Electron Beam As High Frequency Wide Band Electrostatic 3D Kicker

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Space-charge is enough powerful object, so there are some attempts to use it for the beam control

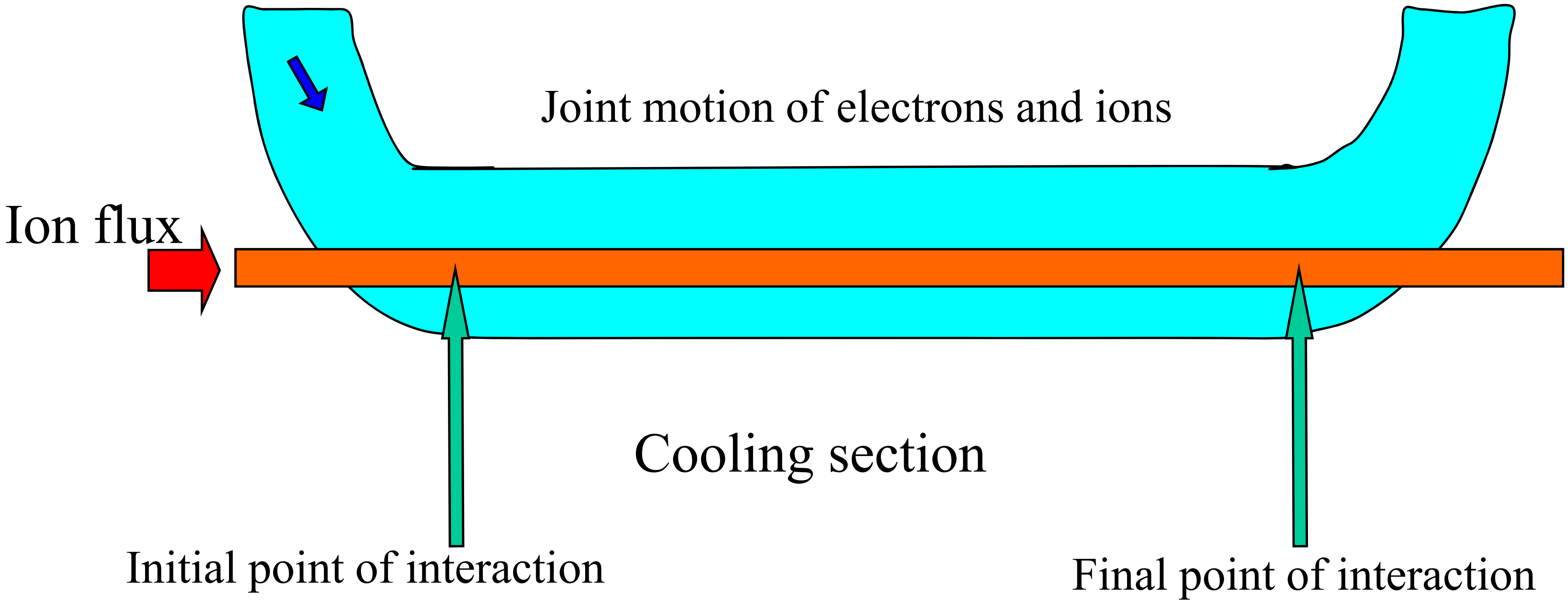
Electron Cooling helps to greatly decrease phase space of stored ion beam

Tevatron Lens controlling of the tune shift with help of space charge of the electron beam

Derbenev's idea about microwave electron-stochastic cooling used for the amplification of the cooling force

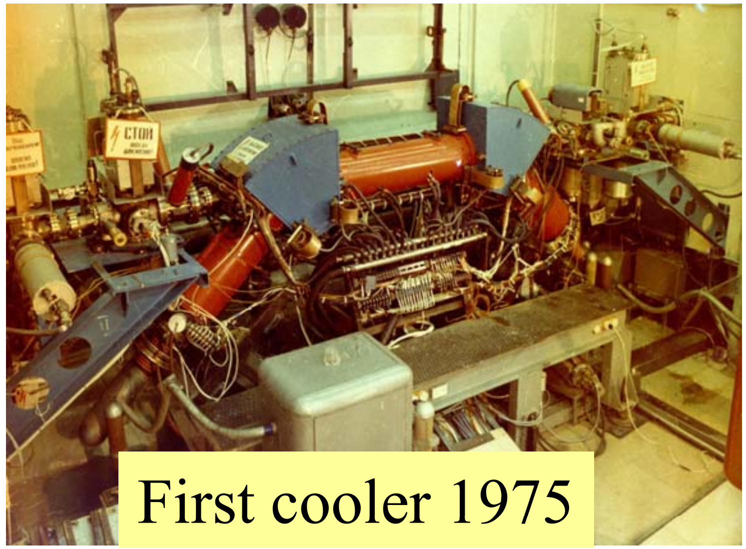
One more idea … ?

Electron cooling

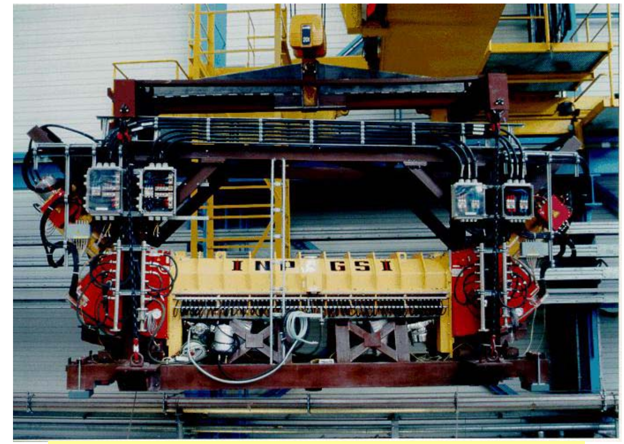


Efficiency of electron cooling increases at low momentum spread in ion beam, meanwhile stochastic is most effective for cooling beams with high emittance

