Electric-field-assisted moderator for generation of intense low-energy positron beams

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In this paper we reexamine an old idea of using an electric-field-assisted moderator (FAM) based on a rare-gas solid (RGS) to form intense low-energy positron beams. Contrary to common belief, the main body of a successful FAM should consist of a dirty (a high level of molecular impurities) RGS which will allow for a high e^+ drift velocity. On top of this layer is condensed a thin layer of a highy-purity RGS. When the e^+ enters this latter region its energy will heat up, and e^+ emission into vacuum will become possible despite a positive e^+ affinity of the RGS. Simple calculations show that the e^+ intensity can be increased by a factor of 100 over what can be achieved using a RGS moderator without an applied electric field and, equally important, the e^+ transverse energy is reduced to less than 0.3 eV. This leads to a gain in brightness by a factor of 1000.
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Currently, significant efforts are taking place around the world toward the development of intense low-energy positron beams. Almost entirely, the main push concentrates on the production of stronger β^+ sources and the application of high-current and high-energy (100's of MeV) e^- linear accelerators (LINAC's) to produce intense sources of high-energy positrons. For a general reference to intense e^+ beams, see Ref. 1.

Many new low-energy positron techniques need in excess of $10^8 e^+$/s in order for them to become practical. This includes low-energy positron diffraction,[2] two-dimensional angular correlation of annihilation γ rays,[3] the low-energy positron microscope,[4] and possibly the formation of a positron microprobe. The development of intense e^+ beams is also important for exotic experiments such as Bose condensation[5] and for Ps liquid studies.[6]

A low-energy positron beam can be formed by stopping high-energy β^+ particles in a rare-gas solid[7] (RGS). For a RGS the e^+ affinity, ϕ_+ is positive and, therefore, the driving force of RGS moderators is hot e^+ diffusion and if an e^+ encounters the external surface before its kinetic energy has fallen below the vacuum level emission may occur. Below the threshold for positronium formation, only the weak phonon interaction is available for further e^+ slowing down. When a RGS moderator is combined with a 100-m Ci ^{22}Na source, an e^+ beam intensity of $1-5\times10^6 e^+$/s, and with an energy width of $\sim$2.5 eV may result.[8]

When a RGS is used to convert β^+ particles into low-energy positrons, it should be possible to enhance the e^+ intensity by applying an electric field E across the RGS. Several discussions of a field-assisted moderator (FAM) exist in the literature,[9] and some years ago, the first FAM was produced[10] using solid Ar and an enhancement of the moderator efficiency, ϵ_+ by a factor of 3 was observed as compared to the zero-field value. This first production of a FAM was important in the sense that it showed that it is possible to construct a FAM for the generation of e^+ beams. However, the achieved gain in the e^+ intensity was modest. The purpose of this paper is to prove that it is possible to construct a powerful FAM based on a RGS.

Below, we discuss the physics of a RGS-based FAM ignoring the effect of charging of the RGS by the β^+ source. In the Appendix, however, we will address the charging of the RGS, an effect that will strongly reduce the electric field in the bulk of the RGS unless special precaution is taken.

It is not difficult to estimate ϵ_+ for a FAM. By ignoring finer details, we assume an exponential stopping profile of the β^+ particles given by $(1/\rho_o)e^{-\rho/\rho_o}d\rho$, where ρ is the distance into the FAM expressed in mg/cm^2 and ρ_o is a characteristic constant being about 22 mg/cm^2 for ^{22}Na.[11] Let L be the thickness of the RGS, w the drift velocity and τ the e^+ lifetime; then, with D representing the density of the RGS we can express ϵ_+ as

$$\epsilon_+ = \left(\frac{C_{\beta^+}\cdot D}{\rho_o}\right)\int_0^L e^{-Dx/\rho_o}e^{-(L-X)/w\tau}dx\Big|_{(\partial\epsilon_+/\partial L)=0}$$
$$= C_{\beta^+}(DW\tau/\rho_o)^{1/[1-(DW\tau/\rho_o)]} = 0.016, \tag{1}$$

where we used D=2g/cc and $w\tau=(10^6\text{cm/s})(4\times10^{-10}\text{ s}) = 4\times10^{-4}$ cm. C_{β_+} is the fraction of β^+ particles that escapes the ^{22}Na source, and we have assumed $C_{\beta_+}=0.5$. With this value of ϵ_+ an e^+ beam intensity of $5\times10^7 e^+$/s should be possible using about 100 m Ci of ^{22}Na to supply the β^+ particles. The value of $w=10^6$ cm/s corresponds to the saturation drift velocity w_{sat} of excess electrons (w_{sat} for the e^+ is not known) in high-purity RGS's.[12]

