Holistic Cathode Design:
Structuring the cathode surface to cancel the space charge limit

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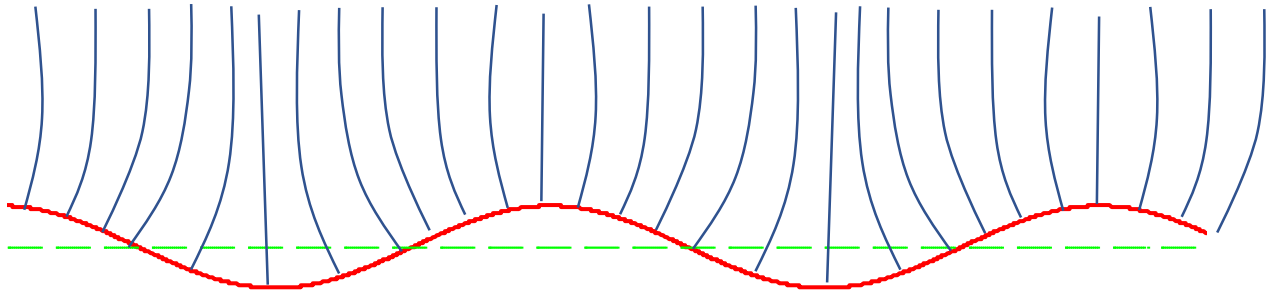
A holistic cathode design using a contoured surface which shapes the applied field's enhancement to cancel the space charge limit and linearize the field is described.

The basic idea:

- **Modulate the surface height to enhance the applied field and cancel the space charge field.**
  - **Field enhancement at the tops of a cosine-like surface height modulation can double the applied field near the cathode where the image-charge field is the largest.**
  - **Lowering the spatial frequency of the modulation increases the distance the enhanced field extends into the vacuum and gives better overlap with the image-charge field.**
  - **The image-charge field can be cancelled both in it's z-extent and field strength by tuning the amplitude and wavelength of the cosine-modulated surface.**
  - **Use the 3rd harmonic of the cosine-modulated surface spatial frequency to flatten the enhanced field**



Immediately after photoemission, There are four major fields acting on the electrons:

1) Fields due to physical roughness generating varying field enhancement and transverse fields.

2) Fields due to the electron bunch's image charge. Space charge limited emission is reached when the image charge field cancels the applied field.

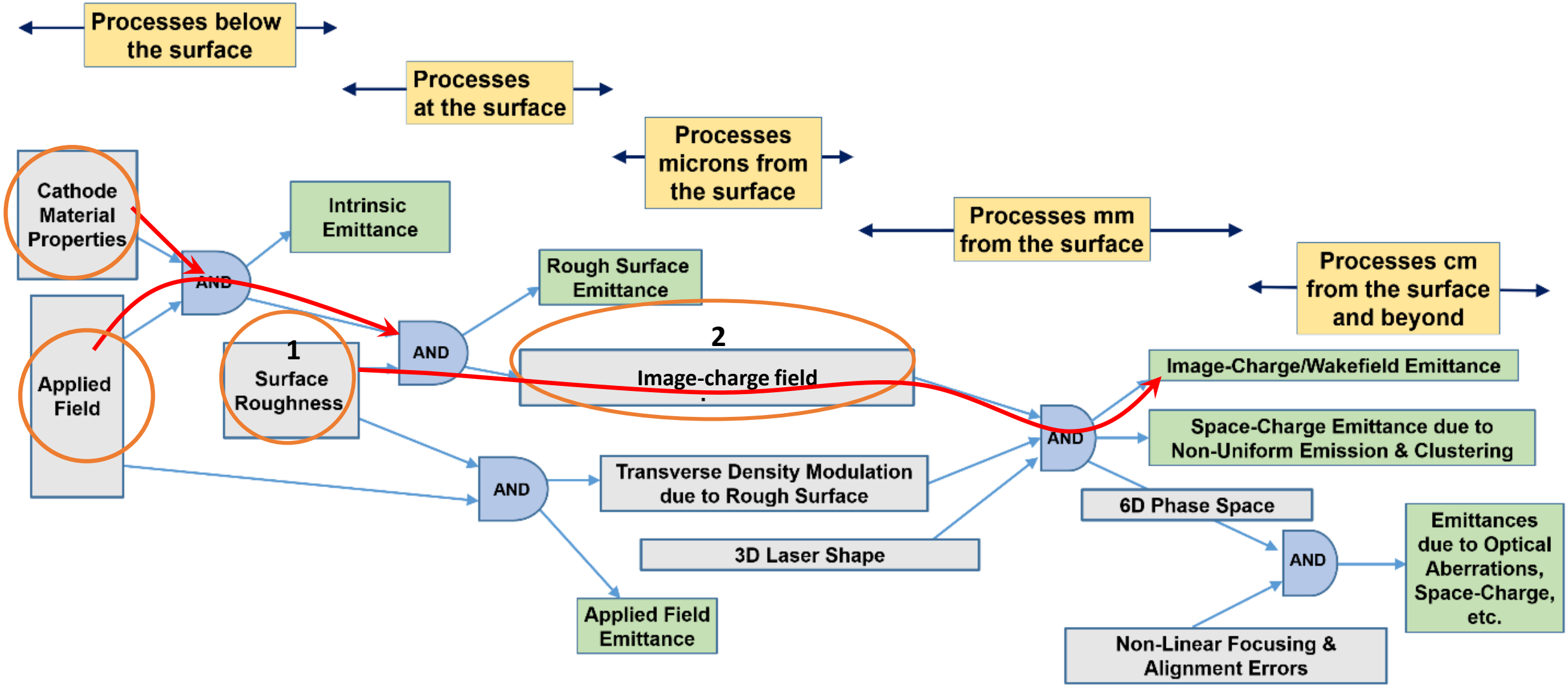
3) Fields due to chemical roughness caused by variations in the chemical potential and work function across the cathode surface.

