ARD-ST3 Annual Workshop

Beam Dynamics in RF Photoinjectors

- RF gun cavity fields
- Single particle dynamics
- RF effects on longitudinal phase space
- RF effects on transverse phase space
- Space charge dynamics
- Emittance optimization

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PITZ, DESY,
Zeuthen, 21.07.2018

HELMHOLTZ
ASSOCIATION

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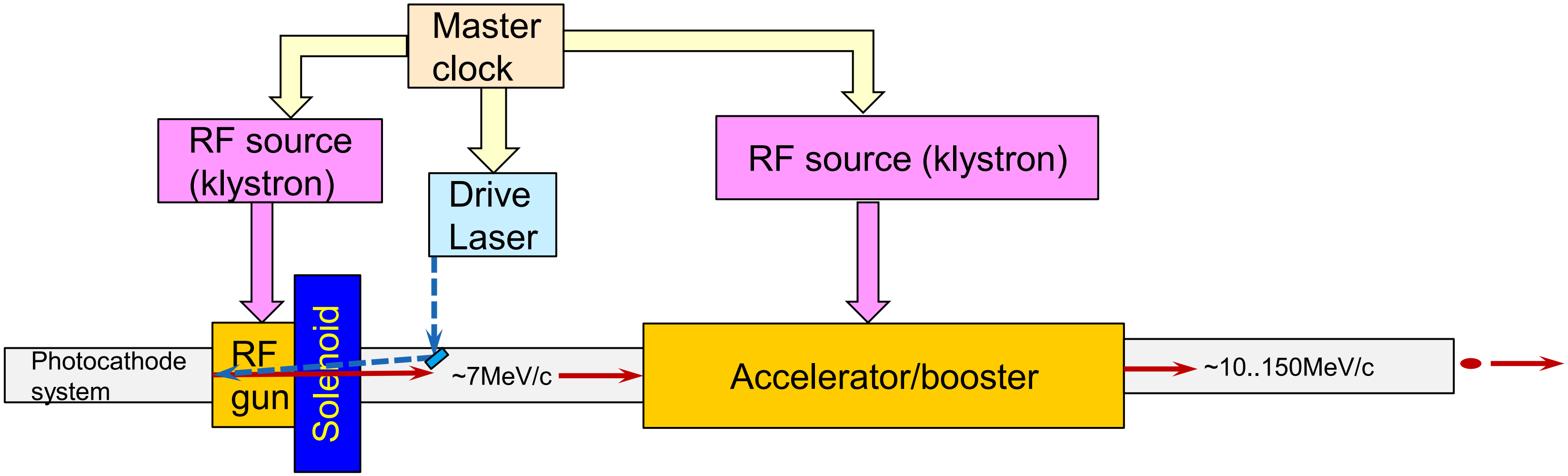
Principal Layout of a Photoinjector

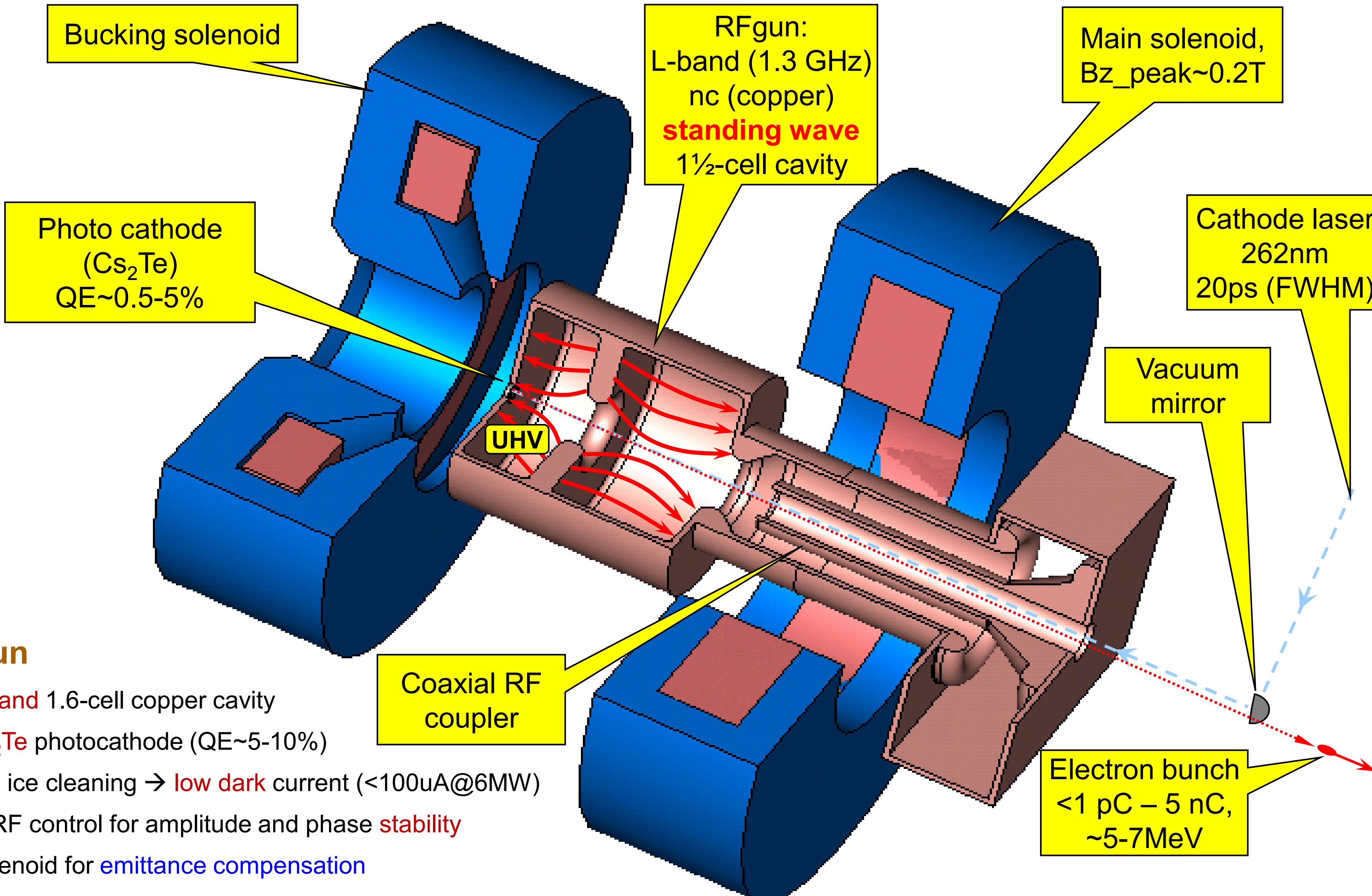


Main goal→ generation of electron beams with:

- High phase space density
  - High bunch charge (~nC)
  - ps pulse duration
  - Low transverse emittance $\varepsilon_{x,n} = \sqrt{\langle x^2\rangle\langle p_x^2\rangle - \langle xp_x\rangle^2} \cong \beta\gamma\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$
- Required pulse train structure
- Required stability
- …

Transverse, normalized brightness $B_n = \dfrac{2I}{\pi^2\varepsilon_{x,n}\varepsilon_{y,n}}$

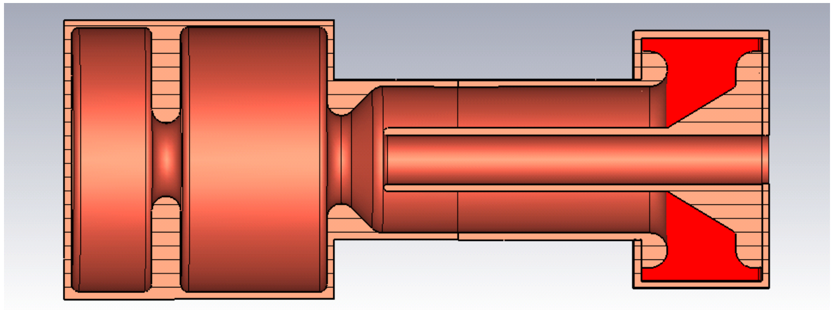
RF Photogun (PITZ/FLASH/XFEL)

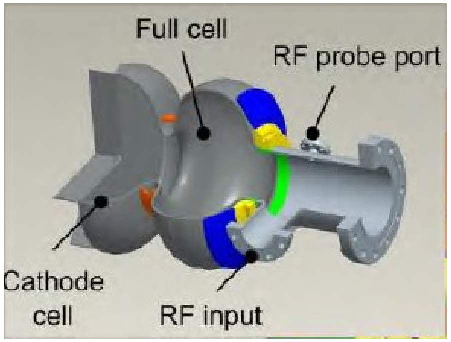


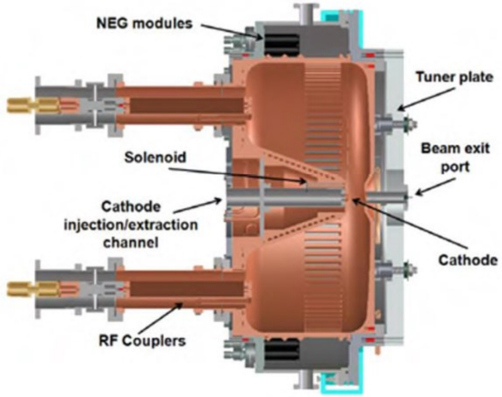
RF gun

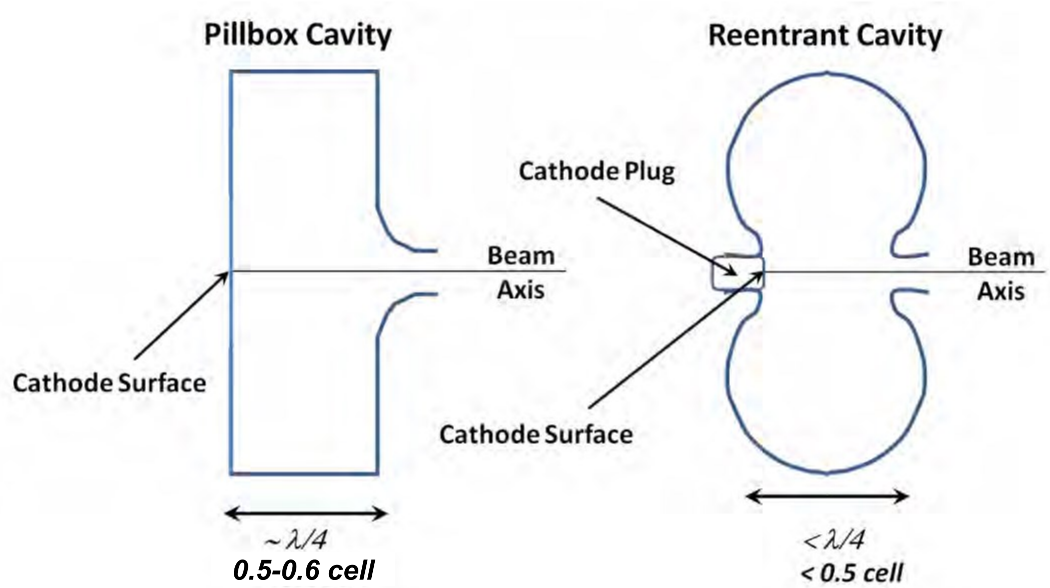
- L-band 1.6-cell copper cavity
- Cs_2Te photocathode (QE~5-10%)
- Dry ice cleaning → low dark current (<100uA@6MW)
- LLRF control for amplitude and phase stability
- Solenoid for emittance compensation

RF Gun cavity: photocathode cell









TM modes of a gun cavity

Electric and magnetic field components of the transverse magnetic modes, TM_{mnp}, of a **pillbox** cavity gives

$$E_z = E_0 J_m(k_{mn}r)\cos(m\theta)\cos(k_z z)\sin(\omega t + \varphi_0)$$

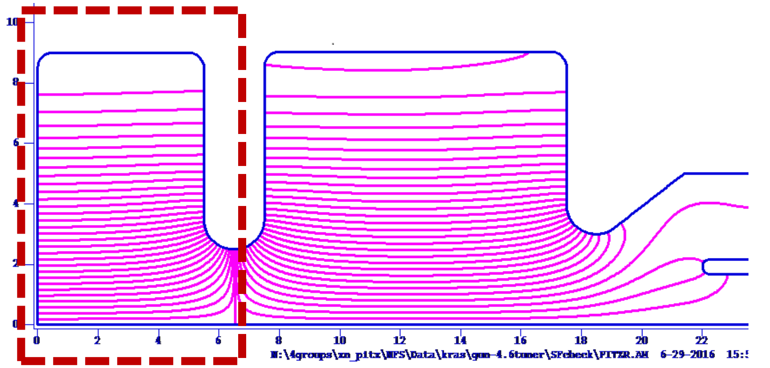
$$E_r = -\frac{k_z}{k_{mn}} E_0 J'_m(k_{mn}r)\cos(m\theta)\sin(k_z z)\sin(\omega t + \varphi_0)$$

$$E_\theta = \frac{m k_z}{k_{mn}^2 r} E_0 J_m(k_{mn}r)\sin(m\theta)\sin(k_z z)\sin(\omega t + \varphi_0)$$

$$B_z = 0$$

$$B_r = -\frac{m\omega}{k_{mn}^2 c r} E_0 J_m(k_{mn}r)\sin(m\theta)\cos(k_z z)\cos(\omega t + \varphi_0)$$

$$B_\theta = -\frac{\omega}{k_{mn} c} E_0 J'_m(k_{mn}r)\cos(m\theta)\cos(k_z z)\cos(\omega t + \varphi_0)$$



E_0 is the field normalization (→E_{cath})

J_m is the mth-order Bessel function

$k_{mn} = \mu_{mn}/R$ - the transverse wave number

μ_{mn} is the n^th zero of the m^th-order Bessel function,

ω is the RF angular frequency

$k_z = p\pi/L$ - the longitudinal wave number

The dispersion relation:

$$\frac{\omega^2}{c^2} = (k_{mn})^2 + (k_z)^2 = \left(\frac{\mu_{mn}}{R}\right)^2 + \left(\frac{\pi p}{L}\right)^2$$

- Rotational symmetry → m=0
- Modes along the z-axis (L=λ/2):
  - 0-mode → p=0
  - π-mode → p=1 ($k_z = 2\pi/\lambda$)

TM$_{011}$ mode of a gun cavity

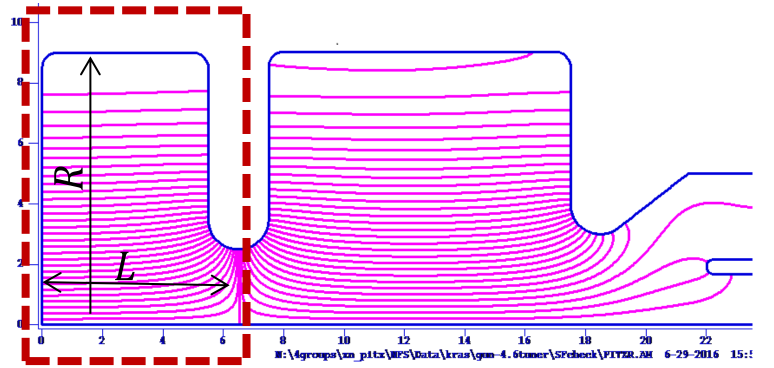
- Rotational symmetry → m=0
  - $k_{01} = 2.405/R$
- Modes along the z-axis (L=λ/2):
  - π-mode → p=1 ($k_z = \frac{\pi}{L} = \frac{2\pi}{\lambda}$)

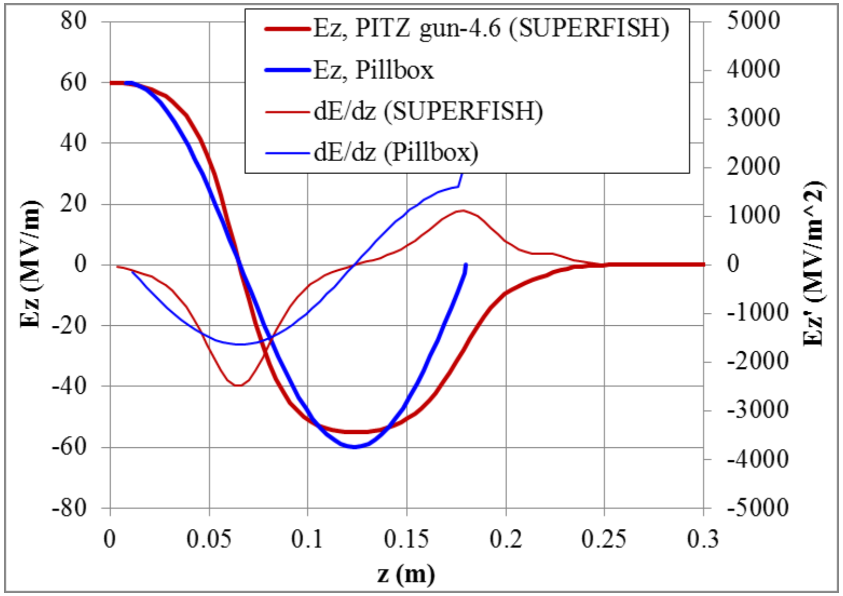
$$E_z = E_0 J_0(k_{01} r)\cos(k_z z)\sin(\omega t + \varphi_0)$$

$$E_r = \frac{k_z}{k_{01}} E_0 J_1(k_{01} r)\sin(k_z z)\sin(\omega t + \varphi_0)$$

$$B_\theta = \frac{\omega}{k_{01} c} E_0 J_1(k_{01} r)\cos(k_z z)\cos(\omega t + \varphi_0)$$

$$\frac{\omega^2}{c^2} = (k_{01})^2 + (k_z)^2 = \left(\frac{2.405}{R}\right)^2 + \left(\frac{\pi}{L}\right)^2$$





NB: 1. paraxial approximation: $E_r \propto E_z'(r=0)$
2. SUPERFISH: higher order harmonics incl.

