Low-energy beam preparation for the next generation antimatter experiments

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3rd ONLINE Ukrainian Teacher Programme

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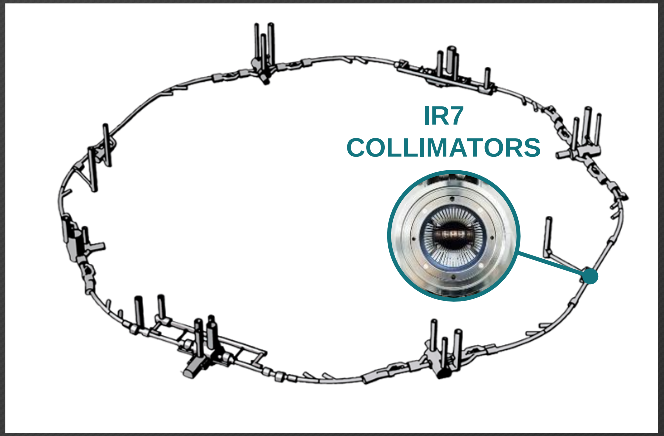
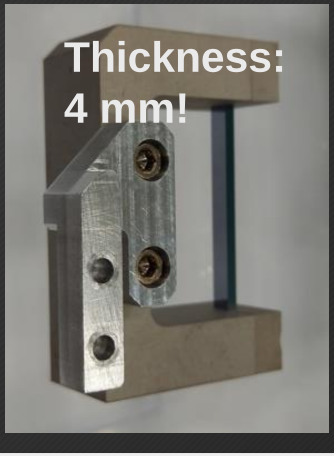
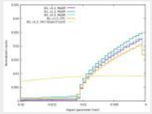
My current occupation and project

- Fluka simulation studies of LHC collimation system in view of HL-LHC upgrade
- Protection of superconducting magnets from possible quench
- Ion beam collimation with channeling crystals



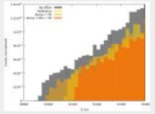


SixTrack- Fluka coupling
calculation of “touches” distribution
on primary collimators

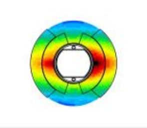


(We are here)

Lossmap calculation in Fluka
Impacts from primary and secondary particles on
machine aperture (IR7 straight section + DS)

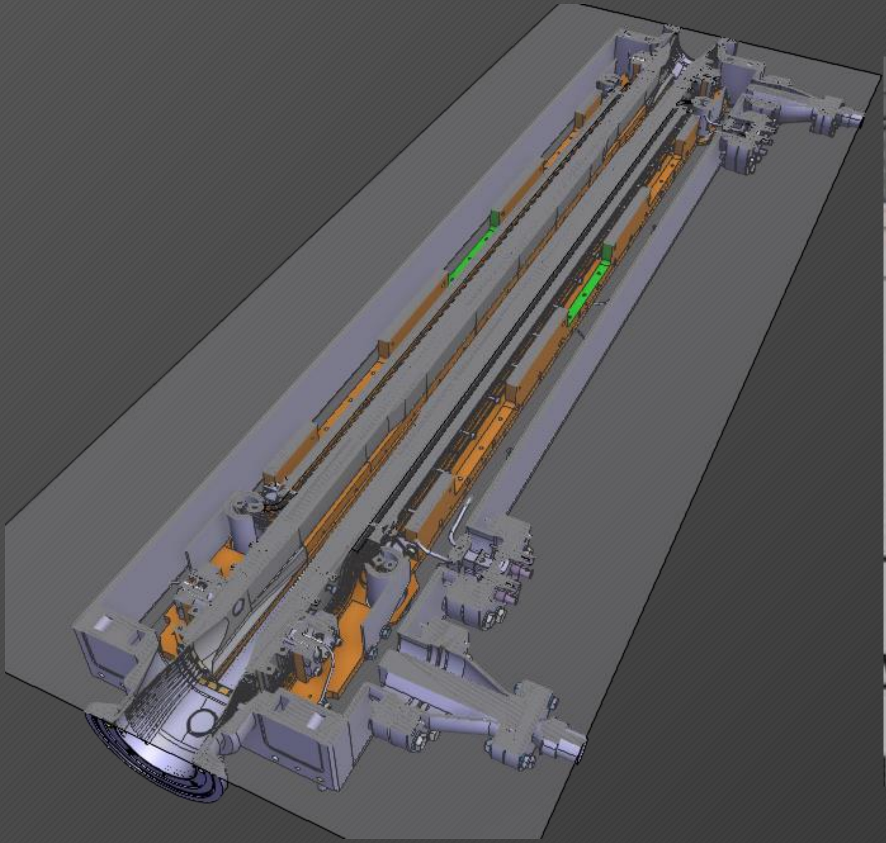


Energy deposition scoring in Fluka
Scoring of energy deposition in DS magnet coils
for 0.2h BLT: 8.81E11 p/s (2760 bunches, 2.3E11 p/bunch)

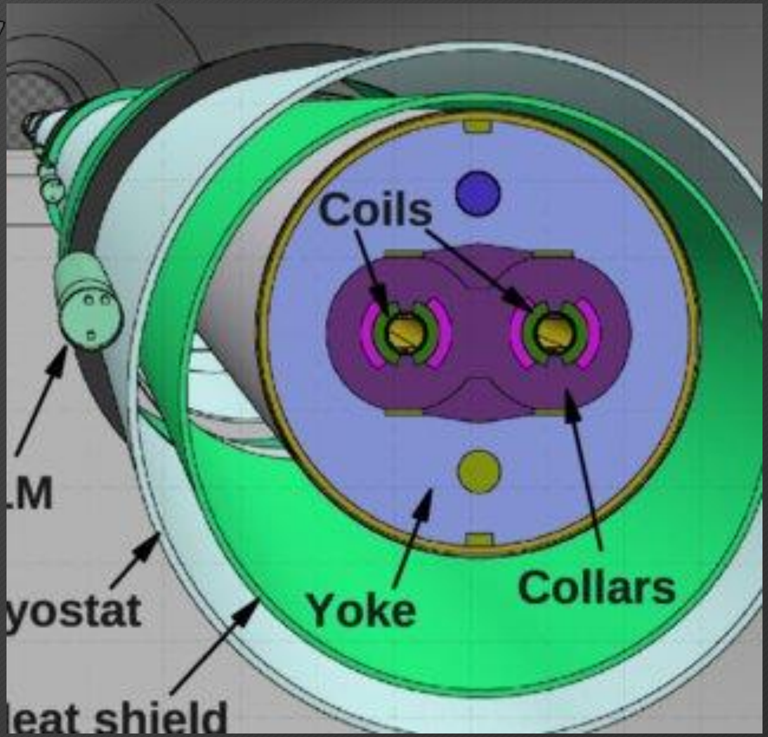


More in details

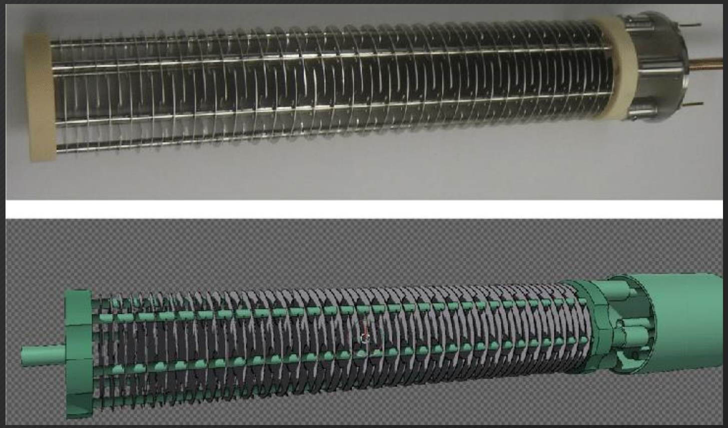
- Collimators



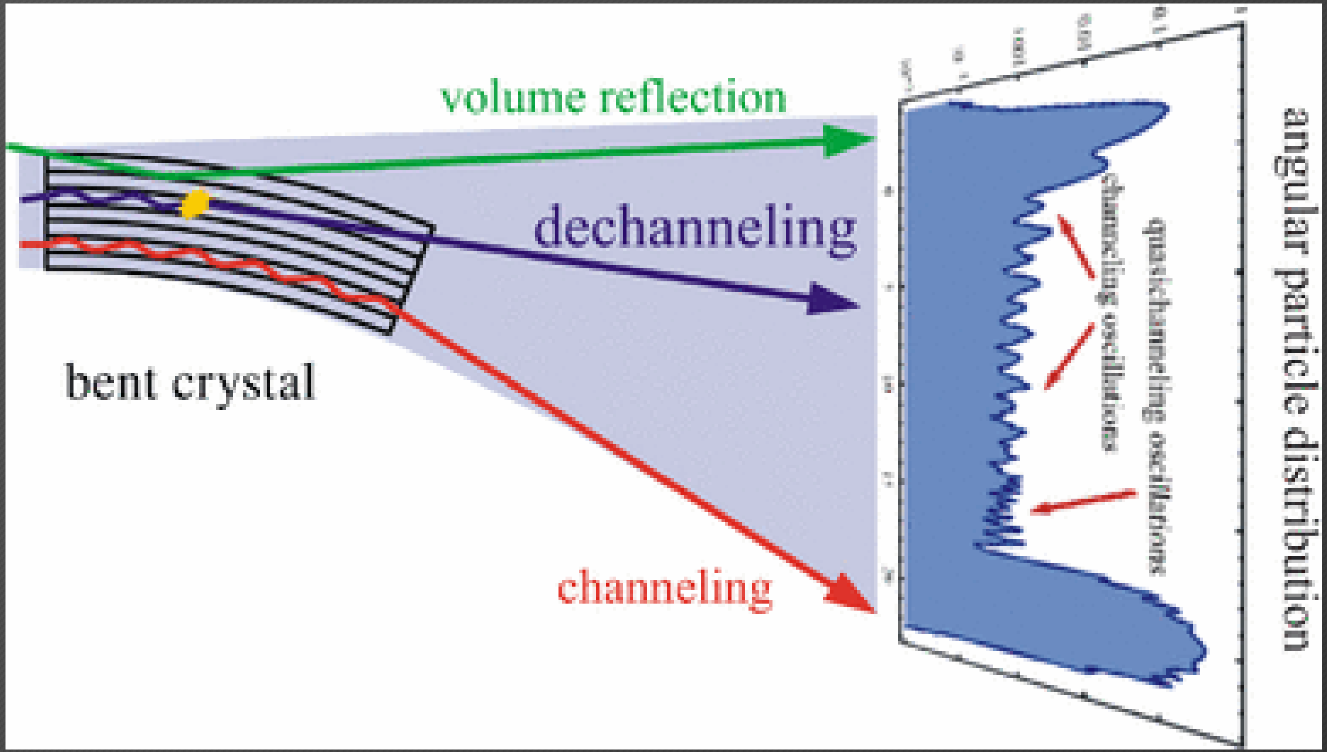
- Superconducting magnets

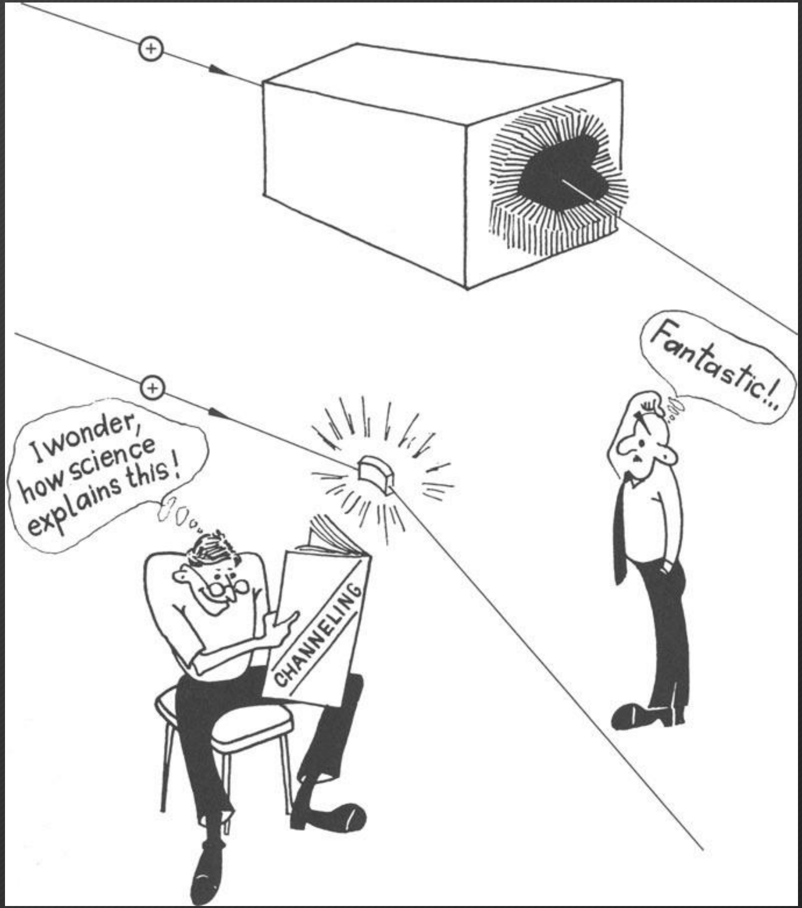


- BLMs



Crystal channeling and bending





Standard collimation system in LHC

Stored energy in the machine:

- LHC design: **360 MJ**

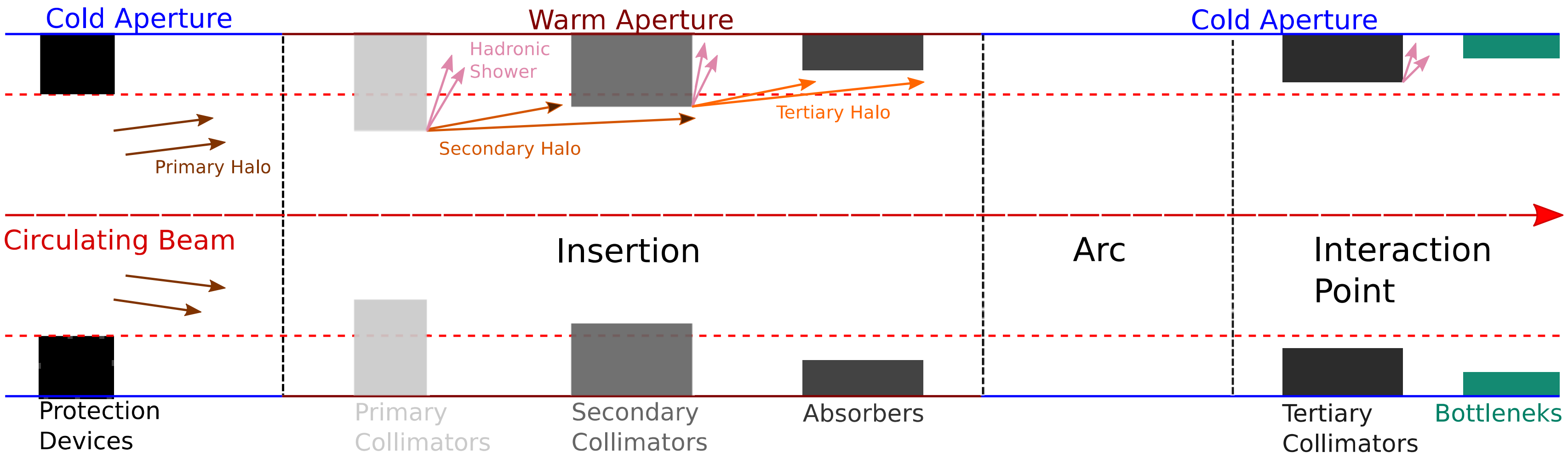
Superconducting magnets (T = 1.9 K)

- quench limit ~ **15-50mJ/cm^3**

To protect the superconductive magnets from energy deposition induced by lost particles

Collimation system is needed!

