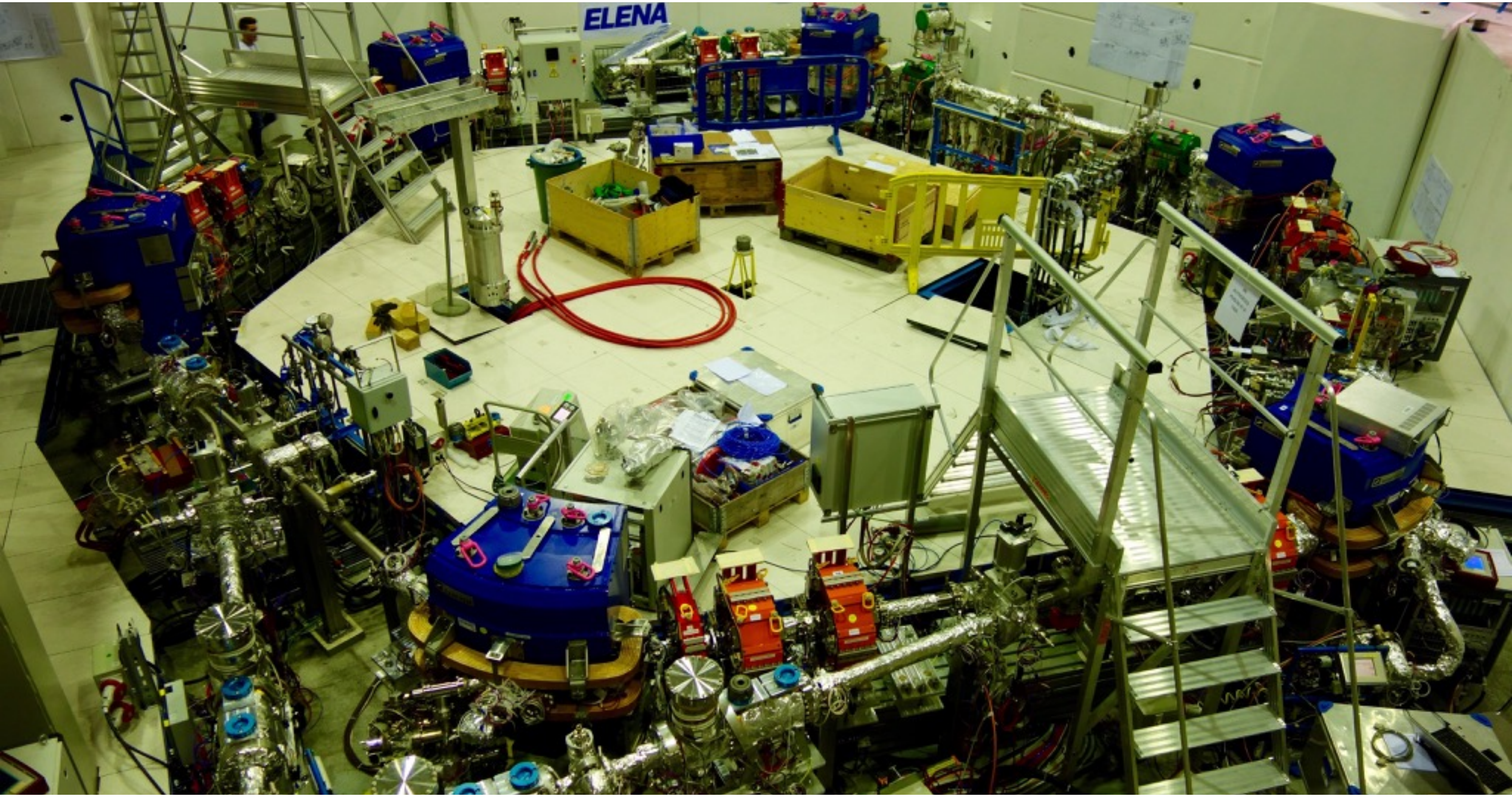
2nd MINI-WORKSHOP ON GBAR ANTIPROTON TRAP (09/02/2017)



Design study of a drift tube decelerator for an ultra-slow antiproton beam in ASACUSA

