Design of a Compact Electron Gun for the HV Electron Cooler for the NICA Collider

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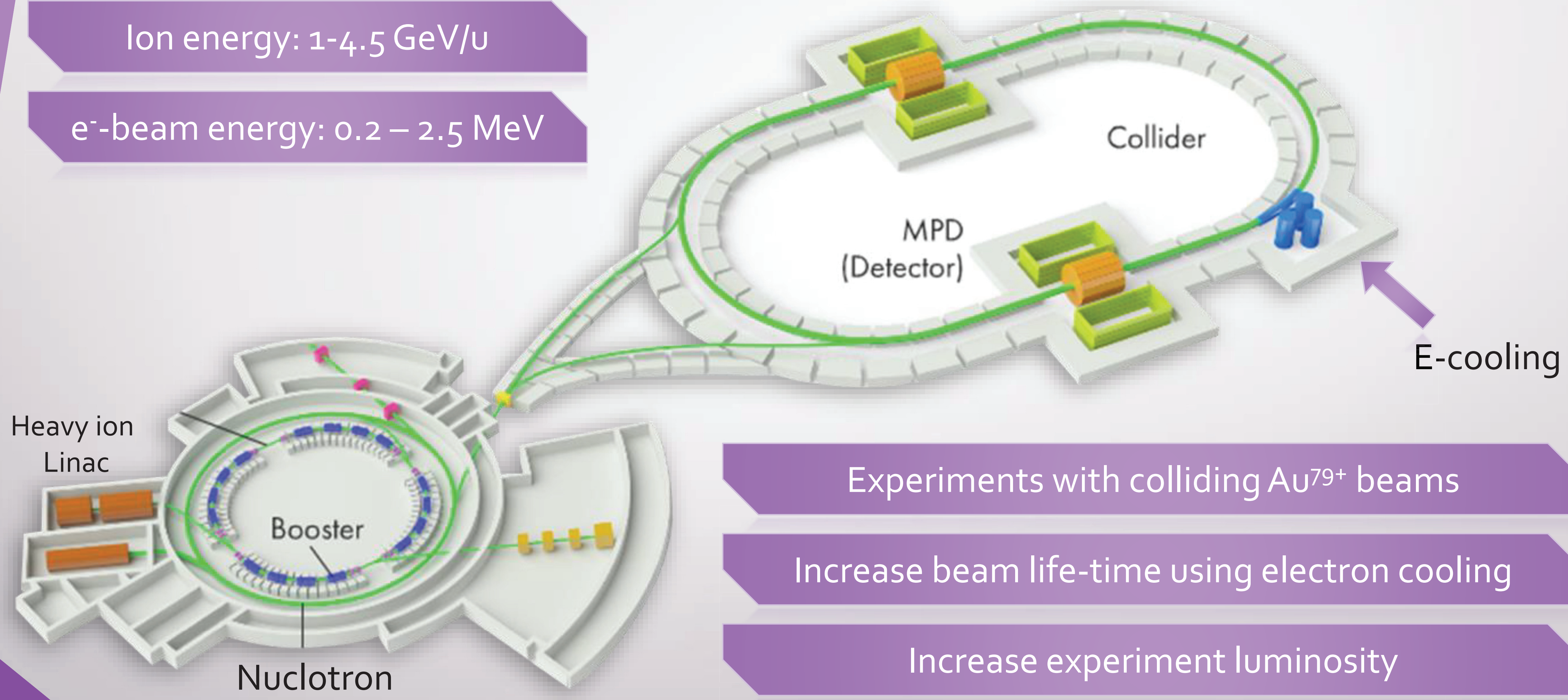
Electron cooling system for the NICA collider