One way to increase ϵ_+ over the value given in Eq. (1) is to increase w_{sat}. To see how this is possible, let us make an analytical approach to the problem. By assuming a constant mean free path λ, we can write the rate of change of the e^+ energy as

$$\frac{d\epsilon}{dt} = -\frac{\delta\epsilon v}{\lambda} + \frac{e^2\lambda E^2}{mv}, \tag{2}$$

where $\delta\epsilon$ is the average energy loss per collision, v is the actual velocity of the e^+ ($v \gg w$), and E is the applied electric field. On the right-hand side of Eq. (2), v/λ is the scattering rate, whereas the second term equals ewE. If we assume $d\epsilon/dt=0$ we obtain the average e^+ energy as

$$\langle\epsilon\rangle = \frac{1}{2}\frac{e^2\lambda^2E^2}{\delta\epsilon}. \tag{3}$$

The positron mobility μ is given as

$$\mu = \frac{e\lambda}{mv}. \tag{4}$$

By solving Eq. (3) for v and substituting that expression into Eq. (4), and by using $w=\mu E$, we obtain

$$w = w_{sat} = \left(\frac{\delta\epsilon}{m}\right)^{1/2}. \tag{5}$$

It is observed that w does not depend on E and, therefore, we equate this value of w to w_{sat}. Equation (2) is not valid for small E, as we have ignored elastic and superelastic collisions and furthermore assumed $\delta\epsilon$ to be constant. At large E these effects become unimportant, and Eq. (2) represents a reasonable approximation. The significance of Eq. (5) is that w_{sat} is linked directly to $\delta\epsilon$.

Equation (5) suggests that w_{sat} can be increased by adding an amount of molecular impurities to a RGS whereby $\delta\epsilon$ increases. An effect like this was demonstrated for excess electrons in Ref. 13. By adding a few percent of molecules like H_2, N_2, CH_4, C_2H_6, and C_3H_8 to liquid Ar, Kr, and Xe, they were able to increase w_{sat} by a factor between 2 and 7 depending on the added molecules and the particular rare-gas liquid.

Let us now discuss how to construct a FAM based on a RGS. To ensure a high value of w_{sat} for the positrons, the main body of the moderator should consist of a solid mixture of rare-gas atoms and suitable molecules (a few percent). We designate this part of the moderator RGSM. The thickness of the RGSM should equal 40 μm if we assume $w_{sat}=5\times10^6$ cm/s. On top of the RGSM is condensed a thin layer of a high-purity RGS, and an electric field is applied across the entire package. Figure 1 shows a sketch of the principle of how such a FAM works (refer to the Appendix for charging effects). For a practical purpose, all the β^+ particles that are absorbed in this FAM are stopped in the RGSM region. If an electric field is not applied, then the high concentration of molecular impurities in the RGSM would lead to complete thermalization of the e^+'s. However, as we wish to apply a sufficiently strong electric field such that w_{sat} can be achieved the average e^+ energy will probably be ~0.5 eV. It is possible that the concentration of molecular impurities in the RGSM should be higher than a few percent whereby the e^+ energy distribution becomes closer to that of a thermalized e^+. In the work of Ref. 13, no maximum of w_{sat} was found as a function of the concentration of molecular impurities in the rare-gas liquids. It may even be possible that the RGSM should consist entirely of a molecular solid providing ϕ_+ for this solid is less than that of the RGS top layer. If the RGSM consists of a molecular solid then $w_{sat}>10^7$ cm/s may be possible. As the e^+'s drift into the high-purity RGS top layer, the e^+ energy distribution will heat up and the e^+'s will scatter off the RGS-vacuum interface until either annihilation takes place or the e^+'s acquire an energy parallel to the surface normal greater than ϕ_+ whereby emission into vacuum may occur.

