ZAP Study of Collective Effects in PEP: 9x9 Collider Optics*

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Abstract

In this note, single and multi-bunch collective instabilities are considered for PEP operating in a 9x9 bunch configuration. The lattice is based on a vertically separated beam 'pretzel' design which allows for collisions at the TPC (IR2) only. Threshold current levels and linear instability growth rates are calculated with the storage ring design code 'ZAP'. Single bunch instabilities should not be a problem for total circulating currents of 100nA (18 bunches, 5.6mA/bunch). Coupled-bunch growth rate calculations are based on a line broadening technique for the higher-order cavity modes. In the longitudinal case, feedback will be required. For the transverse coupled bunch instabilities, growth rates are about 5 times less.

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I. Introduction

To increase the luminosity in PEP, it is planned to operate the accelerator in a 9x9 bunch mode^[1] with the counter-propagating beams vertically separated everywhere but in the IR hall. Several important operational aspects have been considered, including RF drive^[2,3] and beam lifetime^[4]. Results from these studies show considerable promise for the 9x9 bunch scheme. The present PEP RF system should be adequate for beam currents up to 94mA^[2], and up to 190mA if RF isolators and beamloading compensation steps are taken^[3]. Unless otherwise specified, the beam current quoted in this report refers to the sum of the e⁻ and e⁺ current. Acceptable beam lifetimes (~4hrs at 100nA) should be possible following 150 to 200 hours of wall conditioning at full current^[4]. In this note, single bunch current limits and linear growth times of coupled bunch oscillations are considered for the 9x9 separated beam optics.

The recommended accelerating voltage for PEP is 30MV. This voltage provides an RF aperture of 0.68% (typical momentum spread 0.1%). At a peak voltage of 30MV, the bunch length is about 2cm, well below $\beta_g^* = 4cm$ at the IR. The longitudinal broadband impedance of PEP is typically quoted as $Z_{\parallel}/\omega = 3\Omega$, of which 2/3 or more is attributed to the RF cavities^[5].

The format of this paper will follow the basic logic required of the ZAP^[6] user: single bunch threshold calculations followed by estimates for coupled bunch mode growth. In the next section, PEP machine parameters relevant to the ZAP calculations are given, and the models used by ZAP are reviewed. Discussion of the results is found in section III. The first data concern an RF voltage scan around the nominal 30MV operating point. According to these calculations, filling 50mA into each 9 bunch beam results in single bunch currents well below the transverse instability threshold. In fact, the bunch lengthening threshold is not reached until about 60nA/beam (6.7mA/bunch) with this optics at 13.7GeV. Next, growth times for coupled bunch modes are computed. For 9x9 operation, the inter-bunch spacing is reduced by a factor of 3 relative to the 3x3 case. The ZAP runs quoted here indicate that the short bunch interval will require fast, high power feedback systems to operate near 100nA in the 9x9 bunch regime.

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II. 9x9 PEP Machine Parameters and ZAP Algorithms

The following machine parameters have been calculated with COMFORT for a 9x9 separated-bunch lattice. This lattice is expected to closely resemble the actual configuration to be used on PEP. Quantities of interest to the ZAP calculations are indicated with an asterisk:

PEP Machine Parameters: COMFORT (9x9 lattice)

$E = 13.7\text{GeV}^*$	$\delta P/P = 0.00091^*$	$U_0 = 18.78\text{MeV}^*$
$V_{RF} = 30\text{MV}^*$	$\nu_{RF} = 353.21\text{MHz}^*$	$(\delta P/P)_{RF} = 0.00675^*$
$\Phi_s = 141.23^\circ$	$\nu_s = 5.826\text{kHz}$	$\alpha = 0.0026^*$
$\nu_x = 20.70^*$	$\sigma_x^* = 0.32\text{mm}$ (at the IP)	$\tau_x = 10.7\text{mS}$
$\nu_y = 17.76^*$	$\sigma_y^* = 0.013\text{mm}$ (" ")	$\tau_y = 10.7\text{mS}$
$\nu_s = 0.0043$	$\sigma_s = 19.43\text{mm}^*$	$\tau_E = 5.35\text{mS}$

*Used as input to ZAP.

