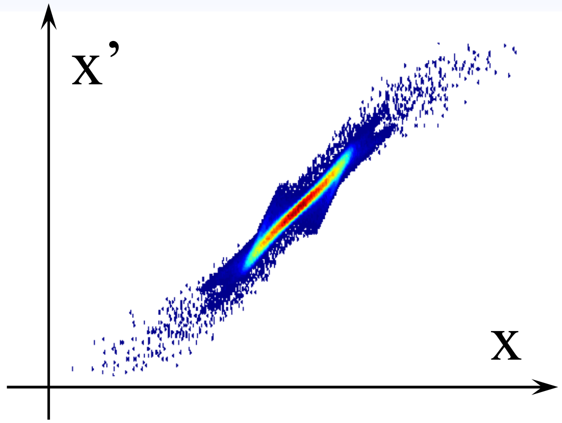
High Brightness Electron Beams

Introduction to the physics of high-quality electron beams

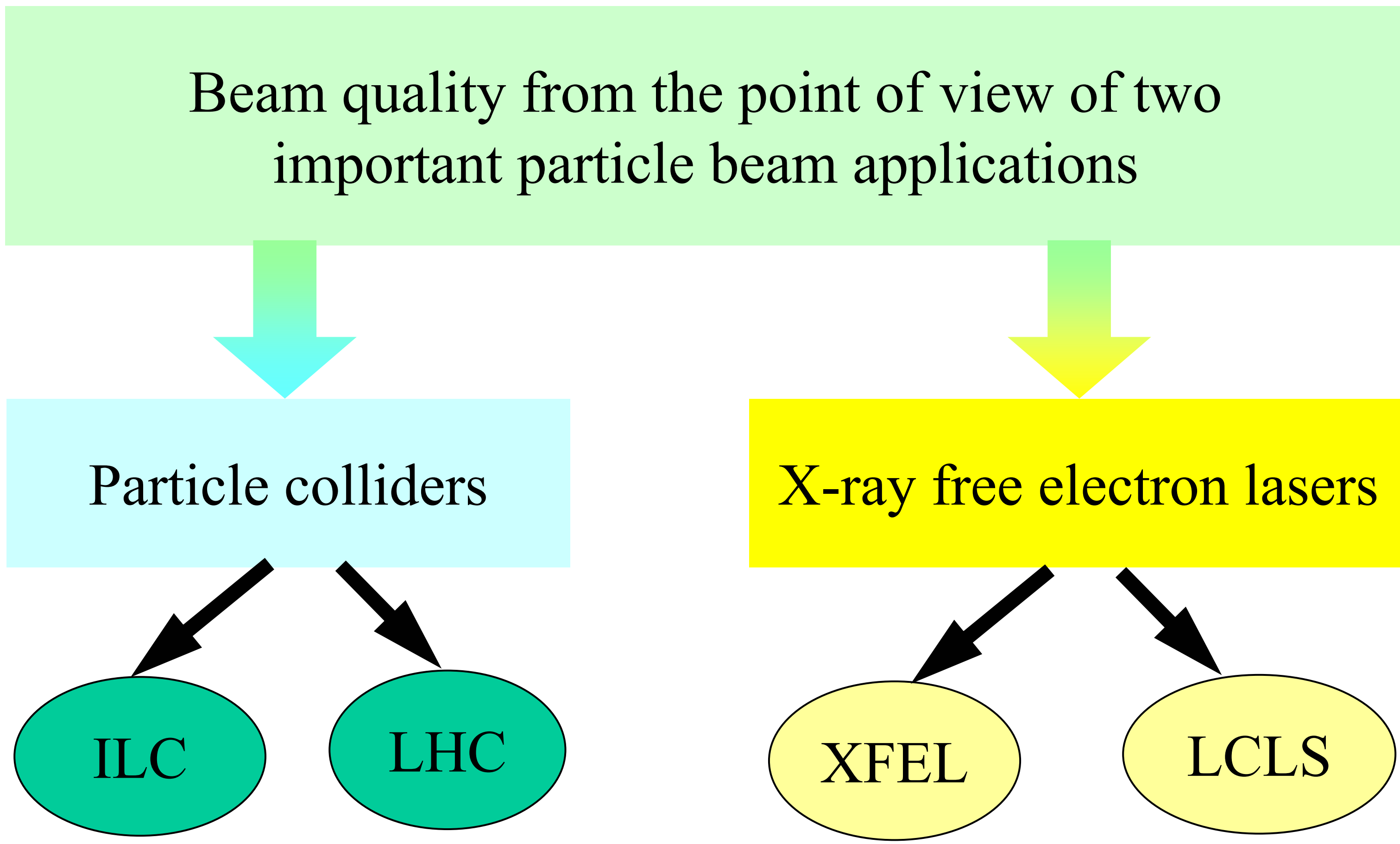


Mikhail Krasilnikov
Photo Injector Test facility, Zeuthen (PITZ)

The plan for this morning

- Motivation for high-quality electron beams
- Description of beam quality
  - Beam brightness, peak current and emittance
- Evolution of beam quality in a linear accelerator
  - Emittance growth and compensation
  - Emittance conservation
  - Bunch compression

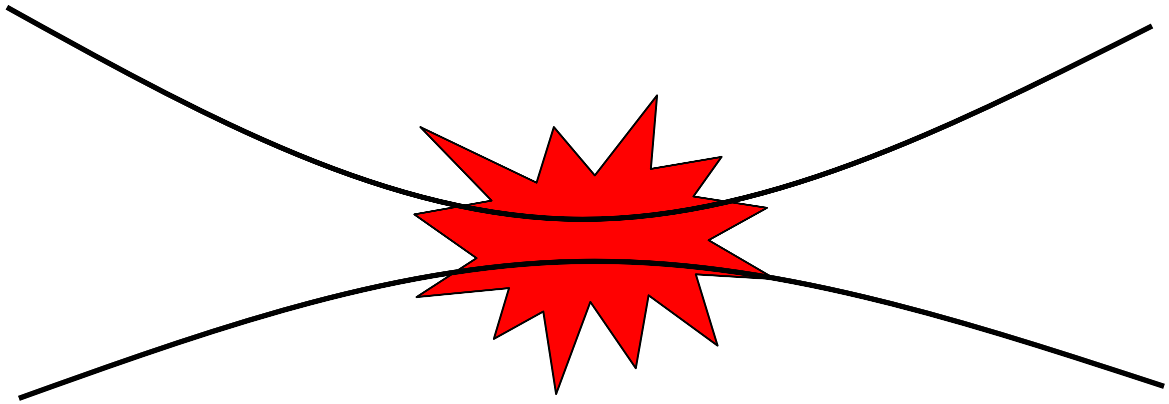
Motivation for high-quality electron beams



Particle colliders → high luminosity

The number of collisions at the interaction point depends on the density of particles there:

- beam current (number of particles)
- beam focal spot size



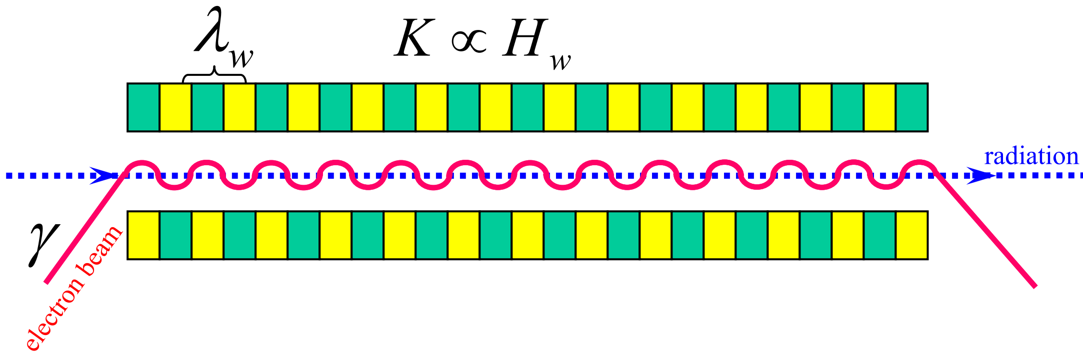
$$L \propto \frac{N_1 N_2}{\sigma_x \sigma_y}$$

Linear collider → one shot at the interaction point (before the beam dumped)

Circular machine → considerations can be a little different

Free Electron Lasers

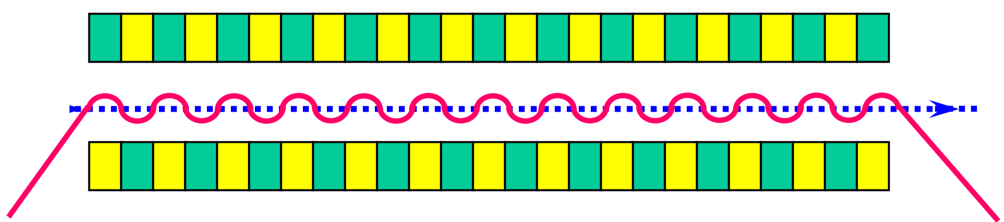
In a free-electron laser (FEL), the magnetic field of the undulator magnet causes the electrons to oscillate transversely and at resonant wavelength λ_{ph}



$$\lambda_{ph} = \lambda_w \frac{1 + K^2}{2\gamma^2}$$

These oscillations induce micro-bunching on a scale of λ_{ph}, which causes electrons within the micro-bunch to radiate coherently at the resonant wavelength.

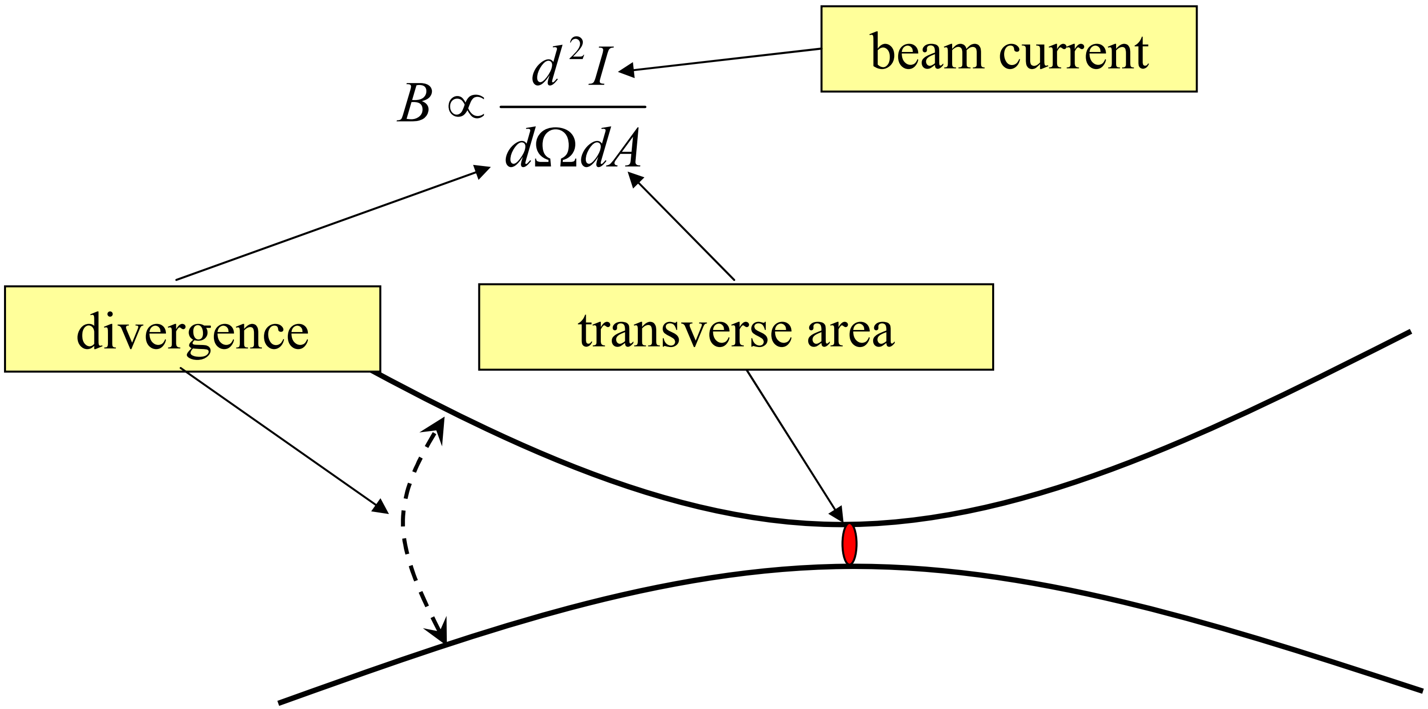
In the **oscillator** configuration, the laser light reflects back and forth between mirrors, gaining strength on each pass.



