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Analytic voltage depression calculation of arbitrary electron beams in misaligned coaxial gyrotron cavities

Joachim Franck, Konstantinos A. Avramidis, Gerd Gantenbein, Stefan Illy, Ioannis Gr. Pagonakis, Manfred Thumm, *Fellow, IEEE*, and John Jelonnek, *Senior Member, IEEE*

***Abstract*—Coaxial-cavity gyrotrons for electron cyclotron heating in plasma experiments for nuclear fusion can operate with very high-order modes, having reduced mode competition and decreased voltage depression compared to hollow-cavity tubes. However, since exact alignment of coaxial insert and cavity wall can only be ensured up to a certain precision, the effects of misalignment must be properly understood. In this work an efficient method is presented to determine the voltage depression on beam electrons for arbitrary misalignment between cavity wall and insert, and for a beam with arbitrary shape and density distribution. This method has been verified using a 3D code, and it can be generalized to some other geometries.**

***Index Terms*—Gyrotron, electron beam, voltage depression, mirror charge, misalignment, coaxial cavity.**

I. Introduction

As a means of electron cyclotron heating of plasmas relevant for magnetically confined fusion, gyrotrons with output power around or above 1 MW and frequencies from 140 GHz upwards have been built for experiments such as Wendelstein 7-X [1], will be used in ITER [2], and are foreseen for subsequent demonstration fusion power plants [3]. An important issue concerning high-power high-frequency gyrotrons is the dense mode spectrum and thus strong competition between modes, see e.g. [4]. One possible method of reducing this mode competition is to use coaxial-cavity gyrotrons [5], where a longitudinally corrugated metallic insert is placed along the gyrotron axis, inside the annular electron beam, reaching from the electron gun through the interaction region (cavity) well into the quasi-optical launcher. As a convenient side-effect, a grounded coaxial insert reduces the voltage depression on the beam electrons.

Ideally, emitter, cavity wall and, if present, coaxial insert have axially symmetric cross-sections and are concentric within the gyrotron. However, perfect alignment and circularity cannot be achieved in practice and some mechanical misalignments can be present in an evacuated tube.

In addition, due to possible mutual misalignment of the coils during manufacturing of the superconducting gyrotron magnet, its magnetic axis might not be an exactly straight line, leading to a possible displacement of the electron beam in the cavity region. However, in an assembled tube, one usually has the freedom to center the beam either with the insert or with the wall (or neither) by moving or tilting the gyrotron with respect to the magnet or by using dipole coils.

The described misalignments will in general influence the performance of gyrotrons. First, a misaligned beam with respect to any wall can lead to unequal voltage depression on the beam electrons, which increases their energy spread and thus affects interaction efficiency. Second, a misaligned insert will lead to TE mode patterns which are no longer axisymmetric and which might have a field maximum with a radius other than in the aligned case (if still circular at all). Third, a misaligned beam might no longer be located everywhere at this field maximum. All these situations would lead to a decrease of interaction efficiency, output power, and stability of the gyrotron; and since these requirements are critical, in particular for high-power fusion gyrotrons, proper analysis of possible misalignment and related effects is necessary.

Concerning voltage depression, exact analytic formulas are known for simple cases, such as for thin beams in perfectly aligned hollow (1) or coaxial (2) cavities [6]

$$U_{\text{hollow}} = \frac{K_{\text{beam}}}{2\pi\varepsilon_0}\ln\left(\frac{R_{\text{beam}}}{R_{\text{W}}}\right) \tag{1}$$

$$U_{\text{coaxial}} = \frac{K_{\text{beam}}}{2\pi\varepsilon_0}\ln\left(\frac{R_{\text{beam}}}{R_{\text{W}}}\right)\cdot\frac{\ln(R_{\text{beam}}/R_{\text{I}})}{\ln(R_{\text{W}}/R_{\text{I}})} \tag{2}$$

(where K_{beam} is the linear charge density of the beam, R_{beam} is the beam radius, R_{W} is the cavity wall radius, R_{I} is the coaxial insert radius; see Section II) but also for thick beams, see e.g. [7]. However, it is not immediately clear how to generalize

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those formulas to misaligned geometries such that they still describe proper solutions of the underlying Dirichlet problem. On the other hand, full 3D simulations of electron trajectories in gyrotron cavities (or other capacitors) are time- and/or resource-consuming.

