Electron Cooling

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Electron Cooling (an introduction)

- What
- Why?
- Basic theory of electron cooling
- Electron cooling hardware
- Diagnostics

What is electron cooling?

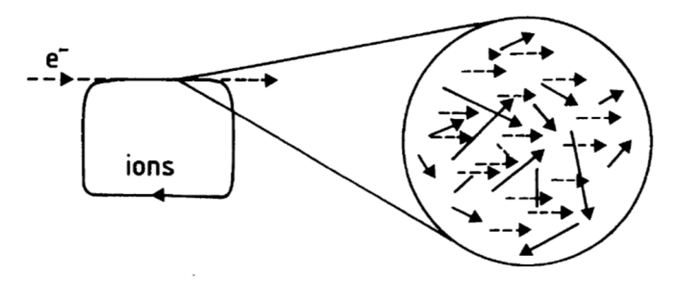
- A fast process to shrink the size, divergence and energy spread of a stored charged particle beam without the loss of intensity.
  - Phase-space compression.
- Proposed by G. Budker in 1966.
- First demonstration on the NAP-M ring in Novosibirsk.

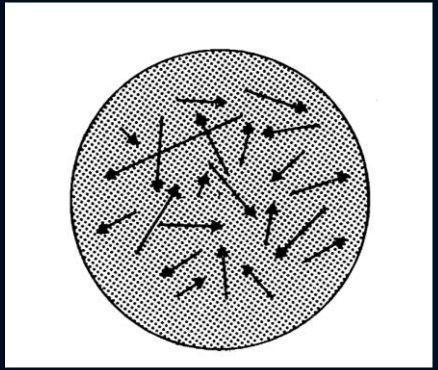
Why electron cooling?

- Loss free compression of ion beams
  - Accumulation of rare species of charged particles
  - Luminosity increase for colliding beam experiments
  - Smaller spot sizes for fixed-target experiments
  - High resolution experiments with internal targets
- Compensation of beam heating effects
  - Intrabeam, residual gas and internal target scattering
- Electron target for precision experiments e.g. recombination

Electron cooling theory

To cool a stored ion beam with electrons a monochromatic electron beam is overlapped with the ion beam in a straight section of the ring.
The velocity of the electrons is made to match the average velocity of the ion beam.

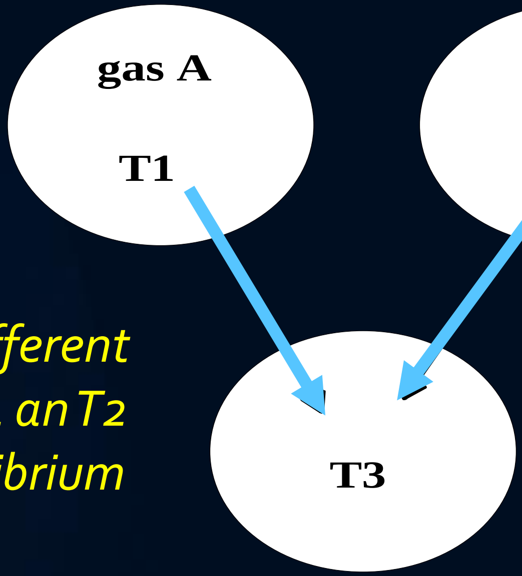




In the rest frame of the electrons the ions are seen as passing through the electron gas with a variety of velocities
The ions transfer their energy to the electrons through Coulomb scattering.
The electrons are continuously renewed -> heat exchanger

Analogy with the mixing of gases

Two gases of different temperatures T1 an T2 tend to an equilibrium temperature T3



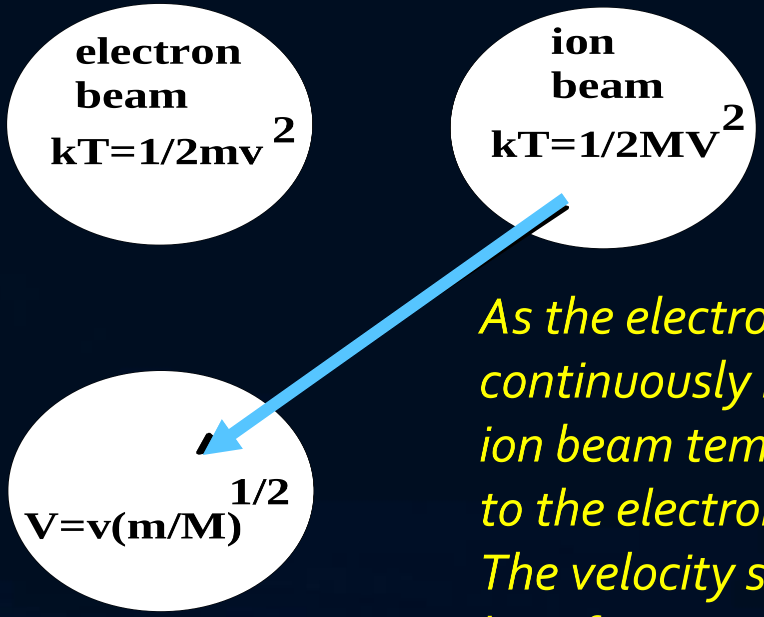
gas A

T1

gas B

T2

T3



electron beam

$kT=1/2mv^2$

ion beam

$kT=1/2MV^2$

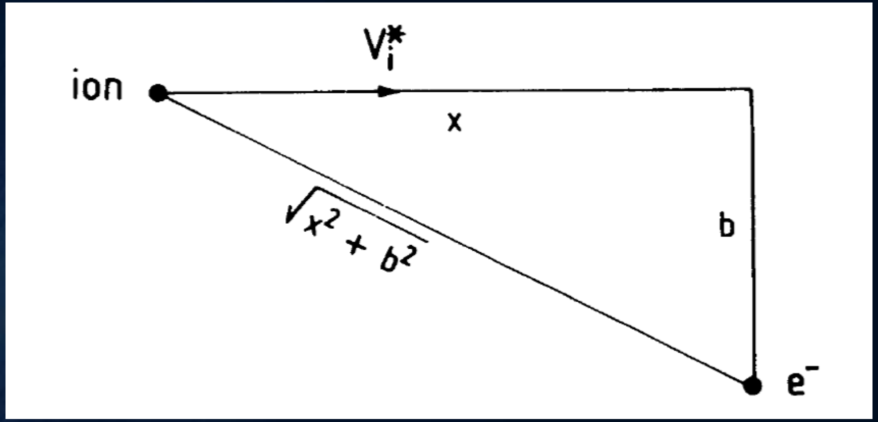
$V=v(m/M)^{1/2}$

As the electron beam is continuously renewed, the ion beam temperature tends to the electron beam temperature. The velocity spread is reduced by a factor $(m/M)^{1/2}$

The cooling force

Consider a single electron-ion collision in the electron beam rest frame.

The ion moves with a velocity V_i^* and scatters from the electron at impact parameter b.



The momentum transfer is:

$$\Delta P^* = \int_{-\infty}^{\infty} \varphi_c \, dt = \int_{-\infty}^{\infty} \frac{Ze^2}{x^2+b^2} dt$$

φ_c being the Coulomb force

As we consider times from negative to positive infinity we can neglect the longitudinal part of the force and we can replace the Coulomb force with the transverse component

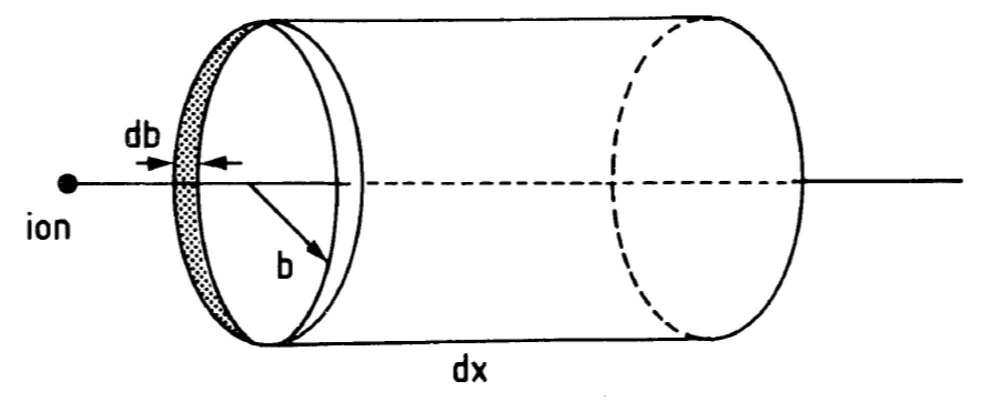
$$\varphi_{\perp} = \varphi_c \frac{b}{\sqrt{x^2 + b^2}}$$

$$\Delta P^* = \int_{-\infty}^{\infty} \varphi_{\perp} dt = \frac{Ze^2}{V_i^*} \int_{-\infty}^{\infty} \frac{b\, dx}{(x^2 + b^2)^{3/2}} = \frac{2Ze^2}{V_i^* b}$$

The energy transferred from the ion to the electron is

$$\Delta E^*(b) = \frac{\Delta P^{*2}}{2m_e} = \frac{2Z^2 e^4}{m b^2 V_i^{*2}}$$

So far we have only considered a single electron-ion collision.
When an ion passes through a large number of electrons, we have to integrate over all possible impact parameters to obtain the energy lost as it travels a length dx through an electron cloud of density n_e^*.



$$-\frac{dE^*}{dx} = 2\pi \int_{b_{min}}^{b_{max}} b\, db\, n_e^* \Delta E^*(b) = \frac{4\pi Z^2 e^4}{m_e V_i^{*2}} n_e^* ln \frac{b_{max}}{b_{min}}$$

$$ln \frac{b_{max}}{b_{min}} = L_c$$

Logarithmic ration of maximal to minimal impact parameters is called the Coulomb logarithm

Minimum impact parameter is determined by the maximum momentum transfer to the electron (head-on collision):

$$\frac{2Ze^2}{V_i^* b_{min}} = \Delta P_{max}^* = 2m_e V_i^* \rightarrow b_{min} = \frac{Ze^2}{m_e V_i^{*2}}$$

Using the classical electron radius $r_e = \frac{e^2}{m_e c^2}$ we obtain: $b_{min} = Z r_e \beta_i^{*-2}$

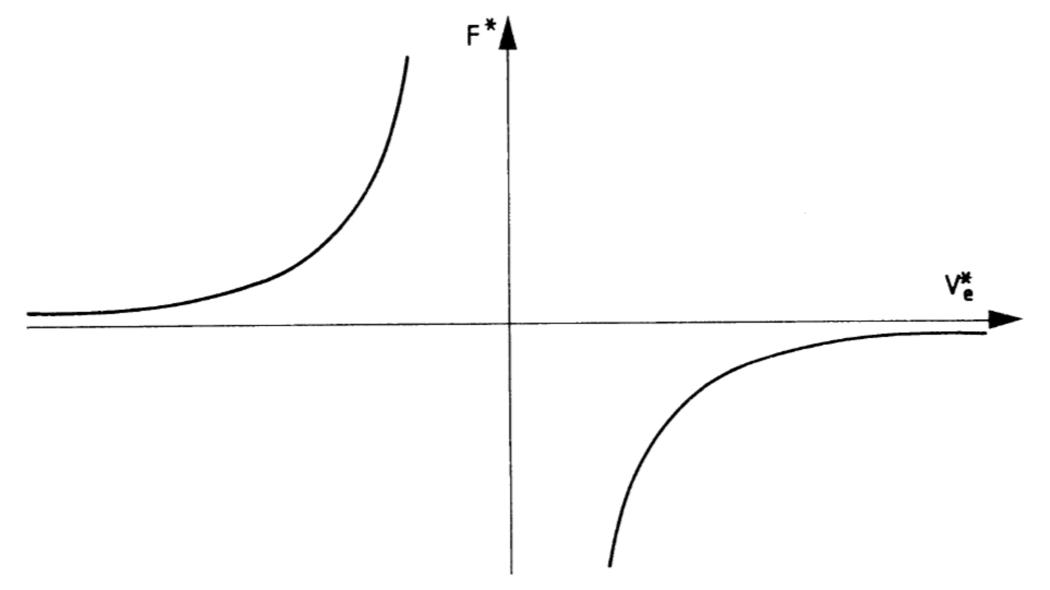
In a system of charged particles the Coulomb field is shielded and falls off exponentially at the Debye radius

$$r_D = \sqrt{\frac{m_e V_e^{*2}}{8\pi e^2 n_e^*}}$$

The Deybe radius is usually smaller than the electron beam radius. If not the latter is taken as the maximum impact parameter $b_{max} = r_D \text{ or } r_0$

We can finally write the cooling force as:

$$F^* = \frac{4\pi Z^2 e^4}{m_e V_i^{*2}} n_e^* L_c = -4\pi Z^2 e^2 c^2 r_e n_e^* L_c V_i^{*-2}$$



Cooling rate (time)

The rate of velocity change at which the ion is slowed down in the electron gas can be written as:

$$\delta^* = -\frac{{dV_i^*}/{dt}}{V_i^*}$$

Using the following relations:

$$E^* = \frac{m_i}{2} V_i^{*2}$$

$$\frac{dV_i^*}{dt} = \frac{dV_i^*}{dE^*}\frac{dE}{dx}\frac{dx}{dt} = \frac{1}{m_i V_i^*} F^* V_i^*$$

The friction rate can be expressed as:

$$\delta^* = -\frac{F^*}{m_i V_i^*} = -\frac{F^*}{p_i^*}$$

The inverse of the friction rate is defined as the cooling time.

$$\tau^* = \frac{1}{\delta^*} = -\frac{P_i^*}{F^*}$$

Inserting $r_i = \frac{e^2}{m_i c^2}$ we obtain $\tau^* = \frac{V_i^3}{4\pi Z^2 c^4 r_i r_e n_e^* L_c}$

To get the cooling time in the laboratory frame we note that $n_e = \gamma n_e^*$, hence

$$\tau = \frac{\gamma \tau^*}{\eta} = \frac{\gamma^2 V_i^3}{4\pi Z^2 c^4 r_i r_e n_e L_c}$$

where η is the ratio of the cooling length to the ring circumference

We have considered electrons has being stationary. However, they have a finite temperature T_e and hence a velocity distribution $f(V_e)$ which can be considered to be Maxwellian characterised by its velocity spread Δ_e.

$$T_e = \frac{m_e \Delta_e^2}{2} \qquad\qquad f(V_e^*) = \frac{e^{-V_e^{*2}/\Delta_e^2}}{\Delta_e^3}$$

To account for this we have to replace the ion velocity with the ion-electron velocity difference and average over the electron velocity distribution.

