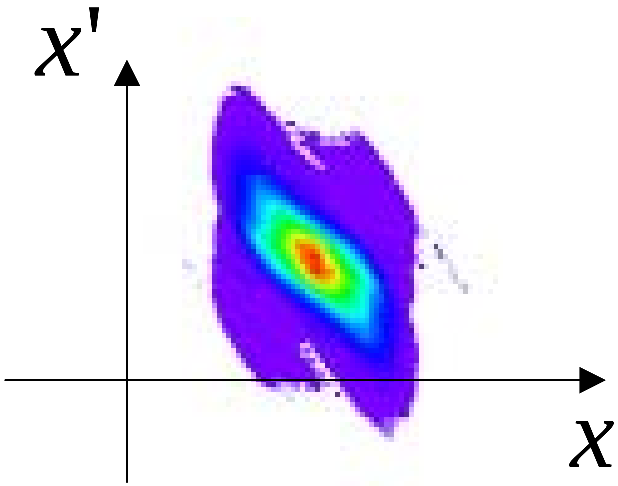
Introduction to the physics of high-quality electron beams



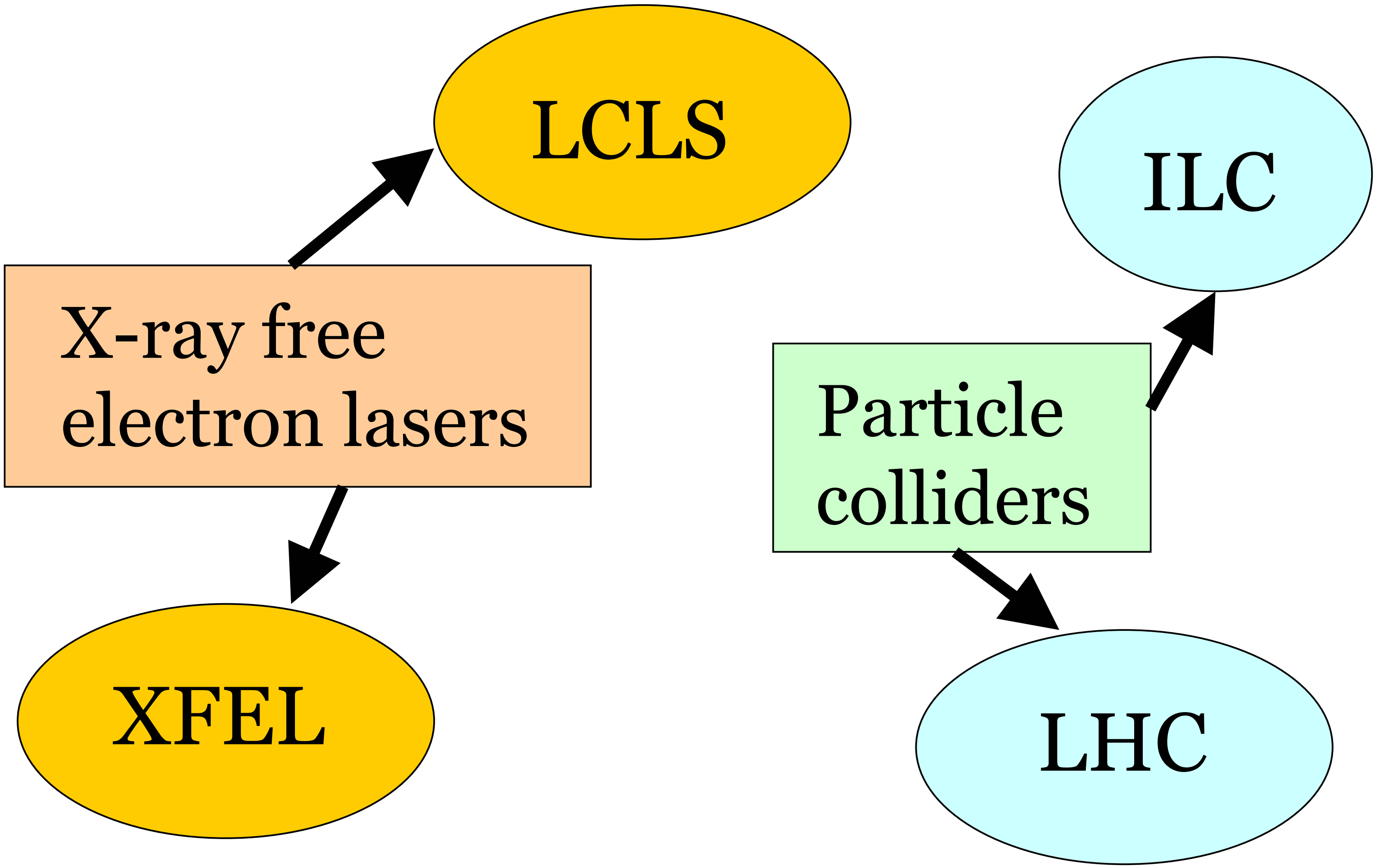
Chase Boulware

Photo Injector Test facility, Zeuthen (PITZ)

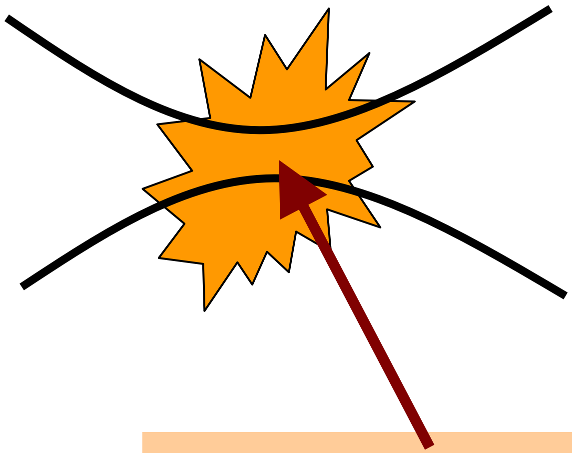
The plan for this morning

- Motivation for high-quality electron beams
- Description of beam quality
  - beam brightness and emittance
- Evolution of beam quality in a linear accelerator
  - emittance growth and compensation

Beam quality from the point of view of two important particle beam applications



High luminosity in a collider requires tight focusing of beams.

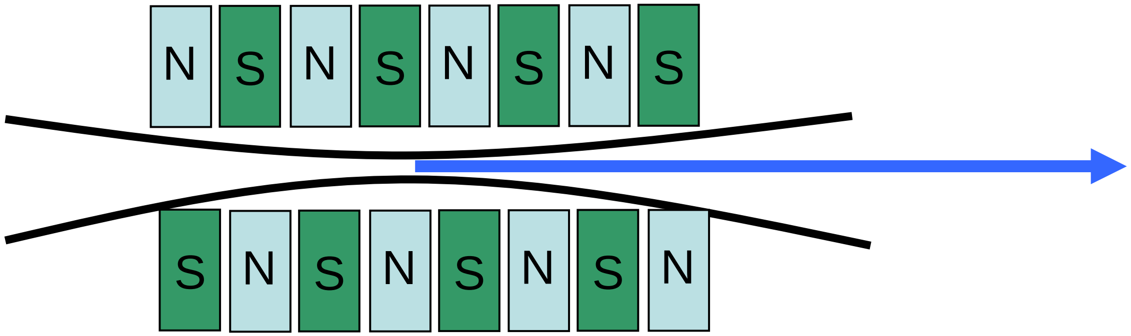


The number of collisions at the interaction point depends on the density of particles there:

- particle current
- beam focal spot size

In a linear collider, you only get one shot at this interaction point before the beam is dumped – in a ring the considerations can be a little different.

A free-electron laser requires the electrons to be focused into the optical beam over the undulator length.



The X-ray FEL is a little like the linear collider in the sense that all the action has to take place on a single pass (no mirrors for X-rays).

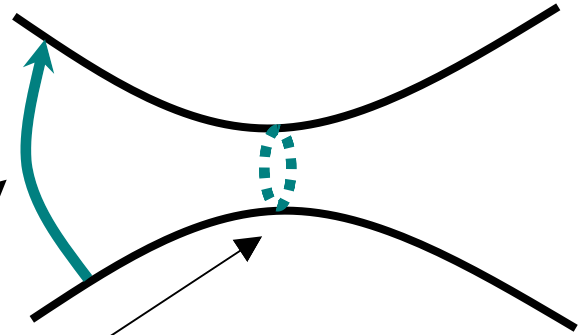
Beam brightness is a local property that measures the achievable current density for a given angular acceptance.

current

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

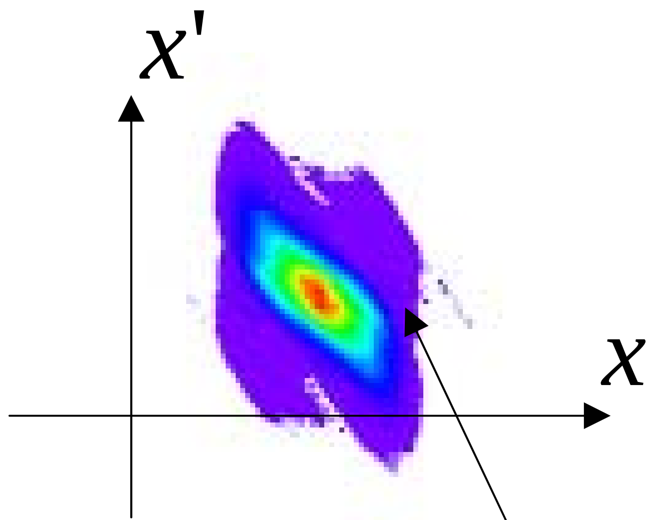
divergence

transverse area



The natural coordinates for looking at the beam brightness distribution are called the "trace space."

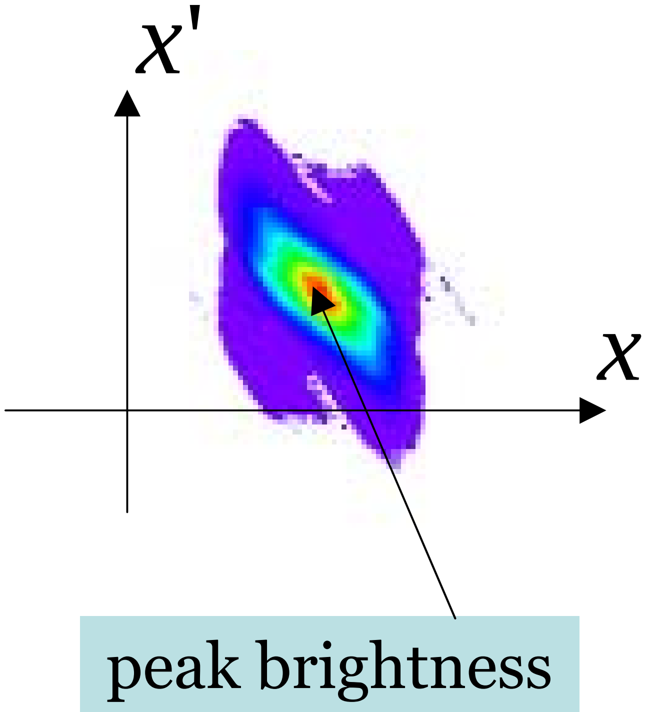
$$B = \frac{d^2 I}{dA d\Omega} = \frac{d^4 I}{dx dy dx' dy'}$$

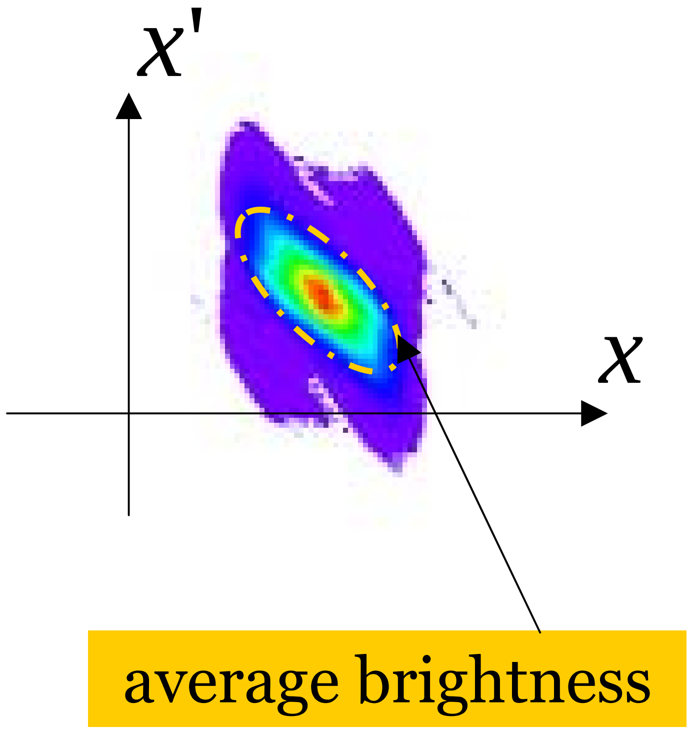


x and *y* are the coordinates transverse to the beam motion (along *z*) and the primes indicate derivatives with respect to *z*

differential intensity at a given point on this picture gives *dI/dxdx'*

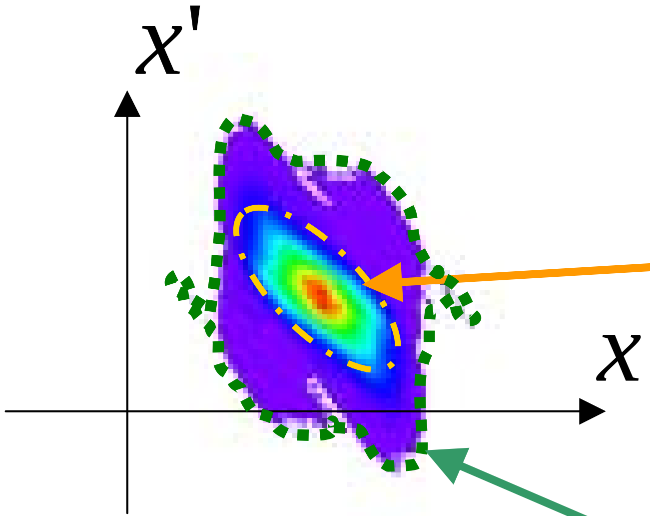
For a given beam, we can define the peak brightness and the average brightness.





