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Electron Sources: Single Particle Dynamics, Space Charge Limited Emission

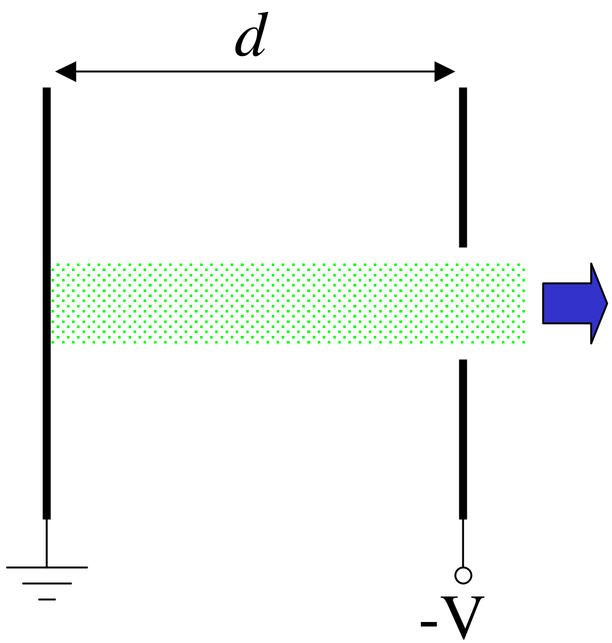
Contents

- Child-Langmuir limit
- Space charge limit with short pulses
- Busch's theorem
- Paraxial ray equation
- Electrostatic and magnetostatic focusing
- RF effects on emittance
- Drift bunching

Child-Langmuir limit

So far we have discussed current density available from a cathode.

Child-Langmuir law specifies maximum current density for a space-charge limited, nonrelativistic, 1-D beam *regardless* of available current density from the cathode. The law has a limited applicability to photoguns (applies to continuous flow, few 100s kV DC guns), but provides an interesting insight.



1D problem.

Poisson eq. + energy cons.

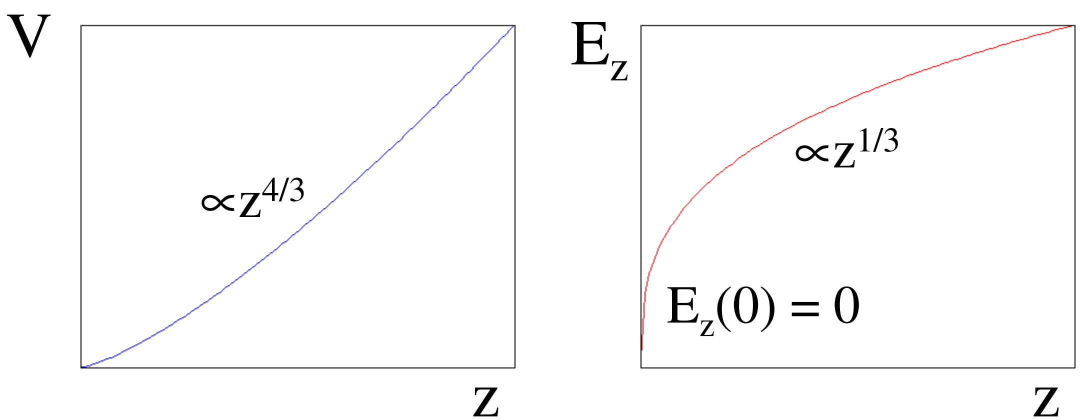
$$\frac{d^2V}{dz^2} = -\frac{\rho}{\varepsilon_0} \qquad \frac{1}{2}mv_z^2 = eV$$

Child-Langmuir derivation

Eliminating ρ and v_z from the Poisson equation, we arrive at

$$\frac{d^2V}{dz^2} = -\frac{J_z}{\varepsilon_0}\sqrt{\frac{m}{2eV}}$$

Solving for V: $$V = \left(-\frac{9J_z}{4\varepsilon_0}\sqrt{\frac{m}{2e}}\right)^{2/3} z^{4/3}$$

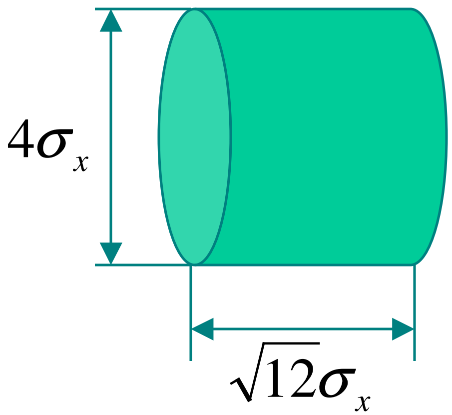


$$J = \frac{4\varepsilon_0}{9}\sqrt{\frac{2e}{m}}\frac{V^{3/2}}{d^2} \qquad J[\mathrm{A/cm^2}] = 2.33E^{3/2}[\mathrm{MV/m}]/\sqrt{d[\mathrm{cm}]}$$

Bunch charge limit in guns

Let's estimate bunch charge limit of a short pulse in a gun.

Assume 'beer-can' with rms $\sigma_{x,y}$ σ_t



also that E_{cath} does not change much over the bunch duration (usually true for photoguns)

If $\dfrac{eE_{cath}\times(c\sigma_t)}{mc^2} \ll 1$ or $\dfrac{E_{cath}[\text{MV/m}]\times(c\sigma_t)[\text{mm}]}{511} \ll 1$

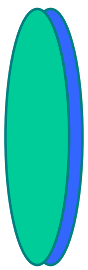
motion during emission stays nonrelativistic.

Aspect ratio of emitted electrons near the cathode after the laser pulse has expired:

$$A = \frac{\perp}{\|} = \frac{2\sigma_x}{3(c\sigma_t)} \frac{mc^2}{eE_{cath}(c\sigma_t)} = \frac{341}{E_{cath}[\text{MV/m}]} \frac{\sigma_x[\text{mm}]}{(c\sigma_t[\text{mm}])^2}$$

Space charge limited extraction

More often than not A >> 1 in photoinjectors, i.e. the bunch looks like a pancake near the cathode (!).