In addition, ZAP requires the following minimum information:

$L = 2200\text{m}$	(accelerator period)
$\langle\beta_x\rangle = 36\text{m}, \langle\beta_y\rangle = 36\text{m}$	(RF straights)
$r_{\text{beam pipe}} = 5\text{cm}$	(waveguide cut-off frequency)
$[Z_n]_{\text{BB Ring}} = 3\Omega$	(, $\perp$ instabilities)
Wall material, Al	(resistive impedance)
Higher Order Cavity Modes	(coupled bunch calculations)
Charge/bunch, #-bunches, σ_l, σ_p	(" " ")

Given the required accelerator constants, ZAP calculates the following quantities as a function of RF voltage:

$$\text{Synchronous Phase Angle } \phi_s = \pi \cdot \sin^{-1}\left(\frac{U_0}{V_{RF}}\right)$$

$$\text{Synchrotron Tune } \nu_s = \left[\frac{-V_{RF} h \eta \cos\phi_s}{2\pi(E/c)} \right]^{1/2}$$

$$\text{RF Acceptance } \frac{\Delta p_{RF}}{p} = \left[\frac{-V_{RF} \frac{2}{\pi} \cos\phi_s - (1 - \frac{2}{\pi} \phi_s) \sin\phi_s}{h\eta(E/c)} \right]^{1/2}$$

$$\text{Natural Bunch Length} \quad \sigma_1 = \eta R \frac{\sigma_D}{v_s}, \quad \eta = \frac{1}{\gamma^2 \eta_r} - \frac{1}{\gamma^2} - \alpha.$$

The calculation for single-bunch thresholds utilizes the following expressions for the average circulating current in a Gaussian bunch^[6]:

$$I_{\text{bunch}}(\mu\text{-wave})^{[7]} = \frac{2\pi\eta(E/c)(\sigma_1)^2}{|Z_0/n|^{BB}} \cdot \frac{\sigma_1}{\sqrt{2\pi} R}$$

$$I_{\text{bunch}}(\text{Fast-Blowup})^{[8,9]} = \frac{4(E/c)v_s}{|Z_1|^{BB} \langle \beta_{RF} \rangle R} \max(b, \frac{\sigma_1^2}{b})$$

$$I_{\text{bunch}}(\text{Mode-Coupling})^{[8]} = \frac{4(E/c)v_s}{\text{Im}(Z_1) \langle \beta_{RF} \rangle R} \cdot \frac{4\sqrt{\pi}}{3} \sigma_1$$

In each case, the current threshold is inversely proportional to the broadband ring impedance. Calculation of the impedance seen by the beam are described in the ZAP manual^[6] and the references contained therein. The longitudinal broad-band impedance of the ring is specified as 3Ω . ZAP constructs a $Q=1$ broadband resonator centered at the beam pipe cut-off frequency from this figure. Most of the impedance contribution comes from higher-order RF cavity modes^[5]. For consistency, the RF broadband impedance and voltage per cell were specified as zero to avoid double-counting of the cavity mode contribution in ZAP. SPEAR-scaling^[10] is applied to the case of short bunch lengths in PEP.

$$\left(\frac{Z_1}{n}\right)^{BB}_{\text{Ring}} = \left(\frac{Z_1}{n}\right)^{BB}_0 \times \left(\frac{\sigma_1}{b}\right)^{1.68} \quad \sigma_1 < b \text{ (optional)}$$

$$Z_1^{BB}_{\text{Ring}} = \frac{2R}{b^2} \left(\frac{Z_1}{n}\right)^{BB}_0 \quad \text{for all } \sigma_1.$$

For the transverse thresholds, the product $Z_1^{BB} \langle \beta_{RF} \rangle$ should actually be $\langle Z_1^{BB} \cdot \beta \rangle$ averaged around PEP. Instead, the impedance is assumed concentrated in the cavities, where the average betatron wavelength is $\sim 36\text{m}$.

