Electron cooling in the CERN accelerator complex

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MSC Seminars 07/03/2024 - indico

Acknowledgements: N. Biancacci, A. Borucka, J. Cenede, A. Frassier, G. Khatri, P. Kruyt, A. Latina, A. Rossi, G. Tranquille, and many more colleagues…

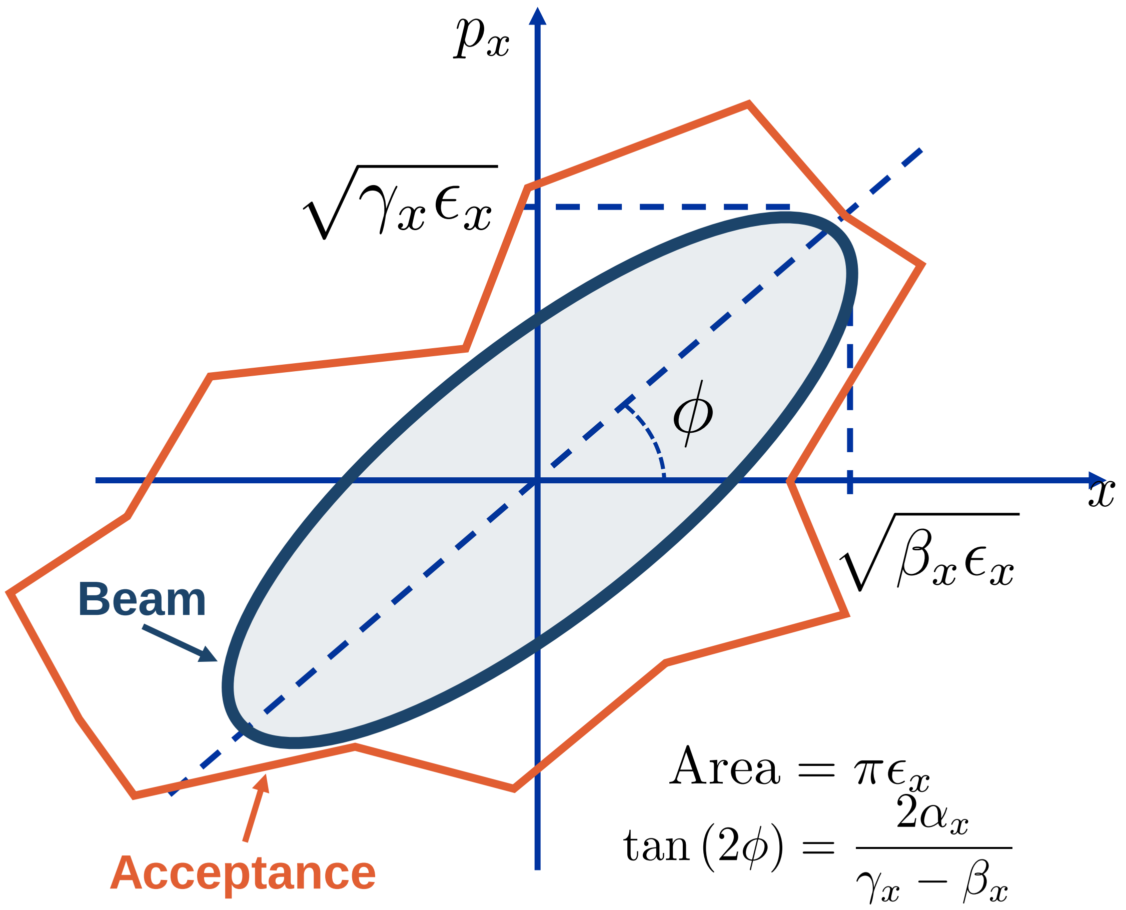
Outline

- **Why cooling?**
- **E-cooling principles**
    - E-cooler hardware implementation and impact on cooling
- **E-coolers at CERN**
    - LEIR
    - AD
    - ELENA

Disclaimer: discussed here **only** the **e-cooler aspects**, not other important effect that affect the circulating beam (e.g. IBS, space charge, impedance …)

Why do we need cooling?

Example: ***transverse phase-space***



- **Beam size** depends on β (depends on the machine optics) and ϵ (property of the beam)

$$\sigma_x = \sqrt{\beta_x \epsilon_x}$$

- In a **collider** we want (to **keep**) **small beam size** to maximise **luminosity:**

$$\mathcal{L} \propto \frac{N_1 N_2 f N_b}{4\pi \sigma_x \sigma_y}$$

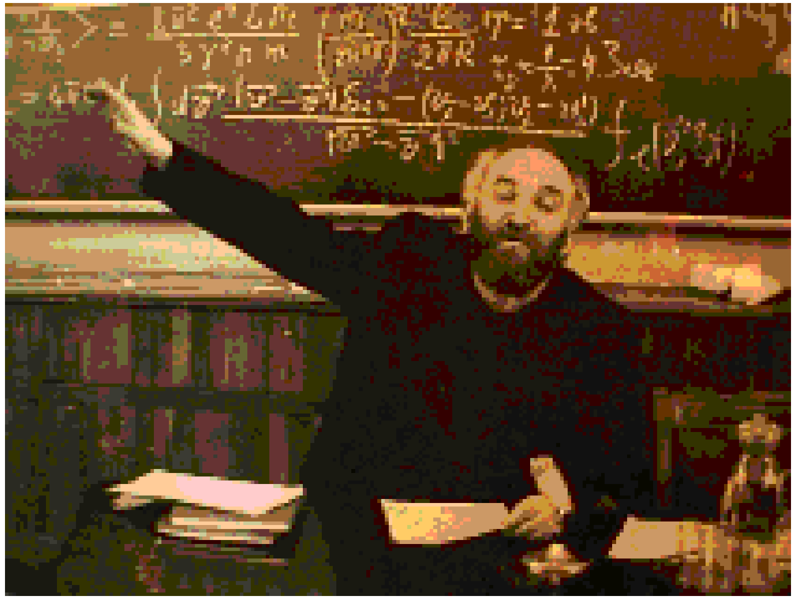
- **Normalised emittance** is constant with energy

$$\epsilon_{x_N} = \beta_{rel} \gamma_{rel} \epsilon_x = \text{const}$$

  - **Good for colliders:** the higher the energy the smaller the beam size
  - **Bad for decelerators**: beam size increases, but the vacuum pipe remains the same ➔ **losses**!

- (+ Need for **counteract heating effects** (e.g. **IBS**,…))
  (+ Allow for **multiple injection/stacking**)

First Idea of Electron Cooling



G.I. Budker is discussing electron cooling

*Electron cooling was **proposed** by **G.I.Budker** in **1965** as a method for preparing of the beams **for hadron colliders**.*

*The **electron beam** moving with the **same average velocity** as proton beam **absorbs** the **kinetic energy of heavy particles** (protons or ions).*

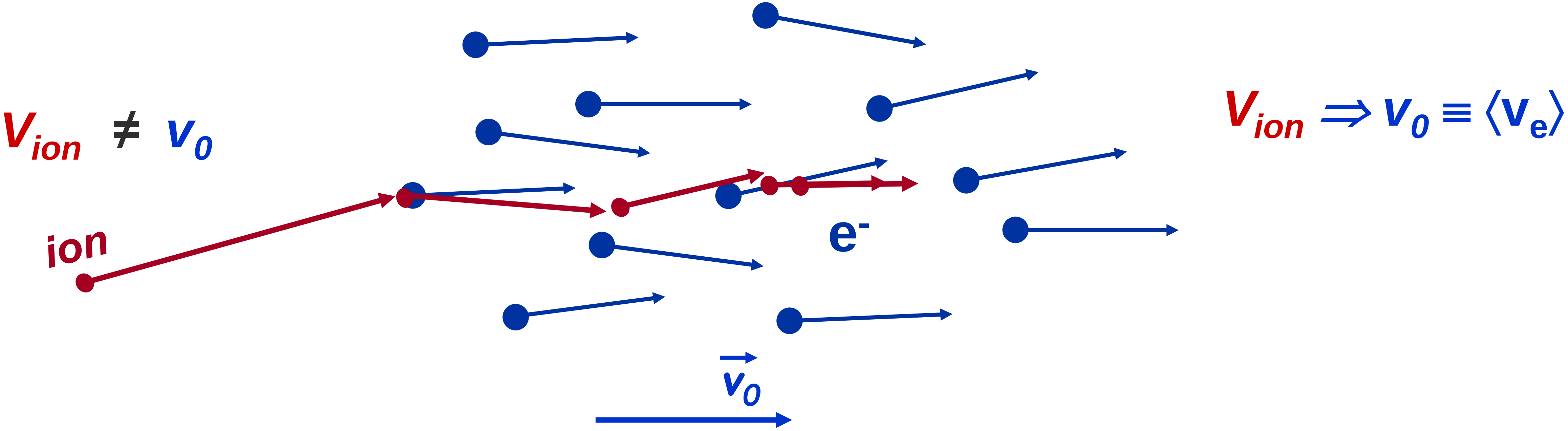
AN EFFECTIVE METHOD OF DAMPING PARTICLE OSCILLATIONS IN PROTON AND ANTIPROTON STORAGE RINGS

A method is proposed for the damping of synchrotron and betatron oscillations of heavy particles, which makes use of the sharp increase in the cross section for the interaction of these particles with electrons at small relative velocity. It is shown that it is possible by this method to compress strongly the proton and antiproton bunches in storage rings, and also to achieve multiple storage of these particles.

Budker, G. I. (1967), *Soviet Atomic Energy* **22** (5): 438–440

Electron Cooling Cartoon

Simple analogy (by I. Meshkov)**:** a **bullet** ("ion") **shot** at a **heap of sand** ("electrons"!) flying with average velocity v_0 :



"Cooling": Talking about Temperatures

Cooling can be represented as a "**hot ion gas**" cooled by a "**cold electron gas**":

$$\frac{1}{2}k_B T_i = \frac{1}{2}m_i v_i^2$$

$$\frac{1}{2}k_B T_e = \frac{1}{2}m_e v_e^2$$

$$T_i \rightarrow T_e \qquad v_i \rightarrow v_e\sqrt{\frac{m_e}{m_i}}$$

The **ion beam temperatures** are connected to terms like **emittance** and **momentum spread**:

Longitudinal

$$\frac{1}{2}k_B T_{\parallel} = \frac{1}{2}mv_{\parallel}^2 = \frac{1}{2}mc^2\beta^2(\frac{\delta p_{\parallel}}{p})^2$$

Transverse

$$\frac{1}{2}k_B T_{\perp} = \frac{1}{2}mv_{\perp}^2 = \frac{1}{2}mc^2\beta^2\gamma^2\theta_{\perp}^2 \qquad \theta_{\perp} \approx \sqrt{\frac{\epsilon}{\beta_{\perp}(s)}}$$

while **electron beam temperature** are primarily given by the e-gun **cathode temperature.**

Note: "k_B" is Boltzmann constant; "v" is meant the r.m.s. 1D velocity spread; ϵ is the ion beam emittance and β(s) its Twiss function

More Formal: Modelling of the Cooling Force

1. **Binary collision model**
   description of the cooling process by successive collisions of two particles and integration over all interactions

2. **Dielectric model**
   interaction of the ion with a continuous electron plasma

3. **Empiric formula** derived from experiments by **V. Parkhomchuk:**

$$\vec{F} = -\frac{n_e q^2 e^4}{4\pi^2 \epsilon_0^2 m_e} \cdot \frac{d\vec{V}}{(dV^2 + \Delta_{\parallel}^2 + \Delta_{\text{magnet}}^2)^{3/2}} \ln\left(\frac{\rho_{\max} + \rho_{\min} + \rho_{\text{L}}}{\rho_{\min} + \rho_{\text{L}}}\right)$$

Electron beam density

“effective e⁻ temperature”

Log of “impact parameters”:

- **Depends on B field, e- temperatures, …**
- **Typically, ≈ 10**

Cooling Time (in lab reference frame)

Carries complexity of defining a model and **depends** on the **regime** of the **interaction**.
Generally, **it follows** the **following proportionality**:

$$\tau \propto \frac{A}{Z^2} \frac{1}{\eta_c} \frac{1}{I_e} \gamma^5 \beta^4 \Theta_i^3$$

Faster for highly charged ions

Inversely proportional to electron beam current (I_e) and cooler/circumference length ratio (η_C)

Quickly increases with beam energy!

Strongly depends on ions temperature: very slow for “hot beams”

Note: independent of ion beam intensity

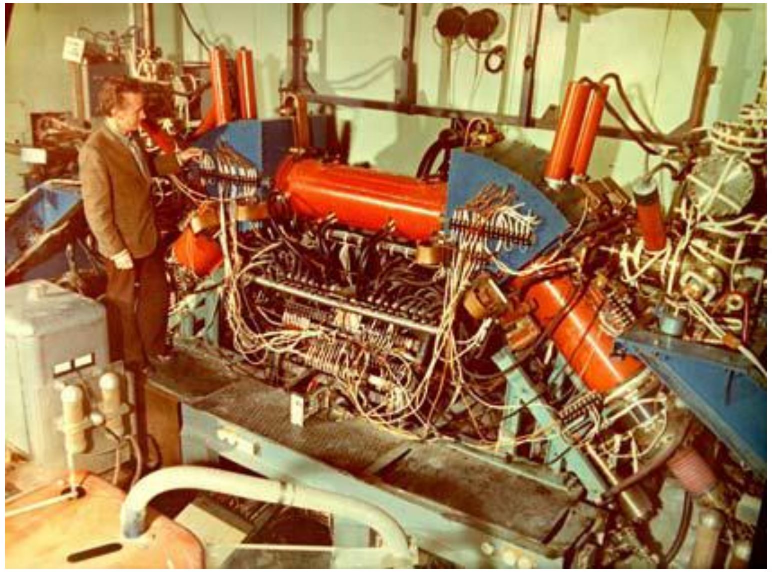
Electron Cooling Implementation in an Accelerator

- **Circulating ion beam is** (typically) **de-bunched (coasting beam)** during the cooling process
- The **circulating ion beam** and an **intense electron beam** share the **same orbit** on a **fraction** of a **circular accelerator**
  - The **electron beam** is **guided** in/out to/from the ions **by** a **longitudinal magnetic field** (besides from the electron beam transport, the magnetic field leads to enhanced cooling)
- **The average velocities** of ion and electron beams are **set** (nearly) **equal**
- **Each electron** interacts with ions only once (**single pass**), i.e. **ions stored** in the ring **keep interacting** with "**fresh**" **electrons**
- The **process** is **repeated long enough** to reach a "**temperature equilibrium**"

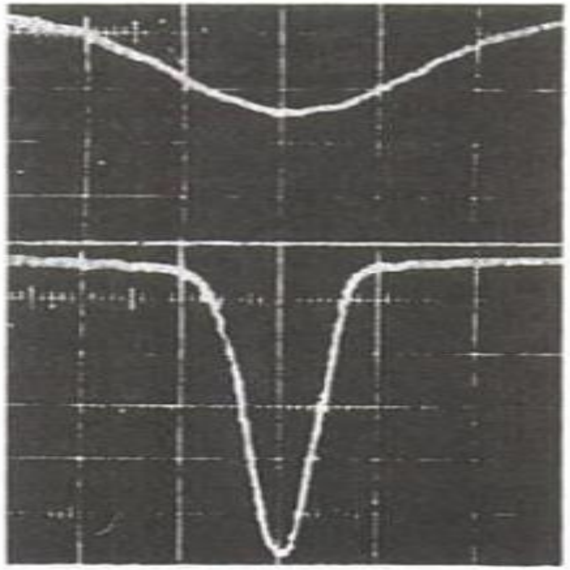
First Experimental Demonstration at NAP-M

The first experiments carried out in Novosibirsk in 1974 demonstrated the high efficiency of this method and triggered the development of heavy particle cooling methods.
The first electron cooler had a cooling length of 1 m.

Electron cooling pioneers in Novosibirsk. Left to right: V Parkhomchuk, A Skrinsky, I Meshkov, N Dikansky.



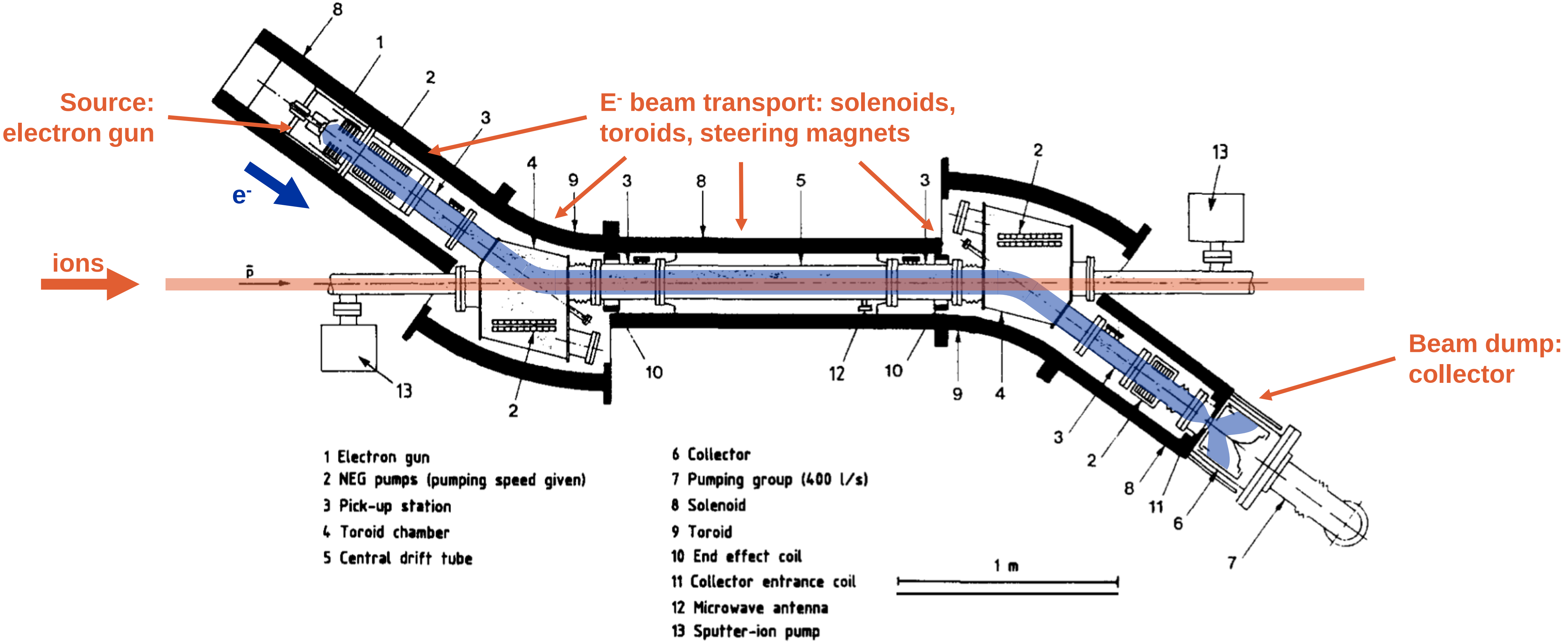
First electron cooler in NAP-M ring



Vertical beam profile at NAP-M without and with electron cooling

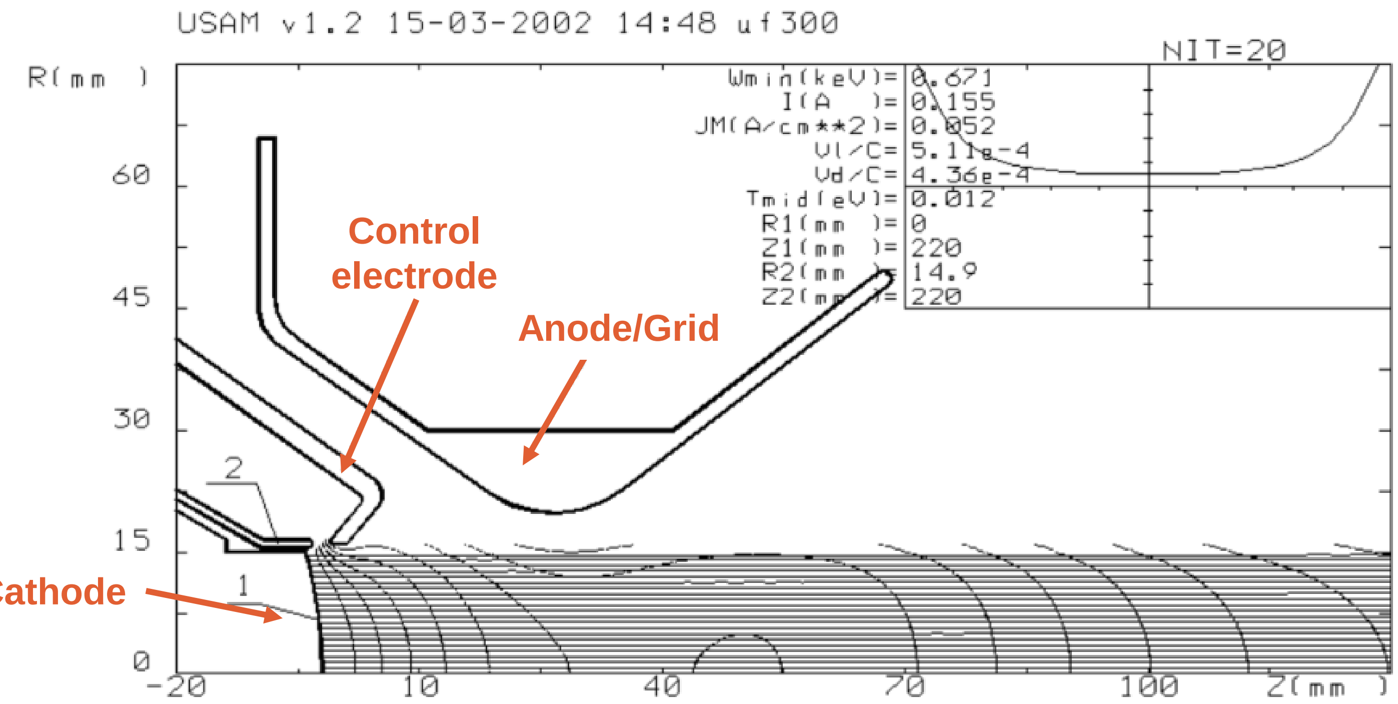
How to Realise Electron Cooling in Practice

