Storage Rings, Internal Targets and PEP*

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Prologue

Most of the talks here will be on physics from accelerators and storage rings rather than the physics of such systems since the "physics" is hard enough without having to worry about the beams or how you get them. As a result, this remains transparent to the user via an equipartition of effort worthy of a business school. This is especially debatable for colliding beam storage rings and leads to the corollary that most rings will be born, live and die as dedicated systems. SPEAR is a notable exception while PEP is not – even though PEP seems to provide more unique opportunities over a broader spectrum of physics. Examples include one and two photon physics with real and virtual photons to make all J^{PC} quark combinations as well as high luminosity QCD confinement studies with internal targets as discussed at this workshop. Some related possibilities include external beams of high energy photons; single-pass, free-electron lasers and x-ray synchrotron radiation which could all be the highest energy, resolving power, intensity and brilliance anywhere. From the viewpoint of accelerator physics, such examples fall into three categories: colliding beam physics, internal and external target physics.

How unique such possibilities are, whether they are truly possible e.g. what modifications might be required and questions of compatibility are discussed. Some systematic accelerator physics studies are suggested with implications for this and other proposed projects. As a fan of Gary Larson, I begin with Fig.1 showing his perspective of the PEP tunnel relevant to this occasion. Figure 2 is about reinventing the wheel(or ring in this case) with a lot of people trying to figure out what it is and how you use it. While one can't be sure what they'll come up with it's certain to be "interesting". However, because there have been several proposals for dedicated rings with properties which seem no better than PEP, perhaps Evelyn Waugh should have the last word here: *"If politicians and scientists were lazier, how much happier we should all be."*

1. Introduction

The goal is to describe storage rings with internal targets using PEP as example. Although fixed-target experiments were suggested some twenty-five years ago[1] little work of this kind has been done[2]. The differences between electrons and heavier particles such as protons, antiprotons or heavy ions is significant and is also discussed because it raises possibilities of bypass insertions for more exotic experiments. Finally, I compare PEP to other rings, in various contexts, while examining and verifying the statements made in the prologue e.g. that it is an ideal ring for many fundamental and practical applications that can be carried on simultaneously.

A. Some History and Perspective

In a sense, the SLAC linac was built to provide space-like photons[3] for deep inelastic scattering experiments on few nucleon systems. Such experiments demonstrated the basic underlying parton structure of the nucleon. In direct contrast, the subsequent development of SPEAR provided highly time-like photons via the (e^+, e^-) annihilation process shown in Fig. 3(b) which led to the first observations of resonant production of charmed quark pairs$(q_c, \bar{q}_c)$ as well as the heavy, electron-like particle called the tau. Related work is still being done at SPEAR together with a considerable amount of synchrotron radiation research.
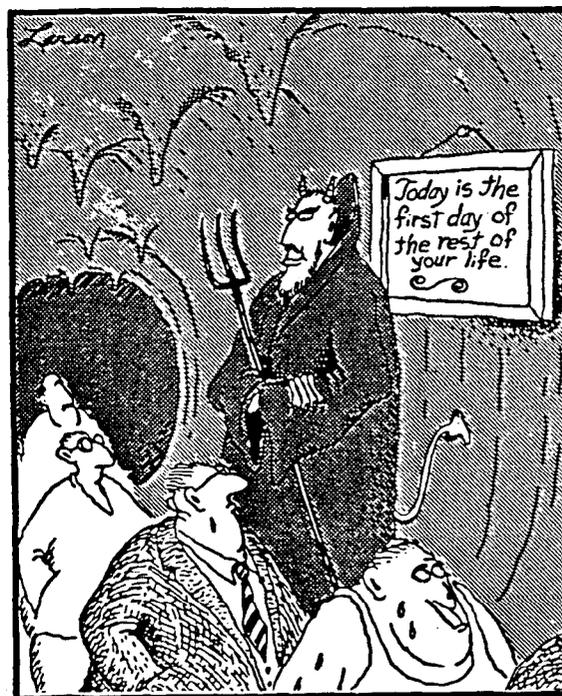
Fig. 1: Perspective of the PEP tunnel.

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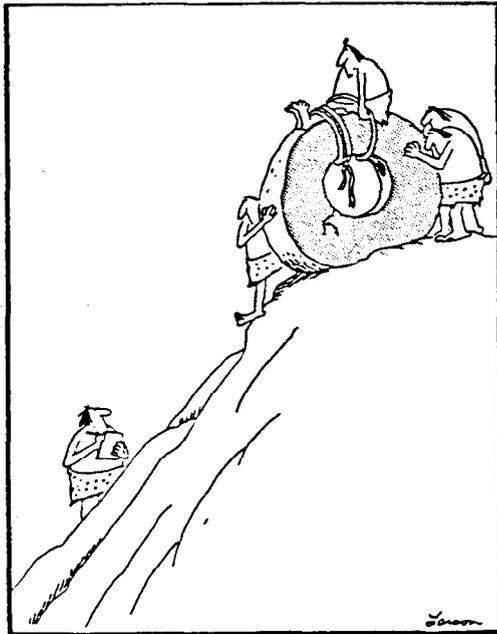
Fig. 2: Early experiments in transportation

With the higher energies available at PEP, higher-order processes become important with the space-like photon production processes of Fig. 3(c) being dominant. This two photon reaction is the main production channel for C-even particles with the physics at the internal vertices in diagrams such as Fig. 3(f) where $X \equiv f\bar{f}$. In all diagrams except Fig. 3(c), the cross sections fall with energy predominately as $1/s$ whereas 3c increases[3,4] in such a way that the crossover between it and processes such as 3b occur at beam energies above $\sqrt{s}/2 = 1 \text{GeV}$ depending on the mass m_f.

Concerning internal targets, the first experimental work at SLAC will be discussed at this workshop. My own interest in this area began in 1981 with the question[5]: "Is it possible to use internal foils to reduce phase space and simultaneously serve as a scattering target for an external, high-resolution spectrometer?" With dispersion at the target and the low ring emittance, this would be a consistent and significant improvement in SLAC's capabilities. Unfortunately, the answer to both questions was no unless the foil was a scraper or stripper which was neither new nor very interesting.

More recently, the subject was again considered[4] at an high energy e^+-e^- workshop on PEP because of new developments in polarized gas targets[6]. In this context, the results were quite positive and led to simple scaling relations for internal target luminosity. Furthermore, this option was just one of several to obtain higher luminosities with alternative incident channels: 1) e-γ, 2) γ-γ, and 3) e-A and γ-A. Using high current, stored bunches to produce the primary photon beam which is Compton converted to high energy by backscattering on a high current, high energy linac beam appeared to be an excellent way to upgrade the effective energy and luminosity of existing storage rings. Reaction rates would be improved because photoproduction cross sections are larger than electroproduction and higher current densities are possible by eliminating the conventional beam-beam interaction. While the primary and secondary photon beams would be a significant new research tool, only the e-A option will be discussed further here.

