Emittance compensation in a superconducting rf gun with a magnetic mode

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External fields are necessary for emittance compensation and beam focusing in rf photoelectron guns. For rf guns with superconducting cavities two fields have been discussed up to now. The first field is a specially designed radial component of the rf field immediately after the cathode and the second is a static magnetic field downstream of the superconducting cavity. In this paper we discuss a third possibility. Inside the cavity the magnetic rf field of a TE mode focuses the electron beam and prevents the increase of the transverse emittance. The results depend only weakly on the phase of the TE mode. For a bunch charge of 1 nC, an emittance of 0.7 mm mrad has been obtained with a surface field strength of the magnetic field below the quench limit.

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I. INTRODUCTION

In recent years a number of projects for linacs with high average current and high brightness electron beams have been started at different laboratories (Ref. [1]). In contrast to storage ring accelerators, the beam parameters of linacs are mainly determined by the injector.

Today, photocathode rf guns are the most advanced type of electron injectors. They are able to produce high peak currents and low emittances, which is necessary for free-electron laser applications (Ref. [2]). However, their low duty factor can limit the performance of superconducting accelerators. Efforts are under way to increase the duty factor of rf guns for the price of cooling problems, high demands on klystron power, and low power conversion efficiency (Ref. [3]). The more elegant way is to combine the high brightness of rf guns with the low rf losses of superconducting cavities.

At the Forschungszentrum Rossendorf a first rf gun with a photocathode inside a superconducting cavity was developed in cooperation with different institutes and successfully operated in 2002 (Ref. [4]).

A disadvantage of the superconducting technology is its sensitivity to external magnetic fields. It is not impossible to apply a static magnetic field of the required strength for the emittance compensation as described in Ref. [5] for the case of a normal conducting rf gun. In Ref. [6] it was shown that the focusing of the static magnetic field can be replaced by rf focusing, which is applicable also in the case of superconducting cavities. rf focusing is achieved by pulling the cathode backward, somewhat behind the back plane of the cavity. Extensive beam dynamics calculations for different bunch charges confirm the advantages of this concept. It is also integrated in a new superconducting rf gun design, which is presently under construction in Rossendorf (Ref. [7]). Another possibility to compensate the emittance growth in the gun is to apply a static magnetic field, which is positioned downstream of the gun cavity. With a sufficient distance and shielding of the magnetic field the superconductivity is not affected and in simulations good beam emittances have been obtained under these conditions (Ref. [8]).

The idea followed in this paper is to replace the static magnetic field by a magnetic rf field, which is an eigenmode of the gun cavity. This mode can be excited together with the accelerating rf field in a superconducting cavity and can be used to compensate the emittance growth.

II. FIGURE OF MERIT FOR ELECTRIC AND MAGNETIC RF MODES INSIDE A PILLBOX CAVITY

For the explanation of the results in the following sections it is useful to discuss the rf fields of the electric and magnetic modes by the simple example of a pillbox cavity. This cavity is a metallic cylinder with radius R and length L. From the Helmholtz equation one obtains for the frequency of the accelerating field (TM_{010} mode) and for the frequency of the magnetic focusing field (TE_{011} mode):

$$f_{TM_{010}} = (c/2\pi)2.405/R, \qquad f_{TE_{011}} = (c/2\pi)\sqrt{3.832^2/R^2 + (\pi/L)^2}. \tag{1}$$

The frequency f_{TM} of the accelerating mode determines the radius R while the frequency f_{TE} of the magnetic mode varies between $1.59 f_{TM}$ and infinity dependent on the cavity length L.

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For the rf field of both modes the following equations can be derived.

TM_{010} mode:

$$Ez = E_0 J_0[2.4048(r/R)]\exp(j\omega t), \qquad Er = 0, \qquad (2)$$

$$B\varphi = j(E_0/c)J_1[2.4048(r/R)]\exp(j\omega t).$$

TE_{011} mode:

$$Bz = B_0 J_0[3.8317(r/R)]\sin(\pi z/L)\exp(j\omega t),$$
$$Br = -B_0\pi[R/(3.8317L)]J_1[3.8317(r/R)]\cos(\pi z/L) \times \exp(j\omega t), \qquad (3)$$

$$E\varphi = -jB_0(c^2/\omega)J_1[3.8317(r/R)]\sin(\pi z/L) \times [R/3.8317(\pi/L)^2 + 3.8317/R]\exp(j\omega t).$$

In a superconducting cavity the magnetic field has to stay below the quench limit of the superconductor. The maximal magnetic surface field B_S for niobium is about 180 mT (Ref. [9]). Optimal beam properties demand strong fields on the symmetry axis of the cavity for fast acceleration and space charge compensation of the electron bunch.