In this paper, a fast, yet reliable method for voltage depression calculations is introduced, generalizing (1), (2) and [7] (9c). The method presented is solely based on the concept of mirror charges, as described in Section II. For coaxial cavities, truncated series of mirror charges are needed; see Section III. Axially symmetric beams greatly reduce the calculation effort, as described in Section IV. Verification of the code with 3D simulations is given in Section V.

II. Method and Formalism

Voltage depression in gyrotrons is relevant mainly in the part of the cavity where the beam-wave interaction takes place. For usual high-power gyrotrons, this is a cylindrical resonator with a smooth metallic wall "W". The insert "I", if present, has a small taper angle (not larger than 2°) and metallic walls, too. Any (longitudinal) corrugations are neglected here, since they are usually small enough that the insert can be regarded as smooth at the relevant distances (possibly with a smaller, "effective" radius). The magnetic field has its maximum in the cavity region, and as a result, its variation along the cavity axis is small in that region. Since the electron guiding centers follow the magnetic field lines, any change in radial position of the electrons along the axis is only of second order with respect to the corresponding axial position. These preconditions allow approximating the electrostatic potential within cross-sections at any position inside the cavity with that in an infinite cylinder having the same geometry as the cavity at that position. Thus, instead of using a 3D Cartesian coordinate system (X,Y,Z) with the Z-axis pointing into the axial direction of the gyrotron, only the 2D cross-section at one fixed position in the cavity Z_{cav}, $(X,Y) \equiv (X,Y,Z_{\mathrm{cav}})$ may be considered, and all locations in the plane are expressed by complex numbers

$$z := X + \mathrm{i}Y\,, \tag{3}$$

where $\mathrm{i} \equiv \sqrt{-1}$ is the unit imaginary number. (Lowercase letters are used for complex numbers/functions and uppercase letters for real (including integer) numbers, with the exception of constants e, π and ε_0.) At any given cross-section and at any given time, the electron beam can be expressed as several fixed electron bundles, each carrying linear charge density $K := \mathrm{d}Q/\mathrm{d}Z \equiv I/V_Z$ (abbreviated "charge" in the following). The potential due to a charge $K^{(0)}$ located at $z^{(0)}$, measured at z, is known from Gauss's law as

$$\Phi\left(z^{(0)}, z\right) = \frac{K^{(0)}}{2\pi\varepsilon_0} \ln\left|\frac{z - z^{(0)}}{L}\right|. \tag{4}$$

Here, L is a characteristic length to cancel out the units in the logarithm. The arbitrary magnitude of L, if taken constant for all charges in a system, defines a voltage normal. The superposition principle holds, namely

$$\Phi_{\mathrm{tot}}(z) = \sum_N \Phi\left(z_N^{(0)}, z\right). \tag{5}$$

Circular inversion m_{S} of point z on a cylindrical surface "S" with center z_{S} and radius R_{S} is described as

$$m_{\mathrm{S}} : z \mapsto z' \quad , \quad (z_{\mathrm{S}} - z)(z_{\mathrm{S}} - z')^* = R_{\mathrm{S}}^2\,. \tag{6}$$