TM rotationally symmetrical modes of a gun cavity

$$-\frac{\partial B_\theta}{\partial z} = \frac{1}{c}\frac{\partial E_r}{\partial t}$$

$$\frac{1}{r}\frac{\partial}{\partial r}(rB_\theta) = \frac{1}{c}\frac{\partial E_z}{\partial t}$$

$$\frac{1}{r}\frac{\partial}{\partial r}(rE_r) + \frac{\partial E_z}{\partial z} = 0$$

Applying polynomial expansion in r

$$E_z(t,r,z) = \left[E_z(r=0,z) - \frac{r^2}{4}\left\{E_z''(r=0,z) + \frac{\omega^2}{c^2}E_z(r=0,z)\right\} + O(r^4)\right]\sin(\omega t + \varphi_0)$$

$$E_r(t,r,z) = \left[-\frac{r}{2}E_z'(r=0,z) + \frac{r^3}{16}\left\{E_z'''(r=0,z) + \frac{\omega^2}{c^2}E_z'(r=0,z)\right\} - O(r^4)\right]\sin(\omega t + \varphi_0)$$

$$B_\theta(t,r,z) = \frac{\omega^2}{c}\left[\frac{r}{2}E_z(r=0,z) - \frac{r^3}{16}\left\{E_z''(r=0,z) + \frac{\omega^2}{c^2}E_z(r=0,z)\right\} + O(r^4)\right]\cos(\omega t + \varphi_0)$$

NB:

1. For the fundamental spatial harmonics:

$$E_z''(r=0,z) = -\frac{\omega^2}{c^2}E_z(r=0,z);\ E_z'''(r=0,z) = -\frac{\omega^2}{c^2}E_z'(r=0,z) \rightarrow \{\} \rightarrow 0$$

2. The curl E Maxwell equation: $\frac{\partial E_r}{\partial z} - \frac{\partial E_z}{\partial r} = -\frac{1}{c}\frac{\partial B_\theta}{\partial t}$ is only approximately fulfilled for finite high order harmonics number

TM rotationally symmetrical modes of a gun cavity

Pillbox model

$$E_z = E_0 J_0(k_{01}r)\cos(k_z z)\sin(\omega t + \varphi_0)$$
$$E_r = \frac{k_z}{k_{01}} E_0 J_1(k_{01}r)\sin(k_z z)\sin(\omega t + \varphi_0)$$
$$B_\theta = \frac{\omega}{k_{01}c} E_0 J_1(k_{01}r)\cos(k_z z)\cos(\omega t + \varphi_0)$$

w/o high order spatial harmonics

$$\frac{\omega}{c} = k = k_z$$

Polynomial expansion in r

$$E_z(t,r,z) = [E_z(r=0,z) - O(r^2)]\sin(\omega t + \varphi_0)$$
$$E_r(t,r,z) = \left[-\frac{r}{2}E_z'(r=0,z) + O(r^2)\right]\sin(\omega t + \varphi_0)$$
$$B_\theta(t,r,z) = \frac{\omega^2}{c}\left[\frac{r}{2}E_z(r=0,z) - O(r^4)\right]\cos(\omega t + \varphi_0)$$

$$E_z(t,r,z) = E_0\cos(kz)\sin(\omega t + \varphi_0)$$
$$E_r(t,r,z) = \frac{kr}{2}E_0\sin(kz)\sin(\omega t + \varphi_0)$$
$$B_\theta = \frac{kr}{2c}E_0\cos(kz)\cos(\omega t + \varphi_0)$$

$$E_z(t,r,z) = \frac{E_0}{2}[\sin(\omega t - kz + \varphi_0) + \sin(\omega t + kz + \varphi_0)]$$

References

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- B. E. Carlsten, “New photoelectric injector design for the Los Alamos National Laboratory XUV FEL accelerator,” Nucl. Instrum. Meth. A, vol. 285, pp. 313-319, December 1989.
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- D. Dowell, J. Lewellen “Photoinjector theory” in “An engineering guide to photoinjectors”, Edited by T. Rao and D. Dowell, 2013, ISBN-13: 978-1481943222 ISBN-10: 1481943227
- K. Floettmann “rf-induced beam dynamics in rf guns and accelerating cavities”, PRST-AB 18, 064801 (2015)
- K. Floettmann “Emittance compensation in split photoinjectors”, PRST-AB 20, 013401 (2017)

Single Particle Longitudinal Dynamics

$$E_z(t,r,z) = \frac{E_0}{2}\left[\sin(\omega t - kz + \varphi_0) + \sin(\omega t + kz + \varphi_0)\right]$$ → standing wave

$$E_z(t,r,z) = \frac{E_0}{2}\{\sin[\varphi(t,z)] + \sin[\varphi(t,z) + 2kz]\}$$

$$\varphi(t,z) = \omega t - kz + \varphi_0$$

$$\beta_z = v_z/c$$

$$\gamma = \frac{\beta_z}{\sqrt{1-\beta_z^2}}$$

$$\frac{1}{\beta_z} = \frac{\gamma}{\sqrt{\gamma^2 - 1}}$$

$$\frac{dz}{dt} = v_z$$

$$\frac{d}{dt}\frac{mv_z}{\sqrt{1 - v_z^2/c^2}} = eE_z(t,r,z)$$

$$d\varphi = \omega dt - kdz = k(cdt - dz) = k\left(c\frac{dt}{dz} - 1\right)dz = k\left(\frac{1}{\beta_z} - 1\right)dz$$

$$\varphi(t,z) = \varphi_0 + k\int_0^z \left[\frac{\gamma}{\sqrt{\gamma^2 - 1}} - 1\right]dz$$

$$\frac{d}{dt}\frac{mv_z}{\sqrt{1-v_z^2/c^2}} = \frac{d}{dz}\frac{mv_z}{\sqrt{1-v_z^2/c^2}}\frac{dz}{dt} = mc^2\beta_z\frac{d}{dz}\frac{\beta_z}{\sqrt{1-\beta_z^2}} = mc^2\frac{d}{dz}\frac{1}{\sqrt{1-\beta_z^2}} = mc^2\frac{d\gamma}{dz}$$

$$\frac{d\gamma}{dz} = \frac{eE_0}{2mc^2}\{\sin\varphi + \sin[\varphi + 2kz]\}$$

$$\boldsymbol{\alpha \cdot k = \frac{eE_0}{2mc^2}}$$

Single Particle Longitudinal Dynamics: energy gain

$$\varphi(t,z) = \omega t - kz + \varphi_0$$

$$\alpha = \frac{eE_0}{2mc^2 k} \approx 0.047 \frac{E_0[MV/m]}{f[GHz]}$$

$$\varphi = \varphi_0 + k \int_0^z \left[\frac{\gamma}{\sqrt{\gamma^2 - 1}} - 1\right] dz$$

$$\frac{d\gamma}{dz} = \alpha k \{\sin(\varphi) + \sin(\varphi + 2kz)\}$$

$$\gamma(z=0) = 1$$

$\int dz$

$\varphi \sim$const

1. *For a half-cell* $0 \le z \le z_i \sim \frac{\lambda}{4}$:

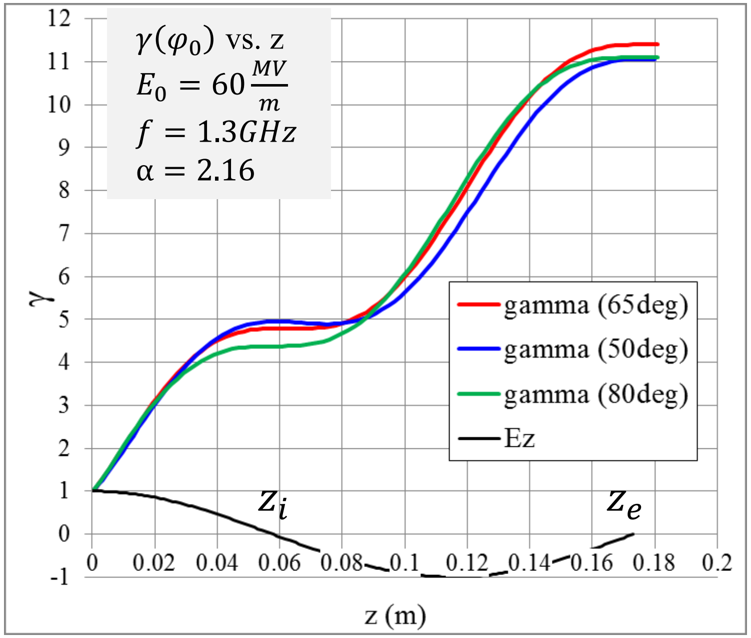
$$\gamma = 1 + \alpha \left\{ kz \sin(\varphi) + \frac{1}{2}[\cos\varphi - \cos(\varphi + 2kz)] \right\}$$

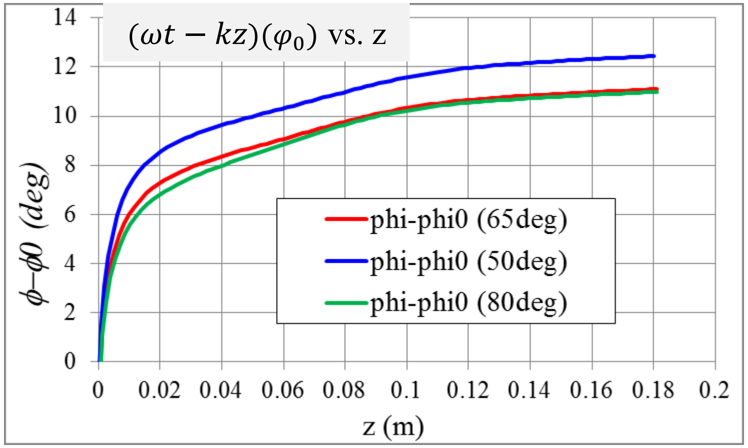
2. *For a full-cell* $z_i \le z \le z_e$:

$$\Delta\gamma = \alpha \left\{ k(z_e - z_i) \sin(\varphi) - \frac{1}{2}[\cos(\varphi + 2kz_e) - \cos(\varphi + 2kz_i)] \right\}$$

max for $\varphi = 90°$

0 if $(z_e - z_i) \sim \frac{\lambda}{2} = \frac{\pi}{k}$





K. J. Kim, NIM A 275, 201 (1989)

Single Particle Longitudinal Dynamics: energy gain

For a half-cell $0 \le z \le z_i \sim \frac{\lambda}{4} \rightarrow kz \approx \frac{\pi}{2}$

$$\gamma = 1 + \alpha\left\{kz\sin\varphi + \frac{1}{2}\left[\cos\varphi - \cos(\varphi + 2kz)\right]\right\} \rightarrow 1 + \alpha\left\{\frac{\pi}{2}\sin\varphi + \cos\varphi\right\}$$

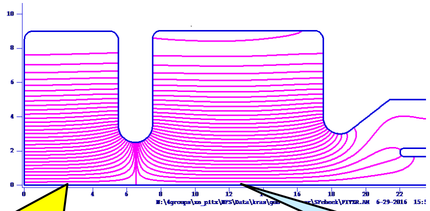
$$\frac{d\gamma}{d\varphi} = 0 \leftrightarrow \varphi = \operatorname{atan}\frac{\pi}{2} \sim 58°$$

In the cathode vicinity $kz \ll 1$: $\gamma \approx \tilde{\gamma} = 1 + 2kz\alpha\sin\varphi$

$$\alpha = \frac{eE_0}{2mc^2k} \approx 0.047\frac{E_0[MV/m]}{f[GHz]}$$

	$f[GHz]$	$E_0[MV/m]$	α	z(v=0.95c)
L-band	1.3	60	2.16	0.10λ
S-band	3	100	1.56	0.13λ

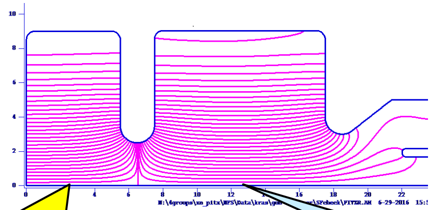
Phase slippage → mainly in the half-cell, in the cathode vicinity!



effective phase $\varphi_{eff} = \varphi_o + \Delta\varphi$

synchronous phase φ_∞

Single Particle Longitudinal Dynamics: energy gain



effective phase
$\varphi_{eff} = \varphi_o + \Delta\varphi$

synchronous phase φ_∞

$$\tilde{\gamma} = 1 + 2kz\alpha \sin\varphi_{eff}$$

$$\varphi = \varphi_0 + k\int_0^z \left[\frac{\gamma}{\sqrt{\gamma^2-1}} - 1\right] dz$$

$$\varphi = \varphi_0 + \frac{\sqrt{\tilde{\gamma}^2-1}-\tilde{\gamma}+1}{2\alpha \sin(\varphi_{eff})}$$

$$\tilde{\gamma} \gg 1 \Leftrightarrow \varphi \to \varphi_\infty$$

Synchronous (asymptotic) phase

$$\varphi_\infty = \varphi_0 + \frac{1}{2\alpha \sin\varphi_{eff}}$$

←K. Floettmann → (BC=1)→ $\Delta\varphi = \frac{1}{2\alpha}$

K-J. Kim: $\varphi_\infty = \varphi_0 + \frac{1}{2\alpha \sin(\varphi_0)} \to \frac{\pi}{2}$

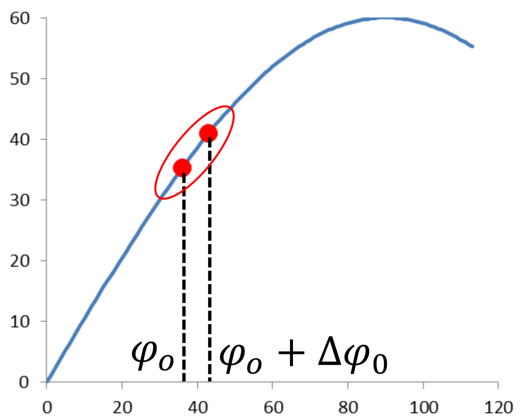
L. Serafini: $\varphi_\infty = \varphi_0 + \frac{1}{2\tilde{\alpha} \sin(\varphi_0)} + \frac{1}{10\tilde{\alpha}^2[\sin(\varphi_0)]^2}$

Longitudinal Dynamics: bunch compression

Synchronous (asymptotic) phase

$$\varphi_\infty = \varphi_0 + \frac{1}{2\alpha \sin \varphi_{eff}}$$

effective phase $\varphi_{eff} = \varphi_o + \Delta\varphi$

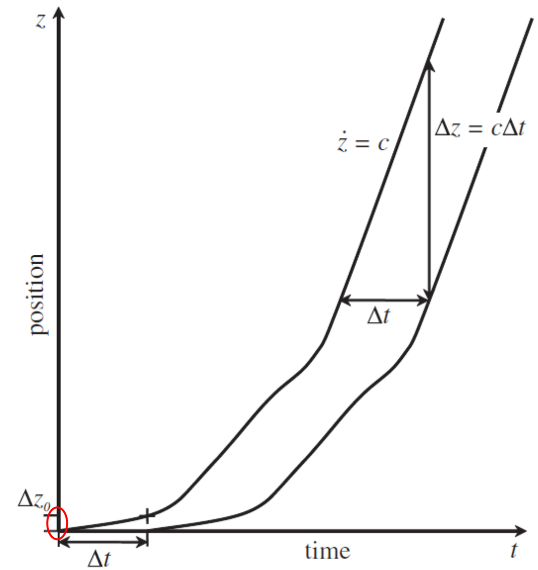


Bunch compression (BC) factor

$$BC = \frac{\Delta\varphi_\infty}{\Delta\varphi_0} = 1 - \frac{\cos \varphi_{eff}}{2\alpha\left[\sin \varphi_{eff}\right]^2}$$

$$BC = 1 \;\Rightarrow\; \varphi_{eff} = \frac{\pi}{2}$$

$$\frac{\pi}{2} = \varphi_0 + \frac{1}{2\alpha}$$



$$\varphi_{eff} = \varphi_0 + \frac{1}{2\alpha}$$

Beam phase in the half-cell

$$\Delta\varphi = \frac{1}{2\alpha}$$

$$\alpha = \frac{eE_0}{2mc^2 k}$$

K. Floettmann, PRST-AB 18, 064801 (2015)

Longitudinal Dynamics: bunch compression

$$\left.\begin{aligned}\tilde{\gamma} &= 1 + 2kz\alpha\sin\varphi \quad \Leftarrow \frac{d}{dz}\\ \varphi &= \varphi_0 + k\int_0^z\left[\frac{\gamma}{\sqrt{\gamma^2-1}} - 1\right]dz \Leftarrow \frac{d}{dz}\end{aligned}\right\} \Rightarrow \int_1^{\tilde{\gamma}}\left[\frac{\gamma}{\sqrt{\gamma^2-1}} - 1\right]d\gamma = 2\alpha\int_{\varphi_0}^{\varphi_\infty}\sin(\varphi)\,d\varphi$$

$\int$

$$\sqrt{\tilde{\gamma}^2-1} - \tilde{\gamma} + 1 = 2\alpha[\cos\varphi_0 - \cos\varphi_\infty]$$

