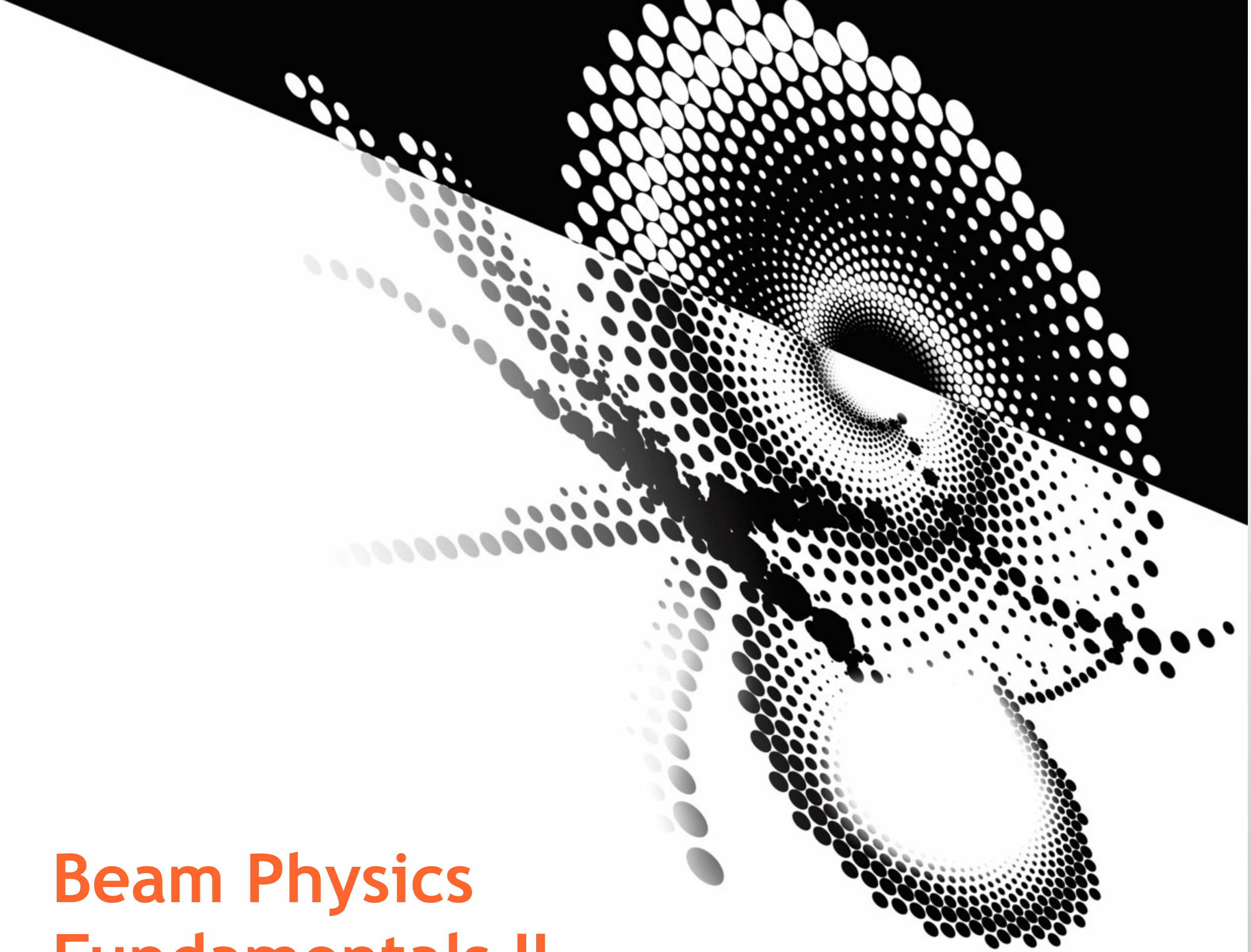


Beam Physics Fundamentals II

AVA Low Energy Antimatter Physics School
25 June 2018, CERN

Javier Resta López
University of Liverpool
The Cockcroft Institute

Outline

- Storage rings
- Beam temperature
- Beam heating
- Beam cooling techniques:
  - Stochastic cooling
  - Electron cooling
  - Laser cooling
- The Antiproton Decelerator
- ELENA
- Electrostatic transfer lines

Storage rings

- Leptons:
  - Electrons, Positrons, (Muons)
  - Colliders
  - Synchrotron radiation facilities
  - SR benefit (cooling, synchrotron light) and nuisance (energy limitation)
  - Radiated power:

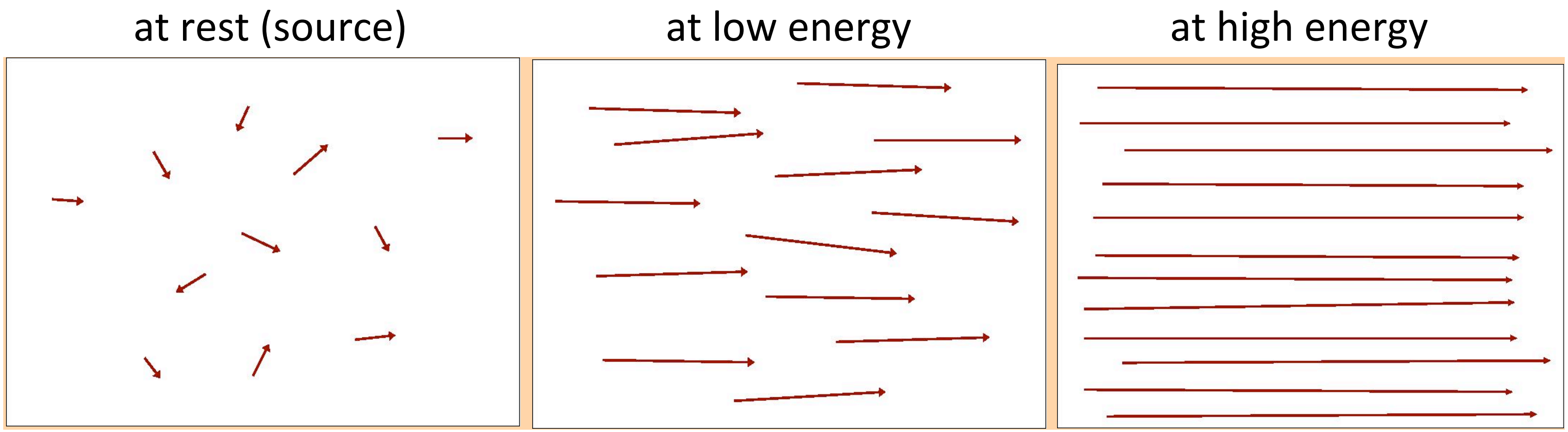
$$P \propto \frac{E^4}{\rho^2}$$

Storage rings

- Hadrons:
  - Protons, Ions, RIBs, Antiprotons
  - Colliders
  - Internal experiments
  - Preparation of secondary beams
  - Cooling provides flexibility for various methods of manipulation
  - Goal: good beam quality, high beam lifetime, high luminosity

Beam temperature

- Thermal particle motion (temperature is conserved)



- Thermal motion is superimposed the average motion after acceleration

- Many processes can heat up the beam: mismatch, space charge, IBS, residual gas, internal targets, external noise, etc.

Beam temperature

- Longitudinal beam temperature

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

- Transverse beam temperature

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

- Particle beams can be anisotropic: $k_B T_{\|} \neq k_B T_{\perp}$

- Do not confuse beam energy with beam temperature!

  (e.g. a beam of energy 100 GeV can have a temperature of 1 eV)

Beam heating

❑ Heating processes:

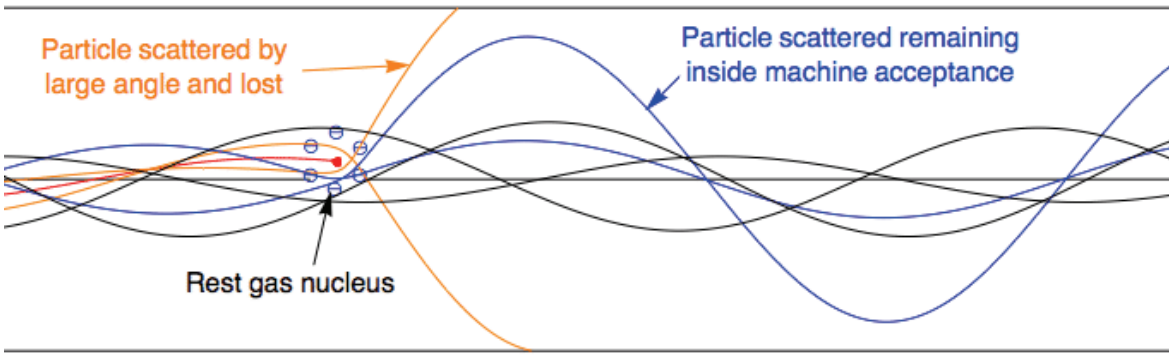
- ❑ Interaction with the **rest gas**:
  - – Nuclear scattering
  - – Single Coulomb scattering

  } ⟶ particle loss if high scattering angle
  - – Multiple Coulomb Scattering (MCS)

- ❑ **IntraBeam Scattering (IBS)**: multiple small-angle Coulomb scatterings of charged particles within the accelerator beam itself.

- ❑ Space charge, tune resonances (optics nonlinearities), impedances, etc.

Rest gas scattering



- Emittance growth caused mainly by Multiple Coulomb Scattering

$$\frac{d\epsilon_{rms}}{dt} = 2\pi \langle \beta_\perp \rangle n_{ms} \ln\left(\frac{280}{\alpha}\right) r_e^2 \frac{(m_e c^2)^2}{\beta c p^2}$$

Relativistic velocity factor: $\beta = v/c$

Average betatron function: $\langle \beta_\perp \rangle = 1/2(\langle \beta_x \rangle + \langle \beta_y \rangle)$

Multiple scattering density: $n_{ms} = \sum_i n_i \frac{Z^2 \ln\left(280/\left(\alpha (AZ)^{1/3}\right)\right)}{\ln(280/\alpha)}$

N. Madsen, CERN/PS/DI Note 99-06, (1999)

IBS

- Multiple small-angle Coulomb scatterings of charged particles within the beam itself
- Exchange of energy between the transverse and longitudinal degrees of freedom, leading to the growth of the beam phase dimensions
- **Emittance growth rates:**

$$\boxed{\frac{1}{\tau_x}, \frac{1}{\tau_y}, \frac{1}{\tau_p} \propto \frac{r_p^2 c}{32\pi\sqrt{\pi}\beta^3\gamma^4\epsilon_x\epsilon_y\sigma_p}\lambda}$$

$$\lambda = \begin{cases} N/C & \text{for coasting beams} \\ N_b/(2\sqrt{\pi}\sigma_s) & \text{for bunched beams} \end{cases}$$

where N is the number of particles in the beam,

and N_b is the number of particles per bunch;

C is the circumference of the ring, σ_s the bunch length, and

σ_p the momentum spread

Beam cooling

- Beam cooling means reduction of beam temperature

- In this context, temperature is equivalent to terms as phase space volume, emittance and momentum spread

- Beam cooling techniques are non-Liouvillean, i.e. violate the assumption of conservative forces

Benefits of beam cooling

- Improved beam quality
  - Precision experiments
  - Luminosity increase (in colliders)
  - Increase lifetime