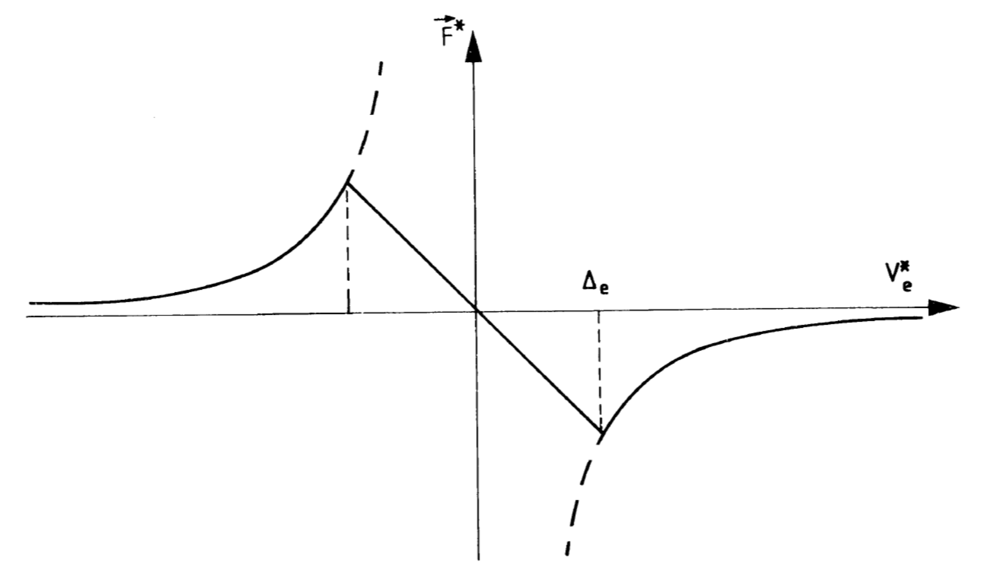
$$u^* = V_i^* - V_e^*$$

The expression for the frictional force becomes:

$$F^* = -4\pi Z^2 e^2 c^2 r_e n_e^* L_c \int f(V_e^*) \frac{u^*}{|u^*|^3} d^3 V_e^*$$

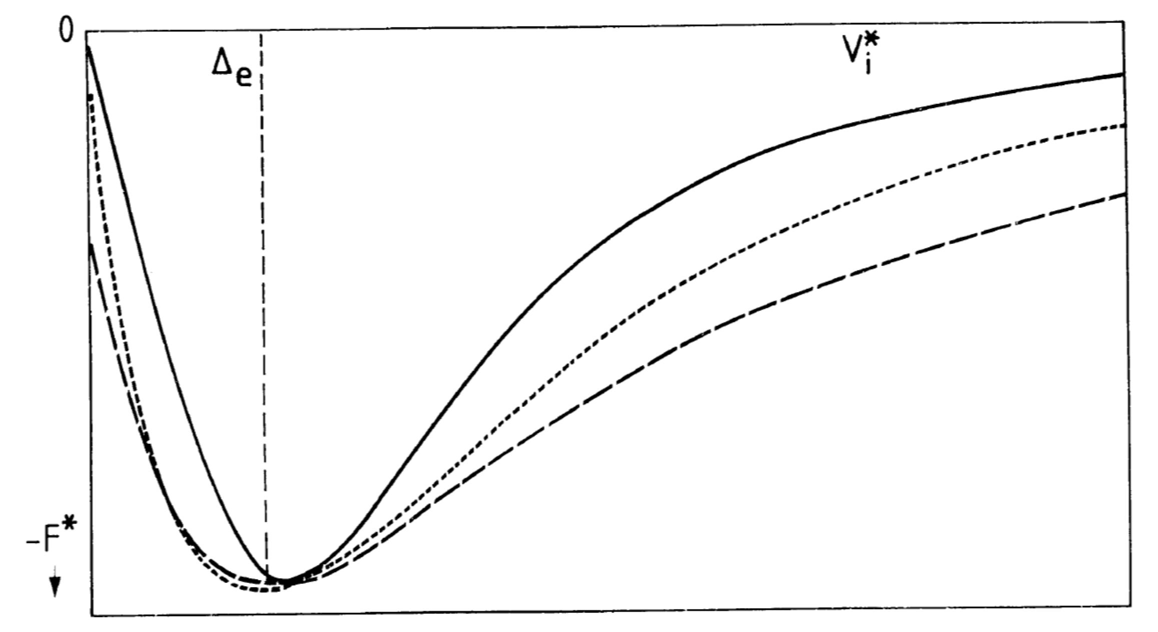
For an electron beam with a rectangular velocity distribution the cooling force is shown below

$$f(V_e^*) = \begin{cases} const, & |V_e^*| \le \Delta_e \\ 0, & |V_e^*| > \Delta_e \end{cases}$$



For a Maxwellian velocity distribution the cooling force has to be evaluated numerically. However a good approximation is:

$$F^* = -12\pi Z^2 e^2 c^2 r_e n_e^* L_c \frac{V_i^*}{\left|V_i^*\right|^3 + 2\Delta_e^3}$$



Using this approximation the cooling time in the laboratory frame can be written as:

$$\tau = \frac{\gamma^2}{\eta} \frac{V_i^{*3} + 2\Delta_e^3}{12\pi Z^2 c^4 r_i r_e n_e L_c}$$

In general the electron temperature T_e is independent of the beam energy and hence Δ_e is a constant of the device.

We can distinguish two domains of cooling:

i. Cooling of hot beams
   - Cooling time is proportional to V_i^{*3}

ii. Cooling of “warm” beams
   - Cooling time practically independent of V_i^* since Δ_e is constant
   - τ is independent of ion beam intensity
   - $\tau \propto \gamma^2$
   - $\tau \propto \frac{1}{r_i Z^2} \propto \frac{A}{Z^2}$
   - $\tau \propto \frac{1}{n_e}$

Equilibrium

Ideally cooling will continue until the ion beam temperature reaches the electron beam temperature

$T_{i_\perp} = T_{e_\perp}$ and $T_{i_\parallel} = T_{e_\parallel}$

Resulting in an ion divergence $\theta_{i_\perp} = \sqrt{\frac{m_e}{m_i}}\theta_{e_\perp}$ and momentum spread $\gamma\frac{\Delta p}{p} = \sqrt{\frac{m_e}{m_i}}\theta_{e_\parallel}$

In practice heating effects will prevent us from reaching this regime

Digression on ion beam and storage ring properties

Beam emittance: The volume of phase space occupied by the beam

6-dimensional space generated by the transverse and longitudinal coordinates and their derivatives

$$(x, x', y, y', E(z), \varphi(\Delta p/p))$$

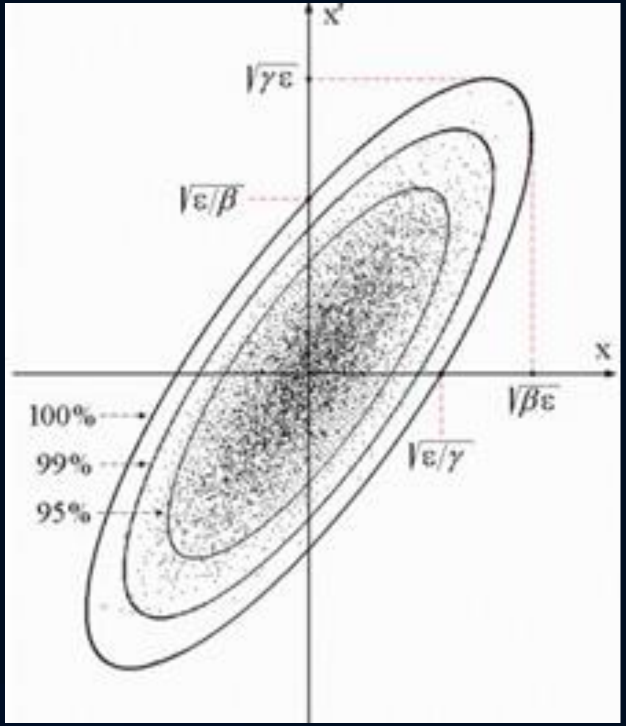
Projections in the 3 dimensions define the transverse and longitudinal emittances.

$$x = \sqrt{\beta\varepsilon} \quad x' = \sqrt{\gamma\varepsilon} \quad r = D\frac{\Delta p/p}{p}$$

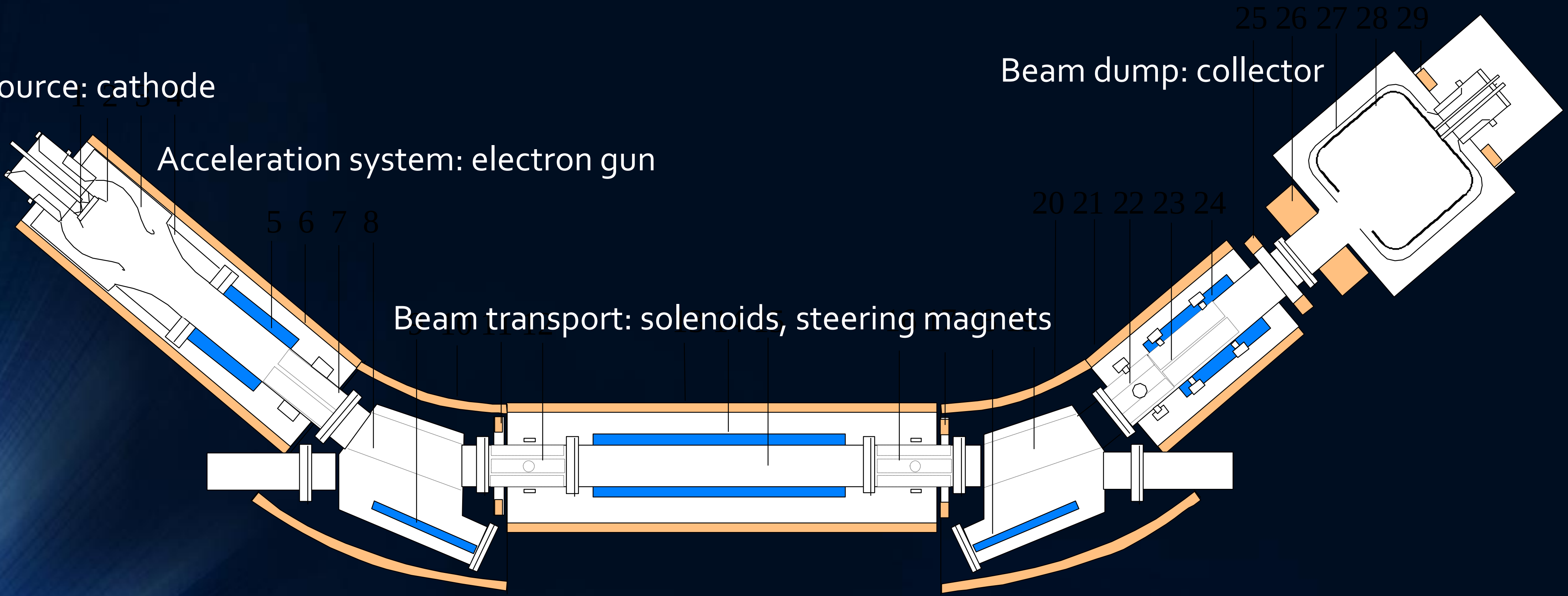
$$T_h = \frac{1}{2}mc^2\beta^2\gamma^2\langle x'\rangle^2$$

$$T_v = \frac{1}{2}mc^2\beta^2\gamma^2\langle y'\rangle^2$$

$$T_{\parallel} = \frac{1}{2}mc^2\beta^2\left(\frac{\Delta p}{p}\right)^2$$



How to build an electron cooler



Source: cathode

Acceleration system: electron gun

Beam transport: solenoids, steering magnets

Beam dump: collector

Vacuum, diagnostics

The electron gun

Electrons are produced in an electron gun where they are accelerated electrostatically to the desired energy.

A thermionic cathode is heated resistively to 1000°C and electrons are emitted from the surface.
Electrons are emitted from the cathode in all directions because of their thermal energy.
Due to space-charge, an electron cloud is formed just in front of the cathode.
Electrons are extracted from this cloud and accelerated to required energy by a series of electrodes.

Cathodes are normally oxide-coated and indirectly heated by a filament.
BaO (or a mixture with SrO and CaO) is the most common used oxide due to its low work function.
Modern cathodes are also doped with chemicals or compounds of metals with a low work function which form a metal layer on the surface to emit more electrons.
The lifetime of these cathodes is determined by the purity of the cathode materials.

The heater consists of a fine wire or ribbon, made of a high resistance metal alloy like nichrome, similar to the heating element in a toaster but finer. It runs through the centre of the cathode, often being coiled on tiny insulating supports or bent into hairpin-like shapes to give enough surface area to produce the required heat. Typical heaters have a ceramic coating on the wire.

The cathode is surrounded by the Pierce shield, an electrode on cathode potential shaped to produce perpendicular potential lines to the beam axis.
Special attention must be paid to the design of the subsequent accelerating electrodes to keep the field lines perpendicular.

The final electron current follows Child's law: $\mathrm{I} = \rho U^{3/2}$

ρ is called the perveance and is essentially determined by the ratio of the beam radius r_o and the cathode-anode distance d.