η = 10^{-4} is the actual performance in LHC

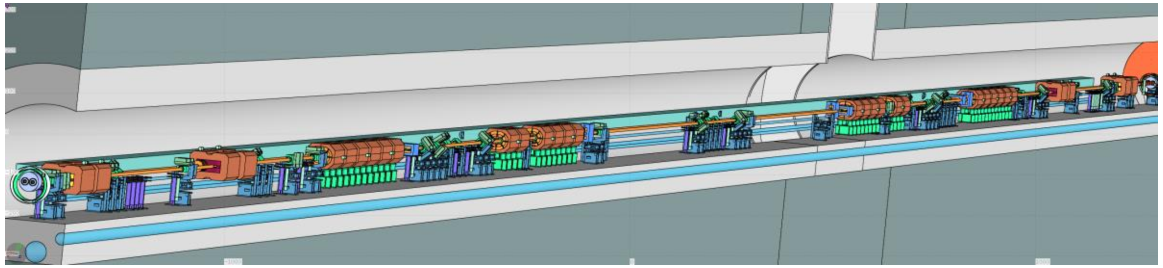


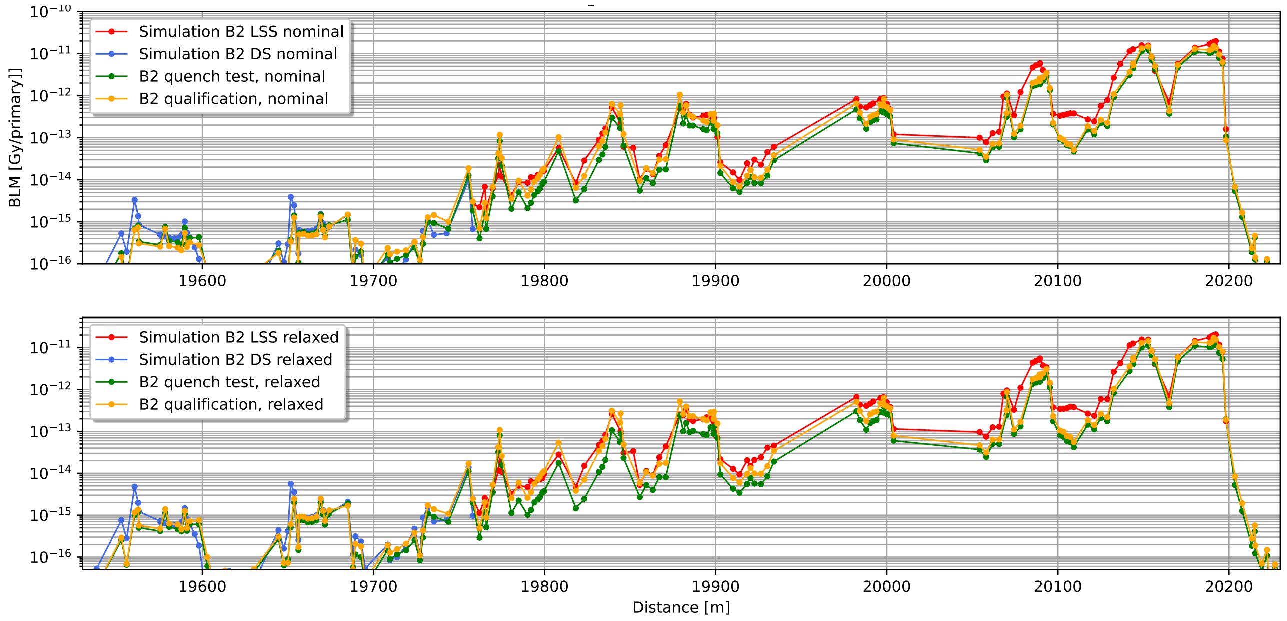
- **Halo cleaning**: reduce the risk of magnet quenches
- **Concentration of losses/activation in controlled areas**

Multi-stage system with ~50 collimators per beam

The cleaning inefficiency with ions drops to 10^{-2}!

Power deposition & quench test studies for IP7

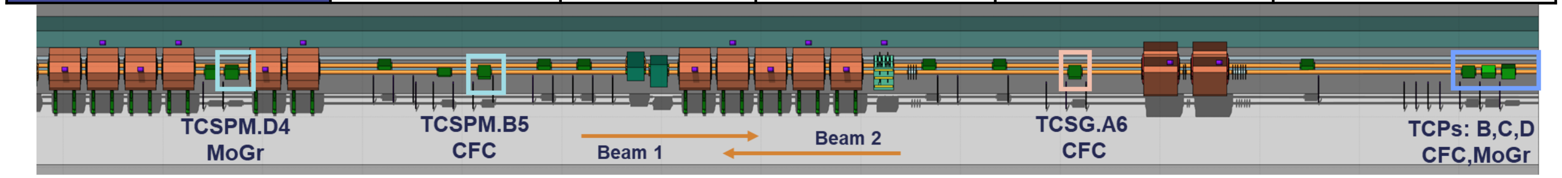


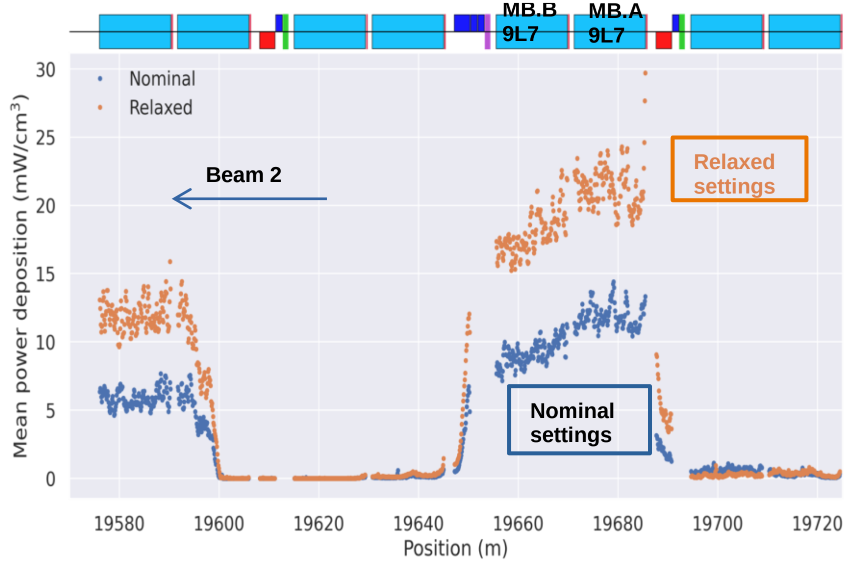


Nominal settings: IP7 TCPs/TCSGs/TCLAs: 5 sigma/6.5 sigma/10 sigma
Qualification test power loss: 5.5 kW
Quench test power loss: 650 kW

Relaxed settings: IP7 TCPs/TCSGs/TCLAs: 5 sigma/8.5 sigma/10 sigma
Qualification test power loss: 4.8 kW
Quench test power loss: 620 kW

Simulation study	TCPPM.C6, J1/2 (full), kW	TCP.B6 J1/2 (full), kW	**TCSG.A6 J1/2 (full), kW**	**TCSPM** J1/2 (full), kW	**TCSPM** Mo coating PPDD, W/**cm^3**
A.Waets 2020, B1, (HL-LHC baseline)	**4.25/4.13 (23.5) MoGr**	**10.12/10.08 (42.5) CFC**	**5.8/5.27 (28.1) CFC**	**5.03/3.75 (19) MoGr B5**	**175 B5**
V.Rodin 2022, B2, (LHC today, depicted)	**4.5/4.07 (23.6) MoGr**	**10.33/10.03(42.52) CFC**	**5.53/5.09 (26.65) CFC**	**1.95/1.92 (8.03) MoGr D4**	**72 D4**

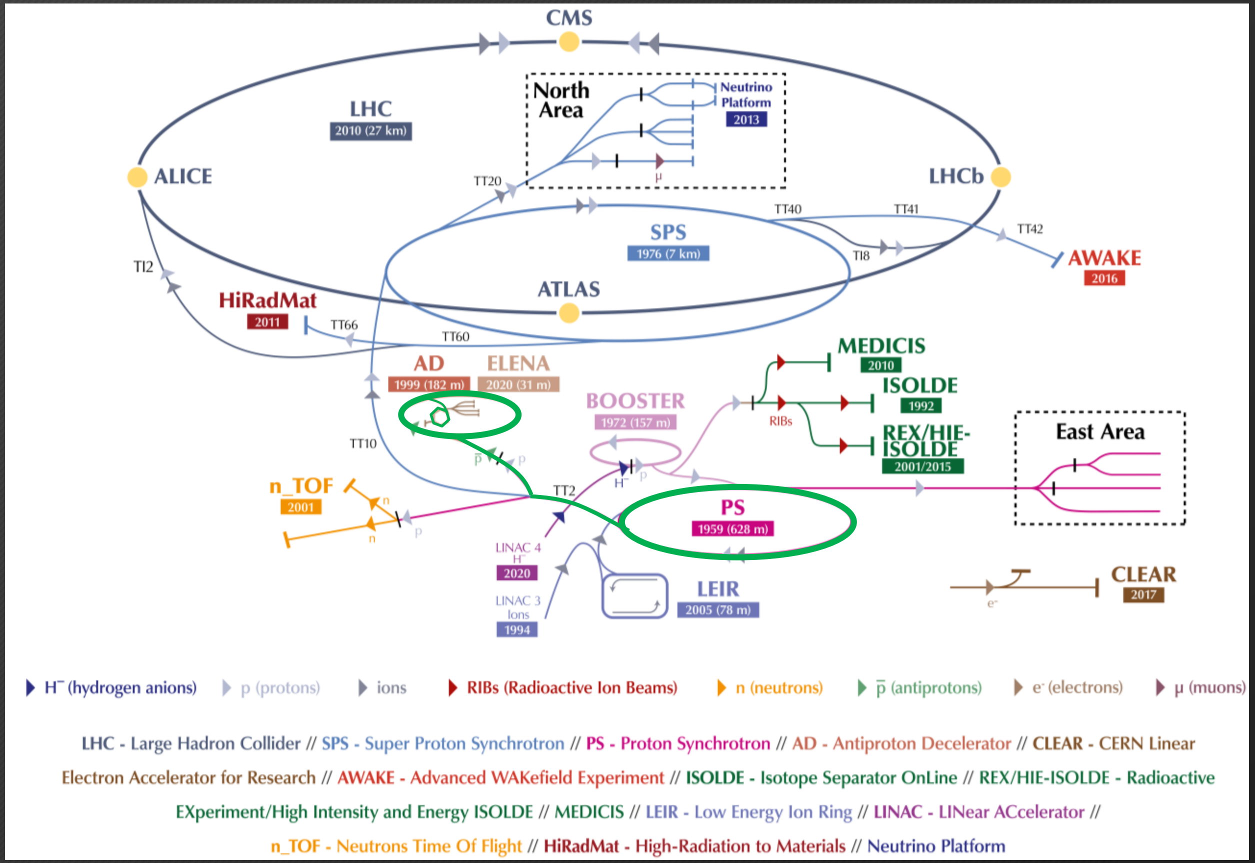




HL-LHC baseline losses ~1MW (0.2h BLT, 8.81E11 p/s)

Availability of antimatter worldwide (and low-energy antiprotons)

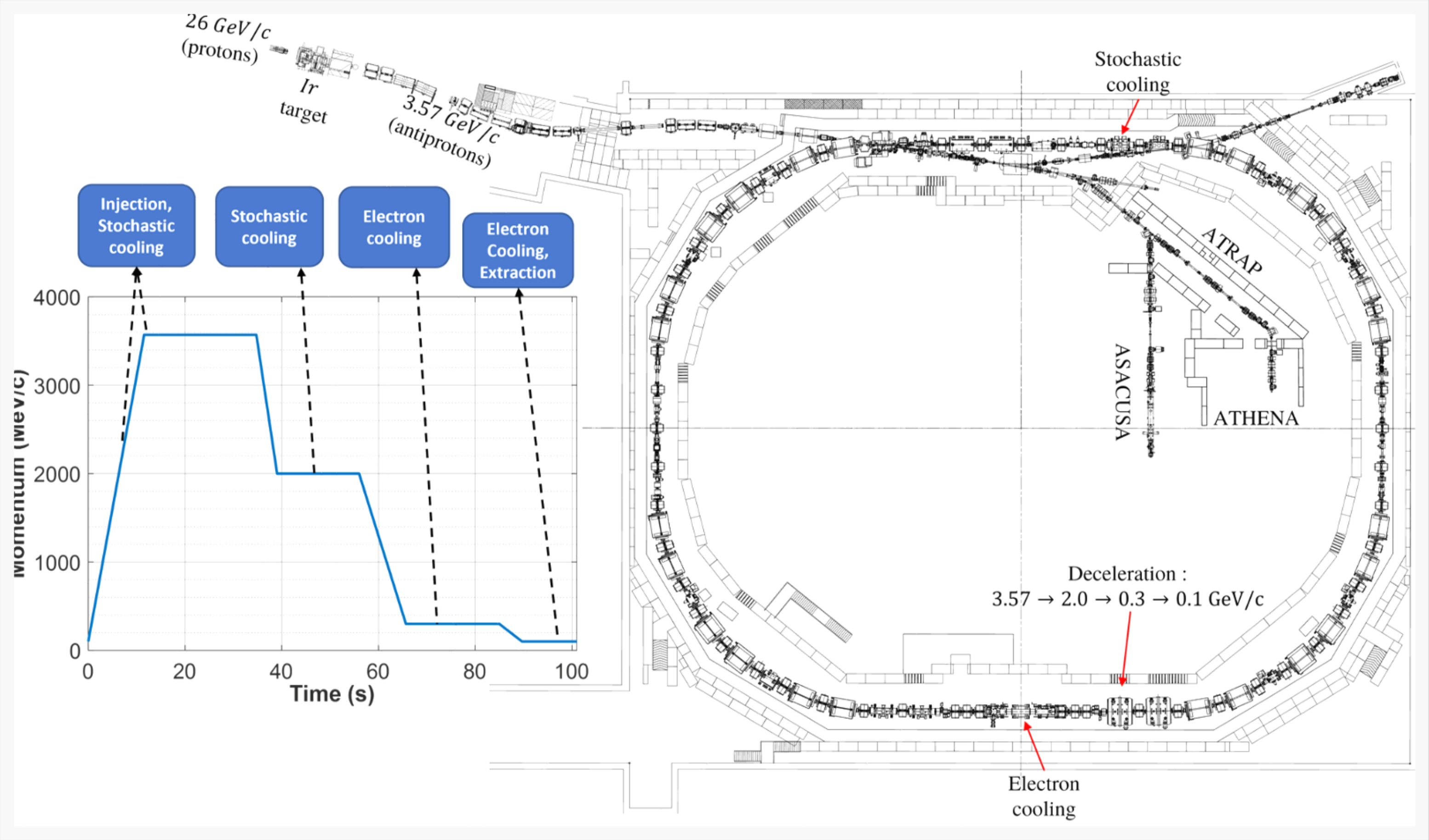
- CERN’s Antimatter factory is the only place providing access to low-energy antiprotons
- Production of antiprotons using a fixed target
- Plans about FLAIR project at FAIR in GSI were postponed
- **Any ideas how we can change this?**



LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive EXperiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform

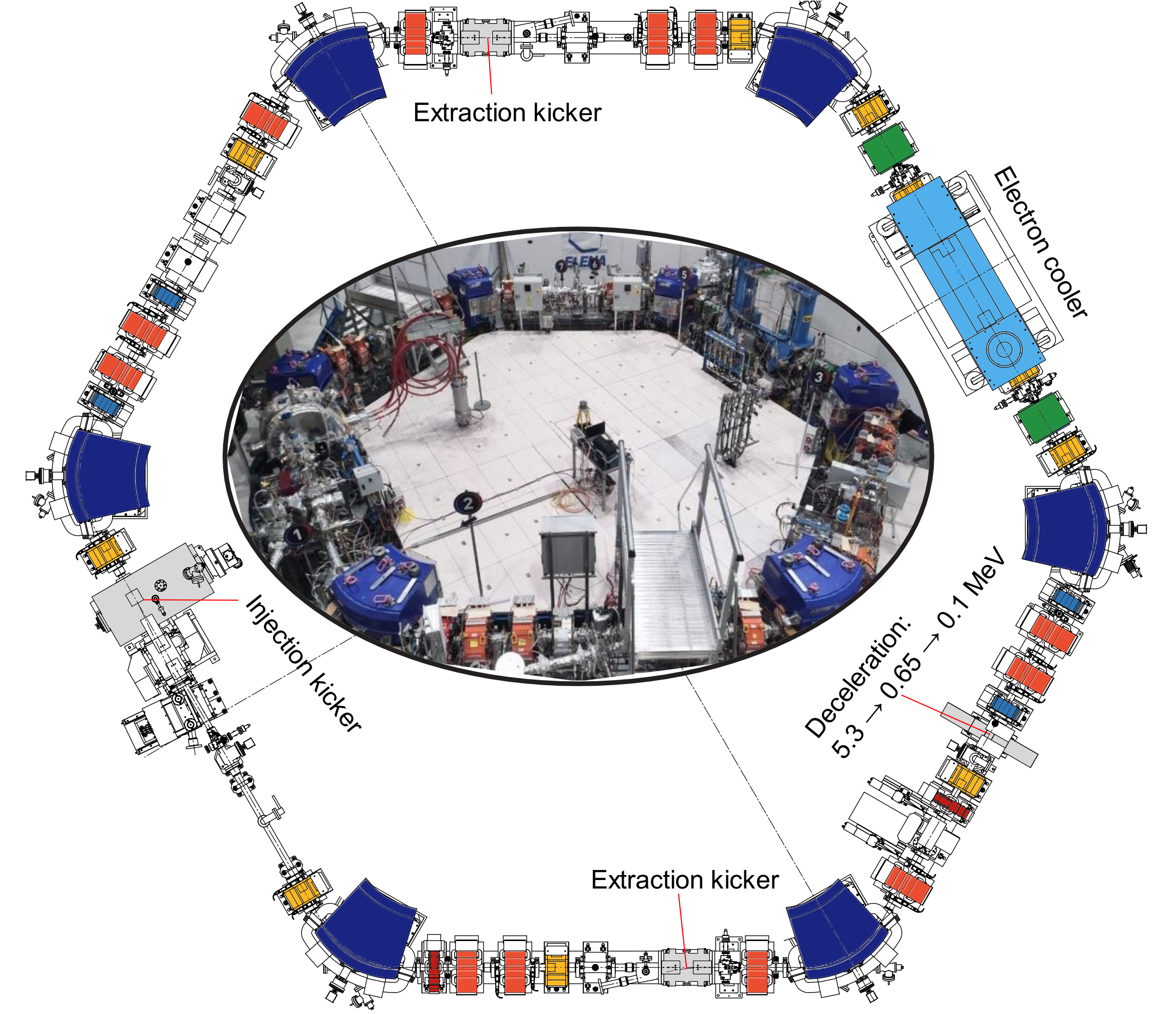
Antiproton Decelerator

- Deceleration of produced protons down to 5.3 MeV/c
- Better beam quality
- First efficient trapping of antiprotons by ATRAP, ATHENA and ASACUSA
- However, the capture efficiency was still below 1 % !!!

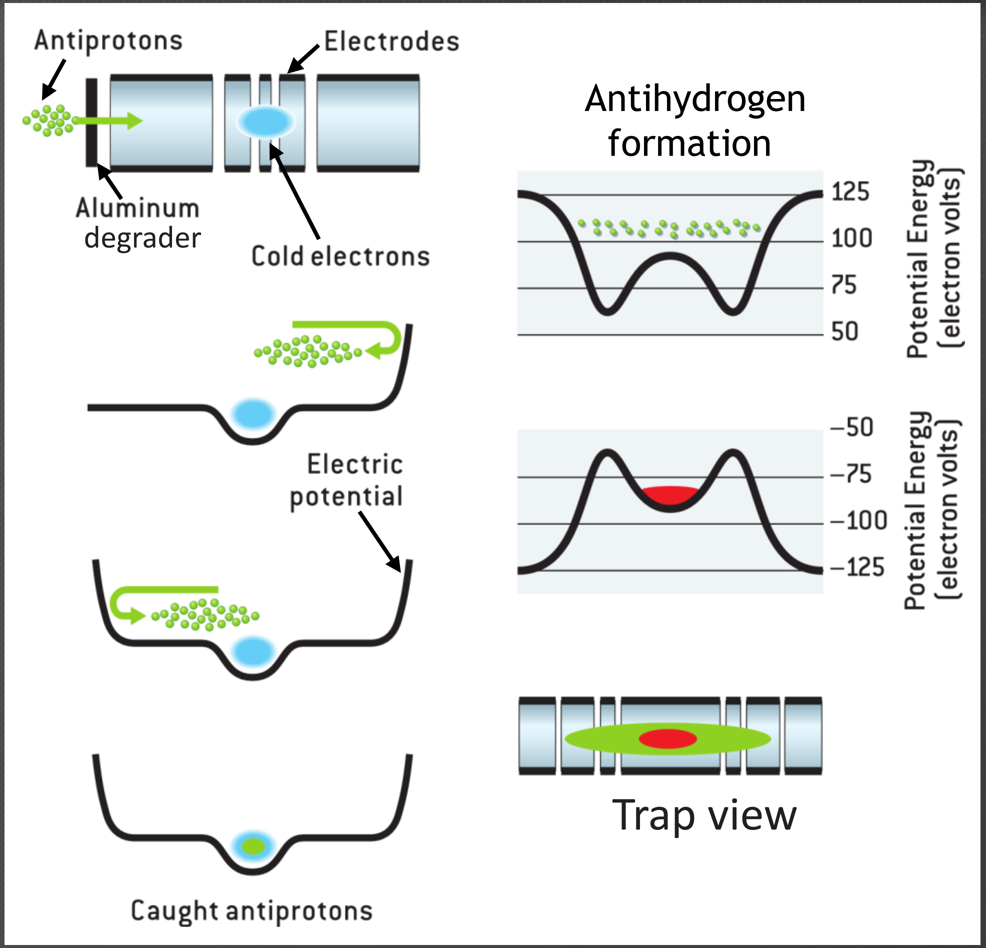


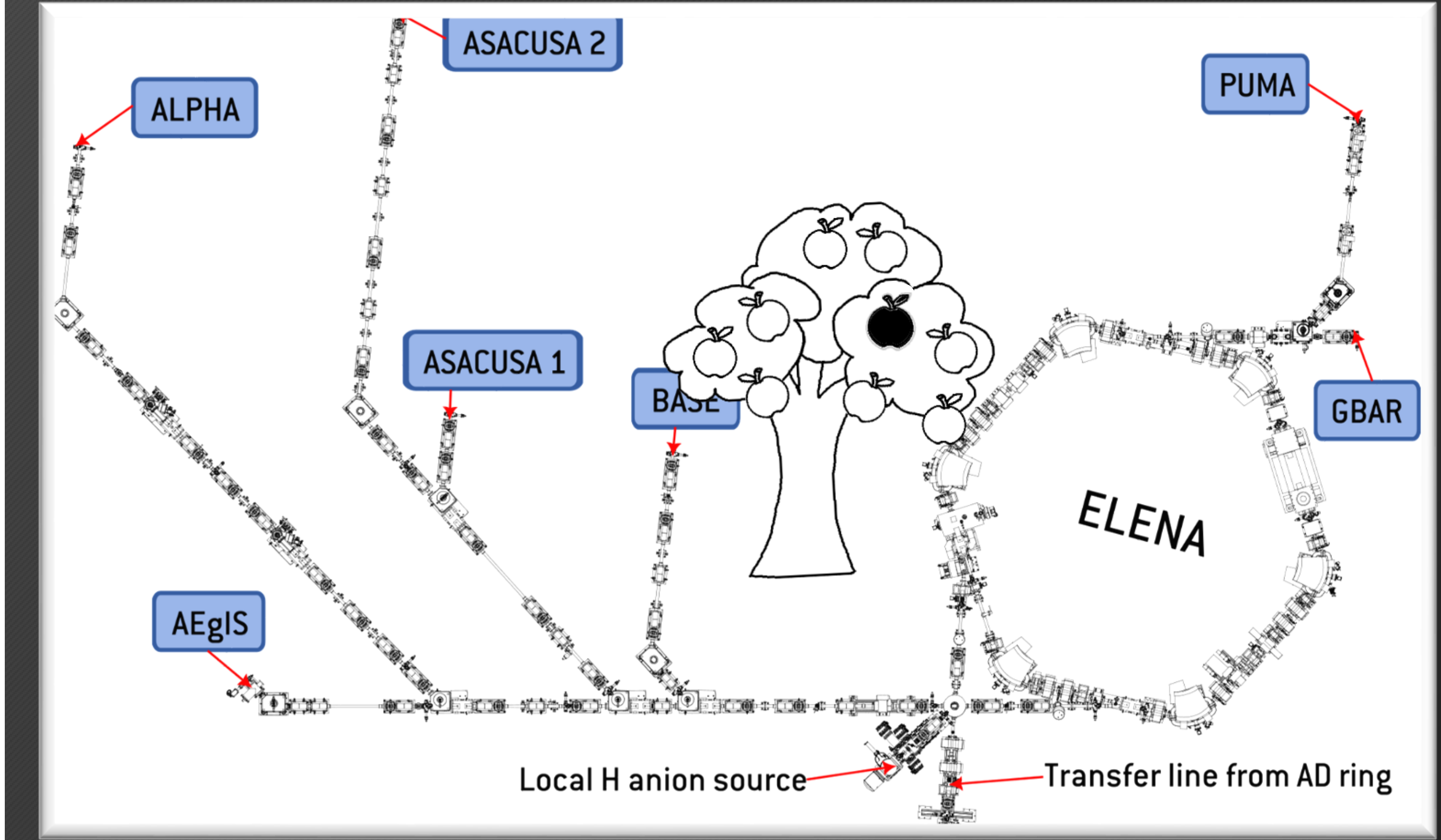
Extra Low ENergy Antiproton ring

- Beam extracted from AD to ELENA
- Further decelerates antiprotons from 5.3 MeV to 0.1 MeV
  - Thinner degrader foils
  - Increased quality and intensity of antiproton bunches received in traps
  - Improved trapping efficiency by factor of 10-100
  - Emittance: 2.5 mm mrad
  - Bunch length: 75-100 ns
  - Total intensity: 3×10^7



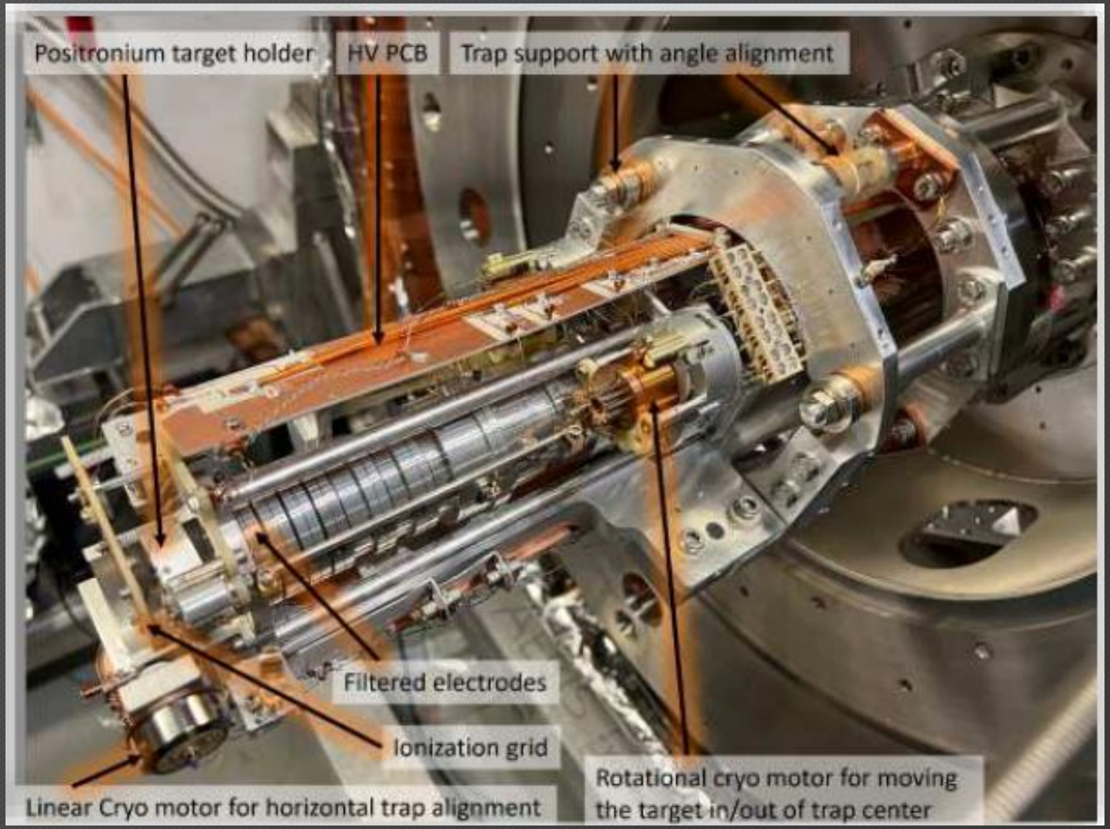
Antiproton experiments and particle traps