At ultra-short wavelength, less than 100 nm, mirrors are not available. In such a case, at high phase space density of an electron bunch the FEL instability develops in a single pass through the undulator, the process is referred to as **s**elf-**a**mplified **s**pontaneous **e**mission (**SASE**).

Free Electron Lasers: beam brightness

High phase space density of an electron bunch → high beam brightness



$$B \propto \frac{d^2 I}{d\Omega dA}$$

Beam brightness is a local property that measures the achievable current density for a given angular acceptance

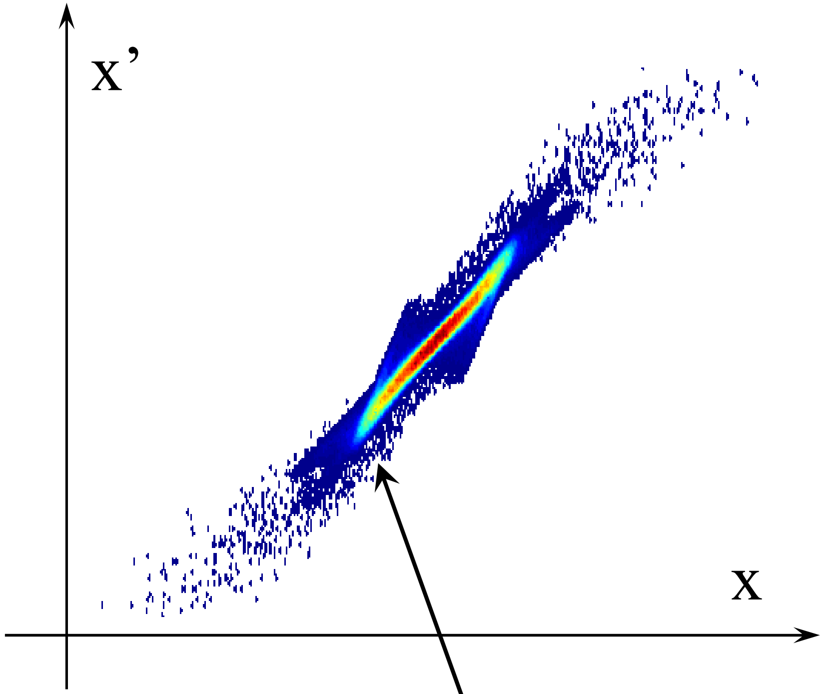
Beam brightness

The natural coordinates for looking at the beam brightness distribution are called the "trace space" → e.g. (X, X')

$$B \propto \frac{d^2 I}{dA\, d\Omega} = \frac{d^4 I}{dx\, dy\, dx'\, dy'}$$

x and *y* are the coordinates transverse to the beam motion (along *z*) and the primes indicate derivatives with respect to *z*

$$x' = \frac{dx}{dz} = \frac{p_x}{p_z}$$

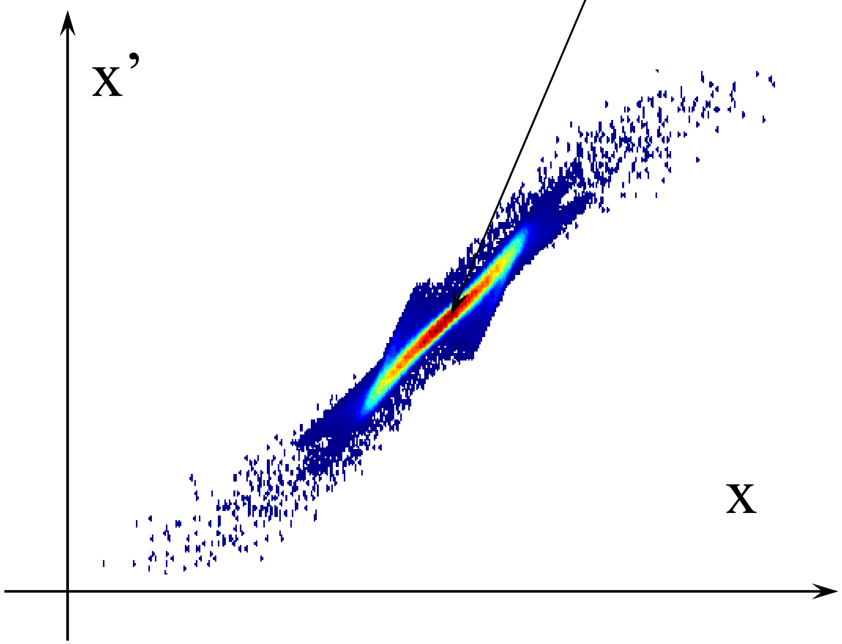


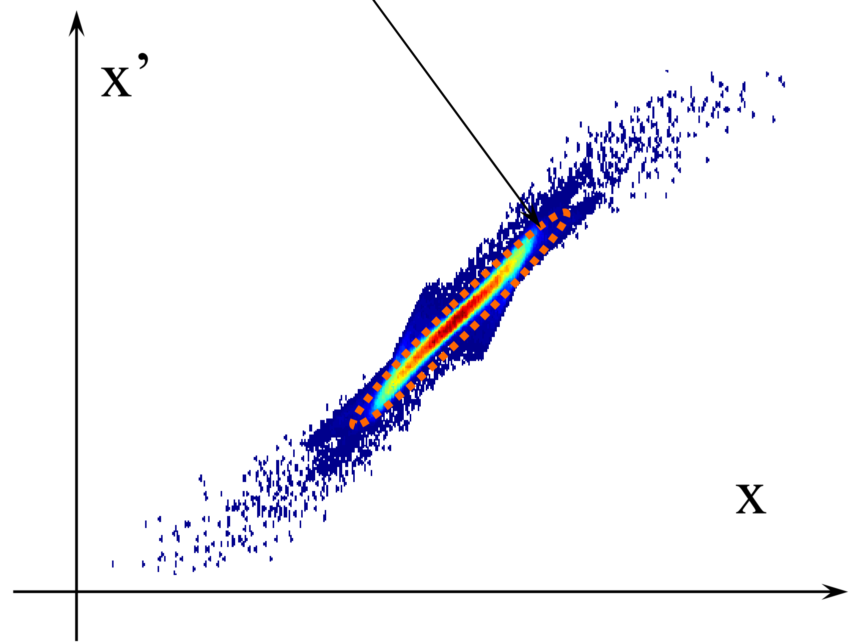
differential intensity at a given point on this picture gives

$$\frac{d^2 I}{dx\, dx'}$$

Peak and average brightness

For a given beam, we can define
the peak brightness and the average brightness

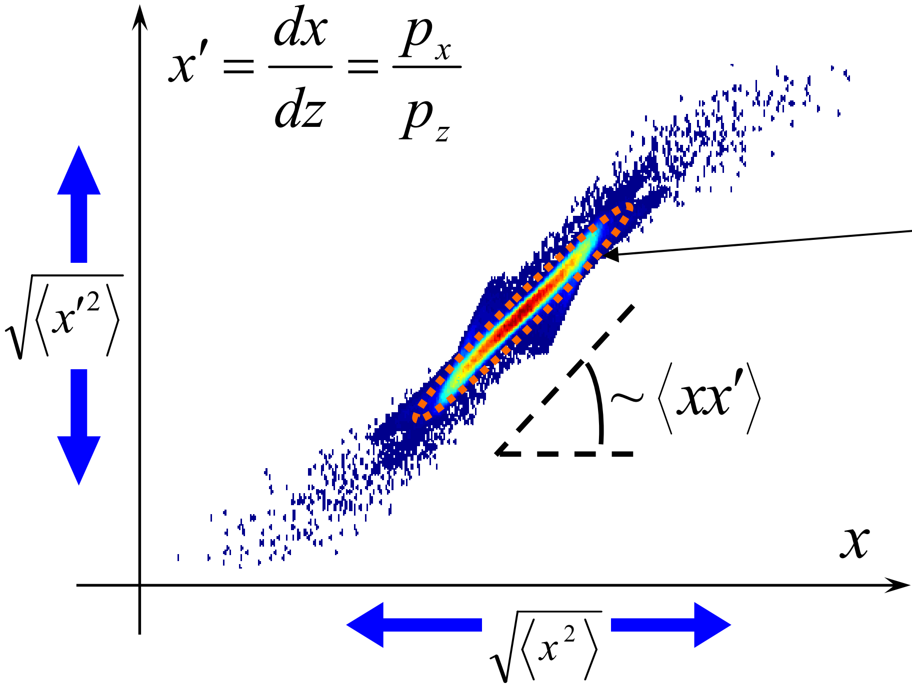




to calculate it, we have to define
the area in trace space

Beam emittance

The area in trace space is called the **emittance** of the beam.



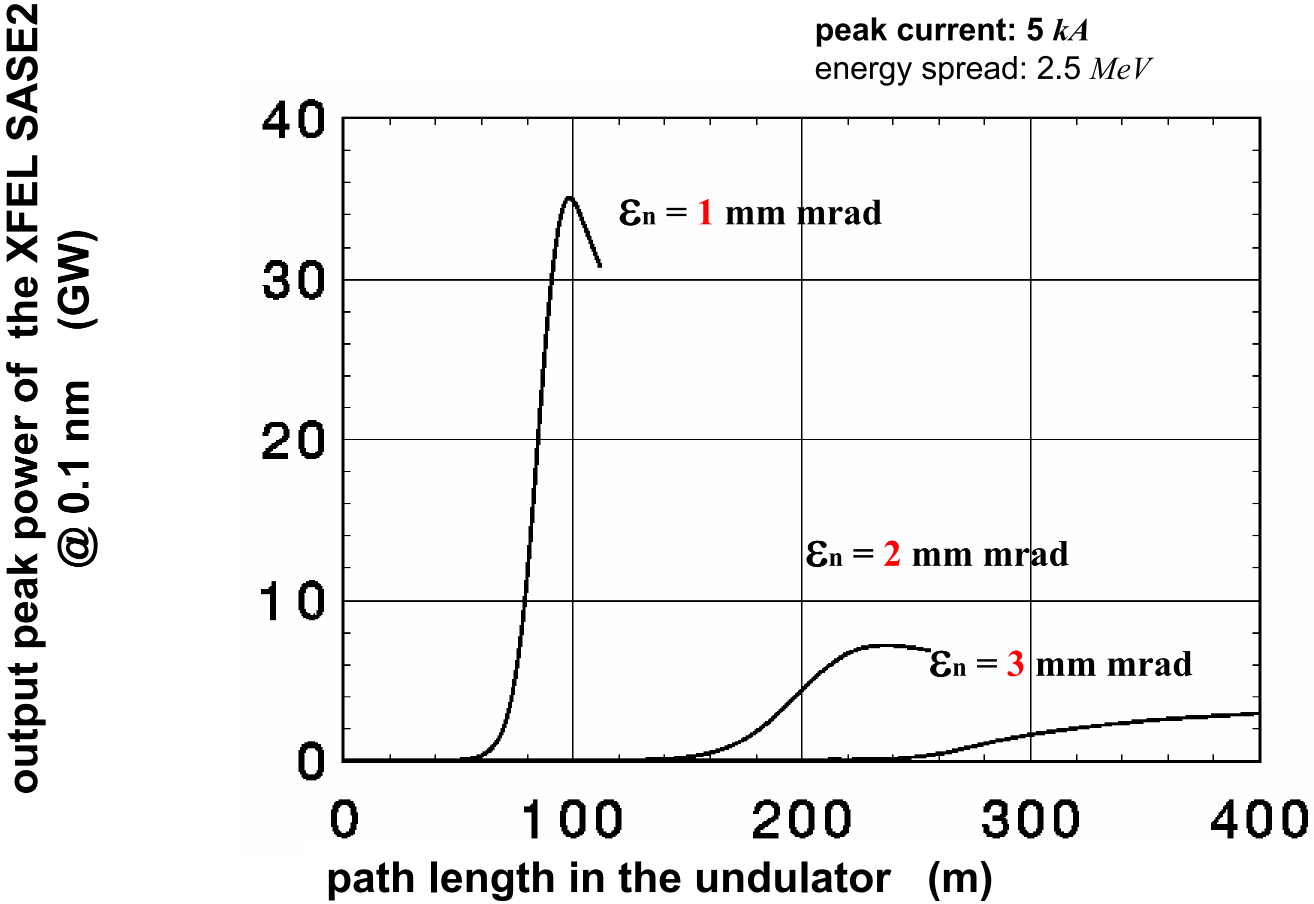
The area bounded by this dotted line is equivalent to the **rms transverse emittance** in x – it has units of length times angle → mm mrad

$$\varepsilon_x = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$$

But acceleration! → normalized phase space $(x, p_x = \beta\gamma x')$

Normalized beam emittance : $\varepsilon_{nx} = \beta\gamma\sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$