4) Fields between the electrons in the bunch. If the bunch charge distribution is parabolic, then these fields expand the bunch linearly and there is no emittance growth.

Fields 3) and 4) are not included in this analysis.

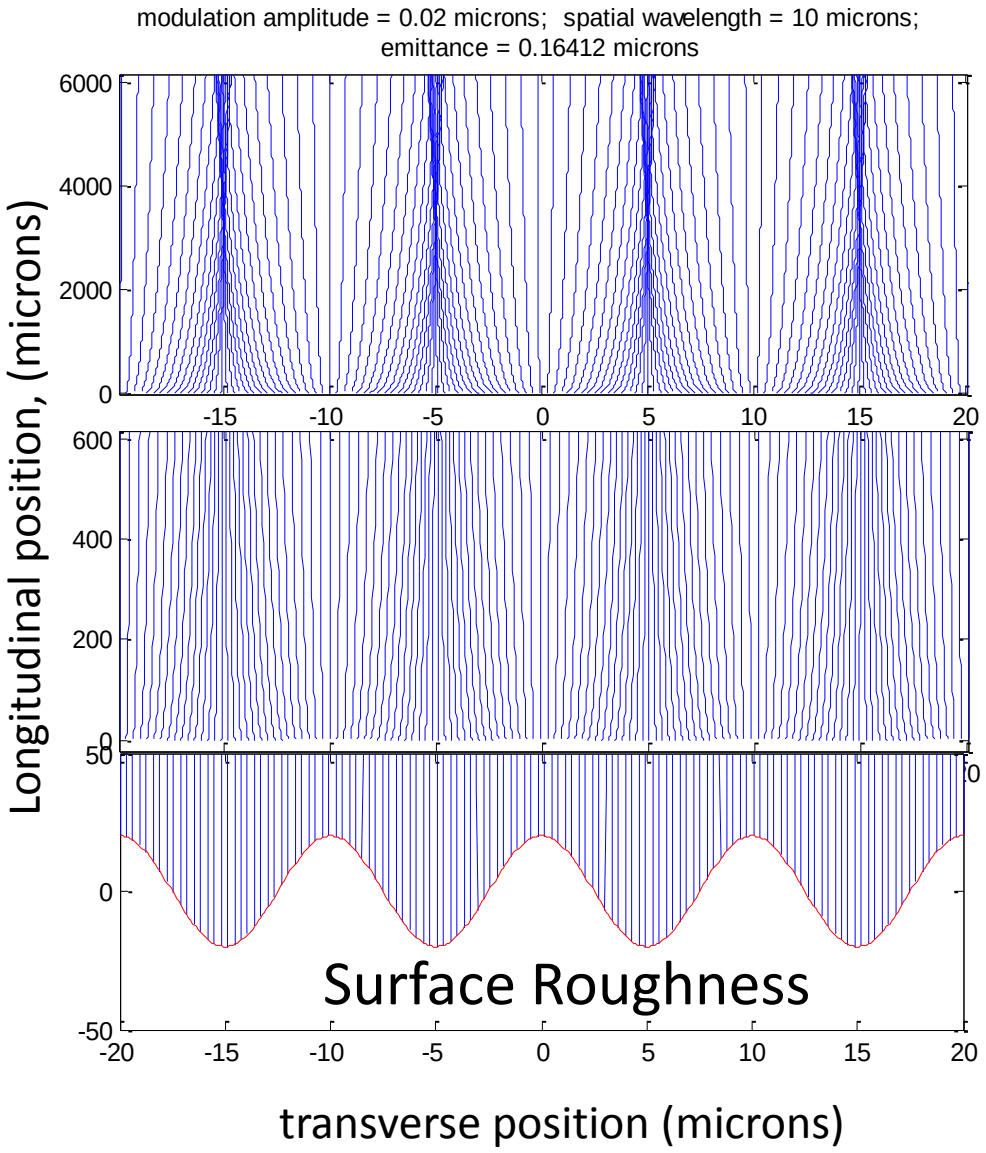
This work shows the roughness field can be used to cancel the image charge field