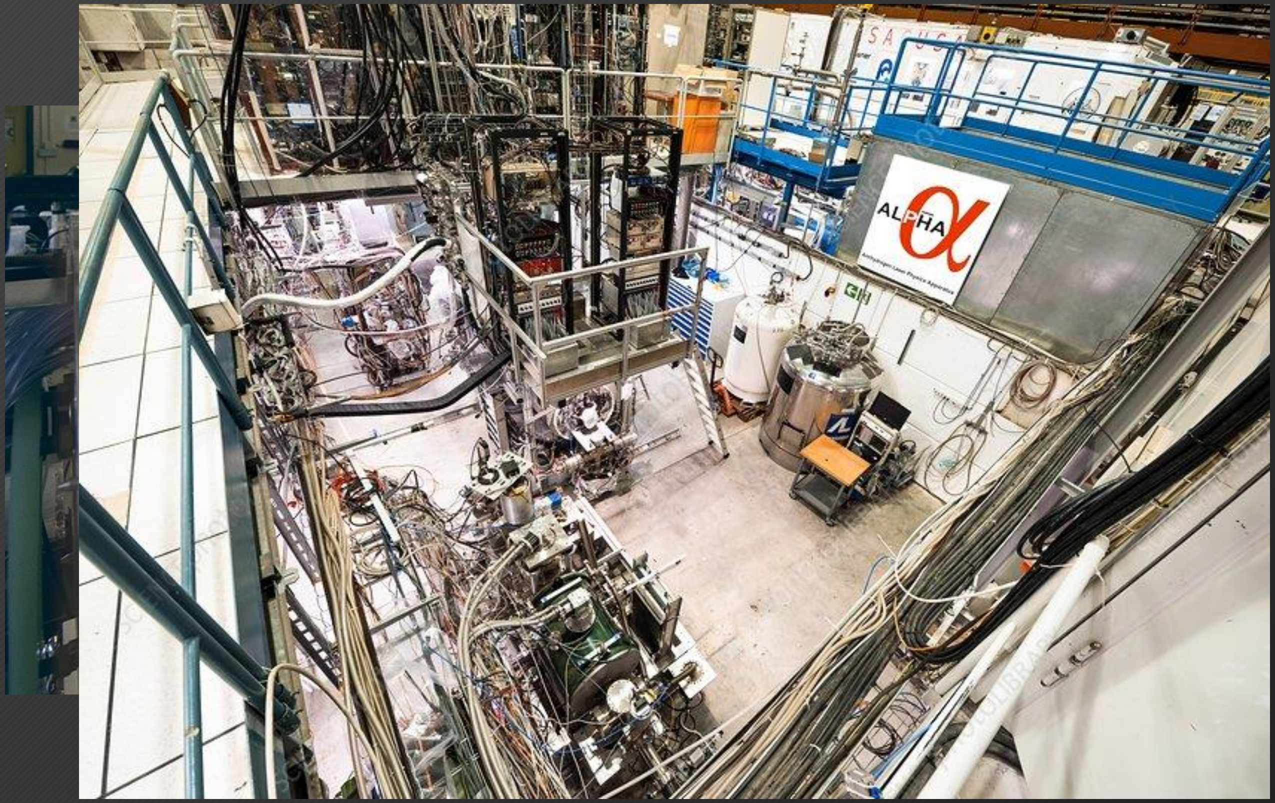




Formation of antihydrogen

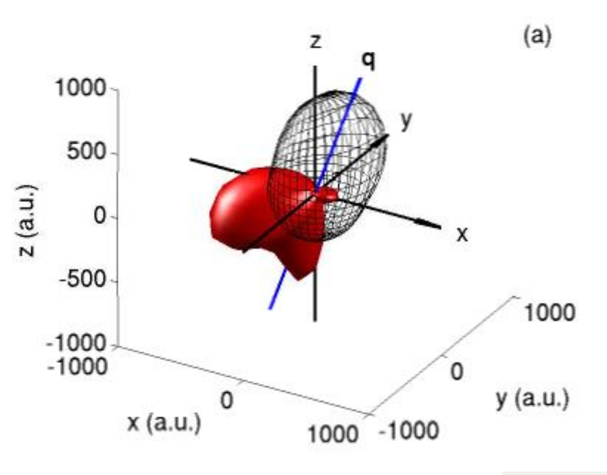
Antimatter experiments

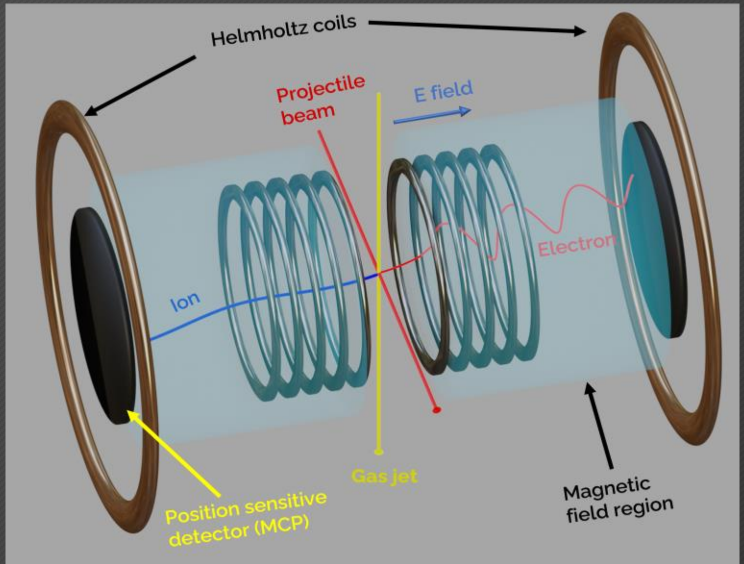


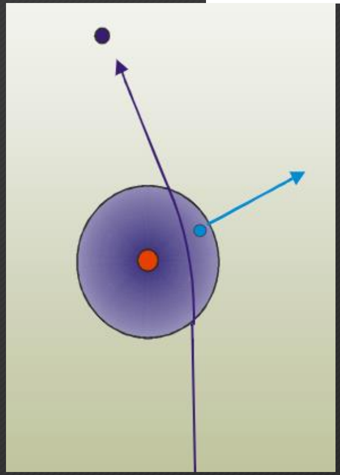


New ~~old~~ ideas: many-body Coulomb problem and differential cross-sections as a theory benchmark

- Difference between Born approximation and proposed theory
- Possible elements for study atomic and molecular H and He
- Some of the ideas suggest production of attosecond electromagnetic pulses
- Requires ~ns antiproton pulses for high precision







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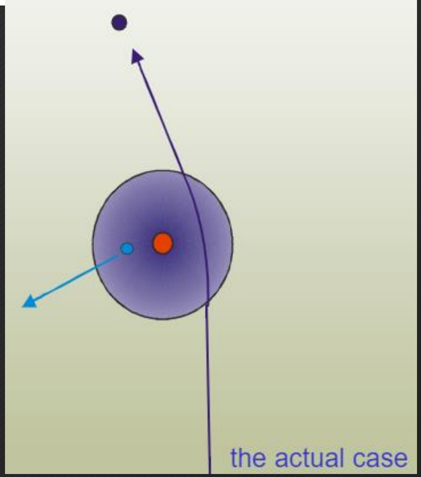
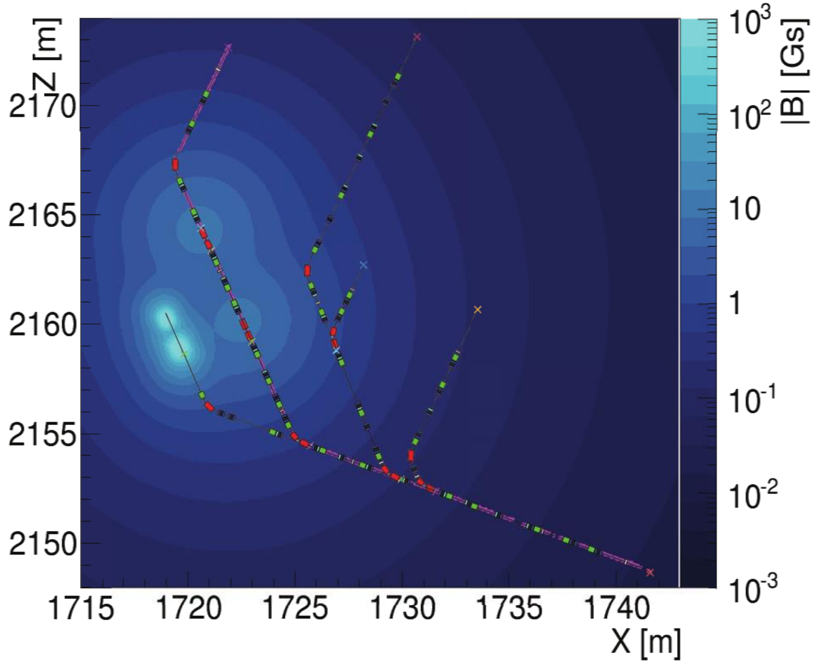
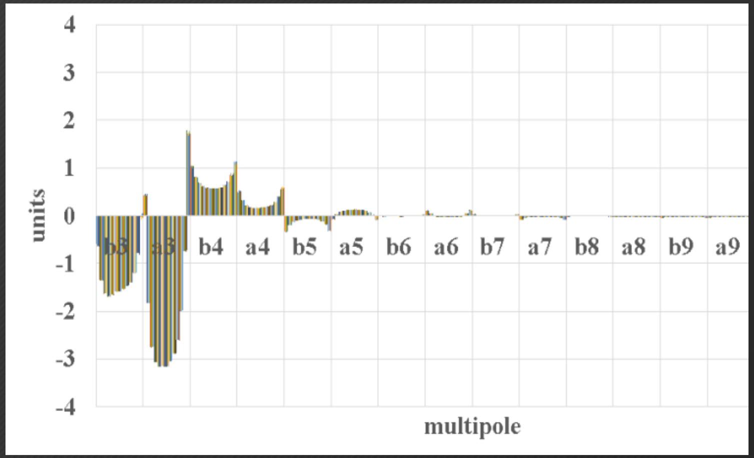


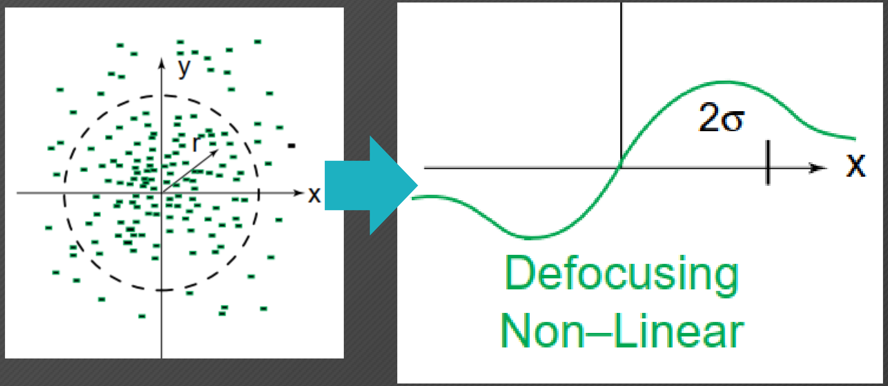
M. McGovern 2009, Phys. Rev A

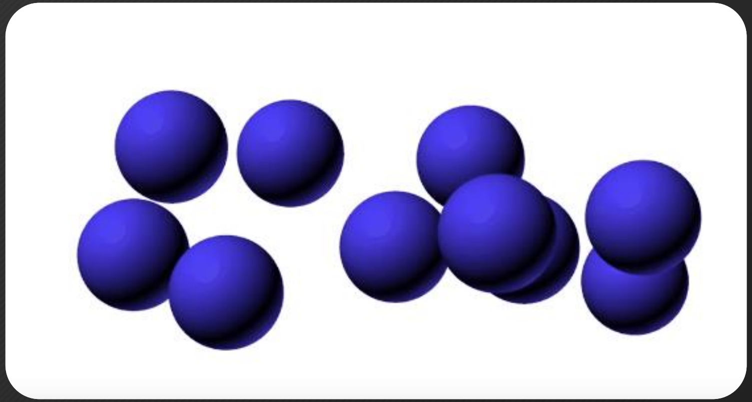
Main challenges

- Element imperfections
- Magnetic stray field
- Collective effects
- Vacuum quality