Hence the ratios

$$F_E = |E_{z(r=0)}^{\max}/B_s^{\max}| \quad \text{and} \quad F_B = |B_{z(r=0)}^{\max}/B_S^{\max}| \qquad (4)$$

of the maximum on-axis fields to the maximum surface field are the figure of merit and characterize the performance of the cavity.

From Eqs. (2) and (3) follows

$$F_E = c/J_1(x_{1\max}),$$
$$F_B = (3.8317/\pi)/J_1(x_{1\max})(L/R), \quad \text{for } L/R < 1.2,$$
$$F_B = 1/J_0(x_{1\max}) \quad \text{for } L/R > 1.2, \qquad (5)$$

where $x_{1\max}$ is the argument where the corresponding Bessel function has its first maximum.

For $L/R = 1.2$ the frequencies behave as $f_{TE_{011}} = 1.93 f_{TM_{010}}$. For $L/R > 1.2$ the frequency of the TE mode approaches the lower limit of $1.59 f_{TM_{010}}$and the maximum of the magnetic field of the mode is located at the center of the cylinder, while for $L/R < 1.2$ the frequency of the TE mode is higher than $1.93 f_{TM_{010}}$ and the maximum of the magnetic surface field is located at the front and back plane of the cylinder.

The radius of the cavity is determined by the frequency of the TM mode [Eq. (1)]. A long cell length L would hence, up to the limit $L/R = 1.2$, help to improve the ratio of on-axis to surface field. However, the cell length is fixed by beam dynamics requirements and in general one finds $L/R < 1.2$ for practical cavities. Figure 1 shows the square of the magnetic surface field B_S of both modes for a pillbox cavity. The maxima of both modes are located at different positions. Moreover, the surface field of the TE mode is a combination of the radial and the longitudinal component, while the surface field of the TM mode is purely azimuthal. Hence the contributions of the modes add up quadratically and the resulting field vector is proportional to the power deposition of the combined rf fields into the cavity wall.

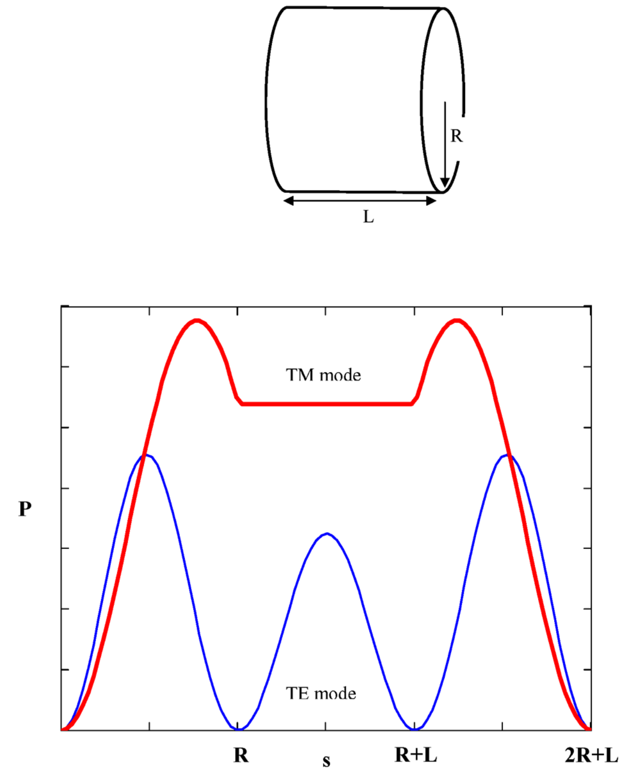

FIG. 1. (Color) Power deposition into the surface of a pillbox cavity for the TM_{010} and the TE_{011} mode along the cavity surface. The plot starts at the center of an end wall, moves out radially, and then proceeds longitudinally.

III. BEAM DYNAMIC OF A 3.5 CELL SUPERCONDUCTING RF GUN

In this section the influence of the magnetic mode on the beam dynamics in a superconducting 3.5 cell rf gun cavity, under construction in Rossendorf (Ref. [7]), will be examined. The geometry and the field distribution of the cavity are shown in Fig. 2.

