THE APPLICABILITY OF NEG COATED UNDULATOR VESSELS FOR THE CLARA FEL TEST FACILITY

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Abstract

CLARA is a FEL test facility at STFC Daresbury Laboratory (DL), UK. The undulator vacuum chamber is 20 m long with inner diameter 6 mm and its vacuum performance can benefit from a NEG coating. The thickness of the coating layer must be carefully optimised. A layer $\approx 1\mu$m would help the vacuum but a thinner layer would be partially transparent for the EM field reducing the resistive wall wakefields due to the NEG. A very thin layer, however, may not yield the necessary vacuum performance. Two types of NEG coatings produced at DL - dense and columnar - were considered. Their bulk conductivities were measured in a separate study. The resistive wall wakefield impedance was calculated following the standard approach for multilayer vessels. A 250 fs rms electron bunch was generated in `ASTRA` and its wakefield was obtained from the vessel impedance. The FEL performance was then studied through `Genesis 1.3` simulations and the result compared to the case with no wakefields. It was found that NEG layers thicker than 100 nm give an unacceptable reduction of the FEL power and the vacuum performance of such thin coatings is unknown. Possible solutions to this problem are discussed.

INTRODUCTION

Since its invention in the 1990s [1, 2], NEG coated beam vacuum chambers are widely used in particle accelerators of synchrotron radiation sources, colliders and heavy ion machines [3–11]. The NEG coating is a chemically active metal film based on transitional metals (Ti, Zr, Hf and V) with thickness 0.5-3 μm. The advantages of fully NEG coated vacuum chambers are: a dramatic reduction in thermal and particle (photon, electron and ion) induced gas desorption [12–17]; introduction of a distributed pumping speed [18–20]; lowering the bakeout temperature from usual 250-300° C to 150-160° C [16–18].

For particle accelerators the NEG coating also provides another advantage: the beam losses due to collisions with residual gas molecules increase with interaction cross section which in turn increases with molecular mass, i.e. the lighter the gas molecules the less harm to the beam from the residual gas at the same gas density. The residual gas spectrum in a conventional vacuum chamber mainly consists of H_2, CO and CO_2 while in the NEG coated vacuum chamber mainly consists of H_2 and CH_4. The latter is much lighter and therefore less harmful to the beam than CO and CO_2.

The NEG coating is the best or only solution to meet the vacuum specification for narrow and long vacuum chambers such as the out-vacuum undulator vacuum chamber. In CLARA, with internal diameter ID = 6 mm, the required pressure below 10^{-8} mbar can be reached after bakeout to 250°C only if the distance between pumps is $L \leq 1.2$ m. Applying the NEG coating would increase in the distance to a reasonable 5-10 m. An additional advantage is that the ASTeC quaternary NEG coating can be activated at 150°C. This not only reduces the specification for the bakeout jackets and power consumption but it also simplifies the bellows unit design considering two times less thermal expansion of the vacuum chamber during NEG activation. In practise, the lumped pumps will be required only at the locations of beam instrumentation.

RESISTIVE WALL WAKEFIELDS

In this section we consider resistive wall wakefield effects in a 3 mm radius circular NEG-coated undulator vessel made of copper. The standard approach to calculating the longitudinal wakefield impedance of the vessels [21–23] has been used. Due to the relatively low repetition rate of CLARA the wakefield heating of the undulator vessel is negligible and this allows us to concentrate on the impact that wakefield effects might have on the beam. In particular the wakefield-induced projected energy spread needs to be carefully optimised as it could affect the FEL power generation process.

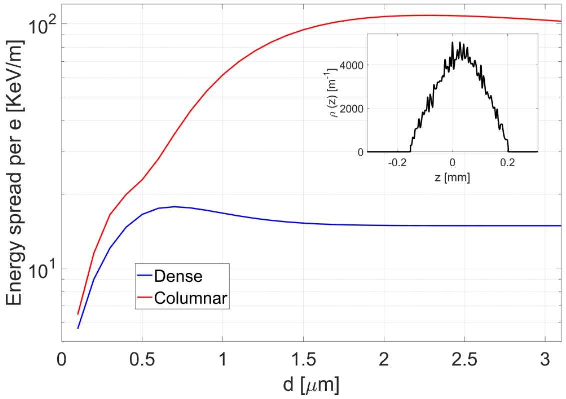

Figure 1: Correlated energy spread per electron for a radius 3 mm copper vessel coated with dense and columnar NEG films, versus film thickness. The inset shows the longitudinal bunch profile used in the calculations.

