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Radio Frequency Photocathode Gun*

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Requirements

It would be convenient to have a single parameter that could be used as a measure of performance of any particular gun. Brightness, defined as current divided by the square of normalized emittance, is a useful parameter, but can be useless if the pulse duration is so small that insufficient total charge is produced. For ultraviolet or X-ray FELs very short pulse lengths are acceptable and brightness gives some measure of performance. For lower frequency FELs the gain time is significant and a very small pulse length is not acceptable. Brightness as a single measure also ignores the fact that pulse compression can be used to raise the current, providing the momentum spread is small. Unfortunately each application has its own requirements and no single parameter describes them.

Simple Theory

It is interesting to start with the simple theoretical predictions of Kwang Je Kim (ref 1). He notes three sources for emittance:

a) Electron Temperature. The electrons emitted from the cathode surface emerge with an energy that is of the order of, but less than, the difference between the photon energy and the surface work function (typically about 0.3 eV). These electrons emerge over a large angular cone. Their initial energy spread does not in general induce a significant final spread in longitudinal energy, that is dominated by other effects, but it does provide a minimum possible normalized emittance that is of the order of:

$$\epsilon_n \approx 3\ 10^{-4}\ r_c$$

where r_c is the cathode radius.

b) Radio Frequency Time Dependent Effects. The electromagnetic fields in a gun induce transverse forces on the electrons which, to first order, produce focussing of the beam. This does not increase the emittance at any given instant of time, but the fact that they are time varying means that emittance, if integrated over the bunch length, is increased. Kim gives as an approximation:

$$\epsilon_n \approx \frac{1}{2\sqrt{2}} \left(\frac{e\,E_o}{m\,c^2}\right) \left(\frac{\omega}{c}\right)^2 \sigma_r^2\ \sigma_z^2$$

One must emphasize that this emittance is not irreversible. It is a distortion of the phase space, not an increase, and it can in principle be corrected.

c) Space Charge Induced Effects. The effects due to space charge, like those from the time variation of the rf, do not increase the phase space or decrease the phase space density. They distort that phase space. When integrated over time for a Gaussian bunch, and with various other assumptions, Kim obtains:

$$\epsilon_n \approx \frac{\pi}{2} \left(\frac{m\,c^2}{e\,E_o}\right) \frac{I}{I_a}\ \frac{1}{(3\ \sigma_r/\sigma_z\ +\ 5)}$$

where $I_a \approx 17,000$ Amps. Note the dependence on rms sigma's to the fourth power, which makes this result very sensitive to the tails of the distributions in radius and length.

Comparison with a simulation and examination of predictions

In figure 1, as a function of accelerated charge, we compare the prediction of these simple formulae with the simulation of a well optimized, but otherwise conventional 3 1/2 cell rf gun (ref 2). The gun was designed for a charge of 1 nC, an rms laser pulse duration of 8 psec and an accelerating gradient of 100 MeV/m. At its design values, an emittance of about 3 mm mrad is obtained. At very low charge, rf effects dominate. At higher charge space charge effects take over and lead to an increasing emittance. Qualitatively, this behavior is well predicted by the theory, but numerical agreement is only obtained after the contributions from rf and space charge have been reduced by a factor of three. The reduction in the rf effects is easily understood from the fact that, in the simulation, the radial and time variations of the illumination, though Gaussian in shape, were cut off at 2 sigma. The reduction of the space charge effects may reflect the imperfection of the assumptions, but may also be thought of as indicating some degree of space charge self cancellation (see correction scheme (e) below).

In figure 2, we plot the predicted emittance as a function of the laser pulse length, for fixed charge. As the pulse length is reduced the current increases and not surprisingly the emittance increases too. But the increase is limited. If one calculated the brightness as the pulse is shortened, it would be seen to rise to very high values. This rise may be compared to that obtained by pulse compression. In both cases there is some loss of emittance both longitudinally and transverse. It is not clear which is the better route.

