COMPACT ELECTRON STORAGE RING CONCEPTS FOR EUV AND SOFT X-RAY PRODUCTION[*]

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Abstract

We discuss the use of two novel techniques to deliver low emittance from a compact electron ring at energies around 1 GeV, suitable for EUV and soft X-ray synchrotron radiation production. The first method is the circulation of non-equilibrium electron bunches, which is made feasible using high repetition rate linacs and very fast bunch-by-bunch injection and extraction. The second method is to utilise a stacked storage ring in which two rings are coupled, and in which the strong damping wigglers in one ring depress the emittance in the other. We present example designs of each approach, noting that these methods may be used in combination with other emittance reduction techniques.

INTRODUCTION

Sophisticated methods have been developed to allow electron storage rings to approach the delivery of diffraction-limited synchrotron radiation, which include the use of complex multi-bend achromats with very strong focusing and high chromaticity as well as the application of unusual techniques such as Robinson wigglers and other techniques to modify the damping partition numbers [1]. A deficit of many of these methods is the requirement for a longer than desired circumference to accommodate the magnetic elements; in addition the very strong focusing may cause dynamic aperture reduction, which gives rise both to a limited beam lifetime and necessitates the use of on-axis injection techniques. Alternatively, energy-recovery linacs may be utilised which may give smaller emittances than storage rings for a given energy and circumference if a suitable high-current injector is available and if beam losses may be sufficiently controlled. We here present two novel concepts that achieve small emittances in a compact ring, without the associated disadvantages of other approaches.

THE NON-EQUILIBRIUM RING

The damping ring is a well-known concept wherein large-emittance bunches reduce in extent over a number of damping times. With a small-enough injected emittance the opposite process is also possible: small-emittance electron bunches may be injected, circulated for less than one damping time, and then ejected [1]. This concept has been previously proposed for Compton photon production [2] and for electron cooling [3], but not previously proposed for synchrotron radiation production. We now show that an energy range exists where the injected emittance from current injectors can be small enough to be beneficial, and where the damping time $\tau_{x,y} = 3m_e^3c^5C\rho/(2\pi r_e J_{x,y}E^3)$ is still sufficiently long that bunches may be replaced every few milliseconds before their emittance grows.

Table 1: Principal Properties of the MAX-II, MAX-III and Super-ACO Storage Rings when Operated in Equilibrium

	MAX-II	MAX-III	Super-ACO
Max. Energy (GeV)	1.5	0.7	0.8
Design current (mA)	200	250	400
C (m)	90	36	72
ρ (m)	3.33	3.036	1.7
T_rev (ns)	300	120	240
$\epsilon_{\mathrm{eq},(x)}$ (nm)	8.9	12.8	38.0
$\tau_{x,y}$ (ms)	6.7	24	18
σ_t (1σ, ps)	53	89	90
σ_E (1σ) ($/10^{-4}$)	7.1	8.6	5.3
J_x	1.0	2.4	1.0

We propose the use of bunch-by-bunch injection and extraction using fast kickers with a pulse length less than ~12 ns, as designed for DAΦNE and by KEK [4, 5]; analogous designs have been proposed to be operated in CW mode for superconducting FELs [6, 7]. If the specified peak-to-peak (p-p) stability of 0.07% can be achieved then the effective emittance dilution from injection is modest at 1 GeV but becomes difficult at higher energies; typical insertion device (ID) straight lengths can then allow injection/extraction whilst allowing ample Touschek and quantum lifetime. The effective current is determined only by the charge of the injected bunches (assumed here to be ~1 nC), and by how the kicker pulse length limits the bunch spacing, i.e. I = 83 mA for 12 ns spacing (6 ns kicker rise and fall time), with $n_b = T_\mathrm{rev}/\tau_b$. The residence time τ_r each circulating bunch remains in the ring is determined by the available repetition rate f_l of the linac; f_l =10 kHz is sufficient to keep $\tau_r < \tau_x, y$, i.e. that $f_l \gg 2\pi r_e JE^3/3m_e^3c^6\rho\tau_b$. The intrabeam scattering (IBS) growth times τ_IBS must also be kept longer than τ_r by keeping the injected bunches long, for example by setting them to the equilibrium stored bunch lengths (typically between 50 and 90 ps); emittance dilution from the kicker voltage change is still small over this time. Other collective effects such as resistive wall instabilities, microbunching and so on will either be small or controllable with feedback [8]. We illustrate this non-equilibrium (NEQ) approach using the existing storage ring designs summarised in Table 1, and where we may reduce from the maximum energy of each. Table 2 gives example operating energies

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Table 2: Non-equilibrium operation of MAX-II [9, 10], MAX-III [11] and Super-ACO [12, 13], assuming an injected bunch length equal to the natural bunch length at full energy. The beam current in all cases is 83 mA, limited by the 12 ns bunch spacing.