Generally, the transverse single bunch current limit exceeds the bunch lengthening threshold, but the physical consequence is fatal. ZAP calculates both transverse instability thresholds (fast blow-up, mode coupling) and uses the lower current value as the current limit.

Results from bunch lengthening calculations as a function of current are fed back into ZAP to calculate the frequency shift of the coupled-bunch oscillation modes. The complex frequency shift is primarily due to wake fields associated with narrow-band high order cavity resonances. With k_b bunches in the ring there are k_b coupled-bunch normal modes. The phase shift between adjacent bunches is $\Delta\Phi = [(2\pi/k_b) \cdot s]$. The bunches couple on a harmonic of the synchrotron frequency, $a\nu_s$ where $a=1,2,3,\dots$. The unperturbed beam motion is therefore described by the pair of quantum numbers (s,a) with a characteristic frequency of oscillation $\omega_p = (pk_b + s + a\nu_s)\omega_0$.

The ZAP algorithm used here for the coherent complex frequency shift of each mode $\Delta\omega_{||s,a}$ is derived from the Sacherer-Zotter formalism^[6,11]

$$\Delta\omega_{||s,a} = i \left(\frac{a}{a+1} \right) \frac{I_b \omega_0^2 \eta}{3(\sigma_y/\sqrt{\pi}R)^3 2\pi (E/c) \omega_s} \cdot [Z_{||}]_{s,a}$$

$$\text{where } [Z_{||}]_{s,a} = \frac{\sum_{p=-\infty}^{\infty} \frac{Z_{||}(\omega_p)}{(\omega_p/\omega_0)} h_a(\omega_p)}{\sum_{p=-\infty}^{\infty} h_a(\omega_p)}$$

is the effective impedance seen by the bunches. The single bunch mode spectrum for Gaussian bunches in the a^{th} - longitudinal oscillation mode is given by

$$h_a(\omega) = \left(\frac{\omega\sigma_l}{c} \right)^{2a} \exp \left[- \left(\frac{\omega\sigma_l}{c} \right)^2 \right] .$$

Transverse coupled-bunch calculations are handled similar to the longitudinal case. The single bunch mode spectrum also includes the $a=0$ (rigid) transverse oscillation. The unperturbed normal mode frequencies exhibit transverse betatron motion, $\omega_p = \nu_{\perp}\omega_0$, so that $\omega_p = (pk_b + s + \nu_{\perp} + a\nu_s)\omega_0$. The approximate expression for the transverse coherent frequency shift is then^[6,11]

$$\Delta\omega_{\perp s,a} = -i \frac{1}{a+1} \cdot \frac{I_b c^2}{4\omega_p \sqrt{\pi}\sigma_l (E/c)} \cdot [Z_{\perp}]_{s,a}$$

$$\text{with } [Z_{\perp}]_{s,a} = \frac{\sum_{p=-\infty}^{\infty} Z_{\perp}(\omega_p) h_a(\omega_p - \omega_s)}{\sum_{p=-\infty}^{\infty} h_a(\omega_p - \omega_s)} .$$

The transverse mode spectrum of each bunch is frequency-shifted by the chromatic frequency $\omega_{\xi} = \frac{E}{\eta} \omega_0$, $\xi = \frac{\delta v_{\perp}}{\delta p/p}$. For zero chromaticity, $\omega_{\xi}=0$. To simplify the calculation,

Landau damping (incoherent tune spread) is neglected.

As pointed out by La Clare^[11], these equations provide only approximate formulae for the eigenvalues as derived from the full matrix solution. They are generally useful for low intensity bunched beam calculations.