$\tilde{\gamma} \gg 1$

$$\cos\varphi_\infty = \cos\varphi_0 - \frac{1}{2\alpha}$$

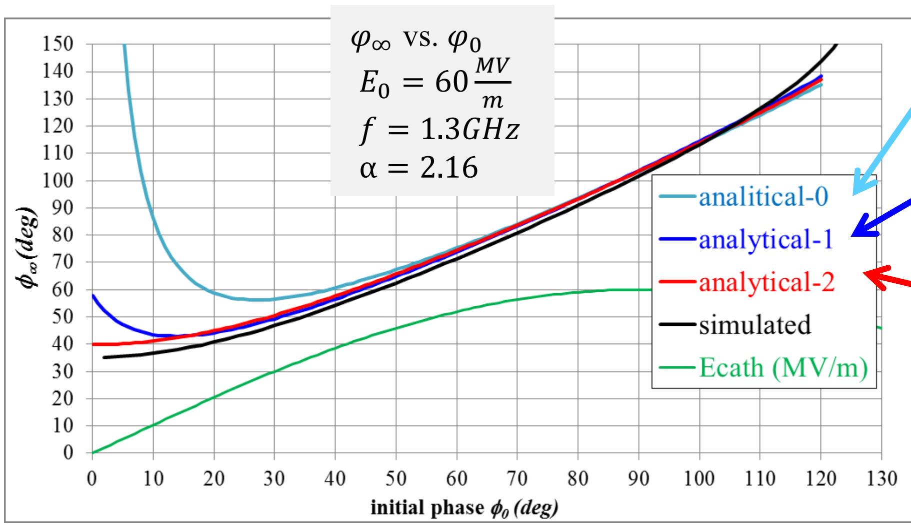
$$-\sin\varphi_\infty\,\Delta\varphi_\infty = -\sin\varphi_o\,\Delta\varphi_o$$

$$BC = \frac{\Delta\varphi_\infty}{\Delta\varphi_0} = \frac{\sin\varphi_0}{\sin\varphi_\infty} = \frac{\sin\varphi_0}{\sqrt{1 - \left[\cos\varphi_0 - \frac{1}{2\alpha}\right]^2}}$$

$$BC = 1 \Rightarrow \cos\varphi_\infty = -\frac{1}{4\alpha}$$

K. Floettmann, PRST-AB 18, 064801 (2015)

Comparison with simulations (numerical integration)



$$\varphi_\infty = \varphi_0 + \frac{1}{2\alpha\sin\varphi_0}$$

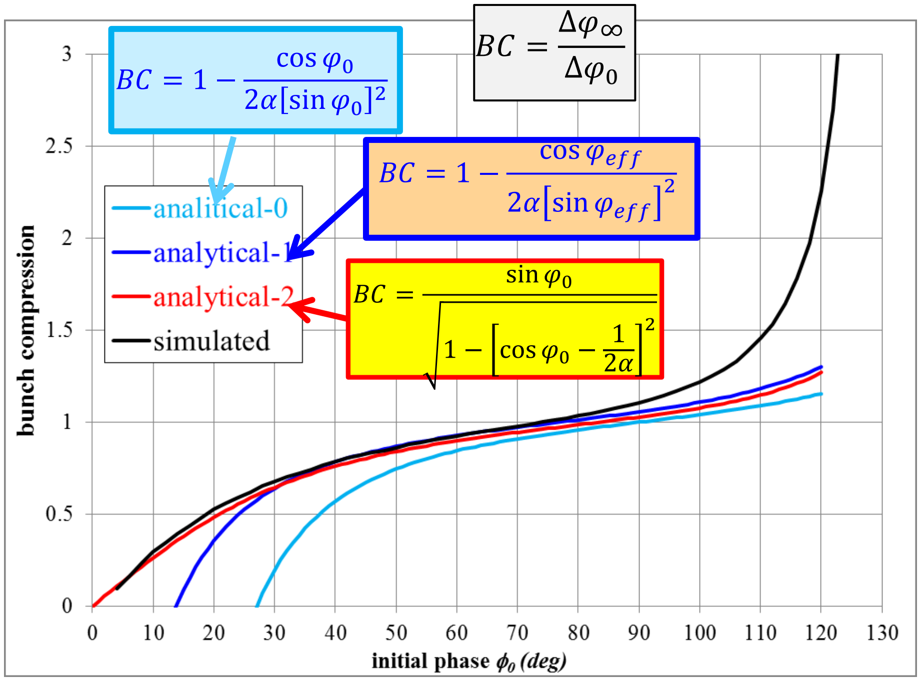
$$\varphi_\infty = \varphi_0 + \frac{1}{2\alpha\sin\varphi_{eff}}$$

$$\cos\varphi_\infty = \cos\varphi_0 - \frac{1}{2\alpha}$$

$$\varphi_{eff} = \varphi_0 + \frac{1}{2\alpha}$$

$$\gamma_{1/2} = 1 + \alpha\left\{\frac{\pi}{2}\sin\varphi_{eff} + \cos\varphi_{eff}\right\}$$

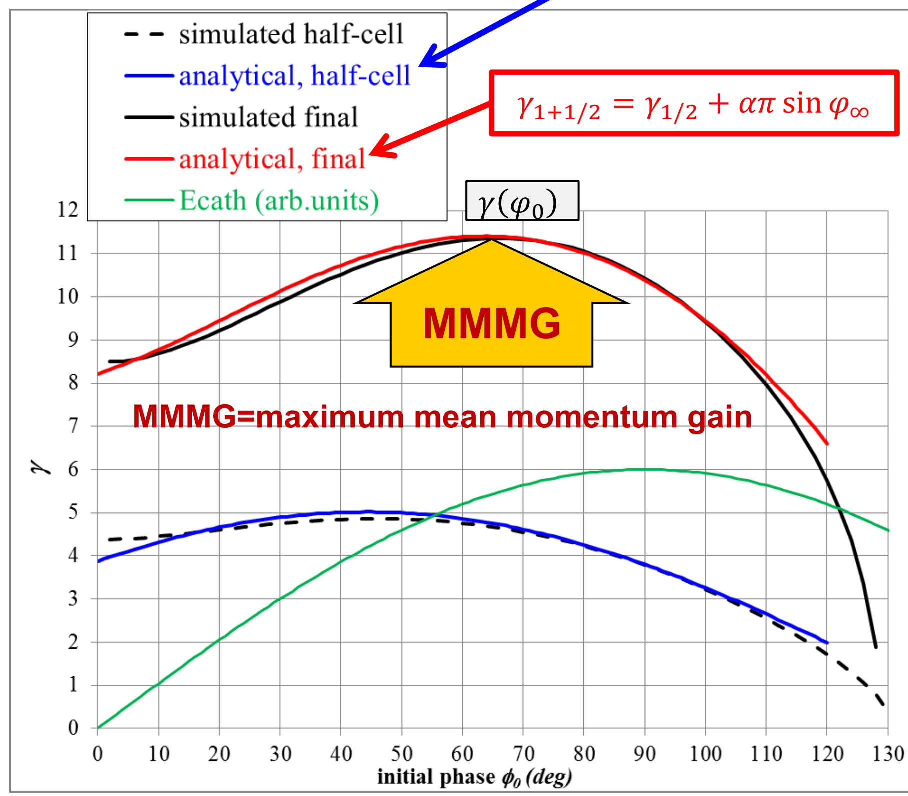
$$\gamma_{1+1/2} = \gamma_{1/2} + \alpha\pi\sin\varphi_\infty$$



$$BC = 1 - \frac{\cos\varphi_0}{2\alpha[\sin\varphi_0]^2}$$

$$BC = 1 - \frac{\cos\varphi_{eff}}{2\alpha[\sin\varphi_{eff}]^2}$$

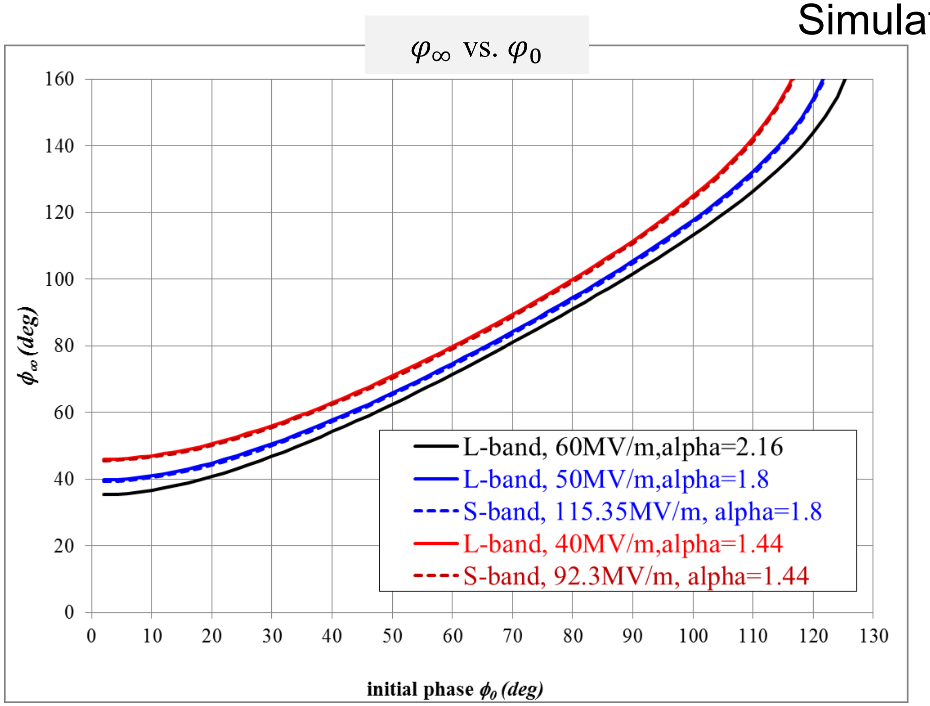
$$BC = \frac{\sin\varphi_0}{\sqrt{1 - \left[\cos\varphi_0 - \frac{1}{2\alpha}\right]^2}}$$

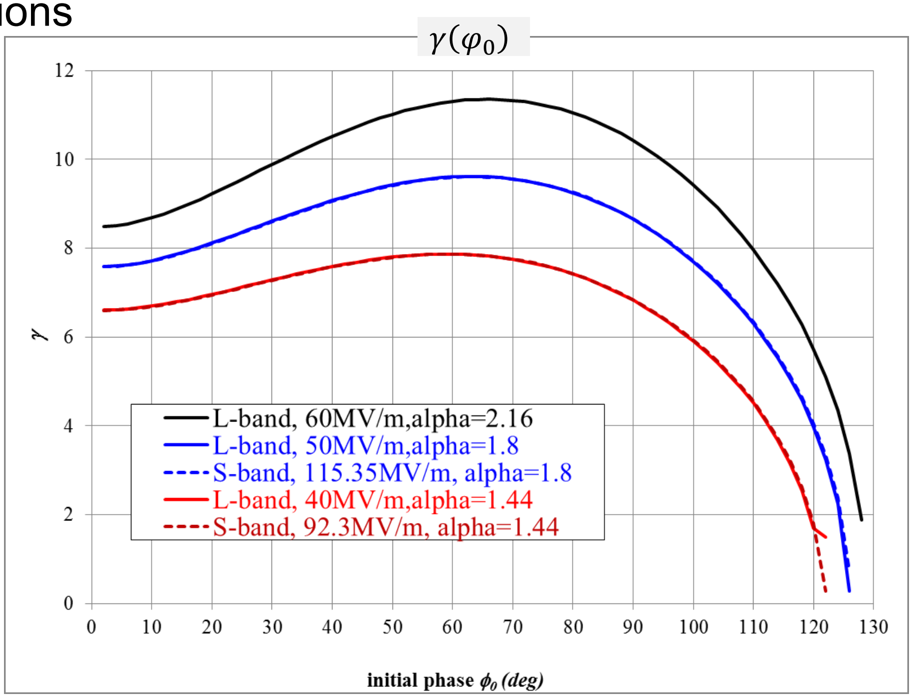


Single Particle Longitudinal Dynamics: parameter α

$\alpha = \dfrac{eE_0}{2mc^2k}$	$E_0[MV/m]$	
	L-band (1.3GHz)	S-band (3GHz)
2.16	60	
1.8	50	115.35
1.44	40	92.3

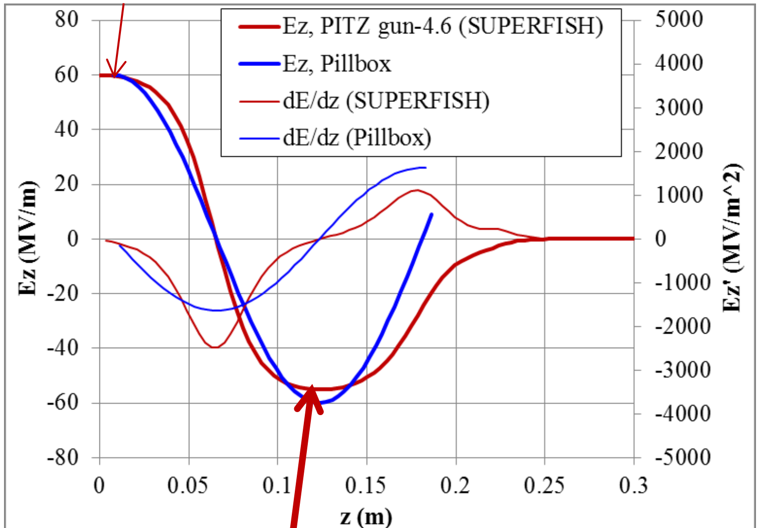
Simulations

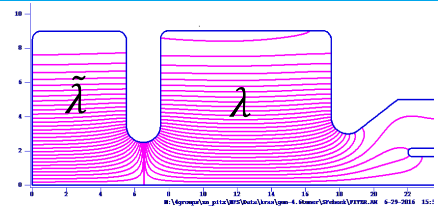




→ "Real life" : 1.6-cell and field balance>1

Elongation of the half-cell → $\tilde{\lambda} = \lambda(1+\delta)$





$$\alpha = \frac{eE_0}{2mc^2k} \rightarrow \tilde{\alpha} = \frac{eE_0(1+\delta)}{2mc^2k}$$

$$\delta\varphi = \frac{2\pi}{4}\delta$$

$$\varphi_{eff} = \varphi_0 + \frac{1}{2\alpha} \rightarrow \tilde{\varphi}_{eff} = \varphi_0 + \frac{1}{2\alpha} - \mu\delta\varphi \qquad \mu \sim 0.5-1$$

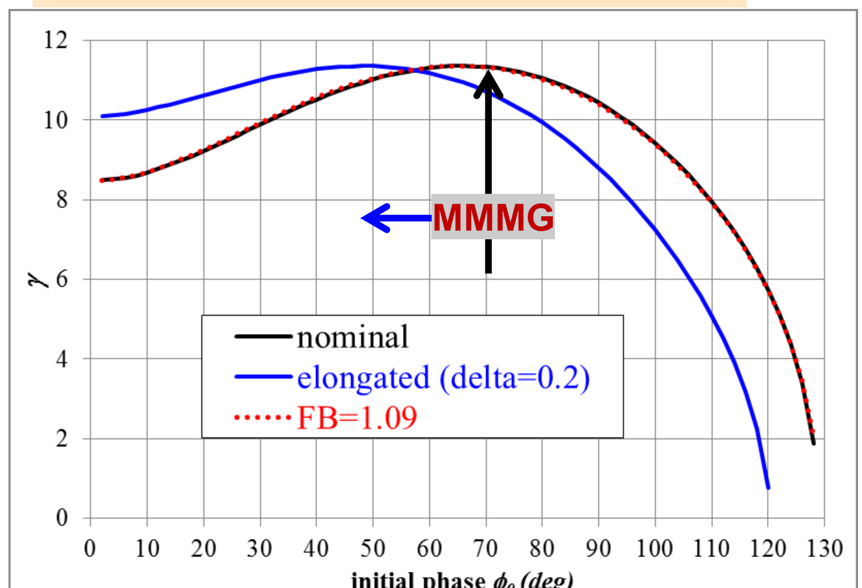
$$\varphi_\infty = \varphi_0 + \frac{1}{2\alpha\sin\varphi_{eff}} \rightarrow \tilde{\varphi}_\infty = \varphi_0 + \frac{1}{2\alpha\sin\tilde{\varphi}_{eff}} - \mu\delta\varphi$$

$$\gamma_{1/2} = 1 + \tilde{\alpha}\left\{\frac{\pi}{2}\sin\tilde{\varphi}_{eff} + \cos\tilde{\varphi}_{eff}\right\}$$

$$\gamma_{1+1/2} = \gamma_{1/2} + \alpha\pi\sin\varphi_\infty$$

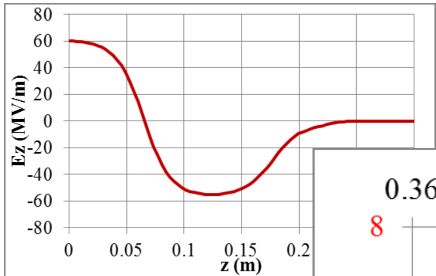
FB = 1.09

Field balance $\mathrm{FB} = \left|\frac{E_{cath}}{\max E_{full-cell}}\right| > 1$



