The CERN Accelerator School

Free Electron Lasers and Energy Recovery Linacs
(FELs and ERLs)
Hamburg, Germany
May 31st - June 10th, 2016

Electron Sources and Injection Systems

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Outline

- Applications of electron sources
  - FEL, ERL, Inverse Compton scattering, …
- Electron source figure of merit
  - Brightness
- Electron injectors
  - Cathode physics
  - Injector gun types
    - Beam dynamics in RF guns
  - Space charge effects
  - Emittance compensation (Ferrario’s lecture)
  - Injection into the linac
    - Acceleration and compression

Motivation

Ultra-high Free Electron Lasers (FELs), Energy Recovery Linacs (ERLs) light sources, Plasma-based accelerators, etc. demand

- *medium/high average current: from* ~μA to mA and higher
- *high brightness electron beams* (HBEBs)
  - ultra-low normalized emittance: ~mm mrad and less
  - high peak current: ~kA
  - beam charge from few pC to 1 nC
    - Careful definition and specific requirements for both electron sources and injection systems
      - The final beam quality is set by the linac and ultimately by its injector and electron source

A large number of quasi-"monochromatic" electrons, concentrated in very short bunches, with small transverse size and divergence, means high particle density 6D phase-space **=> high brightness**

Brightness

1939 von Borries and Ruska (Nobel prize in Physics in 1986 for the invention of the Electron Microscope) introduced the so called beam brightness ("Richstrahlwert") defined as:

$$B_{micr} = \frac{I}{A\Omega} \approx constant$$

The smaller the spot the larger the divergence.

The brightness defines then the quality of the source and determines the kind of experiments

Contrast

$$Brightness = \frac{Ne}{\pi r^2 \pi \alpha^2 \Delta t}$$

Spatial resolution **Coherence** **Time resolution**

5D Brightness

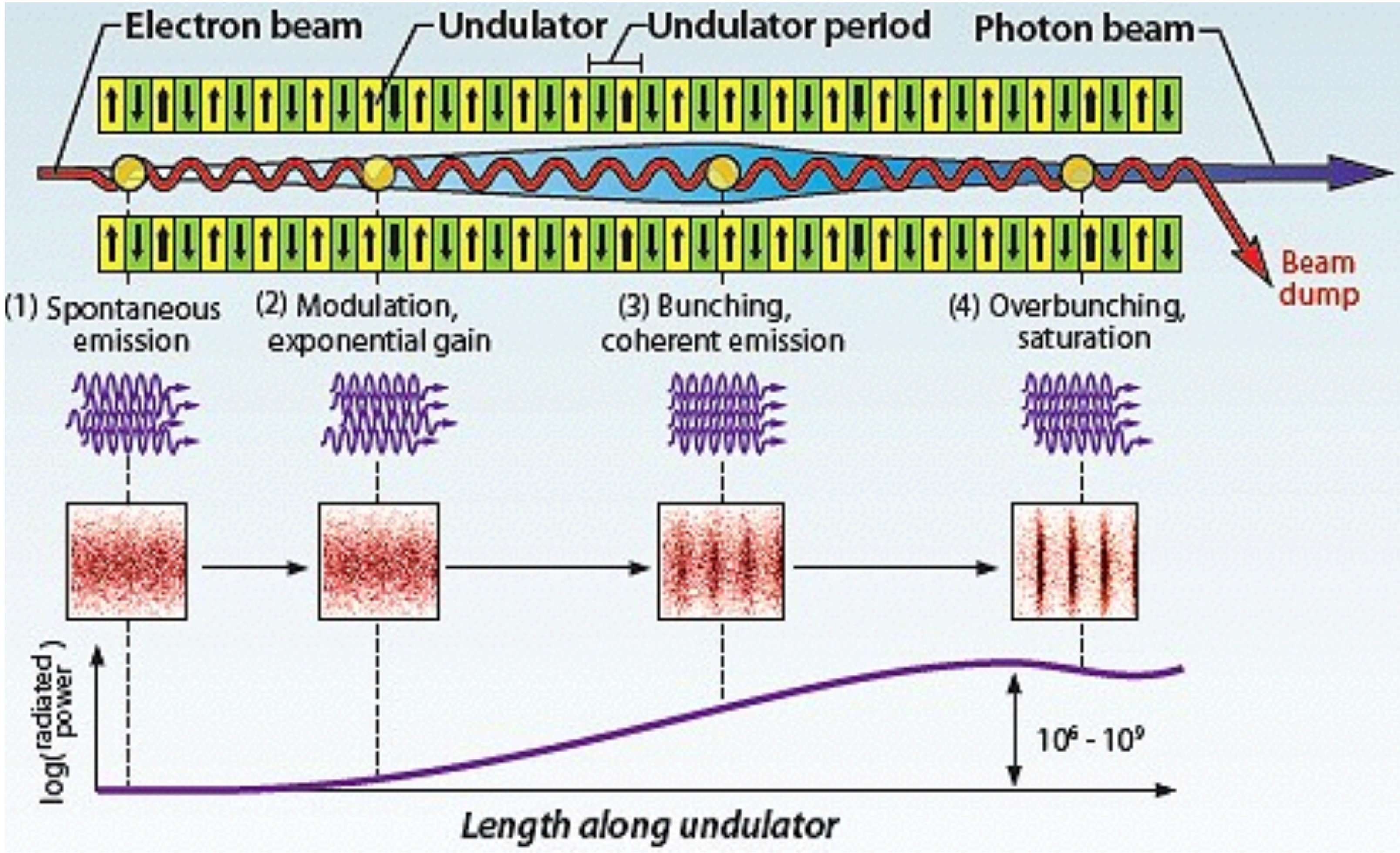
For FEL applications the 5D brightness is often used to compare electron sources

$$B_{5D} = \frac{2I}{\varepsilon_{nx}\varepsilon_{ny}} = \frac{2I}{(\beta\gamma)^2\varepsilon_x\varepsilon_y}$$

and it is the relativistic analogue of the microscopic brightness.

Pierce parameter

$$\rho = \frac{1}{2\gamma}\left[\frac{I}{I_A}\left(\frac{\lambda_u K[JJ]}{\sqrt{8}\pi\sigma_x}\right)^2\right]^{1/3}$$



https://www.lanl.gov/science/1663/june2010/story4b.shtml

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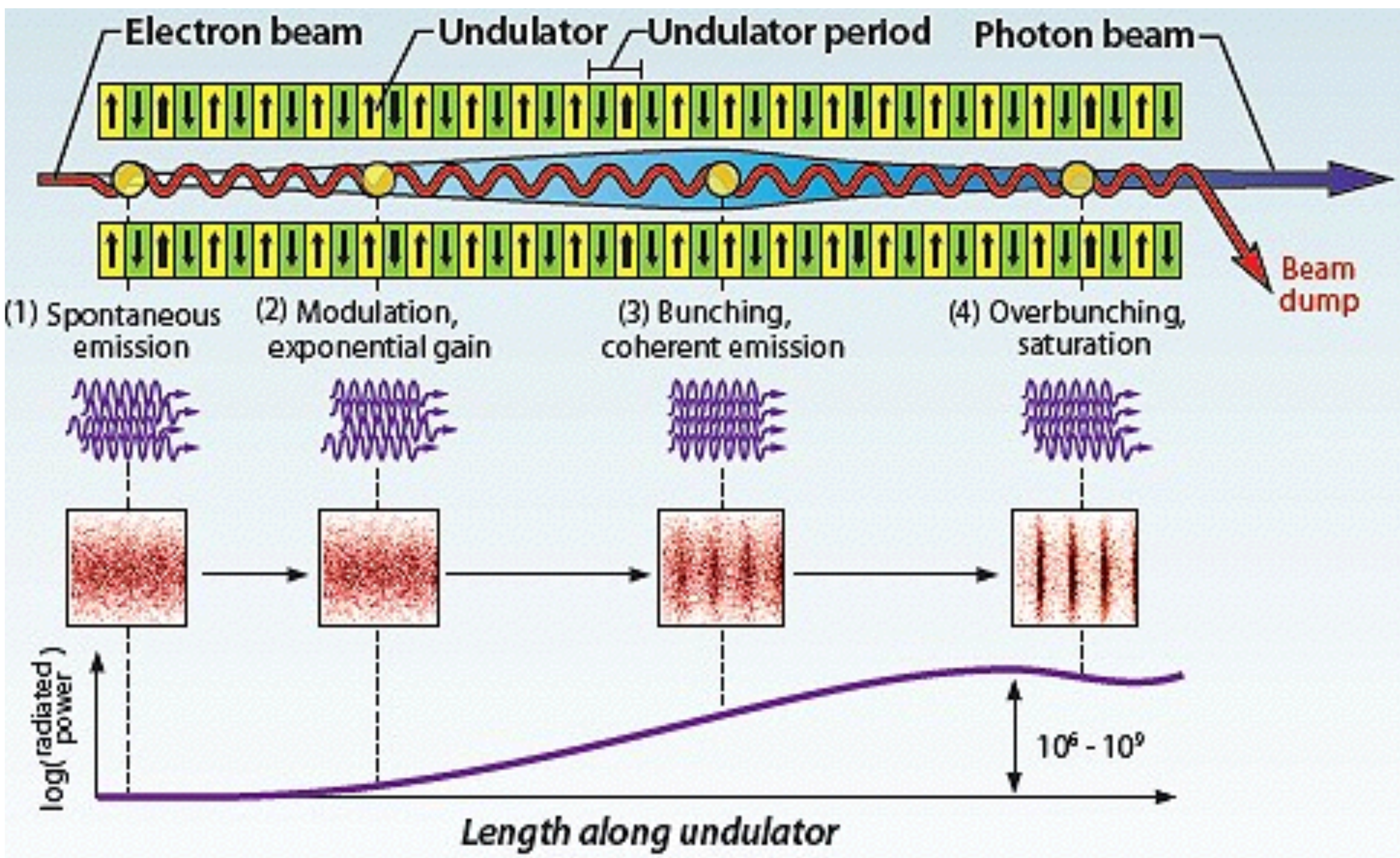

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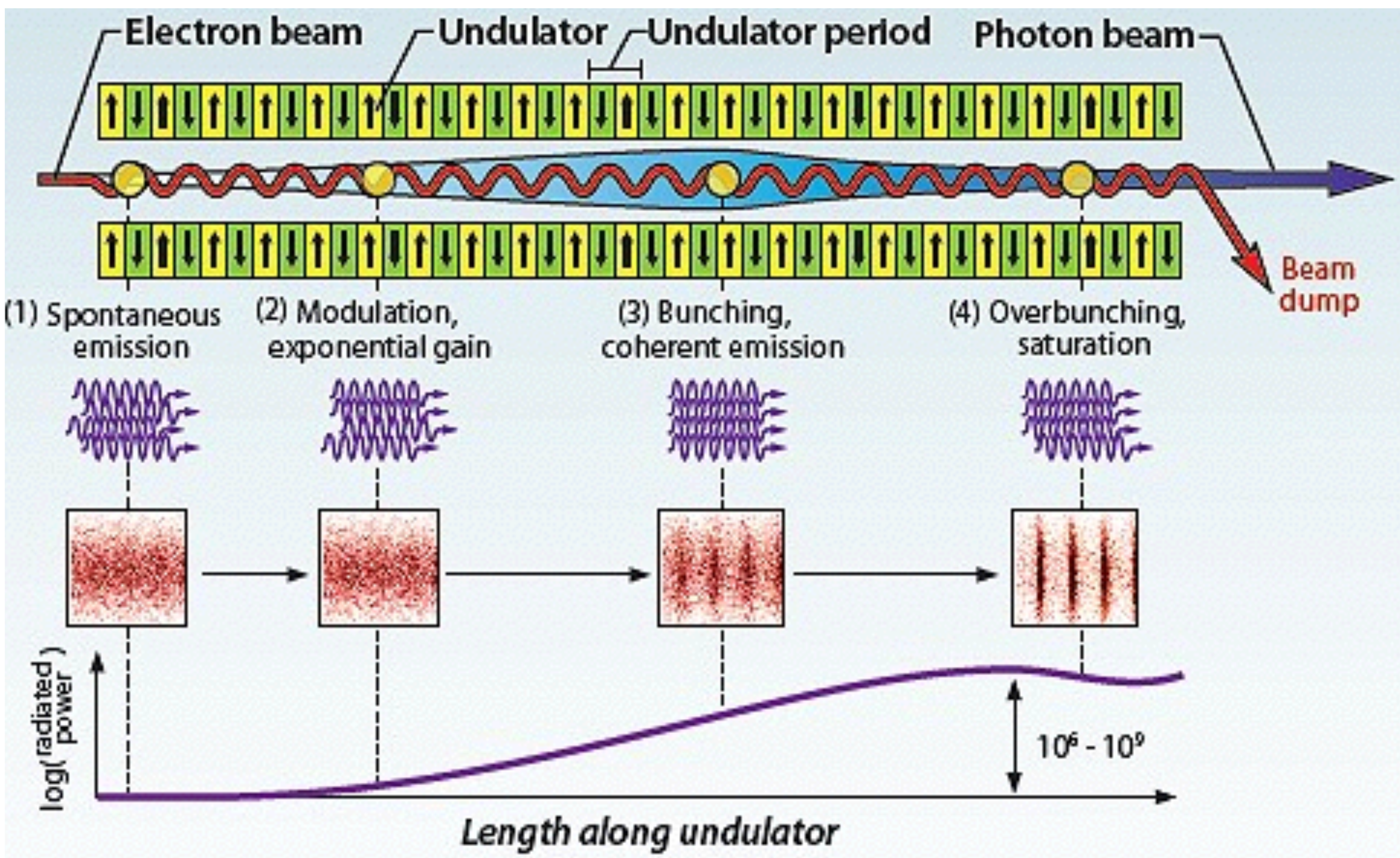

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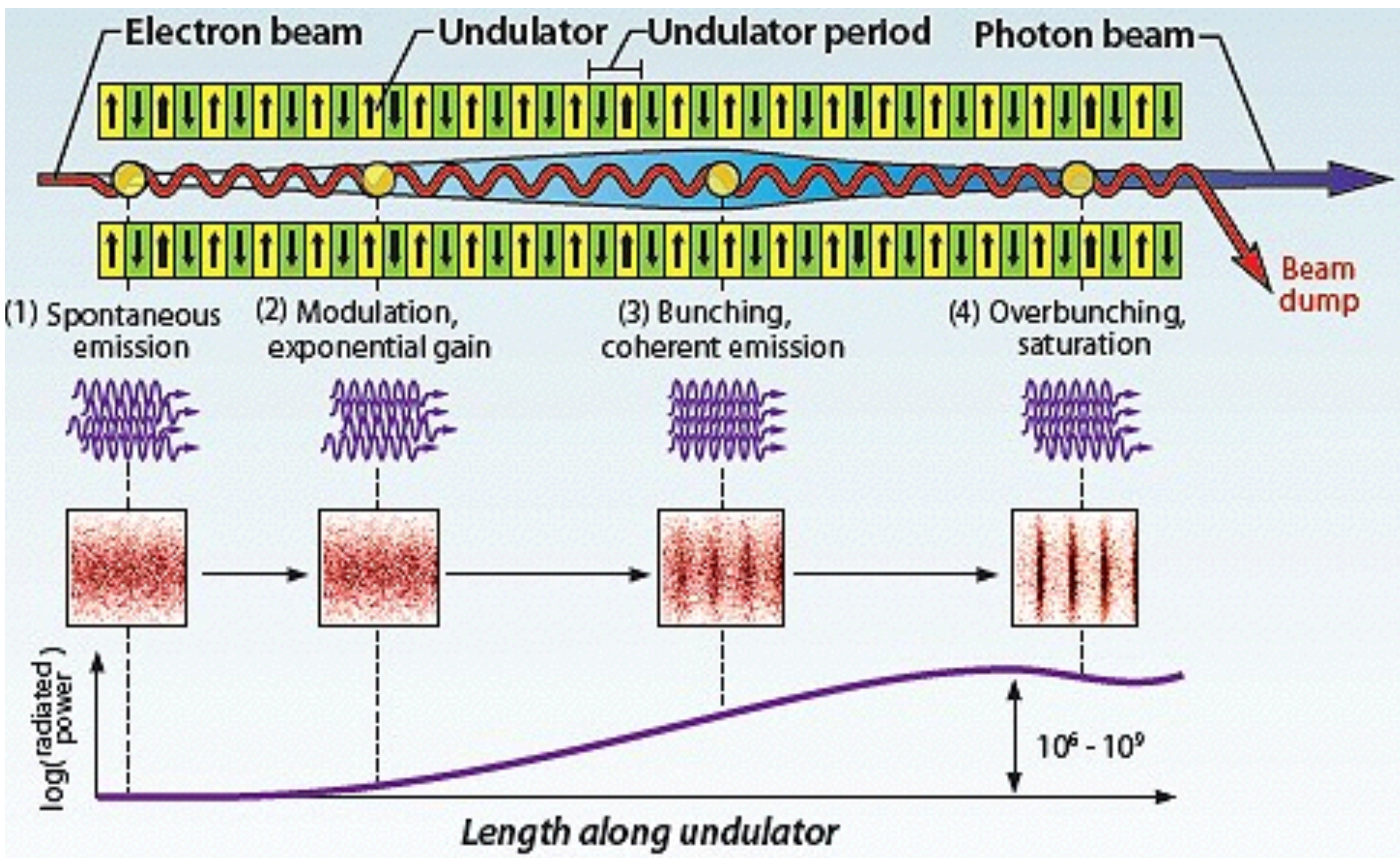

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Saturation power

$$P = P_{in}e^{\frac{z}{L_g}}$$

$$\boxed{L_g \propto B_{5D}^{-\frac{1}{3}}}$$

6D Beam Brightness

The meaningful figure of merit used to describe electron sources should be the 6D beam brightness defined as

$$B_{6D} = \frac{Ne}{V_{6D}}$$

where V_{6D} is the volume occupied by the beam in the 6D phase space (x, p_x, y, p_y, z, p_z)

$$V_{6D} = \int \psi(x, p_x, y, p_y, z, p_z) dx dp_x dy dp_y z dp_z$$

which is proportional to the product of the three normalized emittances

$$\boxed{B_{6D} \propto \frac{Ne}{\varepsilon_{nx}\varepsilon_{ny}\varepsilon_{nz}}}$$

Liouville Theorem

The 6D phase space of non-interacting particles in a conservative dynamical system is invariant -> **Liouville theorem**

As long as the particle dynamics in the beamline elements (transport optics, accelerating sections) can be described by Hamiltonian functions (no binary collisions, stochastic processes, etc.), the phase space density will stay constant throughout the accelerator.

The 6D brightness of a beam is determined by the source and cannot be improved, but only spoiled along the downstream accelerator.

