

Recap: Deceleration, cooling and trap injection

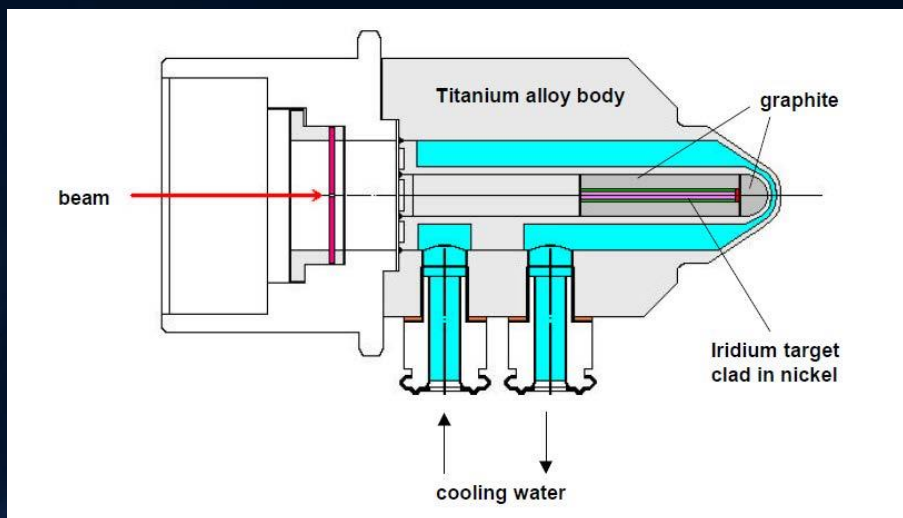
LARS VARMINING JØRGENSEN
CERN
BE-OP-AD

The tricks used to make low-energy antiprotons available to the experiments

- Making antiprotons – the target
- Make them more mono-energetic – bunch rotation
- Stochastic cooling
- Deceleration
- Basic theory of electron cooling
- Electron cooling hardware

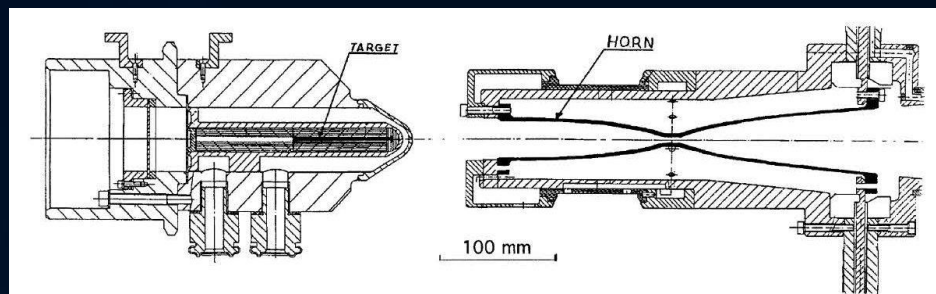
Making antiprotons at the AD

$$p + N \rightarrow N^* + \bar{p} + p + X$$



Ref. :C. Torregrosa, A. Perillo-Marcone, M. Calviani, CERN-ACCC-NOTE-2015-0004

AD target and horn



Facility	Place (Starting year of operation)	Solid target material	Designed for producing	Volume averaged energy density deposition [$J/cm^3/pulse$]	Pulse length [μs]
CERN's AD	CERN (1987)	Iridium	Antiprotons	3400	0.4
CERN's CNGS	CERN (2007)	Graphite	Neutrinos	1900 [27]	10.5
CERN's nToF	CERN (2008)	Lead	Neutrons	8–50	0.01
FNAL's pbar source	Fermilab (1986)	Inconel	Antiprotons	4700 [28]	1.6
FAIR	Darmstadt (2019?)	Ni, Ir or Cu	Antiprotons	N/A	0.05
ESS Lund	Lund (2019)	Tungsten	Neutrons	371 [27]	2860



Target numbers:

Protons:

$\sim 1.5 E13 @ 26 \text{ GeV/c}$

Antiprotons:

$\sim 3 E7 @ 3.57 \text{ GeV/c}$

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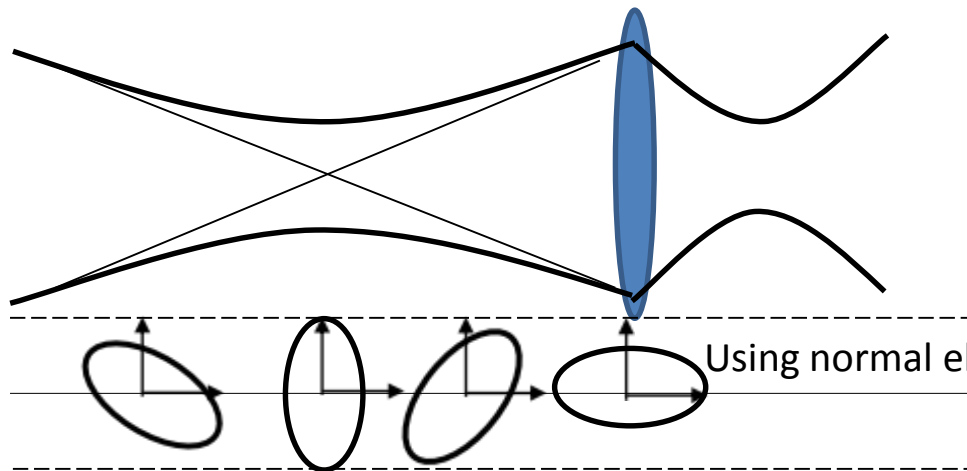
What is emittance?

Liouville's equation.

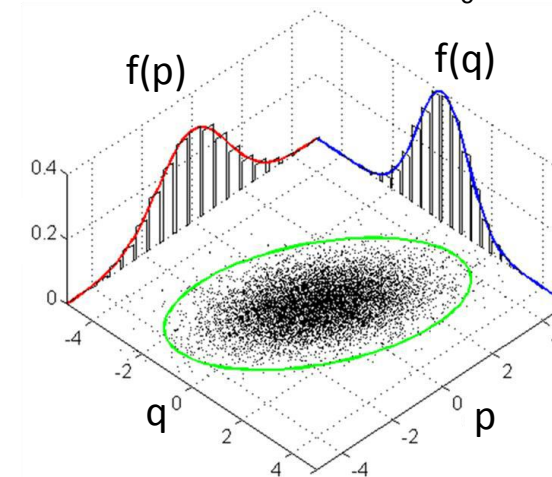
$$\frac{d\rho}{dt} = \frac{\partial \rho}{\partial t} + \sum_{i=0}^n \left(\frac{\partial \rho}{\partial q_i} \dot{q}_i + \frac{\partial \rho}{\partial p_i} \dot{p}_i \right) = 0 \quad \frac{d\rho}{dt} = -\{\rho, H\}$$

Theorem: Emittance can not be changed by lenses

*Emittance only changeable by:
radiation damping, stochastic and electron cooling.*



coordinate q – momentum p
phase space r at t_0

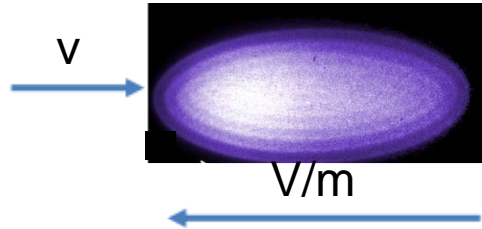


Emittance=Area



Why is stochastic cooling needed?