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AGENDA

① Current a few eV pbar preparation in ASACUSA

② Motivations for a new decelerator

③ Methods for designing

④ Result

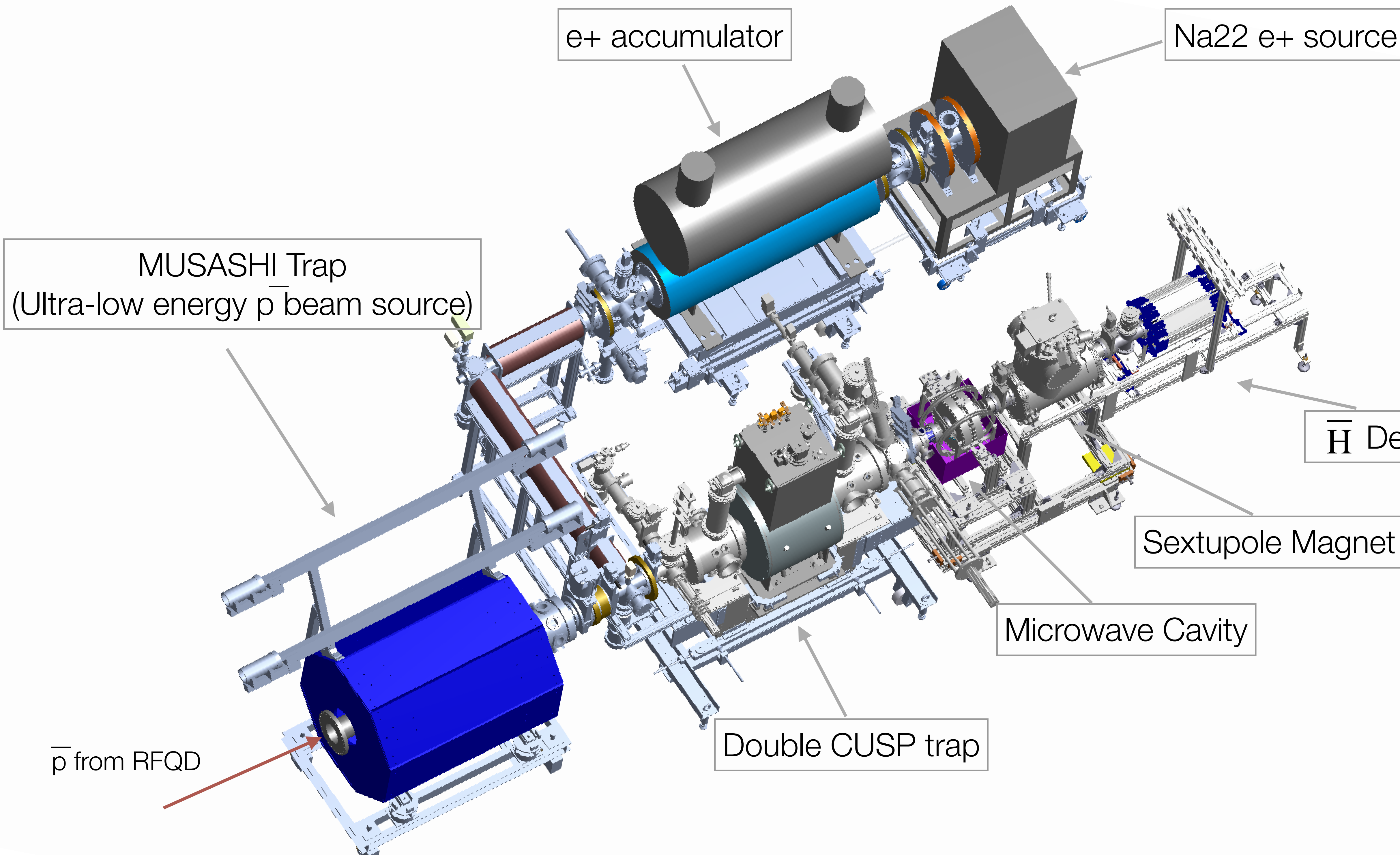
⑤ Comparison with a degrader

⑥ Deceleration at bad beam condition