For short bunch (note a factor of 2 due to image charge)

$$E_{s.c.} = \frac{\sigma}{\varepsilon_0} \rightarrow \begin{aligned} q &= 4\pi\varepsilon_0 E_{cath}\sigma_x^2 \\ &= 0.11 \times E_{cath}[\text{MV/m}]\sigma_x[\text{mm}]^2 \text{ nC} \end{aligned}$$

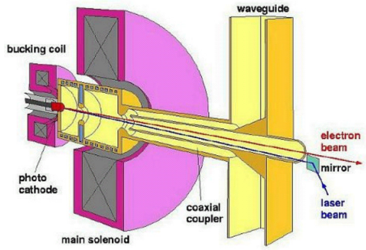
if emittance is dominated by thermal energy of emitted electrons, the following scaling applies (min possible emit.)

$$\epsilon_{n,x} = \sqrt{\frac{q}{4\pi\epsilon_0 E_{cath}} \frac{k_B T_\perp}{m_e c^2}} \qquad \varepsilon_n[\text{mm-mrad}] \geq 4\sqrt{\frac{q[\text{nC}]E_{th}[\text{eV}]}{E_{cath}[\text{MV/m}]}}$$

Typically, the best values achieved in the photoguns are ×3 larger

Cathode Field $\leftarrow E_{th}$ cathode

NCRF

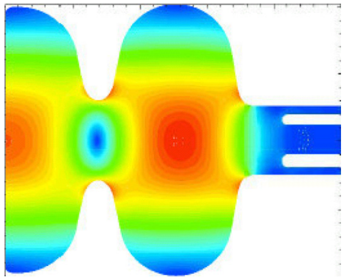


pulsed!

E_{cath} = 120 MV/m
τ_{laser} = 2.7 ps rms
σ_{laser} = 0.5 mm rms

$\tau_{laser} \rightarrow z$ = 0.08 mm

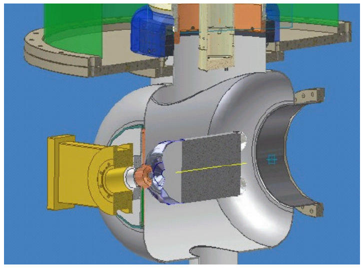
SRF



E_{cath} = 43 MV/m
τ_{laser} = 5.8 ps rms
σ_{laser} = 0.85 mm rms

$\tau_{laser} \rightarrow z$ = 0.12 mm

DC



E_{cath} = 8 MV/m
τ_{laser} = 13 ps rms
σ_{laser} = 2 mm rms

$\tau_{laser} \rightarrow z$ = 0.12 mm

1 nC

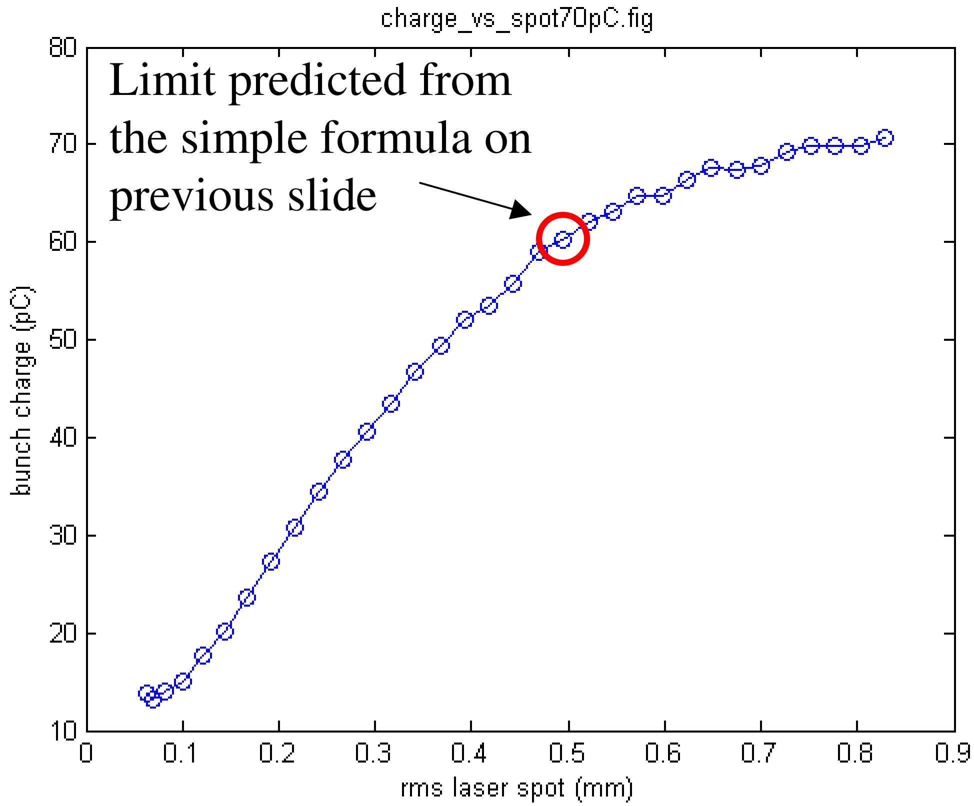
2×18 MV/m   2×6 MV/m   2×1 MV/m

$E_{cath} / E_{s.charge} = E_{cath} / E_{s.charge} = E_{cath} / E_{s.charge}$

same simulated emittance
(but the measured is best for the higher gradient)

Example from R128

Fixed laser power, varied laser spot size at V = 250 kV



Beam dynamics

Beam dynamics without collective forces is simple.

$$\vec{\nabla}\cdot\vec{B}=0 \quad \vec{\nabla}\times\vec{H}=\frac{\partial\vec{D}}{\partial t}+\vec{J} \quad \vec{\nabla}\cdot\vec{D}=\rho \quad \vec{\nabla}\times\vec{E}=-\frac{\partial\vec{B}}{\partial t}$$

$$\vec{B}=\mu\vec{H}$$

$$\vec{D}=\varepsilon\vec{E} \qquad \frac{d}{dt}(\gamma m\vec{\beta}c)=e(\vec{E}+\vec{v}\times\vec{B})$$

$$\vec{\nabla}\cdot\vec{J}+\frac{\partial\rho}{\partial t}=0$$

Calculating orbits in known fields is a single particle problem.