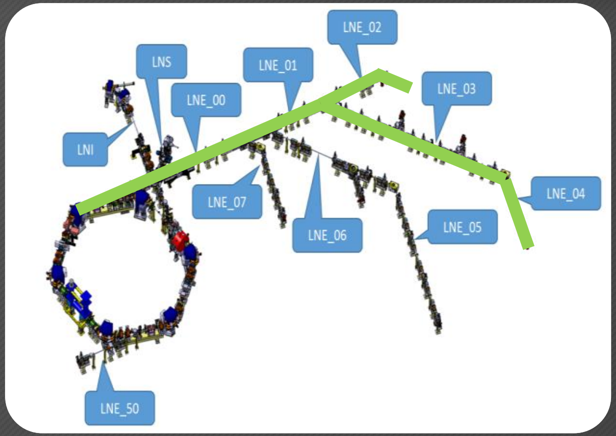


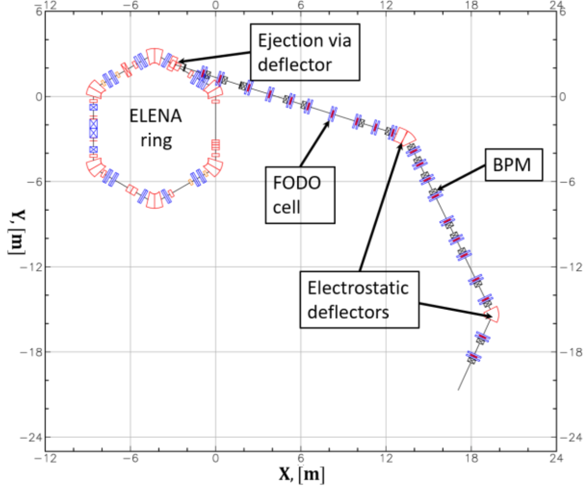


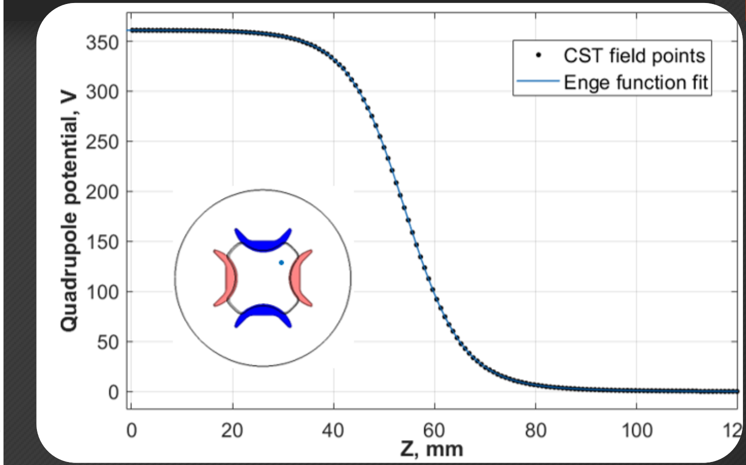


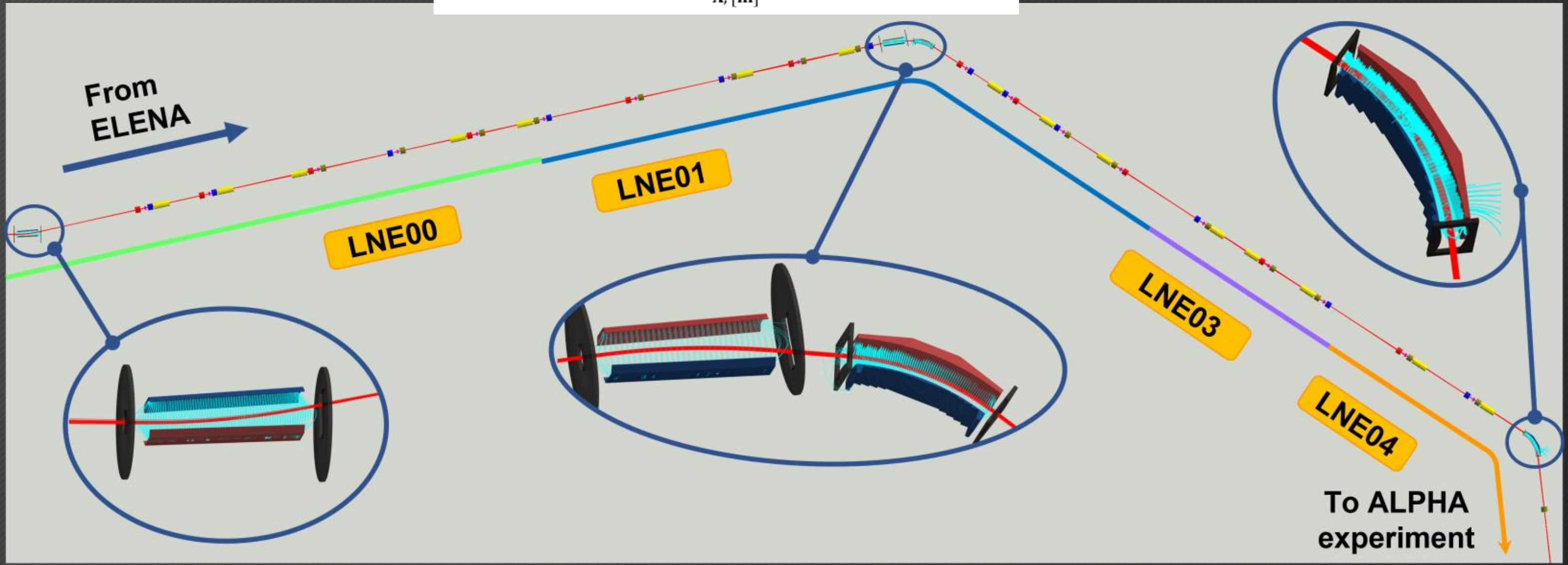


3D tracking studies: ALPHA and AEgIS transfer lines in G4beamline and BMAD

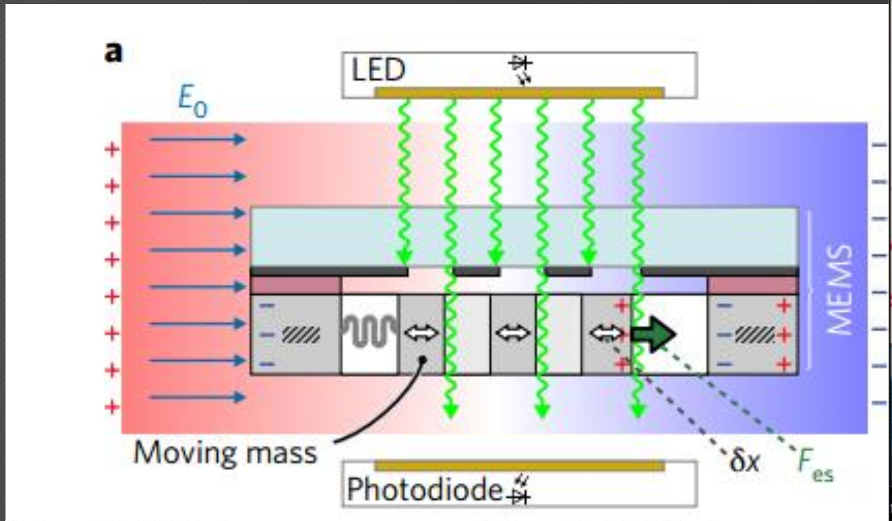


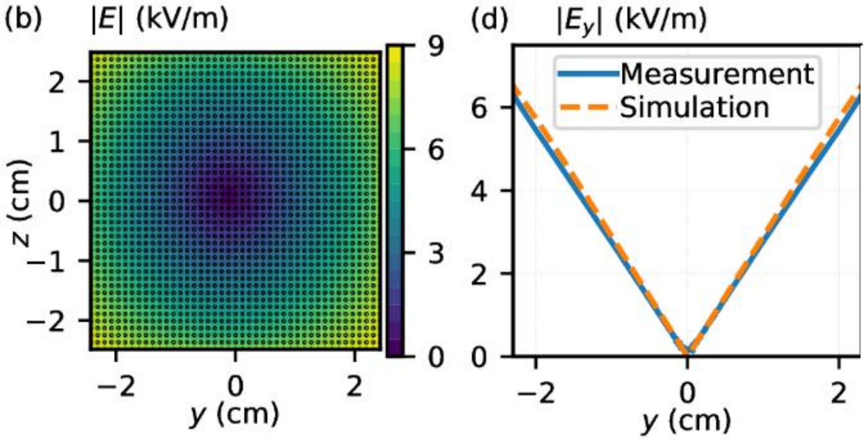


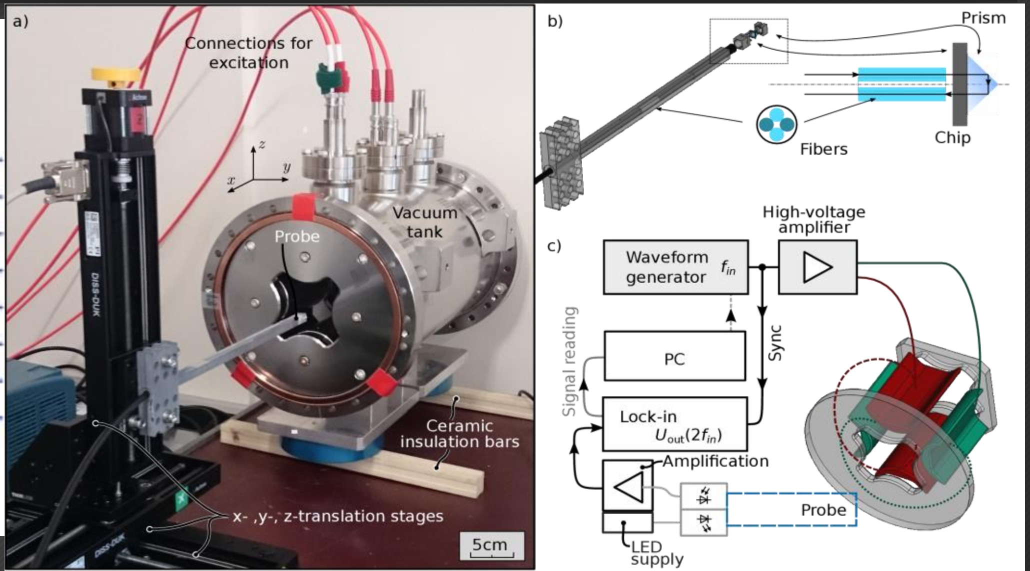


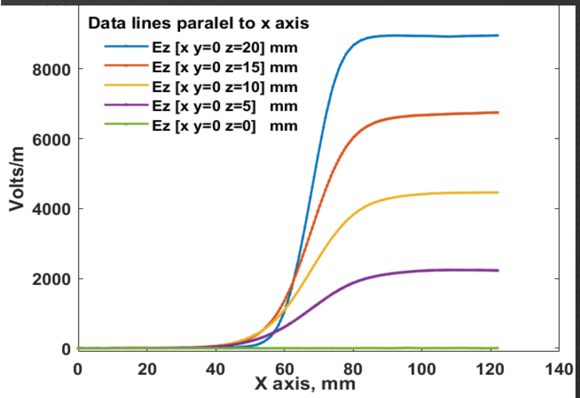


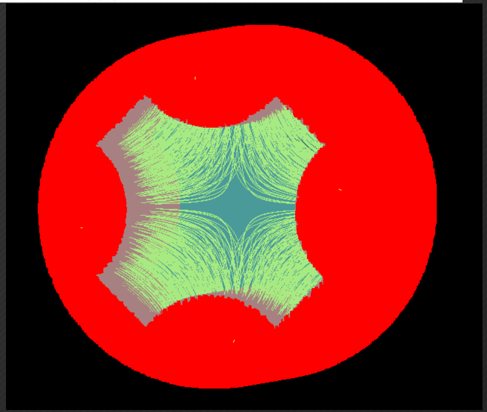
Electrostatic quadrupole 3D field mapping