The brightness generated at the electron source represents the ultimate value

Possible sources of rms emittance growth

Non-linear space charge forces

Non linear forces from electromagnetic components

Synchrotron radiation emission (in magnetic compressors)

Brightness Quantum Limit

Due to the *Pauli exclusion principle*, there is a **maximum brightness theoretically achievable** by an electron beam, as the 6D phase space density is fundamentally limited, with one electron spin up-down pair in each elementary quantum h^3 unit of phase space volume, as set by *Heisenberg uncertainty principle*

$$B_{quantum} = \frac{2e}{h^3}(m_0 c)^3 = \frac{2e}{\lambda_c^3} \approx 10^{25} \frac{A}{m^2}$$

The degeneracy parameter δ represents the number of particles per elementary volume of the phase space

$$\delta = \frac{B}{B_{quantum}}$$

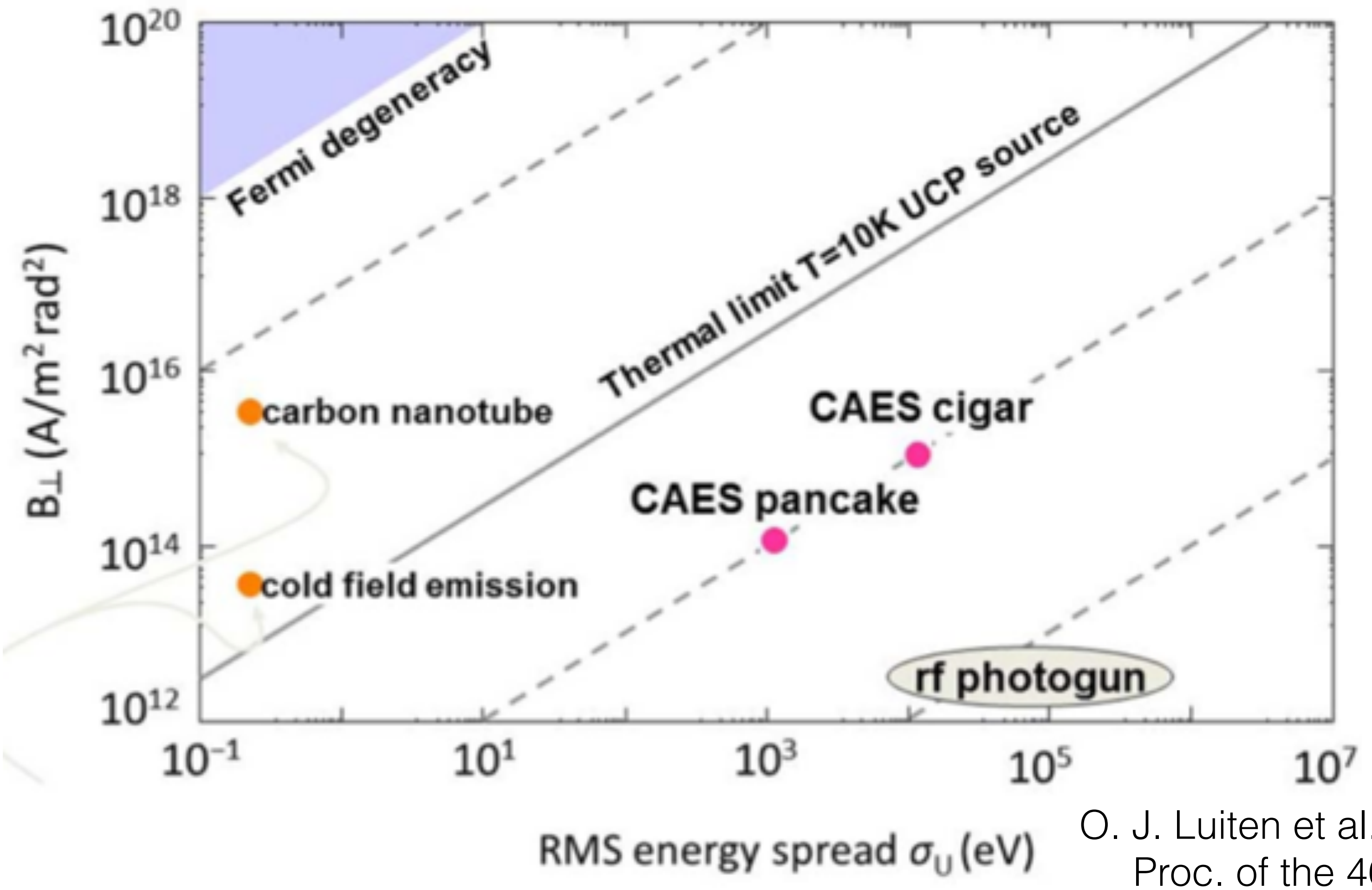
State-of-the-art electron sources

In numbers: $N \approx 10^9 \ , \ \sigma_\gamma \approx 10^{-3} \ , \ \varepsilon_n \approx 1 \ mm \ mrad \ , \ \sigma_t \lesssim 1 \ ps$

$$\boxed{B \approx 10^{15} \ \frac{A}{m^2}}$$

Brightness Quantum Limit

$$B_{6D} \propto \frac{Ne}{\varepsilon_{nx}\varepsilon_{ny}\sigma_t\sigma_\gamma}$$



O. J. Luiten et al., Ultracold electron sources, Proc. of the 46th Workshop of the INFN Eloisatron Project, Erice 2005

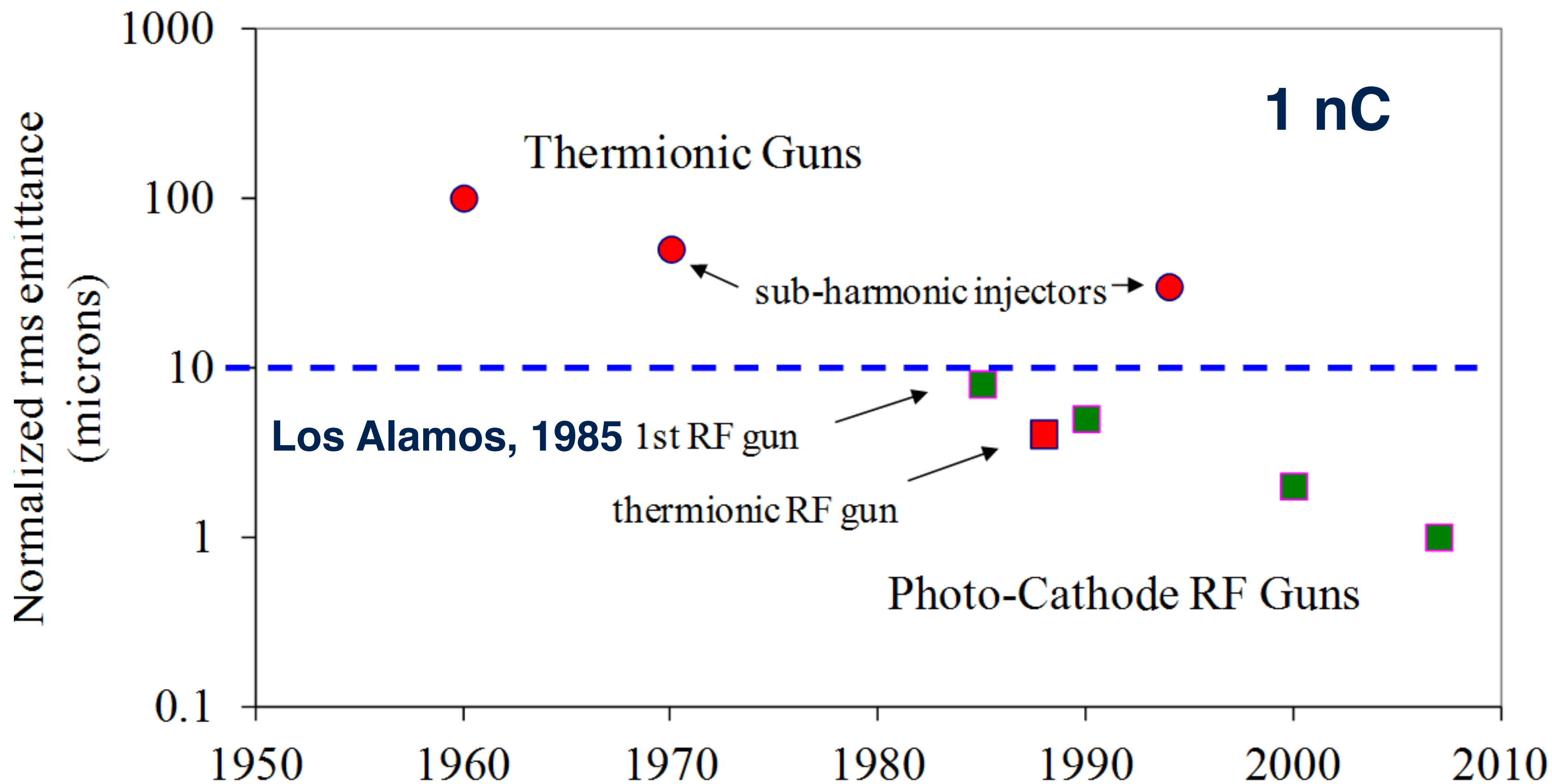
The degeneracy factor inside a metal is ~1.

How do we lose 10^{-11} orders of magnitude then?

Electron emission mechanism and Coulomb interaction

Injectors: a bit of history

An electron Injector is the overall system from the electron source up to energies where space charge forces can be considered negligible



Dowell, Rao, *An Engineering Guide To Photoinjectors*,

The **need for fast and precise control of the electron pulse shape** for better beam quality led to the replacement of thermionic gun with **photocathode RF guns** because of the impressive reduction in transverse emittance (10 times and more), promoted by the **ability to shape drive laser pulses and rapidly accelerate electrons from rest to relativistic energies**

Elements of an Electron Injector

- An electron injector is the first part of the accelerating chain
  - The electron beam generated at rest energy is accelerated and guided up to energies where space charge force effects are negligible and under control, therefore its evolution is not space charge dominated anymore
  - Space charge forces scale inversely with the square of the beam energy
- Space charge forces influence the beam dynamics and are one the main performance limitations in high brightness electron injectors

Emission and initial acceleration

- Thermionic cathode
  - DC gun
  - NCRF gun
- Photo-electric cathode
  - DC gun
  - NCRF gun
  - SCRF gun
- Field emission cathode
  - Pulse-DC
  - RF

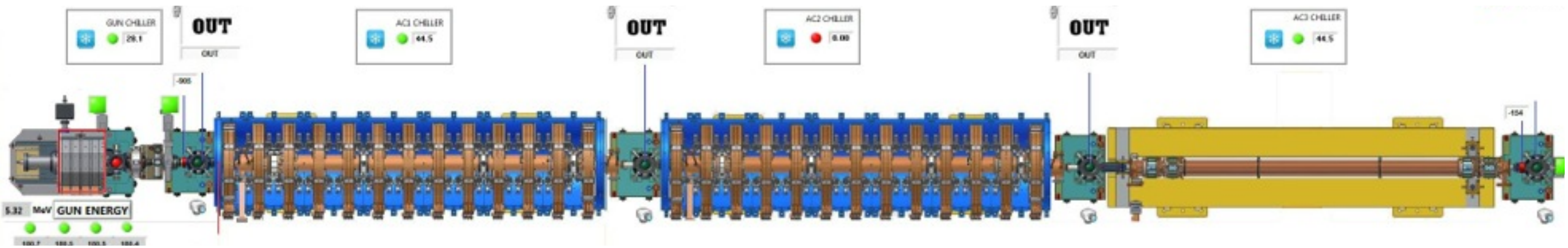
Beam manipulation

- Emittance compensation
  - Solenoid focusing
  - RF focusing
  - Slice phase space matching
- Ballistic compression
  - …
- Magnetic compression
  - RF harmonic linearization
- RF compression
  - Solenoid focusing

Acceleration

- Capture into the booster
- Emittance preservation
- Longitudinal phase space preservation

Elements of an Electron Injector



Emission and initial acceleration

- Thermionic cathode
  - DC gun
  - NCRF gun
- **Photo-electric cathode**
  - DC gun
  - **Normal Conducting RF gun**
  - SCRF gun
- Field emission cathode
  - Pulse-DC
  - RF

Beam manipulation

- **Emittance compensation**
  - Solenoid focusing
  - RF focusing
  - Slice phase space matching
- Ballistic compression
  - …
- **Magnetic compression**
  - RF harmonic linearization
- **RF compression**
  - Solenoid focusing

Acceleration

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High Brightness Photo-injector Components

A **photo-injector** consists of a **laser generated electron source** followed by an electron beam optical system which preserves and matches the beam into a high-energy accelerator

- **Drive laser**
  - To gate the emission of electrons from the cathode
- **Photocathode**
  - Releases picosecond electron bunches when irradiated with laser pulses
- **Electron Gun**
  - Accelerates electrons from the rest
    - The high electric fields produced by rf guns are necessary both to extract the high currents and to minimize the effects of space charge on emittance growth while the bunch is accelerated to relativistic energies where the space-charge forces vanish
  - Acts as strong defocusing lens => **Solenoid magnet**
- **Accelerating system**
  - to mitigate the space charge emittance growth

Typical High Brightness Photo-injector Layout

A **typical photocathode RF system** depicts a **1½-cell gun with a cathode in the ½ cavity** being illuminated by a laser pulse train. At the exit of the gun is a solenoid which focuses the divergent beam from the gun and compensates for space charge emittance. The drive laser is mode-locked to the RF master oscillator which also provides the RF drive to the klystron.

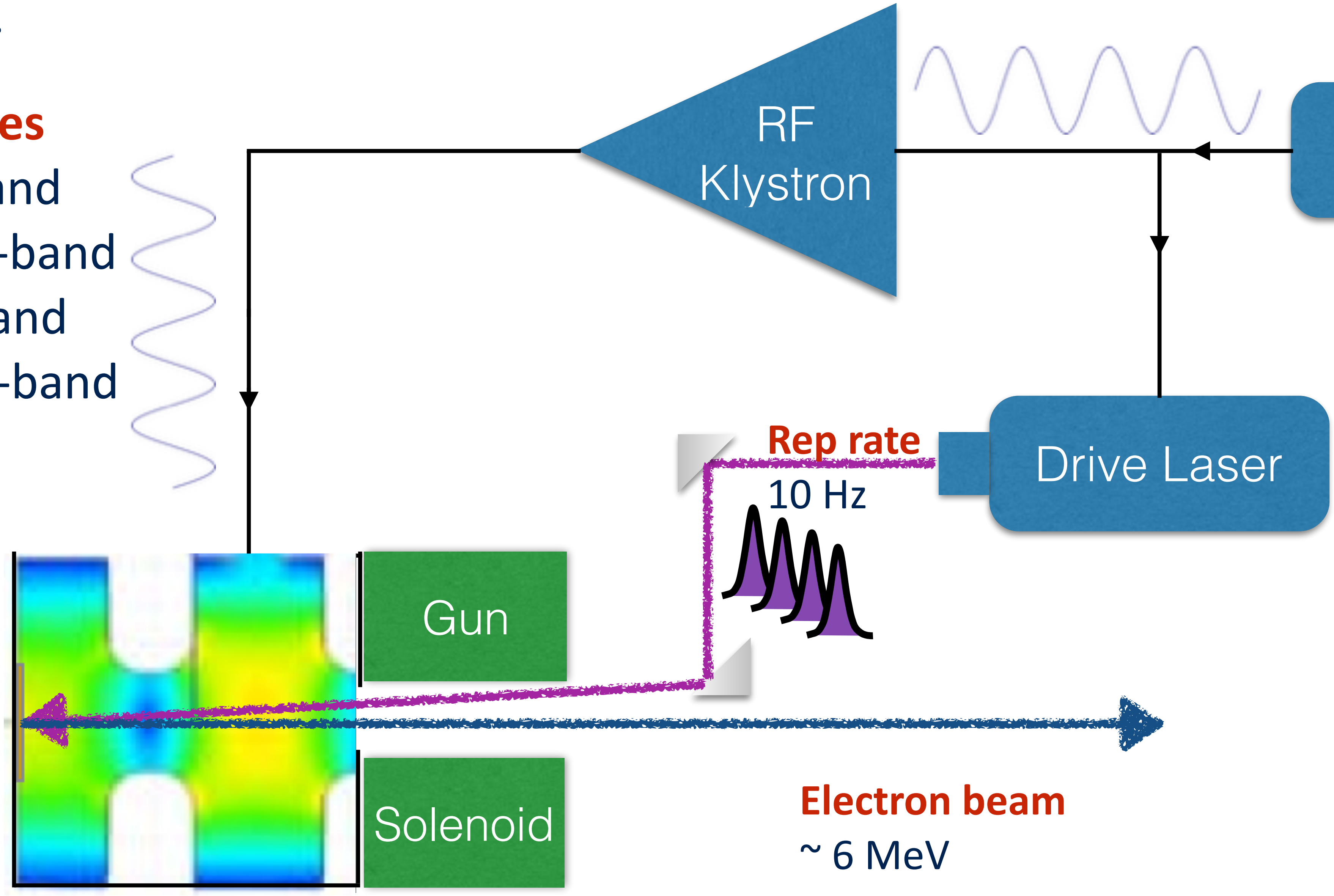
RF frequencies

1.3 GHz: L-band

2.856 GHz: S-band

5.6 GHz: C-band

11- 17 GHz X-band



Drive Lasers

Ti:Sa, Nd:YLF…

Photo-cathodes

Metal: Cu, Mg, …

Semi-conductor: CsTe,CsKSb, …

Cathode physics

- Cathodes are a fundamental part of electron sources
- Most injector systems use photocathodes
    - Exception: SACLA XFEL which uses a thermionic cathode
  - The ideal cathode should have **low intrinsic emittance**, **high quantum efficiency**, **long life-time, uniform emission** and should allow for low energy spread, high current density beams and full control of bunch distribution => **fast response**
- <u>Low charge regime</u>: the ultimate brightness performance of the linac is set by the **cathode intrinsic emittance**
- <u>High repetition rates photon sources</u>: high **quantum efficiency** photocathodes are required

Electron emission

The **emission process determines the fundamental lower limit of the beam emittance,** called as **intrinsic emittance**, which depends on the three emission mechanisms

1. **thermionic** emission

2. **field** emission

3. **photo-electric** emission

The probability of a particle to occupy a given energy state is described by a proper statistic.

Particles which can share the same energy state follow the **Maxwell-Boltzmann (MB) distribution**,

$$f_{MB} = e^{-E/k_B T}$$

while those having only one particle per energy state follow the **Fermi-Dirac (FD) distribution**

$$f_{FD} = \frac{1}{1 + e^{(E-E_F)/k_B T}}$$

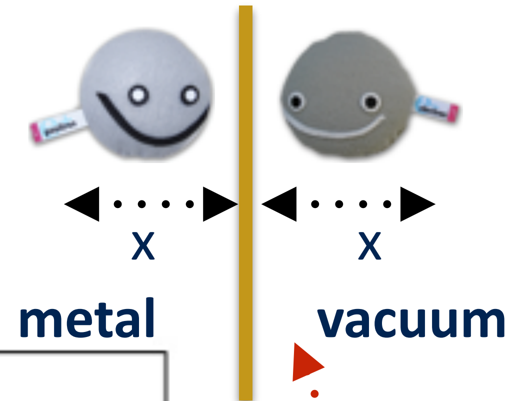
The MB distribution is used for thermionic emission, while **field and photo-emission** calculations use the FD distribution, since the excited **electrons come from energy levels below the Fermi level, i.e. $E<E_F$**

D. Dowell, http://uspas.fnal.gov/materials/10MIT/MIT-High-Brightness.shtml

Fields near the cathode surface

Electric potential energy

$$e\Phi_{tot} = e\Phi_{work} - \frac{e^2}{16\pi\varepsilon_0 x} - eE_0 x$$



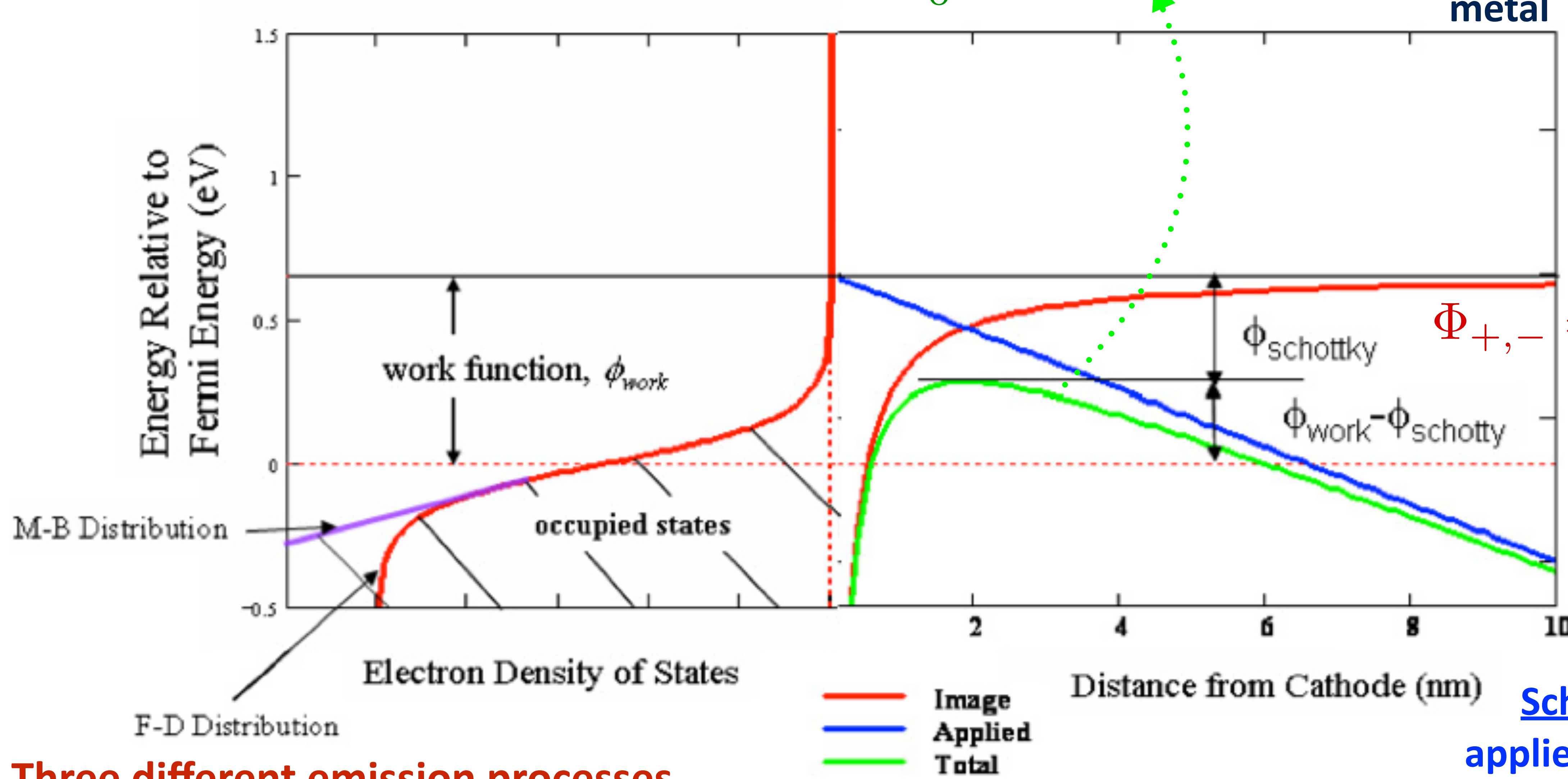


Image charge

$$\Phi_{+,-} = -\frac{e^2}{16\pi\varepsilon_0 x}$$

Schottky effect

applied external field lower the barrier

$$\Phi_{sh} = -eE_0 x$$

Three different emission processes

1. Thermionic emission
2. Photo-electric emission

Require electrons with energies greater than the work function to escape the barrier

