SUPRESSION OF UPSTREAM FIELD EMISSION IN RF ACCELERATORS*

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Abstract

This paper illustrates the idea of suppressing prevalent field emission in RF accelerators in the upstream direction with a rather minor change to the typical configuration, i.e. not requiring a modification to the accelerating structures, but the interconnecting beam tube lengths. An example is presented for a pair of superconducting RF cavities for simplification.

INTRODUCTION

So-called electron loading in radio-frequency (RF) accelerating cavities is the primary cause for cavity performance limitations today. Electron loading can limit the desired energy gain, add cryogenic heat load, damage accelerator components and increase accelerator downtime depending on the induced trip rates. Trip rates are of particular concern for next generation facilities such as Accelerator Driven Subcritical Reactors or Energy Recovery Linacs for Free Electron Lasers.

Electron loading can be attributed to mainly three phenomena, i.e. field emission (FE), multiple impact electron amplification (short: multipacting) and RF electrical breakdown. In all cases, electrons are involved either being released from the enclosing RF surfaces or generated directly within the RF volume by ionization processes with the rest gas (even in ultra high vacuum), e.g. due to cosmic radiation. The free electrons can absorb a considerable amount of the RF energy provided by external power sources thereby constraining the achievable field level and/or causing operational failures.

Field emission has been a prevalent issue, particularly in superconducting RF (SRF) cavities [1], whereas RF electrical breakdown and multipacting can be controllable within limits by adequate design choices. Though SRF cavities may readily exceed accelerating fields (E_{acc}) of 20 MV/m, the onset of parasitic electron activities may start at field levels as low as a few MV/m. Field emission becomes a major concern when the electrons emitted are captured by the accelerating RF field and directed close to the beam axis through a series of cavities or cryomodules.

The electrons can then accumulate a comparable amount of energy as the main beam would over the same distance. This can present a considerable 'dark current' with damaging risks (e.g. when hitting undulator magnets). The electrons can be directed either down- or upstream the accelerator depending on the site and time of origin.

Figure 1 exemplarily shows the energy range of field-emitted electrons numerically computed for an upgrade cryomodule of JLab's electron recirculator CEBAF depending on the initial field emitter location along the cryomodule [2].

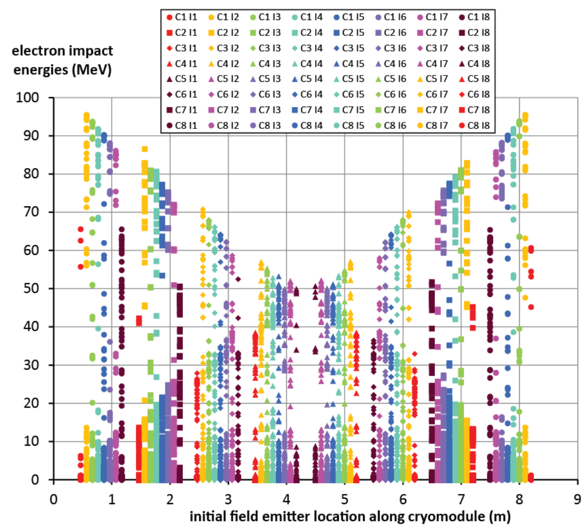

Figure 1: Possible impact energy range of electrons in an upgrade CEBAF cryomodule with all cavities operating at the nominal field level of E_{acc} = 19.2 MV/m totaling 108 MeV energy gain. The results are not fully mirror-symmetric due to numerical differences start conditions.

Housing eight seven-cell cavities, this covers all probable emitter sites seeded around irises, where the electrical surface field peaks (E_{peak}). The energies are plotted over the initial 8 × 8 iris regions covering all possible field emitting surfaces. Same colors represent same iris regions (1 through 8 for each cavity). A color code is given in the legend with C = cavity and I = iris with the corresponding number denoting the site of origin.

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The concern with FE stems from its exponential increase with E_{acc}, which is well verified experimentally. Note that FE is a quantum-mechanical process that can be described by the (simplified) Fowler-Nordheim (FN) equation:

$$J = \frac{I}{A_{eff}} = \frac{(\beta_{enh} \cdot E_{peak})^2}{\phi} \cdot a \cdot 10^{4.52 \cdot \phi^{-0.5}} e^{-\frac{0.956 \cdot b \cdot \phi^{3/2}}{\beta_{enh} \cdot E_{peak}}}. \quad (1)$$

J denotes the peak current density (in A/m^2) (current I over effective emission area A_{eff}), E_{peak} the local surface electrical field (in V/m), Φ the local material work function (in eV) and a and b the 1st and 2nd FN-constants, respectively ($a \approx 1.541434 \cdot 10^6$ $A \cdot eV \cdot V^{-2}$ and $b \approx 6.83089 \cdot 10^9$ $eV^{-3/2} \cdot V/m$). Field emission requires surface fields in the order of GV/m. Peak fields in SRF cavities however only reach up to a few ten MV/m. Therefore a local field enhancement factor β_{enh} is introduced, which in SRF cavities requires $\beta_{enh} > 50$ to produce meaningful emission currents. In fact, such large enhancement factors and higher are often encountered depending on the nature of the field emitter.