In figure 3, we plot the predicted emittance as a function of the illuminated cathode radius. As the radius is reduced the rf and cathode induced emittance is reduced, leaving only a rising contribution from space charge. It is in this region that it will be most interesting to explore methods of space charge emittance correction, because the potential gains are so large. It is true that the current densities from the cathode would be high, but experiments at BNL have shown that metal cathode can be operated in an rf gun at densities of up to 30,000 Amps/mm^2 without difficulty. Approximately this current density would be reached with a cathode illumination radius of 0.4 mm. In such a case the rf and cathode induced emittance would be only $3 10^{-8}$ m: an emittance 100 times smaller and a brightness 10,000 times greater than currently available.

What is the Nature of the emittance growth?

As we have said before, only the cathode's thermal emittance is fundamental and uncorrectable. That from the rf and space charge is only distortion of phase space. In both cases, when otherwise optimized, the main distortion has been shown to be a relatively higher transverse defocussing for longitudinal center of the bunch, compared with the front and back. The second most important effect, in at least one case (ref 3), is a spherical aberration in which the outer radii of the bunch are relatively less defocussed, the effect being not very dependent on the position along the bunch length.

Both of these distortions lend themselves to being corrected.

Correction Methods

a) Modify the shape, in time, of the illumination of the cathode.

b) Clip, or ignore the radial or longitudinal tails of the distributions. Rms emittance gives undue weight to such tails, but an FEL's performance depends more on the central density, and is far less effected by the existence of halos.

c) Raise the accelerating gradient. For single pulses, far higher fields can be obtained without breakdown. Thus the use of switched power or the generation from harmonics of separated single accelerating pulses would allow more rapid acceleration and the resultant suppression of space charge effects.

d) Correct the time dependent focussing effects by the time dependent focussing produced in an rf quadrupole triplet. By bucking such a triplet against fixed field focussing any desired first or second order time dependent focussing effects could be corrected (ref 3).

e) Cancel the space charge effects near the cathode by those after a focussing element. Such correction, when possible, is naturally greater for the high current central region of the bunch than for the lower current tails, thus reducing the time dependent defocussing effects (ref 4).

f) Use higher harmonic rf components to correct longitudinal and transverse time dependencies (ref 5).

g) Shape the cathode, electrodes and radial laser illumination to correct radial higher order abberations.

h) Use an rf sextupole triplet to correct time dependent spherical abberations.

Some of these have been studied and tried, some not, but it is clear that there remains much to be done.

Conclusion

- K.J. Kim's theory, with rf and space charge emittances divided by 3, gives a reasonable initial estimate of uncorrected gun emittances.
- An emittance of the order of $3\ 10^{-6}$m for 1 nC is currently possible.
- There remain many unexplored possibilities for emittance correction.
- An emittance of $3\ 10^{-8}$ m for 1 nC, could be obtained if the space charge effects could be fully corrected. This is a useful goal.