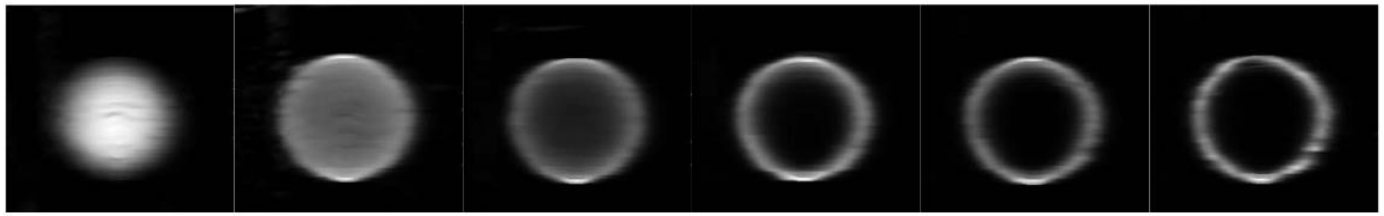
A **guiding magnetic field** carries a DC electron beam from a **cathode** into the ion beam and then to a **collector.**



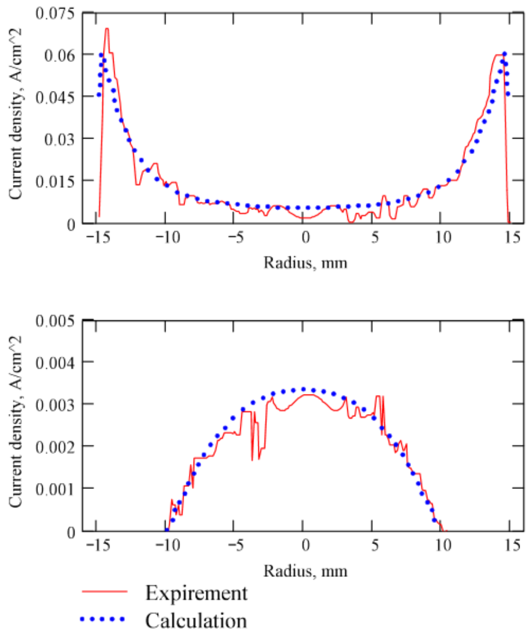
The LEAR (now ~AD) e-cooler, CERN-EP/90-04

Optimized Electron Gun





Electron beam profiles at control electrode potential Uc = 0V, +100V, +200V, +350V, +400V, +600V and anode potential Ua=500V



Calculated and measured beam profiles at control electrode potential UC = +300V, -100V and anode potential UA=500V.

$$\frac{V_{control}}{V_{grid}} \begin{cases} \approx 0.9 \Rightarrow \text{hollow distribution} \\ \approx 0.5 \Rightarrow \text{partially hollow distribution} \\ \approx 0.2 \Rightarrow \text{flat distribution} \\ \approx 0 \Rightarrow \text{parabolic distribution} \end{cases}$$

LEIR-like electron gun, from A. Bubley et al. Proceedings of EPAC 2002

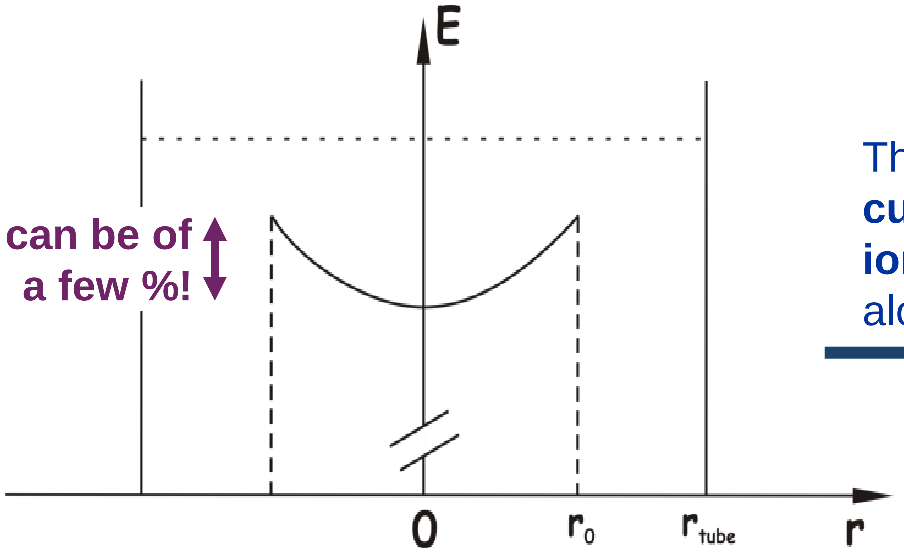
Other Properties of Generated Electron Beam:
Electron velocities

The **longitudinal energy** a of the **electron** beam **is not constant** along its radius (*r*), but it typically **follows the relation**:

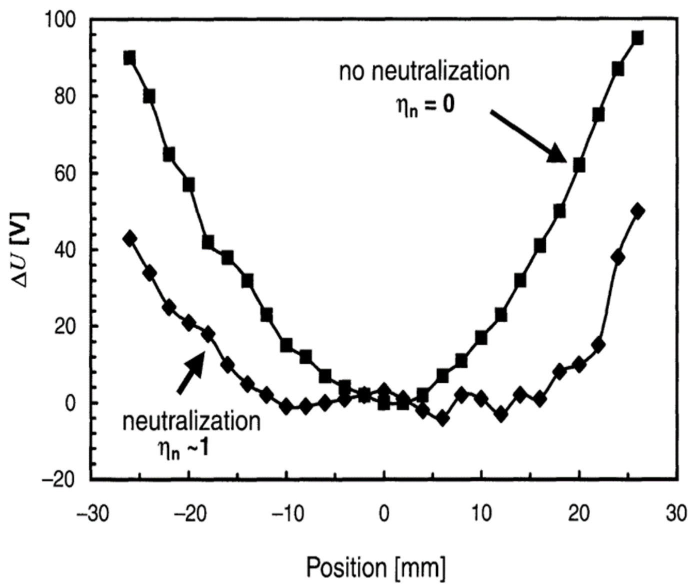
$$\frac{\Delta E(r)}{E_0} \approx 1.2 \times 10^{-4} \frac{I_{\text{e-beam}}[\text{A}]}{\beta^3} \left(\frac{r}{r_0}\right)^2$$

where E_0 is the energy in the center of the beam and r_0 is the beam radius.

It can be of a few %!



This effect can be **partially cured** by **trapping positive ions** in the electron beam along the interaction region!



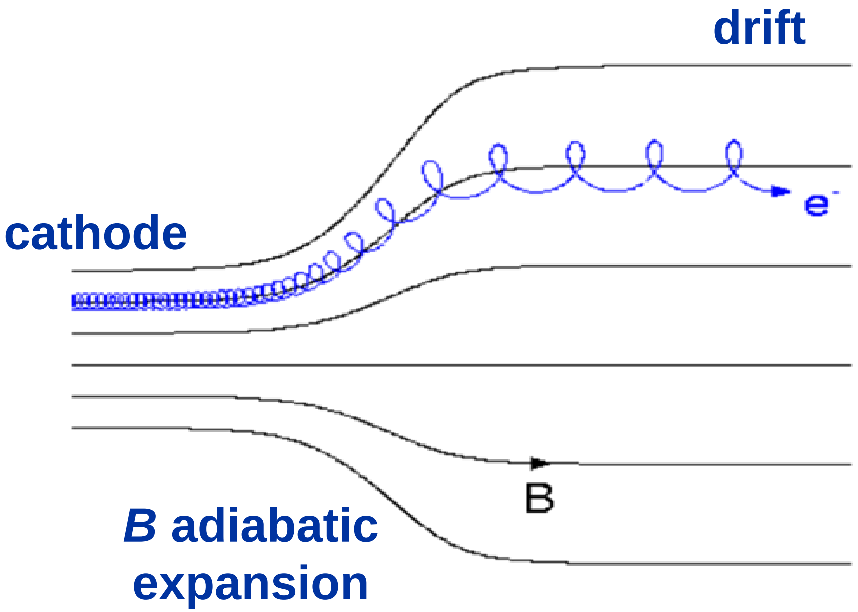
Details on CERN-EP/90-04

(details not discussed here. See CERN-EP/90-04)

Other Properties of Generated Electron Beam:
Electron transverse temperature

The **electron gun** and the **whole cooler** is **immersed** in a **magnetic field** to compensate for space charge forces and to guide the beam.

If one sets a **stronger** magnetic field **in the gun than in the e-/ion interaction region**, then:



1. **Wider electron beam** (**but lower e$^-$ density**)

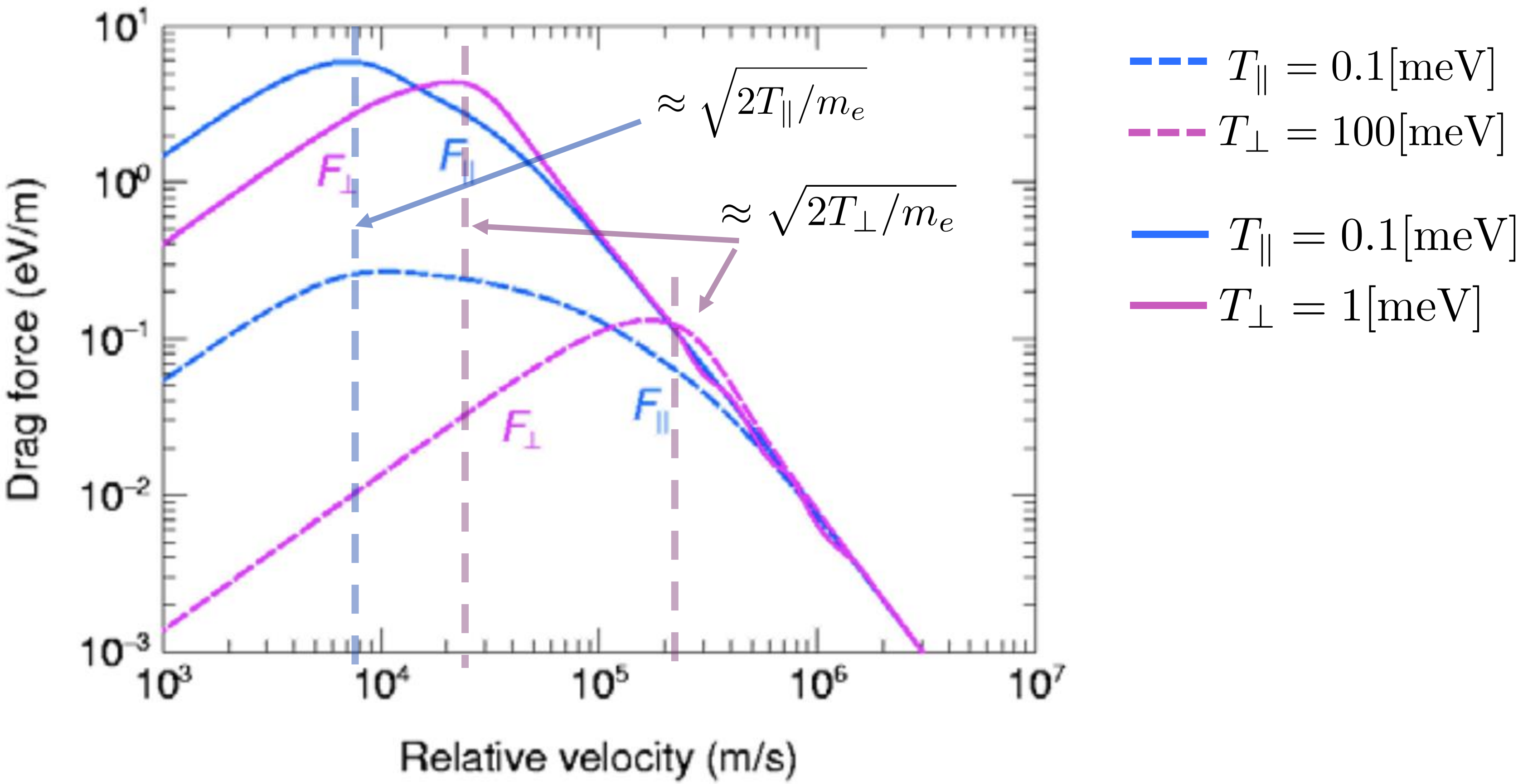
$$Br^2 = const \quad \Rightarrow \quad r_{\text{drift}} \approx r_{\text{cath}} \sqrt{\frac{B_{\text{cath}}}{B_{\text{drift}}}}$$

2. Proportional **reduction** of **transverse temperature** (e.g. up to a factor ~10 in ELENA)

$$k_B T_\perp \approx k_B T_{\text{cath}} \frac{B_{\text{drift}}}{B_{\text{cath}}}$$

Importance of e⁻ temperatures

Stronger force for "low-relative velocity difference" => obtaining smaller beams, faster

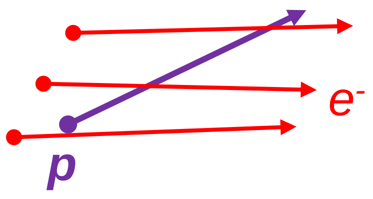


From on CAS2005 proceedings

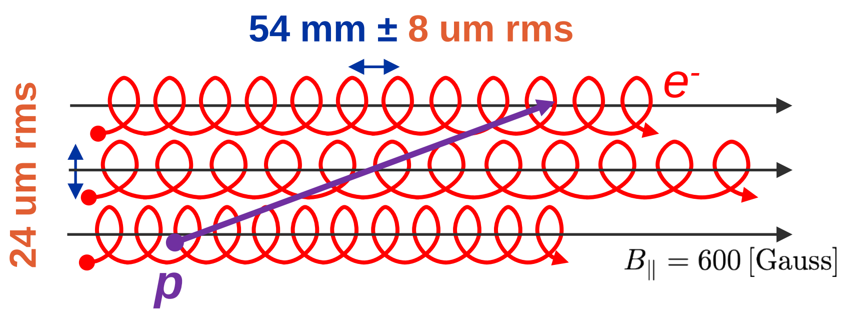
Other Properties of Generated Electron Beam:
Magnetised cooling and field quality

- E-cooling is based on **Coulomb interaction between ions and e$^-$**
- **Greatly enhanced** if several interactions along overlapping region: **magnetized cooling!**
  - Magnetized cooling quickly "**destroyed" by imperfections**!
  - General condition on **magnetic field quality:** $c\gamma\beta B_\perp / B_\parallel \ll \sqrt{\frac{k_B T_{e\parallel}}{m_e}} < \sqrt{\frac{k_B T_{e\perp}}{m_e}}$

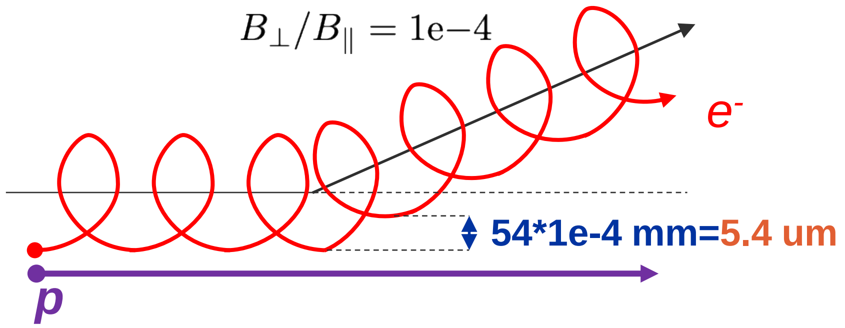
Un-magnetised cooling:
Single interactions per e-



Magnetised cooling:
multiple interactions per e-



e.g.: effect of magnetic field imperfection:
Premature loss of sync. condition…



Here simplified cartoons assuming AD e-cooler @300 MeV/c, and $(T_{e\parallel}, T_{e\perp}) \approx (100, 1)[\text{meV}]$

Electron Beam Power Recovering: the Collector

Typical beam power recuperation parameters:

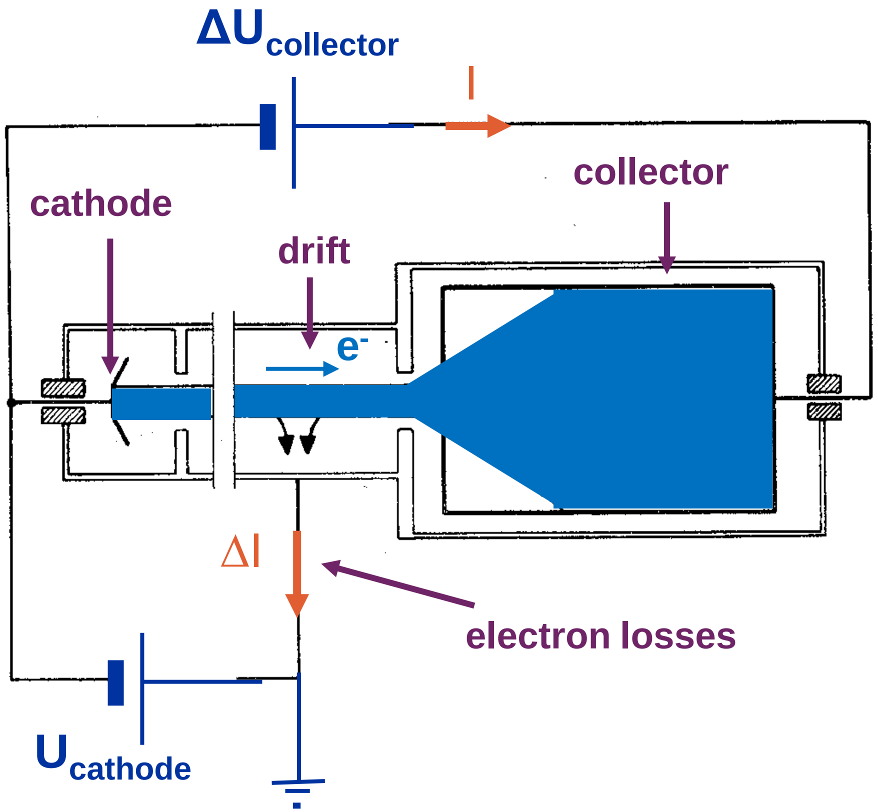
1. Required high electron **collection efficiency** to preserve vacuum and back-scattered electrons

$\Delta I/I$
- **> $3 \cdot 10^{-3}$ => bad**
- **~ $1 \cdot 10^{-4}$ => good**
- **< $1 \cdot 10^{-5}$ => excellent**

2. Collector set to a **potential** with **respect to cathode** to **slow down electrons**. It also follow Child's low

$$I_{max} = P_{collector} \times (\Delta U_{collector})^{3/2}$$

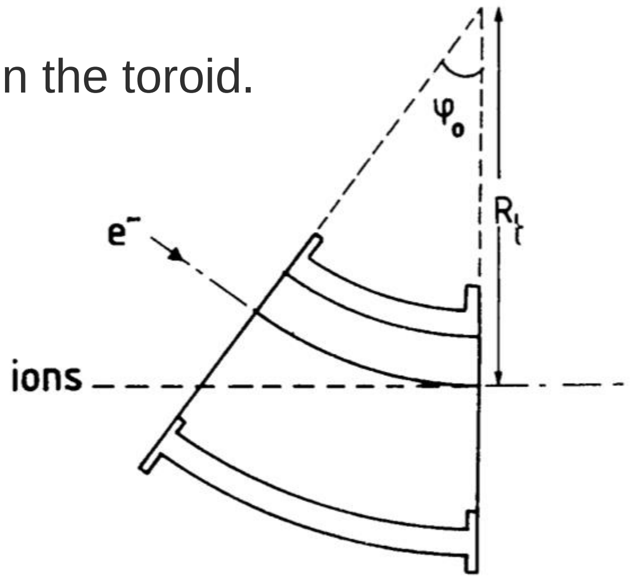
Typical value $P_{collector} \sim 15\ \mu A/V^{3/2}$, e.g. I = 1 A requires $\Delta U_{collector} \geq 1.65$ kV.



