A 5 GeV Injector for PEP *

H.-D. Nuhn, R. Boyce, R. Gould, H. Winick, B. Youngman and R. Yotam
Stanford Synchrotron Radiation Laboratory, P.O. Box 4349, Bin 69, Stanford, CA 94309-0210

Abstract

This paper describes a project for providing SSRL with a dedicated injector for both PEP and SPEAR by upgrading the SPEAR 3 GeV injector synchrotron, a 10 Hz cycling synchrotron served by a 150 MeV linac capable of accelerating 10^{10} or more electrons per cycle now under construction [1], to function at 5 GeV and transporting the electron beam through a 240 m long tunnel to PEP. After injection at 5 GeV, the energy of PEP will be ramped to 6-10 GeV for most anticipated dedicated operation for synchrotron radiation research [2]. As an interim dedicated injector,it will facilitate the utilization and development of PEP as a synchrotron radiation source until a full energy, dedicated injector is warranted.

Introduction

The Stanford Synchrotron Radiation Laboratory (SSRL), a national synchrotron radiation facility, operates 22 experimental stations on SPEAR and two on PEP. Both storage rings now use the SLAC linac as an injector.

The increase in energy of the SLAC linac to 50 GeV, and other modifications made to it for the SLC program, have decreased the availability and increased the complexity and cost of using the linac as an injector to SPEAR (1.5 3.5 GeV) and PEP (5 15 GeV), with serious negative consequences on the synchrotron radiation research program on both of these storage rings.

These circumstances prompted the SSRL proposal to construct a dedicated 3 GeV SPEAR injector so that the large synchrotron radiation research program on SPEAR can be more effectively pursued. The SPEAR injector is now in construction and scheduled for completion in 1990.

PEP now has two undulator beam lines that have been used parasitically during colliding beam operation around 14 GeV and briefly tested during dedicated low emittance operation at 7.1 GeV [3,4]. During the low emittance tests, an emittance of 6 nm radians was measured with the normal damping partition and 4 nm radians in a brief test with a modified damping partition, making PEP the lowest emittance, highest brightness X ray synchrotron radiation source in the world. This has led to increasing interest in the use of PEP as a synchrotron radiation source and to the study of ways in which injection to PEP can be achieved other than with the SLAC linac [5].

In this paper, we present a study of injection to PEP by upgrading the SPEAR injector so that its peak energy is increased to 5 GeV and bringing this beam to PEP via a 240 meter long transport system (see figure 1) located in a tunnel connecting the SPEAR injector to the present electron injection line for PEP. The upgraded synchrotron would then serve as injector to both SPEAR and PEP, an effective and economical arrangement (See also [6]).

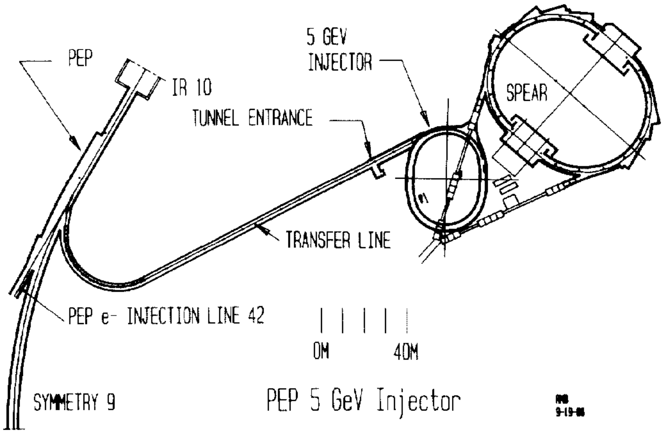

Figure 1: Overview over the Proposed Injector for PEP.

The SPEAR injector is designed so that a positron source can be added later. This use of positrons in both SPEAR and PEP would eliminate the problems that are frequently encountered with positive ion trapping when electron beams are used.

Since most dedicated synchrotron radiation operation of PEP is now anticipated to be at electron energies above 5 GeV, ramping of the electron energy after injection will be necessary. Although this is less desirable than full energy injection, this approach provides the most cost effective and rapid way of achieving injection to PEP independent of the SLAC linac.

