Complex Technological Solutions For Particle Accelerators

Oleg B. Malyshev* and Reza Valizadeh

ASTeC, STFC Daresbury Laboratory, Warrington, WA4 4AD, UK

Abstract

An advantage of complex technological solutions that address a few problems is demonstrated on two examples: laser ablation surface engineering (LASE) and non-evaporable getter (NEG) coated surfaces. NEG coating is not only the best vacuum solution for UHV/XHV accelerator vacuum chamber but can also provide electron cloud mitigation. LASE surface can provide not only SEY <1 (which is sufficient for e-cloud elimination but also reduces thermal and particle stimulated gas desorption). Both LASE and NEG has been characterised for their surface resistance and its impact on a beam wakefield impedance. It has been demonstrated that the surface resistance for both LASE and NEG can be reduced to meet the specification on the required surface resistance and provide the required vacuum and e-cloud mitigation properties.

INTRODUCTION

In a design of particle accelerators there are many specifications. Sometimes, the best solution to meet one specification can make it difficult or even impossible to meet another specification. For example, a small aperture of beam chamber allow to reach stronger magnetic field at reduced cost but could be too small for the beam aperture, cause beam impedance and make it challenging to meet the vacuum specifications. Rough surfaces may be efficient for e-cloud mitigation but increase the beam emittance.

The ASTeC team working on technological solutions for a beam vacuum chamber that address these problem in a complex approach, i.e. developing complex technological solutions to solve a few problems in the most optimum way for the particle accelerator performance. These approached are demonstrated below with two technologies: non-evaporable getter (NEG) coating and laser ablation surface engineering (LASE).

INTERACTION BETWEEN A BEAM AND A VACUUM CHAMBER

A primary role of vacuum chamber is providing a specified level of vacuum in order to minimise the interactions between the beam particles and the residual gas molecules. Thus, accelerator vacuum chamber should meet a number of vacuum specification: on leak tightness, thermal outgassing, photon and electron stimulated desorption (PSD and ESD), etc.

Additional specification may relate to interaction of synchrotron radiation generated by the beam and vacuum chamber or its components: photon reflectivity or absorption, thermal conductivity, photoelectron emissivity.

Finally, there is a direct interaction between the beam and vacuum chamber. Beam aperture defined the beam chamber transversal dimensions. Vacuum chamber material and its geometry defines a resistive wall wakefield impedance which, in turn, may lead to increase of the beam energy spread. Residual gas, photo- and secondary electron emission yield are key parameters for the build up of an electron cloud, which drives both single and multi-bunch instabilities, leading to the betatron tune shift and energy spread as well as an emittance growth.

NEG COATING

NEG coating technology, originally invented in CERN as a vacuum technology, is thin film of transitional metals (Ti, Zr and V) covering an entire surface of vacuum chamber and providing distributed pumping [1-4]. This allows reaching pressures below 10^{-13} mbar in vacuum chambers without synchrotron radiation, and significantly lower pressure in presence of SR than in uncoated chambers [5-6]. Presently, NEG coated chambers are widely used in many particle accelerators [7-14].

Vacuum properties

Over the last 20 years the NEG coating was further developed many focusing in these directions: (1) to increase sticking probability and sorption capacity, (2) to reduce an activation temperature, and (3) to reduce PSD and ESD.

The progress in increasing sticking probability and sorption capacity was achieved by employing an alloy target instead of twisted wires and depositing quaternary Ti-Zr-Hf-V films instead of ternary Ti-Zr-V [15-16]. Thus, the NEG coating pumping properties can be described as: sticking probabilities are $\alpha_{CO} \leq 0.4$, $\alpha_{CO2} \leq 0.6$, $\alpha_{H2} \leq 0.02$, and sorption capacities are $\Theta_{CO} \leq 3$ ML, $\Theta_{CO2} \leq 10$ ML.

The NEG coating activation temperature was reduced from 180 °C for Ti-Zr-V to 150-160 °C for Ti-Zr-Hf-V.

Reduction in PSD and ESD was achieved by careful cleaning of substrate before deposition, in-situ bakeout before deposition, and low background in a deposition chamber as well as high purity of discharge gas [17]. Vacuum firing of substrates allows to further reduce PSD and ESD by an order of magnitude [18].

All these studies were originally focused on columnar structure of the NEG coating. It was shown later that PSD and ESD can be further reduced with dense structure of the NEG coating because it effectively reduces the gas atoms diffusion from the substrate to the beam vacuum, but at the cost of reduced pumping properties [15-18].