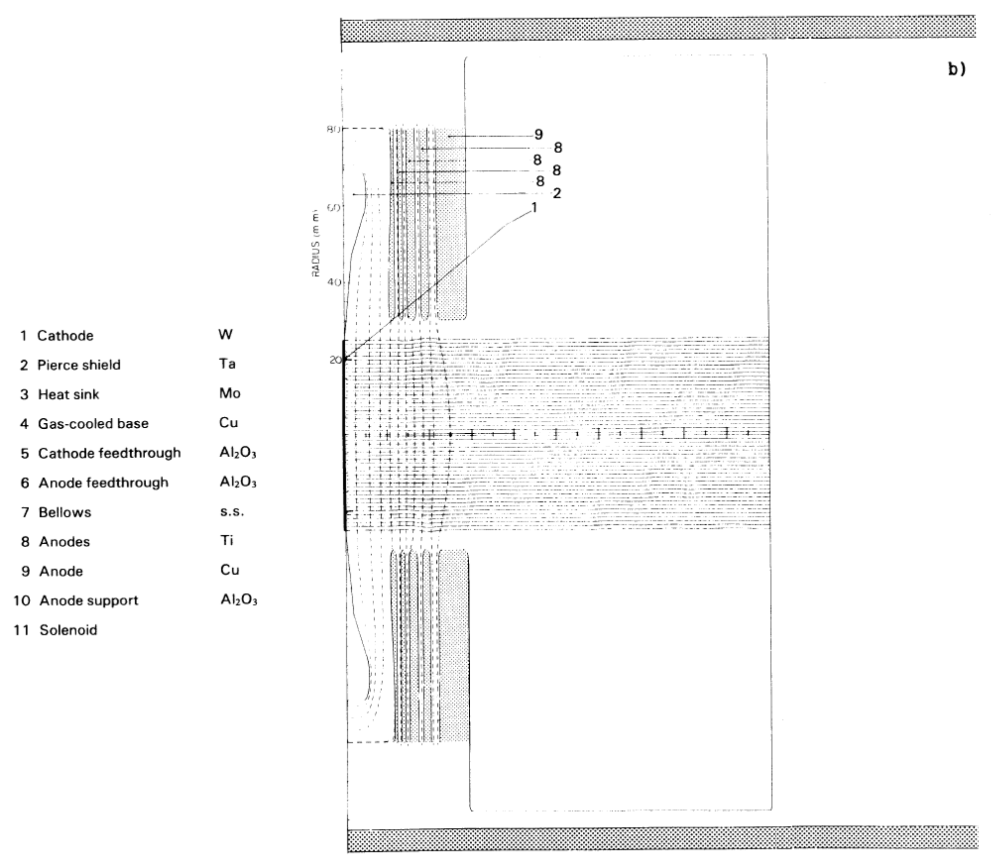
$$\rho = 7.3\ \mu P \left(\frac{r_0}{d}\right)^2$$

The electron gun is embedded in a longitudinal field to avoid the electrons being lost.
Transverse motion of the electrons are transformed into spirals about the magnetic lines with the cyclotron frequency $\omega_c = \dfrac{eB}{m_e \gamma c}$ and radius $r_c = \dfrac{V_{e\perp}}{\omega_c}$

Two types of gun have been used on electron coolers:

- Resonant-optic gun
- Adiabatic gun

Resonant-optic guns require the magnetic field to be matched with the spiral length of the electrons i.e. the time the electrons need to pass through the acceleration column is equal to a multiple n of the inverse of the cyclotron frequency.

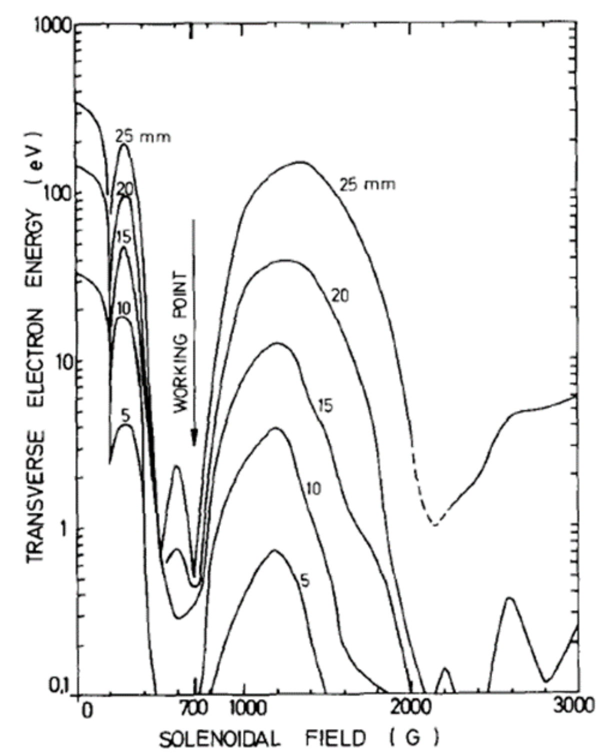


1	Cathode	W
2	Pierce shield	Ta
3	Heat sink	Mo
4	Gas-cooled base	Cu
5	Cathode feedthrough	Al_2O_3
6	Anode feedthrough	Al_2O_3
7	Bellows	s.s.
8	Anodes	Ti
9	Anode	Cu
10	Anode support	Al_2O_3
11	Solenoid	

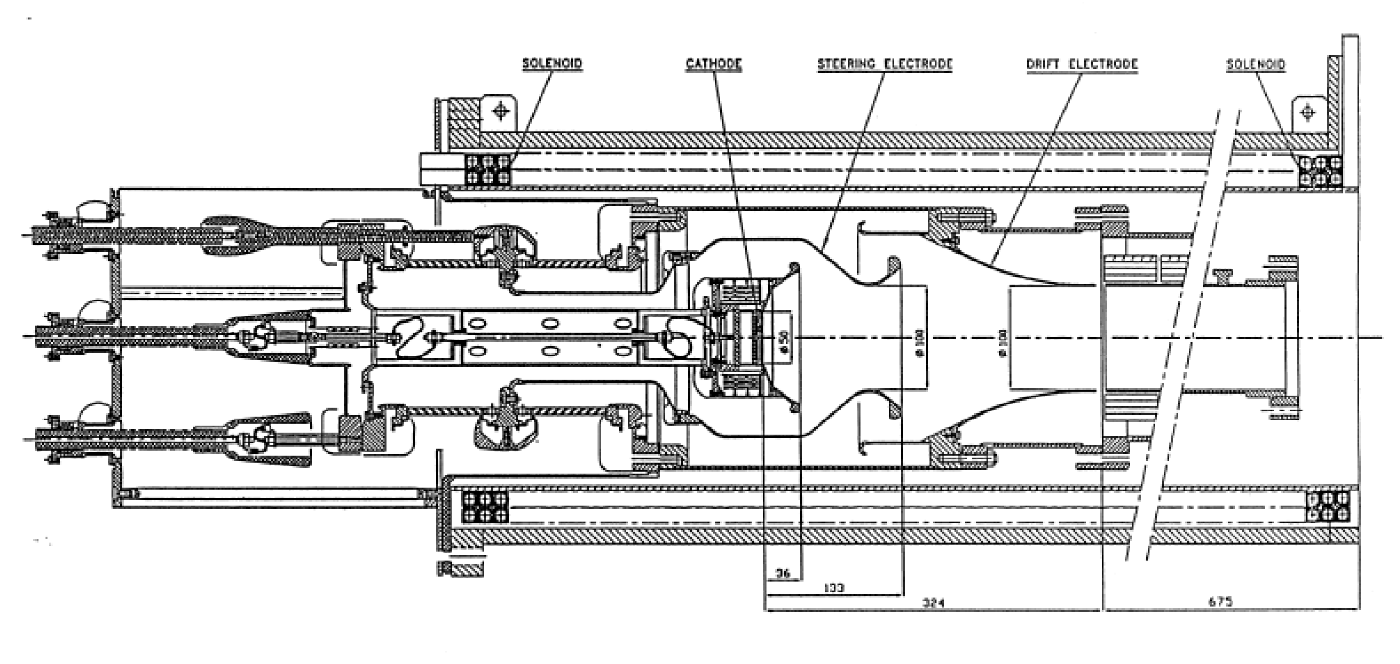
Resulting in the length of the accelerating column

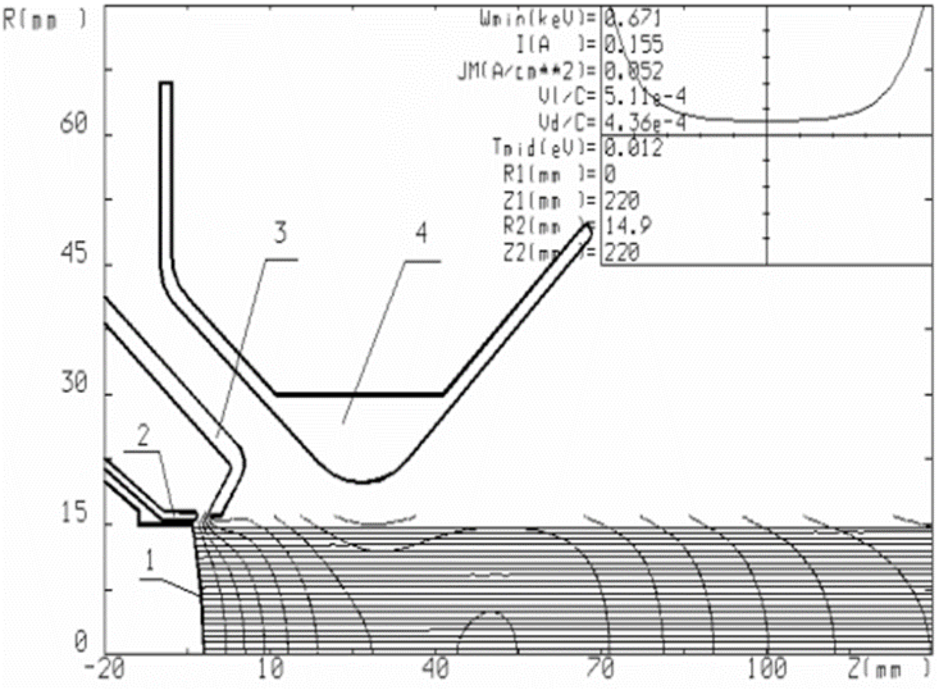
$$\lambda_R = n\frac{V_e}{\omega_c} = n\frac{V_e}{eB}m_e\gamma c$$

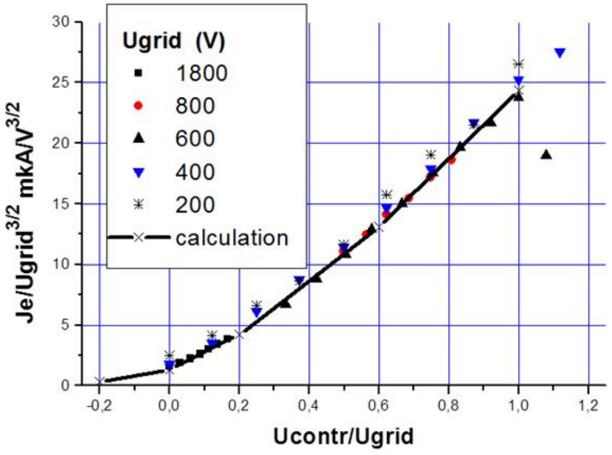
$$B = n\beta\gamma\frac{m_e c^2}{e\lambda_R}$$



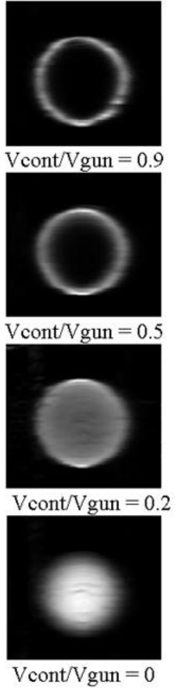
An adiabatic gun works at a fixed value of the magnetic field regardless of the electron energy.

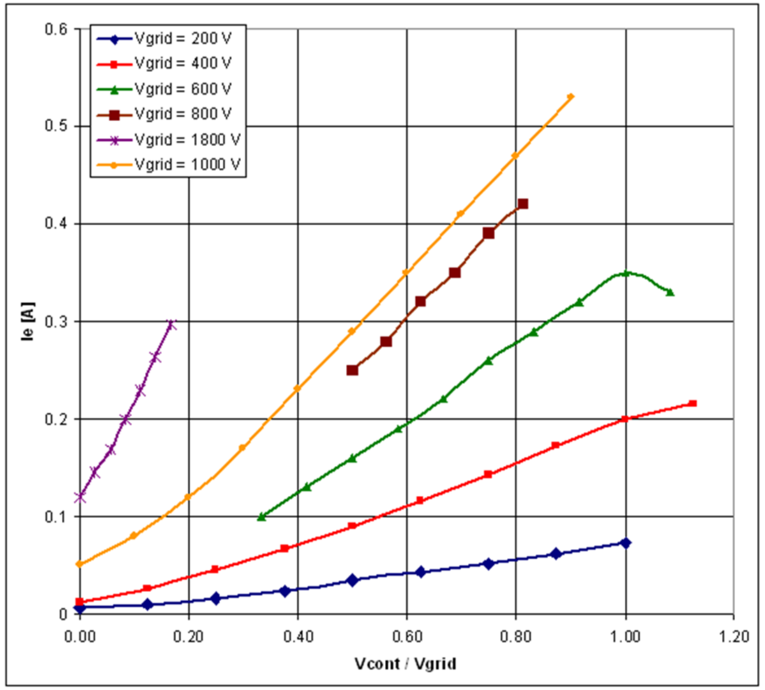






Electron beam current normalized on the grid voltage as a function of V_{cont}/V_{grid} for E_e = 2.5 keV The solid line is calculation of electron gun SuperSam code after fitting the position of the gun electrodes.





1. 14mm convex cathode
2. Control electrode (modifies density distribution and intensity)
3. Pierce electrode
4. Grid electrode (fixes the intensity)

Electron beam transport

After the gun, the electrons enter a drift region where they are transported to the interaction section where the cooling of the circulating ion beam takes place.

In the drift region the electric potential lines are parallel to the electron trajectories with increasing space going from the centre to the edge of the beam. The radial behaviour of the electric field is described by the potential of a homogeneous charge distribution with sharp boundaries.