3. Field emission

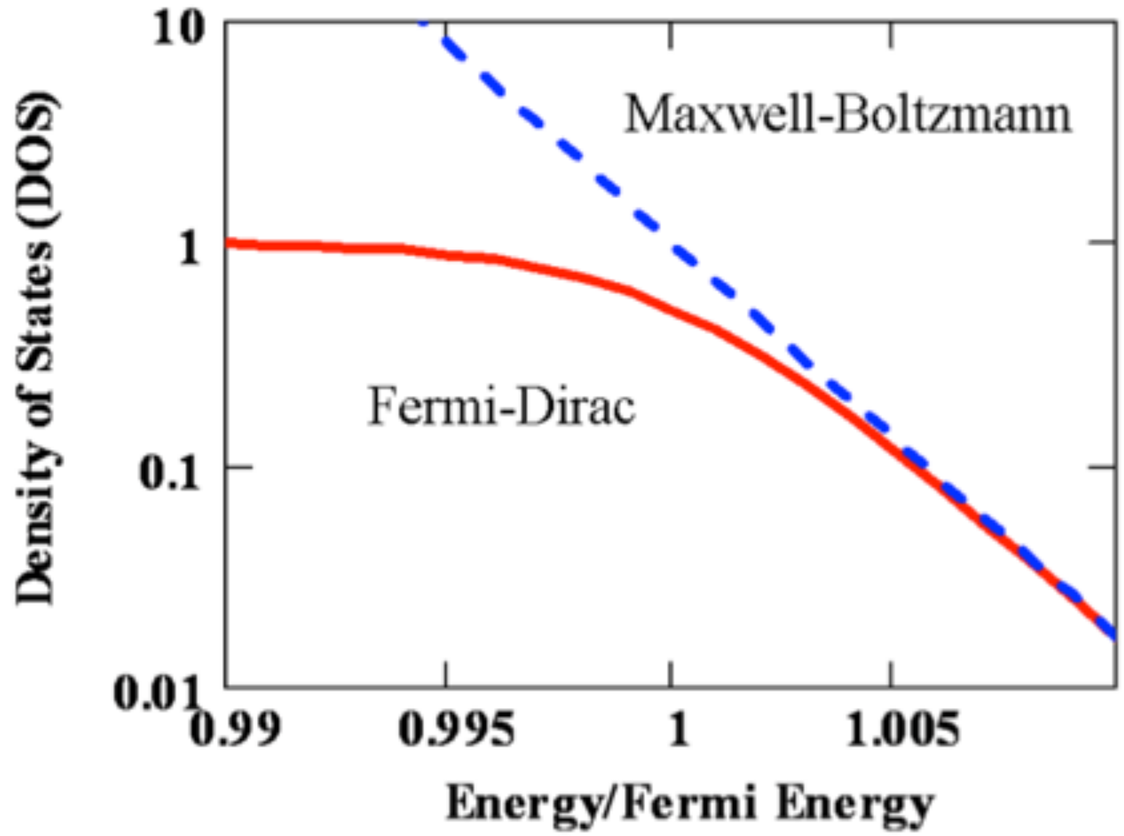
Consequence of the Schottky effect. Electrons tunneling the barrier. Very fast dependence on applied field => DARK CURRENT

Thermionic emission

In order for an electron to escape a metal it needs to have sufficient kinetic in the direction of the barrier to overcome the work function

$$\frac{mv_x^2}{2} > e\Phi_{work} \rightarrow v_x > \sqrt{\frac{2e\Phi_{work}}{m}}$$

Since only the high energy tail of the FD distribution will matter, i.e. for E>EF, we can replace it with the classical MB distribution



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Thermionic emission

Assuming the cathode has an applied electric field high enough to remove all the electrons, but low enough to not affect the barrier, then the thermionic current density for a cathode at temperature T is given by the **Richardson-Dusham equation**

$$j_{th} = n_0 e < v_x >= n_0 e \int_{v_x > \sqrt{\frac{2e\Phi_{work}}{m}}} v_x f_{MB} d\vec{v} = AT^2 e^{-\Phi_{work}/k_B T}$$

A is Richardson constant ~ 1 A/mm^2

The velocity spread emitted thermo-electrons, due to the electron temperature, is given by

$$\langle v_x^2 \rangle = \frac{\int v_x^2 e^{-\frac{m v_x^2}{2K_B T}} dv_x}{\int e^{-\frac{m v_x^2}{2K_B T}} dv_x} = \frac{K_B T}{m}$$

and gives the beam angular divergence, hence its thermionic emittance

$$\epsilon_{thermionic} = \sigma_x \sqrt{\frac{k_B T}{mc^2}}$$

Field emission

- It occurs when **electrons tunnel through the barrier potential** under the influence of very high fields of 10^9 V/m or more.
- Emission is by tunneling
  - the effect is purely quantum mechanical and requires an extremely high electric field to lower the barrier
- It strongly depends on
  - applied electric field
  - material characteristics
  - surface roughness

Fowler Nordheim equation for the field emitted current work function

$$I_{[A]} = 1.56 \cdot 10^{-6} \frac{\beta A_{[m^2]} E^2_{[V/m]}}{\Phi_{[eV]}} 10^{4.52\Phi^{-1/2}} e^{-\frac{6.53 \cdot 10^9 \Phi^{3/2}}{\beta E}}$$

In RF fields is localized at high E field phases, and is then transported trough the machine

L.W.Nordheim, Proc. R. Soc. Lond. A 1928 121, 626-639 doi: 10.1098/rspa.1928.0222

Photo-electric Emission

Spicer's three-step photoemission model

1. Photon energy absorption by electron

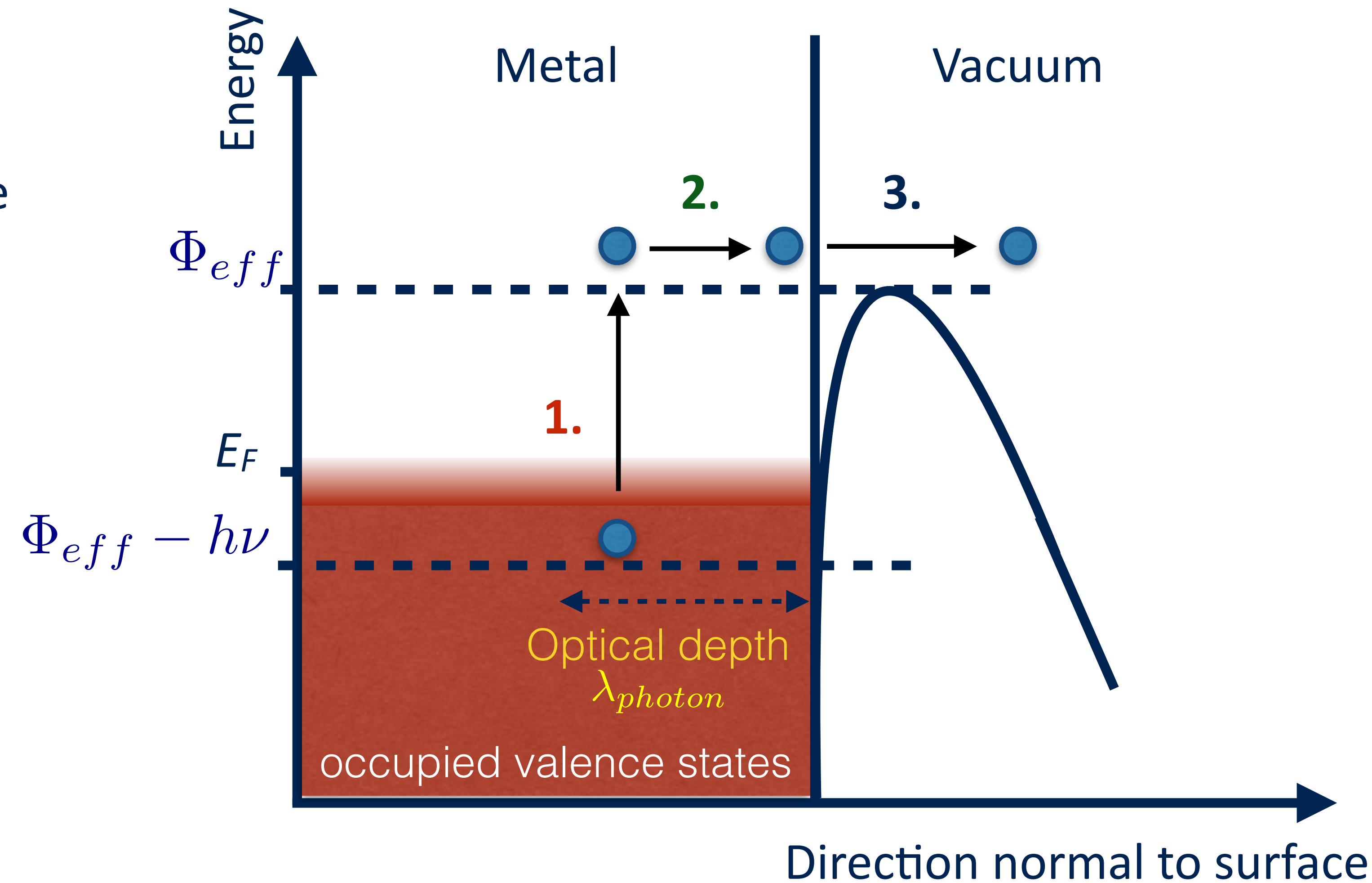
- The optical skin depth depends on photon wavelength (~14 nm for UV light on Cu)
  - reflectivity and absorption as the photons travel into the cathode

2. electron transport to the surface

- electron-electron scattering
- electron-phonon scattering
- angular cone of escaping electrons

3. electron escape through the barrier

- Schottky effect and abrupt change in electron angle across the metal-vacuum interface
- classical escape over the barrier due to the applied field



Quantum Efficiency

Combining the three steps together, the quantum efficiency, QE, can be expressed in terms of the probabilities for these processes to occur

1. **absorption of the photon with energy** $\hbar\omega$
2. **migration including e-e scattering to the surface**
3. **escape for electrons with kinematics above the barrier**

$$QE(\omega) = [1 - R(\omega)] F_{e-e}(\omega) \frac{\int_{E_F+\Phi_{eff}-\hbar\omega}^{E_F} dE \int_{\sqrt{\frac{E_F+\Phi_{eff}}{E+\hbar\omega}}}^{1} d(\cos\vartheta) \int_0^{2\pi} d\phi}{\int_{E_F-\hbar\omega}^{E_F} dE \int_{-1}^{1} d(\cos\vartheta) \int_0^{2\pi} d\phi}$$

Probability of a photon to be absorbed by the metal => **optical reflectivity**

R(w) ~ 40% for metals
R(w)~ 10% for semiconductors

Probability that an electron reaches the surface without scattering => **transport to surface**

e-e- scattering for metals
e-phonon scattering for semiconductors with another electron

Fe-e(w) ~ 0.2

Probability that an electron will be excited into a state with sufficient perpendicular momentum to escape the material => **escape over the barrier**

- occupied states with enough energy to escape ~0.04
- electrons with angle within the max angle for escape ~0.01
- azimuthally isotropic emission ~1

QE(Cu) ~ 0.6*0.2*0.04*0.01*1 **~ $5*10^{-5}$**

*D. H. Dowell, F. K. King, R. E. Kirby, and J. F. Schmerge, PRST AB **9**, 063502 (2006)*

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Intrinsic Emittance

The total energy inside the cathode after absorption of the photon is $E + \hbar\omega$, therefore the total momentum inside and outside is

$$p_{total,in} = \sqrt{2m(E+\hbar\omega)} \qquad p_{total,out} = \sqrt{2m(E+\hbar\omega-\Phi_{eff}-E_F)}$$

The usual definition of rms emittance is

$$\varepsilon_{n,x} = \beta\gamma\sqrt{< x^2 >< x'^2 > - \cancel{< xx' >^2}}$$

=0, **no correlation** between angle and position of electrons out of the cathode

σ_x transverse beam size determined by the size of the source, i.e. laser pulse

$$\varepsilon_{n,x} = \sigma_x \frac{\sqrt{< p_x^2 >}}{mc}$$

p_x transverse momentum determined by the emission process

$$< p_x^2 > = \frac{\int\int\int p_x^2 g(E,\vartheta,\phi)dEd(\cos\vartheta)d\phi}{\int\int\int g(E,\vartheta,\phi)dEd(\cos\vartheta)d\phi}$$

$$g(E,\vartheta,\phi) = [1 - f_{FD}(E+\hbar\omega)]f_{FD}(E)$$

electron distribution function which depends on the emission process

Photo-electric normalized emittance

$$\boxed{\varepsilon_{n,x}^{intrinsic} = \sigma_x\sqrt{\frac{\hbar\omega - \Phi_{eff}}{3mc^2}}}$$

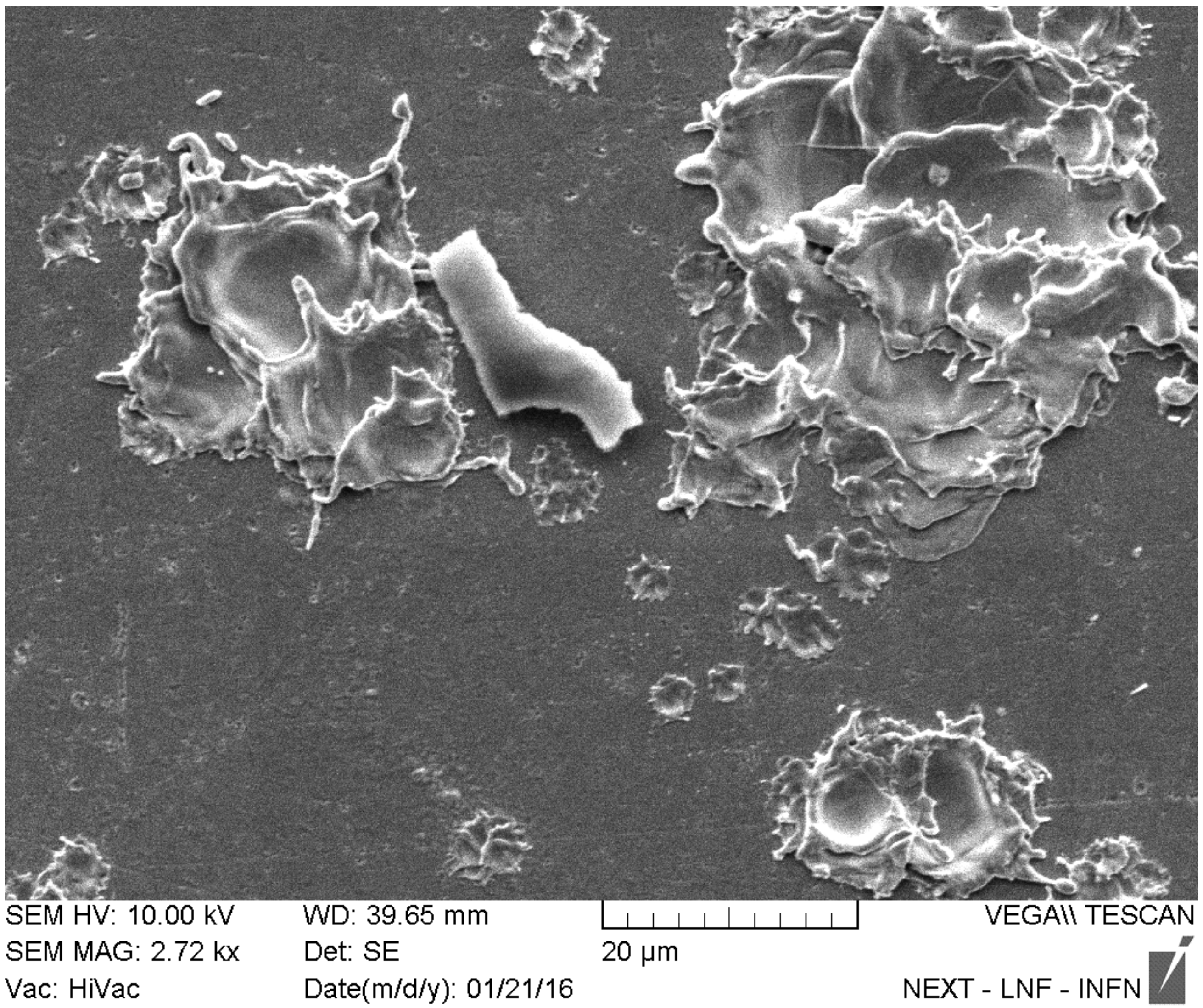
Cu cathode

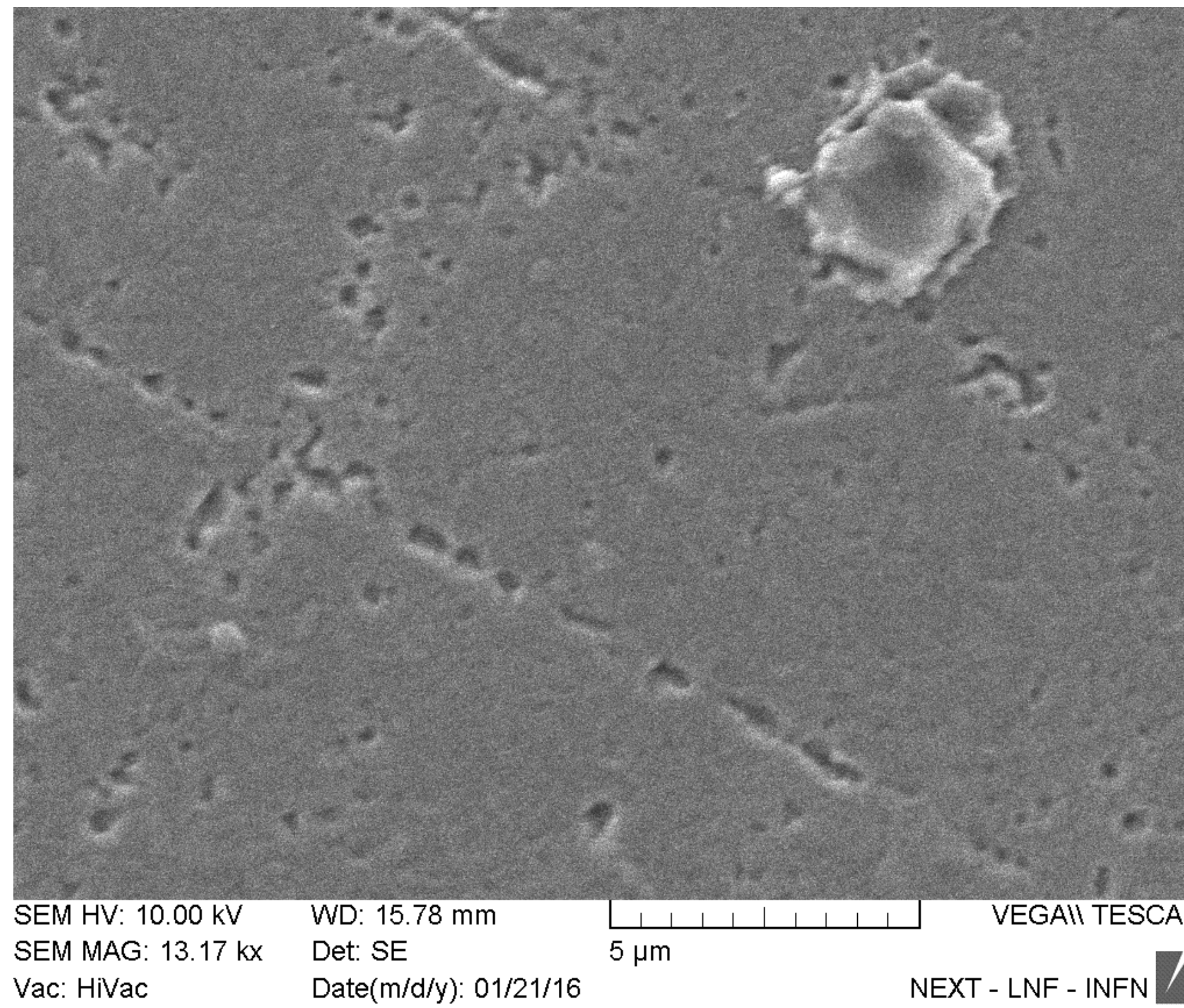
$$\approx 0.4\ mm\ mrad/mm$$

*D. H. Dowell, F. K. King, R. E. Kirby, and J. F. Schmerge, PRST AB **9**, 063502 (2006)*