⑦ Conclusion

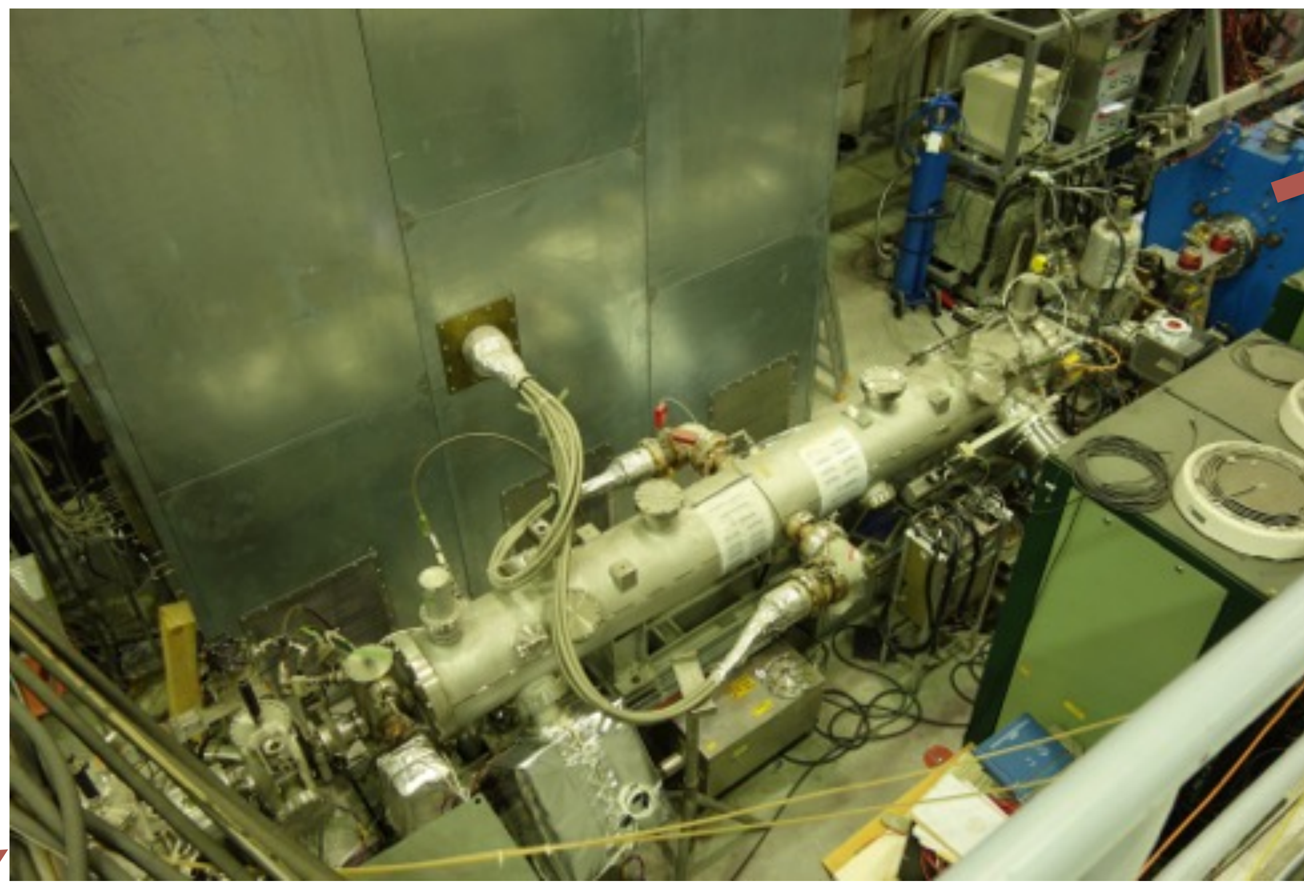
① Current a few eV pbar preparation in ASACUSA

ASACUSA CUSP beam line

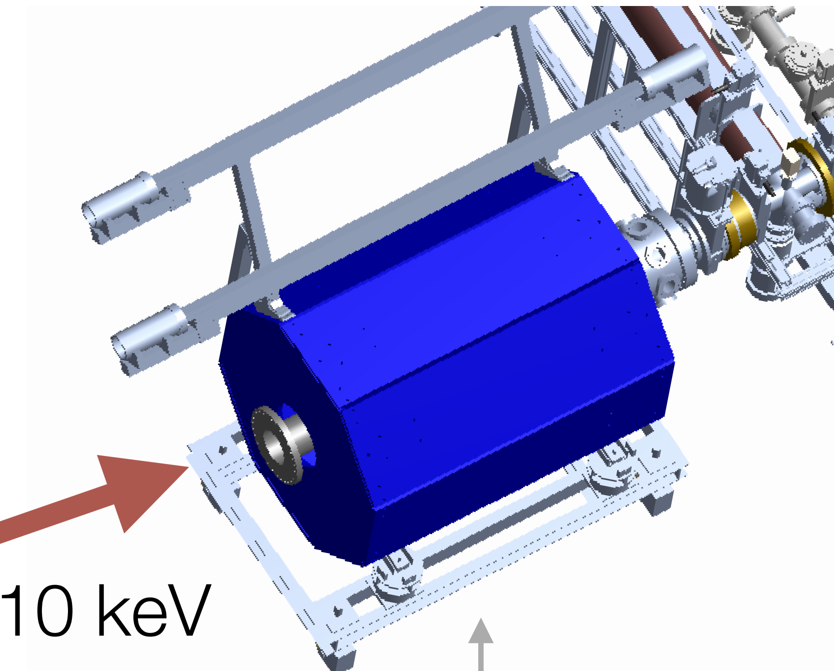


3 steps of the deceleraton

A few eV antiproton is needed for antihydrogen synthesis.