B. A Short History and Description of PEP

Figure 4 shows a schematic layout of the Positron-Electron Project, PEP, as used for colliding beam physics up to 1986. The ring has sixfold symmetry and divides into 12 regions of alternating arcs and long straight sections for experiments called insertions. The odd-numbered regions are the arcs which are subdivided into 19 FODO cells containing a Focusing quad(F), bending magnets with little or no focusing(O) and a Defocusing quad(D). Insertions for injection, extraction or experiments are so labelled because they perturb the otherwise simply periodic structure of identical FODO or unit cells introducing what are called superperiods into the structure. Individual particles can be thought of as oscillators under these focusing forces with frequencies that depend on particle energy.

A good description, including initial operating results and funding history, is available elsewhere[7]. In brief, formal ground breaking took place in June 1977, the ring was completed by April 1980 and delivered $\mathcal{L} > 10^{30} cm^{-2} s^{-1}$ at 11GeV by June.
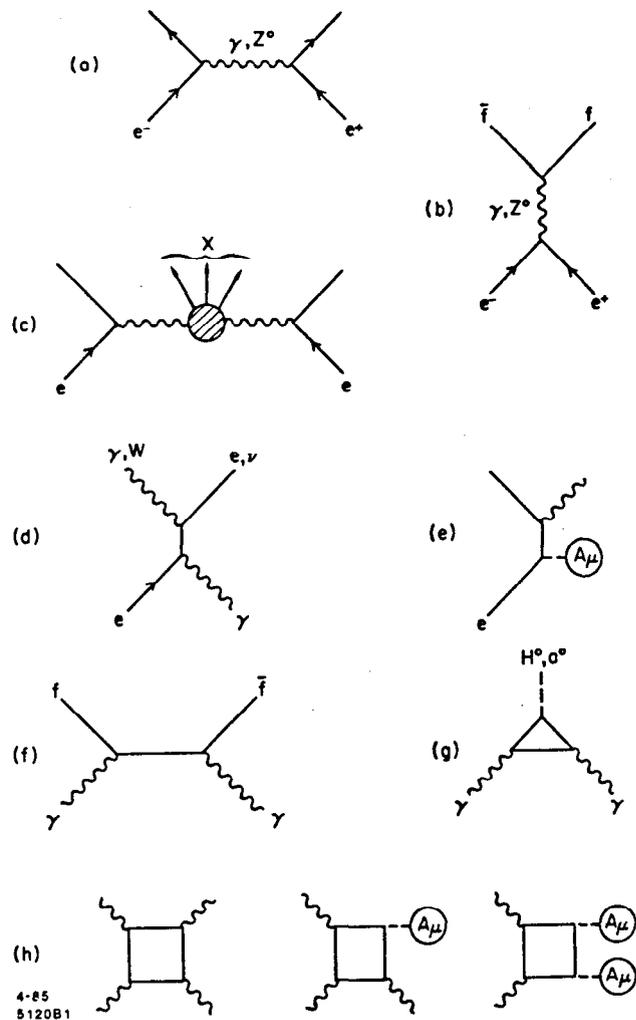
Fig. 3: Low order diagrams in the standard model for: (a,b) elastic, electroweak scattering; (b) electron-positron annihilation into elementary fermions $f = e, \mu, \tau \dots q_u, q_d, q_s \dots \nu_{e,\mu,\tau} \dots$ as well as elementary bosons $(W^\pm, Z^\circ H^\circ, H^\pm ?)$; (c) twoboson, electro-weak production; (d) Compton scattering or conversion $(\gamma \to W^\pm)$; (e) potential bremsstrahlung; (f) two-photon annihilation to fermions; (g) twophoton annihilation to bosons; and (h) photon-photon scattering, inverse photon bremsstrahlung (harmonic production) and Delbrück scattering.

2

MARK II

TUNE MEASUREMENT

REGION 11 | REGION 12 | REGION 1

ASP

REGION 10

W

N

TPC

REGION 2

e⁻ W

ACCELERATOR
AXIS

e⁺

I MONITOR
SCRAPERS

REGION 8

REGION 4

MAC

DELCO

REGION 7

REGION 6

REGION 5

W

SYNCHROTRON
LIGHT MONITOR

HRS
Bypass

PRESENT rf
8 - CAVITIES
2.0 MW

FUTURE rf
12 - CAVITIES

WIGGLER

2-87
5636A2

Fig. 4: Schematic layout of PEP showing some characteristics of interest here.

Typical values circa 1984 with all interaction regions active with good detector deadtimes and beam lifetimes at 14.5GeV were $\mathcal{L} \approx 3 - 4 \times 10^{31}$ giving integrated luminosities per IR of

$$\int_{Day} \mathcal{L}dt \approx 1500 \text{ nb}^{-1} \quad \text{or} \quad \bar{\mathcal{L}} \approx 1.8 \times 10^{31} \text{ cm}^{-2}s^{-1} .$$

This implies reaction rates on the order of 1 event per picobarn of cross section per day.

The different detectors then were an upgraded MarkII from SPEAR which will be used on SLC next. At 2 o'clock was the Time Projection Chamber which can track and identify all particles such as pions, kaons, protons etc. At 4 o'clock was the MAgnetic Calorimeter for measuring total, final state hadron energy including neutrons and K_L^0 followed by the High Resolution Spectrometer at 6 o'clock which had significantly better mass resolution than the other detectors. The Direct Electron Counter identified all final state electrons and the Assymetric Photon search was a supersymmetry experiment looking for new particles like the photino. MAC was also used for these experiments because PEP provided an ideal operating range for them.

Such experiments demonstrated the ability to measure cross sections on the order of tens of femtobarns(10^{-39}cm²) with storage rings which is an impressive achievement. Notice that the basic annihilation cross ection is

$$R = \frac{4}{3}\pi\alpha^2/s = 86.8/E_{cm}(TeV)^2 \text{ fb}$$

for processes such as Fig. 1(b) which is independent of mass m_f.

Some other elements in PEP besides those shown in Fig. 4 include beam position monitors and vacuum hardware around the ring, a tune measuring setup as well as transverse and longitudinal feedback hardware. Table I updates the more important parameters and capabilities of PEP which will be discussed in more detail after we motivate and define some terms.

2. The View From Mt. Hamilton

This section is a description of storage rings for physicists. The first problem is how to confine high intensity bunches of charged particles in stable 3-dimensional potential wells for long periods of time. In the rest frame of the bunch, a transverse electric potential results from transverse magnetic fields and the longitudinal well results from the RF field required to replace energy lost to synchrotron(and bremsstrahlung) radiation. The relativistic equation of motion of charged particles in an electromagnetic field in Hamiltonian form i.e. the total energy as a function of canonical variables q and p is:

$$H\Psi = i\dot{\Psi} = (H_{rad} + H_{part} + H_{int})\Psi$$

$$H_{rad} = \frac{1}{8\pi}(E^2 + B^2)\delta v; \quad H_{part} + H_{int} = \sum_i H_i$$

$$H_i(p,q) = e_i\phi(\vec{r}_i) + [(\vec{p}_i - e_i\vec{A}(\vec{r}_i))^2 + m_i^2]^{1/2}$$

where $A = (\phi, \vec{A})$ is the external field from the magnets, atoms, or lasers as well as the fields produced by the charges themselves. H_{rad} is the field energy and H_i is the total particle energy in the field.