BINP coolers



First cooler 1975



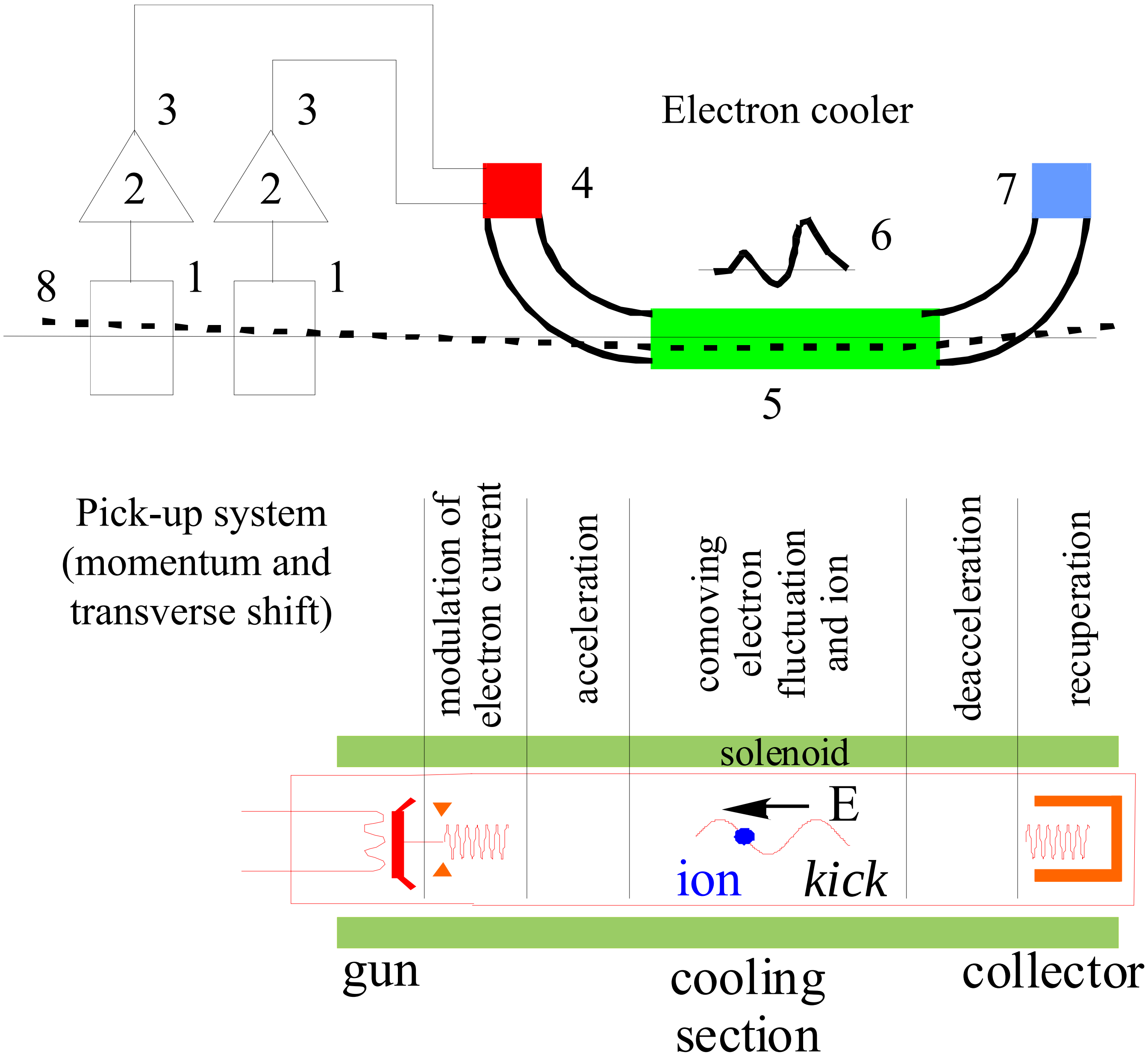
SIS-18 cooler 1998

CSRm 35 kV cooler 2003

CSRe 300 kV 2004

LEIR cooler 2004

Base idea of the cooler as universal 3D kicker



Scheme of the stochastic cooling with electron cooler as 3D pick-up

1 – pick-up system,

2 – hybrid and amplifier,

3 – cable system,

4 – electron gun with the current modulation,

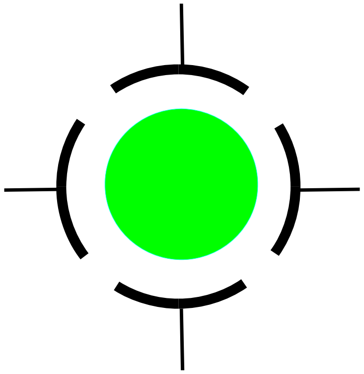
5 – cooling section,

6 – modulation of the space-charge density in the cooling section,

7 – collector of the electron beam,

8 – ion trajectory.

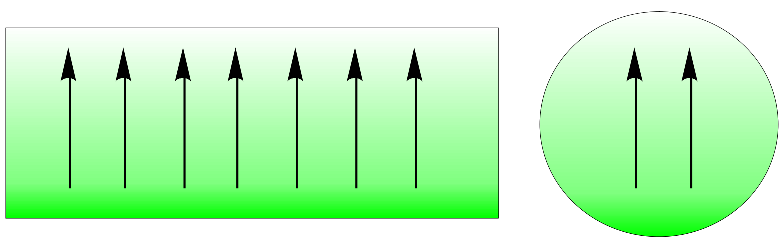
Electrical fields in the electron beam



Electron gun with four-section electrodes enables to obtain dipole and longitudinal modulation of the electron current

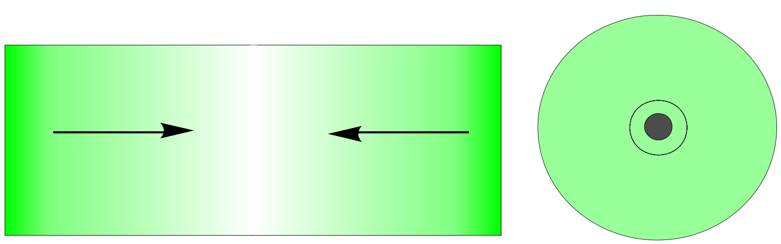
a – electron beam radius
b – radius of the vacuum tube
i – electron current
ξ – "pseudo"-displacement of the center of space charge
E – transverse and longitudinal electric field in the beam frame

Dipole fluctuation of the electron current produces the vertical (or horizontal) electric field



$$E_{\perp} = \frac{2}{\gamma \beta c} \frac{\xi}{a^2} i$$

Longitudinal fluctuation of the electron current produces the longitudinal electric field



$$E_{\parallel} = \frac{1}{\gamma \beta c} \left(2 \ln\left(\frac{b}{a}\right) + 1 \right) \frac{\partial i}{\partial z}$$

Advantages of electron cooler as kicker device

- one device provide 3D kick at the same time;
- velocity matching of kicking impulse with ion in the wide range;
- free aperture, the electron kicker doesn’t decrease the aperture of an vacuum pipe;
- use of both electron and stochastic cooling;
- frequency bandwidth may be very high;
- transverse kicker size can be changed easily according ion beam size;

Possibilities of electron cooler as 3D kicker

Let us to forget many troubles of the stochastic cooling:

- "bad" mixing;
- "good" mixing;
- influence of neighboring particles;
- thermal and another noise;
- so on …

kicker strength is limited by maximal value of fluctuation current

$$\lambda A = \delta A_{\max} \qquad \lambda_{\max} = \frac{\delta A_{\max}}{\sqrt{N_s}\sqrt{A^2}}$$

$$A_C = A - \lambda A$$

$$\frac{\delta}{\delta t}\left(A^2\right) = -2\lambda f_0 \left(A^2\right)$$

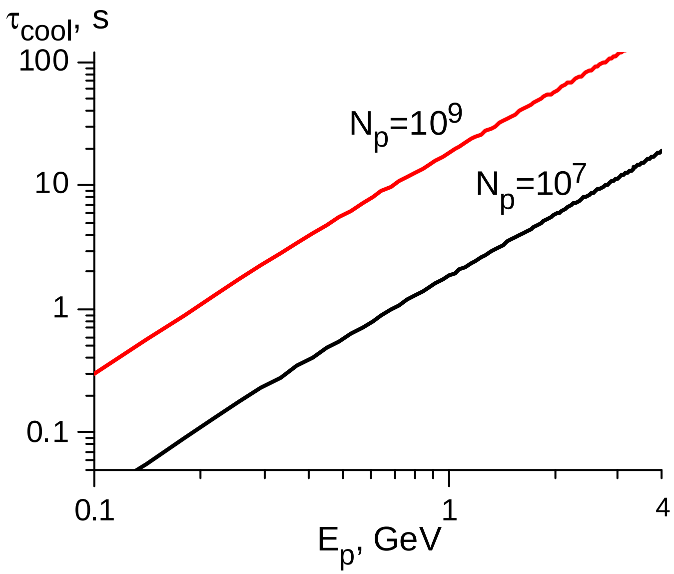
$$\tau_{cool}{}^{-1} = 2\lambda f_0$$

A, A_C – longitudinal or transverse momentum of the particle before and after kick,
f_0 – revolution frequency,
λ – kick amplification parameter,
$\Delta i_{\max}$ – maximum modulation current divided as $1/\sqrt{N_s}$
$N_s = f_0 \cdot N / \Gamma$ number of particles introducing signal on the pick-up
Γ – frequency bandwidth of pick-ups

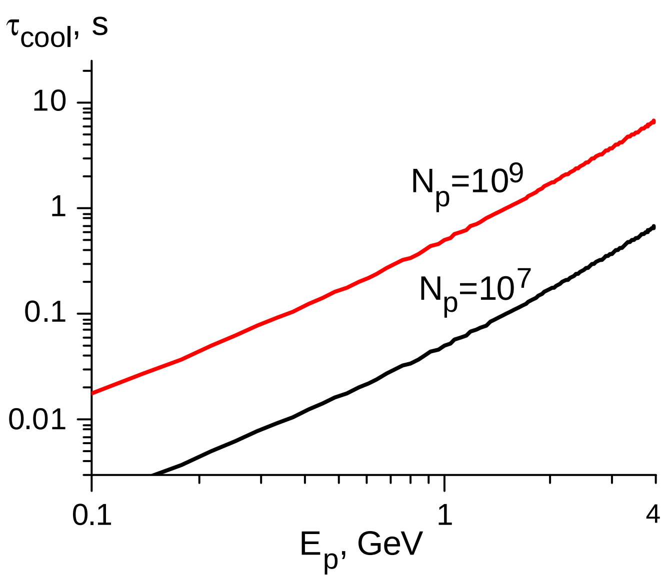
$$\lambda_{\parallel}^{\max} \frac{\Delta p_{\parallel}}{p} = \frac{1}{\gamma^2 \beta^4} r_q \frac{\Gamma l_{cool}}{q \cdot c^2} \frac{\Delta i_{\max}}{\sqrt{N_s}} \left(2 \ln\left(\frac{b}{a}\right) + 1 \right)$$

$$\lambda_{\perp}^{\max} \frac{\Delta p_{\perp}}{p} = \frac{2}{\gamma^3 \beta^3} r_q \frac{l_{cool}}{qca} \frac{\Delta i'_{\max}}{\sqrt{N_s}}$$