How a real cathode looks like

SEM analysis of a copper cathode

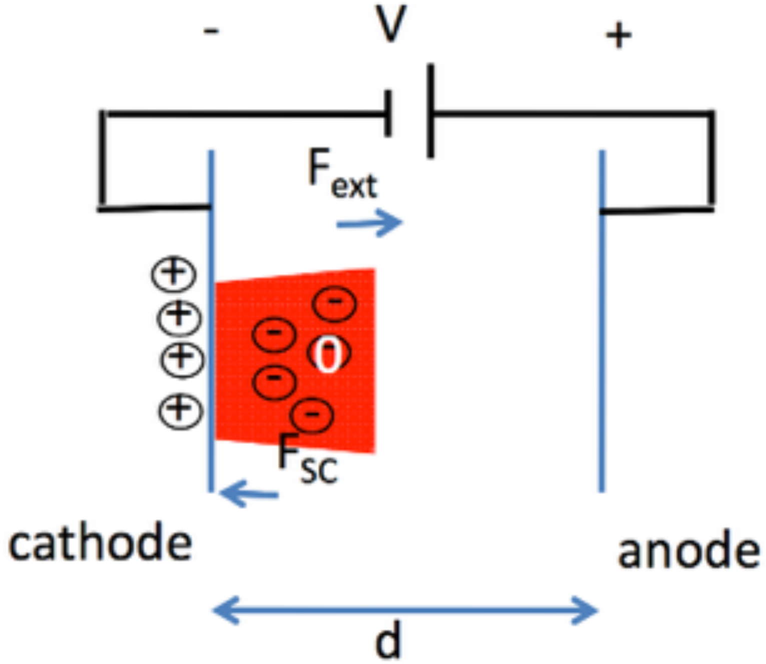




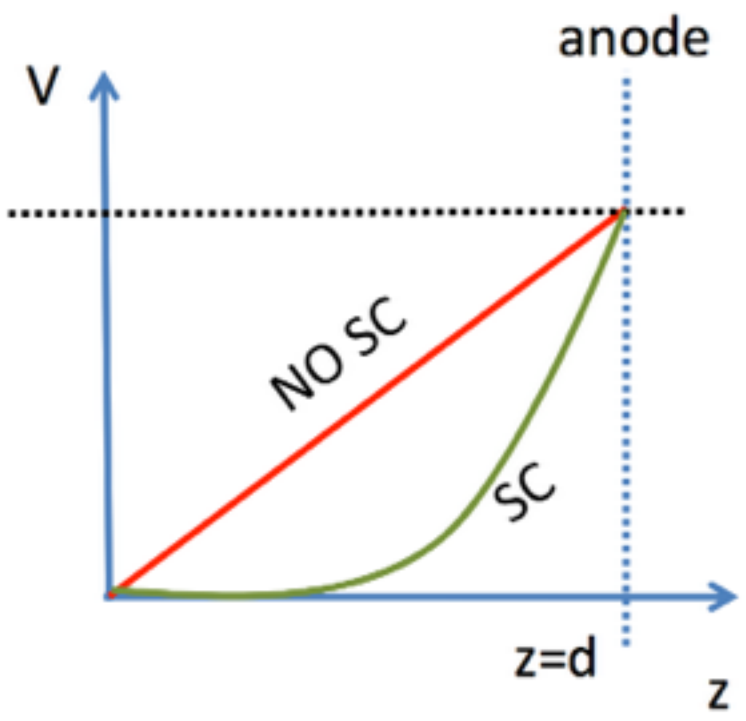
Effects of breakdown

Space Charge Effects

As emitted particles come out from the cathode, they create their own electric field



As electrons are extracted they start to fill the entire region of length d



This field in the beam tail is opposed to the external field, growing with the extracted charge

The effective total potential is distorted by this field

- The potential distortion creates asymmetries in the electron beam (tails) and set a **maximum extractable current in the steady state regime**

Child-Langmuir Law

The maximum current density in an electron source is typically given by the Child-Langmuir law, expressing how the steady state current varies with both the gap distance and the bias potential of the parallel plates:

$$j_{CL,1D} = \frac{4\varepsilon_0}{9}\sqrt{\frac{2e}{m}}\frac{V_0^{3/2}}{d^2}$$

Assumptions

- **infinitely wide beam** in the transverse dimensions (1D approximation)
- the **beam completely fills the accelerating gap** so that a steady state solution can be found
- **relativistic effects** can be **neglected**

BUT

In **state-of-art photo-injectors**

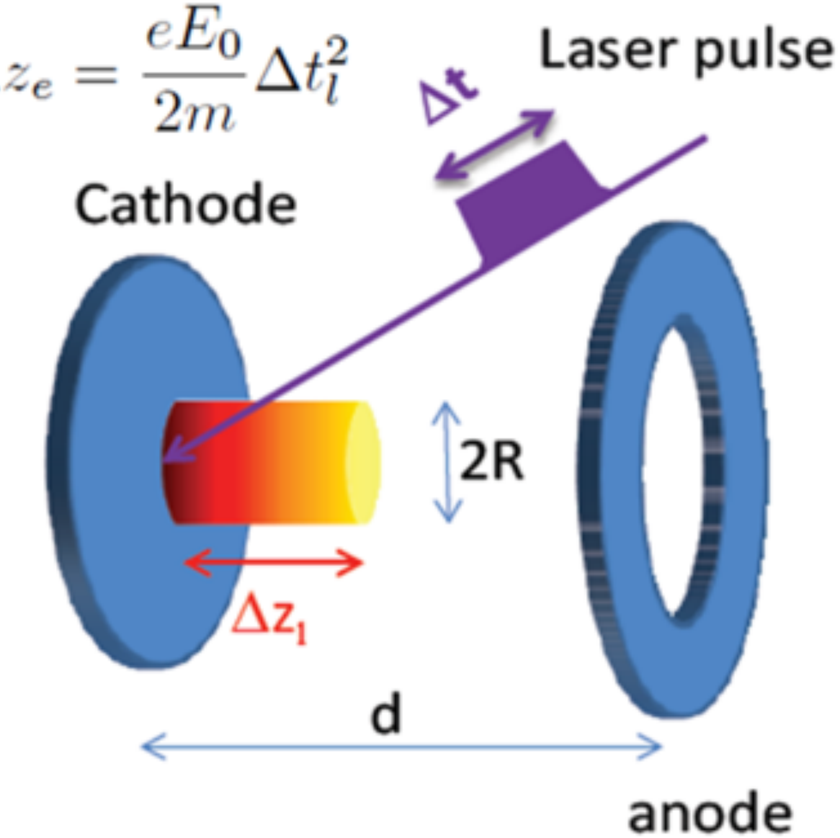
- the initial **electron beam pulse length** is always much **smaller than the accelerating gap**
- the **laser spot size** on the cathode tends to be small (**sub-mm**) to decrease the cathode emittance contribution

The 1D Child-Langmuir formula is not valid anymore

Space Charge Limit

Let's consider short bunches and introduce the **aspect ratio**

$$\Delta z_e = \frac{eE_0}{2m}\Delta t_l^2$$



$\frac{R}{\Delta z_e}$ **<<1 cigar-like beams**

Only a small part of the beam contributes to the space charge field and higher charge can be extracted

$$Q = J_{CL}\pi R^2 \propto \frac{V^{\frac{3}{2}}}{d^2}R^2 \propto (E_0 R)^{\frac{3}{2}}$$

$\frac{R}{\Delta z_e}$ **>>1 pancake-like beams**

The maximum surface density is set by the cathode extraction field

$$\frac{Q}{\pi R^2} < \epsilon_0 E_0$$

Courtesy of P. Musumeci

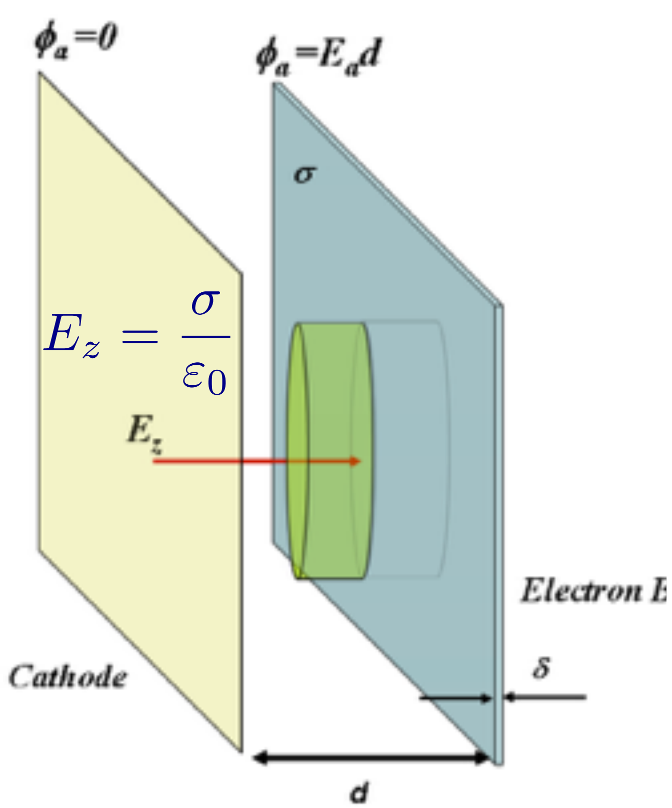
Space Charge Limit

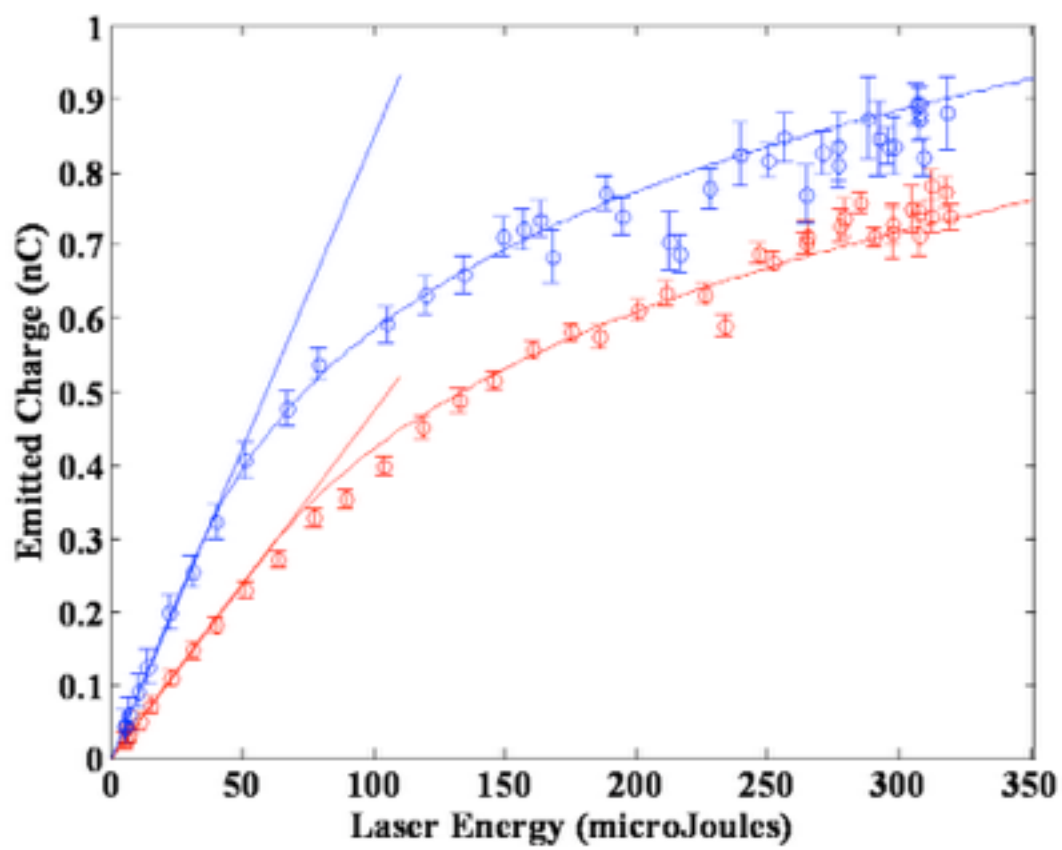
The space charge limit (SCL) is reached when the space charge field equals the applied, external field, E_a, and electron emission saturates

At the space charge limit (SCL) the emitted charge saturates and the emission becomes constant. If the transverse distribution is non-uniform and the cathode is driven to the SCL then different locations will saturate and other areas will not.

In the RF gun the signature observation of the SCL is the non-linear dependence of the charge on the laser energy

$$\sigma_{SCL} \equiv \varepsilon_0 E_a$$





LCLS-gun operating at a peak cathode field of 115 MV/m. The data were taken with the same beam size (1.2 mm diameter) but for different QE

Space Charge Limit Emittance

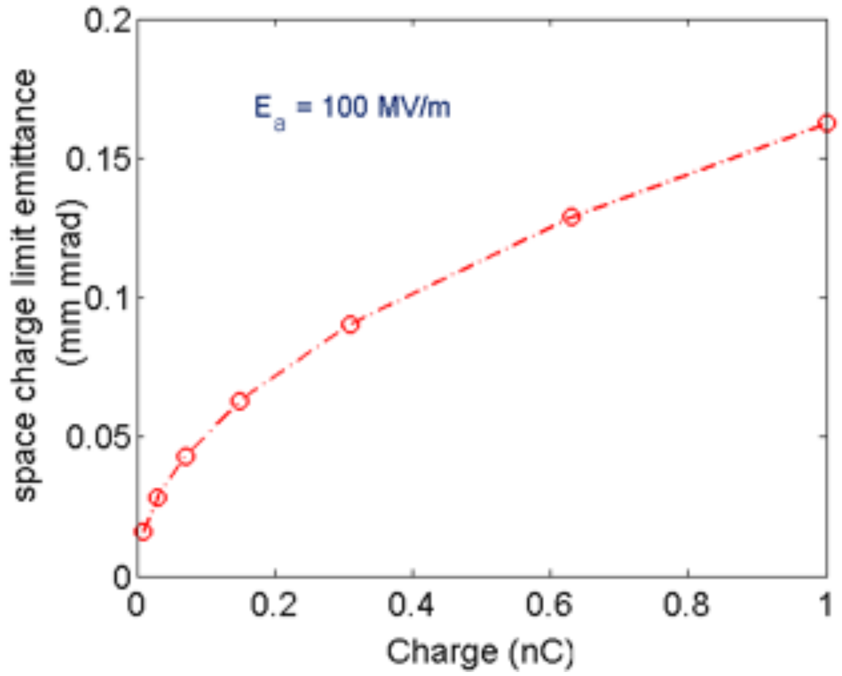
The SCL sets a minimum value for the beam emittance, once the applied field (RF field) value and the requested charge are known.

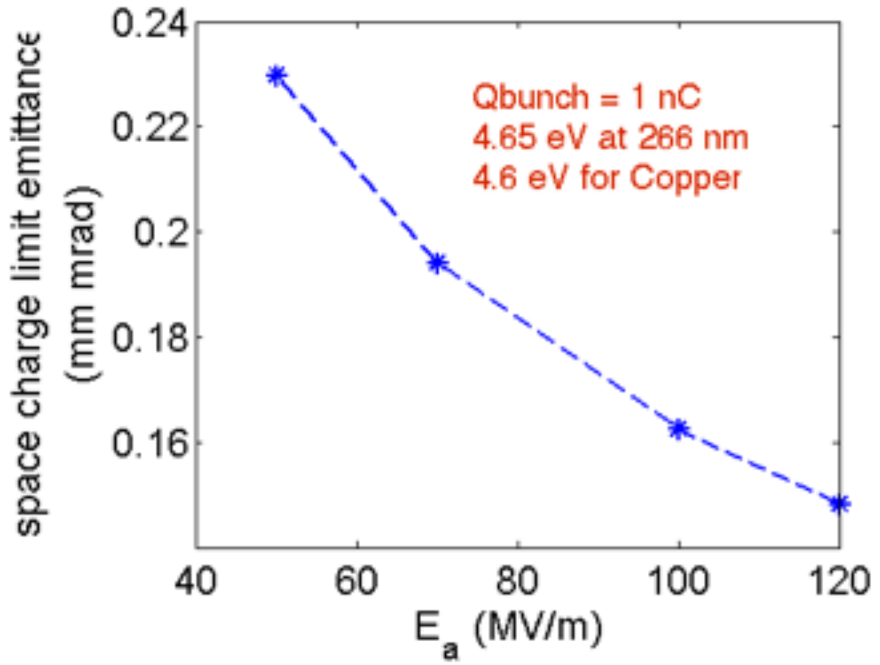
For a cylindrical uniformly filled beam with radius R, the rms size is

$$\sigma_x = \frac{R}{2} = \sqrt{\frac{Q_{bunch}}{4\pi\varepsilon_0 E_a}}$$

Substituting the normalized divergence for photo-electric emission, $\sigma_{x'}$, the normalized cathode emittance results in the SCL photoelectric emittance

$$\boxed{\varepsilon_{photo}^{SCL} = \sqrt{\frac{Q_{bunch}(\hbar\omega - \Phi_{eff})}{4\pi\varepsilon_0 mc^2 E_a}}}$$





RF Gun

Since we wish to accelerate electrons, the relevant modes are those with large longitudinal electric fields, E_z

$$\frac{dU}{dt} = q\vec{v} \cdot \vec{E}$$

These are the transverse magnetic (TM) modes.

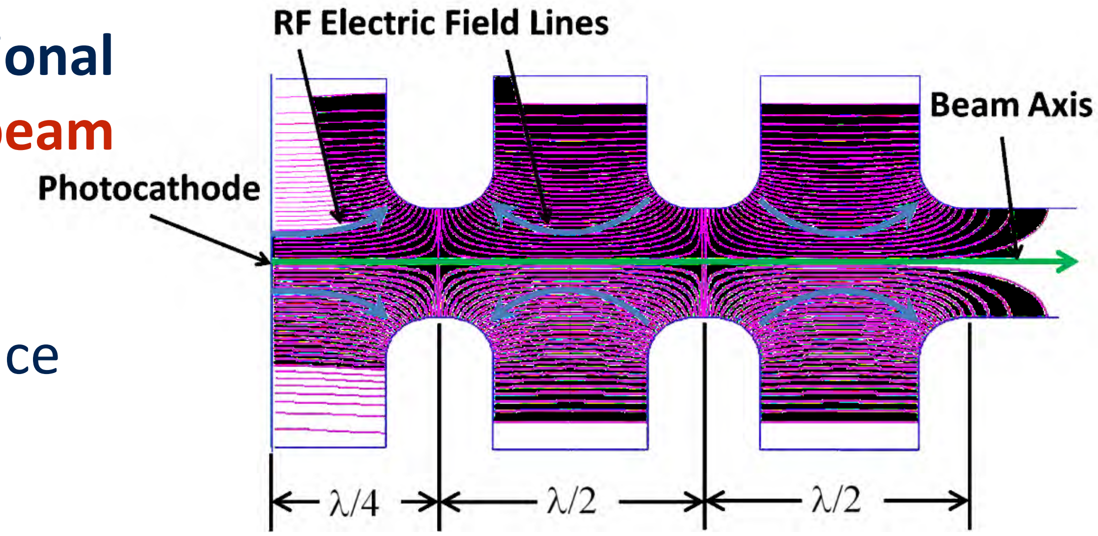
The **TM$_{mnp}$** designation denotes the mode is transverse magnetic since $B_z = 0$

m mode number: azimuth angle, **ϑ-dependence or rotational symmetry of the fields** => ***m = 0* for all RF guns, since a beam with rotational symmetry is desired**

n mode number: radial dependence of the field

p mode number: longitudinal mode of cavity => RF emittance

The full cell length for most RF guns is λ/2 and p = 1.



