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In-situ plasma processing to increase the accelerating gradients of superconducting radio-frequency cavities

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ABSTRACT

A new in-situ plasma processing technique is being developed at the Spallation Neutron Source (SNS) to improve the performance of the cavities in operation. The technique utilizes a low-density reactive oxygen plasma at room temperature to remove top surface hydrocarbons. The plasma processing technique increases the work function of the cavity surface and reduces the overall amount of vacuum and electron activity during cavity operation; in particular it increases the field emission onset, which enables cavity operation at higher accelerating gradients. Experimental evidence also suggests that the SEY of the Nb surface decreases after plasma processing which helps mitigating multipacting issues. In this article, the main developments and results from the plasma processing R&D are presented and experimental results for in-situ plasma processing of dressed cavities in the SNS horizontal test apparatus are discussed.

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1. Field emission and end-group thermal instability limiting the accelerating gradients in the SNS linac

Field emission in superconducting radio-frequency (SRF) cavities is a well-known limiting factor for operation at high accelerating gradients [1–3]. Beyond certain electric field thresholds, the electrons from the metal surface of the cavity have a non-negligible probability of tunneling out. The field emitted electrons are accelerated by the stored electromagnetic fields in the cavity and subsequently deposit their energy by collision with the cavity radio-frequency (RF) surface leading to vacuum activity, increase of the surface temperature and Bremsstrahlung radiation. If the deposited energy-density is larger than the cooling capacity it can also lead to thermal breakdown of the superconductivity.

In the SNS superconducting linac (SCL), the end-groups, i.e. extremities of the accelerating cavities, are particularly prone to thermal instabilities since they are not actively cooled by liquid Helium but rather by conduction from the adjacent end-cells [4]. Experimental evidence has shown that field emission at the SNS is the main limiting factor for reaching higher accelerating gradients in operated cavities [5]. Fig. 1 shows the accelerating gradient and peak surface electric field of all 81 cavities (33 medium-beta cavities and 48 high-beta cavities) at 60 Hz operation in the SNS linac. The average operating accelerating gradient for the two cavity geometries at the SNS is 12.0 and 13.0 MV/m respectively. The corresponding average peak surface electric fields are 32.4 and 35.1 MV/m. The average accelerating gradient for radiation onset is 11.2 MV/m for medium-beta cavities and 9.3 MV/m for high-beta cavities. The radiation originates from electron activity due to multipacting and field emission.

The field emitted current density in the tunneling regime follows the Fowler-Nordheim equation [Wan]

$$J = a\frac{(\beta E)^2}{\phi} e^{-b\frac{\phi^{3/2}}{\beta E} + \frac{c}{\phi^{1/2}}} \quad (1)$$

where $a = 1.54 \times 10^6$, $b = 6.53 \times 10^3$ and $c = 10.4$ are constants, E is the electric field at the cavity surface in MV/m, β is the field enhancement factor, ϕ is the surface work function in eV and J is the current density in A/m^2. The most important feature of the field emitted current is its exponential dependence on the electric field. Once the field emission onset is reached, further increase of the accelerating gradient becomes increasingly difficult, especially for high duty-factor operation. The field emission onset gradient is defined as the electric field level leading to measurable field emitted current or related radiation.

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2. Increasing the work function to increase the accelerating gradient

To mitigate field emission one can minimize the peak surface electric field for a given accelerating gradient, decrease the enhancement factor, or increase the work function.

Minimizing the ratio of the peak surface electric field and accelerating gradient is part of the design optimization of an RF structure. The physics behind the field enhancement factor is still an active topic of research but avoiding microprotrusions and particulate contamination at the cavity surface is important during cavity fabrication [1,6,7], particularly in the high surface electric field regions of a cavity. For cavities in operation at the SNS, a new in-situ plasma processing technique aims at increasing the work function of the cavity inner surfaces to reduce field emission and increase stable accelerating gradients. Based on Eq. (1), the variation of the field emitted current density is given by

$$dJ = \partial_E J dE + \partial_\phi J d\phi \tag{2}$$

The field emitted current remains constant when $dJ=0$. After explicitly calculating the partial derivatives it leads to

$$\frac{dE}{E} = \frac{3}{2}\frac{d\phi}{\phi}\left(\frac{1+2\varepsilon/3+c\varepsilon/3\phi^{1/2}}{1+2\varepsilon}\right) \tag{3}$$

where the parameter epsilon is defined as $\varepsilon=\beta E/b\phi^{3/2}$. In good approximation for SRF cavities $\varepsilon \ll 1$ (e.g. $\varepsilon=0.04$ for $\beta=50$, $E=50$ MV/m and $\phi=4.3$ eV) and since the accelerating gradient E_{acc} is proportional to the surface electric field E it leads at first order to

$$\frac{dE_{acc}}{E_{acc}} = \frac{3}{2}\frac{d\phi}{\phi}(1+\varepsilon f(\phi)) \tag{4}$$

where the function $f(\phi)$ is given by

$$f(\phi) = \frac{c}{3\sqrt{\phi}} - \frac{4}{3} \tag{5}$$

Eqs. (4) and (5) are based on the Fowler-Nordheim equation for field emission in DC fields given in Eq. (1). But, using the equation for field emission in RF fields from [8] yields the exact same result to first order. For the case with $\beta=50$, $E=50$ MV/m and $\phi=4.3$ eV, the first order term is only 1.5% of the zeroth order value. Thus, the zeroth order approximation is sufficient in most cases:

$$\frac{dE_{acc}}{E_{acc}} = \frac{3}{2}\frac{d\phi}{\phi} \tag{6}$$

One concludes that for a cavity performance limited by field emission, increasing the cavity surface work function by 10–20% could lead to a 15–30% increase in the accelerating gradient.