Emittance generating processes vs. distance from the cathode surface

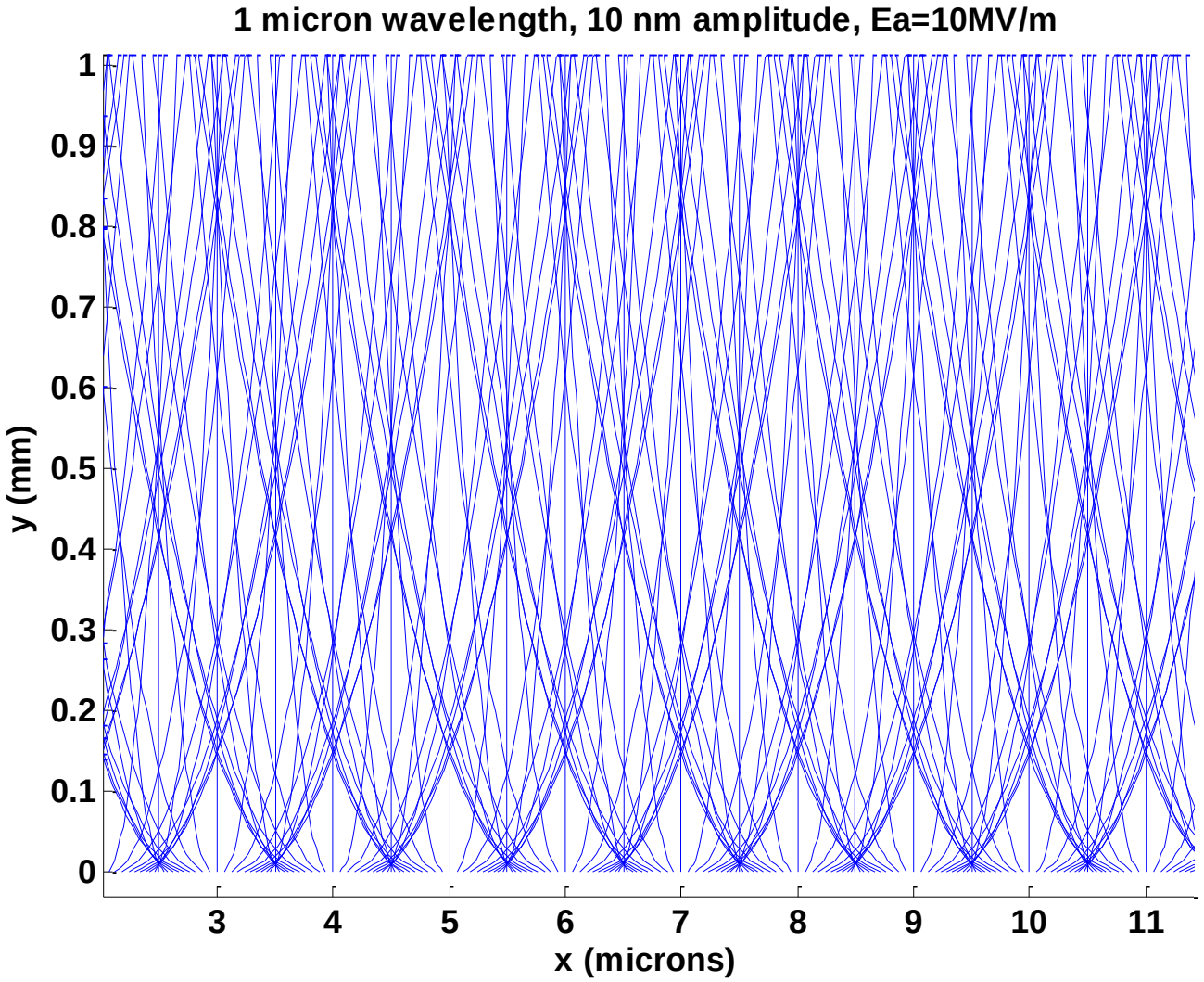


Focusing and Transverse Charge Density Modulations due to Surface Roughness

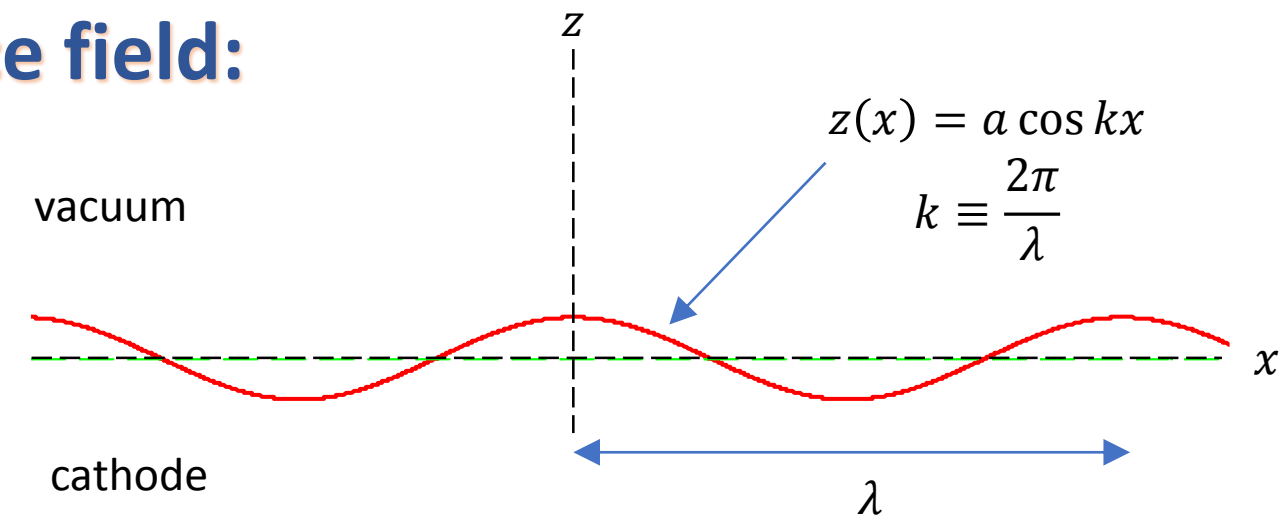
Electrons are focused and go through a crossover a few mm from the cathode for applied fields of 50 MV/m.



Caustics occur at turning points of the ray bundles:



The rough surface field:



Transverse and longitudinal fields of a cosine modulated surface without the small amplitude approximation, $ak \ll 1$.