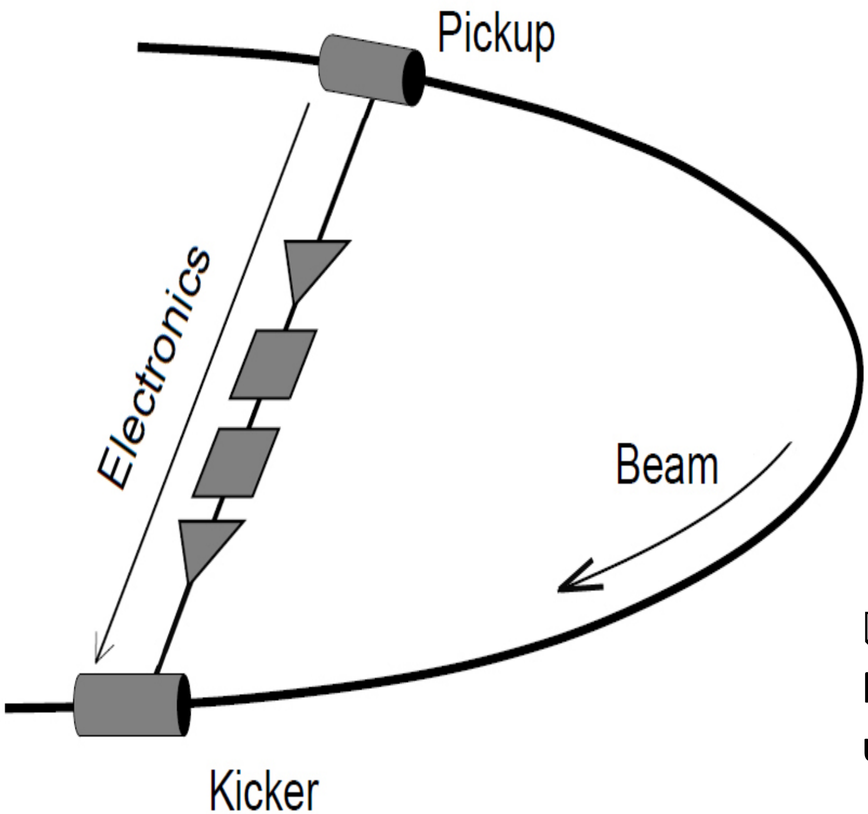
- Compensation of heating
  - Experiments with internal target
  - Colliding beams
  - Other scattering effects, e.g. IBS

- Intensity increase by accumulation
  - Weak beams from the source can be enhanced
  - Secondary beams (antiprotons, rare isotopes)

Stochastic cooling

- First cooling method which was successfully used for beam preparation

S. van der Meer, D. Möhl, L. Thorndahl et al.



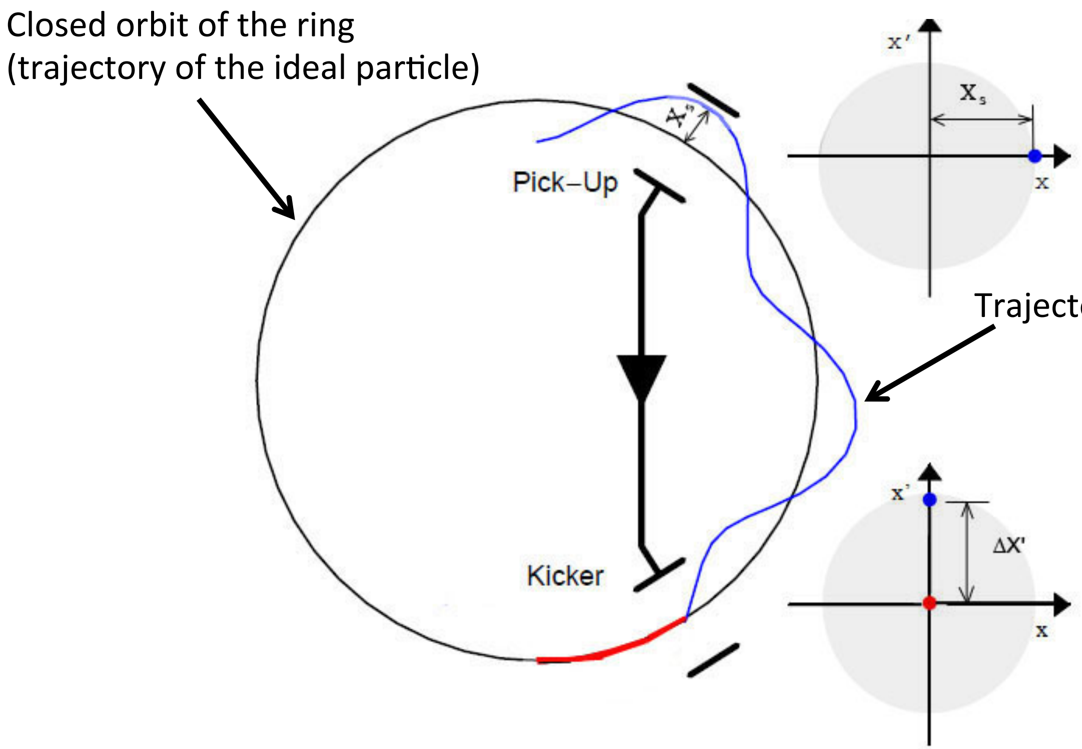
Betatron phase advance (pick-up to kicker): $(n+1/2)\pi$

- Basic principle:

Measurement of deviation from ideal orbit is used for correction kick (feedback)

Stochastic cooling

- Single particle consideration:
  - One particle passing with maximal position at pick-up
  - Requirement: particle crossing the reference orbit at kicker with maximal angle



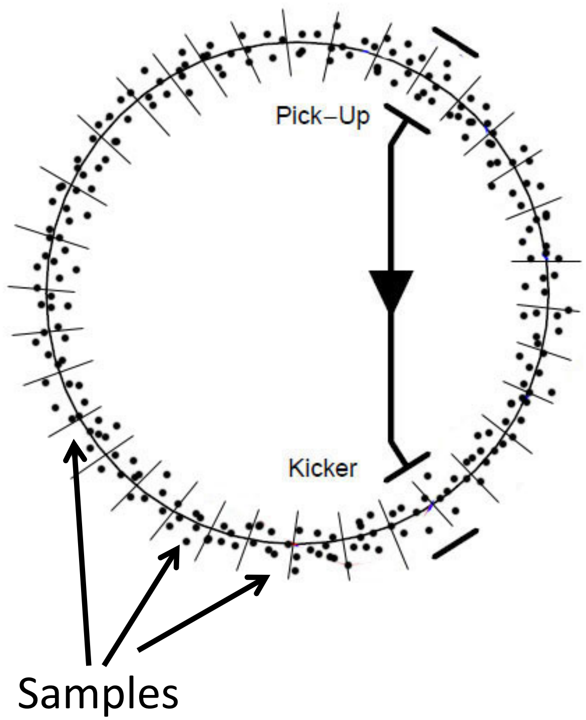
$$\Delta X' = g X_s$$

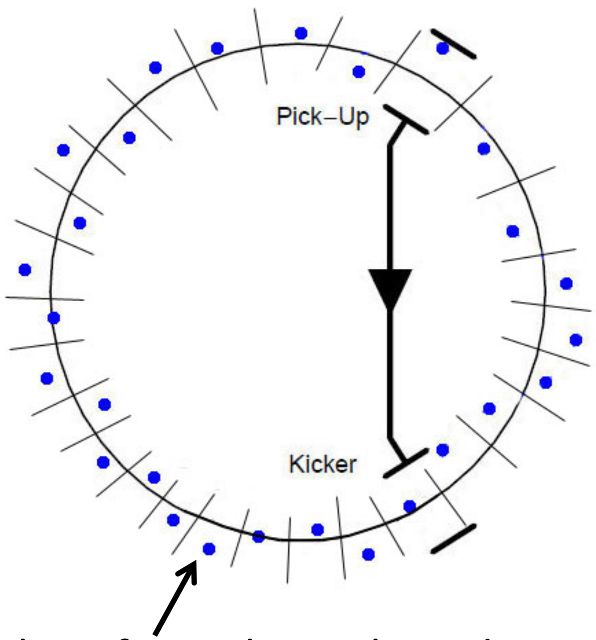
g – normalized gain

$[0 < g < 1]$

Stochastic cooling

- Coasting beam:
  - The coasting beam is sampled. The number of samples and its time length is defined by frequency range [f_1 ; f_2] of SC. Bandwidth $W=f_2-f_1$

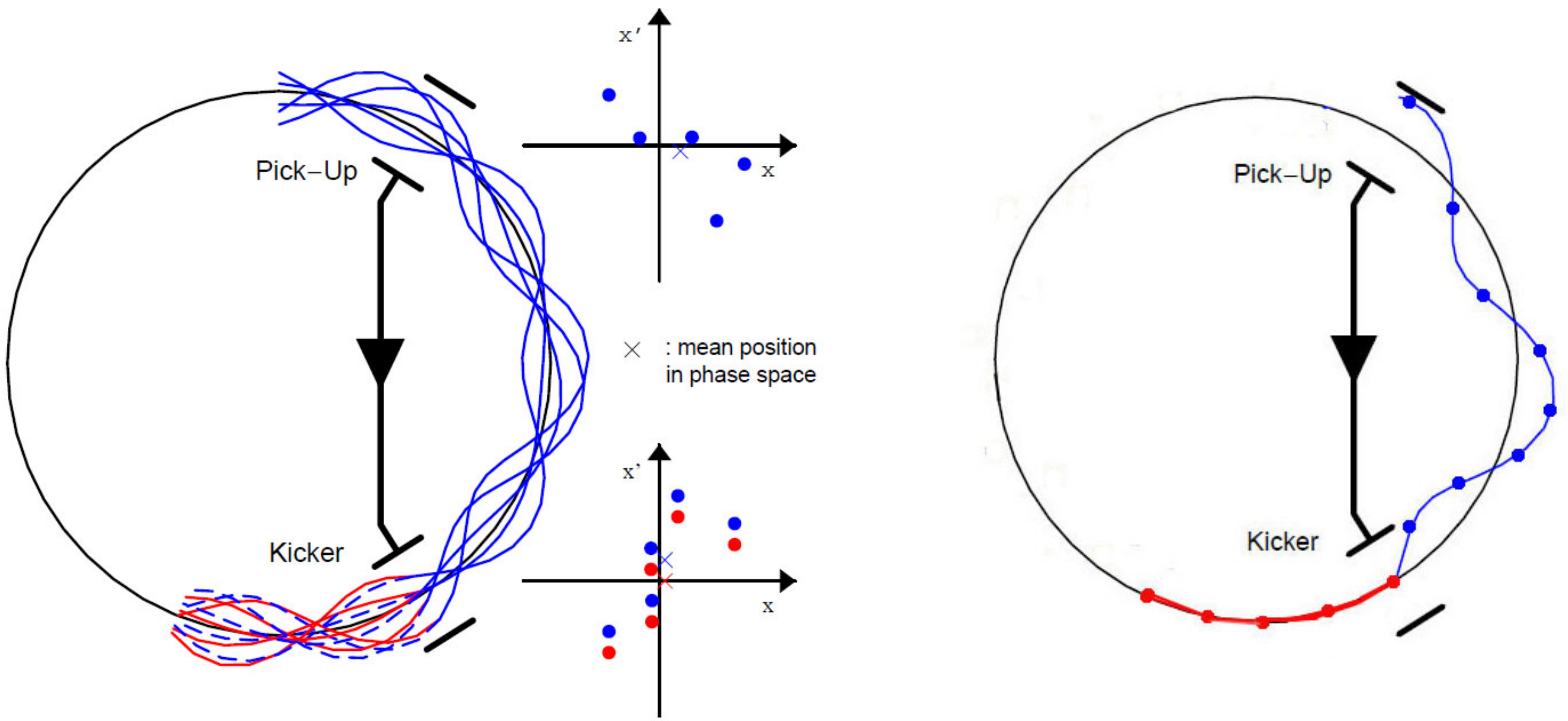




Mean value of sample: Pick-up detects the value of this displacement and forms the signal.