110 keV



MUSASHI Trap
(Ultra-low energy $\bar{p}$ beam source)

2. Degrader foil :
110 keV → ~ 7 keV

3. Electron cooling :
~ 7 keV → a few eV

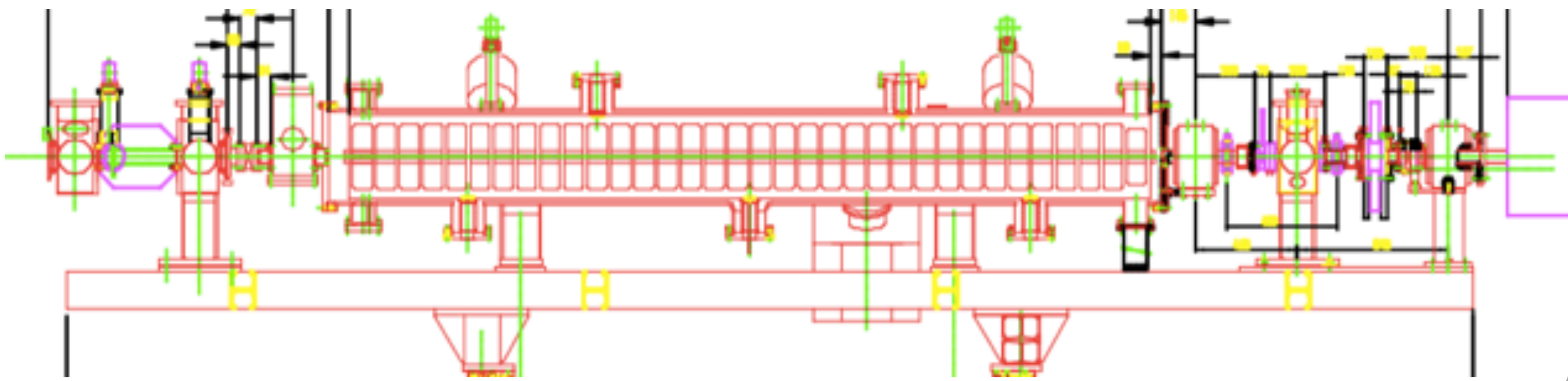
5.3 MeV
from AD

1. RFQD
(Radio Frequency Quadrupole Decelerator)
5.3 MeV → ~ 110 keV (variable)

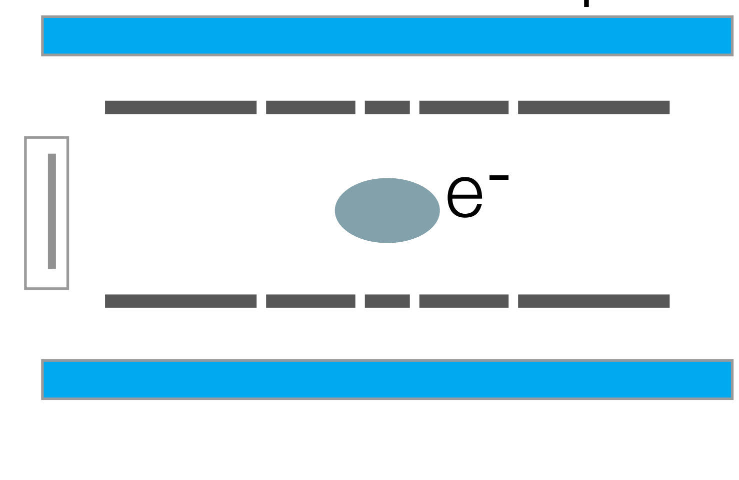
② Motivations for a new decelerator

Drift tube decelerator

RFQD



MUSASHI trap



RFQD : 5.3MeV → 110 keV

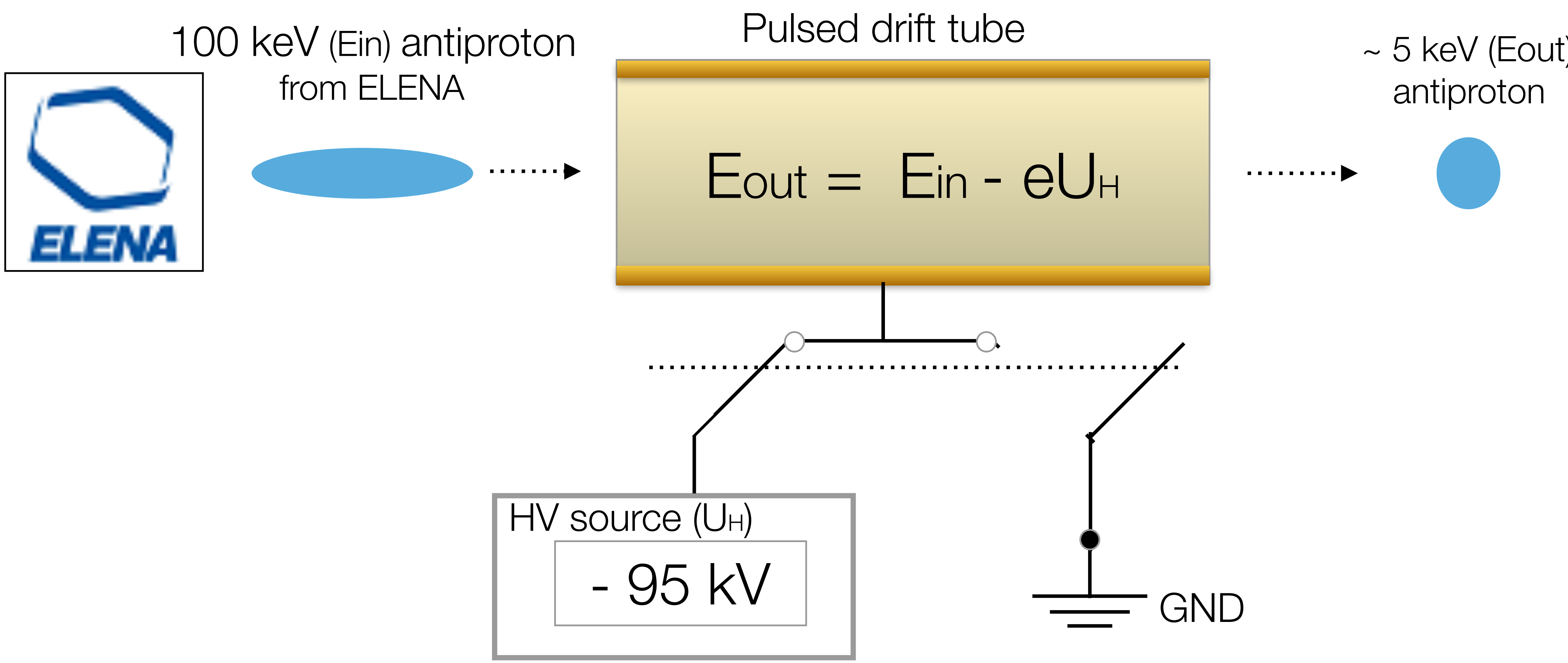
ELENA : 5.3 MeV → 100 keV