	MAX-II		MAX-III		Super-ACO	
Energy (GeV)	0.7	1.0	0.5	0.7	0.5	0.8
n_b	25	25	10	10	20	20
τ_r (ms) for $f_l = 10$ kHz	2.5	2.5	1.0	1.0	2.0	2.0
$\tau_{x,y}$ (ms)	66	23	13,32	4.8,11.5	74	18
$\tau_{\mathrm{IBS}x,init}$ (ms)	13	22	2.0	3.8	4.8	11.7
$\epsilon_{\mathrm{eq},x}$ (nm)	2.73	3.95	6.5	12.8	15.0	38.0
$\epsilon_{\mathrm{inj},x}$, $\epsilon_{\mathrm{inj},y}$ (nm)	0.730	0.511	1.28	1.02	1.02	0.639
$\epsilon_{d,\mathrm{crit}}$ (nm)	0.432	0.148	2.11	1.08	0.604	0.138
$\Delta\epsilon/\epsilon$ (x,y) from p-p stability (%)	16,2.7	22,3.8	1.0,0.7	1.4,1.0	5.0,5.8	8.0,9.4
Dump power (kW) for $f_l = 10$ kHz	7	10	5	7	5	8

for each of the considered rings, and shows that a significant emittance advantage may be obtained using NEQ operation.

IDs will deliver photons comparable to the critical wavelength $\lambda_c = 4\pi\rho/3\gamma^3$ of the main ring dipoles: we may therefore use the diffraction-limited emittance at λ_c, which is $\epsilon_{d,\mathrm{crit}} = \rho/3\gamma^3$, as an estimate of the useful emittance from the IDs; this is compared to the equilibrium and NEQ emittances in Figure 1. Equating $\epsilon_{d,\mathrm{crit}}$ with ϵ_{inj} we obtain the electron energy at which NEQ operation gives an advantage, $E \simeq m_e c^2 \sqrt{\rho/3\epsilon_n}$, around 0.4 GeV to 0.7 GeV for typical dipole bending radii. The beam power deposited at the dump is simply that from the injector, and is readily manageable even at $f_l = 10$ kHz [1]: the beam power is effectively limited by the kicker rise/fall time and is much smaller than the equivalent ERL but with no emittance penalty. Compared to an equilibrium storage ring, the horizontal emittance is reduced significantly with NEQ operation and may be brought close to $\epsilon_{d,\mathrm{crit}}$; the equilibrium vertical emittance is typically smaller than $\epsilon_{d,\mathrm{crit}}$, so the increase from NEQ operation incurs no penalty for most IDs. The range of output photon energies over which NEQ operation gives an emittance advantage is from about ~ 0.1 keV to ~ 2 keV, and such a ring may be added to a suitable high-rate FEL (NLS, LCLS-IISC etc.).

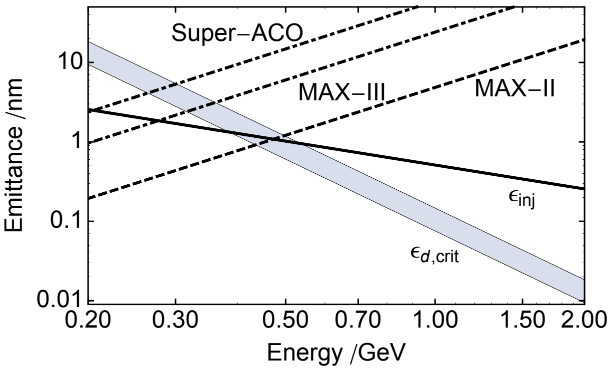

Figure 1: Variation of emittance with energy, comparing an injector (with normalised emittance $\epsilon_n = 10^{-6}$ m) with the equilibrium emittance of the MAX-II, MAX-III and Super-ACO storage rings. Also shown is the range of the diffraction-limited emittance $\epsilon_{d,\mathrm{crit}}$ for bending radii ρ from 1.7 m to 3.33 m.

THE STACKED STORAGE RING

A single-plane storage ring has the well-known equilibrium horizontal emittance of $\epsilon_x = C_q\gamma_r^2 I_5/I_2$, which may be reduced by adding damping wigglers to dispersion-free straights to increase I_2; however, this uses up the straight sections desired for IDs. We instead propose two identical rings stacked one above the other - into the lower ring (*a*) we place damping wigglers whilst the upper (*b*) straights remain free for IDs. A static (DC) magnetic crossover region transfers bunches between rings *a* and *b* once per turn, as shown in Fig. 2 [14]. Assuming ID self-dispersion is small the emittances in each ring are just

$$\epsilon_x^a = C_q\gamma_r^2 \frac{I_5^a}{I_2^a + I_2^{aw}}, \epsilon_x^b = C_q\gamma_r^2 \frac{I_5^b}{I_2^b}, \qquad (1)$$

where I_2^{aw} is the contribution from the damping wigglers in ring *a*. The overall emittance of the coupled stacked storage ring is then just

$$\epsilon_x = C_q\gamma_r^2 \frac{I_5^a + I_5^b}{I_2^a + I_2^b + I_2^{aw}} = C_q\gamma_r^2 \frac{I_5}{I_2 + \frac{1}{2}I_2^{aw}}. \qquad (2)$$