References

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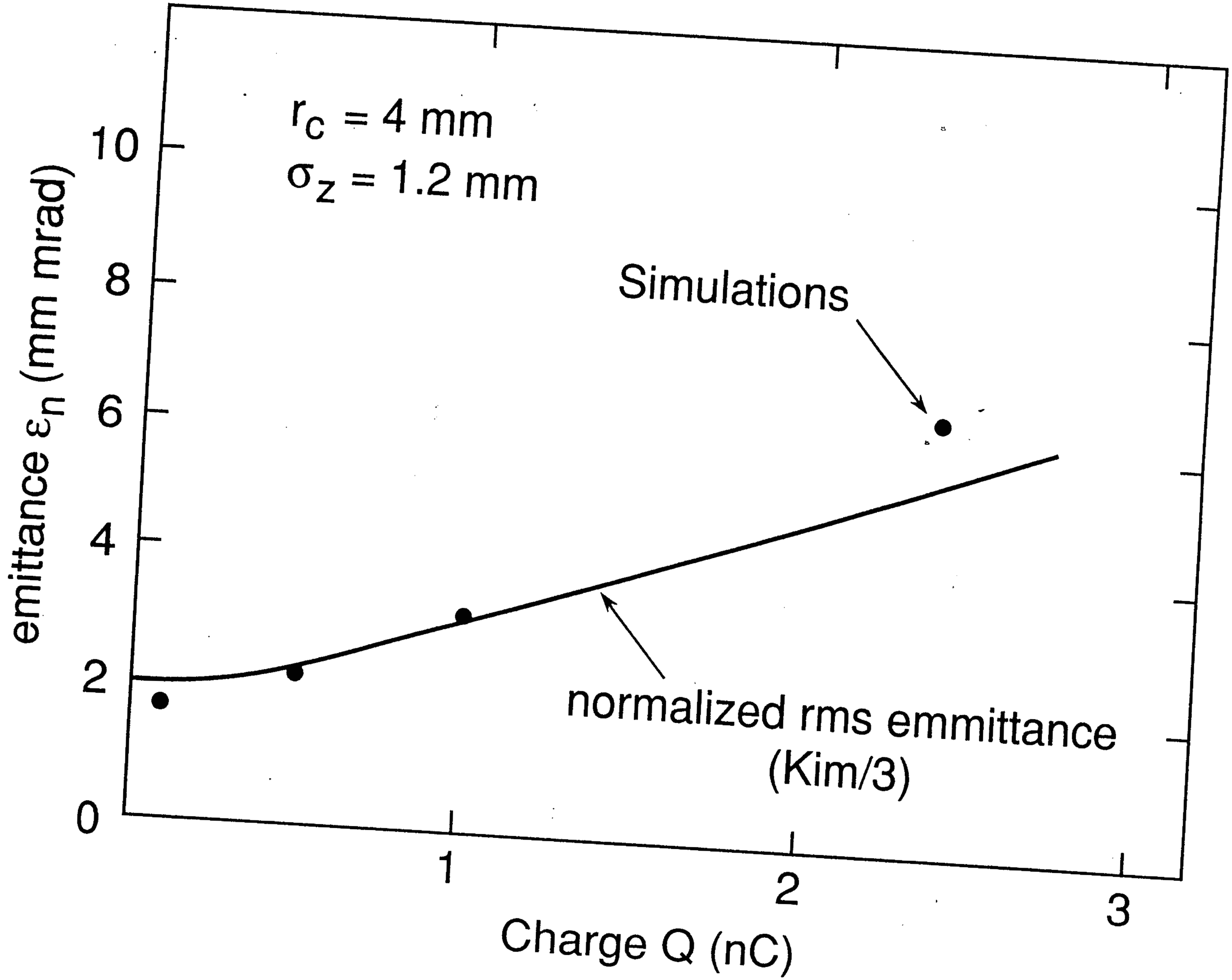
Figure Captions

1. The emittance as a function of total charge. The lines indicate the results of Kwang Je Kim's theory, with the contributions from rf and space charge divided by a factor 3. The points are from the simulation.
2. The theoretical emittance as a function of bunch length. The dotted line represents contributions from the cathode, the dashed line from space charge effects, the dash-dot line from rf effects , and the solid line gives the total.
3. The theoretical emittance as a function of cathode radius. The dotted line represents contributions from the cathode, the dashed line from space charge effects, the dash-dot line from rf effects , and the solid line gives the total.



r_c = 4 mm
σ_z = 1.2 mm
Simulations
normalized rms emmittance
(Kim/3)
emittance ε_n (mm mrad)
Charge Q (nC)
0
2
4
6
8
10
1
2
3