Effects on the phase space

time varying fields:
RF focusing
coupler kicks

aberrations:
geometric
chromatic

collective space
charge forces

bunch phase space

Single particle solution integrated over finite bunch dimensions / energy (this lecture)

Trickier space charge forces (next lecture)

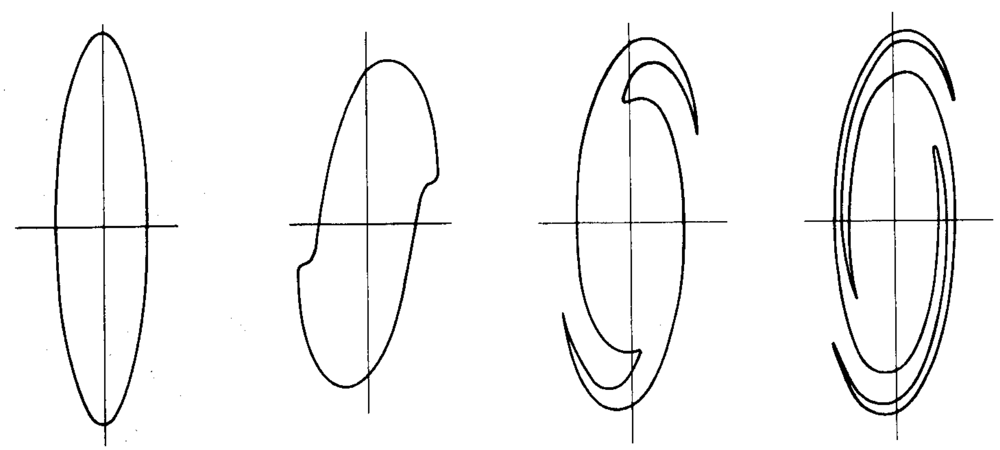
Emittance

Since emittance is such a central concept / parameter in the accelerator physics, it warrants few comments.

For Hamiltonian systems, the phase space density is conserved (a.k.a. Liouville's theorem). Rms (normalized) emittance most often quoted in accelerators' field is based on the same concept and defined as following [and similarly for (y, py) or (E, t)]

$$\varepsilon_{n,x} = \frac{1}{mc}\sqrt{\langle x^2\rangle\langle p_x^2\rangle - \langle xp_x\rangle^2} = \beta\gamma\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2} = \beta\gamma\varepsilon_x$$

Strictly speaking, this quantity is not what Lioville's theorem refers to, i.e. it does not have to be conserved in Hamiltonian systems (e.g. geometric aberrations 'twist' phase space, increasing *effective* area, while *actual* phase space area remains constant). *Rms emittance is conserved for linear optics (and no coupling) only.*

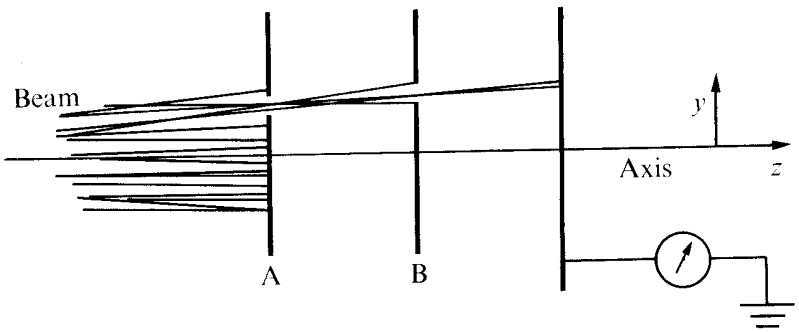


example of beam matched into periodic focusing with spherical aberrations

Emittance measurement

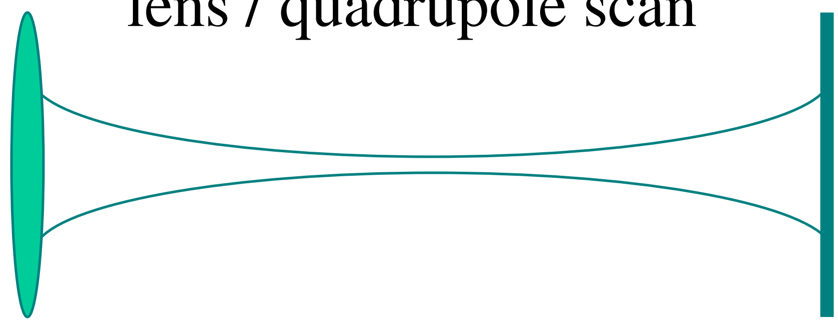
Usefulness of the rms emittance: it enters the envelope equations & can be readily measured, but provides *limited* info about the beam.

slits / pinholes



The combination of two slits give position and divergence → direct emittance measurement. Applicable for space charge dominated beams (if slits are small enough).

lens / quadrupole scan



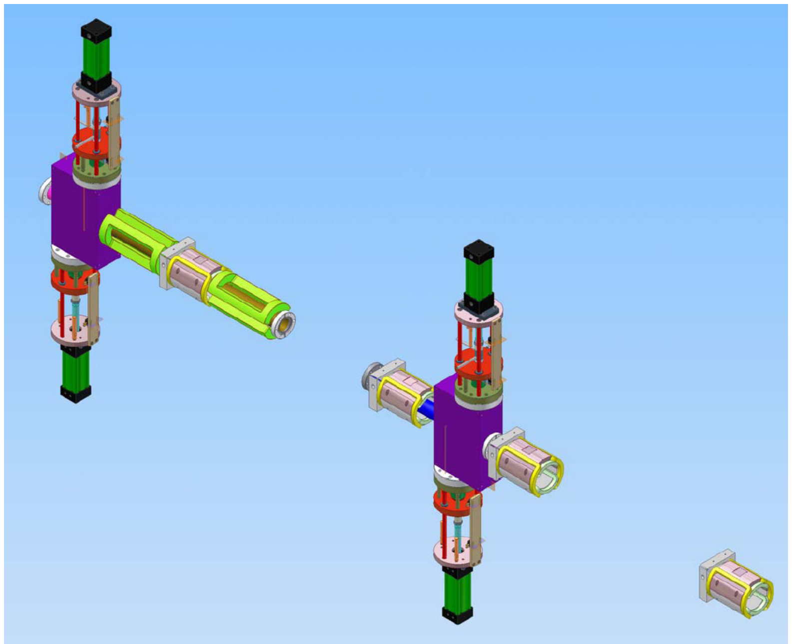
We'll see later that the envelope equation in drift is

$$\sigma'' \approx \cancel{\frac{I}{2I_0}\frac{1}{\gamma^3\sigma}} + \frac{\varepsilon^2}{\sigma^3}$$

Vary lens strength and measure size to fit in eqn with 3 unknowns to find ε.