Possibilities of electron cooler as 3D kicker



Longitudinal cooling time



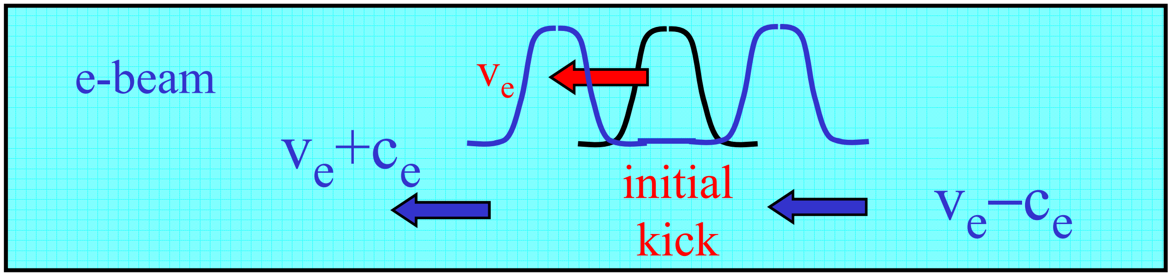
Transverse cooling time

Parameter	Value
modulation of electron current (r.m.s value)	50 mA
total electron current	0.5-1.0 A
cooler length	400 cm
bandwidth of the amplifier	2 GHz
radius of electron beam	0.5 cm
radius of vacuum chamber	5.0 cm
beta-function in cooling section	15 m
revolution frequency	1 MHz
initial emittance (r.m.s value)	10π mm·mrad
initial momentum spread	$5 \cdot 10^{-3}$

kicker strength is enough for the reasonable cooling time in the medium energy range

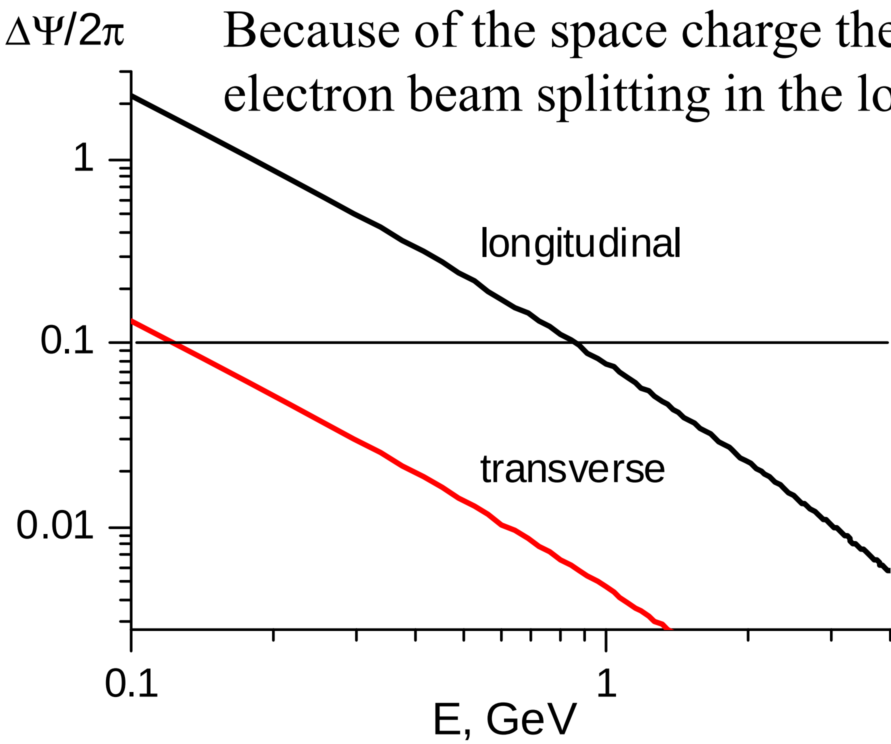
Trouble factors that specific for such kind kicker device

Widening of the kick impulse in the electron beam



there is no problem for the transverse kick but for the longitudinal kick the electron current should be decreased for low energy range

Because of the space charge the initial pulse in the electron beam splitting in the longitudinal direction



Dispersion equation

$$\omega = kv_e \mp \frac{\omega_{pe}}{\sqrt{2}} \frac{a^2}{b} k$$

Transverse kick

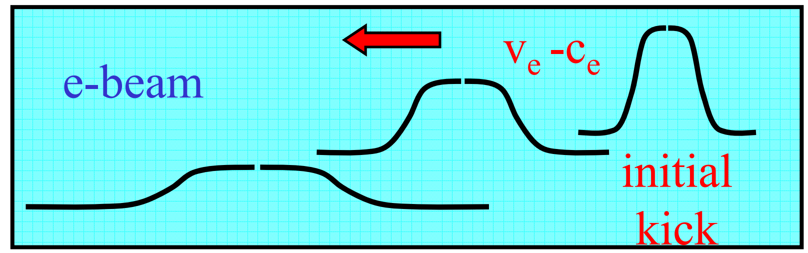
$$\omega = kv_e \mp k \frac{\omega_{pe} a}{\sqrt{2}} \sqrt{\ln\left(\frac{b}{a}\right) + \frac{1}{2}}$$

Longitudinal kick

Splitting of the kick induced by the space charge.
Electron current 0.5 A, radius of electron beam 0.5 cm, frequency bandwidth 2 GHz.

In principle, there is an opportunity to excite only one type of wave (fast or slow) by proper choice of the exciting system. The problem of the pulse dispersion remaining in any way but now it relates to the term of the dispersion equation with power ~k^2.

$$\omega = kv_e \mp k \frac{\omega_{pe} a}{\sqrt{2}} \sqrt{\ln\left(\frac{b}{a}\right)} \cdot \left(1 - \frac{k^2 b^2}{4\ln\left(\frac{b}{a}\right)}\right)$$

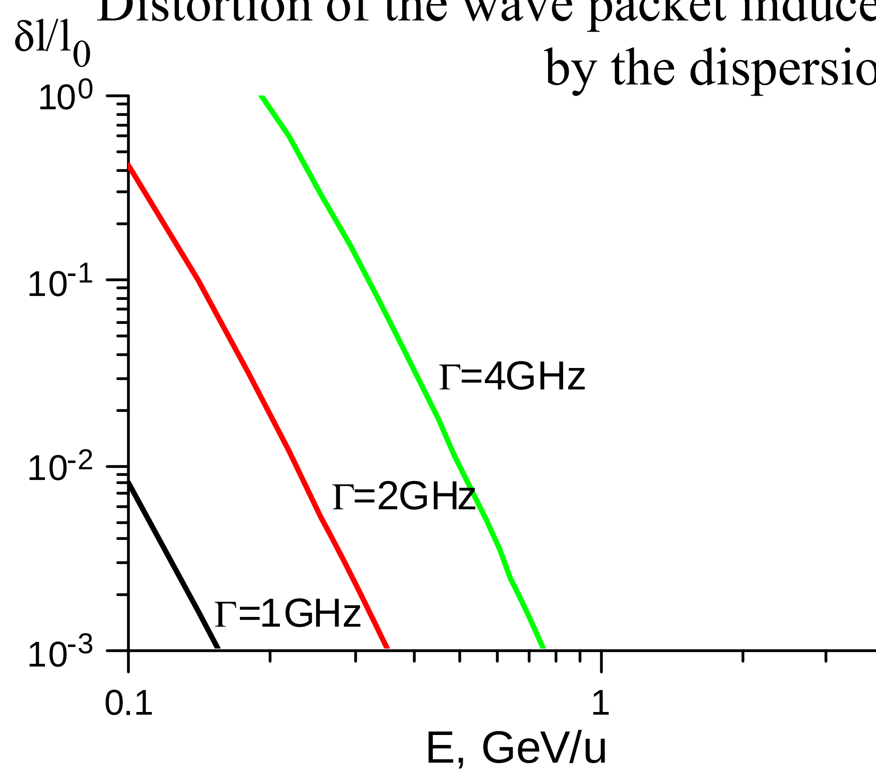


Distortion of the wave packet induced by the dispersion

Dispersion equation of the longitudinal kick with highest power of the wave vector ***k***