Fig. 1

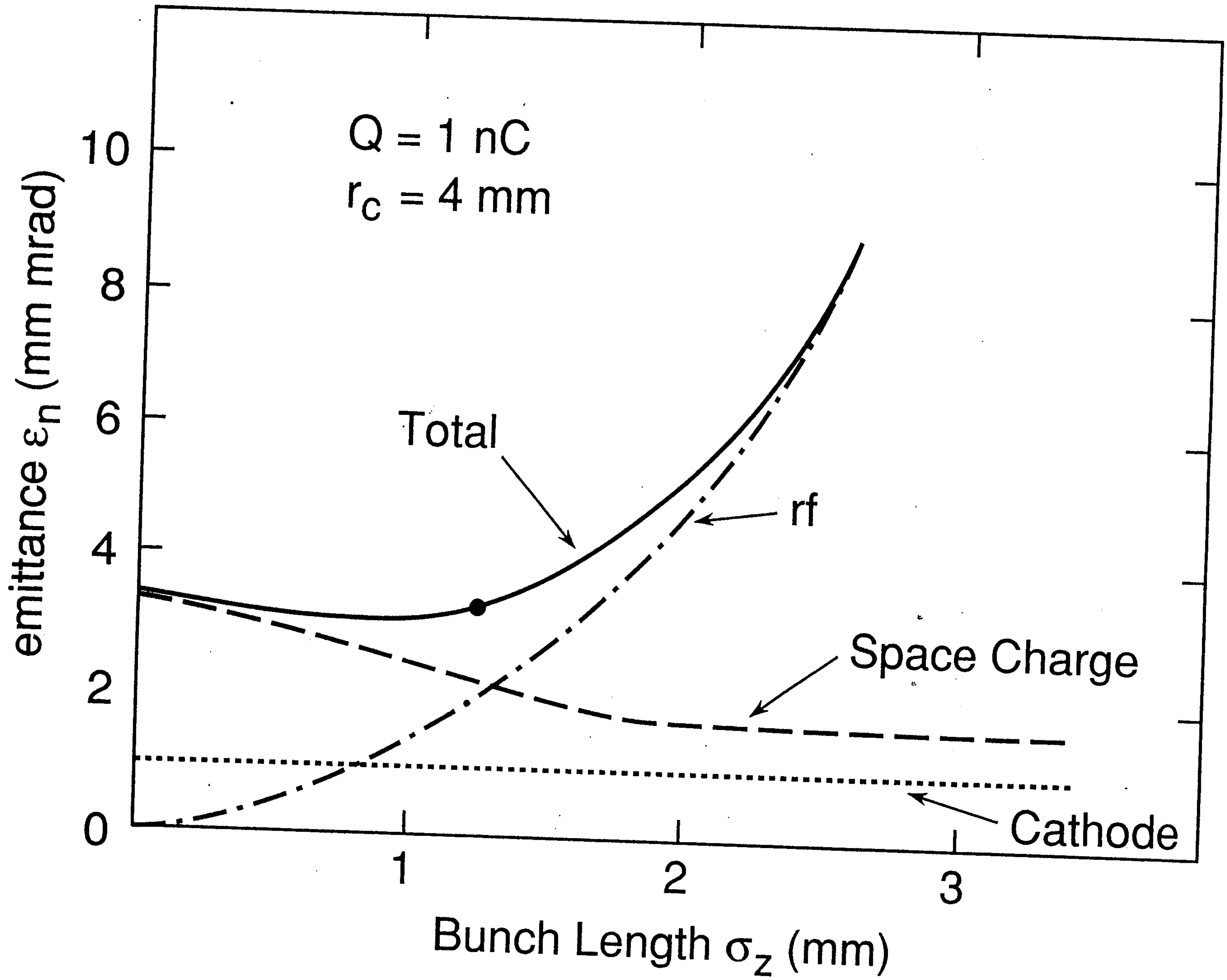
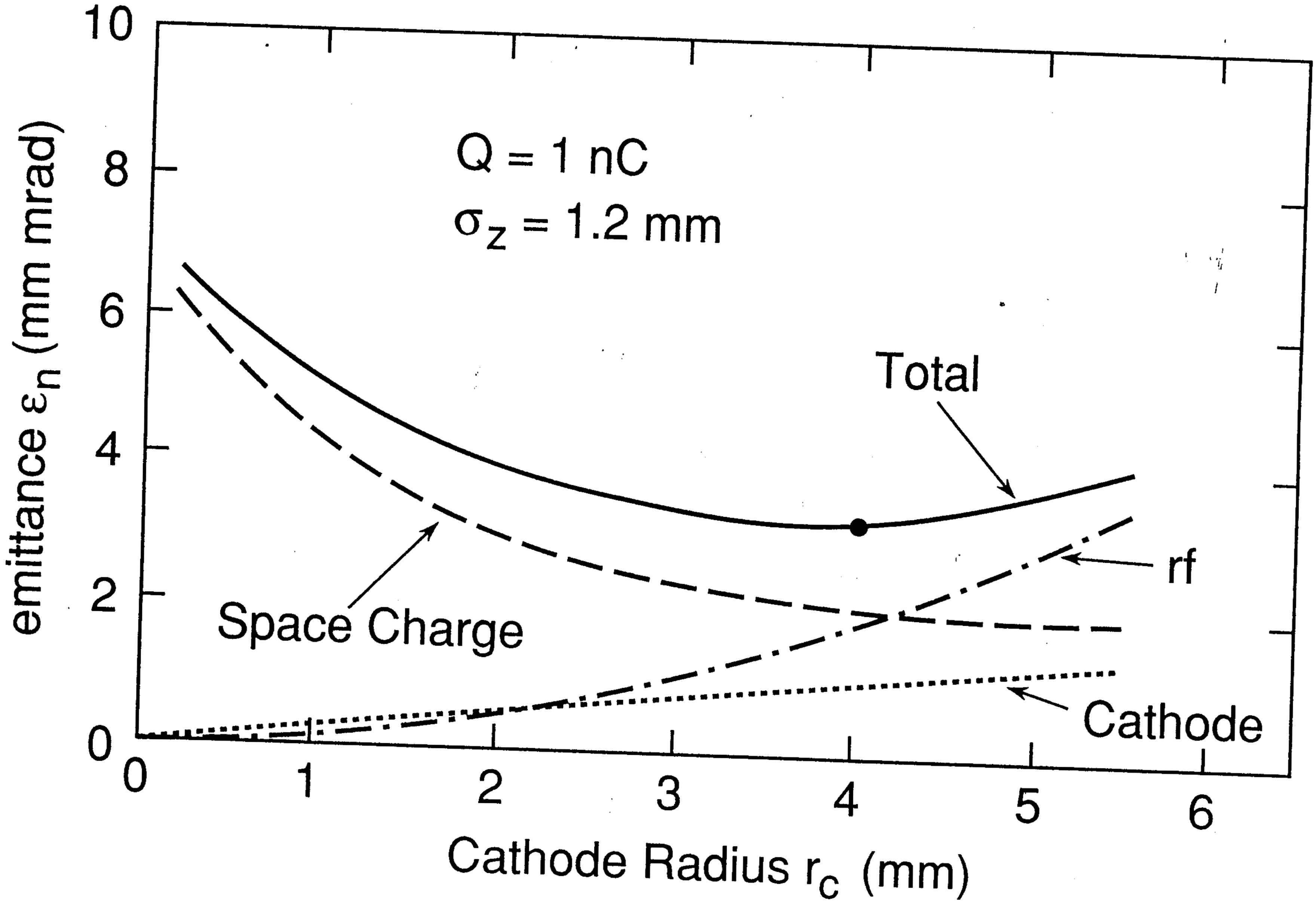

Q = 1 nC
r_c = 4 mm
Total
rf
Space Charge
Cathode
emittance ε_n (mm mrad)
Bunch Length σ_z (mm)
0
2
4
6
8
10
1
2
3

Fig. 2



10
8
6
4
2
0
emittance εn (mm mrad)
Q = 1 nC
σz = 1.2 mm
Total
Space Charge
rf
Cathode
0
1
2
3
4
5
6
Cathode Radius rc (mm)

Fig. 3