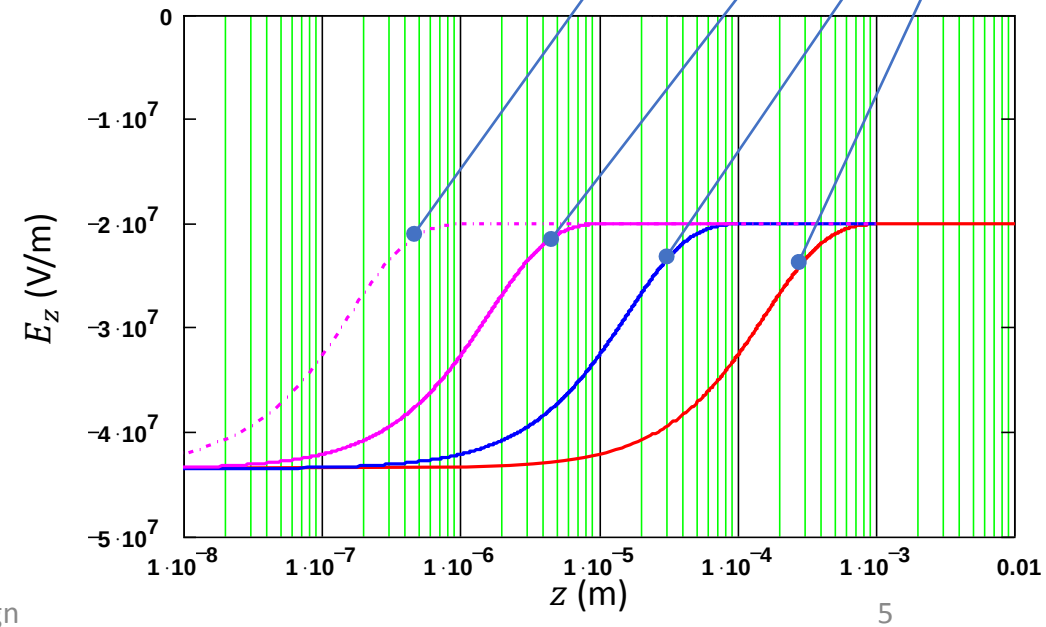
$$E_x = -akE_a(ak\cos kx + 1)\ e^{ak\cos kx}\ \sin kx\, e^{-kz}$$

$$E_z = E_a\left(1 + ak\ e^{ak\cos kx}\ \cos kx\ e^{-kz}\right)$$

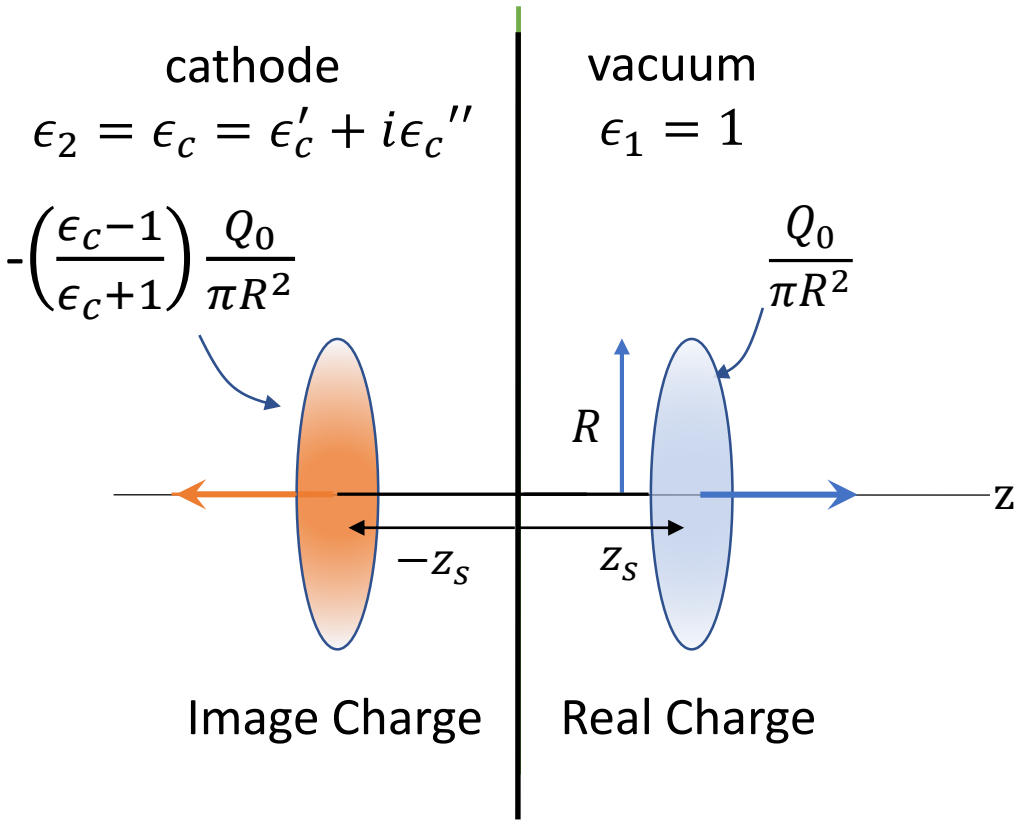
The rough surface field includes the applied field since