Foil degrader : 110 keV → ~ 7 keV

There is no need to use the RFQD after ELENA installation!

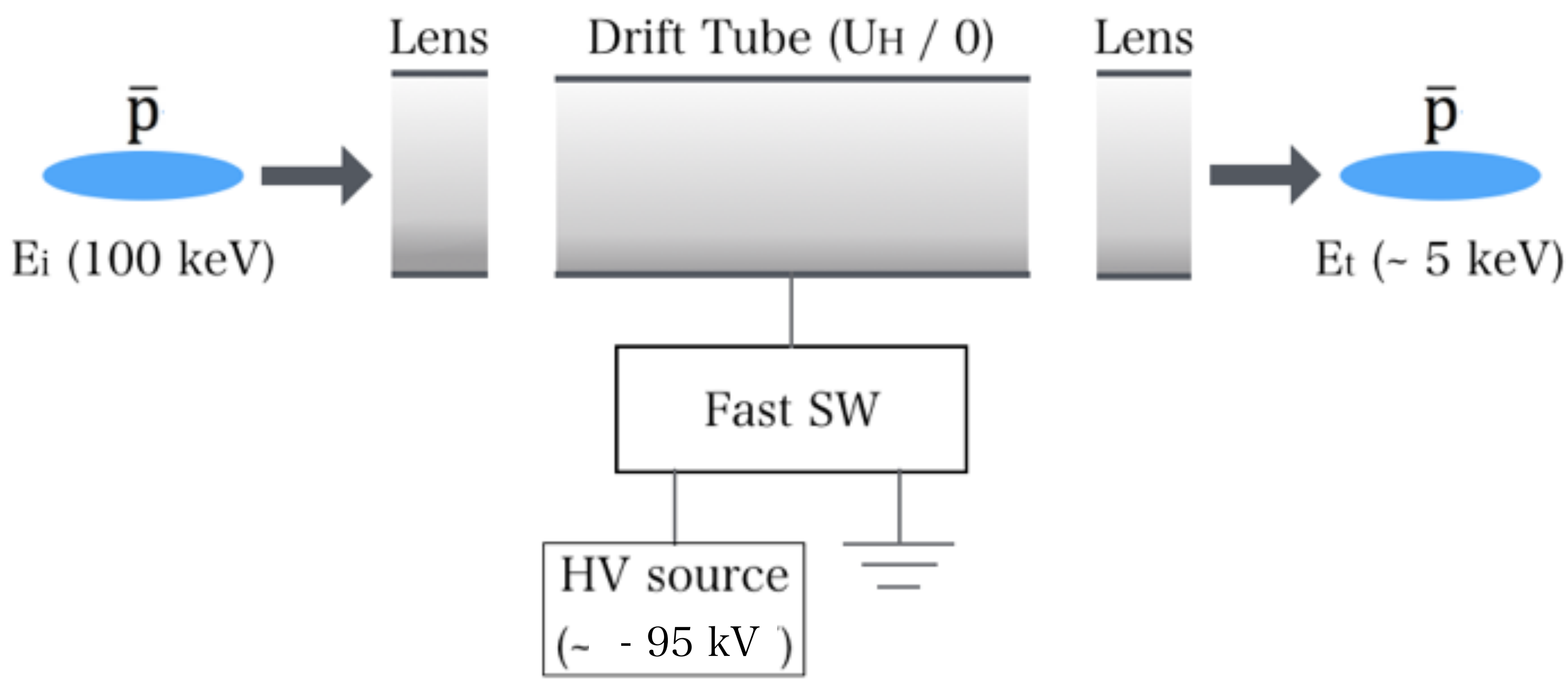
- Amount of antiprotons per unit time from ELENA is less than from AD.
    - To keep or increase its amount, it is key to reduce an annihilation in the degrader, which is equipped before MUSASHI trap and decelerating antiprotons from 110 keV to a few eV.
- A drift tube decelerator can work with no antiproton loss.
    - This can be placed in the space occupied by RFQD.