Consequently, in a hollow cavity, the location of the mirror charge $z^{(1)}$ on cavity wall W is $z^{(1)} = m_{\mathrm{W}}(z^{(0)})$. Its charge is $K^{(1)} = -K^{(0)}$, which results, through (4), in the total potential

$$\Phi\left(z^{(0)}, z^{(1)}, z\right) = \frac{K^{(0)}}{2\pi\varepsilon_0} \ln\left|\frac{z - z^{(0)}}{z - z^{(1)}}\right|, \tag{7}$$

being constant at the cavity wall. A cavity wall at a given potential would then require a proper normalizing additive term. The electrostatic potential resulting from a charged beam, modelled as a sufficiently large number N_{C} of line-charges (not necessarily with equal charge or uniformly distributed; typically $N_{\mathrm{C}} \sim 10000$ is needed), in a hollow cavity can then be expressed by N_{C} original charges, N_{C} mirror charges and a final normalization. The voltage depression on that beam can be determined by calculating the potential at several sample positions inside the beam, which should not be at, close to, or in regular distances from the original line-charges in order to avoid overflows and to obtain meaningful statistical results. For nonuniform beams modelled by a large number of line-charges, however, one can obtain meaningful results if the potentials are determined directly at the charge positions, each time omitting the (infinite) potential of the charge located at that respective position.

III. Coaxial Cavities

In coaxial cavities, the original line charge induces two mirror charges, one at each mirror, $z^{(1)} = m_{\mathrm{W}}(z^{(0)})$ and $z^{(-1)} = m_{\mathrm{I}}(z^{(0)})$. In order to fully account for them, one needs two additional mirror charges, namely the mirror of $z^{(-1)}$ on the wall, $z^{(2)} = m_{\mathrm{W}}(z^{(-1)})$, and of $z^{(1)}$ on the insert, $z^{(-2)} = m_{\mathrm{I}}(z^{(1)})$. The effect of those has to be compensated by another pair of mirror charges, and so on, resulting in a series of charges, $N = 0 \ldots N_{\max}$:

$$z^{(\pm N)} = m_{\begin{Bmatrix}\mathrm{W}\\ \mathrm{I}\end{Bmatrix}}\left(z^{(\mp(N-1))}\right) \tag{8}$$

$$K^{(\pm N)} = (-1)^{\pm N} \cdot K^{(0)} \tag{9}$$

It is obvious that the Dirichlet boundary conditions cannot be exactly fulfilled for a finite number of mirror charges, $N_{\max} < \infty$, and even convergence of the resulting potential for large, but finite $N_{\max}$ is not obvious.

However, one can make use of the fact that insert and wall surfaces of a misaligned cavity define a set of Apollonian circles of the first family (named after Apollonius of Perga, c. 262-190 BCE [8]) with poles $z^{(\infty)}$ and $z^{(-\infty)}$. All iterated mirror charges of $z^{(0)}$ lie on the circle defined by the points $\{z^{(-\infty)}; z^{(0)}; z^{(\infty)}\}$ and converge towards the two poles. This means that, after a certain $N_{\max} = N_{\mathrm{crit}}$, each subsequent mirroring has just the effect that the total charge within a domain located around each pole oscillates by $\pm K^{(0)}/2$ around a mean value (which itself can be either $-K^{(0)}/2$ or $+K^{(0)}/2$), but contributes not otherwise to the shape of the electrostatic field. If one now assigns for the last iteration

$$K^{(N_{\max})} = (-1)^{N_{\max}} \cdot K^{(0)}/2\,, \tag{10}$$

additionally to (9), this oscillation is damped drastically. For most geometries, $N_{\max}\approx 15$ is sufficient for convergence, meaning that the potentials on insert and wall become constant along their circumferences. Grounding (or any other choice of potential on the two surfaces) can be achieved by placing one additional charge on each pole. Voltage depression on a beam modelled with N_C charges can thus be determined as the potential by around $15\cdot N_C+2$ charges.

Fig. 1 shows positions of the original and mirror charges for a configuration with mutually misaligned wall, insert and beam. One can see that for $N>2$, the positions of all mirror charges converge to the pole $z^{(\infty)}\approx 0+0.234\mathrm{i}$.