A simple deceleration of a cloud N of pbars would lead to an increase in phase-space density D [1]



$$D = \frac{N}{\sqrt{E_h E_v} L \Delta p/p}$$

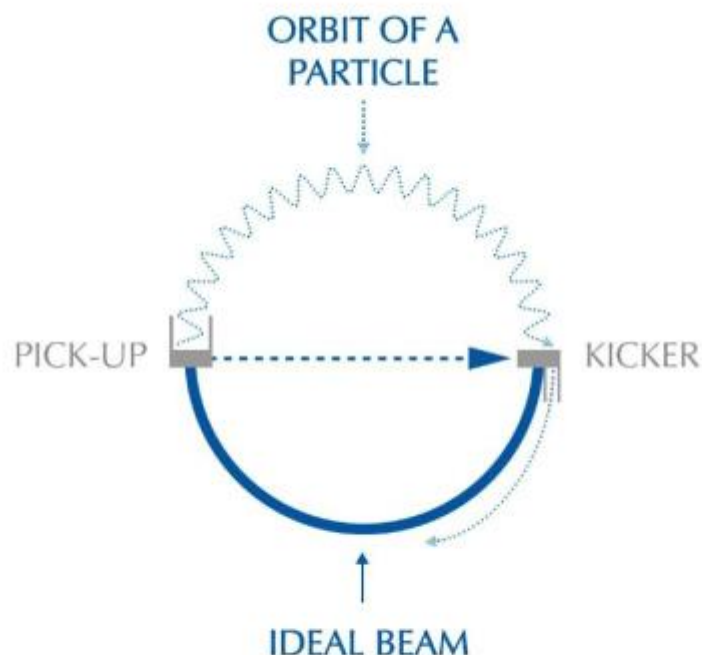
E_h, E_v ... horizontal, vertical emittances
 L ... longitudinal spread
 N ... Number of particles
 $\Delta p/p$... momentum spread

Stochastic cooling



Initially wide spread of momentum and angle emission at pbar production.

As particles travel around, a detector or "pick up" measures their motion and sends a signal across the ring to a corrector, the kicker, which adjusts their angles.



Pick up electrode:

Detect Dp_i and Dx_i of pbars subgroups i , relative to ideal orbiting pbars

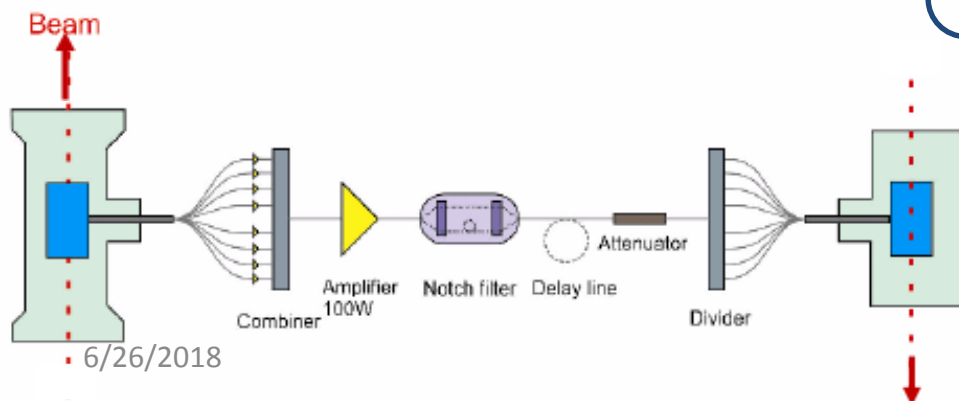
Kicker:

Apply corrective pulses to electrodes

Repeating steps:

$Dp/p \sim 0.07\%$ from initially $\sim 1.5\%$

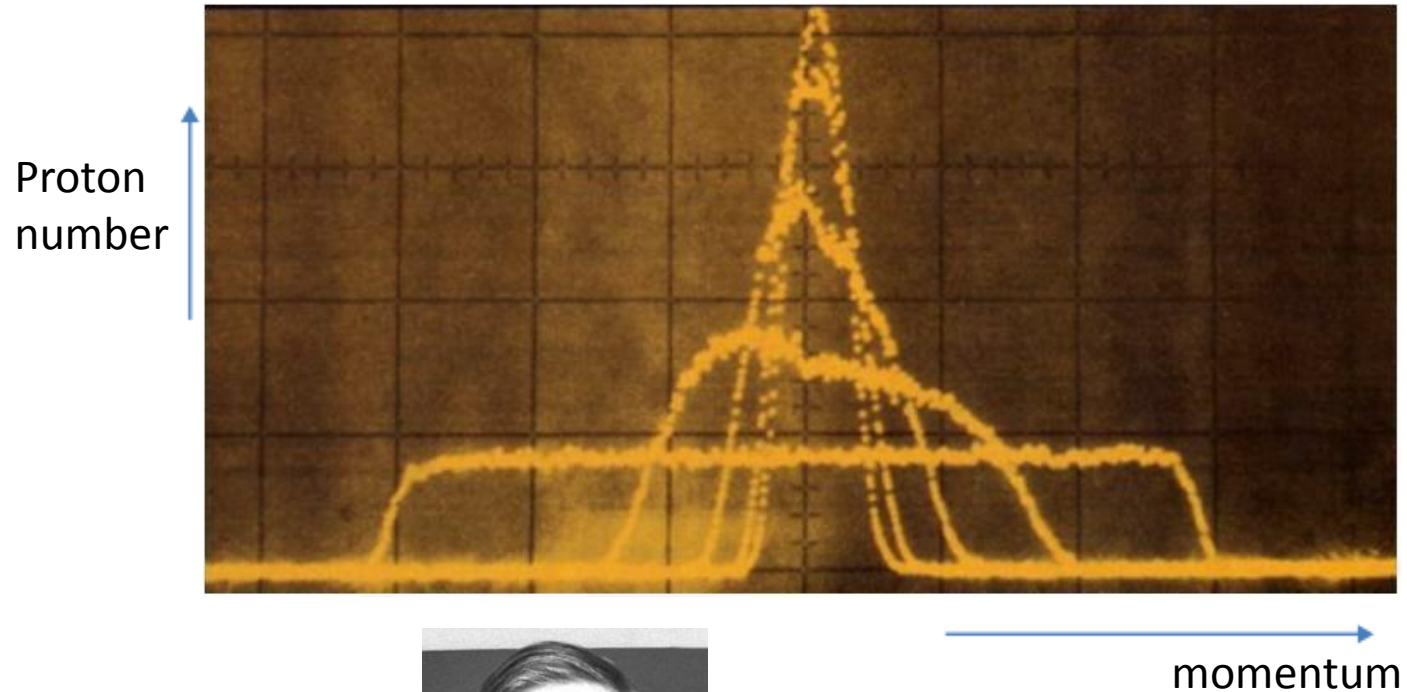
Emittance $\sim 3p$ mm mrad from initially $\sim 200p$



Stochastic cooling



Tested first time 1977 together with electron cooling at CERN in the ICE (initial cooling experiment)