* submitting author, e-mail: oleg.malyshev@stfc.ac.uk

Finally, a dual layer NEG coating consisting of dense NEG coating on a substrate followed by a columnar NEG film allow to combine the best properties of both [19].

PSD and pumping properties were reported in [20].

Secondary electron yield

An additional benefit of NEG coating is that its secondary electron yield (SEY or δ) could reach $\delta_{max} < 1$ [21-22]. Combined with vacuum properties described above it becomes an ideal solution for many applications, see Fig. 1.

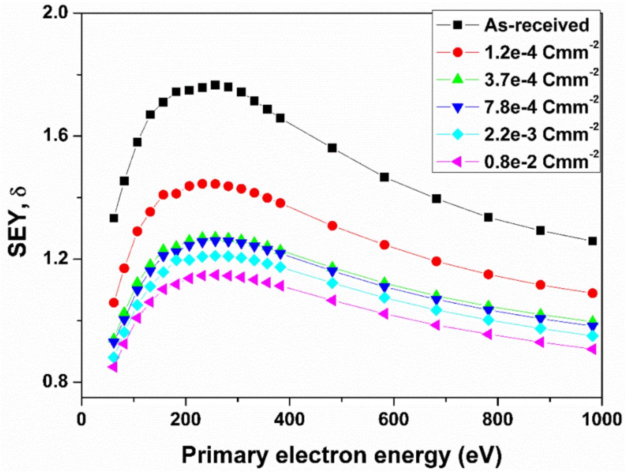

Figure 1: SEY of Ti-Zr-V NEG coating [22].

Photoelectron emission is another important characteristic of NEG; it was shown that it is approximately proportional to SEY [23]; more studies are still required.

Surface resistance

In short bunch accelerators a resistive wall wakefield impedance should be considered very seriously. The electric conductivity of NEG coating was experimentally studied at 7.8 GHz [24], on a facility shown in Fig. 2, and the main results are shown in Fig. 3.

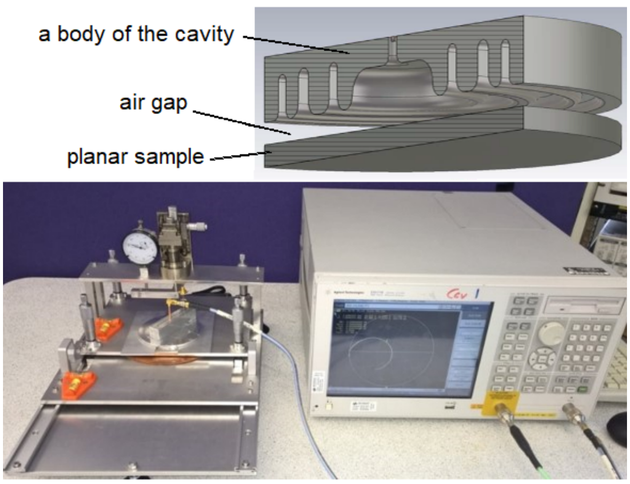

Figure 2: A facility for surface resistance measurements.

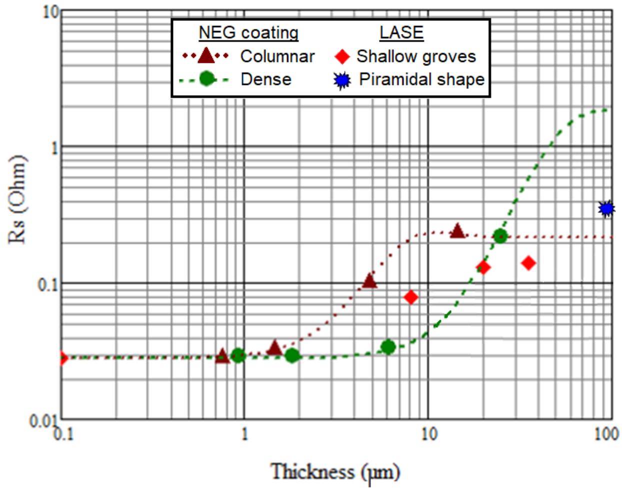

Figure 3: Surface resistance at 7.8 GHz for LASE and NEG coating on a copper substrate.

It was shown that electric conductivity of NEG coating depends on film morphology and varies between $\sigma_d = 1.4\times10^4$ S/m for columnar NEG coating and $\sigma_d = 8\times10^5$ S/m for dense NEG coating.