Table I: Some Representative Storage Ring Parameters for PEP

Characteristic	Value
Nominal Maximum Energy per Beam[a]	17 GeV
Nominal Minimum Energy per Beam[a]	2 GeV
Maximum Current per Beam at 15GeV[b]	46 mA
Number of Particles per Beam at 15GeV	2.1×10^{12}
Maximum Colliding Bunches per Beam	3
Design Luminosity per Interaction Region $\mathcal{L}_{CB}$(Below 15 GeV)	$10^{32}(E/15)^2$ cm⁻² sec⁻¹
Number of Interaction Regions	6
$\mathcal{L}_{IT}$ (Constant τ_t and I)[c]	$10^{34}/Z(Z+1)$ cm⁻² sec⁻¹
Average Vacuum in Ring	10^{-9} Torr
Energy Spread (σ_E/E)	$6.7 \times 10^{-5}E$(GeV)
Natural Emittance (ϵ_z)[d]	$5.5E$(GeV)² Å
Length of Each Straight IR Insertion	120 m
Available Free Length for Experiments	15 m
Circumference	2200 m
Symmetry	6
RF Power Installed[e]	6.0 MW
Number of Accelerating Sections	24
Number of 0.5 MW Klystrons[e]	12
RF Frequency	353.2 MHz
Harmonic Number	2592

a This energy has not been well defined as discussed in the text.
b For single beam operation this scales up as the number of beams.
c Assumes lifetime $\tau_t = 2$h, current I=100mA for atomic number Z.
d This can be significantly reduced as discussed in the text.
e Commercial klystrons are now available with twice this power.

Spin terms are ignored together with the whole question of beam polarization because our concern is with the classical dynamics of motion which should not be influenced by spin effects even for the "small" emittances of interest here. However, if such effects were to be emphasized, superconducting or permanent magnet storage rings would be an ideal place for them.

Retaining only first degree terms in $\vec{A}_o$, in the rest frame, gives

$$H_{oi} - m_i = (\vec{p}_{oi} - e_i \vec{A}_o(\vec{r}_{oi}))^2/(2m_i) + e_i\phi(\vec{r}_{oi}) + V .$$

For a pure electrostatic field ($\vec{A} = 0$) this gives the familiar non-relativistic expression for the energy. Neither H nor H_i includes interaction between particles unless we add a term such as V with subscripts ij, ijk etc. which then gives coupled equations. If we are interested in such beam dynamics as coherent effects within a beam bunch, or various excitation modes in a laser medium, crystal lattice, atom or "elementary" particle we must include such terms.

The fields $\vec{A}$ and ϕ are generally nonlinear due to magnet errors and end fields, the sinusoidal character of the RF and the fields induced by the beam through self forces(e.g. the so-called ponderomotive potentials) or wake fields(interaction with the rest of the external world exclusive of guide fields). Such fields can couple the degrees of freedom of the single particle e.g. provide transverse-transverse (x-y) and transverse-longitudinal (x-z) coupling. Furthermore, since wake fields can be either transverse or longitudinal as well as fast or slowly decaying ($\tau \gtrsim 1/\omega_z$ or $1/\omega_{z,y}$ for fields with Fourier components $\omega \gtrsim c/L$), one expects that both single and multibunch instabilities will be possible.

Even assuming only one beam and one bunch, there are a number of current dependent effects which can cause beam blowup and subsequent particle loss by leakage out of the well. A good general reference for single-particle effects is Ref's. 8& 9. Collective effects have been discussed in Ref. 10. They may be broken down into coherent and incoherent depending on whether there are phase relations between individual particles or not. Where there are, one can think of modes of motion like that of the incompressible liquid drop of Bohr and Mottelson i.e. one has dipole and quadrupole motion that can be quite dramatic. There are many ways to both induce and cure such coherent effects. Thus, as the bunch oscillates, the potential well dynamically distorts which can produce an oscillating force back on the beam that can either drive or damp it. Similarly, the external potential well can be made to act the same way – usually via negative electronic feedback that senses and then feeds back to damp an instability. One can also add harmonic cavities to statically distort the potential well for various reasons[11] such as bunch length control or power consumption.

The canonical position, q, can be understood to represent the transverse displacement x and y from the equilibrium orbit and is a function of time, the independent variable, or equivalently, the distance along the central orbit s (or z). The momentum, $p \approx \gamma m q'$ where $q' = dq/ds$ so the important Liouville invariant is

$$\int pdq = m \int \gamma q' dq \equiv m\gamma\epsilon \equiv m\epsilon_n$$

for any particle with ϵ its area in transverse phase space. A beam of particles has a distribution function in phase space which convention describes by

$$\epsilon_n \equiv \gamma\sigma\sigma' = \gamma\frac{\sigma^2}{\beta}$$

where ϵ_n defines the normalized, "invariant", transverse emittance in any direction with σ, σ' the rms size and divergence and β the focusing or betatron function of the cells in that coordinate(x,y). It is also called a Twiss parameter[8].

The phase space trajectory of a representative particle that defines the rms beam envelop can be expressed[8,9] as

$$q = \sqrt{\epsilon\beta(s)}\cos(\phi(s) - \phi_0)$$

$$q' = -\sqrt{\frac{\epsilon}{\beta}}\left[\sin(\phi(s) - \phi_0) - \alpha\cos(\phi(s) - \phi_0)\right]$$

where $\alpha = \beta'/2$ and the phase

$$\phi(s) = \int_0^s \frac{ds}{\beta(s)}$$

with $\phi(0) = 0$ and $\phi(s)$ is another twiss parameter. Integrated around the ring, it gives the tune or betatron number

$$\nu = \frac{1}{2\pi}\int_0^L \frac{ds}{\beta(s)} = \frac{1}{2\pi}\oint \frac{ds}{\beta} .$$

The transformation of $\{q\} = (q, q')$ from one place to another, $\{q_2\} = R\{q_1\}$, is derivable from these expressions in a number of ways[8] e.g. using two linearly independent solutions such as $\phi_0 = 0, \frac{\pi}{2}$ giving:

$$R_{11} = \sqrt{\frac{\beta_2}{\beta_1}}\left[\cos\Delta\phi + \alpha_1\sin\Delta\phi\right]$$

$$R_{12} = \sqrt{\beta_1\beta_2}\sin\Delta\phi$$

$$R_{21} = \frac{1}{\sqrt{\beta_1\beta_2}}\left[(\alpha_1 - \alpha_2)\cos\Delta\phi - (1 + \alpha_1\alpha_2)\sin\Delta\phi\right]$$

$$R_{22} = \sqrt{\frac{\beta_1}{\beta_2}}\left[\cos\Delta\phi - \alpha_2\sin\Delta\phi\right]$$

where $\Delta\phi = \phi_2 - \phi_1$. These expressions are the first order transformations for the transverse motion of the Hamiltonian system and allow tracking with nonlinear perturbations etc. More importantly we have defined most of the terms used in Table I and needed for a more detailed study of rings such as PEP.