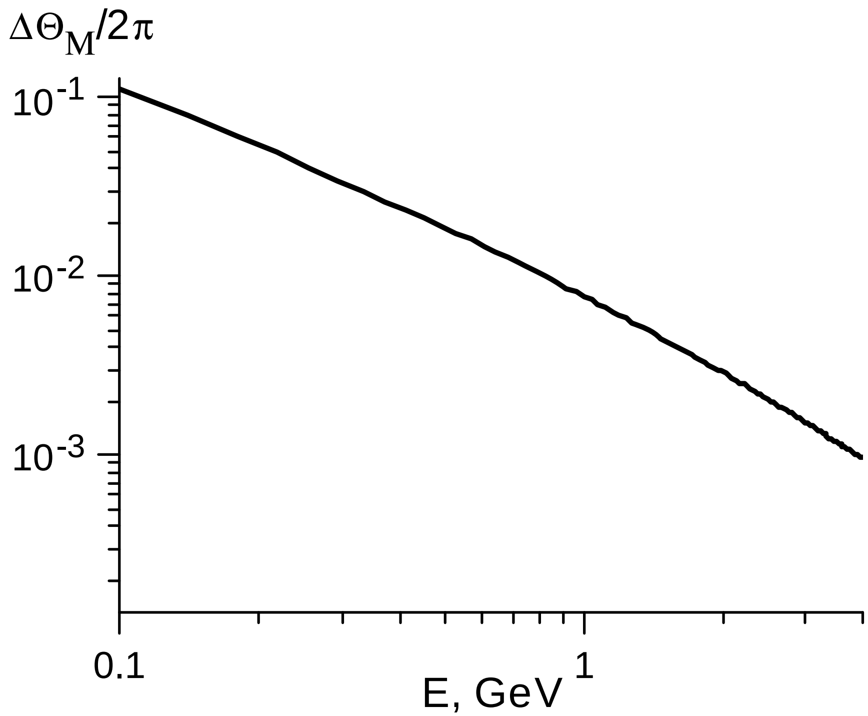
$$a << b,\ \ kb << 1 \qquad \frac{l}{\sigma} = \sqrt{1 + \frac{4D^2 t^2}{\sigma^4}}$$

$$t = \frac{l_{cool}}{\gamma \beta c} \qquad \sigma = \frac{\gamma \beta c}{\Gamma} \qquad D = \frac{1}{2}\frac{\partial^2 \omega}{\partial k^2}$$

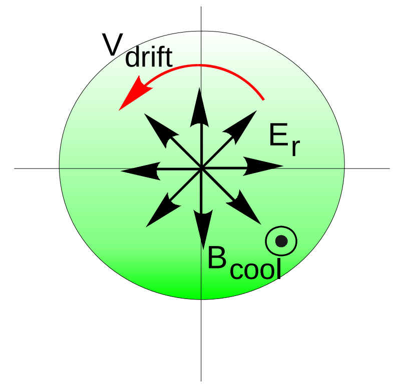


This enables to use the larger value of the electron current and frequency at low energy.

Rotation of the dipole kick in the magnetic field



Rotation angle $\Delta\theta_M$ of the transverse kick in the longitudinal magnetic field



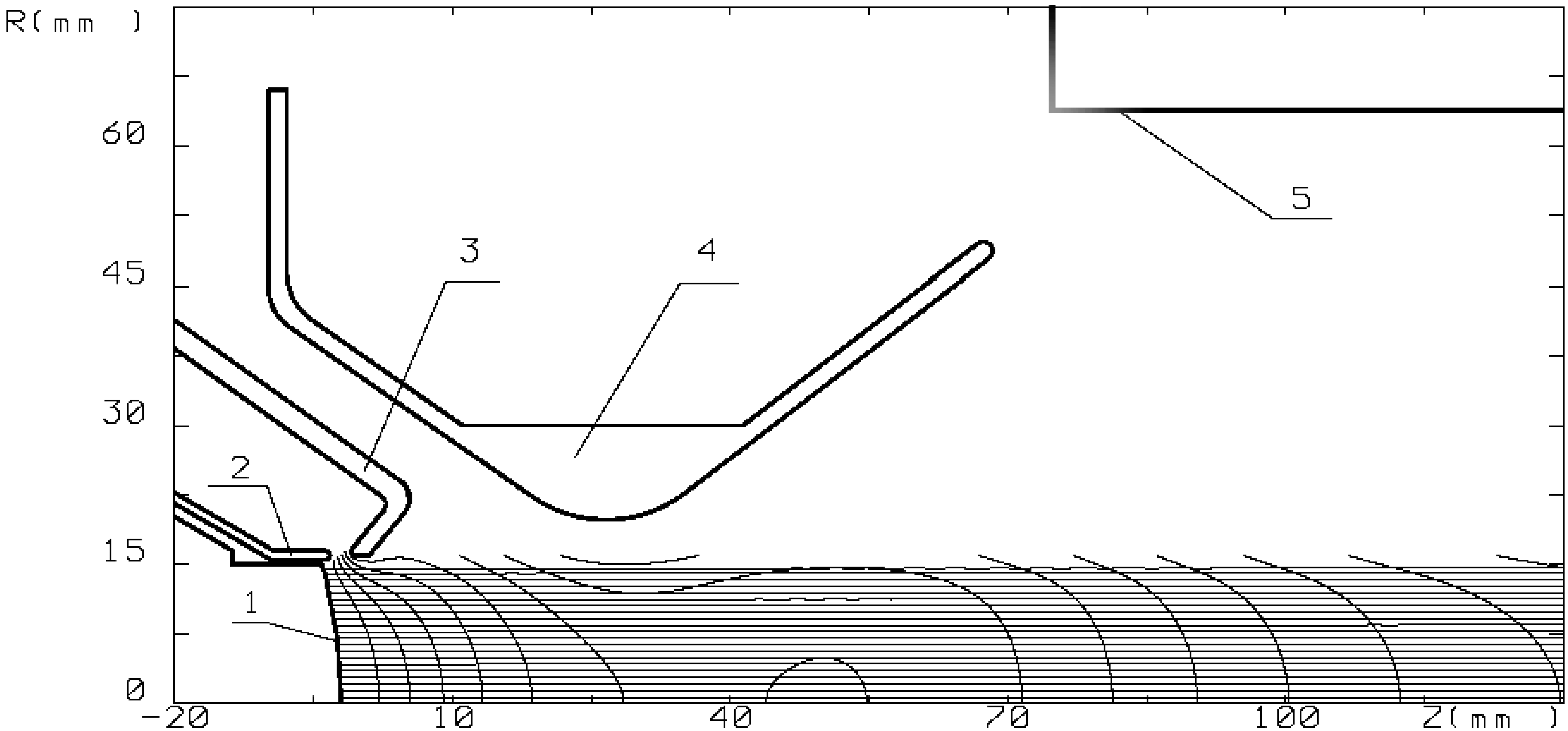
$$E_r = \frac{2}{\gamma \beta c} \frac{r}{a^2} J_e$$

$$\Delta\theta_M = c \frac{E_r}{B_{cool}} \frac{\tau_{flight}}{r}$$

l_{cool}=400 cm
B_{cool}=1 kG
J_e=0.5 A
a=0.5 cm
b=5.0 cm

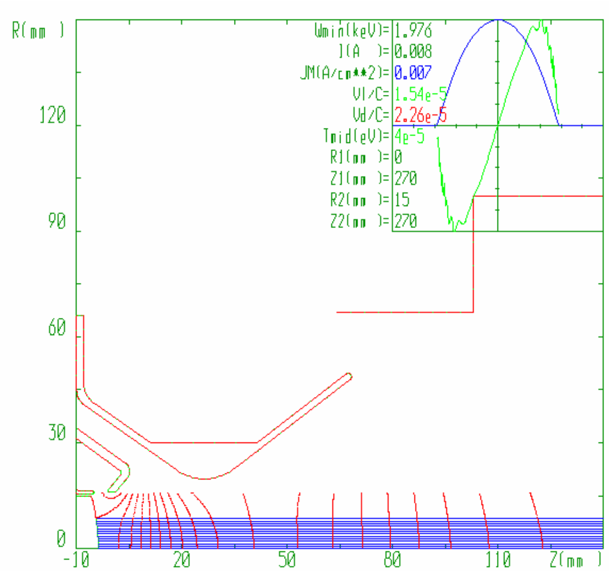
Rotation in the magnetic field is not essential point