Stochastic cooling
invented at CERN by
Simon van der Meer

Nobel Prize 1984

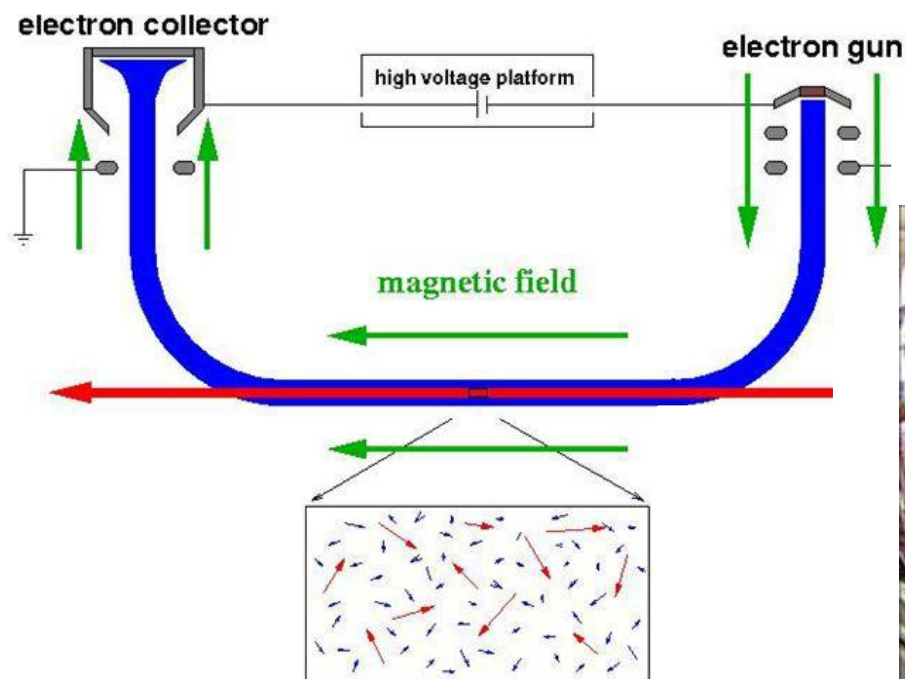


Btw. Stochastic cooling system at AD
completely renovated during LS2

Electron cooling



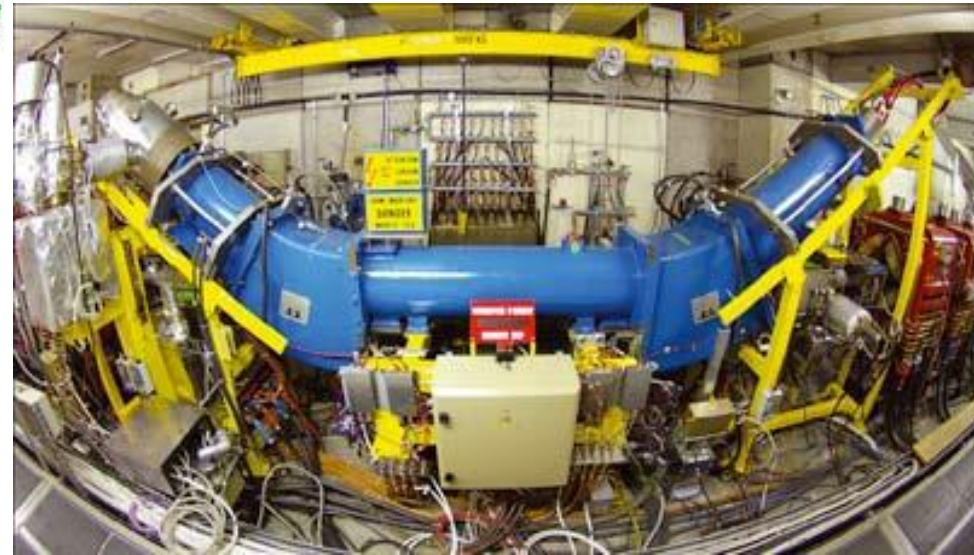
- **Superposition** of cold intense e^- beam with pbars at **same velocity**
- Momentum transfer by Coulomb collisions
- Cooling results from energy loss in co-moving gas of free electrons



In the beam frame:
Cold electrons interact with
hot pbar beam

In the AD:

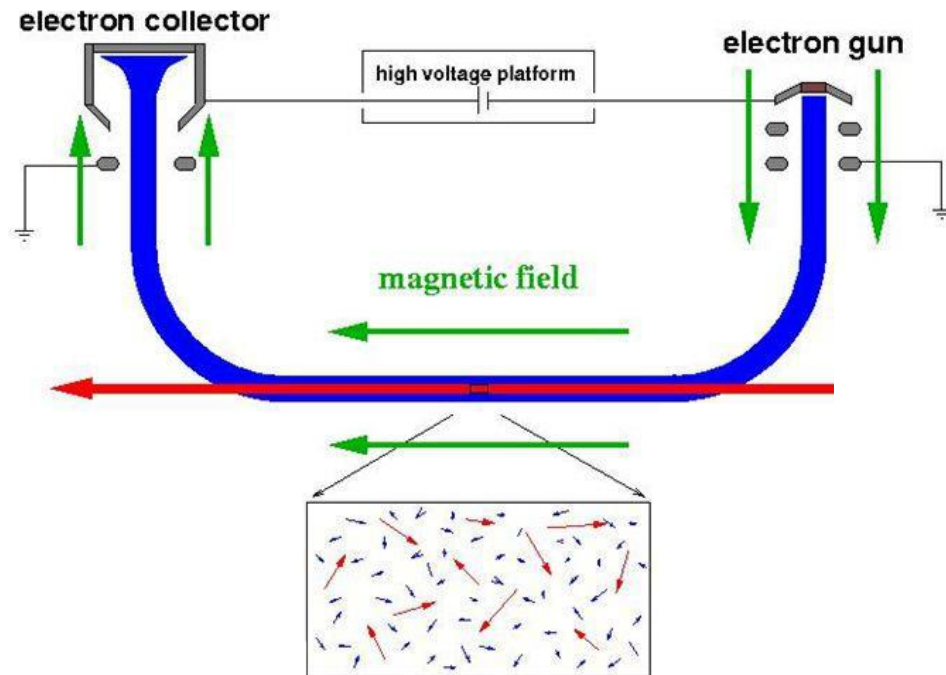
pbar beam merged with \varnothing 50 mm e^- beam of ~ 3 A
collinearly over ~ 2 m



Electron cooling



- **Superposition** of cold intense e^- beam with pbarsat **same velocity**
- Momentum transfer by Coulomb collisions
- Cooling results from energy loss in co-moving gas of free electrons



$$v_e = \beta_e c = \beta_p c = v_p$$

$$E_e = \frac{m_e}{m_p} E_p$$

m_e ...electron mass

m_p ... p mass

E_e ...electron kinetic energy

E_p ... Pbar kinetic energy

e.g. 220 keV **electrons** cool 400 MeV **pbars**

In the beam frame:

Cold electrons interact with

Hot pbars

Antiproton Decelerator (AD)