Why low emittance is so important for FEL



FEL requirements on electron beam parameters

- Energy→ $\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right),$
- Transverse emittance
- Peak current →
- Energy spread→
- Stability
  (charge, energy, timing jitter, …)

➢high energy

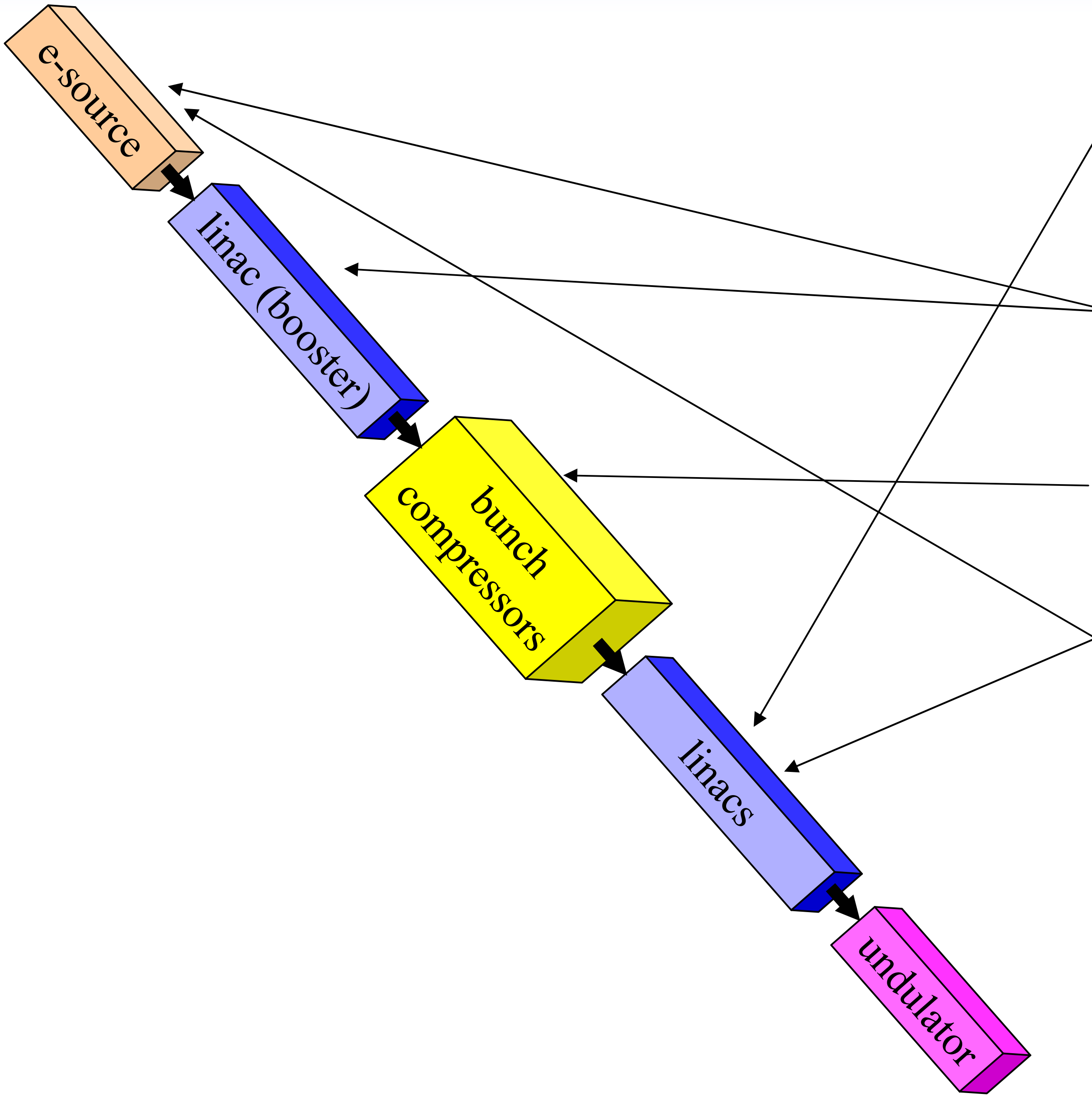
➢low emittance

➢high current
➢short

➢small energy spread

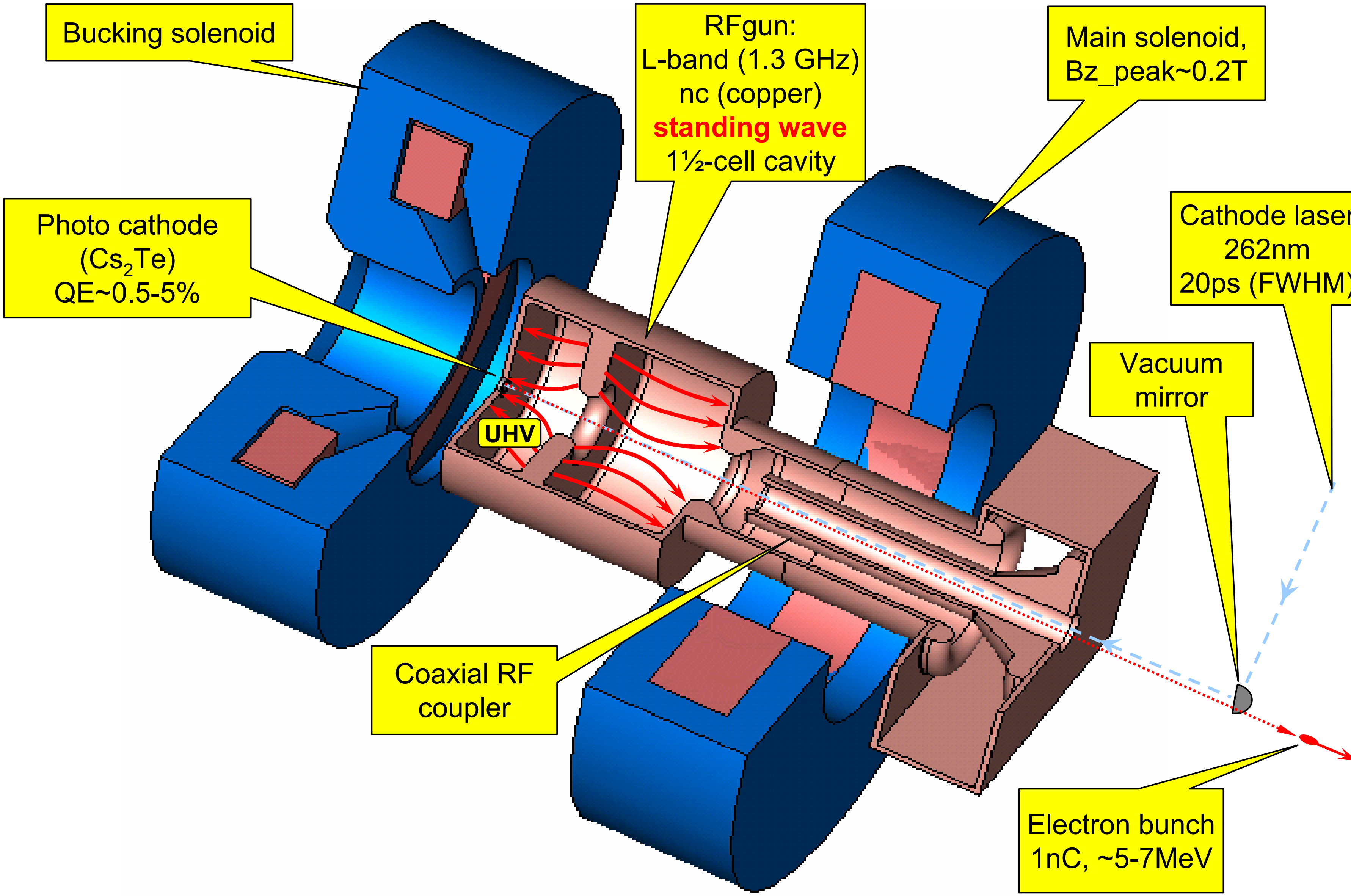
➢stable

LINAC based FELs: generic layout



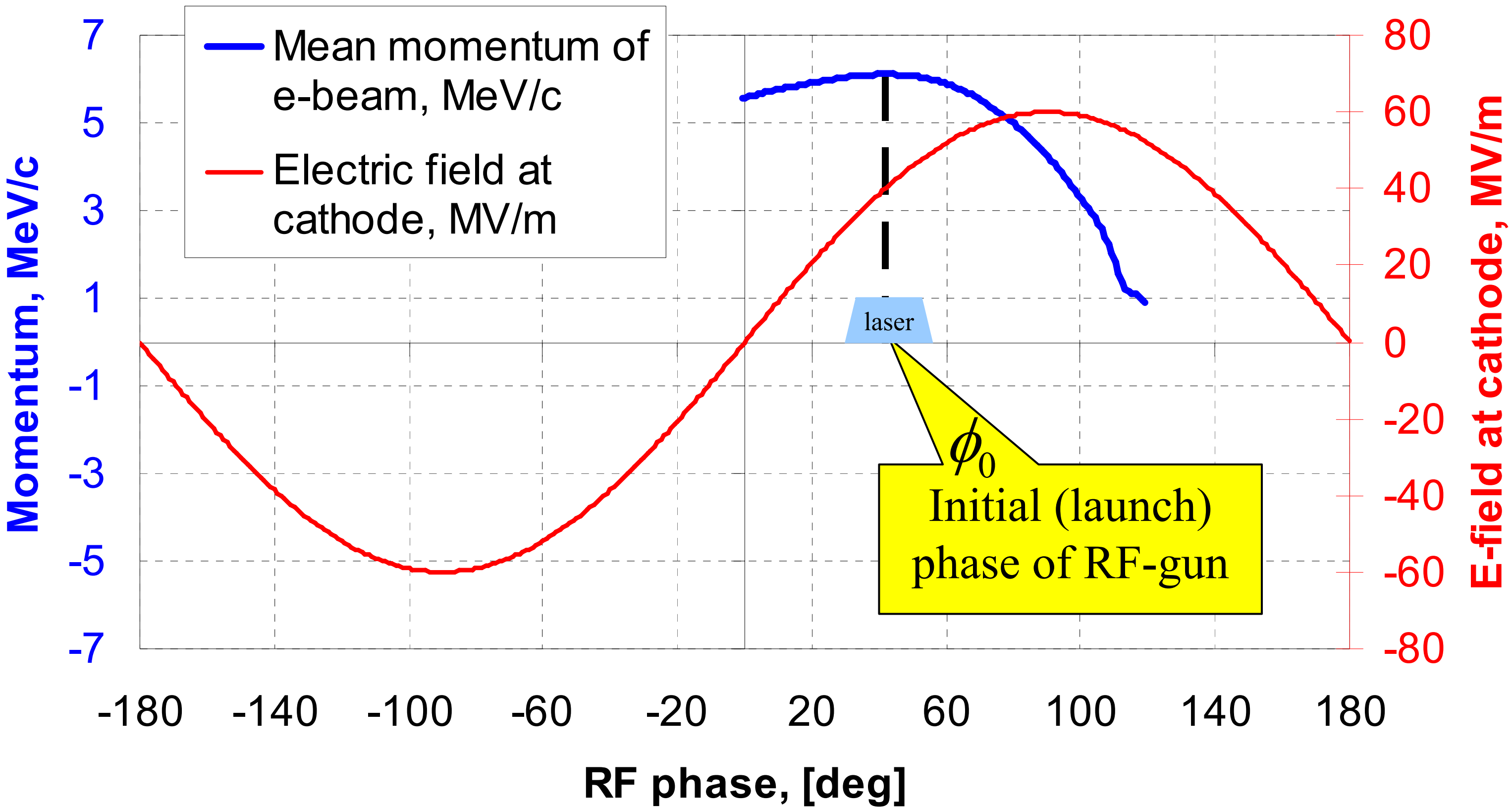
- high energy
- low emittance
- high current
- short
- small energy spread
- stable

