



MSU-270

Field Emission Effects in the Circular Electron Positron Collider (CEPC)

B. B. Levchenko, SINP MSU

- **The CEPC project, basic parameters**
- **Electron cloud effect and CEPC collimators**
- **Beam field elements**
- **Quantum field emission, Fowler-Nordheim theory**
- **Number of secondary electrons per second**
- **Results and Summary**

The CEPC project, basic parameters

There is an ancient methodological principle:

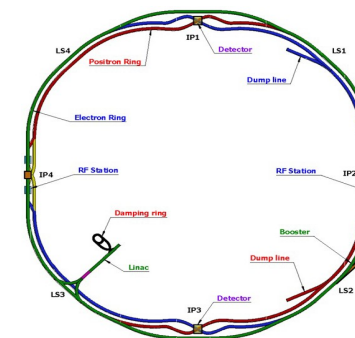
工欲善其事，必先利其器

“If a Master wants to do his work well, he will first sharpen his tools.”



Confucius

On June 30, 2025, Professor Jie Gao demonstrated how this principle is put into practice by telling us about the status of the CEPC project.



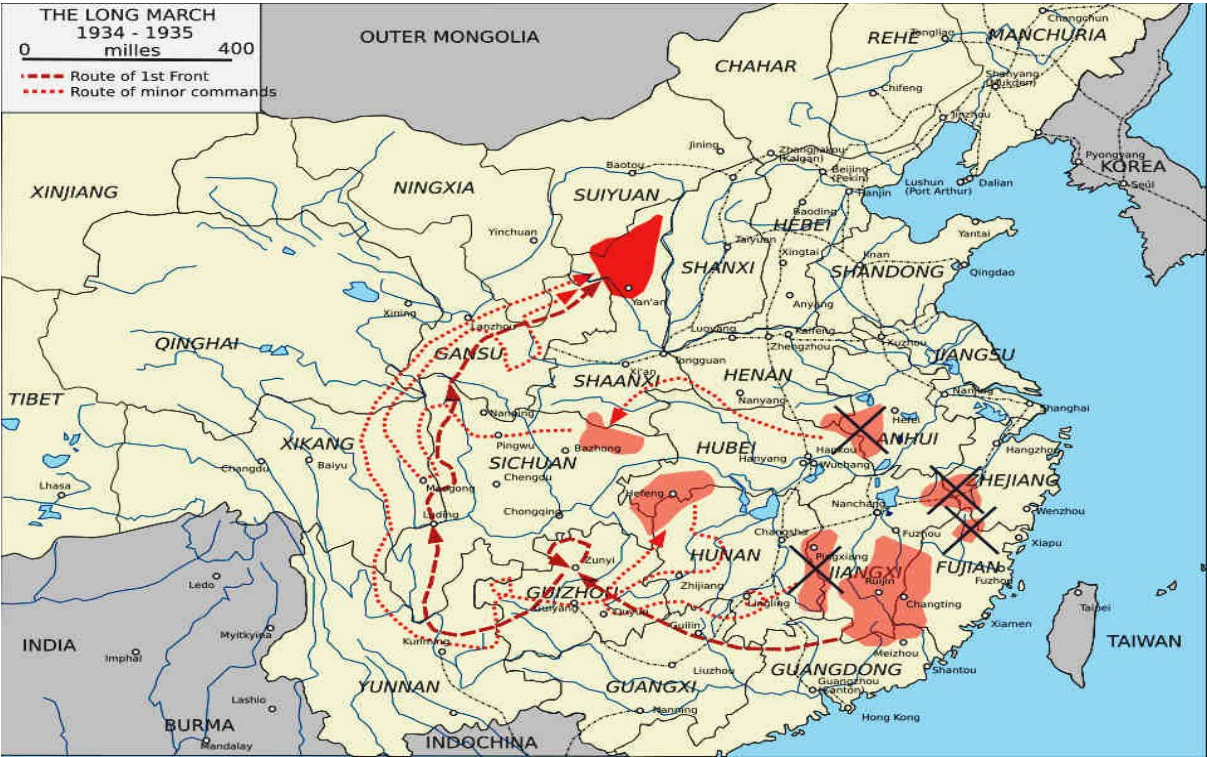
Steps: the idea, CDR, TDR, EDR, samples, prototypes, tests....

	Higgs	Z	W	tt
Circumference (km)	99.955			
Energy (GeV)	120	45.5	80	180
Bunch number	268	11934	1297	35
Bunch population (10^{11})	1.3	1.4	1.35	2.0
Bunch length (natural/total) (mm)	2.3/4.1	2.5/8.7	2.5/4.9	2.2/2.9

The CEPC project is the largest-scale technological and intellectual project in modern China and the world.

In symbolic terms, the CEPC project will be a great achievement on par with 长征 ("Cháng Zhēng") The Long March (the Chinese Red Army, 1934-36, > 10000 km)

The 100-year anniversary of the Long March will be in 2034-2036. That is in 10 years.

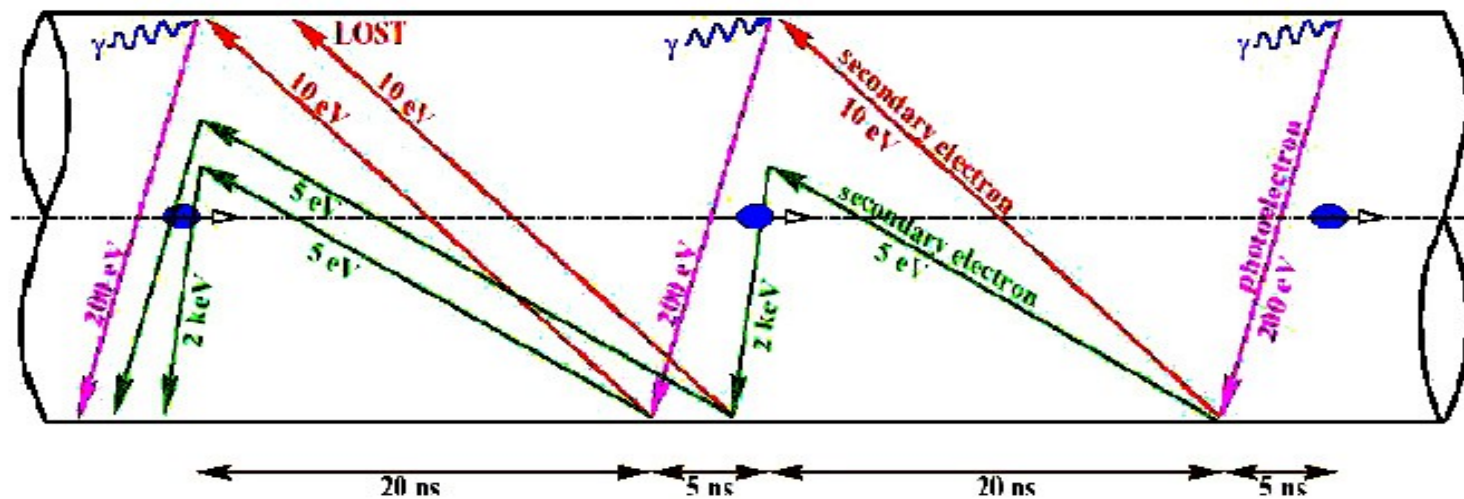


It is our hope that the CEPC inauguration will take place in close proximity to this great date.