Ion energy: 1-4.5 GeV/u

e^--beam energy: 0.2 – 2.5 MeV

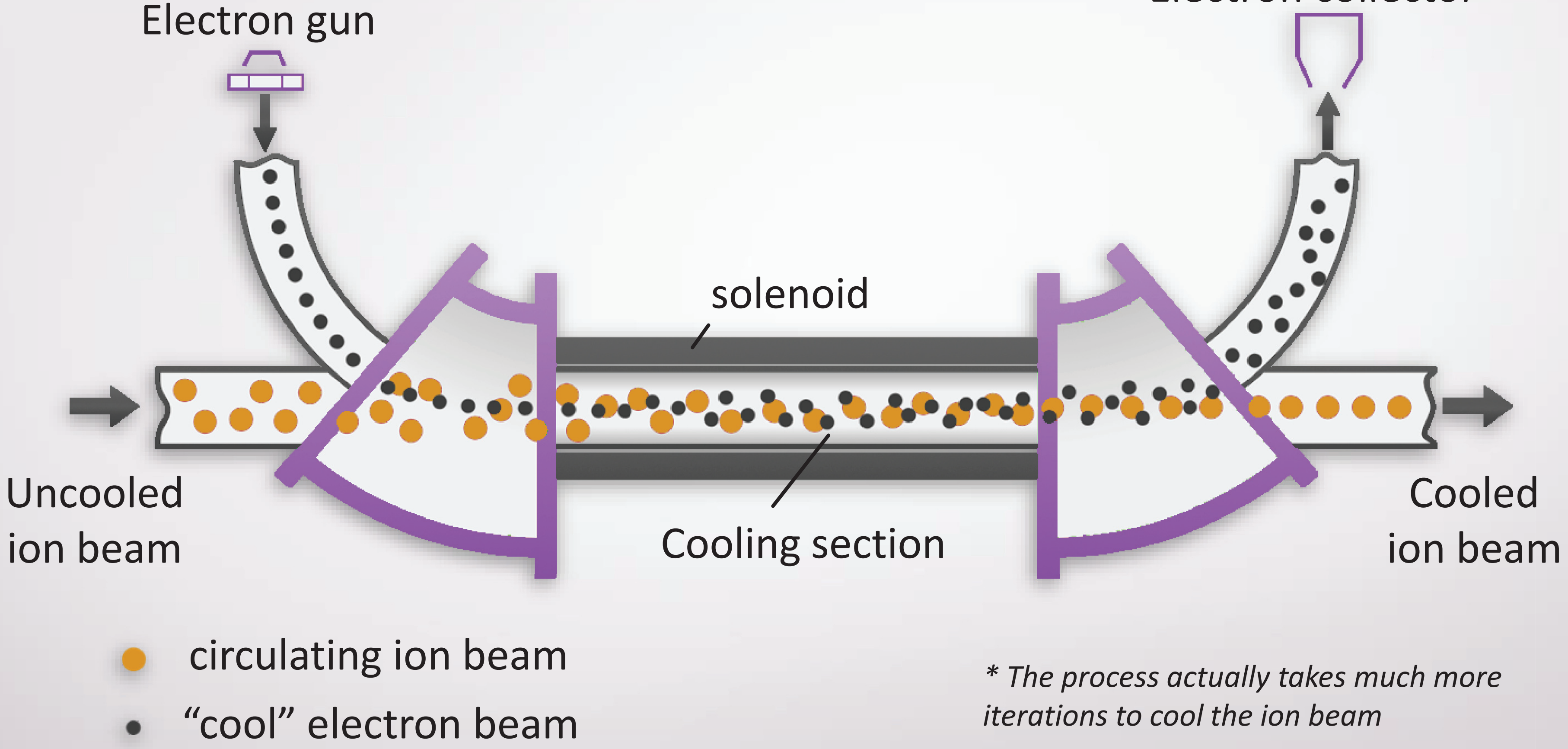


Experiments with colliding Au^{79+} beams

Increase beam life-time using electron cooling

Increase experiment luminosity

The concept of electron cooling

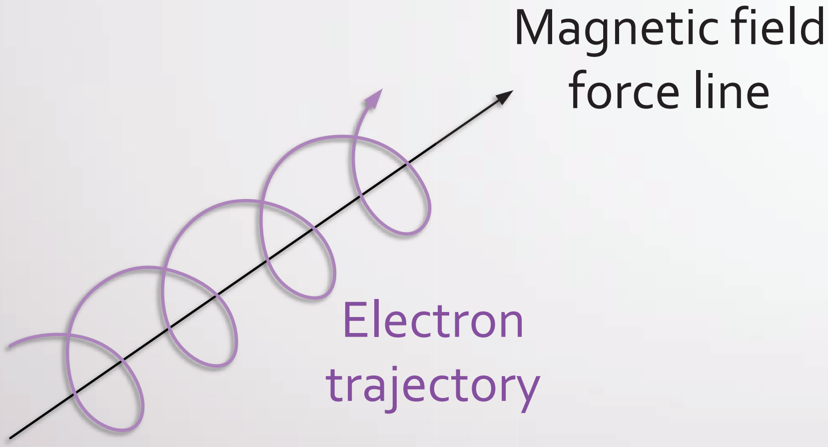


** The process actually takes much more iterations to cool the ion beam*

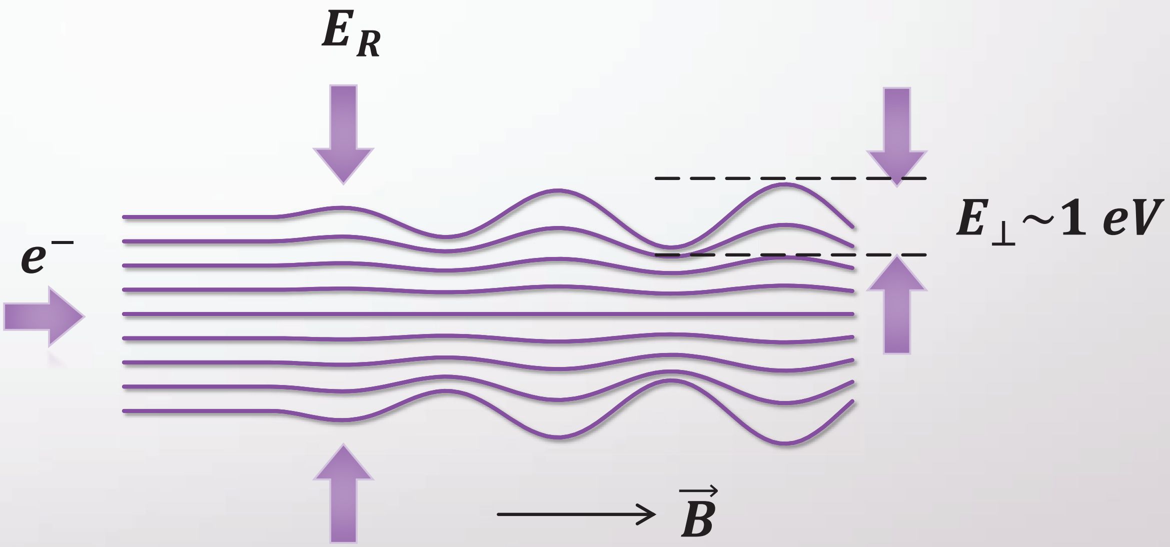
Cooling efficiency depends on the electron beam momentum spread and current density

Electron oscillations

Coherent electron oscillations in the electron beam



Electrical field of the gun has axial symmetry

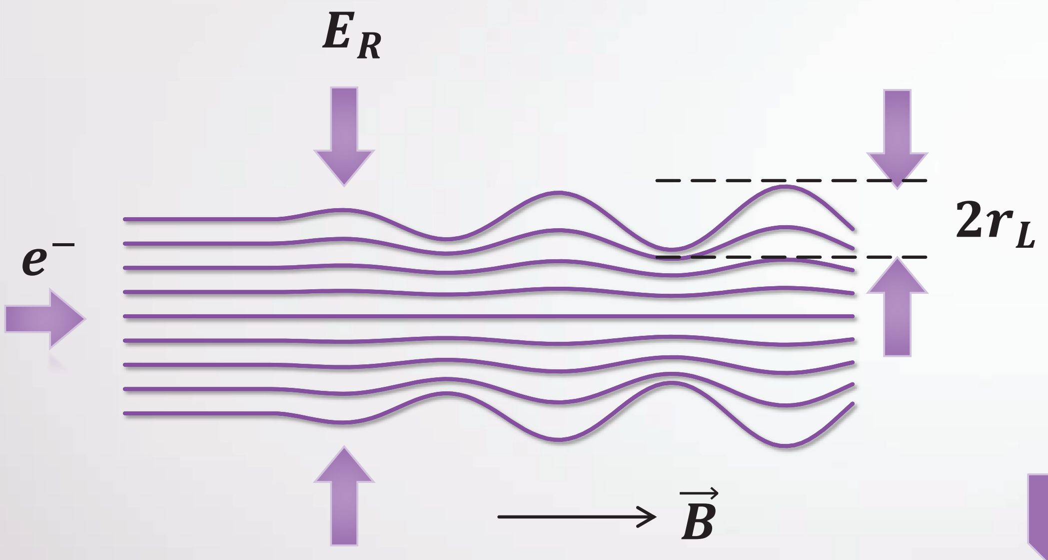


$$T_\perp \approx 0.1\ eV\ (1000\ °C) \ll E_\perp$$

For efficient electron cooling the amplitude of these oscillations must be low

Electrons oscillations energy tolerance

For efficient electron cooling the amplitude of electron oscillations must be low



$$E_\perp = \frac{p_\perp^2}{2\, m_e} \qquad r_L = \frac{p_\perp\, c}{e\, B}$$

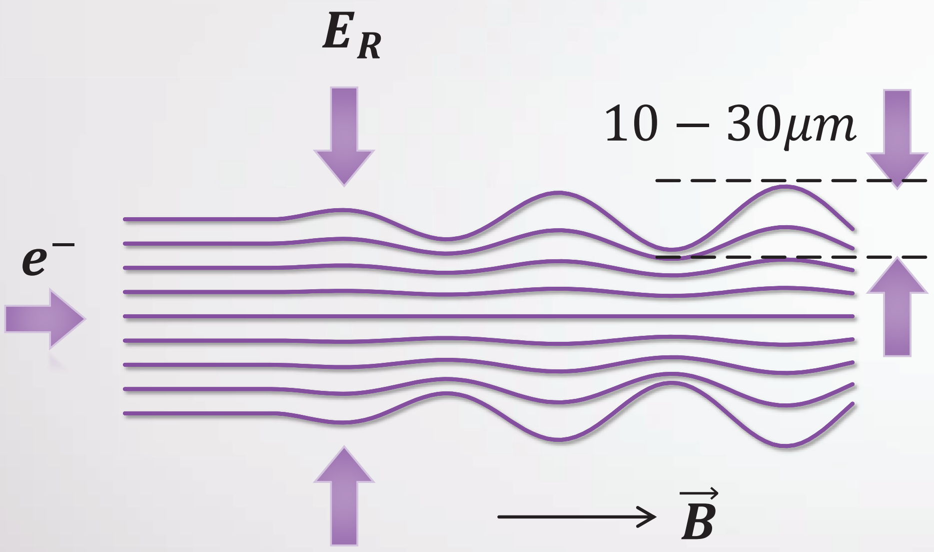
Electrons of the beam oscillate with the same phase (at the beginning)

Beam radius changes due to coherent oscillations of the electrons

We can use BPMs to measure these oscillations

Electrons oscillations energy tolerance

For efficient electron cooling the amplitude of electron oscillations must be low



$$E_\perp = \frac{p_\perp^2}{2\, m_e} \qquad r_L = \frac{p_\perp\, c}{e\, B}$$

BPMs sensitivity: 10-30 μm

*** Guiding magnetic field in the cooling section (B) is about 1-2 kG***

$$E_\perp = 1\ eV \quad \longleftrightarrow \quad r_L \approx 20\ \mu m$$
$$(B = 1.5\ kG)$$

We don’t aim at oscillations energy lower than **1 eV**, as we don’t have means to measure it

Required electron beam current density

Electron beam density is yet another factor that affects the cooling time

Empirical formula for the electron cooling force (beam reference system)

$$\frac{d\overrightarrow{p_i'}}{dt'} = \frac{4Z^2 e^4 n_e' \Lambda}{m_e} \cdot \frac{-\overrightarrow{v_i'}}{\left[v_i'^2 + v_{eff}^2\right]^{3/2}}$$

Estimation for the cooling decrement (observational reference frame):

$$\tau^{-1} \sim j_e \cdot \frac{Z^2}{A} \cdot \frac{4e^3 \Lambda}{\gamma^5 m_e m_p v_0^4} \cdot \frac{1}{x'^3}$$

x' - the maximum angle in the ion beam

** The decrement grows as the transverse temperature decreases, therefore this formula estimates the upper bound for the cooling time*

Required electron beam current density

Parameters of the NICA collider

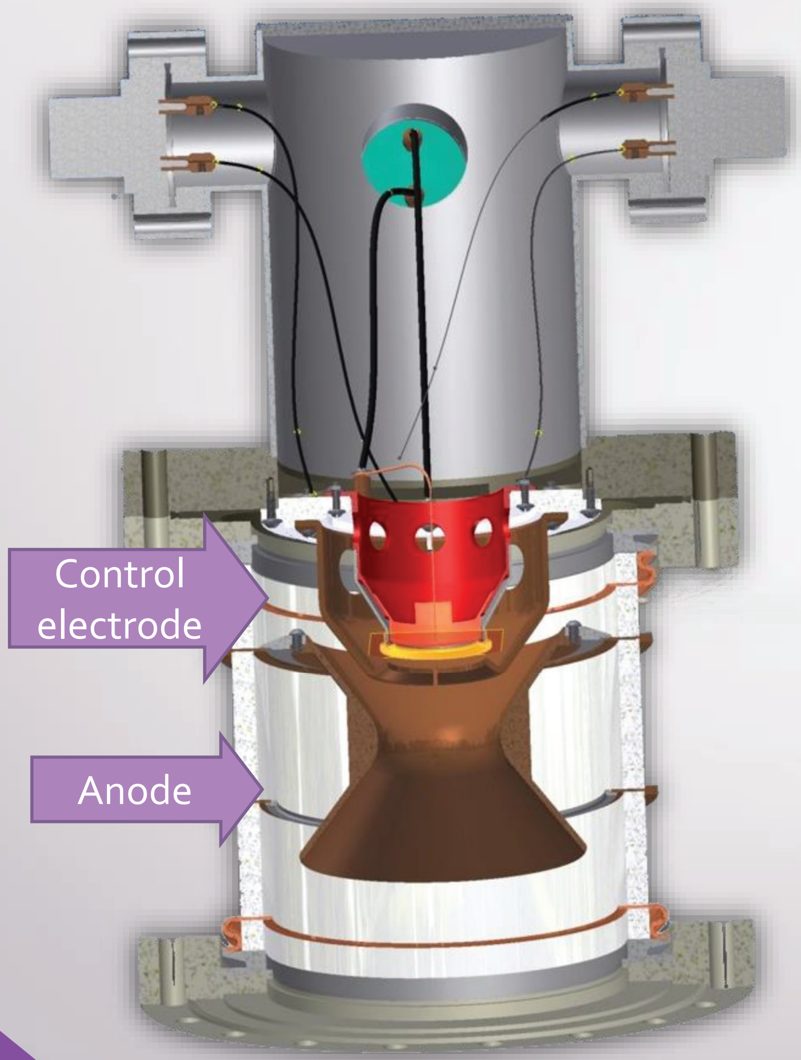
Z / A	79 / 197		
Ion energy, Gev/u	1.0	3.0	4.5
Hor / ver rms beam emittance (unnormalized), $\pi\ mm\ mrad$	1.1 / 0.95	1.1 / 0.85	1.1 / 0.75
Ion energy, Gev/u	1.0	3.0	4.5
IBS growth time, s	160	460	1800
Beta function at the cooling section, m	10		
Circumference of the collider (L_P), m	503		
Length of the cooling section (L_C), m	6		
t_{Cool}, s	16	46	180
j_e, $\mathrm{A/cm^2}$	0.05	0.6	0.8