3. Three Kinds of Luminosity

A good place to begin is to define some different kinds of luminosity and what I mean by high and low luminosity and thick and thin targets etc. Conventional colliding beam luminosity which I will call $\mathcal{L}_{CB}$ has been discussed in detail[9,4].

A. Colliding Beam Luminosity

The incoherent beam-beam interaction between colliding bunches produces strong, nonlinear forces on the bunches which limit the operation of present rings. The leading-order, linear focusing force for head-on $e^{\pm}$ collisions, expressed as a tune perturbation per crossing, is[9]

$$\Delta\nu_{x,y} = \frac{r_e N_e \beta^*_{x,y}}{2\pi\gamma\sigma^*_{x,y}(\sigma^*_x + \sigma^*_y)}$$

where σ is the rms bunch size, N_e is the number of particles per bunch and β^* is the beta function at the crossing point or IR. For protons one would use the classical proton radius, r_p. Notice that γ for 20 TeV SSC protons is the same as for 10 GeV PEP electrons. The limiting magnitude of this number for most electron rings is $\Delta\nu^*_{x,y} \lesssim 0.05$.

With internal targets, this number can serve as a benchmark to compute the allowable number of ions replacing N_e with $-sgn(\frac{q}{e})N_i$, depending on whether we use an $e^{\pm}$ beam, before a clearing field is needed. The expressions are otherwise the same i.e. higher energy beams are preferred. Constraints from the operation of the target are generally more stringent i.e. depolarization and replenishment rates that are possible but multi-bunch instabilities with electron beams also have to be considered.

Although the above expression can be identified with the average, small amplitude tune shift for gaussian bunches it is best thought of as the tune spread in the core of the bunch[9]. At some limiting value of this tune spread $(\Delta\nu^*)$ or bunch current (N^*_e) the bunch cross-section $(\sigma^*_x\sigma^*_y)$ increases, luminosity fails to increase and may decrease and the lifetime may well decrease. If this limit is made the same in both transverse directions by making $\beta^*_y/\beta^*_x \simeq K(\equiv \epsilon_y/\epsilon_x)$, the tune independent, x-y coupling in the machine), one expects the maximum achievable luminosity when $\sigma^*_x \gg \sigma^*_y$ to be:

$$\mathcal{L}_{max} = \frac{(N^*_e)^2}{4\pi\sigma^*_x\sigma^*_y}fn = (\Delta\nu^*)^2(\frac{\gamma}{r_e})^2\frac{\epsilon_x}{\beta^*_y}fn$$

where $\epsilon_x = \pi\sigma^2_x/\beta_x$, f is the revolution frequency and n is the number of bunches per beam. Table II for PEP and SPEAR shows they are both near their limits of $10^{31} < \mathcal{L}_{CB} < 10^{32}$.

B. External Target Luminosity

For resolutions of order 20-50 keV at energies typical of Bates or LAMPF one must use target thicknesses of $t_t \approx 10$-50mg/cm^2. Typical currents with a consistent phase space and energy spread are $I_b \approx 50$-$100\mu\text{A}$. Translating these numbers into an equivalent luminosity gives:

$$\mathcal{L}_{ET} = (\frac{I_b}{e})N_A(\frac{\rho x}{A}) = 3.1 \times 10^{35}\left[\frac{I_b}{100\mu A}\right]\left[\frac{t_t}{10mg/cm^2}\right]\left[\frac{12}{A}\right]$$

where N_A is Avogadro's number, A the gram-molecular weight and A the atomic mass number in carbon units. This is a good benchmark for comparison to other facilities.

Table II: Some current operating parameters for the SPEAR and PEP storage rings for both colliding and single beams. These numbers do not involve the use of wigglers except during PEP injection at 5 GeV.

Energy(GeV)	2 SPEAR	5 PEP	10 PEP	15 PEP	
Beam Current, I_e^{Max}	100	30(?)	120(?)	92	mA
Beam Current, I_t^{Col}	25	5	20	46	mA
Coupling, $K \equiv \epsilon_y/\epsilon_x$	6.3	6.3	7.6	7.6	%
Emittance, $\epsilon_x \equiv \sigma^2_x/\beta_x$	0.195	0.0138	0.055	0.124	mm-mr
Emittance, $\epsilon_y \equiv \sigma^2_y/\beta_y$	12.2	0.866	4.19	9.43	μm-mr
Energy Spread, σ_E/E	0.048	0.033	0.067	0.10	%
Damping Time, $\tau_{x,y}$	28.3	100	27.5	8.2	msec
Revolution Time, T_o	0.78	7.34	7.34	7.34	μsec
IR Beta, β^*_x	0.9/20	3.0/15	3.0/15	3.0/15	m
IR Beta, β^*_y	0.03/35	0.12/0.6	0.12/0.6	0.12/0.6	m
IR Size, σ^*_x	0.42/1.97	0.20/0.45	0.41/0.91	0.61/1.36	mm
IR Size, σ^*_y	.019/0.65	.010/.023	.022/.050	.034/.075	mm
Divergence, $\sigma^*_{x'}$	.465/.099	.068/.030	.136/.061	.203/.091	mr
Divergence, $\sigma^*_{y'}$	.638/.019	.085/.038	.187/.084	.280/.125	mr
Energy Loss/Turn	0.110	0.333	5.33	27.0	MeV
Peak RF Voltage, V_p	0.495	0.650	8.49	39.1	MV
Bunch Length, σ_z	3.5	2.8	2.3	2.0	cm

C. Internal Target Luminosity

One can write the internal target luminosity in terms of the target thickness, n_t, as

$$\mathcal{L}_{IT} = (\frac{I_b}{e})N_A(\frac{\rho x}{A}) = 6.2 \times 10^{32}\left[\frac{I_b}{100mA}\right]\left[\frac{n_t}{10^{15}/cm^2}\right]cm^{-2}s^{-1}$$

One will find that luminosities on the order of 10^{33} are possible without significant effects on the beam. Targets on the order of $n_t \sim 10^{15}/cm^2$ or tens of ng/cm^2 are very thin but since there are more than 10^5 traversals per second the effective thickness is comparable to the high resolution spectrometer targets used at Bates or LAMPF. Such thicknesses appear ideal for optically pumped, polarized targets because of depolarizing effects due to beam heating in solid targets. Furthermore, there appears[6] to be a large range of (A,Z) available including H^1, D^2 and He^3 i.e. the 3, 6 and 9 quark systems.

Because $\mathcal{L}$ does not depend on the beam cross-sectional area, one can consider operating in a mini-maxi β configuration with small angular spreads at the target and higher currents when not simultaneously colliding in other IR's. We discuss this in detail and show the conditions under which one can use such targets in storage rings i.e. their effects on beam lifetime and emittance.