$$E_z = E_a \ \ and\ E_x = 0 \ \ when\ a = 0$$

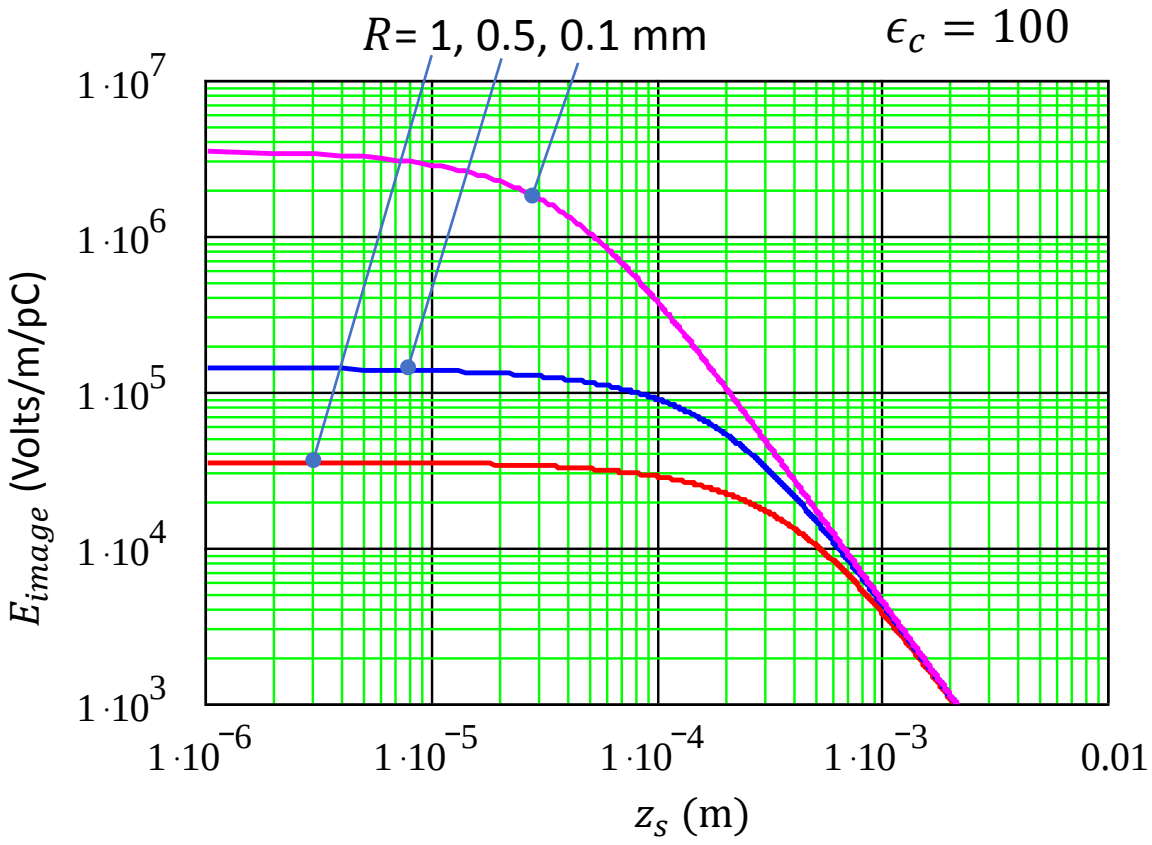
Longitudinal field along the z-axis
ak=0.628, for λ= 0.001, 0.01, 0.1, 1 mm



The image-charge field produced by a disk of charge vs its distance from the cathode

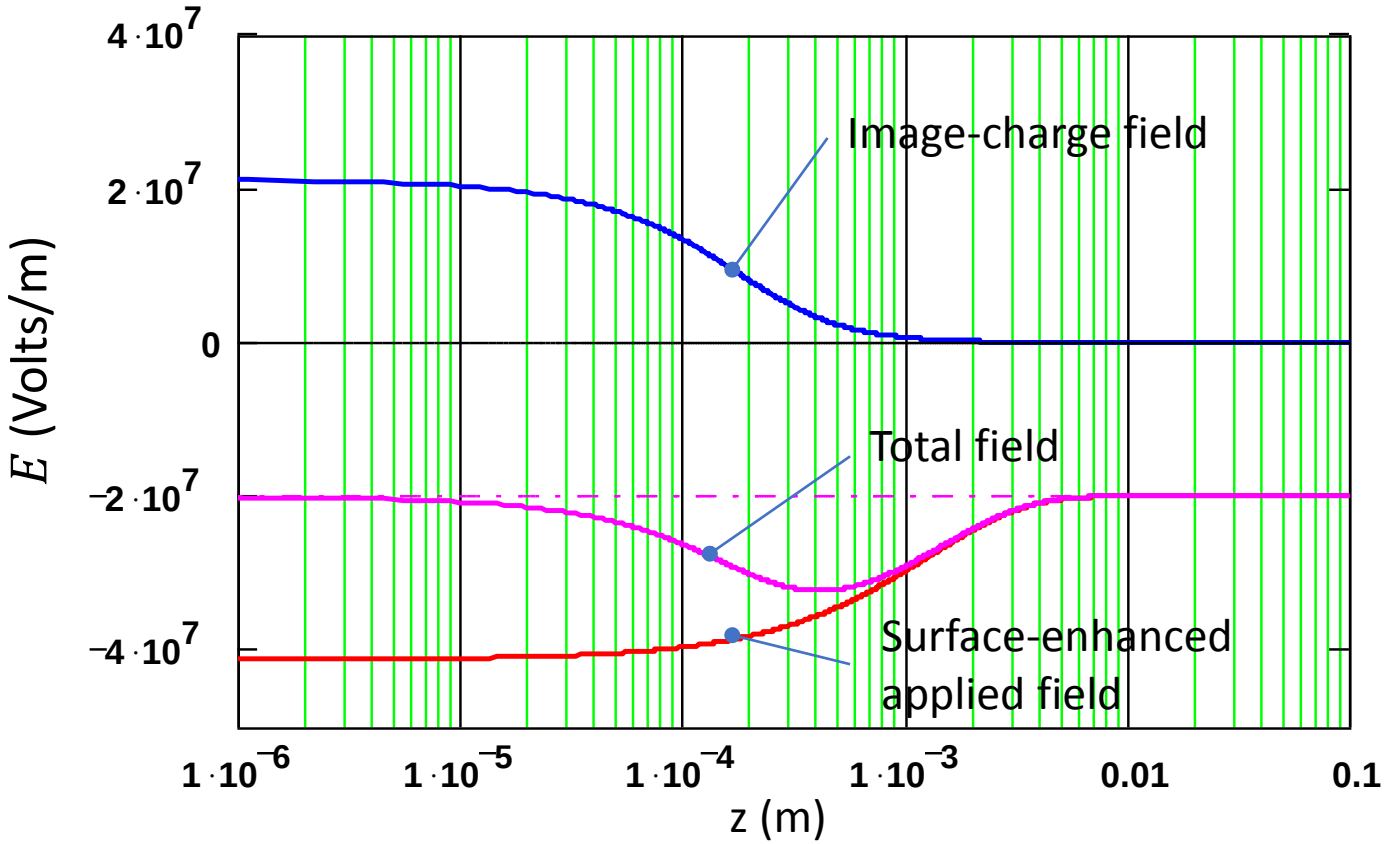


$$E_{image}(z_s) = \frac{Q_0}{\epsilon_0 \pi R^2}\left(\frac{\epsilon_c - 1}{\epsilon_c + 1}\right)\left(\frac{z_s}{\sqrt{{z_s}^2 + \frac{R^2}{4}}} - 1\right)$$



