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SINGLE WAVELENGTH STANDARD WIGGLER FOR PEP*

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I. Summary

A 1λ planar wiggler has been designed that will be used for the initial operation of the 4-18 GeV storage ring PEP. Three of these wigglers will be installed symmetrically around the ring at 120° intervals in three of six available 5 m straight sections with the purpose[1] of providing: (1) beam size control to obtain better luminosities below 15 GeV, and (2) decreased damping times to obtain better injection rates at lower energies. Design goals are discussed and a description of the final system including cost estimates is given. Expected results and usage in PEP are discussed. Some possibilities for production of synchrotron radiation and beam monitoring with shorter wavelength, multiple-period wigglers at PEP energies are also discussed. Comparison to a wiggler now operating in SPEAR is given.

II. Purpose

Although many potential applications of wigglers have been known for a long time, there have been surprisingly few actual applications. The interested reader can consult the proceedings of two recent conferences[2,3] for a good overview of some possibilities as well as pitfalls.

The usefulness of PEP for high energy physics depends on achieving acceptably high luminosities over as large an energy range as practicable. For a constant ring configuration, i.e., one in which the bending and focusing fields scale with momentum or energy, there will be a linear dependence of the transverse beam dimensions on energy because the synchrotron radiation integrals are basically unchanged (see below). This results in a maximum luminosity, $\mathscr{L}_{max}$, which is expected to go as E^4 whenever there is sufficient current to obtain the critical transverse particle densities[1,4] determined by the incoherent beam-beam interaction. When the maximum beam currents are limited by the beam-beam interaction, the maximum theoretical luminosity, $\mathscr{L}_{max}$, at any energy can only be attained when the transverse beam size is increased to the "limiting aperture" value. Wasted aperture therefore implies more time (funds) to achieve a given physics result for energies below the value at which the aperture is supposed to be filled. On the other hand, if the beam size can be kept constant with decreasing energy, then $\mathscr{L}_{max}$ will go as E^2. Thus, since the aperture is designed for 15 GeV, a tunable variation in beam emittance ϵ_x of at least $(15/4)^2$ is desired for operation down to 4 GeV.

Such increases can be achieved using high-field wiggler magnets which increase the quantum excitations of the beam as well as the damping and energy loss but have comparatively small effects on the focusing or tunes. With increasing wiggler strength, the relative dominance of the quantum excitation of radial betatron oscillations and damping changes. We can approximate the ratio of emittance with the wiggler to that without as

$$\left(\frac{\epsilon_x}{\epsilon_{xo}}\right) = \frac{1+\delta_5}{1+\delta_2} \xrightarrow{\delta_2 << 1} 1-\delta_2+\delta_5-\delta_2\delta_5$$

where $\delta_i \equiv \delta I_i/I_i$ with δI_i being due to the wiggler alone and I_i due to the ring without the wiggler. Because the damping term $\delta_2 > 0$, it is actually possible to decrease the beam emittance somewhat if the excitation term δ_5 can be made zero. This will be the case when the wiggler is placed at a location where $\eta = \eta' \simeq 0$. The PEP wigglers are located in the symmetry straight sections where η_x is a maximum. Notice that δ_5 increases much faster with increasing wiggler field (and wavelength) than δ_2 so that the horizontal beam emittance, which is determined by equilibrium between quantum excitation and damping, will grow increasingly fast with wiggler field. A secondary benefit of the wiggler is that it always increases damping, and when the δI_4 contributions are negligible (as in PEP and SPEAR), the radial damping increase is proportional to δI_2, which significantly improves injection rates at lower energies. Synchrotron radiation integrals are discussed in Ref. 5, and Helm has done detailed calculations for the PEP wiggler.[6]

III. Description

The wiggler designed for PEP consists of three rectangular flat-field bending magnets sharing a common return so that the flux path is through successive poles, i.e., along the beam direction ($\hat{z}$) rather than transverse to it as in conventional H- or C- type designs. This should be more efficient for very high fields, reduce costs and improve the accuracy of 2-D field simulations. On the other hand, it implies some care is required to properly terminate the magnet at beam entrance and exit to simplify its subsequent use as well as minimize the effects of stray fields. This is the only region in the magnet where the flux path necessarily goes outside of a plane. Figure 1 shows a POISON calculation typical of those used in the design, and an elevation and end view of the system being built is shown in Fig. 2.