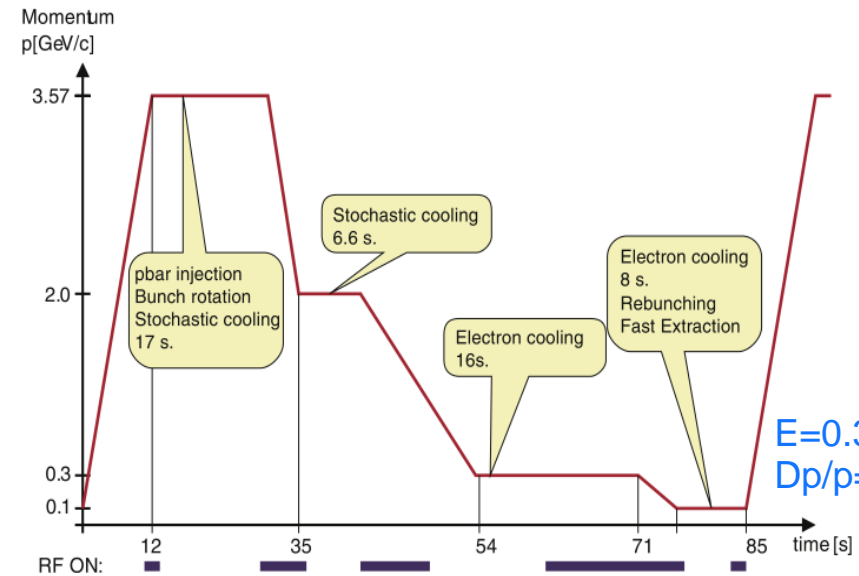
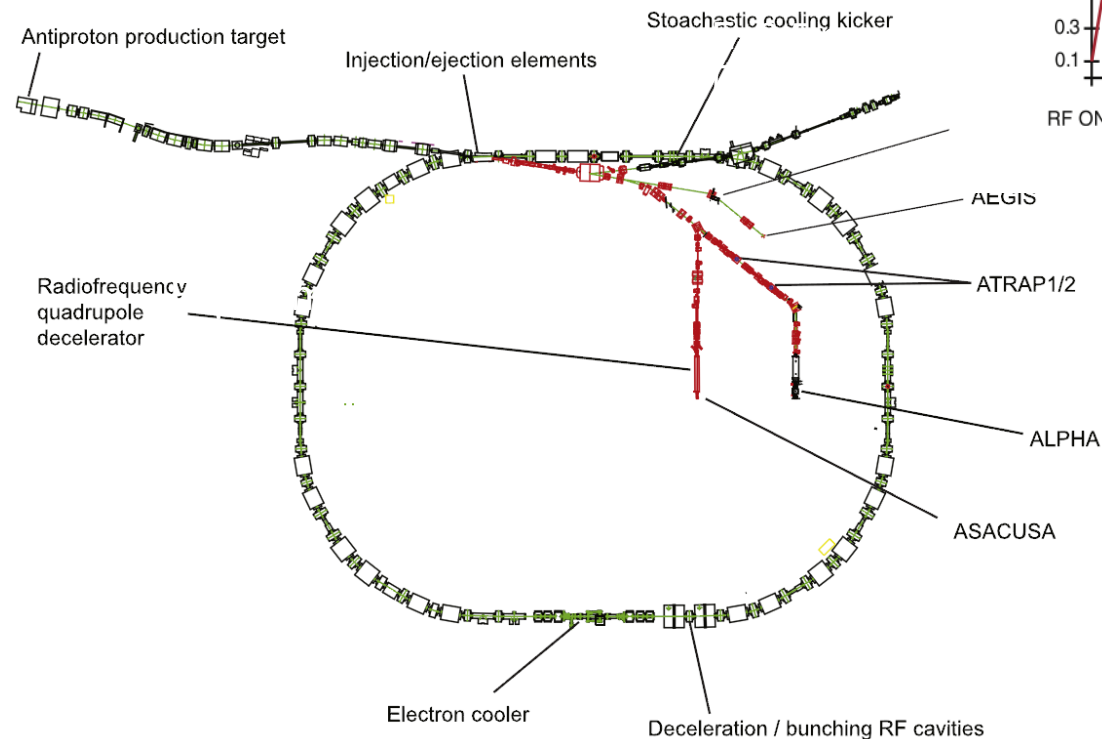
Deceleration is harder than acceleration!

(the other guys at CERN have it too easy ;-)

PS cycle 2.4 sec.

AD cycle ~110 sec

Beam cooling necessary!



$E=0.3$ p mm mrad
 $Dp/p=0.01\%$



AD cooler history:

1970s – ICE

1980 to 1990s – LEAR

2000s AD

AD electron cooler is now more than 40 years old!

AD to get new electron cooler!