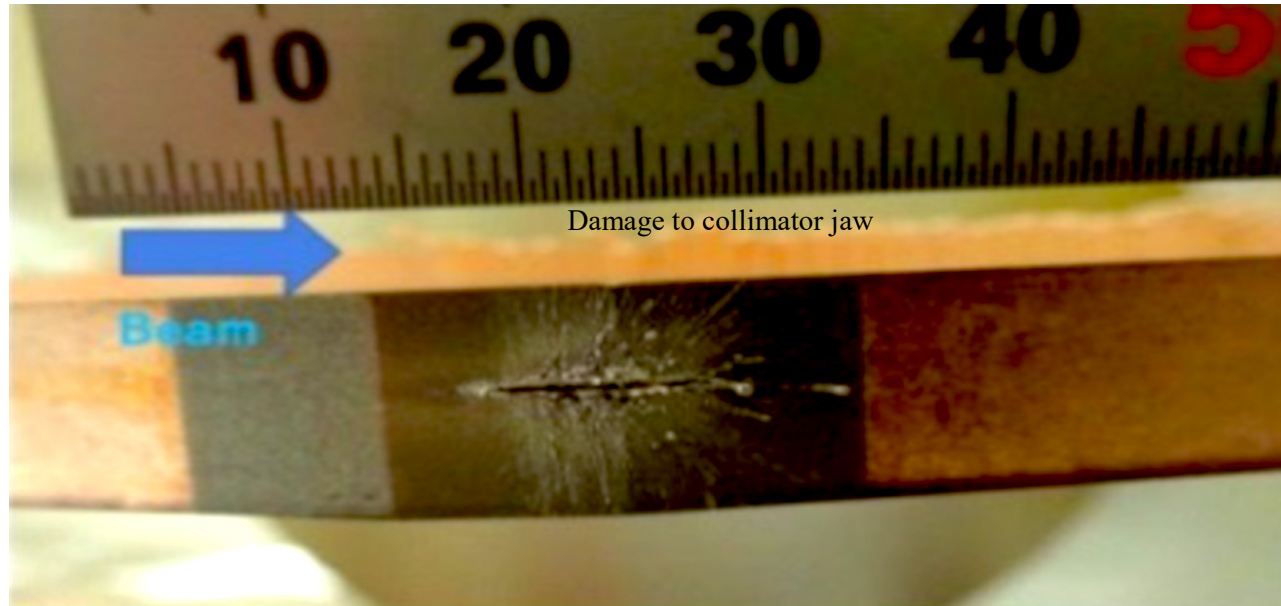
Electron Cloud Effect: the problem with many sources

The formation of an electron cloud in the vacuum tube of the accelerator:

- ▶ synchrotron light removes electrons from chamber wall
- ▶ electrons are accelerated by the beam
- ▶ electrons hit vacuum chamber and generate more electrons
- ▶ electron cloud → instability and heat losses at cryogenic temperatures !



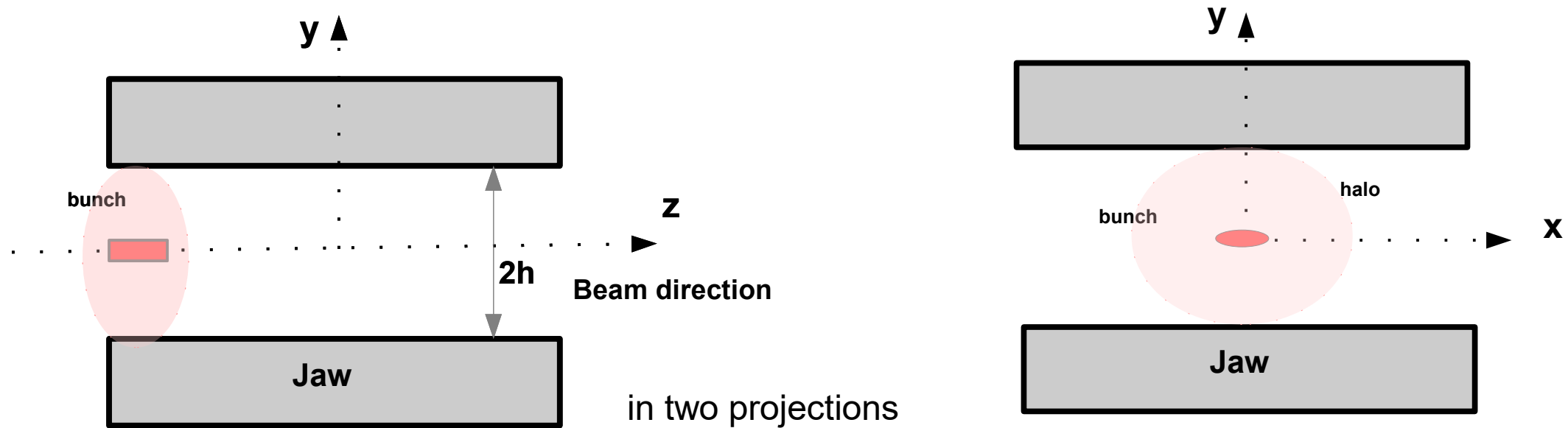
Example: the accident with a beam loss in the Super-KEK-B



Damage to a collimator jaw

A new source of electrons: field emission from collimators (not mentioned in the TDR)

Schematically, a collimator is two parallel plates made of a conductor that is resistant to thermal and mechanical effects