Electron gun with variable beam profile for optimization of electron cooling

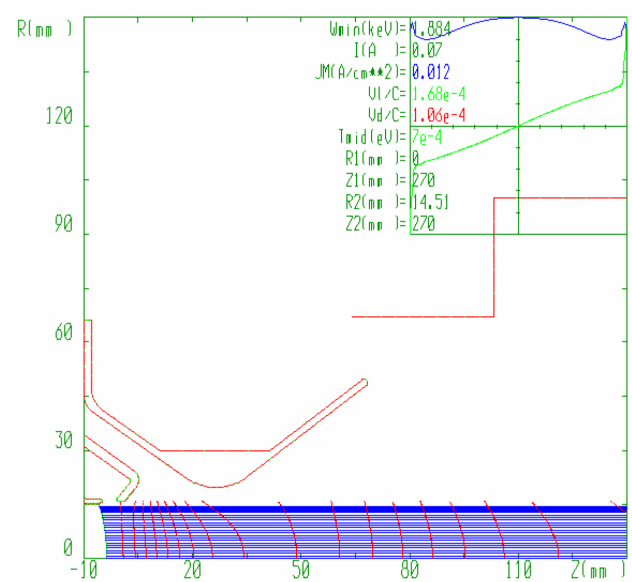


1 – cathode, 2 – focusing electrode, 3 – control electrode, 4 – anode, 5 – drift tube

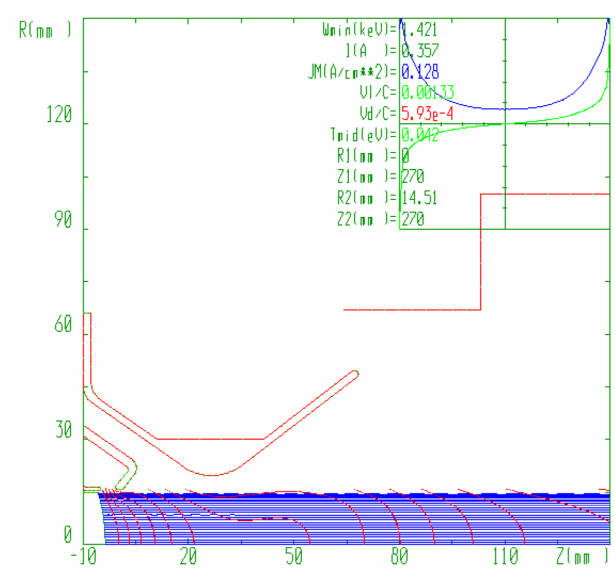
Simulation of main operating modes of the gun



Emission from the cathode center only, $U_{control} < U_{cath}$

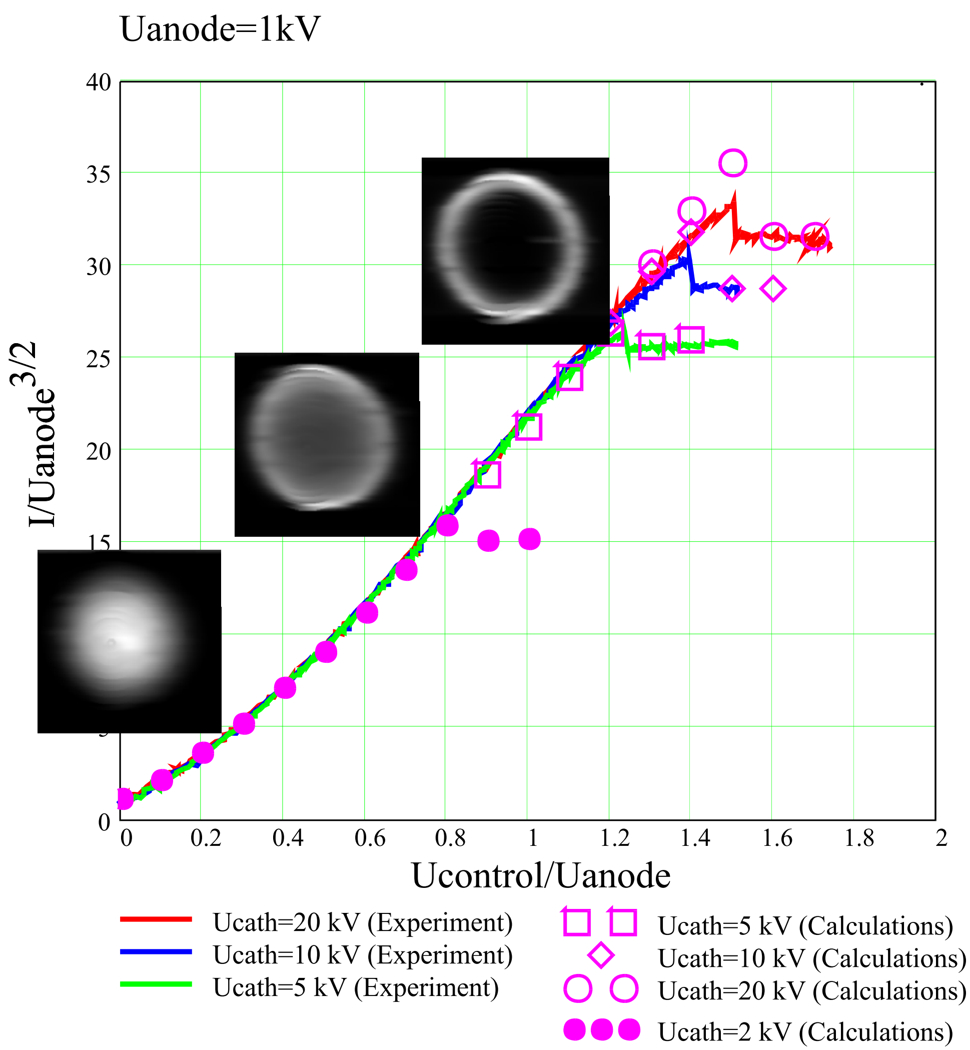


Uniform emission, $U_{controlz}$ about U_{cath}



“Hollow” beam, $U_{control} > U_{cath}$

Gun experimental results



Three electron cooling installations were equipped with this gun: EC-35 (CSRm), EC-300 (CSRe), EC-40 (LEIR).

Proper choice of beam profile provides increase of accelerated current up to 50% (data obtained at CSRm) in comparison with uniform beam!

Axially-symmetric control electrode can be easily divided into four part to provide dipole (in both directions) and longitudinal beam modulation

Methods used for EOS calculation with space charge consideration

- Differential methods
  - FDM, FEM
  - Solve Poisson's equation in differential form or minimize corresponding functional
  - Need mesh covered all space

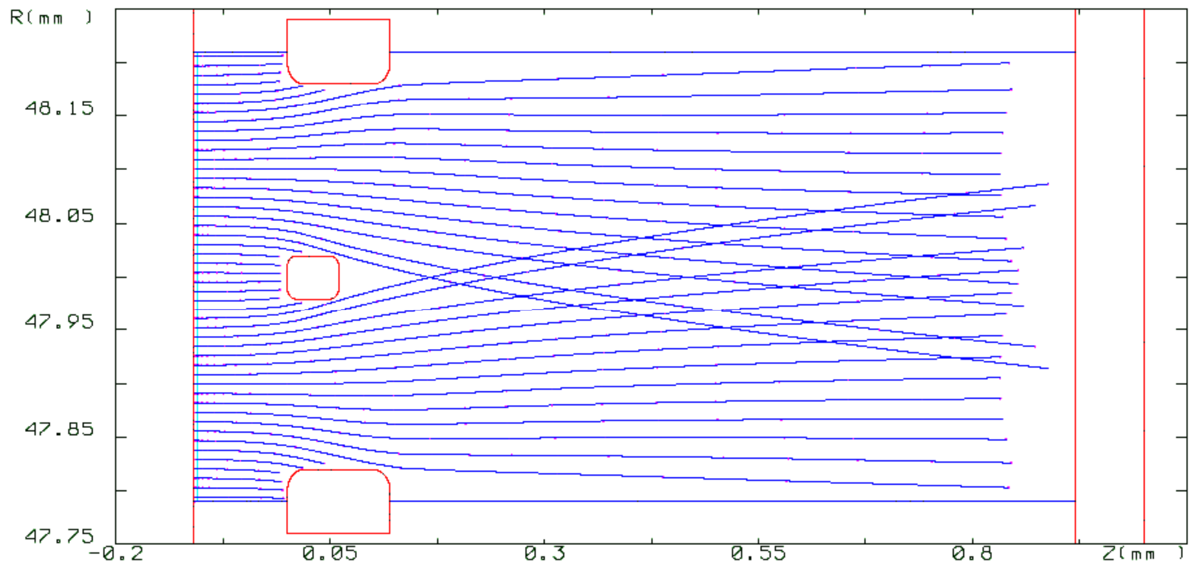
- Integral methods
  - BEM
  - Solve integral equations on boundaries of electrodes and dielectrics
  - Do not need to cover all calculated space by mesh

