Electron and Laser Cooling of Stored Ion Beams at CERN: XSuite Simulations and Measurements

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Outline

- **Motivation:**
  - Beam cooling in stored ion beams at CERN
  - XSuite simulation framework

- **Electron cooling developments at CERN**
  - Studies in LEIR, AD, and ELENA

- **Laser cooling in the SPS (Gamma Factory PoP)**
  - Interplay between IBS and cooling
  - Present activities

- **Summary and outlook**

Motivation: Cooling at CERN

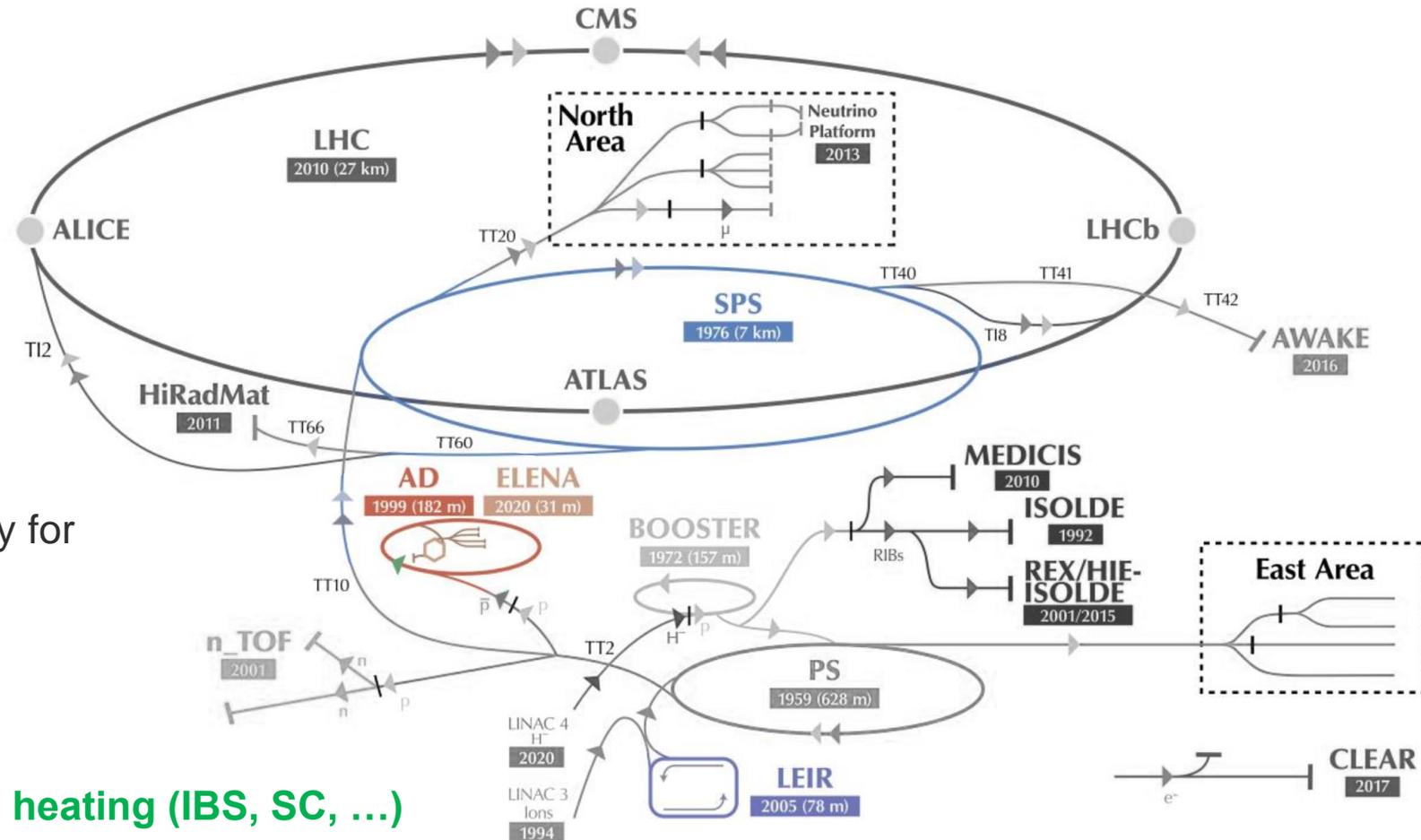- **Beam cooling essential ingredient of several existing machines at CERN:**
  - **S-Cooling** of pbars **AD**
    - See Vasileios's on presentation
  - **E-cooling** of pbars in **AD, ELENA**
    - See Laurette's presentation
  - **E-cooling** of ions in **LEIR**
    - For **LHC** and **Fixed Target Exp.**
- **New developments:**
  - **Gamma factory** proposal
    - See Aurelien's presentation
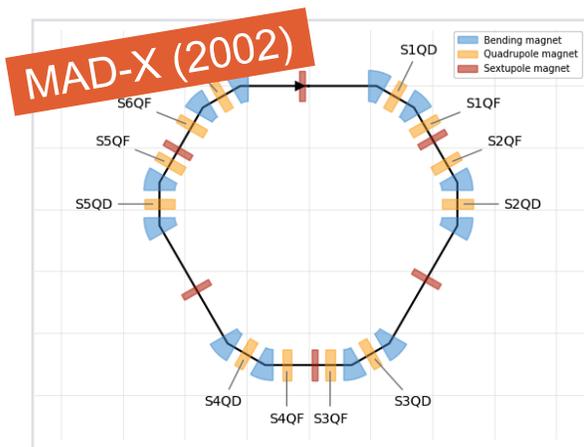 - **PoP experiment**: unique opportunity for testing **laser cooling** at CERN
    - See LOI
- ⇒ **Need for tools for predictive simulations including cooling**
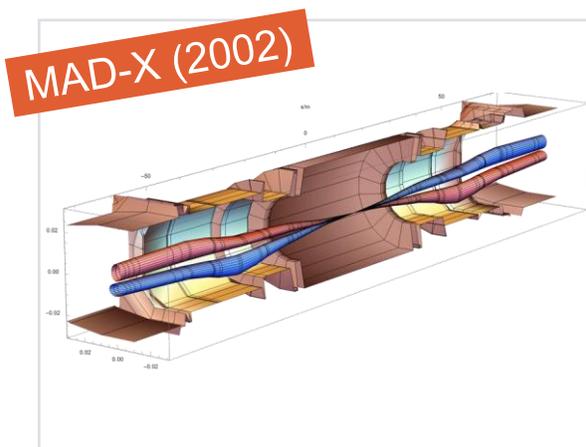 - **Unified environment for cooling + heating (IBS, SC, …)**
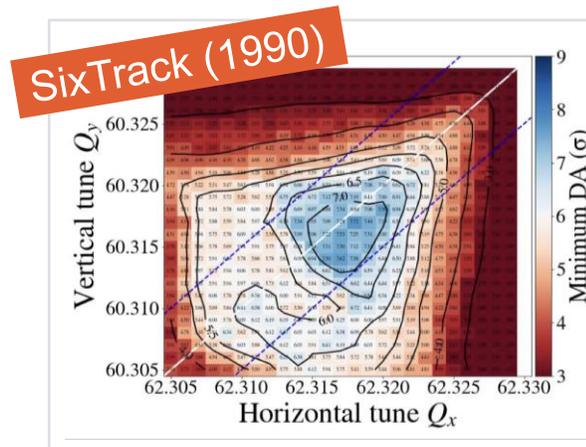
Beam dynamics software landscape at CERN - before