K. Floettmann, PRST-AB 18, 064801 (2015)

Gun-4.6 (PITZ): mean momentum and MMMG phase

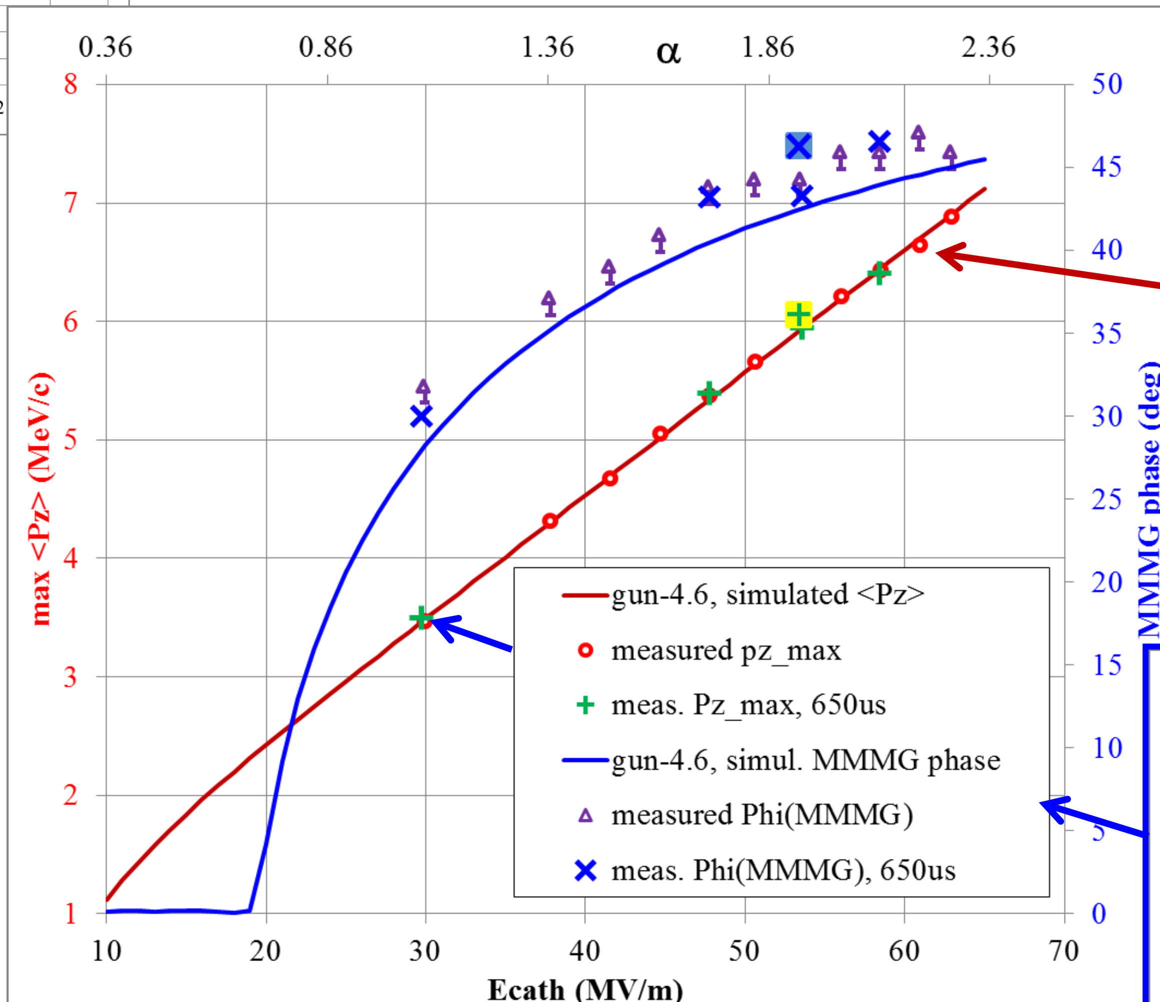


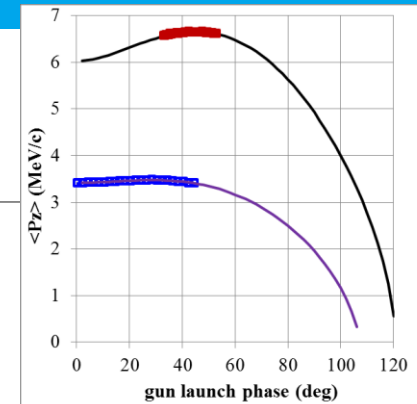
$$\beta_z = v_z/c$$

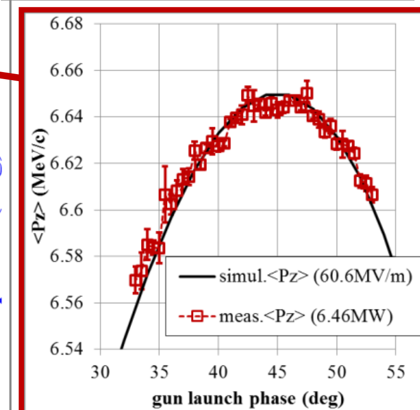
$$\gamma = \frac{\beta_z}{\sqrt{1-\beta_z^2}}$$

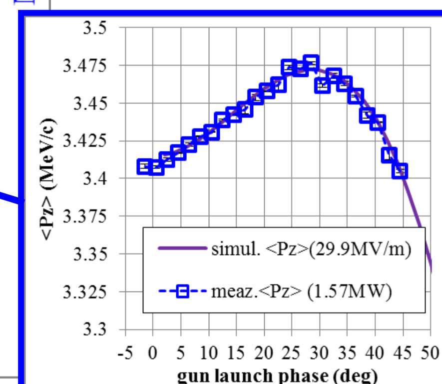
$$\frac{1}{\beta_z} = \frac{\gamma}{\sqrt{\gamma^2-1}}$$

Measurements vs. Simulations







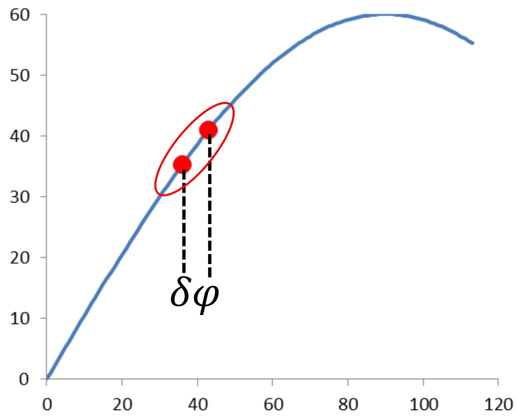


$$P[MW] = 0.00176 \cdot (E_{cath}[MV/m])^2$$

RF-induced energy spread and longitudinal emittance

$$\gamma = 1 + \alpha\left\{\frac{\pi}{2}\sin\varphi_{eff} + \cos\varphi_{eff} + \pi\sin\varphi_{\infty}\right\} \approx 1 + \alpha\left\{\frac{3\pi}{2}\sin\varphi + \cos\varphi\right\} \sim 1 + \hat{\alpha}\sin\hat{\varphi}$$

Kinetic energy after 1 ½ cells: $E_k = mc^2(\gamma - 1) = \hat{E}\sin\hat{\varphi}$



$$\sin\hat{\varphi} \rightarrow \sin\hat{\varphi} + \cos\hat{\varphi}\,\delta\varphi - \frac{\sin\hat{\varphi}}{2}\delta\varphi^2 + \cdots$$

Assuming symmetric distribution $f(\Delta\varphi)$

$$\langle E_k \rangle = \hat{E}\sin\hat{\varphi}\cdot\left(1 - \frac{\sigma_\varphi^2}{2}\right)$$

$$\sigma_E^2 = \langle (E_k - \langle E_k \rangle)^2 \rangle = \frac{\hat{E}^2(\sin\hat{\varphi})^2}{4}\int\left[\delta\varphi^2 - \sigma_\varphi^2\right]^2\rho(\delta\varphi)d\delta\varphi$$

$$\sigma_\varphi = k\sigma_z$$

Nonlinear terms→ $\sigma_E = \xi\sigma_\varphi^2\hat{E}\sin\hat{\varphi}$

RF induced longitudinal emittance:

$$\Delta\varepsilon_z^{rf} = \sigma_z\sigma_E = \xi k^2\sigma_z^3\hat{E}\sin\hat{\varphi}$$

Form-factor: $\xi = \begin{cases} \frac{1}{\sqrt{2}} \rightarrow \rho(\delta\varphi) = Gaussian \\ \frac{1}{\sqrt{5}} \rightarrow \rho(\delta\varphi) = Flattop \end{cases}$

RF impact onto transverse phase space

The radial Lorentz force:

$$F_r = e(E_r - \beta c B_\theta)$$

$$E_z(t,r,z) = E_0\cos(kz)\sin(\omega t+\varphi)$$
$$E_r(t,r,z) = \frac{kr}{2}E_0\sin(kz)\sin(\omega t+\varphi)$$
$$B_\theta = \frac{kr}{2c}E_0\cos(kz)\cos(\omega t+\varphi)$$

$$F_r = eE_0\frac{kr}{2}[\sin(kz)\sin(\omega t+\varphi) - \beta\cos(kz)\cos(\omega t+\varphi)] \overset{\beta\approx 1}{\approx} -eE_0\frac{kr}{2}\cos(2kz+\varphi)$$

$$\frac{dp_x}{dt} = F_x = -eE_0\frac{kx}{2}\cos(2kz+\varphi)$$

$$\Delta p_x = \int_0^z \frac{F_x}{c}dz = eE_0\frac{x}{2c}[\sin\varphi_0 + \sin\varphi_\infty] \approx eE_0\frac{x}{2c}\sin\hat{\varphi}$$

Gun=RF lens:

$$f_x = \frac{x}{x'} = -\frac{2\beta\gamma mc^2}{eE_0\sin\hat{\varphi}}$$

e.g. L-band 1½ gun with 60MV/m

$f_x \sim 0.2m$

RF induced transverse emittance:

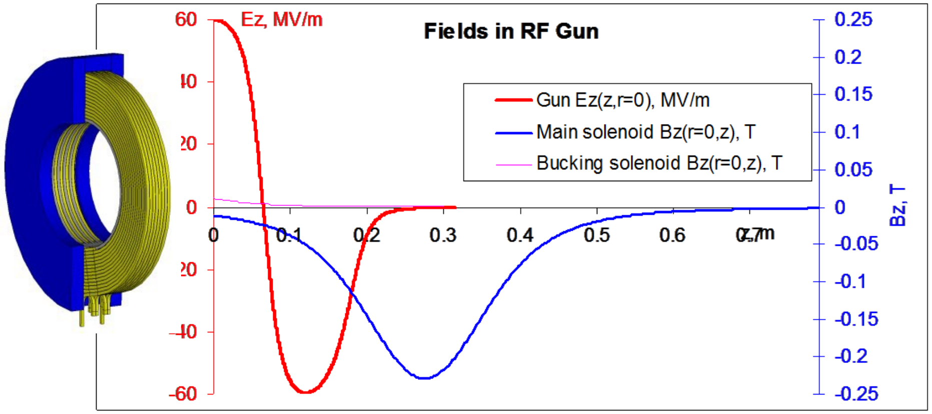
$$\Delta\varepsilon_{n,x}^{rf} = \frac{eE_0}{2mc^2}\sigma_x^2 k\sigma_z\sqrt{[\cos\hat{\varphi}]^2 + [\sin\hat{\varphi}]^2\xi^2k^2\sigma_z^2}$$

Form-factor:

$$\xi = \begin{cases} \frac{1}{\sqrt{2}} \to f(\delta\varphi) = Gaussian \\ \frac{1}{\sqrt{5}} \to f(\delta\varphi) = Flattop \end{cases}$$

Static focusing: Solenoid

Defocusing from RF and space charge → important to focus the beam right after the gun with strong magnetic fields. Solenoids are usually used at low energies, because of their ability to focus at the same time in both transverse planes

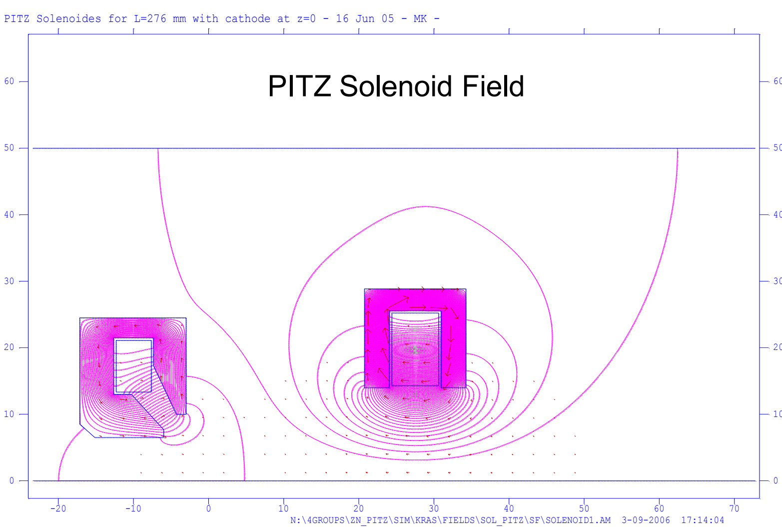


The fields near the axis:

$$B_z(r,z) = B_z(0,z) - \frac{r^2}{4} B_z''(0,z) + O(r^4)$$

$$B_r(r,z) = -\frac{r}{2} B_z'(0,z) + \frac{r^3}{16} B_z'''(0,z) + O(r^5)$$

NB: the beam is both *focused* and *rotated*.



Basic parameters characterizing the solenoid focusing:

$k_s = \frac{eB_{z,max}}{2mc\beta\gamma}$ - focusing strength (depends on the beam energy!)

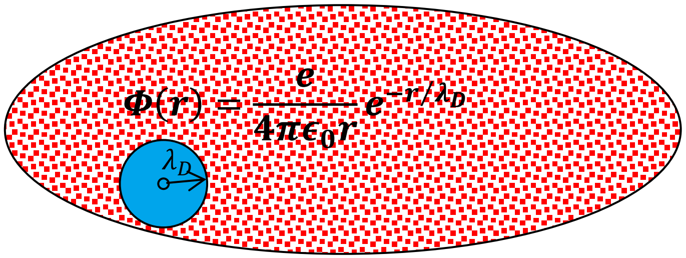
$L_{eff} = \int \left(\frac{B_z(0,z)}{B_{z,max}}\right)^2 dz$ - effective length

$F_{sol} = \frac{1}{k_s^2 L_{eff}}$ - solenoid focal length

Collective effects: space charge (SC)

	Relativistic (lab frame)	Nonrelativistic (co-moving frame)
Plasma frequency	$\omega_p = \sqrt{\dfrac{Ne^2}{\epsilon_0 m \gamma^3}}$	$\omega_p = \sqrt{\dfrac{Ne^2}{\epsilon_0 m}}$
Thermal (uncorrelated) velocity spread	$\sigma_v = \sqrt{\dfrac{k_B T}{m\gamma}}$	$\sigma_v = \sqrt{\dfrac{k_B T}{m}}$
Debye length	$\lambda_D = \dfrac{\sigma_v}{\omega_p} = \sqrt{\dfrac{\gamma^2 \epsilon_0 k_B T}{Ne^2}}$	$\lambda_D = \dfrac{\sigma_v}{\omega_p} = \sqrt{\dfrac{\epsilon_0 k_B T}{Ne^2}}$

a_b- characteristic beam size



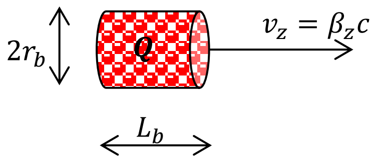
$\lambda_D \gg a_b$	Dominated by single particle dynamics (either energy or beam temperature large) → emittance dominated beams
$\dfrac{1}{\sqrt[3]{N}} \ll \lambda_D \ll a_b$	Dominated by “smooth” space charge forces (if forces are linear → emittance is conserved)
$\lambda_D \ll \dfrac{1}{\sqrt[3]{N}}$	Fields of individual particles becomes important, Coulomb collisions effects are important

For typical photoinjector parameters the smooth SC model can be used

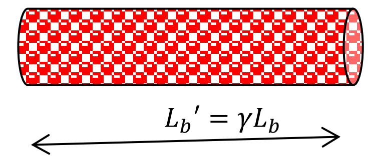
Beam dynamics in photo injectors with space charge

Lab reference frame

$\gamma = \beta_z/\sqrt{1-\beta_z^2}$



Co-moving reference frame→‘



$$\vec{E} = \{\gamma E_x{}', \gamma E_y{}', E_z{}'\}$$
$$\vec{B} = \gamma \frac{v_z}{c^2}\{E_y{}', -E_x{}', 0\}$$

$$\vec{E}' = \{E_x{}', E_y{}', E_z{}'\}$$
$$\vec{B}' = 0$$

The Lorentz force: $\vec{F} = e\left(\vec{E} + [\vec{v}\vec{B}]\right) = \left\{\frac{e}{\gamma}E'_x, \frac{e}{\gamma}E'_y, eE_z{}'\right\}$

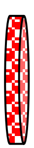
Self field scaling

$$A = \frac{r_b}{L_b} \qquad A' = \frac{A}{\gamma} = \frac{r_b}{\gamma L_b}$$

$A \ll \gamma$

$A' \ll 1$

$A \gg 1$



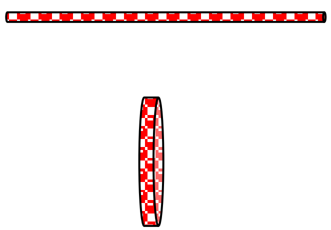
$A' \gg 1$

	$E_x{}'$	$E_z{}'$
$A' \ll 1$	$\propto \left(\frac{Q/L_b{}'}{r_b}\right)$	$\propto O\left(\frac{Q}{L_b'^2}\right)$
$A' \gg 1$	$\propto O\left(\frac{Q/r_b^2}{1}\right)$	$\propto O\left(\frac{Q}{r_b^2}\right)$