Matching the length and strength of surface-enhanced applied field to cancel the image-charge field

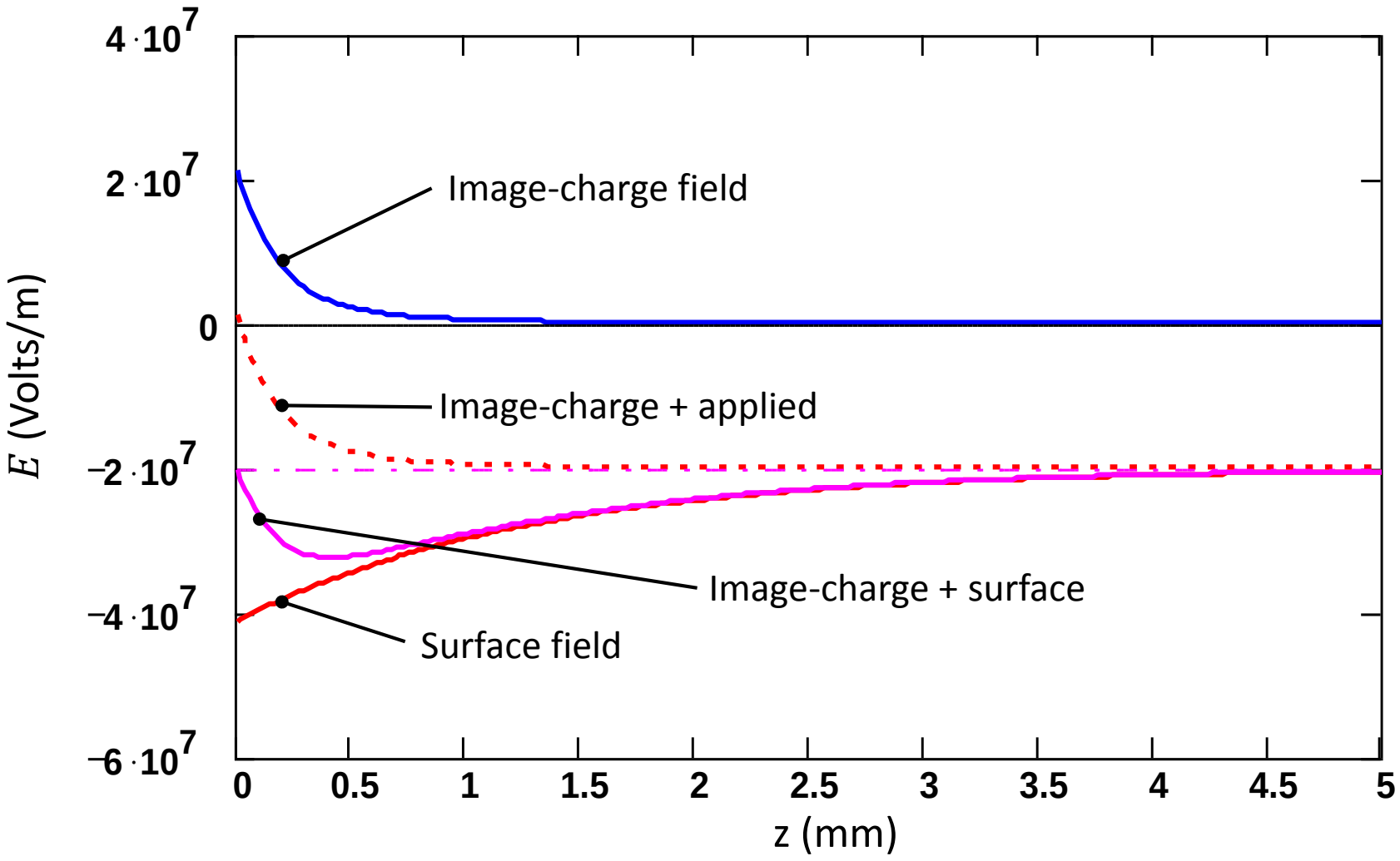
- Complete cancellation isn't possible since the field shapes are different.
- An 8-mm spatial wavelength is needed to match the z-extent of the image-charge field.
- The mismatch gives the electrons a "roller coaster ride" through a dip near z=0.4 mm.



Surface parameters:
a= 0.75 mm
λ= 8mm
k=785.4 /m
ak= 0.589

Image charge parameters:
Q_{bunch}= 150 pC
R=0.5 mm
E_a=-20 MV/m
ϵ_c=100

Surface parameters adjusted to cancel the image charge field at z=0: 8 mm spatial wavelength needed to overlap with image-charge field



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Flattening the enhanced field hilltops with a spatial 3rd harmonic

The surface field without approximations: $E_z = E_a\left(1 + ake^{akcos\,kx}\cos kx\ e^{-kz}\right)$

Expanding $e^{akcos\,kx}$ in powers of $akcos\,kx$ gives

$$E_z = E_a\left(1 + akcos\,kx\,e^{-kz} + (akcos\,kx)^2 e^{-kz} + \cdots\right)$$

and since kx is small:

$$E_z \approx E_a\left(1 + akcos\,kx\,e^{-kz}\right) \approx E_a\left[1 + ak\left(1 - \frac{k^2}{2}x^2\right)e^{-kz}\right]$$