Electron source: RF-Gun



RF phase of the gun

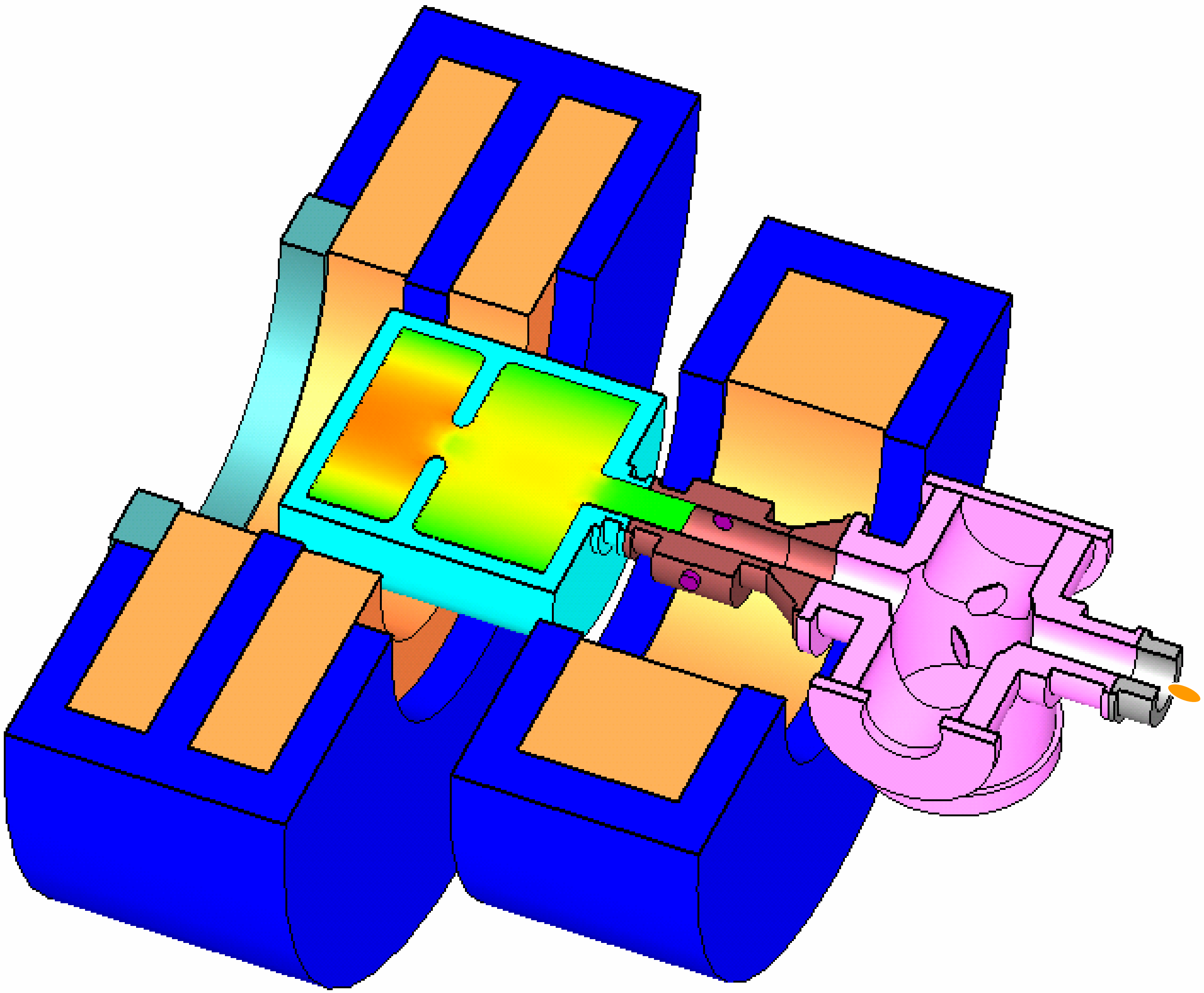
$E_z = E_0 \cdot \sin(\omega t + \phi_0)$ - electric field at the cathode



• The electrons are emitted when the radio-frequency (RF) field is accelerating, and arrive at the next crest in time to get another push

• Finite cathode laser pulse duration (~20ps FWHM) results in the energy spread within the electron bunch

Photo Injector: RF Gun



Forces acting on electron bunch

Lorenz force $\vec{F} = q \cdot \left(\vec{E} + \vec{v} \times \vec{B} \right)$

External forces:

- RF cavity (e.g. RF-gun)

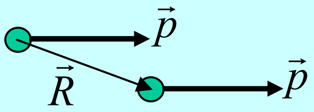
$$\vec{E}(r,z,t) = \{E_r, 0, E_z\}$$

$$\vec{B}(r,z,t) = \{0, B_\varphi, 0\}$$

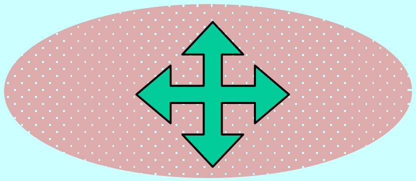
- Gun solenoids

$$\vec{B}(r,z) = \{B_r, 0, B_z\}$$

Space charge force



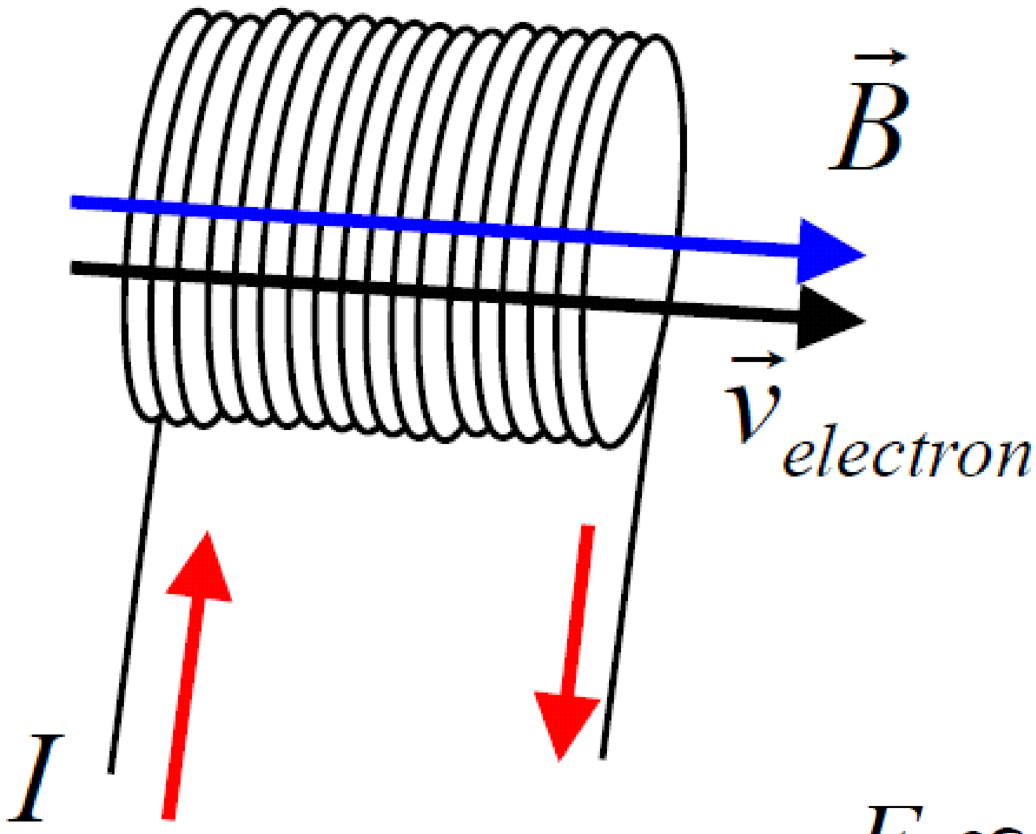
$$\vec{F} = \frac{q}{\gamma} \cdot \frac{\vec{p} \cdot (\vec{p} \cdot \vec{R}) + \vec{R}}{(\vec{p} \cdot \vec{R})^2 + R^2}$$



$$\vec{F} = \frac{eQ}{\gamma^2} \cdot G\left(\gamma \frac{2\sigma_z}{\sigma_x + \sigma_y} \right) \cdot \frac{\vec{r} - \langle \vec{r} \rangle}{V_G}$$

Focusing an electron beam with a solenoid

How does that work?

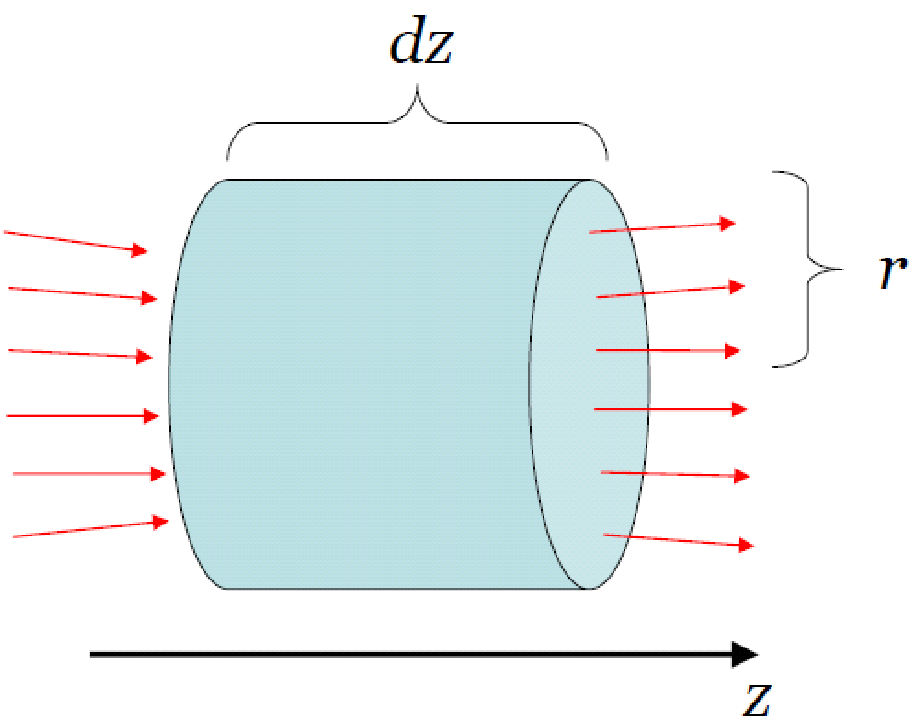


Electrons moving down the axis of an **ideal solenoid** have their velocity parallel to the field, so no force!