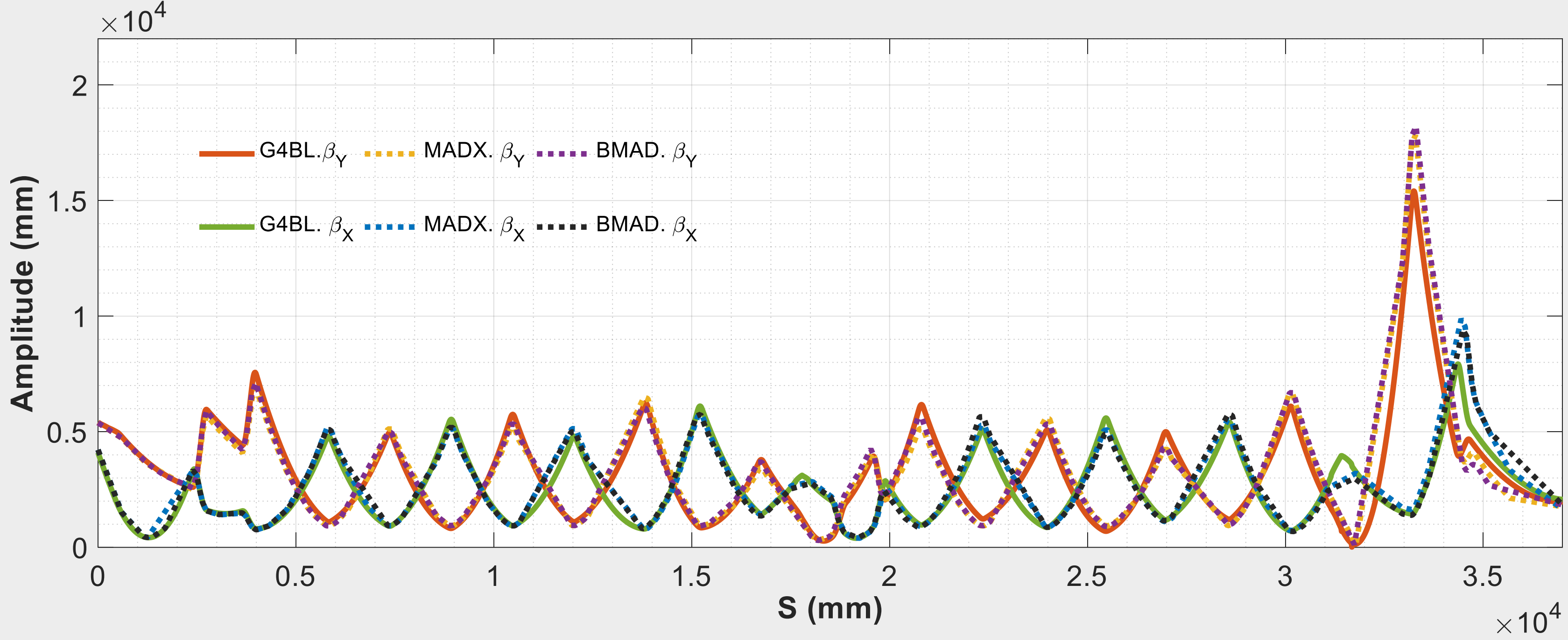


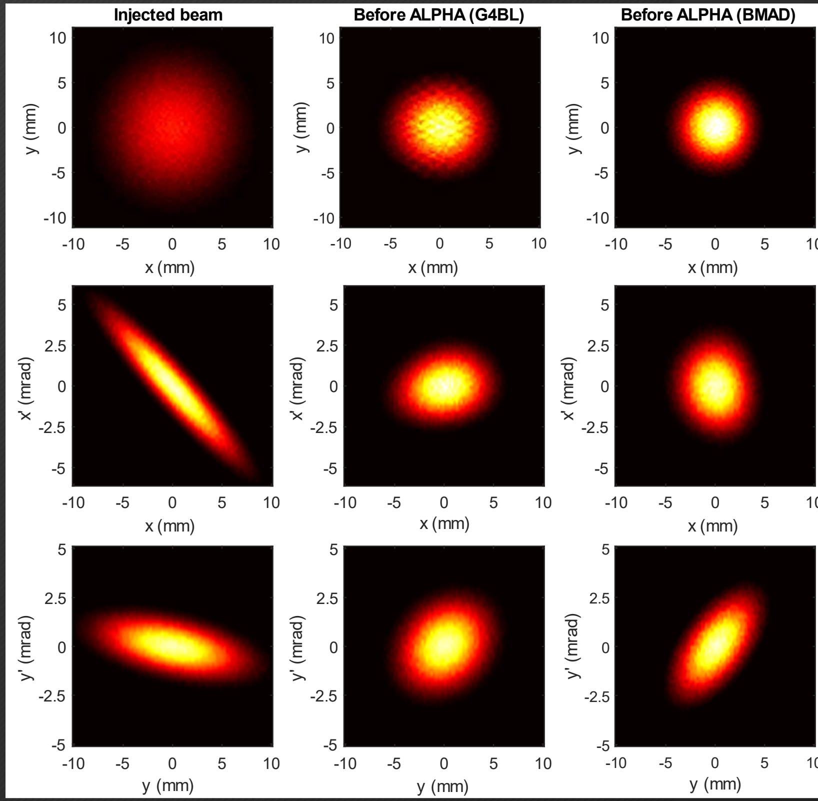




Benchmark against baseline simulations: ALPHA line

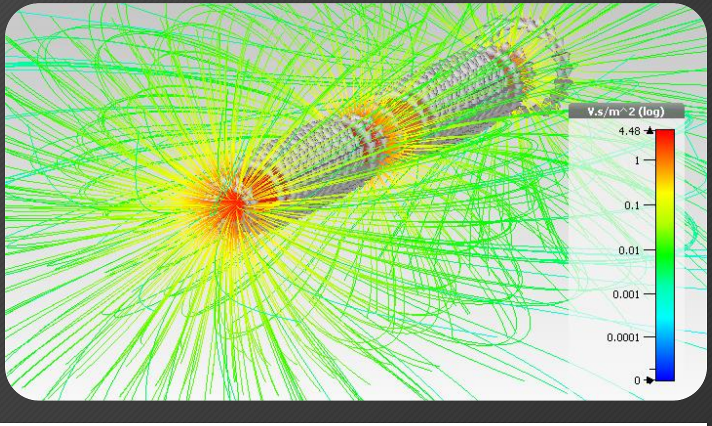
- A small discrepancy at the end due to impact of quadrupole fringe fields and non-identical simulations of electrostatic deflectors

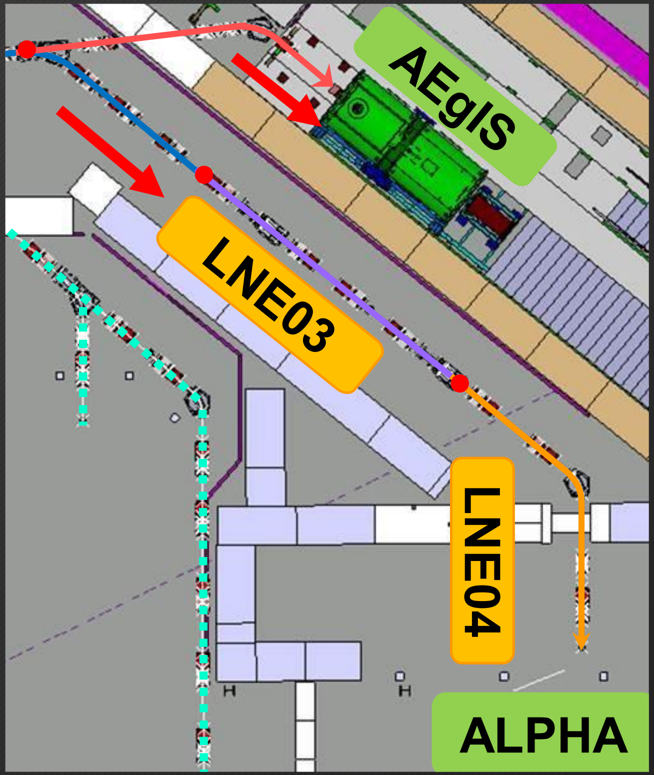


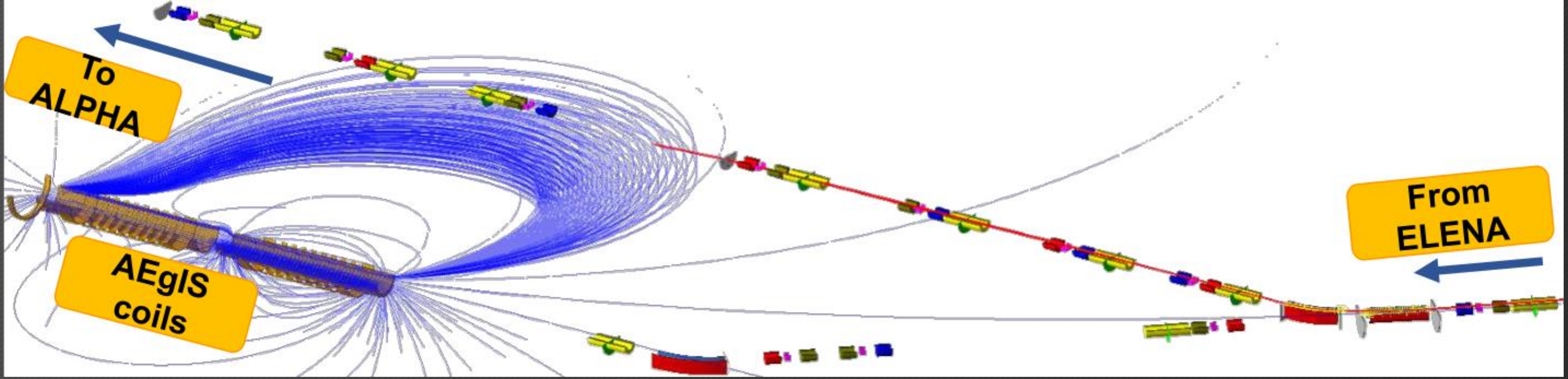


Impact of magnetic stray fields from AEgIS line

- Low energy antiprotons (100 keV) are quite easily deflected by low amplitude magnetic field ~5 Gauss of 4 m length
- This problem can be fixed with beam line shielding or extra kicks from corrector elements

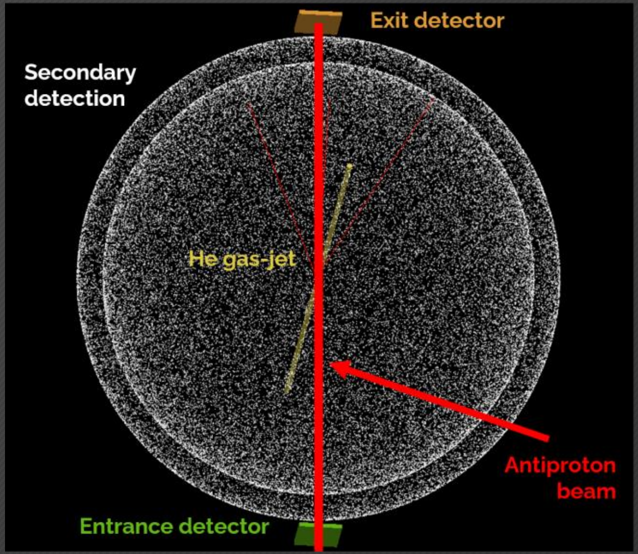


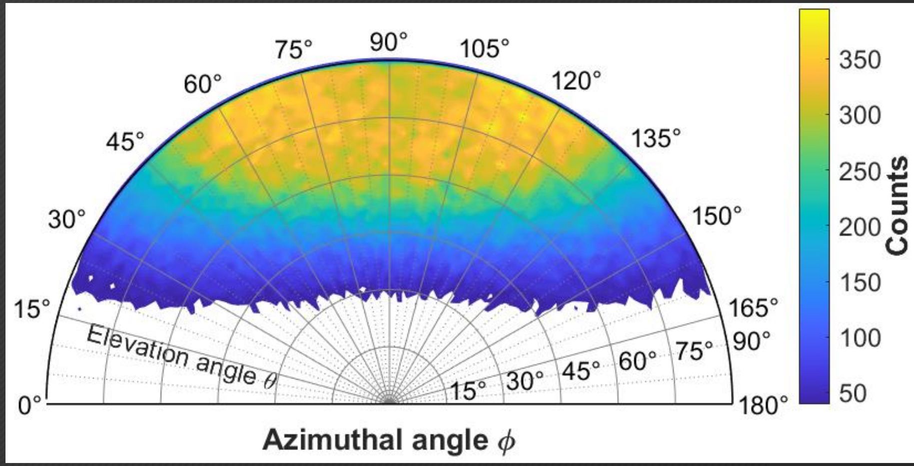


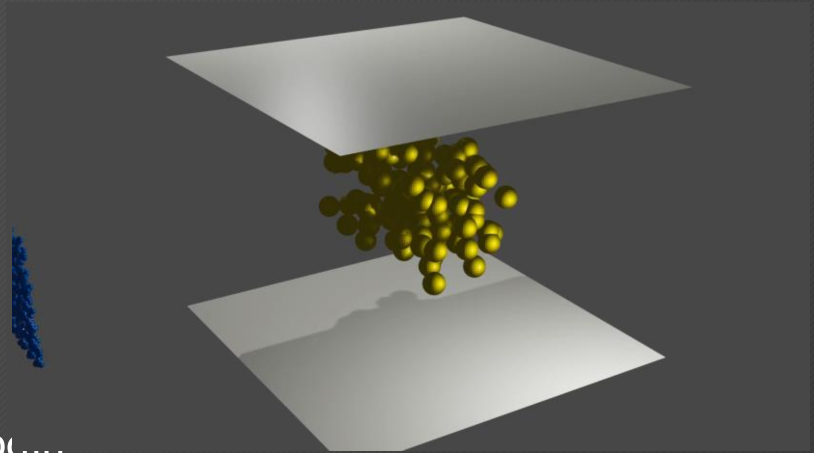


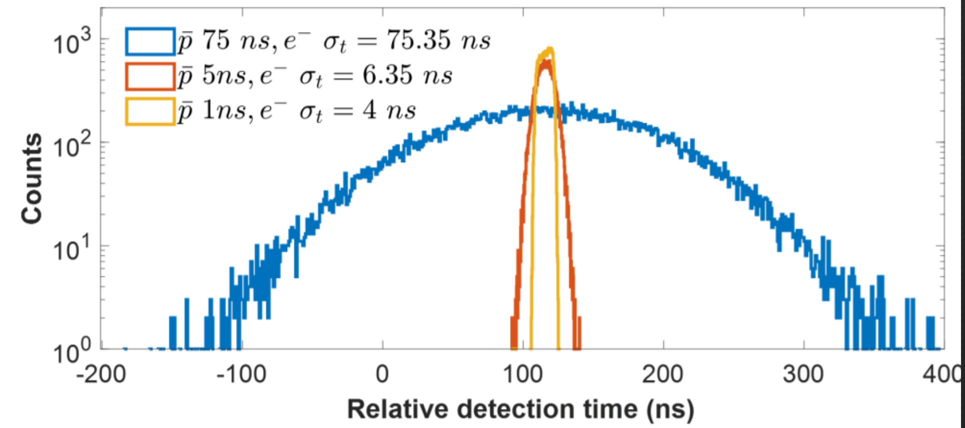
Ideal gas-target conditions: rough estimation in Geant4: impact of bunch length

- N ~10^{14} atoms/m^3 (He gas jet target)
- 2σ beam = jet width
- Ionization cross-section ~64 Mb
- Reaction rates ~ 10^9 per second