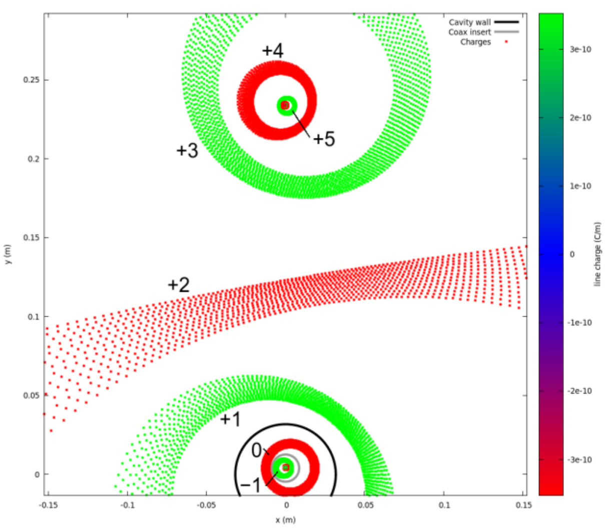


Fig. 1. Original and mirror charges for a misaligned beam (red dots marked with "0"; 2004 charges) and insert (grey circle) in the cavity (black circle), with iteration numbers N indicated. The signs of the charges are color-coded and alternate with each iteration.

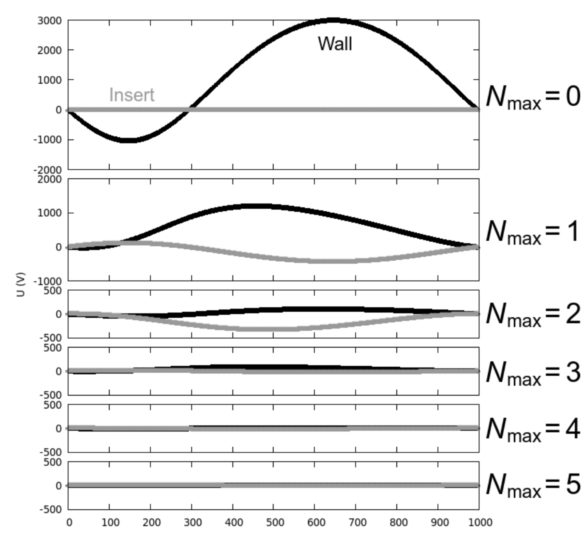


Fig. 2. Electric potential along cavity wall (black curves) and coaxial insert (grey curves) for different numbers of iterations $N_{\max}$. Both circles are sampled with 997 azimuthal positions, the IDs of which are given as the horizontal axis.

The convergence of electric potentials for a configuration similar to Fig. 1 can be seen in Fig. 2. Initially, the electric field of the hollow, symmetric beam vanishes inside and follows (4) outside, hence the curves for $N_{\max}=0$. The first pair of mirror charges partly compensates the unphysical voltage variation along the wall, but also affects the inside of the beam, so the Dirichlet boundary condition on the insert is no longer fulfilled ($N_{\max}=1$). However, with increasing number of mirror charge pairs, both potentials approach constant 0 V along the whole circumference. Already for $N_{\max}=5$, the Dirichlet condition is almost fulfilled.

IV. Axially Symmetric Beams

The electrostatic potential of an infinitely long, annular, homogeneous electron beam with inner radius R_{in} and outer radius R_{out} at the radial distance R can be expressed analytically [7]:

$$\Phi_b(R_{\text{in}}, R_{\text{out}}, R) = \frac{K}{2\pi\varepsilon_0\left(R_{\text{out}}^2 - R_{\text{in}}^2\right)} \cdot \left\{\begin{array}{ll} 0 & , \quad R \le R_{\text{in}} \\ R_{\text{in}}^2 \cdot \ln\left(\dfrac{R}{R_{\text{in}}}\right) - \dfrac{R^2 - R_{\text{in}}^2}{2} & , \quad R_{\text{in}} \le R \le R_{\text{out}} \\ R_{\text{in}}^2 \cdot \ln\left(\dfrac{R_{\text{out}}}{R_{\text{in}}}\right) + \left(R_{\text{out}}^2 - R_{\text{in}}^2\right)\cdot\left(\ln\left(\dfrac{R_{\text{out}}}{R}\right) - \dfrac{1}{2}\right) & , \quad R_{\text{out}} \le R \end{array}\right. \tag{11}$$

This potential can be used directly to calculate the voltage depression on such a beam in aligned hollow or coaxial cavities, see e.g. [7]. However, it is not immediately clear how to generalize this handy approach to misaligned geometries.