The effective impedances, $[Z_{||}]_{s,n}$ and $[Z_{\perp}]_{s,n}$ are based on URMEL calculations for mode parameters (ω_j , R_{sj} , Q_j) for a single PEP cavity as published in the SSC-CDR^[12]. To simulate deviations in the center-line frequencies of the 120 PEP cavities, each mode line is artificially broadened with the area under the resonance curve R/Q held constant. The broadening is continued until the growth rate is equivalent to the radiation damping time in PEP. The underlying rationale for broadening of the higher order mode lines are:

(1) The quality factors are calculated for the unloaded cavity. For a loaded cavity,

$$Q_{\text{load}} = \frac{Q_{\text{unloaded}}}{\beta + 1} \text{ with } \beta=1.5 \text{ the coupling coefficient at the fundamental.}$$

(2) The PEP RF cavities are fed in blocks of five. Since the phase of the HOM oscillation of the entire block can vary from cell to cell, the shunt impedance can be reduced by a factor between 1 and 5. We take the factor to be $1 + \beta = 2.5$.

(3) Since the beta functions vary across the acceleration section, 8 families of cavities with different bore sizes were installed in PEP. This can introduce a spread in the center frequencies of the HOM resonances.

Effects (1) and (2) amount to a reduction of R & Q while leaving the ratio R/Q approximately constant. Effect (3) is simulated by further broadening of the resonance curve. A true statistical calculation simulating center-frequency drift is beyond the scope of ZAP.

To calculate coupled-bunch growth rates, σ_j and σ_p are taken from bunch lengthening calculations at the specified current and bunch pattern, e.g. 9×9 . 18 bunches are used in a single beam to model the 9×9 optics since in PEP the e^-/e^+ bunches arrive at the RF cavities interlaced in time.

In what is to follow, we will first look at single bunch current limits as a function of RF voltage, and then focus on the nominal 30MV case for increasing currents in PEP. Corrections due to potential well distortion are not included in these calculations. The results are fed back into ZAP to estimate linear coupled-bunch growth rates.

III. Results from ZAP Calculations

a. Single Bunch Thresholds

The first set of ZAP calculations consists of solving for the basic single bunch parameters including the current thresholds as a function of RF voltage. The threshold values scale with RF voltage via the natural bunch length and synchrotron tune, and for bunch lengthening, with the SPEAR-scaled longitudinal impedance. For the transverse case, an average betatron wavelength of 36m is used in the RF cavity sections.

The results are plotted in Fig. 1a-c and Fig. 2. Figure 1a shows the SPEAR-scaled longitudinal impedance Z/n (Ohm) and the transverse impedance $Z_1 = \frac{2R}{b^2} |Z_n|_0$ (Ohm/m) as a function of RF voltage. Since the number of cavities is fixed in PEP, the natural bunch length and hence the longitudinal impedance decrease with total RF voltage. The transverse impedance is constant ($Z_1 = 840\text{k}\Omega/\text{m}$), yielding a total impedance of $1900\text{M}\Omega$ when integrated around the ring.

Next, the synchronous RF phase and the synchrotron frequency normalized to the 136.36kHz revolution frequency are plotted (Fig. 1b). PEP is nominally run with a 30MV accelerating voltage, or a synchronous phase of 141° , and a synchrotron tune of 0.042 (5.7kHz). By raising the RF voltage, the synchronous phase advances to maintain a constant beam energy. The synchrotron frequency also increases since the longitudinal restoring force is larger, and the RF momentum acceptance is larger. The nominal RF acceptance of 0.68% yields a beam lifetime of $4\text{-}5\text{hrs}$ due to Bremsstrahlung scattering. Because of the logarithmic dependence on $\delta p/P_{RF}$, the beam lifetime has only a weak dependence on the total RF gap voltage.

In addition, as more RF voltage is applied the natural bunch length decreases because σ_p is constant below the bunch lengthening threshold. See figure 1c. The natural bunch length at 30MV is $\sigma_1 \sim 2\text{cm}$ and can be decreased to almost 1cm at 39MV in this lattice configuration.