K. J. Kim, NIM A 275, 201 (1989).

Beam dynamics in photo injectors with space charge

The Lorentz force: $\vec{F} = e\left(\vec{E} + [\vec{v}\vec{B}]\right) = \left\{\frac{e}{\gamma}E'_x, \frac{e}{\gamma}E'_y, eE_z{}'\right\}$



	$E_x{}'$	$E_z{}'$
$A' \ll 1$	$\propto \left(\frac{Q/L_b{}'}{r_b}\right)$	$\propto O\left(\frac{Q}{L_b'^2}\right)$
$A' \gg 1$	$\propto O\left(\frac{Q/r_b^2}{1}\right)$	$\propto O\left(\frac{Q}{r_b^2}\right)$

	F_x	F_z
$A \ll \gamma$	$\propto \left(\frac{1}{\gamma^2}\right)$	$\propto O\left(\frac{1}{\gamma^2}\right)$
$A \gg 1$	$\propto O\left(\frac{1}{\gamma}\right)$	$\propto O(1)$

$$\vec{F} = \frac{1}{\gamma^2}\vec{f}(\gamma) \qquad \vec{f}(\gamma) \sim \begin{cases} \{O(1), O(1), O(1)\}; A \ll \gamma \\ \{O(\gamma), O(\gamma), O(\gamma^2)\}; A \gg 1 \end{cases}$$

$$\frac{d\Delta\vec{p}}{dt} = \vec{F}$$

$$\Delta\vec{p} = \int \vec{F}dt = \int \frac{\vec{f}(\gamma)}{\beta c \gamma^2}dz \leftarrow \frac{d\gamma}{dz} = \frac{eE_0}{mc^2}\sin\varphi$$

$$\Delta\vec{p} \approx \frac{mc}{eE_0\sin\varphi}\vec{f}(1)\int_1^\gamma \frac{d\gamma}{\beta\gamma^2} = \frac{mc}{eE_0\sin\varphi}\vec{f}(1)\left[\frac{\pi}{2} - \arcsin\frac{1}{\gamma}\right] \xrightarrow{\gamma\gg1} \frac{mc}{eE_0\sin\varphi}\frac{\pi}{2}\vec{f}(1)$$

K. J. Kim, NIM A 275, 201 (1989).

Beam dynamics in photo injectors with space charge

$$\Delta\vec{p} \approx \frac{mc}{eE_0 \sin\varphi}\frac{\pi}{2}\vec{f}(\gamma=1) = \frac{mc}{E_0 \sin\varphi}\frac{\pi}{2}\vec{E}^{sc}$$

$\vec{E}^{sc} = e\vec{f}(\gamma=1)$ - electrostatic field at rest in the lab frame

$$\vec{E}^{sc}(x,y,z) = -\frac{1}{4\pi\epsilon_0}\frac{\partial}{\partial\vec{r}}\iiint \frac{\rho(u,v,w)\,du\,dv\,dw}{\sqrt{(x-u)^2+(y-v)^2+(z-w)^2}} = \frac{\iint \rho(x,y,0)\,dx\,dy}{4\pi\epsilon_0}\vec{\mathcal{E}}(x,y,z)$$

$$\varepsilon_{n,x}^{SC} = \sqrt{\langle x^2\rangle\langle\Delta p_x^2\rangle - \langle x\Delta p_x\rangle^2} \;\Rightarrow\; \varepsilon_{n,x}^{SC} = \frac{\pi}{4}\frac{I/I_0}{\alpha k \sin\varphi}\mu_x(A)$$

$\mu_x(A) = \sqrt{\langle x^2\rangle\langle\mathcal{E}_x^2\rangle - \langle x\mathcal{E}_x\rangle^2}$ transverse space charge "emittance factor"

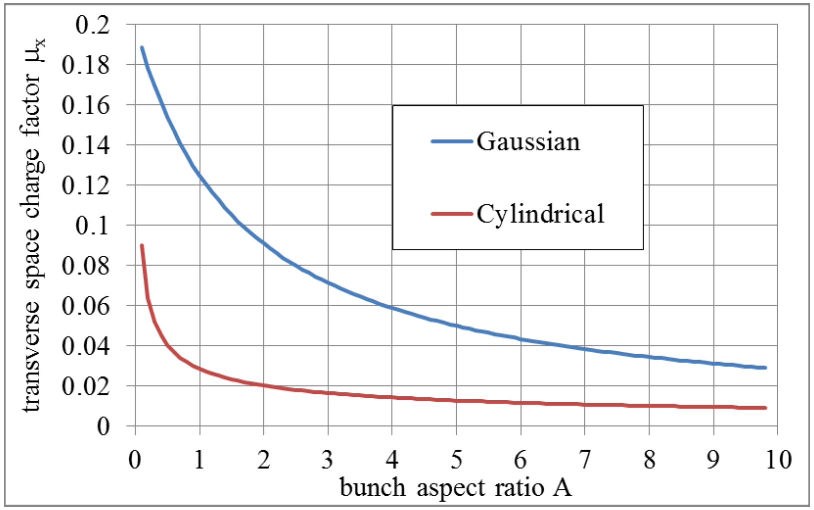
I – peak current

$I_0 = 4\pi\epsilon_0\frac{mc^3}{e} = 17kA$

$\alpha = \frac{eE_0}{2mc^2k}$

A – bunch aspect ratio

$\rho(x,y,z)$	A	$\mu_x(A)$
Gaussian	$A=\frac{\sigma_{x,y}}{\sigma_z}$	$\mu_x(A)=\frac{1}{3A+5}$
Cylindrical (flattop)	$A=\frac{r_b}{L_b}$	$\mu_x(A)=\frac{1}{35\sqrt{A}}$



Photoemission

Laser pulse → Photocathode with applied high RF field → photoelectron bunch

Pulse shape:
temporal profile,
transverse distribution,
Intensity

QE – quantum efficiency
Thermal emittance
Response time
High RF field →Schottky(like) effect

High charge → space charge effects (including image charge)
Intrinsic (cathode) and slice emittance formation

Characteristic emission curves

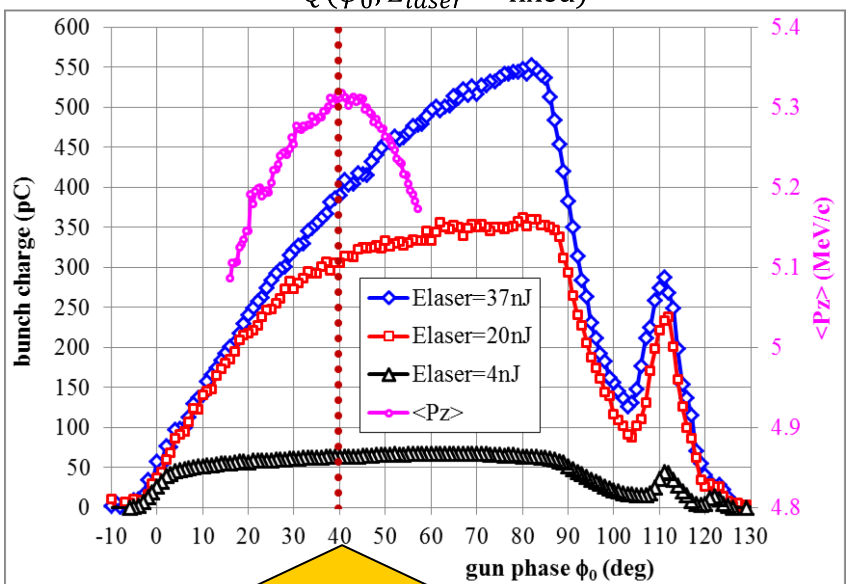
PITZ gun measurements (2013)

Pgun=4MW (Ecath=46MV/m)
$\varphi_0^{MMMG} = 40deg$

Photocathode laser:
temporal Gaussian
2.7ps FWHM
Spot ∅ 1.2mm

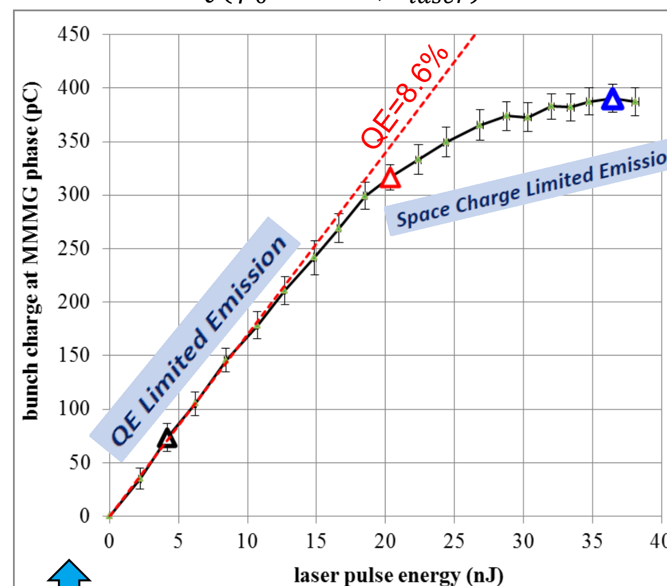
Measurements:
Charge: LOW.ICT1
Pz → LEDA

Gun phase (Schottky) scan:
$Q(\varphi_0, E_{laser} = \text{fixed})$



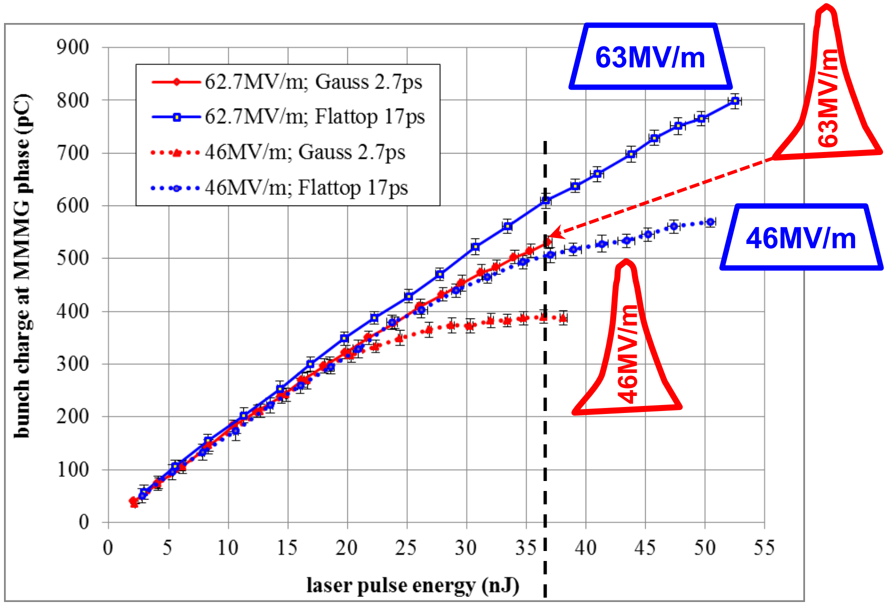
MMMG

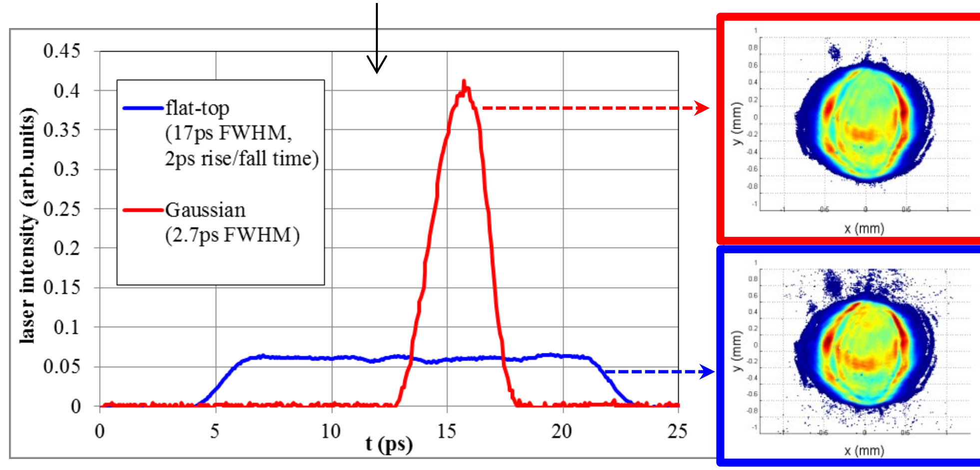
Laser pulse energy scan:
$Q(\varphi_0 = \text{fixed}, E_{laser})$

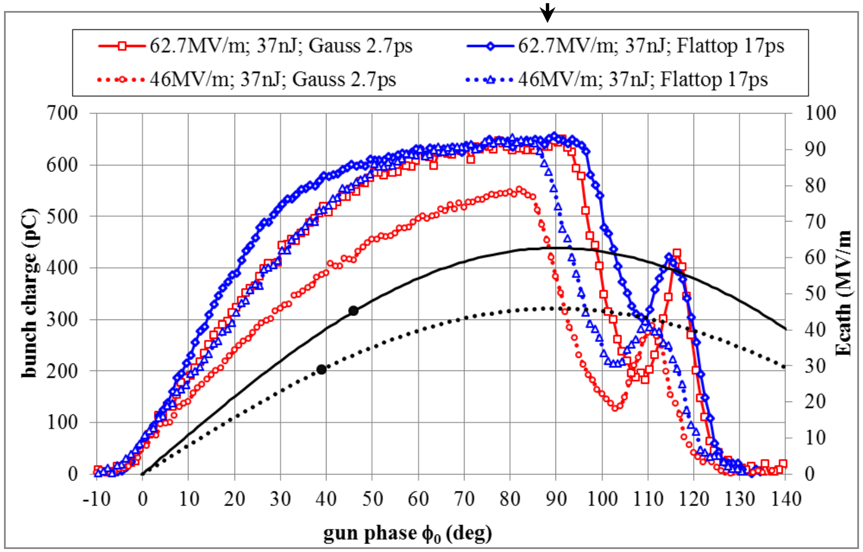


Photoemission: impact of RF gradient and laser pulse temporal profile

Emission curves: $Q(\boldsymbol{E_{cath}}, \varphi_0^{MMMG}, E_{laser}, \boldsymbol{Laser\ temporal\ profile})$







From the parallel plate capacitor (sheet beam) model:

$Q_{SC-lim} = \pi\varepsilon_0 R^2 E_0 \sin\varphi_0 = \pi\varepsilon_0 R^2 E_{cath}$

E.g. for $E_{cath} = 50\frac{MV}{m}$; $R = 0.6mm$;

$\boldsymbol{Q_{QE-lim,PPCM} \cong 500pC}$ **<< observed!!!**

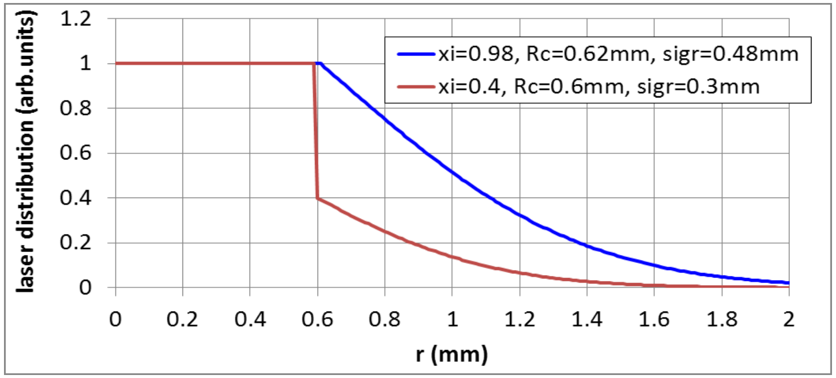
Photoemission depends on:

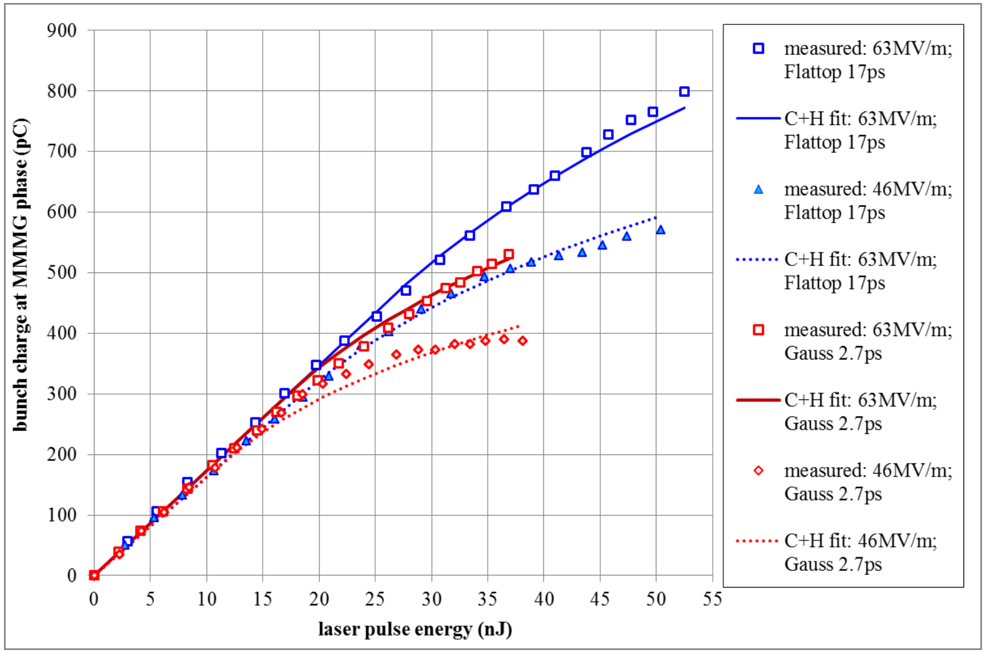
- Ecath → Schottky(like) effect
- Laser pulse duration → scape charge effect
- Emission curves $Q(E_{laser})$ saturate weaker