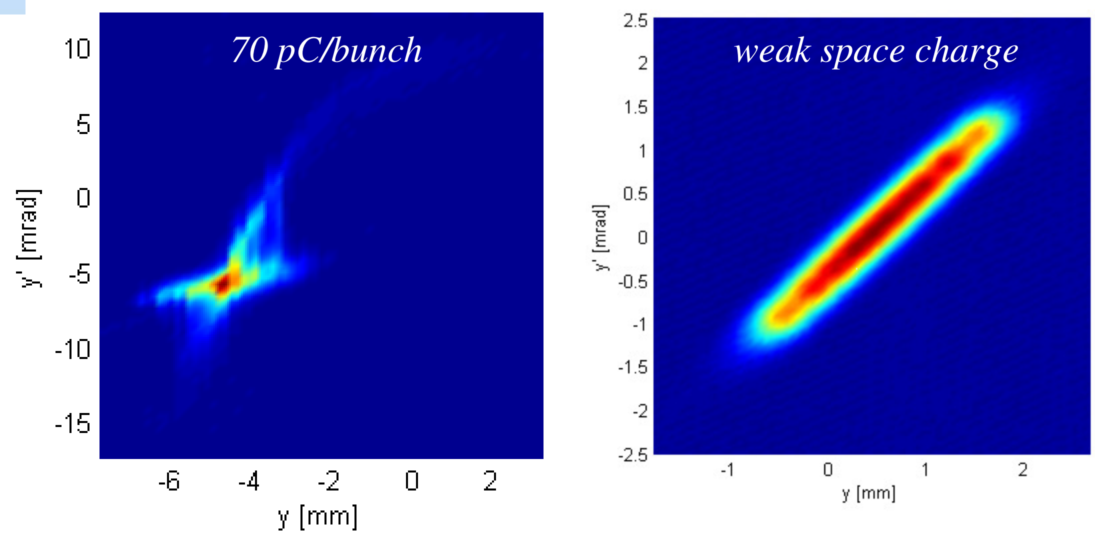
OK to use if $\sigma << \varepsilon_n\sqrt{2\gamma I_0 / I}$

Emittance measurement system



- Main design challenge: for heavily space charge dominated beams, even beamlets passing through the slits are affected by space charge
- E.g. in ERL injector slits are 10 μm
- "Armor" slit intercepts most of the beam; kW beam power handling

measured phase space



Busch's theorem

Consider axially symmetric magnetic field, azimuthal force

$$F_\theta = -e(\dot{r}B_z - \dot{z}B_r) = \frac{1}{r}\frac{d}{dt}(\gamma m r^2 \dot{\theta})$$

Flux through a circle centered on the axis and passing through *e*

$$\Psi = \int_0^r 2\pi r B_z dr$$

When particle moves from (r,z) to (r+dr, z+dz) from $\vec{\nabla}\cdot\vec{B} = 0$

$$\frac{d\Psi}{dt} = 2\pi r(\dot{r}B_z - \dot{z}B_r) \Rightarrow \qquad \boxed{\dot{\theta} = \frac{-e}{2\pi\gamma m r^2}(\Psi - \Psi_0)}$$

$\dot{\theta} = 0$

Busch's theorem simply states that canonical angular momentum is conserved

$$P_\theta = erA_\theta + \gamma m r^2 \dot{\theta} \quad (\Psi \to 2\pi r A_\theta,\, \Psi_0 \to 2\pi P_\theta / e \to \text{get Busch's formula})$$

Magnetized beam (immersed cathodes)

If magnetic field $B_z \neq 0$ at the cathode, the bunch acquires angular velocity

$$\dot{\theta} = -\frac{eB_z}{2\gamma m} \;\rightarrow\; \sigma_{p_\perp} = \gamma m \sigma_{x,y}\dot{\theta}$$

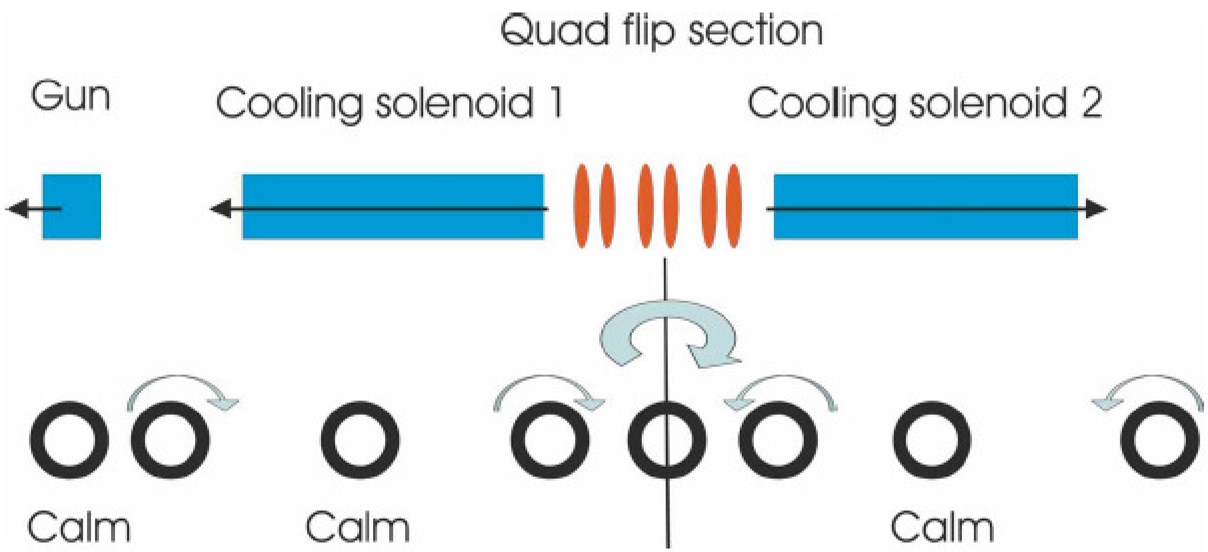
$$\varepsilon_{n,mag} \sim \frac{\sigma_{p_\perp}}{mc}\sigma_x \sim \frac{eB_0}{2mc}\sigma_x^2$$

$$\varepsilon_{n,mag}[\text{mm-mrad}] \sim 0.03B[\text{G}]\sigma_x[\text{mm}]^2$$

Normally, magnetic field at the cathode is a nuisance. However, it is useful for a) magnetized beams; b) round to flat beam transformation.