4. Luminosity Limitations

A. Colliding Beams

Increasing the frequency via superconducting magnets, or the number of bunches or the energy i.e. stiffening the beam are all expected to improve luminosity. Unfortunately, increasing the number of bunches (and duty factor) produces multibunch instabilities and other problems when the total number of bunches exceeds the number of IR's. Thus, one seldom sees a linear increase in luminosity with n unless $\Delta\nu < \Delta\nu^*$. Decreasing either β_y^* or increasing the horizontal emittance ϵ_x reduces the beam-beam force but is difficult because this increases the sensitivity to transverse instabilities. Decreasing β_y^* also implies shorter bunches which increases the sensitivity to transverse-longitudinal couplings i.e. synchrobetatron resonances. Using wigglers in existing rings to increase ϵ_x with *decreasing* energy[12] is now well established and relatively benign but the reverse is not true. In PEP, the wigglers are used to both decrease damping time and increase emittance.

Evidence from many rings has shown[13] that $\Delta\nu^* \lesssim 0.05$ and that it is difficult to keep this matched in both directions with increasing beam currents. Nevertheless, this number can presumably be increased in a variety of ways e.g. by increasing damping by going to higher bend fields (and thus also increasing f) or by incorporating more wigglers. However, because the multipole expansion of the beam-beam interaction goes to high order and these multipoles can't be reduced by simply increasing the aperture as for quadrupoles it is clear that the linear description of the beam-beam interaction is not adequate. At the same time, it is not at all clear how to deal with such nonlinearities or even to simulate them in a self-consistent way. Furthermore, very little effort has gone into this and related questions such as multibunch instabilities.

I will not go into the many attempts to compensate or cancel $\Delta\nu$ except to mention the charge-neutralization scheme of the Orsay Group[14] using 4 beams and double rings. It was hoped this approach would provide an improvement in $\mathcal{L}_{max}$ of two-orders of magnitude but so far has not been made to work. The Stanford single-pass collider (SLC) represents the opposite extreme where it seeks to maximize $\Delta\nu^*$ with high bunch current and low-emittance to enhance luminosity through a pinch effect. Another attitude we have taken is to avoid the beam-beam problem[3,4] through conversion of the charged particles into photons. The limits in this case are presumably the maximum, single bunch currents which a linac can provide and a storage ring can store with good stability and emittance. This can be limited by many external effects before internal space-charge becomes important but again there is very little systematic information available on this question. The "external" photon beam from this technique would also be a unique resource for fixed target experiments.

B. Internal Targets

The current limits discussed above apply here as well. In addition, there is the beam lifetime and emittance due to internal target density. The PEP handbook shows the expected lifetimes due to various sources of loss in PEP. While this implies the importance of three different processes over the range of energies of interest, the most important one for our purposes is atomic bremsstrahlung since we assume the Touschek effect

will only be important near the IR's and that the particle density can easily be varied by the required factor of two or so. This same factor of two might also be obtainable by manipulating $(\beta_{min}^*, \beta_{max}^*)$ in a mini-maxi beta scheme. This is clearly not a problem but bremsstrahlung from "residual-gas" is – because the differential probability for radiation loss is roughly constant up to the full electron energy for the electron energies of interest here.

Integrating Rossi's expression[15] for the differential radiation probability per unit radiation length gives:

$$\int\limits_{(\frac{l_t}{\gamma})_{RF}}^{1} \Psi_{rad}(x)dx = [\frac{4}{3}\ln(\frac{\gamma}{\delta\gamma})_{RF} - \frac{5}{6}]$$

where x is the fractional photon energy, ω/ϵ. The fractional particle loss is then

$$\frac{dN_b}{N_b} = -[\ ]\frac{\rho}{X_o}dx \longrightarrow \frac{1}{\tau} = [\ ]\frac{c\rho}{X_o}$$

assuming a simple target uniformly distributed around the ring like residual gas. Here $1/X_o \equiv N_A\sigma_{rad}/\mathcal{A}$ with σ_{rad} the total bremsstrahlung cross section per nucleus or atom and x is the lineal thickness. In terms of both ring and target components, the expression is

$$\frac{1}{\tau} = [\ ][\sum_i \frac{c\rho_i^{STP}}{X_{oi}}(\frac{P_i}{760}) + \sum_j \frac{c\rho_j^{STP}}{X_{oj}}(\frac{l_t}{l_R})(\frac{P_j}{760})(\frac{273}{T_j})]$$

where l_t/l_R is the ratio of target length to ring circumference. Including both the atomic bremsstrahlung cross section for electrons and nucleus so that $\sigma_{rad}^i = 4\alpha Z_i(Z_i+1)r_e^2[\ln 183/Z_i^{1/3} + \frac{1}{18}]$ but ignoring all but one target component (i.e. considering only the partial lifetime due to the target) in an otherwise perfect vacuum gives:

$$\frac{T_o}{\tau_t} \simeq [\ ]4\sigma_o Z(Z+1)\ln(183/Z^{1/3})[\frac{N_A}{\mathcal{A}}\rho^{STP}l_t(\frac{P}{760})(\frac{273}{T})].$$

The last factor in brackets is just the target thickness n_t (#/unit area), $\sigma_o \equiv \alpha r_e^2$ and T_o is the revolution time around the ring (see Table II). For hydrogen, $\rho_{H_2}^{STP} = 0.090\ kG/m^3$ so for $l_t = 10$ cm

$$n_t = \frac{2N_A}{\mathcal{A}_{H_2}}\rho_{H_2}^{STP}l_t(\frac{P_t}{760}) = 5.38 \times 10^{20}(\frac{P_t}{760})[atoms/cm^2].$$

For $n_t = 10^{14}/cm^2$, this implies $P_t = 1.4 \times 10^{-4}$ Torr or a required differential pumping rate of $\sim 10^{-5}$ Torr at room temperature which is reasonable. One wants this differential rate to roughly correspond to the l_t/l_R factor ($\simeq 4.5 \times 10^{-5}$ in PEP) since the two main, residual gas components observed with mass analyzers are hydrogen and carbon monoxide.

Because the RF capture bucket width can be $\delta\epsilon_e/\epsilon_e \gtrsim \pm 1\%$ in both SPEAR and PEP, the corresponding partial lifetime for a $10^{14}/cm^2$, hydrogen target is:

$$\frac{\tau_l^H}{T_\rho} \simeq (5.31 \times 4 \times 0.58mb \times 10.42 \times 10^{14})^{-1}$$

$$= 7.8 \times 10^{10} \begin{cases} 159 \text{ hrs} & \text{(PEP)} \\ 16.9 \text{ hrs} & \text{(SPEAR)} \end{cases}$$

This indicates these experiments can be done on both SPEAR and PEP without requiring dedicated operation with $\mathcal{L} \gtrsim 10^{33}$ $cm^{-2}s^{-1}$ using state-of-the-art polarized gas targets! This is independent of beam energy and valid for all energies of current interest ($\epsilon \gtrsim 1.5$ GeV) as well as elements with $\alpha Z \ll 1$. PEP, with its large radius and large energy range, would seem to be an ideal system for these experiments especially when multibunch operation with higher duty factor and current is developed. These operating conditions are ideally matched to simultaneous synchrotron radiation operation.