Recently several studies [24–26] reported the experimentally measured bulk conductivity of NEG. Using transmission line theory the surface impedance of the NEG-on-Cu structure can be calculated (see e.g. [25]) and the result substituted in the expression for the longitudinal wakefield impedance [23]. Using the latter quantity and the longitudi-

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nal bunch profile from `ASTRA` the correlated energy spread, as defined in [23] (Eq. 11), can be obtained. Figures 1 shows the results for a radius 3 mm copper ($\sigma_{Cu} = 5.88 \times 10^7$ S/m) vessel coated with a dense ($\sigma_D = 8 \times 10^5$ S/m) and columnar ($\sigma_C = 1.4 \times 10^4$ S/m) NEG film, versus film thickness. NEG conductivity data is from Ref. [25]. As can be seen the higher-conductivity dense film outperforms the lower-conductivity columnar film. In addition, despite the factor of 60 difference in the bulk conductivity values of the dense and columnar NEG the difference in performance of the two coated structure is 30% in the region film thickness values $d \approx 0.5\ \mu m$, which is the region interesting for applications (Fig. 1).

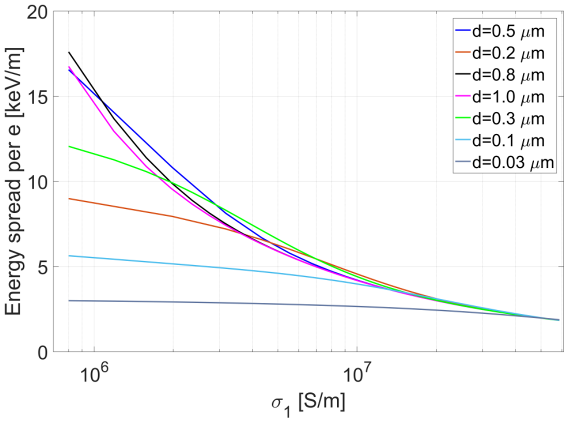

Figure 2: Correlated energy spread per electron for a 3 mm film-coated copper vessel versus the film conductivity.

Figure 2 shows the performance of a material with the vacuum properties of NEG but with higher conductivity. The conductivity values considered range between that of dense NEG and that of copper. As can be seen the performance of all films thicker than 0.5 μm is similar and only weakly depends on the film thickness. The thinner films show deviation from this trend in the region of lower conductivity values.

FEL PERFORMANCE

The three-dimensional code `Genesis 1.3` was used to study the impact of the wakefields on the FEL performance. The wakefields are incorporated into the simulations by expressing them as an energy change as a function of longitudinal coordinate within the electron bunch. This energy change is continually applied as the bunch propagates through the FEL undulator. The wakefields degrade the FEL performance via the loss of bunch mean energy and an increase in the projected energy spread which cause, respectively, a shift and a spread in the FEL resonance. It has been shown in further simulations that these effects can be compensated by application of an optimised undulator taper. However, to determine the baseline vacuum vessel specification for CLARA the criteria was imposed that the use of tapering should be reserved for contingency only, and that without the use of tapering the FEL pulse energy should not be degraded by more than 2% due to resistive wall wakefields.

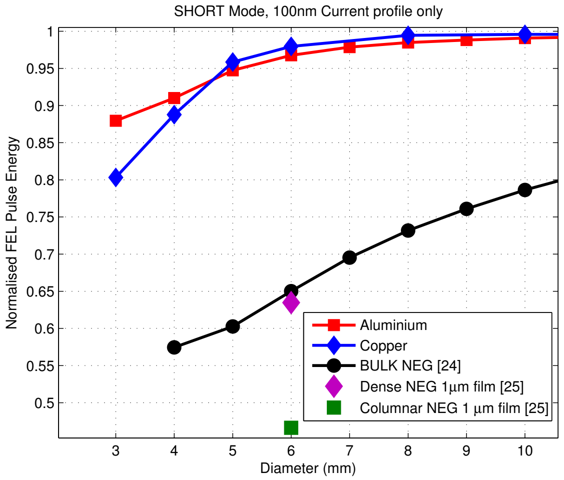

Figure 3: 100nm FEL pulse energy, normalised to the case with the vessel diameter set to 50 mm, as a function of vessel internal diameter.