The average brightness is not locally defined, but is a property of the whole beam.

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

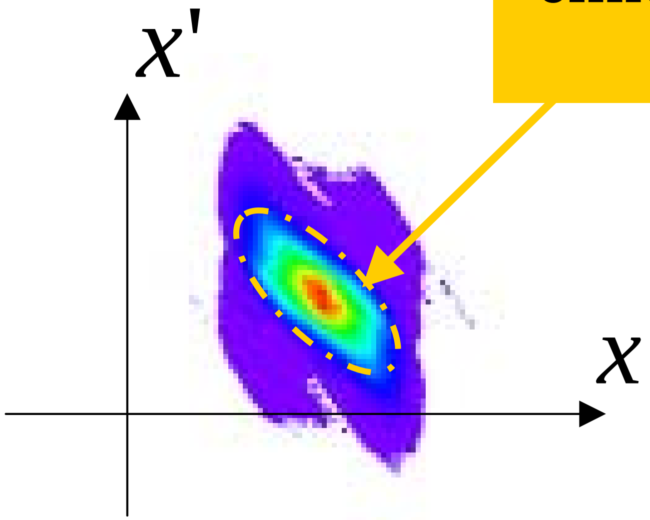


contour containing 90% of particles

Edge contour – containing all particles

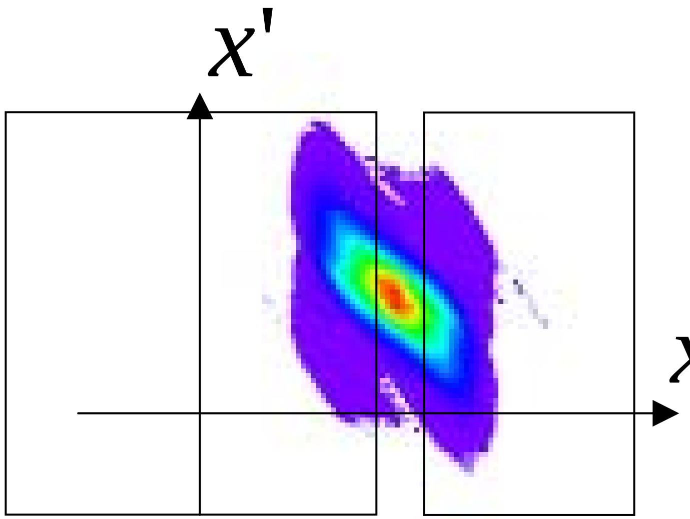
The area in trace space is called the emittance of the beam.

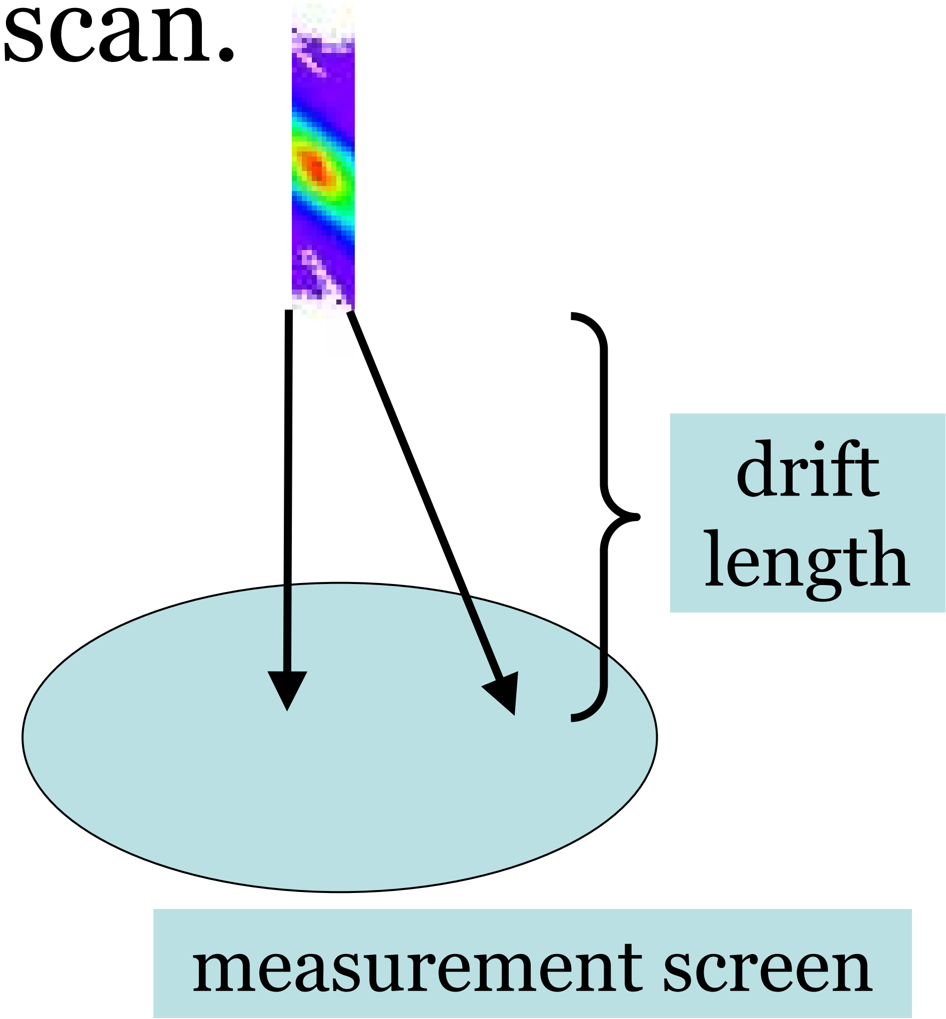
The area bounded by this dotted line is equivalent to the rms transverse emittance in *x* – it has units of length times angle.



Emittance is sometimes quoted in units of "π mm mrad", where the π implies this elliptical shape.

We can measure the emittance in several ways, but the simplest is a slit scan.





Focusing beams: photons and electrons

In photon optics, the achievable focus depends on the wavelength of the light and the beam quality.

$$r_{\text{focal spot}} \approx M^2 \lambda$$

Electrons have a wavelength and a beam quality, too, but they also repel one another so that can contribute to the focal spot size.

Focusing beams: photons and electrons

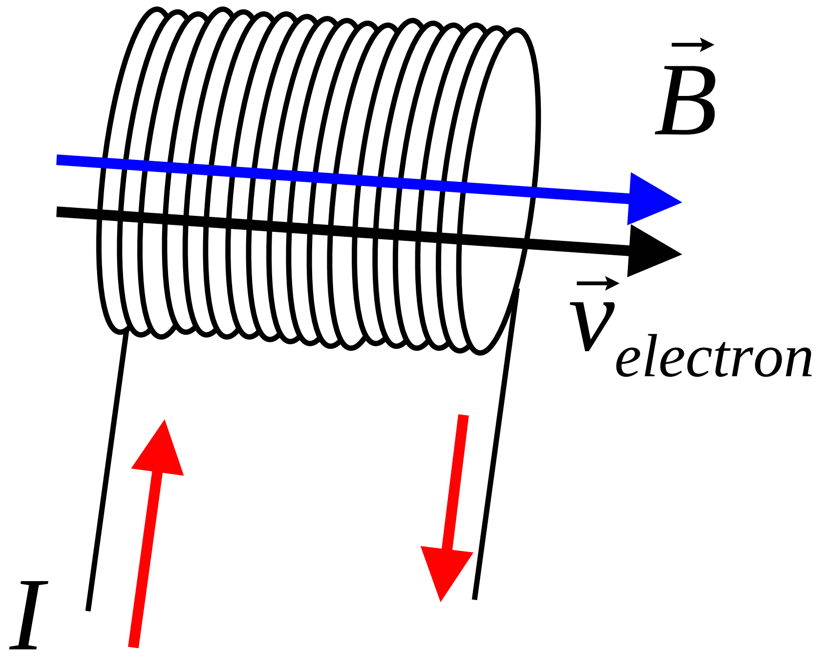
In photon optics, the achievable focus depends on the wavelength of the light and the beam quality.

Electrons have a wavelength and a beam quality, too, and they also repel one another so that can contribute to the focal spot size.

$$\lambda_{\text{de Broglie}} = \frac{h}{p} = \frac{h}{\gamma m_e v}$$

energy	γ	λ de Broglie
1 keV	1	40 pm
1 MeV	3	0.8 pm
1 GeV	2,000	1 fm

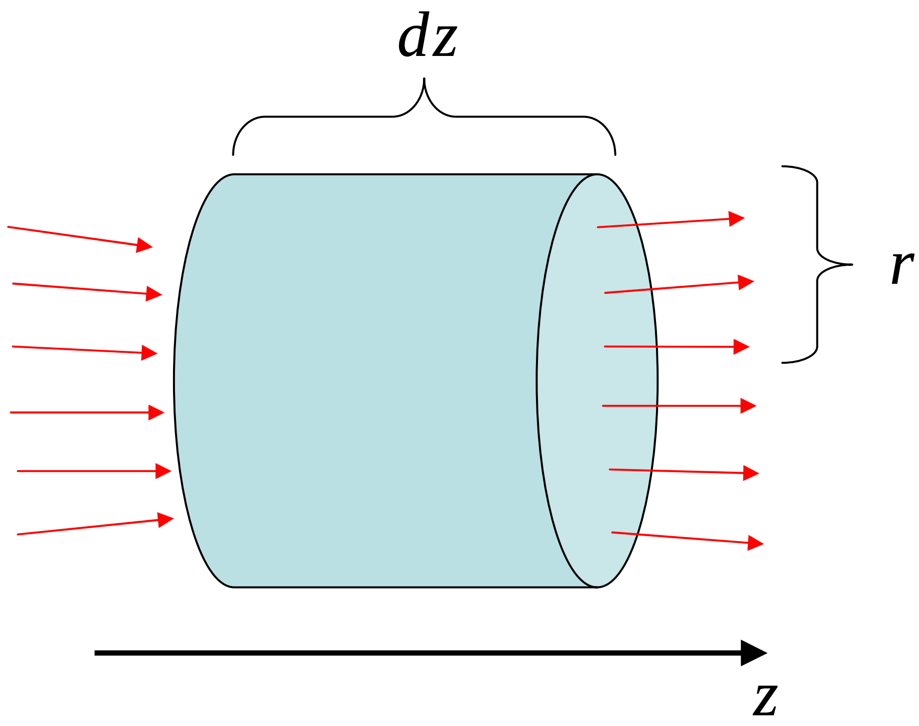
Focusing an electron beam with a solenoid: how does that work?



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

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

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



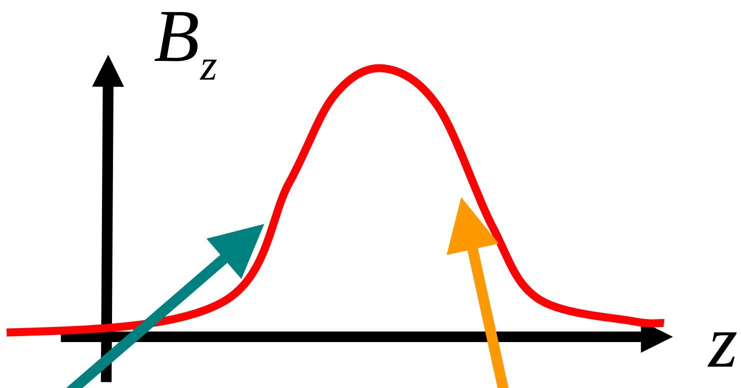
Gauss' Law tells us that when the magnetic field changes along *z*, it must have a radial component also.

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

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

The electrons do feel a force from these fringe fields.

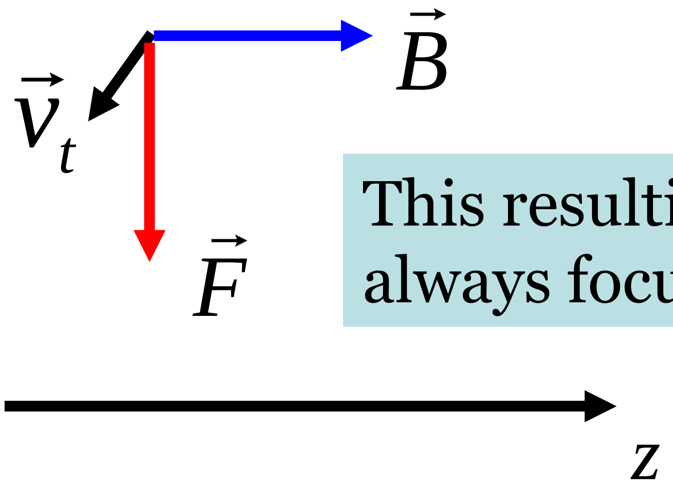
$$B_r = -\frac{r}{2}\frac{dB_z}{dz}$$



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.