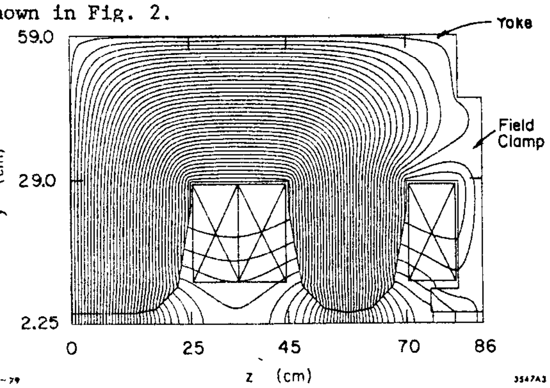

Fig. 1. POISON plot showing magnetic fields and circuit for the upper quarter of the PEP wiggler which is mirror symmetric about y = z = 0. The beam direction is along $\hat{z}$.

No steel piece is greater than 30 cm thick, and all are of SAE 1006 steel. Poles are made with 60° and 45° cuts to approximate a Rogowski profile and are welded onto the upper and lower yoke blocks. The result is final machined to obtain a flat and parallel surface, i.e., gap height through the magnet. The surface finish is 125 and the gap height variation is restricted to 0.025 mm. Top and bottom halves are mirror symmetric about the median plane so that the enclosed vacuum chamber is not captive, i.e., the magnet can be installed or removed from the ring without loss of vacuum. Because the flux path in the vicinity of the beam is confined to a plane, the field clamp is split along a vertical line rather than in the median plane. Table I

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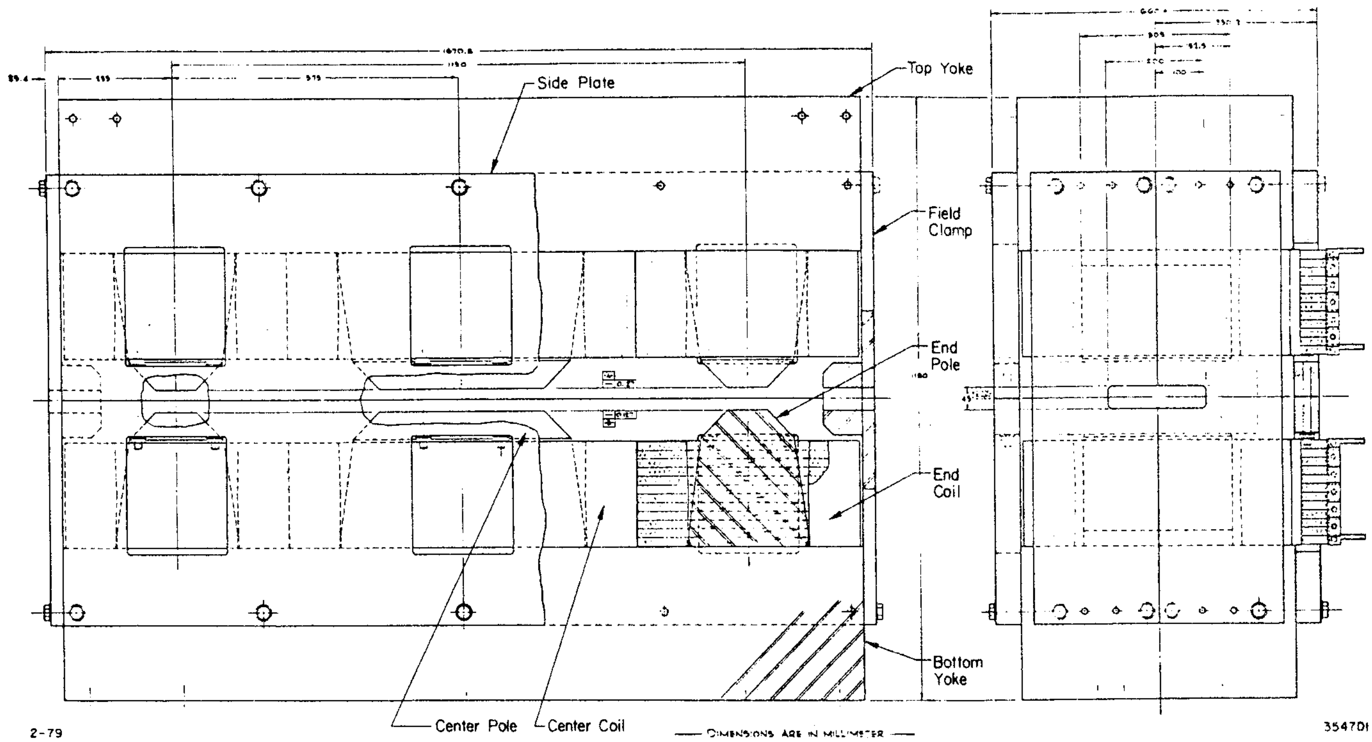