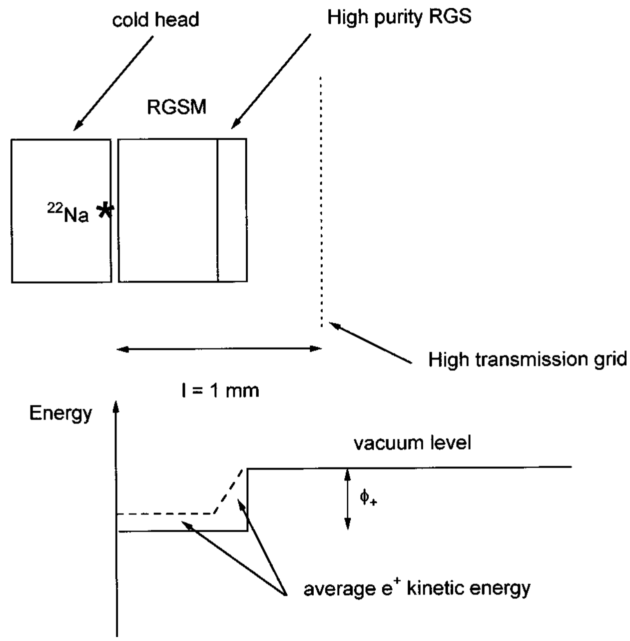

FIG. 1. Sketch of the principle of how a field assisted moderator for generation of intense e^+ beams can be realized. The lower part of the figure illustrates the potential energy of the e^+'s in the moderator as well as their average kinetic energy.

For a practical realization of the FAM construction of Fig. 1, two critical parameters have to be discussed. First, what is a suitable molecular impurity that should be added to the RGSM part of the FAM. Second, we must make some estimate of the electric field strength needed such that the e^+ can escape into vacuum from the high-purity RGS top layer.

For the molecules to be added to the RGSM part of the moderator, it is very important that these are not able to react with the e^+ to form a bound state. From gas-phase studies of e^+ interactions with molecules,[14] it is well known that e^+ becomes trapped on many heavier hydrocarbons, whereas e^+ does not seem to attach to simpler molecules like H_2, N_2, O_2, CO, CO_2, and CH_4. We emphasize that it is not obvious that the gas-phase results apply when these molecules are in a solution of a RGS. The choice of suitable molecules to add to the RGSM must result from experiments.

To estimate the electric-field strength needed to ensure that e^+ emission into vacuum can occur from the RGS top layer, we use the results of Gullikson and Mills,[7] who measured the values of ϕ_+, $\delta\epsilon$, and λ for e^+ interaction with solid Ar to be $\phi_+=1.7$ eV, $\delta\epsilon=6$ meV, and $\lambda=20$ nm. For solid Xe the corresponding numbers are $\phi_+=1.6$ eV and $\delta\epsilon=3$ meV, whereas the value of λ was not given for this solid, so we have assumed it to be equal to that for Ar. In Table I we give the fraction R of e^+'s which enter the RGS top layer that is emitted into vacuum as a function of electric-field strength. The values of R were calculated assuming isotropic scattering, an initial e^+ energy of 20 K and an e^+ lifetime of 0.4 ns. Quantum reflection of the e^+ wave

TABLE I. Calculated values of R as a function of electric-field strength E for various combinations of ϕ_+ and $\delta\epsilon$. The uncertainties of R are less than 5%.

RGS	E (kV/mm)	ϕ_+ (eV)	$\delta\epsilon$ (meV)	R
Ar 1	10	1.7	6	0.96
Ar 2	9	1.7	6	0.93
Ar 3	8	1.7	6	0.9
Ar 4	7	1.7	6	0.77
Ar 5	6.5	1.7	6	0.58
Ar 6	6	1.7	6	0.31
Xe 1	10	1.6	3	0.98
Xe 2	9	1.6	3	0.94
Xe 3	8	1.6	3	0.96
Xe 4	7	1.6	3	0.95
Xe 5	6	1.6	3	0.89
Xe 6	5	1.6	3	0.68
Xe 7	4.8	1.6	3	0.64
Xe 8	4.5	1.6	3	0.49
Xe 9	4.3	1.6	3	0.36
Xe 10	4	1.6	3	0.18
Xe 11	10	1	3	0.98
Xe 12	8	1	3	0.98
Xe 13	6	1	3	0.97
Xe 14	5	1	3	0.91
Xe 15	4	1	3	0.75
Xe 16	3.7	1	3	0.61
Xe 17	3.5	1	3	0.49
Xe 18	3.2	1	3	0.23
Xe 19	3	1	3	0.11

function at the RGS-vacuum interface is not included in these calculations, as this effect is not the limiting factor.

