Prospects for Future RF Gun Developments

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An increasing number of high brightness beam applications relies on the performance of RF Guns, e.g.:

- FELs (q > 100pC)
- THz sources based on wake fields (q > 100 pC)
- Compton sources (q > 100pC)
- ultrafast irradiation (q 10 – 250 pC)
- electron diffraction (q ≈ 100fC)
- time resolved electron microscopy (q ≈ 10fC)
- ultrafast fields (magnetism) (q > 10 pC ?)
- advanced acceleration techniques (q > 10 pC ?)

Developments in the field of RF Guns will have a major impact!
A factor of 2 in the emittance is already significant.

Recent developments allow us to envisage a new generation of RF Guns with significantly improved performance.

Recent developments:
- stable operation at higher rf fields
- new beam dynamics concepts

What is required to make the step from vison to reality?

Ultimate Emittance Limits

The emittance of an RF gun is ultimately limited by
I -the thermal emittance and by
II- non-linear space charge fields at the cathode

I) Thermal Emittance (at the example of CsTe):

$$\varepsilon_{th} = \sigma_c \sqrt{\frac{2E_{kin}}{3m_e c}}$$

E_{kin} = kinetic energy of the electrons, depends on work function and laser photon energy

σ_c = rms beam size on the cathode

What limits the spot size?

Ultimate Emittance Limits

minimal spot size on the cathode is given by the space charge limit
- plate capacitor model

$$E_{sp} = E_{acc}$$

$$E_{sp} = \frac{q}{\varepsilon_0 A}$$

A = emission area = $2\pi\left(2\sigma_c\right)^2$

$$E_{acc} = E_0 \sin\phi_0$$

E_0, ϕ_0 = gradient and rf phase during emission

Be aware of two photon emission!

Ultimate Emittance Limits

II) non-linear space charge fields during emission

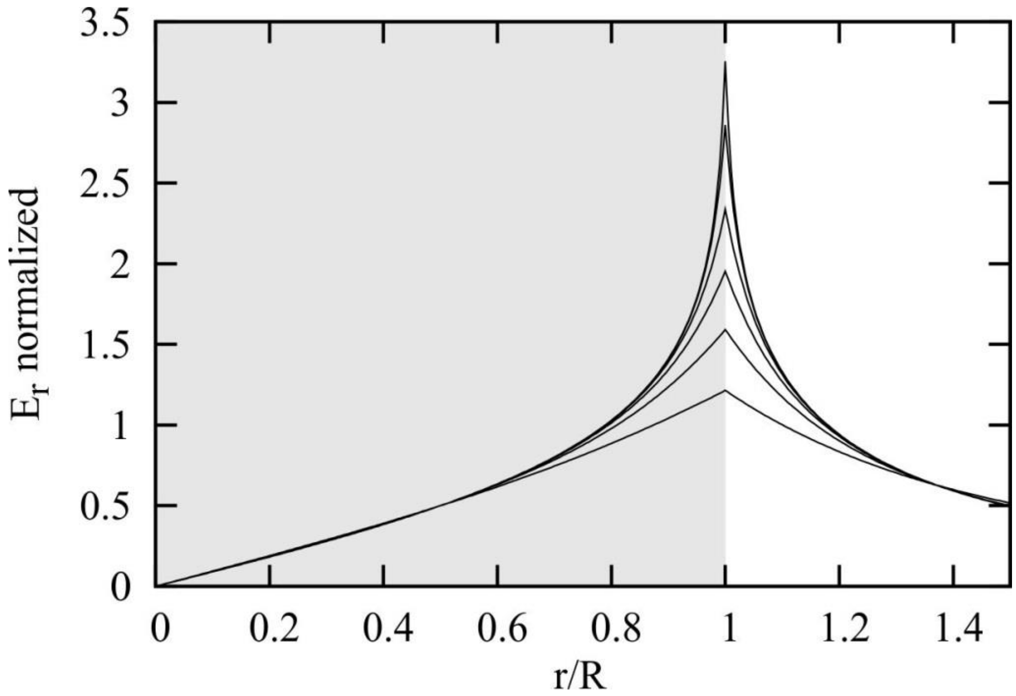
electrons start with ~zero velocity at the cathode. As a result a the charge density in front of the cathode scales as:

$$\rho = j\left(\frac{2e}{m_e}E_0 \sin\phi_0 z\right)^{-1/2}$$ without space charge

$$\rho \propto jz^{-2/3}$$ space charge limited emission

i.e. a thin layer of high charge density forms in front of the cathode which all particles have to pass