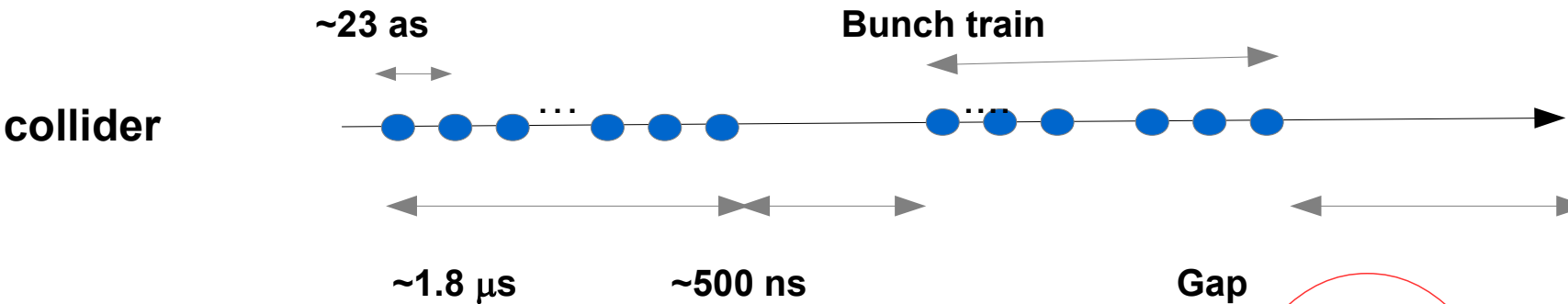
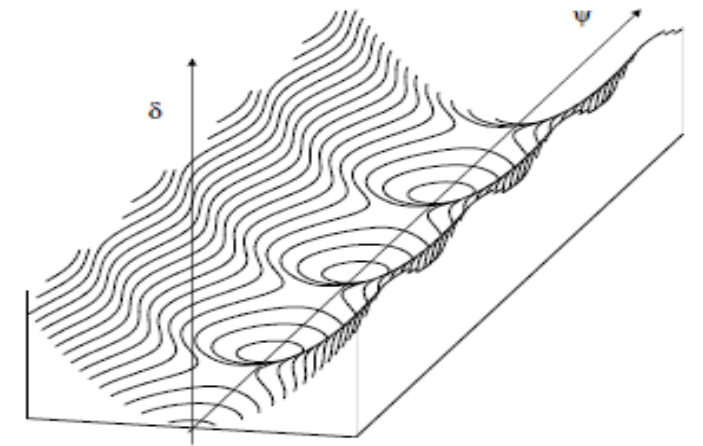
CEPC employs two types of collimators: one for reducing background and another for machine protection.

The latter has smaller gaps designed to handle significant beam loss in the event of a beam failure.

In particular, collimators are absorbing particles from the beam halo.

Positron beam in an accelerator

- The beam is not a steady stream of particles. It is bunched.
- A bunch is like a railcar with passengers.
- The beam consists of several trains that follow one another.



A phase space picture of potential RF buckets where bunches are located.

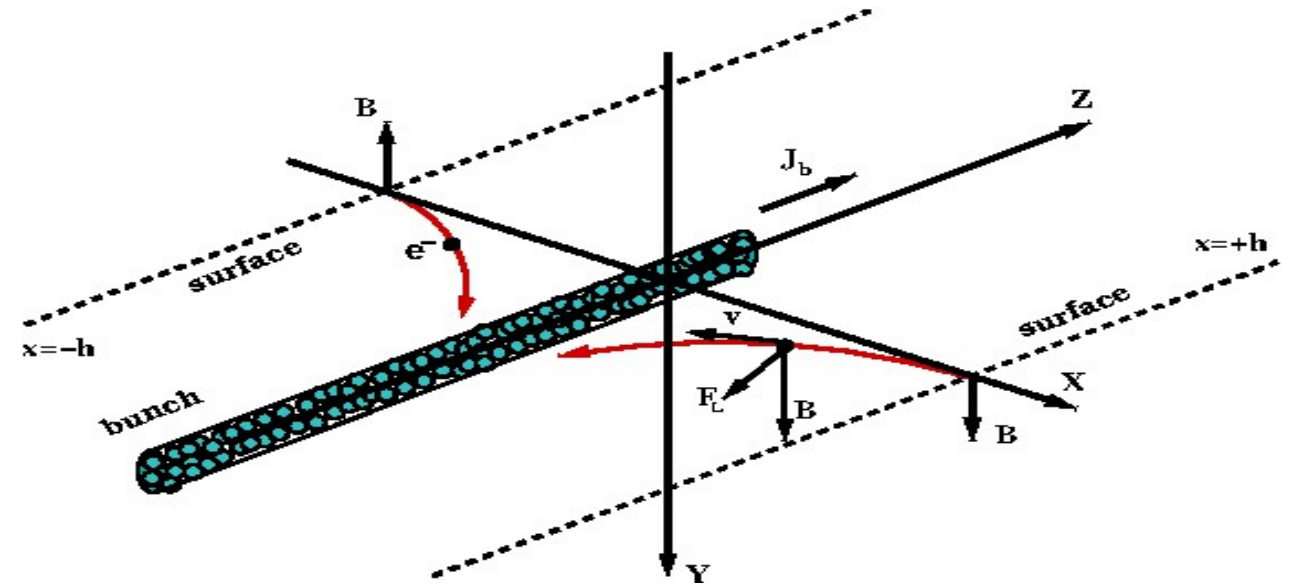
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Modification of the electric field of relativistic particles if particles forms a Bunch



$$\vec{E} = \kappa \frac{q \gamma}{r^2} \left[\frac{1 - \beta^2}{1 - \beta^2 \sin^2 \theta} \right]^{3/2} \frac{\vec{r}}{r}$$

The relativistic Lorentz-contracted Coulomb electric field around a particle.



Cylindrical bunch,

$$\rho = q \lambda / \pi a^2$$

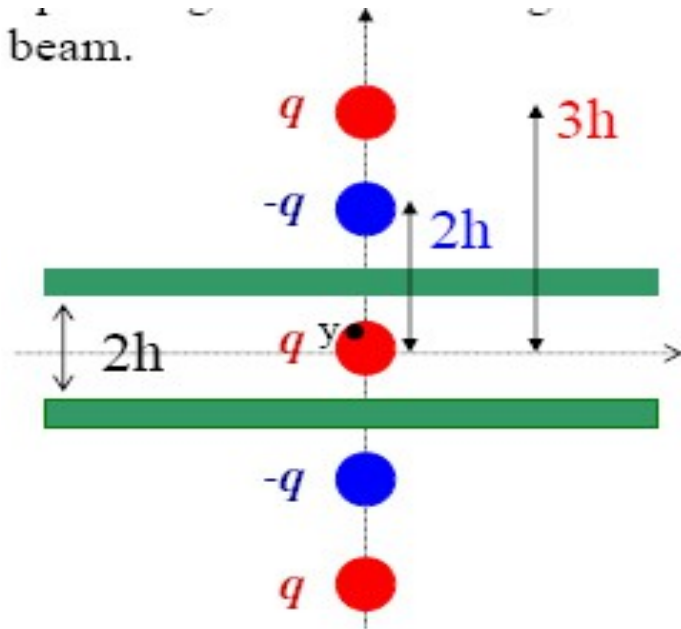
$$E(r, z, t) = \kappa \frac{2q \lambda}{r} [\theta(z - \beta ct) - \theta(z - \beta ct - L)]$$

$$E(r, z, t) = \kappa \frac{2q \lambda(z, t)}{r}$$

B. Levchenko, 2019

$\gamma \rightarrow \infty$, arbitrary linear density

Bunch placed between conducting plates



The resulting fields are the sum of the **direct field** and fields from the **image charges**.

