PEP-X IMPEDANCE AND INSTABILITY CALCULATIONS [*]

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INTRODUCTION

PEP-X, a next generation, ring-based light source is designed to run with beams of high current and low emittance. Important parameters are: energy 4.5 GeV, circumference 2.2 km, beam current 1.5 A, and horizontal and vertical emittances, 185 pm by 8 pm. In such a machine it is important that impedance driven instabilities not degrade the beam quality.

In this report we study the strength of the impedance and its effects in PEP-X. For the present, lacking a detailed knowledge of the vacuum chamber shape, we create a straw man design comprising important vacuum chamber objects to be found in the ring, for which we then compute the wake functions. From the wake functions we generate an impedance budget and a pseudo-Green function wake representing the entire ring, which we, in turn, use for performing microwave instability calculations. In this report we, in addition, consider in PEP-X the transverse mode-coupling, multi-bunch transverse, and beam-ion instabilities. More details of this work can be found in Ref. [1].

Table 1: Selected PEP-X parameters.

Parameters	Value	Units
Circumference, C	2199.32	m
Energy, E	4.5	GeV
Average current, I	1.5	A
Bunch population, N_b	2.2	10^{10}
Number of bunches, n_b	3154	
Bunch length, σ_z	3	mm
Energy spread, σ_p	1.14	10^{-3}
Synchrotron tune, ν_s	0.0077	
Momentum compaction, α	5.81	10^{-5}
Tunes, ν_x, ν_y	87.23, 36.14	
Average β function, β_y	9.7	m
Longitudinal damping time, τ_s	10.8	ms

IMPEDANCE BUDGET

For broad-band, longitudinal impedance calculations for PEP-X we consider the objects: RF cavities, BPM's, undulator tapers, wiggler tapers, bellows slots and masks, and the resistive wall (RW) of the beam pipe (see Fig. 1). For these objects (except for the RW wake, which is done analytically) we numerically obtain the longitudinal wakefield of a Gaussian bunch of length $\sigma_z = 0.5$ mm—significantly shorter than the nominal $\sigma_z = 3$ mm—to a distance of 60 mm behind the driving bunch. The calculations are performed using the time-domain, finite-element Maxwell equation solver, T3P [2]. The contributions from all the impedance objects in the ring are finally summed up, to yield a wake that can be used as a pseudo-Green function in instability calculations. A second goal of this work is to obtain an impedance budget, a table that can give us an idea of the relative importance of the impedance sources at nominal bunch length, $\sigma_z = 3$ mm.

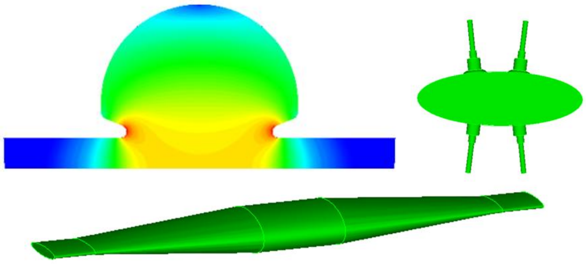

Figure 1: The RF cavity (with fundamental electric field pattern; (top, left), the BPM assembly (top, right), and a pair of undulator transitions (bottom)—on different scales.

PEP-X has four kinds of beam pipes: the arcs pipes are elliptical (and Al), in the straights they are round (Al), in the undulators elliptical (Cu), and in the wigglers rectangular (Al). The RW wake for a Gaussian bunch in a beam pipe is analytical and well known; to obtain this component of the PEP-X ring wake we properly weight by the different chamber geometries. The RF cavities are 16 PEP-II–type cavities, which are cylindrically symmetric and easy to calculate. The 839 BPMs are of button type with 7 mm diameter, and require 3D calculation.

Among the more challenging objects for finding the short bunch wake are the wiggler and collimator tapers. These transitions are long and gentle to reduce their wake effect, and they are 3D. In the wiggler case they connect the rectangular wiggler chambers (vertical half-height $b_y = 7.5$ mm) to the round straights (radius $b = 24$ mm), at an angle in y of 6°, and in the real machine the transitions will be meters apart. Details of how we approximate the wake for this, as well as other contributors to the PEP-X impedance can be found in Ref. [1].

We have also calculated the contribution of coherent synchrotron radiation (CSR) in the bending magnets of the ring. In the DBA bends, the bending radius 40 m and total length 83 m; in the TME they numbers are 111 m, 466 m. The cross-section of the bend chambers is basically elliptical, with half-width 37.5 mm, half-height 12.5 mm. We used a recently developed theory [3] of the CSR impedance for a vacuum chamber of rectangular cross section and also the parallel plate model [4], and applied them to the bends of PEP-X; we found that the two calculations agree very well (on the $\sim 10\%$ level). Comparing the CSR wake to

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[*] Work supported by the U.S. Department of Energy under contract DE-AC02-76SF00515.

the sum of the other wakes, we find it is relatively small (peak-to-peak variation ~ 150 V/pC when $\sigma_z = 0.5$ mm), and we do not include it in our pseudo-Green function.