In addition to the values of R for the ''measured'' values of ϕ_+, $\delta\epsilon$, and λ for solid Ar and Xe, we have included a sequence of calculations in which we lowered ϕ_+ to 1 eV. If the e^+ affinity is mainly determined by the e^+ polarization of the RGS then ϕ_+ should be less than 1 eV.

Although the e^+ energy distribution in the high-purity RGS may never come into equilibrium with the E, it is reasonable to expect R to be a simple function of the following scaling parameter $E^2/(\delta\epsilon\phi_+)$ for a fixed value of λ [see Eq. (3)]. That this is indeed the case is shown in Fig. 2. A good, but slightly too low, estimate of the required electric-field strength is obtained by equating $\langle\epsilon\rangle=\phi_+$ leading to $E=(2\delta\epsilon\phi_+)^{1/2}/(e\lambda)$. On the right-hand y axis is shown the predicted e^+ intensity $(\epsilon_+R)N_+$ where N_+ is the β^+ activity of a 100-m Ci ^{22}Na source.

An inspection of Table I shows that for the examples treated, E should be in the range 5–10 kV/mm to obtain maximum e^+ intensity. If E is applied in the way shown in Fig. 1, the actual potential of the cold head should be twice that implied by the distance 1 to the ground grid due to the dielectric constant of the RGS. If the grid can be positioned right at the FAM surface, then the dielectric constant of the RGS is not an issue, and the electric field in the moderator is simply given by the applied voltage divided by the thickness of the FAM.

The values of R given in Table I and Fig. 2 are slight

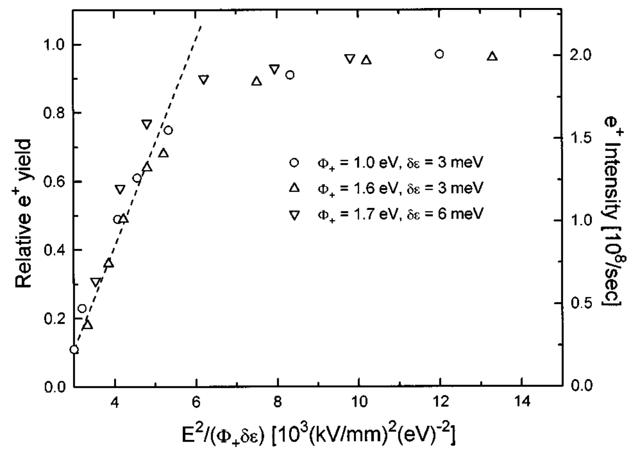

FIG. 2. An illultration of how the relative e^+ yield depends on the scaling parameter $E^2/(\phi_+\delta\epsilon)$. On the right-hand y axis is shown the predicted e^+ intensity using a 100-m Ci ^{22}Na source to supply the β^+ particles. The total moderator efficiency corresponds to $\epsilon_+R=0.062R$.

overestimates as the e^+ energy was allowed to increase beyond the first encounter with the RGS vacuum interface. This was done to enable R to be displayed as function of the scaling parameter $E^2/(\phi_+\delta\epsilon)$. However, the maximum energy the e^+ can gain from E in the RGS top layer of thickness l' is eEl'. To estimate l', we write the average e^+ energy as

$$\langle\epsilon\rangle=eEl'-n_c\delta\epsilon, \tag{6}$$

where n_c is the average number of positron collisions during its drift through the RGS top layer. Using $n_c=2(\epsilon)l'/(\lambda^2eE)$, we can write

$$l'=\frac{\phi_+}{E-5\dfrac{\delta\epsilon\phi_+}{E}}\,[\mu\mathrm{m}], \tag{7}$$

where we have used $\langle\epsilon\rangle=\phi_+$. The units of E, ϕ_+, and $\delta\epsilon$ are kV/mm, eV, and meV.