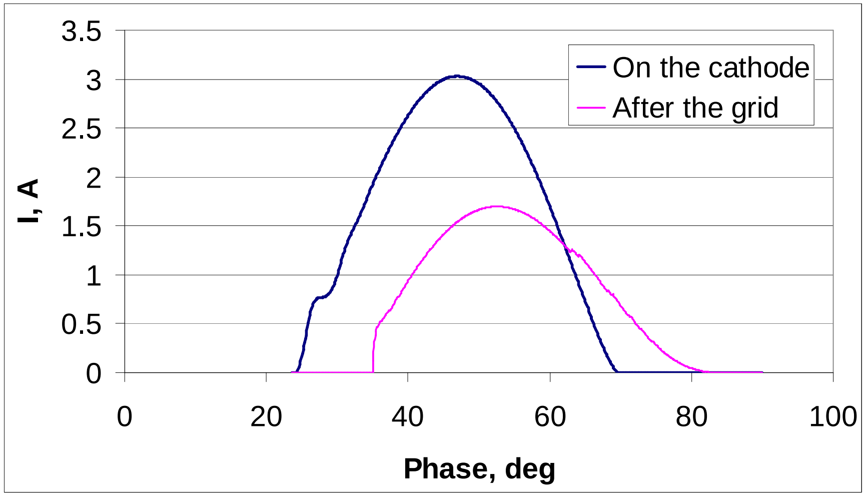
UltraSAM program for calculation of static EOS with space charge consideration

- Boundary elements method
  - Solution for charges; calculation of potential and field needs additional integration
  - Task with open boundaries;
  - No numerical differentiation at filed calculation
- Analytical separation of integral equation kernel singularity and solution singularity
- Curved meshes for space charge description
  - Model of emission with consideration of magnetic field on cathode
  - Beam model allowing virtual cathode consideration

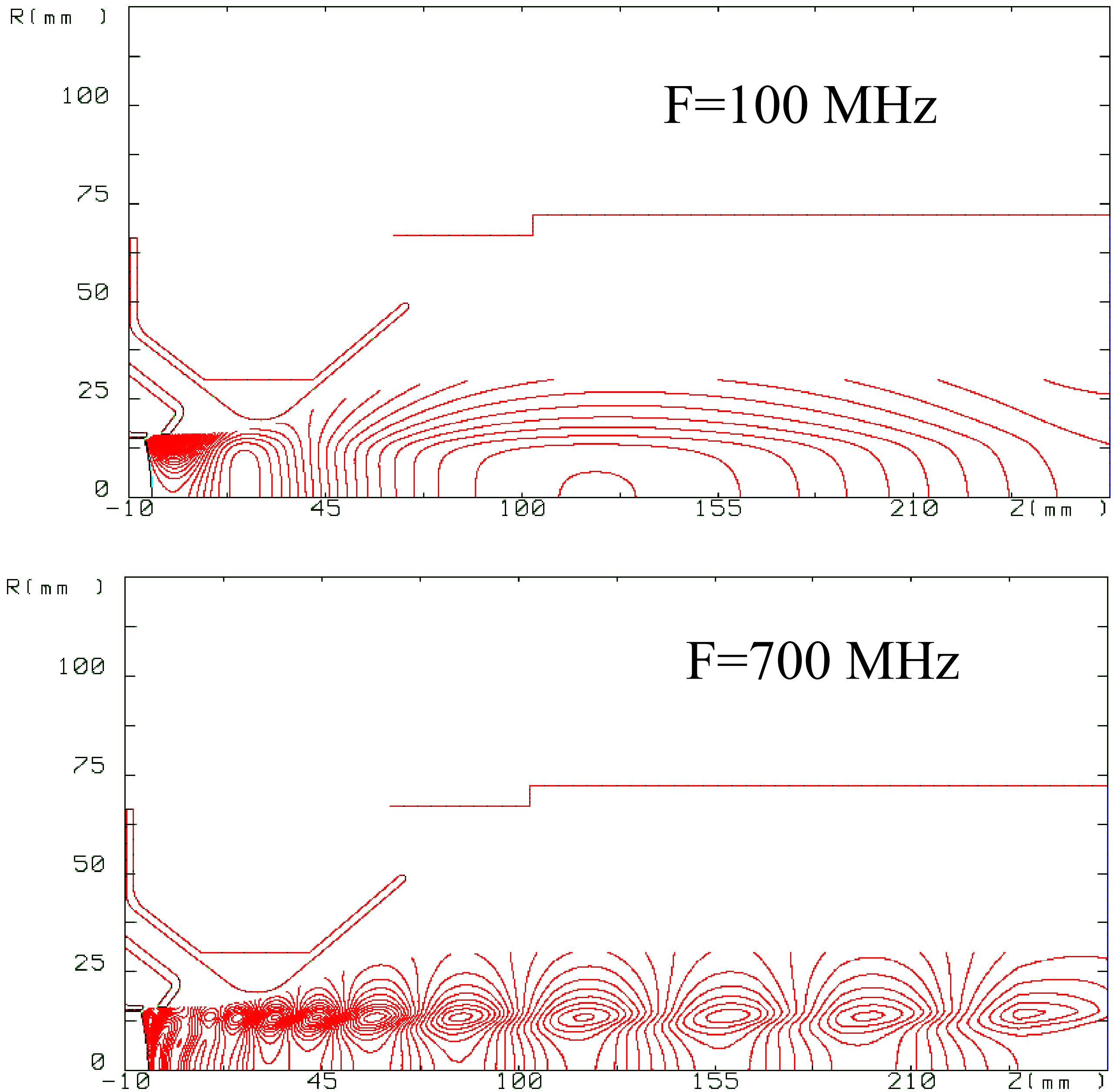
Modification of UltraSAM code for calculation of non-static EOS

- Potentials of electrodes are not constant
- Typical system size is greater than the wave-length - neglect retarded potentials, curling fields