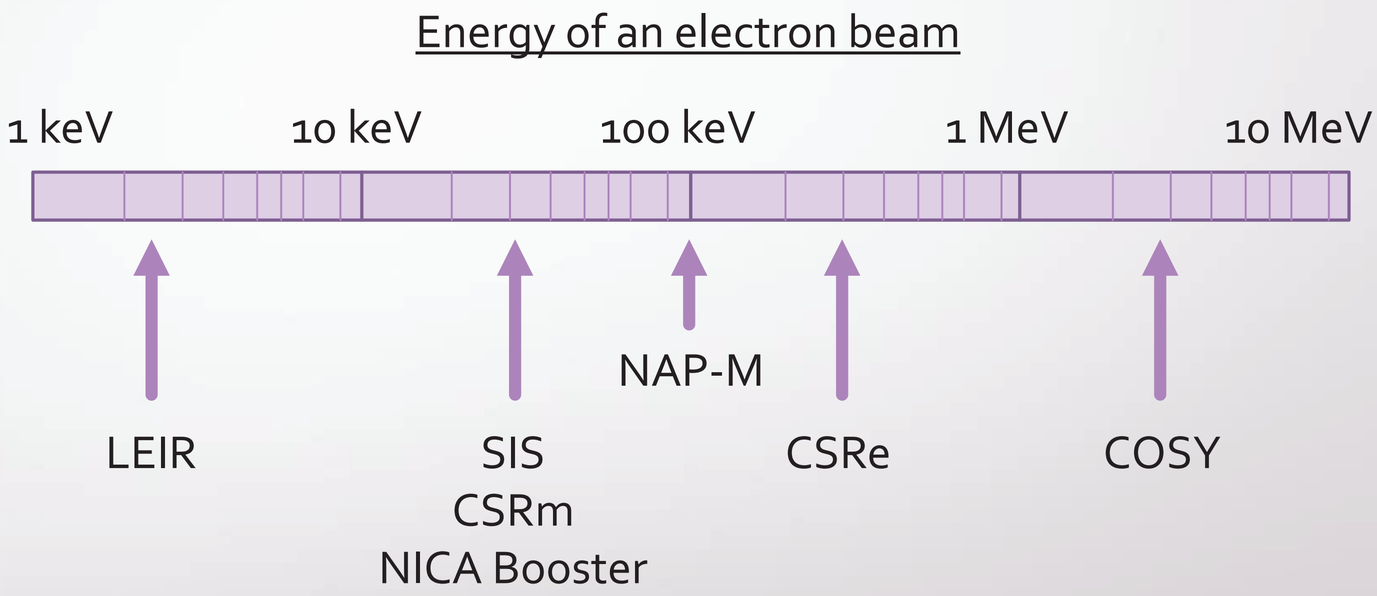
$$t_{Cool} \approx \frac{x'^3}{j_e} \cdot \left(\frac{Z^2}{A} \cdot \frac{4e^3\Lambda}{\gamma^5 m_e m_p v_0^4} \right)^{-1} \cdot \frac{L_P}{L_C}$$

Necessary electron current density
$\boldsymbol{j_e \approx 1A/cm^2}$

Electron gun

Electron cooling systems produced in BINP

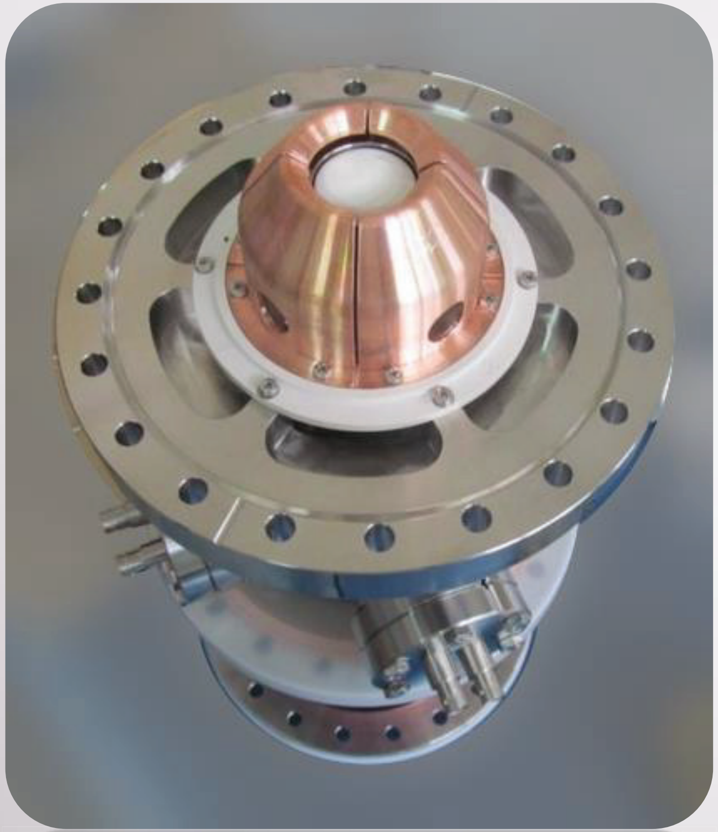




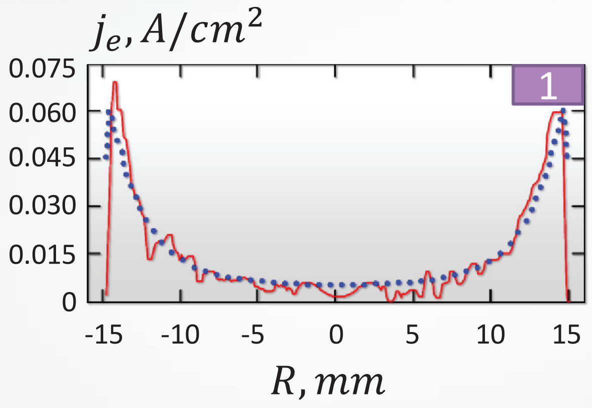
Electron gun has a control electron to vary a beam profile

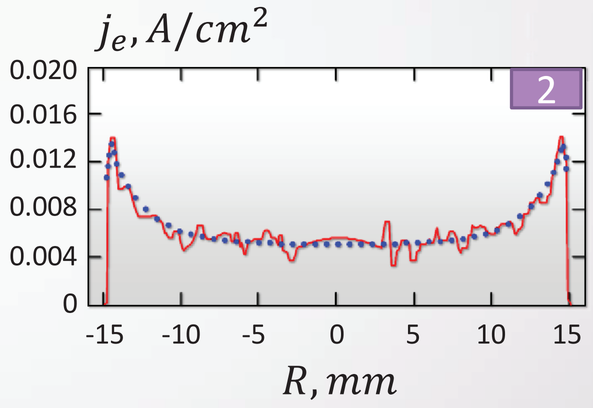
(COSY, NICA Booster) Using a four-sector control electrode