Drift tube decelerator



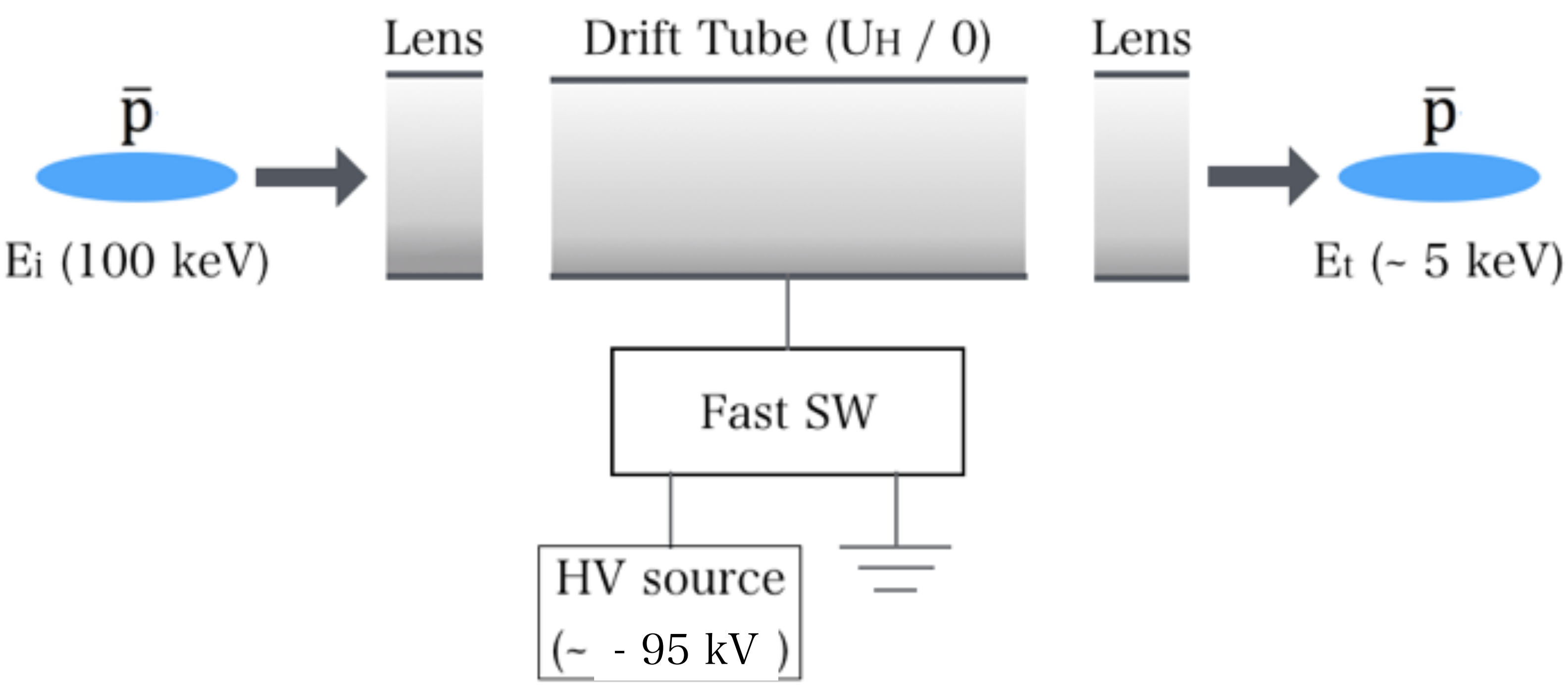
- Kinetic energy of antiprotons can be reduced by injecting them into a long metal tube on high electrostatic potential.
- Its deceleration is accomplished by changing its potential to ground before antiproton passes through the tube.