By making $I_2^{aw} \gg I_2$ (by restricting the ring dipole field) the upper ring *b* now obtains the emittance of ring *a* whilst being free of wigglers; injection is carried out into ring *a* so that the transfer region does not use up any more space in ring *b* than injection did. The vertical bends in the crossover introduce some vertical emittance $\epsilon_y \sim \theta^3$ but much smaller than ϵ_x as it is kept small by the horizontal contribution to I_2; the contribution to I_2 from the vertical bends also helps to reduce ϵ_x.

We illustrate the stacked storage ring approach for a simple 0.7 GeV ring utilising double-bend achromats with no dipole gradient, with properties summarised in Table 3; a racetrack optics is required to fit a suitable transfer region in a small overall circumference. The single-particle emittances in each plane are then

$$\epsilon_x = C_q \gamma_r^2 \frac{I_{5x} + \frac{1}{2} I_{5x}^{aw}}{I_{2x} + I_{2y} + \frac{1}{2} I_2^{aw}} \simeq 1534 \text{ pm-rad} \quad (3)$$

$$\epsilon_y = C_q \gamma_r^2 \frac{I_{5y}}{I_{2x} + I_{2y} + I_2^{aw}} \simeq 110 \text{ pm-rad} \quad (4)$$

In this example the beam heights in rings *a* and *b* are 60 cm apart, sufficient to locate separate focusing elements for each ring; engineering concepts exist for a dual ID on a single carriage. $I_{2x} = 0.94$ m^{-1} whilst $I_2^{aw} = 5.63$ m^{-1}. The optimised optics gives $I_{5x} = 497 \times 10^{-6}$ m^{-1}, whilst the small self-dispersion of the wigglers means that all six contribute a total $I_{5x}^{aw} = 593 \times 10^{-6}$ m^{-1}. In the transfer section control of the dispersion in the four 20 cm vertically-bending dipoles (0.88 T) allows $I_{5y} = 594 \times 10^{-6}$ m^{-1}. Although small, the bending in the vertical plane induces additional damping of $I_{2y} = 0.11$ m^{-1}. Assuming full beam coupling, the equilibrium emittance at 100 mA current including IBS is 1429 pm-rad in both planes. We consider an example 4 m-long $\lambda_u = 30$ mm undulator optimised to cover a wavelength range of 20-120 eV. At 20 eV the diffraction-limited emittance is 1600 pm-rad; without ring *a*, ring *b* would have an emittance of 8358 pm, so the stacked ring approach has significantly reduced the emittance without adding circumference. This method can be applied to any ring design which can be made wiggler-dominated. We note that since the storage ring itself is a small part of the cost of a synchrotron radiation facility, use of a stacked ring does not unduly add to the cost.

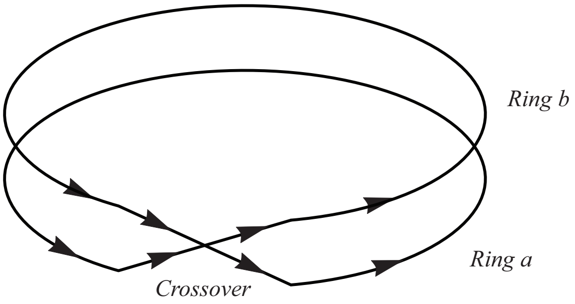

Figure 2: Schematic illustration of a stacked storage ring; bunches execute one turn around ring *a*, are transferred to ring *b* where they execute another turn, and then back to ring *a*.

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Table 3: Parameters of Example Stacked Storage Ring Design

Energy (GeV)	0.7
Cell Structure	8 (16) cell DBA
Design Current (mA)	100
Circumference (m)	165.6 (331.2)
Dipole Field B_0 (T)	0.35
Dipole Bend Radius ρ_0 (m)	6.67
Dipole Length (m)	2.62
Wiggler Peak Field B_w (T)	1.6
Total Damping Wiggler Length (m)	24
RF Frequency (MHz)	499.654
RF Voltage (MV)	1.0
Harmonic Number	$552 = 2^3 \cdot 3 \cdot 23$
$\epsilon_{x,y}$ (full coupling, pm)	1429
ϵ_x (single ring, pm)	8358
σ_E (1σ)	0.1 %
σ_t (1σ, ps)	39.5
U_0 (keV)	26.2

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