Warning: reflected electrons can** go back to the drift and **perturb cooling, i.e. increase T_{elect}

Merging the Electrons with the Ions

Effects on the Circulating Beam



1. Deflection of the **circulating beam** due to the **integrated transverse field** in the toroid.

$$\Theta[rad] = \frac{\int B_z dl}{B_0 \rho_0}$$

2. Tune shift due to the focusing effect of the **electron beam acting as a lens**

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

3. The **solenoidal field** of the cooler **twists the ion beam** by an angle **inducing coupling**:

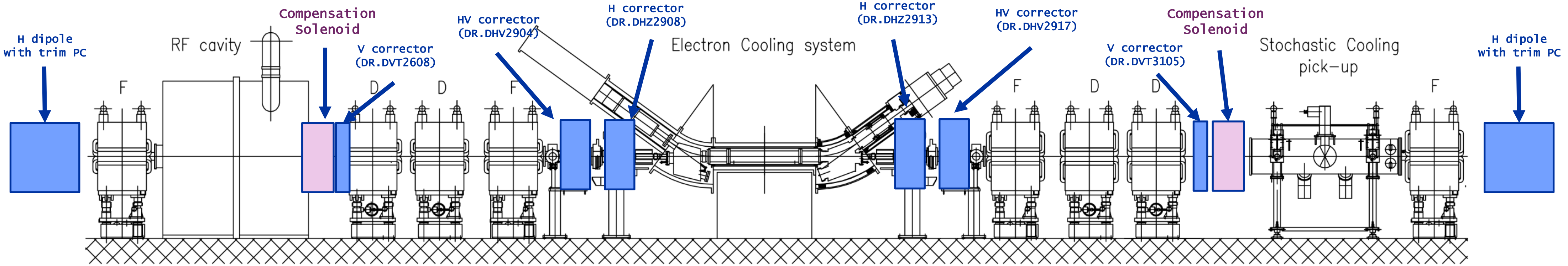
$$\vartheta[rad] = \frac{L}{\beta c} \omega_c \frac{m_e}{m_i}$$

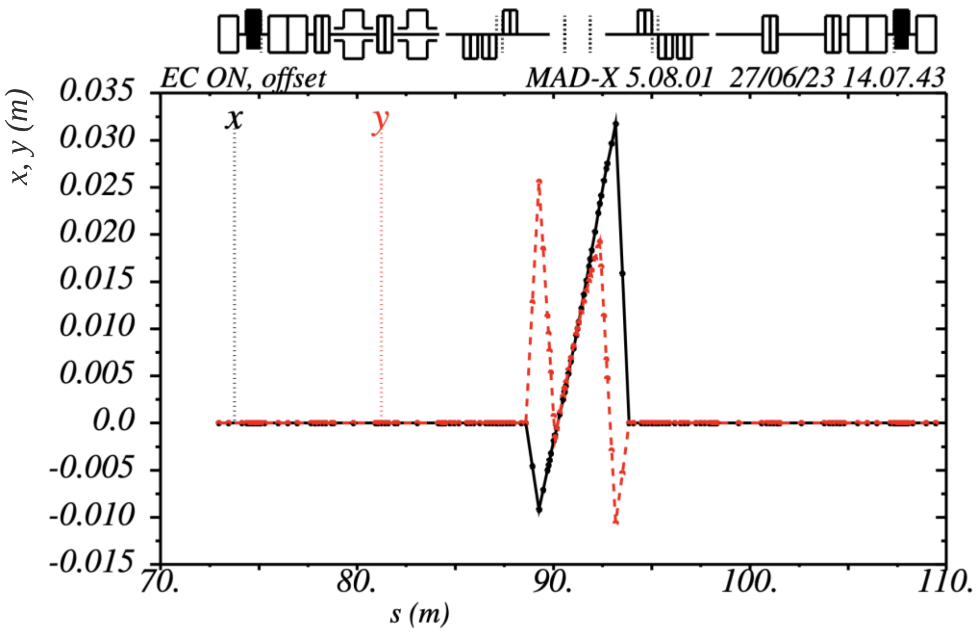
Effect more important when working close resonances

All those effects** are typically **compensated** also with **solenoids** and **steerers close to the electron cooler.

Details on CERN-EP/90-04

One Integration Example: AD





- **Orbit correctors, needed to:**
  - **Compensate kick from toroid**
  - **Tune pbar-e$^-$ trajectory alignment** in cooling section
- **Compensation solenoids:**
  - **Correct for coupling** induced by cooler solenoid
- **Note:** typically, **DC e-cooler magnets**

⇒ **Varying impact** along accelerating cycle

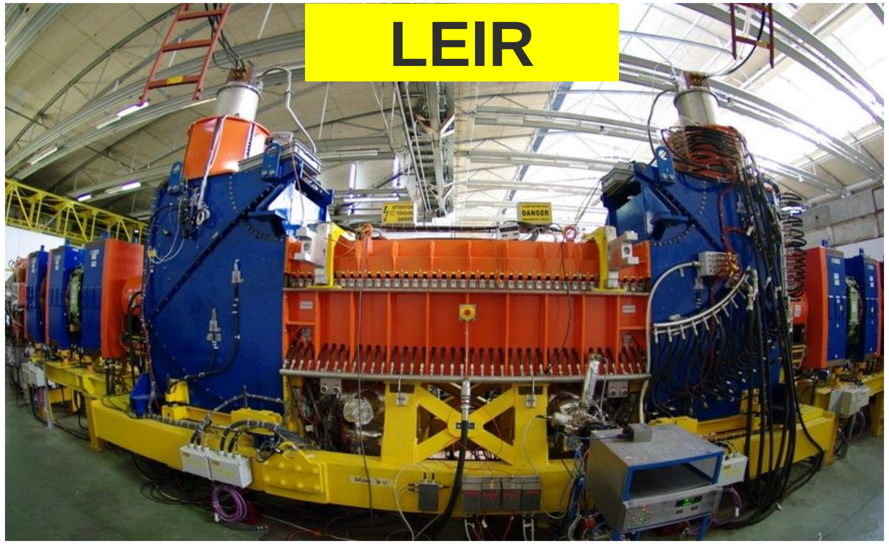
⇒ **Complex operation tools** and tuning procedures

Some General Performance Limiting Factors

- **Magnetic field imperfections** (straightness of longitudinal magnetic field in the cooling section, kicks in the transport line, all **increasing** the “**effective**” **electron temperatures**)
- **Ripple of accelerating voltage** also affective effective electron temperatures
- **Ion recombination** and consequent **beam losses** (but it can be used for beam diagnostics)
- **Beam control** (**alignment between two beams** requires good diagnostics)
- Technical/technological (**manufacturing issues** incl. **tolerances** etc., **vacuum compatibility**)
- **Reliability** issues with **increasing complexity**

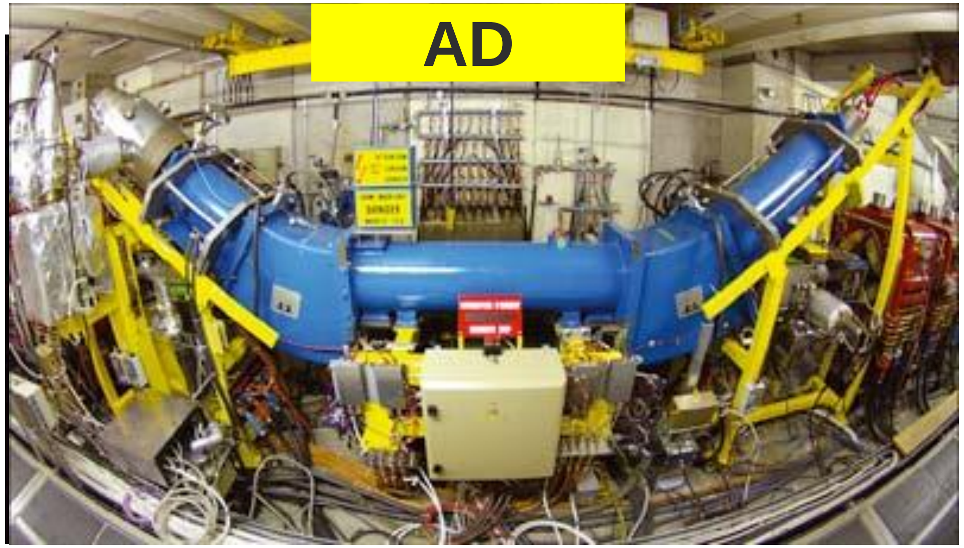
Electron Coolers at CERN

Currently we have three electron coolers in operation at CERN



LEIR e-cooler was **designed specifically** for the **LHC ion chain** and uses the **most advanced technologies**:

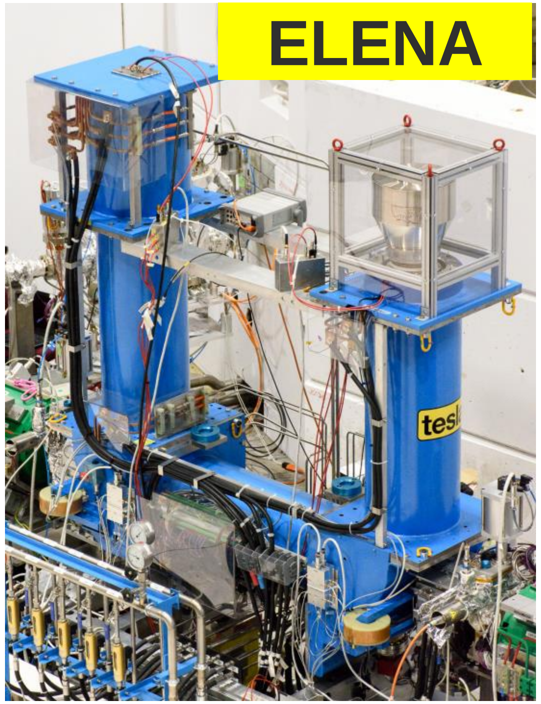
- **Variable density electron gun**
- **Beam expansion**
- **Pancake structure of magnets**
- **Electrostatic bend** for improved vacuum



First used in the Initial Cooling Experiment (**ICE**) in 1977-80, then used in **LEAR** (1982-97).

Finally moved to the **AD** (since 1999).

It **might "retire" soon** with the advent of a new electron cooler specifically designed for AD.



The **smallest**, **start** operation **in 2018** and required **challenging manufacturing/optimization** of the very **low magnetic field** (100 Gauss)

CERN Coolers Main Parameters

Each cooler is designed with specific parameters to match the accelerator needs

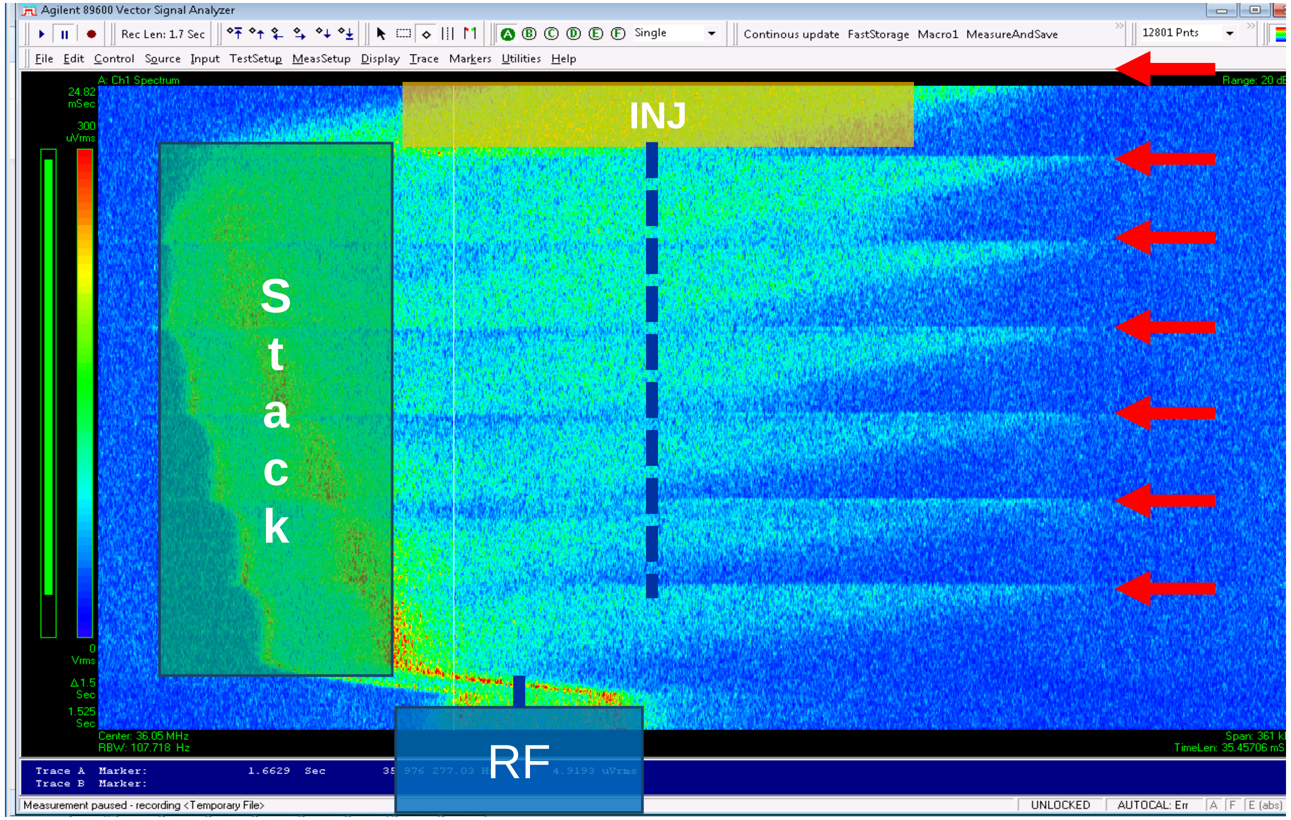
	LEIR	AD		ELENA	
(Main) Ion particle	$^{208}Pb^{54+}$	pbar	pbar	pbar	pbar
Ion momentum	~88 MeV/c/u	300 MeV/c	100 MeV/c	35 MeV/c	13.7 MeV/c
Electron kinetic energy	2.3 keV (<6.5 keV)	25.5 keV (<35 keV)	2.9 keV	355 eV	55 eV
Relativistic beta	0.094	0.305	0.106	0.037	0.015
Electron current	600 mA	2.5 A	100 mA	5 mA	1 mA
Cooling length	2.5 m	1.5 m		1 m	
Ring length	78.54 m	182.43 m		30.41 m	
Gun magnetic field	Up to 2.3 kG	590 G		Up to 1 kG	
Drift magnet field	750 G	590 G		100 G	
Electron beam radius (drift)	14 - 25 mm	25 mm		8 to 25 mm	

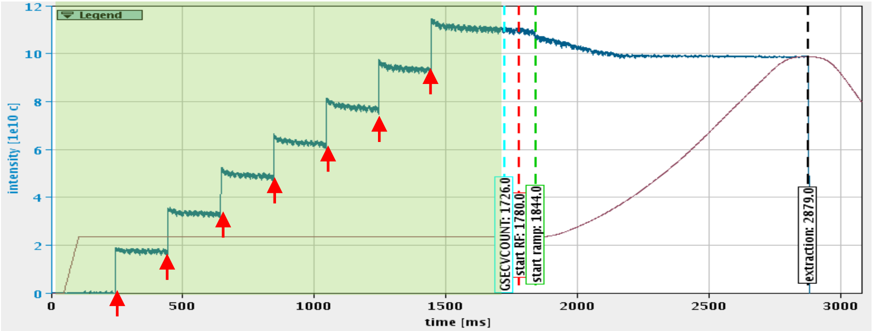
E-Cooling in LEIR

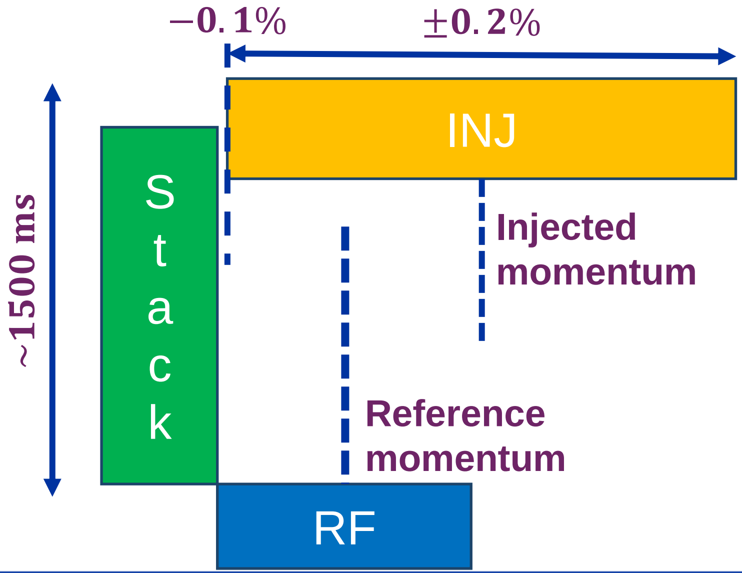
E-cooling in LEIR

LEIR injection process is based on multiple (up to 8) injections of Linac3 pulses: stacking in momentum and transverse phase space.

Cooling essential also for dragging the mean energy!