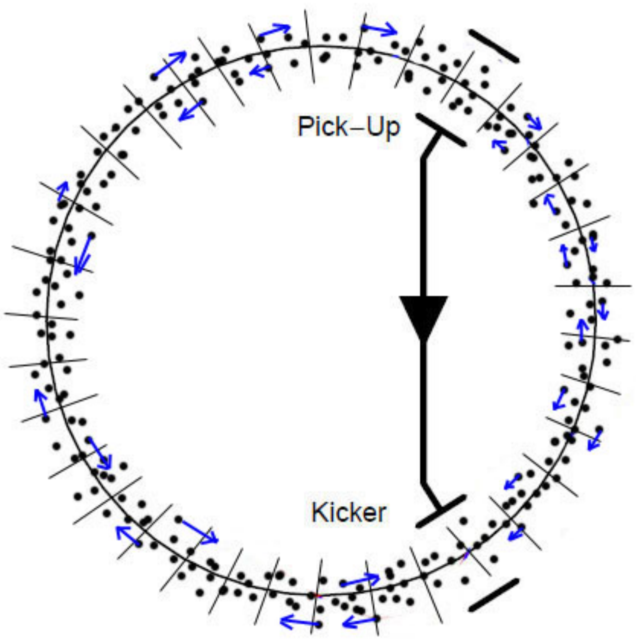
Stochastic cooling

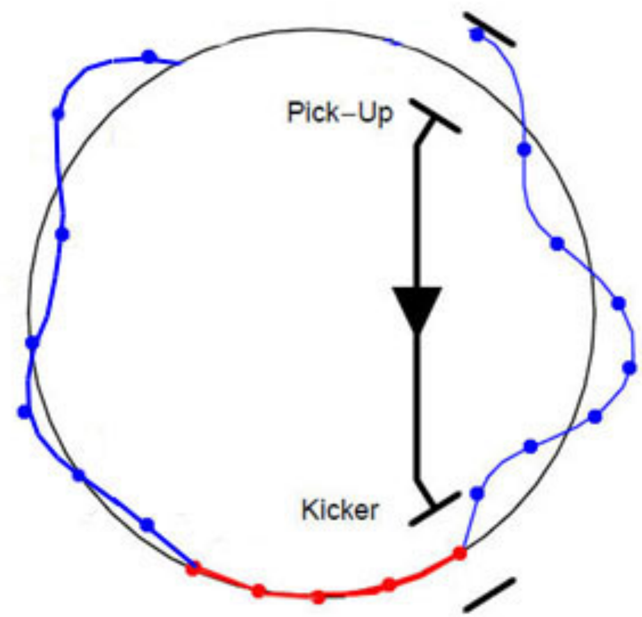
- Sample of particles passing the kicker gets correction of the mean position
- The individual particle coordinate is reduced by the mean value of the ensemble. After one turn one has not fully achieved cooling



Stochastic cooling

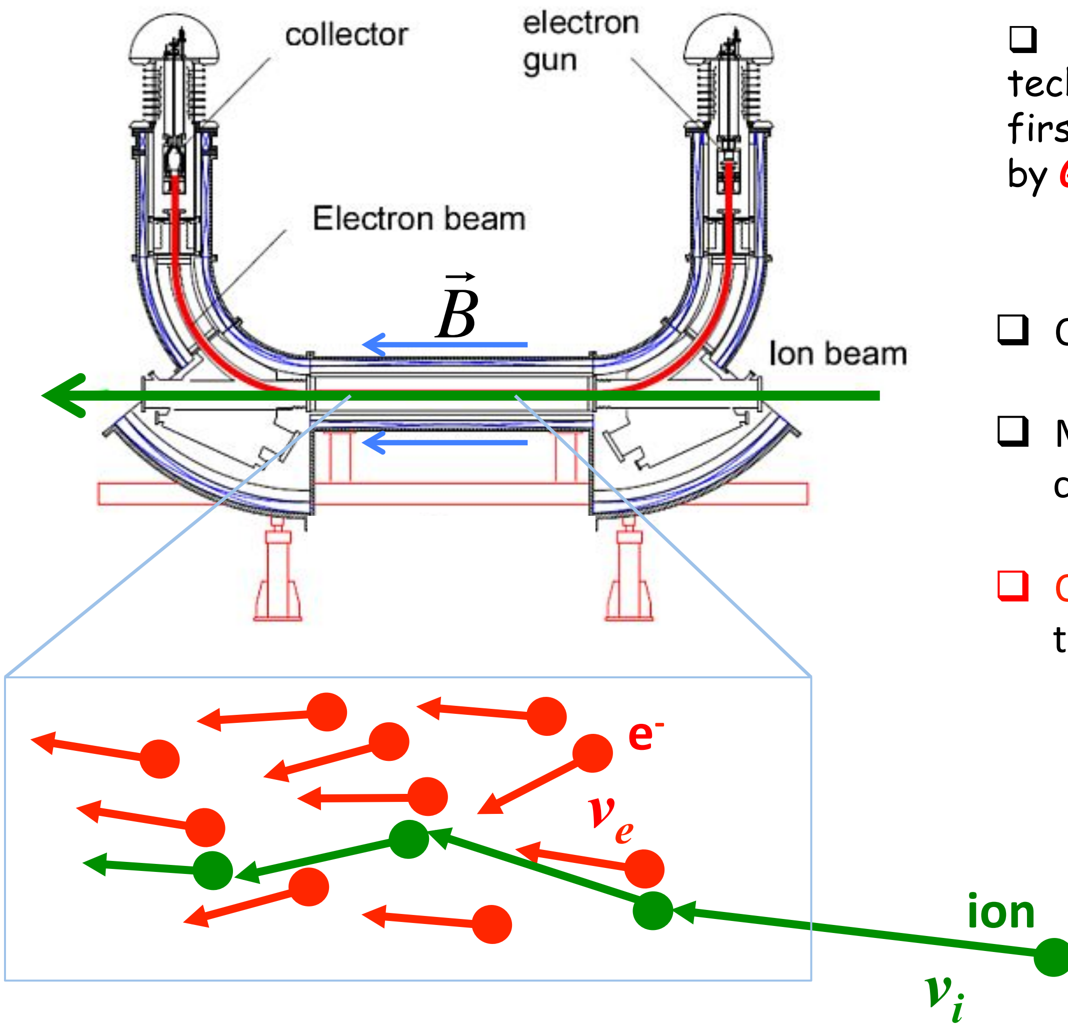
- Mixing:
  - All particles migrate from one sample to another one. This particle migration is called “mixing”.



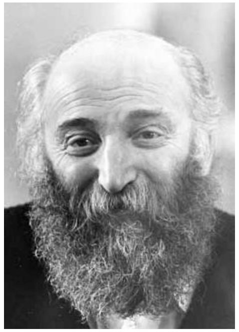


  - Because of mixing the new mean value of sample is formed.
    At the next turn the pick-up detects this value and then the kicker corrects it again

Electron cooling



- Consolidated technique, first proposed by **G. Budker** in 1966



- Cold electrons interacting with hot ions
- Momentum transfer by Coulomb collisions
- Cooling force results from energy loss in the co-moving gas of free electrons

Equilibrium:

$$k_B T_i = k_B T_e \quad \text{or} \quad m_i v_i^2 = m_e v_e^2$$

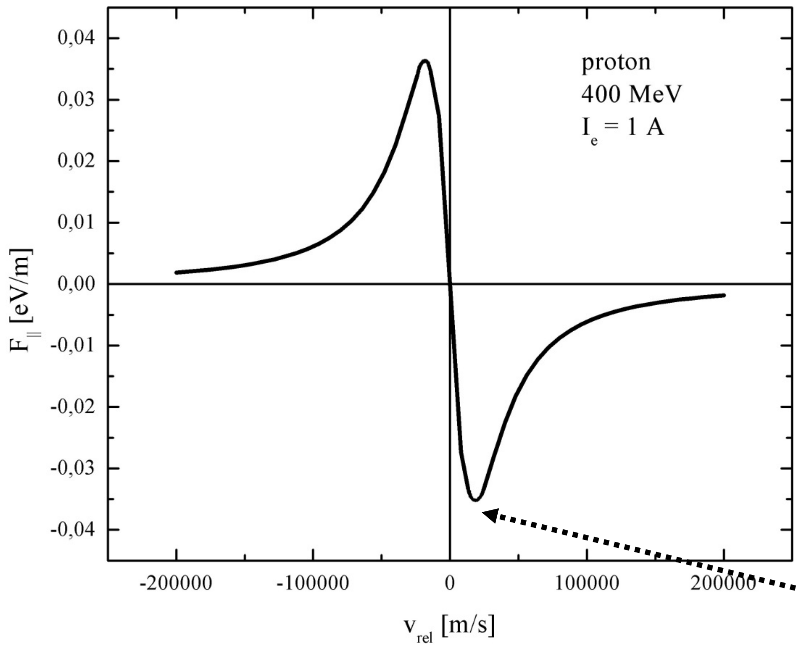
$$v_i = v_e \sqrt{\frac{m_e}{m_i}}$$

Electron cooling

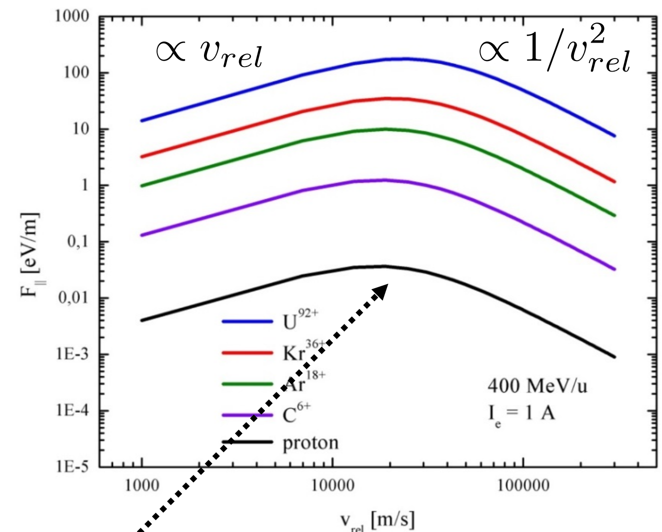
- Friction force

$$\boxed{\overrightarrow{F}(\overrightarrow{v_i}) = -\frac{4\pi Q^2 e^4 n_e}{(4\pi\epsilon_0)^2 m_e}\int L_C(\overrightarrow{v}_{rel}) f(\overrightarrow{v_e}) \frac{\overrightarrow{v}_{rel}}{v_{rel}^3} d^3\overrightarrow{v_e}}$$