CERN has a long history of powerful software tools for beam physics applications, typical examples:
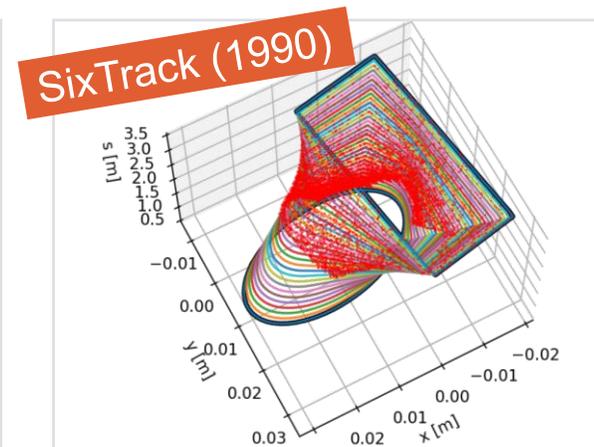

Lattice Design

Optics (calculation & design)

Tracking (dynamic aperture)

Collimation

Impedances

Beam-Beam Effects

Space Charge

Intra-Beam Scattering

Beam dynamics software landscape at CERN - now

Xsuite is now the main production tool, replacing many legacy codes now to be discontinued
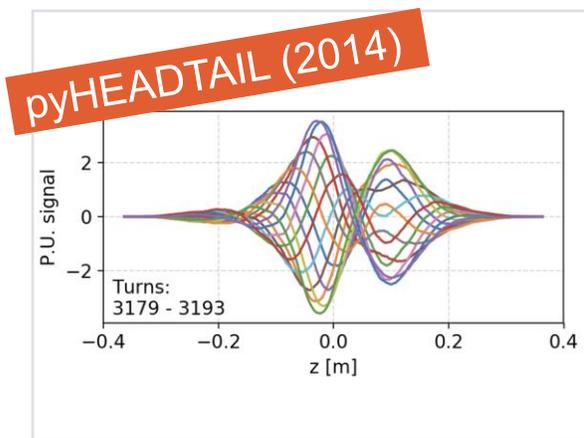

Lattice Design

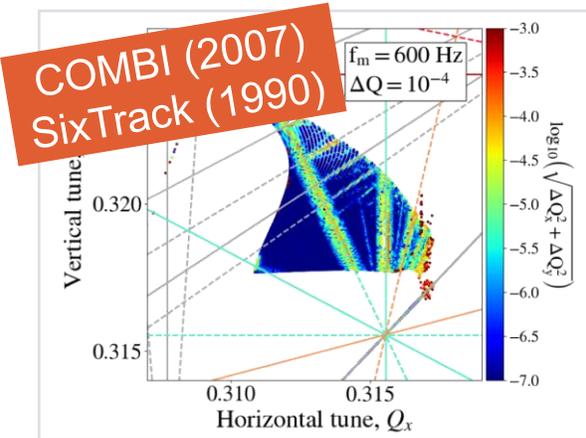Optics (calculation & design)

