CIRCULATING NON-EQUILIBRIUM LOW EMITTANCE BEAMS IN CESR

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1. Introduction

The photoinjector creates a train with length the circumference of the storage ring. The ultra-low emittance bunches fill every 1.3 GHz bucket. At 70 pc/bunch, the average current for the duration of the train is 100 mA. The train is accelerated to 90M through the 10m ERL cryomodule. The beam is transferred to the synchrotron, and accelerated to 3GeV. The beam is extracted from the synchrotron and injected on axis into the storage ring with the help of a full turn kicker-inflector. Bunch by bunch feedback eliminates coherent betatron motion within 20 turns. The synchrotron accelerates and transfers a fresh train of bunches at 60Hz. The spent beam is extracted with the same kicker-inflector pulse, decelerated in the synchrotron and dumped at 100MeV.

The equilibrium horizontal emittance in CESR at 3GeV (assuming reconfigured hard bends) is 7.2nm-rad. The radiation damping time is 155 msec. The beam circulates in the storage ring for 16msec, about 1/10 of a damping time. The emittance of the beam at the time it is injected into CESR is assumed to be much less than the equilibrium in CESR. The emittance of the circulating beam approaches that equilibrium exponentially, so that at extraction time

$$(\epsilon_x - \epsilon_i)(1 - e^{-t/\tau}) + \epsilon_i = 0.92 \text{nm} - \text{rad}$$

where ϵ_x is the equilibrium emittance and ϵ_i is the emittance of the injected beam.

A 100mA, 3 GeV beam, with $\epsilon_x < 0.92$nm-rad circulates in CESR. The fresh beam is injected on the same turn that the spent beam is extracted. The only interuption to the xray user is the 20 turns during which the residual oscillations of the injected bunches are damped with feedback.

We choose to operate at 3GeV rather than higher energy because of the strong energy dependence of the damping time. At 5GeV, damping time is nearly an order of magnitude less than at 3GeV, leaving little time before the beam damps to its equilibrium emittance.

2. Linac

2.1. Injector.

2.2. Acceleration.

3. Synchrotron

3.1. **Impedance.** In order to minimize dilution of the emittance of the accelerated beam, both transverse and longitudinal, it will be necessary to significantly reduce the impedance of the synchtrotron. As the magnets are inside the vacuum chamber, the beam sees magnet laminations and then a gross discontinuity at the transition to the adjacent bend. We proposed to insert a thin conductive sleeve, perhaps metalized ceramic or glass, or thin aluminum or copper. The conductivity of the sleeve is limited by the requirement that the 60Hz time varying field easily penetrate. We choose a material with skin depth $\delta >> d$ at 60Hz with d the thickness, and $\delta << d$ at $f > 1.3$GHz. We see in Figure 1 that 0.5mm copper or aluminum is suitable. The skin depth of both metals is much greater than 0.5mm at 60Hz and much less than 0.5mm at frequencies greater than 1GHz. There would need to be holes in the tube for pumping, and perhaps contact with circulating water for cooling ? We also need to consider the heating due to wakes and the oscillating magnetic field. Insertion of the tubing would provide an opportunity to remedy the discontinuity between bends and to install modern beam position monitors which will be essential to maintain beam quality.
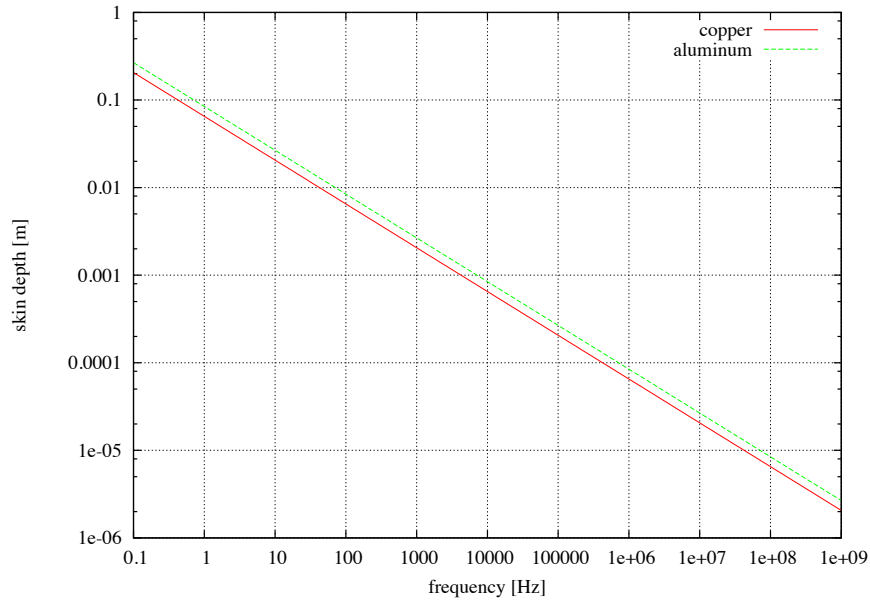