$$\overrightarrow{v}_{rel} = \overrightarrow{v_i} - \overrightarrow{v_e}$$



Increases with charge Q^2

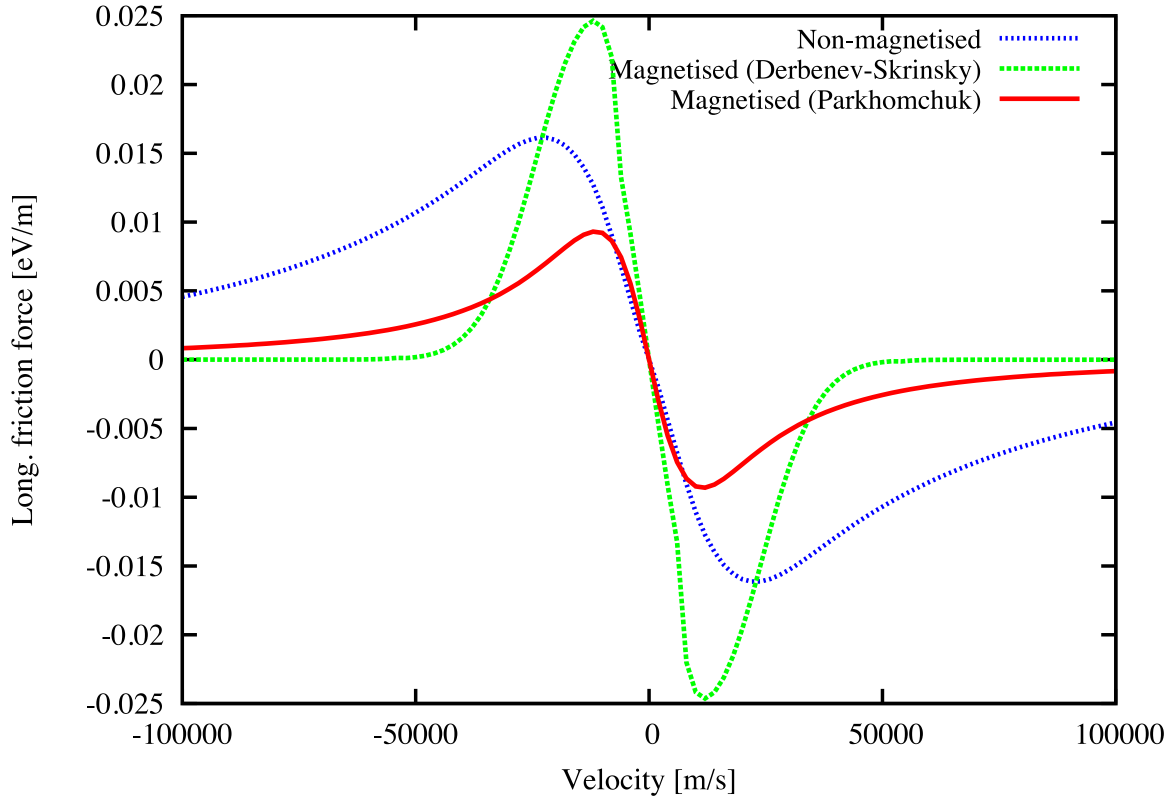


Maximum of cooling force at effective electron temperature

M. Steck (GSI) et al.

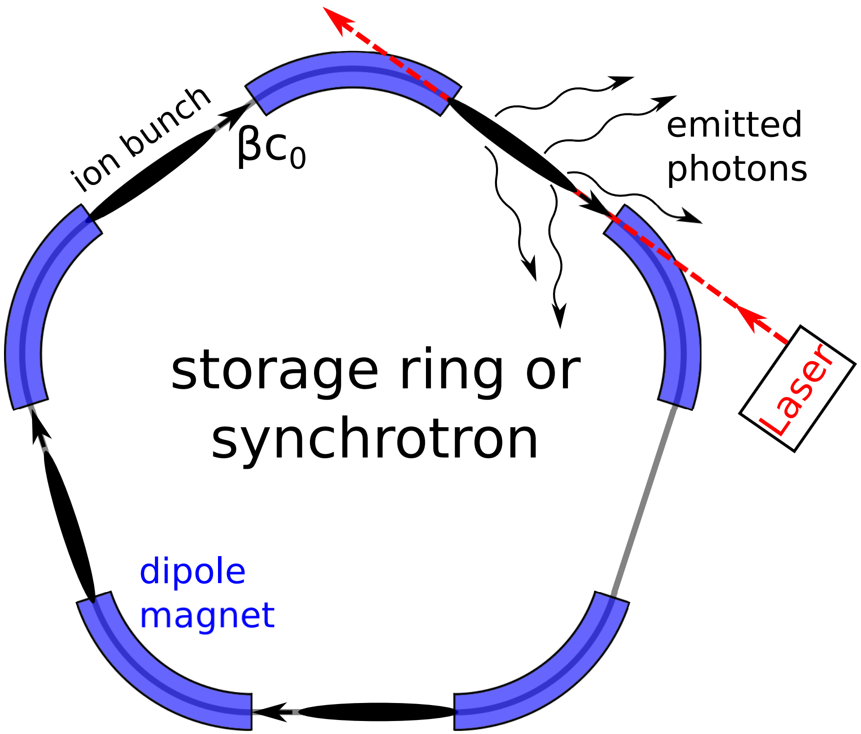
Electron cooling

- Friction force. Different models, e.g.



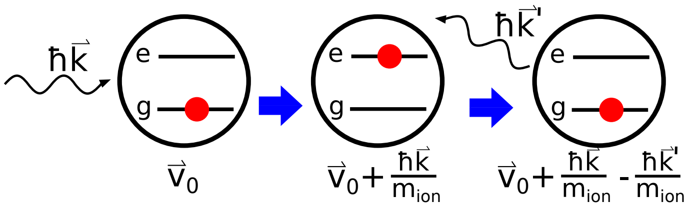
Example of longitudunal e-cooling friction force in the context of ELENA simulations

Doppler Laser cooling



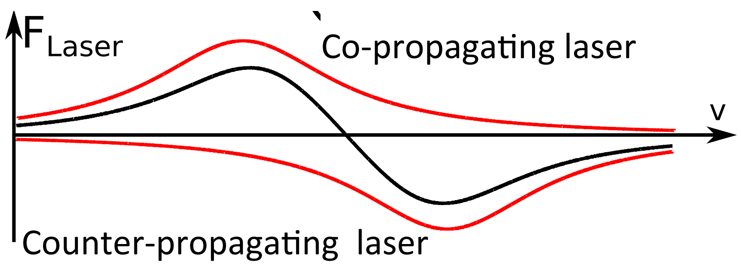
For certain type of ions only, e.g. $^{7}Li^{1+}$, $^{9}Be^{1+}$, $^{24}Mg^{1+}$, $^{12}C^{3+}$

Resonant ion-photon interaction



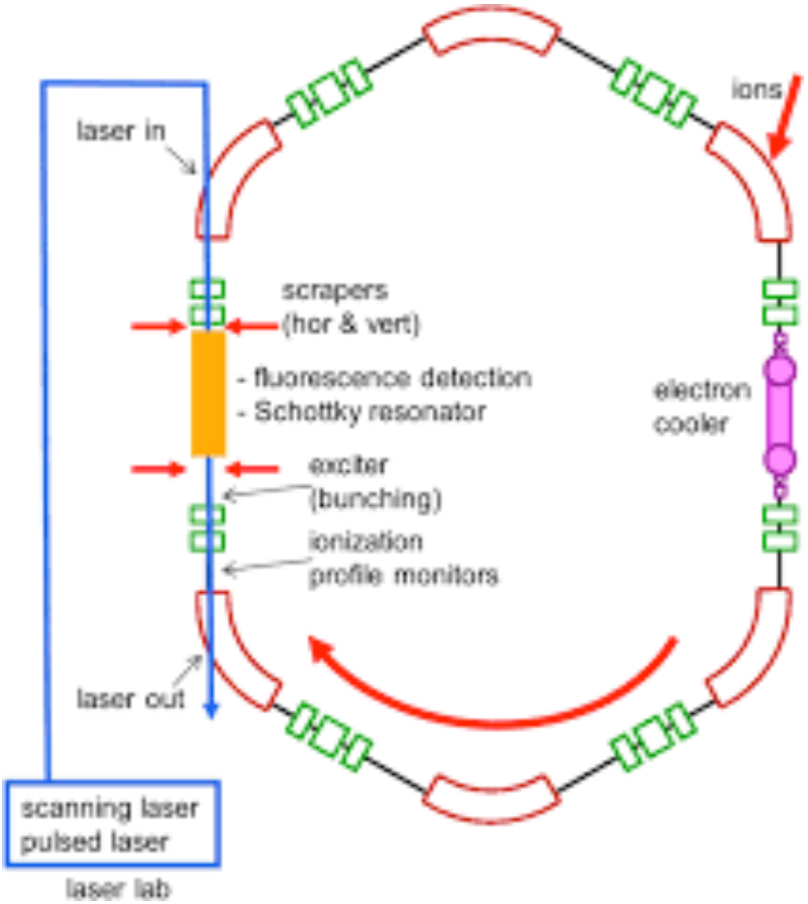
Directed excitation and isotropic emission result in a transfer of momentum

Friction force:

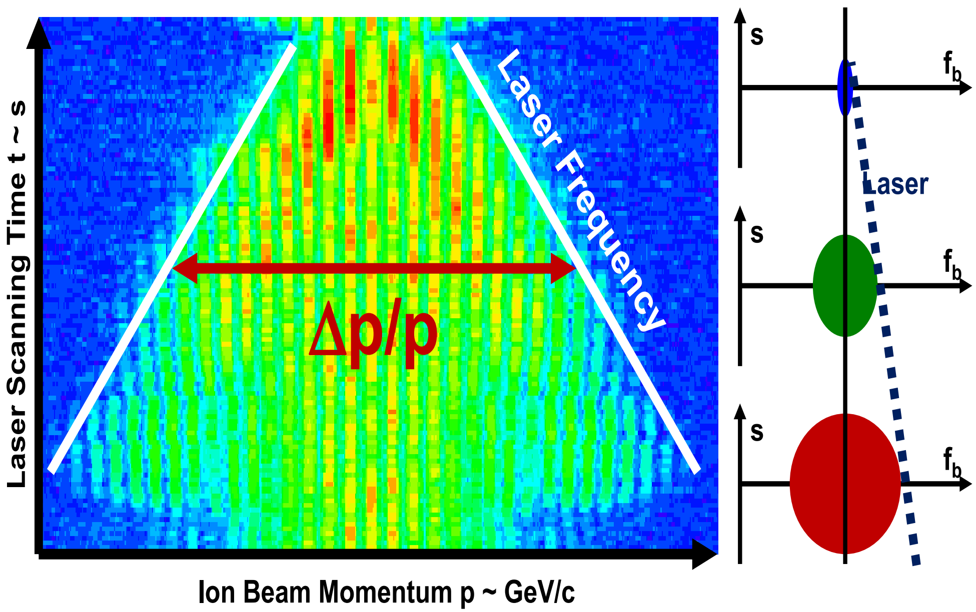


Doppler Laser cooling

- Example: C^{3+} laser cooling in ESR at GSI



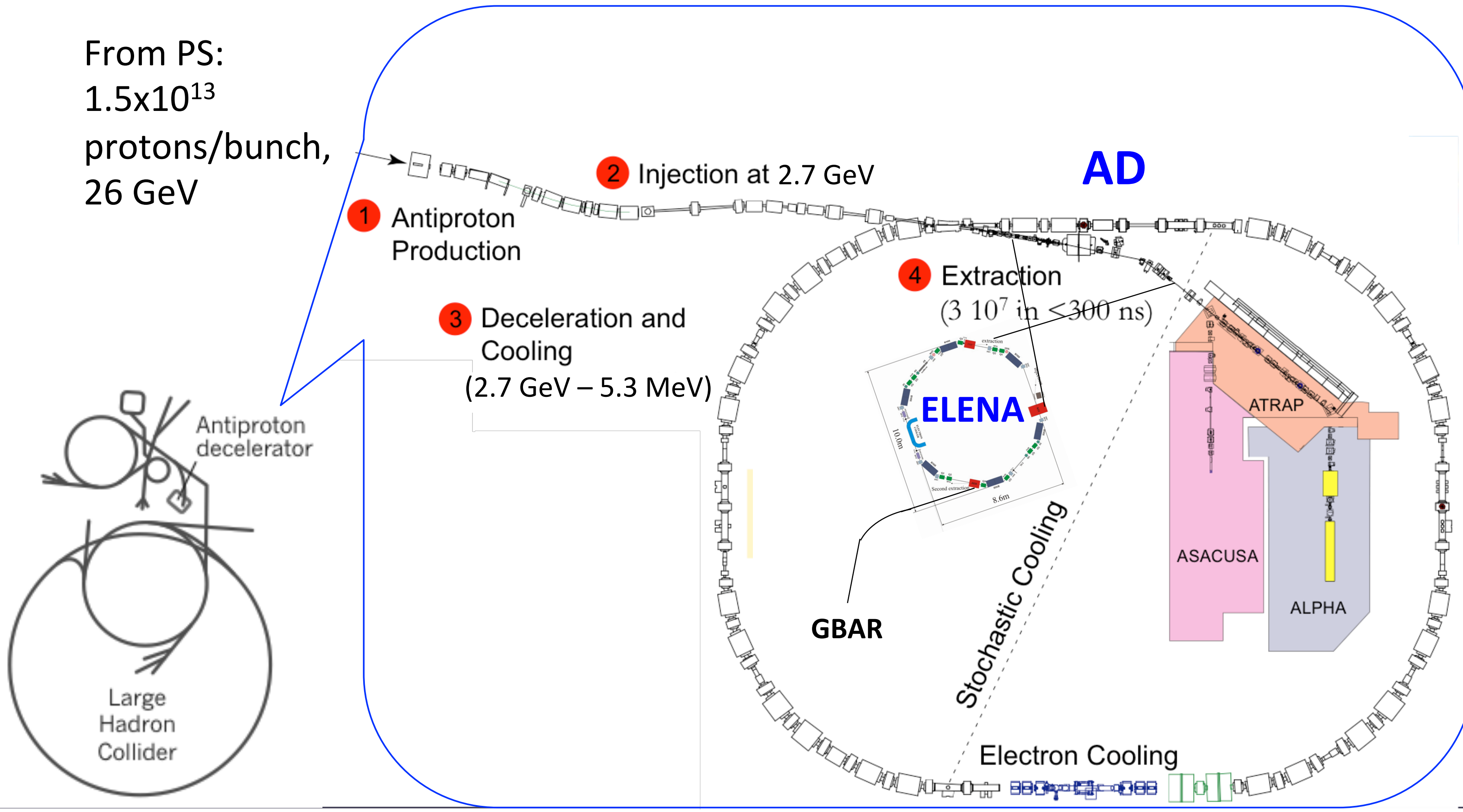
Scanning the laser frequency



M. Bussmann et al.

AD-ELENA complex

From PS:
1.5×10^{13}
protons/bunch,
26 GeV



Antiproton Decelerator

❑ Main parameters

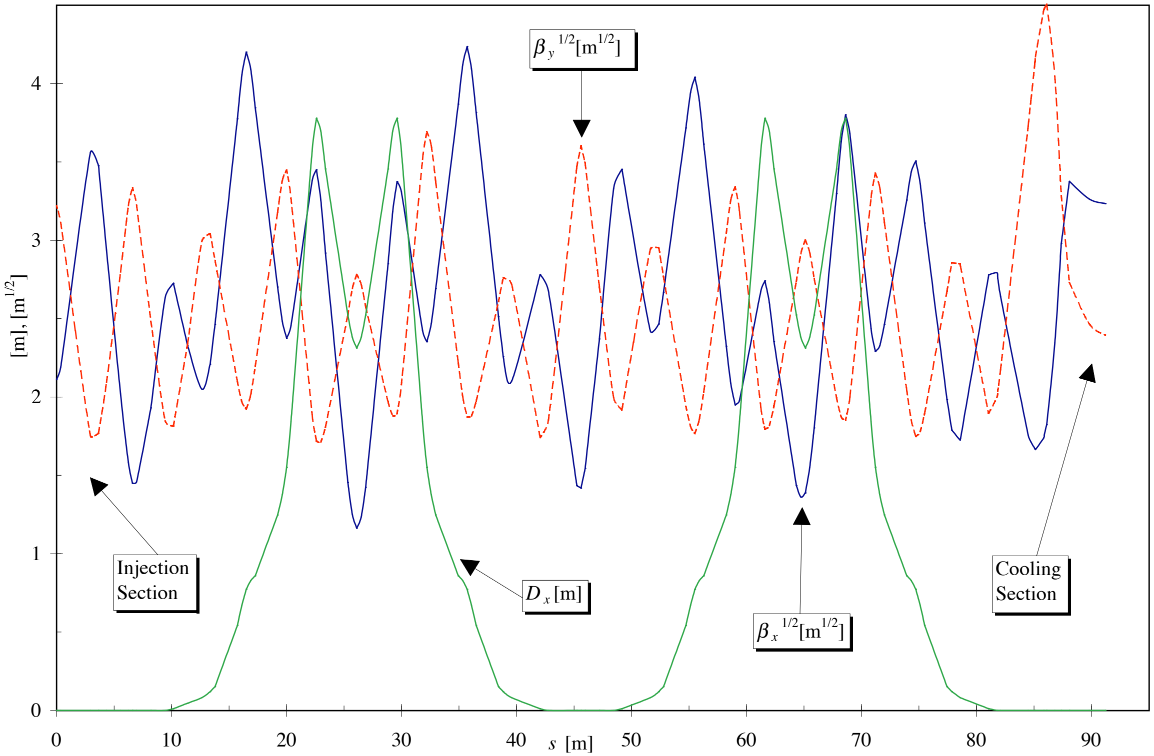
• Circumference	182 m
• Production beam	$1.5*10^{13}$ protons at 26 GeV
• Injected beam	$5*10^{7}$ pbars/cycle
• Beam momenta max-min	3.57 – 0.1 GeV/c
• Momenta for beam cooling:	
– Stochastic	3.57 and 2.0 GeV/c
– Electron	0.3 and 0.1 GeV/c
• Acceptances:	
– Transverse	200 pi mm mrad
– Longitudinal	$\pm 30\ 10^{-3}$
• Ejected beam at 100 MeV/c or 5.3 MeV:	
– Intensity	$\sim 3\ 10^{7}$
– Transverse emittances	5 pi mm mrad (dense core ~1 pi mm mrad)
– Momentum spread	$1*10^{-4}$
– Bunch Length	~200 ns
• Vacuum pressure, average	$4*10^{-10}$ Torr
• Cycle length	100 s

Antiproton Decelerator

❑ Ring Optics

4 arcs: chromaticity correction, dispersion suppression

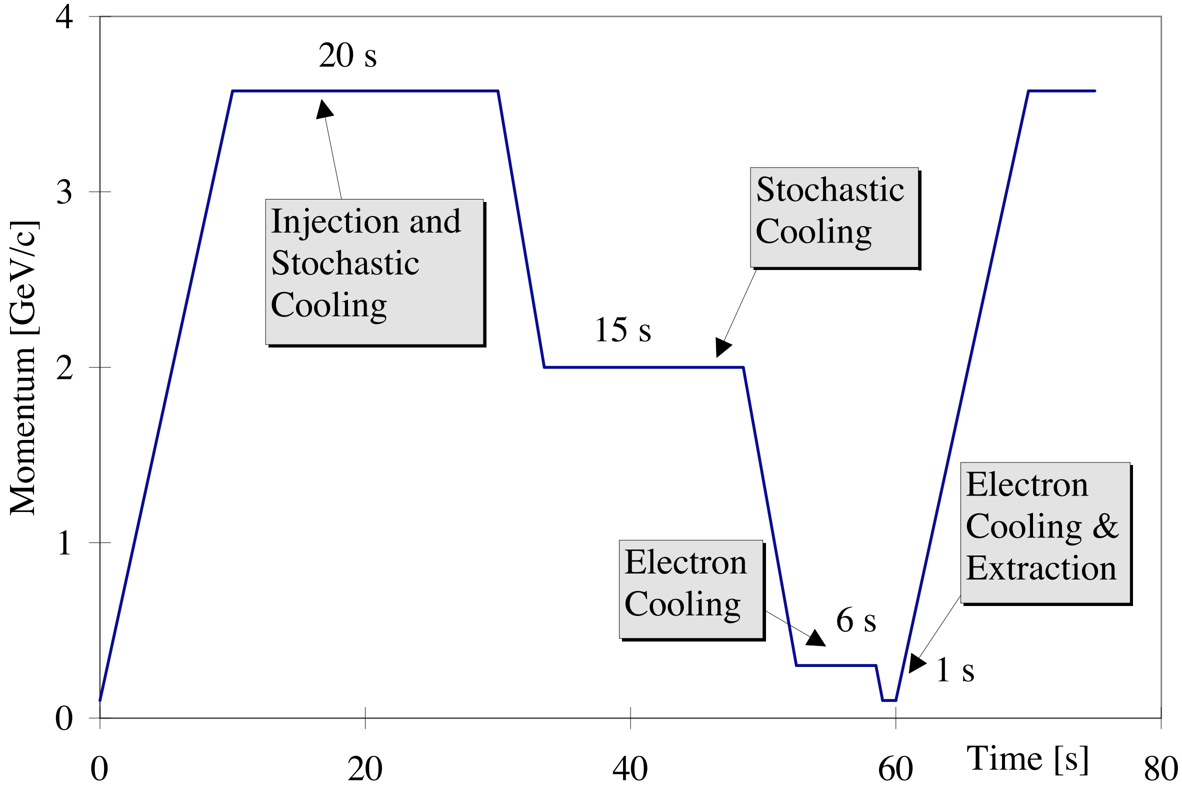
4 dispersion free straight sections: s-cooling, e-cooling, RF, diagnostics



S. Baird et al., Proc. of PAC1997
P. Beloshitsky et al, Proc. of PAC2001

Antiproton Decelerator

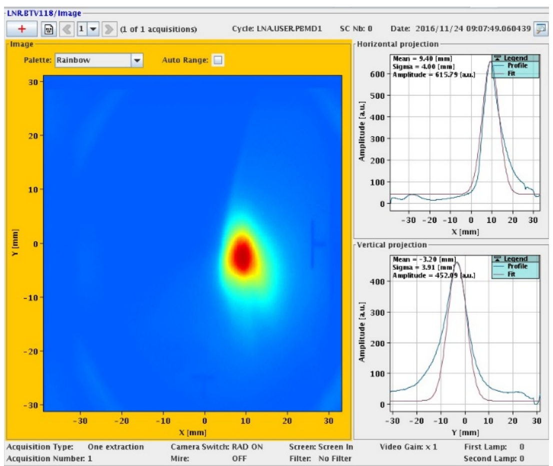
- Deceleration cycle

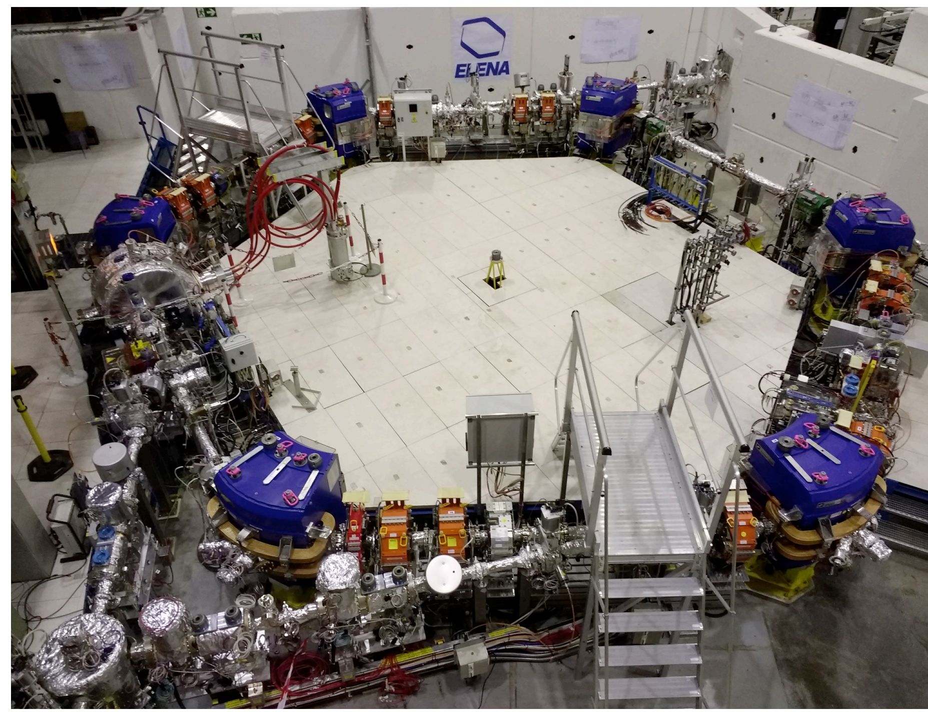


ELENA

- **ELENA** will bring a 10 to 100-fold increase in the experiments' efficiency, as well as the possibility to accommodate an extra experimental area to investigate gravitation with antihydrogen (GBAR)