One possibility for a full energy injector would be a higher energy synchrotron (about 10 12 GeV) located in the PEP tunnel using the SPEAR injector as a pre injector via the transfer line. The cost of such a full energy injector would be substantially reduced by not having to provide a pre injector and by using small aperture magnets, since the aperture requirement would be reduced with the high injection energy that would be available.

Booster Synchrotron

A major part of this project will be the upgrade of the 3 GeV booster synchrotron that is now under construction by SSRL as a dedicated injector to SPEAR [1]. The upgrade to 5 GeV will not change the layout nor the lattice of the booster. Table 1 lists the parameters characterizing the booster synchrotron showing values that are relevant to 5 GeV where applicable.

Lattice Type:	FODO	
Magnet Structure:	separated function	
Cell Length:	6.683	m
Total Number of FODO cells:	20	
Bending Radius:	12	m
Bending Field:	1.4	T
Beam Emittance / E^2:	21	nm rad
RF Frequency:	358.54	MHz
Harmonic Number:	160	
Momentum Compaction:	0.03335	
Revolution Frequency:	2243.28	kHz
Horizontal Damping Time:	1.027	msec
Vertical Damping Time:	0.966	msec
Energy Damping Time:	0.469	msec
Energy Loss Per Turn:	4.61	MeV
RF Voltage:	7.52	MV
Bunch Length: (1 σ)	2.74	cm
Energy Spread: (1 σ)	0.123	%
Energy Acceptance:	0.65	%
Synchrotron Frequency:	71.11	kHz

Table 1: Main Parameters of the Booster Synchrotron

RF System

The SPEAR booster RF system uses a surplus SPEAR 358.54 MHz cavity and klystron. The additional voltage necessary for 5 GeV operation will be supplied by three additional RF cavities, of the former SPEAR II RF system, driven by two klystrons. The difference between the frequencies, of the PEP RF system (353.21 MHz) and that of the booster synchrotron complicates multi bunch injection as discussed later.

The average power required for 5 GeV operation is 50 kW, assuming that the voltage is modulated with beam energy and the RF voltage is reduced to zero in the descending part of the 10 Hz magnet cycle, that is after the 5 GeV beam is extracted. The peak power requirement is 400 kW.

Extraction System

The booster synchrotron will be used to accelerate either a single bunch or a short train of bunches. When the electrons reach the 5 GeV extraction energy, a fast vertical extraction scheme will be used to extract all bunches in one turn. A ferrite kicker magnet will be powered by a delay line pulser so that the rise of the magnetic field occurs during the time interval between passages of the bunch train at the kicker. The kicker will deflect the electron bunches horizontally by about 3 mrad into the gap of a Lambertson septum, which kicks the bunches vertically by about 63 mrad. The magnetic field of the kicker magnet is kept constant for the time that the bunch train needs to pass the kicker magnet. When the magnetic field of the kicker magnet is set to its maximum value, the design path is lead into the septum. The acceptance of the septum gap is large enough to accept ± 3 σ of the horizontal emittance of the electron beam. With the electrons in its gap, the kicker has only two states: either switched off or set to its maximum value. Therefore, the electrons stay either on the design orbit or they are lead into the gap of

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the septum. This scheme guarantees reduced extraction losses. An upgraded version of the beam extraction system for the beam transport to SPEAR will be used for both the beam transport to SPEAR and to PEP.

The extraction kicker is built as a window frame magnet consisting of blocks made from Ni Zn ferrites and a single-turn copper coil. The kicker magnet can be put into a vacuum tank, or a ceramic vacuum chamber can be placed into the gap of the kicker magnet. The latter design requires higher PFN voltages due to the larger gap height. To reduce the inductance of the whole assembly, the kicker magnet is divided into 3 subunits, which will be operated by three different pulsers. The PFN consists of a number of 10 m long HV coaxial cables charged by a power supply during the 100 msec between two extraction events. The PFN will be connected to the kicker and a load resistor by a high voltage thyratron. Table 2 lists the design specifications of the kicker unit.