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

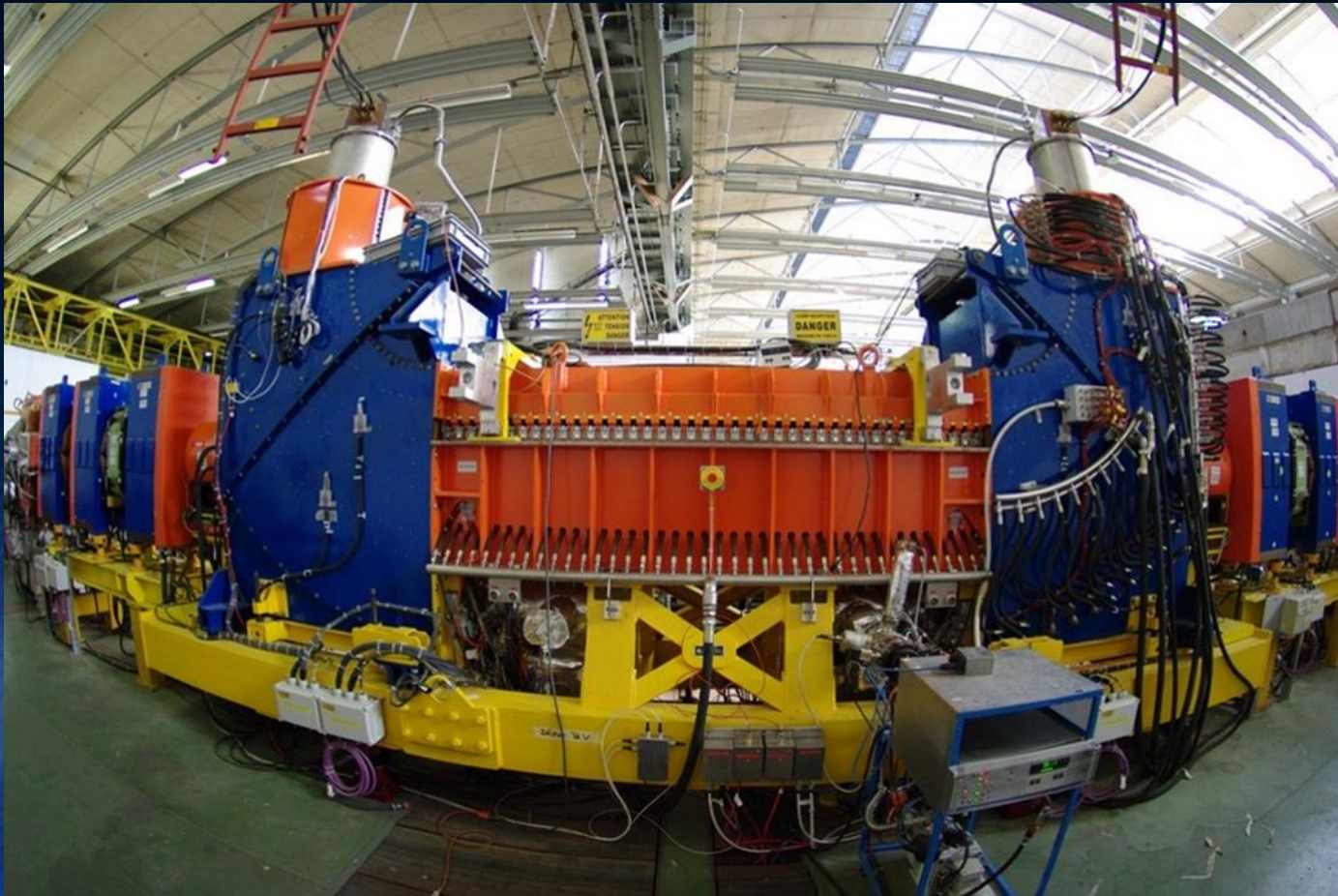
Electron cooling at CERN

- We now have 3 operational electron coolers at CERN

Stochastic cooling

- Stochastic cooling – now only one system at CERN - used at the AD

Electron coolers at CERN



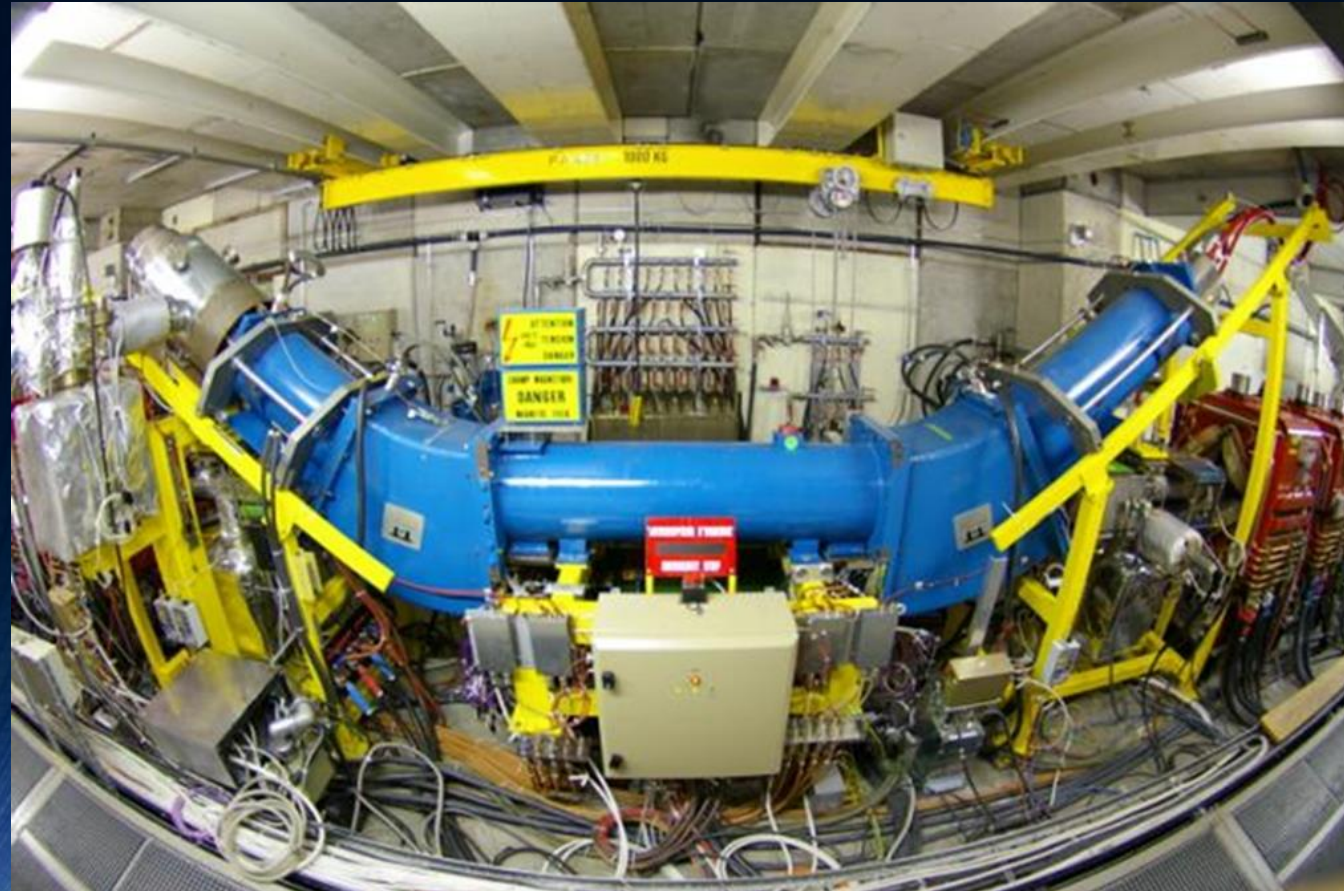
LEIR

E_e up to 6.5 keV

$I_e = 600$ mA

$k = 3$, $r = 14$ to 25mm

B (in cooling section) = 750 G



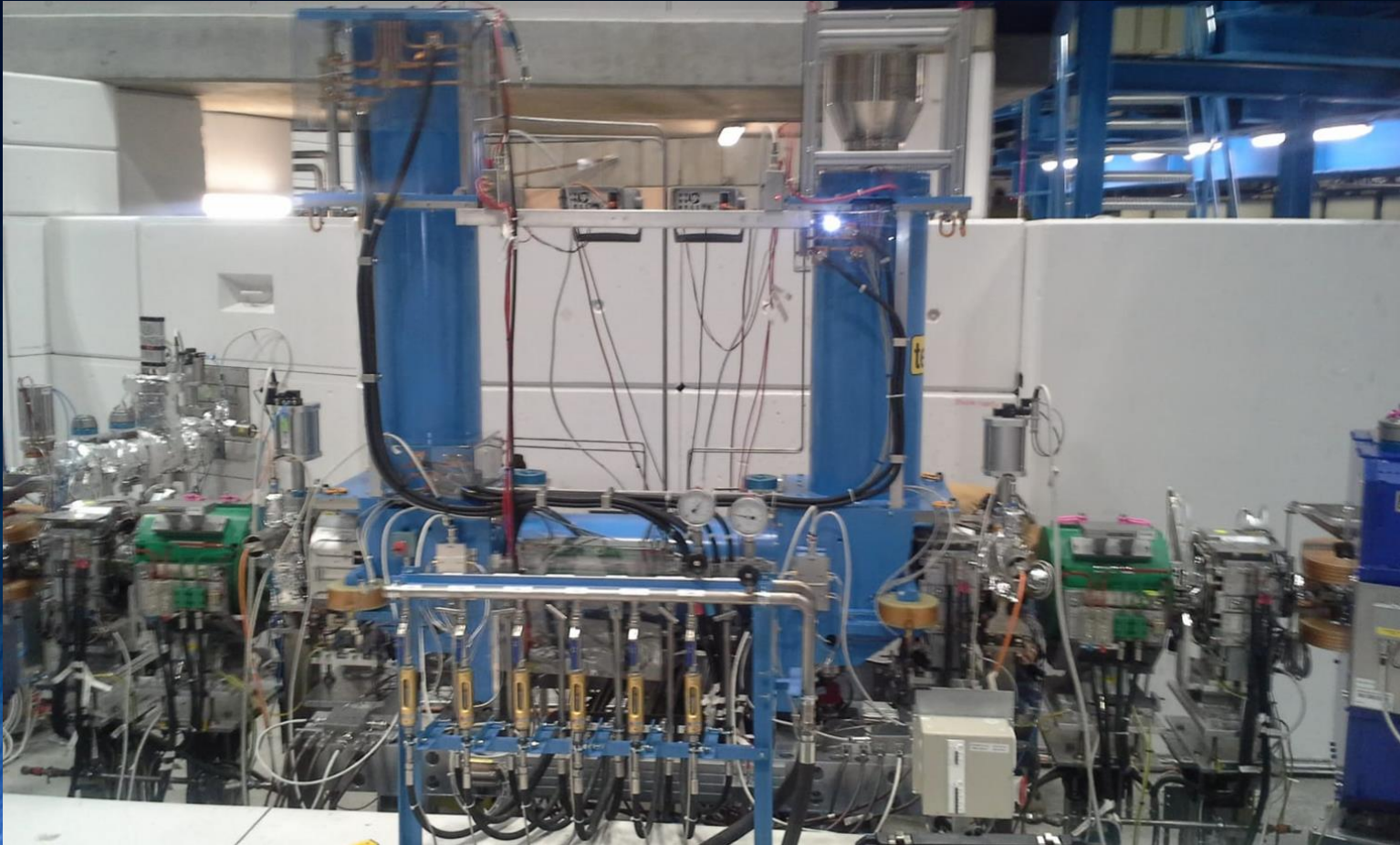
AD

E_e up to 35 keV

$I_e = 2.5$ A

$B = 600$ G

40 years old!



ELENA

Compact cooler

E_e up to 355 eV

$I_e = 5\text{ mA}$

$k = 10$, $r = 8$ to 25 mm

B (in cooling section) = 100 G

Being commissioned

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).