- Currently under commissioning





18th Nov. 2016: First H- beam in ELENA

2nd August 2017: First 5.3 MeV pbar beam in ELENA

ELENA

Main parameters

Circumference (m)	30.4
Nominal (dynamic) vacuum pressure (Torr)	3×10^{-12}
Machine tunes Q_x/Q_y	2.3/1.3
Repetition rate (s)	$\approx$100
Kinetic energy range (MeV)	5.3–0.1
Momentum range (MeV/c)	100–13.7
Beam intensity (number of $\bar{p}$)	$\sim(1\text{–}3)\times 10^7$
Transverse acceptance (μm)	75
Ejected emittance (rms) $\epsilon_{x,y}$ (π mm mrad)	$\sim$1
Ejected relative momentum spread (rms) σ_p/p (%)	$\sim$0.05
Number of ejected bunches	4
Ejected bunch length (m)	1.3

❑ Ring optics

Good tunability in the range $2 < Q_x < 2.5$ and $1 < Q_y < 1.5$

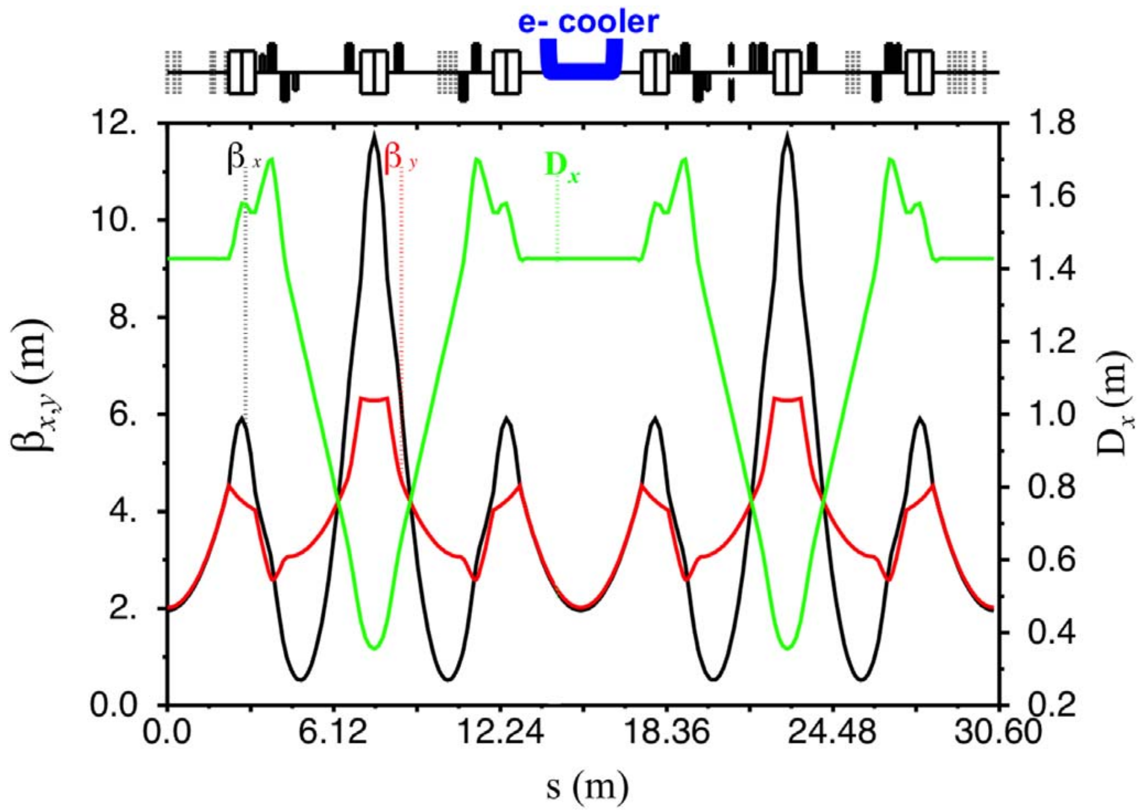
Hexagonal lattice

Periodicity of two:
- e-cooling section + 2 standard sections
- Injection section + 2 standard sections

3 families of quadrupoles (each of 4 members)

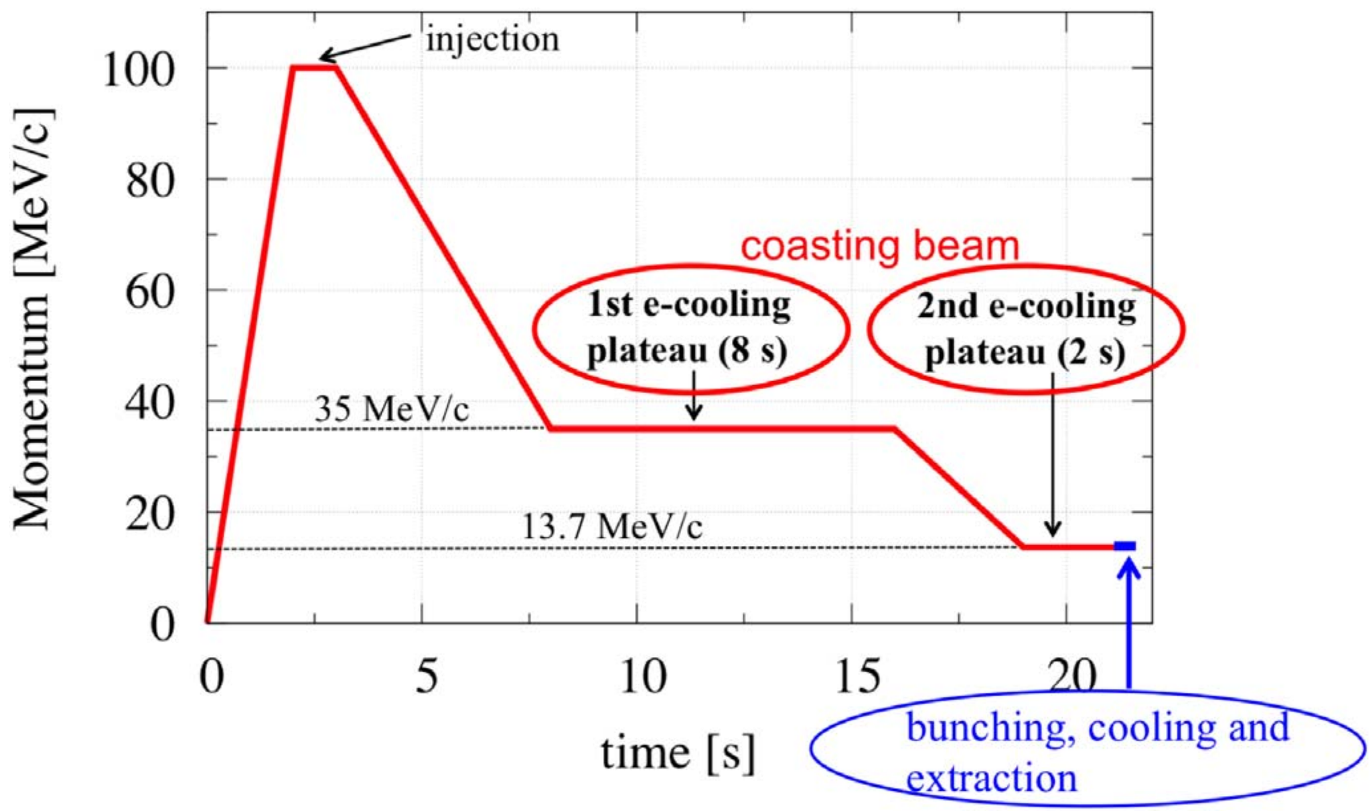
2 skew quadrupoles

2 families of sextupoles (each of two members)