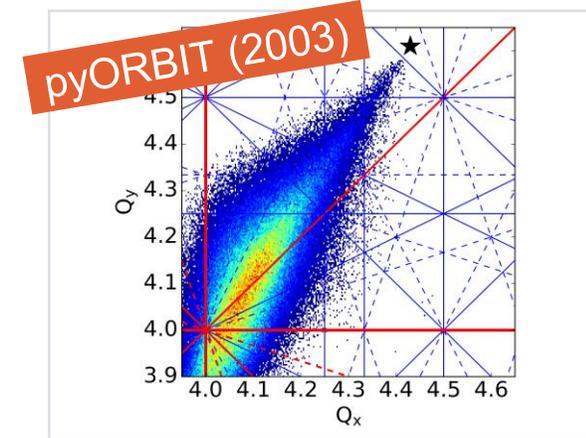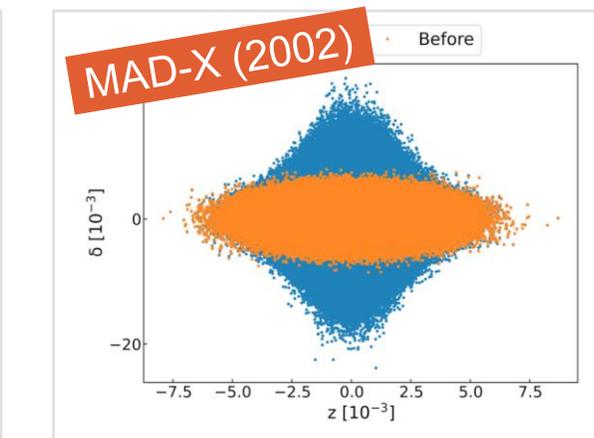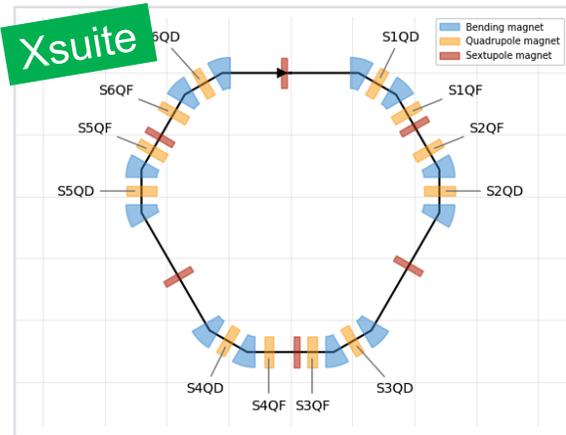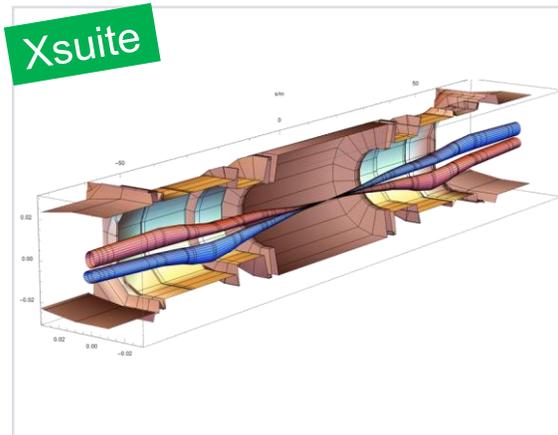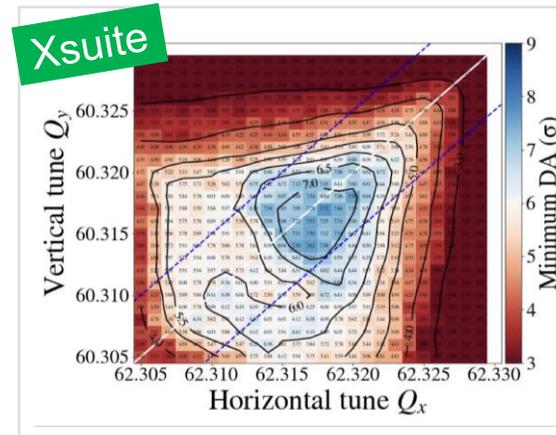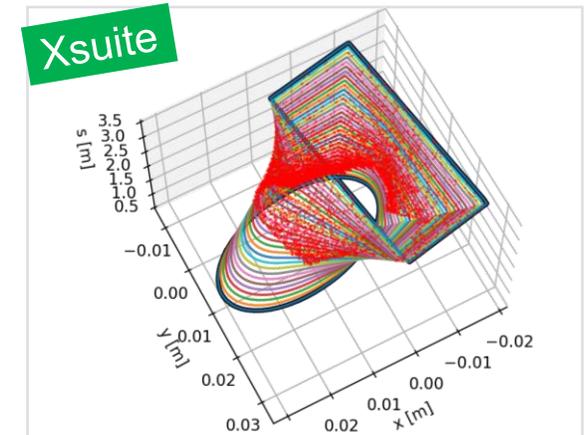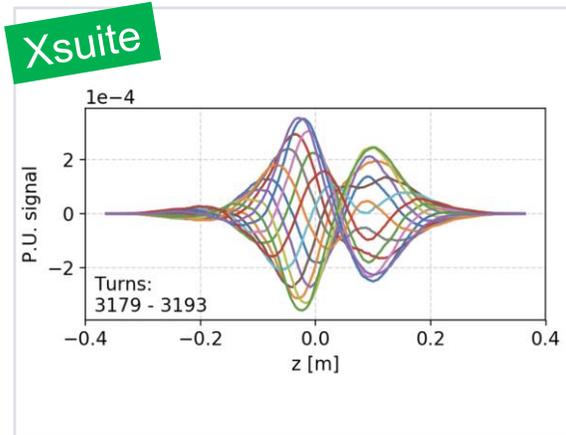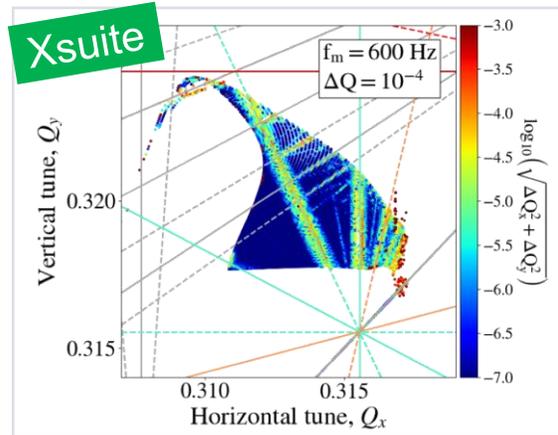Tracking (dynamic aperture)

Collimation

Impedances

Beam-Beam Effects

Space Charge

Intra-Beam Scattering

Xsuite Development Approach

For full list of features, see documentation: xsuite.web.cern.ch

- **Target requirements:**
  - **One toolkit** from low-energy hadron rings to high-energy lepton colliders
  - **Heterogeneous simulations made natural**, as opposed to ad-hoc model translations between tools
  - **Modern user-interface: Python**, with its ecosystem of scientific computing tools
  - **GPU support built-in**, in addition to single- and multi-threaded CPU

- **Agile development:**
  - **Community effort:** users can (and do!) become developers
  - **Fast release cycle:** up to a few new versions per month!