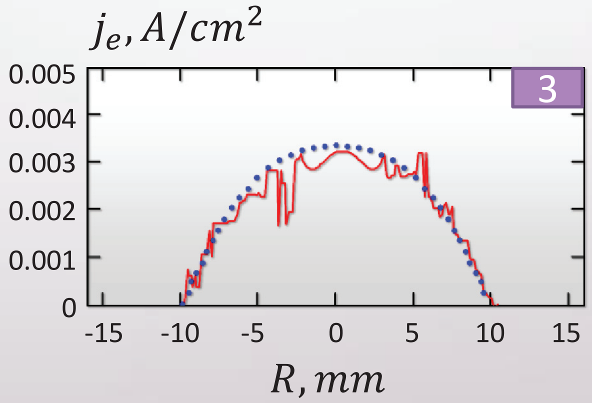
Four-sector control electrode



Variable electron beam current density



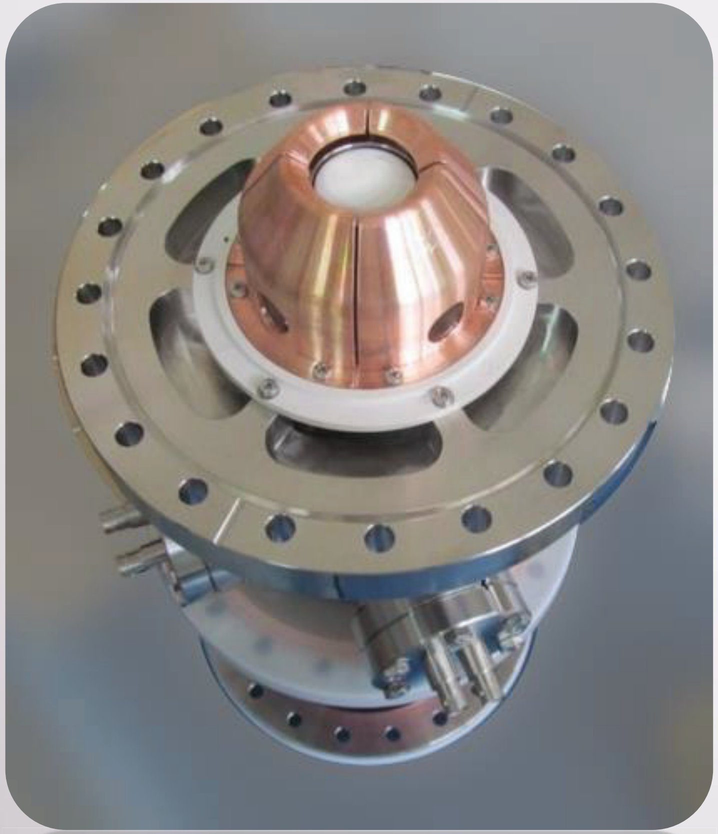




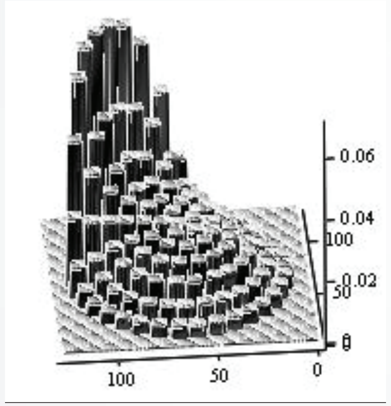
Regime	U_{anode}, V	$U_{control}$, V
1: Hollow	500	300
2: Flat	500	100
3: Thin	500	−100

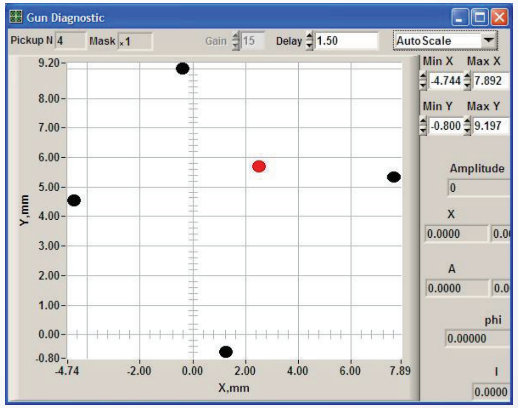
** Red curve is measured current density, and the blue curve is calculated.*

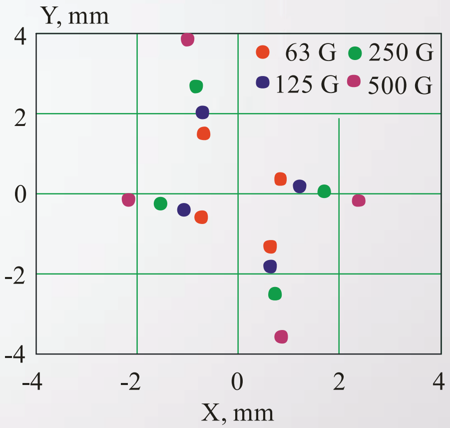
Four-sector control electrode



Four-sector control electrode







** Voltage is applied to a single sector.*

** Varying magnetic field.*

Measuring the position of the modulated beam part using BPM

We can measure beam position, size and rotation

Towards higher electron current density

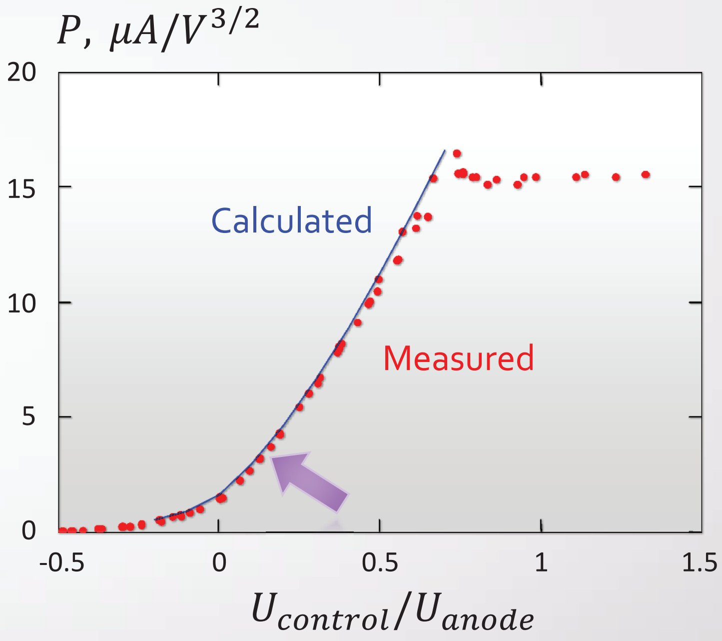
Why not to reuse the existing electron gun?

- The electron current density is not enough for the electron cooler for the NICA collider

- The electron beam is unnecessarily large.

Ion beam diameter (rms) for the NICA collider is just about **0.6 cm**

Using the smaller beam we can achieve greater current density at the same overall current