Magnetized beam (example: ion cooler)

Similarly, rms emittance inside a solenoid is increased due to Busch's theorem. This usually does not pose a problem (it goes down again) except when the beam is used in the sections with non-zero longitudinal magnetic field. In the latter case, producing magnetized beam from the gun becomes important.



Paraxial ray equation

Paraxial ray equation is equation of 'about'-axis motion (angle with the main axis small & only first terms in off-axis field expansion are included).

$$\dot{\gamma} = \gamma'\dot{z} = \gamma'\beta c$$

$$\dot{r} = r'\dot{z} = r'\beta c$$

$$\ddot{r} = (r'\beta c)'\beta c = r''\beta^2 c^2 + r'\beta'\beta c^2$$

$$\frac{d}{dt}(\gamma m\dot{r}) - \gamma m r\dot{\theta}^2 = e(E_r + r\dot{\theta}B_z)$$

with $-\dot{\theta} = \frac{q}{2\gamma m}\left(B_z - \frac{\Psi_0}{\pi r^2}\right)$ and $\dot{\gamma} = \beta e E_z / mc$

$$\ddot{r} + \frac{\beta e E_z}{\gamma mc}\dot{r} + \frac{e^2 B_z^2}{4\gamma^2 m^2} r - \frac{e^2 \Psi_0^2}{4\pi^2\gamma^2 m^2}\frac{1}{r^3} - \frac{eE_r}{\gamma m} = 0$$

eliminating time and using $E_r \approx -\frac{1}{2} r E_z' = -\frac{1}{2} r\gamma'' mc^2 / e$

const

$$\boxed{r'' + \frac{\gamma' r'}{\beta^2\gamma} + \left(\frac{\gamma''}{2\beta^2\gamma} + \frac{\Omega_L^2}{\beta^2 c^2}\right) r - \left(\frac{P_\theta}{\beta\gamma mc}\right)^2 \frac{1}{r^3} = 0}$$

$$P_\theta \equiv erA_\theta + \gamma m r^2\dot{\theta}$$

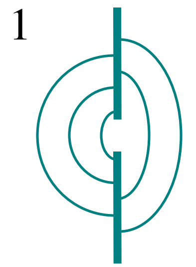
$$\Omega_L \equiv -eB_z / 2\gamma m$$

$$\boxed{\theta_L = \int_0^z \Omega_L \frac{dz}{\beta c}}$$

Focusing: electrostatic aperture and solenoid

With paraxial ray equation, the focal length can be determined

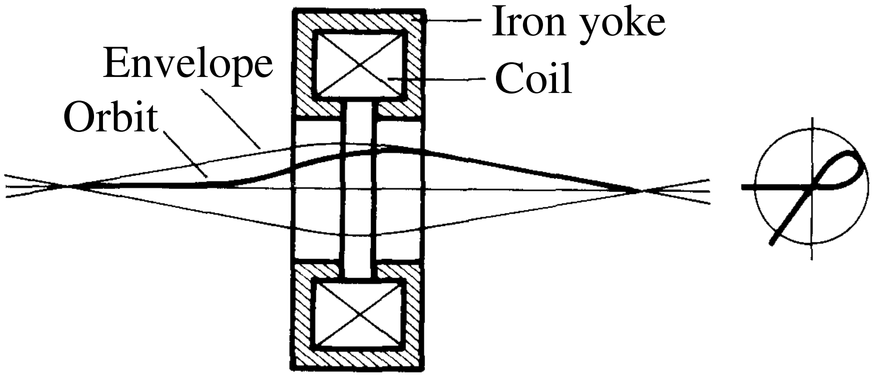
electrostatic aperture



$$f = 4V \frac{1+\frac{1}{2}eV/mc^2}{1+eV/mc^2}\frac{1}{E_2 - E_1}$$

eV is equal to beam K.E., E_1 and E_2 are electric fields before and after the aperture

solenoid



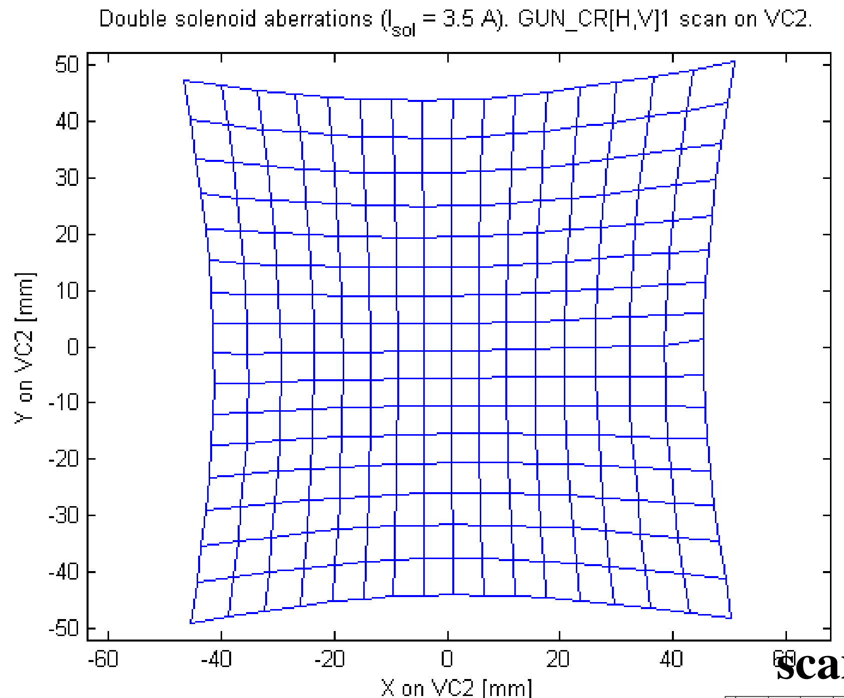
$$\frac{1}{f} = \int \left(\frac{\Omega_L}{\beta c}\right)^2 dz$$

$$= \int \left(\frac{eB_z}{2\beta\gamma mc}\right)^2 dz \approx \frac{1}{4}\left(\frac{e}{cp}\right)^2 B_z^2 L$$