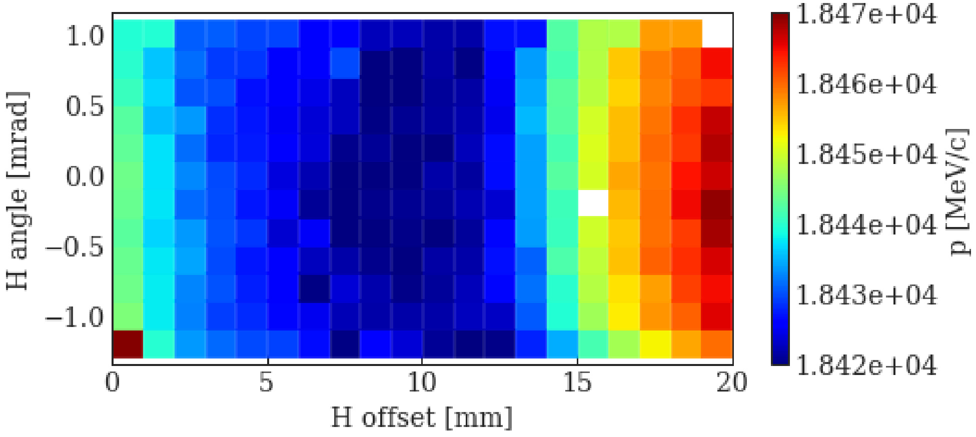


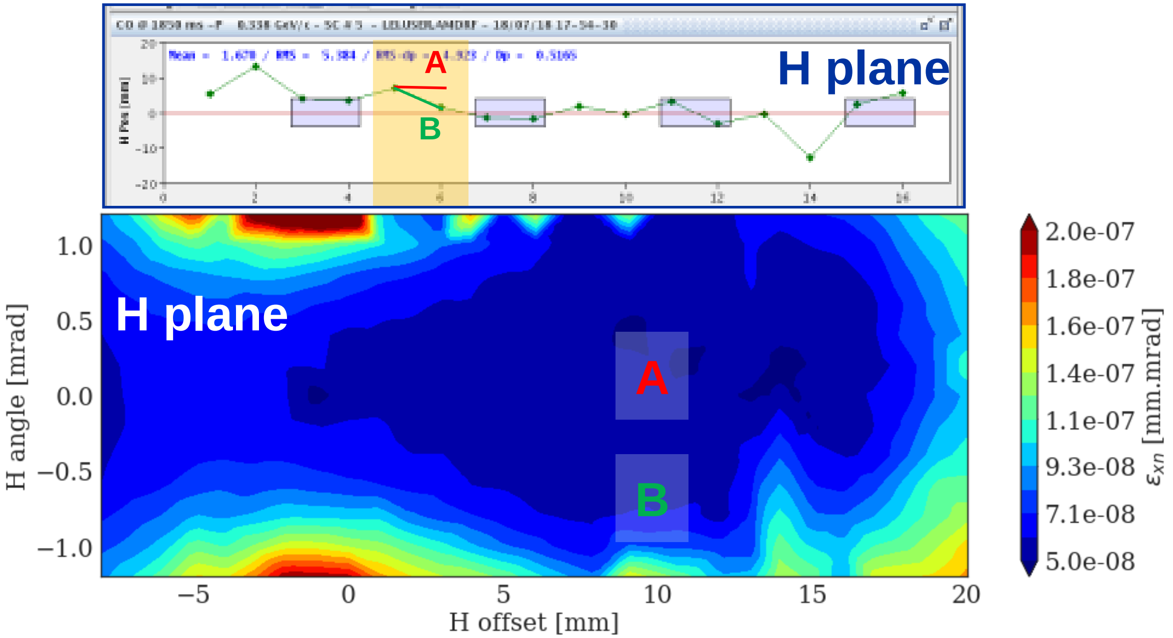


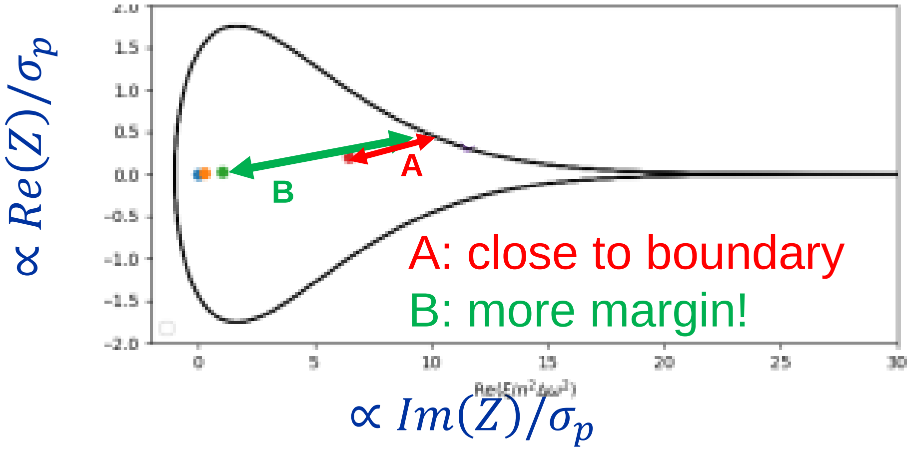


LEIR Ion-Electron Orbit Overlap Adjustment

- **Final ion beam profile strongly dependent on ion-electron relative trajectory.**
- **It can be seen with cooling maps,** i.e. scan on the ion orbit
  - One can see the **electron velocity profile** looking at final momentum and minimize the final emittance
  - **Note: best cooling is not necessarily the optimum!** Impedance-induced instabilities might require some "heating" of the circulating ions, e.g. with an angle.





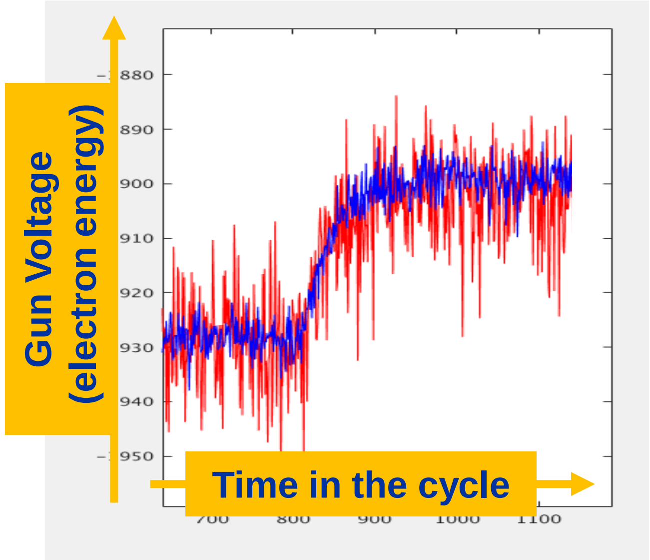


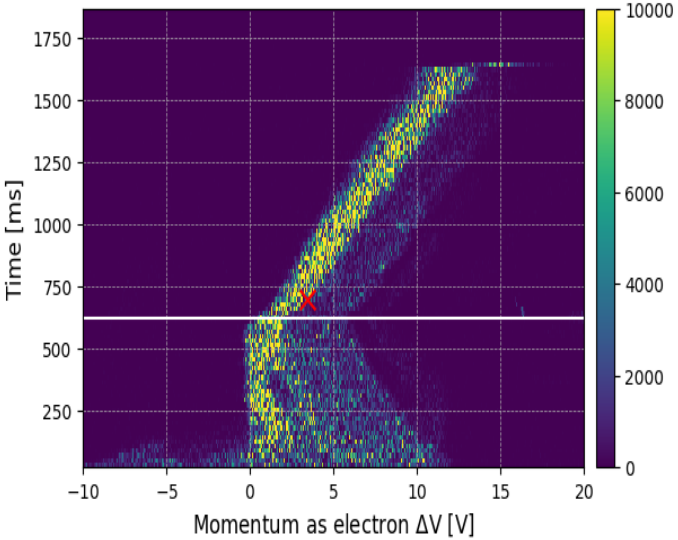
More Details in CERN-ACC-NOTE-2020-0023 and N. Biancacci ABP-IWG#11

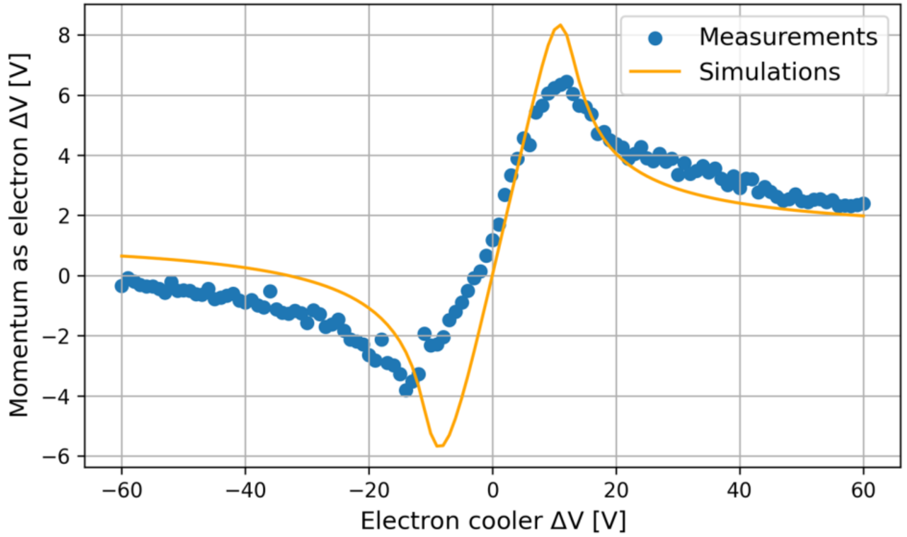
LEIR: Measurement and Simulation of Cooling Force

- The **longitudinal force** can be **measured** during MDs by **applying a voltage step on $V_{cathode}$** and **measuring** the **speed** for the **ions** to follow the **change of their mean momentum.**

- Measurement can be compared with several **simulations codes**, e.g. RF-Track, Betacool, JSPEC, PyHEADTAIL, Xsuite…





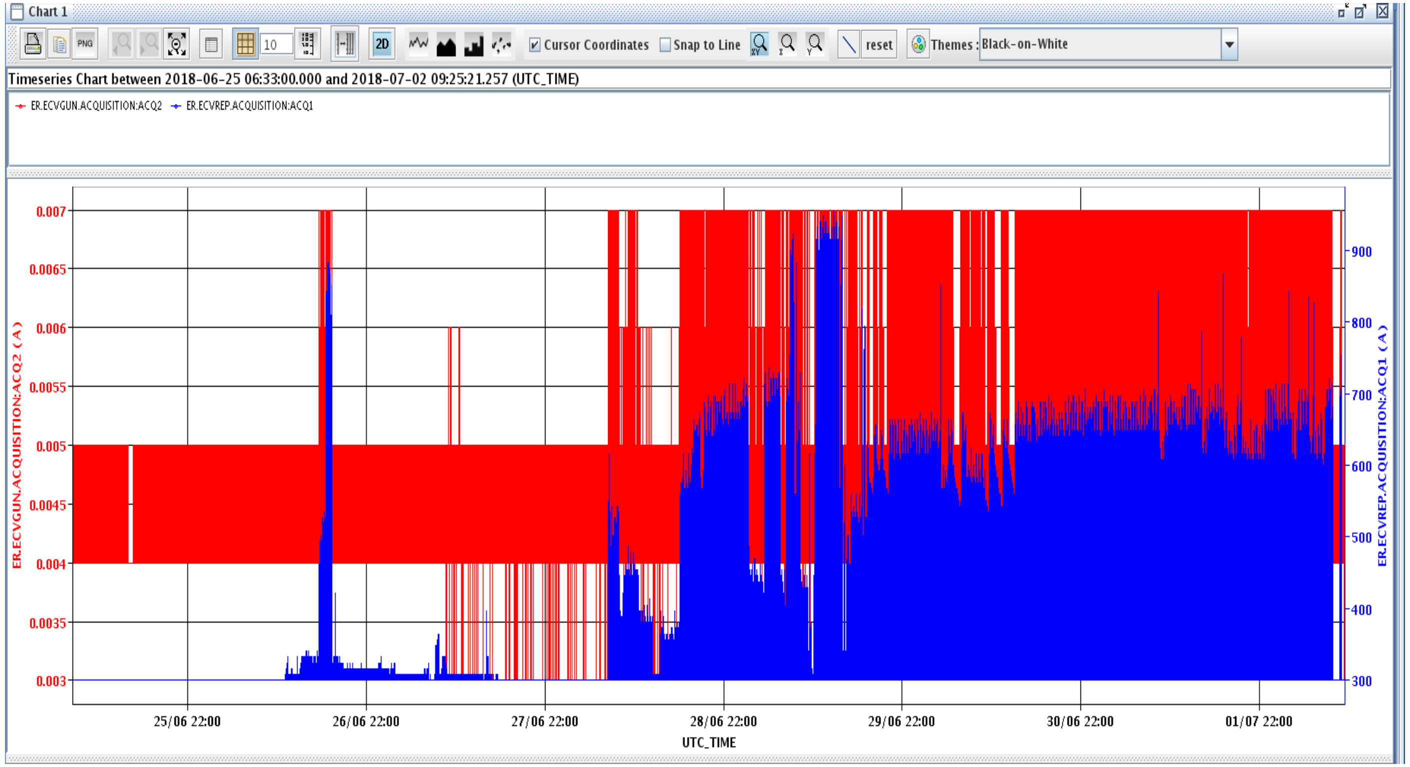


More Details in A. Latina ABP-IWG#11, B. Veglia COOL2019, P. Kruyt Ph.D thesis

Importance of Magnetic and Electrostatic Settings

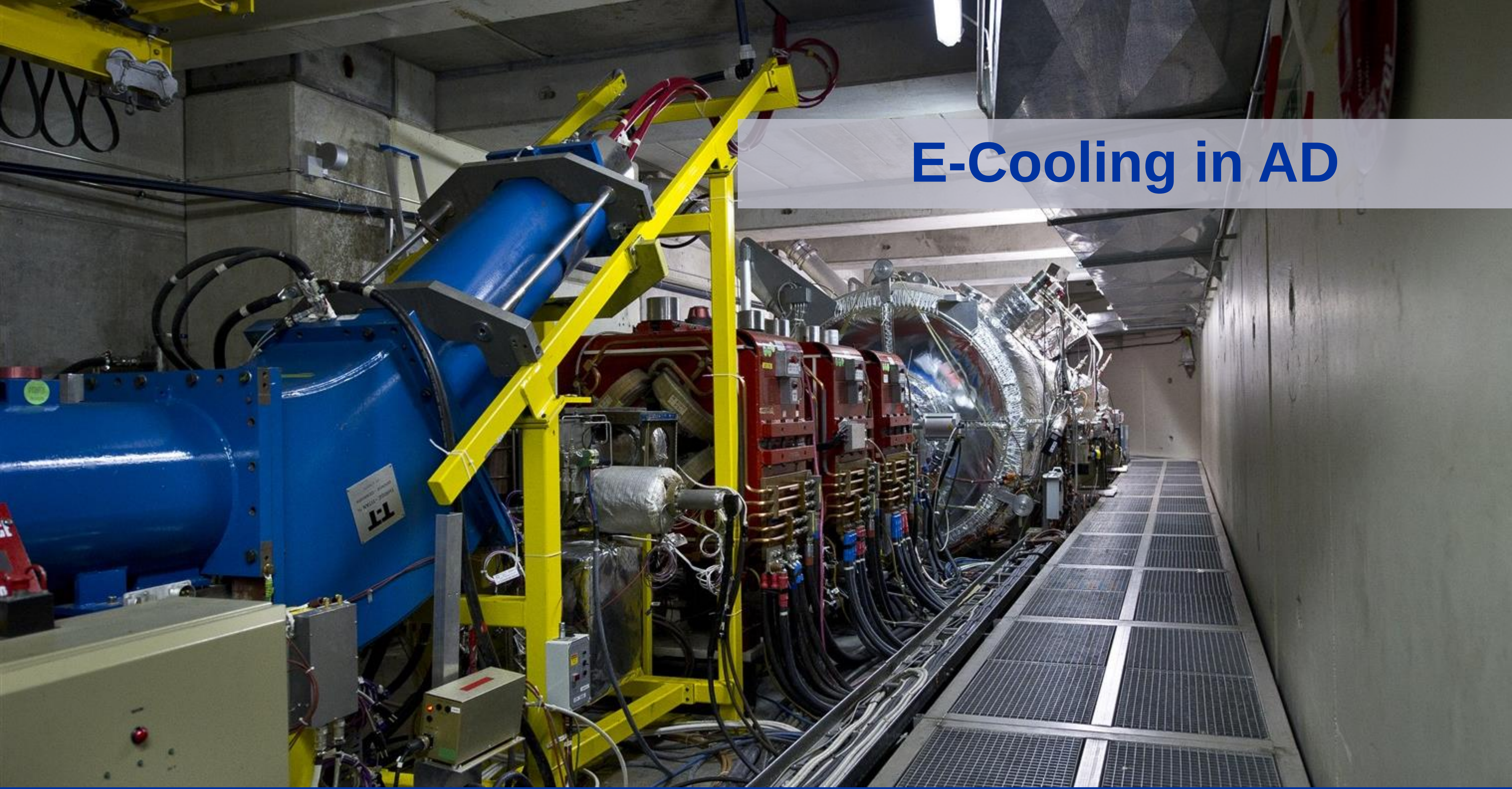
Collector and **repeller currents** (and vacuum) are **important diagnostics observables!**

- They **can reveal problems with the electron ”transport”** to the collector, and consequent degradation of cooling performance.



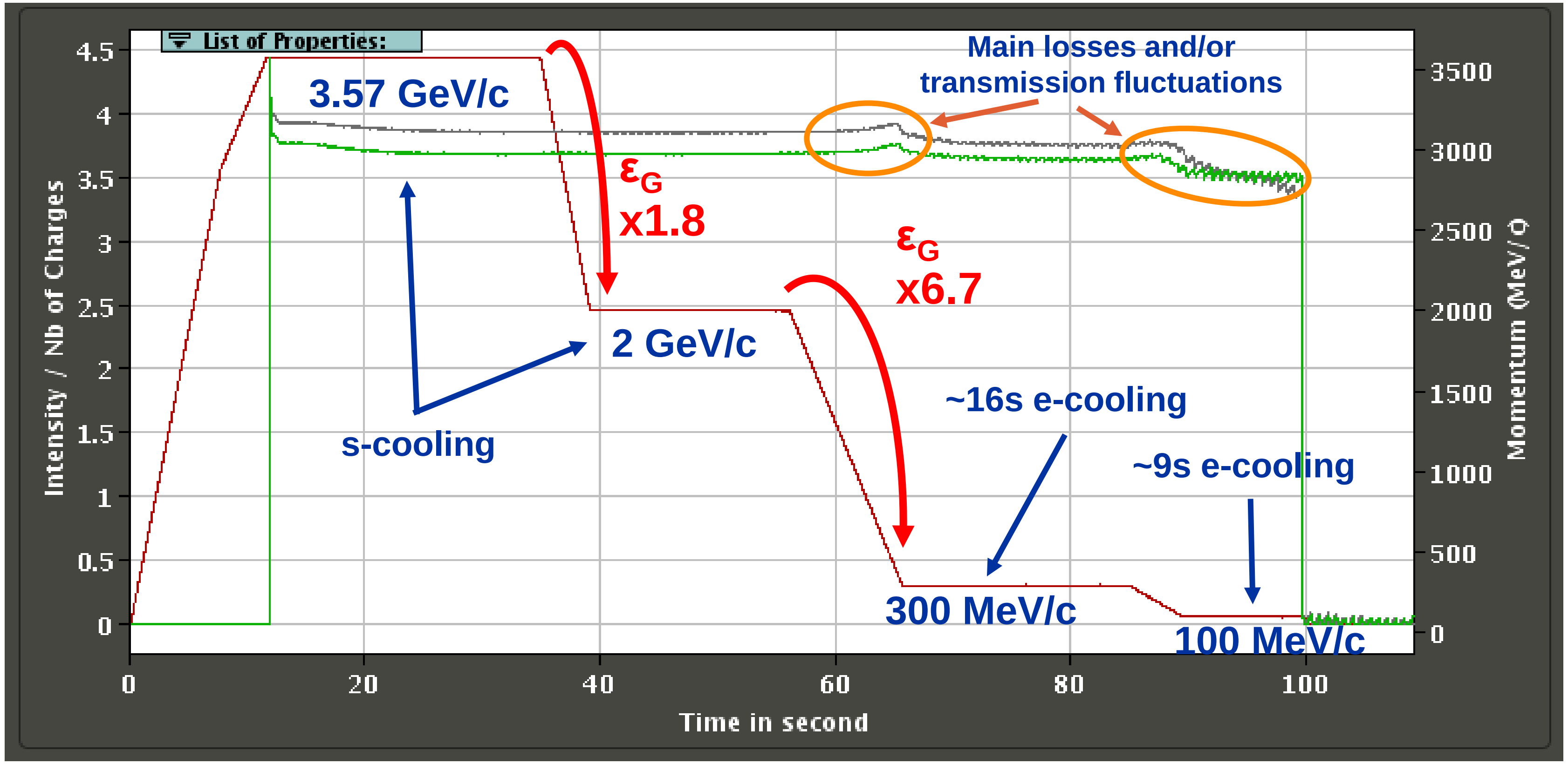
From LEIR elogbook 02/07/2018 11:42:
We found losses on the repeller electrode which changes the regulation of Vgun. How these losses occurred we do not know as identical settings on other cycles did not produce the same situation. ***Are the machine orbit correctors close to the e-cooler affecting the electron beam trajectory****? The current in* ***ER.ECNDV9 was changed from 0.5 A to -0.5A*** *and this cured the problem. The new value of ER.ECNDV9 has been copied onto all the cycles.*
AF & GT