However, one can use the findings in Section III and the fact that an axially symmetric charge distribution cannot be distinguished from a line charge when seen from positions outside of this distribution. Hence, the mirror charge of a whole axially symmetric beam can be expressed by one line-charge only, rather than the N_C mirror charges per iteration required for the general, nonsymmetrical distribution discussed in Section II. Therefore, voltage depression on gyrotron-relevant annular, homogeneous thick (or thin) beams in a coaxial cavity, still with arbitrary mutual misalignment of beam and metallic wall(s), can be expressed analytically using (11) and only around 32 mirror charges in total according to Section III. Similar to Fig. 1, these mirror charges of the charge center have alternate signs and converge to the poles of the insert-wall geometry. Using the same geometry as in Fig. 2, the simplified method returns exactly the same curves.

For hollow cavities, only one mirror charge is sufficient to substitute the cumulative effect of mirror charges of all beamlets. For annular beams, the charge center is located outside of the area of charge density and, in coaxial cavities, usually lies within the insert. This ensures that the sample positions can never coincide with line-charges, as opposed to the general situation in Section II.

For illustration, Fig. 3 shows how the voltage depression within a very thick beam is distributed if the beam is misaligned in an aligned cavity and is closer to the insert than to the wall. Despite the untypical thickness and large misalignment, the depression on beams of typical thickness and position in such geometries is basically the same: high depression (HD) at the beam center on the distant side of the insert (red), low depression (LD) at the outer fringe of the beam on the near side (blue), and very low depression (VLD) close to the insert (green).

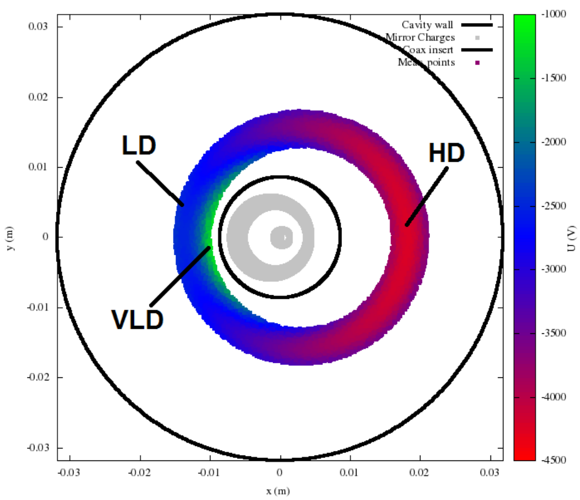


Fig. 3. Voltage depression on the charges of a very thick, misaligned beam in an aligned coaxial cavity, calculated using mirror charges. The grey structures within the insert are the corresponding mirror charges. "HD": high-depression region, "(V)LD": (very-)low-depression region; see text.

V. VERIFICATION

Based on the above considerations, the C++ code *WickedQueen* was developed to calculate voltage depression on annular or arbitrary charged beams, based purely on physics in two dimensions. For verification the gyrotron design (MIG, magnet, beam tunnel, cavity) given in [9-10] ($TE_{49,29}$ mode setup, I_{beam}=69.3 A) was considered, using *Ariadne* [11] as 3D electron beam trajectory code. Misalignment was achieved by a lateral shift of the magnetic axis relative to the gyrotron geometry by up to 1 mm, resulting in a beam shift of 0.88 mm in the cavity region. For simplification of the geometry definition in *Ariadne*, no misalignment between cavity wall and insert was considered. Further simulation parameters are given in Table I.