FIGURE 1. Skin depth versus frequency for copper and aluminum

3.2. Radiation damping. The combination of gradient and bend in the synchrotron magnets results in anti-damping of the horizontal motion. In order to minimize emittance growth we install quadrupole wigglers in the L3 straight. We propose to install a pair of wigglers, each with 50 0.1m poles with alternating $k = \pm 0.1$ (2.5 times the gradient in the normal synchrotron bends and magnetic field $B = \pm 3B_0$ where B_0 is the field in the bends). Then we recover damping in all three dimensions. At 3GeV horizontal damping time is $\tau_x = 296$msec and $\tau_z = 74$msec. Equilibrium horizontal emittance at 3GeV is 53 nm-rad. Parameters of the synchrotron lattice at 3GeV with quadrupole wigglers and 6MV(714MHz equivalent) RF are shown in the table

TABLE 1. Synchrotron parameters at 3GeV

Parameter	Value
Energy[GeV]	3.0
ϵ_x[nm-rad]	53
τ_x[msec]	296
τ_z[msec]	74
σ_l[mm]	6.1
α_p	9.9×10^{-2}
RF(714 MHz) [MV]	6
Energy loss/turn[keV]	86

The emittance at a particular energy asymptotically approaches the equilibrium value.

$$\epsilon(t) \;=\; (\epsilon_0 - \epsilon_i)(1 - e^{-t/\tau}) + \epsilon_i$$

where ϵ_0 is the equilibrium and ϵ_i the emittance at $t = 0$. τ is the damping time. Then for a time $\Delta t << \tau$

$$(1) \qquad\qquad \to d\epsilon = (\epsilon_0 - \epsilon_i)\frac{\Delta t}{\tau}$$

The damping time τ and the equilibrium emittance ϵ_0 both depend on the energy. And if we suppose that the energy changes linearly with time we can write

$$\epsilon_0(t) = \left(\frac{E't}{E_f}\right)^2 \epsilon_f$$

and

$$\tau(t) = \left(\frac{E_f}{E't}\right)^3 \tau_f$$

where E_f is the final energy and E' is the change of energy with time. If we suppose that the euilibrium emittance is always much greater than the actual emittance (ϵ_i) then Equation 1 becomes

$$d\epsilon = \epsilon_0(t)\frac{\Delta t}{\tau(t)}$$

Substitute the above time dependencies and integrate and we have

$$
\begin{aligned}
\int_0^{t_f} d\epsilon &= \frac{\epsilon_f}{\tau_f} \int_0^{t_f} \left(\frac{E't}{E_f}\right)^2 \left(\frac{E't}{E_f}\right)^3 dt \\
&= \frac{\epsilon_f}{6\tau_f} \left(\frac{E'}{E_f}\right)^5 t^6 |_0^{t_f} \\
&= \frac{\epsilon_f}{6} \frac{t_f}{\tau_f}
\end{aligned}
$$