C. Accelerator Physics Studies

Systematic machine physics studies on PEP with a single beam that are relevant to these questions include bunch cross-section measurements versus all of the following: bunch current (N_b); bunch number (n_b) and distribution; both high and low $\beta_{x,y}^*$; ν_s, σ_z, σ_ϵ and V_{RF}; and $\nu_{x,y}$. These should be done at a couple of energies e.g. a low (5 GeV), intermediate (10 GeV) and high energy (15-17 GeV). Any instabilities observed should be characterized by their threshold behavior (N_{th}) versus these parameters including possible differences between electrons and positrons.

5. PEP Capabilities

Designing storage rings for a specific process in Fig. 3 might emphasize energy spread for Fig. 3(b) and electron polarization for Fig. 3(c) but the most important parameters characterizing both accelerators and storage rings are the energy range (C-M) and the beam current or luminosity available over this range. While the primary goal is to reach higher energies, it also seems important to improve the luminosity and range of capabilities of existing facilities. The PEP storage ring, with its large, single-beam energy range $(E_b \sim 2 - 17(25)$ GeV) in conjunction with the SLAC high energy, high current, low emittance linac beam provides some unique opportunities. Here we will discuss some of the factors each application wants and try to show how PEP can supply them.

A. Synchrotron Radiation

Figure 5 compares the synchrotron light spectra available from the cell bending magnets for a number of existing and proposed facilities. While most of these have wigglers which enhance such spectra, these comparisons appear to be easily biased and also change rapidly. Nonetheless, PEP has some unique possibilities here as well e.g. it has 5m symmetry straight sections midway between interaction regions which already have 2T wigglers as shown in Fig. 4. In addition, I have shown some bypass possibilities in Fig. 4 and from Table I and Figs. 4 and 6 one sees there are already several long, straight

insertions with lengths up to 120m which could be used for coherent undulators. Because there are also a number of new, low emittance configurations possible for PEP[16], some of which are shown in Table III, such options seem inevitable.
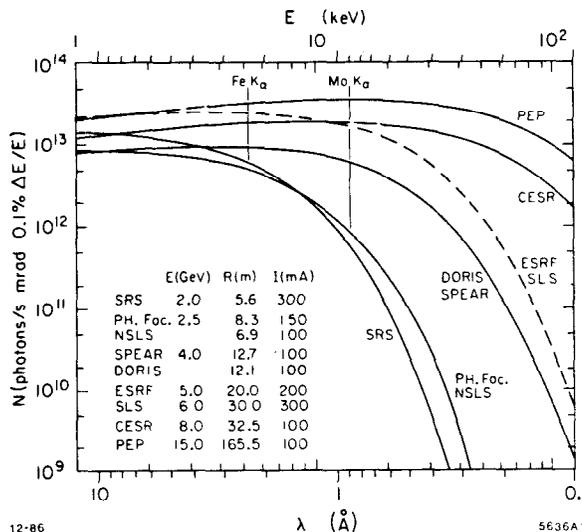
Fig. 5: Comparison of PEP's synchrotron radiation spectrum with a number of existing and proposed rings such as the European Synchrotron Radiation Facility and the Argonne Synchrotron Light Source.
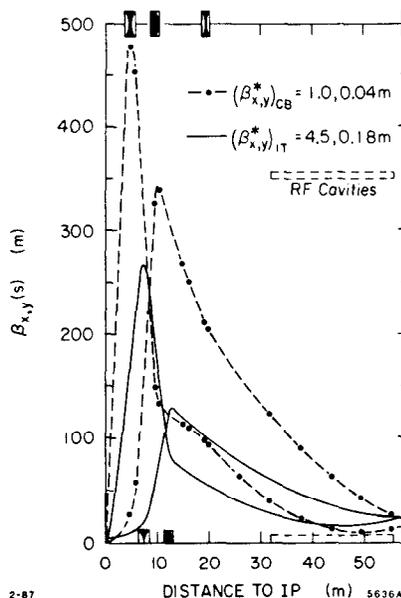
Fig. 6: Beta functions for the new colliding beam configuration of Table III around the Interaction Region(IR) and RF cavities.

For high brightness you need low emittance. Let's compare to SLS whose design emittance[17] at 6 GeV is $\epsilon = 65\text{Å}$ compared to PEP's 45Å. This can also be improved[18] by at least another factor of two by using Robinson wigglers to increase the horizontal damping partition, J_x. It seems almost too good to be true but higher brightness also requires high current capability at the lower energies which is discussed in the next section.

Table III: Some New Operating Configurations for use at PEP.

	Mini-Beta 1-Fold	Low Emittance 6-Fold	Low Emittance 1-Fold	
Hor. Tune, ν_x	21.28	29.28	29.28	
Vert. Tune, ν_y	18.22	13.20	13.20	
Mom. Comp., α	0.00255	0.000986	0.000973	
$\epsilon_x/E(GeV)^2$	5.49	1.30	1.27	Å·GeV^{-2}
$(\sigma_E/E)/E(GeV)$	0.00666	0.00666	0.00666	%·GeV^{-1}
β_x^* IR	1.00	67.9	54.0	m
β_y^*	0.04	100.0	356.6	m
η^*	-0.093	-2.0	0.0	cm
β_x Cell	22.6	20.8	20.2	m
β_y	36.8	43.0	44.0	m
η	1.23	0.55	0.51	m
β_x S.P.	32.3	26.0	26.4	m
β_y	5.5	5.7	5.3	m
η	1.49	0.62	0.53	m
β_x^* 5 IR's	4.50		79.3	m
β_y^*	0.18		96.6	m
η^*	0.004		0.0	cm

B. Internal Targets

PEP, with its large radius ($2\pi\bar{R} = 2.20$ km) and large energy range would also seem to be an ideal system for these experiments especially when multibunch operation with higher duty factor and current is developed. The beam lifetime was shown to be the product of three terms, relating to the RF capture bucket, the electron-nuclear bremsstrahlung cross-section and the target thickness. The log factors can each be approximated by 5, so one has:

$$\mathcal{L}_{IT} = \left(\frac{I_b}{100mA}\right)\left(\frac{2}{\tau(h)}\right)\left(\frac{T_o(\mu s)}{7.34}\right)\left(\frac{1}{Z(Z+1)}\right) \times 10^{34} \ cm^{-2}s^{-1}.$$

Such conditions are ideally matched to simultaneous synchrotron radiation operation so long as there is no significant increase in emittance. The lifetime due to single coulomb scattering goes as $E^2 A_s^2/Z^2 \beta_t \beta_s n_t$ and is orders of magnitude larger than for bremsstrahlung so that setting the aperture (or scrappers) at $\pm A_s$ allows an analytic approach to emittance growth and indicates no growth at PEP for bremsstrahlung limited target densities. This also allows experiments when an internal target with variable n_t is available. Lower emittance (higher tune) configurations than used in Table I for colliding beam operation are clearly possible at lower energies because the goals are reversed. At some point emittance growth could become a problem but only at the lowest energies where currents are also a problem. Similarly, the harmonic number of the ring is $h = 2592$ but only three bunches per beam have been seriously studied.