$\Rightarrow$ **The coolest place to simulate cooling!**

Physics modules

Xtrack Single particle tracking engine	Xpart Generation of particles distributions
Xfields Computation of EM fields from particle ensembles	Xdeps Data flow manager, deferred expressions
Xcoll Particle-matter interaction and collimation	Xwakes Wakefields and impedances

Xobjects
Interface to different computing platforms
(CPUs and GPUs of different vendors)

CFFI   PyOpenCL   CuPy   OpenMP

intel   AMD   NVIDIA

ELECTRON COOLING

Electron Cooling Model Choice: Parkhomchuk

- **All CERN e-coolers assumed to work in "magnetized cooling" regime**
  - Relatively low energy (<30 keV) DC e⁻ beams in 100 to 750 Gauss field

- **Best represented by empiric formula** derived from experiments by **V. Parkhomchuk:**
  - Still, **several parameters not easily accessible** (e.g. B field quality, e⁻ temperature and profiles)

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

- **Constants**
- **Scaling with e⁻ beam density and ion charge**

Electron-ion velocity difference
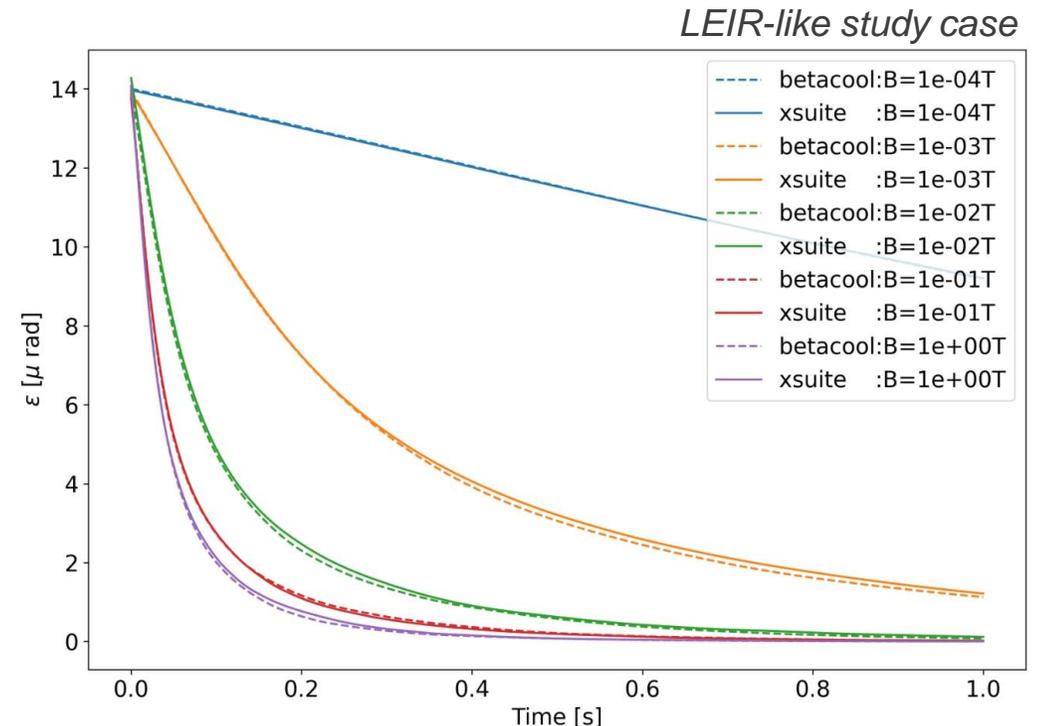- **Include normalisation by "effective e⁻ temperature"**

Log of "impact parameters":
- **Linked to probability of interaction**
- **Depends on B field, e⁻ temp., …**
- **Typically, ≈ 10**

Benchmark with Betacool

- **Betacool** by A. Sidorin **is presently not actively maintained** (to our knowledge)

- **JSPEC**, **PyOrbit**, **PyHEADTAIL** implementations of Parkhomchuk model exist

  - Implementations **derived from Betacool,** or similar

⇒ **Went back to the origin: Betacool**

- **Thorough check of the physics implemented, including minor bug fixes in Betacool:**

  - Improper handling of space-charge neutralisation

  - Wrong sign used in the rotation of the e⁻ beam

- **Additional (undocumented) effect of electron beam rotation on transverse e⁻ temperature was not fully understood**

  - This **feature** was **NOT imported in XSuite**, as its implementation was not properly validated