Photoemission: laser transverse halo impact

Laser temporal profile: Core + Halo model (**C+H**)

$$F_l(r) = \frac{E_l}{\pi R_c^2 + 2\pi\xi{\sigma_r}^2}\begin{cases} 1, & if\ \ r \le R_c \\ \xi e^{\frac{R_c^2 - r^2}{2\sigma_r^2}}, & if\ r > R_c \end{cases}$$





$$Q = Q_{core} + Q_{halo}$$

$$Q_{core} = \frac{1}{1+\xi\cdot\eta}\begin{cases} Q_{exp}, & if\ \ Q_{exp} \le Q_{max} \\ Q_{max} & if\ \ Q_{exp} > Q_{max} \end{cases}$$

$$Q_{halo} = \frac{\eta}{1+\xi\cdot\eta}\begin{cases} \xi\cdot Q_{exp}, & if\ \ \xi\cdot Q_{exp} \le Q_{max} \\ Q_{max}\cdot\left(1+\ln\frac{\xi\cdot Q_{exp}}{Q_{max}}\right) & if\ \ \xi\cdot Q_{exp} > Q_{max} \end{cases}$$

$$Q_{max} = \rho_{scl}\cdot\left(\pi R_c^2 + 2\pi\xi{\sigma_r}^2\right)$$

$$\frac{\rho_{scl}(flat-top)}{\rho_{scl}(Gaussian)} \approx 1.51$$

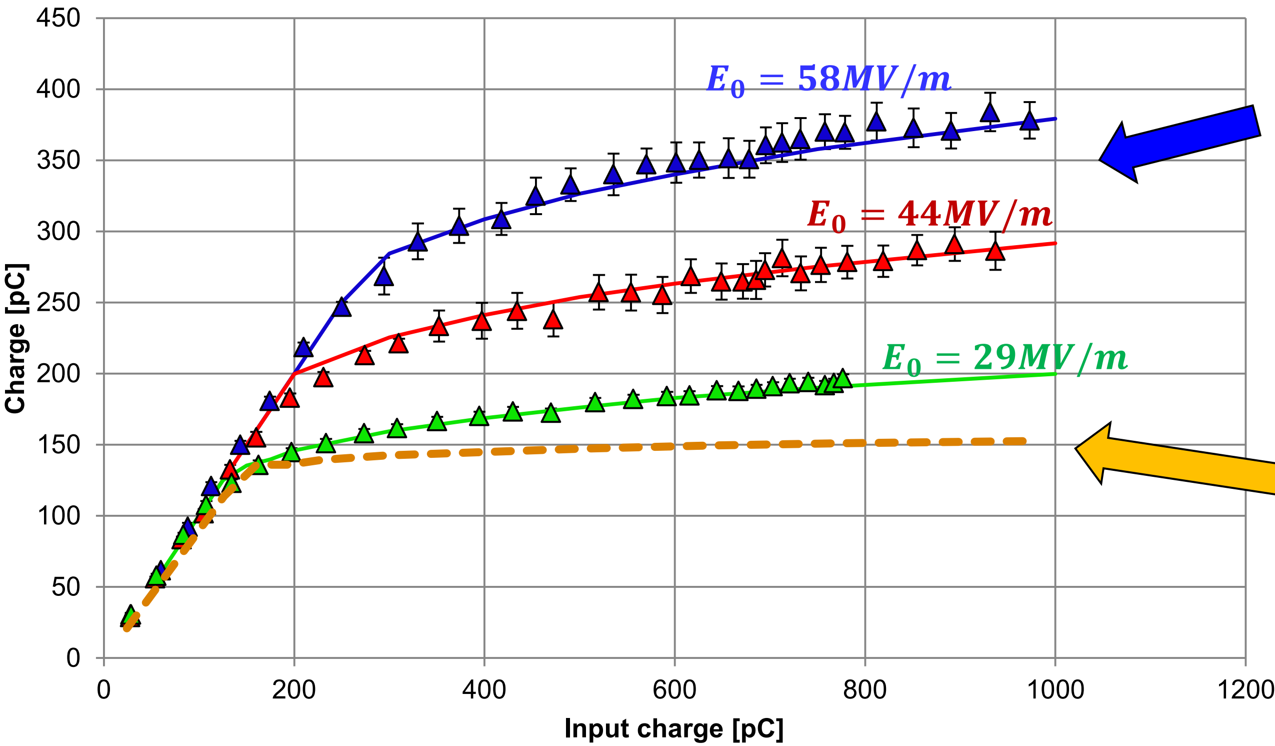
SC

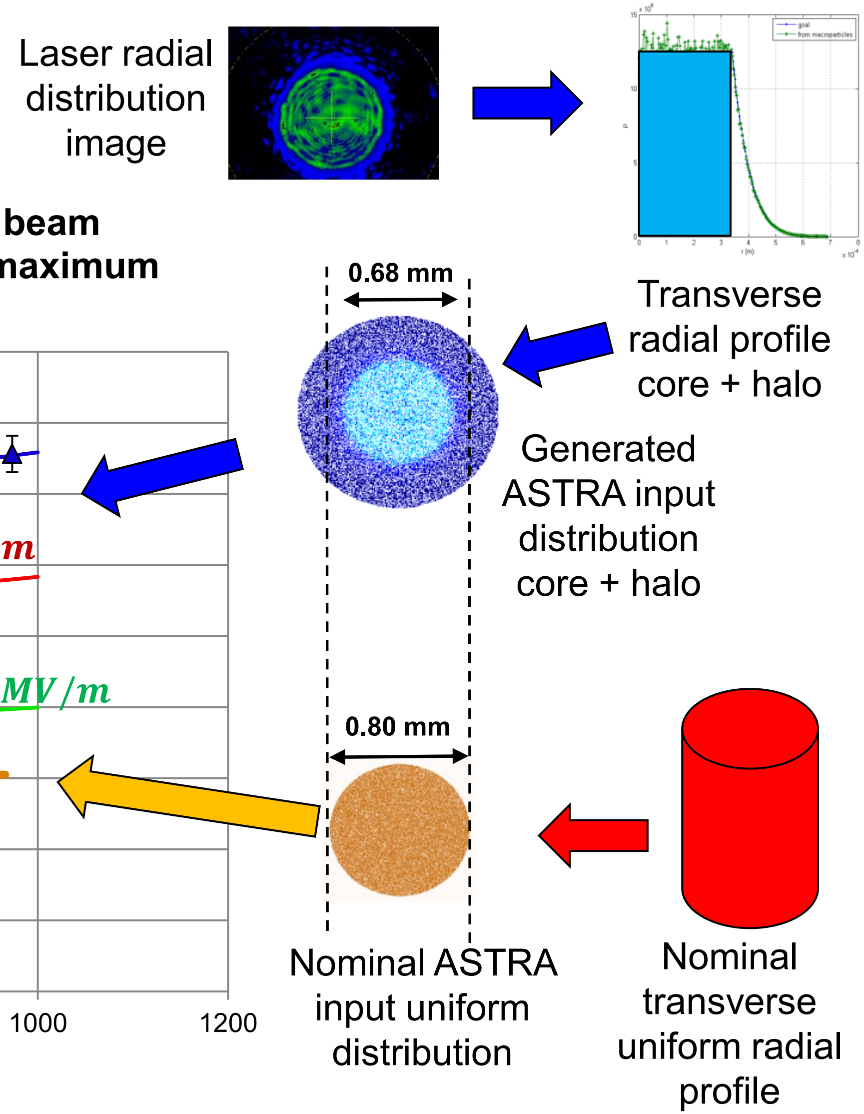
Cathode laser pulse length (FWHM) ratio is ~6

Core + Halo Model applied to ASTRA simulations

If a uniform distribution is used instead, the charge saturates

Extracted charge with core + halo for 0.8 mm beam diameter with 1.5 ps rms Gaussian temporal at maximum cathode field

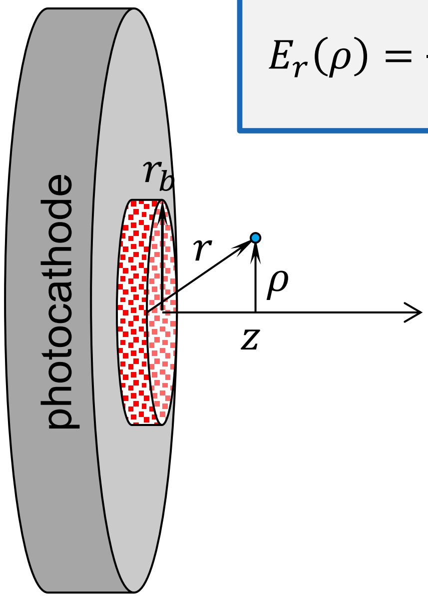


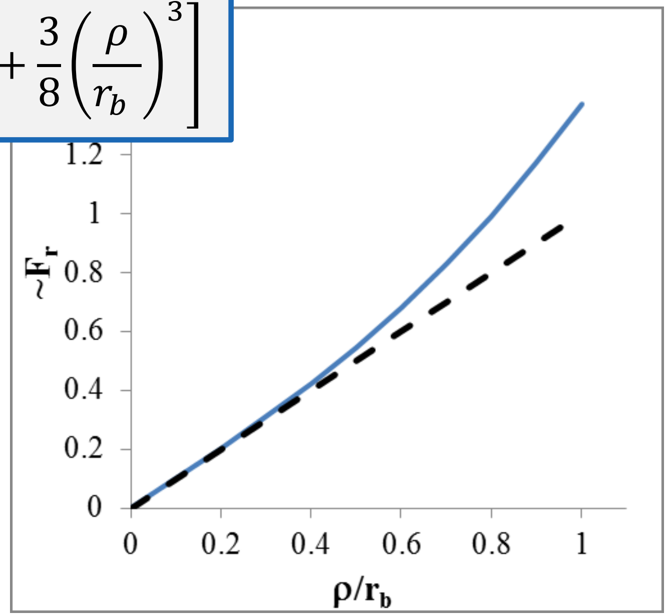


Photoemission: slice emittance formation

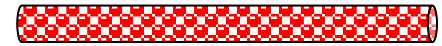
Very short non-relativistic bunch at the cathode → nonlinear Lorentz force

$$E_r(\rho) = \frac{\sigma_0}{4\epsilon_0}\left[\frac{\rho}{r_b} + \frac{3}{8}\left(\frac{\rho}{r_b}\right)^3\right]$$





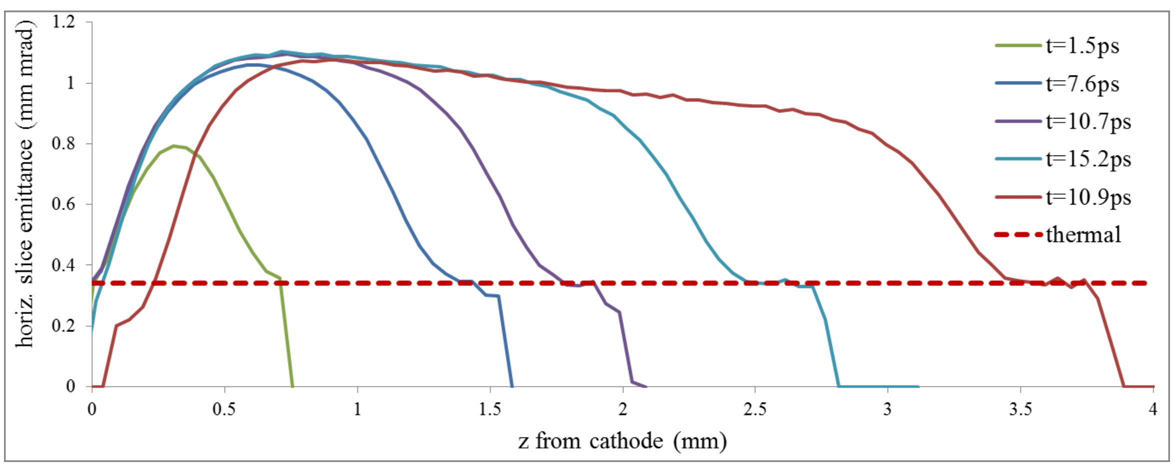
NB: for infinitely long cylinder



$$E_r(\rho) = \frac{Q/V}{2\epsilon_0}\rho$$

$$F_r(\rho) = \frac{eI\rho}{2\pi\epsilon_0\gamma^2\beta c r_b^2}$$

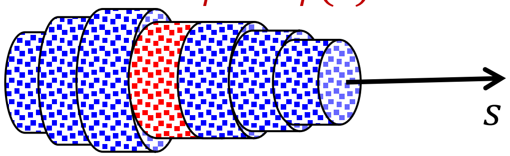
Space charge term in the envelope equation



Emittance compensation: beam envelope equation

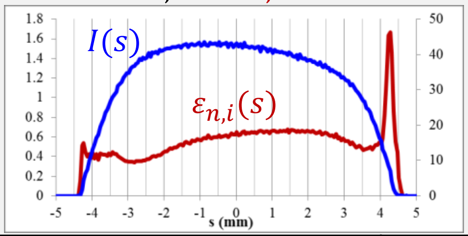
$\sigma_r = \sigma_r(s)$ – rms envelope of a beam slice

$$\frac{d^2\sigma_r}{dt^2} = \beta^2 c^2 \frac{d^2\sigma_r}{dz^2} = \beta^2 c^2 \sigma_r''$$



Emittance "pressure" term

$$\varepsilon_{n,i} = \varepsilon_{n,i}(s)$$



~ change in slope of particle trajectory

RF focusing/defocusing

$$mc^2\gamma'' = -\frac{2eE_r}{r}$$

Angular momentum

$$P_\theta = mr^2\gamma\dot{\theta} + erA_\theta$$

$$\sigma_r'' + \frac{\gamma'}{\beta^2\gamma}\sigma_r' + \left[\frac{\gamma''}{2\beta^2\gamma} + \left(\frac{eB}{2mc\beta\gamma}\right)^2\right]\sigma_r - \frac{I}{2I_o\beta^3\gamma^3}\frac{1}{\sigma_r} - \frac{1}{\beta^2\gamma^2}\left[\varepsilon_{n,i}^2 + \left(\frac{P_\theta}{mc}\right)^2\right]\frac{1}{\sigma_r^3} = 0$$

"adiabatic damping" of transverse particle angles

$$mc^2\gamma' = eE_z$$

Static magnetic field (solenoid) focusing

$$k_s^2 = \left(\frac{eB}{2mc\beta\gamma}\right)^2$$

External radial focusing strength:

$$K_r = \left[\frac{\gamma''}{2\beta^2\gamma} + \left(\frac{eB}{2mc\beta\gamma}\right)^2\right]$$

Space charge

NB: $F_r(\rho) = \dfrac{eI\rho}{2\pi\epsilon_0\gamma^2\beta c r_b^2}$

Beam generalized perveance:

$$P = \frac{eI(s)}{2\pi\epsilon_0 m\gamma^3\beta^3c^3} = \frac{2I(s)}{I_0\beta^3\gamma^3}$$

$$I_0 = 4\pi\epsilon_0\frac{mc^3}{e} = 17kA$$

Emittance compensation: beam envelope equation

$$\sigma_r'' + \frac{\gamma'}{\beta^2\gamma}\sigma_r' + K_r\sigma_r - \frac{I}{2I_o\beta^3\gamma^3}\frac{1}{\sigma_r} - \frac{1}{\beta^2\gamma^2}\left[\varepsilon_{n,i}^2 + \left(\frac{P_\theta}{mc}\right)^2\right]\frac{1}{\sigma_r^3} = 0$$

$\frac{I}{2I_o\beta\gamma} \gg \frac{\varepsilon_{n,i}^2}{\sigma_r^2}$ ➔ space charge dominated

$\frac{I}{2I_o\beta\gamma} \ll \frac{\varepsilon_{n,i}^2}{\sigma_r^2}$ ➔ emittance dominated

For space charge dominated case in absence of acceleration

$$\sigma_r'' + K_r\sigma_r - \frac{I}{2I_o\beta^3\gamma^3}\frac{1}{\sigma_r} = 0$$

Serafini and Rosenzweig (Phys. Rev. E **55** (1997) 7565).