The fields are calculated with the SUPERLANS code (Ref. [10]). The three full cells have the TESLA geometry (Ref. [11]) and the accelerating mode has the standard frequency of 1.3 GHz. The magnetic mode is mainly located inside the half cell and has a frequency of 3.953 GHz, which one could easily shift to 3.9 GHz by small changes of the cell geometry. Figure 3 shows the field distributions on the axis of the cavity which enter the tracking calculation of the electron beam.

The magnetic field has a steep maximum immediately downstream of the cathode and is zero at the cathode itself. The electric field has a maximum at the cathode,

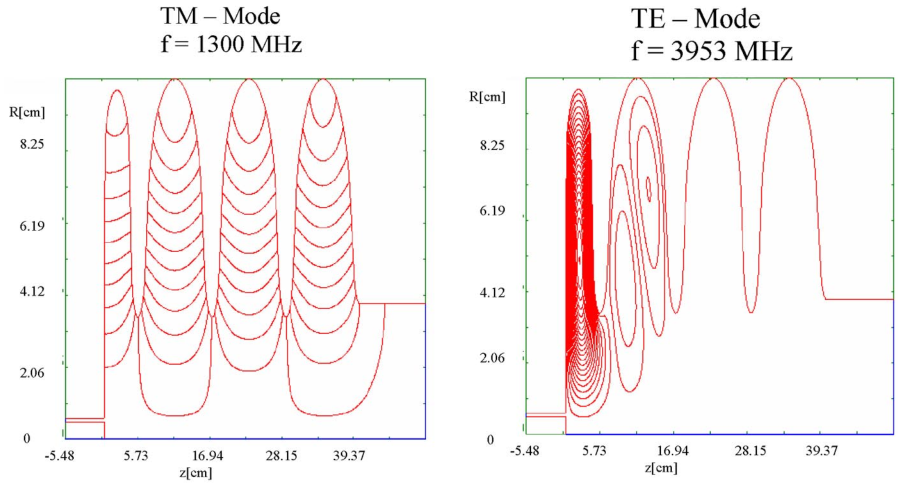

FIG. 2. (Color) Field distribution of the TM_{010} mode ($rB_\varphi = \text{const}$) and the TE_{011} mode ($rE_\varphi = \text{const}$) in a $3\frac{1}{2}$ cell cavity. The full cells have a standard TESLA shape.

consequently at this point the radial field component is zero and the rf field is not focusing at the cathode. The field is normalized to a maximum on-axis field of 50 MV/m, which corresponds to an average accelerating gradient of 25 MV/m in the standard TESLA cells.

For the tracking simulation the code ASTRA (Ref. [12]) is used, which takes into account the external fields of both modes and the internal space charge field of the electron bunch. The properties of the electron beam are evaluated at some distance behind the gun cavity. For bunch charges as large as 100 pC transverse emittances smaller than 1 mm mrad are easily obtained even for magnetic rf fields smaller then 100 mT on the axis. The case of a bunch charge of 1 nC will be discussed in more detail. For the incoming laser pulse a transverse flattop profile with constant longitudinal density and a length of 20 ps is assumed. By minimizing the transverse emittance an optimal radius of 1.2 mm was found. For these start values the beam parameters for different field strengths of the magnetic mode have been calculated. Thermal emittance effects are not taken into account. The results are summarized in Fig. 4 and Table I.

Without the magnetic rf field the transverse emittance is 2.7 mm mrad. At $B_z^{\max} = 340$ mT the transverse emittance reduces to 0.5 mm mrad. The beam cross section σ_x has a minimum approximately at the same magnetic field 1.65 m downstream of cathode.