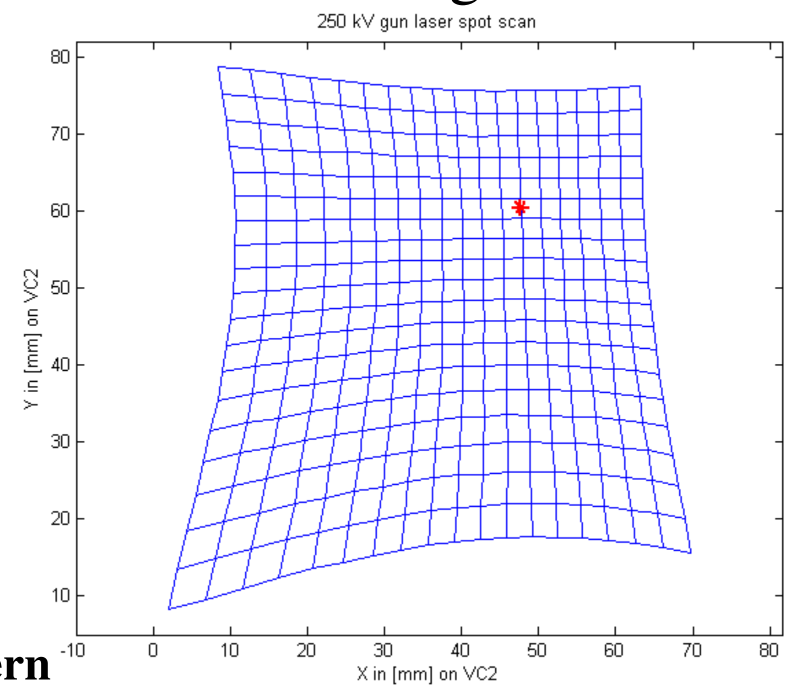
$$cp/e[1\,\mathrm{MeV/c}] \rightarrow (B\rho)[33.4\,\mathrm{G\text{-}m}]$$

R128 data: pincushion effect

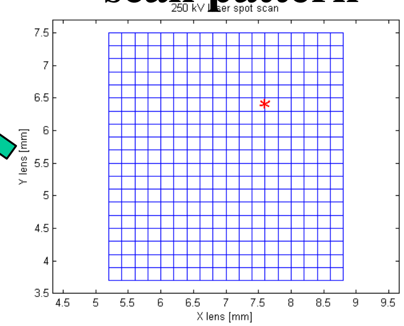
Double-solenoid



DC gun



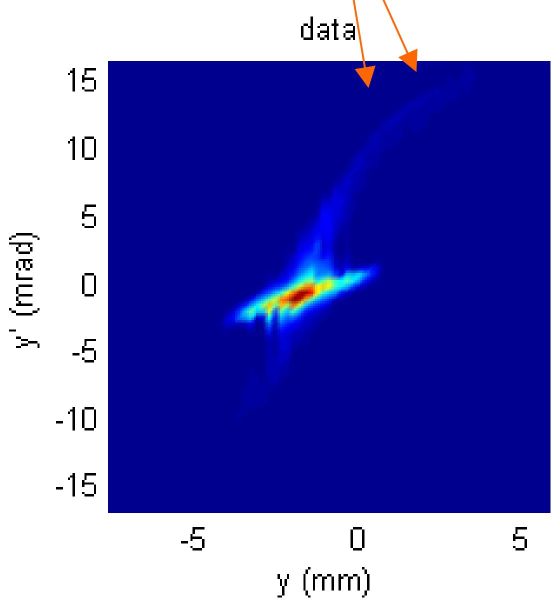
scan pattern



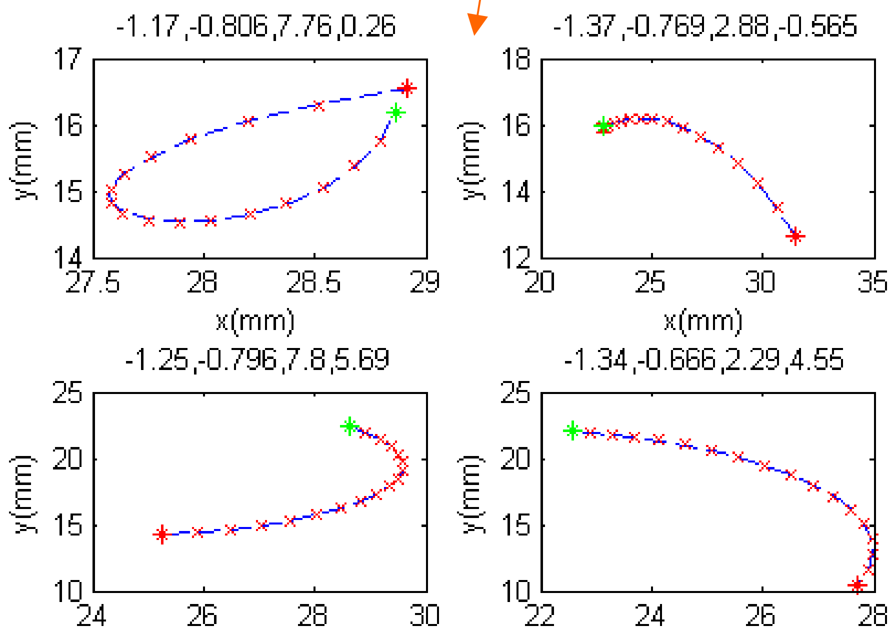
Solenoid: a fascinating lens

Thick lens + Larmor rotation produce interesting results

Misaligned solenoid with space charge beam produces asymmetric tail in the phase space



Beam-based alignment: solenoid current scan



RF focusing effect

SW longitudinal field in RF cavities requires transverse components from Maxwell's equations → cavity can impart transverse momentum to the beam