Emitted electrons eventually hit surfaces internal or external to cavity cryomodules depending on the site and time of origin, which determines trajectories and energies. Upon impact, electrons not only can create additional heating, but also can induce secondary particle showers and gamma rays via bremsstrahlung. This in turn can cause radio-activation of accelerator components once electrons accumulate energies above the threshold for neutron production, which is in the order of 10 MeV for the metals employed. For instance, very high radiation levels and radio-activation due to FE has been a concern in CEBAF upgrade cryomodules [2]. The primary process for neutron production by electrons is the absorption of bremsstrahlung photons, i.e. via photonuclear reactions [3]. The threshold energy can thus be obtained within a few cavity cells depending on field levels.

Maintaining extremely clean environments throughout cavity fabrication, post-processing and assembly is of major importance to mitigate particulates that may create FE sites. However, the existence of field emitters cannot be excluded even when obeying strict protocols following industrial standards. Based on today's experience a large fraction of SRF cavities remain plagued by FE.

COUNTERMEASURE BY DESIGN

A practical method to suppress FE in accelerating structures even in presence of field-emitting sites can be conceived by a subtle change. Though important for SRF cavity cryomodules, the method applies generally to any type of RF accelerator. The benefit is a significant reduction of energy accumulation of upstream traveling field-emitted electrons. This mitigates dark current directed to the injector. The method is deemed most efficient for speed-of-light (β =1) structures accounting for the fact that the electrons are swiftly accelerated to relativistic energies once captured by the RF field such that the travel distance per RF period is nearly equal to that of the main beam. The method does not require an alteration of the cavity design. We propose to merely adjust the beam tube length (L_{tube}) between cavities to obey:

$$L_{tube} = \left(N + \frac{1}{2}\right) \cdot L_{cell} \approx \left(N + \frac{1}{2}\right) \cdot \frac{\beta\lambda}{2}. \quad (2)$$

Herein L_{cell} is the cavity cell length (~βλ/2, λ = wavelength of accelerating mode) and N an integer number. L_{tube} is often chosen to be $3 \cdot L_{cell}$ in SRF cavity cryomodules (e.g. EU-XFEL, LCLS-II, CEBAF upgrade cryomodules (except the middle section)). This implies that RF fields in cavities oscillate synchronously at all times. The main beam accelerated in one cavity will then experience the same accelerating field after passage to the next cavity without phase adjustment (theoretically and assuming constant velocity). However, the RF phase can be technically tuned for each cavity depending on the tube length. The cavity interconnecting tube length cannot be chosen arbitrarily small, since it has to accommodate space for fundamental power couplers, pick-up probes for RF feedback control as well as HOM dampers and bellows depending on design requirements.

One also has to take into account isolation requirements between couplers of neighbouring cavities to avoid cross-talk effects that impede the low level RF control. This for instance concerns crosstalk between a power coupler of one cavity and the pick-up probe of the adjacent cavity or two power couplers facing each other. When using stainless steel bellows between cavities, the thermal losses in the bellows favour to place cavity flanges further away from the cavity cells. All above considerations usually make N = 0 and 1 impractical in SRF cryomodules. For N = 2 ($L_{tube} = 2.5 \cdot L_{cell}$) however one obtains a reasonably long section for practical and thermal requirements, while saving cryomodule length and thus costs compared to $3 \cdot L_{cell}$. Otherwise N = 3 should be chosen.

Figure 2 shall demonstrate the benefit considering two interconnected cavities for simplicity. It depicts the RF amplitude (normalized) in both cavities as a function of time when utilizing $L_{tube} = 3 \cdot L_{cell}$ and $L_{tube} = 2.5 \cdot L_{cell}$, respectively. For $L_{tube} = 3 \cdot L_{cell}$ there is no phase difference between the RF field amplitudes of the cavities (top plot). The main beam is represented by blue dots. The first bunch (leftmost dot) occupies one of the possible RF buckets at the chosen start time. At this moment one may imagine that the bunch center is in the mid of the last cell of the upstream cavity when the field just peaks (+1). This yields maximum acceleration downstream. After traveling a time corresponding to a length of $L = L_{tube} + L_{cell}$ the bunch will pass the center of the 1st cell of the subsequent cavity (2nd blue dot) experiencing an accelerating field again (+1).