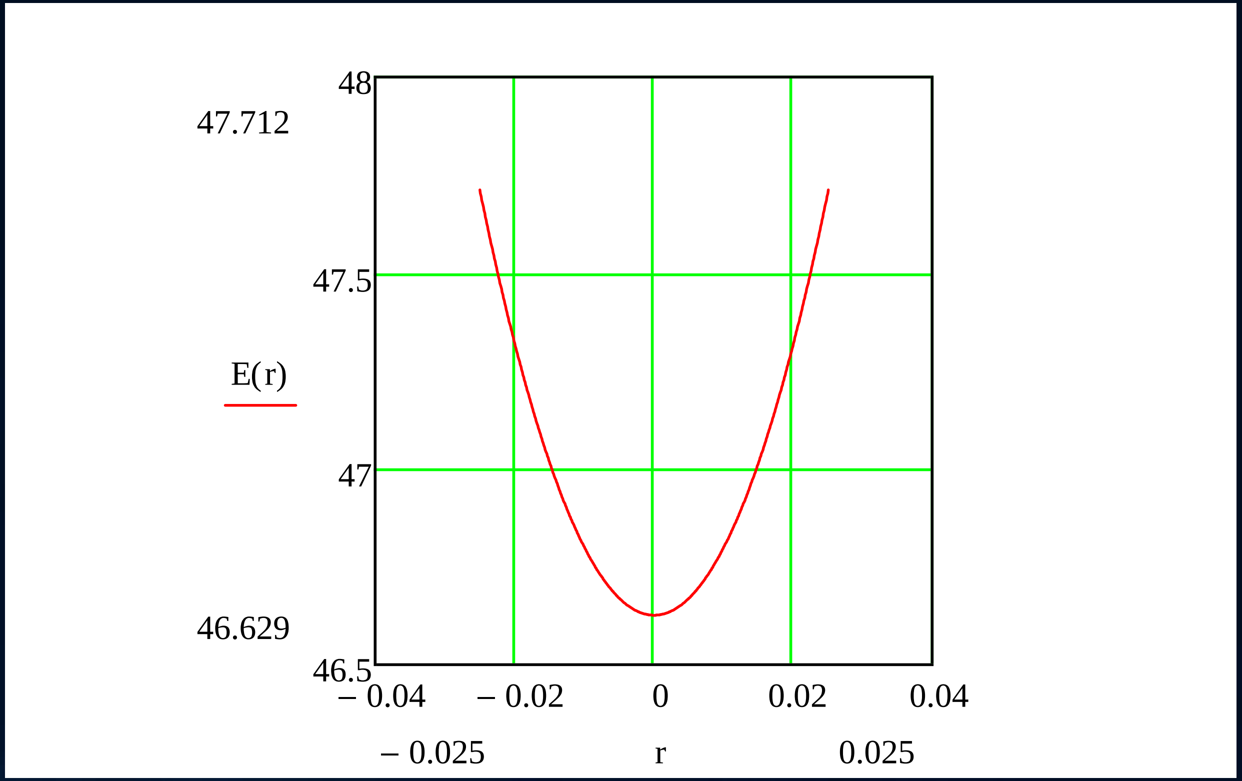
$$\Delta U = \frac{m_e c^2}{e} n_e r_e \pi r^2, \qquad r \le r_0$$

Substituting for $n_e = \dfrac{I}{\pi r_0^2 e \beta c} = \dfrac{\rho U^{3/2}}{\pi r_0^2 e \beta c}$ and $eU = \dfrac{m_e c^2 \beta^2 \gamma}{2}$

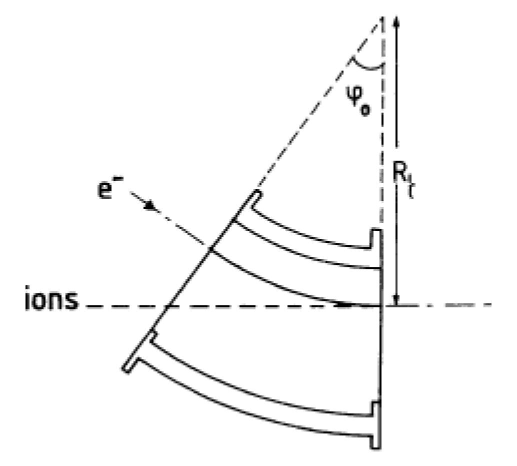
$$\frac{\Delta U}{U} = \frac{r_e \rho}{ec} \sqrt{\left(\frac{m_e c^2}{e}\right)^3 \frac{\gamma}{2}} \frac{r^2}{r_0^2}$$

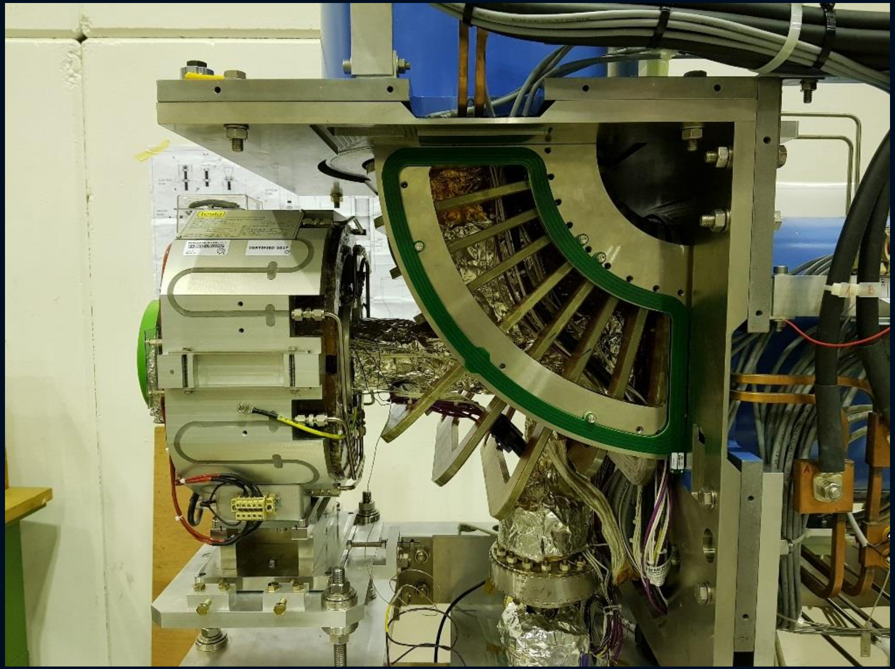
The change of electric potential across the electron beam has two consequences:

- A radial electron velocity distribution of a parabolic form
- ExB situation leading to an azimuthal drift of the electron beam with velocity: $V_d = \frac{r}{\omega_c} \frac{r_e}{2\gamma^2} n_e c^2$



The magnetically confined electrons are bent into the interaction region with a curved solenoid or toroid. An additional dipole field is required to compensate the centrifugal force experienced by the electrons.





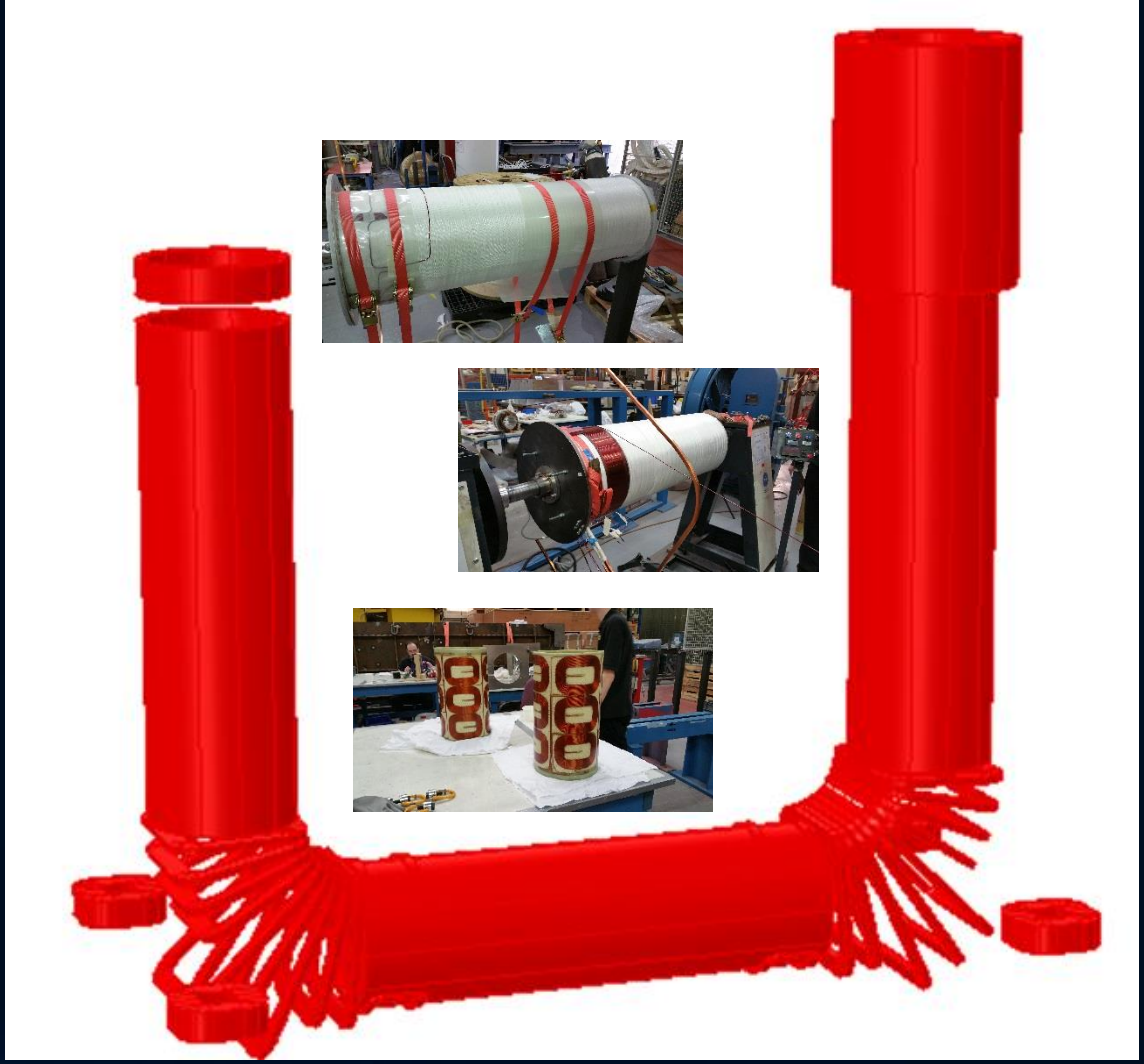
The properties of the magnetic field are important to guarantee a good cooling efficiency of the ion beam and to ensure that the electron beam is not heated. In the cooling region the angle between the magnetic field lines and the ion beam should be small compared to the average transverse temperature of the electron beam.