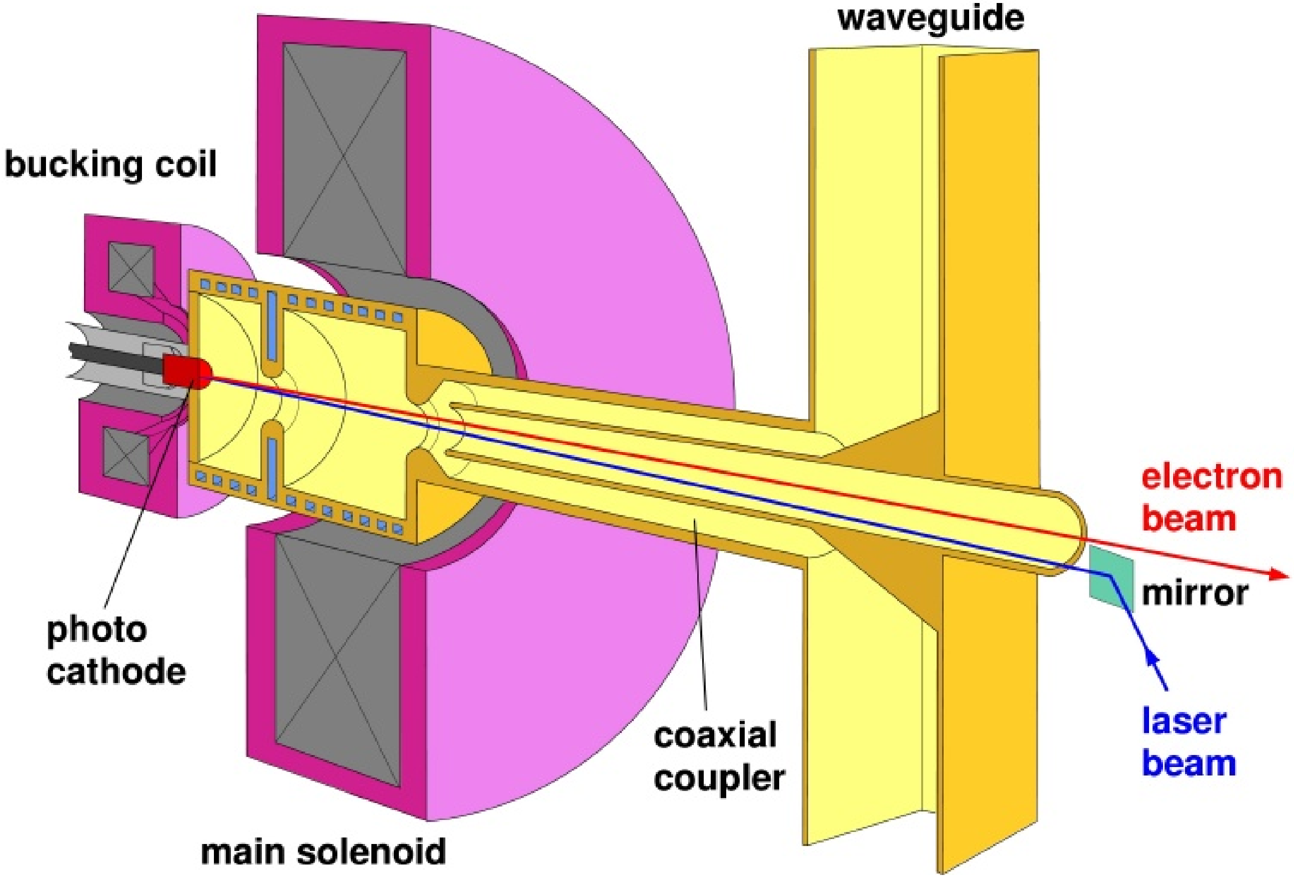
Electrons with angular momentum then feel a force from the main solenoid field.



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.

Solenoids at PITZ: we use a second coil to make sure the field is zero at the cathode.



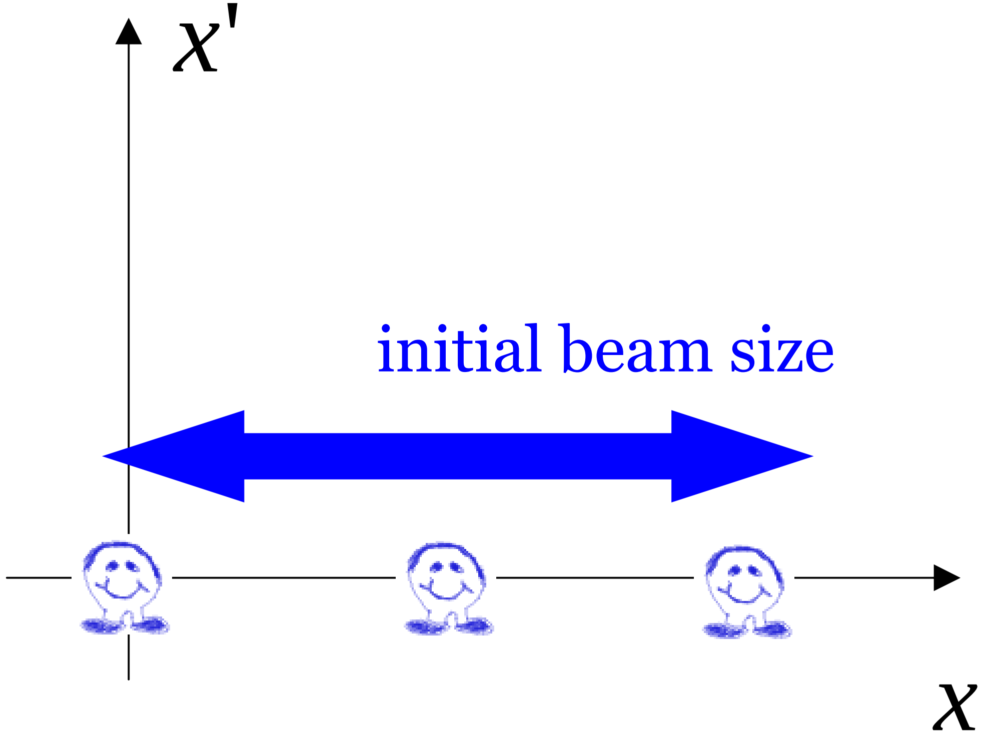
Now that we know how to focus the beam, what does the focal spot have to do with the emittance?

In photon optics, the achievable focus depends on the wavelength of the light and the beam quality.

Electrons have a wavelength and a beam quality, too.

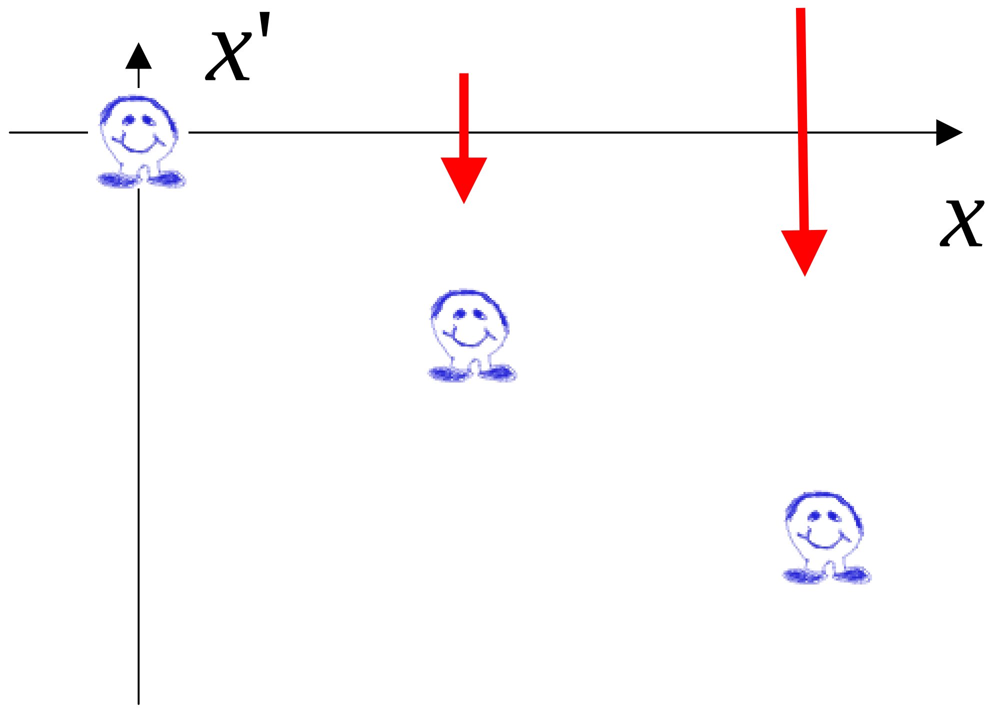
For electron beams, the beam quality is the emittance.

In a perfect beam, all the electrons are parallel and the emittance is zero.



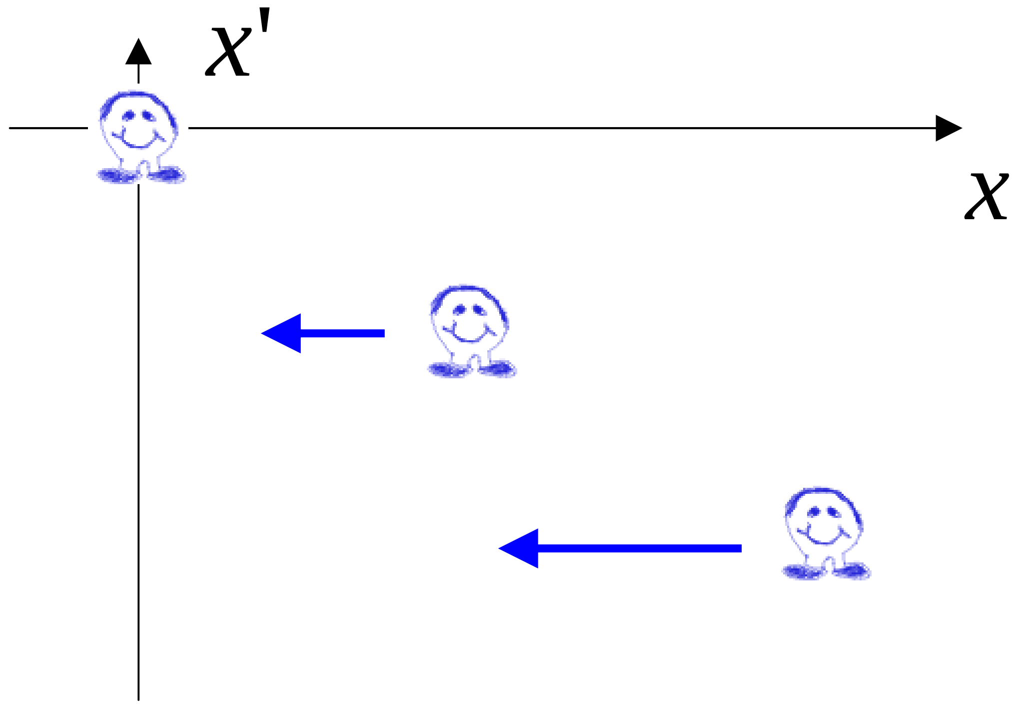
An electron lens changes the trajectory angle based on the particle's position.

Focusing this beam with a linear lens gives the electrons a trajectory angle proportional to their position.