Scaled coordinates, $\delta_x = x/h, \delta_y = y/h, \bar{\delta}_x = \bar{x}/h, \bar{\delta}_y = \bar{y}/h$

Exact two-dimensional (2D) solutions for

$$\vec{E}(x, y, z, t), \quad \vec{B}(x, y, z, t)$$

1D, B. Levchenko, 2010

2D, B. Levchenko, 2020

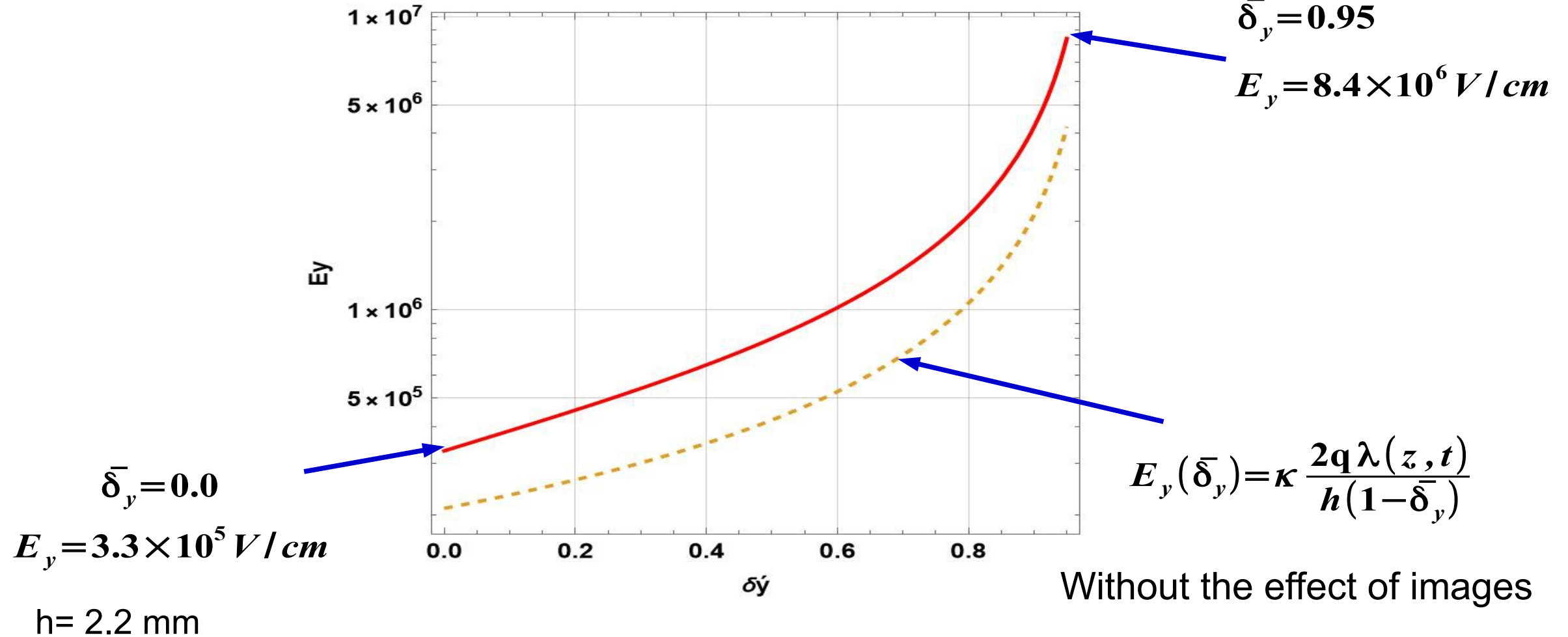
An infinite sequence of fields of image charges

$$E_{y, tot}(\delta_x, \delta_y, \bar{\delta}_x, \bar{\delta}_y) = \kappa \frac{2q\lambda}{h} \frac{\pi}{8} \left[\frac{\sin[\pi(\delta_y + \bar{\delta}_y)/2]}{\sinh^2[\pi(\delta_x + \bar{\delta}_x)/4] + \cos^2[\pi(\delta_y + \bar{\delta}_y)/4]} + \frac{\sin[\pi(\delta_y - \bar{\delta}_y)/2]}{\sinh^2[\pi(\delta_x - \bar{\delta}_x)/4] + \sin^2[\pi(\delta_y - \bar{\delta}_y)/4]} \right]$$