LEIR-like study case

Legend:
- betacool: B=1e-04T (dashed)
- xsuite : B=1e-04T
- betacool: B=1e-03T (dashed)
- xsuite : B=1e-03T
- betacool: B=1e-02T (dashed)
- xsuite : B=1e-02T
- betacool: B=1e-01T (dashed)
- xsuite : B=1e-01T
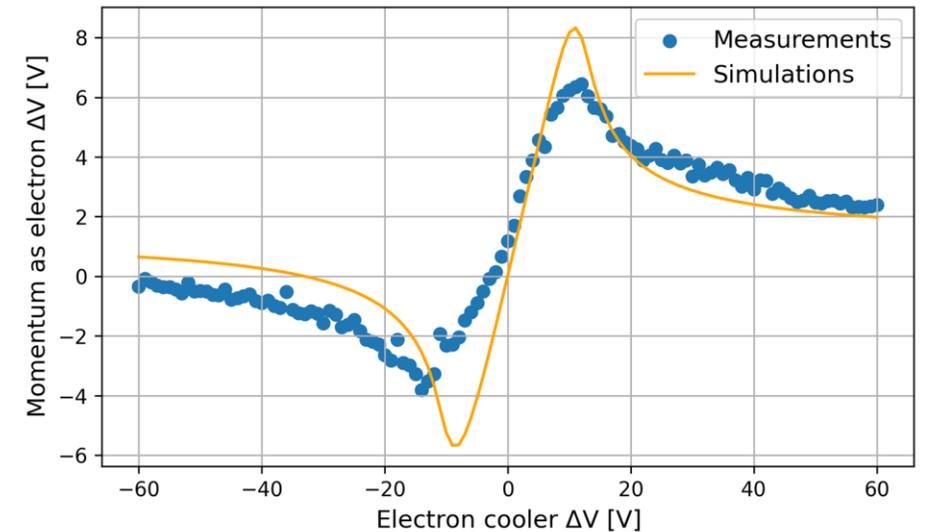- betacool: B=1e+00T (dashed)
- xsuite : B=1e+00T
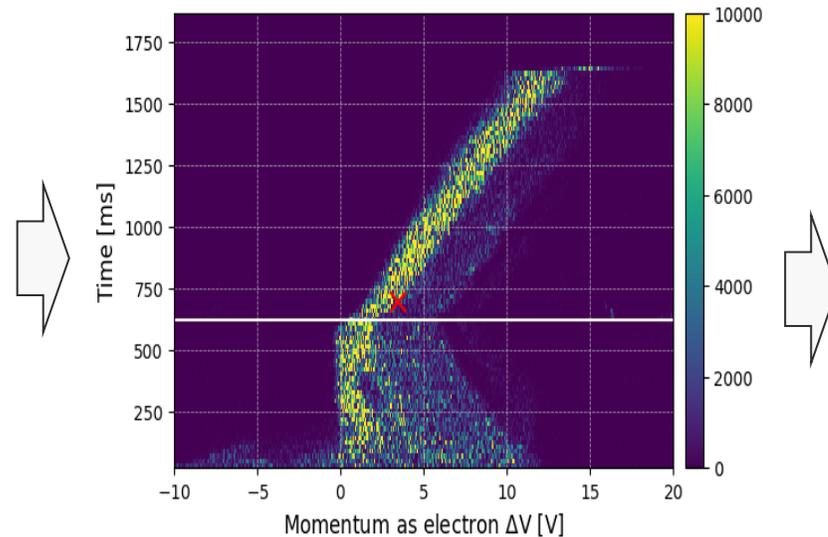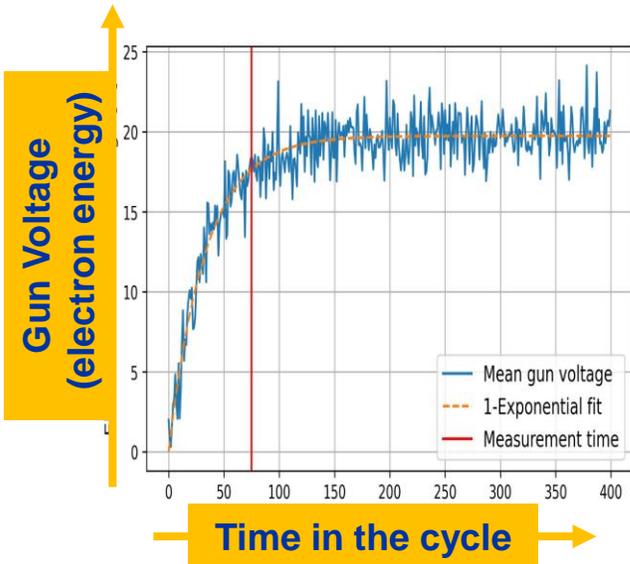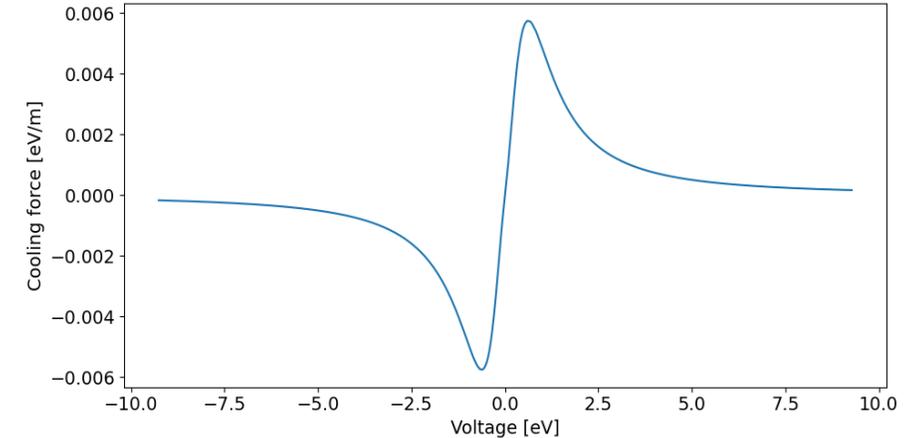
Axes: $\varepsilon\ [\mu\,rad]$ vs Time [s]

⇒ **Validated and documented e-cooling implementation now available in Xsuite!**

Measurement and Simulation of Cooling Force

- **Longitudinal Friction Force is the most typically measurement:**

  1. **Pre-cool** the circulating beam

  2. **Apply a voltage step** on the gun voltage (i.e. e⁻ energy)
     - **First pitfall:** actual voltage/e⁻ energy **not instantaneous**

  3. **Measure derivative of ion momentum variation**
     - **Second pitfall: Limited measurement resolution**
       ⇒ **simulate the whole dynamic process (in Xsuite)!**