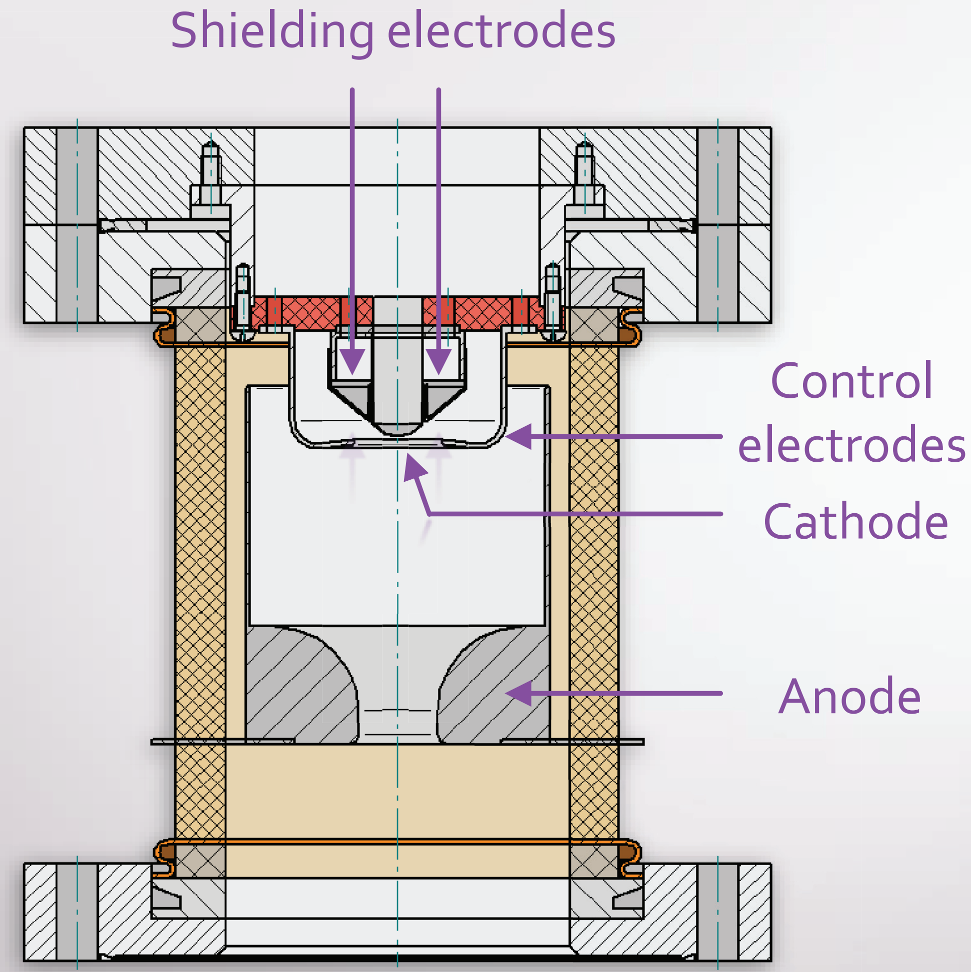


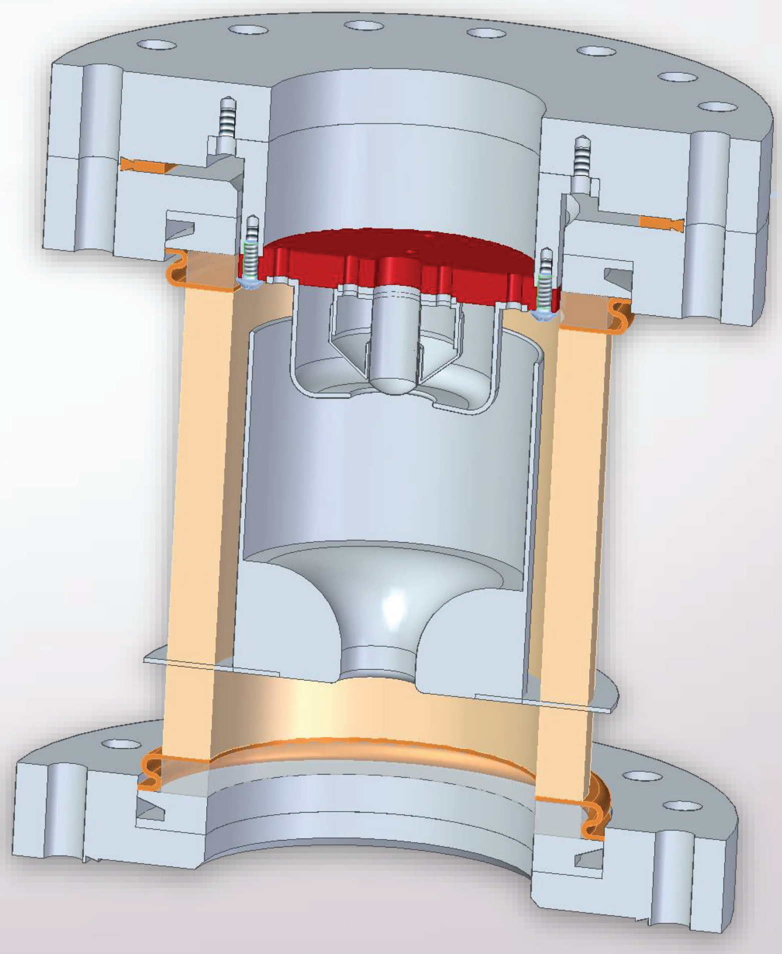
The perveance of the electron gun for the COSY electron cooler.

U_{anode}	$U_{control}$	R_{beam}	j_e
$10\ kV$	2 kV	3 cm	$0.56\ A/cm^2$

We designed a new gun, which can provide a **1 cm** diameter beam with current up to **1 A**