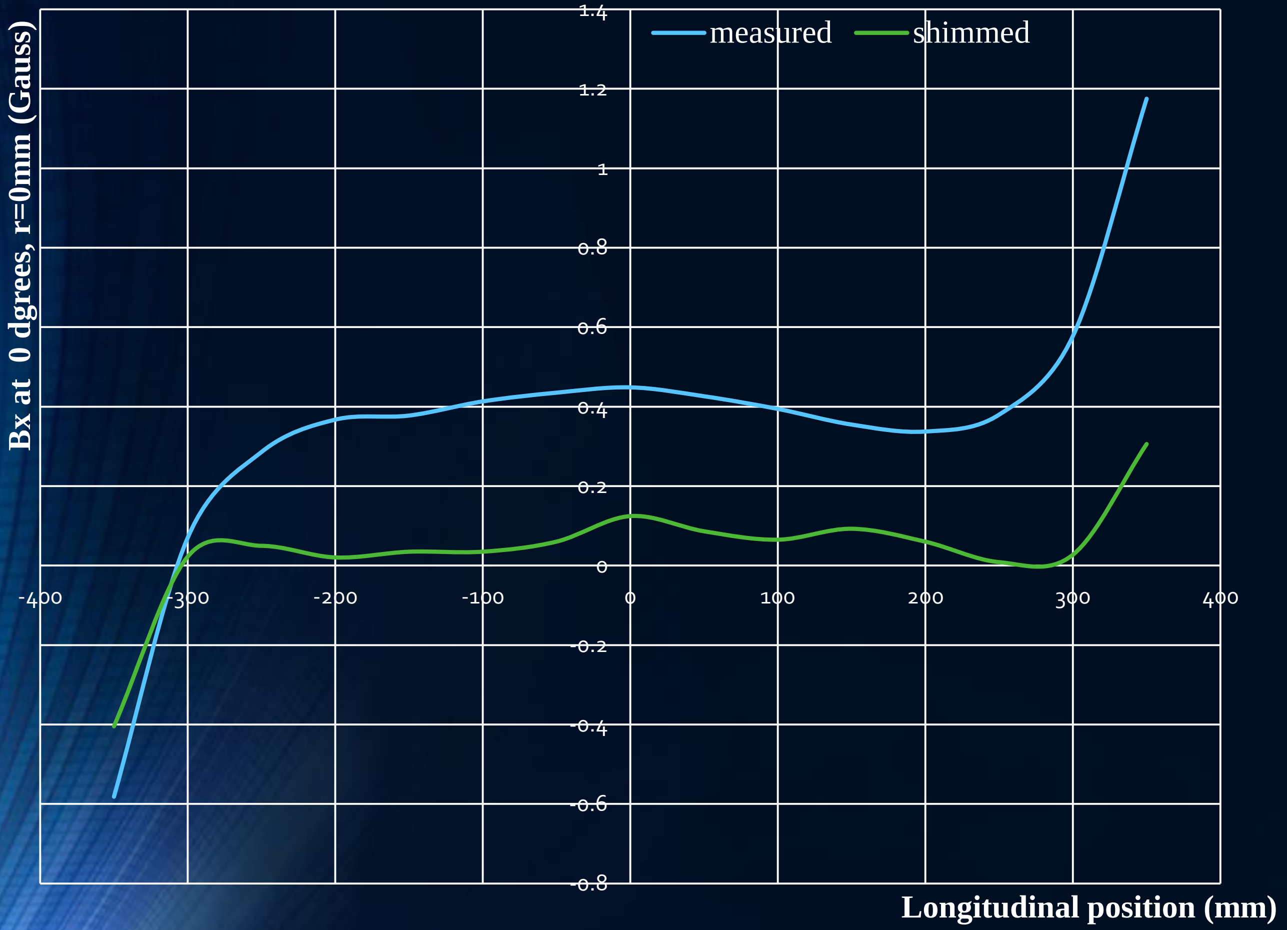
ELENA cooler magnetic system components

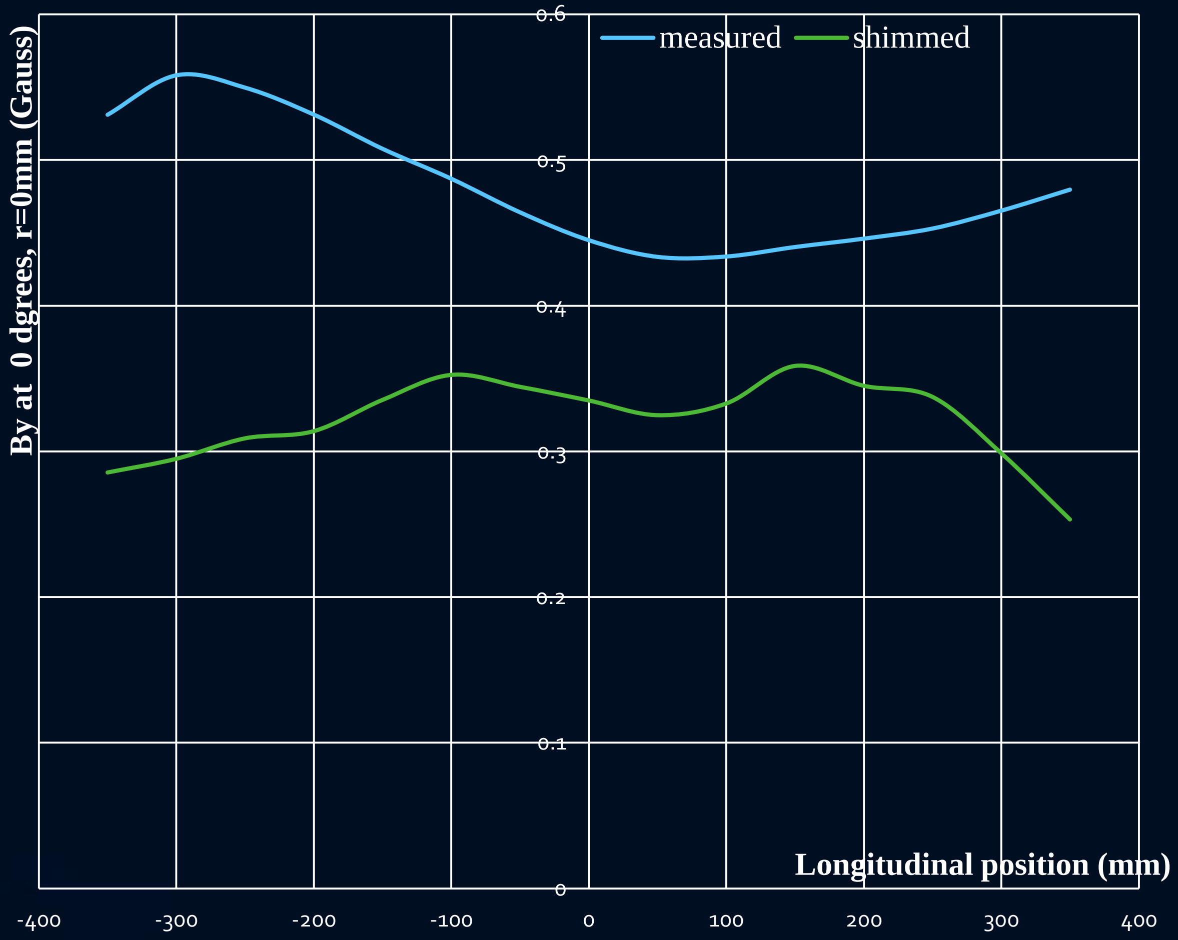
- Main cooler solenoid
- Gun solenoid
- Collector solenoid
- Expansion solenoid
- Squeeze coil at collector
- 2 x Toroid section consisting of

  9 racetrack coils each
- Various corrector coils to

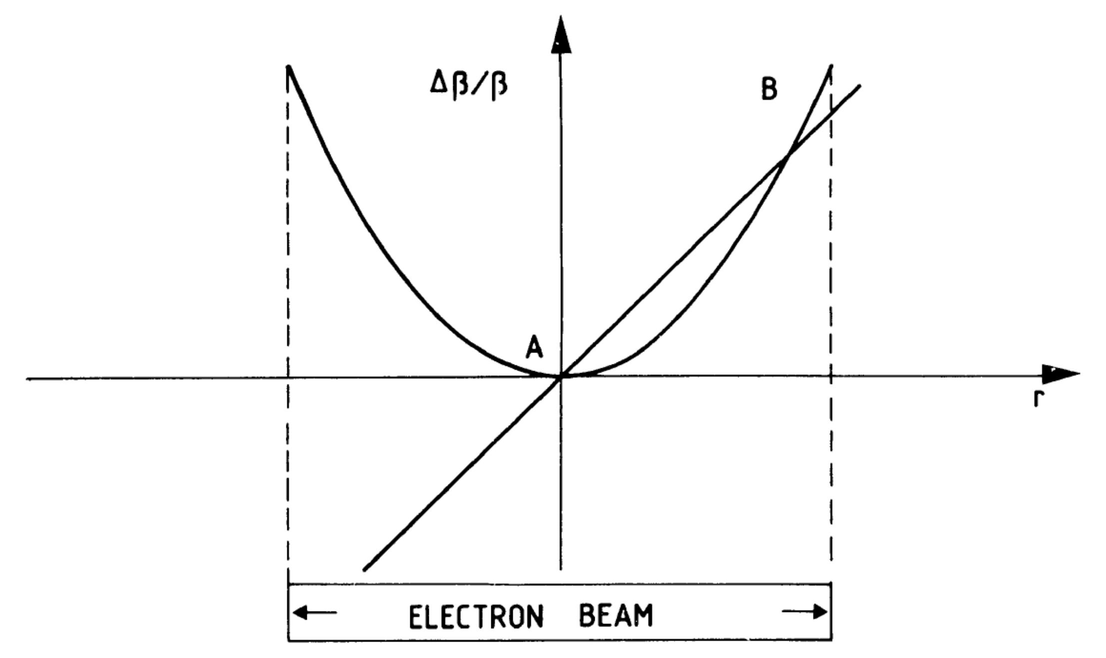
  ensure good field quality
- Orbit correctors
- Solenoid compensators



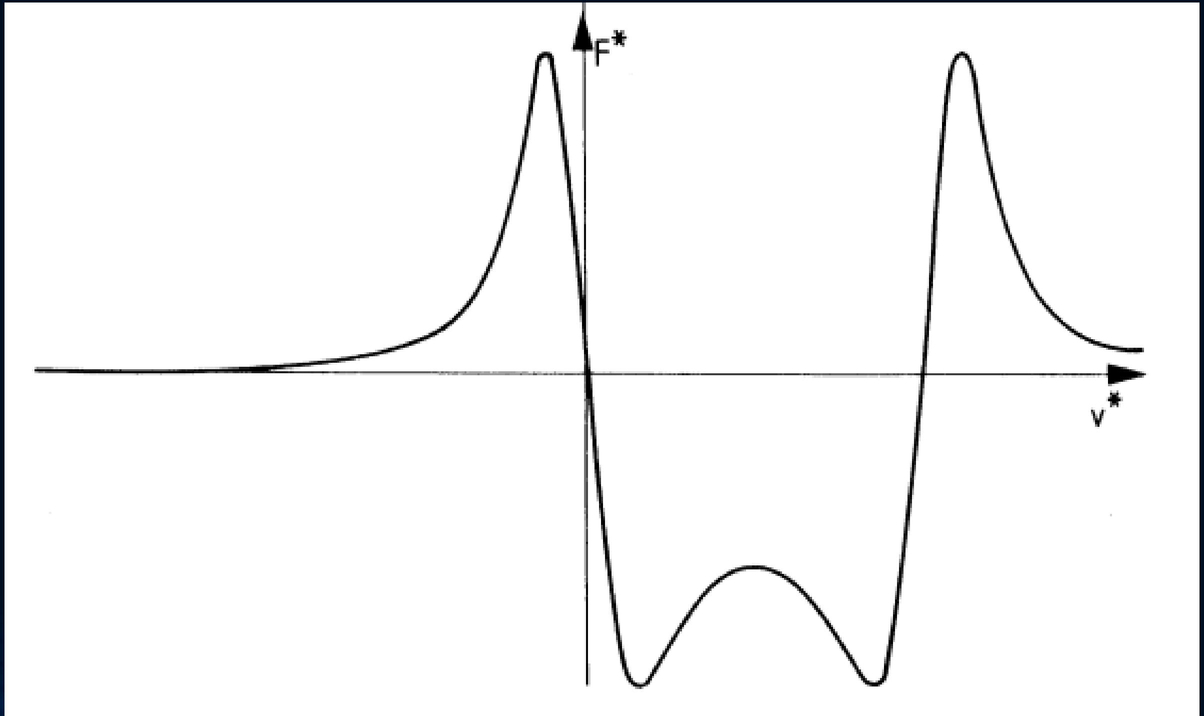

measured
shimmed
Bx at 0 dgrees, r=0mm (Gauss)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-400
-300
-200
-100
0
100
200
300
400
Longitudinal position (mm)


measured
shimmed
By at 0 dgrees, r=0mm (Gauss)
0.6
0.5
0.4
0.3
0.2
0.1
0
Longitudinal position (mm)
-400
-300
-200
-100
0
100
200
300
400