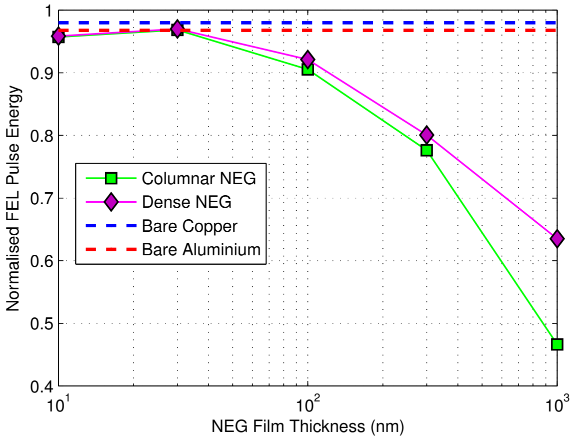

Figure 4: Normalised FEL power as a function of NEG film thickness, for a coated 6 mm diameter vessel. Also shown for reference are the normalised FEL powers for 6 mm diameter bare aluminium and copper vessels.

Figure 3 shows the FEL pulse energy at the nominal saturation point, normalised to the case with the vessel diameter set to 50 mm as a control case, as a function of the vessel internal diameter. The electron bunch profile is as shown in Fig. 1 and corresponds to the defined SHORT mode of CLARA operation with peak current $I = 400$ A, beam energy $E = 240$ MeV, bunch charge $Q = 250$ pC and rms slice energy spread $\sigma_E = 25$ keV. For uncoated aluminium and copper vessels the wakefield-induced degradation of the FEL pulse energy is 2-3% for a diameter of 6 mm. This result defines the nominal 6 mm diameter of the vessel. Also shown are the results for bulk NEG and 1 μm dense and columnar films which show an unacceptable level of degradation in FEL performance. As would be expected from the energy spread calculations shown in Fig. 1, the degradation of the FEL performance is worse for the lower conductivity columnar film than the higher conductivity dense film.

Figure 4 shows the normalised FEL pulse energy as a function of NEG film thickness for dense and columnar NEG and a 6 mm diameter vessel. For reference the results with uncoated copper and aluminium vessels are shown as the dashed lines. To meet the criteria of a maximum 2% degradation in FEL power the film thickness for both the dense and columnar NEG films would need to be less than 30 nm. To simplify the analysis we have assumed that the bulk conductivity of NEG film is independent of the film thickness.

In addition, it can be seen (Fig. 4) that for layers thinner than 300 nm the performance of the dense and columnar films is practically the same. This conclusion is in agreement with the result presented in Fig. 1. In order to satisfy the criteria of maximum 2% degradation of the FEL power the induced energy spread must be less than ≈3 keV/m (see Fig 2). Using a very thin ($d < 30$ nm) NEG film could result in a coating that does have the necessary vacuum properties.

NEG coatings were intensively studied mainly for 1μm-thick films and one can find references considering 0.5μm films. Additional studies should be performed for thickness values lower than 0.5 μm. It is expected that 200 nm thick NEG can still be used but its lifetime may be reduced. The lifetime of 1 μm-thick NEG film is limited to 50-100 activations, thus, even if this lifetime is scaled linearly, the lifetime of a 200 nm-thick film will be approximately 10-20 activations, while a 30 nm-thick coating will be limited to 2-3 activations. Therefore, future pumping studies should be focused on 100-200 nm thick NEG coatings. To reduce the surface resistance the NEG coating should be based on higher-conductivity materials. In Fig. 2 we assess the benefits of using a coating with vacuum properties similar to that of NEG but with higher conductivity. In order to keep the energy spread at the ≈3 keV/m level with $d > 100$ nm films the NEG film bulk conductivity needs to be $\sigma \geq 3 \times 10^7$ S/m, as Fig. 2 shows. This value is a factor of 40 higher than the measured conductivity of dense NEG.