Figure 3 shows calculated values of R and the e^+ intensity versus l' for various field strengths for the parameters $\phi_+=1$ eV, $\delta\epsilon$=3 meV, and λ=20 nm. For these parameters, Eq. (7) reads

$$l'=\frac{1}{E-\dfrac{15}{E}}\,[\mu\mathrm{m}], \tag{8}$$

showing that this way of estimating l' puts us on the right track.

Figure 3 also shows measured e^+ intensities for a standard RGS moderator[8] (without an electric field) and for a tungsten film.[15] Our calculated e^+ intensity for the RGS moderator for $E=0$ also shown in Fig. 3 compares favorably to the experimental value. Figure 3 shows that the electric field may increase the e^+ intensity by almost two orders of magnitude.

In Fig. 4 we show the brightness B and transverse energy ϵ_t of the emitted e^+'s versus l' for the same values of the parameters as in Fig. 3. The values of B are obtained as B

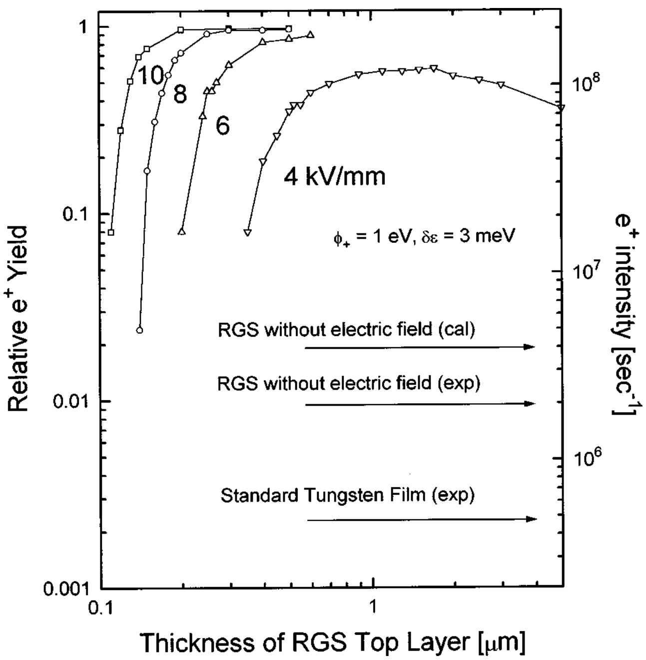

FIG. 3. Relative e^+ yield R vs the thickness of the RGS top layer for various electric-field strengths. The right-hand y axis shows the predicted e^+ intensity. Also shown is the e^+ intensities when a standard RGS and a tungsten film moderator are used to form a low-energy e^+ beam. All the e^+ intensities assume that the β^+ particles are supplied by a 100-m Ci ^{22}Na source.

$=R/\epsilon_t$. It is obvious that to obtain a small value of ϵ_t, l' should be small such that only few inelastic collisions take place and E should be large to ensure a sufficient e^+ energy gain. At 10 kV/mm the brightest e^+ beam results with $l'=0.14\ \mu$m, yielding an e^+ intensity of $1.4\times10^8 e^+$/s with $\epsilon_t=0.13$ eV, whereas at 4 kV/mm the corresponding numbers are $l'=0.52\ \mu$m, $0.8\times10^8\ e^+$/s, and $\epsilon_t=0.19$ eV. To compare B to a standard RGS moderator and to a tungsten film, we assume the e^+ beam diameters to be identical. With

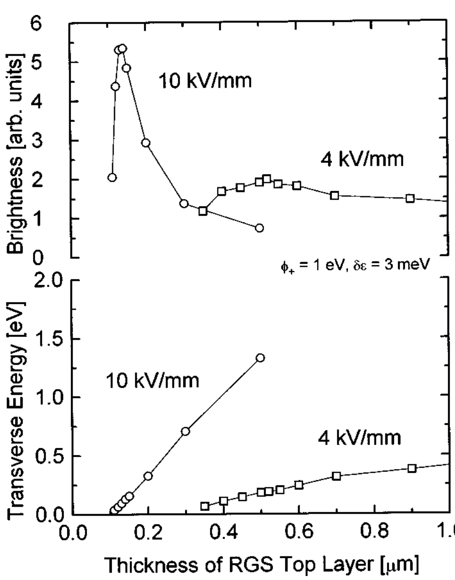

FIG. 4. Brightness and the transverse energy of the emitted positrons vs thickness of the RGS top layer for various electric-field strengths (see text).

this restriction we can calculate B to be $B=0.06$ (tungsten) and $B=0.006$ (RGS) showing that the present scheme of producing a low-energy e^+ beam may result in a brightness gain of 100–1000.