The longitudinal emittance, the energy width, and the beam cross section would be excellent input parameters for a following linear accelerator. However, two open problems remain. The first problem is the tuning of a cavity with respect to the frequency of two modes. Here a tuner is required, which has 2 degrees of freedom and allows one to set the frequency of the TM mode to

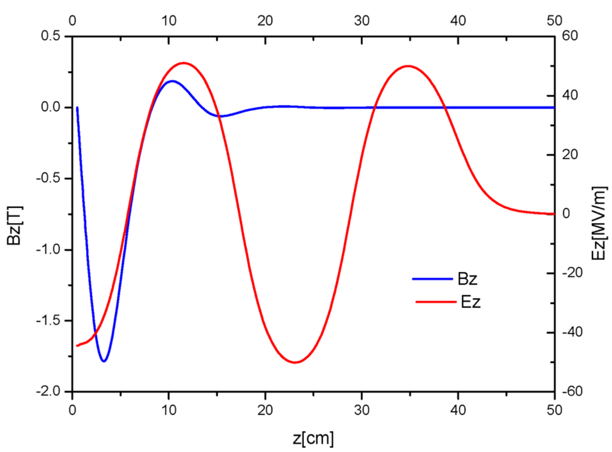

FIG. 3. (Color) Electric and magnetic field strength of the TM_{010} and the TE_{011} mode on the axis of the $3\frac{1}{2}$ cell cavity.

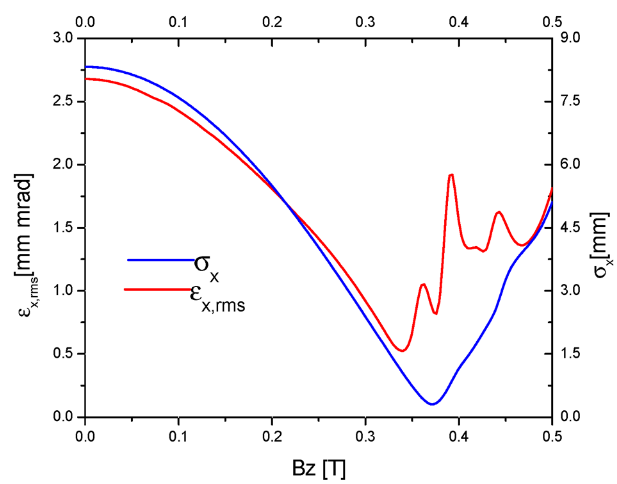

FIG. 4. (Color) Transverse emittance and beam size as a function of the magnetic field amplitude at $z = 1.65$ m. $E_z^{\max} = 50$ MV/m.

TABLE I. Optimal rf and beam parameters for a superconducting rf gun with an additional magnetic rf field inside the cavity. The amplitude of the magnetic surface field is above the quench limit.

Field parameter TM_{010} mode	Field parameter TE_{011} mode	Start parameter of the bunch	Bunch parameter at $z = 1.65$ m
$f = 1.3$ GHz	$f = 3.953$ GHz	$Q = 1$ nC	$\sigma_{x,\mathrm{rms}} = 0.3$ mm
$\Phi = 60°$	$\Phi = 115°$	Flattop profile	$\sigma_{z,\mathrm{rms}} = 2.1$ mm
$E_z^{\max} = 50$ MV/m	$B_z^{\max} = 338$ mT	$r = 1.2$ mm	$\varepsilon_{x,\mathrm{rms}} = 0.5$ mm mrad
$B_s^{\max} = 110$ mT	$B_s^{\max} = 223$ mT	$l = 20$ ps	$\varepsilon_{z,\mathrm{rms}} = 41$ mm keV
			$E = 10.2$ MeV
			$\Delta E = 20$ keV

1.3 GHz and the frequency of the TE mode to 3.9 GHz. Having in mind the results of Sec. 1 one could try to design a tuner which changes nearly independently the radius and the length of the first cell of the rf gun cavity. After successful tuning one could generate electron bunches with any time structure compatible to the 1.3 GHz frequency. Without tuning, a constant ratio of the phases of the two modes is realized only in those rf buckets where the condition $nf_{\mathrm{TM}} = mf_{\mathrm{TE}}$, where n and m are integer numbers, is valid.

For other buckets the phase of the TE mode varies between 0° and 360° for a constant injection phase of the electron beam with respect to the 1.3 GHz. The transverse emittance for phase angles of the TE mode between 0° and 180° has been calculated. The results are presented in Fig. 5. This interval is sufficient, since the beam parameters depend only on the square of the magnetic field.

The emittance changes between 0.5 and 1.8 mm mrad. The maximum emittance is obtained shifted by 90° with respect to the minimum at $\Phi_{\mathrm{TE}} = 39°$.