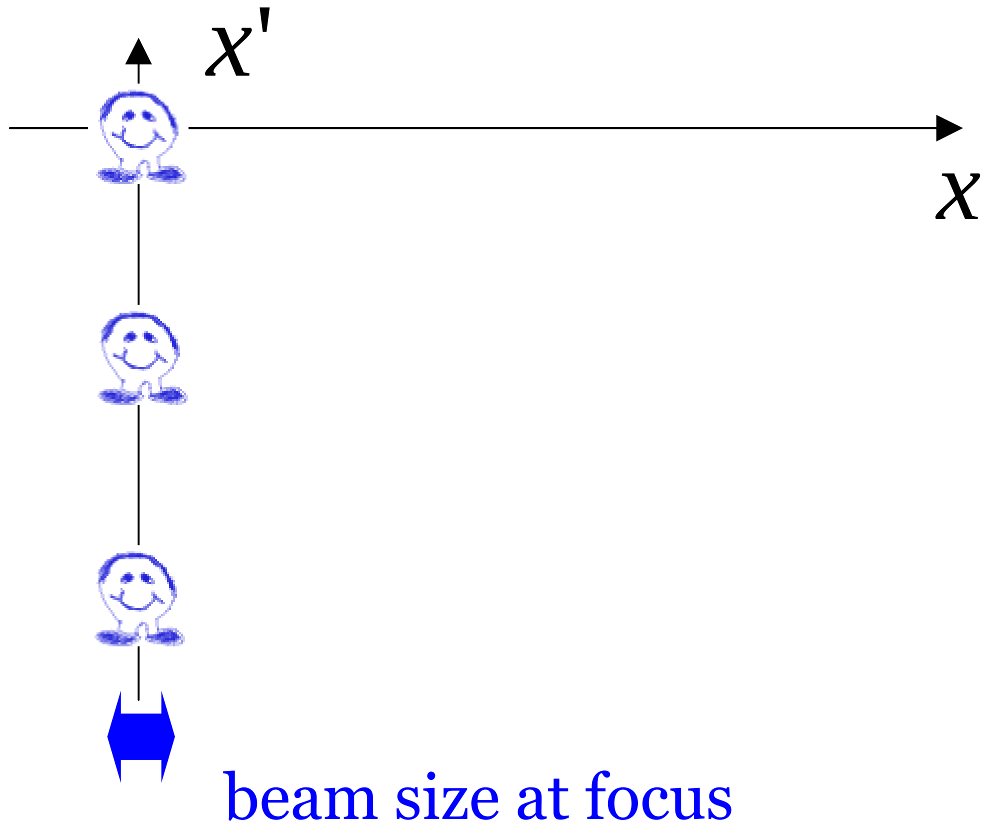
After the lens, the trace space is sheared as the beam drifts through a field-free region.

Particles with nonzero trajectory angle move in phase space as the beam moves down its axis of motion.



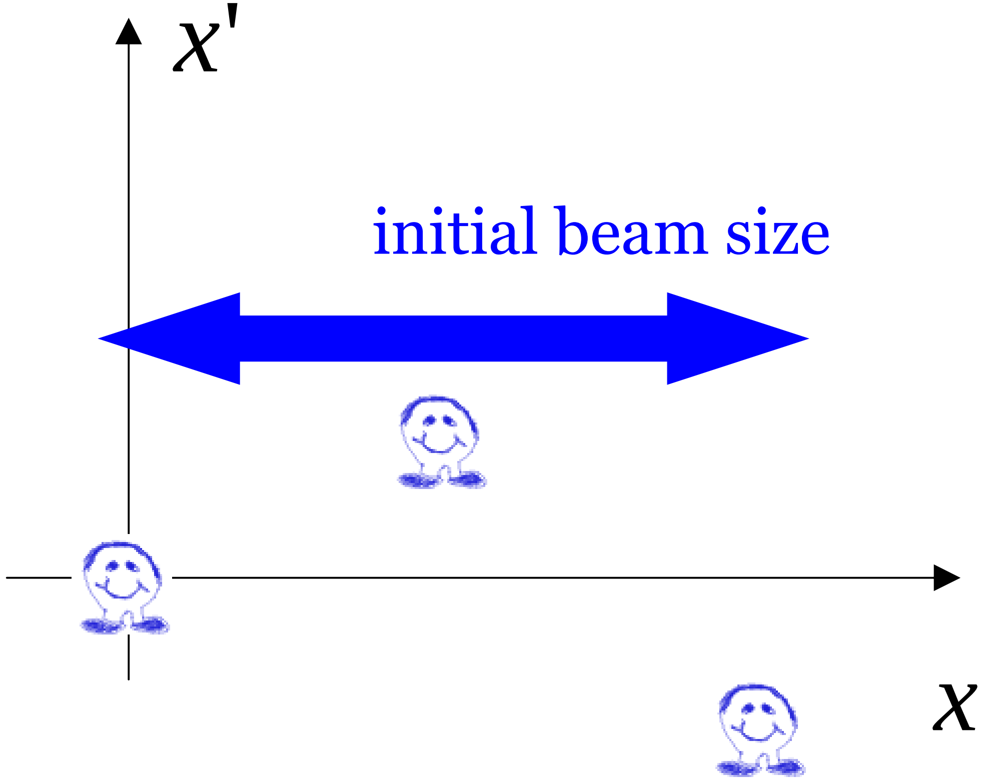
We ignore the wavelength of the electrons, and for now, the electric repulsion, to see what happens at the focus.

All the particles in this perfect beam cross the axis at the same time, giving a nice focal spot.



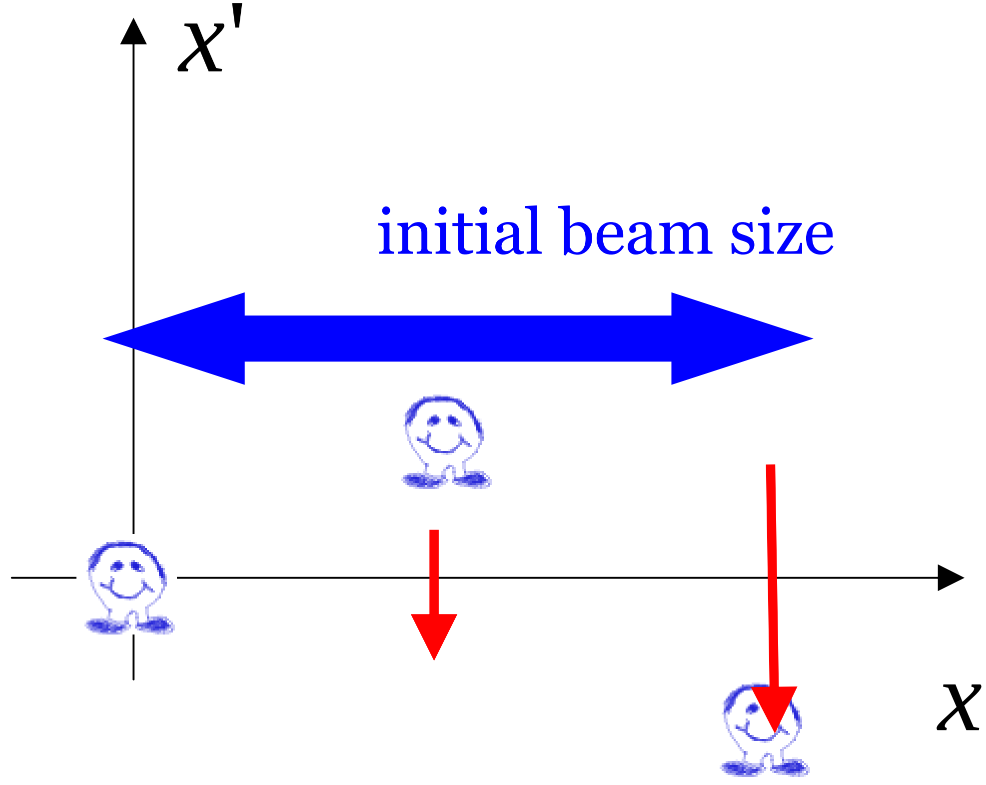
OK, now a beam with nonzero emittance and the same initial size.

This initial emittance can come from several sources.



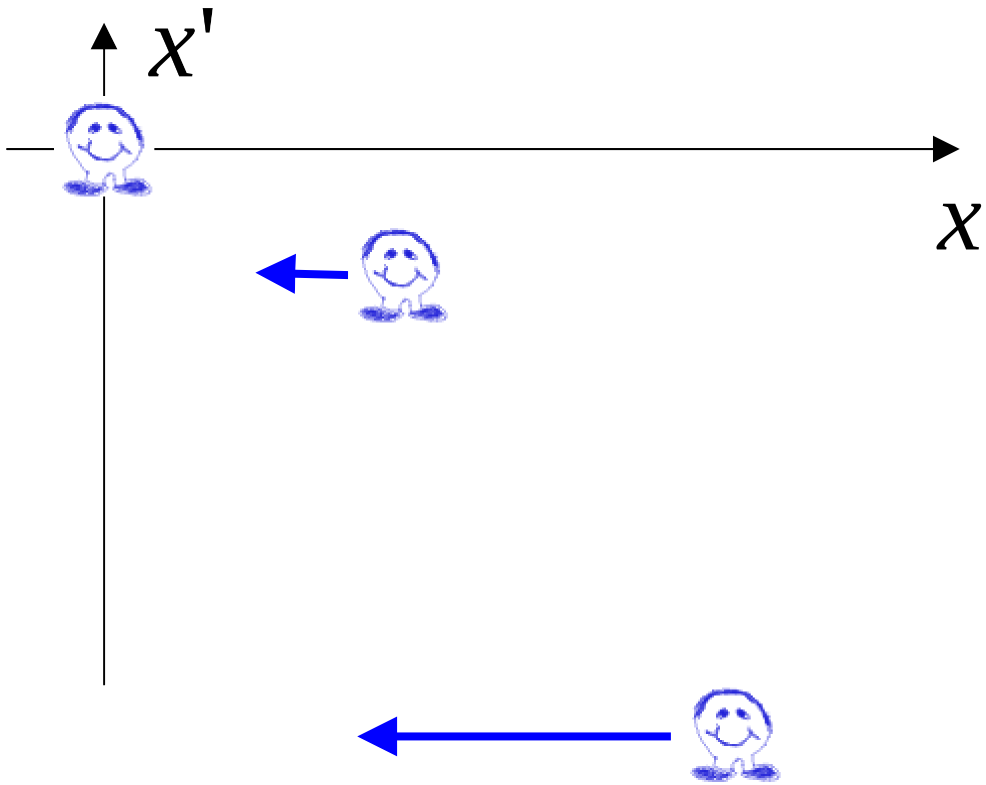
The focusing lens acts in the same way on this beam.

The 'kick,' or change in trajectory, only depends on *x*-position.



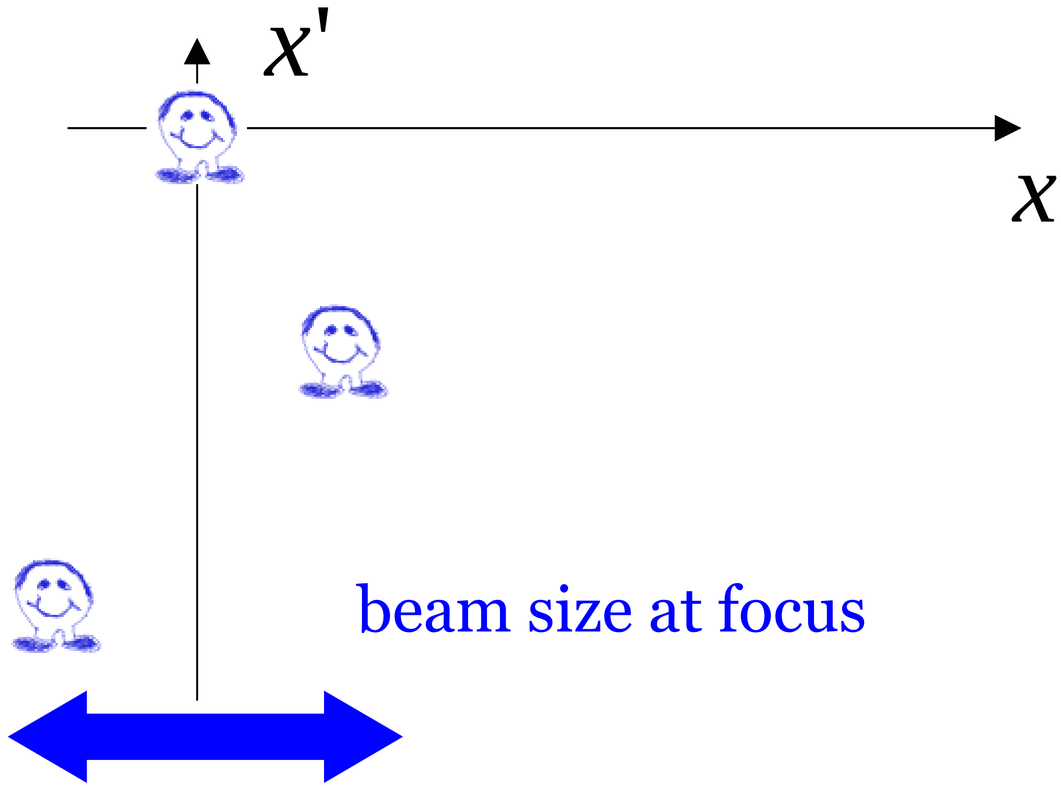
The rate of drift across the phase space diagram now does not have a linear relation to the *x*-position.

Remember that the prime is a derivative with respect to *z*, which is the position of the beam along its axis of average motion.