- **First measurements with Mg^{7+} not perfect**
  - No time to measure all beam parameters; not enough pre-cooling; …

Longitudinal Cooling Force: Pb^{54+} case

- **Much better agreement after constraining beam parameters as much as possible !**
  - E.g. **measure** effects such as e$^-$ beam "**neutralisation**"
  - **Only e$^-$ T** (T$_\perp$=100 meV; T$_\parallel$=1 meV), **and profile** (flat) **still guessed**

More exotic effects under investigation in LEIR

- **Fast "run away" observed during Mg^{7+} measurements**
  - Not seen with standard Pb^{54+} beam

- Tried to explain it by **interplay between e$^-$ space charge + ion-e$^-$ offset + transverse heating**
  - **Unrealistic dispersion needed**, not possible to reproduce

  $\Rightarrow$ **Better machine control or e-cooling models might be needed**

Impact of field quality on new AD e-cooler

- **New AD e-cooler is being built**
  - See also Laurette's and Gunn's presentations

- **Specification on field quality was required**
  - Ideal problem **addressed in Xsuite !**
    - **Comparison** between **Parkhomchuk's effective temperature** approach and **sum of shorter coolers** with given angular spread
    - Impact **most sever at highest energies** (i.e. 300 MeV/c for AD)
  - $\Rightarrow$ **Provided specification for magnet design (rms < 1e-4)**

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

The ELENA cycle

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

- **Pbar repetition rate is very slow** for any e-cooling study/setup

  - **Good news:** **No H- lifetime degradation observed with e-cooling! We can use H⁻ for most studies!**

  - **Bad news:** **H⁻ lifetime strongly affected by vacuum levels in the ring** (typically 10^{-11} mbar)

- **Limited beam instrumentation** available in the machine: **only scraper measurements** for transverse profile

  - **Bad news:** typical scraping time > cooling time constant; and **poor performance with H⁻** (requires in-vacuum MCPs)

  - **Good news** (low energy only): beam can be fast-extracted on **transfer line profile monitors**

  - **Future?** (for H⁻ only): Promising **development using neutrals monitors** – see Gerard's <u>presentation</u>

E-cooling studies in ELENA

- **Transverse cooling measurement extracting beam at different times on a profile monitor**

  - Generally, **good agreement between measurements and simulations !**

- **Wish to test impact of field quality** (by spoiling it with available correction coils) on cooling efficiency

  - **Better studied at higher energy**, where impact is more sizeable but **no fast transverse measurement available**

    - **Promising results with H⁰ monitor** – see Gerard's <u>presentation</u>

Measurements and simulations at 13.7 MeV/c

Simulations at 35 MeV/c

ELENA magnetic field quality somewhere in this range

LASER COOLING

Gamma Factory PoP Experiment in 'a nutshell'

- **Strong multidisciplinary interest in producing high-intensity gamma-ray flux**
  - see Aurélien's presentation
- **Concept based on partially stripped ions (PSI) excited by a laser**
  - **exploiting Doppler shift twice**: to excite otherwise inaccessible levels and **boost photon energy**
- **Need for a demonstrator, which appears feasible in the SPS**
  - Excellent **opportunity to test laser cooling** at the highest ion energies ever achieved

SPS Pb ions

3.5 m

$\hbar\boldsymbol{k}$

θ

$\gamma m\boldsymbol{v}$

$\gamma m\boldsymbol{v} + \hbar\boldsymbol{k}$

$\gamma m v \gg \hbar k_1 \gg \hbar k$

$\hbar\boldsymbol{k}_1$

$\gamma m\boldsymbol{v} + \hbar\boldsymbol{k} - \hbar\boldsymbol{k}_1$

θ

Input laser

Fabry-Perot cavity

Gamma rays

Courtesy gamma factory collaboration

Laser Cooling in Xsuite

- **Principle: selective particle momentum reduction**

- **First implementation in Xsuite by** A. Petrenko

- **Requires to solve optical Bloch equations**
  - Done for pulsed **Fourier-limited** and **CW lasers**
  - **Chirped** lasers explored, but **not yet implemented**

- **Multi-thread + GPU support essential for long simulations**

From L.Eidam

Benchmark with Literature: Lanzhou experiment

- **Replicating published measurement with CW laser**
  - Requires to account for doppler effect **correction due to emittance**

Effect on zero-emittance beam

Broadening due to emittance

- **Results compatibles with published data**
  - Uncertainty given by **varying laser beam size at IP**

	Experiment	Original simulation	Xsuite
FWHM dp/p	**5.7e-6**	5.7e-6	**[2e-6, 7e-6]**

Parameters for PoP experiment

- **Choice of parameters dependent on:**
  - **accessible energy levels**
  - **available laser parameters**
  - **machine optics and ion beam constrains**

