Internal Targets in Storage Rings*

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Abstract

While fixed-target experiments in storage rings were suggested more than twenty-five years ago[1], little work has been done[2] and virtually none in this country although interest seems to be growing[3]. We survey the advantages, limitations and possibilities. Luminosities of $\mathcal{L} \approx 10^{33} cm^{-2}s^{-1}$ for electrons up to 15 GeV should be achievable now with the PEP storage ring at SLAC with good beam lifetime and emittance for target thicknesses $n_t \sim 10^{15}/cm^2$. This is thin but *ideal* for optically pumped, polarized gas targets. Providing longitudinally polarized beams at such targets would provide a unique facility for high luminosity $\vec{e}_{\pm}+\vec{\gamma}$, $\vec{e}_{\pm}+\vec{A}$ and $\vec{\gamma}+\vec{A}$ experiments. Other possibilities include the production of both external and internal beams for basic and applied science. Multiple bypass insertions are considered for thicker targets as well as production and storage of exotic, short-lived beams or for production of photon beams with undulators. The related question of multi-turn injection *and* extraction is also considered in such a context. Several systematic machine physics studies are suggested *e.g.* ion-induced, multi-bunch instabilities with $e_{\pm}$ beams. The SLAC storage ring PEP is used as an example because it is ideal for simultaneous production of internal target, external target and colliding beam luminosities. The differences between electrons and heavier particles such as protons, antiprotons or heavy ions are discussed where possible.

1. Introduction

The goal is to describe storage rings with internal targets using PEP as example since it is ideal for many fundamental and practical applications that can be carried on simultaneously. Figure 1 shows a schematic layout of the Positron-Electron Project, PEP, as used for colliding beam physics. The ring has sixfold symmetry and divides into 12 regions of alternating arcs and long straight insertions for experiments. A good description, including initial operating results and funding history, is available elsewhere[4]. The ASsymetric Photon search was a supersymmetry experiment looking for new particles like the photino. MAC was also used for such experiments which demonstrated the ability to measure cross sections on the order of tens of femtobarns(10^{-39}cm^2) with colliding beams. Table I gives some important characteristics and scaling relations for PEP.

2. 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. From the standpoint of accelerator physics one can define three categories: colliding beam physics, internal and external target physics. These have significant differences in center of mass energies, detectors and machine perturbations but can all be done simultaneously with little compromise. Such perspectives simplify long range planning and increase the usable lifetime and benefit/cost ratio. Colliding beam luminosity $\mathcal{L}_{CB}$ has been discussed elsewhere[5,6]. Ref. 6 studied additional ways of avoiding the beam-beam interaction while providing high energy photon beams.

A. External Target Luminosity

For resolutions of order 20-50 keV at energies typical of Bates or LAMPF one uses targets of thickness ≈10–50mg/cm^2. Currents that are consistent with these resolutions are typically I_b ≈50–100μA. Translating these numbers into an equivalent luminosity gives:

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

where N_A is Avogadro's number, $\mathcal{A}$ the gram molecular weight and A the atomic mass number in carbon units. This is a good benchmark for comparison to conventional facilities.

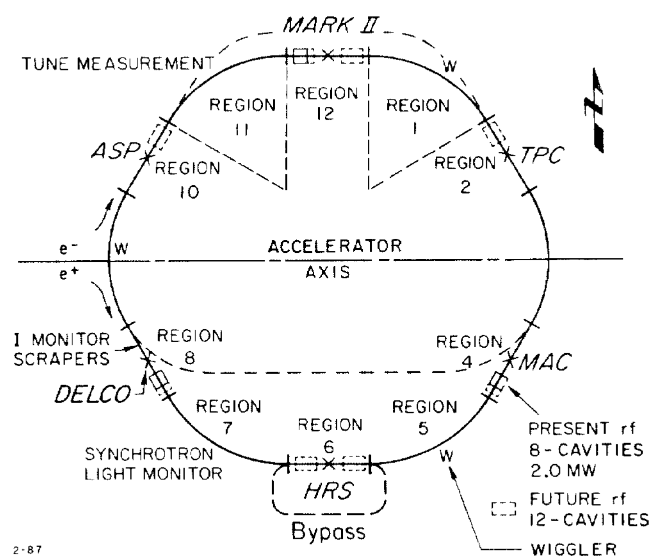

Fig. 1: Schematic layout of PEP showing some characteristics of interest such as wigglers (W) near the symmetry points, detectors around the interaction regions (X) and various bypass possibilities shown by the dashed lines.

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B. Internal Target Luminosity

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

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

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 the currents are greater than for $\mathcal{L}_{ET}$ because of the more than 10^5 traversals per second in the ring. Such thicknesses appear *ideal* for optically pumped, *polarized* targets because of depolarizing effects due to beam heating in solid targets. Furthermore, there appears[7] 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-section, one can operate in a mini-maxi β configuration with small angular spreads at the target *and* small $\mathcal{L}_{CB}$. Considerably thicker targets are also possible through the use of "target scrapers" and a better understanding of dynamic aperture.