E-Cooling in AD



A typical AD cycle nowadays - figure of merits:

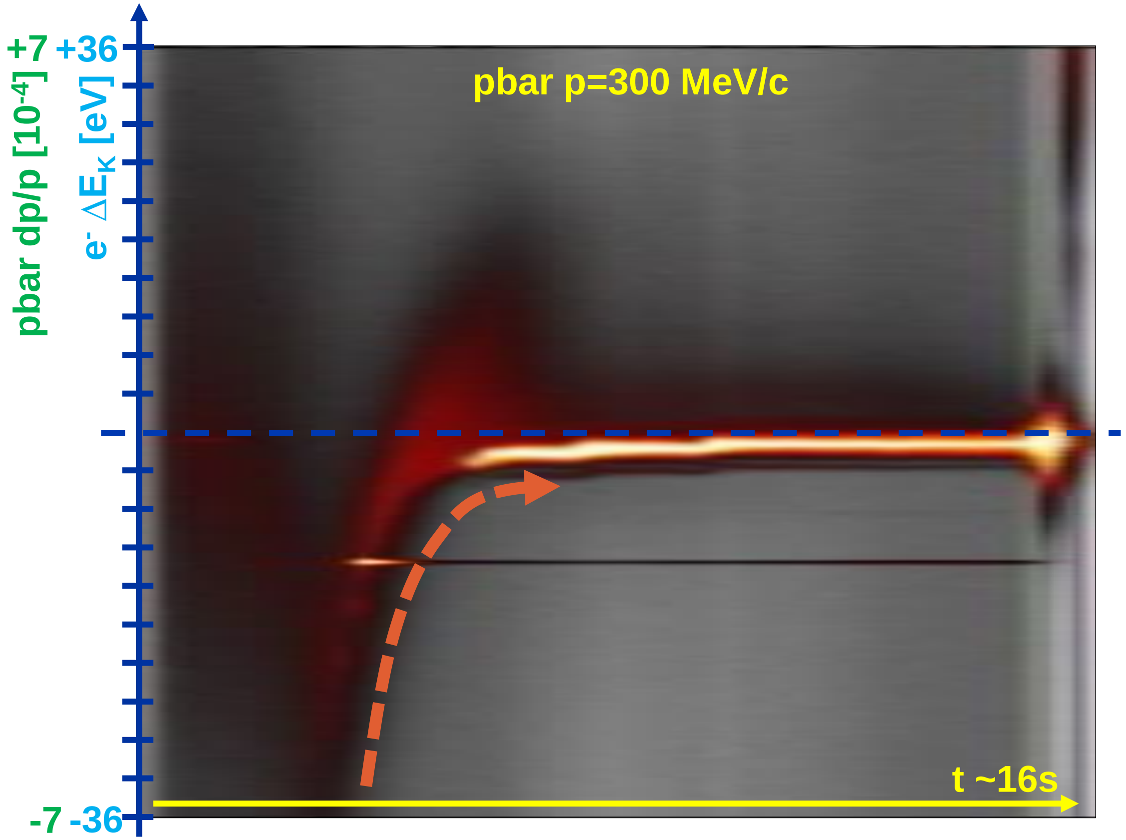
- **Captured intensity** (linked to target + DI + s-cooling performance)
- **Tranmission along the cycle** (linked to optics control and s-/**e-cooling** performance)
  - **Cycle length** (mainly driven by s-/**e-cooling** performance, and **tollerated losses**…)
- **Number of cycles** for physics (affected by **systems**, inc. e-cooling, **reliability**)

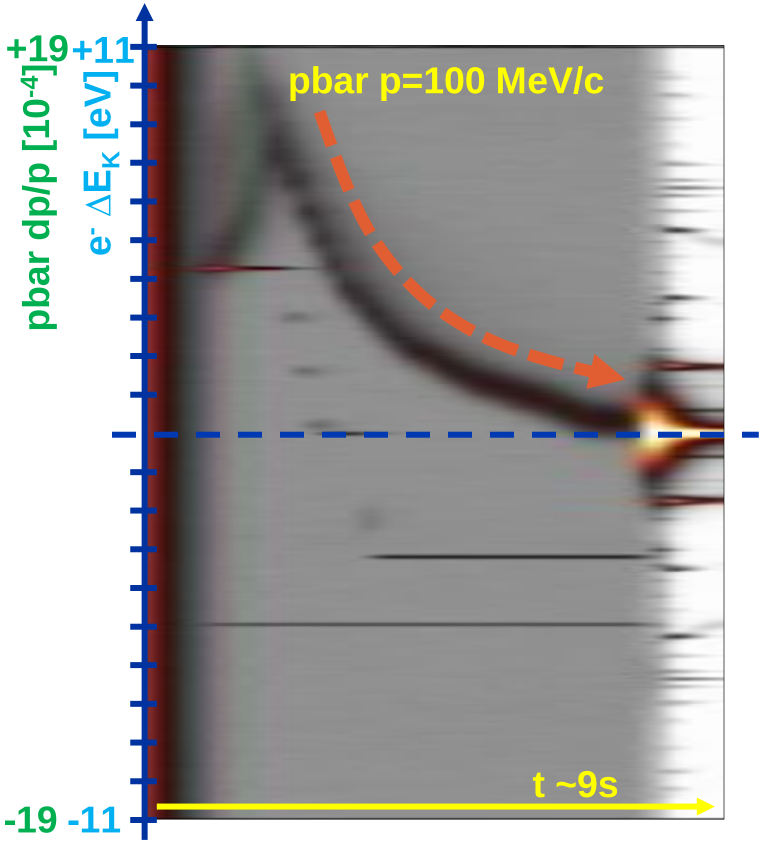


Rough estimate of longitudinal e-cooling performance

Longitudinal cooling relatively fast as seen from Schottky

- **Energy drift (due to HV power supply and/or e⁻ space charge) clearly observable**
- **Sudden lost of e-cooling performance requiring full retuning observed a few times/year**

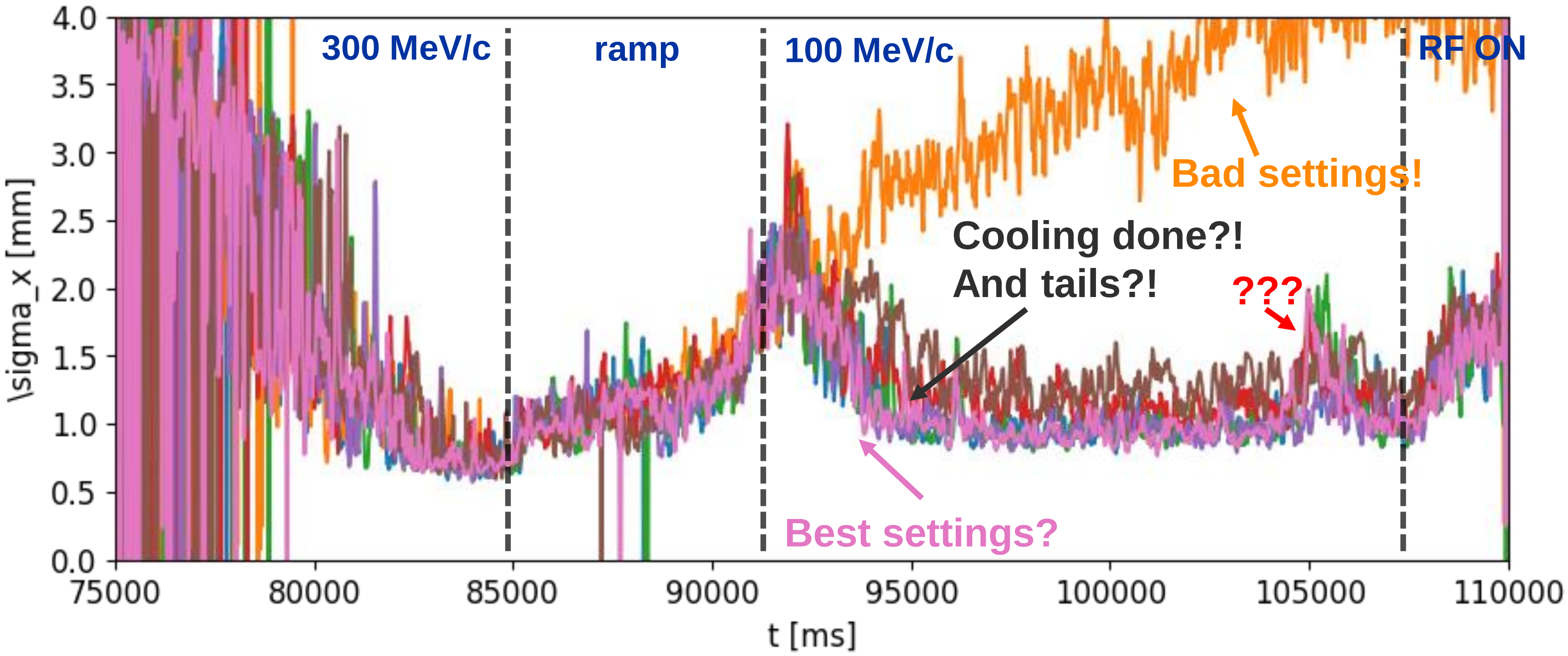




Rough estimate of transverse cooling performance

More difficult to assess!

- Main measurement technique based on **punctual (slow!) scraper measurements…**
- **AD IPM (Ionization Profile Monitor)** allows to **measure** beam size **all along the cycle**
  - **Some limitation on its use**: no gas injection, affecting trajectory of circulating beam…
  - It **allowed to reduce 100 MeV/c plateau by a few seconds**!



New AD e-cooler: an Improvement Opportunity!

First motivation for a new e-cooler is to improve AD reliability

- E.g. issues with e-cooler collector **in 2018** caused the **loss** of about **30% of the beam cycles** for physics!

Additionally, one could ultimately aim for:

- **20% cycle length reduction** to ~90 s (based on AD 1996 design link)
  - from ~16 s to ~5 s at 300 MeV/c;
  - from ~9 s to ~2 s at 100 MeV/c
- **Reduce beam losses**
  - Today, **we lose ~10-20% distributed between 2 GeV/c and 35 MeV/c**
- Increasing maximum **e-cooler energy to 500 MeV/c** could be an **asset**
  - **Better equalisation** of emittance **blow up** during deceleration (x4, x5 instead of x6.7, x3)
  - **Higher chance to cool transverse tails** left behind by s-cooling at 2 GeV/c
  - But **might be limited by other factors** (e.g. field strenght/quality?)

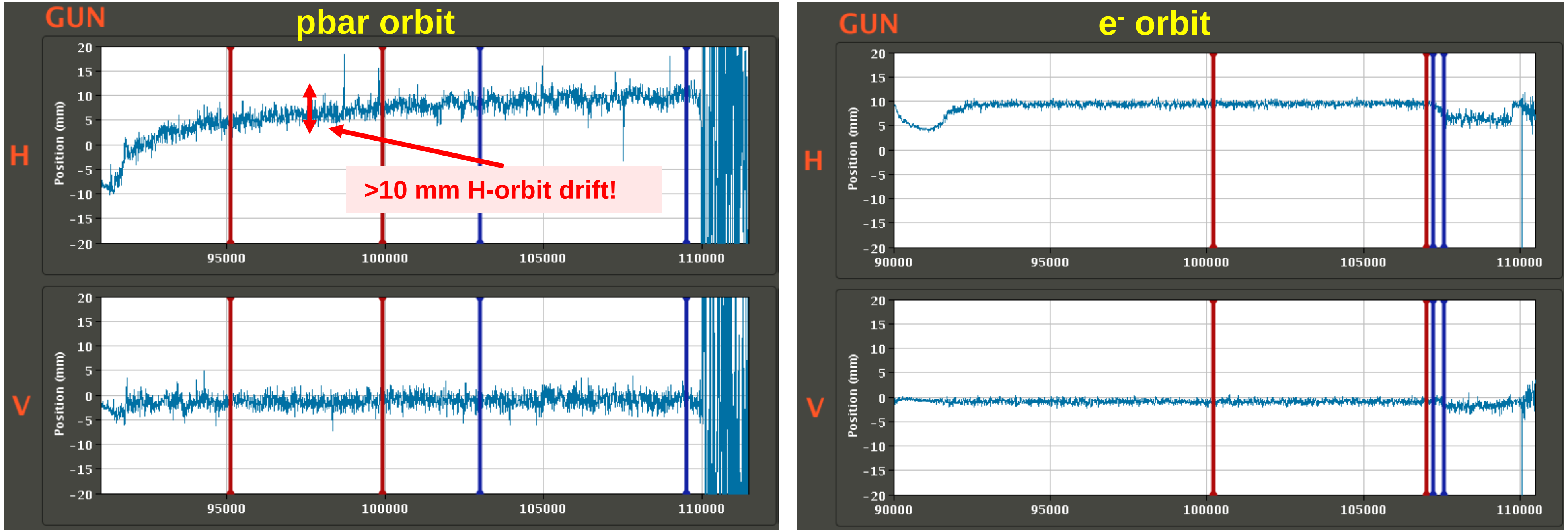
Note: part of observed AD performance loss not necessarily linked to the e-cooler itself!

⇒ In parallel, we **are investing** in our capability of **controlling** and **tuning** the **whole machine!**

One example: how well do we control pbar/e$^-$ orbit overlap?

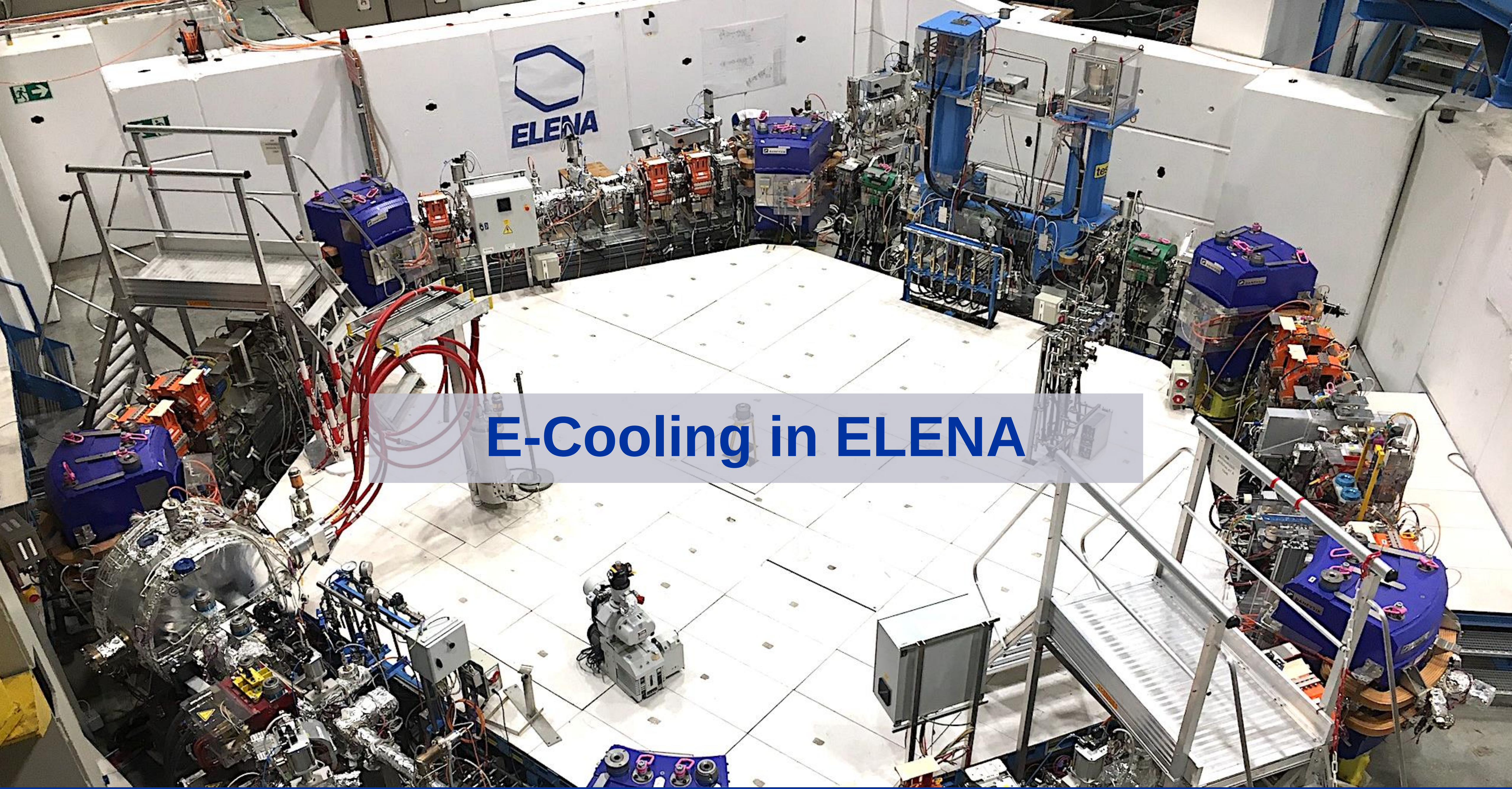
e$^-$ (and pbar) orbit measurement in the e-cooler recently re-established

- It requires to **modulate e$^-$ beam intensity**
- **Much faster setup of cooling** (at least at first order)!