Drift tube decelerator

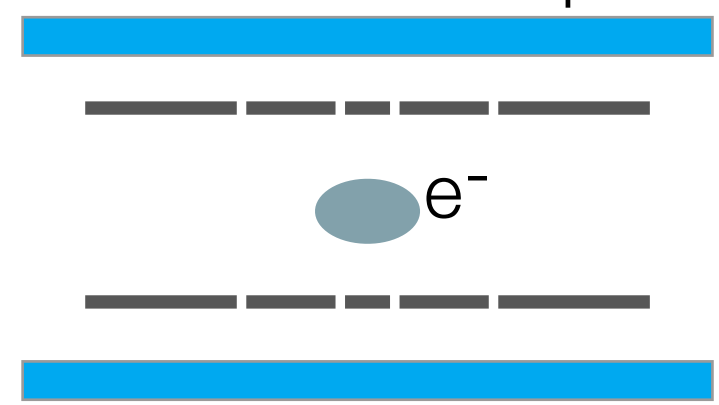


- Upstream and downstream lenses are needed.
  - There is a strong focusing field in the edge of the drift tube. Down stream lens is also needed to inject antiprotons to MUSASHI trap with small beam size.
- It is important to put focusing lenses in proper position and set proper focusing strength.

Requirement for MUSASHI



MUSASHI trap



For electron cooling, the radius of antiproton in MUSASHI should be less than the radius of electron cloud,

$$r_e = 3.4 \ \text{mm}.$$

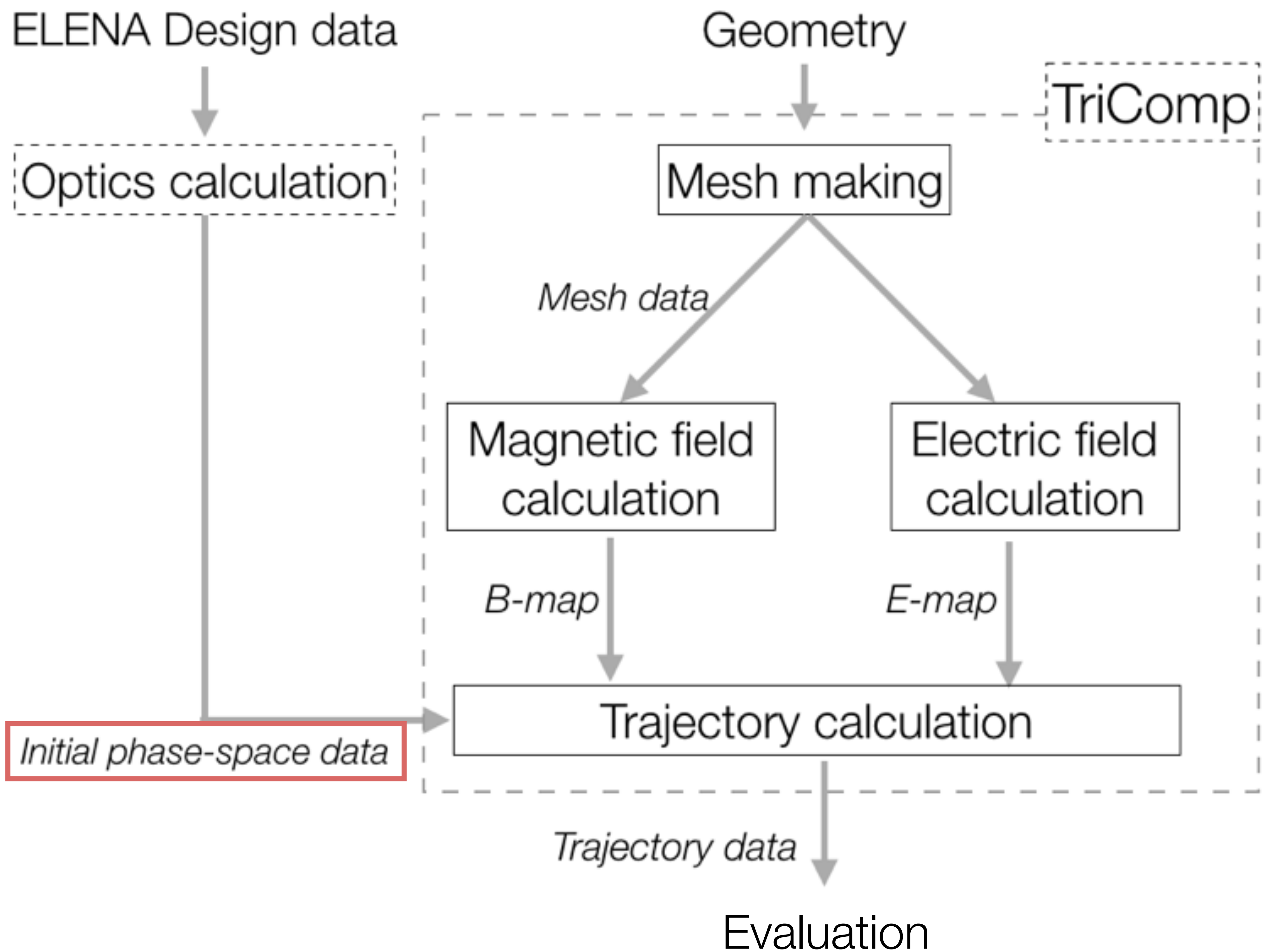
N. Kuroda et al., Phys .Rev. Lett. **100**, 203402 (2008)