A major limitation on the total and single-bunch currents is the impedance of the ring which is dominated by limiting apertures such as the RF cavities shown in Figs. 4 and 6 and, of course, any gas cell – especially one that is poorly designed. A considerable amount of work has gone into the design of the PEP vacuum and RF system[19] and this has undergone several changes[20] based on optics changes and measurements of the limiting currents observed[21]. Figure 7 shows the latest calculations for PEP based on Table I and the new colliding beam configuration[22] in Table III. Figure 6 shows $\beta_{x,y}$ in the vicinity of the cavities. This distribution is clearly not optimal and never was which explains why the previous single-bunch, fast, head-tail threshold was roughly consistent[21] with the PEP transverse cavity impedance.
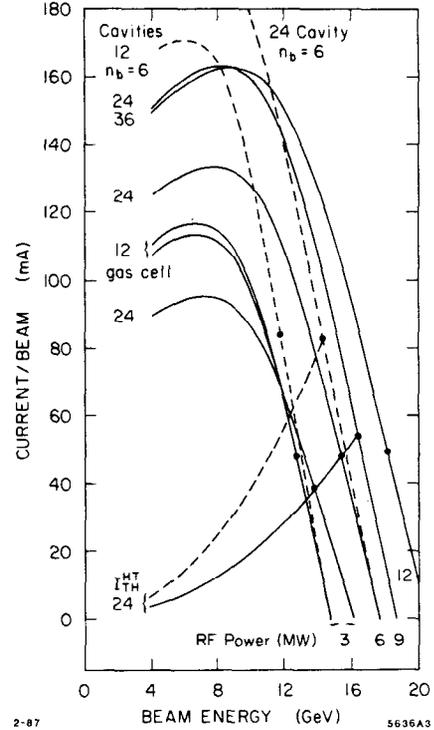
Fig. 7. Some representative RF limited current characteristics for PEP. Currently it runs with three bunches per beam with 24 cavities and 6 MW (Table I). Solid curves assume 3 bunches and dashed 6 bunches per beam. The intersection of these curves with the predicted current limits from the single-bunch, fast head-tail effect are shown as dots marking the dominance of these two regimes.

A number of different possibilities are considered in Fig. 7 such as adding and removing cavities, increasing the number of bunches and running with a single gas cell such as the one described in Ref. 23 with conditions where the effects should be most evident. A properly terminated cell of this type does not influence the beam significantly but the reverse may not be true. Although the beam will tend to drop some energy in it, this should be small in the practical domain of operation. The limit will be determined by multibunch instabilities and could cause depolarization. This is another area for study and testing.

One predicts from Fig. 7 that the current becomes RF limited below the dots on each curve i.e. at higher energies. The dots represent the threshold for dominance of the the transverse mode coupling instability or fast, head-tail effect[20,21]. To my knowledge there is no evidence for multi-bunch instabilities in PEP except for those associated with colliding beam operation. N-bunch, single beam operation can be thought of

as N coupled oscillators with N normal modes which require N-independent tuning knobs which are available from the RF cavities around the ring. The present distribution is not optimal for this but could certainly be improved. Several points can now be made. First, higher energies are best, both from the maximum single bunch limit and for multi-bunch operation i.e. we don't want to simply remove our sources of pickup and feedback and also that the bunch spacing and harmonic number are so large in PEP that it is certainly possible to use feedback to deal with such problems. Also, while one expects coupled bunch instabilities and other problems, a stable, single bunch current of $\approx$ 1 mA at 4.5 GeV has been verified so we have used very conservative numbers for the beam currents at the lower energies in the various Tables. Concerning higher energies, Fig. 8 shows a typical magnetization cycle that every cell dipole magnet was subjected to and measured along. While the current supplies will only go to about 17 GeV the magnets go much higher and the character of the curves imply reasonably simple operation from $2 < E(\text{GeV}) < 25$. Several systematic machine physics studies on PEP are clearly suggested by such questions.
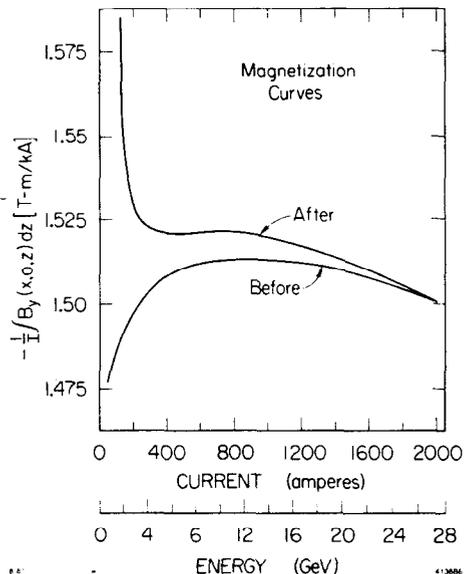
Fig. 8. Field integrals measured before and after subjecting a virgin PEP bending magnet to a magnetization cycle. Every PEP magnet was measured in this way with data taken from 1-27 GeV.

Other questions also include various polarization effects. The scattering of circularly polarized light by $e^{\pm}$ can be used to measure polarization of the $e^{\pm}$ and can also be used to induce it but with poor efficiencies at these energies. A low-energy, polarized electron beam can be used in a similar way to the photon beam to measure the polarization of a stored electron beam or to polarize photons via Compton scattering. Implementing longitudinal polarization with the new, efficient, tensor polarized gas targets could then provide an absolutely unique facility for nuclear QCD studies from 2-17(25) GeV that would allow high luminosity $\vec{e}+\vec{\gamma}$ and $\vec{e}+\vec{A}$ and $\vec{\gamma}+\vec{A}$ studies etc. A number of alternative insertions to provide longitudinal polarization in one or more interaction regions are possible in PEP but IR 6 appears best.

6. Compatibilities

Table IV is a "truth" table showing some possible operating modes and how they interrelate to one another. No doubt everyone would like an IR hall for detectors, spectrometers, bypasses or future possibilities. While SR is produced everywhere, the IR and symmetry straight sections are the most popular for them as well. Typically, the dispersion functions are minimal near the IR and maximal at the SP so the wigglers in SP 1, 5 and 9 improve luminosity below 15 GeV by increasing emittance while putting them near the IR would have the reverse effect. Their roles for luminosity would reverse above 15 GeV. The use of dispersion at the IT implies one is using dispersion matching to achieve higher energy resolution e.g. even though PEP has a very low energy spread compared to the linac, it can still be improved to do high resolution spectrometer studies at much higher energies than Bates or LAMPF. I won't discuss the various uses of wigglers implied in the Table but leave this as a topic for future discussion among interested parties.