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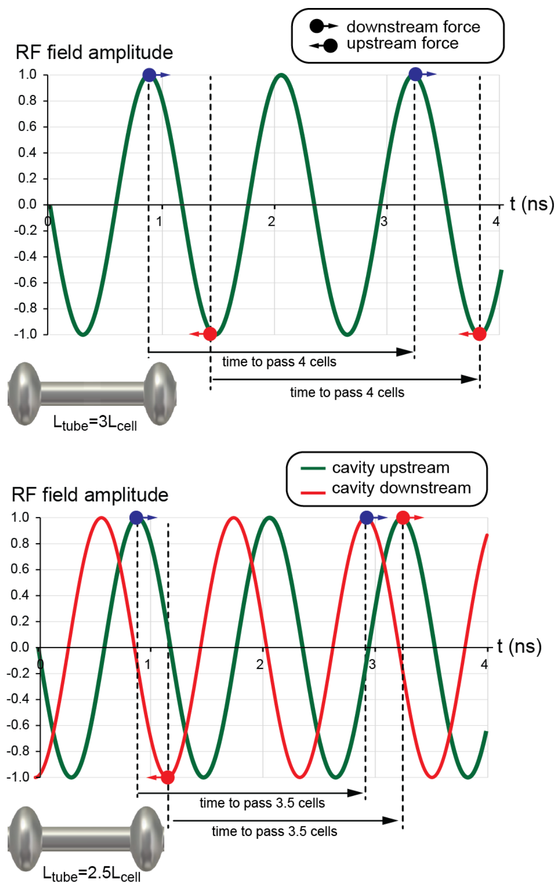

Figure 2: Normalized RF field amplitudes as a function of time for two adjacent cavities. Top: Intermediate tube length $L_{tube} = 3 \cdot L_{cell}$. Bottom: Intermediate tube length $L_{tube} = 2.5 \cdot L_{cell}$. See text for further explanation.

Field-emitted electrons moving downstream would be accelerated in the same way once efficiently captured by the RF assuming no significant phase slippage occurs. Electrons directed upstream will have to start when the field peaks in the opposite direction (-1) corresponding to a 180° phase shift to the accelerating field in the same cell. Assuming this to be the time when field-emitted electrons arrive in the mid of the 1st cell in the downstream cavity (leftmost red dot), these will reach the end cell of the upstream cavity when the field peaks again for further acceleration upstream (-1 at 2nd red dot). Consequently in this case ($L_{tube} = N \cdot L_{cell}$), electrons may accumulate the same energy gain whether directed up- or downstream. For the case when $L_{tube} = 2.5 \cdot L_{cell}$ (bottom plot) the RF phase of the downstream cavity (red curve) has to be adjusted in order to be synchronous with the main beam (blue dots). This requires a relative RF phase shift of 90° with respect to the upstream cavity (green curve). Field-emitted electrons directed downstream would still experience energy accumulation as in the former case. However, field-emitted electrons originating in the downstream cavity will have to start when the field peaks in opposite direction (-1). If we assume the 1st red dot (leftmost) corresponds to the time the electrons are located in the center of the 1st cell of the downstream cavity - not restricting generality - then by the time the electrons travel to the end cell of the upstream cavity the RF field will be decelerating (+1). Therefore, field-emitted electrons directed upstream in the way described above will lose all the energy accumulated previously.

Note that in reality field-emitted electrons are emitted during a finite phase range. This causes differing trajectories and energy spread among particles. Perfect energy annihilation cannot be achieved for all possible trajectories.