$$F \propto \vec{v}_{electron} \times \vec{B} = 0$$

Focusing an electron beam with a solenoid

In a **real solenoid**, Maxwell doesn't allow just this field along the axis

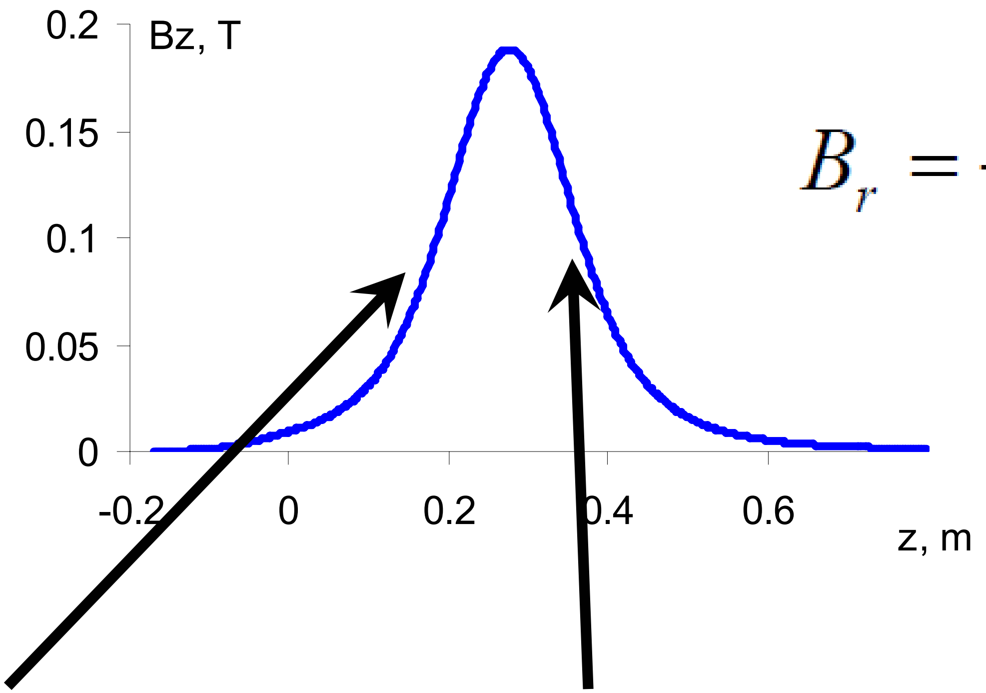


Gauss' Law tells us that when the magnetic field changes along *z*, it must have a **radial** component also.

$$2\pi r B_r = \pi r^2 \frac{dB_z}{dz}$$

$$B_r = -\frac{r}{2}\frac{dB_z}{dz}$$

Focusing an electron beam with a solenoid



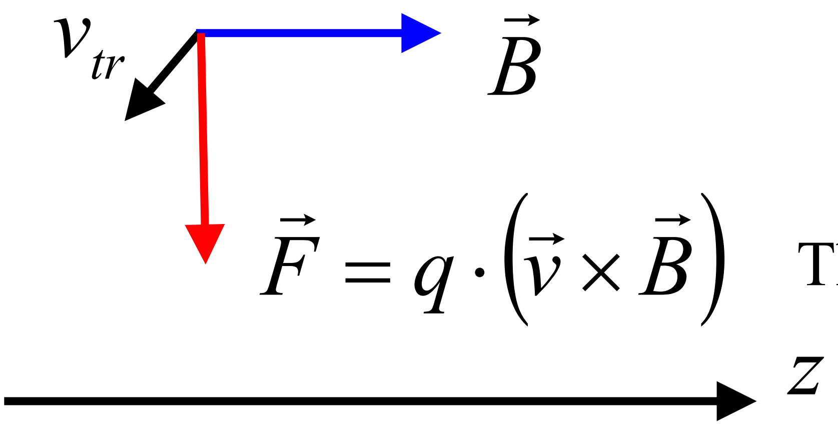
$$B_r = -\frac{r}{2}\frac{dB_z}{dz}$$

In the first half of the solenoid, the field imparts a twisting motion to the electron beam

In the second half, the force is in the opposite direction, removing the beam's **angular** momentum

Focusing an electron beam with a solenoid

Electrons with **angular** momentum then feel a force from the main solenoid field



$$\vec{F} = q \cdot \left(\vec{v} \times \vec{B} \right)$$

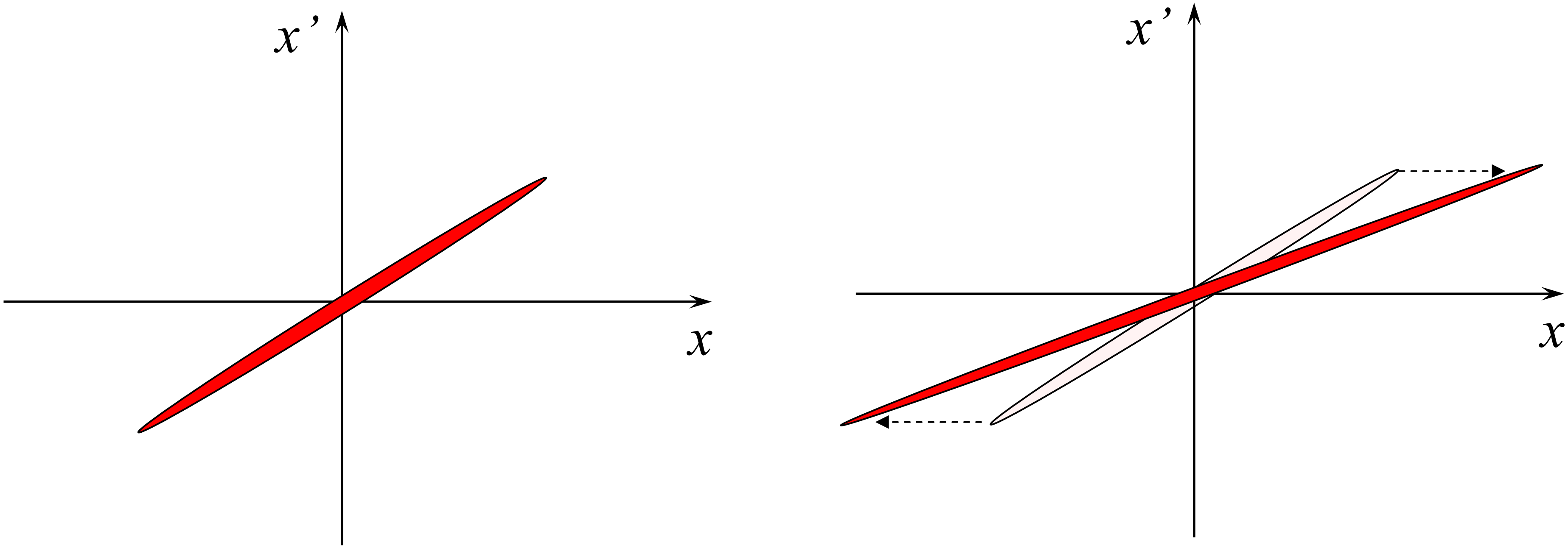
This resulting force is always focusing

The focal length of the solenoid changes with the inverse of the B-field *squared*, because the fringe fields and the main field are both involved

Emittance compensation with a solenoid

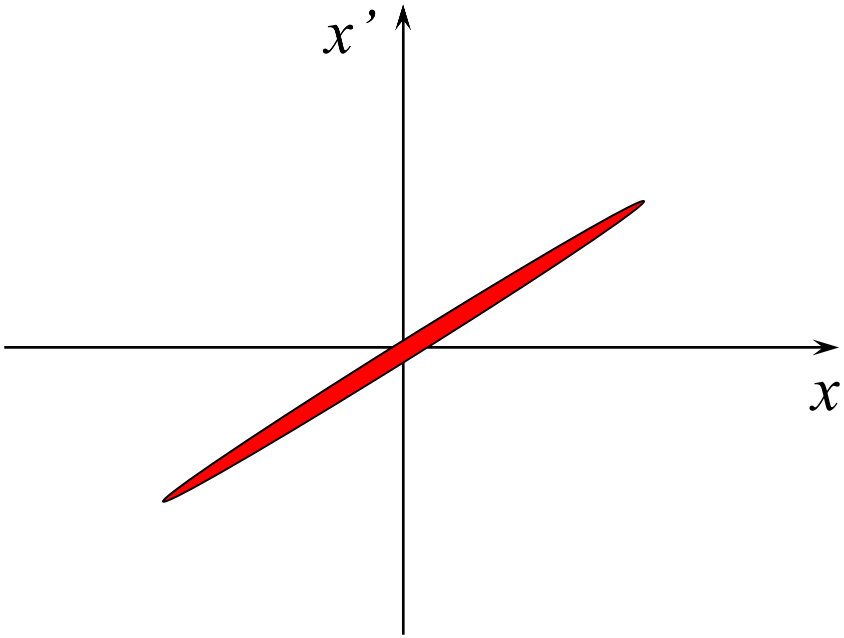
Now that we know how to focus the beam, what does the focal spot have to do with the emittance?

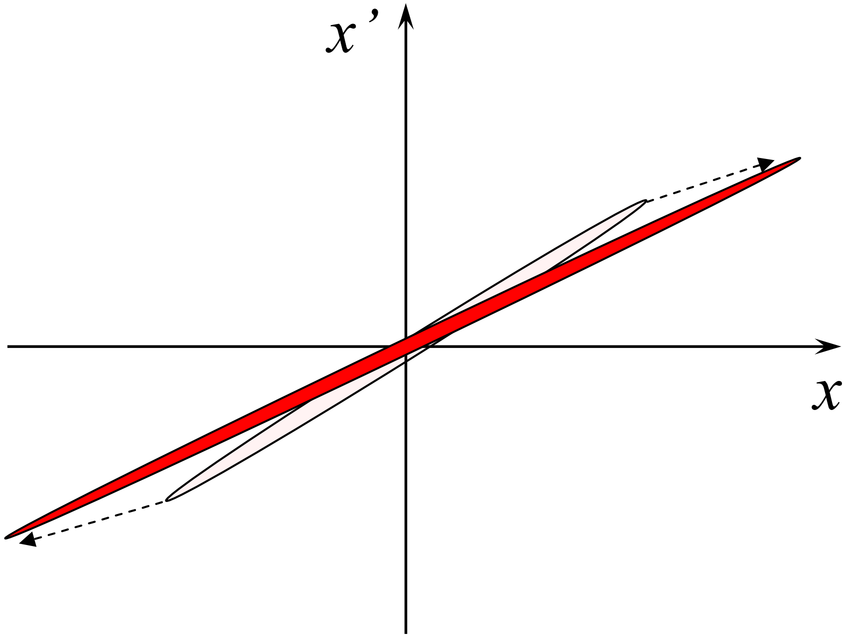
Beam phase space in a **drift** **without** space charge



Emittance compensation with a solenoid

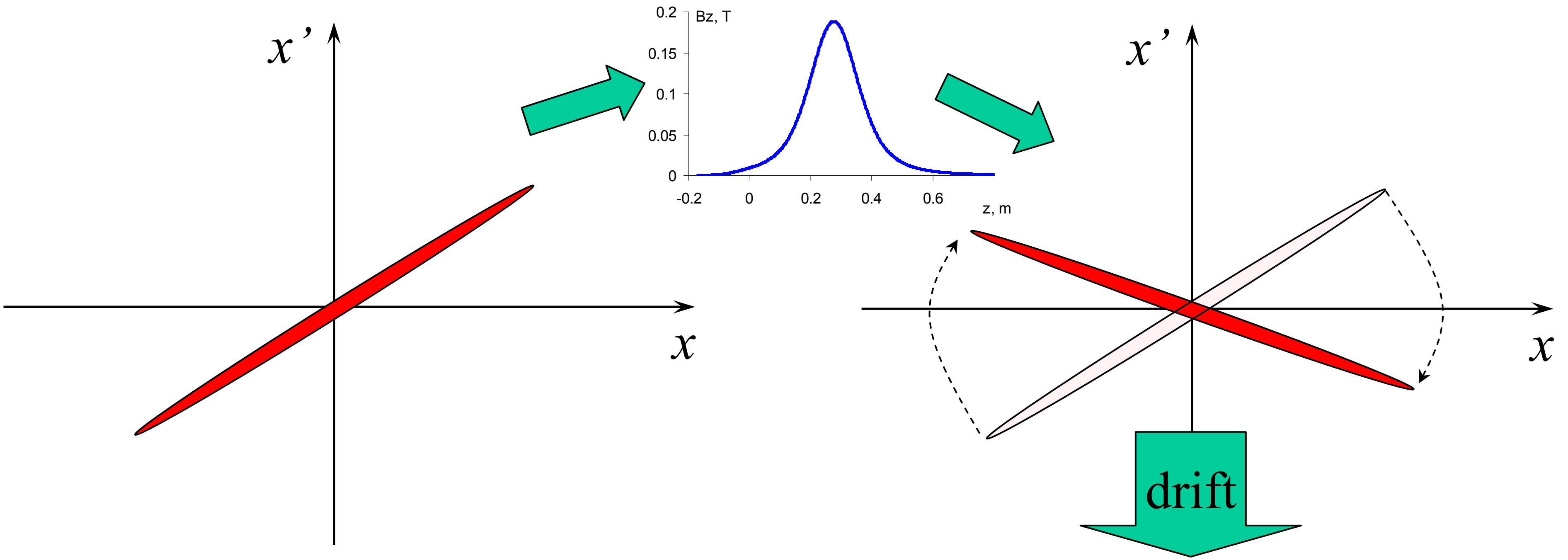
Beam phase space in a **drift** **with** space charge