Ultimate Emittance Limits

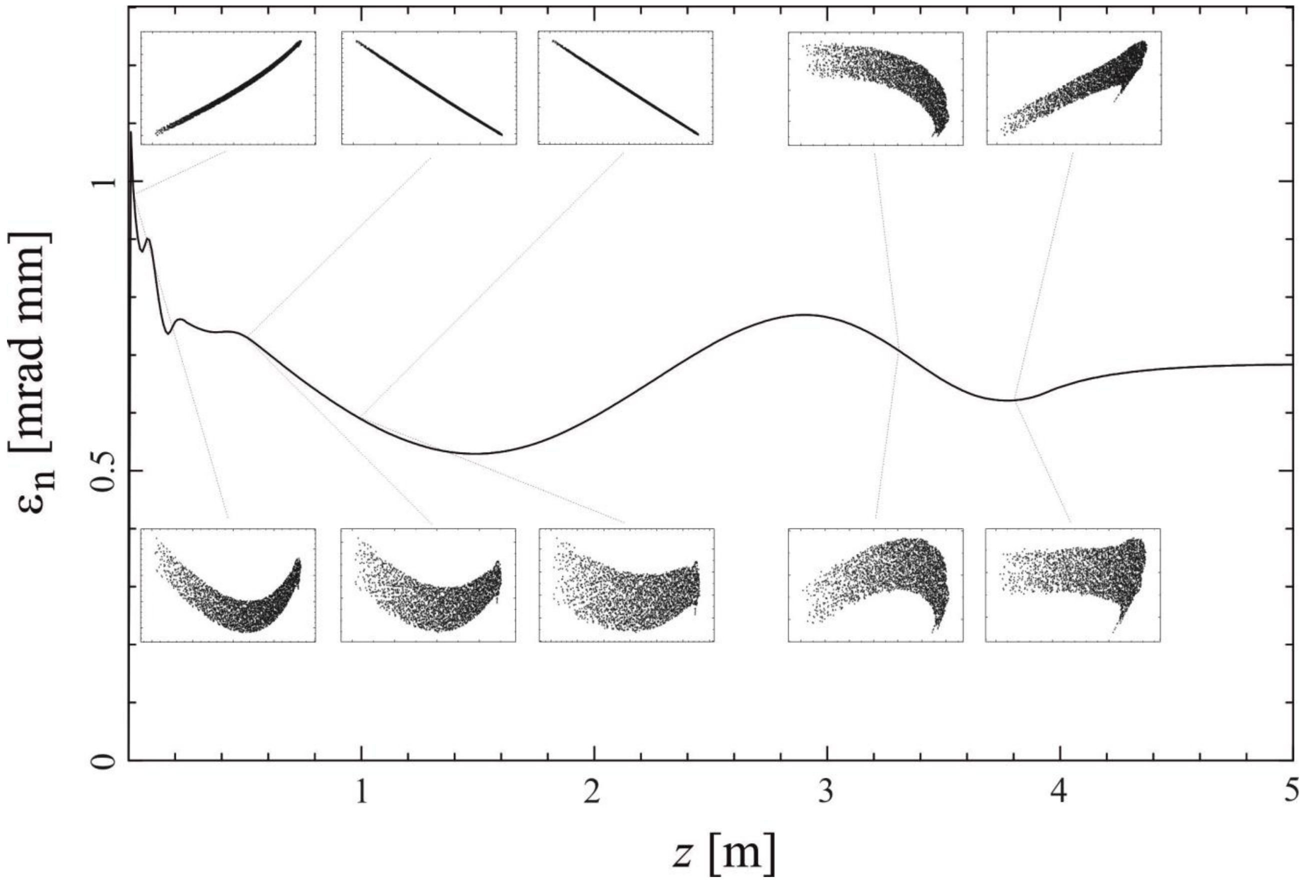


transverse space charge field for varying aspect ratios

$$A = R/L$$

of uniform charge cylinders.
The most linear curve: A = 1.0, followed by
A = 2.5, 5.0, 10.0, 25.0, 50.0
The field is normalized to 1 at r/R = 0.5.