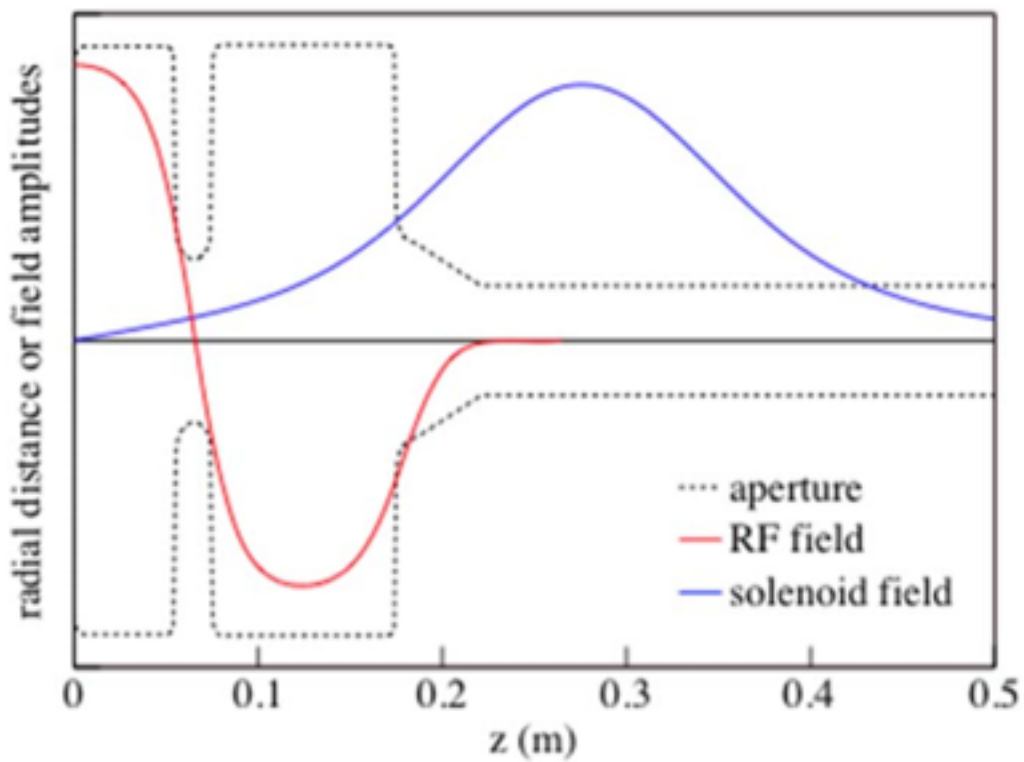
The longitudinal electric field for a pill box cavity is

$$E_z^{mnp}(r,z) = E_0 J_m(k_{mn}r)\cos(m\theta)\cos\left(\frac{2p\pi z}{\lambda}\right) e^{i\omega \frac{z}{c}}$$

Consider the pi-mode for a one and a half cell gun, therefore m=0, n=0, p=1, then the gun field

$$\boxed{E_z = E_0 \cos(kz)\sin(\omega t + \phi_0)\ ,\ \ k = \frac{\omega}{c}}$$

RF Gun



First order approximation from Maxwell equations solution for fundamental accelerating mode in a pillbox cavity.

Maxwell's equation **connect the momentum kicks of the radial electric field to the z- and t-derivative of the longitudinal electric field**:

$$E_z = E_0 cos(kz) sin(\omega t + \phi_0)$$

$$E_r = \frac{kr}{2} E_0 sin(kz) sin(\omega t + \phi_0) = -\frac{r}{2}\frac{\partial}{\partial z}E_z$$

$$B_\theta = c\frac{kr}{2} E_0 cos(kz) cos(\omega t + \phi_0) = \frac{r}{2c}\frac{\partial}{\partial t}E_z$$

Radial force

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

Optical properties of the gun RF field

The radial momentum kick is

$$\Delta p_r = e \int E_r \frac{dz}{\beta c} = -\frac{e}{2} \int \frac{r}{\beta c} \frac{\partial E_z}{\partial z} dz$$

If we assume that the RF field is a constant step function in over the gun length, and integrate the force impulse over the position at the exit iris, the change in radial momentum is obtained

$$\Delta p_r = -\frac{eE_0}{mc^2} r \sin\phi \qquad (\phi = \omega t + \phi_0 - k_z z_f)$$

Moving from cylindrical to cartesian coordinates we obtain the change in transverse momentum at the exit of the iris in terms of a kick angle

$$\Delta p_x = \beta\gamma x' = -\frac{eE_0}{2mc^2} x \sin\phi \quad \Rightarrow \quad x' = -\frac{eE_0}{2\beta\gamma mc^2} x \sin\phi$$

If we define the angular kick the beam gets at the iris exit in terms of the RF gun focal length

$$x' = \frac{x}{f_{RF}} \qquad \boxed{f_{RF} = -\frac{2\beta\gamma mc^2}{eE_0 \sin\phi}}$$

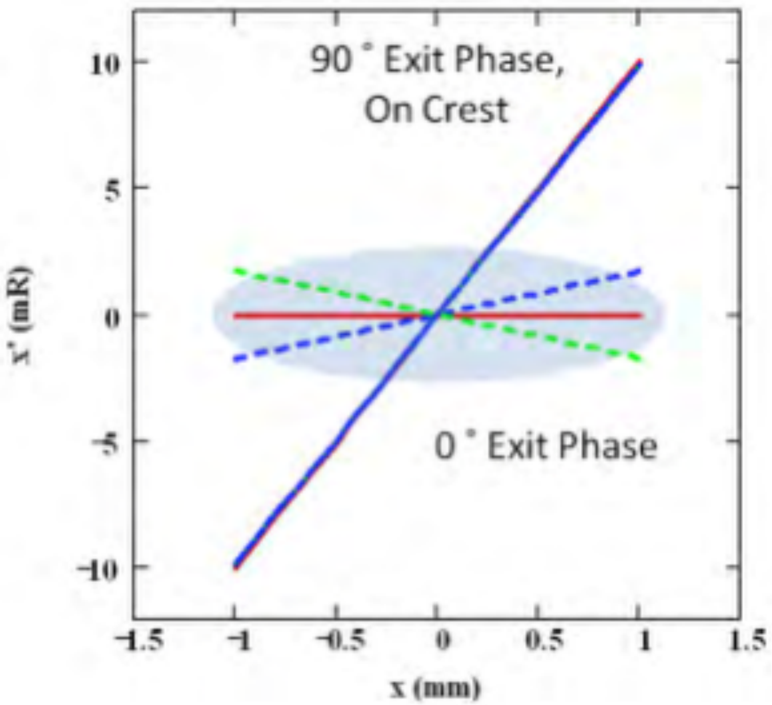
The beam out of the gun require a focusing force

In numbers: $E_0 = 110\ MV/m\ ,\ E_{gun} = 5\ MeV \quad \phi = 30\,\deg$

$$f_{RF} \approxeq -18\ cm$$

Linear and non-linear RF emittance

Phase dependent focal strength: electrons at various longitudinal positions along the bunch length, arriving at different phases at the gun exit, experience different kicks



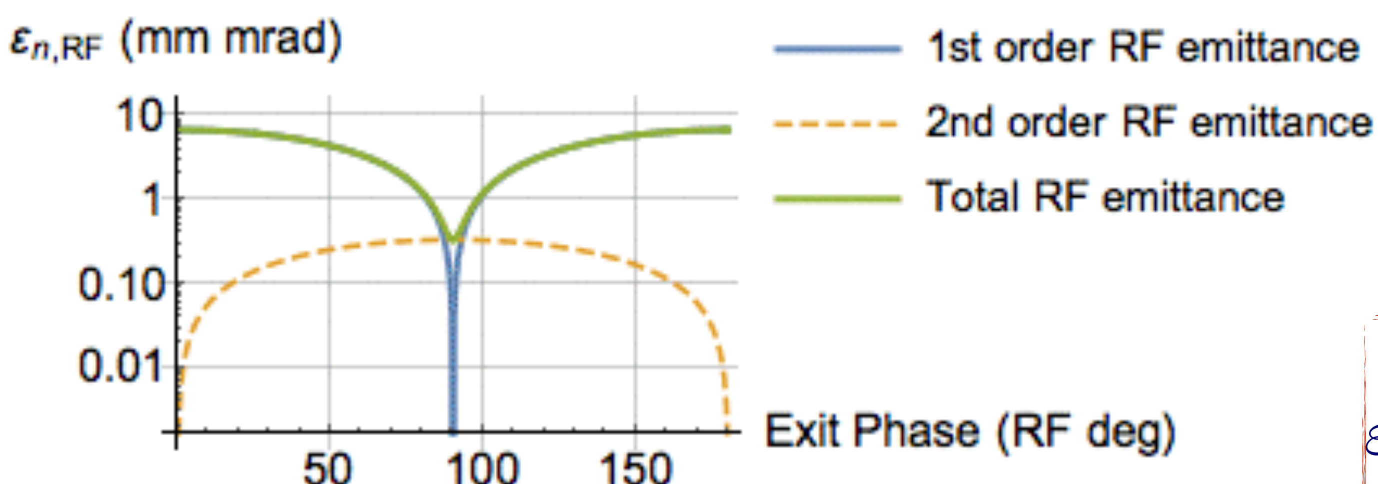
0 deg
red solid: center slice
blue dash: head slice
green dash: tail slice
90° phase spaces
all lie on the same diagonal line
The linear (first-order) emittance for an exit phase of 90° is zero, as shown by the diagonal line.

$$x' = \frac{x}{f_{RF}} \to \Delta x' = -\frac{d}{d\phi}\left(\frac{1}{f_{RF}}\right)\Delta x\Delta\phi$$

$$\sigma_{x'} = \frac{eE_0\cos\phi}{2\gamma mc^2}\sigma_x\sigma_\phi$$

$$\varepsilon_n = \beta\gamma\sqrt{< x^2 >< x'^2 > - \cancel{< xx' >^2}} = \beta\gamma\sigma_x\sigma_{x'}$$

Correlation is neglected for exit phase far from 90 deg



$$\sigma_\phi = 4\,\mathrm{deg} \Leftrightarrow 10\ ps\ \ FWHM$$

$$\sigma_x = 1\ mm\ ,\ \ E_0 = 100\ MV/m$$

$$\boxed{\varepsilon_n^{RF} = \frac{eE_0}{2mc^2}\sigma_x^2\sigma_\phi\sqrt{\cos^2\phi + \frac{\sigma_\phi^2}{2}\sin^2\phi}}$$

1st order RF emittance linear in σ_ϕ

Phase Scan Measurement

In RF photo-injectors the external field on the cathode varies with time

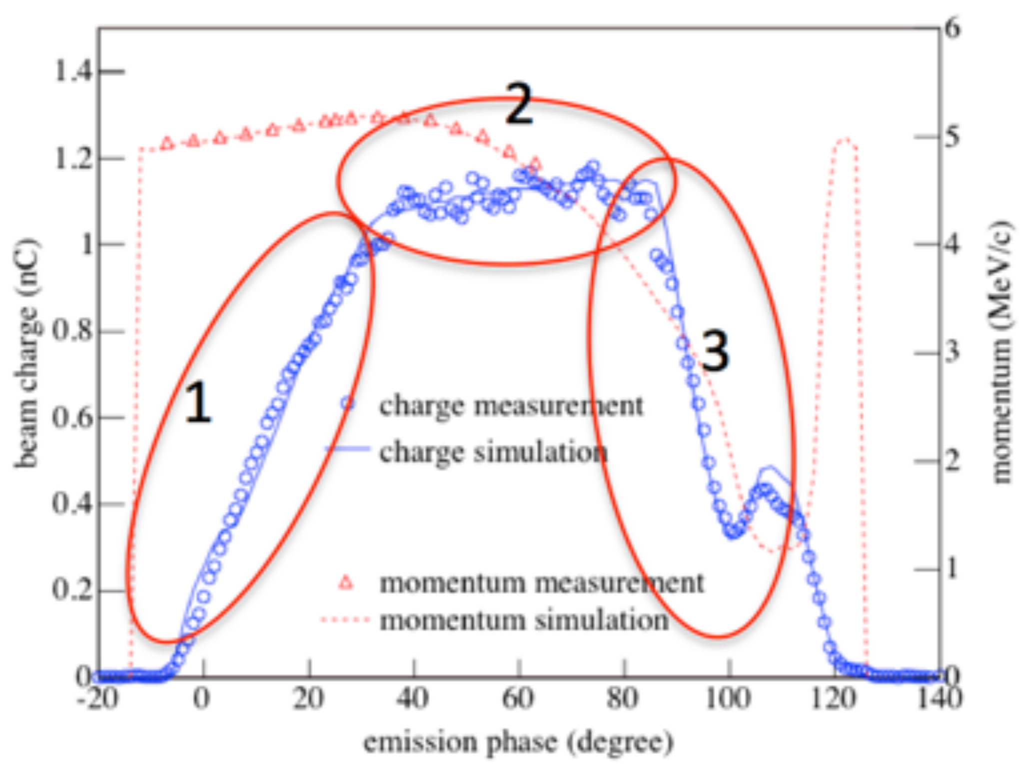
- the transported charge can be measured as function of gun RF injection phase

Phase Scan

1. space charge limited emission:
   - the emission is limited by the applied field;
   - as we increase the acc. field on the cathode at the emission the charge rapidly increase

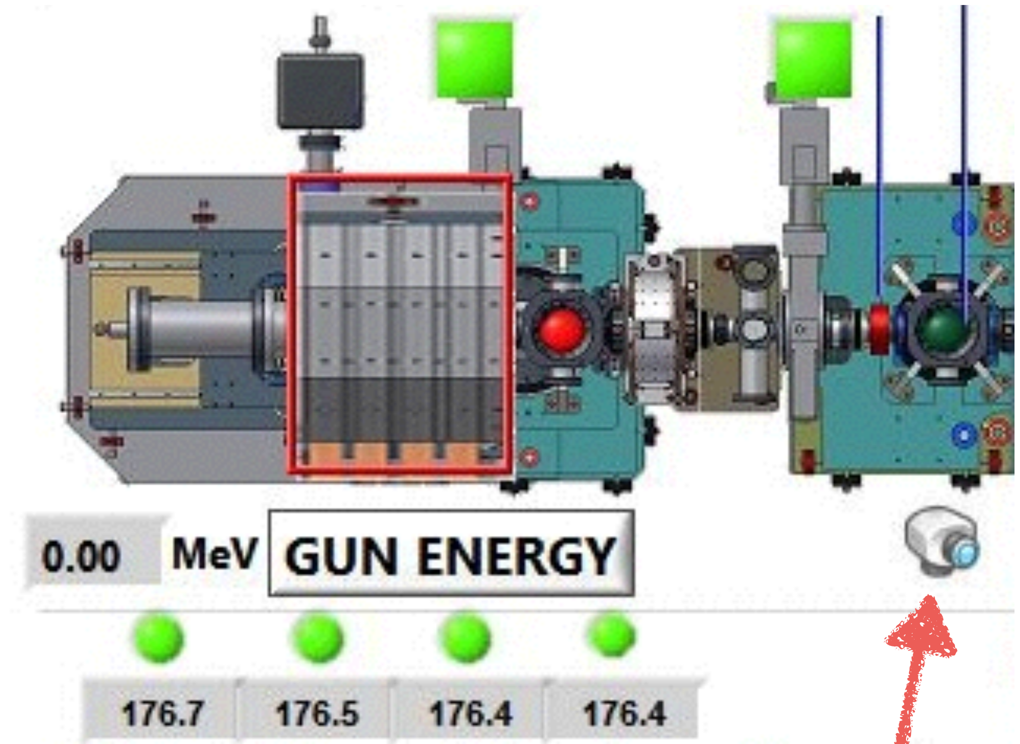
2. Shottky enhanced emission:
   - extracted charge is not enough to overcome the external field;
   - the emission current density is enhanced by the Shottky effect ($(E_{rf})^{1/2}$)

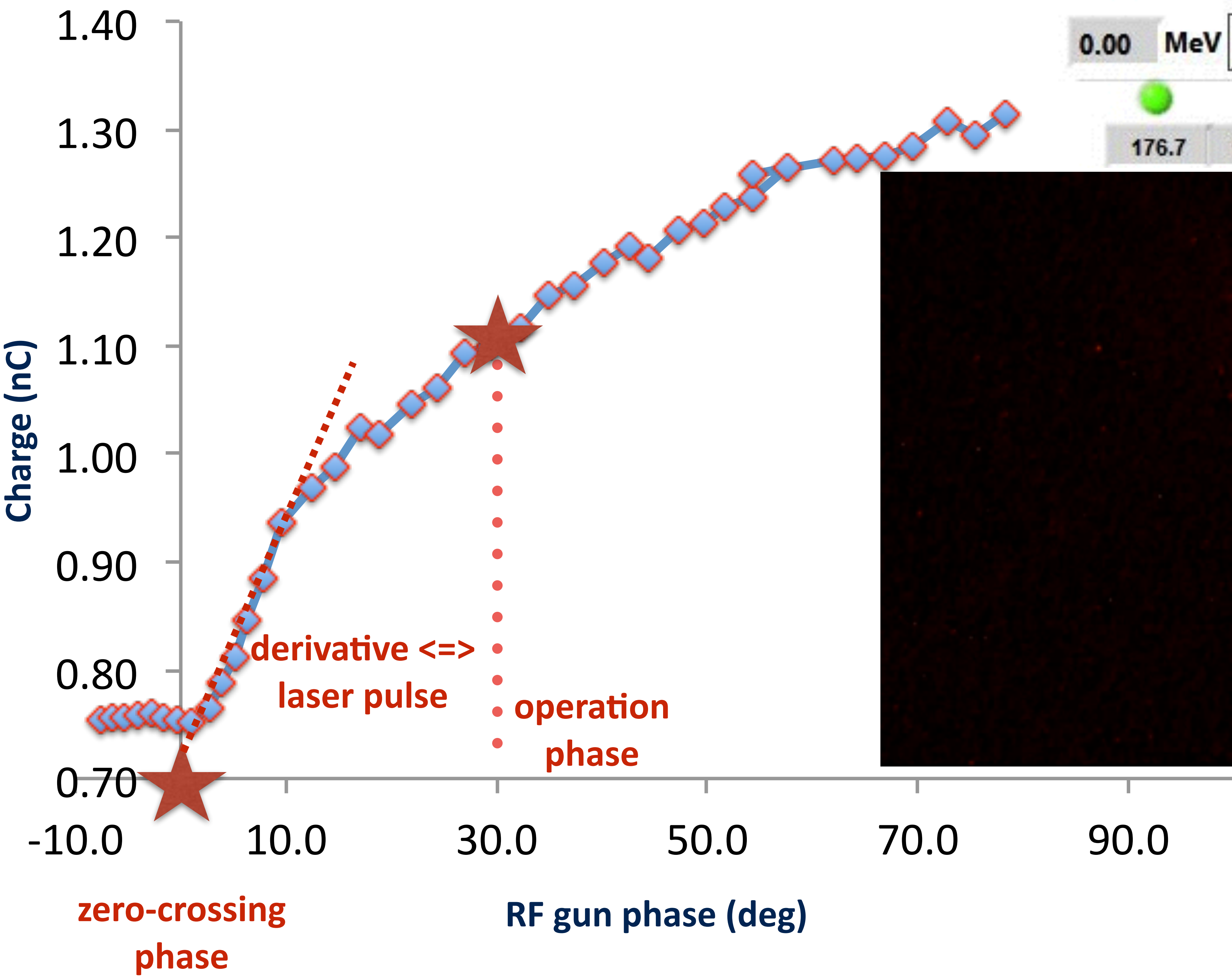
3. charge cut due to the trasport line:
   - transport dependent on the focusing fields (solenoid) and to the aperture of the beam pipe
   - over-focusing due to transverse rf fields