It reveled that **overlap is varying along a plateau** (here 100 MeV/c) due to **drift of pbar orbit**

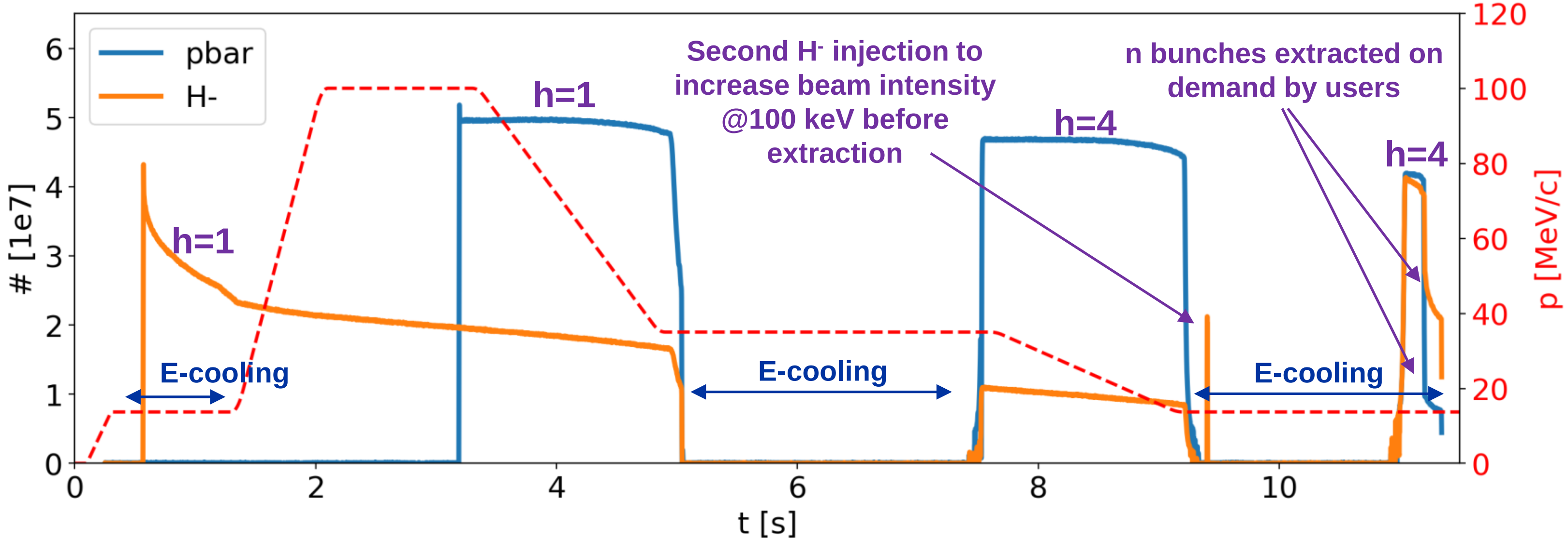
- It could be **detrimental for cooling performance**, and **not linked to e-cooler device itself**
- **Possibly linked to field lag in “wide” bends** (normally compensated by BHZ-TRIM PC…)



E-Cooling in ELENA

The ELENA cycle

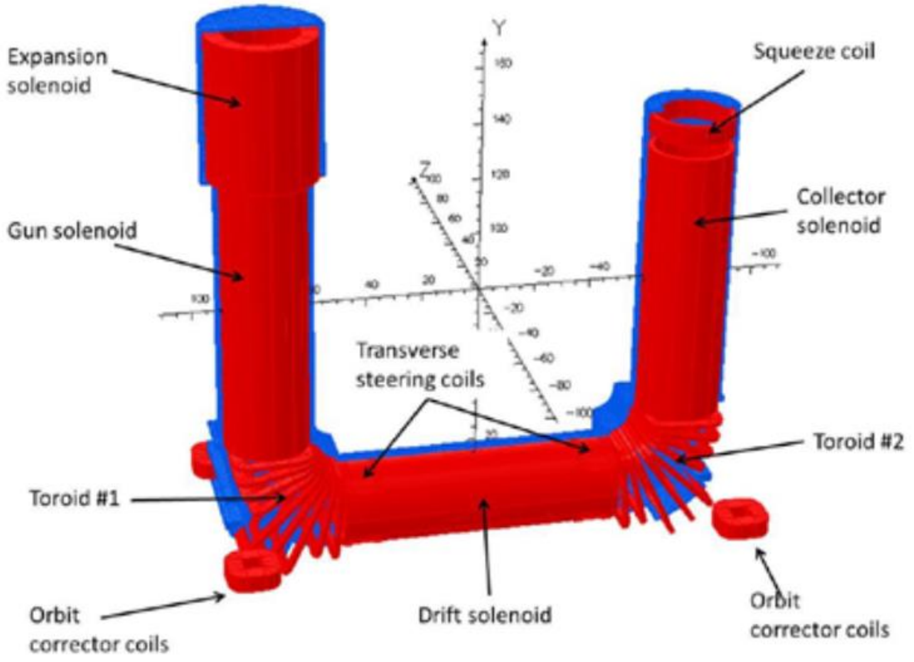
Running with two (magnetically-equal) ~15-second-long pbar or H^- cycles

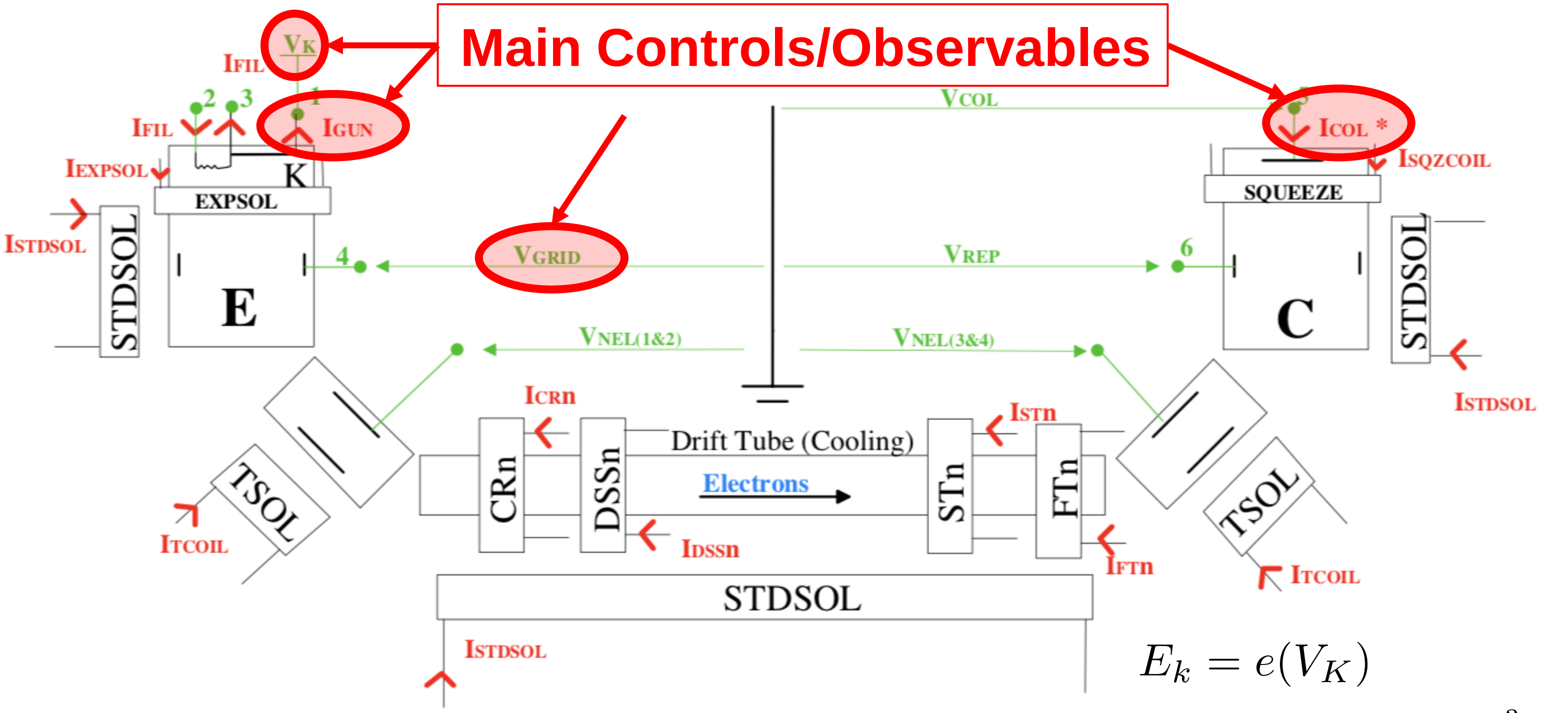


- **Margin of improvement:**
  - **Transmission**: today at up to **~10% losses** (sometimes **further degradation linked to AD e-cooling** performance)
  - **Cycle length:** not important if we run in the shadow of AD (baseline), but **relevant if we wait for ELENA extraction before restart AD** (as **today**!)
- **Repetition rate is very slow for any study/setup with pbar**
  - **Good news: No H- lifetime degradation observed with e-cooling! We can use H- for most studies!**
  - **Bad news: H- source reliability** questionable, known to be prone to hardware faults…
  - **Bad news: H- lifetime strongly affected by vacuum levels in the ring** (typically 10^{-11} mbar)

ELENA E-Cooler Hardware

- **Complex magnetic design by G. Tranquille (see e.g. IPAC2016, IPAC2018)**
- **Very low voltages and e- energy.** => All PC referred to ground
  - **Easier to handle** (but also **more difficult to spot electron losses**: one must rely on power converter accuracies)
- **In operation since 2018, no major hardware issues observed so far**





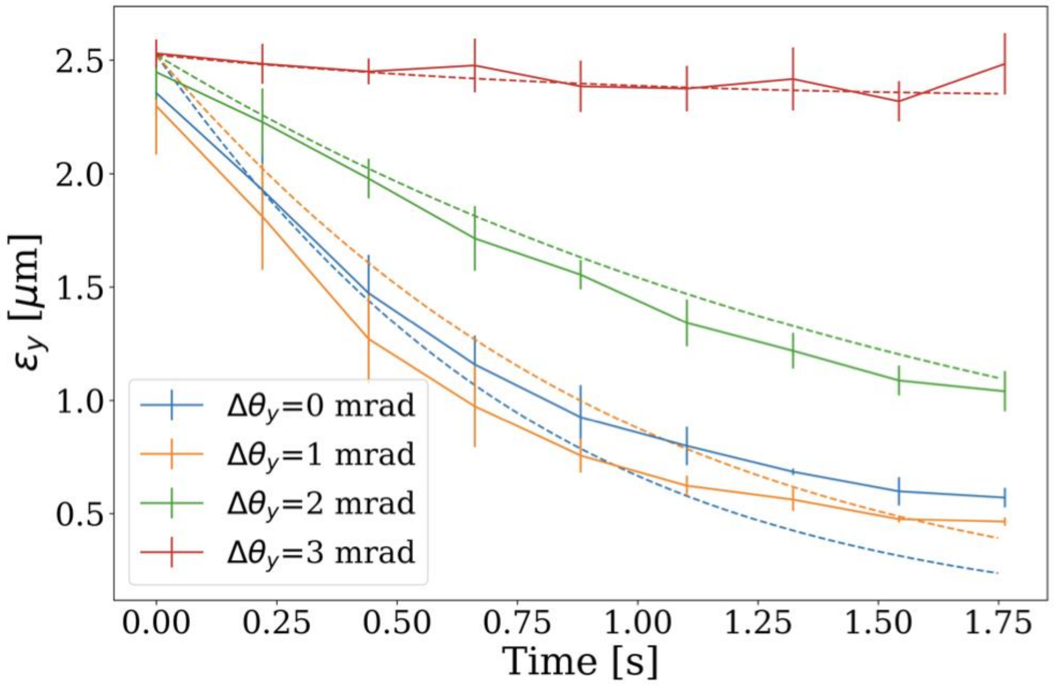
$$E_k = e(V_K)$$

$$I_e = P(V_K - V_G)^{\frac{3}{2}}$$

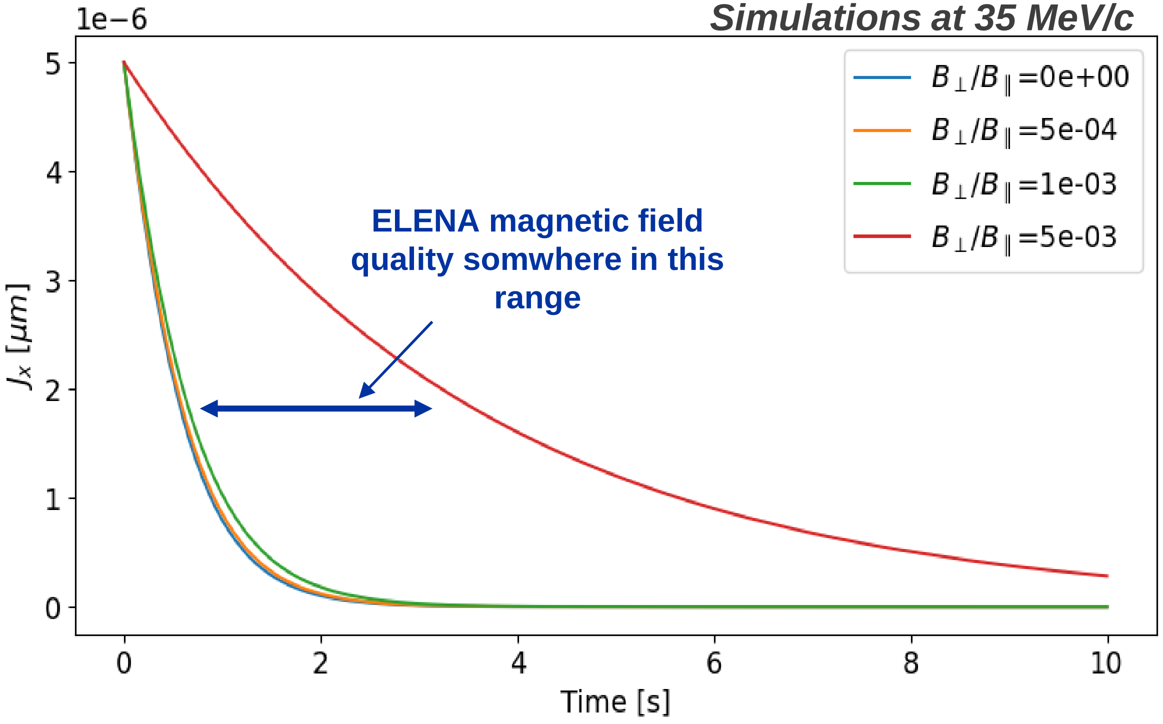
E-cooling studies in ELENA

- **Test bed for Xsuite e-cooling model benchmark (P. Kruyt (soon to finish his PhD))**
  - Generally, **good agreement between measurements and simulations**
  - **Still to test impact of field quality** degradation (introduced with correction coils) on cooling efficiency

Measurements and simulations at 35 MeV/c



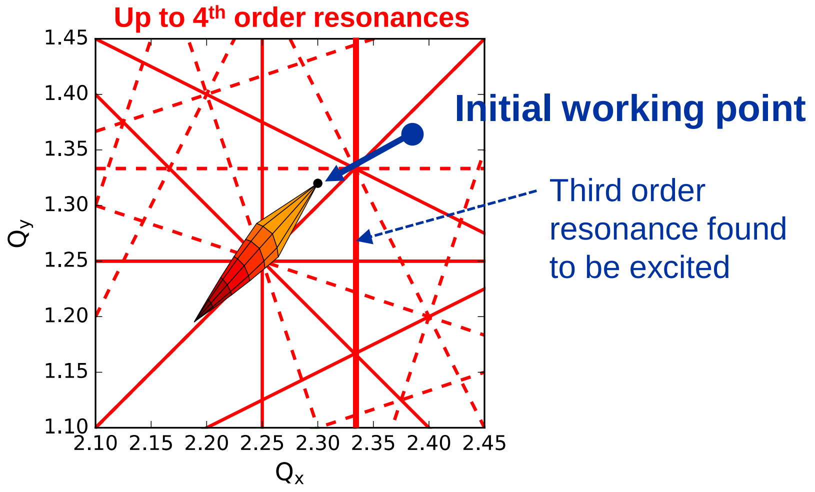
Simulations at 35 MeV/c



MD example: ELENA emittance at ejection

A typical challenge in low energy synchrotrons:

- **Possibly *excited resonance* limit the possible *tunes* that one can use in a machine, e.g. ELENA**
- ***Space-charge effect* induces a *tune spread* experienced by the beam depending on particle particle density within the beam**
  - i.e. smaller *beam size* (or *emittance*) = higher *tune spread*

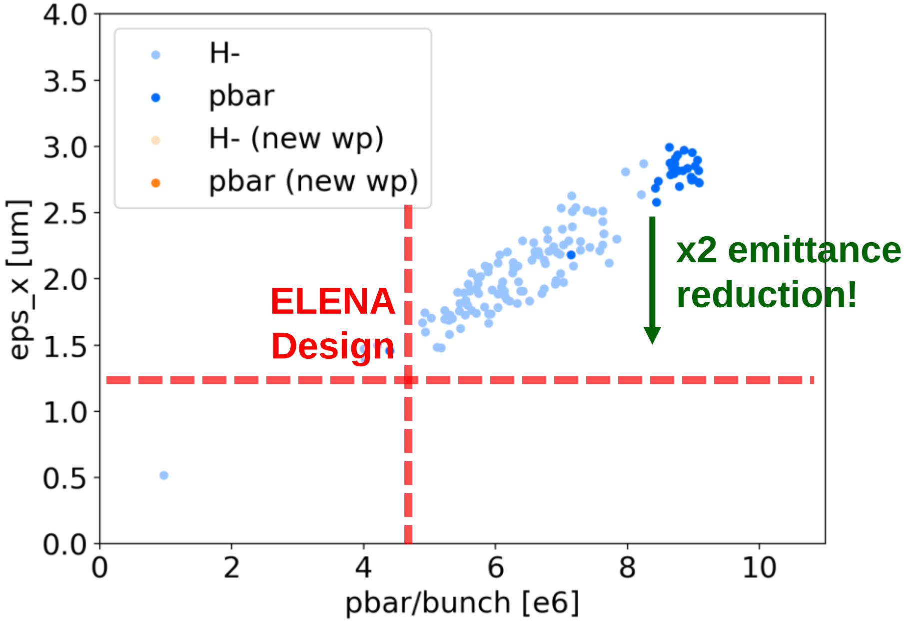


An optimisation example:

- **Observation: the beam emittance at ELENA extraction was above the design value**
- **We simulated expected tune spread due to space charge, and measured excitation state of resonance by scanning the tune diagram**
- **We identified a more robust working point**

⇒ **Factor 2 emittance reduction obtained in 2023**

⇒ **Used in operation in 2024**



Summary

- **Electron cooling** is an **essential instrument** for **ion** and **antimatter physics** at CERN
  - It is **based** on **energy exchange** between **"hot" ions** and **"cold" e^-** which are continuously renewed
  - It requires that the **mean velocity** of **e^-** is **matched** with the **ions** velocity
  - The **alignment between the beams is fundamental**, despite sometimes it is useful to introduce some misalignment "not to cool too much"
  - **Schottky diagnostics** is the key to **spot any problems** and **make first order corrections**
  - The **electron transport** must be optimized to **minimize losses**, which are **detrimental for cooling efficiency**
- **Three electron coolers** are **in operation at CERN**
  - **LEIR**: probably the **most versatile**, it has several parameters to adjust the **electron beam generation.**
  - **AD**: the **oldest** at CERN, but also the **most powerful**. **Little adjustment possibilities**, requiring to **watch e^- losses.**

    $\Rightarrow$ **Looking forward to restart AD with the new e-cooler after LS3!**
  - **ELENA**: the **smallest**, it needed **careful design** and **optimization** of **magnetic field** (100 Gauss, 10^{-3} straightness!)
- Actual **cooling performance** depends on **many parameters and effects** also proper of circulating ions
  - **Not covered here! Space charge, Intra Beam Scattering, Vacuum, Impedance and other instabilities …**

Thanks for your attention and questions!