ELENA

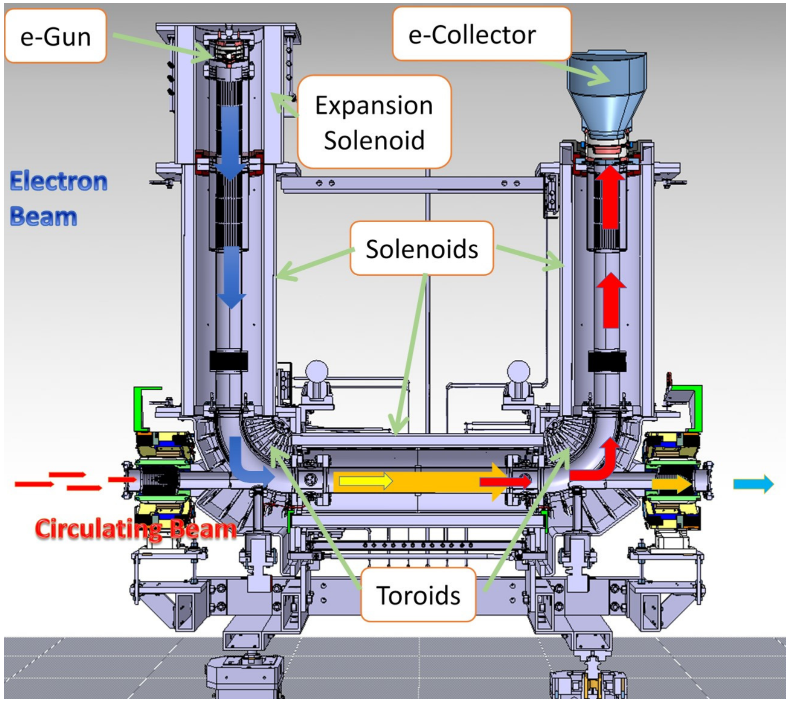
- Deceleration cycle



ELENA e-cooler

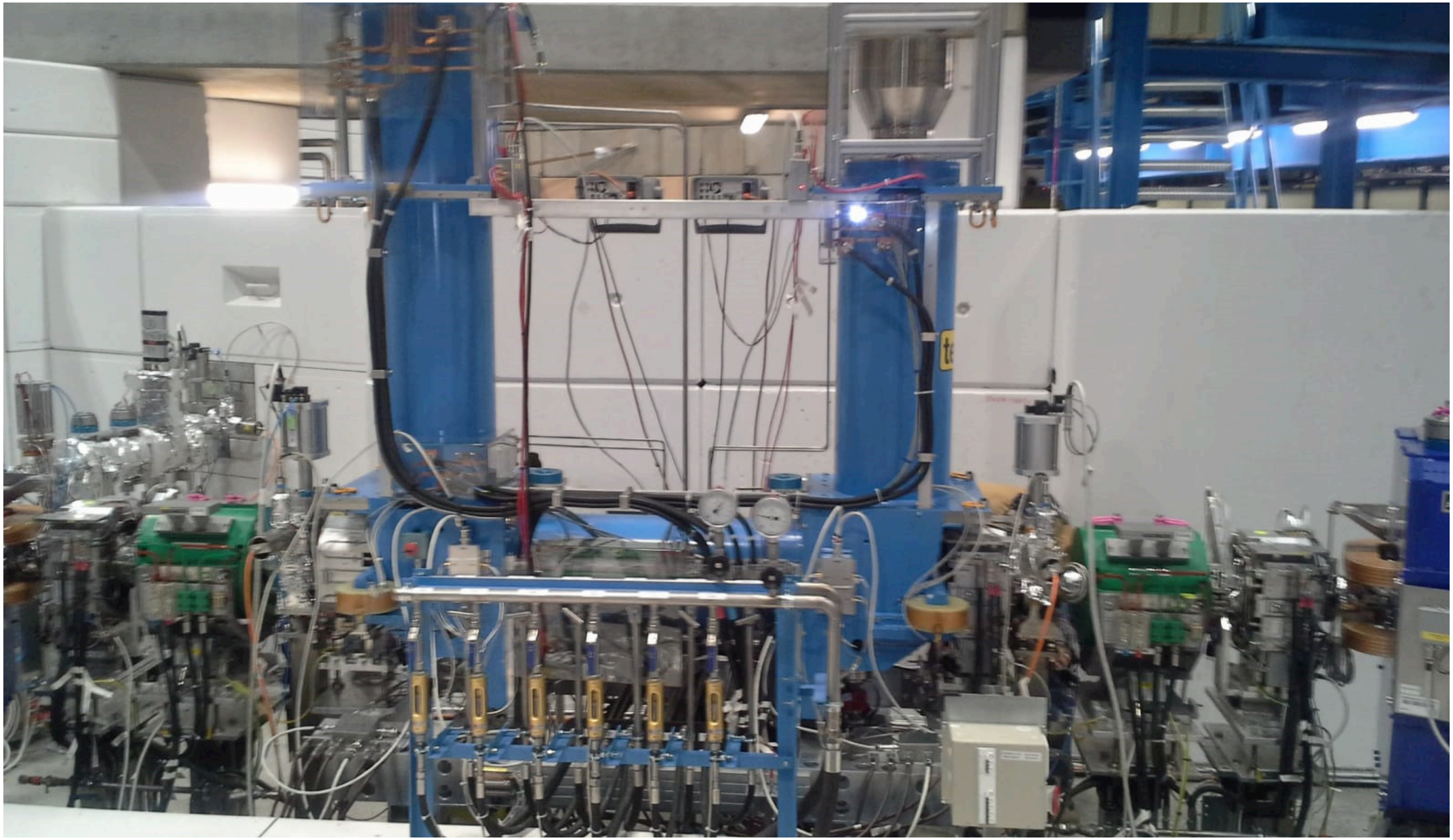
❑ Parameters

Momentum (MeV/c)	35	13.7
β	0.037	0.015
Electron beam energy (eV)	355	55
Electron current (mA)	5	1
B_{gun} (G)	1000	
B_{drift} (G)	100	
Expansion factor	10	
Cathode radius (mm)	8	
Electron beam radius (mm)	25	
Flange-to-flange length (mm)	2330	
Drift solenoid length (mm)	1000	



Gerard Tranquille, Proc. of IPAC2018
See talk by Gerard Tranquille, this School

ELENA e-cooler

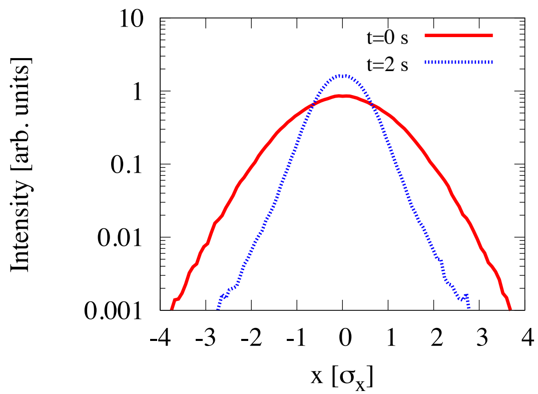


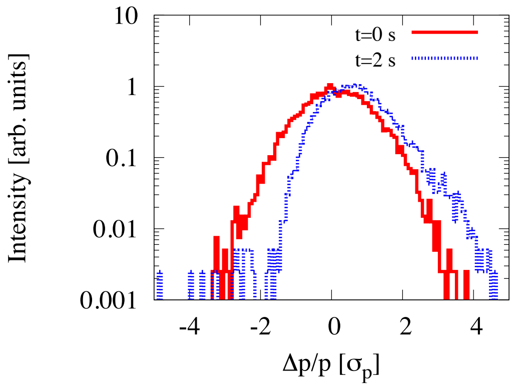
See talk by Gerard Tranquille, this School

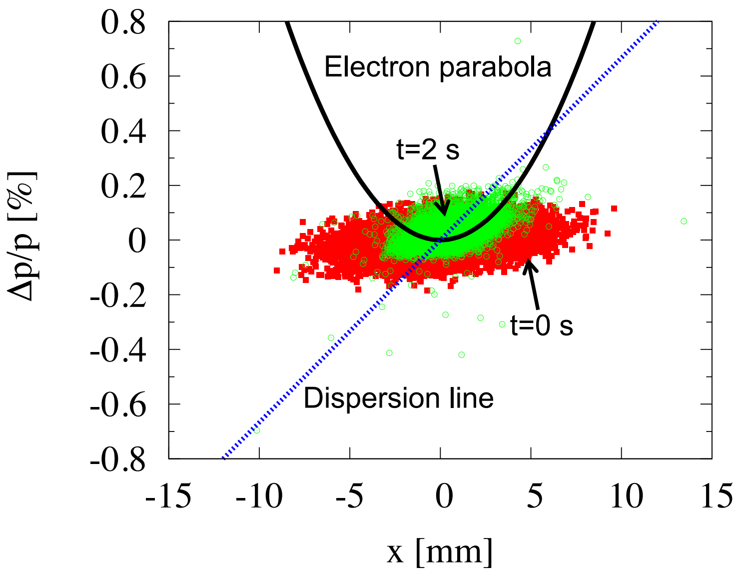
ELENA e-cooler simulations

❑ E-cooling at 100 keV

Beam profile evolution







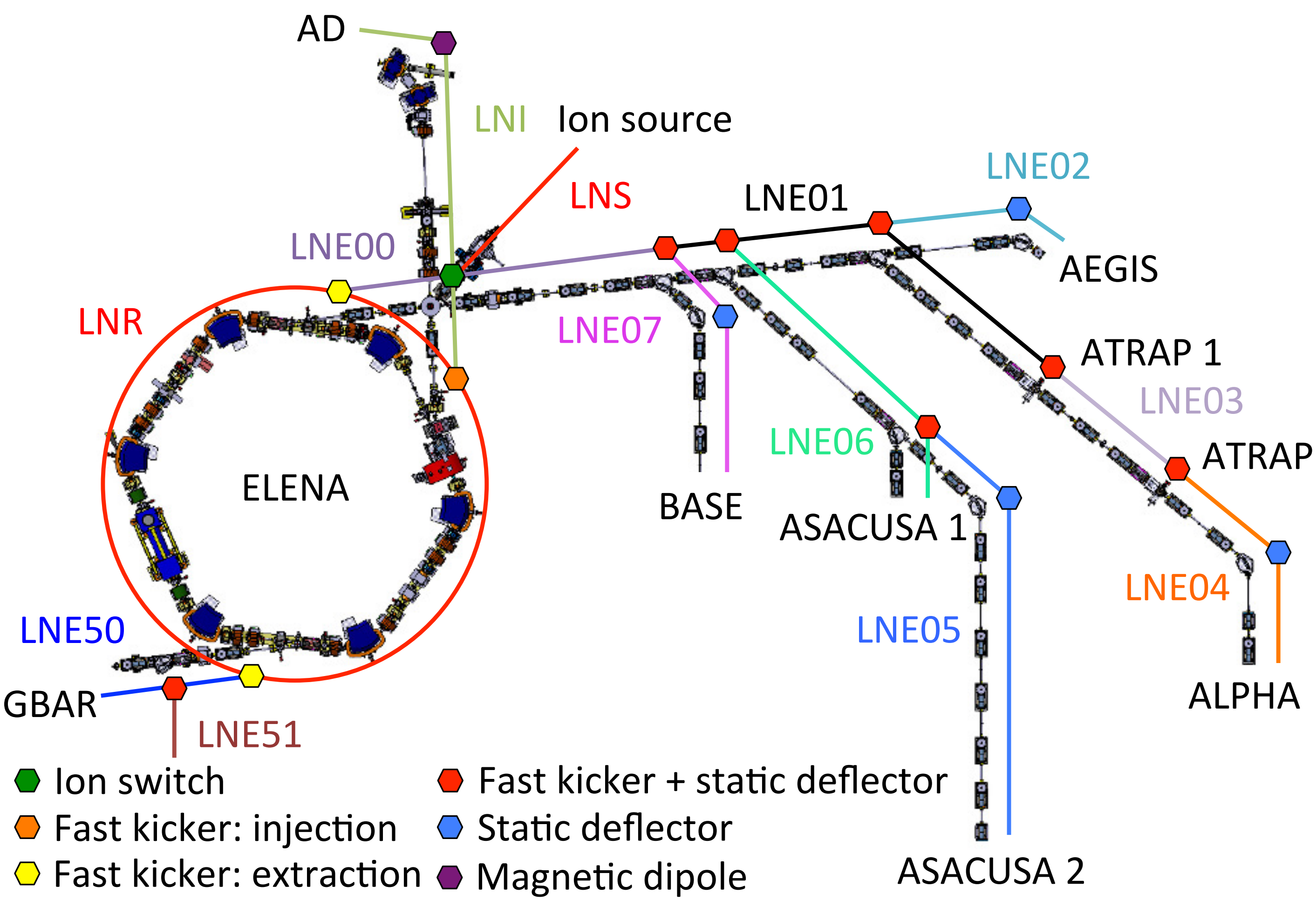
Including:

- e-beam with space charge
- IBS
- Rest gas scattering (3×10^{-12} Torr)

Electrostatic transfer lines

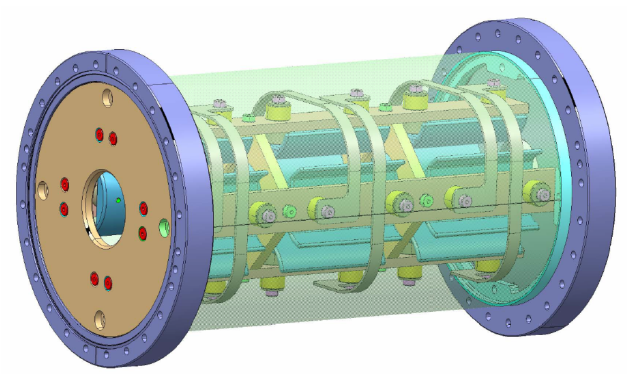
- Electrostatic or magnetic beamline?
- A low velocities electric fields may be more efficient
- 100 keV is still in the reachable range for electrostatic elements
- Advantages of electrostatic:
  - No hysteresis
  - Better stability. Easy field shaping
  - Low power consumption
  - Cheap power supplies
  - Good magnetic shielding possibilities
- Disadvantages:
  - Safety with high-voltage
  - Interlocking against sparks