Similar comments apply when the RF voltage is decreased below the 30MV level. In this case, however, the effects are more pronounced due to the sinusoidal nature of the RF waveform, and the decrease in gap voltage leads to poor performance of the accelerator. In particular, the bunch length rapidly approaches $\beta^* = 4\text{cm}$, the longitudinal broadband impedance seen by the bunch increases, and transverse instability thresholds decrease due to the full-off in v_g .

Referring now to Fig. 2, the threshold current levels for the onset of longitudinal and transverse single-bunch instabilities are plotted as a function of RF voltage. Both threshold values increase with applied voltage. In the longitudinal case, bunch compression at high RF voltages is offset by the (SPEAR-scaled) impedance reduction. Bunch lengthening clamps the peak current at the threshold value as more charge is added while σ_L and σ_p broaden beyond their 'natural' values. In the transverse plane, the current threshold increases because the synchrotron frequency goes up with voltage and the head-tail mixing time is reduced.

Note that at the nominal 30MV operating point, ZAP predicts that the transverse threshold is about 1.5-2 times larger than the turbulent bunch lengthening limit. The threshold value $I_1=10.9\text{mA}$ at 30MV should be considered as only a coincidental agreement with PEP measurements of $I_1 \sim 9-10\text{mA}$. The expression for I_1 is the result of several analytical approximations, and the 36m betatron wavelength used to emphasize the broadband impedance in the RF cavities is only an average quantity. Nevertheless, the scaling trend with RF voltage is apparent, and the single bunch current is well above the maximum 5.2mA/bunch requirement for the first phase of 9x9 colliding beam experiments with $\sim 100\text{mA}$ in PEP.

With RF isolators, it is estimated that 190mA currents are possible with improved matching power matching circuits^[3]. In this case, the transverse single bunch current limit becomes a problem for 9x9 bunch operation.

Figures 3a,b show the total number of electrons per bunch and the bunch length due to turbulent bunch-lengthening above the threshold current for the case of 6, 12 and 18 bunches. For the standard 3x3 configuration, bunch lengthening should occur above about 40mA

total current. In the 9x9 bunch configuration, the total current at threshold is ~120mA, and less than 50% bunch lengthening is expected for currents up to 200mA. In the next section, these values for the total charge/bunch, bunch length, and the energy spread will be used to estimate coupled-bunch instability growth rates.

b. Coupled-Bunch Instabilities

We turn now to the question of multi-bunch instabilities, and the problem becomes much more complicated. First, the time interval between bunch passings is decreased from 2.4 μ s in a 3 bunch PEP beam to only 800ns in the 9 bunch beam. At the position of the PEP RF cavities, the e^+/e^- bunch crossings occur at approximately twice this frequency, or 400ns. By comparison, the e-folding time for a typical $Q=5 \times 10^4$, $\omega=5 \times 10^9$ parasitic cavity mode is about 20 μ s. The savings with the 9x9 bunch scheme, however, is that less charge per bunch is required, and the induced cavity voltage is proportional to the total charge/bunch.

To estimate the growth rates, the HOM line broadening technique is used. For both the longitudinal and transverse motions, the HOM resonance curves are uniformly broadened until the fastest growing mode just exceeds the respective radiation damping time for a 6 bunch beam (3x3) carrying 40mA. The 3x3, 40mA configuration is found to be stable in PEP at 13.7GeV. These values for the line broadening are then used to extrapolate to the 9x9 configuration over a range of currents.

The fastest growing longitudinal and transverse coupled-bunch modes are plotted as a function of the line broadening factor Figs. 4a,b. Both the radiation damping time and the anticipated feedback response time are indicated on these plots. The broadening factors are estimated to be 70 and 40 for the longitudinal and transverse motions, respectively. The corresponding decay times for the HOM cavity resonances are decreased to about 300-400ns.

It should be stressed that line broadening is only an approximate technique designed to make a frequency-domain analysis of the coupled-bunch problem conform to experimental data. The analysis is by no means exact. In practice, both the HOM and bunch spectra in PEP will be time dependent (cavity temperature, RF phase jitter), and the e^-/e^+ arrival times at the RF cavities are not exactly symmetric. The results should be interpreted as "order of magnitude".