Kick Angle	3	mrad
Integral Magnetic Field	0.0834	T m
Number of Sub Units	3	
Length of each Sub Unit	0.3	m
Number of turns	1	
Gap Height	0.025	m
Aperture Width	0.054	m
Magnetic Field	0.0500	T
Excitation Current Coil	1.1	kA
PFN Voltage	22.12	kV
Inductance	0.82	μHy
Rise Time	133	nsec
Flat Top Time	100	nsec

Table 2: Design Specifications of the Booster Extraction Kicker System

To reduce its power dissipation, the Lambertson septum is powered with current pulses much shorter than the cycle time of the booster synchrotron. This requires the construction of a pulser circuit and more care is required (laminated core etc.) in the construction of the septum magnet. There is a pulser for the septum in discussion that would produce current pulses that have the shape of one period of a sine wave rather than a rectangular shape. But nevertheless, there is a 'flat top' region at maximum amplitude where the change of amplitude in less then 0.1 % over a time interval long enough for the extraction. Table 3 shows some properties of the Lambertson septum magnet and the pulser circuit.

Kick Angle	63	mrad
Integral Magnetic Field	1.05	T m
Core Length	1.6	m
Magnetic Field	0.656	T
Gap Width	20	mm

Table 3: Design Specifications of the Booster Extraction Septum System

It may be possible, on the other hand, to operate the septum magnet in series with the booster dipoles, instead of using a separate pulser. The necessary amplitude control could be achieved via additional turns in the septum coil that are operated by a small dc power supply.

Magnets

The magnets in the 3 GeV booster synchrotron have been designed to be operated at the 5 GeV level. The bending magnets will require a field of approximately 1.4 T at 5 GeV and have been tested to that level as part of the 3 GeV Injector project.

The resonant network supply system (White circuit) for the dipole and quadrupole magnets is designed for a 3 GeV operation. Upgrade of the power supplies and the resonant network will be required for 5 GeV operation. The upgrade will include the increase of the power supplies capability to supply power from ≈ 500 kW to ≈ 1250 kW, and adding chokes and capacitors to the resonant network.

Vacuum System

The vacuum chamber wall of the booster synchrotron will experience a significantly greater heating rate when operating for 5 GeV injection into PEP in comparison to 3 GeV when injecting into SPEAR. The peak incident heat rate is 2.13 W/cm, of which 90 % is absorbed by the chamber, and the remainder absorbed by the structures adjacent to the vacuum chamber. At lower electron beam energies, greater proportions of the incident beam are absorbed by the chamber wall. Note that the synchrotron radiation power is proportional to the fourth power of the electron beam energy. At 5 GeV, the power is 7.7 times that produced at 3 GeV.

The average power incident upon the chamber is less than the peak power because of the cyclic operation of the injector synchrotron. Electrons are injected into the booster at 150 MeV and raised to 5 GeV in a sine wave. At the top of the curve, the electrons are extracted and directed to PEP. Thus, the chamber is heated for the first half of the sine wave only. A numerical integration of the power equation results in an average heating of the chamber wall of 0.3 W/cm. At worst, this results in chamber temperatures that are 215° C above ambient. Air blowing over the chamber at 1 m/sec will reduce the temperature increase to 12.5° C.

Additional work must be done to assure both the necessity and the adequacy of forced air cooling. The chamber temperature will have a transient component due to the sinuously varying electron beam energy. Peak temperatures and stresses must be calculated and metal fatigue effects examined. Thermal tests should be performed with a prototype magnet, chamber, and cooling devices. Heating may be provided with a resistive electric element, temperatures measured with thermocouples, and the effects of natural and forced convection determined. Strain gauges may also be attached to the chamber and stresses measured. The air cooling system can be run over a "long" period of time to discover any problems with dust and contaminant build up on the vacuum chamber and effects of the temperature of the chamber.

Shielding

It may be necessary to add an additional 90 cm to the concrete shielding on both sides of the ring enclosure of the 3 GeV booster synchrotron, making a total thickness of ≈152 cm for the walls. The roof of the shielding structure may need to increase from 66 cm to 155 cm or an adequate and agreed upon method of keeping personnel off the roof must be found. However, the final shielding design can wait until experience has been gained by running the booster synchrotron at 3 GeV and perhaps even 5 GeV, and accumulating actual radiation level measurements outside the existing shielding.

Transfer Beamline

A Beam Transport System, operating at 5 GeV, is being designed to transfer the electron bunches from the 5 GeV booster synchrotron to the PEP ring. The electron injection into PEP will be done by using the last part of the PEP electron injection line. To increase the transfer and injection efficiency, matching sections will be inserted into the FODO lattice of the Transport System to match the electron optical parameters of the last part of the Transport System to the last part of the PEP electron injection line.