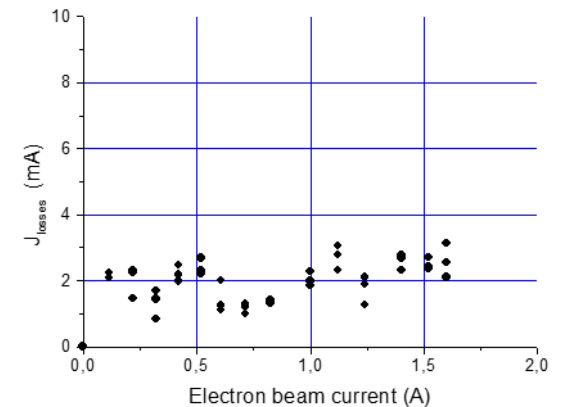
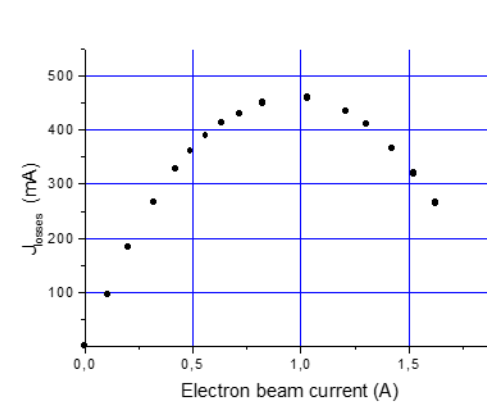
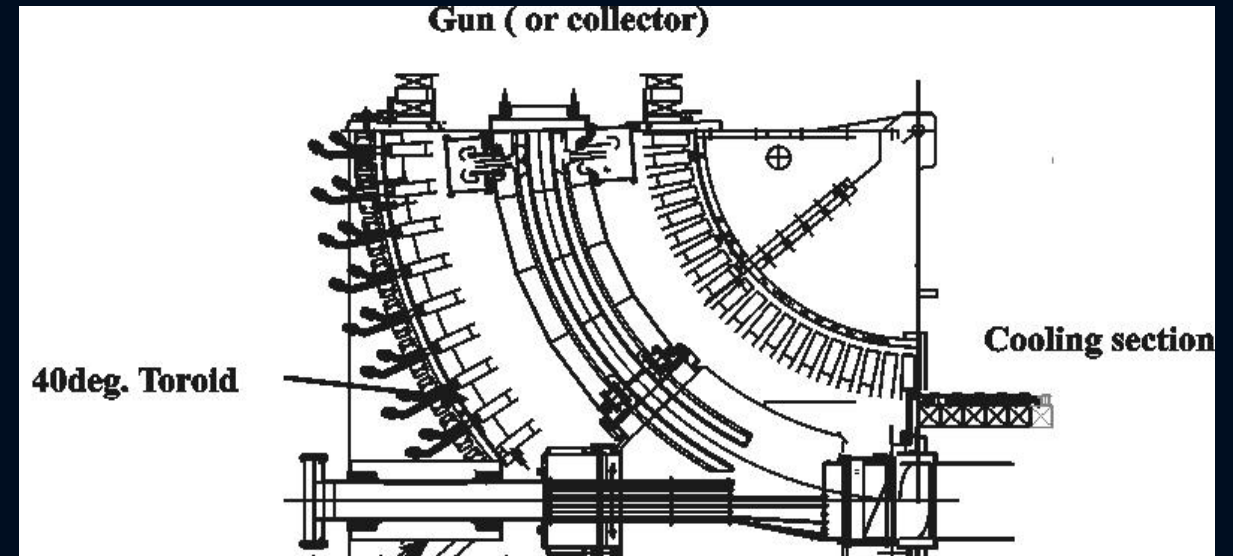
NEG coating of the vacuum chamber for increased pumping.

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.

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

$$B_o = 0.235\text{T}, B = 0.075\text{T}, r_o = 14\text{mm} \Rightarrow r = 24.8\text{mm}$$

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

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

$$B_o = 0.235\text{T}, B = 0.075\text{T}, E_o = 100\text{meV} \Rightarrow E = 32\text{meV}$$

Effects of the cooler on the circulating beam

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

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

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

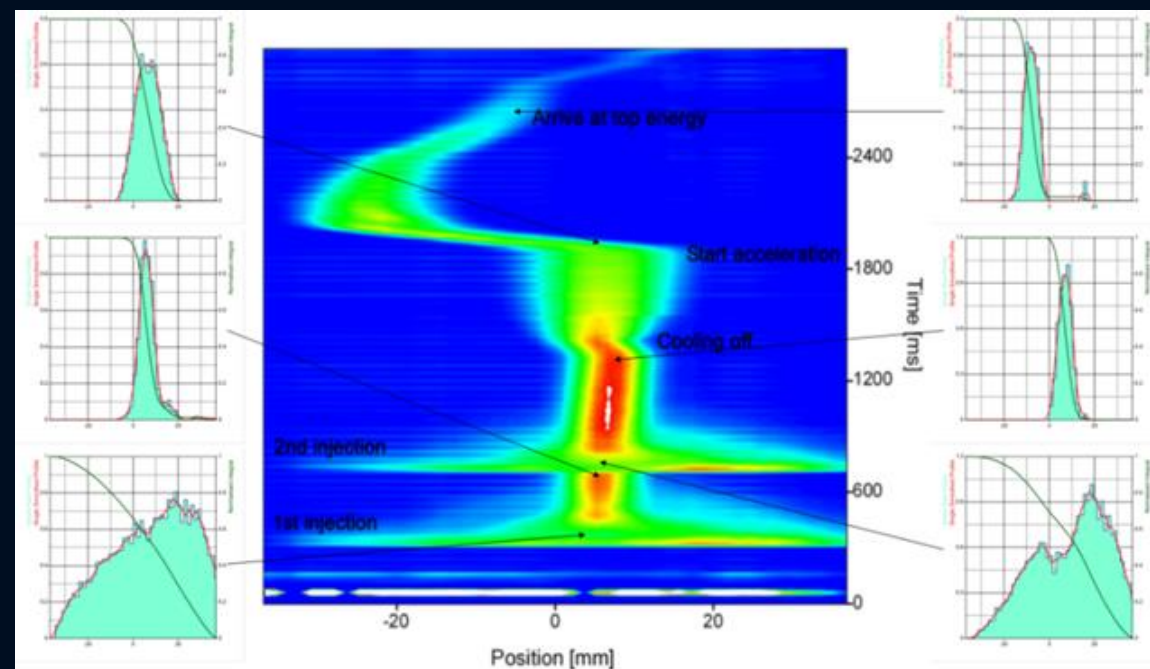
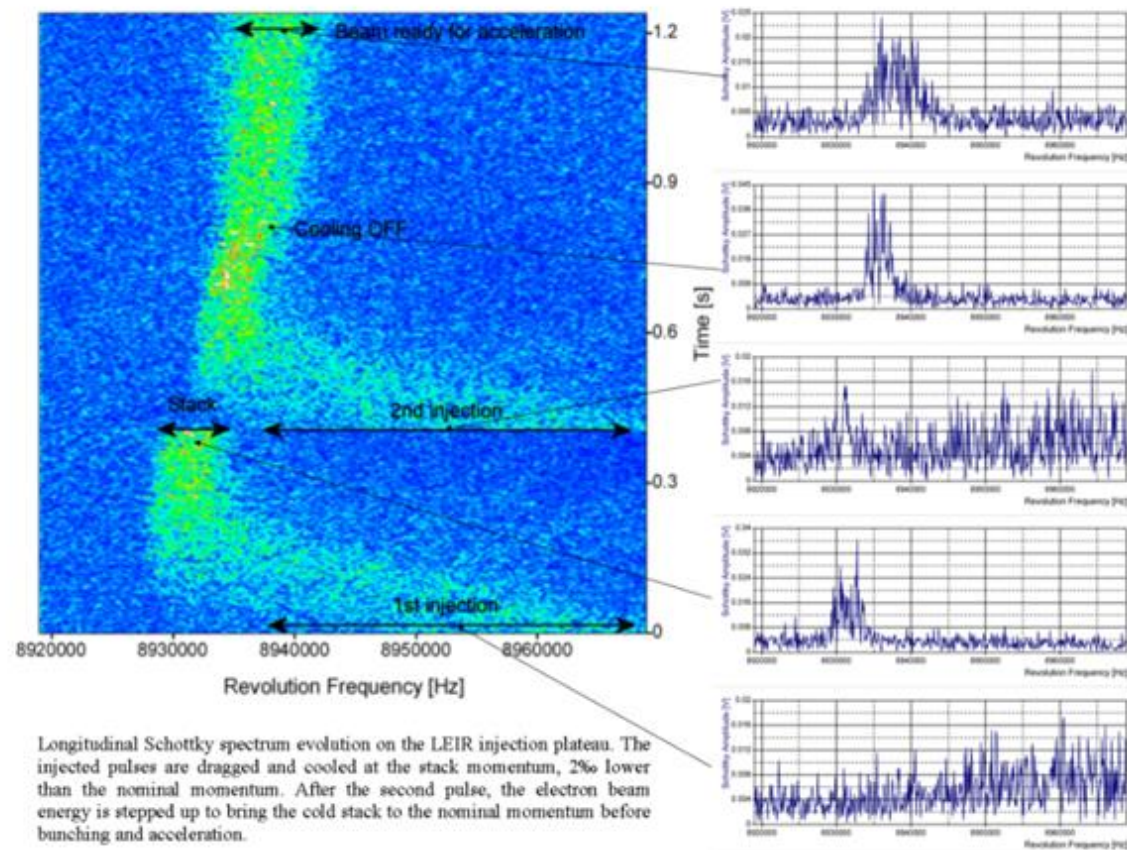
$$\Delta \nu = 0.5 \langle \beta_{h,v}^* \rangle n_e r_p \beta^{-2} \gamma^{-3} L$$