$\Rightarrow$ **Multi-parameter exploration accessible within Xsuite**

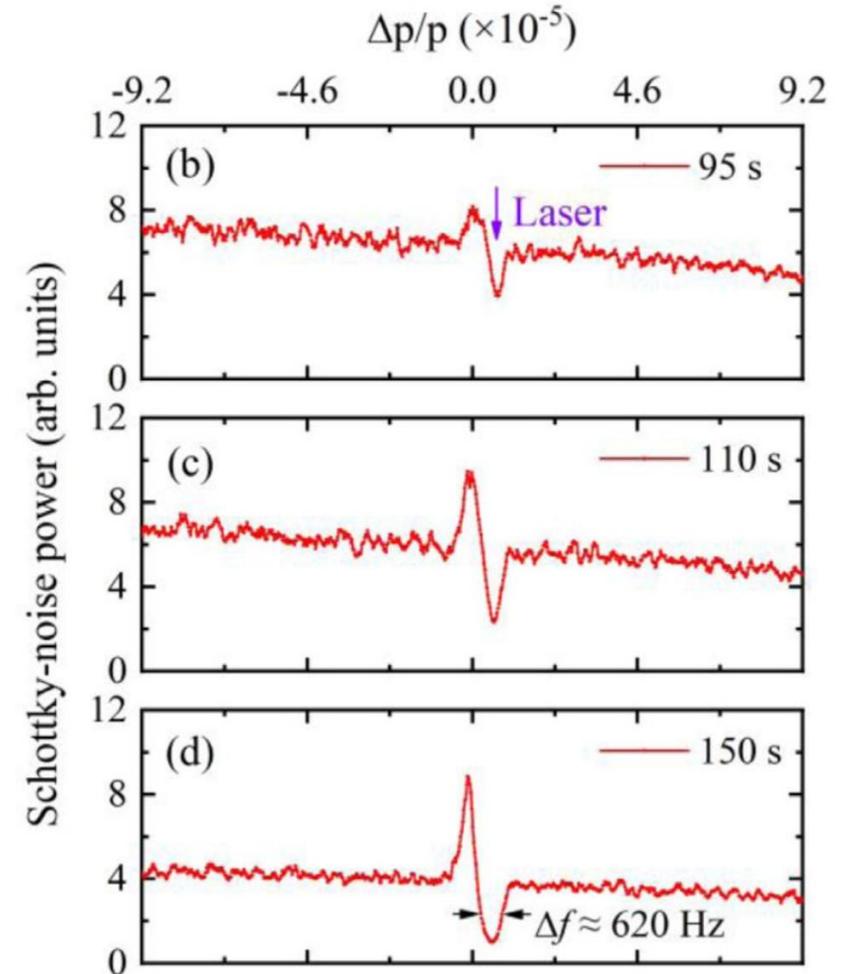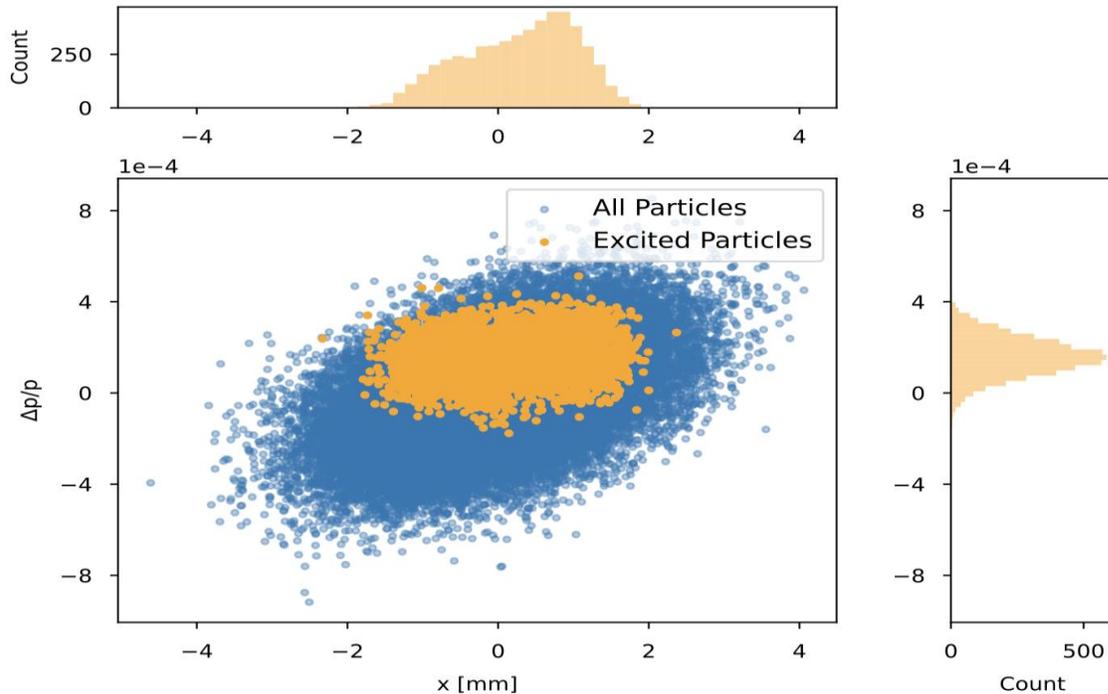| Parameter	Value
Laser Parameters	
Wavelength (λ)	$1031\,\mathrm{nm}\,(1.2\,\mathrm{eV})$
Single pulse energy at IP (E)	$5\,\mathrm{mJ}$
Laser waist radius at IP	$1.3\,\mathrm{mm}$
Collision angle (θ_L)	$2.6\,\mathrm{degrees}$
Fourier-limited pulse width (σ_t)	$2.74\,\mathrm{ps}$
Twiss Parameters at the Interaction Point	
β_x, β_y	$54.47\,\mathrm{m}, 44.40\,\mathrm{m}$
α_x, α_y	$-1.55, 1.32$
D_x	$2.4\,\mathrm{m}$
D'_x	0.09
Machine Parameters	
Transverse tunes (Q_x, Q_y)	$26.299, 26.249$
Harmonic number (h)	4620
RF voltage (V)	$7\,\mathrm{MeV}$
Ion Beam Parameters	
Ion species	$^{208}\mathrm{Pb}^{79+}$
Ion mass (m)	$193.687\,\mathrm{GeV}/c^2$
Mean Lorentz factor (γ)	96.3
Number of ions per bunch (N)	0.9×10^8
RMS relative energy spread (σ_E/E)	2×10^{-4}
Normalized transverse emittances (ϵ_n)	$1.5\,\mathrm{mm\,mrad}$
RMS bunch length (σ_z)	$6.3\,\mathrm{cm}$
Excited state lifetime	$76.6\,\mathrm{ps}$
Ion excitation energy ($h\omega_0$) [181, 182]	$231\,\mathrm{eV}$