CONCLUSION

The applicability of NEG coatings in the undulator vessel of CLARA has been analyzed. A stringent criterion of ≤ 2 % degradation of the FEL power output has been adopted. It is shown that the use of a 1μm-thick coating results in prohibitively large performance degradation. The acceptable thickness value is smaller than 30 nm and the actual type of coating - dense or columnar - is irrelevant. The vacuum properties of such ultra-thin films are not satisfactory. The application of $d \geq 0.5$ μm films would require bulk conductivity exceeding 3×10^7 S/m. For a less stringent maximum power degradation of 10 % the acceptable NEG thickness is 100 nm.

REFERENCES

[1] C. Benvenuti. Proc EPAC ’98, p. 200.

[2] C. Benvenuti, P. Chiggiato, F. Cicoira and V. Ruzinov. Vacuum 50, 57, 1998.

[3] R. Kersevan. Proc. EPAC-2000, p. 2291.

[4] F. Mazzolini, J. Miertusova, F. Pradal, L. Rumiz. Proc. EPAC 2002, p. 2577.

[5] J.D. Herbert, O.B. Malyshev, K.J. Middleman and R.J. Reid. Vacuum 73, p. 219, 2004.

[6] D. J. Wang, J. R. Chen, G. Y. Hsiung, et al. J. Vac. Sci. Technol. A 14, 1996, p. 2624.

[7] C. Herbeaux , N. Béchu and J-M. Filhol. Proc. EPAC08, Genoa, Italy, p. 3696.

[8] A. Hansson, E. Wallén, M. Berglund, et al. J. Vac. Sci. Technol. A 28, 2010, p. 220.

[9] M.C. Bellachioma, J. Kurdal, M. Bender, et al. Vacuum 82, 2007, p. 435-439.

[10] D. Weiss, P. He, H.-C. Hseuh, R.J. Todd. Proc. PAC-2005, p.3120.

[11] E. Mahner. Vacuum 81, 2007, pp. 727-730.

[12] C. Benvenuti, A. Escudeiro Santana and V. Ruzinov. Vacuum 60, p. 279, 2001.

[13] V.V. Anashin, I.R. Collins, R.V. Dostovalov, et al. Vacuum 75, 2004, pp. 155-159.

[14] P. Chiggiato and R. Kersevan, Vacuum 60, p. 67, 2001.

[15] F. Le Pimpec, O. Grobner, and J.M. Laurent, Nucl. Instrum. Methods Phys. Res. B 194, p. 434, 2002.

[16] O.B. Malyshev, R. Valizadeh, R.M.A. Jones, A. Hannah. Vacuum 86, 2012, pp. 2035-2039.

[17] O.B. Malyshev, R. Valizadeh, B.T. Hogan and A. Hannah. J. Vac. Sci. Technol. A 32, 061601, 2014.

[18] C. Benvenuti, P. Chiggiato, P. Costa Pinto, et al. Vacuum 60, 2001, p.57.

[19] C. Benvenuti, P. Chiggiato, P. Costa Pinto, et al. Vacuum 71, 2003 p.307-315.

[20] O.B. Malyshev, R. Valizadeh and A. Hannah. Vacuum 100, 2014, p.26-28.

[21] B. Zotter, S. Kheifets, Impedances and Wakes in High-Energy Particle Accelerators, World Scientific, 1990.

[22] A. Chao, Physics of Collective Beam Instabilities in High-Energy Accelerators, Willey & Sons, 1993.

[23] G. Stupakov, K. L. F. Bane, P. Emma, and B. Podobedov, Phys. Rev. ST Accel. Beams **18**, 034402, 2015.

[24] E. Koukovini-Platia, G. Rumolo, C. Zannini, in: Proceedings of IPAC, Dresden, Germany, 2384, 2014.

[25] O. B. Malyshev, L. Gurran, P. Goudket, K. Marinov, S. Wilde, R. Valizadeh and G Burt, NIM A **844**, 99-107, 2017.

[26] E. Koukovini-Platia, G. Rumolo, C. Zannini, Phys. Rev. AB **20**, 011002, 2017.