The second problem of this calculation is the maximum magnetic field at the surface of the cavity. For the optimum transverse emittance of 0.5 mm mrad the maximum magnetic surface field $Bs^{\max}$ of the TE mode is 223 mT, which is above the limit of 180 mT given in Ref. [11]. In order to check the sensitivity of the results to the amplitude of the magnetic mode, $Bs^{\max}$ has been reduced to 160 mT and the electric field strength of the accelerating mode $Ez^{\max}$ has been varied. The results are shown in Fig. 6.

In addition, the radius of the electron bunch at the cathode has been varied. Table II presents the beam parameters in the optimum.

The changes caused by the lower amplitude of the magnetic mode are not too drastic. In order to reduce space charge effects the radius of the bunch at the cathode increases to $r = 1.8$ mm. As a result of the lower focusing strength of the magnetic field the electron beam has a larger cross section and its minimal emittance is shifted to 3.7 m downstream of the cathode.

For the optimal parameter set the transverse emittance changes only between 0.7 and 1.1 mm mrad in the whole phase interval of the TE mode (see Fig. 7). So the phase dependence is even smaller in this case as in the case of the stronger magnetic field.

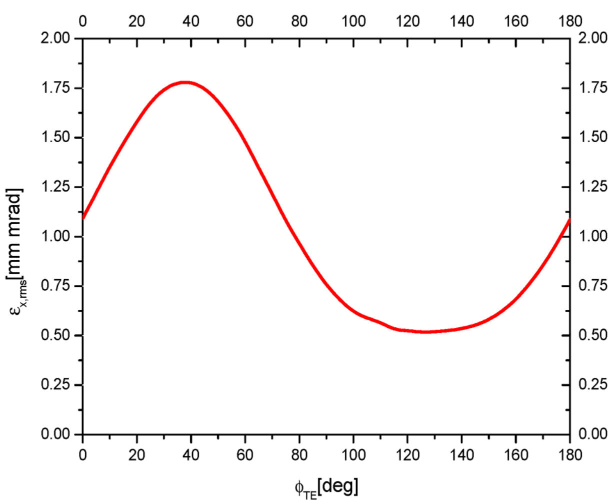

FIG. 5. (Color) Dependence of the transverse emittance on the phase of the TE mode. $E_z^{\max} = 50$ MV/m.

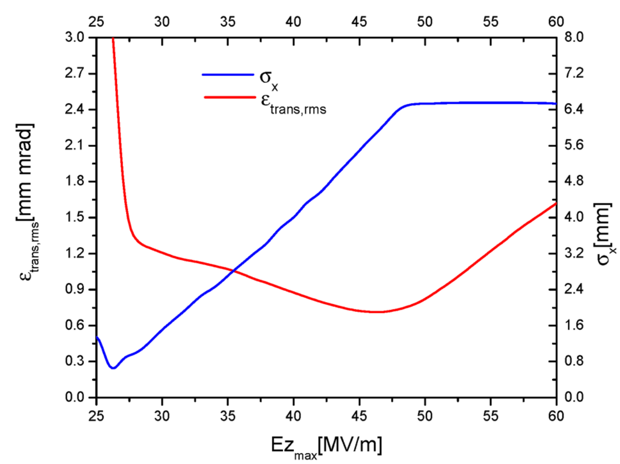

FIG. 6. (Color) Transverse emittance and beam size as a function of the accelerating field amplitude. $B_z^{\max} = 243$ mT.

TABLE II. Optimal rf and beam parameters for a superconducting rf gun with an additional magnetic rf field inside the cavity. The amplitude of the magnetic surface field is below the quench limit.

Field parameter TM_{010} mode	Field parameter TE_{011} mode	Start parameter of the bunch	Bunch parameter at $z = 3.76$ m
$f = 1.3$ GHz	$f = 3.953$ GHz	$Q = 1$ nC	$\sigma_{x,\text{rms}} = 5.8$ mm
$\Phi = 64°$	$\Phi = 140°$	Flattop profile	$\sigma_{z,\text{rms}} = 2.0$ mm
$E_z^{\max} = 46$ MV/m	$B_z^{\max} = 243$ mT	$r = 1.8$ mm	$\varepsilon_{x,\text{rms}} = 0.7$ mm mrad
$B_s^{\max} = 101$ mT	$B_s^{\max} = 160$ mT	$l = 20$ ps	$\varepsilon_{z,\text{rms}} = 37.6$ mm keV
			$E = 9.4$ MeV
			$\Delta E = 25.0$ keV