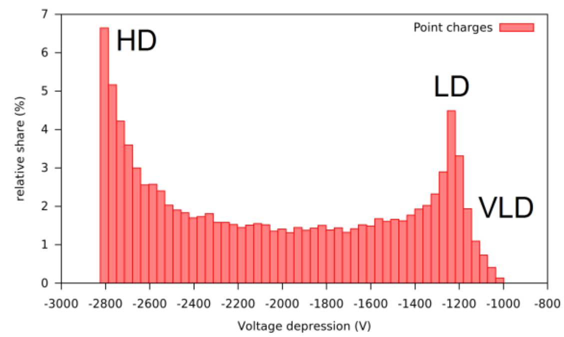
Two scenarios have been used for comparison with the depression voltages directly obtained from *Ariadne*. In the first scenario, the beamlet positions given by *Ariadne* were taken and the voltage depression at these positions was calculated according to Section III, each time omitting the charges' self-potential. In the second scenario, the given beam was approximated by an annular beam with uniform charge distribution (as opposed to the distribution given by *Ariadne*, which is more concentrated in the middle – not towards the center – of the beam, obviously due to space-charge effects) and the voltage depression was calculated according to Sections III and IV. In both cases, the number of mirror charges per original charge, N_{max}, was 15.

Fig. 4 shows the corresponding voltage depression distributions over the particles. In all three cases, there are two statistical maxima: around −1.1 kV where the beam is closest to the insert (LD region), and around −2.8 kV where the beam is farthest away from the insert (HD region). The characteristic tail at the low-depression end (VLD region) is present in all three cases.

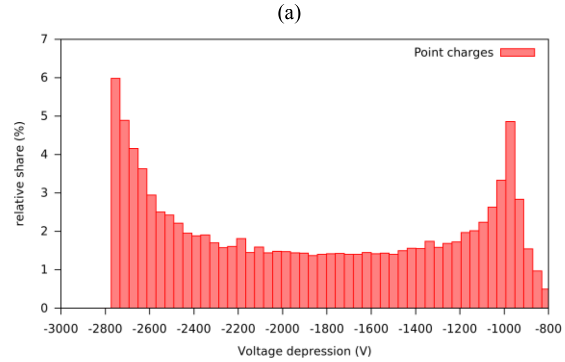
The error resulting from the coincidence of charges and measurement points in scenario #1 (cf. Section II), compared to scenario #2, is negligible.

TABLE I
SIMULATION PARAMETERS (SEE TEXT).

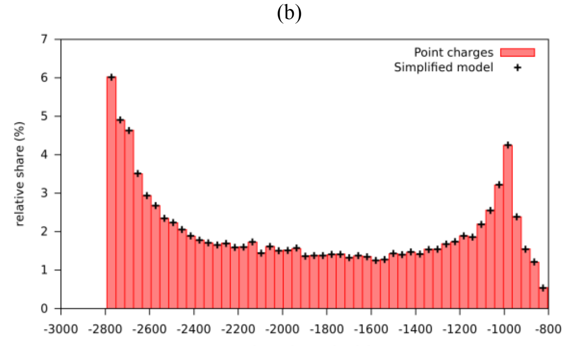
Parameter	*WickedQueen*	*Ariadne*
Cavity wall radius (mm)	31.78	
Insert radius (mm)	8.60	
Beam radius (mm) inner / central / outer	10.10 / 1.26 / 10.42	
Beam misalignment (mm)	0.88	
Axial electron velocity β_z	0.325	
Number of electrons	36259	36360



(a)



(b)



(c)

Fig. 4. Histograms of the voltage depression distributions calculated with (a) *Ariadne*, (b) *WickedQueen* scenario #1 (original charge positions), and (c) scenario #2 (homogeneous beam). "HD", "(V)LD" as in Fig. 3.

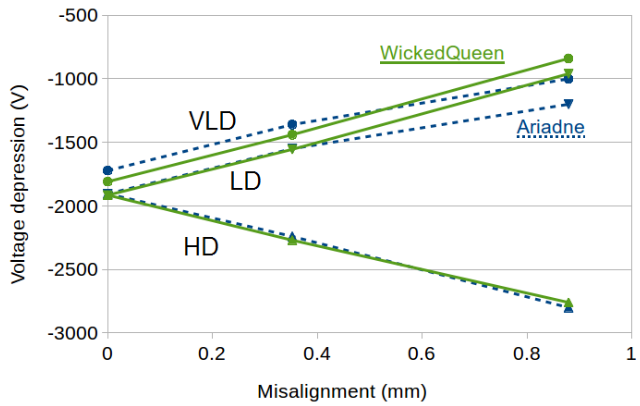


Fig. 5. Positions of the high-depression (HD) peak, of the low-depression (LD) peak and of the end of the low-depression tail (VLD) for the 3D simulation (blue, dotted) and the 2D method (green, lines), and for three misalignments.