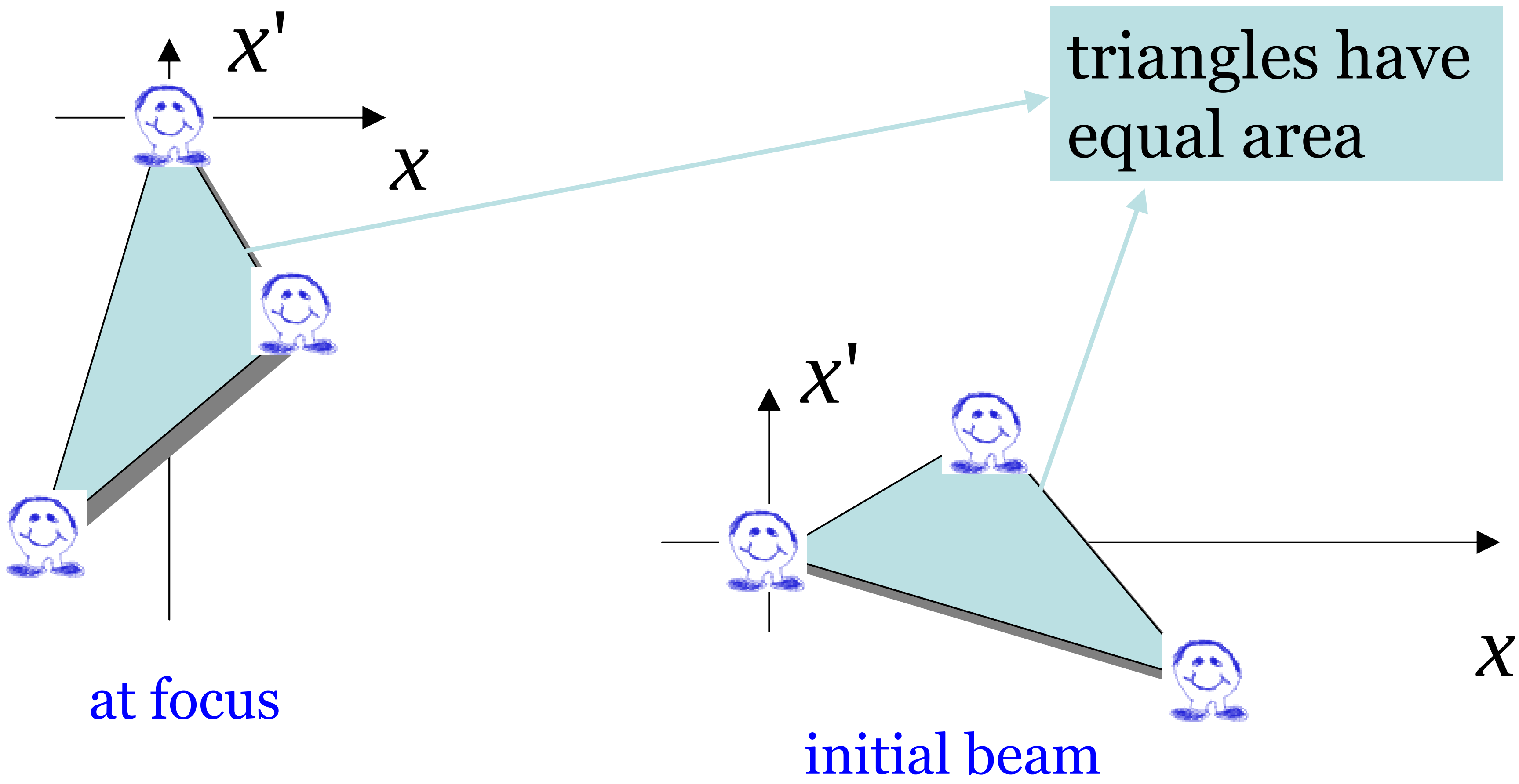


The beam size at the focus is now a result of the initial emittance.

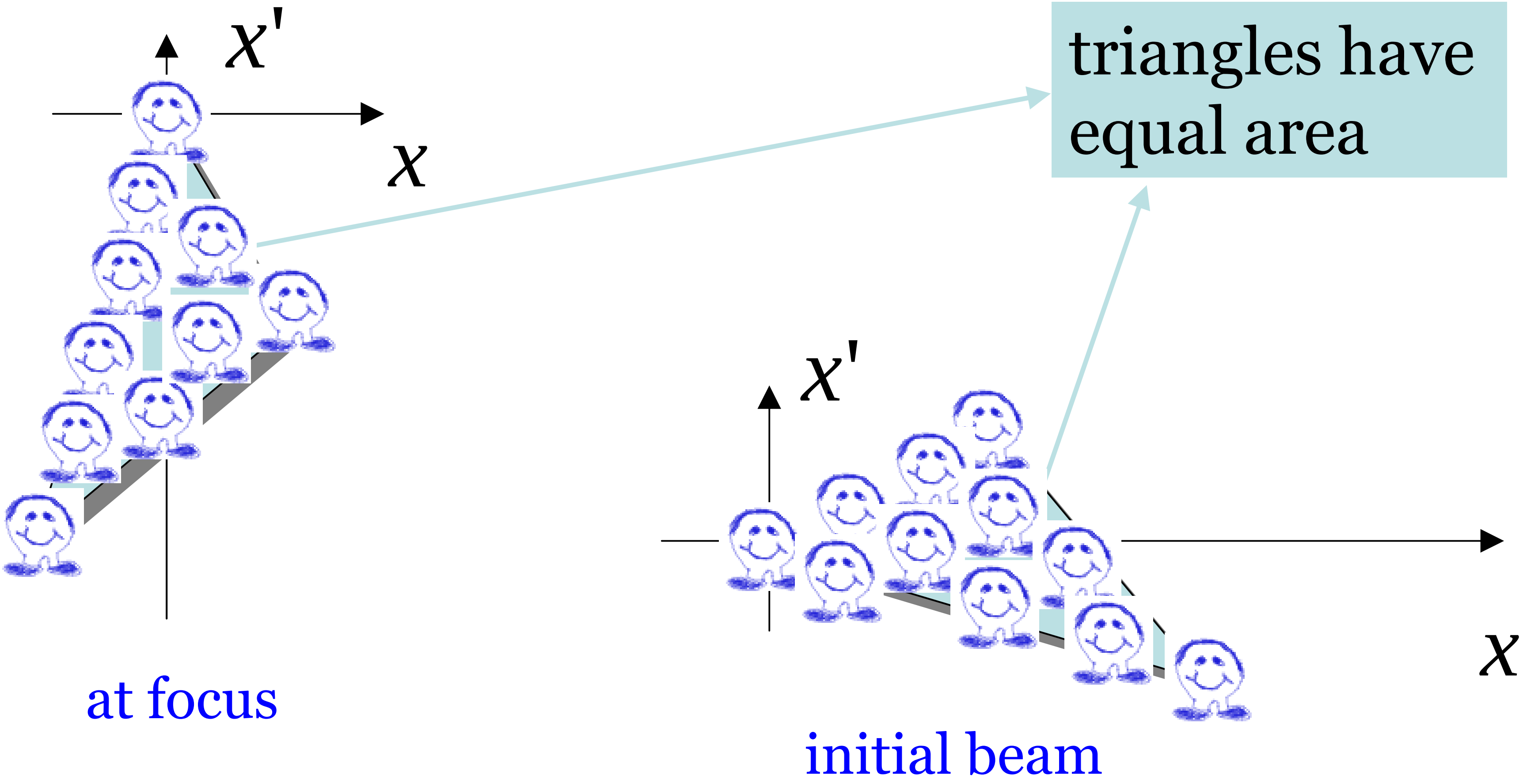
The spread in initial angle is transformed into a spread in position at the focal point.



We notice that the emittance has not changed after the lens or during the drift to the focus.

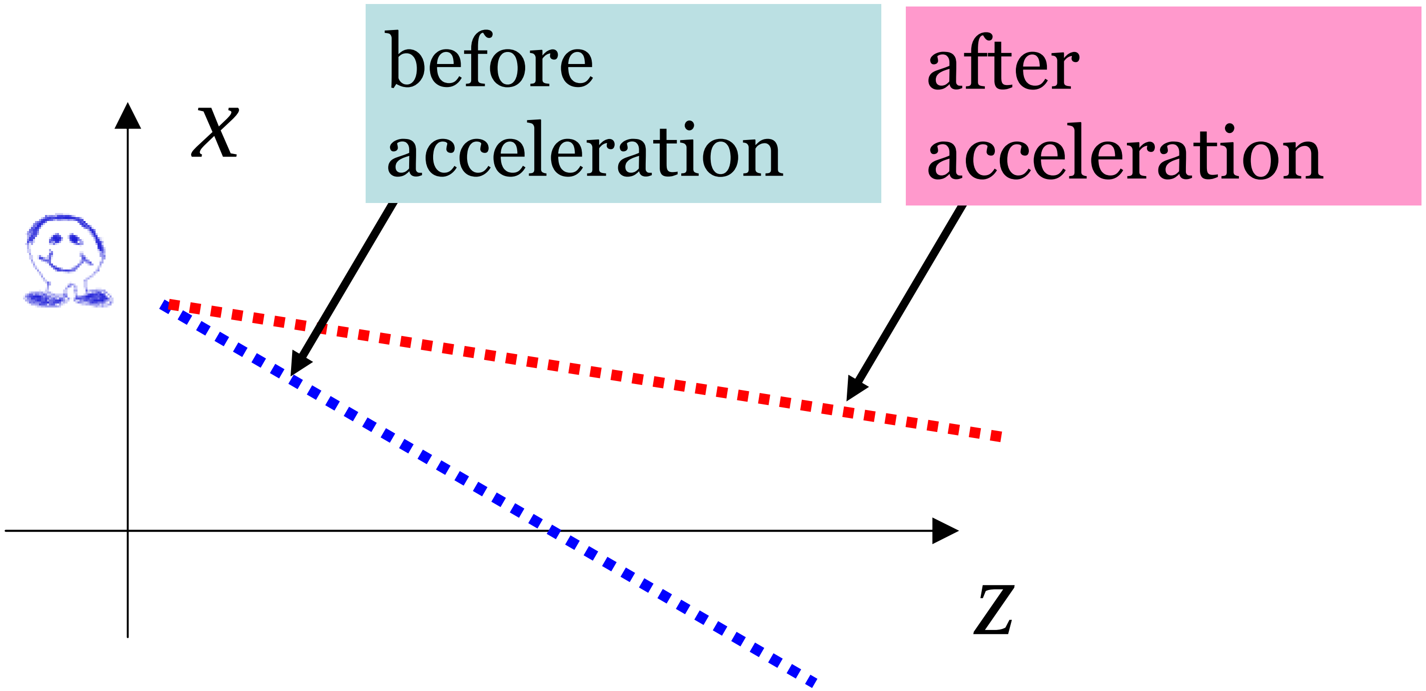


We notice that the emittance has not changed after the lens or during the drift to the focus.

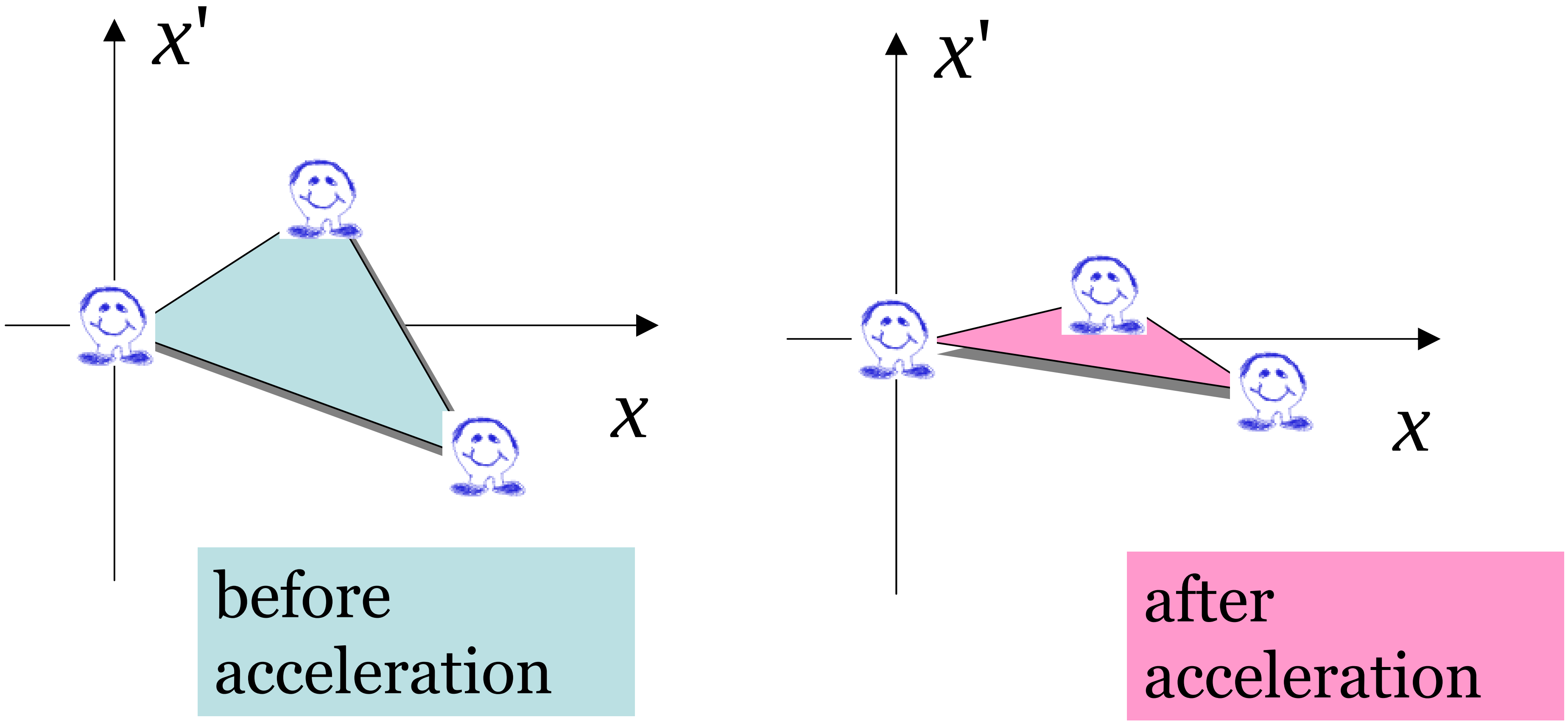


So, the beam drifting along has a constant emittance, which doesn't even change after a "linear" lens. What about accelerating the whole beam?