For the parameters $\phi_+=1.7$ eV, $\delta\epsilon$=6 meV, and λ=20 nm, the brightest e^+ beam produces $1.3\times10^8 e^+$/s with $\epsilon_t=0.33$ eV at 10 kV/mm and $l'=0.32\ \mu$m, whereas at 6 kV/mm and $l'=0.7\ \mu$m we obtain $0.5\times10^8 e^+$/s and $\epsilon_t=0.32$ eV. The maximum e^+ intensities are $1.8\times10^8 e^+$/s at 10 kV/mm and $l'=0.6\ \mu$m and $0.7\times10^8 e^+$/s at 6 kV/mm and $l'=2\ \mu$m.

Let us now discuss the value of the average energy loss $\delta\epsilon$ per e^+ collision. Equation (5) gave us a relationship between $w_{\rm sat}$ and $\delta\epsilon$. If we assume $w_{\rm sat}$ for e^+ to be equal to that for excess electrons we can calculate the average energy loss per collision in a RGS to be $\delta\epsilon$=0.6 meV which is a much more reasonable value than that deduced by Gullikson and Mills,[7] when compared to the maximum phonon energy available. The implication of Ref. 7's findings is that practically all e^+ scattering in RGS's is inelastic. The much smaller value of $\delta\epsilon$ obtained by use of Eq. (5) allows room for elastic e^+ scattering in RGS's as well. A recent determination of $\delta\epsilon$ for solid Ar gave 1.1 (+0.4, −0.5) meV,[16] in fair agreement with our estimate of 0.6 meV. The result of the above analysis may reduce the values of E given in this paper by a factor of 2–3. This should allow the FAM configuration of Fig. 1 to work with a potential difference of 3–5 kV between the cold head and the ground grid ($l=1$ mm) which is low enough for many types of e^+ experiments.

If the present approach to a FAM is realized, it will result in an e^+ beam intensity 100 times higher than that of a standard RGS moderator and, equally important, with a considerable reduction of ϵ_t. The total brightness gain is about a factor of 10^3.

By using a 100-m Ci ^{22}Na source to supply the β^+ particles an e^+ beam intensity greater than $10^8 e^+$/s and with an ϵ_t less that 0.2 eV may result. Such an improvement will allow standard university laboratory e^+ beams to be used in the development and use of the many new e^+ techniques mentioned at the beginning of this paper.

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APPENDIX: CHARGING EFFECT

Somewhat arbitrarily, we shall assume that on average 300 electron–positive-ion pairs are created in the RGSM per emitted β^+ particle. Using a 100-m Ci ^{22}Na source, that amounts to the generation of 10^{12} electron-ion pairs/s. By ignoring the dielectric constant of the RGSM, the number of stored positive charges on the cold head in the absent of charging of the RGSM is 5×10^{10} for the configuration shown in Fig. 1. Furthermore, we ignore geminate electron–positive-ion recombination and assume that all secondary electrons that are emitted into the vacuum are returned to the RGSM by the e^+ beam potentials. For homogeneous electron–positive-ion recombination we can write the rate constant k as

$$k = 4\pi D r_c, \tag{A1}$$

where D is the diffusion coefficient of the electrons and r_c is the separation distance of a charge pair where the Coulomb energy equals the characteristic kinetic energy ϵ_c of the electron. By using $D/\mu = \epsilon_c/e$ we can rewrite Eq. (A1) as

$$k = \frac{\mu e}{\epsilon} = 10^{-4}\ \mathrm{cm}^3/\mathrm{s}, \tag{A2}$$

where we have assumed an electron drift velocity of 10^7 cm/s at a field strength of 10^5 v/cm. In Eq. (A2), ϵ is the dielectric constant. Equations (A1) and (A2) represent upper limits of the recombination rate constant. The average time the secondary electrons spend in the RGSM before they are collected at the cold head equals that of the positrons (=0.2 ns) so for half of the secondary electrons to recombine with the positive ions requires a density of positive ions in the RGSM of 3.5×10^{13} cm^{-3}, corresponding to a total number of positive ions in the RGSM of 1.5×10^{11}, a number that is comparable to the number of positive charges stored on the cold head in absent of charging. For this reason, we shall ignore electron–positive-ion recombination as long as the electrons are free to recombine at the cold head. In principle, an electron gun giving mA's of electrons could be used to control the density of positive ions proving the power dumped on the RGSM is sufficiently low, and that the implantation energy is below the ionization threshold of the moderator.