Ultimate Emittance Limits



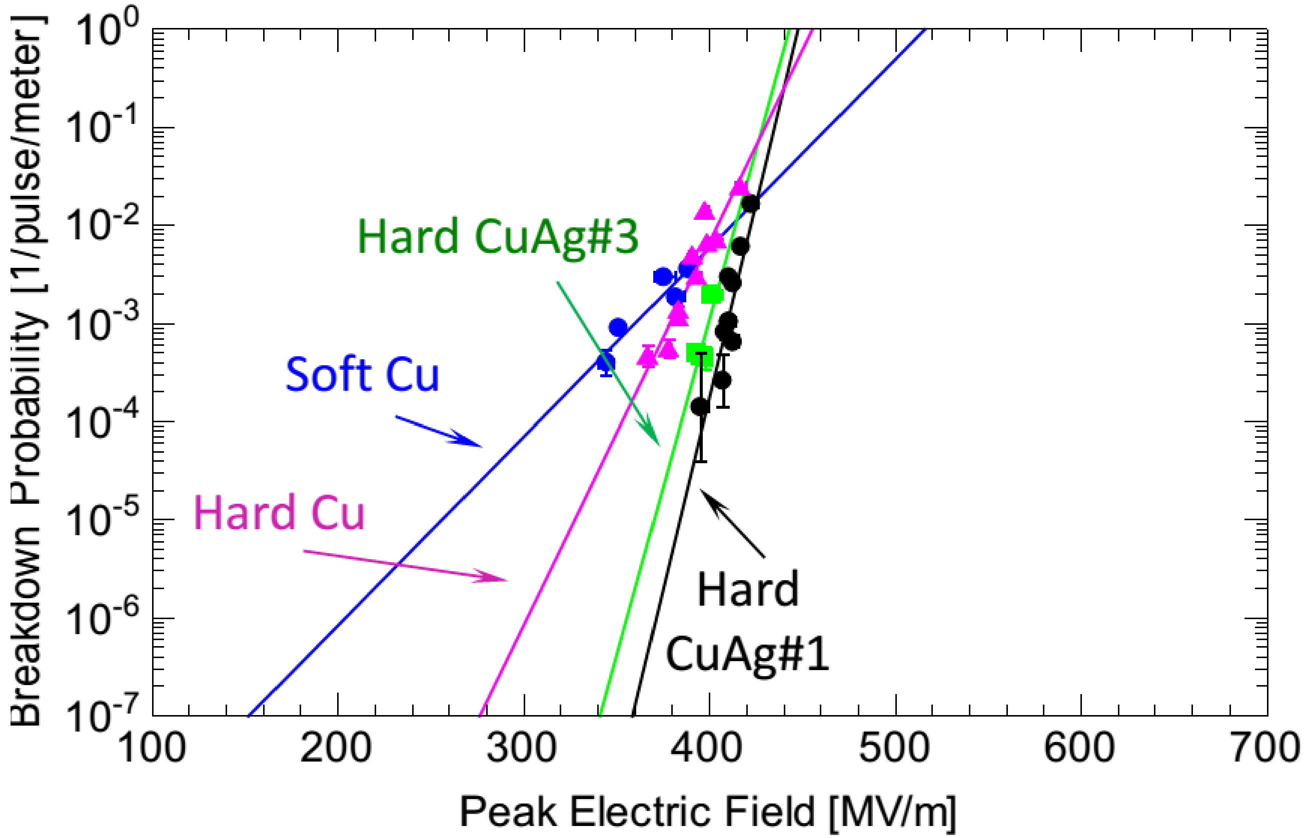
Effect of the non-linear space charge field on the slice emittance: slice emittance vs z in the XFEL injector

K. Floettmann, 'Emittance compensation in Split Photo Injectors', submitted for publication

How to improve the emittance

- increase the gradient of the gun and reduce the spot size
- shift to higher emission phase and reduce the spot size
- start with longer emission time, i.e. reduce the emission current