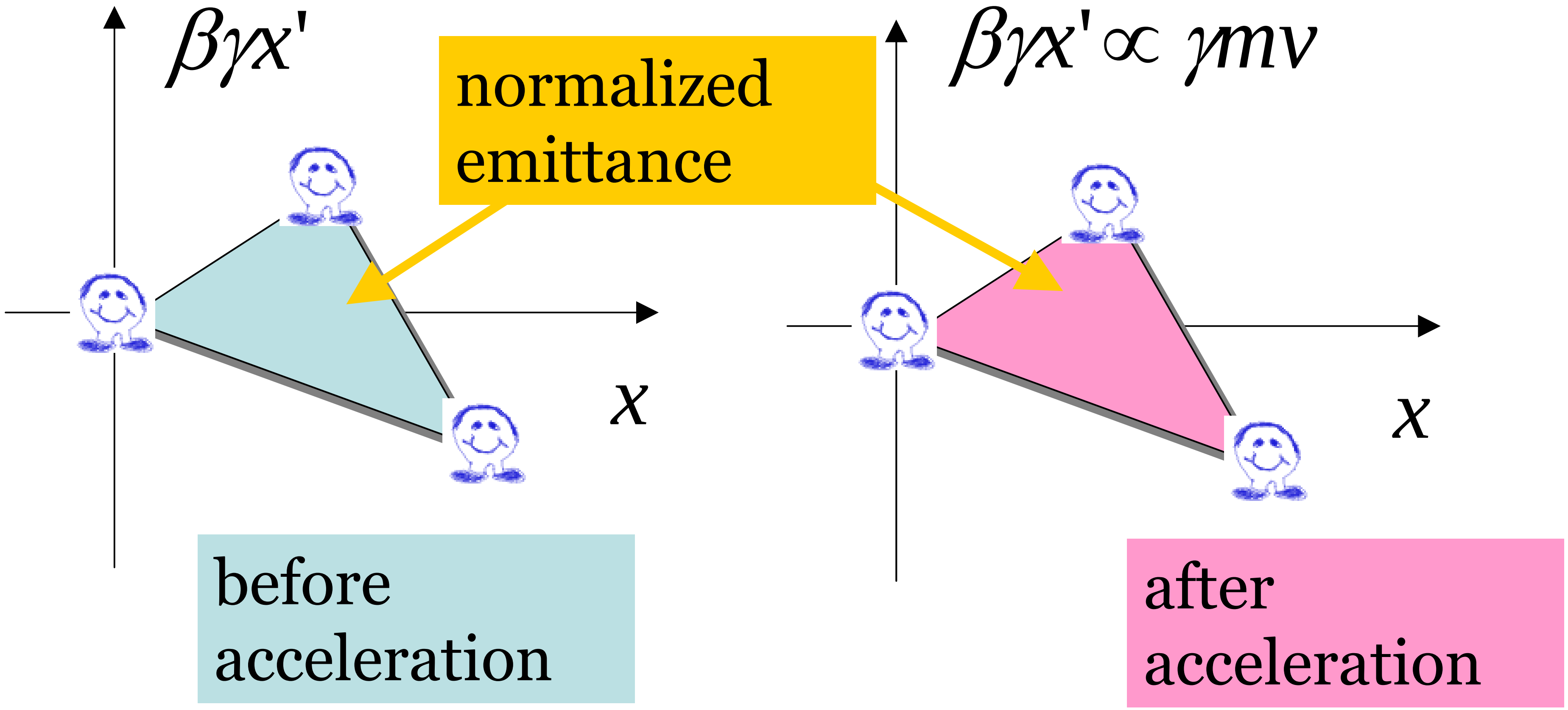
$$x' = \frac{dx}{dz}$$



Accelerating the beam reduces the emittance.



If we rescale the vertical axis according to the momentum, we can preserve the area.



So far…

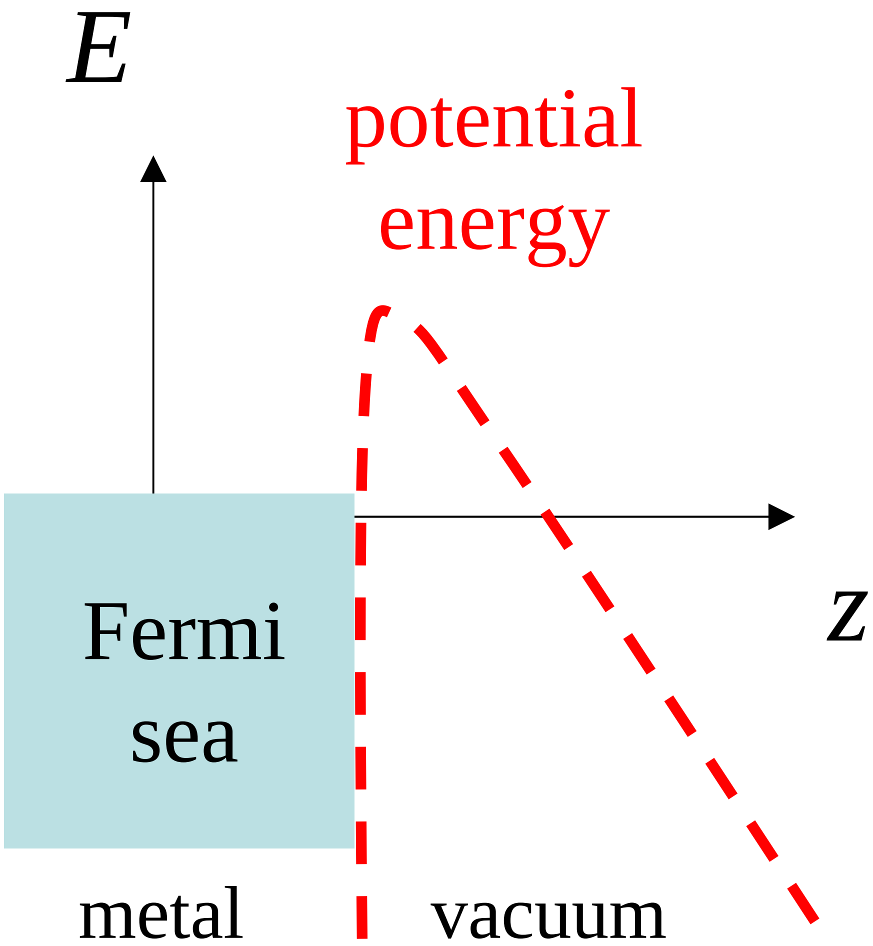
- FELs and linear colliders need particle beams that can be well-focused.
- Overall quality of particle beams is described by average brightness or by emittance.
  - emittance is conserved during beam drift and focusing (and acceleration, for normalized emittance)

NEXT:

Where does initial emittance come from?

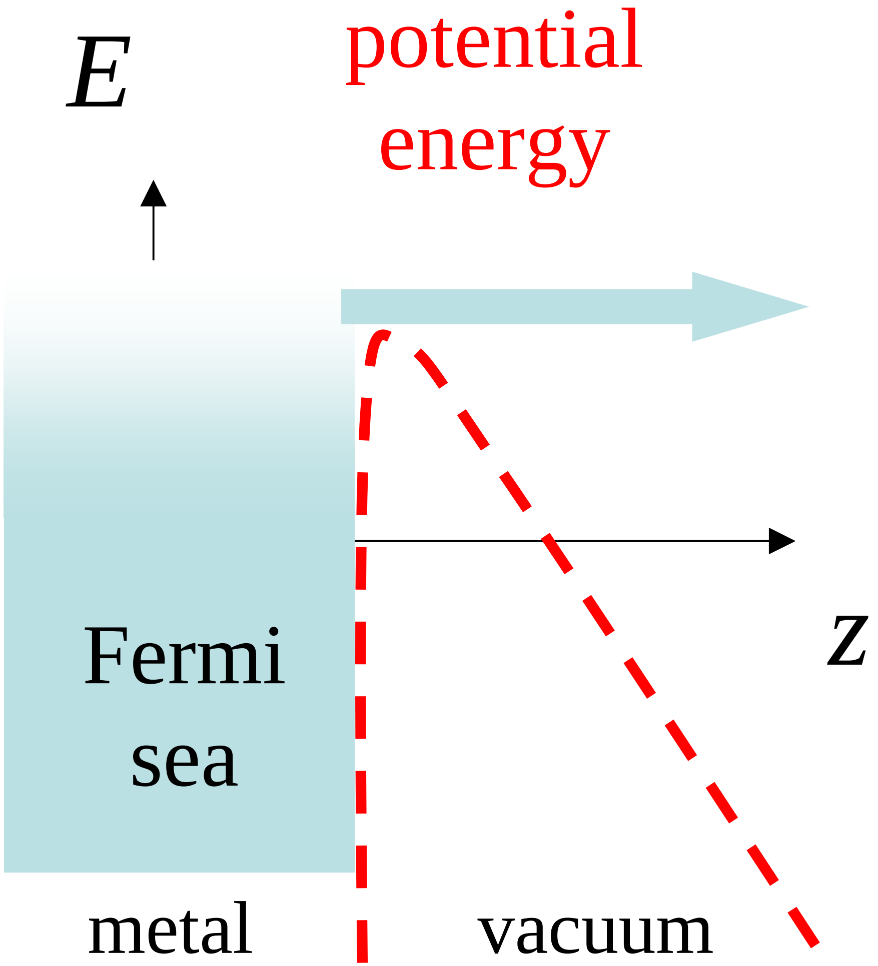
When is normalized emittance not conserved?

Beam initial emittance depends on the nature of the source.



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

Beam initial emittance depends on the nature of the source.

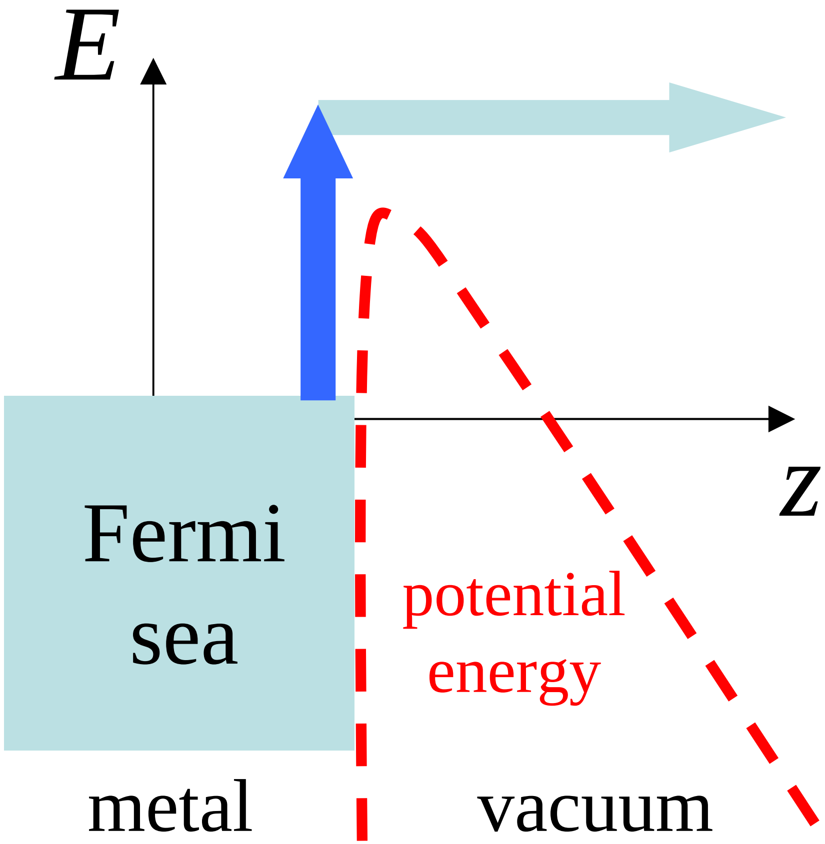


In thermionic emission, the temperature of a filament is raised until electrons spill over the vacuum barrier.