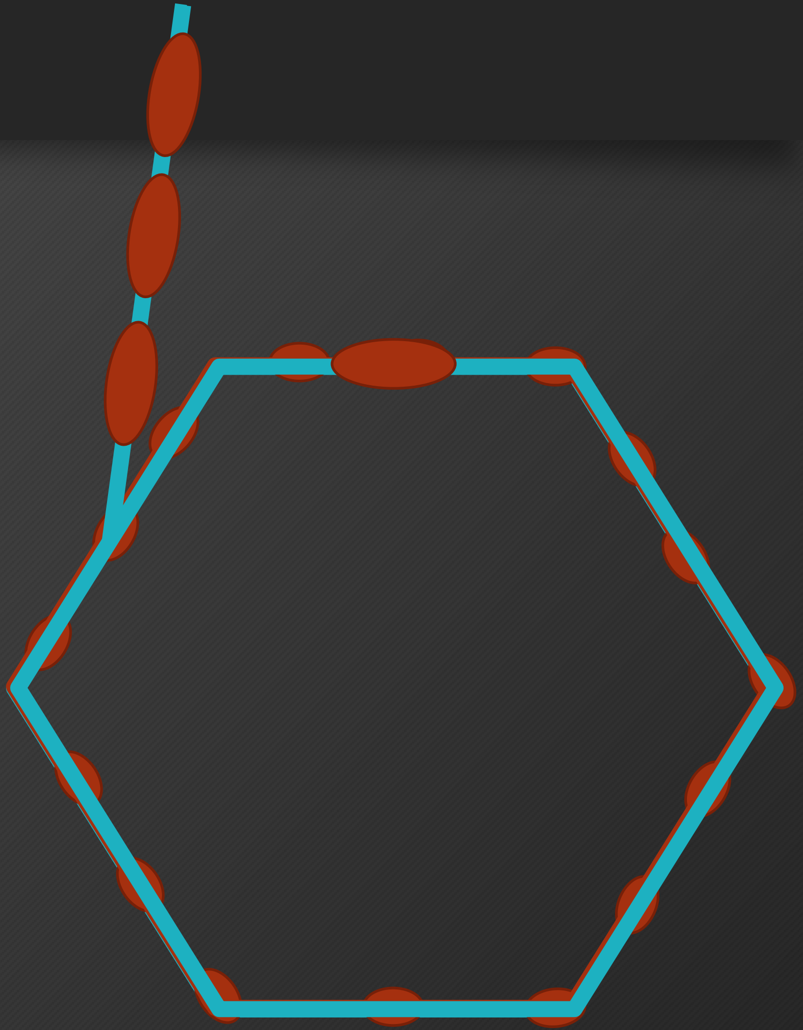






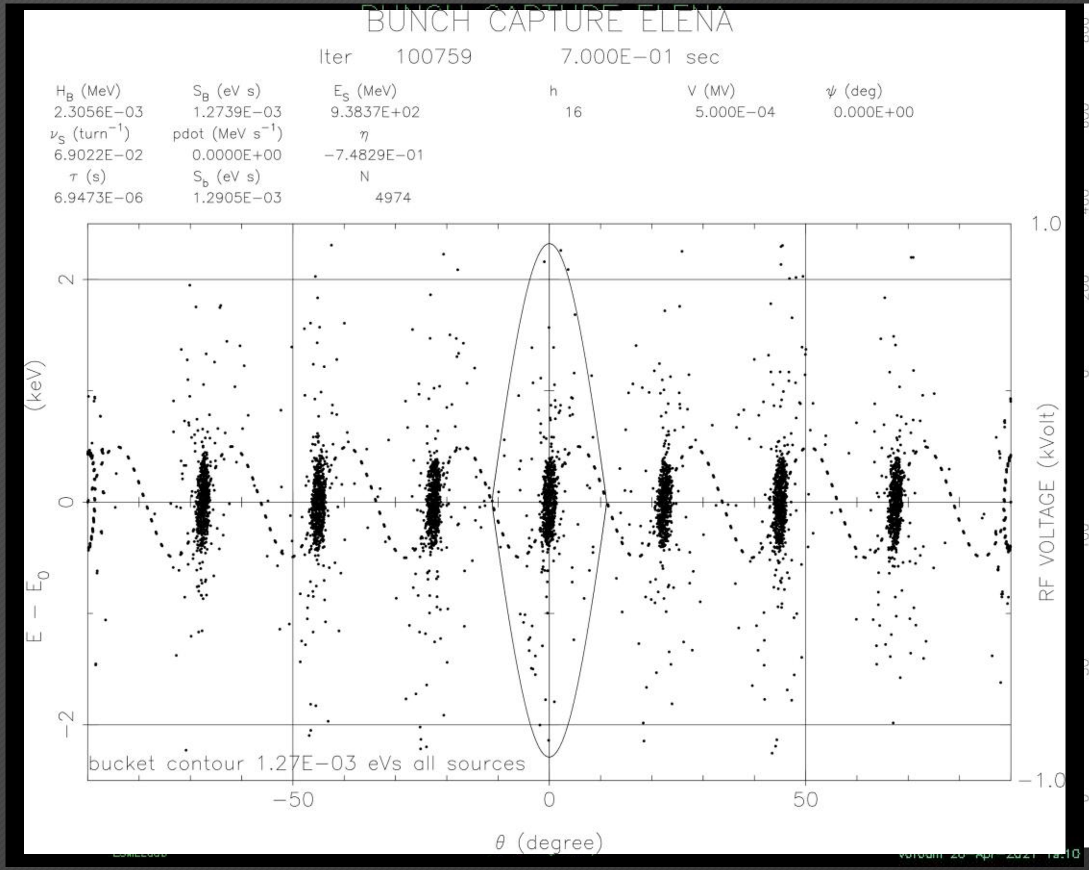


Impact of collective effects: Alternative mitigation



- Decrease in bunch population is required by factor >10
- Compression by de-bunching and re-bunching could solve the problem
- Adiabatic bunching with h>10 or bunch splitting (no possibility)

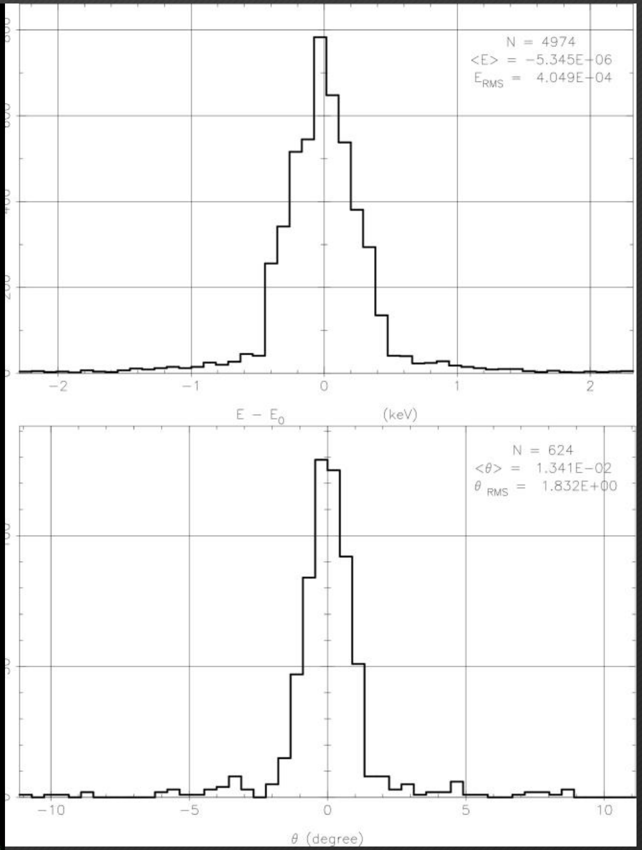
Impact of collective effects: re-bunching



BUNCH CAPTURE ELENA

Iter 100759 7.000E−01 sec

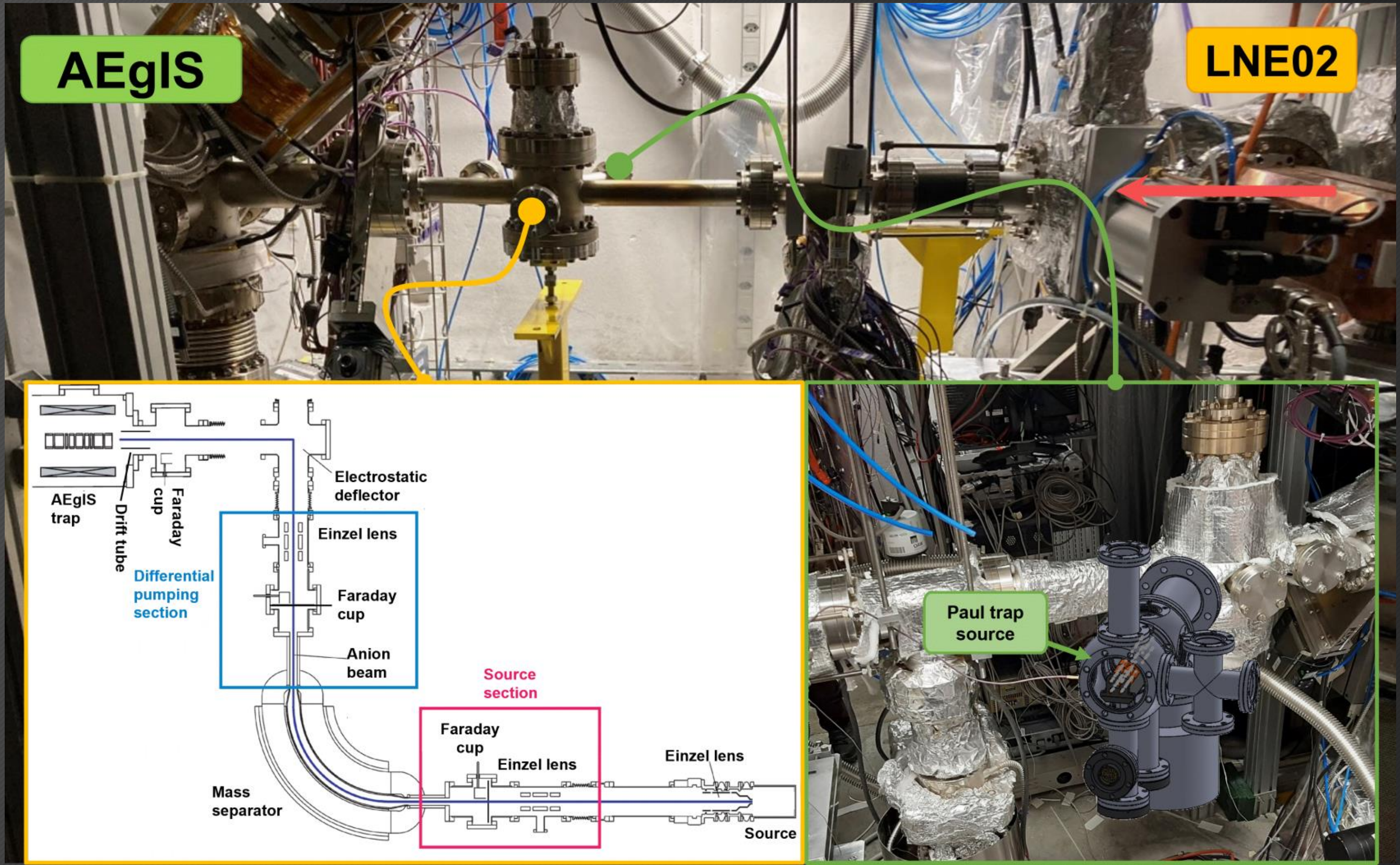
H_B (MeV)	S_B (eV s)	E_S (MeV)	h	V (MV)	ψ (deg)
2.3056E−03	1.2739E−03	9.3837E+02	16	5.000E−04	0.000E+00
ν_S (turn^{-1})	pdot (MeV s^{-1})	η			
6.9022E−02	0.0000E+00	−7.4829E−01			
τ (s)	S_b (eV s)	N			
6.9473E−06	1.2905E−03	4974			



N = 4974
<E> = −5.345E−06
E_{RMS} = 4.049E−04

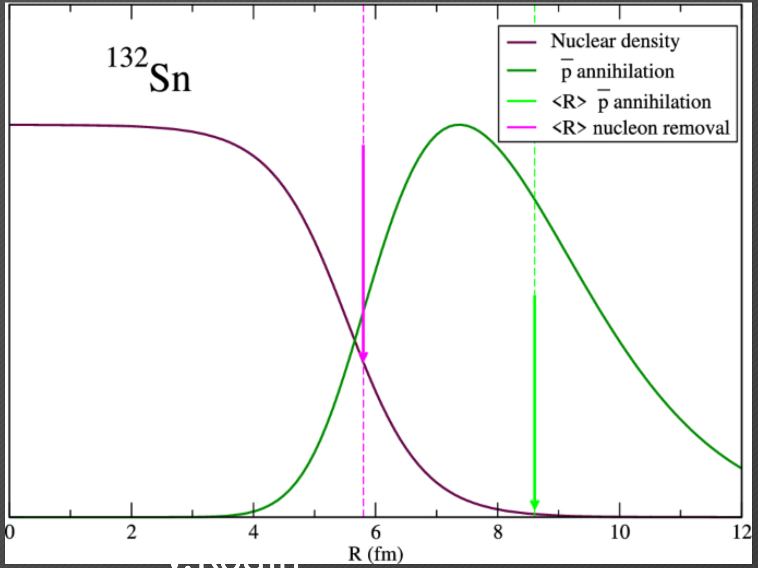
N = 624
<θ> = 1.341E−02
θ_{RMS} = 1.832E+00