For this first layout, the design of the booster synchrotron dipole and quadrupole magnets are used to model the Transport System. The layout of the dipole system is determined by survey rather than electron optical requirements. These survey requirements are the location of the booster extraction beam line, the location of the PEP electron injection beam line, a lower limit for the arc radius determined by the properties of the mining machines, the properties of the booster shielding and the PEP tunnel.

The PEP ring is located in a plane 10 m below the level of the booster synchrotron. To accommodate for this difference in elevation of the booster, the beam is bent downwards by ≈ 3° after leaving the synchrotron tunnel and continues its downward slope until it reaches the PEP electron injection line. In the large arc, the slope will be achieved by mounting each dipole magnet slightly rotated with respect to each other. These sloped and rotated dipole magnets cause a beam rotation around the longitudinal axes of 8°. The beam has a flat shape when extracted from the booster synchrotron (A coupling of less than 10 % is anticipated in the booster synchrotron). A beam rotation as mentioned, therefore, increases the effective vertical emittance more than it decreases the effective horizontal emittance. If the quadrupole magnets were not tilted with respect to the horizontal plane, according to the local beam rotation, there would be a coupling of the two planes which could possibly be compensated by an additional triplet of skewed quadrupoles in the last part of the PEP electron injection line.

The beam focusing will be done by a FODO lattice which has different cell lengths in the arc above the booster (13 m), in the long straight section (15 m), and in the large arc near PEP (19 m). In the arcs, the cell length is chosen so that there are two bending magnets between successive quadrupole magnets. The distance between quadrupoles in the long straight section was chosen to have a value midway between the cell lengths in the two arc sections.

Horiz. emittance	526	nm rad
Vert. emittance	53	nm rad
(10 % coupling)		
Energy spread	0.122	%

Table 4: Parameters of the Ejected Beam

The β function and the dispersion function in both the horizontal and the vertical plane have to be transformed by the optics of the transport system so that these functions have the same values both in PEP and in the transport line at the PEP injection septum. This matching minimizes the maximum beam dimensions of the injected beam in PEP at the given emittances.

To provide orthogonal sets of parameters for adjusting each of these functions, it is necessary to use quadrupole magnets that adjust a given optical function in a section of the transport beam line where the values of all other