Brillouin flow: $\sigma_r'' \to 0$

➔ equilibrium beam size:

$$\sigma_{r,eq}(s) = \sqrt{\frac{I(s)}{2I_o\beta^3\gamma^3K_r}}$$

NB: $K_r \sim$ same for all slices

More general case (including emittance term):

$$\tilde{\sigma}_{r,eq}^2 = \frac{\sigma_{r,eq}^2}{2} + \sqrt{\left(\frac{\sigma_{r,eq}^2}{2}\right)^2 + \frac{\beta^2\varepsilon_{n,i}^2}{K_r}}$$

Emittance compensation: beam envelope equation

$$\sigma_{r,eq}(s) = \sqrt{\frac{I(s)}{2I_o\beta^3\gamma^3K_r}}$$

$$\sigma_r'' + K_r\sigma_r - \frac{I}{2I_o\beta^3\gamma^3}\frac{1}{\sigma_r} = 0$$

Small oscillations near equilibrium: $\sigma_r(s) = \sigma_{r,eq}(s) + \delta\sigma_r(s)$

$$\delta\sigma_r'' + 2K_r\delta\sigma_r\left[1 - \frac{1}{2}\frac{\delta\sigma_r}{\sigma_{r,eq}}\right] \approx 0$$

$$\delta\sigma_r(z,s) = \frac{\delta\sigma_r'(0,s)}{\sqrt{2K_r}}\sin\left(\sqrt{2K_r}z\right) + \delta\sigma_r(0,s)\cos\left(\sqrt{2K_r}z\right)$$

$$\sigma_r(z=0,s) = \sigma_{r,eq}(s) + \delta\sigma_r(s) = \sigma_0$$
$$\sigma_r{}'(z=0,s) = 0$$

$$\sigma_r(z,s) = \sigma_{r,eq}(s) + [\sigma_0 - \sigma_{r,eq}(s)]\cos\left(\sqrt{2K_r}z\right)$$

Emittance compensation: beam envelope equation

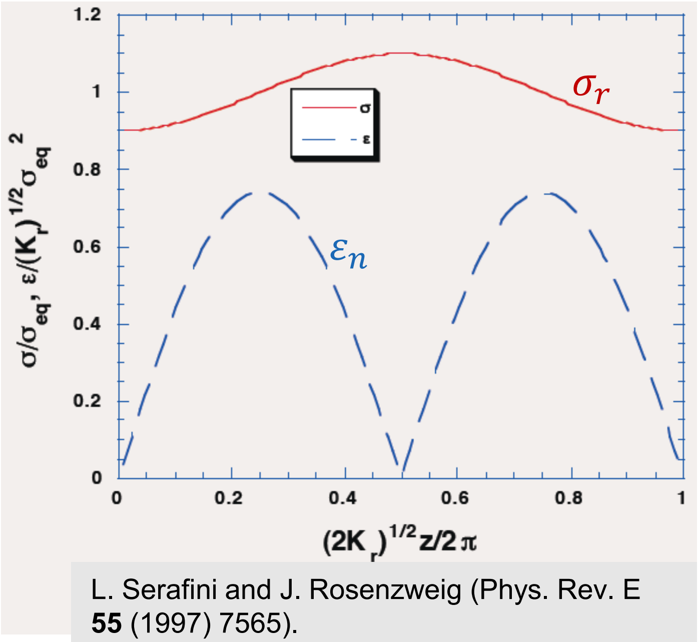
$$\sigma_r(z,s) = \sigma_{r,eq}(s) + \left[\sigma_0 - \sigma_{r,eq}(s)\right]\cos\left(\sqrt{2K_r}z\right)$$

$$\sigma_r'(z,s) = -\sqrt{2K_r}\left[\sigma_0 - \sigma_{r,eq}(s)\right]\sin\left(\sqrt{2K_r}z\right)$$

Weighted average over distributed slices $I(s)$ assuming $K_r = const$ and expanding around symmetric beam current profile at I_p

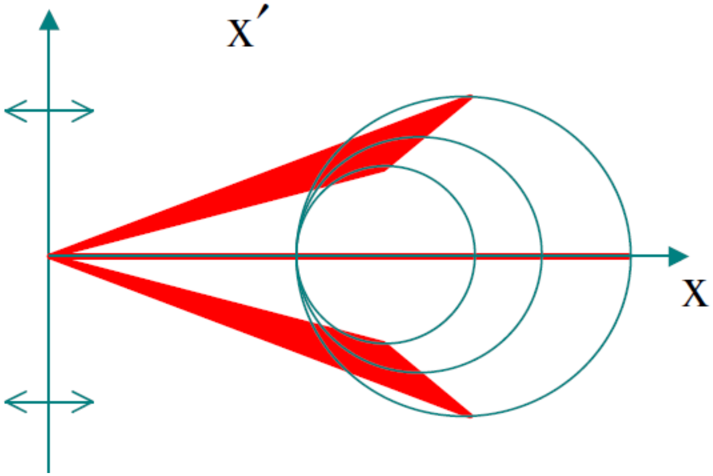
$$\varepsilon_n = \frac{\beta\gamma}{2}\sqrt{\langle\sigma_r^2\rangle\langle\sigma_r'^2\rangle - \langle\sigma_r\sigma_r'\rangle^2} \approx \beta\gamma\sigma_0\frac{\delta I_{rms}}{\sqrt{2}}\left|\frac{\partial}{\partial I}\left(\frac{\sigma_r'}{\sigma_r}\right)\right|_{I_p}$$

$$\varepsilon_n = \beta\gamma\sigma_0\sigma_{r,eq}(I_p)\frac{\delta I_{rms}}{2I_p}\left|\sin\left(\sqrt{2K_r}z\right)\right|$$

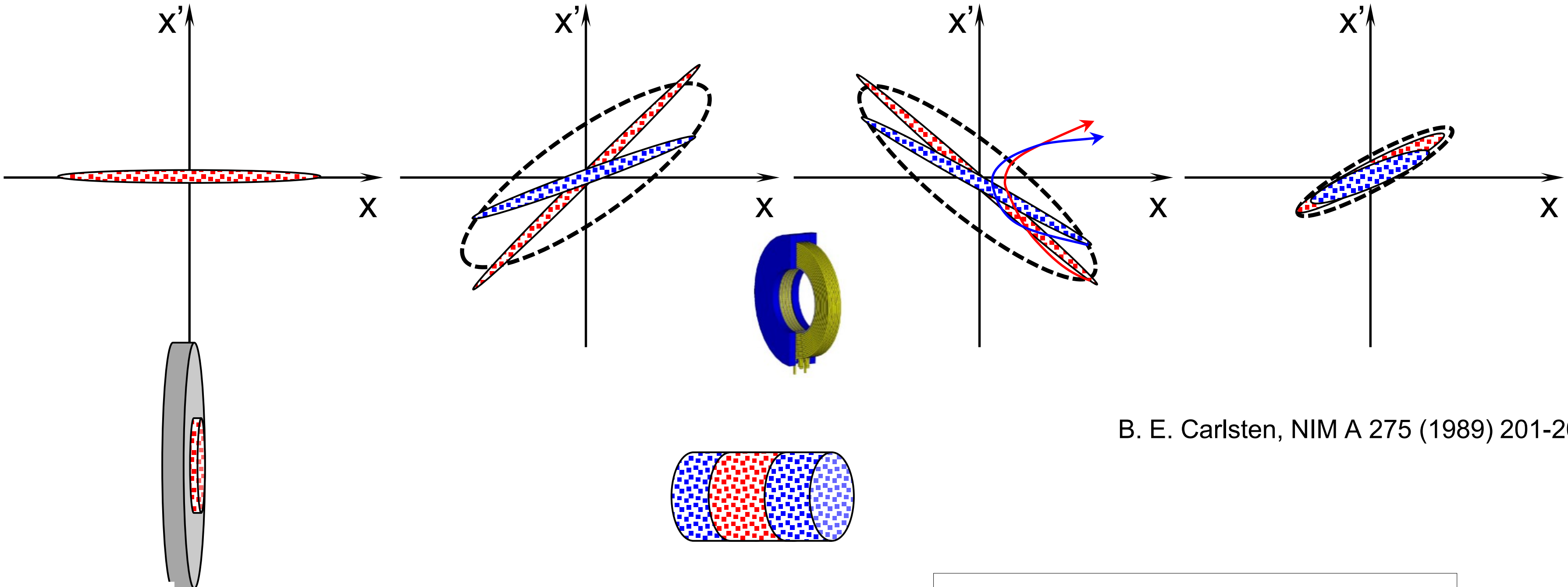


L. Serafini and J. Rosenzweig (Phys. Rev. E **55** (1997) 7565).

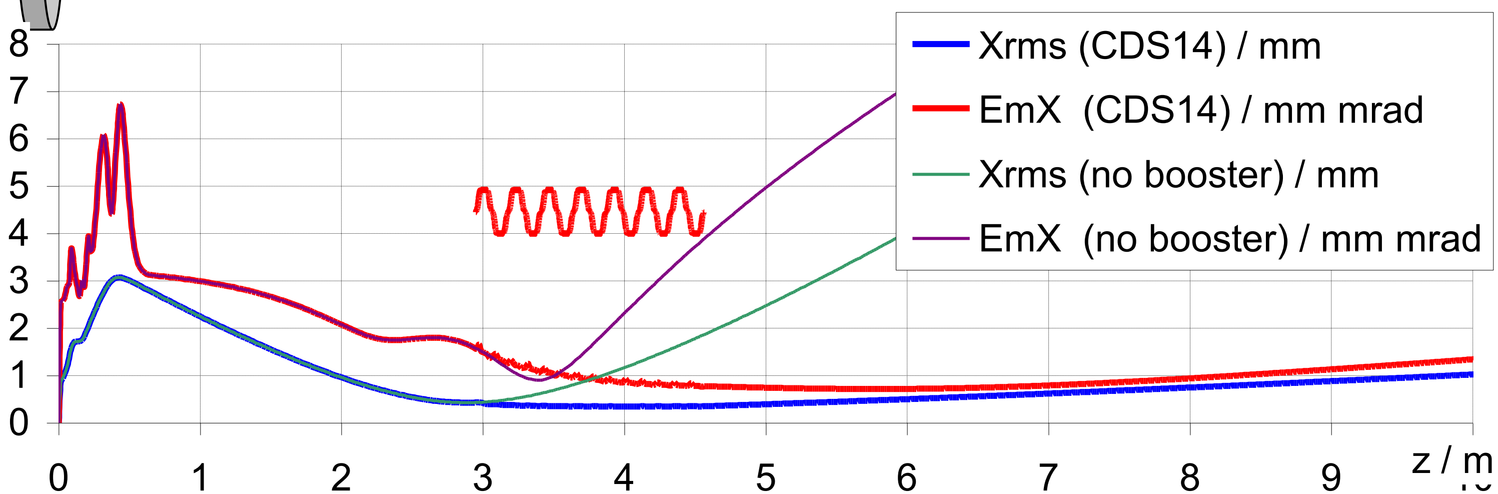
- slices oscillate in phase space around different equilibria but with the same wave number
- The projected emittance oscillates with the same wave number, but is shifted by $\pi/2$



Projected emittance growth compensation



B. E. Carlsten, NIM A 275 (1989) 201-208

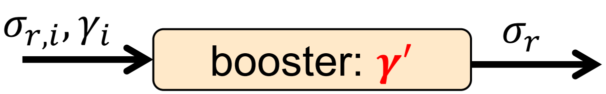


Emittance conservation by further acceleration

$$\varepsilon_n = \beta\gamma\sigma_0\sigma_{r,eq}(I_p)\frac{\delta I_{rms}}{2I_p}\left|\sin\left(\sqrt{2K_r}z\right)\right|$$

- Solving the envelope equation with acceleration, but w/o space charge term → the oscillation wave number ($\sqrt{2K_r}$ before) is reduced by $\sim\gamma' = \frac{eE_{booster}}{mc^2}$ - the oscillation is not damped, but strongly stretched
- Matching the beam to the first accelerator module (booster) needs to be included as part of emittance compensation and should obey the following basic conditions at the entrance to the linac: the beam is at a waist: $\sigma_r' = 0$ and the waist size at injection is determined by a balancing of the RF transverse force with the space charge force
- Balancing the focusing term with the defocusing space charge term leads to a solution of the beam envelope equation w/o emittance term ($\beta = 1$):

$$\sigma_r'' + \frac{\gamma'}{\gamma}\sigma_r' + K_r\sigma_r - \frac{I}{2I_0\beta^3\gamma^3}\frac{1}{\sigma_r} = 0,$$

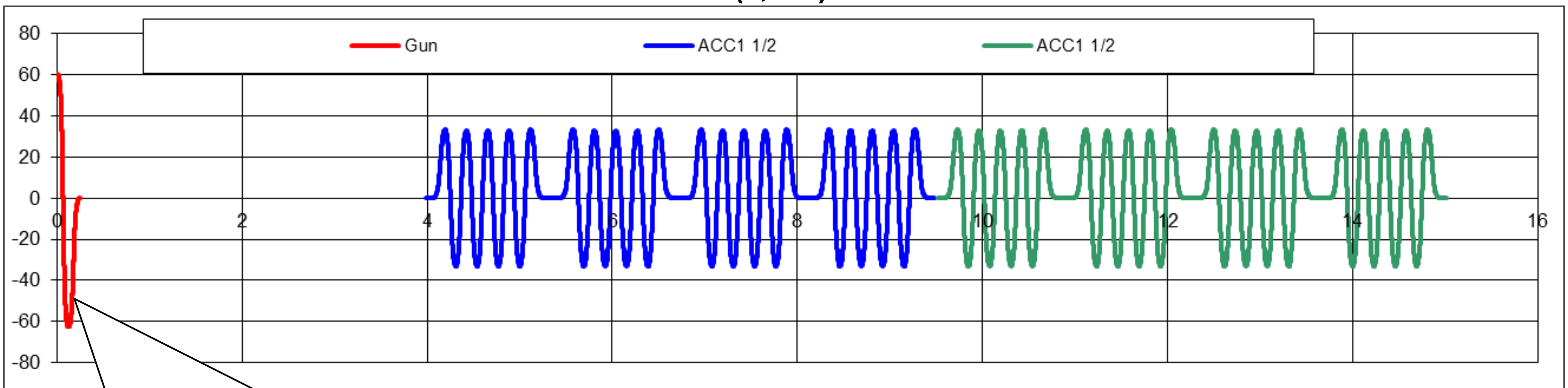


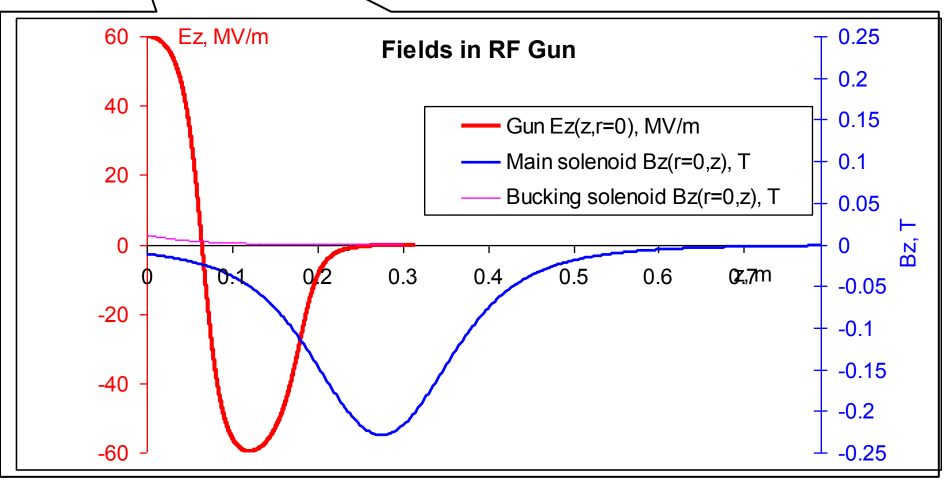
This yields the so-called matched invariant envelope ($\sigma_r = \sigma_{r,i}\sqrt{\frac{\gamma'}{\gamma_i}}$) → the Ferrario working point:

$$\gamma' = \frac{2}{\sigma_{r,i}}\sqrt{\frac{2I}{3I_0\,\gamma_i}}$$

BUT: In practice (simulations) it does not work → space charge cancelling due to the acceleration happens in much shorter distance than the full acceleration ➔ this gradient ~ good starting point for **beam dynamics simulations**

Beam dynamics simulations: Setup





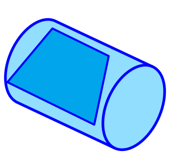
Goal (e.g.): minimum emittance for 1nC

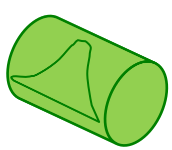
$$\varepsilon_x = \sqrt{\varepsilon_{cath}^2 + \varepsilon_{RF}^2 + \varepsilon_{SC}^2 + 2\varepsilon_{RF}\varepsilon_{SC}J_{RF-SC} + ..}$$

$$\varepsilon_{cath} \propto \varepsilon_{therm} \sim \sigma_{xy}^{laser}$$

$$\Delta\varepsilon_{n,x}^{rf} = \frac{eE_0}{2mc^2}\sigma_x^2 k\sigma_z\sqrt{[\cos\hat{\varphi}]^2 + [\sin\hat{\varphi}]^2\xi^2 k^2\sigma_z^2}$$

$$\varepsilon_{SC} = \frac{\pi}{4}\frac{I/I_0}{\alpha k \sin\varphi}\mu_{xy}\left(\frac{\sigma_{xy}}{\sigma_z}\right)$$





Optimization of the XFEL photo injector

Cathode laser (XYrms, [Trms]) +
gun parameters (RF Phase, Bz_peak, sol.pos)

0 step. “tune” the bunch charge:
Qbunch→Q=1nC(@z=7cm)

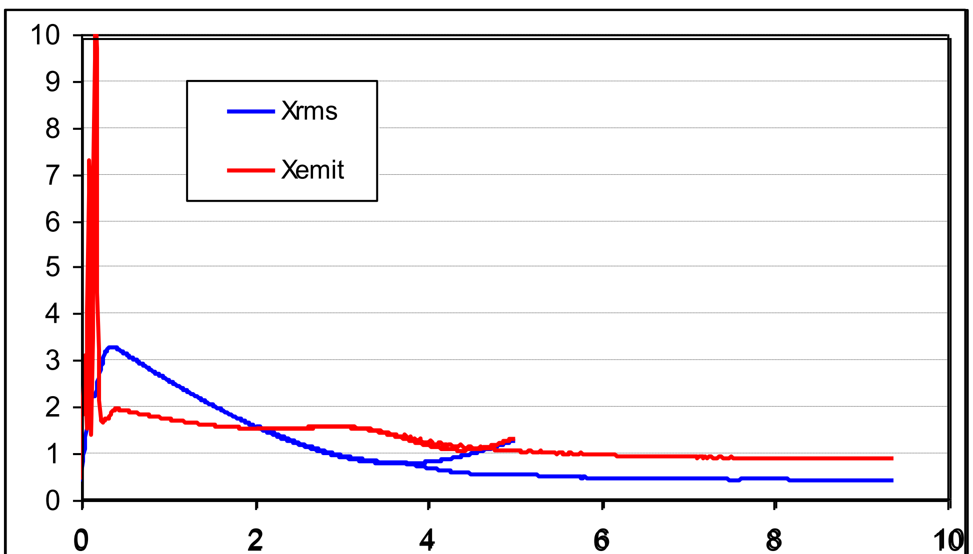
1 step. Run ASTRA till z=5m

Xrms,Xemit

Booster optimization
(booster cavity z-position,
gradient and RF phase)
Initial guess: booster matching conditions