In Fig. 2 we present the total wake contributions (at $\sigma_z = 0.5$ mm) of the different types of impedance objects in the PEP-X ring. The convention here is that the front of the bunch is to the left, and energy loss is positive. We see that the dominant contributors at this bunch length are the resistive wall wake and the undulator and wiggler transitions. These wakes when summed give the pseudo-Green function wake that we use in the simulations (see Fig. 3).

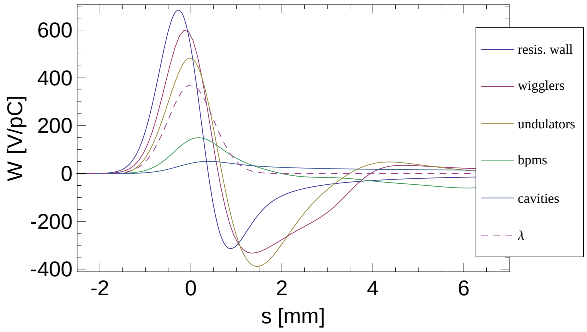

Figure 2: Main contributors to the pseudo-Green function.

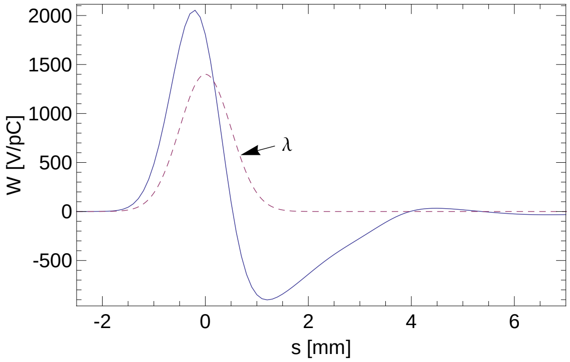

Figure 3: The pseudo-Green function wake that represents the PEP-X ring. Also shown is the $\sigma_z = 0.5$ mm Gaussian driving bunch shape λ, with the head to the left.

For the impedance budget we want a measure, at nominal bunch length ($\sigma_z = 3$ mm), for all the object types in the ring, for the real and imaginary parts of the impedance. For the real part we have the loss factor k_l; for the imaginary part we fit the bunch wake to

$$W(s) = -Rc\lambda(s) - Lc^2\lambda'(s) \ , \tag{1}$$

with fit parameters R and L, and take the L—the "effective inductance"—as that measure.

In Table 2 we give the impedance budget at nominal bunch length, showing the total number N_{obj}, loss factor k_l, and inductance L for all the object types considered. We see that the loss is dominated by the RW, RF cavities, and the BPMs, and the main inductive objects are the wiggler tapers, the RW, and the undulator tapers.

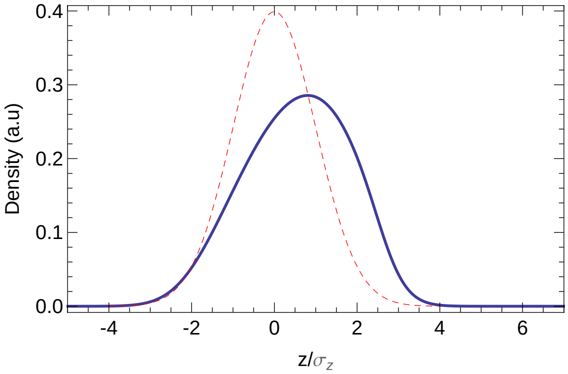

Figure 4: Bunch shape in PEP-X at $I = 1.5$ A, and at zero current (dashes). The head is to the right.

Table 2: Impedance budget for PEP-X giving, by object type, the total number, loss factor, and inductance.

Object	N_{obj}	k_l [V/pC]	L [nH]
RF cavity	16	14.7	–
Undulator taper (pair)	30	1.8	8.8
Wiggler taper (pair)	16	4.2	11.9
BPMs	839	11.8	3.2
Bellows slots	720	.0	.3
Bellows masks	720	3.7	2.7
Resistive wall wake		21.3	11.3
Total		57.5	38.2

COLLECTIVE EFFECTS

Microwave Instability

As a first step in stability analysis, using the pseudo-Green function we solve the Haïssinski equation to find the equilibrium bunch distribution. An example at the nominal total beam current is shown in Fig. 4. One can see an increase in rms length of 25%. Note that a positive effect of this is that the Touschek lifetime, which is quite short ($\sim$ 30 min) and is an issue for PEP-X, will thus be increased by 25%.