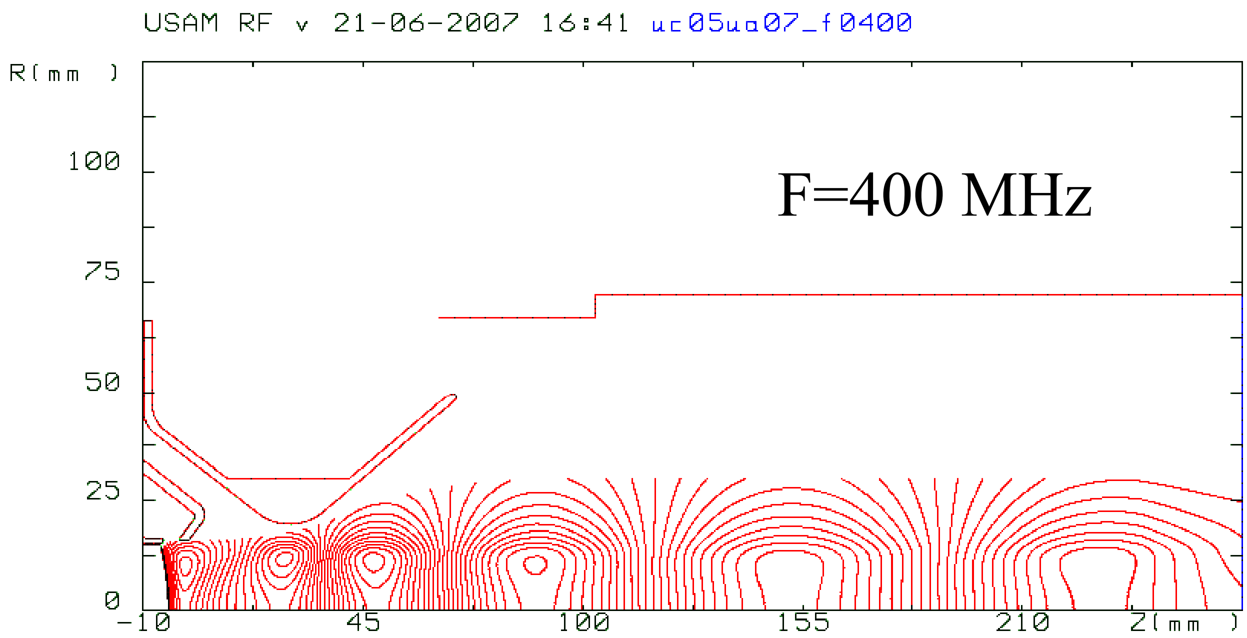




What can we expect from the usual electron gun



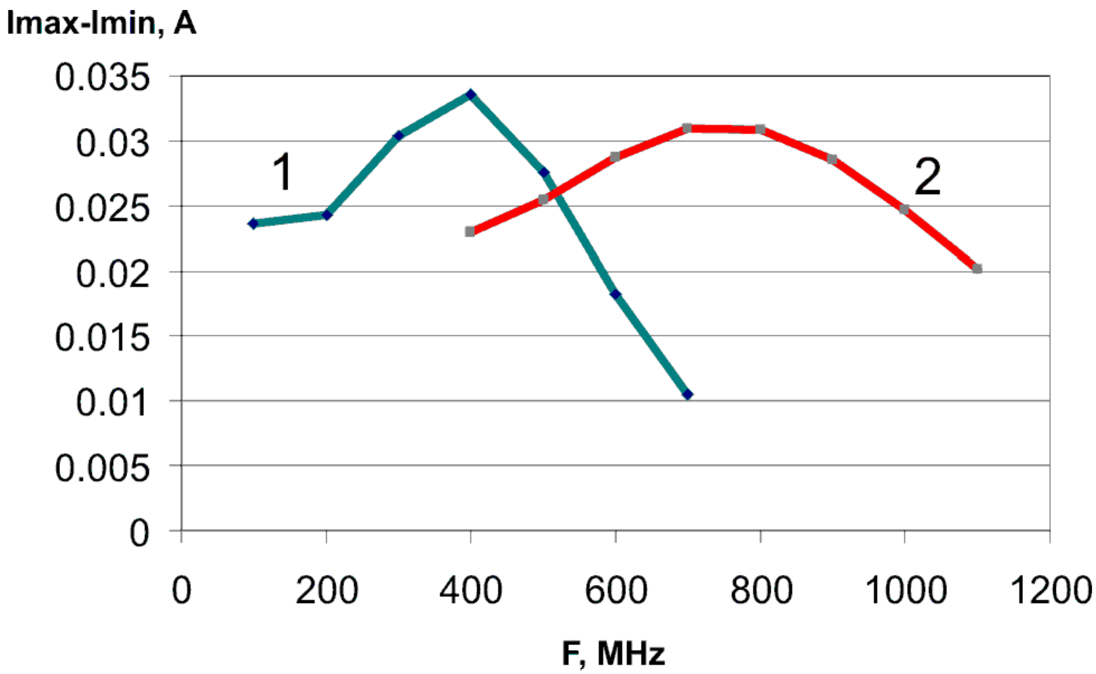
Equipotential lines of the space-charge modulation at 100 and 700 MHz



One can expect increasing of current modulation when the length of the current perturbation is comparable with length cathode -anode

The reducing of the gun size enables to obtain the highest frequency. Characteristic frequency of gun is defined by its geometrical size. Other way is changing of construction of the electron gun.

Current modulation versus frequency



So, the existing construction of the electron gun may enable to have a response of the control grid 1-1.5 mA per V.

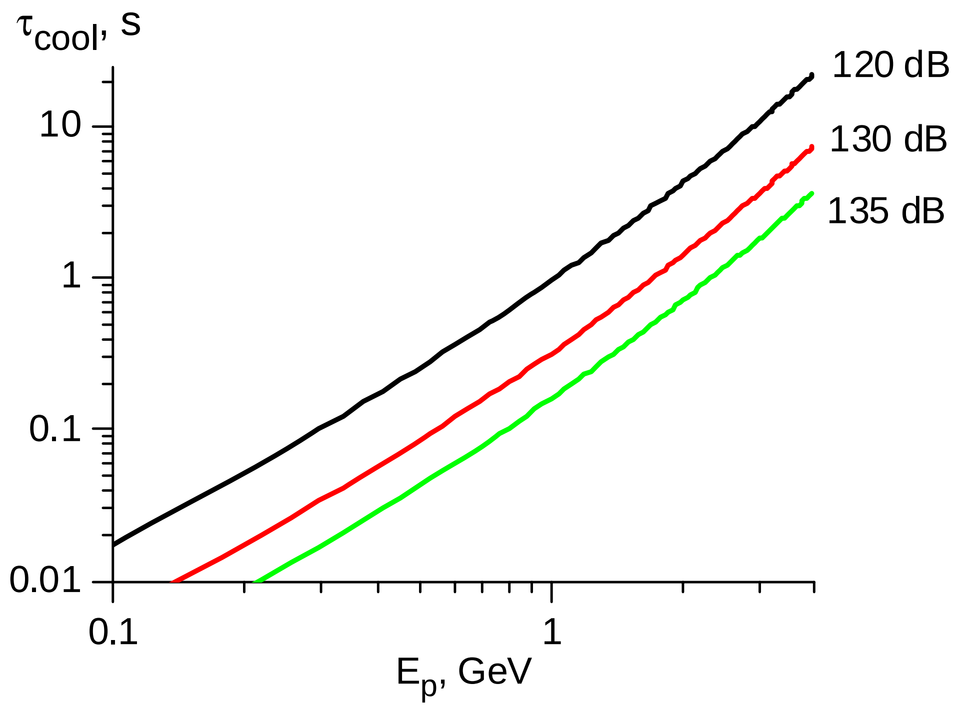
1 is usual BINP electron gun used in EC-35 (CSRm), EC-300 (CSRe), EC-40 (LEIR)
2 is variant 1 decreases in scale 2

Modulation of current at gun exit versus frequency at 20 V modulation voltage, I_{mid}=0.3 A

Supposing 50 mA as limits for current modulation the estimation 50 W for the maximum input power of operation can be derived

Cooling rate for the fixed input power for the electron gun

$$P_{thermo} = 4kT\,\Gamma \qquad P_{particle} = N_s \frac{(k_a\,\Gamma q\rho)^2}{\rho}$$



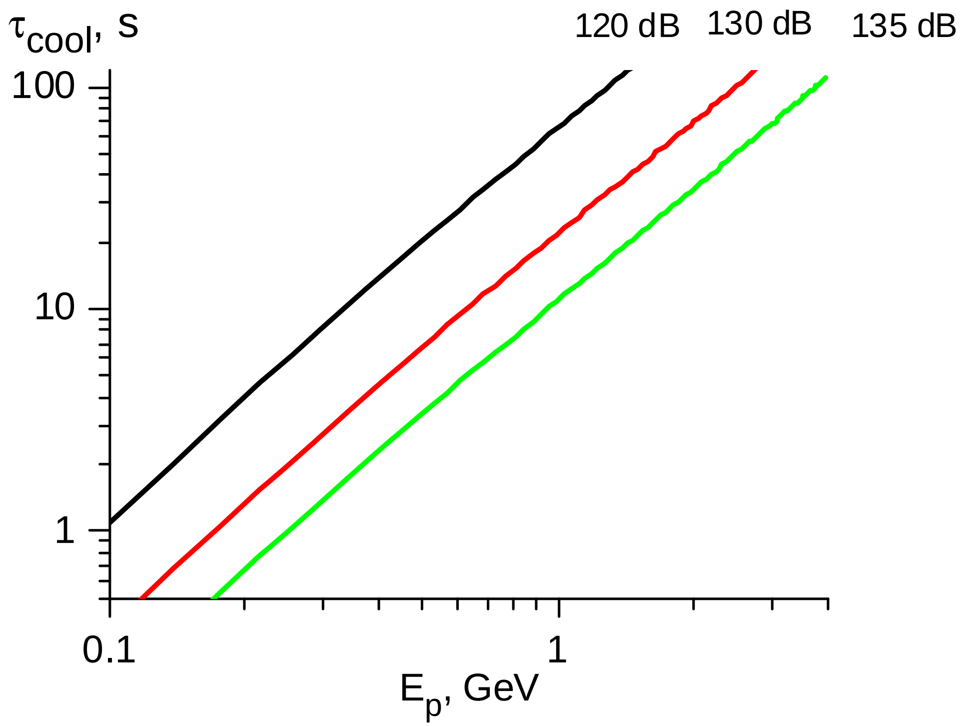
Transverse cooling time versus energy at the different values total amplifier gain

k_a dB	P_{thermo} W	$P_{particle}$ W
120	3.3	1.3
130	30	12
135	120	50

So, the non special RF electron gun can produce the kick enough for obtaining the reasonable cooling time about 1 s or less in the middle energy range.