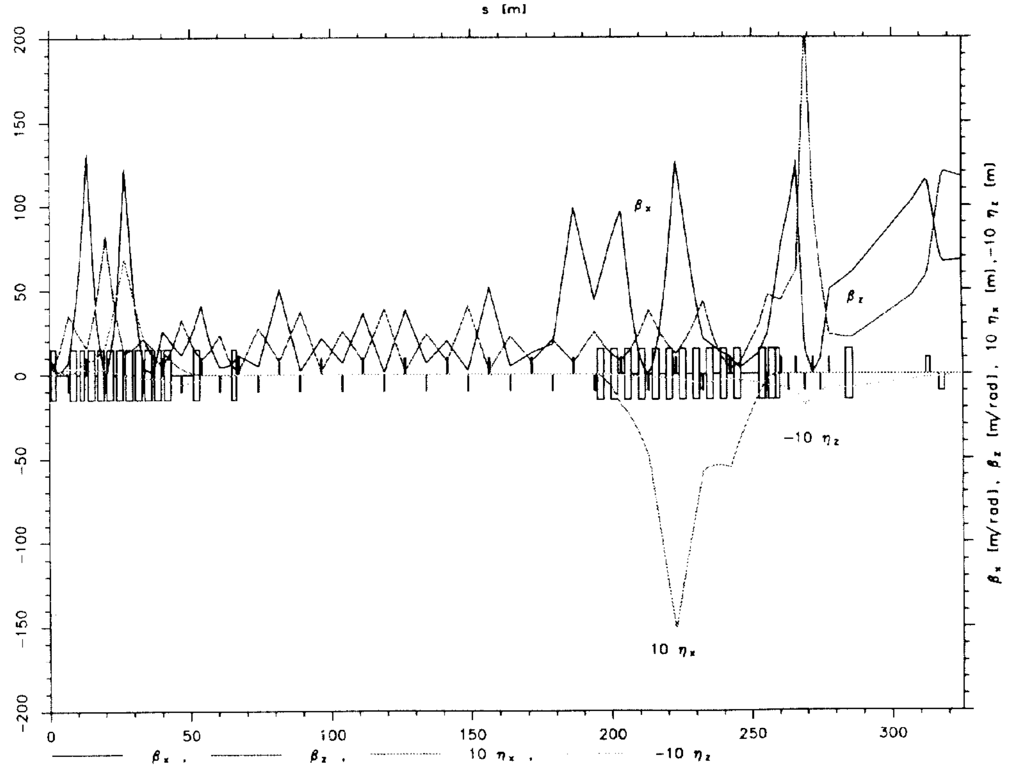

Figure 2: Lattice of the Transfer Beamline.

functions are zero or very small compared to the value of the function to be adjusted. For this reason, the long straight section in the transfer line is chosen to be a dispersion free section.

Figure 2 shows the optical functions (β_x, β_z, 10 η_x,-10 η_z) along the transfer beam line beginning at the middle of the F quadrupole magnet preceding the Lambertson septum in the booster lattice and ending at IP10 in the PEP lattice. To simplity the identification of locations in the plot with locations in the transfer line in figure 1, a beam line plot sketch is overlaid in the middle of that plot. Dipoles are marked with boxes symmetrically to the center line, F quads with upright, and D quads with downward boxes. The last three boxes are in IR10 of PEP and denote the Lambertson septum, B11, and the quads Q_2 and Q_1 (from the left to the right). In this last part, the functions β_x, β_z and η_x are the same as they are in the PEP low emittance optic at this place, η_z should be zero in this section.

It should be possible to operate with a larger size vacuum chamber in sections with a large dispersion and β function. There were only preliminary optics calculations possible at this time and more detailed calculation will be carried out to obtain a more precise description of the envelope.

PEP 5 GeV Injection and Ramping

To store a 5 GeV electron beam with a very long quantum lifetime in PEP, an overvoltage factor of 1.63 is sufficient. However, for a bunch injected from the booster synchrotron with a one σ bunch size of 11.6° RF phase and ± 0.123 % energy deviation, the PEP RF bucket is too small even to capture 3 σ in energy deviation of the injected beam. Therefore, to minimize the injection loss even for a single bunch injection scheme, the RF voltage at injection has to be higher than necessary to store a damped beam.

Multibunch Injection into PEP

To decrease the time periods necessary to fill PEP up to the required electron intensity, it will be helpful to accelerate a short train of several bunches in the booster synchrotron rather than one at a time. When trying to transfer those bunch trains from the booster synchrotron into PEP, problems in placing each of the bunches properly into a bucket arise due to the different RF frequencies.

Since energy spread of a single bunch during injection, as well as the spacing of the bunches within a train of bunches, requires a large bucket size, the best thing to do is not to ramp the PEP RF but let it stay at a value suitable for top energy operation.

Due to the different RF frequencies, it will be necessary to develop a special transfer timing system to inject into PEP. This will include a phase locked loop circuit which makes it possible, together with a larger bucket size, to inject trains of up to 8 bunches in PEP. This will be possible even when leaving 1 or two empty buckets between two adjacent bunches to combat multibunch instabilities.

Ramping Efficiency and Reliability

Since the proposed injector to PEP is limited to 5 GeV, it is necessary to develop low energy injection and ramping techniques for PEP. During a dedicated low emittance operation at 7.1 GeV, multi bunch instabilities limited the currents in PEP to about 15 mA. At lower energy, instability thresholds will set in at even lower currents so that it will be necessary to raise these thresholds. After some experience has been gained in injecting and ramping PEP, and with suitable increase in threshold for instabilities such as may be expected with the implementation of feedback system, it should be straightforward to inject and ramp 50-100 mA in PEP.

Thresholds for Multibunch Instabilities

Based on the recommendation of a workshop held by SSRL in November 1988 [7], work is now under way to implement a wide-band longitudinal feedback system in PEP. It may be necessary to also implement a transverse feedback system to reach the highest levels. This is because calculated rise times for transverse instabilities, although longer than for longitudinal instabilities, are still short compared to the damping time due to synchrotron radiation emission at electron energies around 6-10 GeV in PEP.

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