Two different simulation techniques were employed to study the microwave instability (see Ref. [5]): one using a linearized Vlasov (LV) approach, which computes the growth rate of the instability for a given wake, and a second one using a Vlasov-Fokker-Planck (VFP) solver to simulate longitudinal beam dynamics. According to the LV approach the threshold, the point where the growth rate equals

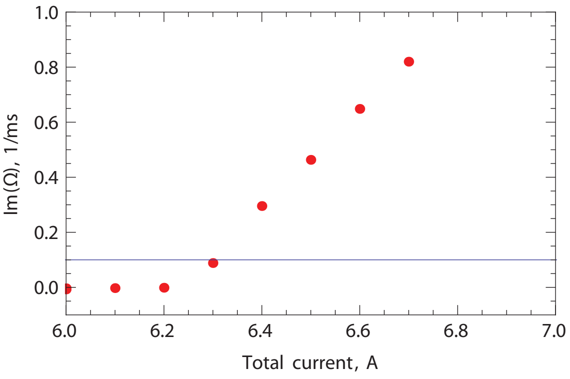

Figure 5: The growth rate of the microwave instability as a function of current.

the synchrotron radiation damping rate $1/\tau_s$, is $I \approx 6.3$ A (see Fig. 5). The VFP solver yields stability at 6 A and mild instability at 7 A, corroborating this result. For the current pseudo-Green function for PEP-X, the microwave threshold considerably exceeds the nominal beam current.

Transverse Mode Coupling Instability (TMCI)

Normally in light sources with small aperture insertions, the RW impedance is the dominant driver to the transverse mode coupling instability (TMCI). In PEP-X it is the 105 meters of wiggler insertions that dominate. We use the standard eigenvalue formalism [6],[7], where the threshold to TMCI is found when head-tail modes with different synchrotron sidebands merge (see Fig. 6); our calculations yield a single bunch threshold $I_b^{th} \cong 0.72$ mA, which is above the nominal single-bunch current $I_b \cong 0.48$ mA.

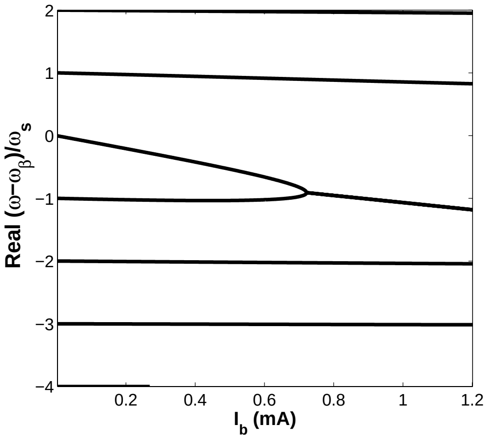

Figure 6: TMCI in PEP-X due to RW impedance.

Transverse Multibunch Instability

The RW impedance is often the dominant contributor to the transverse coupled bunch instability in storage rings. Assuming only this source of impedance, the growth rate can be estimated as [8]

$$\Gamma = \frac{c(I/I_A)}{4\gamma\sqrt{C(1-[\nu_y])}}\langle\beta_y A_y\rangle\ , \tag{2}$$

$$\langle\beta_y A_y\rangle = \frac{c}{\pi}\sqrt{\frac{Z_0}{\pi}}\sum_i \frac{\ell_i\beta_{yi}}{b_i^3\sqrt{\sigma_{ci}}}\ , \tag{3}$$

with $I_A = 17$ kA, $[\nu_y]$ the fractional part of ν_y, $Z_0 = 377\ \Omega$; for region i of the ring, ℓ_i is length, b_i is vertical half-height, and σ_{ci} is conductivity (other parameters are defined in Table 1). For PEP-X we find that $\langle\beta A\rangle = 4.2\times10^5/\sqrt{\mathrm{m}}$, and $1/\Gamma = 0.14$ ms (corresponding to approximately 19 revolutions), very challenging to control.

Fast Ion Instability (FII)

Ions generated by beam-gas ionization can be trapped by the electron bunches. The ion-cloud can cause beam instability, emittance blow-up, and tune shift. Extensive multiparticle tracking of this effect was performed for PEP-X. For example, assuming a pressure of 1 nTorr, 5% coupling, and a beam fill pattern consisting of 19 bunch trains, each with 166 bunches, the vertical growth time is 34 μs.

The feedback response time of the present PEP-II feedback system is $\sim$ 500 μs, but our calculated FII growth time is ten times faster. The instability growth rate can be reduced by having a better vacuum ($P \leq 0.1$ nTorr), a larger number of bunch trains, and/or a reduced number of bunches with a larger ion clearing gap. Faster feedback may also be possible. In summary, the FII may be a critical issue for PEP-X, mainly due to the ultra small emittances.

CONCLUSIONS

In this report we have summarized recent PEP-X impedance and instabilities calculations. For the longitudinal plane, we generated an impedance budget and a pseudo-Green function, which was then used to find the threshold to the microwave instability. The threshold appears to be above the nominal current.

Also investigated were the TMCI and Transverse multibunch instabilities due to the resistive wall, and the fast ion instability. At the moment it appears that the latter two effects are quite challenging, and they require more study.

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