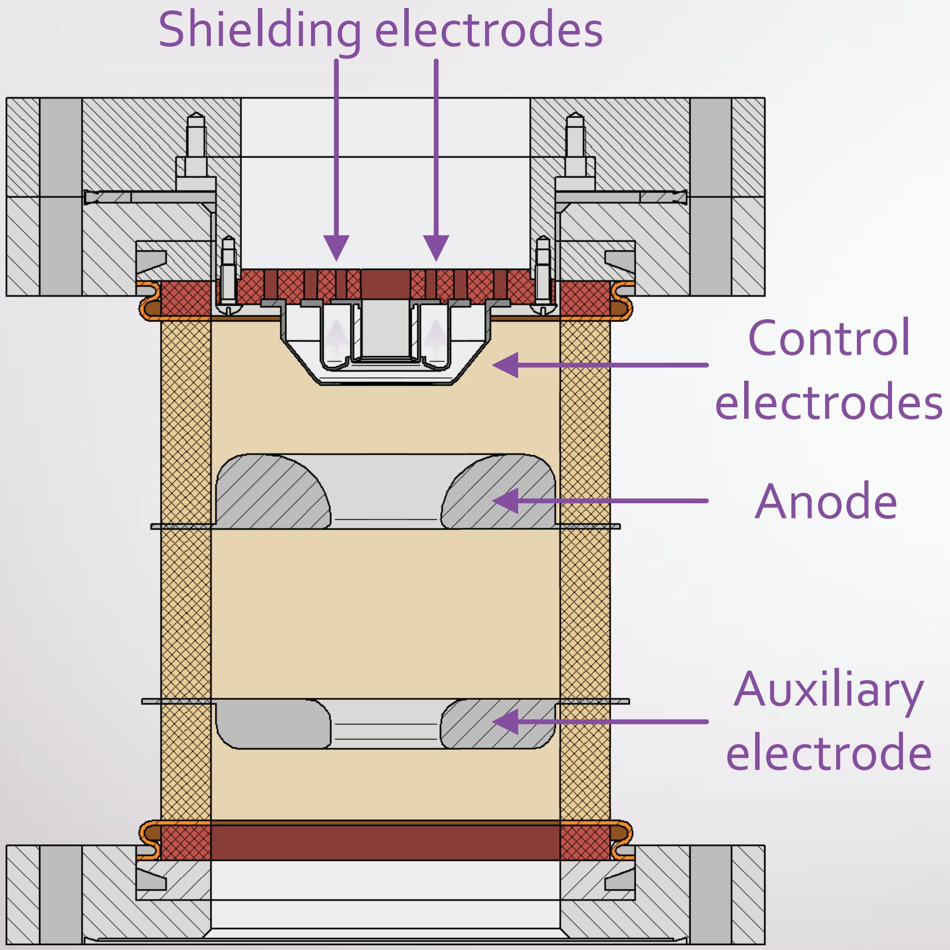
Electron gun with a convex cathode

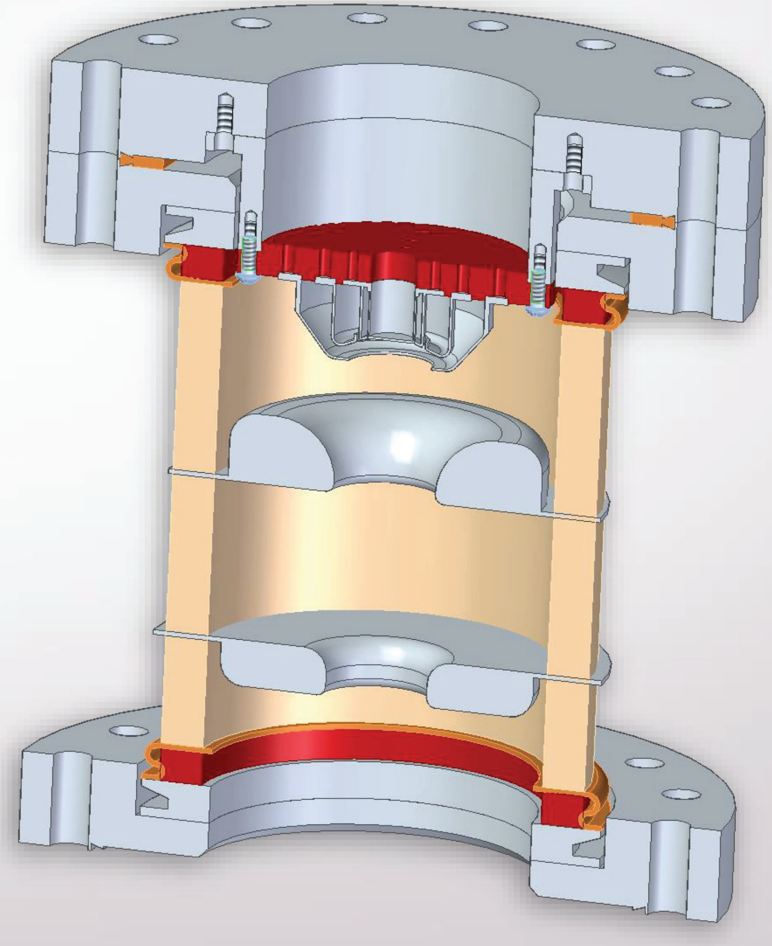




Using a convex cathode to get more current

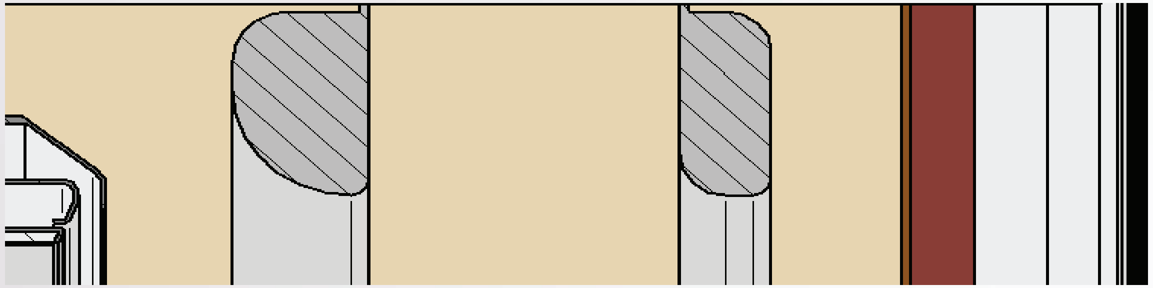
Electron gun with a flat cathode



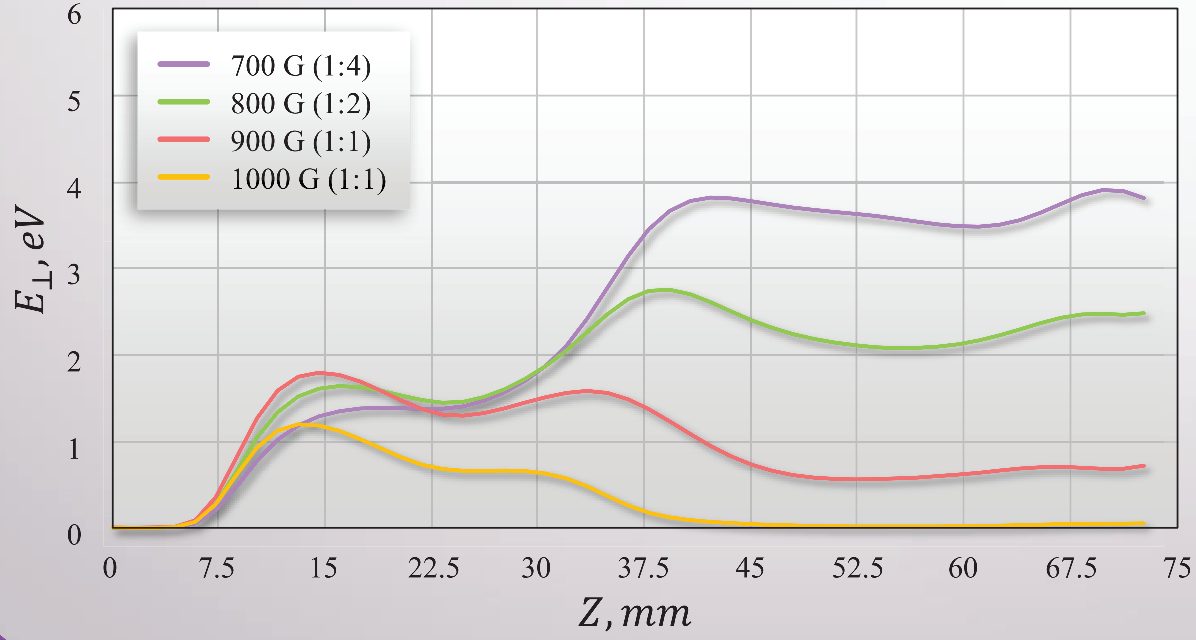


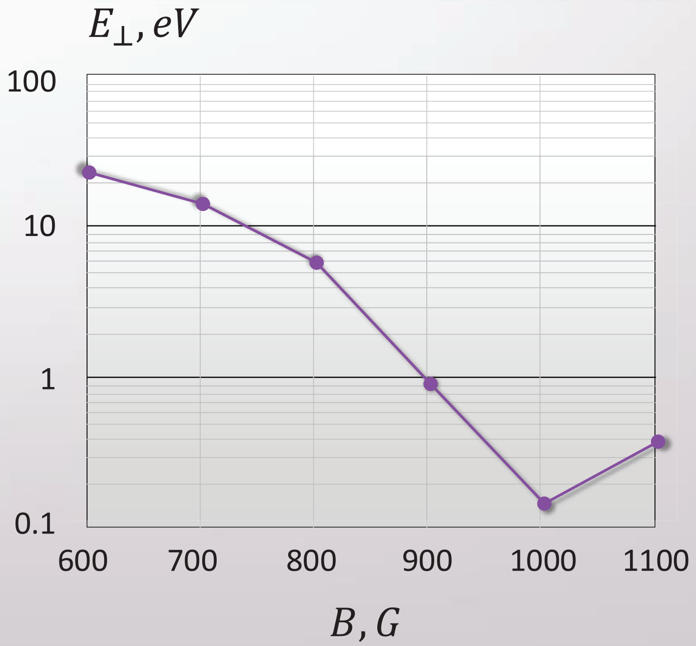
Using Pierce optics to get a beam with minimal transverse momentum spread

Resonant behavior of the electron beam

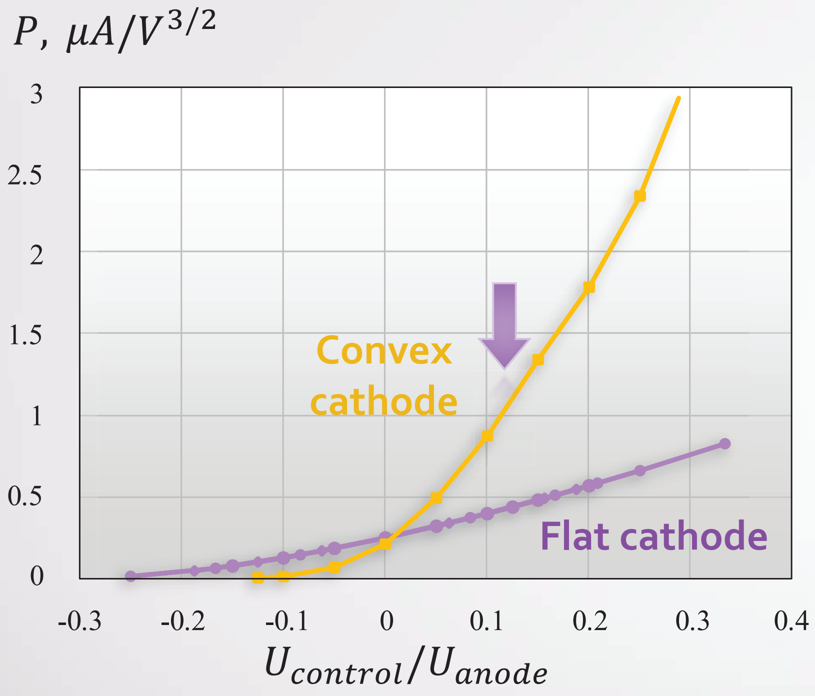


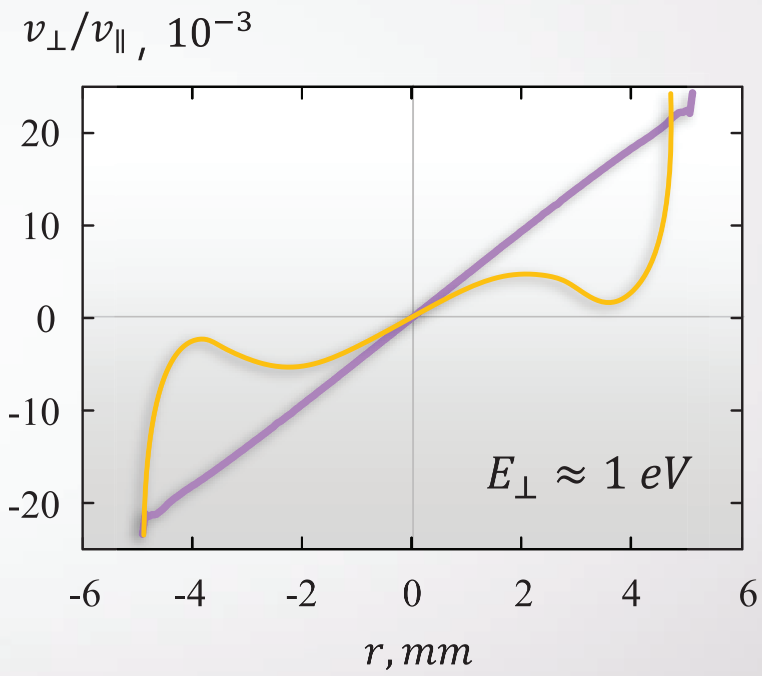
The resulting momentum spread depends on the configuration of the electrical fields and the guiding magnetic field





Comparison of the two electron guns



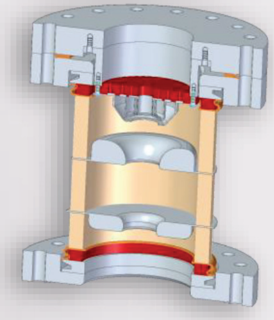


A convex cathode has a larger emissive surface and higher electrical field strength due to its curvature, therefore its perveance is higher.

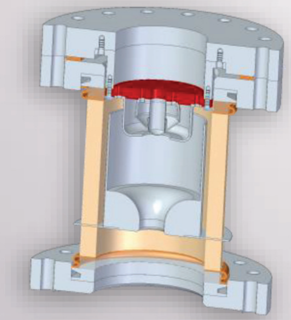
In case of a gun with a flat cathode, the momentum spread can be diminished using an electrostatic lens, while a gun with a convex cathode has a more complex velocities distribution.

