DESIGN OPTIMIZATION AND IMPEDANCE SOURCES IN LOW EMITTANCE RINGS (LER)

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Abstract

There is a clear trend today that future ultra-low emittance rings adopt vacuum chambers with a significantly reduced radius of aperture. A big effort would be needed to keep the machine impedance on the same level as before.

INTRODUCTION

A major goal of many of the next generation light source rings is to store an electron beam whose transverse emittance is diffraction limited over the main photon energy range of interest. This follows the fact that the principal figure of merit of the light source rings is the brilliance, which is inversely proportional to the product of electron beam transverse emittances and linearly proportional to the electron beam intensity. To increase the brilliance, therefore, we must lower the electron beam emittance and increase its intensity. As to the lowering of the emittance, the most effective and classically known method is to divide a bending magnet into many pieces and optically approach the condition known as the theoretical minimal emittance (TME) in each of these dipoles.

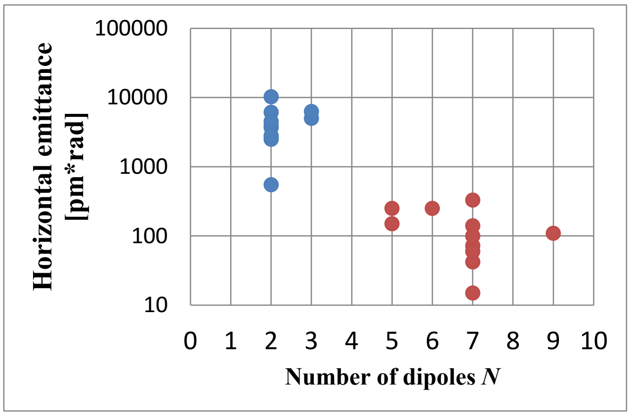

Figure 1: Horizontal emittance versus number of dipoles per achromat in light source rings (blue: existing, red: recent & future rings).

The TME scales as the inverse cube of the number of dipoles and so the effort is made to get as close as possible to this ultimate value. Over the last decades, there have been breakthroughs in beam dynamics studies, beam diagnostics and related technologies such as on magnets and vacuum, which allowed the number of dipoles per achromat to be increased from two or three of the 3rd generation light sources, to typically 7, thus enabling to gain a reduction factor of 30-40 on the horizontal emittance, according to the above cubic law (Fig. 1). Such magnet lattices are generally called MBAs (Multi-Bend Achromat).

There is however an important chain of consequences of the employed strategy generally appearing on the design aspects of modern and future low-emittance rings (LERs): The need to approach the TME condition in every dipoles requiring strong quadrupole focusing across the entire achromat (in the range of 100 T/m as compared to 20 T/m of the 3rd generation) → Reduced magnet bore radii → Smaller beam pipe half aperture b → Poorer vacuum conductance → NEG coating in a large part of the ring for vacuum pumping (Fig. 2). In addition, MBAs generally require the magnet lattice to be tightly packed with dipoles, quadrupoles, sextupoles and all other standard vacuum components such as flanges, BPMs etc. A chain of consequences emerges on the electron beam dynamics as well: Approaching TME with MBA lattice → Small horizontal dispersion all along the ring, weaker radiation damping and large natural chromaticities → Strong sextupoles → Small transverse dynamic apertures. Ultra-low emittance → Enhancement of IBS and Touschek scattering.

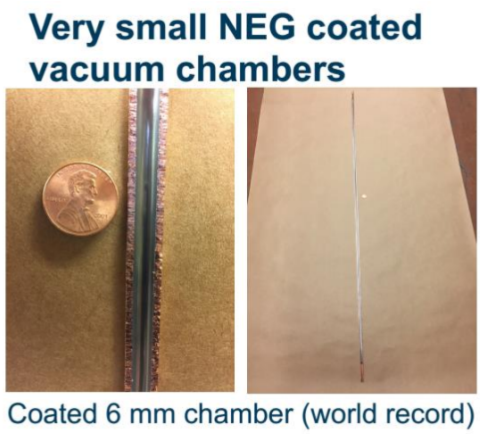

Figure 2: NEG coating on a 6-mm diameter beam tube at Advanced Light Source (D. Robin, LER2016, SOLEIL [1]).