The cooling section



Have to match velocities, position and angle



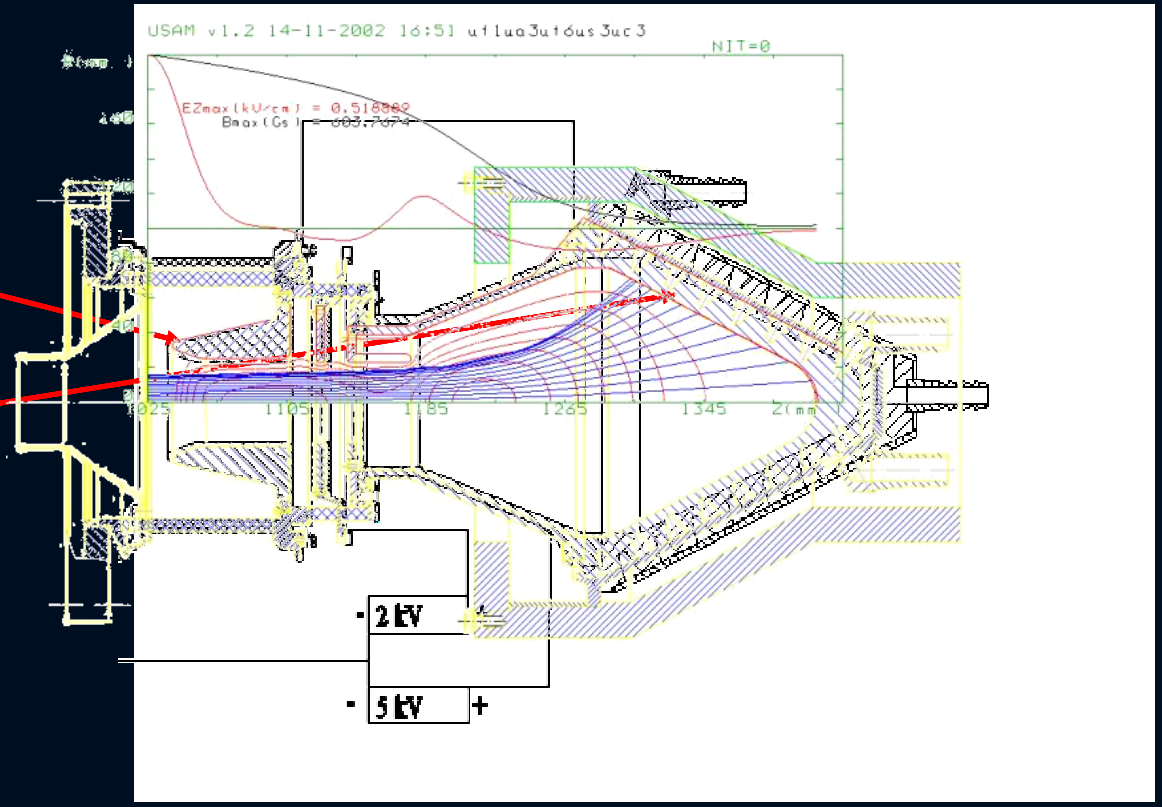
Electron beam collector

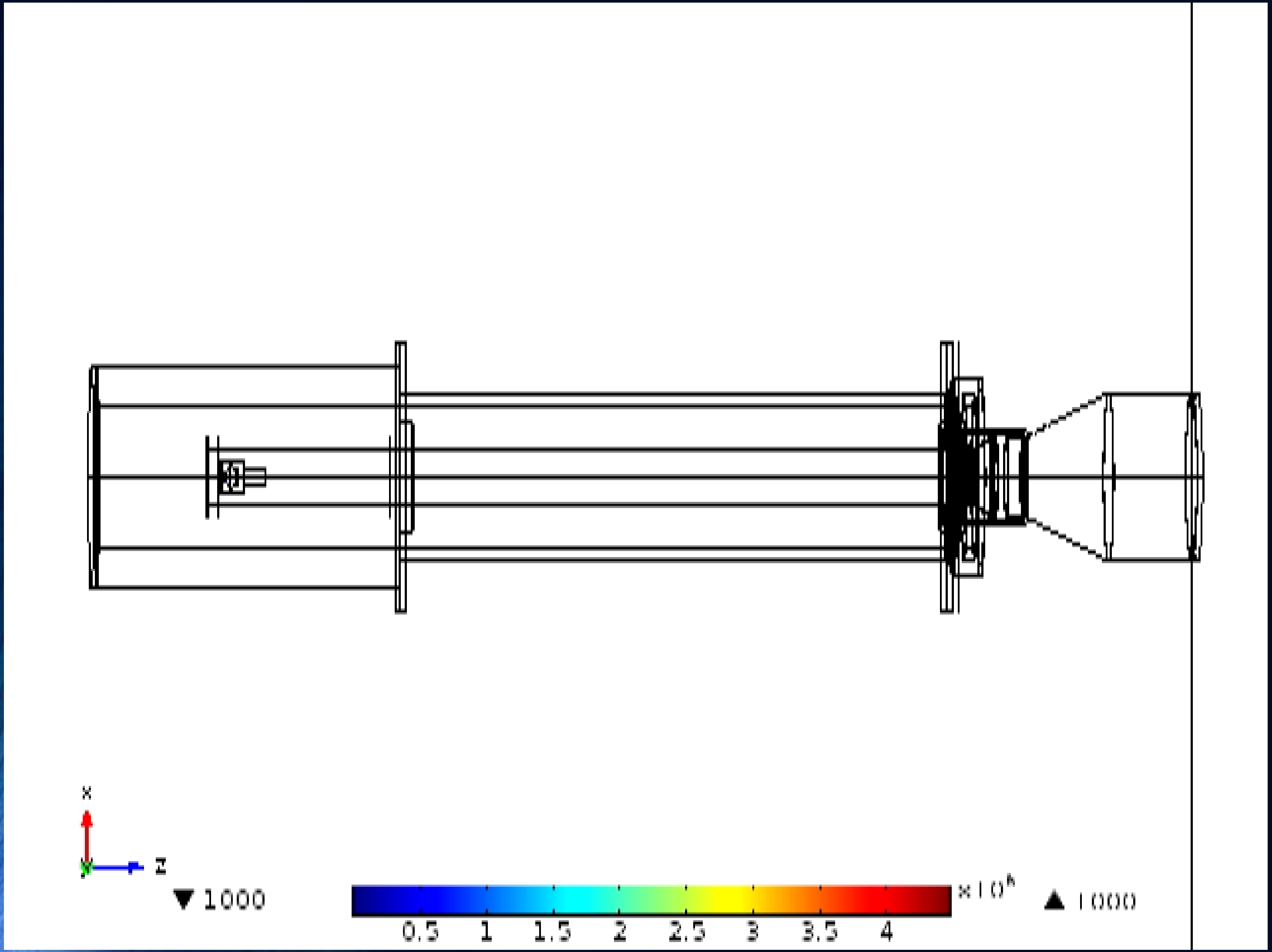
Reduce the power of the electron beam to the lowest possible value.
Capture the electrons with maximum efficiency.

Electrons are decelerated in the collector. The remaining power is dissipated on the collector surface. Deceleration is done in two steps to avoid the formation of a virtual cathode at the collector entrance

Secondary electrons emitted from the collector surface or reflected electrons can bounce back and forth between the gun and collector and be lost on the vacuum chamber. Careful design and the use of the magnetic field can improve the collection efficiency

- Suppressor electrode slows down the primary electrons at the collector entrance.
- Magnetic field is reduced to spread out the electrons on the collector surface.
- Surface on which the electrons are collected is water cooled.




x
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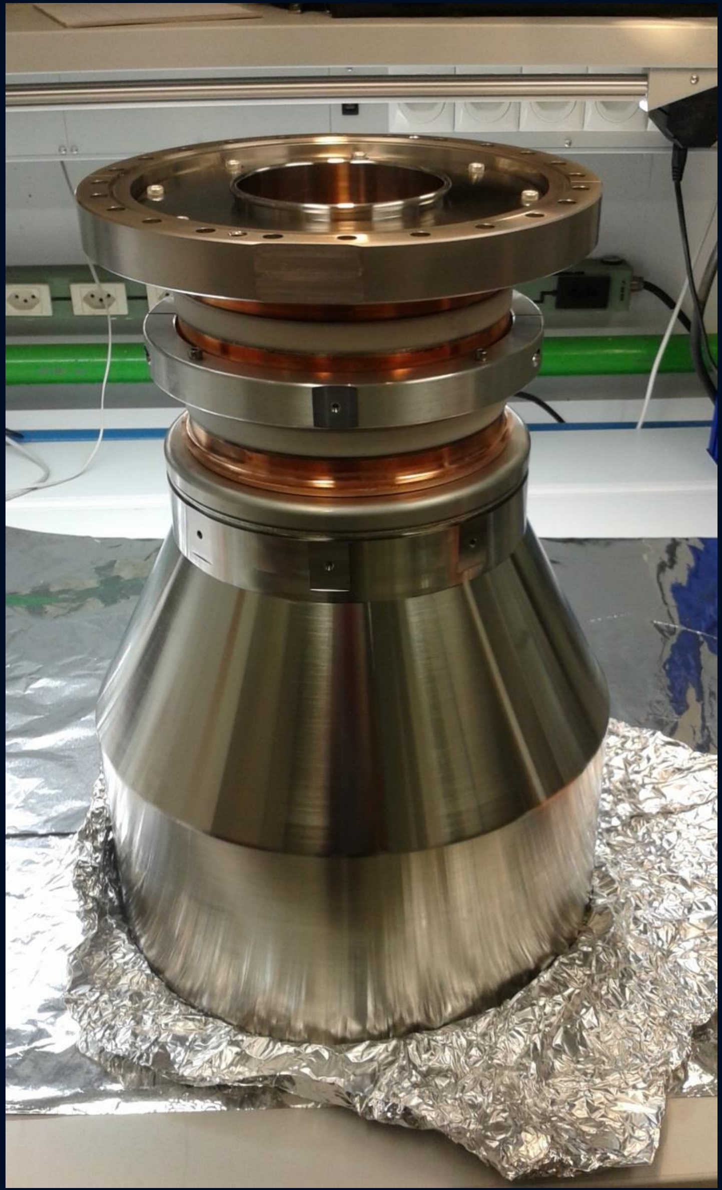
▲ 1000

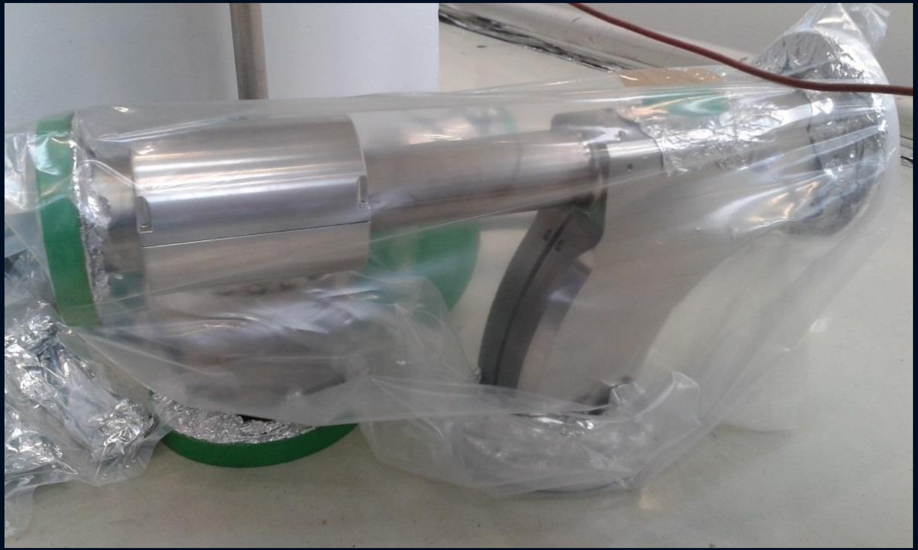


Vacuum system

Electron coolers operate under ultra-high vacuum conditions ($<10^{-10}$ Torr).
Main outgassing comes from:

- Hot cathode
- Collector
- Electron loss on the vacuum chamber

Cooler must be bakeable.
Differential pumping system between gun/collector and cooling section.
Careful choice of vacuum chamber material (316LN stainless steel, avoid trapped volumes).
NEG coating of the vacuum chamber for increased pumping.

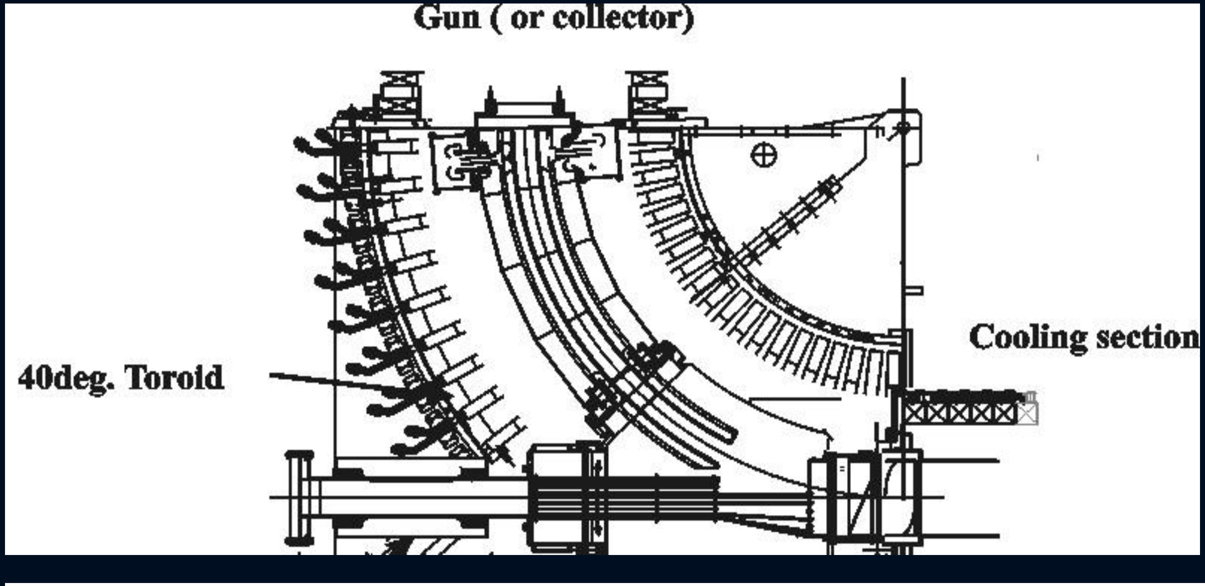


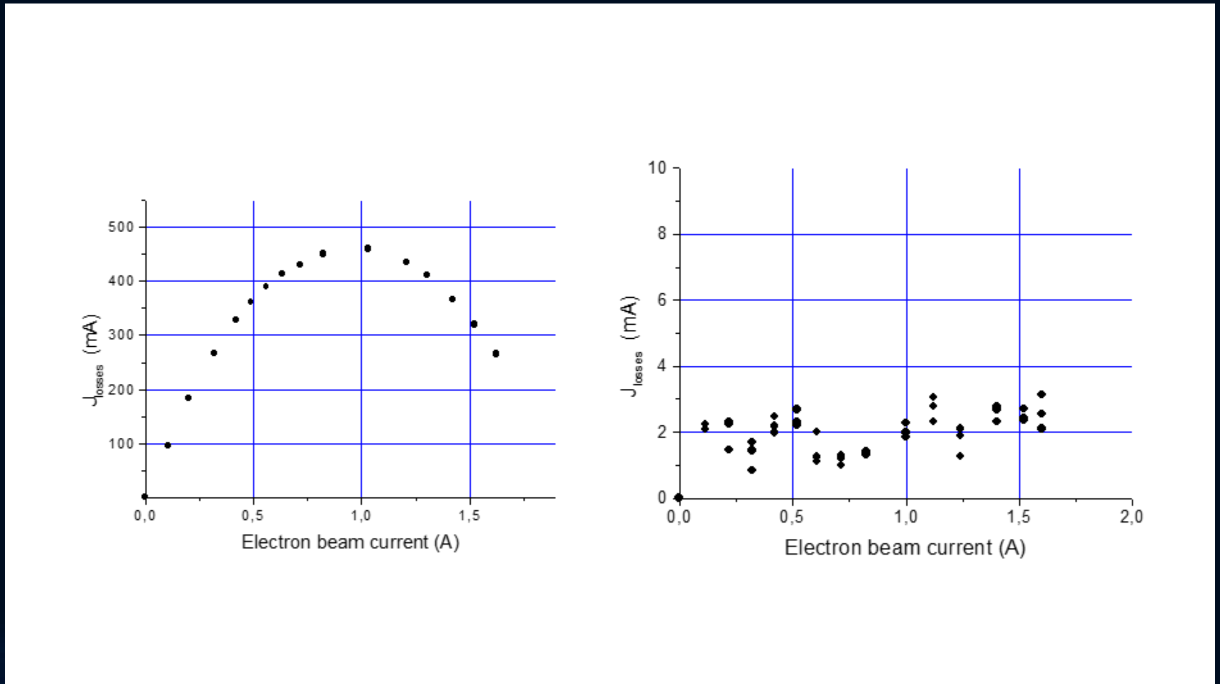
Additional effects to improve cooling

- Flattened electron beam distribution
  - After acceleration in the gun the longitudinal velocity spread is compressed giving a smaller longitudinal temperature
- Magnetised electron cooling
  - Electrons make many rotations enhancing the exchange of energy
- Beam expansion
  - Reduction of the electron transverse temperature
- Electrostatic bend in the toroids
  - ExB field for full compensation of the excitation of reflected electrons in the vertical B field of the toroid

Electrostatic bend

- Electrons experience a centrifugal force in the toroid.
- This drift can be compensated by an additional magnetic field in the opposite direction.
- Reflected and secondary electrons however are excited by this field and can oscillate between the gun and collector before being lost.
- Complete compensation is obtained by superimposing an electric field on the magnetic field





Beam expansion

- Needed for:
  - Adapting the electron beam size to the injected beam size for optimum cooling.

$$B_{//} r^2 = const \Rightarrow r = r_o \sqrt{\frac{B_o}{B}}$$

B_o=0.235T, B=0.075T, r_o=14mm => r=24.8mm

  - Reducing the magnetic field in the toroids, thus reducing the closed orbit distortion.
  - Reducing the transverse thermal temperature of the electron beam.

$$\frac{E_t}{B_{//}} = const \Rightarrow E = E_o \frac{B}{B_o}$$

B_o=0.235T, B=0.075T, E_o=100meV => E=32meV

Effects of the cooler on the circulating beam

Deflection of the circulating beam due to the vertical field in the toroid.

$$\Theta[rad] = \frac{\int B_z dl}{B_0 \rho_0} \qquad \Delta x = \frac{B_0 R_t^2}{B_0 \rho_0} |\phi_0 - tan\phi_0|$$

Tune shift due to the focusing effect of the electron beam.