Thus, the surface resistance of NEG coatings depends not only on film morphology but also on substrate material, film thickness and RF frequency [25] as demonstrated on Fig. 4.

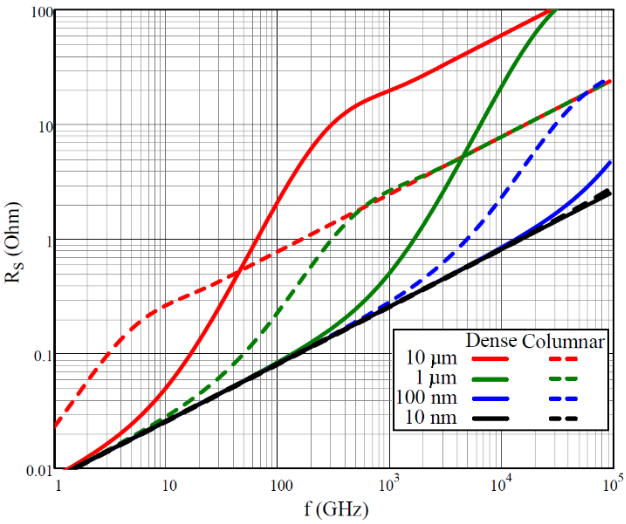

Figure 4: A calculated surface resistance of NEG coated copper as a function of RF frequency for different thickness of dense and columnar films.

Limitations

Physical vapour deposition (PVD) is a well-developed technology for film coating. It was demonstrated that vacuum chamber of different geometries can be successfully coated. However, it is still challenging to coat narrow vacuum chambers with a cross sectional size smaller than 5 mm.

LASE

Laser surface engineering is a technology that has been intensively developing over last ~25 years. Various structures or an hierarchy of structures could be formed as desired, using varied types of lasers [25-28].

Secondary electron yield

In 2014, it was discovered that the LASE surface can provide the surface with $\delta_{max} < 0.8$ on copper, aluminium and stainless steel surfaces [29,30]. Figure 5 shows an example of LASE surface obtained with a 355-nm laser with 40-kHz repetition rate, 10-μm pitch and 15 μm beam sport size. Figure 6 shows SEY for four samples obtained with different power and scan speed.

Further development allows reducing SEY to $\delta_{max} < 0.6$ [31-32]. The main advantage of this technology is that the laser surface treatment does not require vacuum, LASE can be done in air or in controlled gas atmosphere at atmospheric pressure.

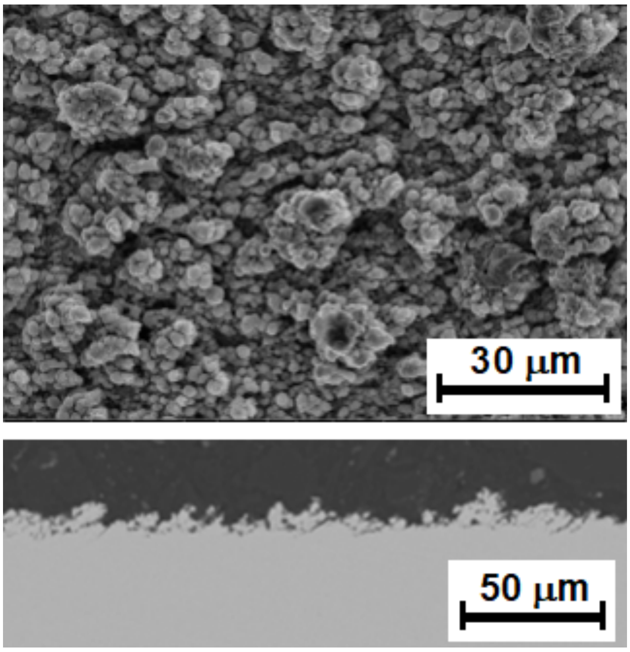

Figure 5: SEM images of LASE surface of Cu sample.

Over 100 structures were created and tested by ASTeC team, and more than 60% provide a surface with $\delta_{max} < 1$ [33]. An experimental study of a LASE treated screens on SPS confirmed the efficiency of e-cloud mitigation [34].

Vacuum properties

Thermal outgassing of Cu and 316LN surfaces with LASE is not greater than without LASE.

It is interesting that ESD of Cu surface with LASE treated in air and Ar is an order of magnitude lower than untreated Cu surface [35].

There still no data for PSD from LASE surface; however a PSD experiment will be performed in a few months on KARA with the H2020 EuroCirCol collaboration.