Table I - PEP Wiggler (1λ) Summary

Number of Poles	3
Maximum Central Induction B_o (kG)	20.0
Pole Width w (mm) - Coordinate direction ($\hat{x}$)	304.8
Gap Height G (mm) - Coordinate direction ($\hat{y}$)	45.0
Mechanical Pole Length - Inner (mm) ($\hat{z}$)	500.0
Mechanical Pole Length - Outer (mm) ($\hat{z}$)	250.0
$\frac{1}{2I}\int B_y(x,o,z)\,dz$ for $B_o = 20$ kG (kG - m/kA)	10.2
Effective Magnetic Pole Length - Inner (mm)	447.1
Effective Magnetic Pole Length - Outer (mm)	223.6
Magnetic Wavelength λ_W (mm)	1375.0
Total Magnet Length L(m) - Clamp-to-Clamp	1.671
Total Magnet Width W (mm)	661
Amperes for 20 kG	413
Turns per pole	120
Power (kW) for 20 kG	46
Amperes per mm^2 (Al Coil)	3
Total Flow Rate (gpm)	10
Maximum Temperature Rise (°C)	25
Total Magnet Weight (kg)	5500

contains the pertinent information for the wiggler design shown in Fig. 2. Table II contains the expected cost for the three wigglers now being built. The design is quite inexpensive for the capability it provides. All costs are included except for the primary power supply.

Even though this design would appear to be an ideal case for a 2-D field simulation, the large range of fields required imply the need for a dynamic correction element. We will use two adjustable currents per wiggler (actually one current and one shunt associated with a single supply). Since all wigglers will run on the same primary current which is tuned to provide the desired field (or δI_2, δI_3, etc.) there will be one supply and three bypass circuits. The latter will be used to insure $\int B\,ds = 0$ for each wiggler.

Table II - Cost for Three Wiggler Systems

ITEM	COST
Steel	15K
Steel Fabrication	42K
Coils - Fabricated	25K
Hardware - Cooling Manifolds, Fittings, Etc.	6K
Support Struts and Fixtures	9K
Magnet Assembly and Retrofit	3K
Bypass Shunts and Controls	6K
	106K

Figure 3 shows the equivalent circuit for one wiggler. If two independent current sources are used, it is necessary to reduce the effect of current ripple and the possible instantaneous differences in current that may exist when the ripples are not in phase. Techniques available are: filtering the supply outputs, using solid iron poles that allow eddy currents and use

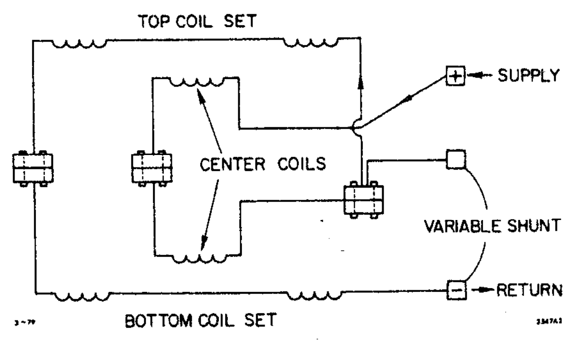

Fig. 3. Electrical schematic showing two knob system used to tune the field (δI_2, δI_5, etc.) and make $\int B\,ds = 0$.

of sufficiently thick vacuum chamber walls between the poles and beam. Design of the magnetic circuit which couples the fields resulting from the two currents also helps. Notice that in the present design with a single current, supply ripple effects are minimal because $\int B\,ds = 0$.