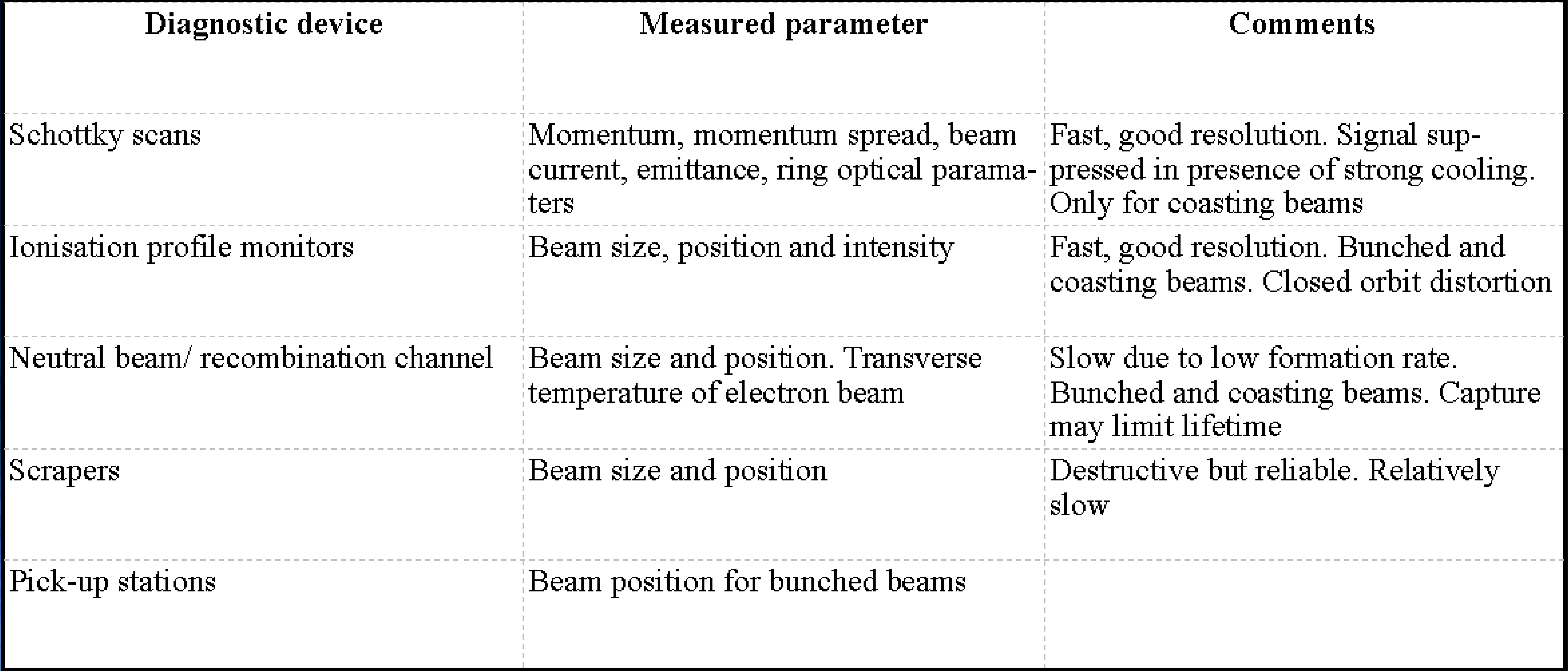
$$\Delta \upsilon = 0.5 \left\langle \beta_{h,v}^* \right\rangle n_e r_p \beta^{-2} \gamma^{-3} L$$

The solenoidal field of the cooler twists the ion beam by an angle:

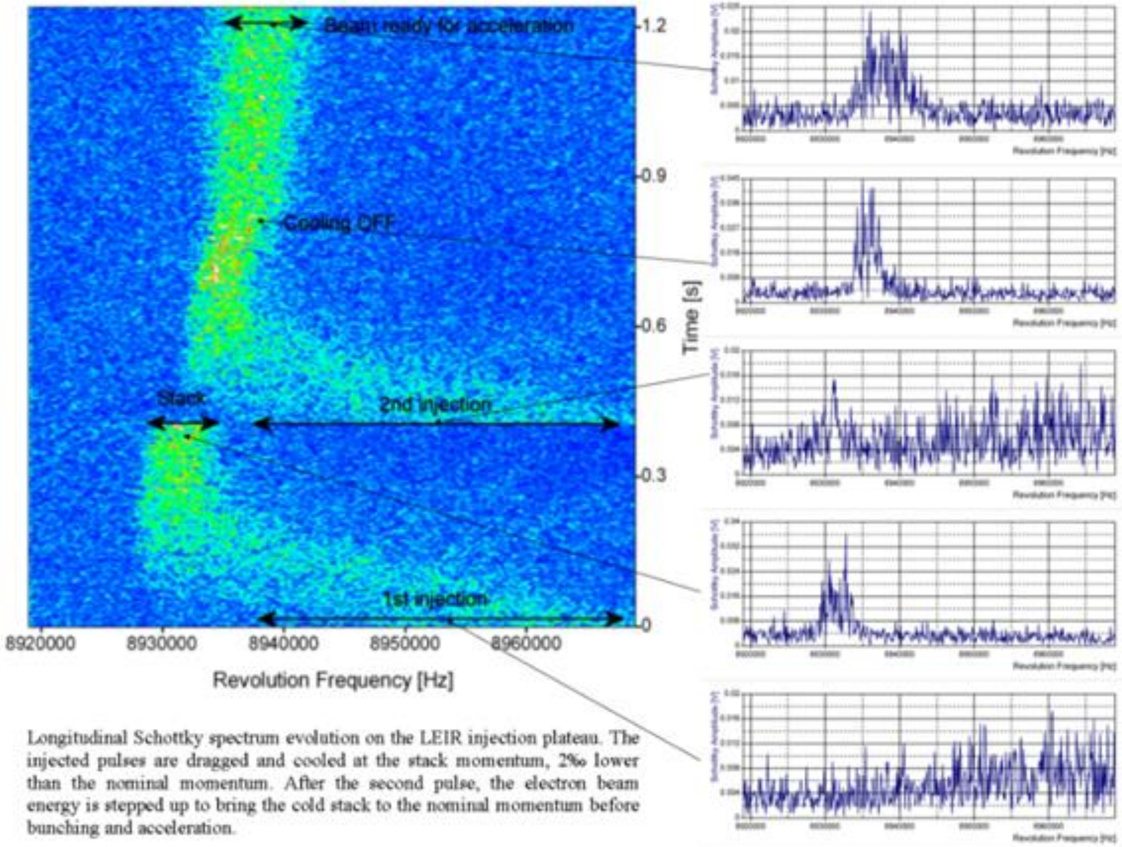
$$\vartheta[rad] = \frac{L}{\beta c} \omega_c \frac{m_e}{m_i}$$

Effect is negligible unless working close to a resonance

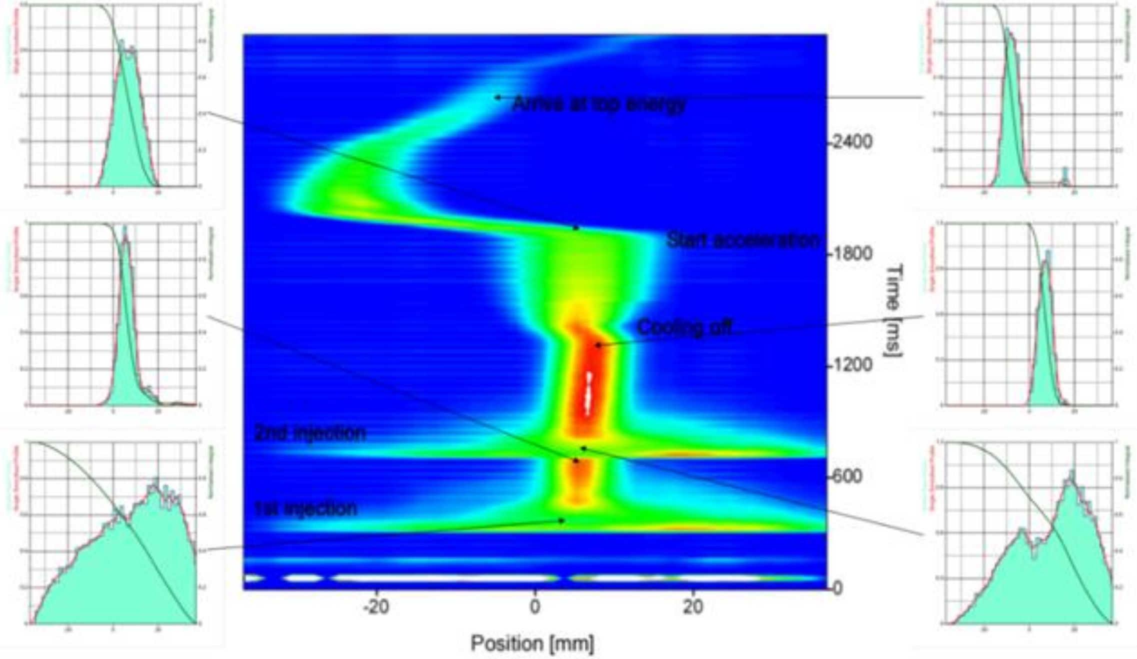
DIAGNOSTICS ON ION BEAMS FOR ELECTRON COOLING



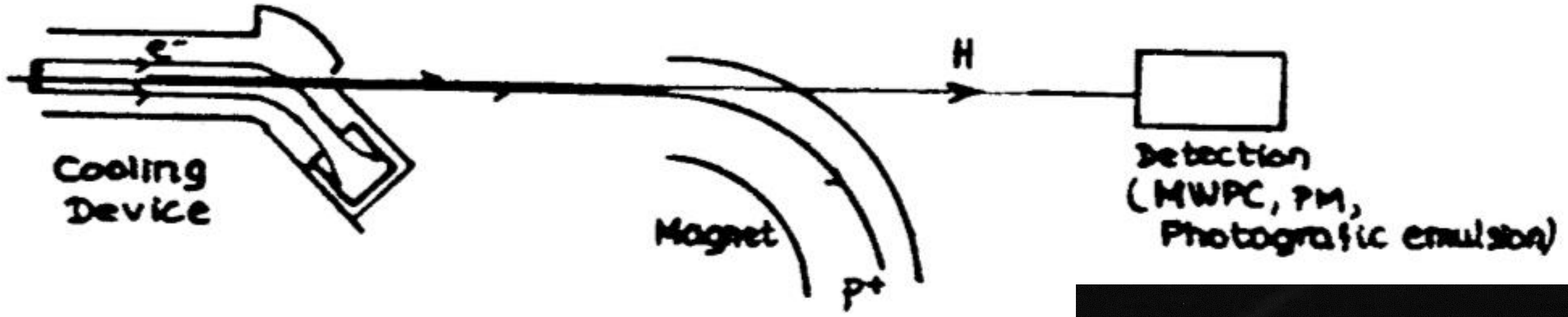
Diagnostic device	Measured parameter	Comments
Schottky scans	Momentum, momentum spread, beam current, emittance, ring optical paramaters	Fast, good resolution. Signal suppressed in presence of strong cooling. Only for coasting beams
Ionisation profile monitors	Beam size, position and intensity	Fast, good resolution. Bunched and coasting beams. Closed orbit distortion
Neutral beam/ recombination channel	Beam size and position. Transverse temperature of electron beam	Slow due to low formation rate. Bunched and coasting beams. Capture may limit lifetime
Scrapers	Beam size and position	Destructive but reliable. Relatively slow
Pick-up stations	Beam position for bunched beams	

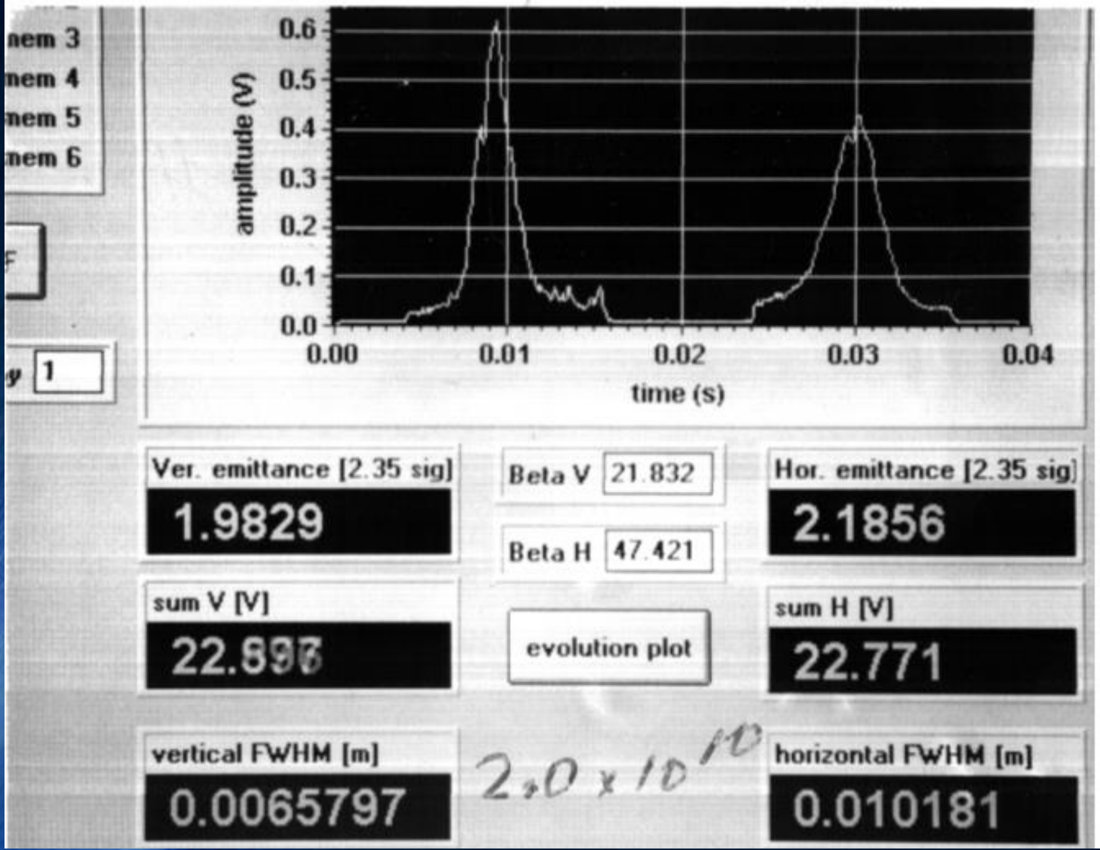


Longitudinal Schottky spectrum evolution on the LEIR injection plateau. The injected pulses are dragged and cooled at the stack momentum, 2‰ lower than the nominal momentum. After the second pulse, the electron beam energy is stepped up to bring the cold stack to the nominal momentum before bunching and acceleration.