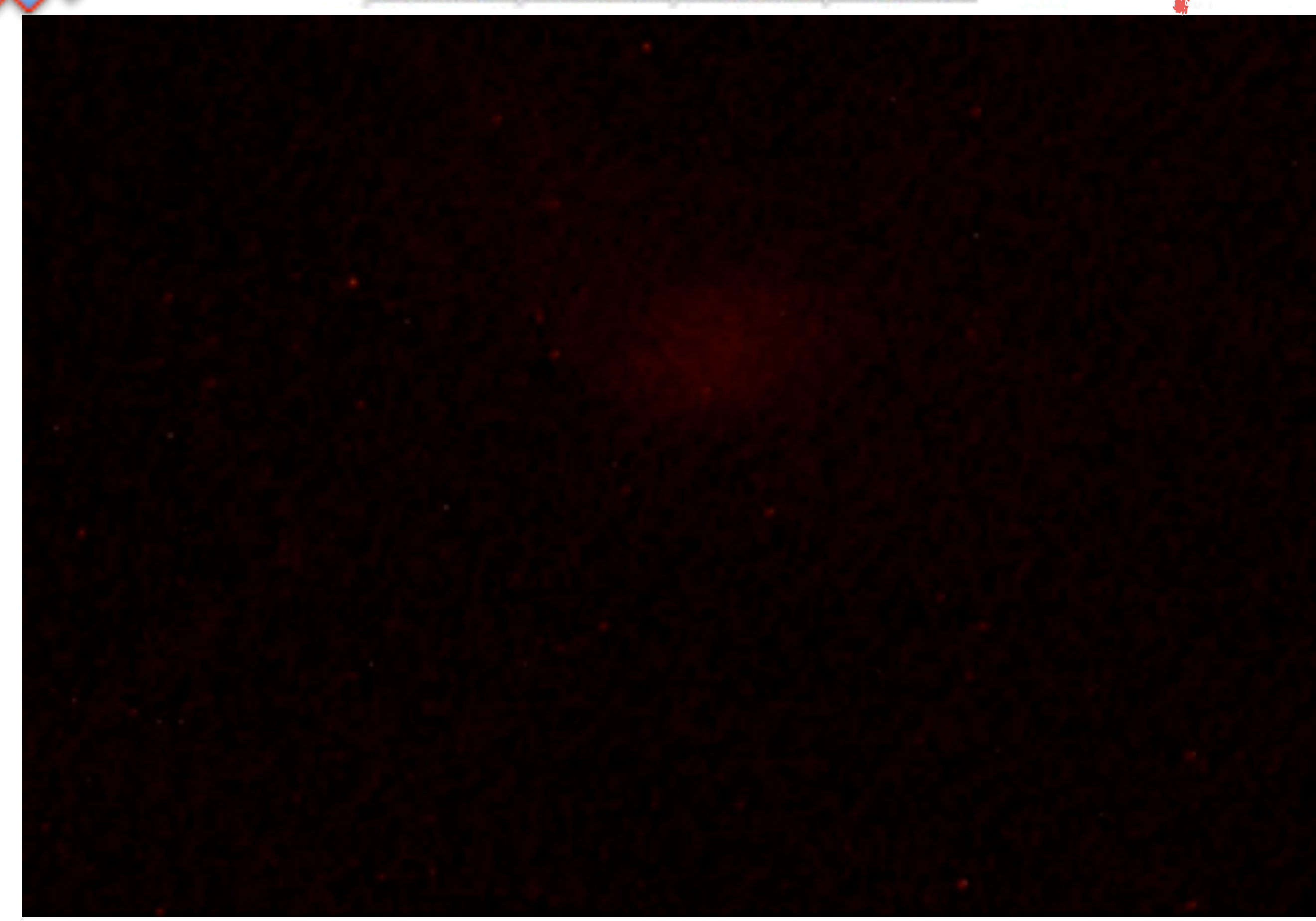


Courtesy of D. Filippetto

Phase Scan


0.00
MeV
GUN ENERGY
176.7
176.5
176.4
176.4


1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
Charge (nC)
-10.0
10.0
30.0
50.0
70.0
90.0
RF gun phase (deg)
derivative <=> laser pulse
operation phase
zero-crossing phase

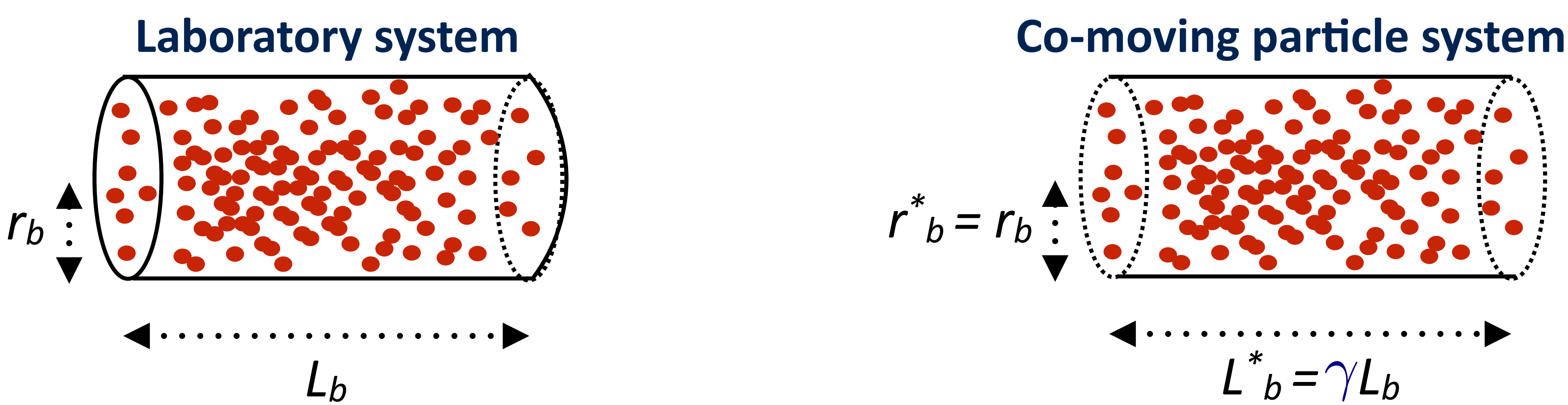


Space Charge Effects

Space charge forces influence the beam dynamics and are one of the main performance limitations in high brightness photo-injectors

Let's consider first space charge forces in highly relativistic bunches

- Laboratory system: N relativistic electrons uniformly distributed in a cylinder with radius r_b and length L_b
- Co-moving particle coordinate system: electrons are at rest and a pure Coulomb field inside the bunch



$\gamma \gg 1\ ,\ L_b^* \gg L_b$: the approximation of infinitely long cylindrical charge distribution is valid and the electric field has only a radial component

$$E_r^*(r) = -\frac{Ne}{2\pi\varepsilon_0 L_b^*}\frac{r}{r_b^2}\ ,\ r \leqslant r_b$$

$$E_r^*(r) = -\frac{Ne}{2\pi\varepsilon_0 L_b^*}\frac{1}{r}\ ,\ r \geqslant r_b$$

Space Charge Effects

Transforming back to the laboratory frame the radial component of the electric field yields to a radial electric field and an azimuthal magnetic field

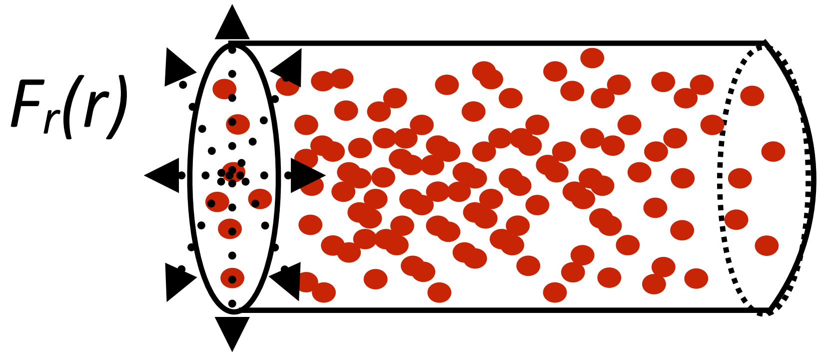
$$E_r(r) = \gamma E_r^*(r) = -\frac{Ne}{2\pi\varepsilon_0 L_b}\frac{r}{r_b^2}$$

$$B_\phi = \frac{v}{c^2}E_r(r)\ ,\ \ r \leqslant r_b$$

The force a test electron inside the bunch experiences due to the E_r and B_{phi} field is determined through the Lorentz force

$$\vec{F} = -e(\vec{E} + \vec{v} \times \vec{B})$$

$$F_r(r) = \frac{Ne^2}{2\pi\varepsilon_0 L_b}\frac{r}{r_b^2}\left(1 - \frac{v^2}{c^2}\right) = \frac{Ne^2}{2\pi\varepsilon_0 L_b}\frac{r}{r_b^2}\frac{1}{\gamma^2}$$



The overall force points outwards and is then a defocusing force, which vanishes for $\gamma \to \infty$

Space Charge Dependence on Charge Density Distribution

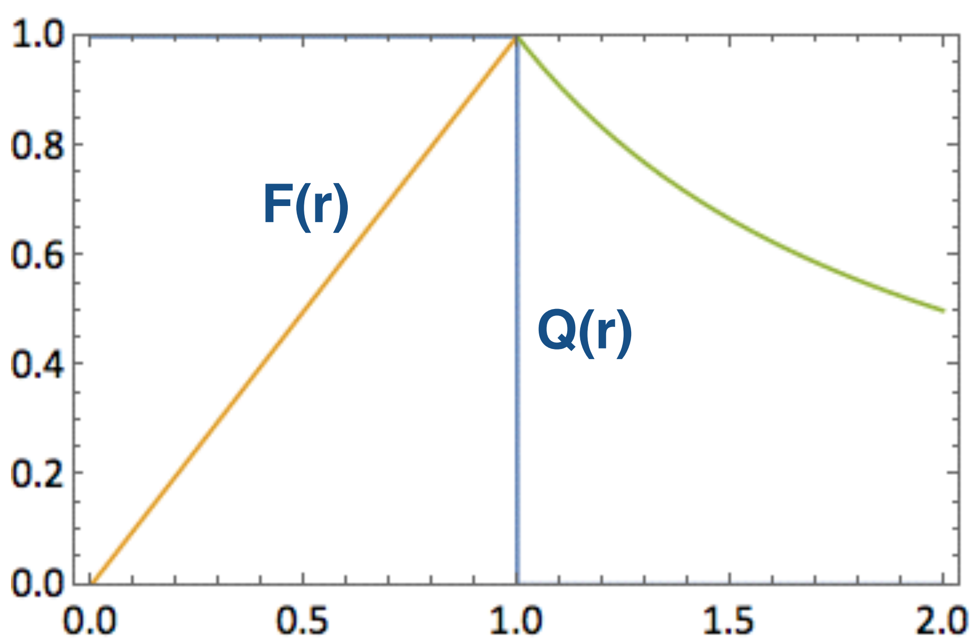
The repulsive space charge forces remain an unavoidable problem: **is it possible to counteract these internal forces at least partially by applying an external focusing field?**

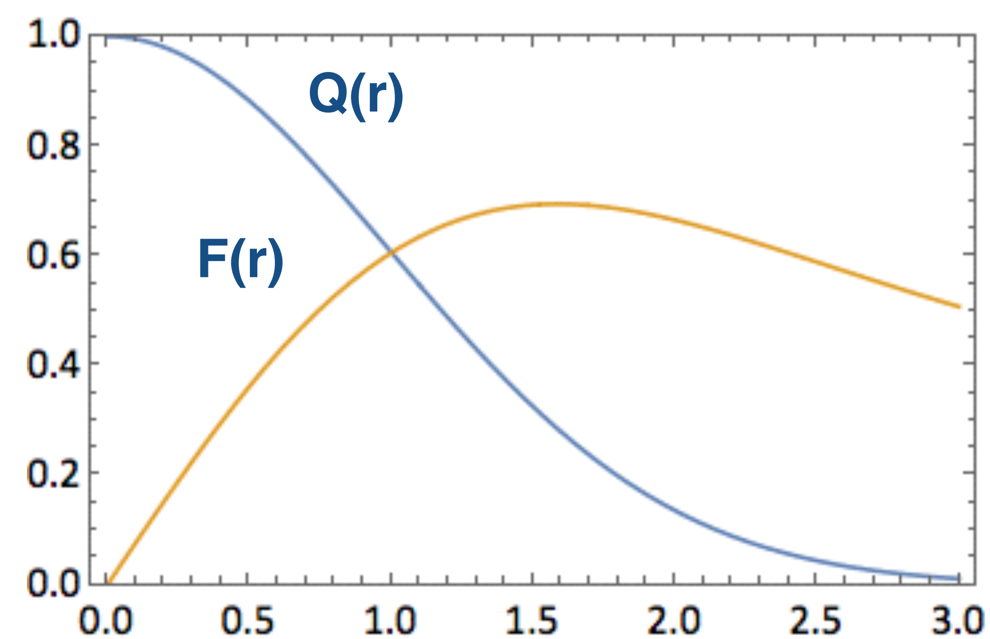
For the cylindrical electron bunch with constant charge density, this is possible because **the total space charge force depends linearly on the displacement *r* from the axis**

$$F_r(r) = \frac{Ne^2}{2\pi\varepsilon_0 L_b} \frac{r}{r_b^2} \frac{1}{\gamma^2}$$

What happens in case of a Gaussian transverse density distribution?

$$F_r(r) = \frac{Ne^2}{2\pi\varepsilon_0 L_b r} \left[1 - e^{-\frac{r^2}{2\sigma^2}}\right] \frac{1}{\gamma^2}$$





(Gun) Compensating Solenoid

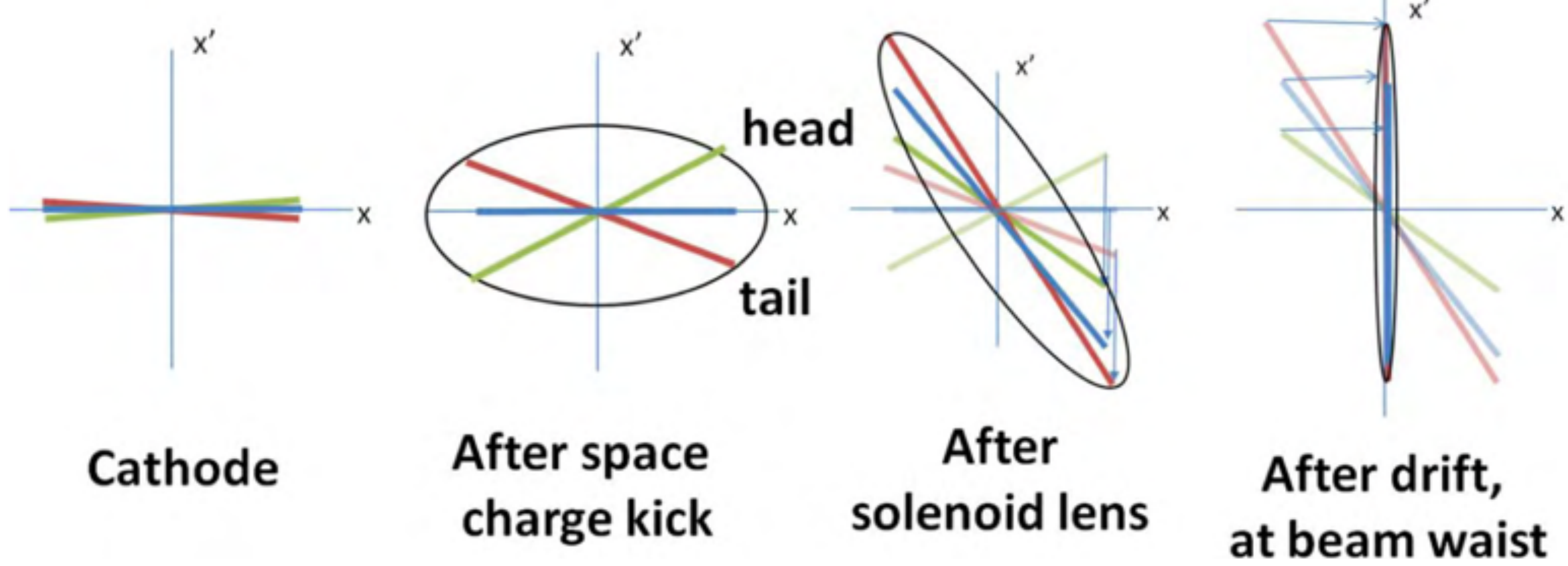
- The beam wants to diverge for 2 reasons
  - **Space charge**
    - The electron bunch coming off the cathode is very dense and wants to expand violently due to the electrostatic force
  - **Divergent RF Fields within the RF gun**
    - Anytime the electric field varies longitudinally there is a radial field
- The **solenoid focuses the low energy beam radially**
- Beam enters the end radial field of the solenoid and gets a transverse kick divE=0 => $\Delta r' \propto -r\frac{dE_z}{dz}$
- This new transverse motion crosses the longitudinal field and rotates inward or outward depending on the solenoid polarization
- The particle is then closer in (assuming focusing) when passing through the end radial field at the opposite end of the solenoid and since it is further in the kick is less

Multiple Role of the Gun Solenoid

- It cancels the strong negative RF lens effect
- it is **crucial for emittance compensation** by aligning the slices transversely along the bunch to minimize the projected emittance
- **Imaging the electron emission from the cathode** to have a good representation of the true **QE map**

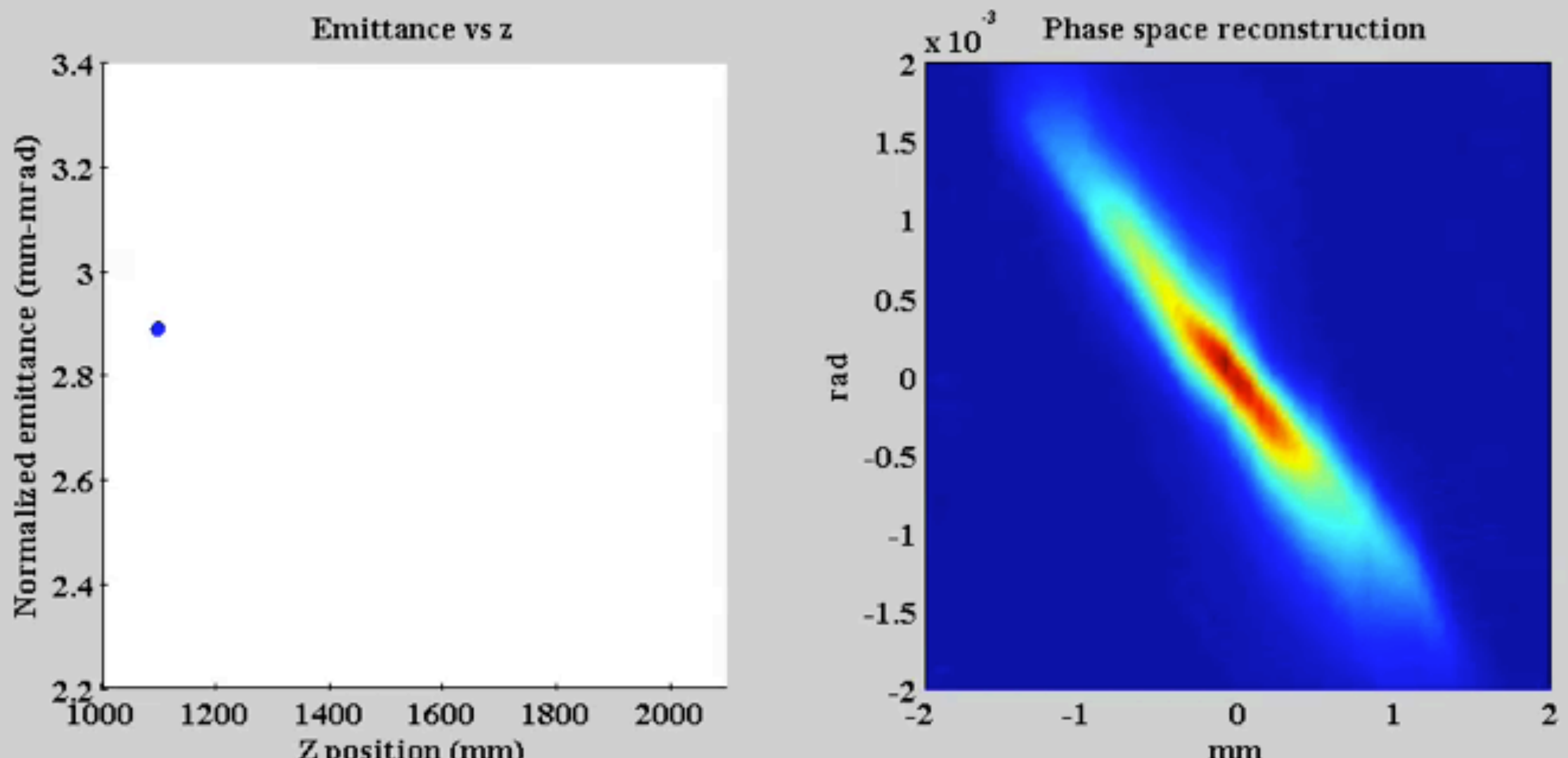
Matching the low energy beam to the booster linac

At or near the waist, the slices are once again lined up and the emittance goes through a minimum



- Then, it is necessary to carefully match the beam into a high-gradient booster to damp the emittance oscillations. The required matching condition is referred to as the Ferrario working point (M. Ferrario et al., "HOMDYN study for the LCLS RF photo-injector", SLAC-PUB-8400, LCLS-TN-00-04, LNF-00/004(P))
- The working point matching condition requires the **emittance to be a local maximum and the envelope to be a waist at the entrance to the booster**. The waist size is related to the strength of the RF fields and the peak current.
- RF focusing aligns the slices and acceleration damps the emittance oscillations.
- **Experimental evidence of emittance oscillations in the drift before the booster has been proved at the SPARC high brightness photo-injector**