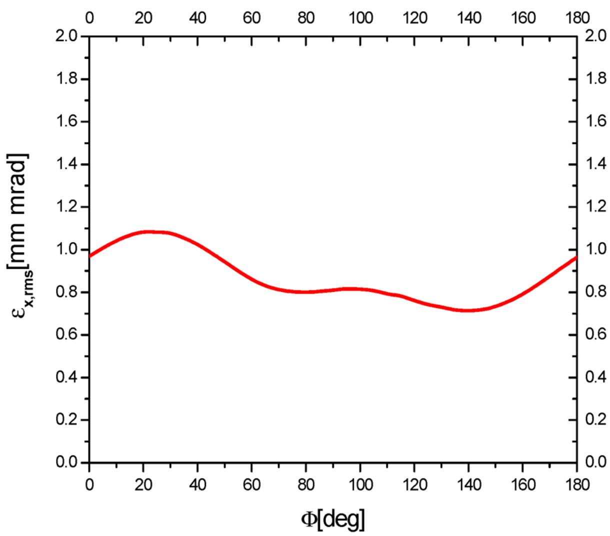

FIG. 7. (Color) Dependence of the transverse emittance on the phase of the TE mode. $B_z^{\max} = 243$ mT.

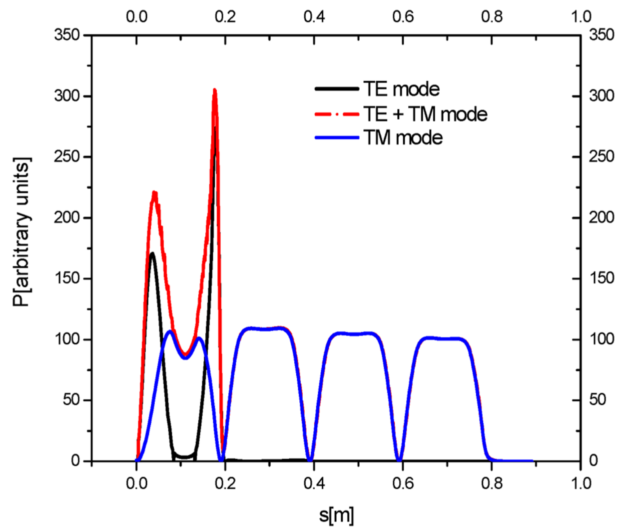

FIG. 8. (Color) Power deposition into the surface of the 3.5 cell cavity for the TM_{010}, the TE_{011}, and the sum of the TM_{010} and TE_{011} mode along the cavity surface.

IV. THE MAXIMUM AMPLITUDE OF THE MAGNETIC SURFACE FIELD

Figure 8 shows the power deposition into the surface of the cavity dependent on the length parameter, i.e., along the cavity surface as discussed in the previous section. It is very essential that the power maximum of the TE mode and that of the TM mode are at different locations. In general, the power deposition of the TE mode is near to the iris and that of the TM mode is near to the orbit maximum of a cavity. In the case of the 3.5 cell rf gun cavity the ratio of the maximum magnetic on-axis field to the maximum surface field is found as $F_B = 243\ \text{mT}/160\ \text{mT}$ and the corresponding ratio of the TM mode is $F_E = 46\ \text{MV}\,\text{m}^{-1}/101\ \text{mT}$.

At the position of the maximum surface field of the TE mode the contribution of the TM mode is, however, only 48.2 mT.

Both field components are perpendicular to each other, so the maximum field strength at the surface of the cavity used in the previous calculation is 167.1 mT.

V. CONCLUSION

Superconducting rf guns are able to operate in the cw mode and create large average currents. In order to obtain small emittances for bunch charges $Q \geq 1$ nC external fields for emittance compensation and beam focusing are necessary. Such a field could be a static magnetic field downstream of the superconducting cavity (Ref. [8]) or a specially enhanced radial component of the accelerating field (so-called rf focusing in Ref. [6]). In the present case a magnetic rf mode inside the cavity, which creates a well-located, time-dependent magnetic field around the cavity axis in analogy to the static field in normal conducting rf guns, has been used. As a result emittances smaller than 1 mm mrad have been obtained for a bunch charge of 1 nC. The magnetic surface field is lower than the quench limit and the dependence on the phase of this additional rf mode is not essential.

First measurements of the magnetic rf field of the TE_{011} mode in a single cell superconducting cavity are published in Ref. [13].

ACKNOWLEDGMENTS

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