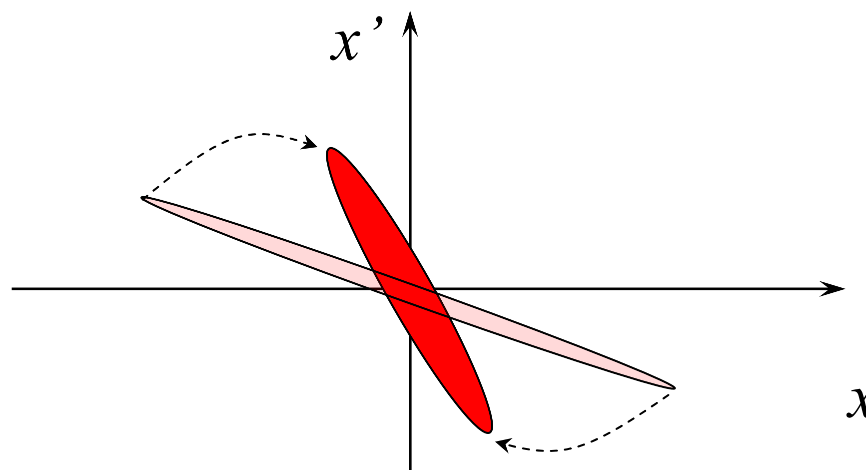




Emittance compensation with a solenoid

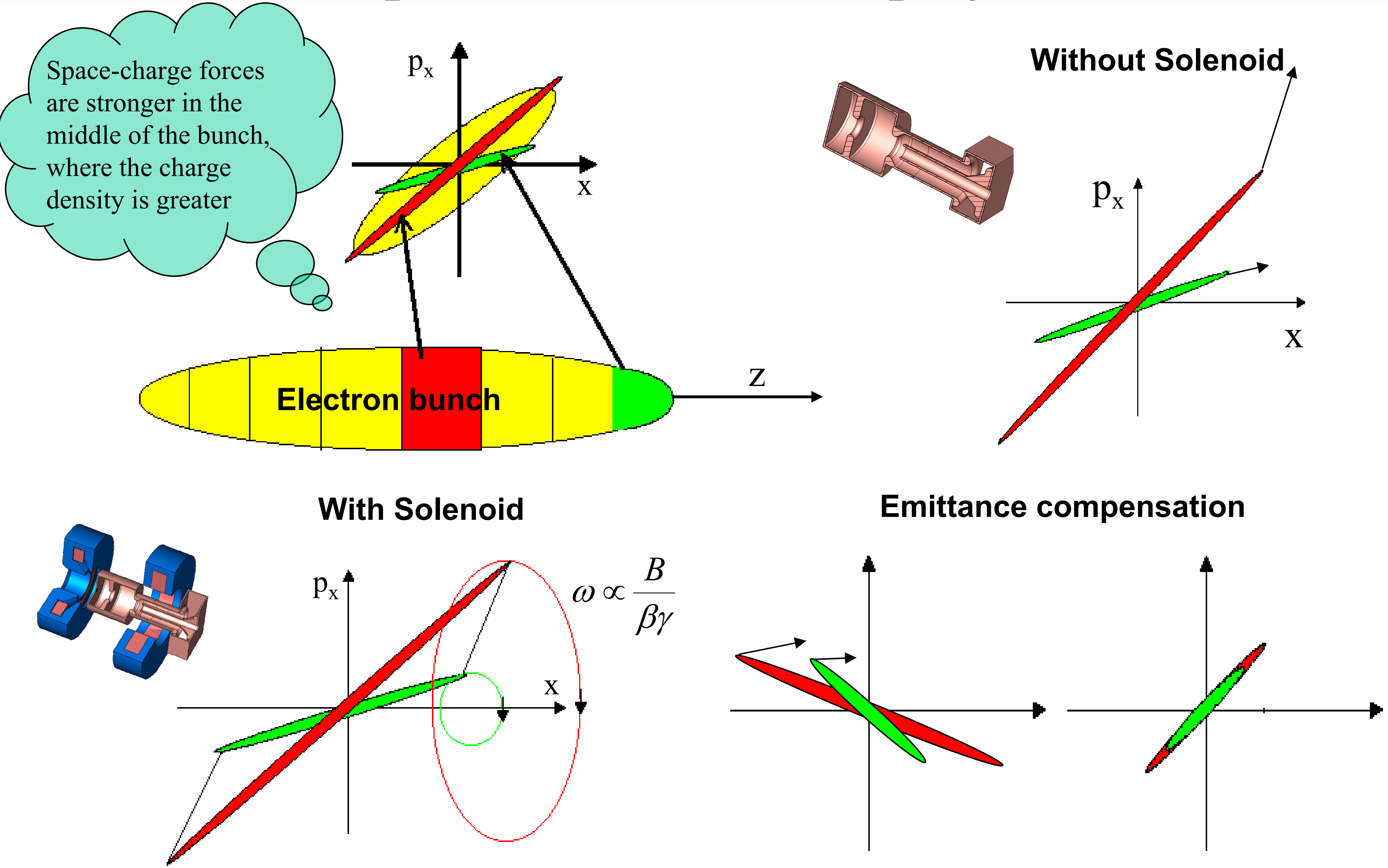
Beam phase space in a **solenoid with** space charge





In linear fields the ellipse area (beam emittance) remains constant!

Emittance compensation: slice and projected emittance



We use the solenoid focusing to compensate the space-charge emittance growth

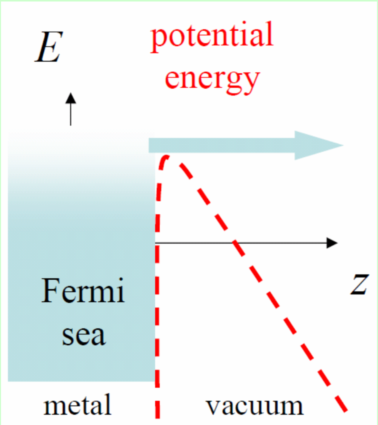
What is a lower limit for the emittance

Where does initial emittance come from?

Beam initial emittance depends on the nature of the source

Thermal emittance sets a lower bound on the beam emittance

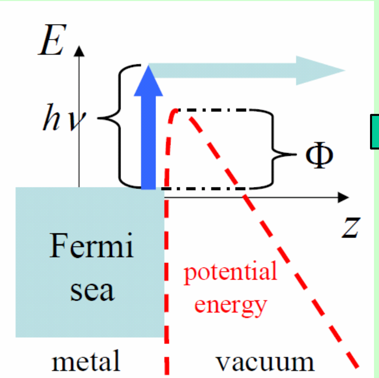
In **thermionic** emission, the temperature of a filament is raised until electrons spill over the vacuum barrier



Transverse velocity is random, with rms value depending on temperature

$$v_{rms} \propto \sqrt{k_B T}$$

In a **photocathode**, electrons are liberated by absorbing photons



Transverse velocity is also random, but the rms value depends on the energy difference between the photon and the work function

$$v_{rms} \propto \sqrt{h\nu - \Phi}$$

Space charge forces within a bunch

In statistical mechanics:

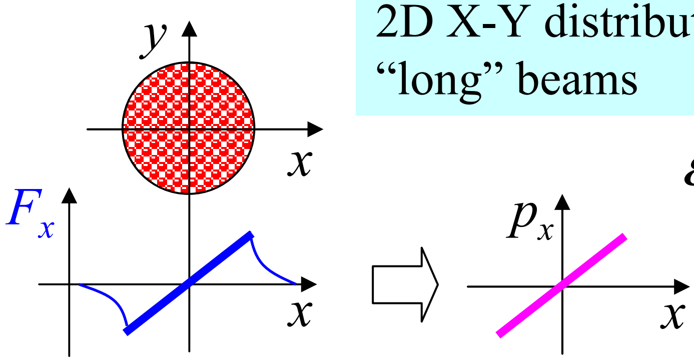
microcanonical distribution = ***linear*** forces and the **phase space** remains ***const***

1959: *I.M. Kapchinsky and V.V. Vladimirsky*

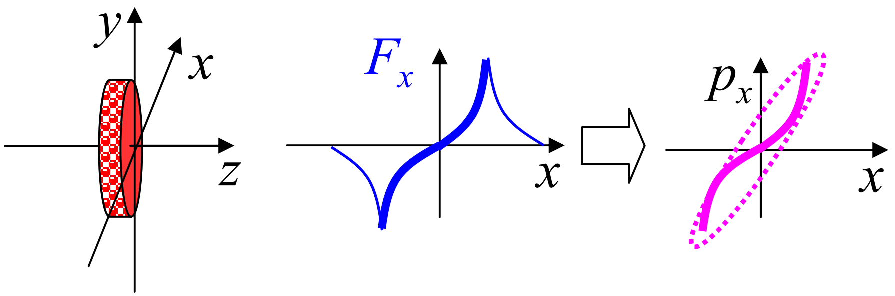
transverse beam dynamics of this distribution in linacs ➔ **K-V distribution**

2D X-Y distribution
"long" beams

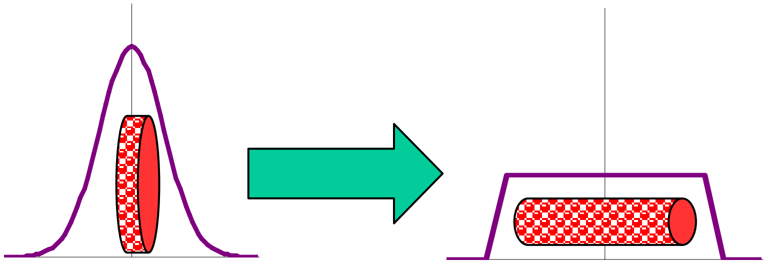
$\varepsilon = inv$



Short bunch → **nonlinear** transverse space charge force → nonlinear phase space



Space charge forces within a bunch



Flat-top temporal electron bunch

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- reduce space charge force nonlinearity→