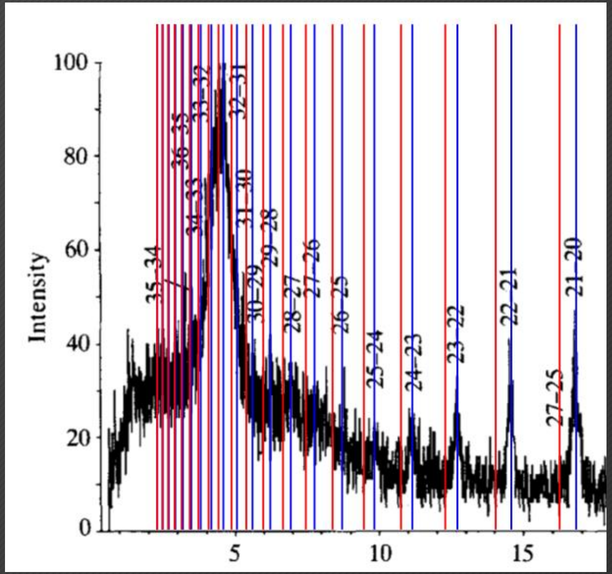
Antiprotonic atoms at AEgIS experiment

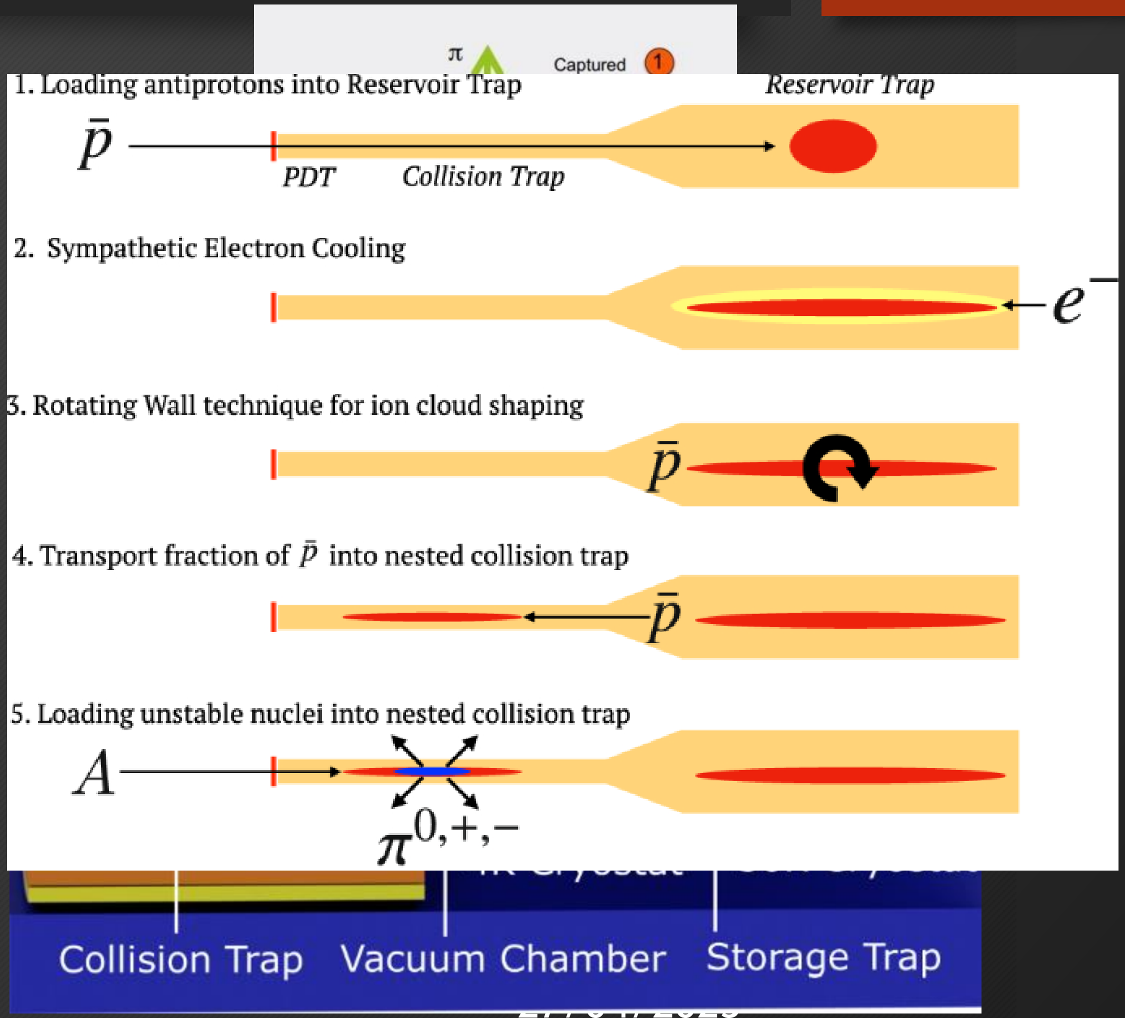


Physics behind antiproton atoms

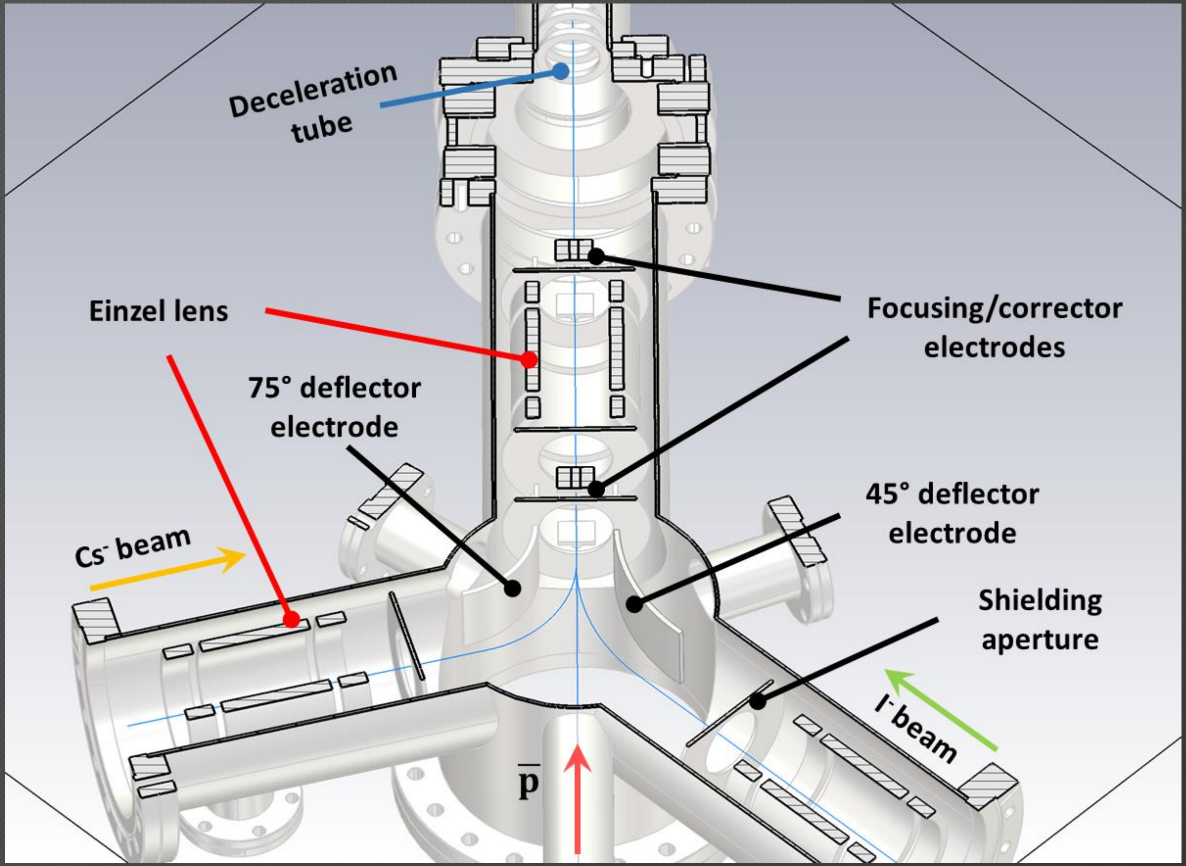
- The first results were obtained in the past with He and other atoms as result of antiproton capture in solid targets
- Possibility to characterize neutron tails of the nucleous or its shape

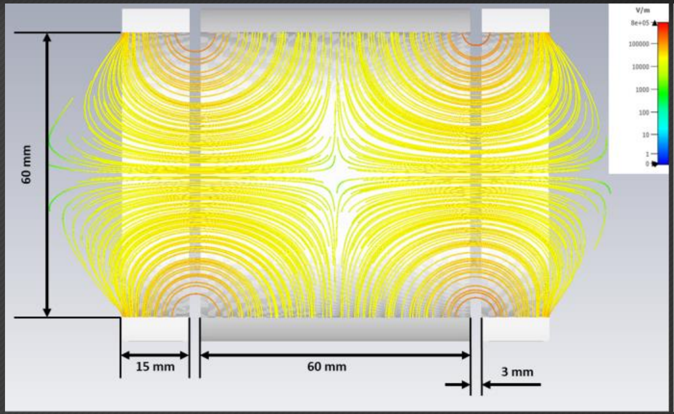


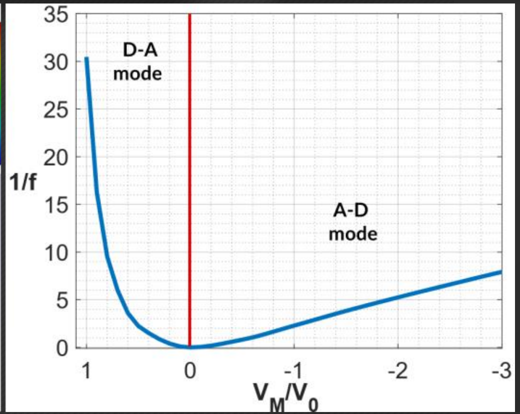


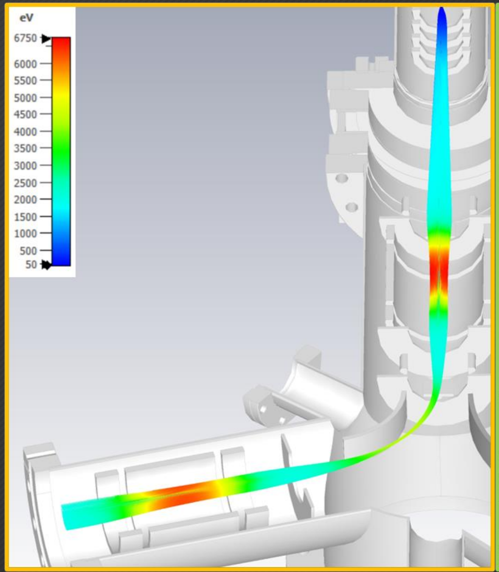


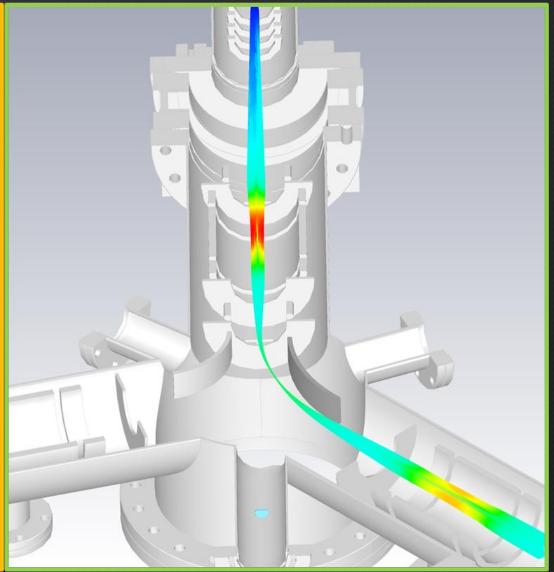
Designed injection/extraction beamline for anions (<5 keV)



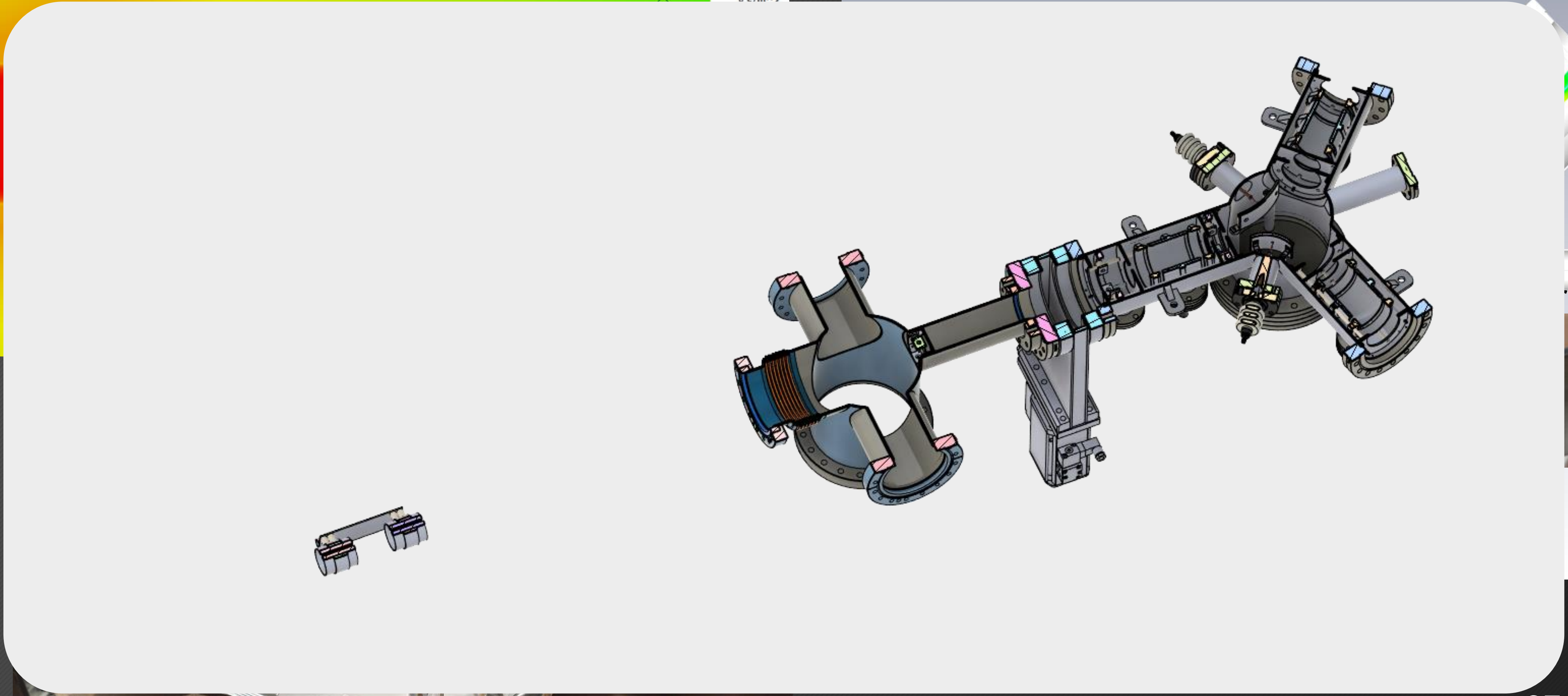




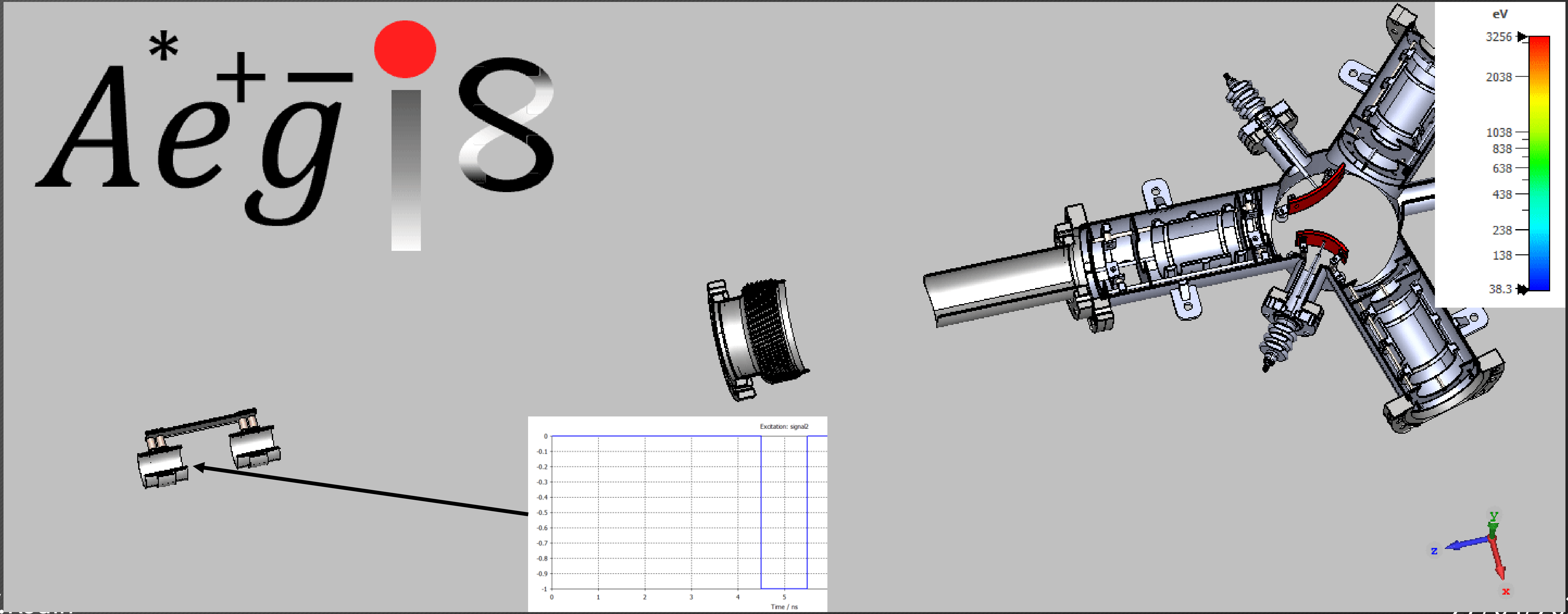




Stray magnetic fields



Dynamic tracking simulations: stray fields+3D PIC space-charge



Thank you for your attention!
Any questions are welcome?