…and some references…

- **Several references on E-Beam website**
- **Functional Specification for the New AD E-cooler EDMS#2772724**
- **General review of cooling techniques on ICFA Newsletter #65**
- ***H. Poth* - Electron cooling, theory, experiment, application, CERN-EP/90-04 (doi)**
- **Many slides presented here have been adapted from:**
  - *G. Tranquille* – A&T Seminar 2019 - 40 Years of Electron Cooling at CERN – indico
  - *M. Bai* – BND School 2015 – Introduction to electron cooling – indico
  - *I. Meshkov* - ASAO2014 – Beam Cooling Techniques – indico
  - *H. Danared* – CAS2005 – Beam Cooling – presentation – proceedings
  - *N. Biancacci and A. Saa Hernandez* – E-BEAM 2019 – LEIR e-cooler op experience – indico
  - *… and many others! Thanks to all of you!*

CERN

Other Properties of Generated Electron Beam:
Electron beam current

Electron current extracted from the “space-charge” cloud in front of the cathode, and it is **described by Child’s law**:

$$I_{gun} = P(V_{cathode} - V_{anode})^{3/2}$$
$$P = \text{Gun perveance}$$
$$\approx 7.3 \times 10^{-6}(r_0/d)^2[\mathrm{AV}^{-3/2}]$$
$$r_0 = \text{cathode radius}$$
$$d = \text{cathode} - \text{anode distance}$$

Note: **perveance** can be **affected** by **control electrodes**, like in the case of **LEIR**’s cooler from previous slide…

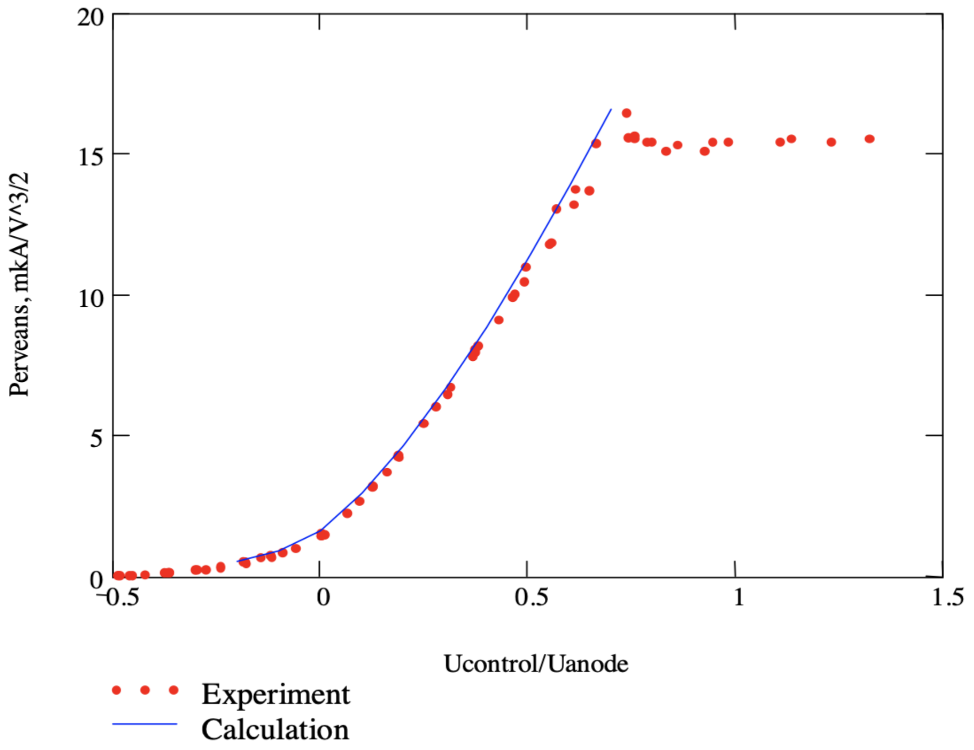


Figure 3: The perveance of the electron gun as the function of the control electrode potential normalised to the anode potential.

From A. Bubley, The Electron Gun with Variable Beam Profile for Optimization of Electron Cooling, EPAC2002, WEPRI049

Other Properties of Generated Electron Beam:
Electron longitudinal temperature

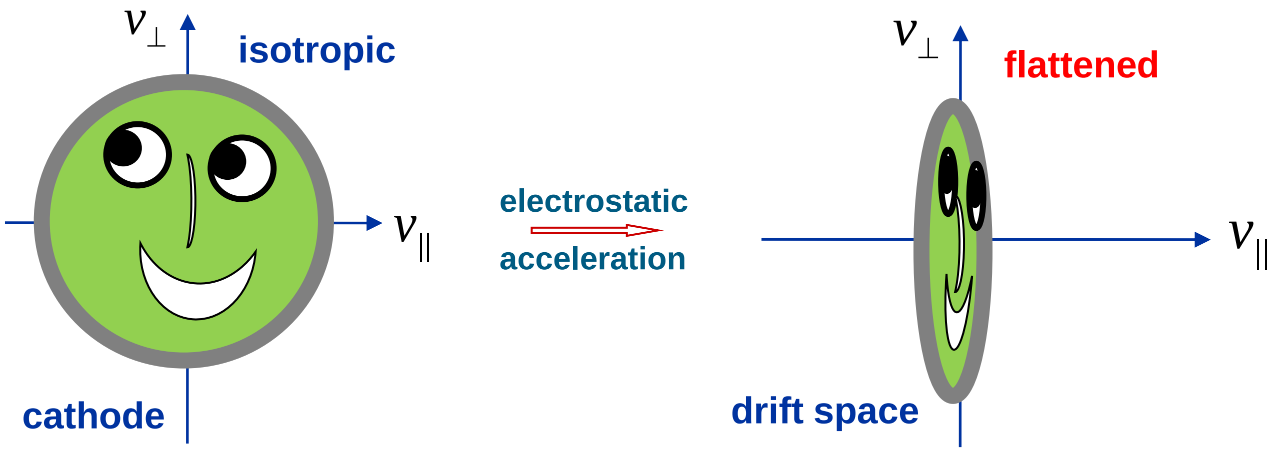
The **electron velocities** at the **cathode** is typically assumed to be **Maxwellian**:

$$f(\vec{v}) \equiv \frac{1}{(2\pi k_B T/m_e)^{3/2}} e^{-\frac{1}{2}m_e\vec{v}^2/k_B T}$$

rms kinetic energy →

$$\frac{1}{2}m_e v_{rms}^2 = \frac{3}{2}k_B T$$

After acceleration, the **longitudinal temperature** in the **moving frame shrinks**:



$$k_B T_\perp \approx k_B T_{cath} \qquad k_B T_\parallel \approx \frac{(k_B T_{cath})^2}{4E_0}$$

(non relativistic case)

Example: $\mathbf{k_B T_{cath} = 0.1eV}$ (T_{cath}=1100 K)
acceleration voltage U_0 = 2.3 kV, i.e. $\mathbf{E_0}$**=2.3 keV**
then $\mathbf{k_B T_{//} = 10^{-6}}$ **eV**

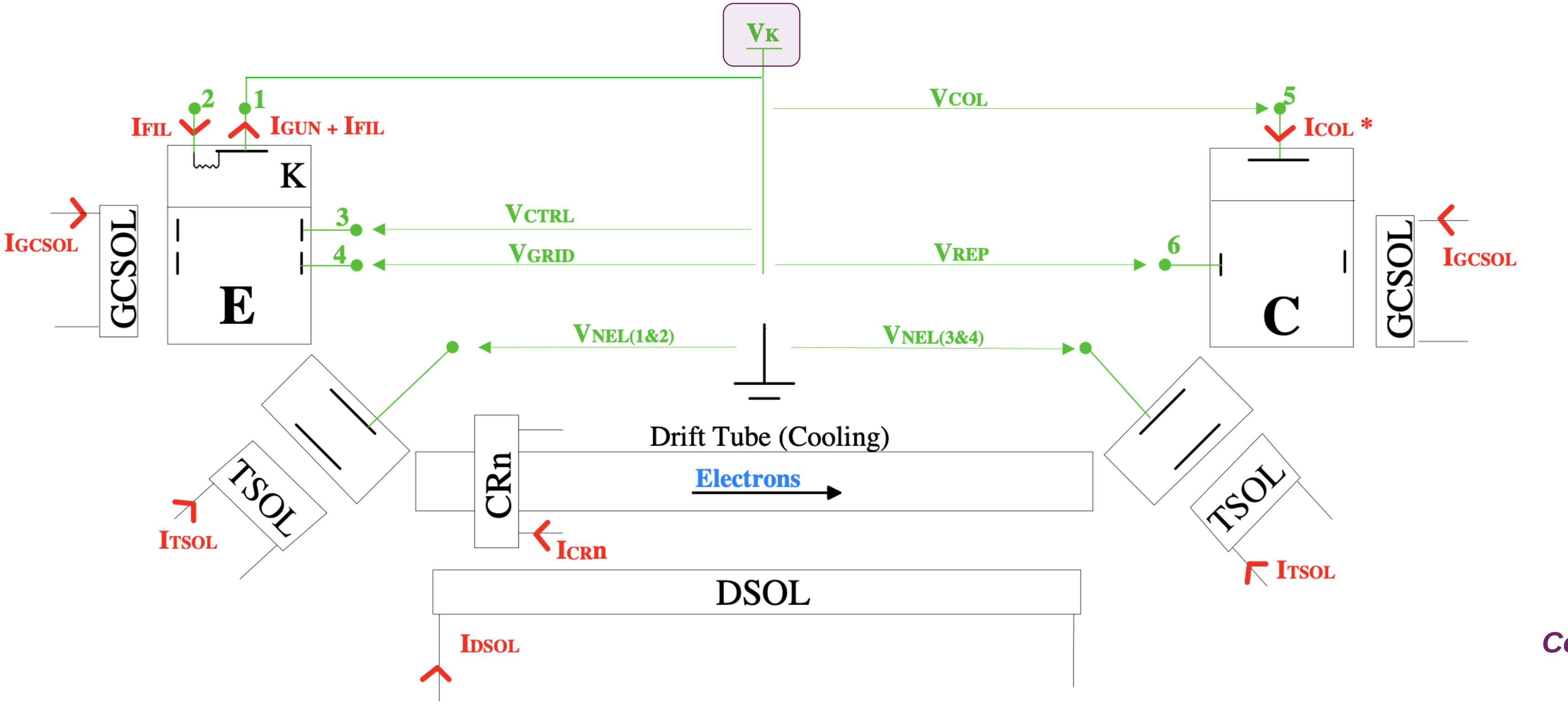
In practice: **longitudinal temperatures** of the order of ~$\mathbf{10^{-3}}$ **eV** due to scattering processes

LEIR e-cooler main hardware parameters

Voltages referred to cathode (***V_k***), which defines the **e^- energy**:

(*not taking into account space charge corrections*)

$$\gamma_{rel_{e-}} = \gamma_{rel_{ions}} = 1 + \frac{eV_K}{m_e c^2}$$

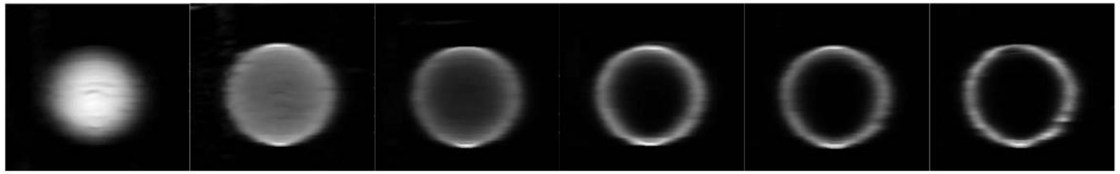


Courtesy of A. Frassier.

Main solenoid and **corrector coils** currents are typically **set during first commissioning** and **can hardly be adjusted** as there are **no obvious observables** but **e^- losses/vacuum**.

LEIR E-Cooler Gun Settings

- **Transverse beam distribution** can be adjusted (as already seen):



$$\frac{V_{control}}{V_{grid}} \begin{cases} \approx 0.9 => \text{hollow distribution} \\ \approx 0.5 => \text{partially hollow distribution} \\ \approx 0.2 => \text{flat distribution} \\ \approx 0 => \text{parabolic distribution} \end{cases}$$

- **Electron current** depends from both V_{grid} and $V_{control}$ in a **non trivial way** as **Perveance** (***P***) **is not constant**.

$$I_{gun} = P(V_{grid})^{3/2}$$

Perveance naïve fit looking at available data:

$$P = 9.06(\frac{V_{control}}{V_{grid}} + \frac{1}{2})^{5/2}$$

Dashed lines generated using “fitted” Perveance

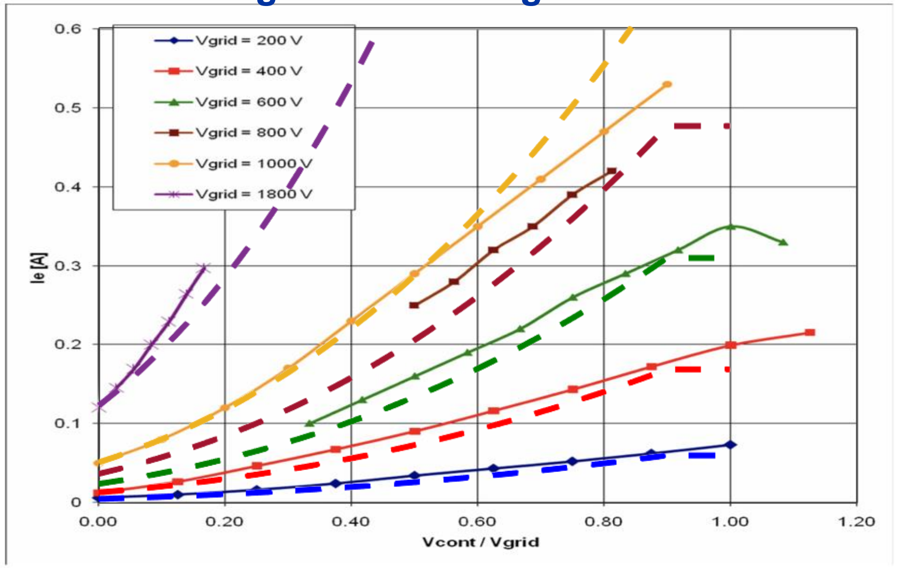
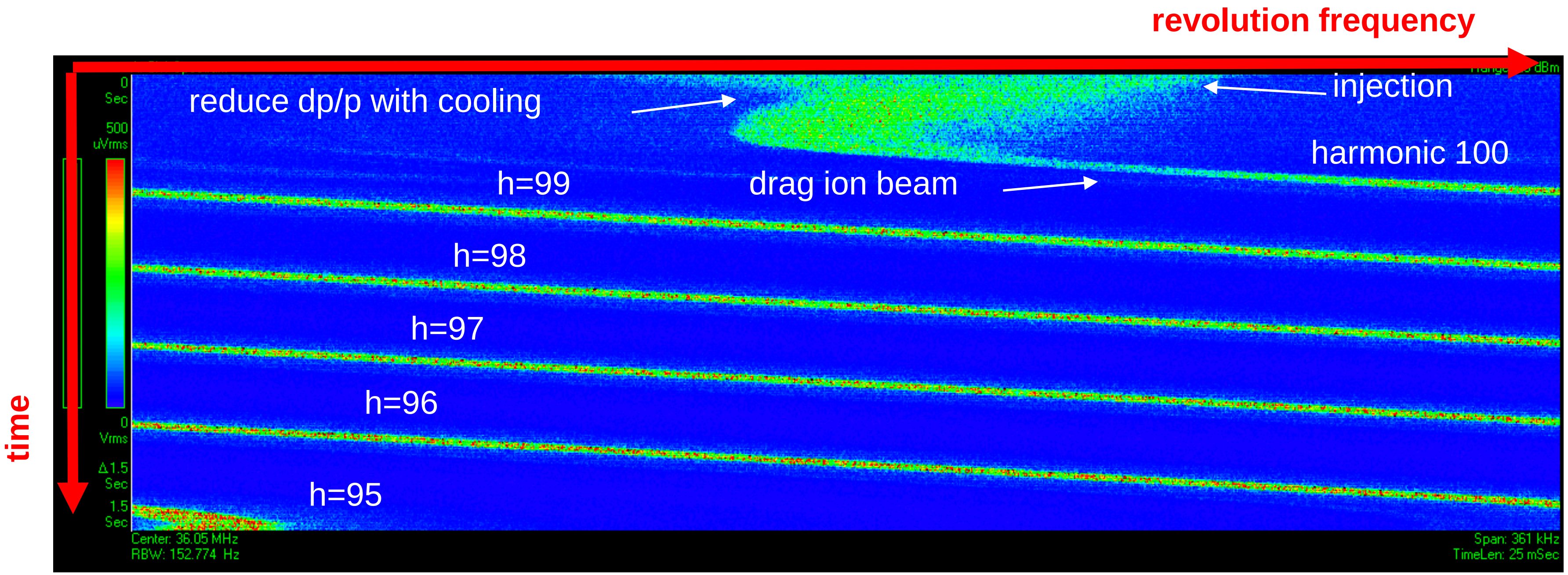


Figure 1: Electron beam current as a function of the ratio V_{cont}/V_{grid} , for an electron beam energy $E_e = 2.3$ keV.

LEIR: Ion Acceleration with the Electron Cooler

The same concept can be used to accelerate the beam! Just **keep increasing** the **Vgun** while **adjusting magnetic cycle** to follow increase of ions momentum

- **Very slow process!** Managed to **increase momentum** only of about **6%** in **~1 second** for a low intensity ion beam.

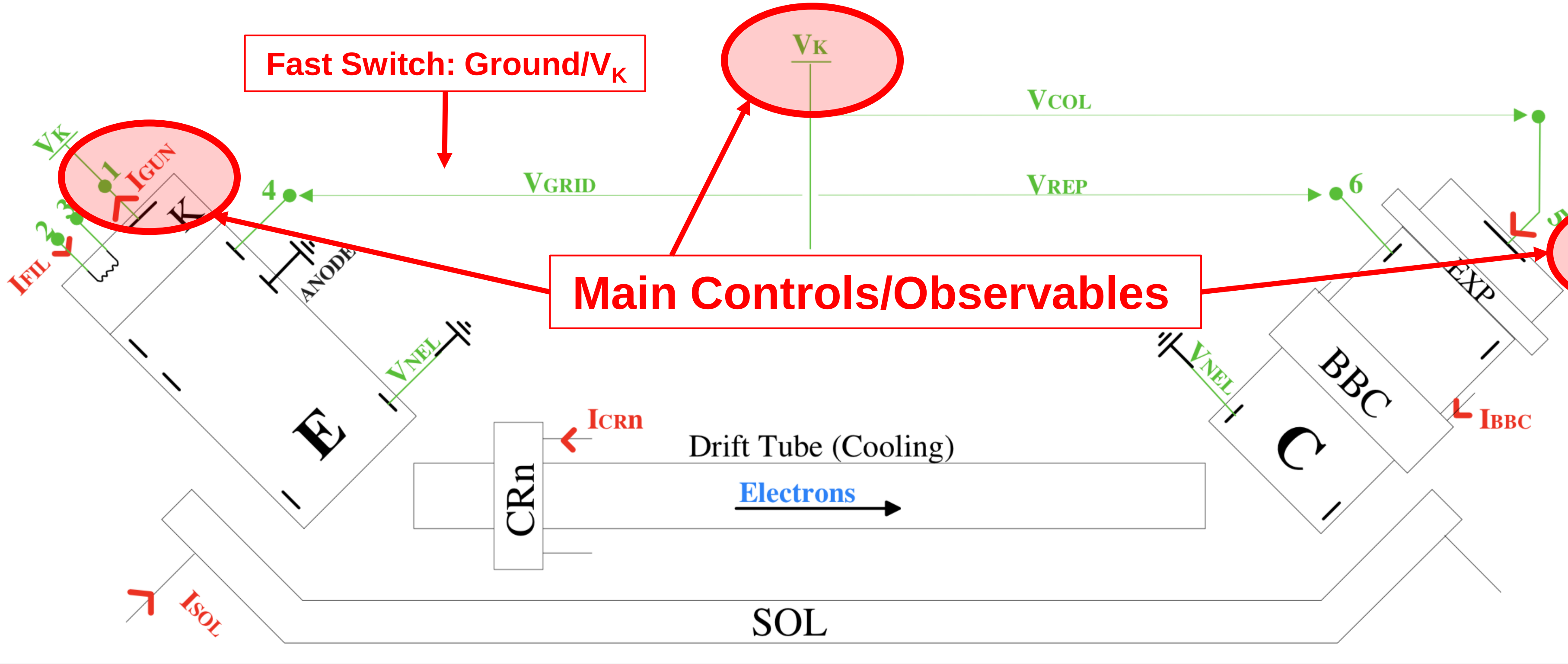


Longitudinal Schottky

More Details in CERN-ACC-NOTE-2020-0023 and A. Saa Hernandez E-BEAM#2

AD E-Cooler Power Supplies

Circuitry is very similar to the LEIR e-cooler one, but with some more simplifications and less tuning knobs (e.g. simpler gun, single PC for main solenoids/toroids)



$$E_k = eV_K$$

$$I_e = PV_K^{\frac{3}{2}}$$

$$P = 0.58 \times 10^{-6}$$

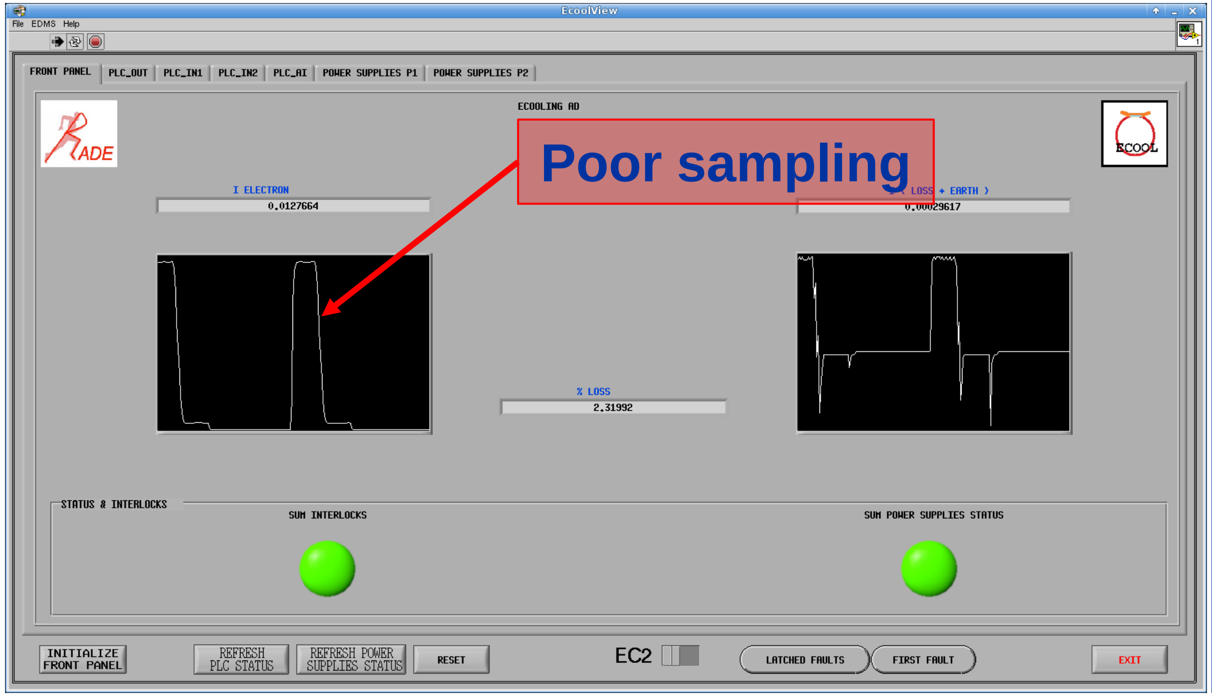
"Effective" perveance might decrease with time due to thermionic cathode aging…