More vacuum evaluation testing should be done in the future for each material (different types of stainless steel, Cu and Al and their alloys, other materials of interest) and after various LASE procedures; this incudes effect of different cleaning procedures, bakeout, vacuum firing, etc.

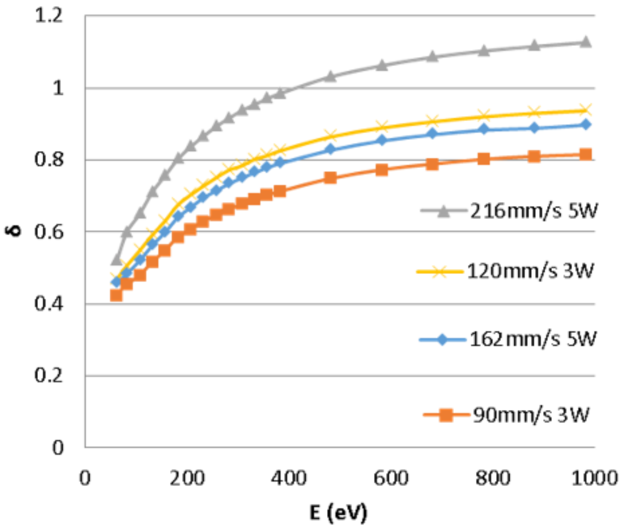

Figure 6: SEY as a function of incident electron energy for cupper samples after LASE treatment with laser power of 3 and 5 W and various laser scan speeds.

Surface resistance

LASE surface consist of a superposition or an hierarchy of few structures [31,32]: grooves with a depth between a few and 100 μm, submicron structures and ~100 nm structures. All these types of structures could increase the surface resistance. Calculating the surface resistance with surface roughness parameters does not provide correct results. Therefore, the surface resistance must be obtained experimentally. The surface resistance of the LASE surfaces shown in Fig. 3 was measured at 7.8 GHz on the same facility as NEG coating [31,35]. A Horizontal (Thickness) axis corresponds to the depth of surface layer affected by LASE (it is visible on cross sectional SEM images). The thinner this layer the lower the surface resistance of LASE surface.

Limitations

There are still a few problems that should be addressed. One of the main problems is particulate generation during LASE process. There is ongoing work to reduce particulate generation by varying laser parameters, applying gas flow, cleaning, etc., and to calculate a possible impact on the beam quality.

COMPARISON OF IMPACT OF E-CLOUD MITIGATION ON OTHER SYSTEMS

A comparison of impact of e-cloud mitigation with NEG coating and LASE on other systems is simplistically summarised in Table 1. Although the table is not complete, it allows to see that the characterisation of both NEG coatings and LASE surfaces has targeted a possible impact on other systems. Many experimental data have been obtained and published.

However, some data has been already obtained but not published yet, there are a few ongoing experiments to obtain the data and some important data are still missing.

The available information is sufficient to conclude that both technologies are, in general, compatible with particle accelerators; however, further characterisation of these technologies is still required for more confidence and for obtaining more data for a specific type of NEG coating or LASE surface in application to an upgraded or a new machine.

Table 1: Impact of e-cloud mitigation on other systems.

	LASE	**NEG coating**
SEY	$\delta_{max} < 0.6$	$\delta_{max} < 1$
PEY	PEY likely to scale with SEY.	PEY scaled with SEY [23]
Vacuum		
Thermal outgassing	Low	Negligible
PSD	To be studied (for example in the KARA experiment)	Lower than for 316LN • BINP and ESRF data, • experience from many machines
ESD	Much lower than for Cu	Much lower than for 316LN
Bakeout/activation temperature	150 – 300 °C	150 – 250 °C
Cryogenic vacuum system	Talks at this workshop: R. Cimino and a team (INFN); T. Sian (ASTeC);	BINP data [20]; A facility is under development in ASTeC
Beam wakefield impedance	Low R_s LASE surface development [36]	Low R_s NEG coating development (A. Hannah's talk at this workshop)
UFO	Particulate generation measurements and control [36]	Film delamination is negligible

CONCLUSIONS AND FUTURE DEVELOPMENT

The NEG coating originally developed as a vacuum solution and the LASE surfaces originally developed as a e-cloud mitigation solution have been developed to meet more specifications and become complex solutions for solving a few problems: UHV/XHV vacuum, e-cloud mitigation and wakefield beam impedance. An attention is paid to multiple specification and avoid the creation of new problems to other systems.

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