$N=10^9$, $\Gamma=1$ GHz, f0=1 MHz, $\rho=50$ Ohm, $T_{ampl}=60$ K, Lcool=4 m, βcool=15 m, $Z_{gun}^{-1}=1$ mA/V

Longitudinal stochastic cooling rate



Longitudinal cooling time versus energy at the different values total amplifier gain

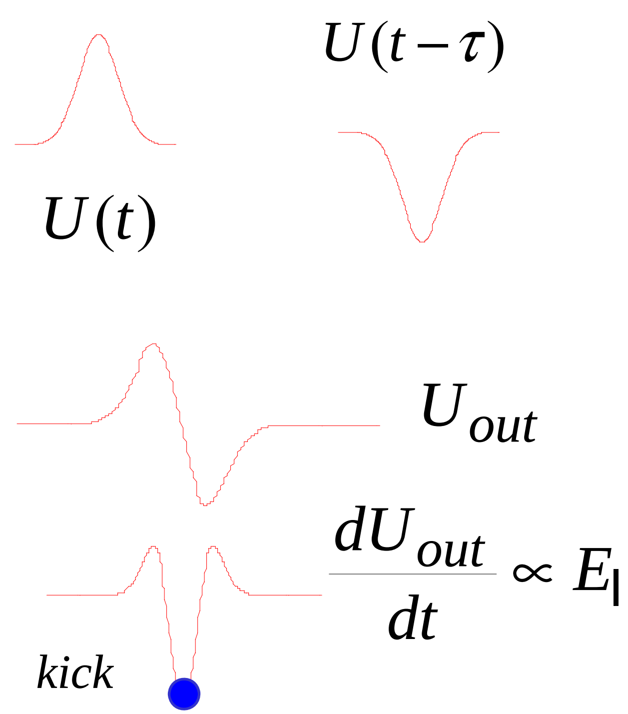
N=10^9, Γ=1 GHz, f0=1 MHz, ρ=50 Ohm, T_{ampl}=60 K, Lcool=4 m, βcool=15 m, Z_{gun}^{-1}=1 mA/V

$$E_{||} = \frac{1}{\gamma \beta c}\left(2\ln\left(\frac{b}{a}\right)+1\right)\frac{\partial i}{\partial z} \propto \frac{\partial}{\partial t} U_{control}$$

If the Thorndahl's filter

$$U_{out} = U(t) - U(t-\tau)$$

is used, then the filtering signal can be applied to the modulation system of the electron gun directly because the impulse corresponds the desirable shape of the kick.

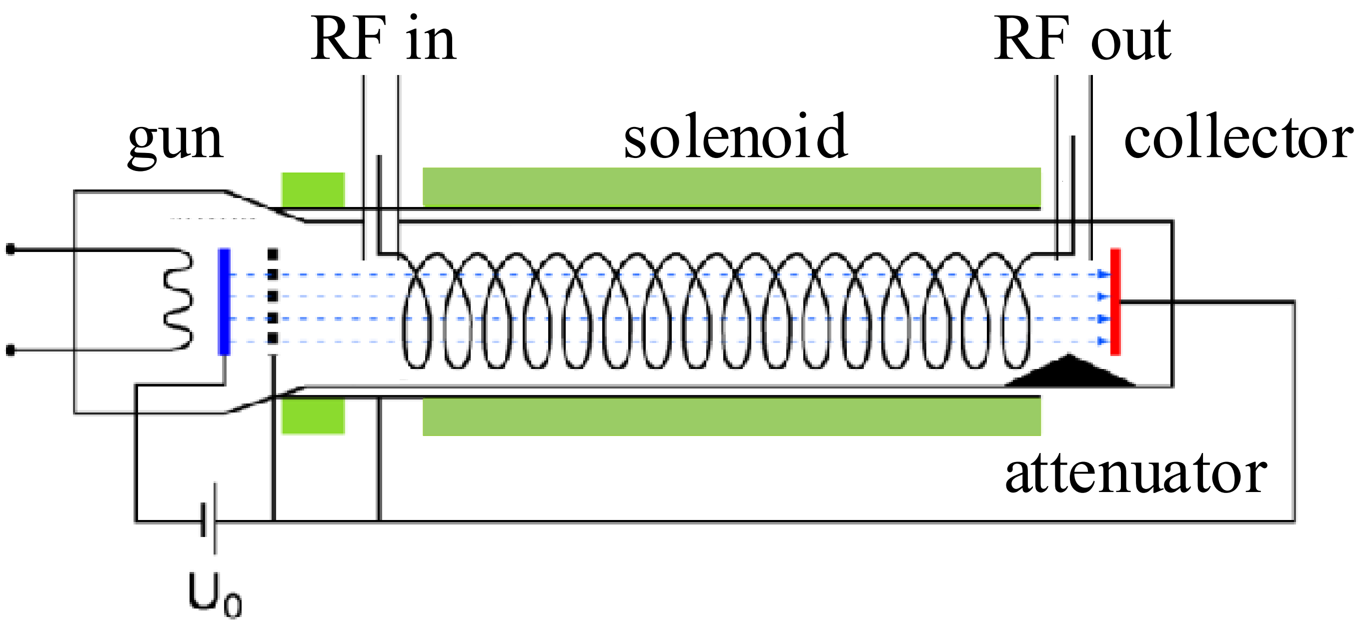


Wideband electron gun

Travelling-wave tube realized the example of the construction that can be used for the wideband electron gun

Some parameters of the mini travelling-wave tubes:

amplifier	---- up to 30-50 dB
wideband	---- up to 20 GHz
power (continuous regime)	---- up to 100 W



used in estimation:
30 dB
1-2 GHz
50 W

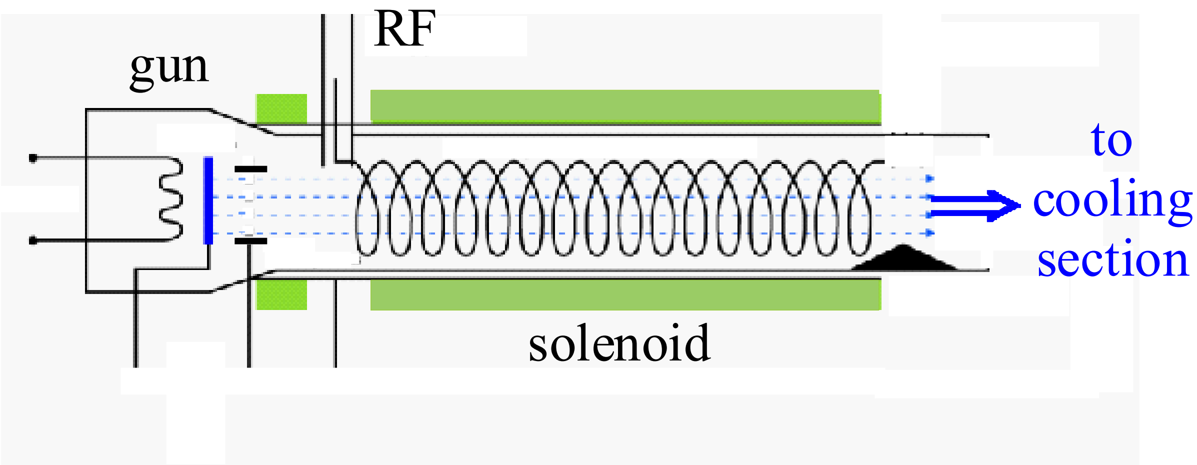
Classical scheme of the travelling-wave tube

a lot of the component of the scheme inherent in electron cooler

Wideband electron cooler

Some intermediate section of the electron beam system at the fixed energy in the range 1-5 kV can be equipped by the delay-line system. The effective interaction between electron flow and RF fluctuation has a result of the growth of the current fluctuation in the electron beam. So, the electron gun of the cooler can work as final amplifier.

kick amplification of the cooler electron system	30 dB
preamplifier gain	100 dB
wideband	2 GHz
power of preamplifier	0.05 W
transverse and longitudinal cooling time	in region 1-10 sec



RF pulse with the electron beam moves to the cooling section directly

Summary

1. The use of the electron cooler as kicker in the middle range of the energy (0.1 – 1 GeV/u for heavy charge particle) may have the following advantages:

    one device provide 3D kick at the same time;
    velocity matching of kicking impulse with ion in the wide range;
    free aperture;
    use of both electron and stochastic cooling;
    frequency bandwidth may be very high;
    very low power of the amplifier device.

2. The most points of the technical realization look realizable.
3. Further improvement of the gun construction may follow the way of the traveling wave tube (TWT) device. The output parameters of a compact industrial TWT look very perspective.