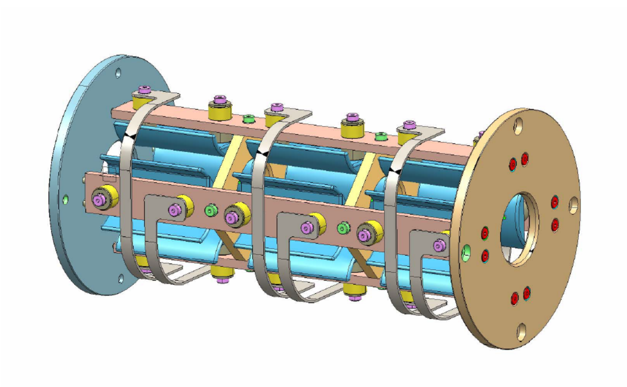
ELENA Electrostatic transfer lines



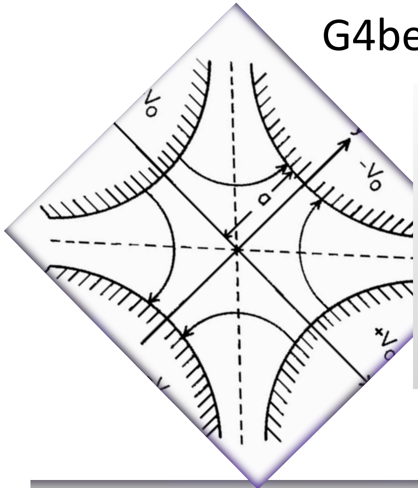
M. A. Fraser et al., Proc. of IPAC2015

Electrostatic quadrupoles

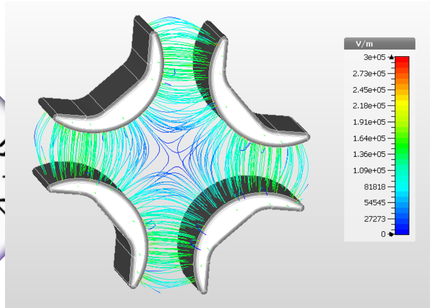




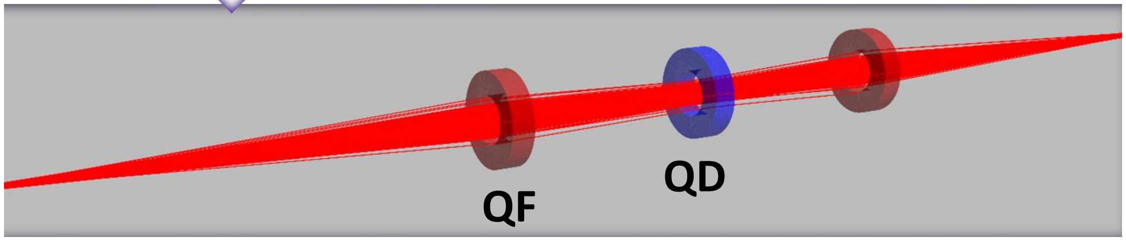
W. Bartmann et al.



G4beamline model



$$k_{el} = \frac{qE_0}{\gamma m a v^2}$$

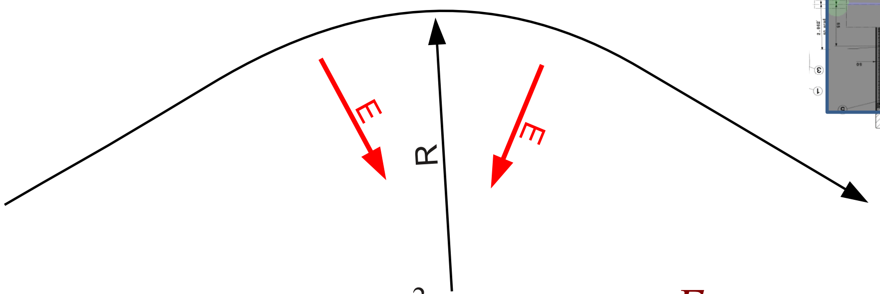


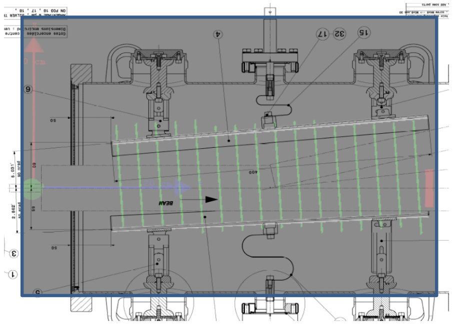
V. Rodin

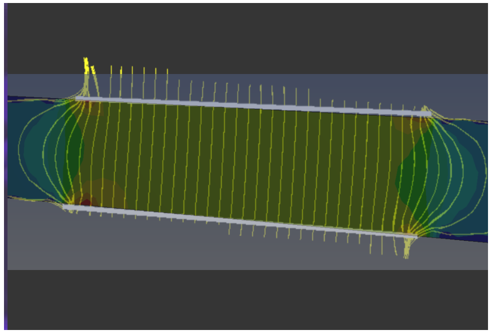
Bending elements

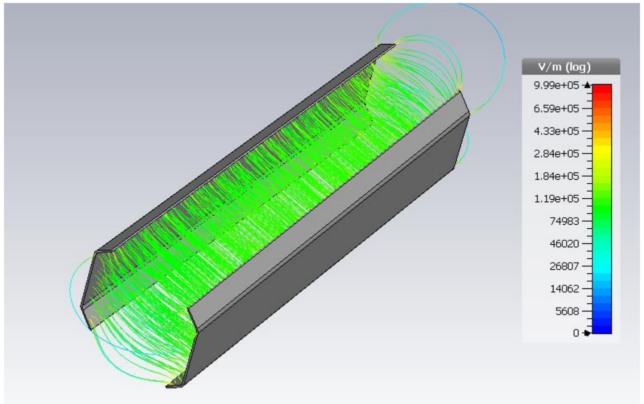
- Fast deflectors

CAD and CST models









$$F = qE = ma = m\frac{v^2}{R} \rightarrow \quad R = \frac{2}{E}\frac{E_{kin}}{q}$$

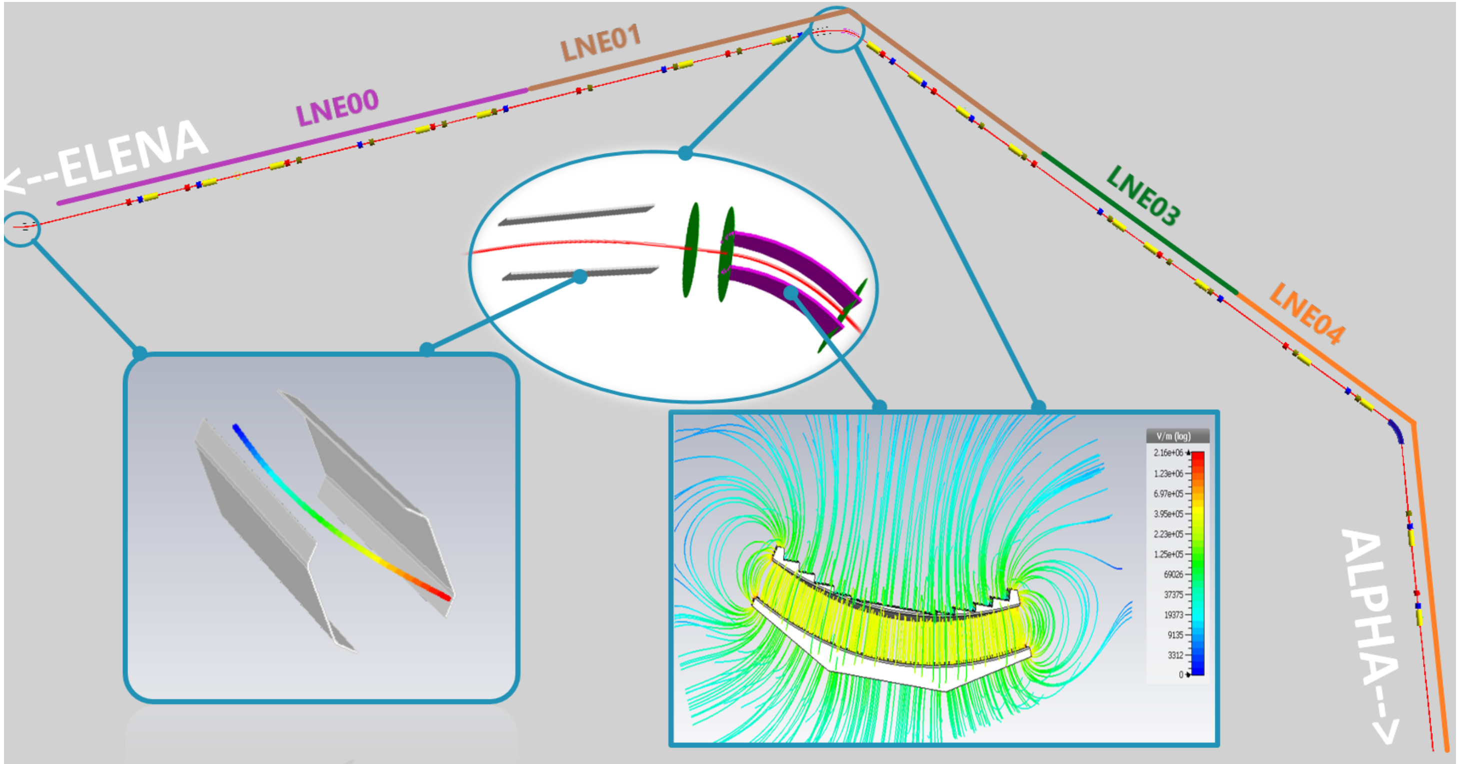
Bending radius depends only on the $\mathbf{E_{kin}/q}$ of the particle.
Independent of mass.

V. Rodin

Bending elements

- Fast deflector + bend

G4beamline model of TL from ELENA to ALPHA



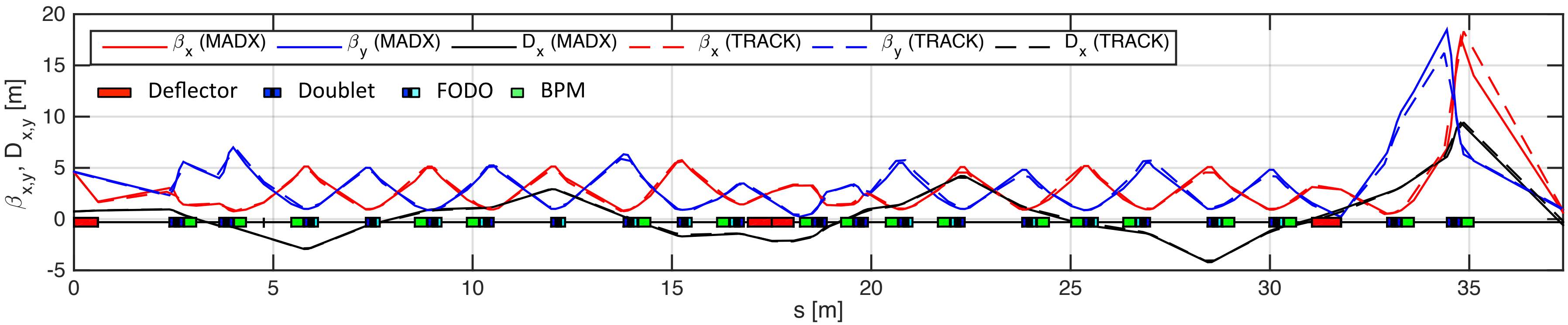
Fast deflector

Bend + fringe field effects

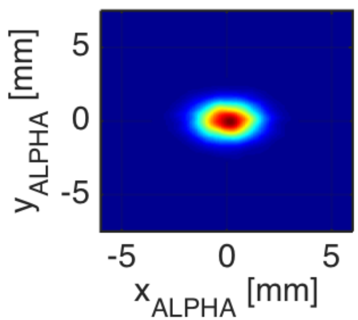
V. Rodin

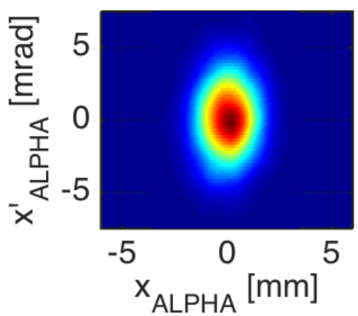
Transfer line optics

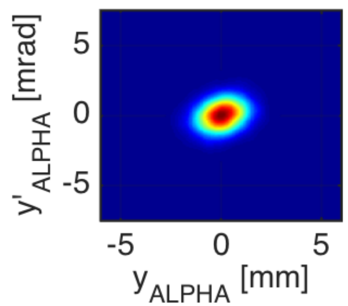
- Example: from ELENA ring to ALPHA



- Predicted beam profile and phase space at ALPHA from tracking simulations







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