Fixed value

Due to the image charges

Example : Electric field strength at a jaw surface vs $\bar{\delta}_y$



The bunch got closer and closer to a jaw surface: $\bar{\delta}_y \rightarrow 1$

Field emission: Essential ingredients

Quantum tunneling

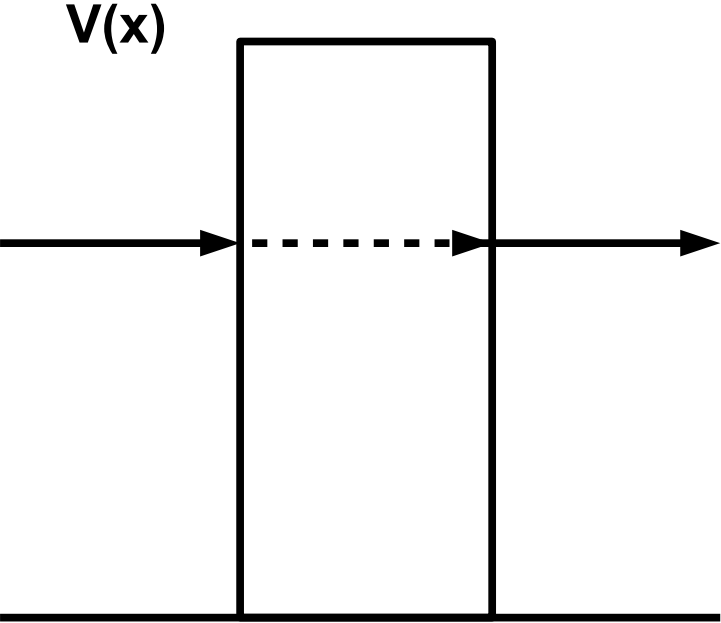
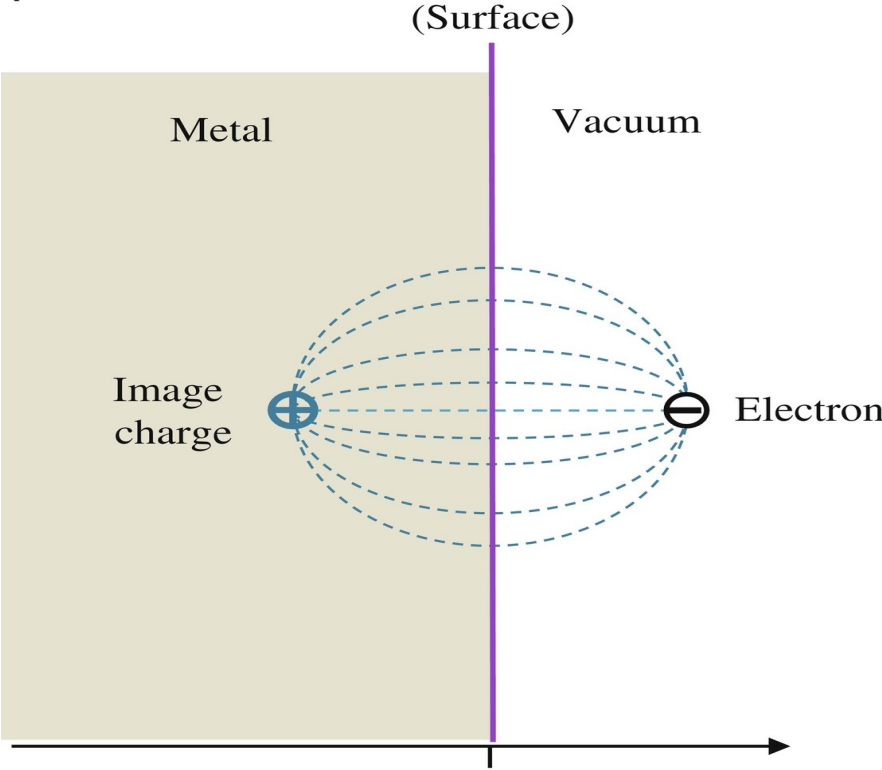


Image charge effect



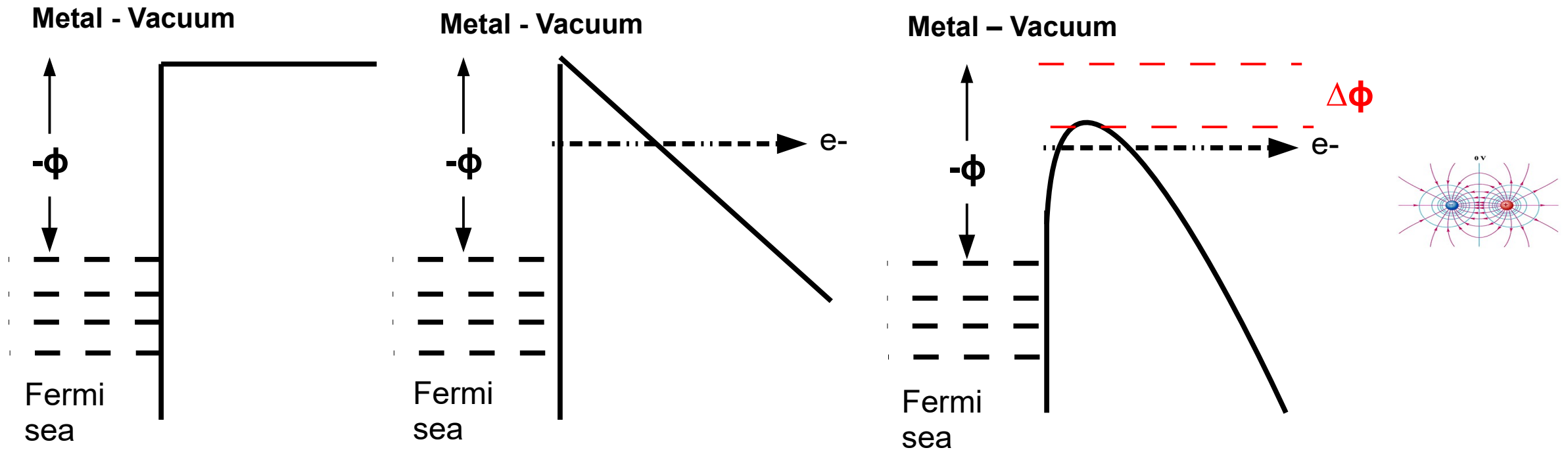
An electron is levitating close to the surface.

Potential barrier at a metal-vacuum Interface in an electric field

Field emission via Quantum tunnelling effect

Fowler, Nordheim, 1928

Metal acts as a potential well for electrons. Φ – work function (eV).



External field:

$$V(x) \sim 0$$

$$V(x) \sim -eEx$$

$$V(x) \sim -eEx - e^2/4x$$

Image potential

Fowler- Nordheim field emission current of electrons

Fowler, Nordheim, 1928

$$J_{FN} = A \frac{E_y^2}{\phi t^2(\tau)} \exp \left\{ -B \frac{\phi^{3/2}}{E_y} \theta(\tau) \right\}$$

nonperturbative feature

Here

$$A = \frac{e^3}{8\pi h} = 1.5414 \times 10^{-6}, \quad B = \frac{8\pi \sqrt{2m}}{3eh} = 6.8309 \times 10^7, \quad \tau = \frac{\sqrt{e^3 E_y}}{\phi} = 3.7947 \times 10^{-4} \frac{\sqrt{E_y}}{\phi}$$

$t(\tau)$ and $\theta(\tau)$ are the Nordheim functions that account for the image charge effect and are expressed via elliptic integrals.

Comparison of the Fowler- Nordheim theory with data

The theory only agrees with the experimental data if $E \rightarrow \beta E$.

β - the field enhancement factor: $1 \div 10^3$ and more...

For an ideal flat surface, $\beta = 1$.

Such a surface is an abstraction !