Table 1 (found in the Appendix due to its size) presents the half aperture b's adopted for some of the newly constructed and future ultra LERs. We can see that the chains described above have serious influences on the beam collective effects: First of all, the smaller vacuum chamber aperture globally around the ring shall inevitably enhance the impedance. The extensive use of NEG coating shall also have a non-negligible impact of the machine impedance (to be addressed again later). The smaller

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horizontal dispersion shall reduce the magnitude of momentum compaction which in turn shall influence the beam collective motions. The weaker radiation damping tends to lower the instability thresholds.

CHARACTERISTICS OF THE RESULTANT IMPEDANCES

With much smaller vacuum chamber apertures adopted all around the ring, both the geometric and resistive-wall impedances are expected to become much larger for the ultra-low emittance rings. Indeed, it is well known that the longitudinal impedance scales inversely linear or higher and the transverse impedance to b^{-2} and higher. In particular, the transverse resistive-wall impedance has the well-known dependence of inversely to the cube of *b*. For this reason, it is clear that the transverse impedance of next generation LERs shall be resistive-wall dominated. Other major contributors are usually tapers, BPMs, shielded bellows, flanges, cavities, kickers, absorbers, and scrapers etc. due to their geometry. While insertion devices, particularly those which are under vacuum, would always remain as large contributors due to their particularly small gaps, the taper transitions tend to have smaller angles as the apertures in the magnet sections themselves are smaller. However, the last is not true with cavity tapers so they are expected to remain as large contributors in the impedance budget. Due to the enhanced proximity to the beam and to their high number, components such as BPMs are expected to make large contributions for the impedance and therefore, special care for the accurate evaluation of their impedances, both amplitude and frequency wise, along with effort to minimize them with optimized designs is demanded. A triangular shape BPM button electrode developed at SIRIUS is a good example, pushing the dangerous trapped mode frequencies away to high frequencies and keeping the button diameter large not to lose the BPM reading accuracy, which is vital for ultra LERs (Figs. 3). The 3D EM field solvers such as CST microwave studio [2], GdfidL [3] and ECHO3D [4] are widely used in the community to evaluate and minimize the geometric impedance of various vacuum components.

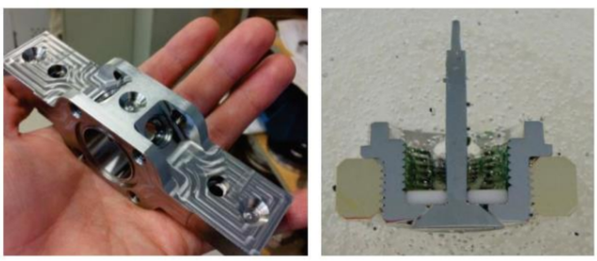


Figure 3: Bell-shaped BPM button developed at SIRIUS, optimized to increase the button cut-off frequency without losing the button sensitivity (A.R.D Rodrigues et al., IPAC2015 [5]).

The fact of chamber walls getting much closer by to the beam requires all kinds of surface impedances involved to be well understood and controlled. This is particularly true for those arising from coating on the surface, whether it is the coating of poor electric conductivity materials such as NEG on a good conductivity substrate such as copper, or the opposite such as titanium coating on a ceramic chamber to improve the image current flow on the wall. Many studies have been made analytically with methods such as field matching technique and surface impedance models [6]. Numerical codes such as ImpedanceWake2D (IW2D) developed at CERN [7] are also widely used. Since vacuum pumping using NEG coating appears to become an indispensable technique for future ultra-low emittance rings, the possible impact of NEG coating on the machine impedance must be carefully studied. An early observation was made at ELETTRA using the transverse coherent detuning of the beam [8] (Fig. 4).