Using the estimates for the line broadening factors, we plot the fastest growth rates for the coupled bunch modes $s=1$ (longitudinal) and $s=0$ (transverse) in Figs. 5a,b. For longitudinal motion, the growth time is found to initially decrease very rapidly with current

with a 6 bunch beam in PEP. Operating with 18 bunches, the initial growth rate is $\sim 1\text{ms}$ (at 40mA) but the decrease is much less as a function of beam current. A fast, powerful cavity feedback system will be required to achieve the $\sim 100\text{mA}$ circulating currents of interest.

The new SSRL longitudinal feedback system^[13] is designed to cover all longitudinal mode numbers 's' for up to 18 bunches in PEP, and damp instability growth on the 1ms timescale. This system should allow initial 9x9 collider optics studies with beam currents on the order of 50mA depending on the actual growth rates encountered in practice.

In the case of transverse coupled-bunch instabilities, the growth times are about a factor of 5 less for the 18 bunch beam at all currents. The present PEP transverse feedback can damp growth rates down to 2.5ms for a 3x3 configuration.

A new transverse feedback system scheduled for installation in PEP^[14] has been designed with sufficient bandwidth and bunch deflection power to suppress 18 bunch mode growth on a 1ms time scale. Pending the success of this new system, transverse coupled-bunch instabilities will be controllable for circulating currents in excess of 100mA. The unique feature of the 9x9 collider optics which may complicate instability suppression is that the beams are vertically separated and pass through the RF cavities off-axis. Coupling to parasitic cavity resonances may be enhanced.

IV. Conclusions

One of the near term accelerator physics plans for PEP is to operate with a colliding 9x9 bunch configuration. The plan is to improve the luminosity by increasing the collision frequency and the total circulating current. To investigate some of the beam dynamics issues in this new configuration, the lattice design code 'ZAP' was used, and estimates for single and multi-bunch instabilities were obtained.

Operating PEP at the nominal 30MV peak accelerating voltage, we find that the turbulent bunch lengthening threshold is about 6.7mA/bunch, or a total current of 120mA carried in 18 bunches. At the highest anticipated currents of 200mA, the 2cm natural bunch length increases to only $\sigma_p=3\text{cm}$. Bunch lengthening is not foreseen as a problem.

Estimates for the transverse instability threshold were obtained by using an average value of $\beta_{\perp}=36\text{m}$ in the RF cavities where most of the impedance is localized. At 30MV, the transverse single bunch limit was found to be on the order of 11mA. This estimate should only be considered approximate since the expression for the threshold current is only accurate within about a factor of two. Typical single bunch current limits measured in

PEP are on the order of 9-10mA. Both the longitudinal and transverse limits can be raised by increasing the RF voltage with a fixed number of cavities.

Coupled-bunch growth rate calculations were obtained by uniformly broadening the HOM cavity resonances until the growth rates were on the order of the damping times for a 3x3 40mA beam. The broadening factors were found to be 70 and 40 for the longitudinal and transverse modes, respectively. These values were then used to estimate the growth rates for the 9x9 bunch configuration modeled as a single 18 bunch beam. For the longitudinal case, the fastest growth times were on the order of 1ms for 40mA in this beam, decreasing to about 500 μ s at beam currents approaching 100mA. The new longitudinal feedback system being installed in PEP will have to operate at maximum power to suppress mode growth at these currents.

Estimates for the transverse coupled bunch motion show that the growth times are about 5 times longer. The 18-bunch transverse feedback system planned for PEP will also be required to damp the transverse coupled-bunch instabilities.

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Longitudinal-Z/n (Ohm)

Synchronous Phase (degrees)

Bunch Length (mm)

Figure 2

Figures 3a,b

Figure 4a

Figure 4b

Figure 5a

Figure 5b