The origin of β is the morphology of the surface

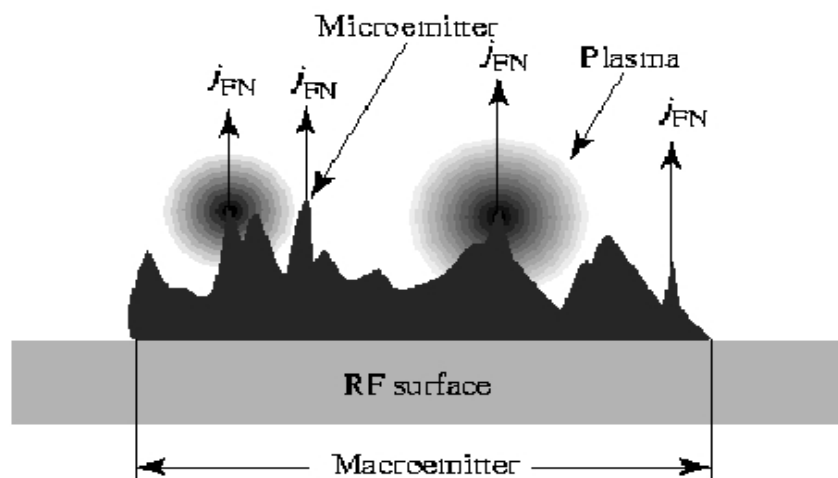
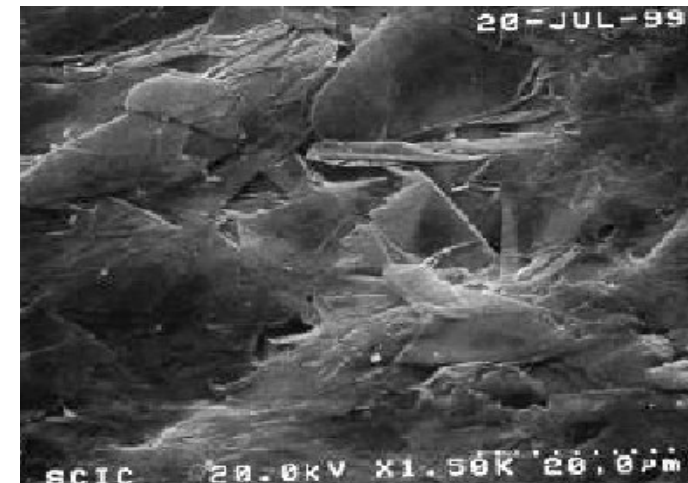
LHC collimator



Close view



Microphoto



Schematic morphology of a surface.

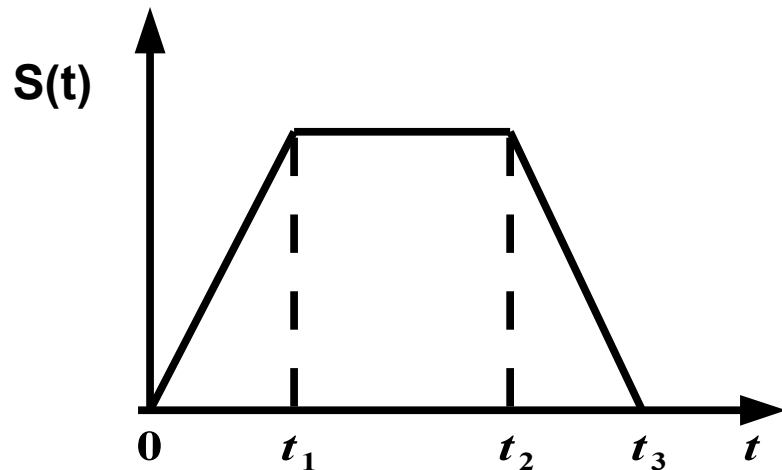
Microtips can appear even on an optically polished surface.

Number of extracted electrons per second

$$N_e(\beta_{FN}) = n_b N_r \Sigma \int \int \int \frac{1}{e} J(\beta_{FN} E_y) \Theta(z, t) dx dz dt$$

Here

$$\Theta(z, t) = [\theta(z - \beta ct) - \theta(z - \beta ct - L_b)] \rightarrow dx \int \Theta(z, t) dz dt = \int S(t) dt$$



The area covered by the field of a bunch in the collimator.

In the end

$$N_e(\beta_{FN}) = n_b N_r L_b L_j \frac{2}{ec} \Sigma \int_0^{x_m} J(\beta_{FN} E_y(x, \bar{\delta}_y)) dx$$

L_b – bunch length,

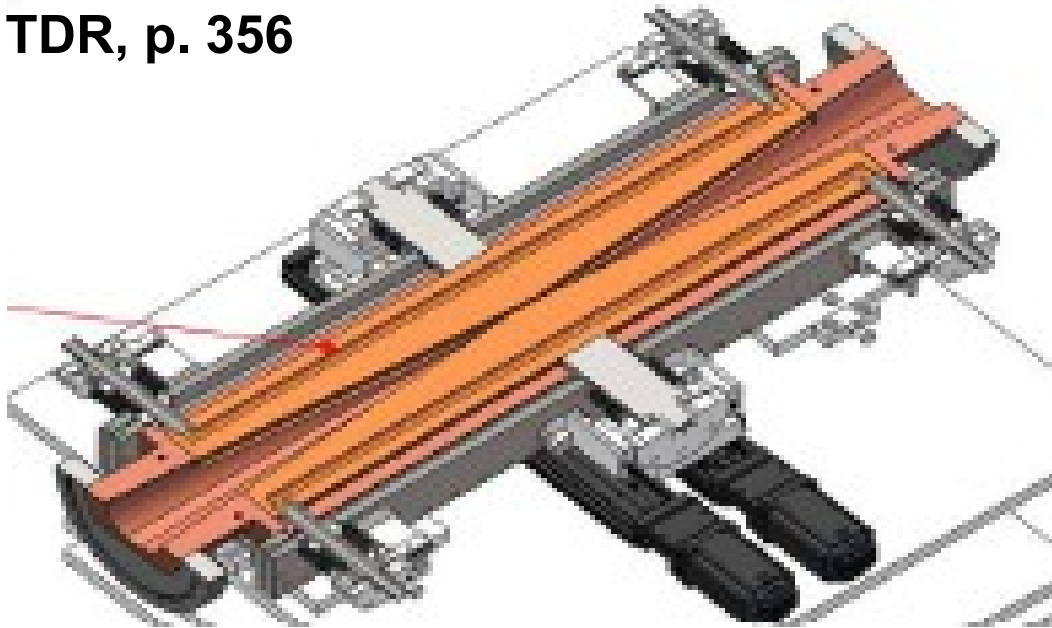
L_j – a jaw length,

n_b – number of bunches

N_r – number of beam revolutions per second

CEPC movable collimators for reducing background

TDR, p. 356



Made from GlidCopAl-15 copper.