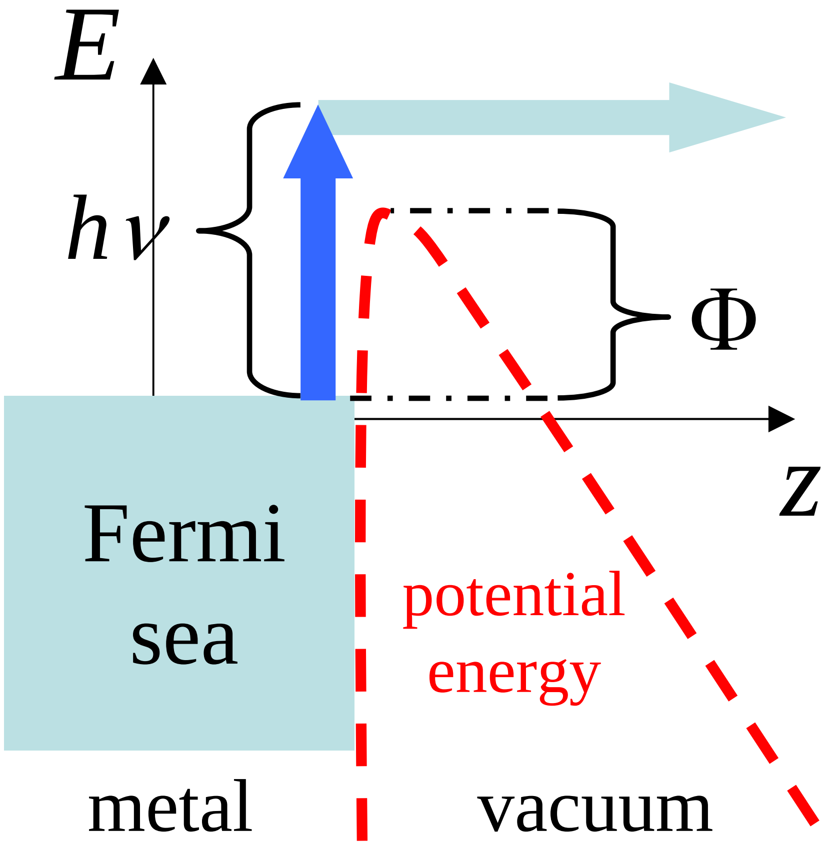
$$v_{rms} \propto \sqrt{k_B T}$$

Transverse velocity is random, with rms value depending on temperature.

In a photocathode, electrons are liberated by absorbing photons.



In a photocathode, electrons are liberated by absorbing photons.

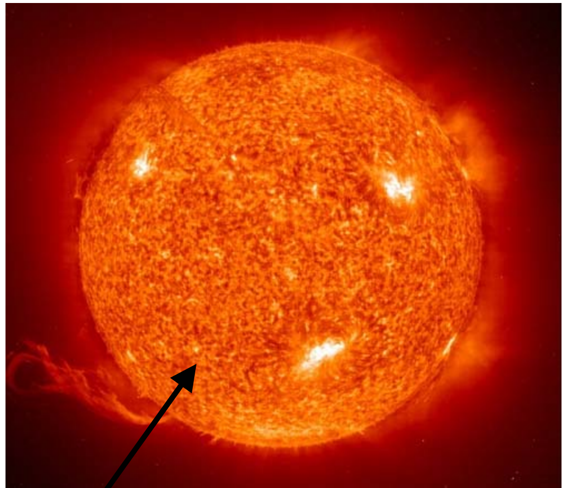


$$v_{rms} \propto \sqrt{h\nu - \Phi}$$

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

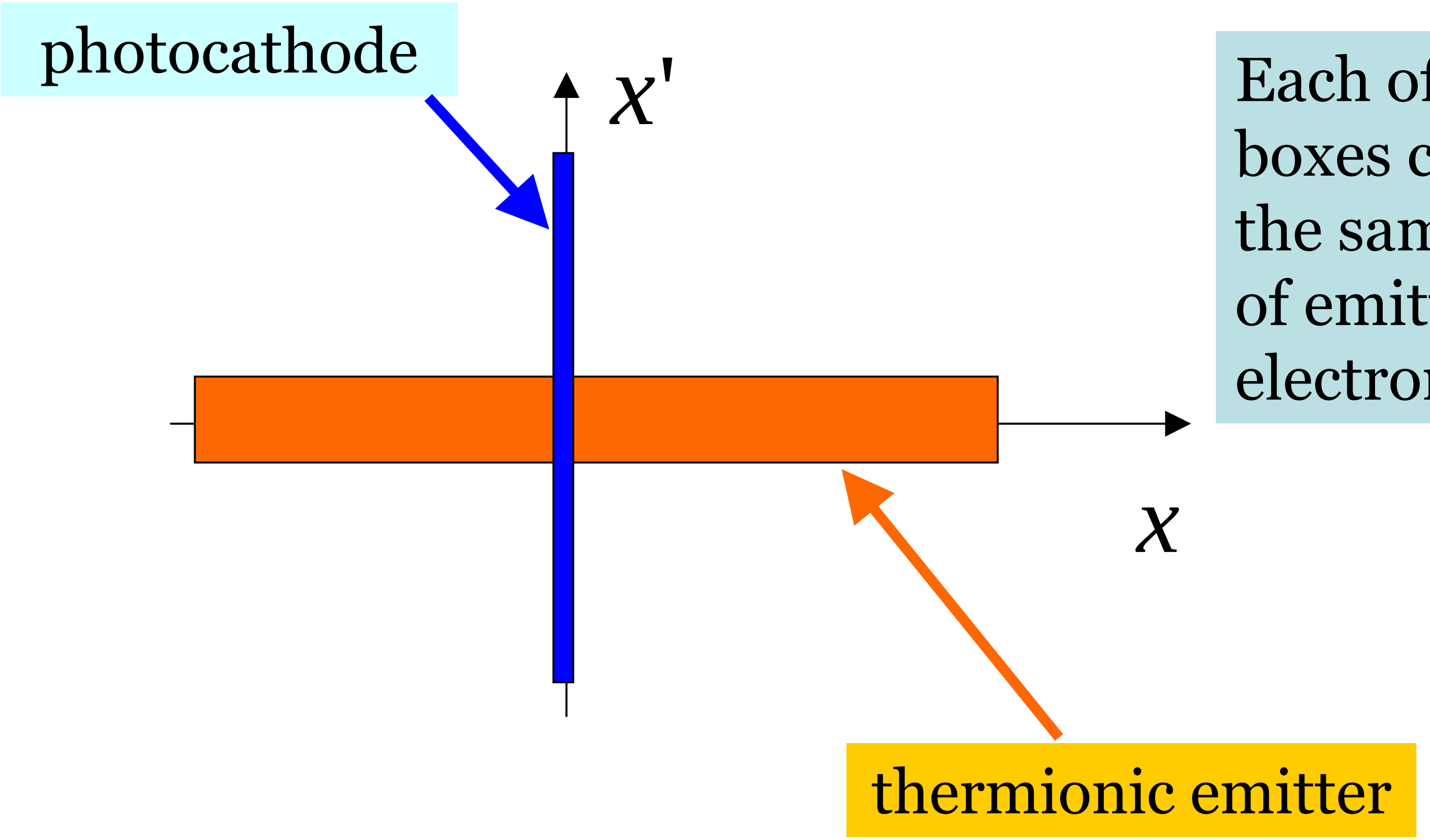
The transverse velocity spread is actually much greater from a photo cathode than a thermionic cathode, but the thermal emittance is better?

For the PITZ photocathode, the photon energy is about 1 eV higher than the work function – and 1 eV corresponds to a temperature of 10,000K!



surface of Sun: 6,000 K

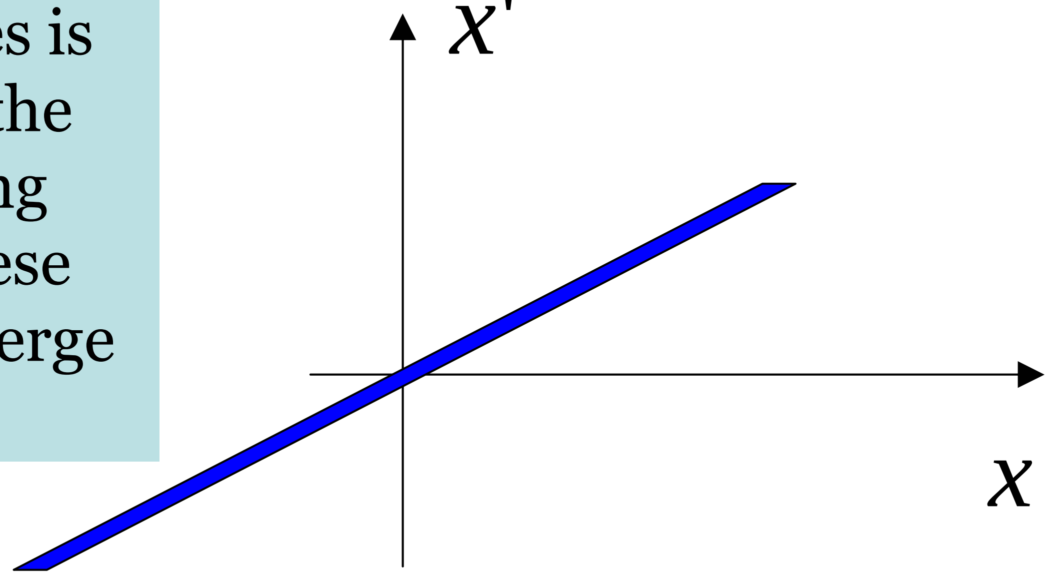
The current density is *much* higher from a photocathode, so the initial beam size is much smaller.



Each of these boxes contains the same number of emitted electrons.

This thermal emittance sets a lower bound on the beam emittance.

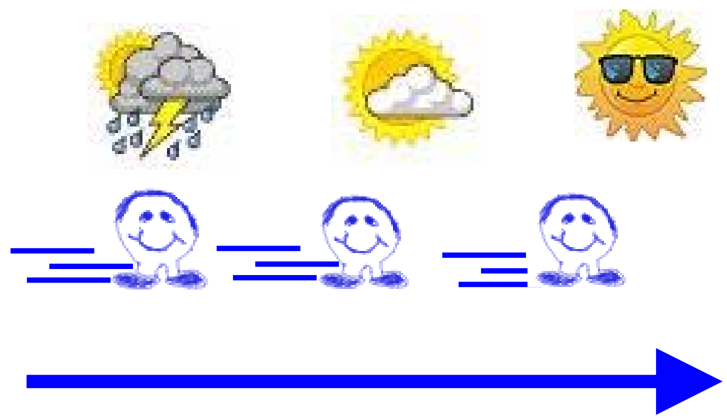
The spread in trajectories is random with respect to the position, and our focusing elements can't adjust these trajectories so they converge in one spot.



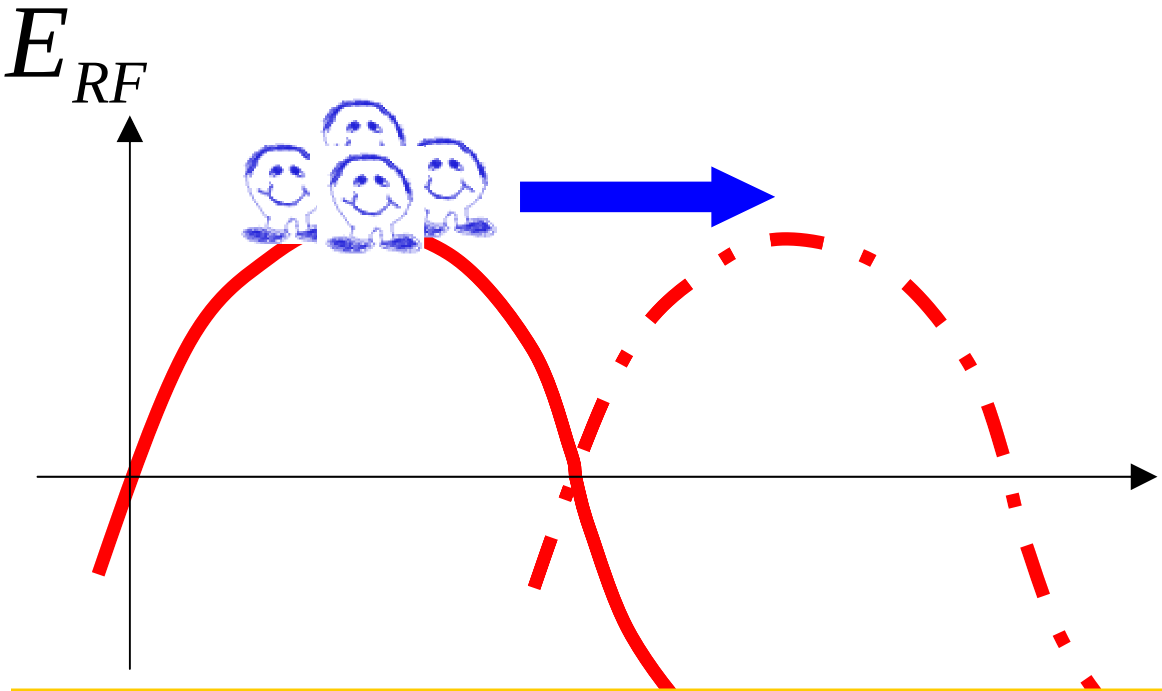
As the beam moves through the beam pipe, the trace space gets sheared and kicked so that it rotates, but the area doesn't change.

But if we think of our beam as a bunch of electrons with a length along the beam pipe, the situation becomes a little more complicated.

The electrons at the head of the bunch can see different conditions from those at the tail, and this leads to emittance growth for the beam bunch as a whole.