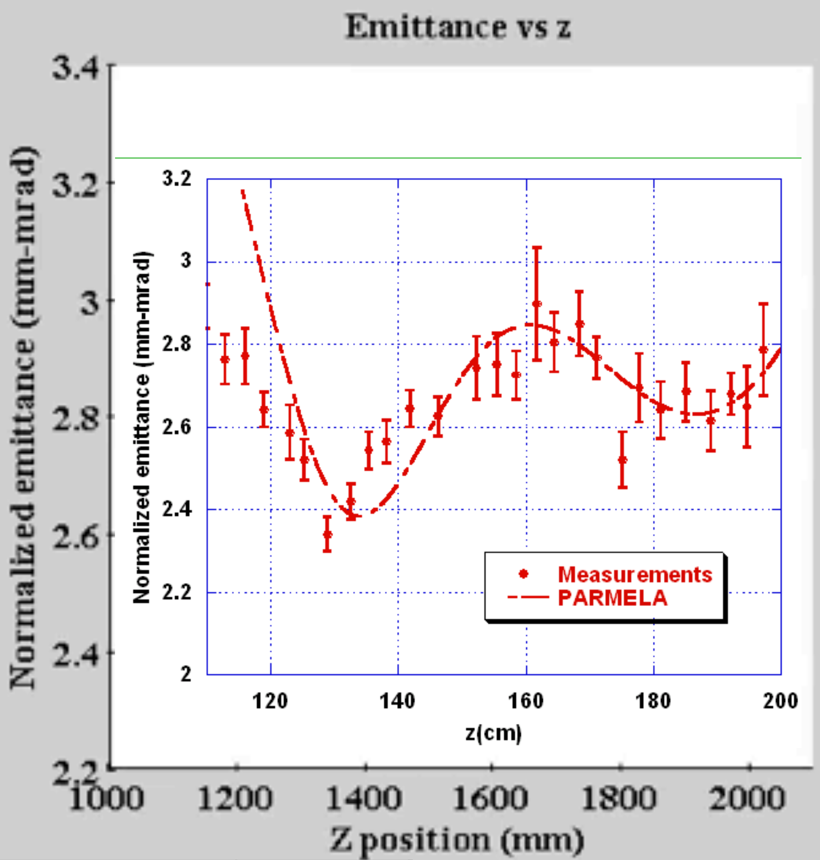
Matching the low energy beam to the booster linac

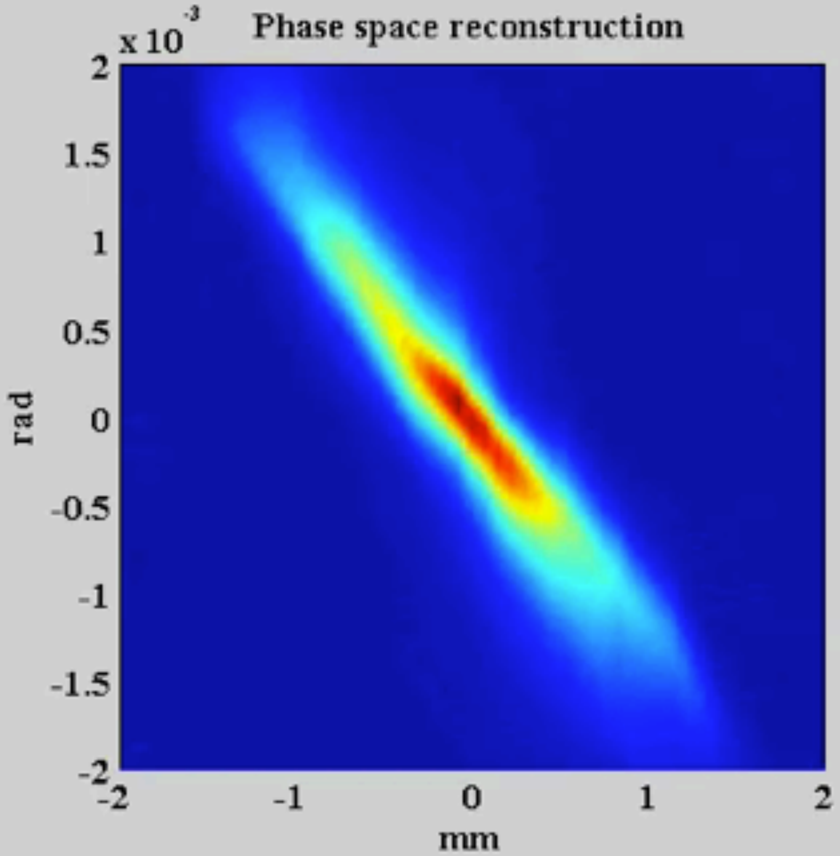


charge	0.5 nC
pulse length (FWHM)	5 ps
rise time	1.5 ps
rms spot size	0.45 mm
RF phase (φ-φ_{max})	+12°

M. Ferrario et al., *Direct Measurement of double emittance minimum in the SPARC high brightness photo-injector*
PRL **99,** 234801 (2007)

Matching the low energy beam to the booster linac





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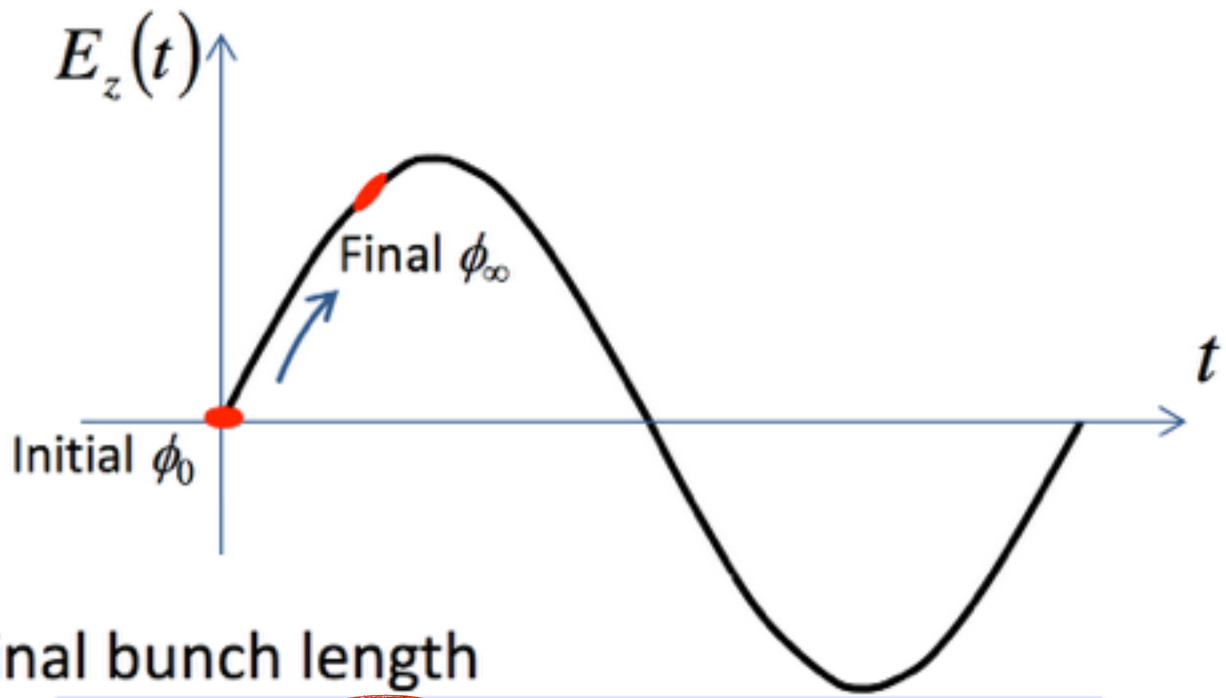
…

- To preserve brightness, it is desirable to accelerate the beam as quickly as possible, thus ‘freezing-in’ the space charge forces, before they can significantly dilute the phase space
  - RF gun
- Space charge can be controlled by reducing the beam charge density, especially in the cathode region where the beam energy is low
  - Larger transverse beam sizes at the cathode to reduce the density, but this increases the cathode intrinsic emittance
- Space charge can be also controlled by increasing the bunch length
  - Increase of longitudinal emittance
    - This in turn necessitates **compression methods**

RF Compression: Velocity Bunching

Sub-relativistic electrons (β_c < 1) injected into a traveling wave cavity at zero crossing move more slowly than the RF wave (β_{RF} ~ 1). The electron bunch slips back to an accelerating phase and becomes simultaneously accelerated and compressed.



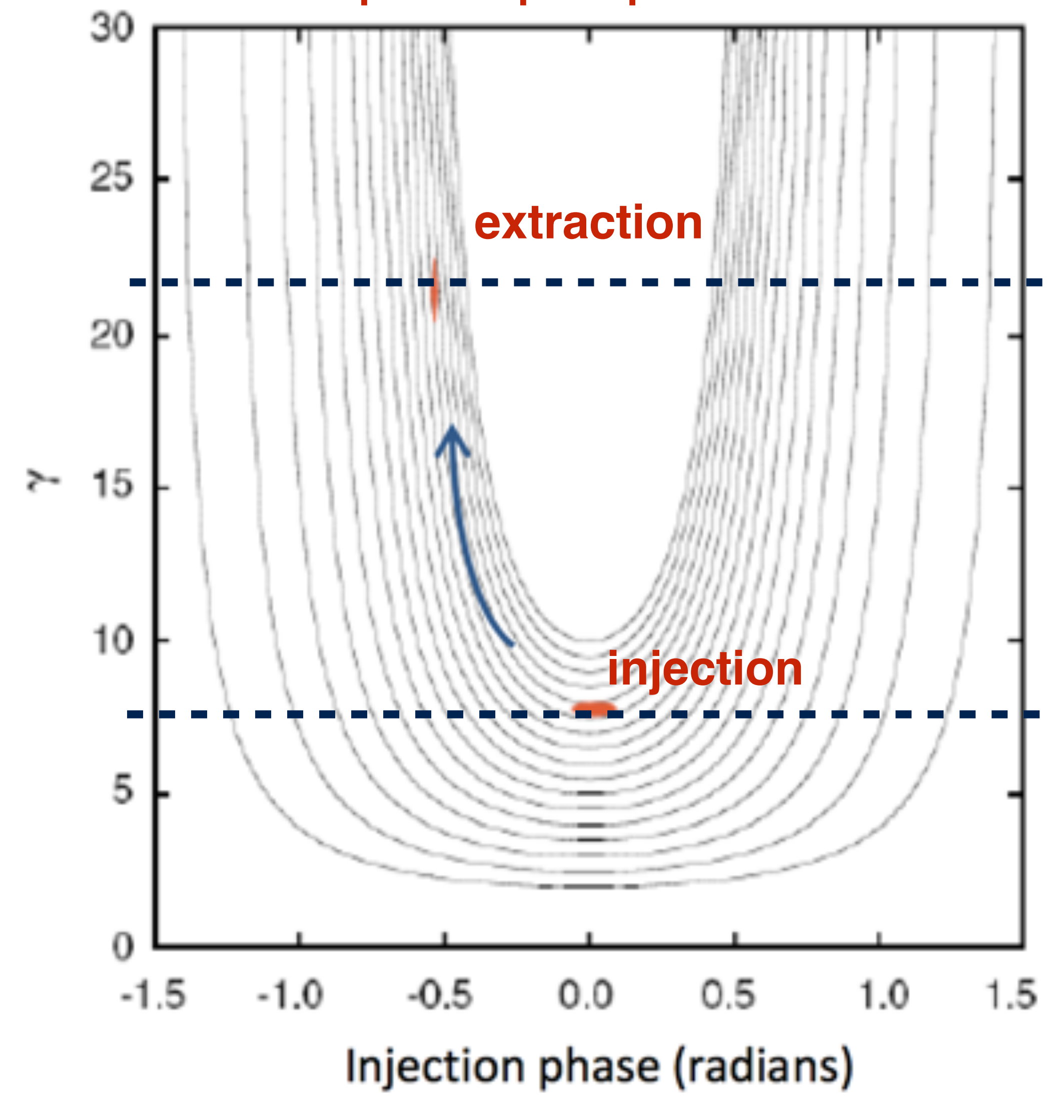
Final bunch length

$$\sigma_{z_f} = \frac{\sin\phi_0}{\sin\phi_\infty}\sigma_{z_i} + \frac{1}{2\alpha\gamma_0^2\sin\phi_\infty}\sigma_{\gamma_i}$$

Injection phase slippage

Contribution from initial energy spread

Zoom in of the phase space plot for a slow wave



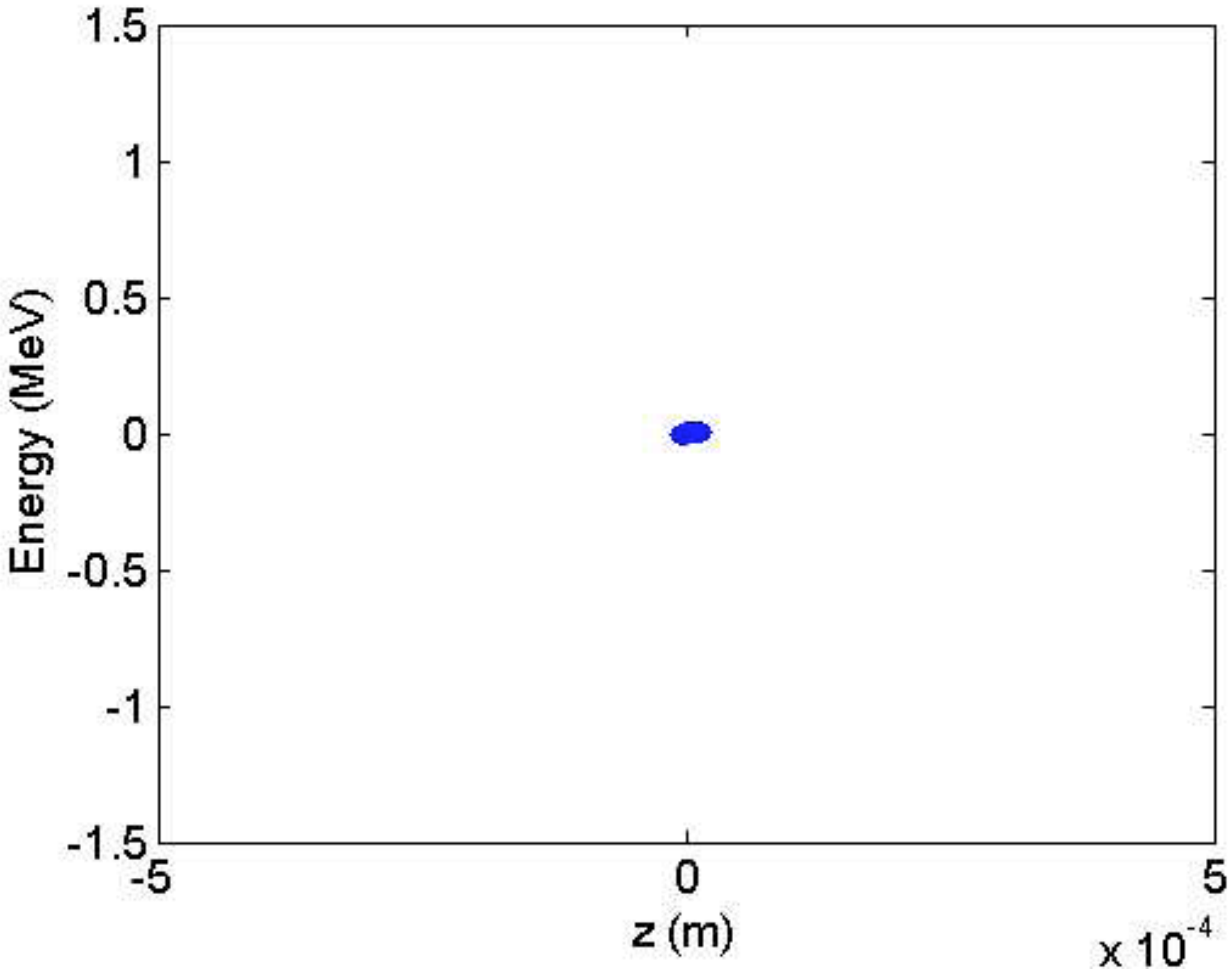
Initial β_c = 0.994 at 4 MeV

- **L. Serafini and M. Ferrario**, *Velocity Bunching in Photo-injectors*, Physics of, and Science with the X-Ray Free-Electron Laser, edited.by S. Chattopadhyay et al. © 2001 American Institute of Physics

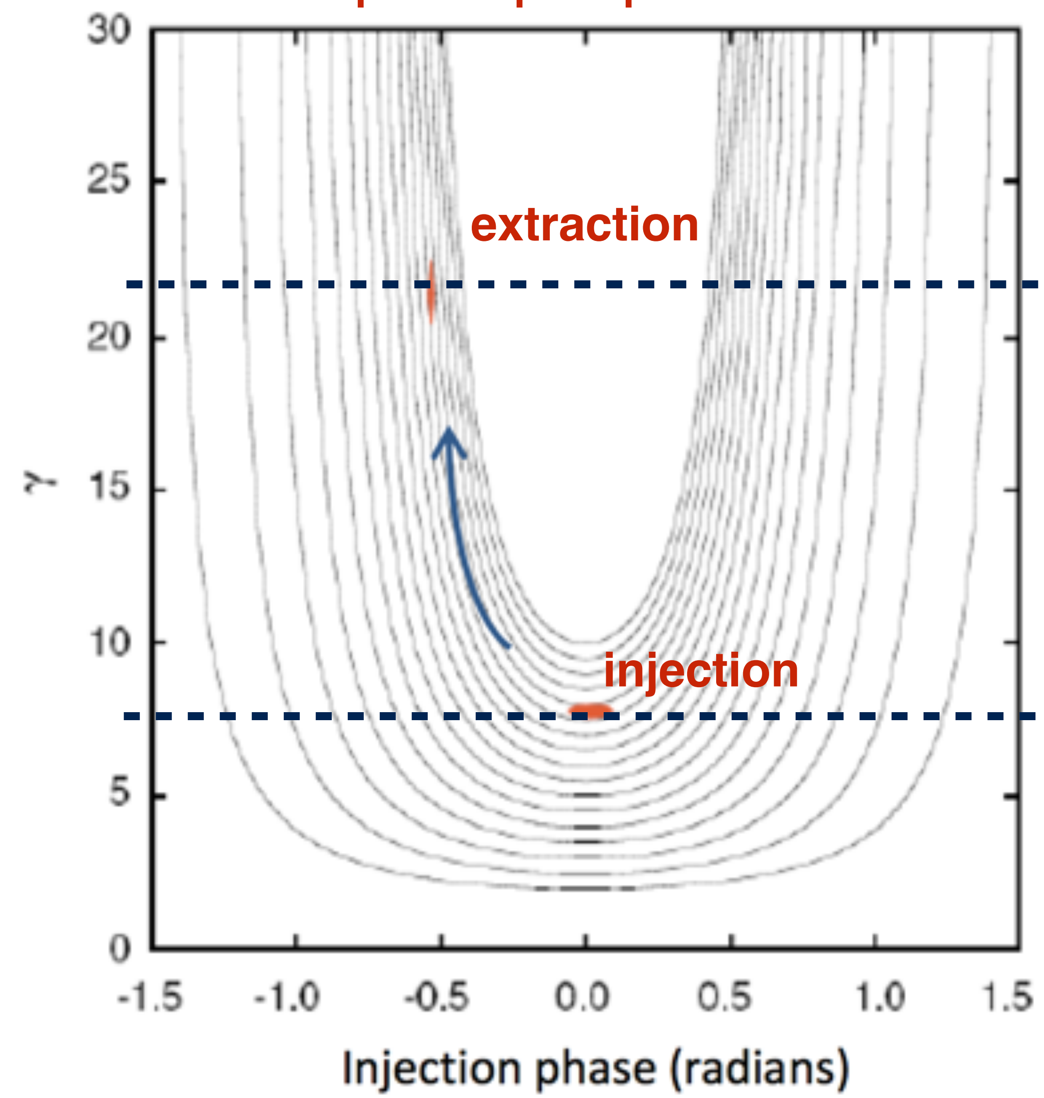
RF Compression: Velocity Bunching

An energy/phase correlation is imparted and removed smoothly, through phase slippage and acceleration, inside of the RF linac section.