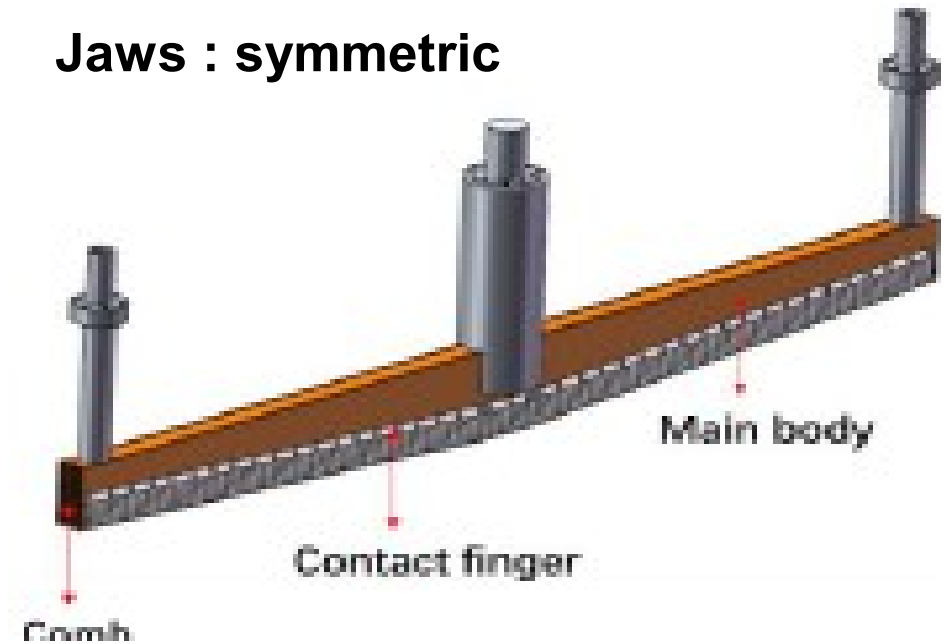
$\Phi=4.5$ eV

The physical aperture varying within the range of 4.4–20 mm.

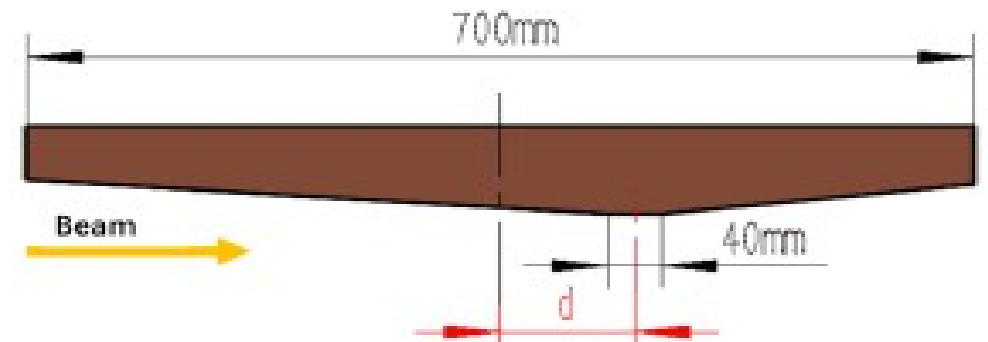
Half-gap $h = 2.2-10$ mm..

Flat part: 40 mm \times 21 mm

Jaws : symmetric

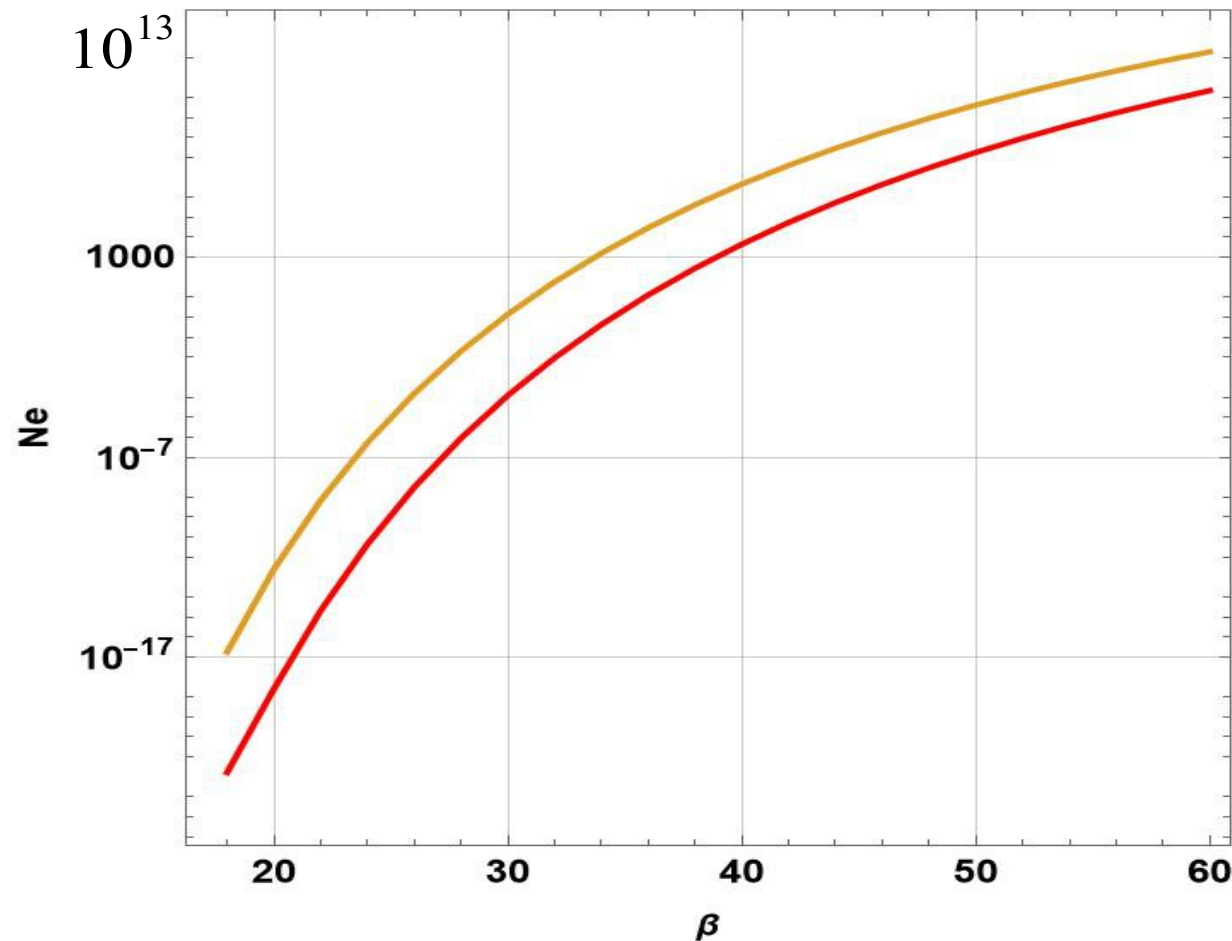


asymmetric jaws



Results: Collimator for reducing background: TDR, Ch. 4.3.10.4

Number of electrons emitted per second



$h = 2.2 \text{ mm}$

Red line: $\bar{\delta}_y = \bar{y}/h = 0$
a bunch without offset ($y=0$)

Yellow line: $\bar{\delta}_y = 0.1$

The offset leads to a 10^4
increase in N_e .