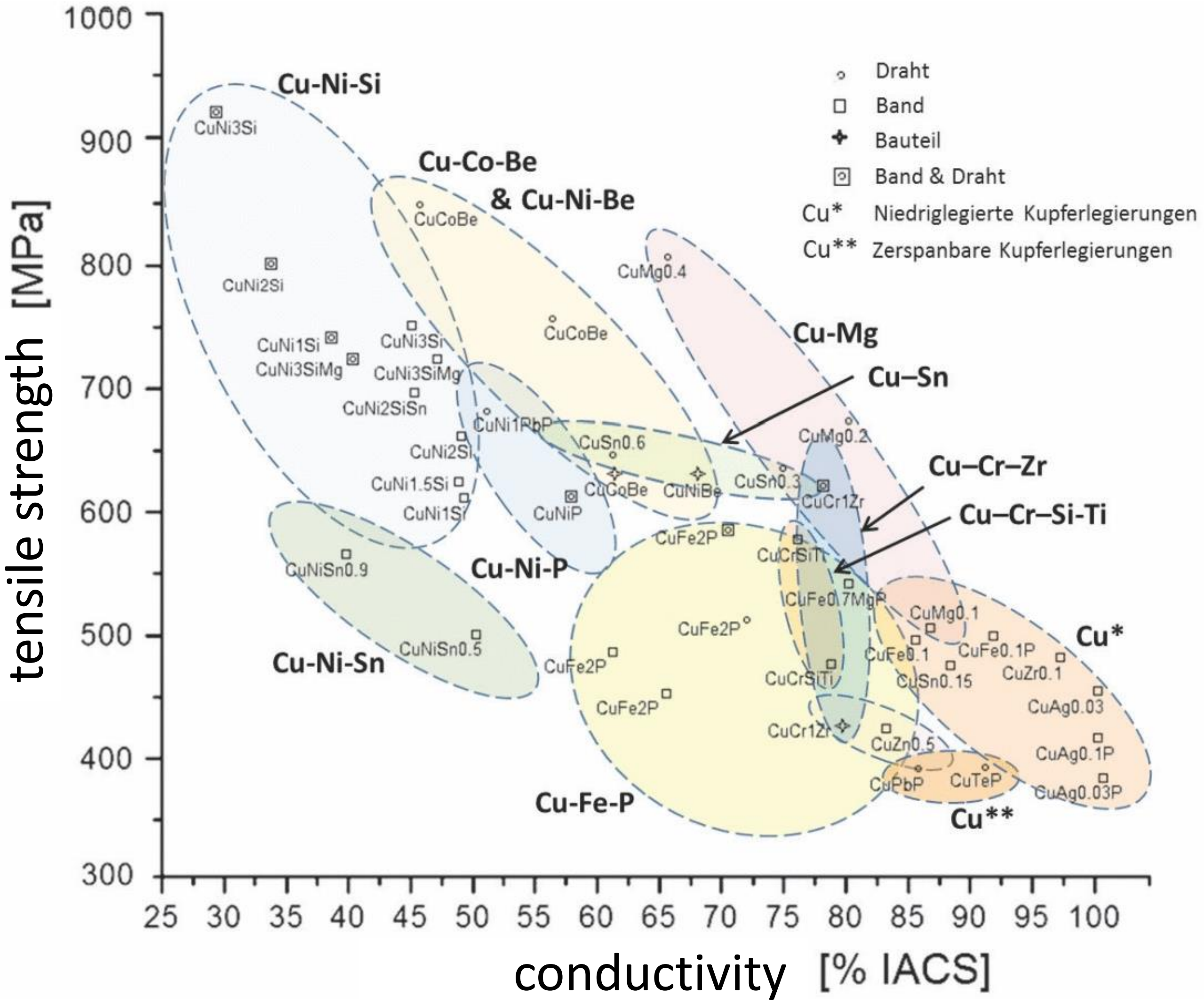
Operation at Higher Gradients:



Breakdown probability of cavities made of different materials and production methods

V. Dolgashev, EAAC 2015)

Operation at Higher Gradients:



Operation at Higher Gradients:

Problem I

High tensile strengths are only achieved for cold worked copper (OFHC and alloys).

Thus a new joining technology is required, for example clamping (Alesini, INFN, EAAC 2015).

Local softening of the cavity cylinder should be no problem as long as the iris stays cold and keeps its tensile strength:

- inductive brazing
- e-beam or laser welding
- ....

?????

Or hardening by a special heat treatment after brazing????

Operation at Higher Gradients:

Problem II

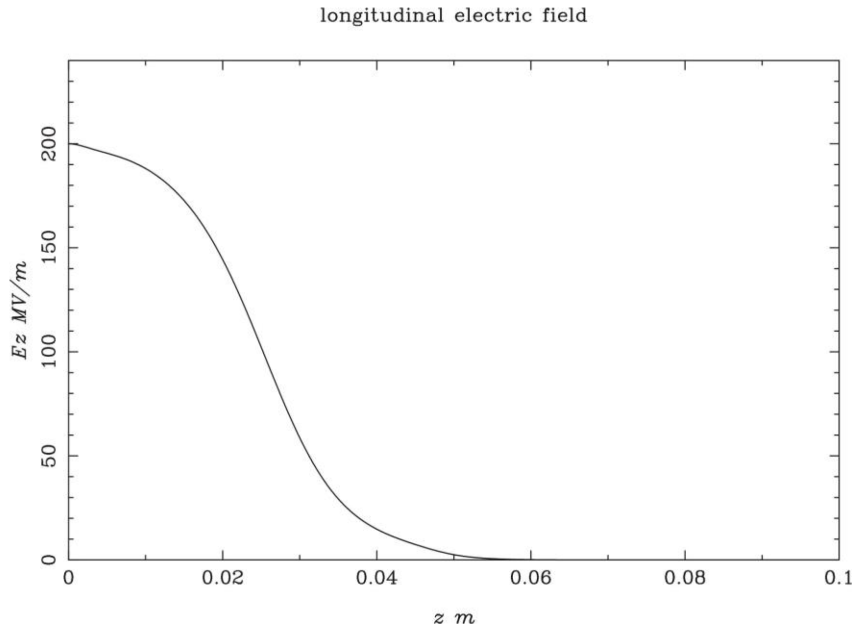
- Higher gradients require significantly higher rf power
- Higher gradients lead to higher energies, which can be a disadvantage in some cases (emittance compensation, velocity bunching)

A possible scenario is to work with only a half cell cavity.