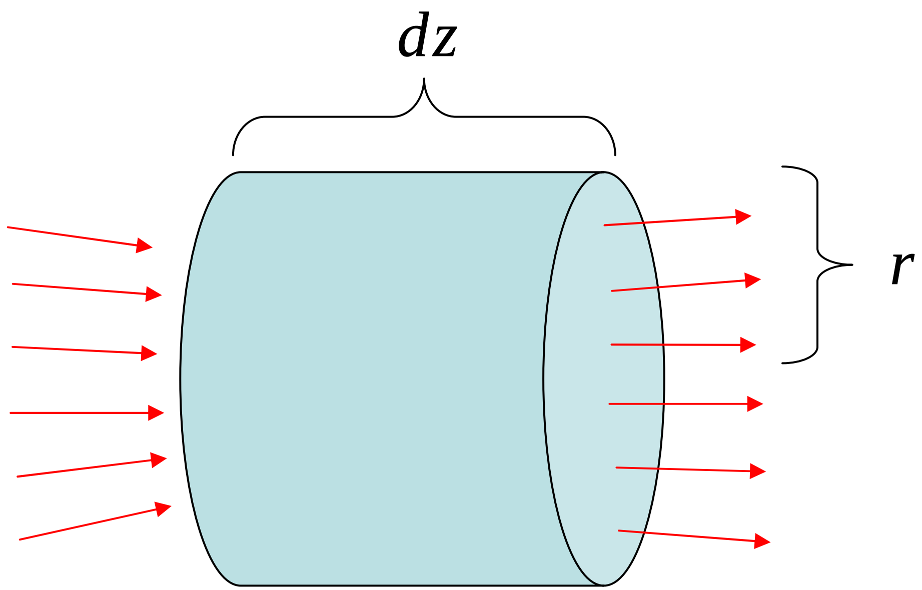
Electrons at PITZ are accelerated using radio-frequency (RF) waves.



The electrons are emitted when the RF field is accelerating, and arrive at the next crest in time to get another push.

The bunch length here is exagerrated. The RF frequency is 1.3 GHz, which means the 20 ps long bunch only stretches over about 1 degree in RF phase.

The slightly different phases seen by different parts of the bunch lead to a stretching, but also differential focusing.

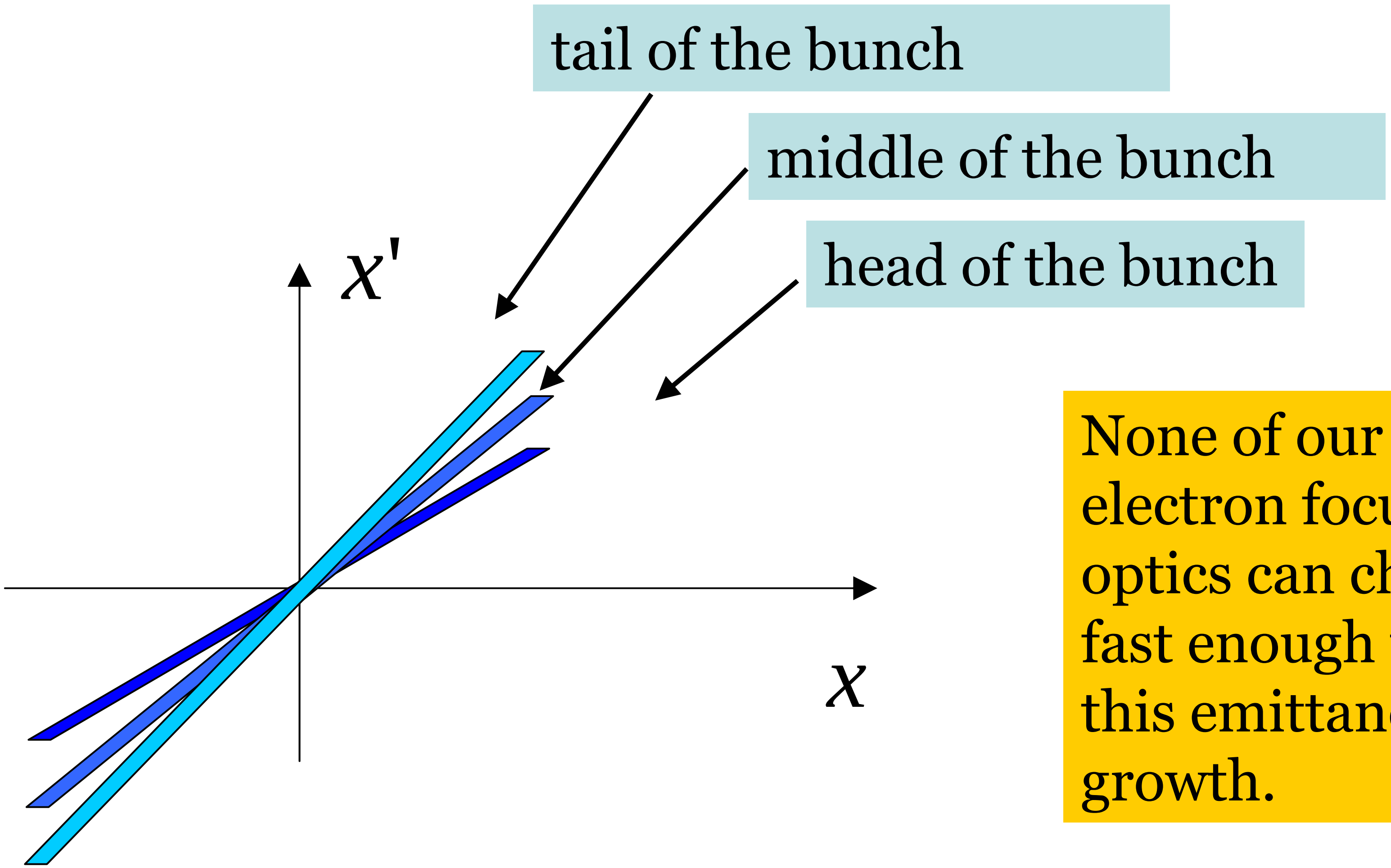


Gauss' Law tells us that when the electric field changes along *z*, it must have a radial component also.

$$2\pi r E_r = \pi r^2 \frac{dE_z}{dz}$$

$$E_r = \frac{r}{2}\frac{dE_z}{dz}$$

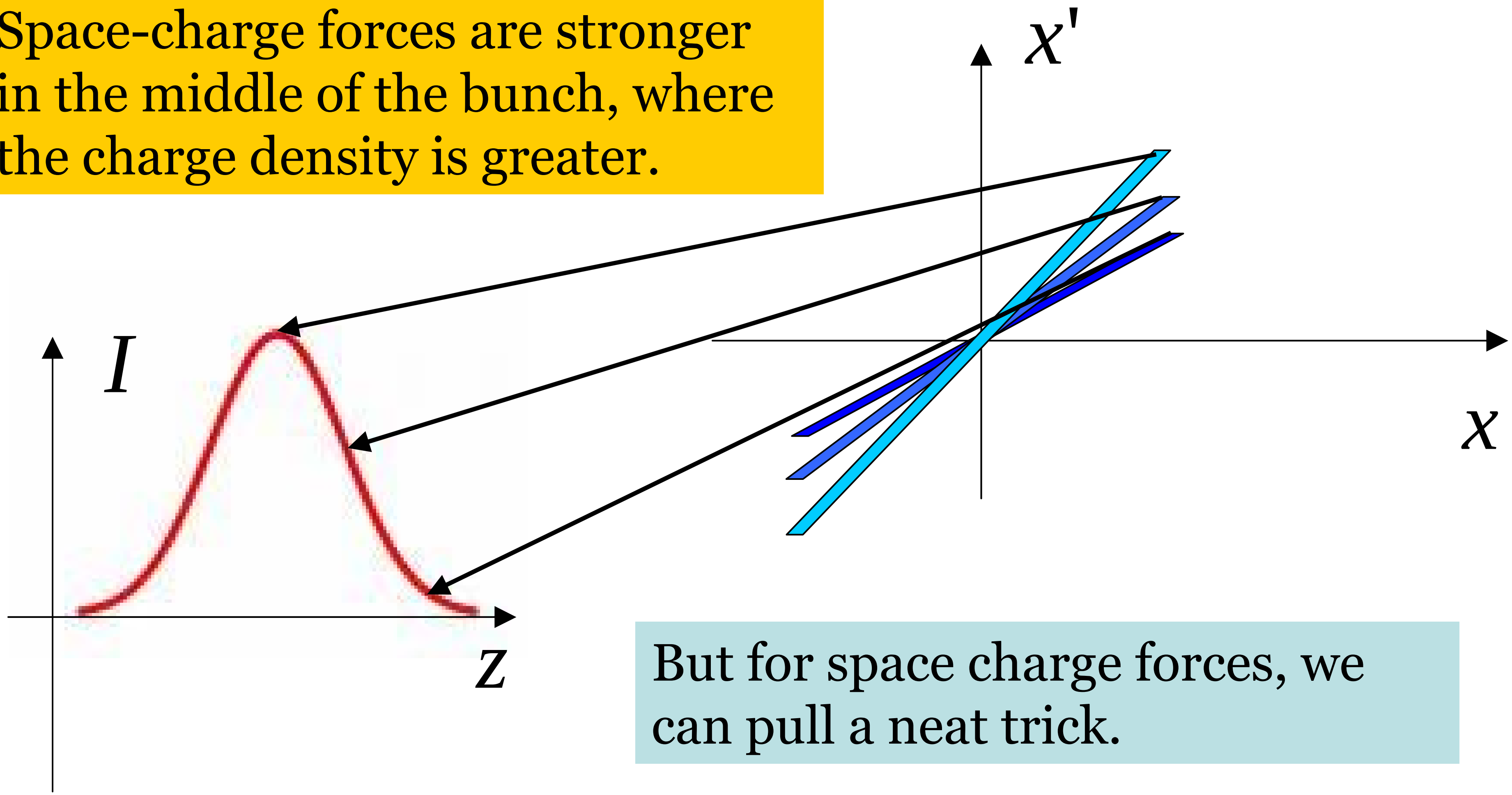
The emittance for the whole bunch (projected emittance) is increased as the trace space distribution is smeared out.



None of our electron focusing optics can change fast enough to fix this emittance growth.

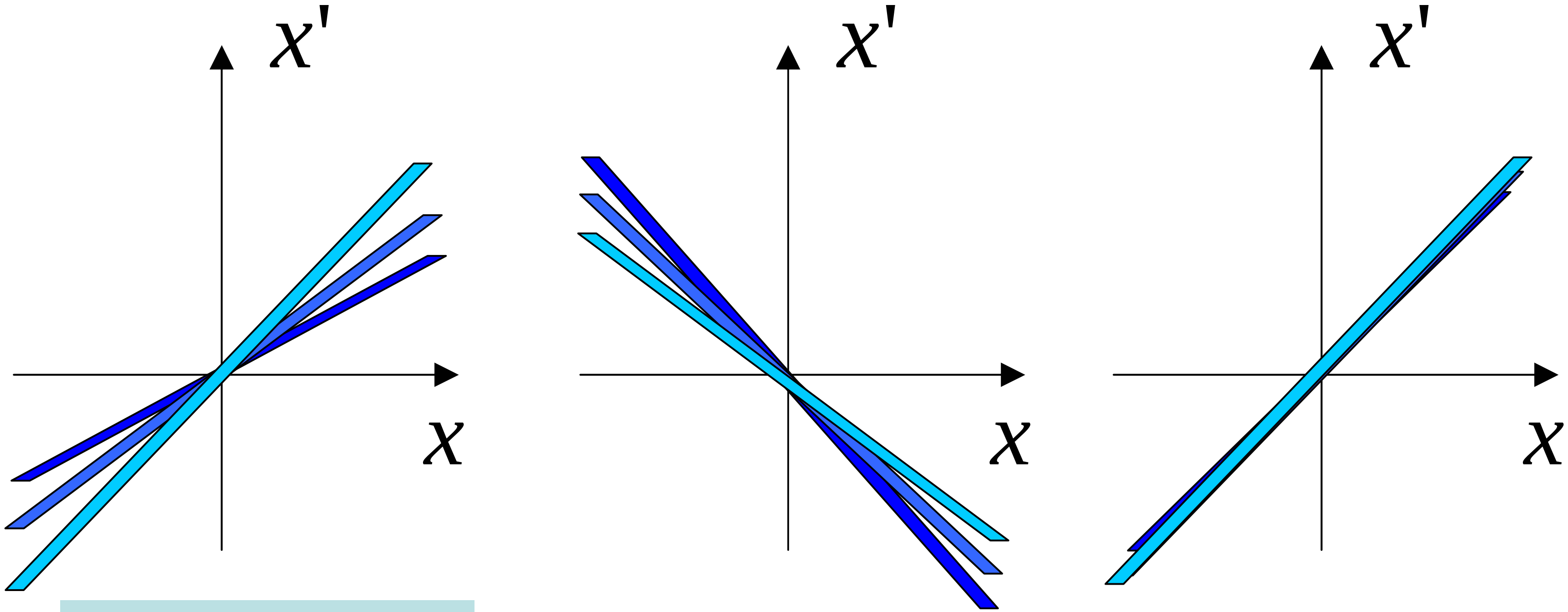
Repulsive space-charge forces smear out the trace space, too.

Space-charge forces are stronger in the middle of the bunch, where the charge density is greater.



But for space charge forces, we can pull a neat trick.

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



before solenoid

immediately after solenoid

after drift through a waist

The plan for the morning

- Motivation for high-quality electron beams
- Description of beam quality
  - beam brightness and emittance
- Evolution of beam quality in a linear accelerator
  - emittance growth and compensation

Tomorrow!

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