The beam has no initial phase-energy correlation, injected at the zero-crossing of the wave, and ends with maximum energy spread and minimum phase extent



Zoom in of the phase space plot for a slow wave



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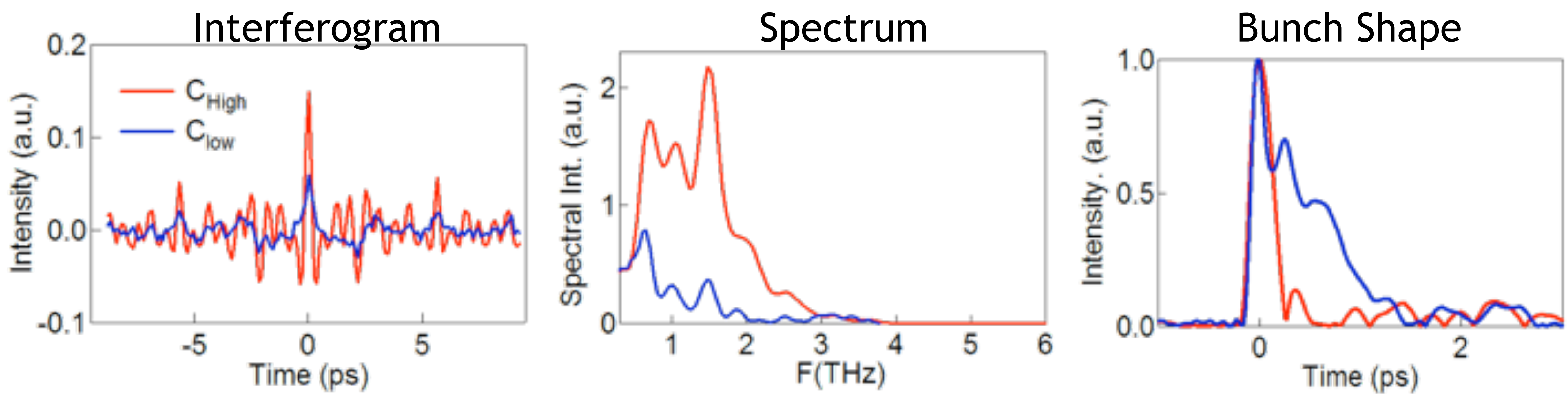
Velocity Bunching

- It has been demonstrated to be well **integrated in emittance compensation schemes**
  - *M. Ferrario et al., Experimental Demonstration of Emittance Compensation with Velocity Bunching, Phys. Rev. Lett.* ***104****, 054801 (2010)*
- Compression happens along **rectilinear trajectories**
  - **No Coherent Synchrotron Radiation** which causes emittance dilution
- Compression and acceleration take place at the same time and within the same accelerating cavity
  - space charge force mitigation

Velocity Bunching

- **High compression factors**, larger than 20, can be achieved **if phase spread of the injected beam is limited**
  - Proper laser pulse shaping or higher harmonic linearizing cavity

C_{low}= 9 => RMS bunch length ~280 fs
C_{high}= 24 => RMS bunch length ~100 fs



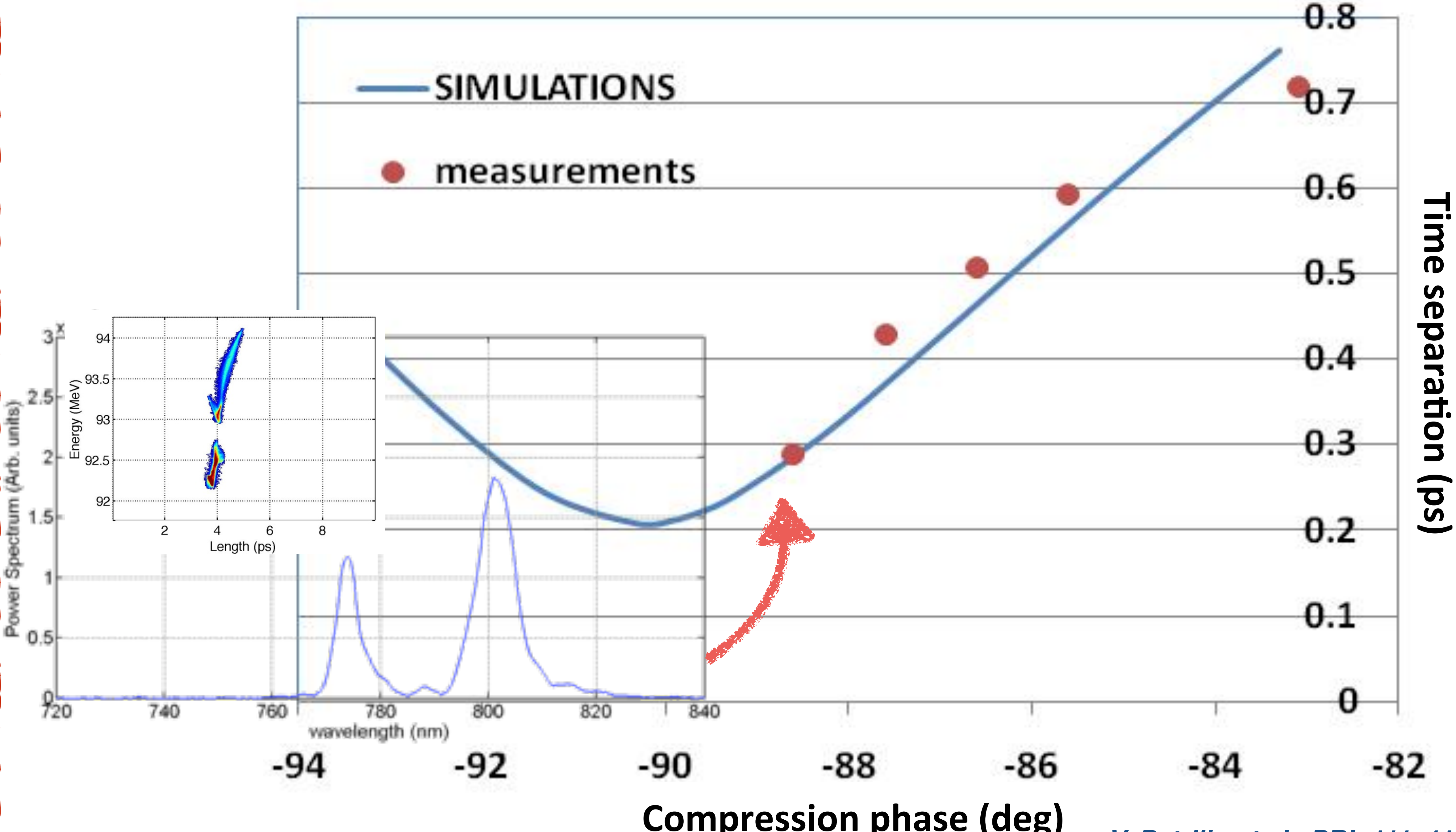
Maximum Compression Regime

Electron Beam Parameters			THz Pulse Parameters			
Energy (MeV)	Charge (pC)	Bunch length (fs)	Spectral Range (THz)	Energy/Pulse (μJ)	Electric Field (MV/cm)	Pulse length (fs)
114	530	100	0.3-3	40	1.3	<200

F. Giorgianni et al., Proc. SPIE 95090O (12 May 2015); doi: 10.1117/12.2178970

Velocity Bunching

- VB allows for multi bunch train configurations (**laser comb technique**) used, for instance, in **tunable 2-color FEL emission**, narrow-band THz radiation and resonant plasma wakefield acceleration schemes



V. Petrillo et al., PRL 111, 114802 (2013)

Velocity Bunching

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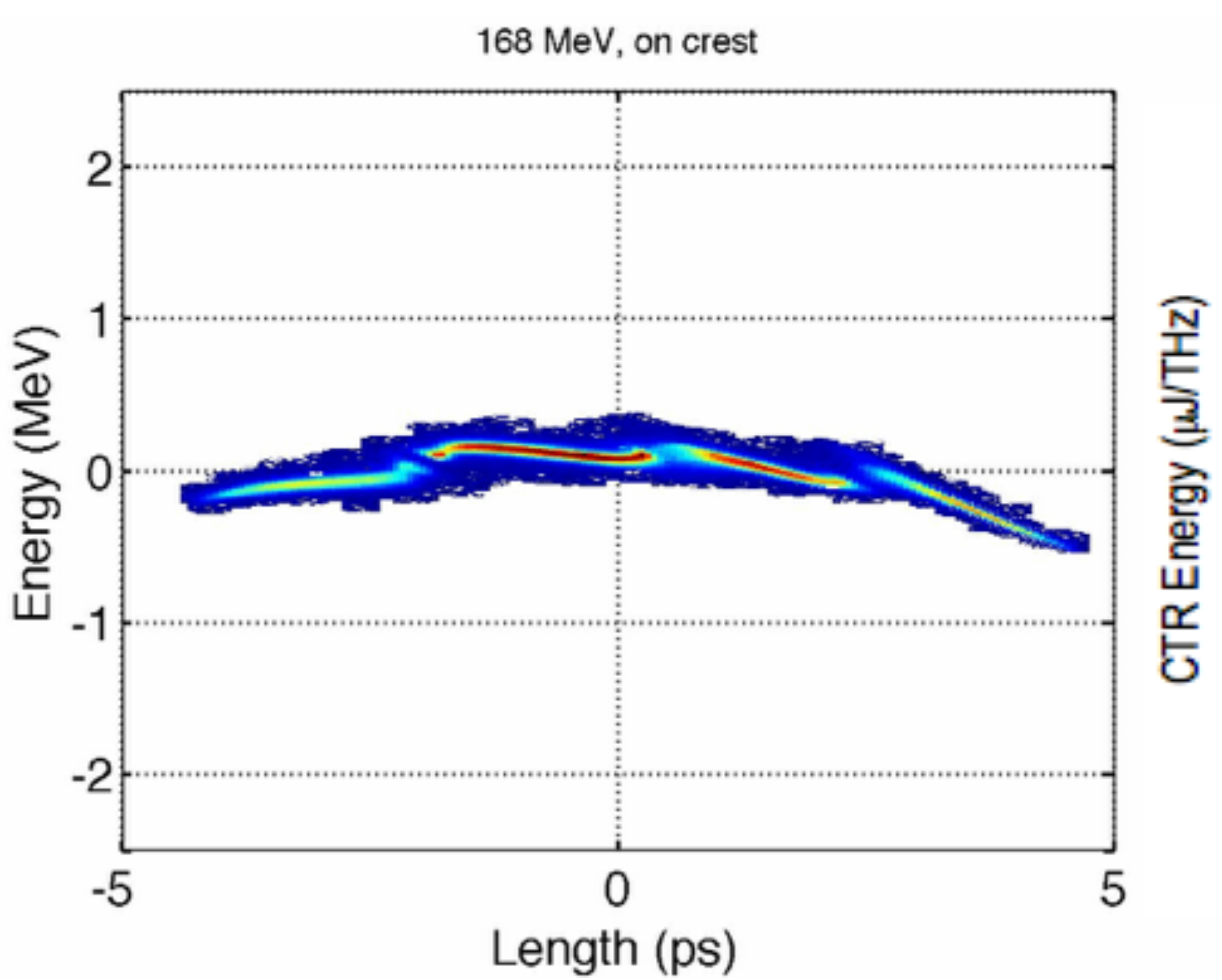

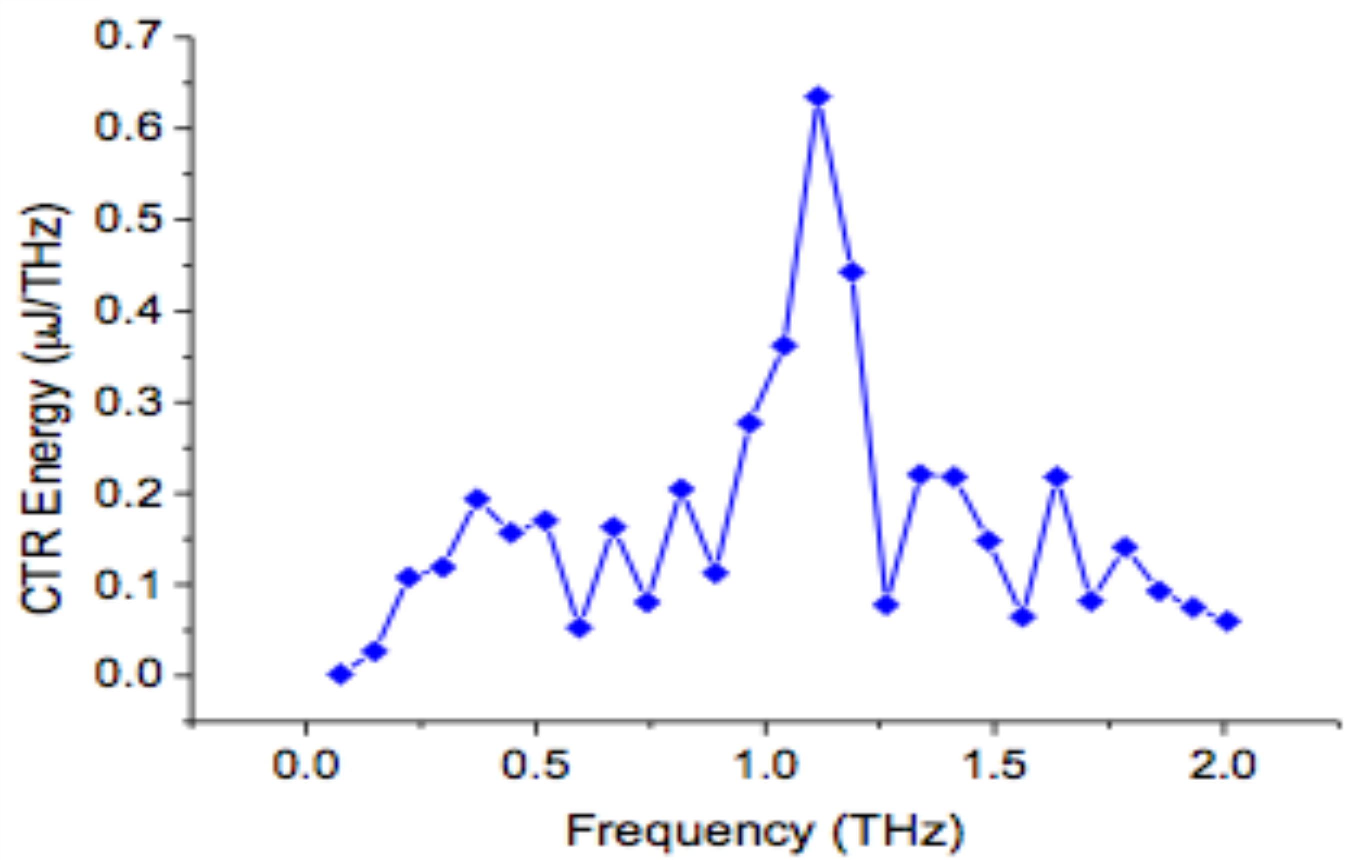

E. Chiadroni et al., J. Phys.: Conf. Ser. 357 012034 (2012)

Velocity Bunching

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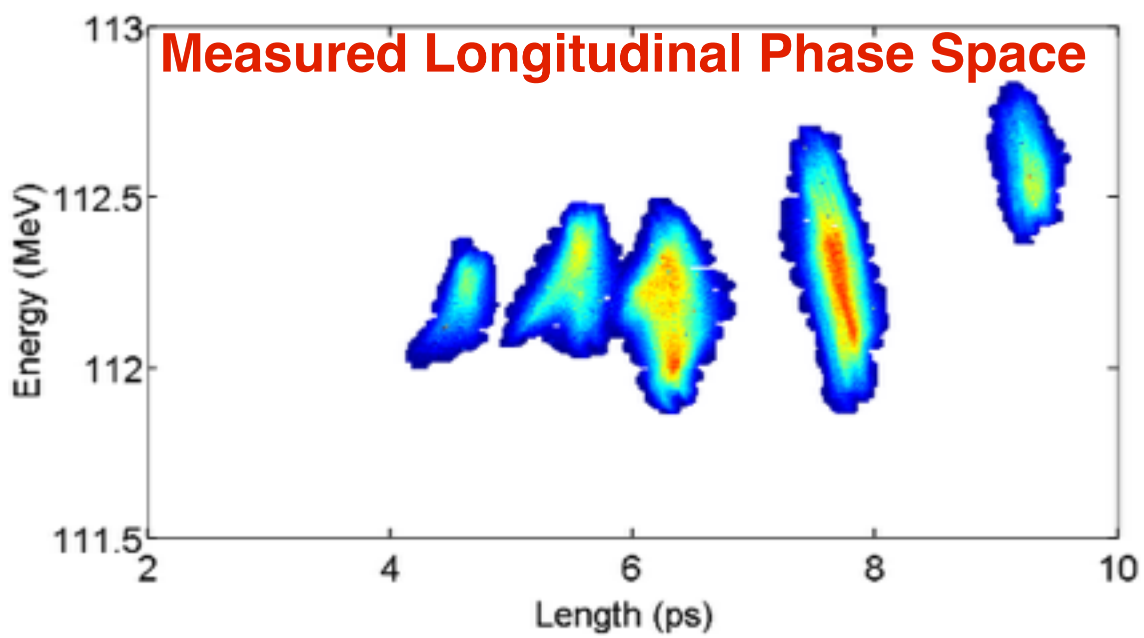

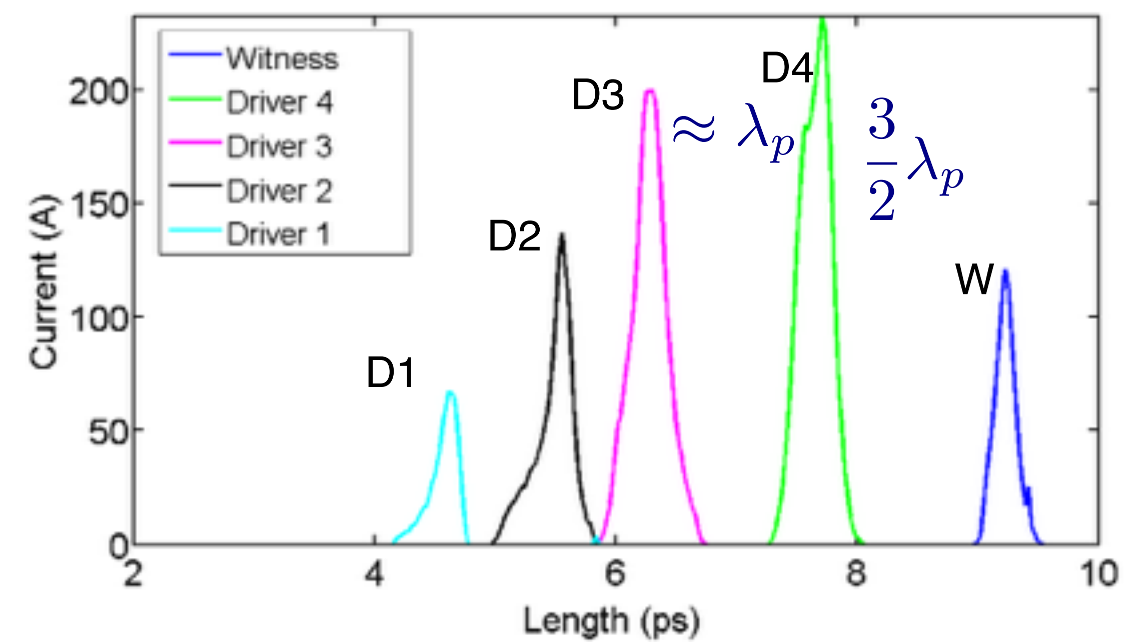

	Beam Energy (MeV)	Energy spread (%)	Bunch duration (ps)	Charge (pC)
Witness Beam	112.58(0.03)	0.084(0.003)	<0.088(0.001)	24.04(0.28)
Driver 4	112.28(0.03)	0.159(0.003)	0.042(0.001)	74.91(0.46)
Driver 3	112.17(0.03)	0.112(0.003)	0.092(0.001)	69.39(0.36)
Driver 2	112.26(0.02)	0.087(0.003)	0.113(0.001)	36.34(0.20)
Driver 1	112.20(0.02)	0.045(0.004)	<0.100(0.024)	36.34(0.20)
Whole Beam	112.27(0.03)	0.162(0.003)	1.275(0.003)	220.00(0.78)

E. Chiadroni et al., Proc. of HBB 2016, Havana

Conclusions

- The electron source is one of the key components since the brightness generated at the electron source represents the ultimate value
- The final application must drive the choice of both electron source and injector
- Common issues are stability and reliability

Bibliography and Acknowledgment

The material for this lecture has been liberally taken from talks/papers/lectures/proceedings/notes from a large number of people which I acknowledge here together with a list of references

- W. Anders, I. Bazarov, L. Cultrera et al., *An Engineering Guide to Photo-injector*, Editors D.H. Dowell and T. Rao, ISBN-13: 978-1481943222, ISBN-10: 1481943227
- http://uspas.fnal.gov/materials/10MIT/MIT-High-Brightness.shtml
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