Chambers (1965) and Rosenzweig & Serafini (1994) provide a fairly accurate (≥ 5 MeV) matrix for RF cavities (Phys. Rev. E **49** (1994) 1599 – beware, formula (13) has a mistypo)

Edges of the cavities do most of the focusing. For $\gamma >> 1$

$$\frac{1}{f} = -\frac{\gamma'}{\gamma_2}\left[\frac{\cos^2\varphi}{\sqrt{2}} + \frac{1}{\sqrt{8}}\right]\sin\alpha$$

with $\alpha = \dfrac{\ln(\gamma_2/\gamma_1)}{\sqrt{8}\cos\varphi}$

γ_1, γ_2, γ', φ Lorentz factor before, after the cavity, cavity gradient and off-crest phase

On crest, and when $\Delta\gamma = \gamma' L << \gamma$:

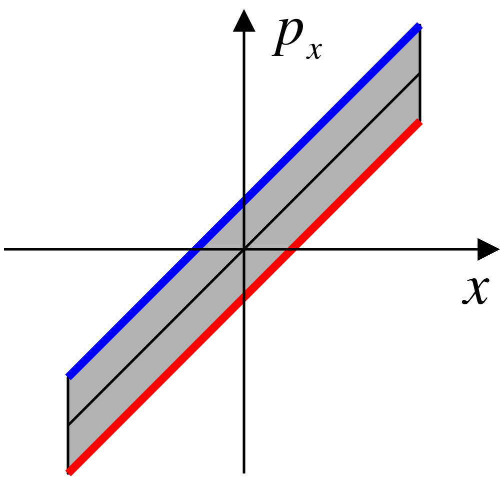
$$\frac{1}{f} \approx -\frac{3}{8}\frac{\gamma'^2 L}{\gamma^2}$$

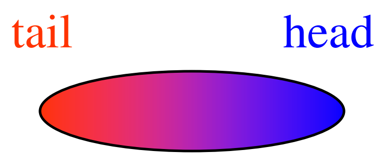
Emittance growth from RF focusing and kick

$$\varepsilon_n = \frac{1}{mc}\sqrt{\langle x^2\rangle\langle p_x^2\rangle - \langle x p_x\rangle^2}$$

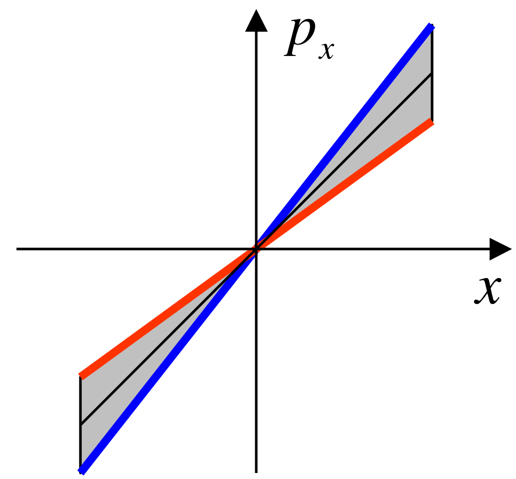
$$p_x(x,z) = p_x(0,0) + \frac{\partial p_x}{\partial x}x + \underbrace{\frac{\partial p_x}{\partial z}z}_{kick} + \underbrace{\frac{\partial^2 p_x}{\partial x \partial z}xz}_{focusing} + \ldots$$

kick





focusing



RF focusing and kick

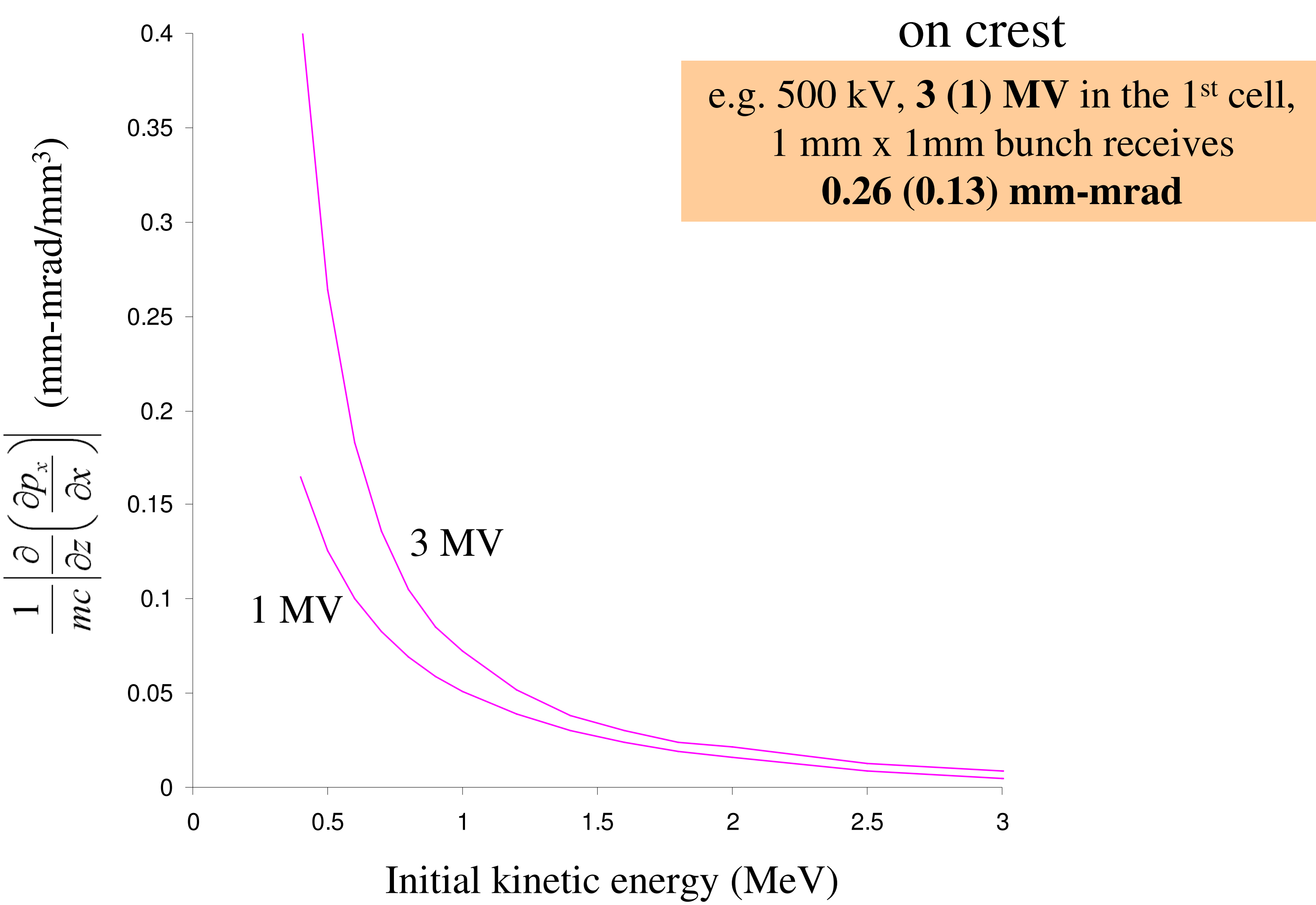
$$\varepsilon_n^2 = \varepsilon_0^2 + \varepsilon_{kick}^2 + \varepsilon_{focus}^2$$