This is for the fundamental wavelength expanded about $kx = 0$.
For the third harmonic the expansion is about $kx = \pi$ which changes – to + and k=>3k

$$E_{3z} = E_a\left[1 + 3ak\left(1 + \frac{9k^2}{2}x^2\right)e^{-3kz}\right]$$

$$E_z = E_a\left[1 + a_1 k\left(1 - \frac{k^2}{2}x^2\right)e^{-kz}\right] \qquad E_{3z} = E_a\left[1 + 3a_3 k\left(1 + \frac{9k^2}{2}x^2\right)e^{-3kz}\right]$$

cancel these terms

Setting the summed x^2 terms to zero, where the fields peak at z=0, we have: $a_3 = \frac{a_1}{27}$

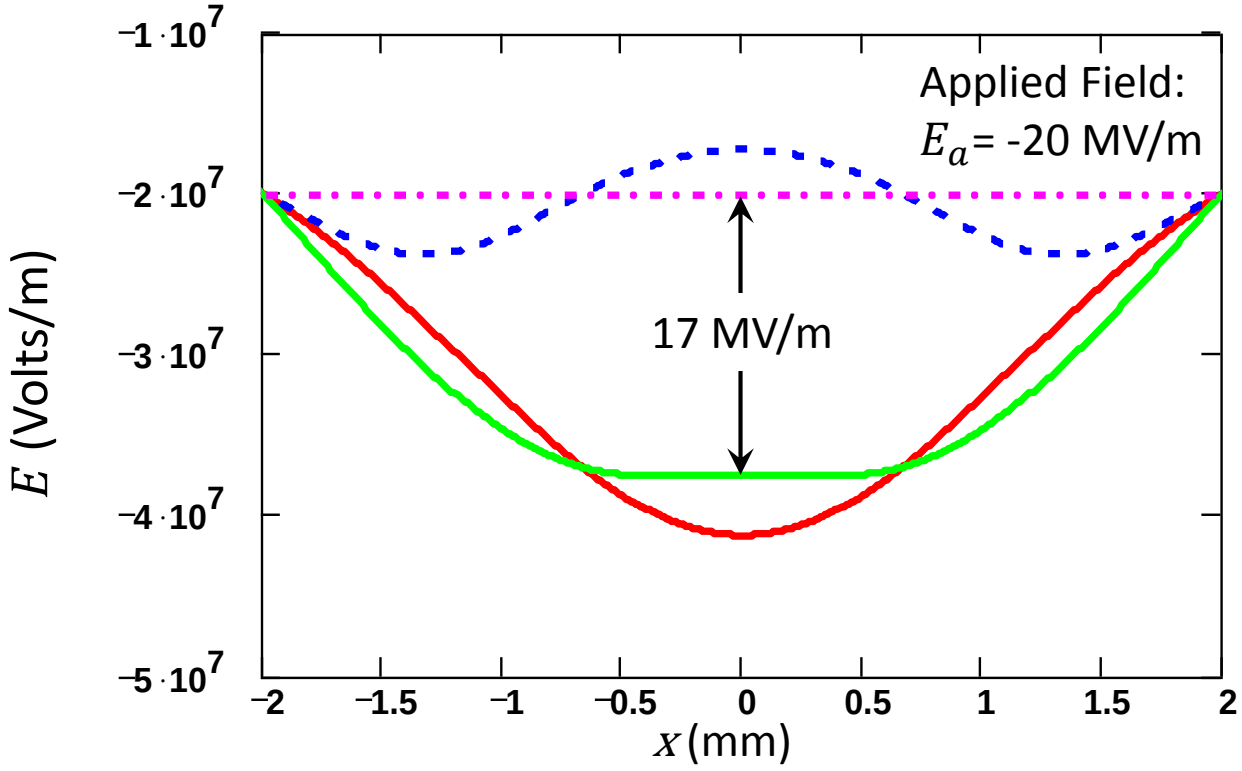
However because kx is not small compared to 1, the next order terms, $O(x^3) + O(x^4)$ etc. need to be included.

Numerically one finds a larger result: $a_3 = \frac{a_1}{11}$

Adding a third harmonic flattens the field at the hilltops where the electrons are being launched

The enhanced, flat field region is 1.85-times the applied field

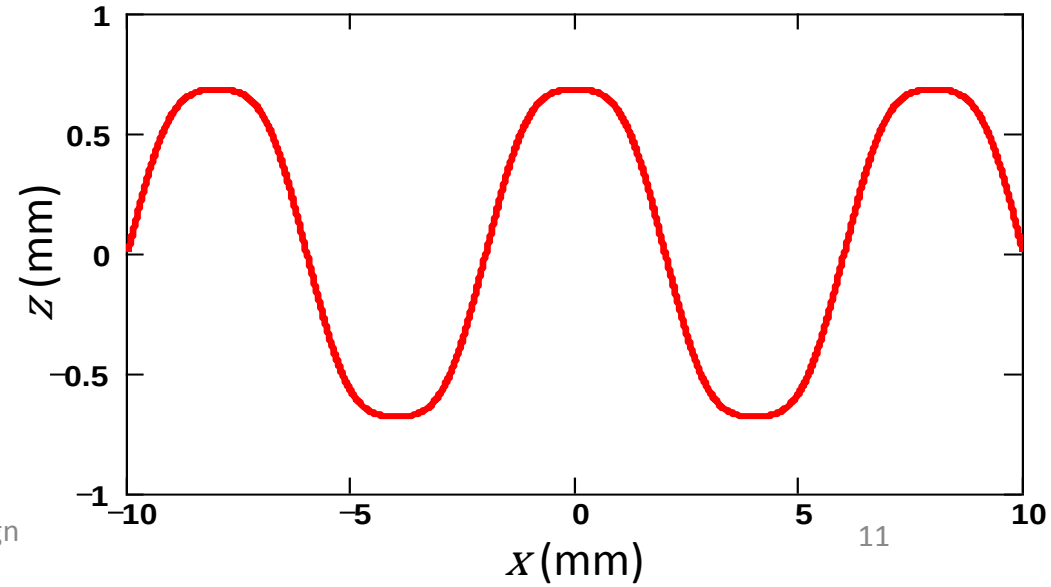
The 20 MV/m applied field is enhanced a factor of 1.85 to 37 MV/m. The field is flat over the photocathode's 1 mm diameter area.