Horizontal beam profile evolution during a complete LEIR cycle measured on the ionisation profile monitor. Two LINAC pulses are cooled-stacked at 4.2 MeV/n in 800 ms, then the beam is bunched and accelerated to 72 MeV/n for transfer to the next machine in the chain, the PS. The measured emittance at extraction is typically 0.4 µm.





y 1

Ver. emittance [2.35 sig] 1.9829

Beta V 21.832

Beta H 47.421

Hor. emittance [2.35 sig] 2.1856

sum V [V] 22.896

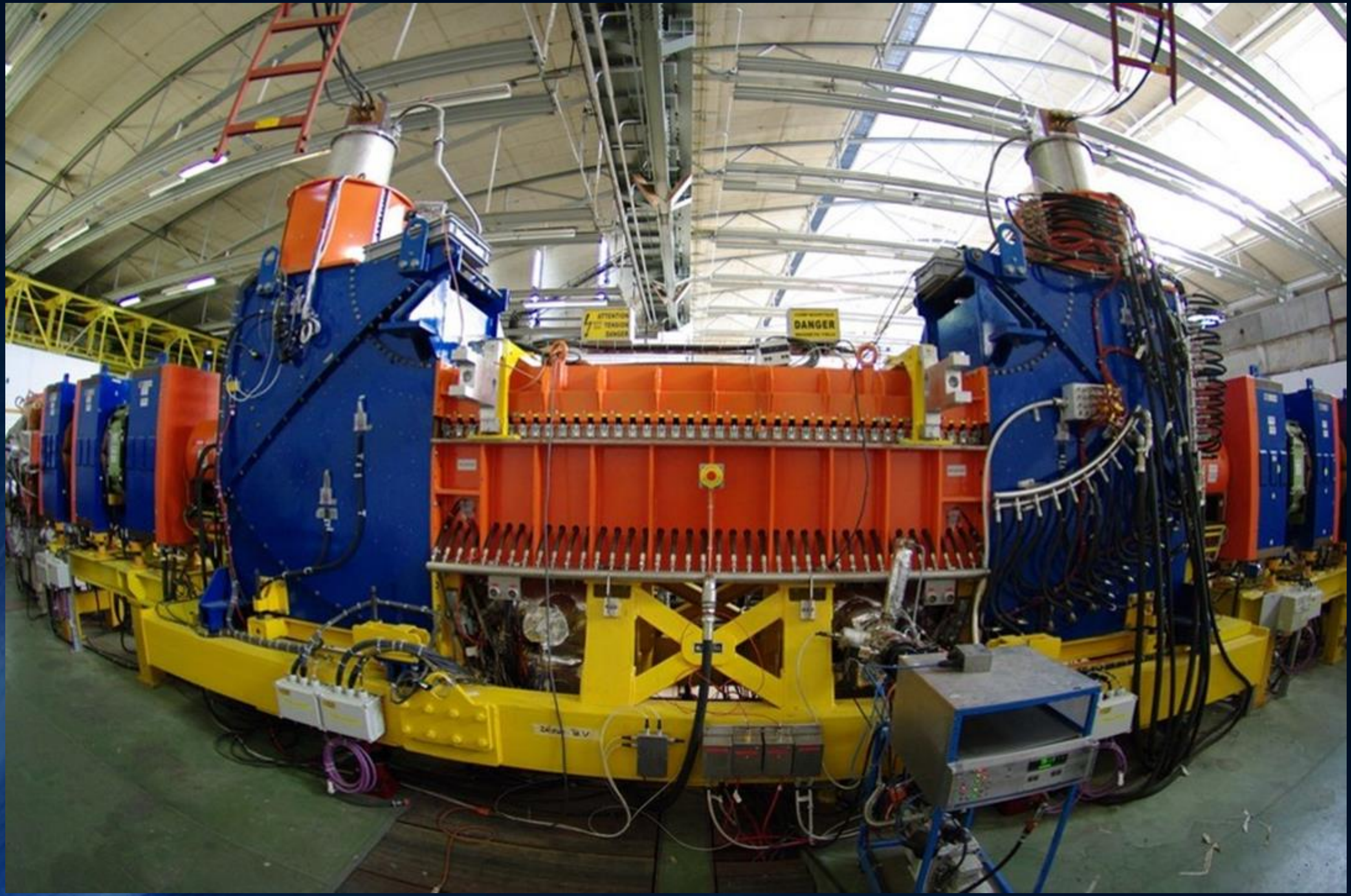
sum H [V] 22.771

vertical FWHM [m] 0.0065797

$2{,}0 \times 10^{10}$

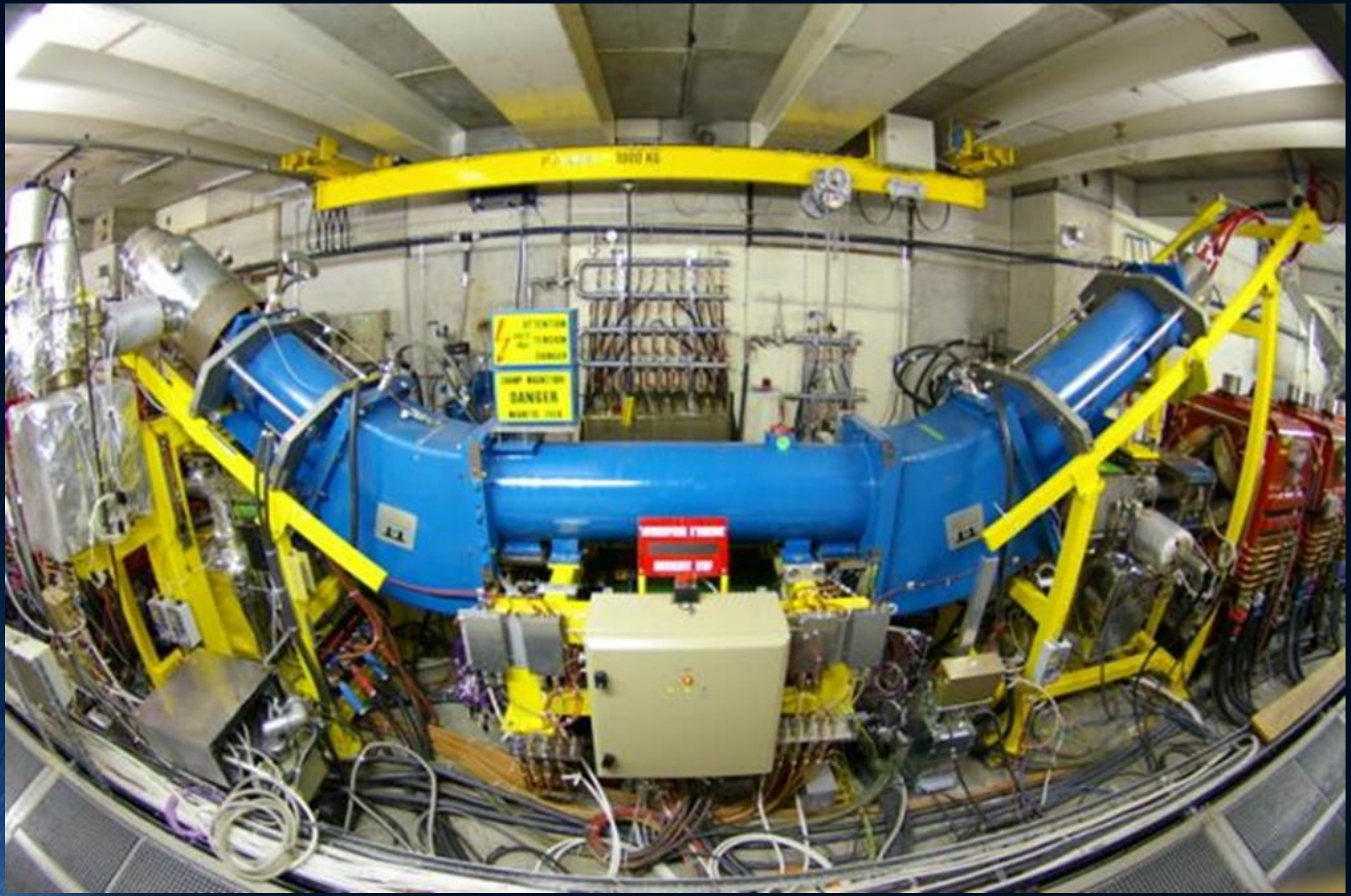
horizontal FWHM [m] 0.010181

Electron coolers at CERN



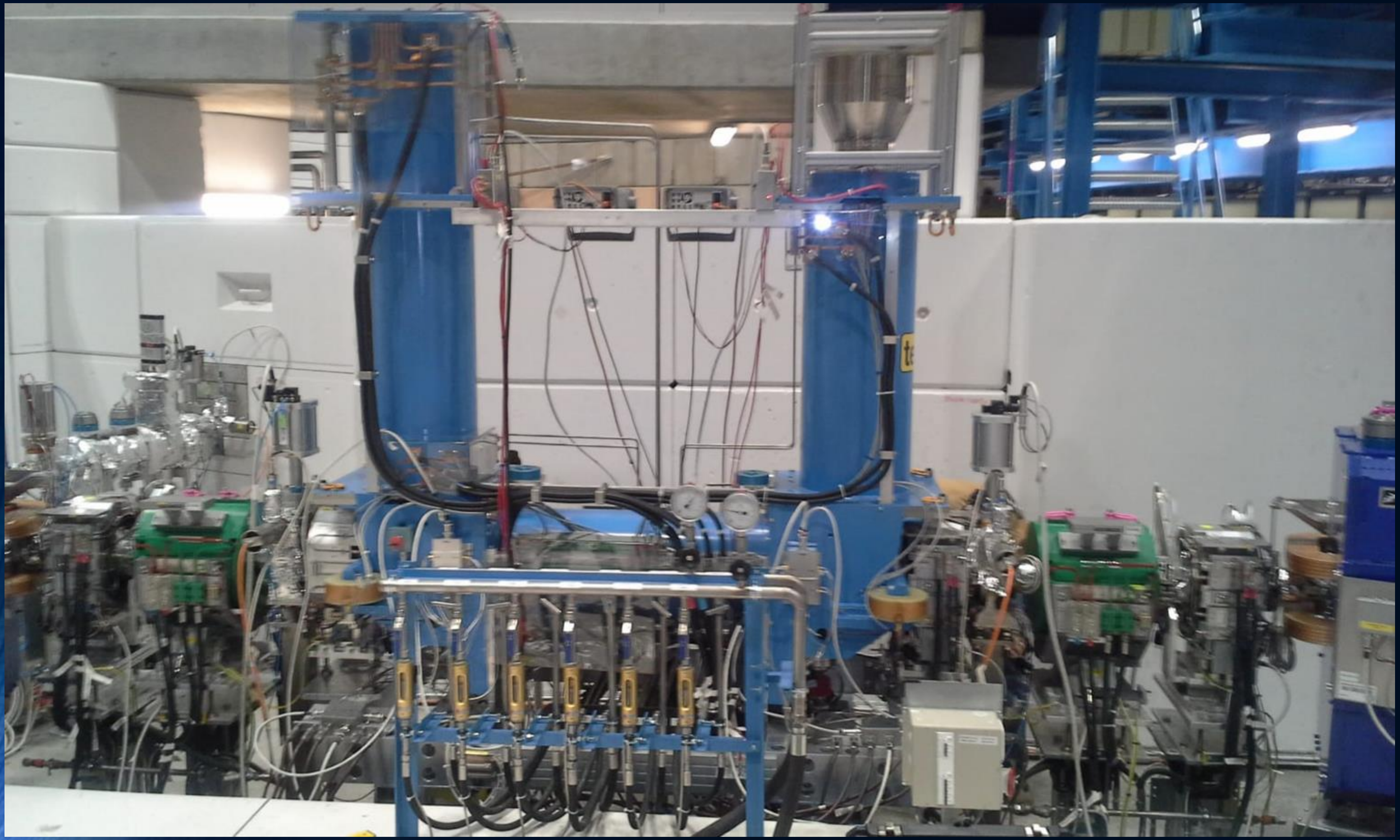
LEIR

E_e up to 6.5 keV
Ie = 600 mA
k = 3, r = 14 to 25mm
B (in cooling section) = 750 G



AD

E_e up to 35 keV
Ie = 2.5 A
B = 600 G
40 years old!



ELENA

Compact cooler
E_e up to 355 eV
Ie = 5m A
k = 10, r = 8 to 25mm
B (in cooling section) = 100 G
Being commissioned