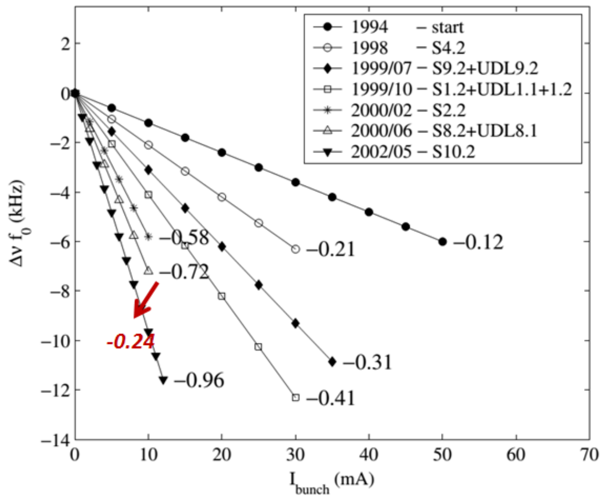
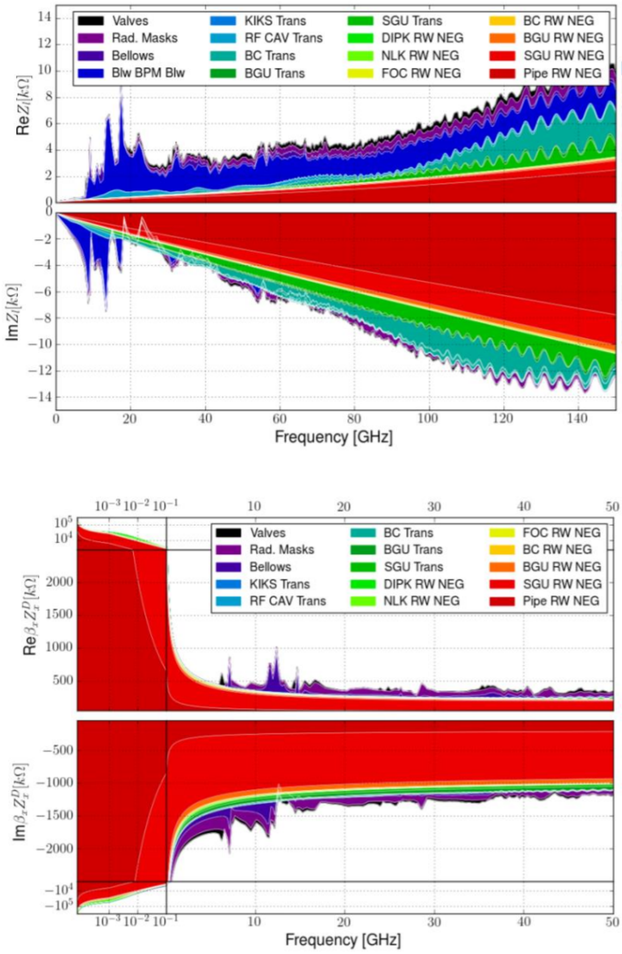


Figure 4: Increased transverse coherent detuning by nearly a factor of 2 observed at ELETTRA for a NEG-coated chamber as compared with those w/o coating [8].

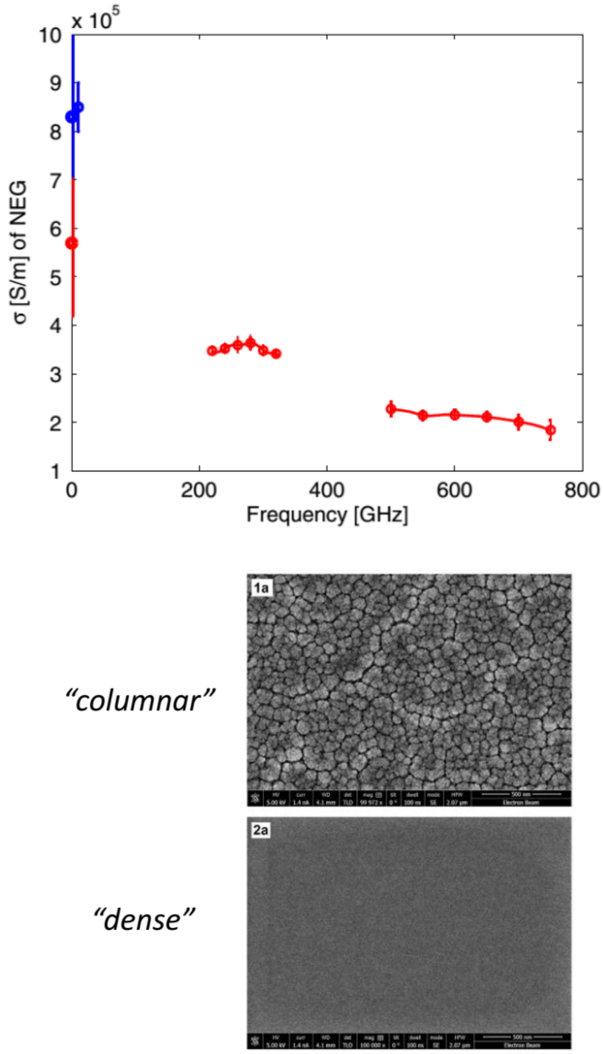
A first analysis using the field matching method had shown that a micron level thin NEG coating would be transparent to beam from its real part of the impedance, but its imaginary part would be enhanced by nearly a factor of two in the frequency range seen by the beam [9]. The impedance budget evaluated at SIRIUS indeed indicates that the impedance is dominated by the resistive-wall and that there is the aforementioned enhancement by roughly a factor of two in the reactive part [10] (Figs. 5). The frequency dependence of the conductivity of NEG was studied at CERN showing factors of worsening towards hundreds of GHz [11] (Figs. 6 upper). Recent studies reveal the importance of the physical state of NEG as an outcome of deposition on the electric conductivity [12] (Figs. 6 lower).