In Fig. 4(c), the voltage depression histogram of the homogeneous beam with all (>1000000) individual mirror charges is shown together with a histogram calculated using 30 point-like mirror beams (black crosses). Both distributions agree perfectly, confirming the considerations in Section IV.

In Fig. 5, the positions of the two peaks and of the end of the low-depression tail in the histograms (equivalent to Fig. 4(a) and (c) are plotted for three different misalignments and for both codes. One can see that the simplified method agrees well with the numerical calculation for the HD peak, while the low-depression regions disagree slightly. As one can see from Fig. 4, this is not caused by the different charge densities (as the distributions in scenarios #1 and #2 practically coincide), and it was also found that the actual velocity distribution of the electrons is neither responsible for this effect. Thus, one may conclude that this disagreement is caused by the finite length of the realistic cavity (it is of the order of the cavity radius) as simulated in *Ariadne*. This finite length leads to axially dependent space charge, voltage depression, and beam radius, the combined effect of which might lead to the observed discrepancy. In any case, the difference of 0.2 kV is smaller than the usual accuracy of high-voltage measurements.

VI. Summary and Outlook

A method to determine the voltage depression on charged particle beams in hollow and coaxial gyrotron cavities has been developed, using a finite number of mirror charges, with arbitrary accuracy. Verification with a 3D trajectory code shows that this method, albeit purely two-dimensional, returns accurate results, both qualitatively and quantitatively. For axially symmetric beams, calculation can be simplified drastically without loss of accuracy, since no more than 40 charges have to be taken into account. Apart from misalignments, it is self-evident that the proposed method can also be used to calculate the depression on electron beams in symmetric geometries which, however, have azimuthally or radially varying current density, such as investigated in [12]. For aligned cavities, algebraic infinities (such as $z^{(\infty)}=\infty$) have to be treated properly, e.g. using projective geometry in the code, as we have done for the calculations in Section V.

With the help of the new code, systematic studies on voltage depression in coaxial cavities with mutually misaligned wall, insert, and thick symmetric beam can be conducted, which will be the subject of later publications.

The presented method can be generalized in at least two ways. First, the discussed considerations are also valid for mirrors with infinite radius, i.e. straight lines on the X-Y plane, as long as they are parallel. In this case, the mirror charge locations do not converge; however, their distance from the region of interest (the original charge) increases linearly with every iteration step, while their potential grows only logarithmically, ensuring convergence of the total potential. Second, the infinite mirror-charge method can be generalized to higher dimensions. One could for example consider three dimensions: metallic spheres and/or planes and point-like charges.

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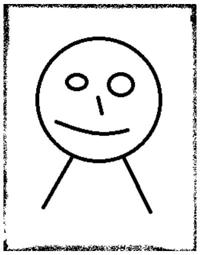

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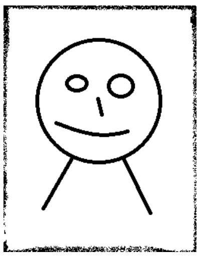

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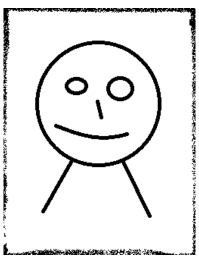

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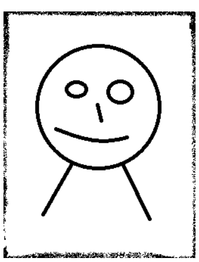

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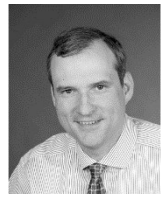

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