First trial (to be optimized)

6 MW = 165 MV/m

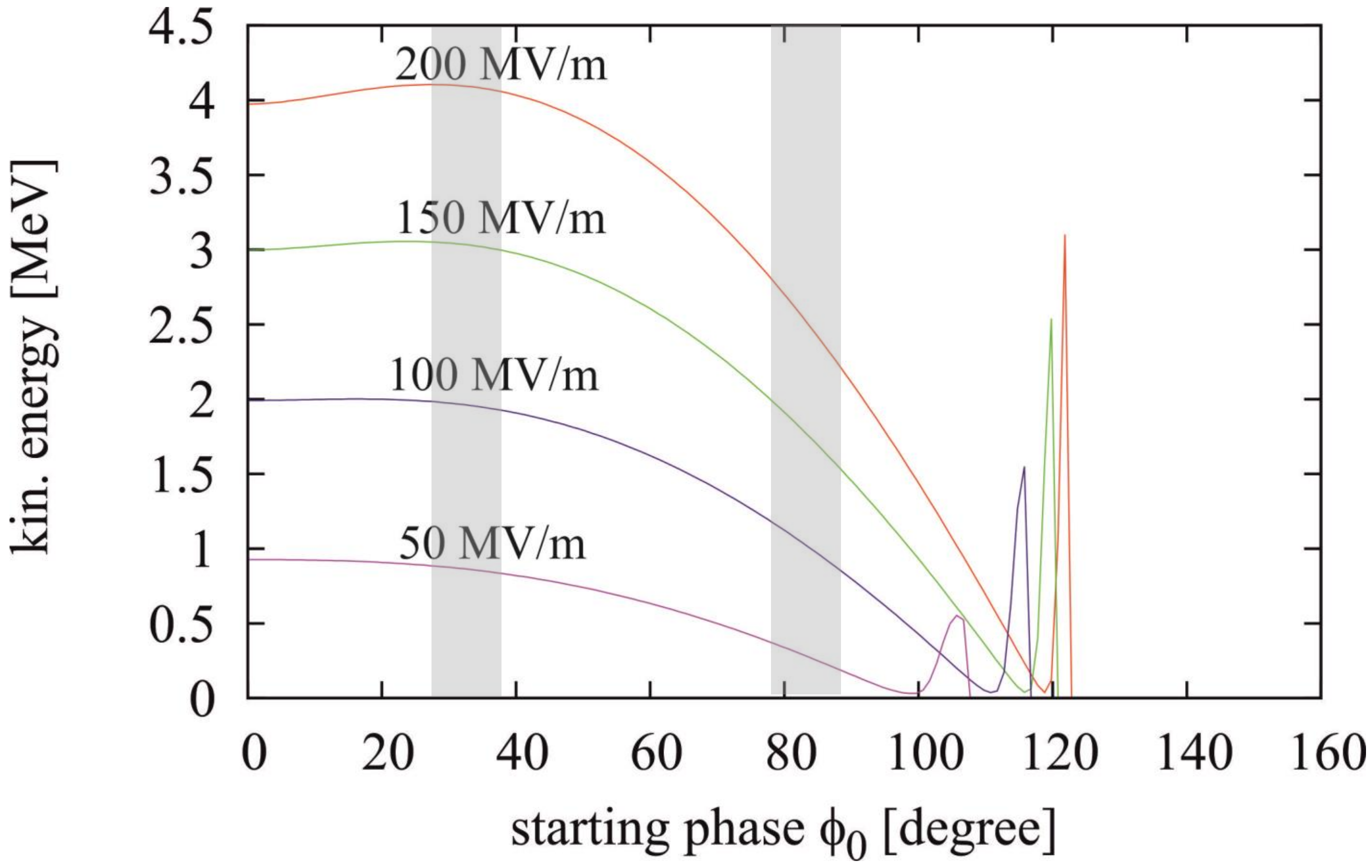
9 MW = 200 MV/m



Operation at Higher Gradients:

Standard operation phase

Can we go here?



Operation with long emission time at higher emission phase:

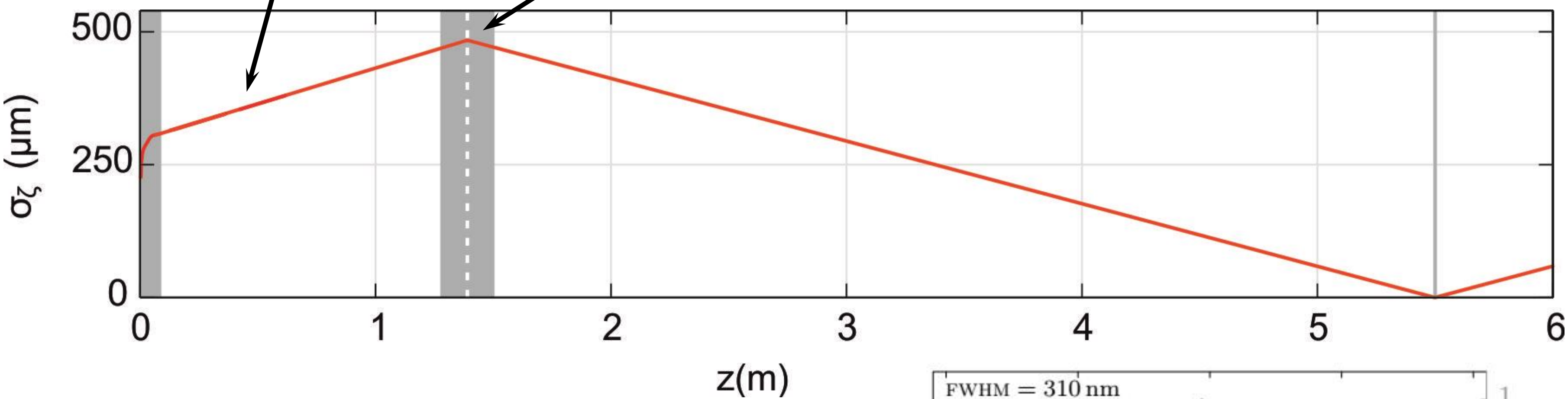
new concept for longitudinal phase space linearization requires operation at high emission phase and enables longer emission time

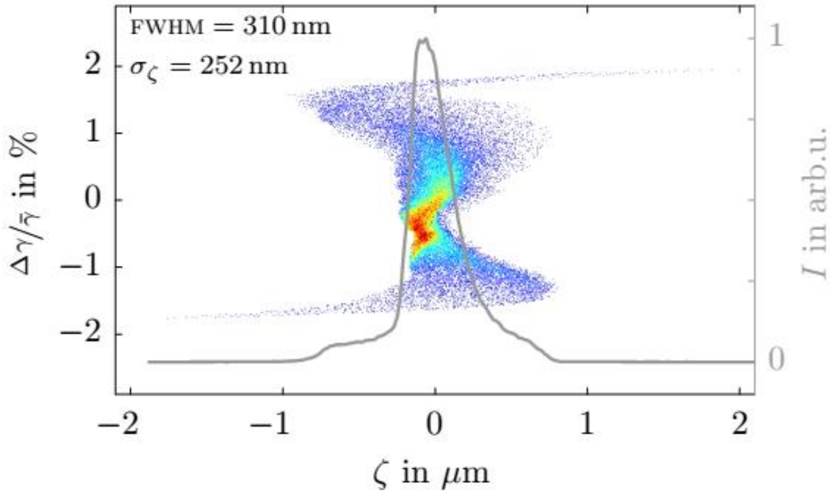
- significantly improved bunch compression or energy spread compensation
- transverse dynamics needs to be studied in more detail
- should help at low charge
- high charge requires emittance compensation, more studies are needed

Longitudinal Dynamics: Stretcher Mode

Correction of non-linearities up to third order in the buncher cavity

bunch expands





B. Zeitler et al. 'Linearization of the longitudinal phase space without higher harmonic
PRST-AB 18, 120102, 2015.

Operation with long emission time at higher emission phase:

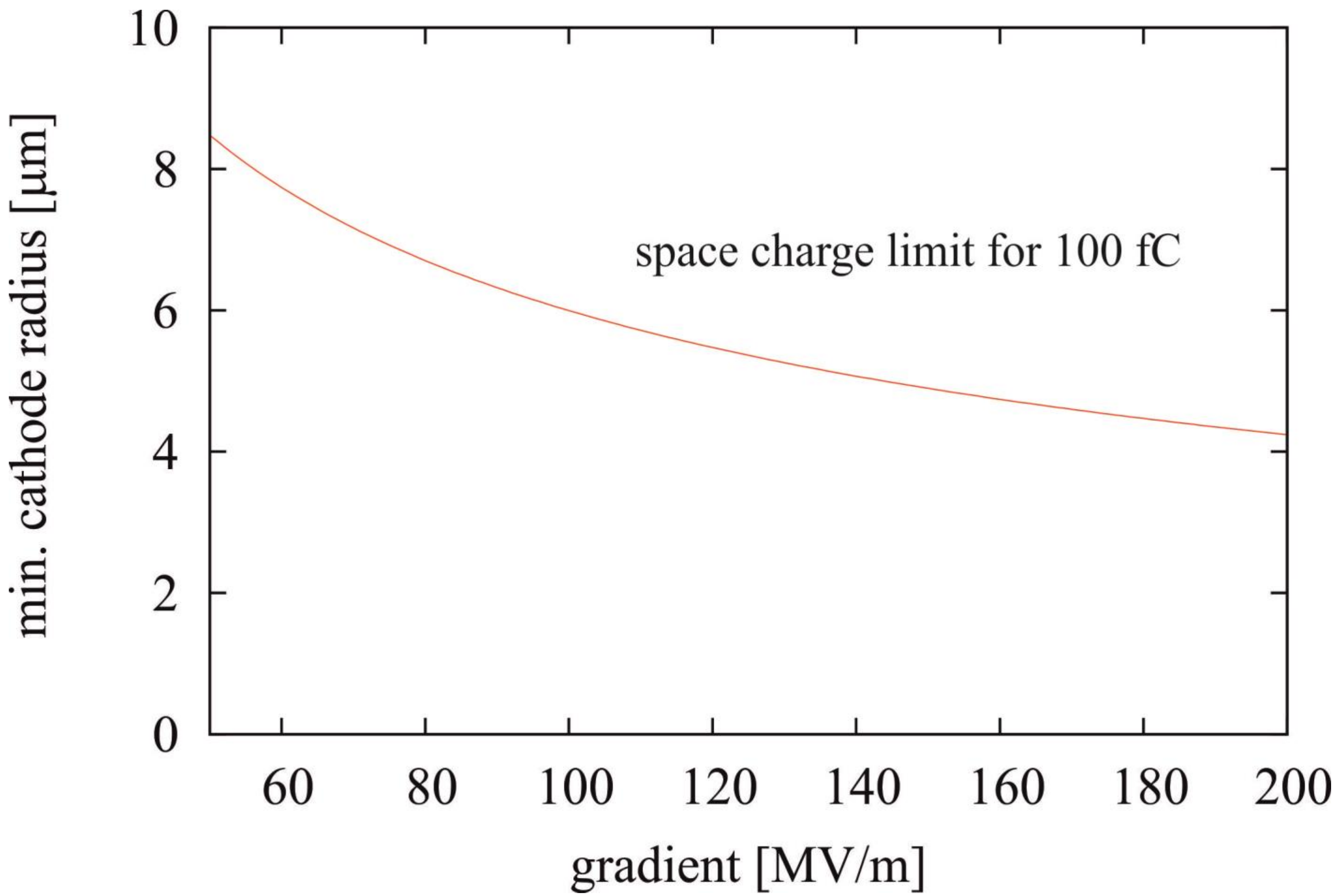
The length of the half cell influences the energy – phase relation:

Present guns (1 ½ cells, LCLS, XFEL, FLASH, AREAL) work with an elongated half cell. This shifts the optimal emission phase (max. energy) to lower values! Seems to improve emittance compensation process at high charge, but certainly not optimal for low charge

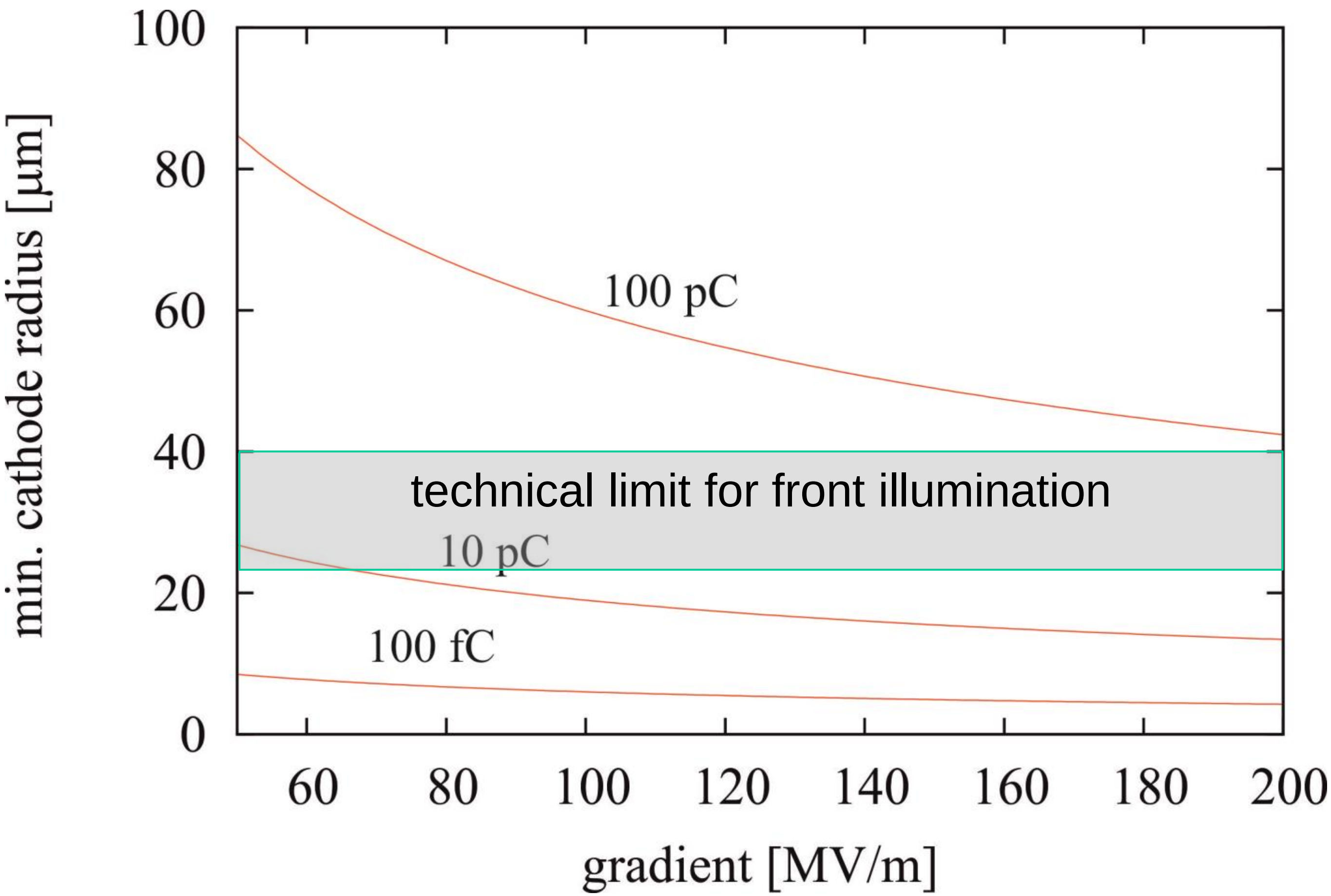
Optimization of cell length needs to be revisited:

- Short cell should be better at lower charge (REGAE & AREAL)!
- Can we reduce the cell length and still optimize the emittance compensation for high charge operation?
- How does it work for a half cell gun?

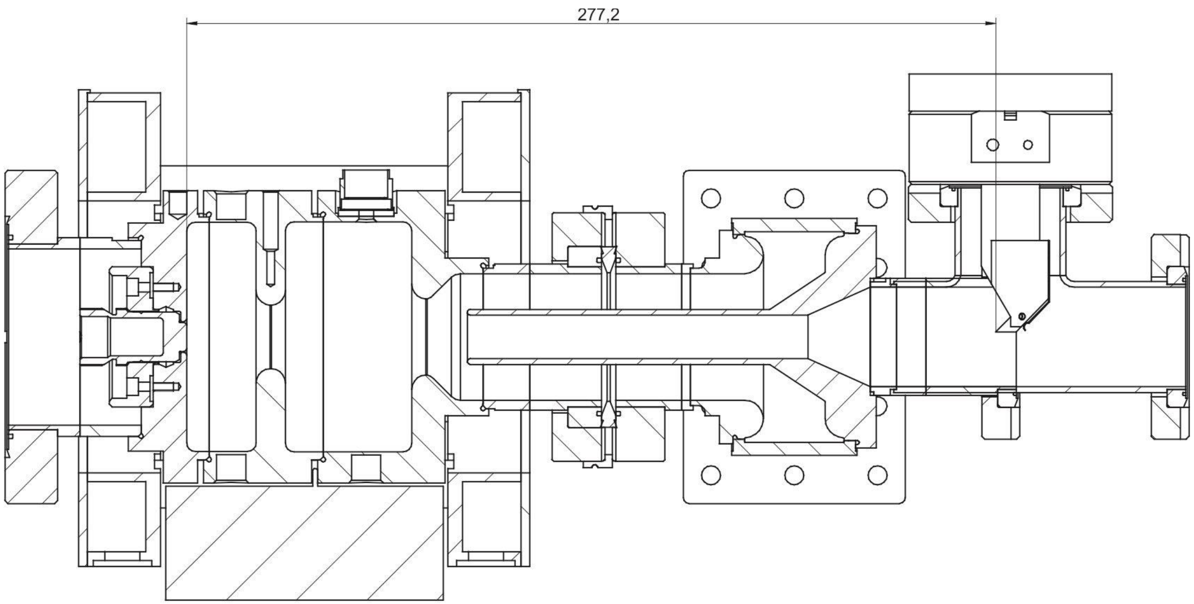
Technical challenge: space charge limited spot size



Technical challenge: space charge limited spot size



Technical challenge: space charge limited spot size



minimal spot size requires minimal cathode – mirror distance and minimal distance of mirror edge to electron beam to increase the aperture

- ➢ half-cell gun allows further reduction
- ➢ back illumination will remove many constrains
- ➢ back illumination allows to gain space for focusing solenoid

Summary

The new generation of RF Guns is looming at the Horizon but lots of work is still to be done:

Technical developments:

- test high gradient operation, new joining technologies, different Cu-alloys…
- back illumination
- half-cell gun design incl. improved focusing scheme
- …

Beam dynamics:

- study ½ cell vs. 1 ½ cell
- optimize cell length
- transverse dynamics at high emission phase
- study non-linear space charge dynamics
- …