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

$$\vartheta[rad] = \frac{L}{\beta c} \omega_c \frac{m_e}{m_i} \quad \text{Effect is negligible unless working close to a resonance}$$

DIAGNOSTICS ON ION BEAMS FOR ELECTRON COOLING

Diagnostic device	Measured parameter	Comments
Schottky scans	Momentum, momentum spread, beam current, emittance, ring optical parameters	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	



The approximation 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:

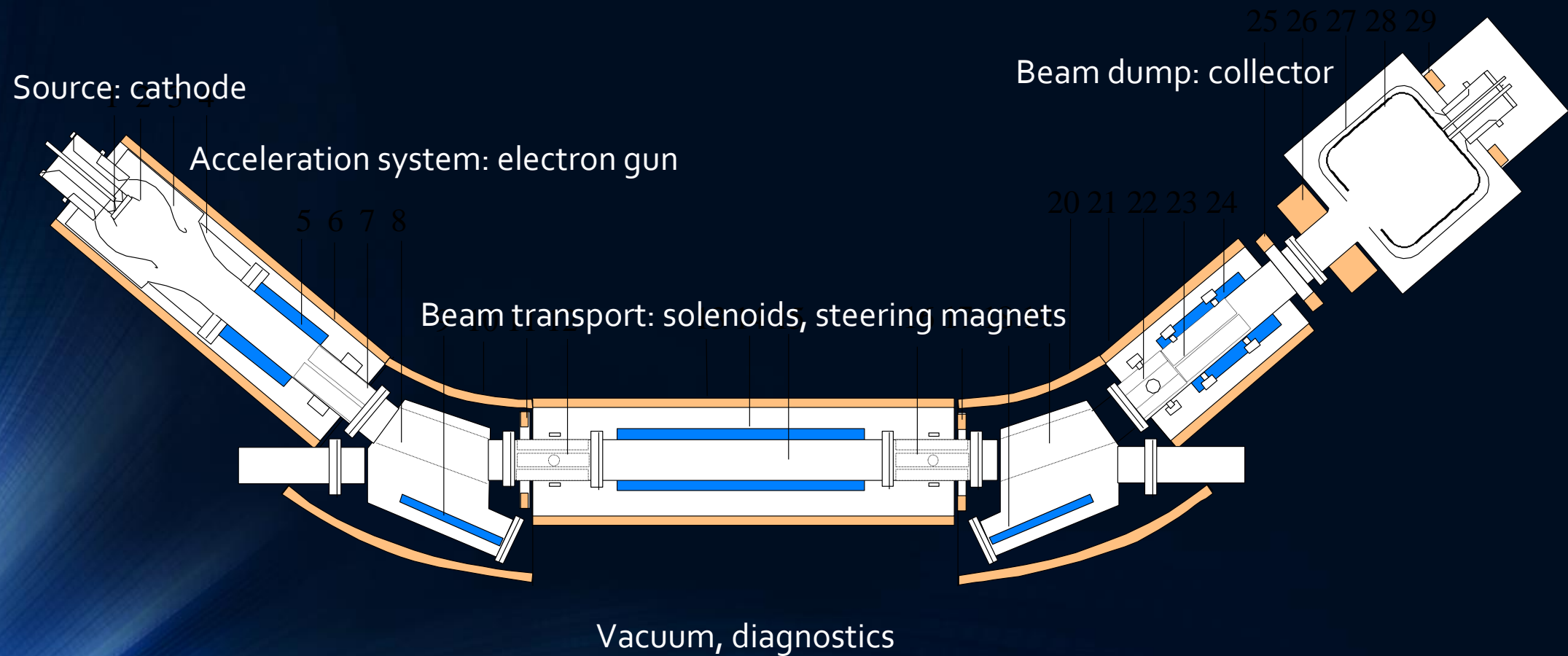
i. Cooling of hot beams

- 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
- $\tau \propto \gamma^2$
- $\tau \propto \frac{1}{r_i Z^2} \propto \frac{A}{Z^2}$
- $\tau \propto \frac{1}{n_e}$

How to build an electron cooler



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: $I = \rho U^{3/2}$

ρ is called the perveance and is essentially determined by the ratio of the beam radius r_0 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.

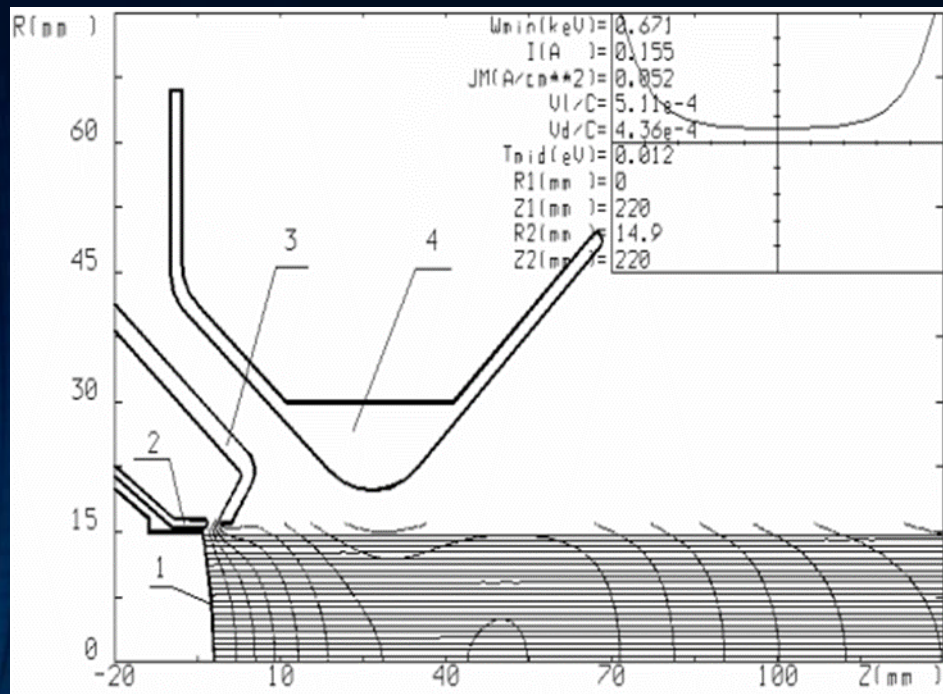
Transverse motion of the electrons are transformed into spirals about the magnetic lines with the cyclotron