AD Tools: E$^-$ Beam Current Monitor (similar in LEIR)

Controlling e-cooler interlocks and e- beam current/losses with two independent tools:

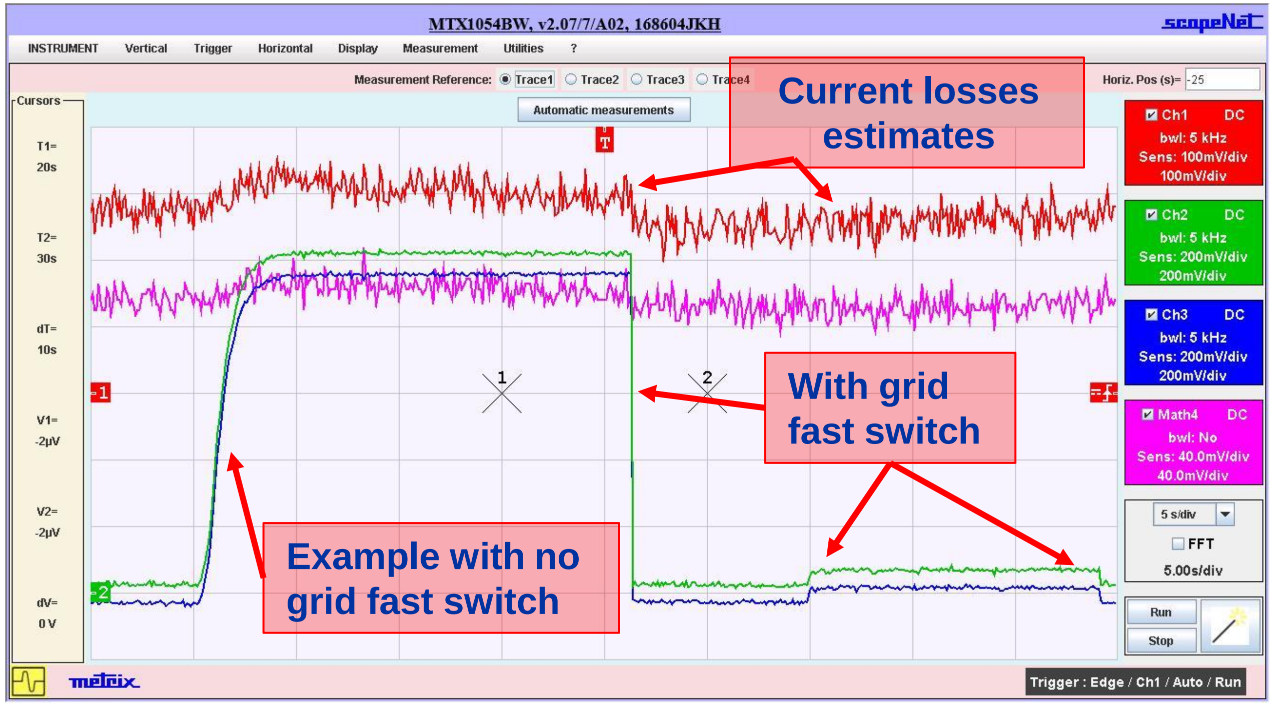
LabView: Mixture between BI PLC communication and Power Converters FESA classes

- Estimates e- beam current via $I_{collector}$; losses via I_{katode}

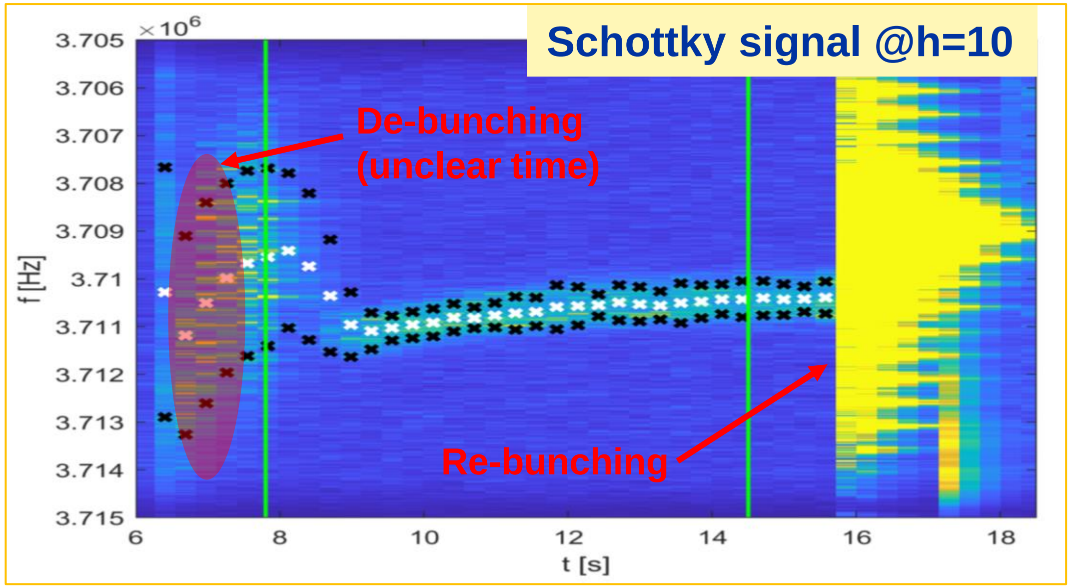


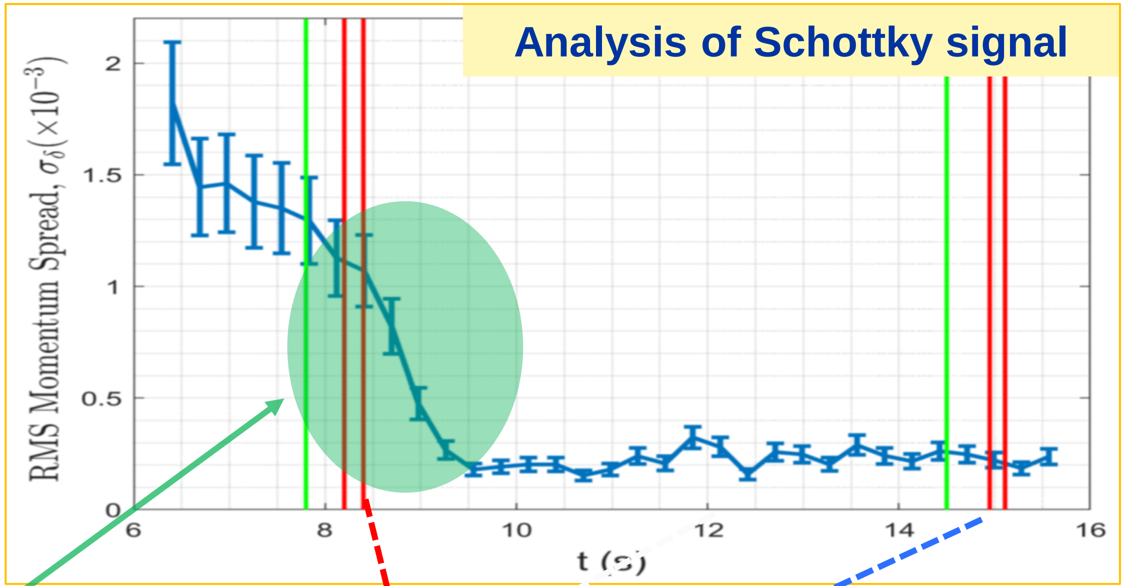
VirtualScope installed in the HV Cage:

- Clearly showing fast switches "stopping" (or not) the beam
- Similar view available also for LEIR

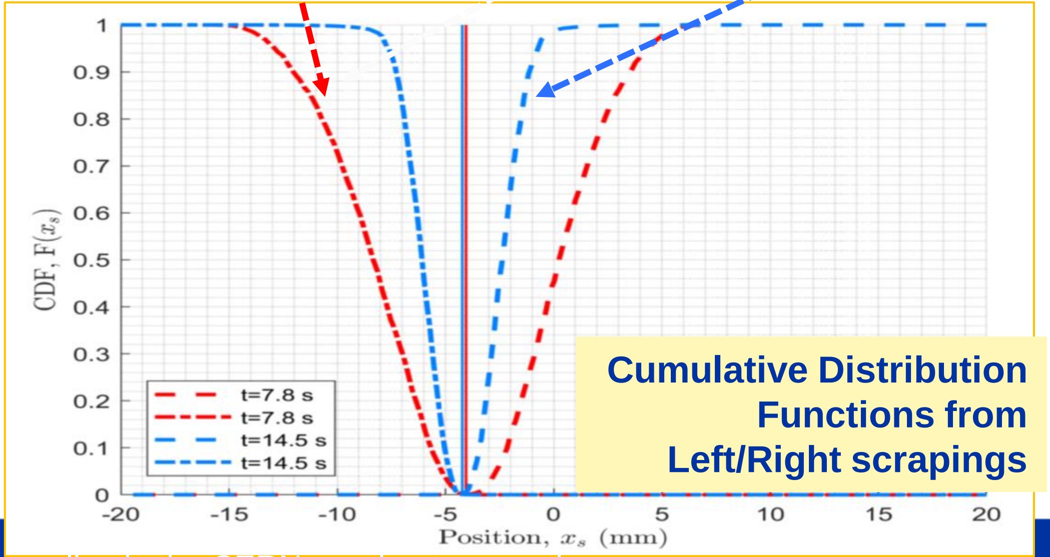


ELENA: Some detailed analysis of Cooling





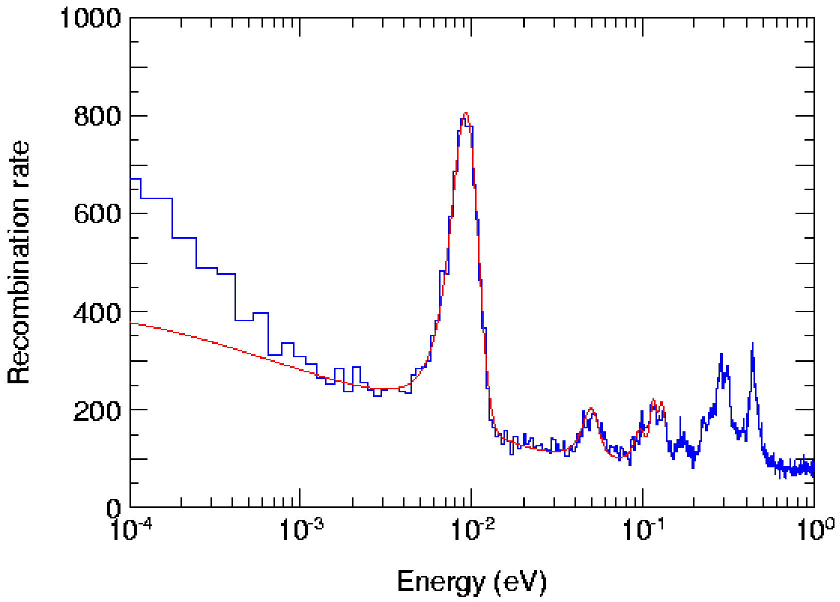
- **Longitudinal cooling time** of the order of **1 s**
  - **Momentum spread ~2.5e-4 compatible with expectations**
- Clear **reduction** of transverse **beam size**
- Some **drift** of **mean energy**
  - **e- beam energy drift?**



From J.Hunt PRAB

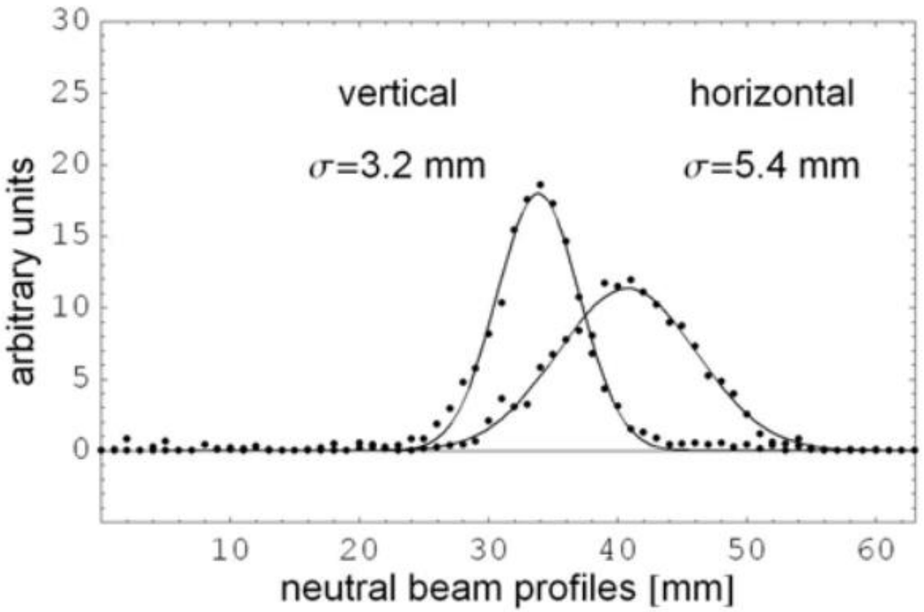
Beam diagnostics based on recombination

CRYRING



Measured rate coefficient for dielectronic recombination of F6+. The red curve was obtained by fitting a theoretical cross section calculated by Eva Lindroth at Stockholm University to the large peak at 10-2 eV, the shape of which is sensitive to both transverse and longitudinal electron temperatures. This fit gave kTperp = 1.5 meV and kTpar = 0.10 meV. The rate is in arbitrary units and the calibration of the experimental energy scale is only approximate. (CRYRING webpage)

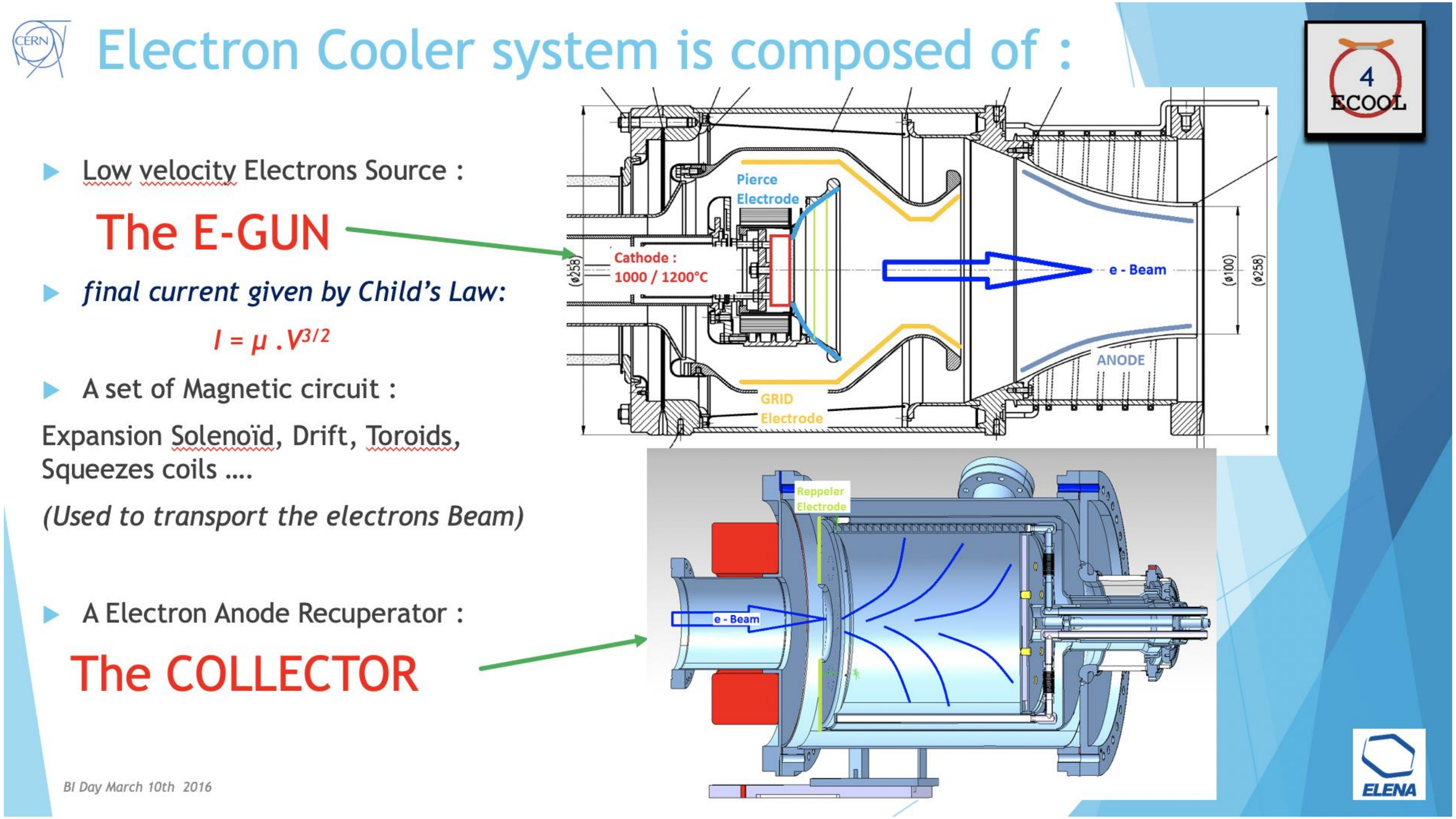
COSY



Horizontal and vertical H 0 profiles with a 0.35 mrad horizontally misaligned electron beam. Electron beam current 130 mA.

M. Bai – BND School 2015 – indico

ELENA Gun and Collector



From- J. Cenede — BI Day 2016