IV. Expected Results and Usage

Table III summarizes some characteristics of the SPEAR and PEP storage rings as well as predictions[6] for the effects of specific wigglers on their respective operation. For constant configurations as used in ramping up or down in energy, one can scale predictions with beam energy or wiggler field at fixed energy whenever the ring optics are unperturbed by the wiggler, e.g., through radial orbit distortions (via $\int B_W\,ds \neq 0$) or vertical tune shifts ($\Delta\nu_y$). A maximum tune change of 0.017 is a factor of 4 less than the synchrotron tune or the maximum beam-beam tune shift expected at an interaction region. A tune change of this magnitude is easily measured and corrected.

Table III - SLAC Wigglers

	SPEAR	PEP
Maximum Field, B_o	18 kG	19 kG
Number of Periods	3	1
Wavelength of Wiggler	0.3429 m	1.375 m
Energy Range of Ring	1-4 GeV	4-18 GeV
Primary Intended Use	S.R.	Beam Emittance
Status	Operational	Construction
Beam Characteristic at Wiggler:		
β_x (m)	14.4	32.7
β_y (m)	3.1	5.0
η (m)	2.9	1.47
α_x, α_y, η'	0	0
Ring Circumference, L	234.13	2200.0 m
Energy for Calculation	1.5	4 GeV
Number of Wigglers in Ring	1	3
Energy Loss (U/U_o) and (α_x/α_{xo})	1.10	2.12
Energy Spread - σ_E/σ_{E0}	1.24	3.45
Energy Shift - $\delta E/E$	-8×10^{-6}	-2.4×10^{-3}
Horizontal Tune Shift $\Delta\nu_x$	10^{-6}	8×10^{-6}
Vertical Tune Shift $\Delta\nu_y$	0.012	0.017
Horizontal Emittance ϵ_x/ϵ_{xo}	1.31	13.0
Momentum Compaction $\delta\alpha_p/\alpha_p$	-2×10^{-5}	3×10^{-4}

No increase in RF power is necessary to make up the energy losses per turn (U/U_o) due to the additional synchrotron radiation (SR) from the wigglers because they are turned off at energies above 15 GeV and only reach full field well below 10 GeV. Consequently, the maximum critical energy and brightness of SR produced in the wiggler occur in between these two energies. The relations are easily derived.[7] While the local SR power from the wigglers is presumably not a problem for the RF system, it does require careful consideration in the vacuum system because it is significantly larger than produced elsewhere in the ring. One solution is to use the radiation for beam monitoring and SR experiments since $\epsilon_c > 100$ keV.

The transverse damping rates (α_x/α_{xo}, α_y/α_{yo}) in PEP[1,6] follow the energy loss so another benefit of wigglers is to moderate increasing damping times with decreasing energy. Injection can then occur at higher pulse rates. At 4 GeV and 20 kG, the injection rate is expected to be 2.4 times better than without the wiggler.

Because the energy spread goes as

$$\left(\frac{\sigma_E}{\sigma_{E0}}\right)^2 = \frac{1+\delta_3}{1+\delta_2} \xrightarrow{\delta_2 \ll 1} 1-\delta_2+\delta_3-\delta_2\delta_3 ,$$

standard wigglers generally increase the energy spread[7] because $\delta_3 > \delta_2 > 0$. However, since the energy spread $\sigma_E(E)$ goes as E^2 without the wiggler,[5] it follows that maintaining a constant transverse beam size with decreasing energy, also leads to a more nearly constant energy spread.

Because wigglers provide a simple means of smoothly increasing beam size and damping, over a large range, they appear to be ideal for luminosity control which can be optimized on a minute-to-minute basis as the stored beams decay. Together with the other reasons just given, not to mention their demonstrated economy, wigglers would appear preferable to other schemes such as use of RF as long as the beams are predictable or at least their variations with energy. Since improved luminosity has been demonstrated at SPEAR,[8] wigglers will be installed for initial operation of PEP.

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