  → reduced slice emittance
- space charge density reduced

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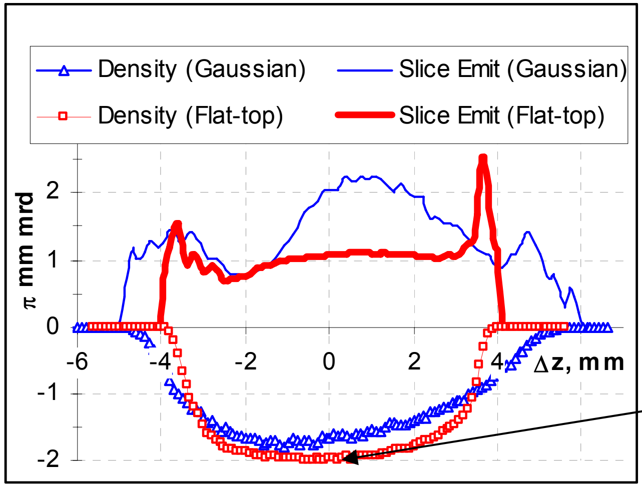
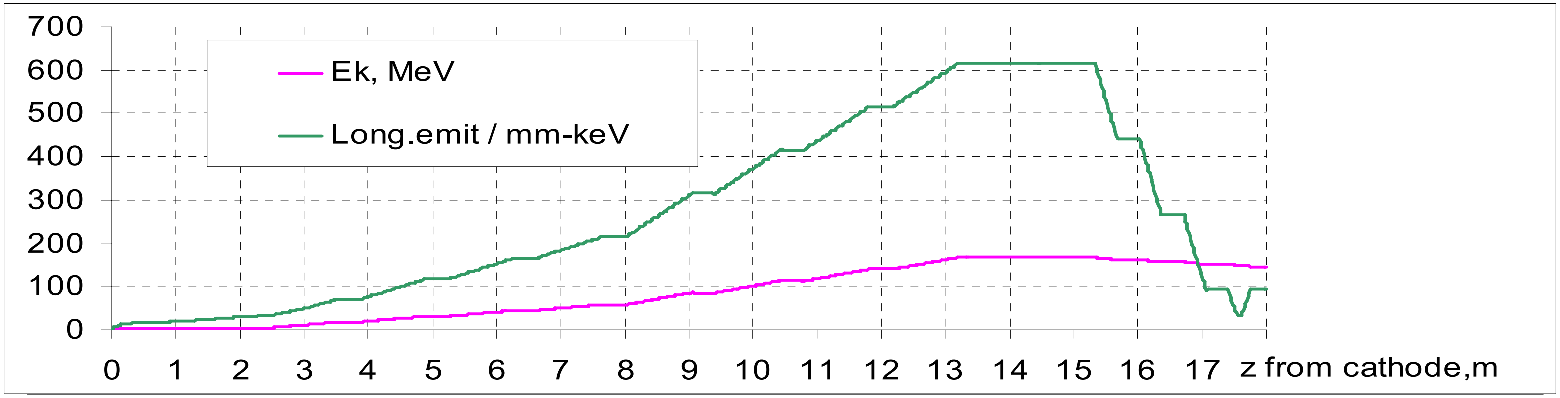
- but during emission bunch is short
- beam peak current also reduced



Peak current ~ 50A

Photo injector concept: space charge effect reduction



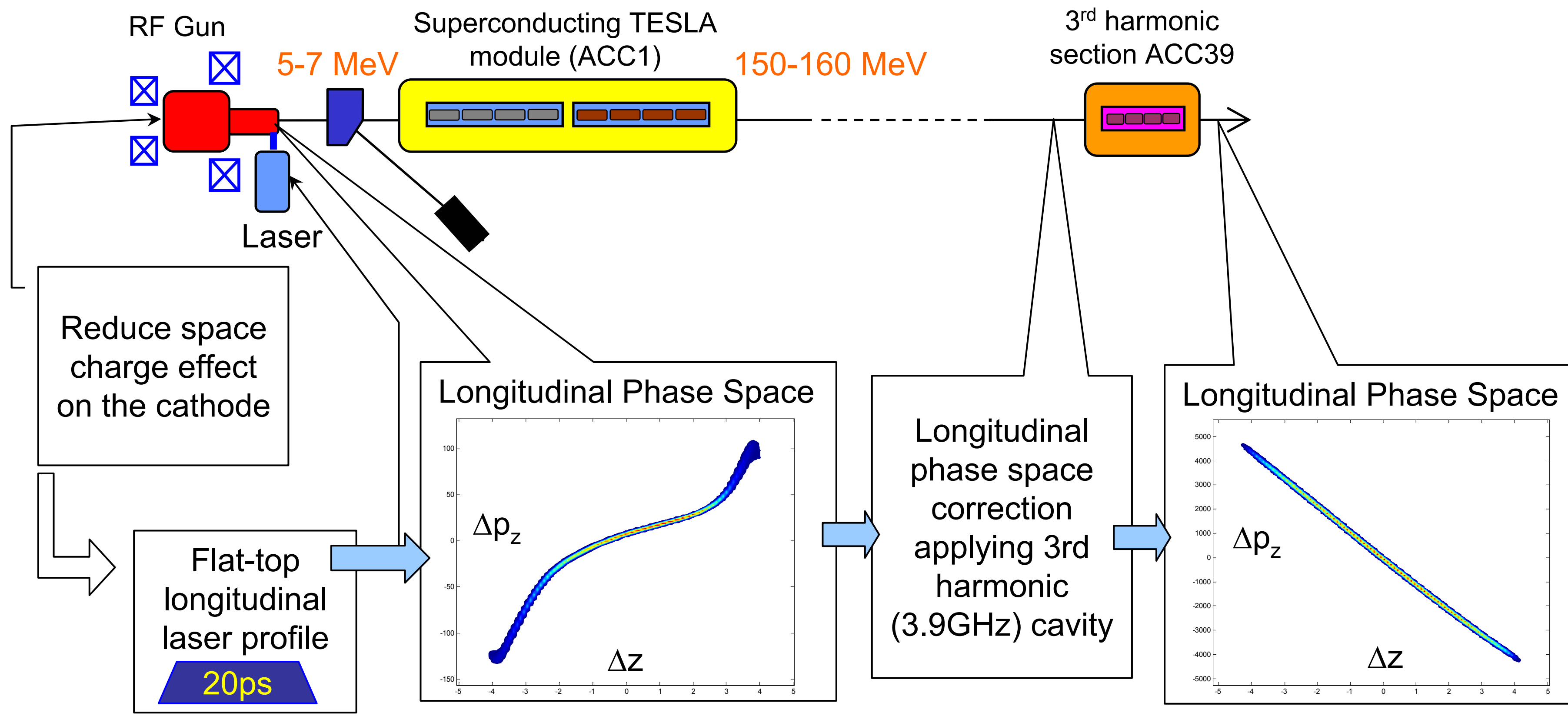
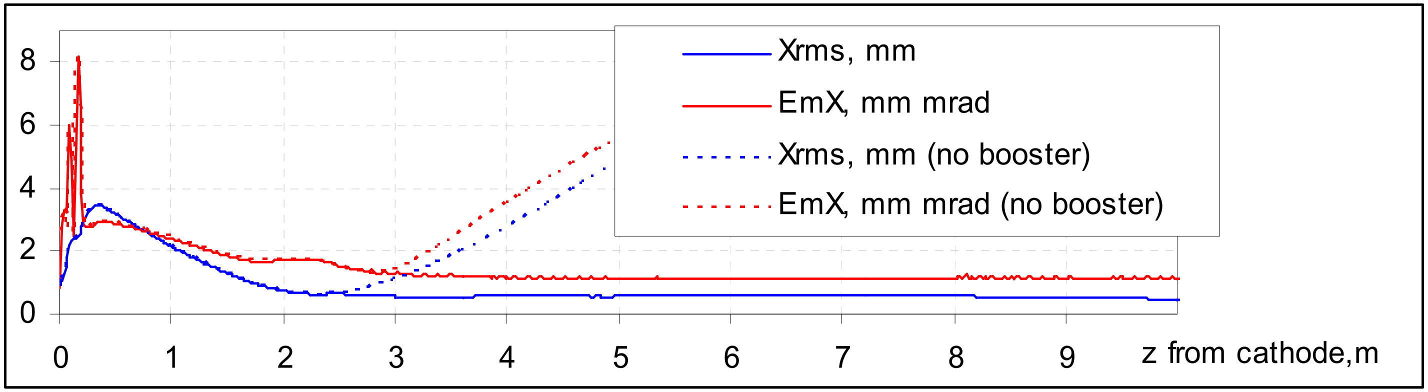
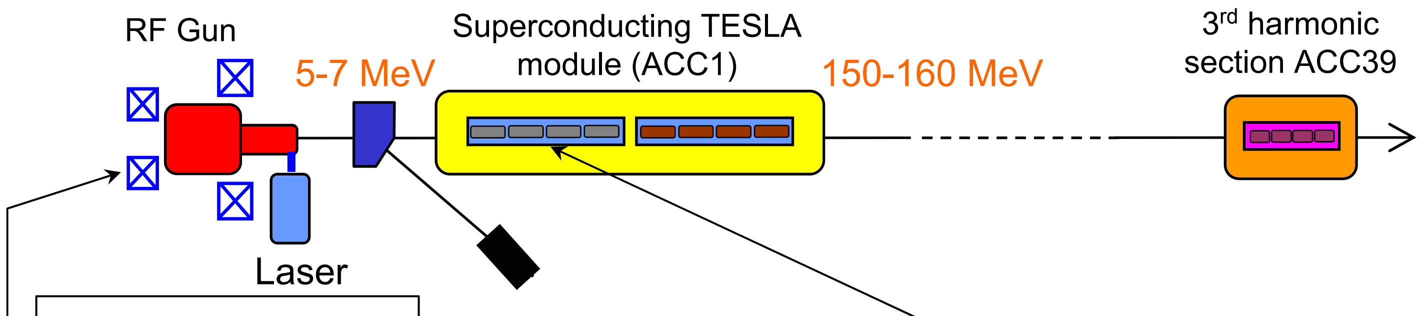


Photo injector concept: emittance conservation

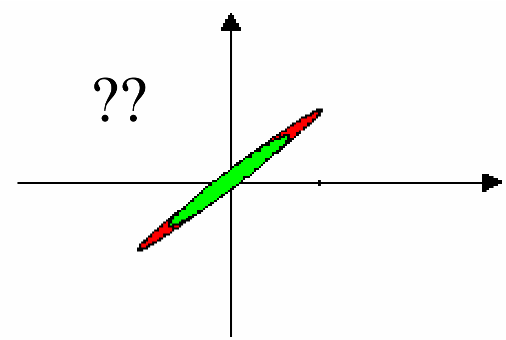




Space charge compensating scheme by applying solenoid field

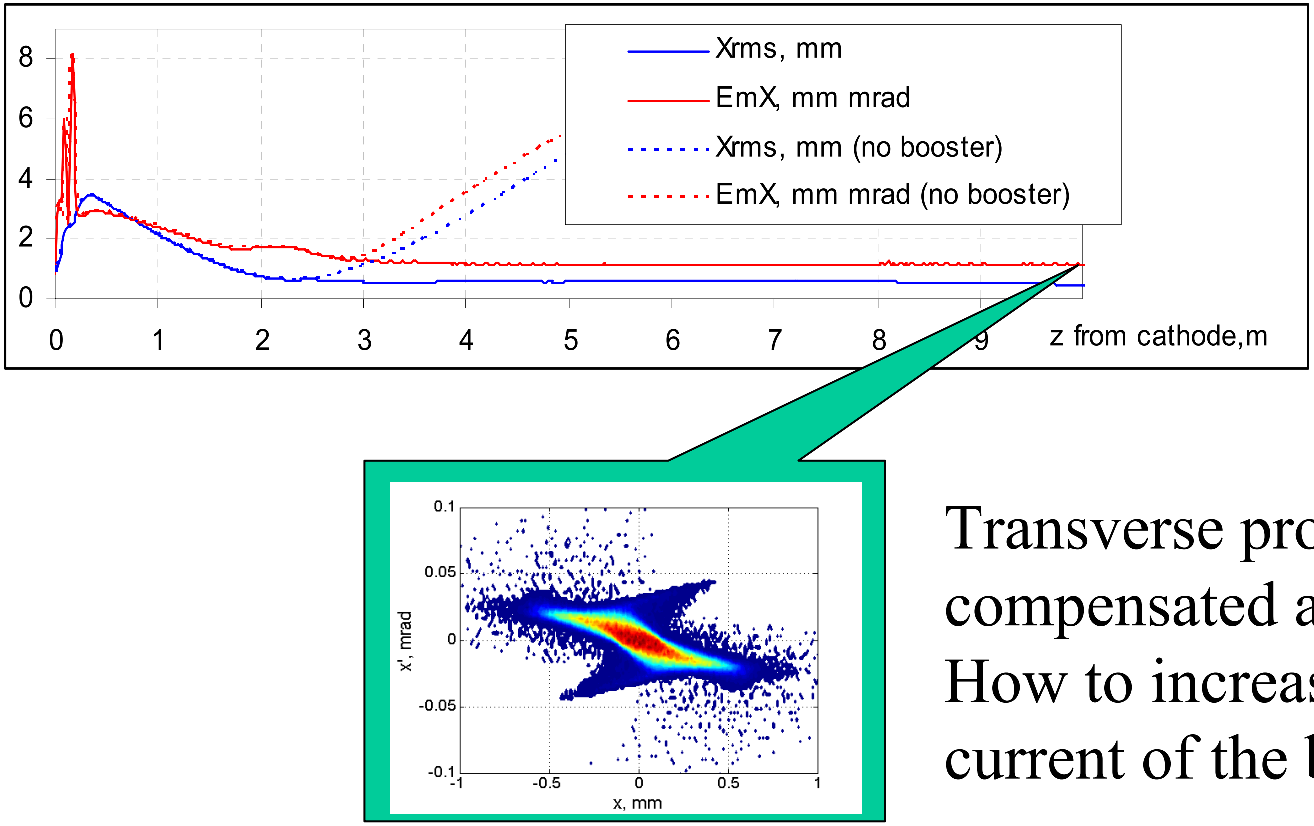
Emittance conservation using booster with proper position and gradient - matching conditions:

$$\gamma' = \frac{2}{\sigma_w}\sqrt{\frac{I}{3I_0\gamma}}$$



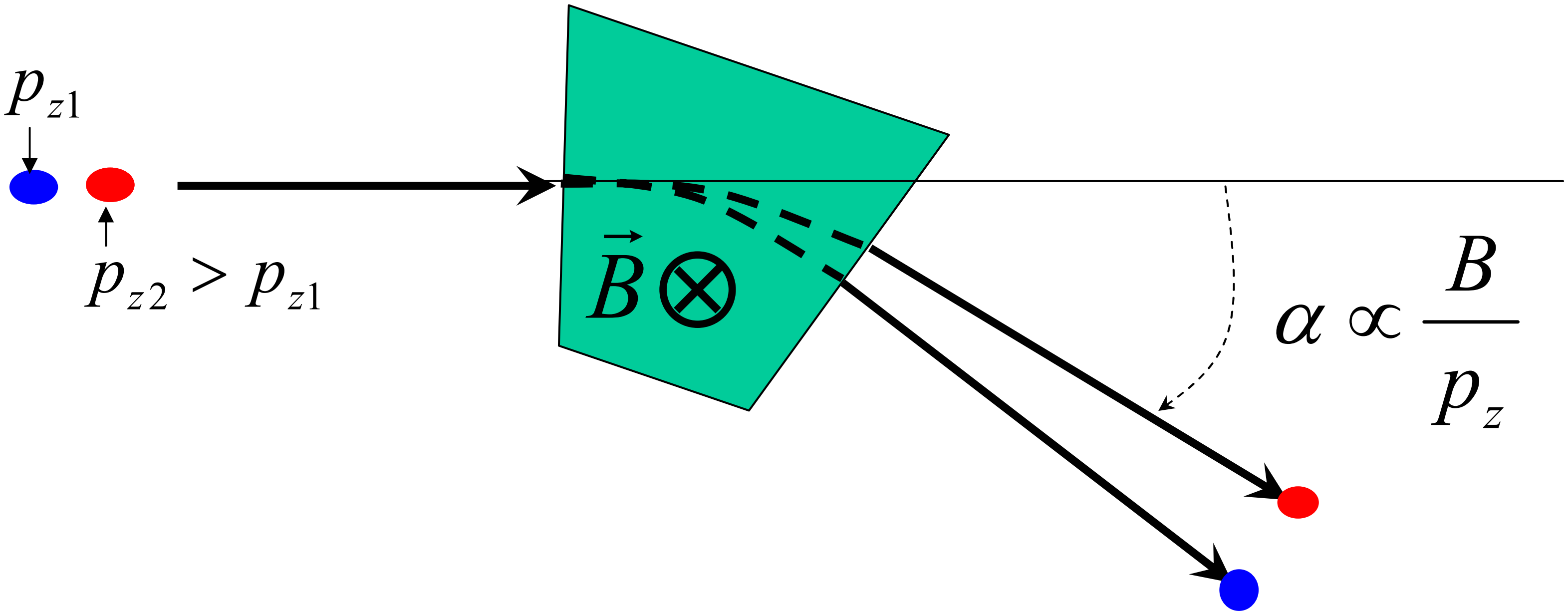
$$\vec{F} = \frac{eQ}{\gamma^2}\cdot G\left(\gamma\frac{2\sigma_z}{\sigma_x+\sigma_y}\right)\cdot\frac{\vec{r}-\langle\vec{r}\rangle}{V_G}$$

Photo injector concept: beam peak current



Transverse projected emittance compensated and conserved. How to increase the peak current of the beam?

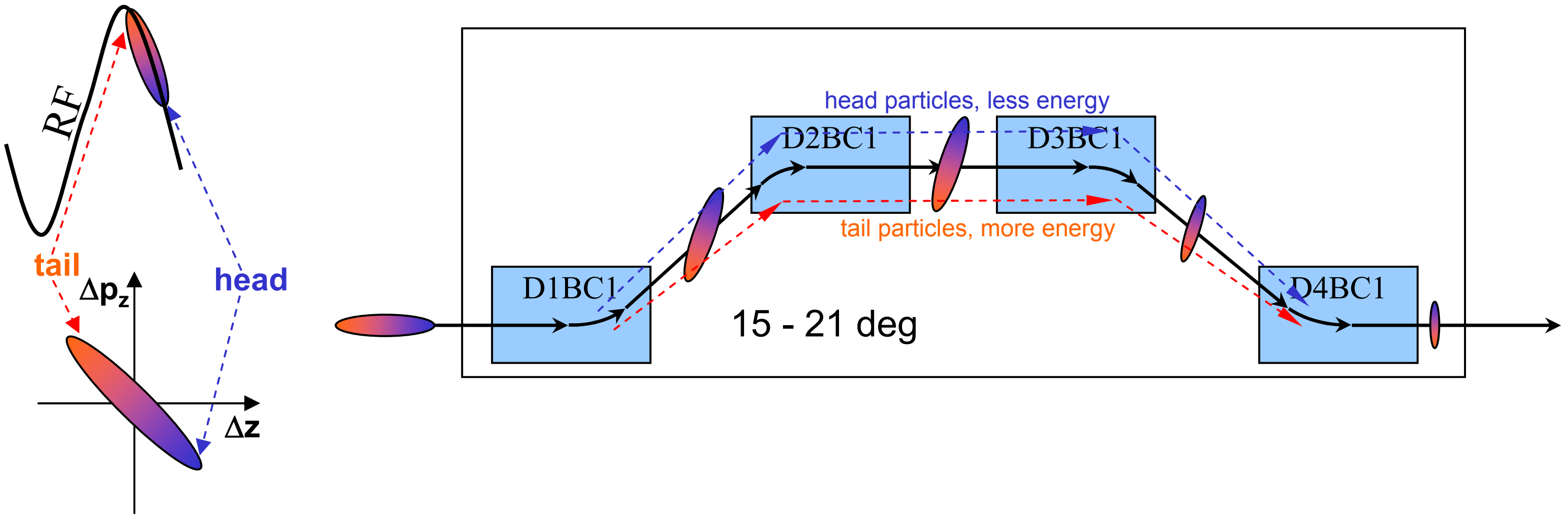
Particle in a field of magnetic dipole



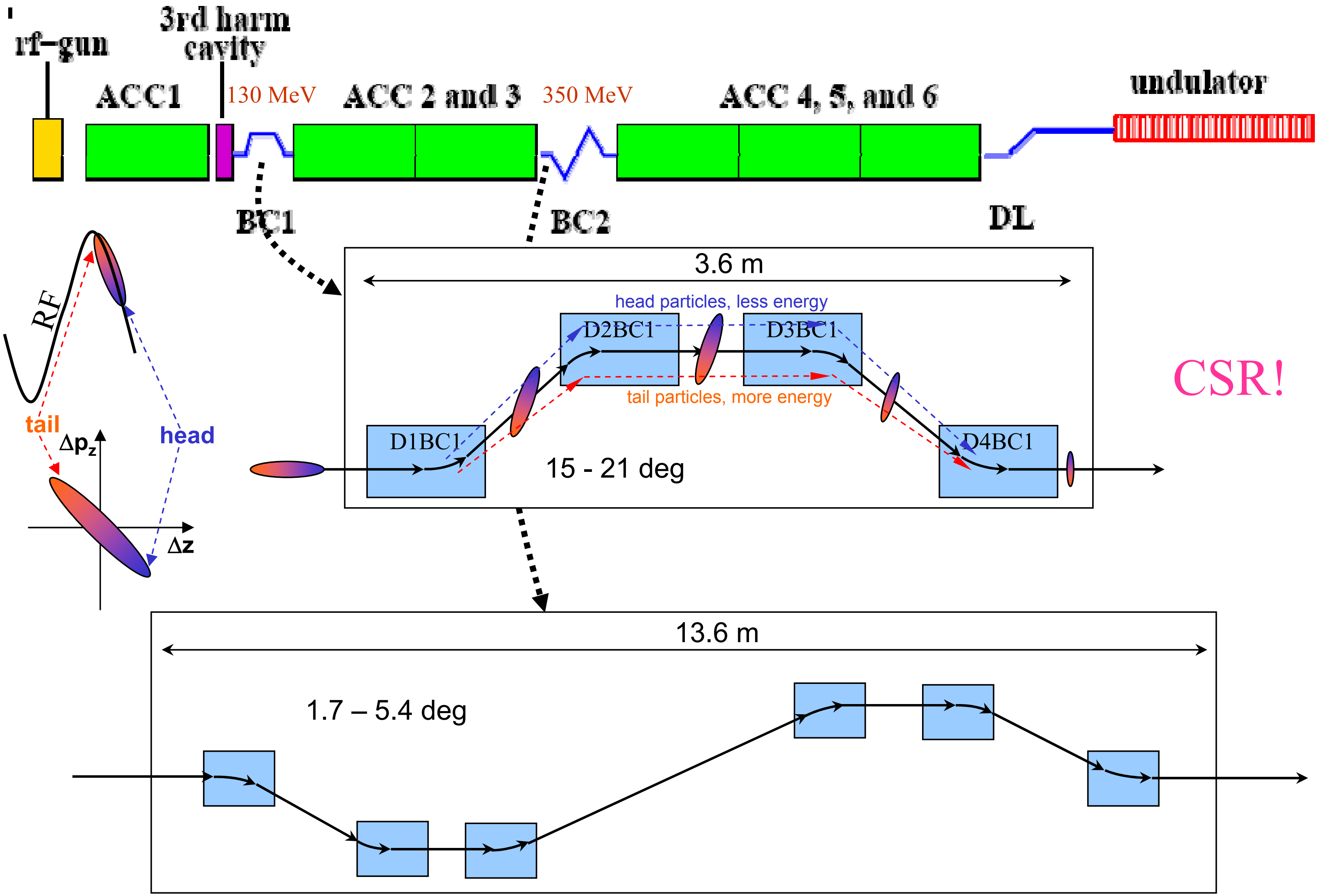
Electrons with higher longitudinal momentum (energy) are less bended by a dipole magnet

!But: Coherent Synchtotron Radiation (CSR) could delute transverse phase space

Bunch Compression (Chicane BC)



Bunch Compression (Chicane BC)



Conclusions

- FELs and linear colliders need particle beams that can be well-focused
- Overall quality of particle beams is described by average brightness or by emittance
- Linear accelerators are capable to produce high brightness electron beams:
  - Emittance compensation technique
  - Emittance conservation principle
  - Bunch compression

On 18.08.2009!

Frank Stephan from PITZ, will tell you all about the actual machine that we use to create these electron beams and characterize electron guns