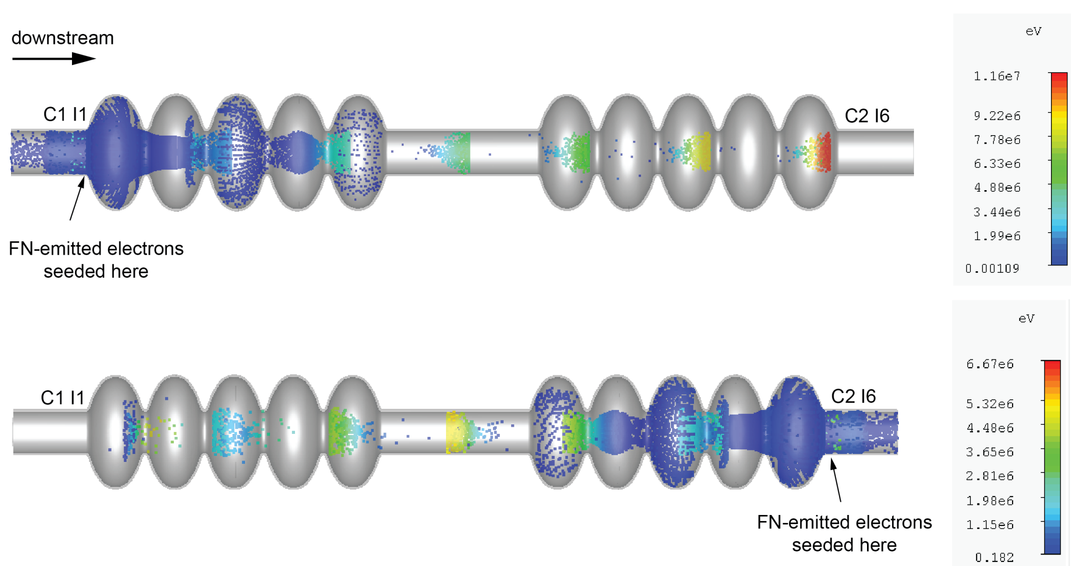

Figure 3: Electrons traveling through two five-cell cavities, which are phased to provide maximum energy gain for the main beam. Top: Electrons are continuously field-emitted at the 1st iris of cavity 1 (C1 I1). Bottom: Electrons are continuously field-emitted at the last iris of cavity 2 (C2 I6).

Trajectories also depend on the specific cavity shape. The proposed method however provides a significant reduction of upstream energies in all conceivable cases when obeying Eq. (2).

Figure 3 illustrates two numerical case studies for a string of two five-cell cavities. The difference is only the initial FE region. In both cases electrons are seeded into the RF volume according to the Fowler Nordheim equation covering several RF cycles sufficient for electrons to pass the full string. It allows electron bunches being emitted over a relatively wide phase space at times when the field peaks. The colors correspond to the electron energy as denoted in the legends. The cavity interconnecting tube length is $L_{tube} = 2.5 \cdot L_{cell.}$ The RF frequency is 1.5 GHz yielding an active length of ~0.5 m for a single cavity. Both cavities are operating at E_{acc} = 12.5 MV/m corresponding to 6.25 MeV energy gain per cavity. The cavities in both cases are phased such that a main bunched beam at $\beta = 1$ would experience the maximum energy gain of 12.5 MeV passing both cavities. In the upper plot the field-emitters symmetrically occupy the region around the 1st iris of cavity 1 upstream (C1 I1). Here, those electrons captured close to the beam axis experience an energy gain of 11.6 MeV at the exit of cavity 2, slightly short of the 12.5 MeV feasible, which is a consequence of the particles emitted only with a few eV at the surface. In the bottom plot the seeding site is around the last iris of cavity 2 (C2 I6). Now only cavity 2 provides ideal conditions for acceleration in upstream direction with the maximum energy reached within the beam tube, whereas cavity 1 decelerates the beam. Some electrons come to almost a complete stop at the exit of cavity 1 (upstream) and present the least harm with regard to electron loading effects. This is in principle agreement with the simplified analytical approach depicted in Fig. 2. Some electrons initially dragging behind the leading particles however can exhibit a large phase slippage and are therefore not as efficiently decelerated. These may accumulate a few MeV energy again within cavity 1, which is yet significantly lower than in case of $L_{tube} = N \cdot L_{cell.}$ Furthermore, the maximum energy accumulated is likely to decrease in a longer chain of cavities for the same particles as long as $L_{tube} = (N+1/2) \cdot L_{cell}$.

SUMMARY

A practical method has been described for the suppression of upstream-directed field emission in RF accelerators. The method is not restricted to a certain number of cavity cells, but ideally requests similar operating field levels in all cavities to efficiently annihilate the once accumulated energy. Such a field balance is desirable to minimize dynamic RF losses, but not necessarily achievable in reality depending on individual cavity performance (e.g. early Q_0-drop or quench field). Yet, even with some discrepancy in operating fields one can expect a significant energy reduction for upstream-directed electrons within a relatively short distance. Electrons will then impact surfaces at rather low energies. With the dark current being reduced, so are issues with heating and damage of accelerator components as well as radiation levels including neutron generation and thus radio-activation. The only implication is that the accelerator cannot be used for scenarios, which envision the acceleration of beams in both directions.

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