Transverse Cooling Enabled by Dispersion Coupling

- **Dispersion at the IP converts longitudinal cooling into transverse cooling**
  - Strong transverse cooling reduces longitudinal cooling

$\Rightarrow$ **Full optimisation possible with Xsuite**

- **Vertical cooling achieved through transverse plane coupling**

Cooling rates for different ions (without IBS)

- **Several ions could be potentially injected - and cooled – in the SPS:**

  - **Note:** much **faster cooling for lower-charge** and **lower-mass** ions thanks to larger excitation energy and consequent **larger absorption kicks**

  - Xsuite **implementation can provide** information about **energy and distribution of produced photons**

Envelope of photon energy and angular distribution

Cooling with IBS Studies

- **IBS has a two-fold impact:**
  - **Slower cooling time**
  - **Larger equilibrium emittance**

- **Using 15-85 percentile to better represent non-Gaussian core**
  - Often an issue of IBS computations
  - Contributes to blurry border definition

Ongoing Work: Devise Operational Scenario for PoP

1. **Check compatibility of design with nominal SPS beams**

2. **Verify beam steering margins, considering corrector strength and aperture**

3. **Put everything together: devise start-to-end simulation of the cooling experiment in Xsuite**

Check on aperture restrictions (for all other beams)

Beam control at the IP

Summary and Outlook

- **Parkhomchuk e-cooling model integrated and validated in Xsuite**

  - Measurements in ELENA and LEIR consistent with simulations

  - e$^-$ space-charge effects essential to capture the correct behaviour

- **Laser-cooling capabilities advancing in Xsuite**

  - CW and pulsed laser-cooling modules nearing completion

    - Merge request for next Xsuite release in progress

  - Chirped-laser option under development (lower priority, as not useful for PoP)

- **Provided first SPS PoP Performance Estimates**

  - Cooling vs heating interplay now accessible within a single, well-supported simulation framework

- **SPS Proof-of-Principle and new AD e-cooler provide key validation opportunities**

  $\Rightarrow$ **"Cool" times ahead of us after CERN Long Shutdown 3**

  Thanks for your attention and comments !

APPENDIX

Electron Coolers at CERN

Currently we have three electron coolers in operation at CERN (30 keV – 55 eV):

LEIR

AD

ELENA

LEIR e-cooler was **designed specifically** for the **LHC ion chain** and uses the **most advanced technologies** at that time (~2004):

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

- See **Gunn's contribution**

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

CERN Electron 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	

Overview of the new AD cooler magnet system

Y-chamber in TF region

Drift ID fixed by BPMs

Space for gun support (cantilever)

Space for vacuum flange

E-cooling Parameters in Simulations

Parameter	Value
LEIR e-cooler parameters	
e^- kinetic energy E_k (keV)	2.2
Relativistic β	0.094
e^- beam current I (mA)	300
Cooler length L (m)	2.5
Transverse e^- temperature $T_\perp$ (meV)	100
Longitudinal e^- temperature $T_\parallel$ (meV)	1
Magnetic field ($B_\parallel$) 0.075	T
Field imperfection $B_\perp/B_\parallel$	1×10^{-3}
e^- beam radius (mm)	25
LEIR optics parameters at e-cooler	
Beta functions β_x/β_y (m)	5 / 5
Dispersion D_x/D_y (m)	0 / 0
Machine tunes Q_x/Q_y	1.84 / 2.72
Fully stripped ion beam parameters (e.g. Mg^{12+})	
Geometrical emittances ϵ_x/ϵ_y (µm)	14 / 14
Momentum spread $\Delta p/p$ (uniform)	$\pm 2 \times 10^{-3}$

Parameter	Value
ELENA e-cooler 100 keV parameters	
e^- kinetic energy E_k (keV)	0.054
Relativistic β	0.014
e^- beam current I (mA)	0.34
Cooler length L (m)	1
Transverse e^- temperature $T_\perp$ (meV)	100
Longitudinal e^- temperature $T_\perp$ (meV)	1
Drift solenoid field B (T)	0.0097
Drift $B_\perp/B_\parallel$	1×10^{-3}
e^- beam radius (mm)	14
ELENA Optics parameters at e-cooler	
Beta functions β_x/β_y (m)	1.7/2.7
Dispersion D_x/D_y (m)	1/0
Machine tunes Q_x/Q_y	2.36 / 1.39
H^- beam parameters	
Geometrical emittances ϵ_x/ϵ_y (µm)	2.5 / 2.5
RMS $\frac{\Delta p}{p}$	1×10^{-3}
Twiss parameters at SEM	
Beta functions β_x/β_y (m)	7.6 / 1.3
Dispersion D_x (m)	0.2

Examples of Previous Laser Cooling Experiments

Facility (ring)	Ion species	Beam energy (typical)	Relativistic β	γ	Notes / references
CSRe (IMP Lanzhou)	O^{5+}	275.7 MeV/u	**0.636**	**≈ 1.295**	Laser cooling of *bunched* relativistic O^{5+}; Schottky diagnostics. Currently the highest-β/γ demonstration.
ESR (GSI Darmstadt)	C^{3+}	122 MeV/u	0.47	1.13	Multiple campaigns (2004–2013, 2021+): broadband and narrowband cooling; extensive spectroscopy with β≈0.47.
TSR (Heidelberg)	$^{7}Li^{+}$ (and others)	~7–13 MeV (few MeV/u)	≈ 0.05	≈ 1.001	First storage-ring laser-cooling demonstrations (longitudinal), ~5% of c.
S-LSR (Kyoto, ICR)	$^{24}Mg^{+}$	35–40 keV	≈ 9×10^{-3}	≈ 1.00004	Low-energy ring; 1D laser cooling and studies of coupling / ordering.