For “an ideal surface”, $\beta < 30$, $N_e \sim 0$

**At $\beta \geq 50$, $N_e \sim 10^{11} \div 10^{12}$ and
of the same order as a bunch content !**

18 movable collimators will be employed in the positron ring to reduce beamstrahlung backgrounds from the IR and minimize multi-turn losses.

CEPC collimators for machine protection TDR, p. 151, Table 4.2.6.10

Design of collimators for the machine protection is **part of the ongoing EDR program.**

With smaller gaps designed to handle significant beam loss in the event of a beam failure.

Name	half gap (mm)
APTY1	0.03~3.24
APTY3	0.065~4
APTX1	1.44~7.32

Assumptions

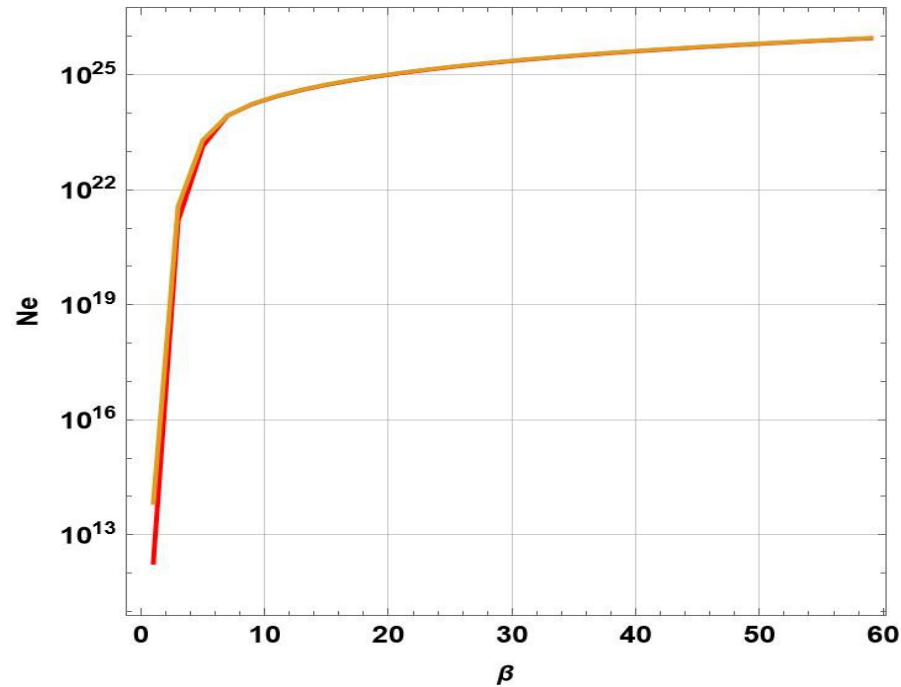
Made from GlidCopAl-15 copper.
 $\Phi=4.5$ eV

Half-gap
h = 0.03-3.24, 0.065~4.

Flat parts: 40 mm × 21 mm

Results: Collimators for machine protection: TDR, Table 4.2.6.10

Number of electrons emitted per second

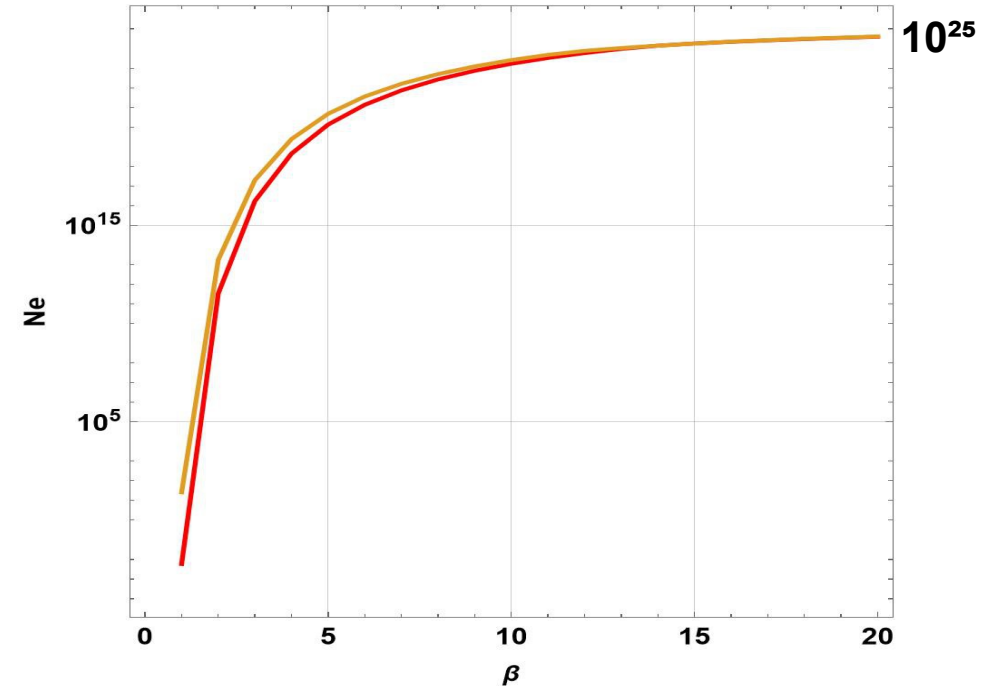


$h = 0.03$ mm (APTY1)

Red line: bunches without offset ($\delta_y^- = 0$)

$h = 0.065$ mm (APTY3)

Yellow line: $\delta_y^- = 0.1$



Ne per sec >> # of positrons in the beam.

These **h** values lead to disastrous scenarios and the formation of very dense electron clouds!

Summary

- A novel source of secondary electrons contributing to ECE is analyzed.
- The electric self-field of positron bunches is amplified by the image charge effect. The self-field of a bunch initiates emission of electrons from collimators.
- We estimate the number of electrons, N_e , emitted by a single collimator per second under the influence of the positron beam.
- The amount of N_e is very sensitive to the quality of the collimator surface characterized by the parameter β .
- Due to the field emission effect, the number of secondary electrons may exceeds the number of particles in the beam by several orders of magnitude at the minimum collimator half-widths specified in the TDR.
- However, it is possible to put the problem under control if appropriate measures will be undertaken.

References

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