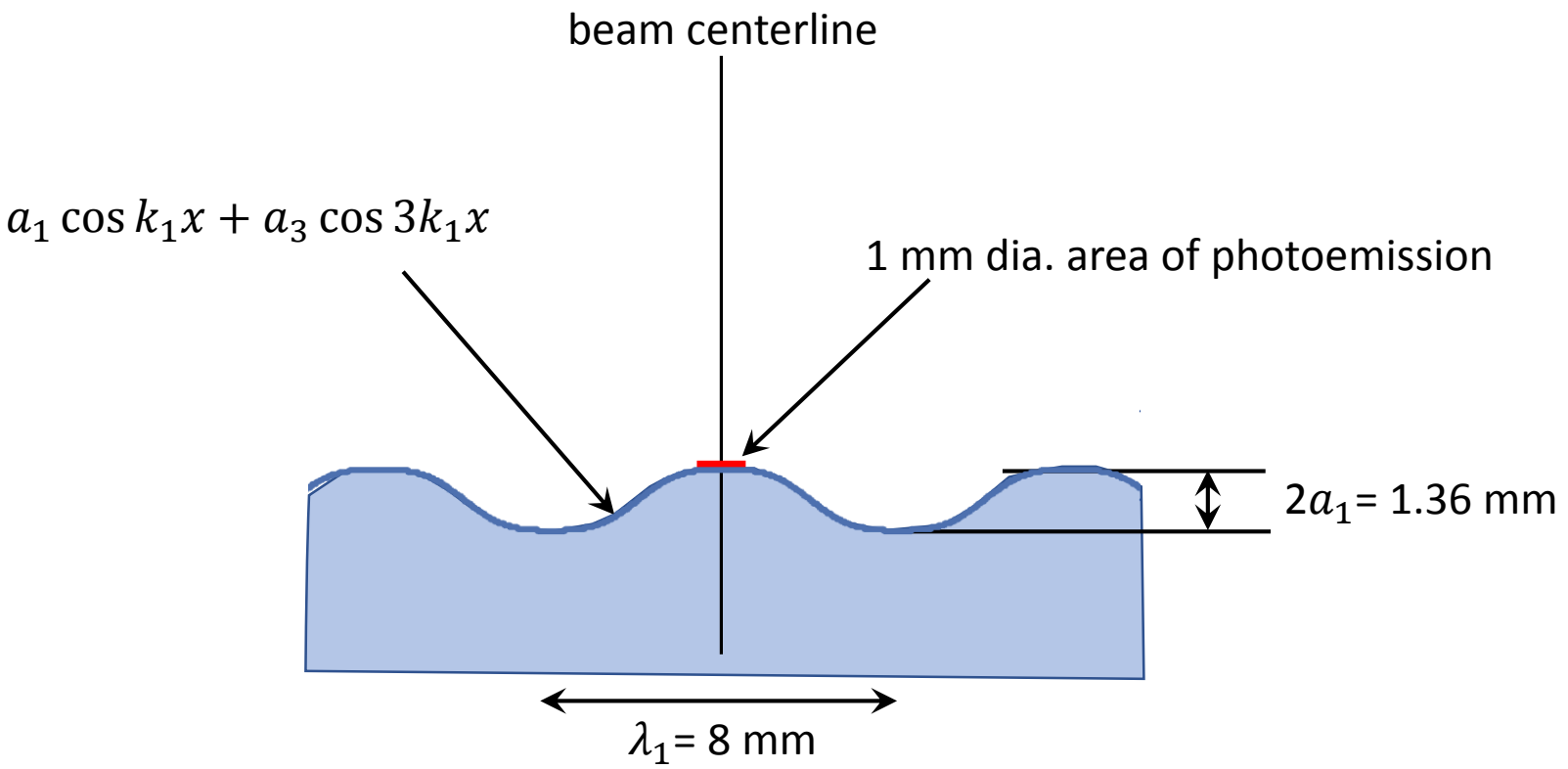
Surface Parameters:

λ_1= 8 mm	λ_3= 2.67 mm
a_1= 0.750 mm	a_3= -0.068 mm
k_1= 785/m	$k_3 = 3k_1$ = 2356/m
$a_1 k_1$=0.59	$a_3 k_3$=0.16

$$a_1 \cos k_1 x + a_3 \cos k_3 x$$



The cathode surface profile which cancels the image-charge field and corrects the enhanced-field non-linearity



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a_3= - 0.068 mm
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$a_3 k_3$=0.16

Summary

- There are four fields acting on electrons close to the cathode:
  - Surface Roughness: enhancement of the applied field by variations in the surface height.
  - Image-charge field: self-attraction of the electrons to their 'images' inside the cathode.
  - Chemical roughness: local variations in the work function, crystal faces, etc.
  - Self-fields of the electron bunch: space charge repulsion between the electrons.
- The properties of the surface roughness and the image-charge fields are described
- It is shown that the surface parameters can be 'tuned' to cancel the image-charge field. And thereby cancel the space-charge limit.
- A holistic design is described which:
  - Uses field-enhancement of the applied field to cancel the image-charge field
  - Applies the 3rd spatial harmonic to flatten the enhanced field
  - Produces a surface field enhancement of 1.85
  - Provides a 1 mm diameter flat field area for photoemission
- 2D theory was described, need to expand to 3D.