dipoles each 1.473 m long. The maximum strength of the 88 quadrupole magnets is 2.34 T/m^{-m}. Between the bending magnets and the quadrupole, there is enough space to accommodate sextupole magnets for chromaticity correction.

To inject the linac beam which is chopped at the electron source to have macrostructure of 476 MHz in the stretcher ring, the equilibrium orbit is distorted by a set of four fast bumper magnets. The injection septum magnets put the beam in the ring in such a way that the radial phase space is hollow. At the end of the injection period, the bumper magnet system is turned off adiabatically. The chopper system and the ring RF system are to be phase-locked to facilitate a synchronous transfer of beam into the ring.

The extraction makes use of a third integer resonance $v_x = 22/3$. The resonance sextupole magnet will be located in a region with larger dispersion function. The purpose of this is to reduce the energy spread of the extracted beam. The field strength of the sextupole magnet seen by the circulating particle is a function of the betatron amplitude and by the particle energy due to a large dispersion function. A particle with its equilibrium orbit going through the center of the resonance magnet will see only a sextupole field. Particles with higher energy, thus, larger orbit, will also see a positive quadrupole field, and its ν_x value, move closer to the resonance value of 22/3. Particles with lower energies are farther away from the stopband. By slowly decreasing the RF frequency (i.e., increasing energy of electrons), the particle will be squeezed out of the stable region along the three arms of the separatrix. The electrons jump from one arm to the next, each turn with increasing displacement. When the increase per turn of this displacement is large enough, the electrons will enter an extraction septum. By having two or three septa separated by multiples of 120^o in the betatron phase, one can extract two or three beams simultaneously. It turns out that, in practice, the extraction efficiency decreases with the area inside the separatrix. By having a hollow radial phase space or by $(n-\nu_x)$ tickler, the extraction efficiency can be kept high. The energy spread of the extracted beam is expected to improve by the following relation:

$$\frac{\Delta P}{P} = \frac{\sqrt{\beta_{xR}\varepsilon}}{\eta_{xR}}$$

where:

β_{xR} = the value of β_x at the resonance magnet,

ε = the linac emittance, and

η_{xR} = the dispersion function at the resonance magnet.

Using values typical of the lattice, i.e., β_{xR} = 8 m, η_{xR} = 1 m, and $\varepsilon = 2.5 \times 10^{-7}$ mrad, we find:

$$\frac{\Delta P}{P} = 1.4 \times 10^{-3}$$

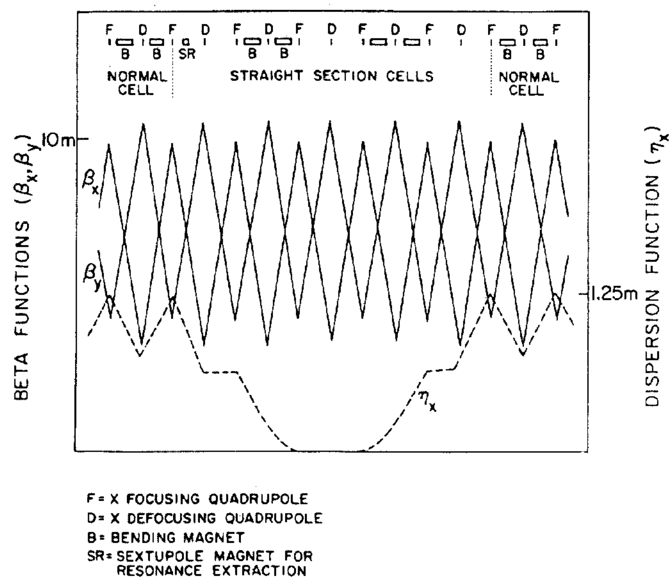

Fig. 1. Beta and Dispersion Functions for Lattice Structure Proposed for Linac Stretcher Ring System

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