CONCERNED COLLECTIVE EFFECTS AND INSTABILITIES

The beam-induced heating of vacuum components would probably be the most concerned collective effect for many ultra LERs with low-gap chambers, as a trouble on a single component can seriously ruin machine operation. Not only, but the FBII (Fast Beam-Ion Instability) that causes beam losses and prevents ones from operating the ring in ¾ filling at 500 mA at SOLEIL is considered to be originated in beam-induced heating of (some unknown) vacuum components generating sudden local outgassing [13]. Loss factors and trapped modes must be carefully studied from the geometric and non-geometric (metallic coating) impedance of each vacuum component, and the results, formulated in beam-induced power, need be evaluated in terms of "heat (temperature)" in collaboration with drafting office engineers by tracing the passage of the EM fields and their possible conversion into heat.



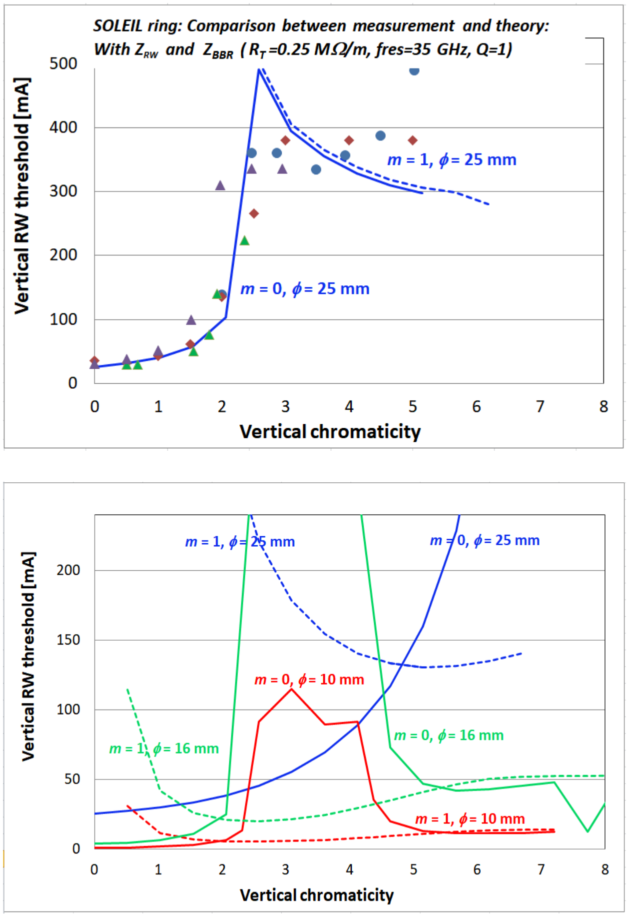
Figures 5: (Upper) longitudinal and (lower) transverse impedance budget obtained for SIRIUS. The red part represents the resistive-wall contribution [10].