- Kick effect on emittance is energy independent (modulo beam size) and can be cancelled downstream
- RF focusing effect scales $\propto \frac{1}{\gamma}$ (in terms of p_x) and generally is not cancelled

$$\varepsilon_{kick} = \frac{1}{mc}\left|\frac{\partial p_x}{\partial z}\right|\sigma_x\sigma_z$$

$$\varepsilon_{focus} = \frac{1}{mc}\left|\frac{\partial^2 p_x}{\partial z \partial x}\right|\sigma_x{}^2\sigma_z$$

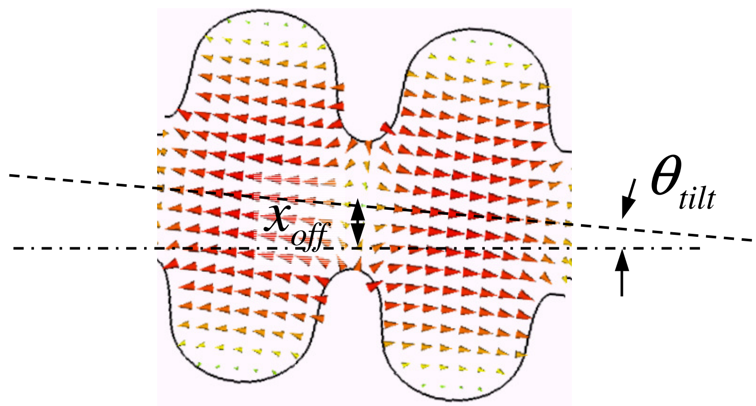
Example: RF focusing in 2-cell SRF injector cavity



RF tilt and offset

$$\varepsilon_{kick} \approx \sigma_x \sigma_z \left[\underbrace{\theta_{tilt} \frac{\Delta E}{mc^2} k_{RF} \sin\varphi}_{\text{tilt}} + \underbrace{x_{off} \frac{1}{mc} \frac{\partial}{\partial z}\left(\frac{\partial p_x}{\partial x}\right)}_{\text{offset}} \right]$$

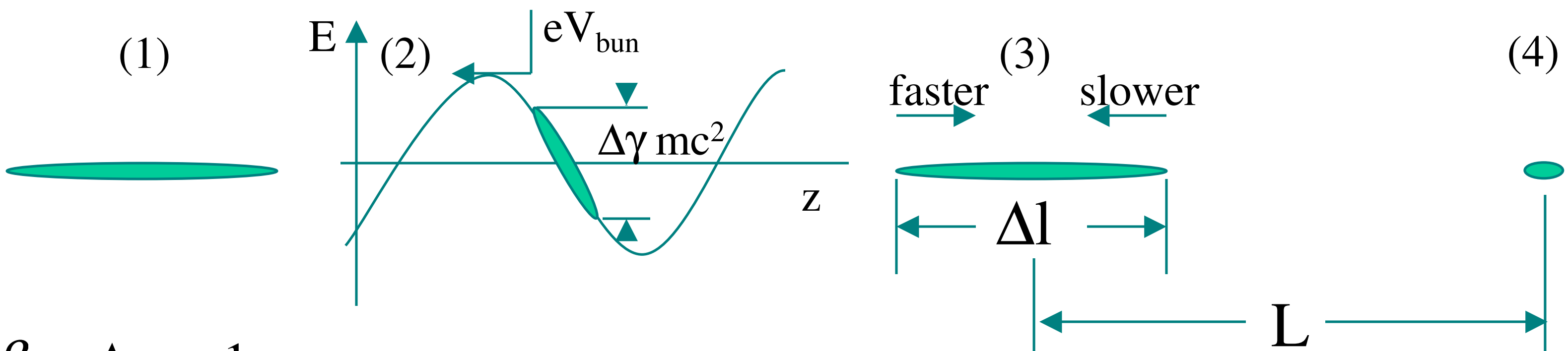
e.g. **3 MeV** energy gain
for 1 mm x 1mm yields
0.16 sin φ mm-mrad
per mrad of **tilt**



- One would prefer on-crest running in the injector (and elsewhere!) from tolerances' point of view

Drift Bunching: Simple Picture

For bunch compression, two approaches are used: magnetic compression (with lattice) and drift bunching. Magnetic compression relies on path vs. beam energy dependence, while drift bunching relies on velocity vs. energy dependence (i.e. it works only near the gun when $\gamma \geq 1$).



$$\frac{\Delta\beta}{\beta} \approx \frac{\Delta\gamma}{\gamma}\frac{1}{\gamma^2 - 1}$$

$$L = c\beta\frac{\Delta l}{c\Delta\beta} = \frac{\Delta l}{(\Delta\gamma/\gamma)}(\gamma^2 - 1) = \frac{\lambda_{RF}}{2\pi}\frac{E}{eV_{bun}}\left(\frac{E^2}{(mc^2)^2} - 1\right)$$

Next lecture's preview

- Space charge treatment
  - Debye length
  - Plasma frequency
  - Beam temperature
- Stationary distributions
- Emittance growth due to excess free energy
- Beam envelope equation
- Concept of equivalent beams
- Emittance compensation
- Computational aspects