The beam is accelerated to 3GeV in about 8 msec. The damping time and equilibrium emittances at 3GeV are 296 msec and 53nm-rad respectively. Then on extraction into CESR

$$\epsilon = 239 \text{ pm} - \text{rad}$$

For a fixed ratio of accelerating voltage to beam energy, the bunch length scales linearly with energy. The

$$
\begin{aligned}
d\sigma &= \sigma_0(t) \frac{\Delta t}{\tau(t)} \\
&= \frac{\sigma_f}{\tau_f} \int_0^{\tau_f} \left(\frac{E't}{E_f}\right) \left(\frac{E't}{E_f}\right)^3 dt \\
&= \frac{\sigma_f t_f}{5\tau_f}
\end{aligned}
$$

Using the parameters in the table above we find that the bunch length on extraction from the synchrotron is

$$\sigma_l = 132 \mu\text{m}$$

3.3. **Synchrotron RF.** As the linac will be operating at 1.3GHz, we replace the synchrotron RF system with 1.3GHz superconducting cavities, perhaps consisting of 2-3 HTC installations. Ignoring synchrotron radiation for the moment, the energy gain per turn is about 1MeV. The average power required to accelerate the beam to 3GeV is

$$P = E_f I \frac{\tau_{rev}}{\tau_{acc}} = (3\text{GeV})(100\text{mA}) \frac{0.00254}{16} = 48\text{kW}$$

The energy loss due to synchrotron radiation at 3GeV is 86 KeV/turn, corresponding to 8.6 kW, but even that only during the acceleration half of the cycle. RF power requirements are modest. In order to have sufficient over voltage $V_{rf} >$3MV.

4. CESR

We suppose that the hard bends are replaced with achromats compatible with 2m insertion devices. The relevant parameters of the modified lattice are shown in the table The emittance of the circulating beam approaches the equilibrium value exponentially, so that at extraction time is

$$(\epsilon_x - \epsilon_i)(1 - e^{-t/\tau}) + \epsilon_i = 0.92\text{nm} - \text{rad}$$

TABLE 2. CESR parameters at 3GeV

Parameter	Value
Energy[GeV]	3.0
ϵ_x[nm-rad]	7.1
τ_x[msec]	155
τ_z[msec]	77
σ_l[mm]	4.1
α_p	4.6×10^{-3}
RF(500 MHz) [MV]	6

where ϵ_x is the equilibrium emittance and ϵ_i is the emittance of the injected beam.

The length of the bunch injected from synchrotron into CESR is $\sigma_l = 132\mu$m. The bunch length after 16 msec is

$$\sigma_l^f = (\sigma_l^0 - \sigma_i^i)(1 - e^{-t/\tau}) + \sigma_l^i = 876\mu\text{m}$$

CESR beam parameters just before extraction are summarized in Table **??**.

TABLE 3. CESR Beam parameters

Parameter	Injection	Extraction
Energy[GeV]	3.0	3
ϵ_x[nm-rad]	0.239	0.92
σ_l[μm]	132	876

4.1. **CESR RF.** Replace 500MHz system with 1.3 GHz for compatibility with linac and synchtrotron. For bunch length calculations above we assume $V_{rf}(1.3\text{GHz}) = \frac{500}{1300}V_{rf}(500\text{MHz})$ and $V_{rf}(500\text{MHz}) = 6\text{MV}$

5. INSERTION UNDULATORS

Exploit the low emittance with narrow gap superconducting undulators to generate hard xrays. The lattice can accomodate 4 2m undulators in zero dispersion straights.

6. BEAM DUMP

Extracted the decelerated beam at 100MeV from the synchrotron. The average power into the dump is

$$(100\text{MeV})(100\text{mA})\frac{0.00254}{16} = 1.6\text{kW}$$

7. SYNCHROTRON UPGRADE SCENARIO