Figures 6: (Upper) experimental study of NEG electric conductivity versus frequency [11]. (Lower) experimental study of surface resistivity of two types of NEG [12].

Transverse single bunch instabilities (TMCI, head-tail and post-head-tail), which are already strongly existing in the present LERs, can only be expected to get stronger. However, some of the physical effects which are likely to get stronger in future LERs such as the transverse nonlinear optics and bunch lengthening with harmonic cavities, may give rise to significant mitigating (stabilizing) effects. Care must also be taken since it was recently found, however, that additional longitudinal tune spread arising from harmonic cavities could significantly lower the TMCI threshold [14]. The effectiveness of the conventional stabilization methods such as shifting of the chromaticity to positive and bunch by bunch feedback must be well studied. Longitudinally, bunch lengthening is expected to be always present and may even be enhanced due to the reactive effect of NEG coating. The microwave instability, for which the standard longitudinal feedback provides no cure, must be avoided above all in LERs that make use of higher harmonics of the undulator spectra as the associated beam energy spread widening seriously spoils them. Since the instability is excited due to high frequency resistive components of the longitudinal impedance, bunch lengthening with harmonic cavities could help mitigate the instability. Since MBA lattices tend to have longer radius of curvature for bending magnets, along with reduced chamber apertures, the so-called the shielding parameter of the instability [15] should tend to increase. One would therefore expect the CSR instability to be less influential. Detailed studies are required to verify such zeroth order reflection.

The resistive-wall (RW) instability may be said to be the most concerned beam instability for many present and future light source rings as the resistive-wall impedance is large for these machines as already explained and as most machine operate in high multibunch current where the instability becomes important. For example at SOLEIL whose nominal current is 500 mA in the multibunch filling, the threshold of instability is merely around 30 mA vertically at zero chromaticity. However, the threshold generally rises quickly as we shift the chromaticity to positive due to head-tail damping (Figs. 7 left). Many light sources actually operate in such a manner. However, the chromaticity shift may induce beam lifetime drop through reduced off-momentum dynamic aperture. Bunch by bunch feedback may be used instead to avoid such issues. Both the time domain multibunch tracking and frequency domain Vlasov solvers can well follow these instabilities in general. An example of the results obtained with a Vlasov solver is shown in Figs. 7 (right) for the parameters considered for the SOLEIL upgrade, where the vacuum chamber half aperture of b = 5 mm is assumed. The low thresholds found with the resistive-wall impedance alone are alarming, but several elements that are not yet included in this computation, such as the broadband impedance, the low beta nature of the upgraded lattice, as well as bunch lengthening cavities, found to bring about significant stabilization in a recent study for this instability as well [16], are expected to much improve the situation. Caution must be taken if there is a non-negligible portion of non-circular cross section vacuum chambers in a ring, as quadrupolar wakes arising from them may be strong enough, due to their small aperture, to distort the ultra-low emittance tuning and spoil the target emittance. The effect is expected to be particularly strong for electrons in a high intensity bunch. Studies made at SOLEIL indicated that the betatron tune shifts in an intense bunch of 20 mA get nearly 20 times larger than in multibunch at 500 mA (Fig. 8) [17]. Since the quadrupole wakes come from the imaginary part of the impedance, NEG coating is expected to enhance the effect.



Figures 7: (Upper) vertical resistive-wall (RW) instability threshold versus chromaticity, computed with the expected RW and broadband resonator impedance, in comparison with measured thresholds for the present SOLEIL ring. (Lower) expected RW instability threshold for the SOLEIL upgrade for different $\phi = 2 \times b$ values, by taking into account the RW impedance alone (i.e. no headtail damping). Index m stands for azimuthal (headtail) modes.