The effect of charging of the RGSM is that the electric field in the bulk of the moderator almost vanishes. In the upper part of Fig. 5 we show how the field changes as function of charge-up of the moderator. Starting with no charge-up, the total number of positive charges in the moderator is increased in incrementals of 5×10^8 ions distributed according to the β^+ implantation profile used in Eq. (1). The trend shown in Fig. 5 (upper part) continues until the total amount of positive charges is a little greater (due to the finite thickness of the moderator) than the number of positive charges on the cold head in absent of charging. At this stage the electric field reverses direction close to $z=0$ and, therefore, prevents electrons from being collected at the cold head. With further β^+ injection, electron–positive-ion recombinations occur near the crossing point of the electric field (that is the position where the electric field is zero) which move toward the surface of the moderator. When a steady-state condition is reached, most of the positive charges are localized close to the surface (on the vacuum side) of the moderator, leaving only a weak electric field in the bulk of the moderator that even point in the wrong direction.

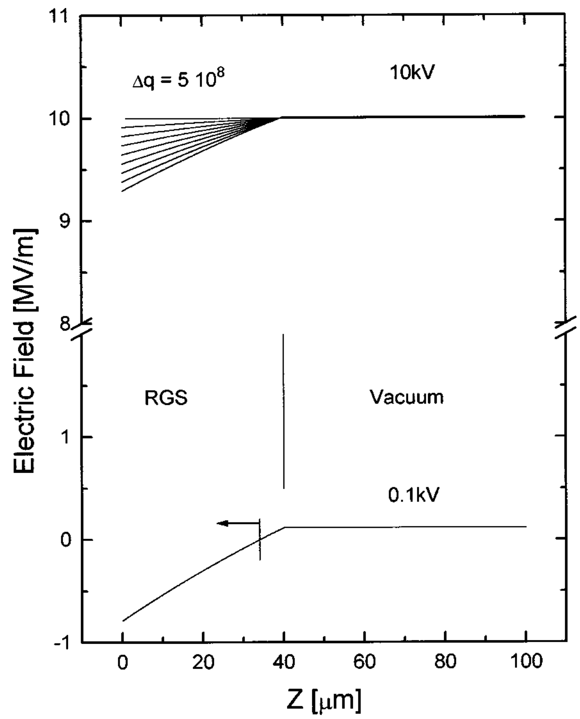

FIG. 5. How the electric field in the moderator changes as a result of charging (upper part). The lower part shows the electric field after a sudden reduction of the moderator voltage from 10 to 0.1 kV.

One way to overcome this severe charging problem is to use a pulsed e^- gun combined with periodical suddenly drops of the moderator potential, as illustrated in Fig. 5. By suddenly decreasing the moderator voltage from 10 to 0.1 kV, a negative electric field is created that extends almost to the moderator surface. If the moderator is now bombarded with electrons, then electron–positive-ion recombinations will occur on the right-hand side of the crossing point. The electron bombardment is continued until the crossing point has moved all the way to the cold head leaving the moderator almost free of positive ions, and then the 10 kV is pulsed on again and the electric field in the moderator will behave according to the upper part of Fig. 5.

With the values of the charging parameters given above, the moderator voltage should be lowered to 0.1 kV for 0.5 ms at a repetition rate of 200 Hz and the pulsed e^- should deliver a peak current of at least 2 μA. The net effect of this procedure is that the low-energy e^+ intensity is reduced about 10% as compared to the values given in the main body of this paper. The extra energy spread of the low-energy e^+ beam introduced due to the variation of the electric field in the vacuum (see Fig. 5) can be compensated for by an appropriate time-dependent beam potential somewhere in the beam line or in the moderator section.

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