frequency

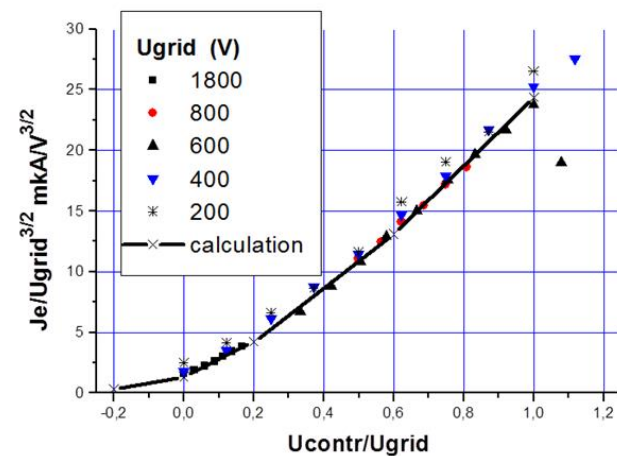
$$\omega_c = \frac{eB}{m_e \gamma c}$$

and radius

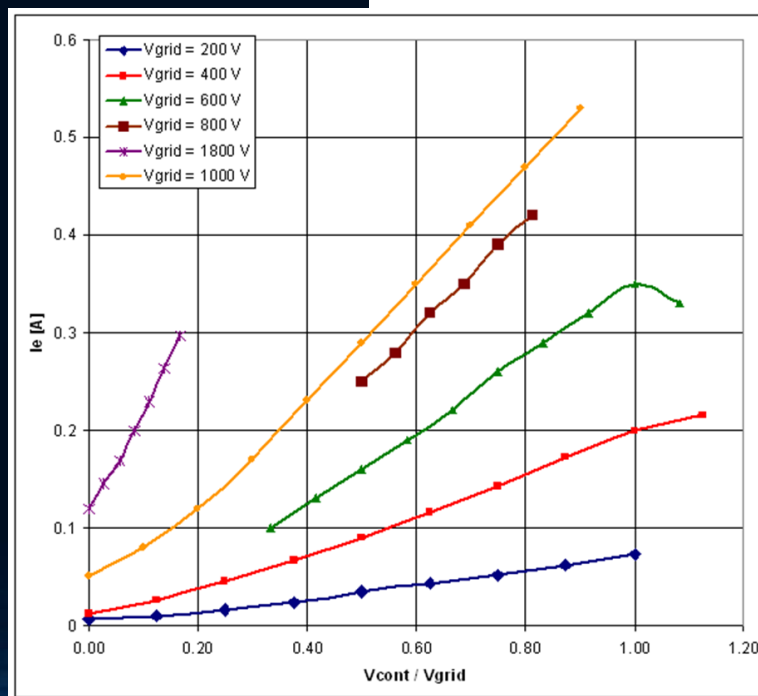
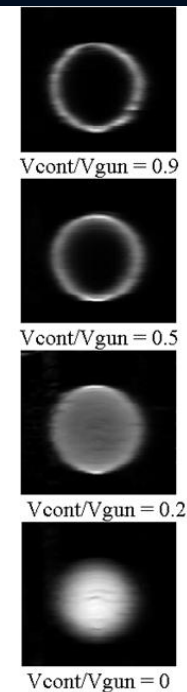
$$r_c = \frac{V_{e\perp}}{\omega_c}$$



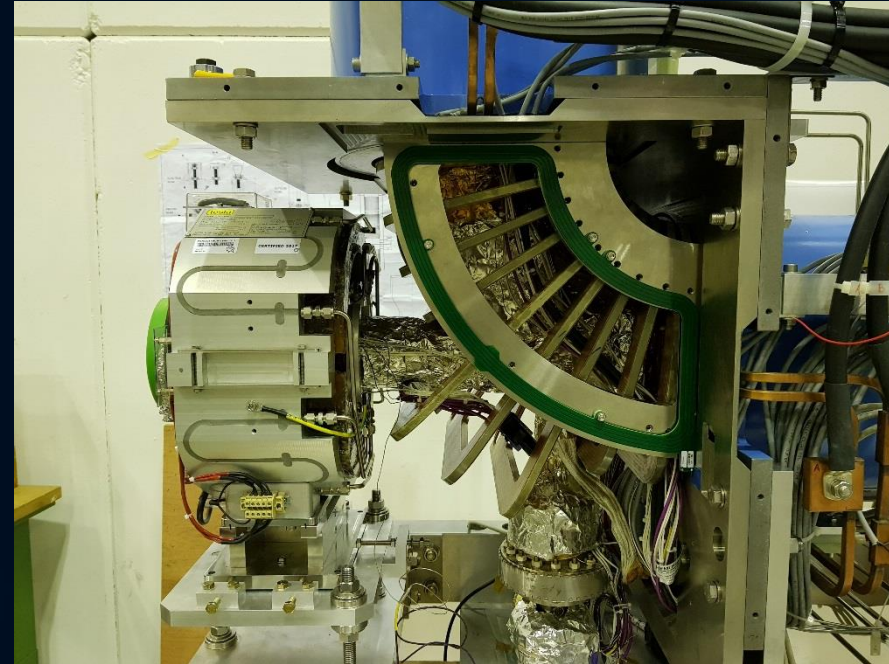
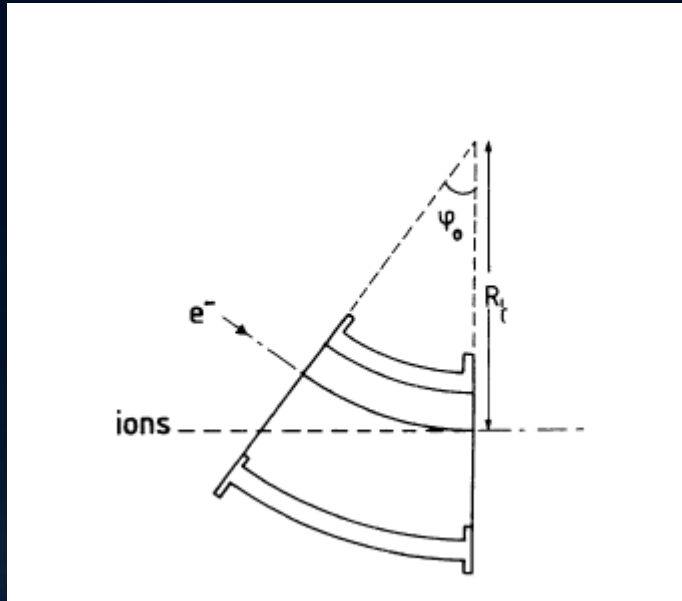
1. 14mm convex cathode
2. Control electrode (modifies density distribution and intensity)
3. Pierce electrode
4. Grid electrode (fixes the intensity)



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



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