3. Luminosity Limitations

A. Tune Perturbation and Stability

The leading-order, linear focusing force, expressed as a tune perturbation per crossing, is

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

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_x)[d]	$5.5E(\text{GeV})^2$ 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 τ_t = 2h, 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.

where σ is the rms bunch size, N_i the number of ions, q the particle beam charge $\pm$e and β^* the beta function at the target. For protons one would use the classical proton radius, r_p etc. The limiting magnitude for most electron rings is $\Delta\nu_{x,y} \lesssim 0.05$. With internal targets, this number can serve as a guide to compute the number of ions allowed before a clearing field is needed although target constraints on depolarization and replenishment rates or ion associated multi-bunch instabilities are probably more important. Such questions are interesting and should be studied. An appropriately designed target would also allow study of wake fields, plasma lenses and their control of β^* as well as various tune modulation and feedback effects just to mention a few possibilities.

B. Lifetime and Emittance

While several different processes have to be considered at PEP energies, the most important is atomic bremsstrahlung since Touschek will only be important near the IR's and the particle density can easily be varied by the amount required. This is not a problem except for high tune, low energy configurations. However, bremsstrahlung is a problem because the differential probability for radiation loss is roughly constant up to the full electron energy.

Integrating Rossi's expression[8] for the differential radiation probability per unit radiation length gives:

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

where x is the fractional photon energy, ω/ϵ. One then finds[3,6] the lifetime for targets in an otherwise perfect vacuum to be:

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

where l_t is the target length, $\sigma_o \equiv \alpha r_e^2$ and T_o is the revolution time. We see the beam lifetime is a product of three terms, relating to the RF capture bucket, electron-nuclear bremsstrahlung cross-section and target thickness. Feynman's rule for the log factors then gives the simple scaling relation:

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

The lifetime from single coulomb scattering is proportional to $E^2A_s^2/Z^2\beta_t\beta_s n_t$ and is orders of magnitude larger than for bremsstrahlung. Such expressions allow analytic and experimental study of emittance growth through use of the variable aperture A_s which implies no problems for our bremsstrahlung limited target densities. This is only a problem for low energies and emittances where beam currents are also a problem.

C. Current Limitations

A major limitation on total and single-bunch currents is the impedance of the ring which is dominated by limiting apertures such as RF cavities and gas cells. A lot of work has gone into the design of the PEP vacuum and RF system[9] and it has undergone several changes[10] based on observations of the limiting currents[11]. Figure 2 shows the latest calculations for PEP based on Table I and a new mini-beta configuration[12] to be tested this fall. A number of different possibilities are considered such as adding and removing cavities, increasing the number of bunches and running with a single gas cell, properly terminated, such as described in Ref. 13.

One predicts 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[10,11]. There is no evidence for multi-bunch instabilities in PEP except for those associated with colliding beam operation but only 3-bunches have been seriously studied. 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. Several points should 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. Also, the bunch spacing and harmonic number are so large in PEP that it is certainly possible to use feedback to deal with such problems.

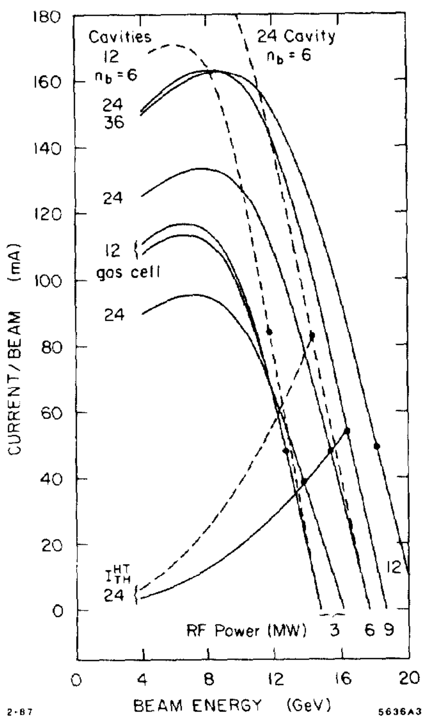

Fig. 2. Some representative RF limited current characteristics for PEP. Currently it runs with three bunches per beam with 24 cavities and 6MW(Table I). Solid curves assume 3 bunches and dashed 6 bunches per beam. The intersection of these curves with the predicted current limits from the single-bunch, fast head-tail effect are shown as dots marking the dominance of these two regimes.

4. Compatibilities

Table 2 is a "truth" table showing some possible operating modes and how they interrelate. While SR is produced everywhere, the IR and SP are the most popular sources. Typically, the dispersion functions are minimal near the IR and maximal at the SP so the wigglers in SP 1,5&9 in Fig. 1 improve luminosity below 15GeV by increasing emittance while putting them near the IR would have the reverse effect. Their roles for luminosity would reverse above 15GeV. The use of dispersion at the IT implies one is using dispersion matching to achieve better energy resolution. Although PEP has a very low energy spread, this allows high resolution spectrometer studies at much higher energies than Bates or LAMPF.

Table II: 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[14] 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

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