Table IV: Operational compatibilities between Colliding Beam physics(CB), Internal Target physics(IT) and Synchrotron Radiation physics(SR). "D" stands for experiments requiring Dispersion, "SP" stands for Symmetry Point, "IR" for Interaction Region, "U" for Undulator, "W" for standard Wiggler and W_R is a Robinson wiggler located at high η e.g. at the SP.

E(GeV)	5	10	15	20
CB	W_{SP}	W_{SP}		W_{IR},W_R
IT	Any	Any	Any	Any
ITD	U	U	U	U
SRSP	U,W_R	U,W_R	U,W_R	U,W_R
SRIR	U,W	U,W	U,W	U,W

7. A Few Conclusions (and Possibilities)

There are a remarkable number of possibilities available that can be arranged into an interesting, long-range program with well defined stages. First on the list is the new mini-beta upgrade which allows a variable mini-maxi scheme as shown in Table III. This will be tested this fall. Variable density targets, in conjunction with wigglers could improve low-energy, colliding beam operation by providing independent control over longitudinal and transverse phase space. Implementing longitudinal polarization with the new, efficient, tensor polarized gas targets could then provide an absolutely unique facility for nuclear QCD studies from 2-17(25) GeV. Multi-bunch operation in a dedicated mode of operation or even CB mode could provide high duty factors whose magnitude needs to be studied. It seems clear that an energy closer to 15 than 5 is preferred on most grounds.

Implementing a high energy photon facility would augment the internal target program as well as the high energy physics studies since one wants to use such beams near their source even though good external photon beams will naturally arise. There are many interesting research and development projects here such as the study of high current, high density bunches;

development of highly segmented, fast, efficient photon detectors and the development of long, combined function undulators to name a few. An injection IR is clearly preferred for this work which would allow high luminosity $\vec{e} + \vec{\gamma}$ and $\vec{\gamma} + \vec{A}$ studies as well as $\vec{\gamma} + \vec{\gamma}$ over a large energy range.

There are many interesting accelerator physics studies e.g. we don't really understand the low energy limits of the ring such as the fundamental limits on single and multi-bunch beams as a function of energy or operating configuration. How should one use the various wigglers, bunch lengthening cavities, higher order multipoles, internal targets and various types of feedback to control or optimize current and aperture limitations? It is interesting that a long list of such projects for PEP compiled in 1982 has gone virtually untouched even though they might have justified PEP as a national test facility.

Some of the things discussed here could be started now and when PEP resumes operation and probably should because they impact longer range planning and funding. Samuel Butler viewed "progress" as a form of generic cancer when he said: *All progress is based on a universal innate desire on the part of every organism to live beyond its means.* A possible antidote to this is better long range planning for proposed uses and funding commitments. Past parochialism or specialization in both areas is neither efficient nor effective and this seems a good place to try something different.

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References

1. W.C. Barber, G.K. O'Neill, W.K.H. Panofsky and B. Richter, "Experimental Test of QED, Proposal to U.S.A.E.C.," May 1958.

2. V.F. Dmitriev, D.M. Nikolenko, S.G. Popov, I.A. Rachek, Yu.M. Shatunov, D.K. Toporkov, E.P. Tsentalovich, Yu.G. Ukraintsev, B.B. Voitsekhovskii and V.G. Zelevinsky, "First Measurement of Asymmetry in Electron Scattering by a Jet Target of Polarized Deuterium Atoms," Phys. Lett. 157B (1985) 143.

3. I assume a natural metric for four-vectors with $p \equiv (\epsilon, \vec{p})$ and $\hbar = c = 1$ so $s = (\omega_1 + \omega_2)^2 - (\vec{k}_1 + \vec{k}_2)^2 \equiv 4\omega_1\omega_2$ for collinear collisions between real photons. For a discussion of the various processes in Fig. 3, see J.E. Spencer and S.J. Brodsky, IEEE Trans. Nucl. Sci. NS-32 (1985) 3431 and Ref. 4 below.

4. J.E. Spencer, "Higher Luminosities via Alternative Incident Channels," SLAC-PUB-3645, April 1985.

5. J.E. Spencer, "Storage Rings, Internal Targets and Such," Argonne Workshop on High Resolution Spectrometers, PEP-PTM-366, Sept. 1981.

6. R.J. Holt, "Polarized Gas Targets in Electron Rings," CEBAF Workshop, June 1984.

7. J.M. Paterson, Proc. XI-th Int'l. Conf. on High Energy Accelerators, CERN, July 1980; J.R. Rees, IEEE Trans. Nucl. Sci. NS-28 (1981) 1989; R.H. Helm *et al.*, IEEE Trans. Nucl. Sci. NS-30 (1983) 2001.

8. E. Courant and H. Snyder, Ann. Phys. 3 (1958) 1.

9. M. Sands, "The Physics of Electron Storage Rings – An Introduction," SLAC-121, 1970.

10. C. Pellegrini, Lectures at Varenna Summer School, June 15-30, 1969.

11. R. Gram and P. Morton, "Advantages of Second Harmonic RF Cavities," SLAC-TN-30, Dec. 1967; A. Hofmann and S. Myers, "Beam Dynamics in a Double RF System," XI-th Int'l. Conf. on High Energy Accelerators, CERN, July 1980.

12. J.M. Paterson, J.R. Rees and H. Wiedemann, PEP-Note-125 (1975); W. Brunk, G. Fischer and J. Spencer, IEEE Nucl. Sci. 26 (1979) 3860.

13. See for example: H. Wiedemann, SLAC-PUB-2320, 1979.

14. J.E. Augustin *et al.*, VII-th Int'l. Conf. on High Energy Accelerators, Vol. 2 (1969) 113.

15. B. Rossi, "High Energy Particles," Prentice Hall, Inc. (1952).

16. M. Donald, L. Rivkin and A. Hofmann, "Low Emittance Configuration for PEP," PEP-PTM-257, Oct. 1985.

17. Y. Cho *et al.*, "Conceptual Design of the Argonne 6 GeV Synchrotron Light Source," IEEE Trans. Nucl. Sci. NS-32 (1985) 3383.

18. A. Hofmann, Private Communication.

19. P.B. Wilson, "Stored Current in PEP Using the Measured Ring Impedance," PEP-PTM-216, March 1980; K.L.F. Bane, "RIPPLES," PEP-PTM-125, Nov. 1975.

20. P.B. Wilson and L. Rivkin, "Threshold Current for the Transverse Single-Bunch Instability in PEP," PEP-NOTE-374, Aug. 1982; R.D. Ruth, "Single Bunch Instabilities in an SSC".

21. P.L. Morton and PEP Group, "Correlation Between Experimental and Theoretical Results for the Fast Head-Tail Instability in PEP," SLAC-PUB-3175, July 1983.

22. M. Donald and D. Helm, private communication.

23. R.G. Milner, R.D. McKeown and C.E. Woodward, "Study of Spin Relaxation by a Charged Particle Beam in a Polarized ^{3}He Gas Target," Nucl. Instrum. Methods, to be published.

24. J.E. Spencer, "Harmonic Strengths of the PEP Dipoles and Some Related Effects and Lessons," PEP-PTM-367, Sept. 1981.