Comparison of the two electron guns

Varying beam current density (B = 900 G)

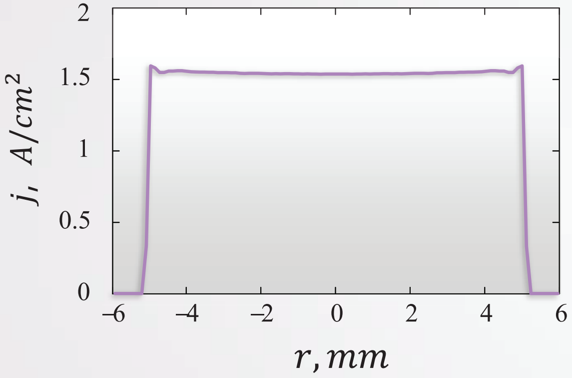


Flat cathode

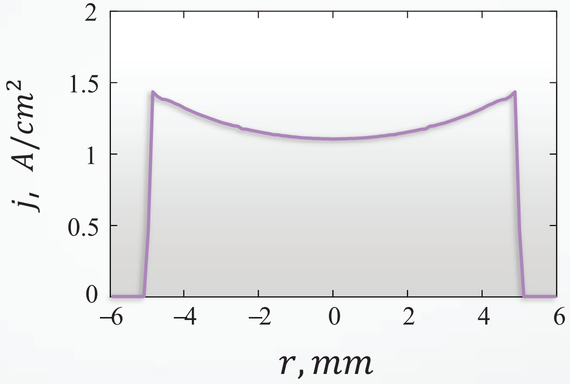


Convex cathode

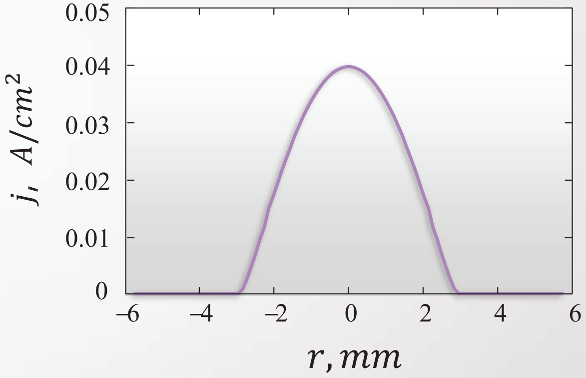
U_A = 20 kV, U_C = 2.5 kV



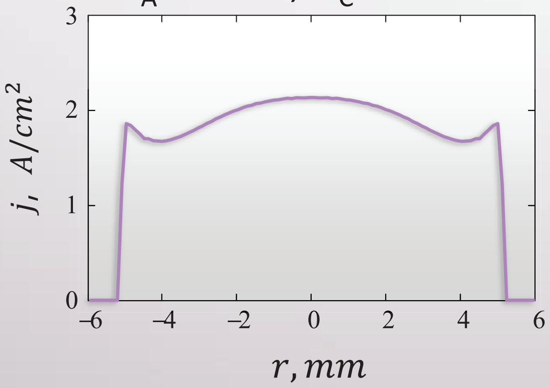
U_A = 10 kV, U_C = 4 kV



U_A = 11 kV, U_C = -3 kV

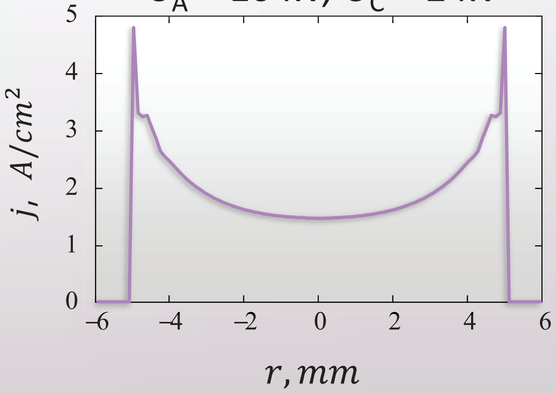


U_A = 15 kV, U_C = 1.3 kV



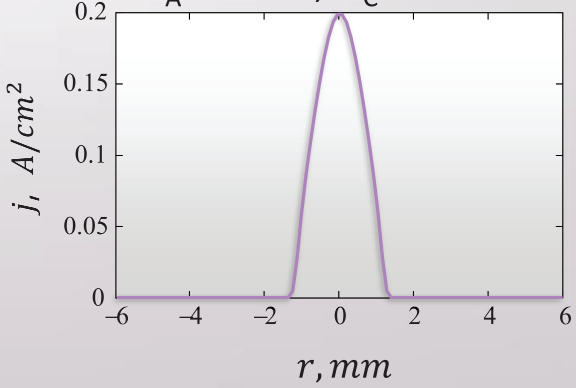
Flat beam

U_A = 10 kV, U_C = 2 kV



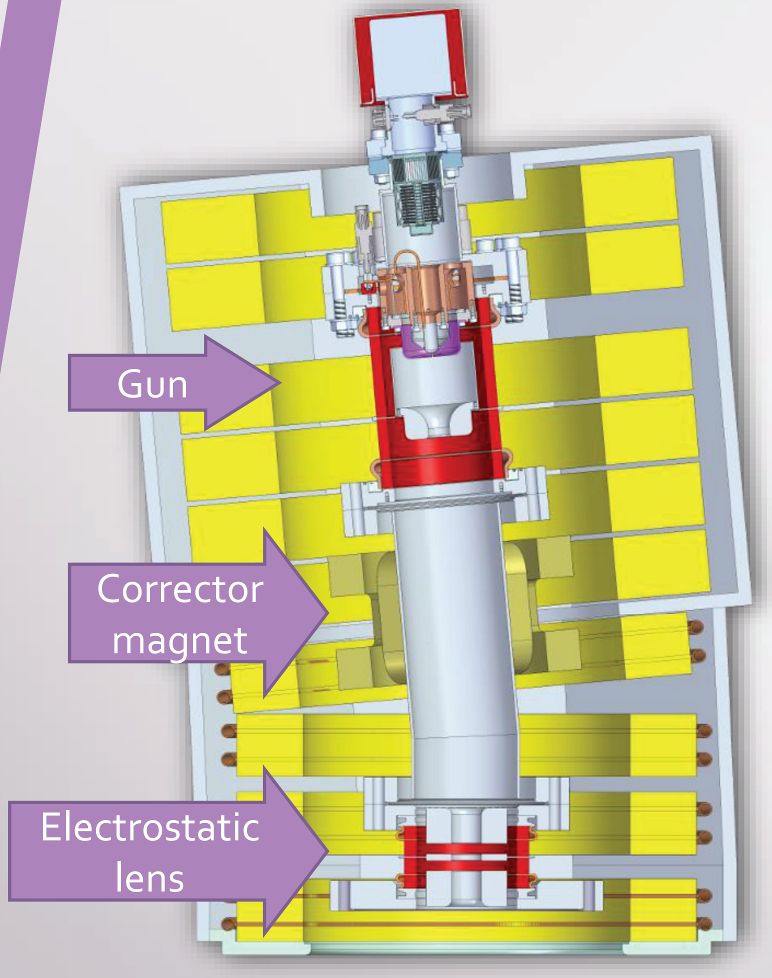
Hollow beam

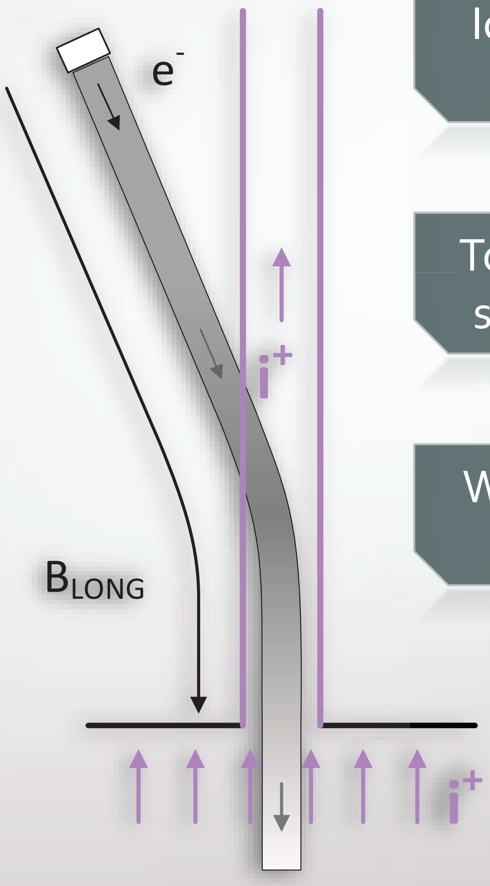
U_A = 18 kV, U_C = -2.5 kV



Thin beam

Electron beam bending





Ions caught into acceleration tube can hit the cathode and damage it

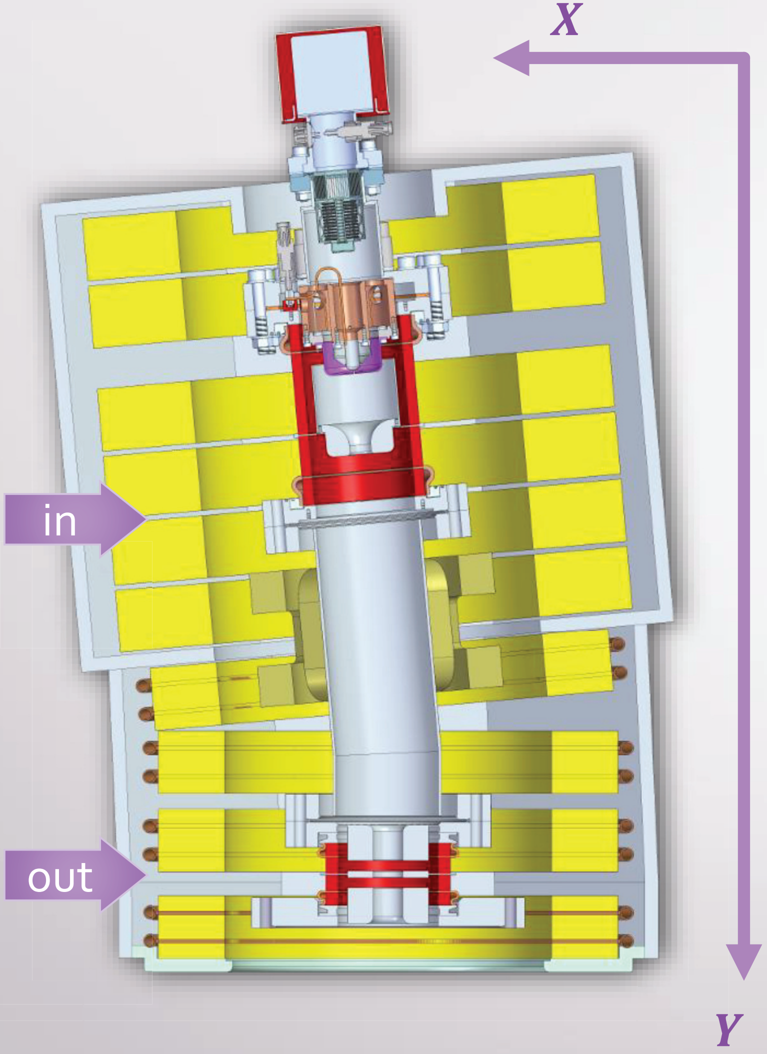
To ensure the safety of the cathode, the gun is shifted from the axis of the acceleration tube