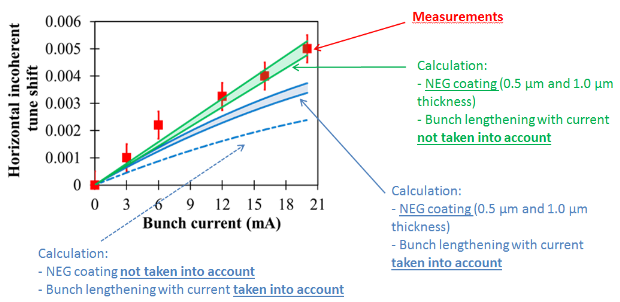


Figure 8: Measured (red square) horizontal incoherent tune shift as a function of bunch current. Values expected from theory: w/o NEG coating and with bunch lengthening (blue dashed line); with NEG coating (0.5 and 1.0 µm thickness) and with bunch lengthening (blue area); with NEG coating (0.5 and 1.0 µm thickness) and w/o bunch lengthening (green area) [17].

SUMMARY

There is a clear trend today that future ultra-low emittance rings adopt vacuum chambers with a significantly reduced radius of aperture b. As the wakefields scale basically as b^{-n} ($n \geq 1$), their sensitivity to the sources of impedance could only be larger. A big effort would be needed to keep the machine impedance on the same level as before. Innovative vacuum components designs, including coating technology, should be made in collaboration with machine physicists to keep machine heating and beam instability under control. Special efforts would be required to avoid heating due to ceramic chambers and trapped modes, as well as to develop means to cleverly evacuate generated heat without damaging vacuum components. Due to its b^{-3} dependence, the contribution of the transverse resistive-wall impedance to the total impedance budget would tend to dominate the rest. For the SOLEIL case as an example, the value of b for the standard chamber of 12.5 mm is to be reduced to 5 mm for the upgraded ring, meaning that the transverse resistive-wall impedance shall increase by a factor $(12.5/5)^3 = 15.6$. The NEG coating would non-negligibly enhance the impedance, but its impact should appear in the reactive part amplifying bunch lengthening and coherent tune shifts as long as the beam is only sensitive to the low frequency part of the impedance. The cross section of low-gap chambers may better be kept circular to avoid quadrupolar wakes that could spoil the ultra-low-emittance tuning especially for high intensity bunches. Due to lower vacuum chamber gaps and the proximity of vacuum components in future rings, the risk of wakes interference should be carefully monitored.

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APPENDIX

	E [GeV]	b [mm]	crossection	remarks	b [mm]	crossection	remarks	b [mm]	crossection	remarks
ALS-U	2	**6.5**	circular	Strongly focusing sections	**10**	circular	Outer arc sections			
APS-U	6	**11**	circular	Hybrid of NEG coated Cu, Cu plated SS with NEG strips, bare Al	**3 × 8**	non-circular	Al chambers, 125 m in total	**3**	circular	Al chambers, 50 m in total
DIAMOND-II	3.5	**10**	circular	Thickness 1 mm, Chamber design at early stage						
ELETTRA-II	2 - 2.4	**11**	circular	Cu and SS in some parts	**4.5 × 20**	non-circular	Al NEG coated (4 and 5 m long)	**3**		IVU × 3 (4 m); Wiggler×2 with b = 5 mm (1.5 m) Al + NEG
ESRF-EBS	6	**10**		In moderate focusing sections	**6.5**		In strongly focusing sections	**4**		Straight sections
HEPS	6	**11**	circular	Standard chambers	**2.5**	non-circular	CPMU chamber	**~4**	non-circular	IAU chamber
MAXIV 3 GeV	3	**11**	circular	copper, NEG coated	**4 × 18**	non-circular	Aluminium, EPU chambers, NEG coated, 4 m long	**2**	non-circular	IVUs and wiggler 2.1 m long
MAXIV 1.5 GeV	1.5	**11 × 20**	elliptical	SS	**11 × 29**	non-circular	SS, Arc sections	**4 × 18 (or 4 × 28.5)**	non-circular	EPU chambers, NEG coated, 3.2 m long
NSLS-II	3	**12.5 × 38**	non-circular		**2.5 - 3.5**	non-circular	IVU × 10	**6.0 - 8.0**	non-circular	EPU × 7; DW × 3 have b = 7.5 mm
SLS-II	2.4	**9**	circular	Design at early stage (cf. A. Zandonella's talk)						
SOLEIL-U	2.75	**5 to 8?**	circular?	Likely be NEG coated						

Table 1: Half aperture b values for some of the recently constructed and proposed LERs.