3. Hydrocarbon contamination degrades the work function of niobium surfaces

The average work function of polycrystalline niobium reported in the literature is 4.3 eV [9]. It is worth noting that the work function for Niobium has an unusually large dependence on its crystal structure, with literature reporting up to 0.8–0.9 eV spread [9,10]. Due to its strong affinity with oxygen, the Niobium surface typically has a 5–10 nm thick Niobium oxide layer, with Nb_2O_5 as its outmost layer. The work function of the Niobium pentoxide reported in the literature is 5.2–5.3 eV [11], while the lower oxides have smaller work functions, for example 4.2 eV for NbO [12]. Surface oxidation, dislocations, contaminants, and adsorbates at cryogenic temperature can change the work function and affect the field emission process [13–15]. Thus, the work function for the surface of cavities in operation is difficult to know in practice.

Residual gas analysis of thermally cycled cryomodules at the SNS have shown evidence of volatile hydrocarbons being released from the inner surfaces of cavities, in addition to expected gases such as nitrogen, oxygen, water, argon and carbon dioxide found in air. Fig. 2 shows the partial pressure of various masses measured during the warm-up sequence of the cryomodule CM012 at the SNS from 2 K to room temperature using a residual gas analyzer (RGA) [16]. Hydrogen (H_2), methane (CH_4) and ethylene (C_2H_4) were identified from their mass, fragmentation patterns in the RGA and from the temperature at which they were released from the surface [16–18].

All RGA signals measured during thermal cycling of cavities must come either from released gases that were condensed on the surface at cryogenic temperature or from volatile species produced on the surface during cavity operation for example by the interaction of electrons with surface contaminants [19]. The exact initial chemical composition and bonding strength of hydrocarbons on the SNS cavity surfaces are not known so far, but evidence of hydrocarbons on other cavities have been reported in the literature [11,19,20].

SIMS (secondary ion mass spectrometry) measurements of niobium samples fabricated for plasma-surface studies at the SNS also showed evidence of hydrocarbons at and near the metal

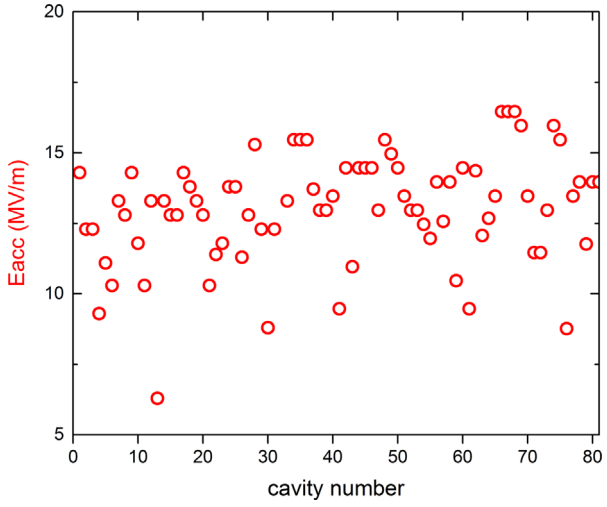

Fig. 1. Accelerating gradient (Eacc) of SNS cavities in operation at 60 Hz repetition rate.

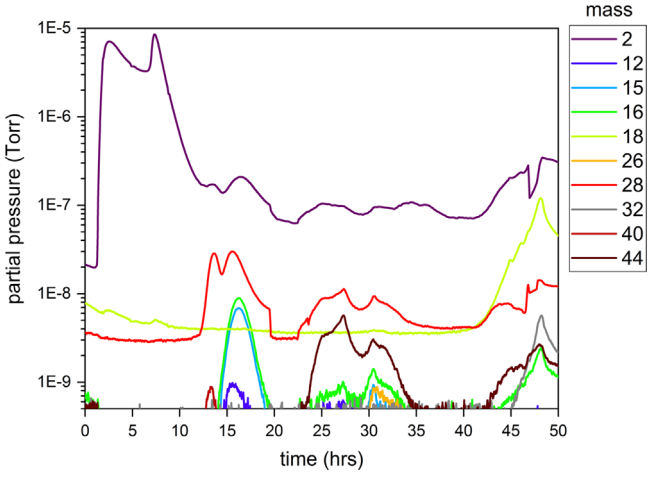

Fig. 2. Residual gas analysis during warming up of the cryomodule CM012 at SNS from 2 K to room temperature. Hydrocarbons such as methane (mass 16 at the 16 h mark) and ethylene (mass 28 at the 31 h mark) are released from the cavity surfaces.