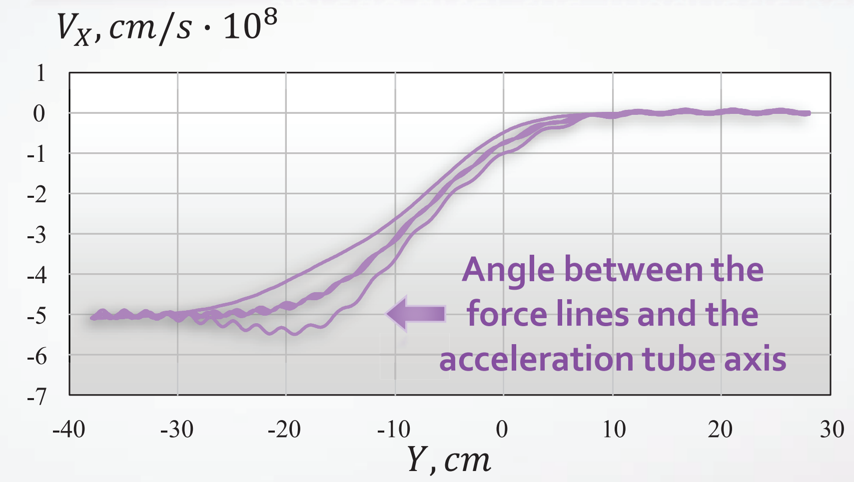
We use magnetic bending to hide the cathode from the line of incident ions

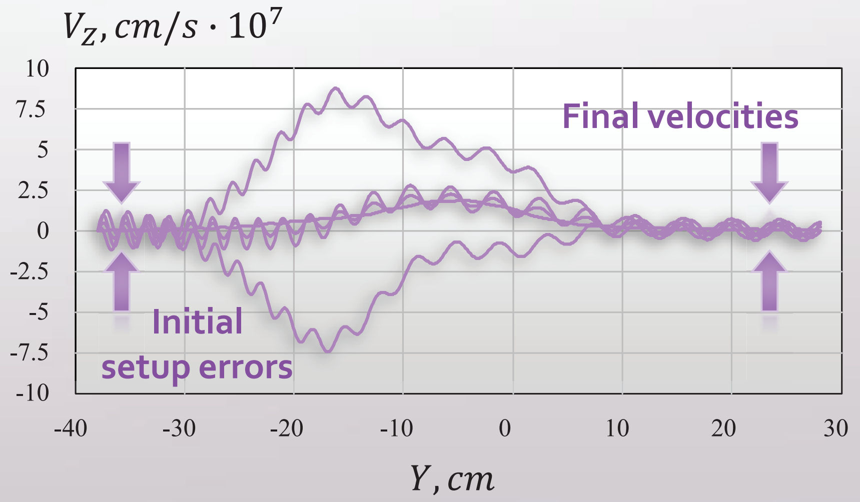
Additional corrector magnet is used to compensate the electrons drift in the magnetic bend

Electron beam bending

Using test particles to estimate the beam momentum spread after the magnetic bending





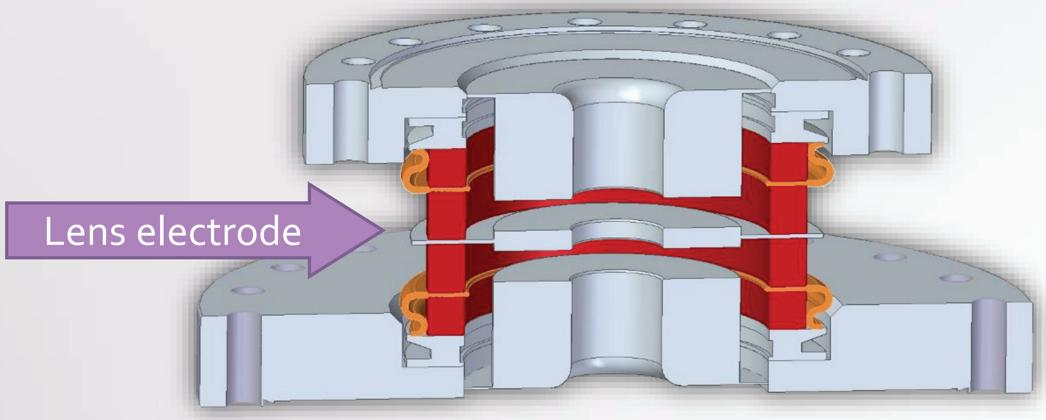


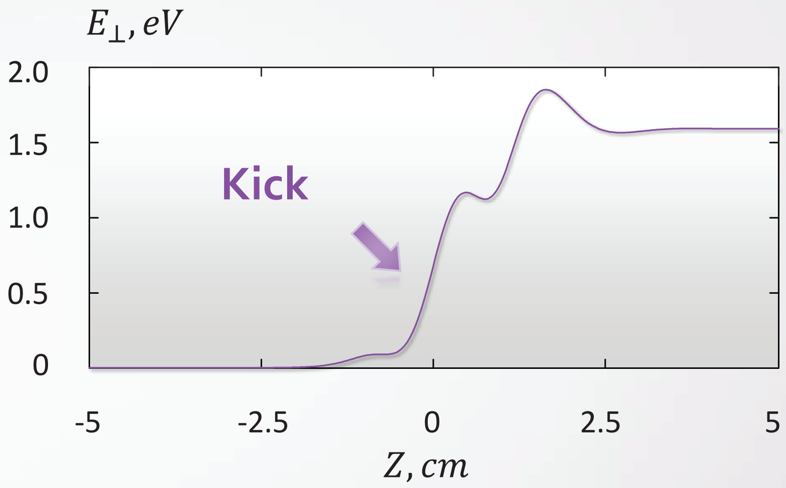
$$E_{\perp}^{in} \approx 0\ eV$$

$$\Downarrow$$

$$E_{\perp}^{out} \approx 0.04 eV$$

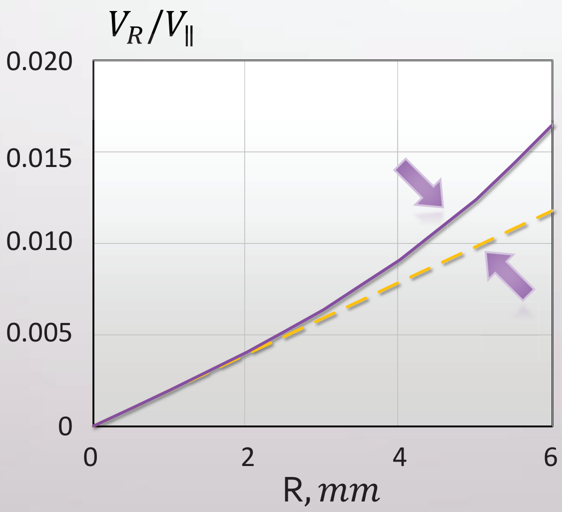
Electrostatic lens

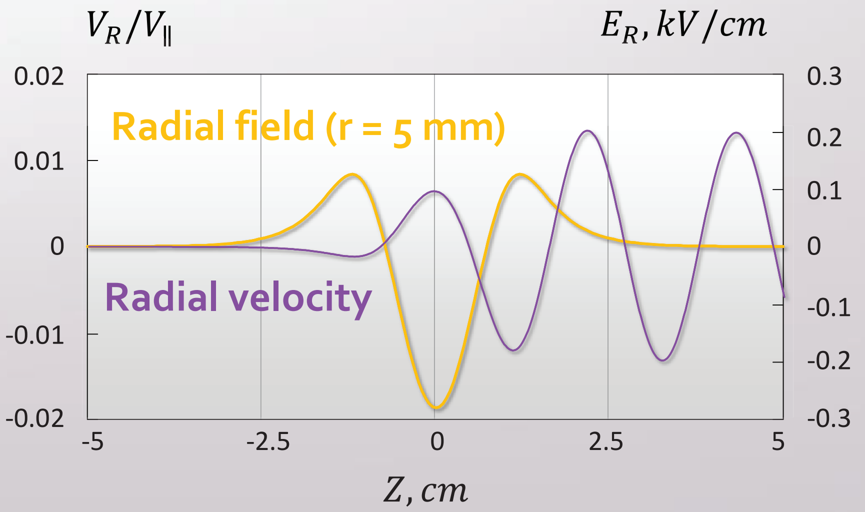




The lens can suppress oscillations with energy up to 1.5 eV

The lens force is slightly non-linear with the radial coordinate.





Thank you for your attention!