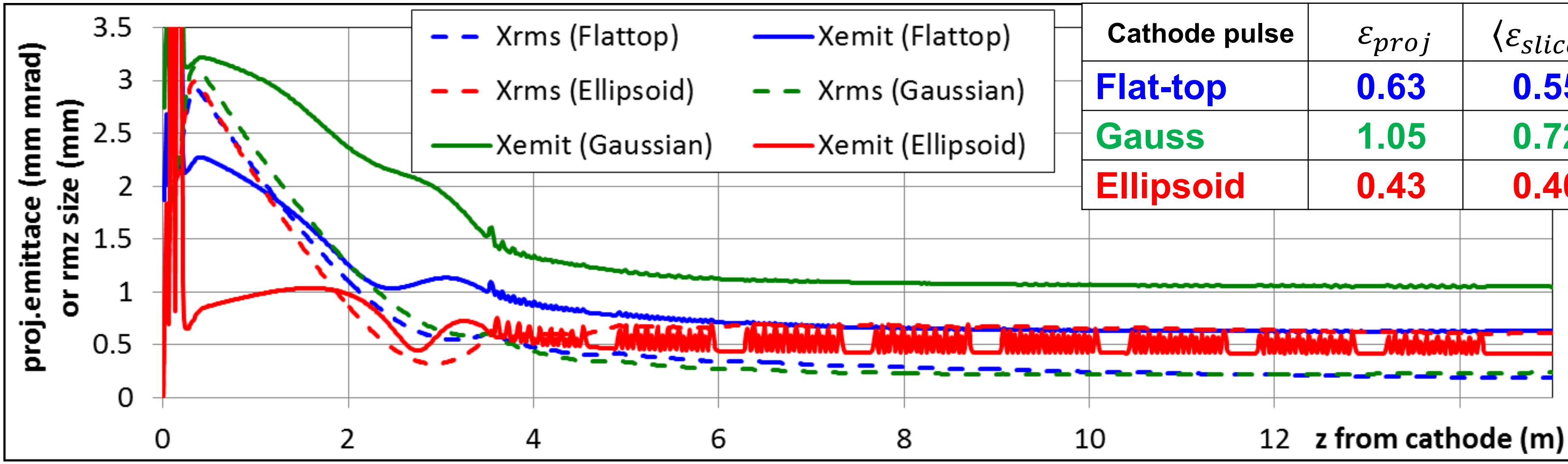
ΔE → ?

Emittance*Penalty

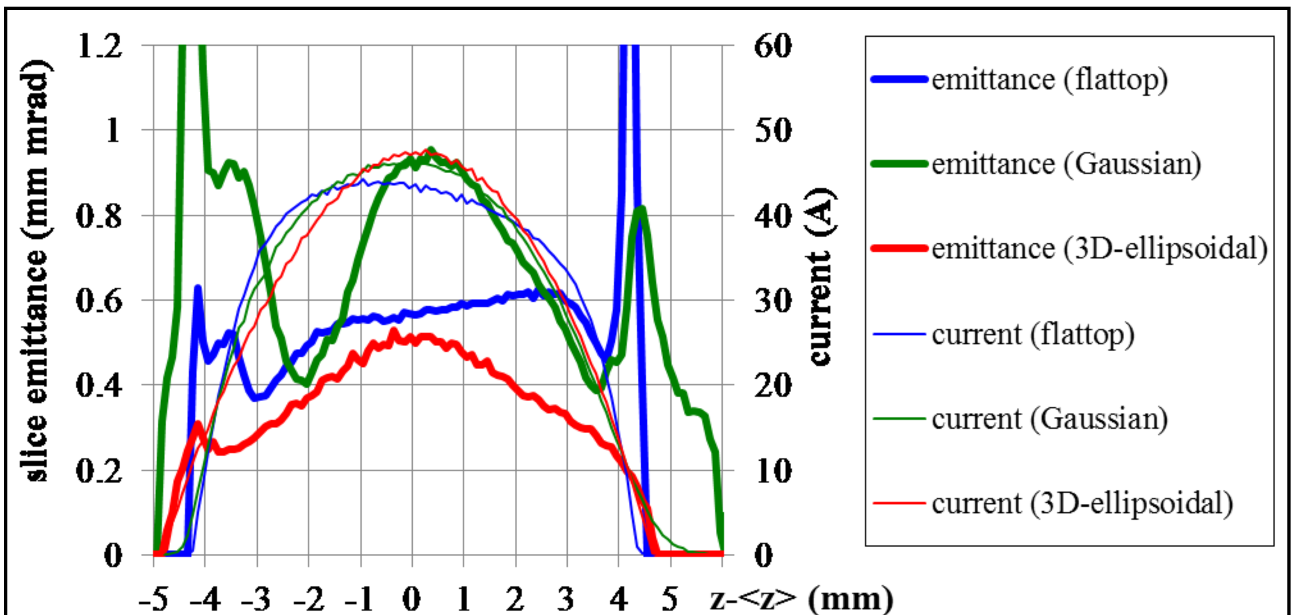


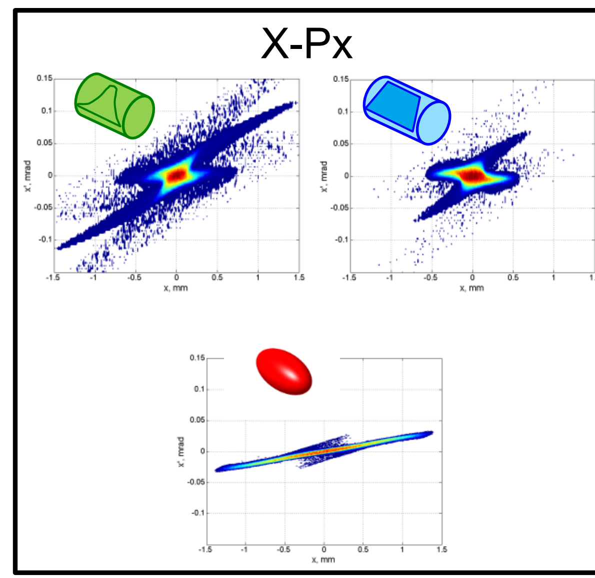
+ tolerances study

XFEL Photo injector optimization (1nC)



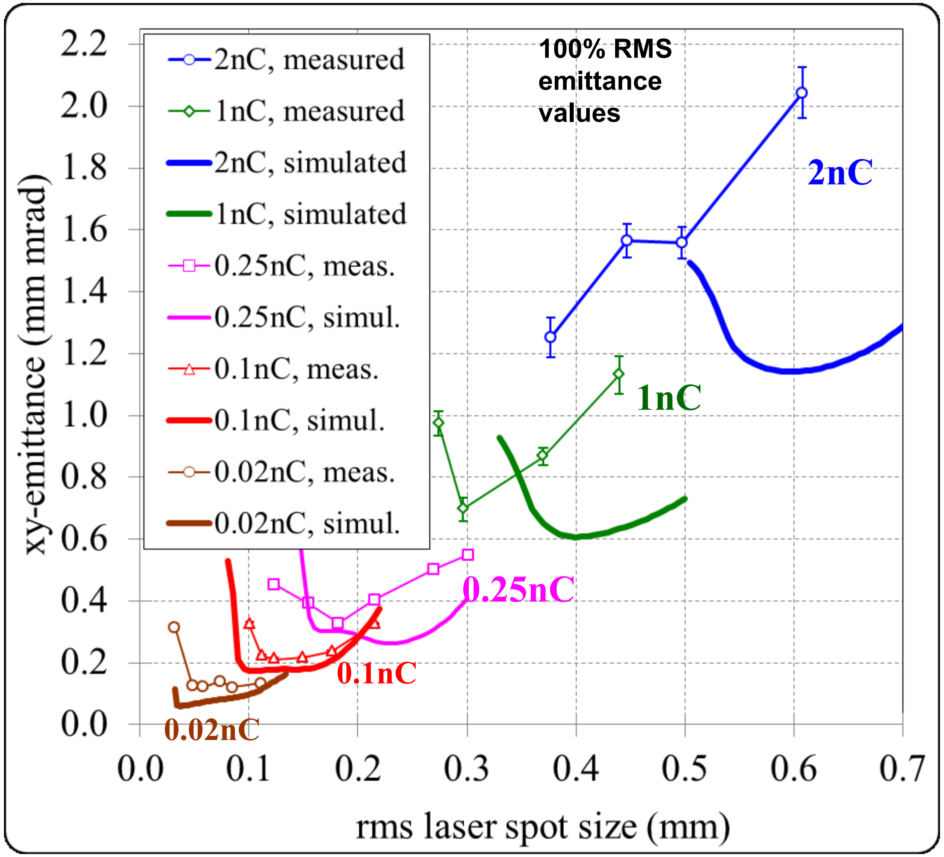
Cathode pulse	ε_{proj}	$\langle\varepsilon_{slice}\rangle$
Flat-top	0.63	0.55
Gauss	1.05	0.72
Ellipsoid	0.43	0.40



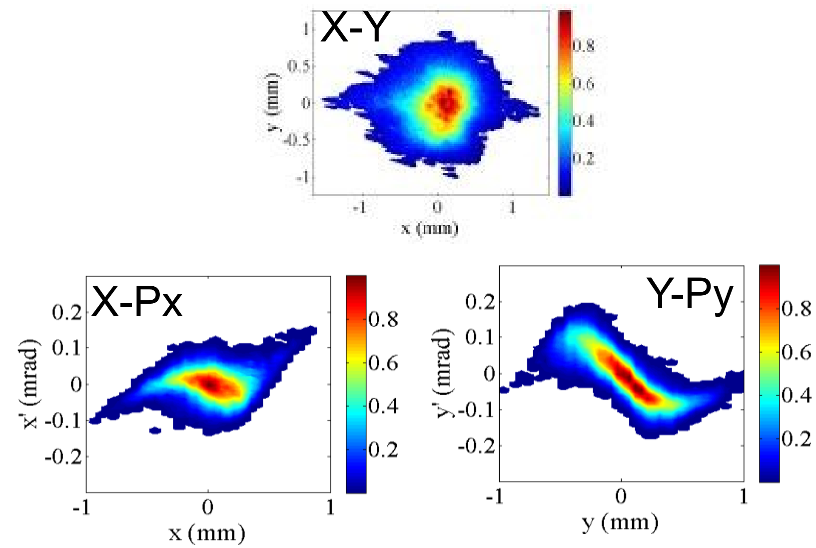


Measurements vs. Simulations: PITZ case

PITZ: Measured emittance versus laser spot size for various charges w.r.t. simulations



Measured 1nC electron beam



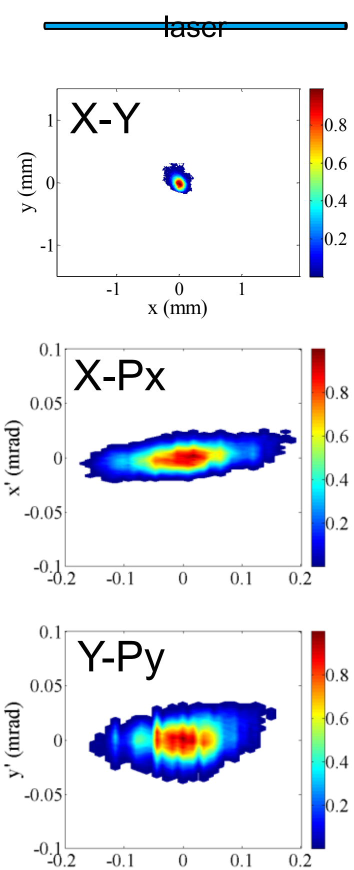
- Optimum machine parameters (laser spot size, gun phase,):
  experiment ≠ simulations
- Difference in the optimum laser spot size is bigger for higher charges (~good agreement for 100pC)
- Simulations of the emission needs to be improved → step 1: Cathode laser core+halo model

Emittance and Brightness versus Bunch Charge

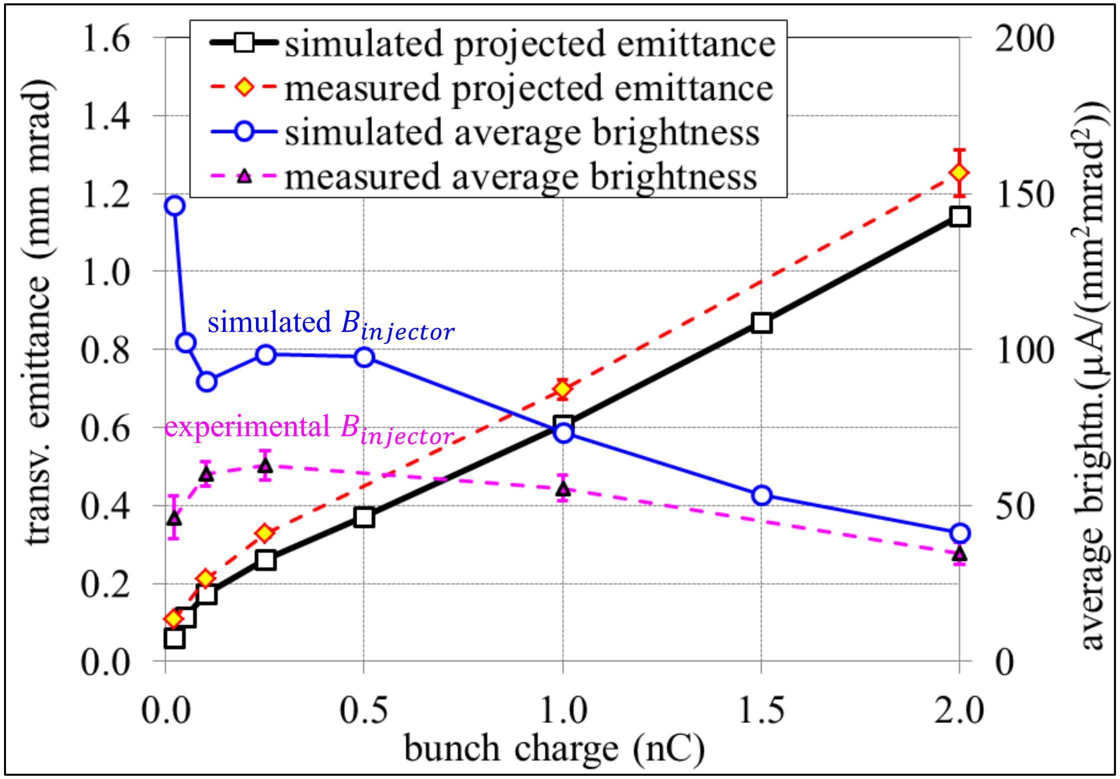
Cathode laser pulse duration was fixed at 21.5 ps (FWHM) for all bunch charges!

$$B_{injector} = \frac{I_{injector}}{\varepsilon_x \varepsilon_y} = \frac{Q \cdot NoP \cdot RR}{\varepsilon_x \varepsilon_y}$$

20pC measured

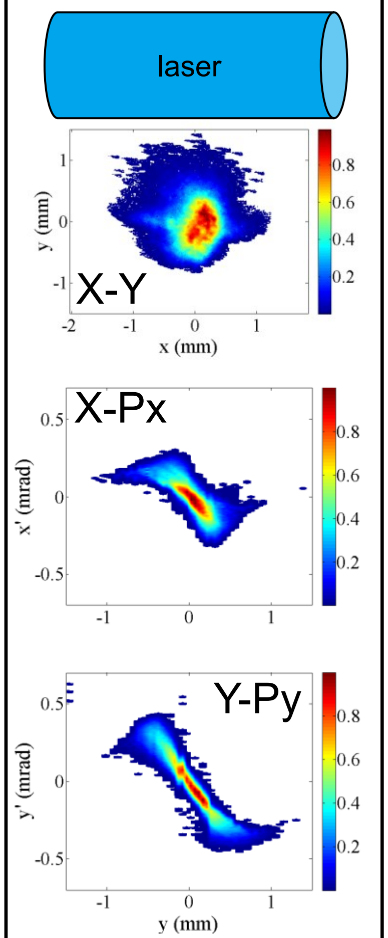


~linear SC



Bunch charge reduction at fixed cathode laser pulse duration → space charge (SC) modification

2nC measured



nonlinear SC

Beam dynamics in RF photo injectors: summary

- RF photo injectors → high brightness electron beams (high charge, low emittance)
- Beam dynamics in photo injector – analytical models:
  - RF-gun: rapid variation of the phase in the half-cell of the gun cavity, parameter α
  - RF induced transverse and longitudinal emittance
  - Space charge mitigation → emittance growth compensation with solenoid
  - Beam envelope equation: invariant envelope, matching in the booster
- Still beam dynamics simulations are needed for fine optimization
- Experimental data and beam dynamics results are becoming closer, but still there are discrepancies remaining