③ Methods for designing

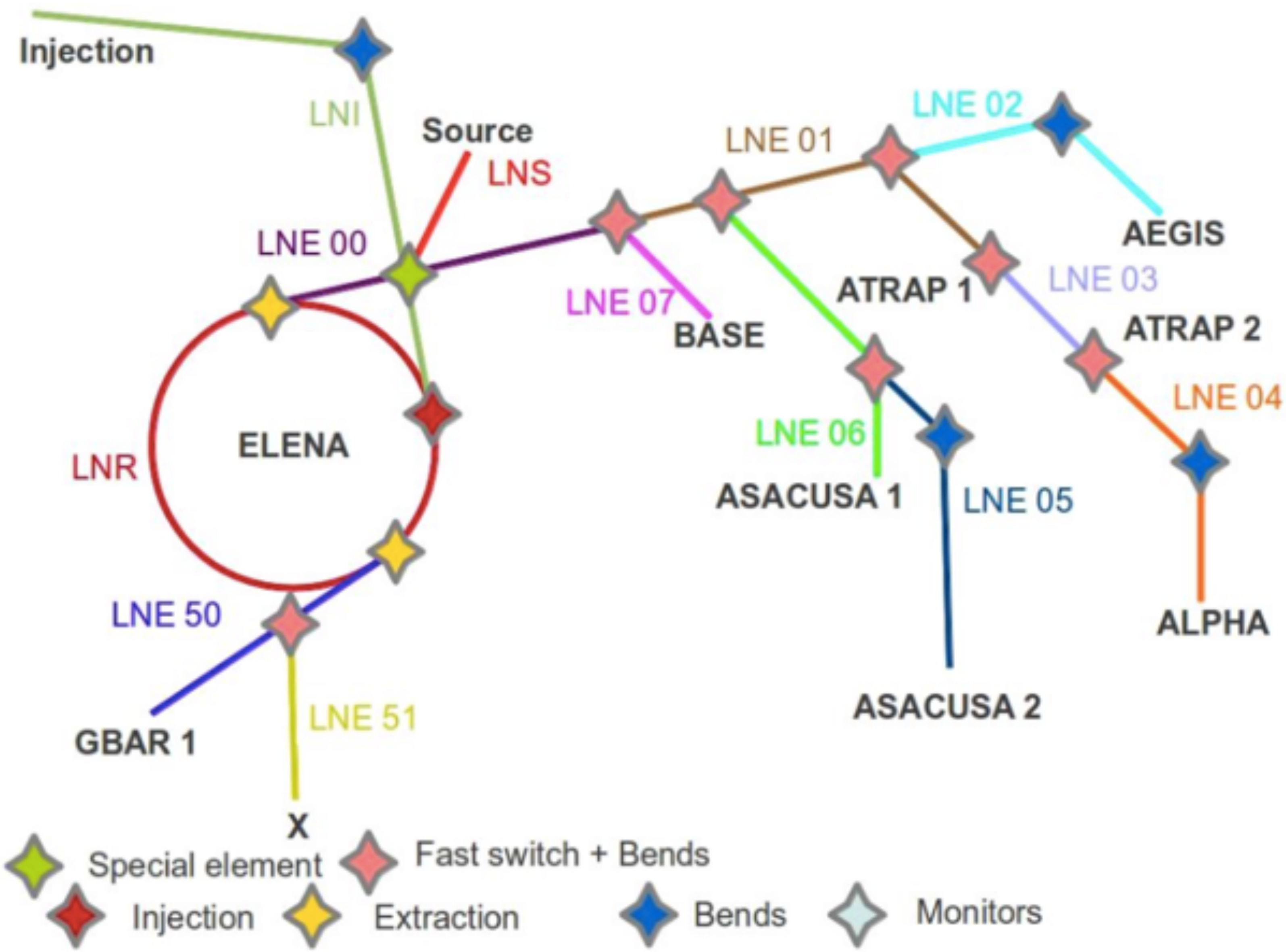
Calculation software

- Electromagnetic field and trajectory calculation
  - TriComp (2D FEM software, Field Precision LLC)
    - Software version : 8.0
    - PC : windows 8.1 pro, 64 bit
- Determination of an initial beam condition
  - MAD-X : An accelerator optics calculation software. Distributed by CERN.
  - ROOT : C++ package for scientific analysis. Distributed by CERN.

Calculation flow



Determination of an initial beam dataset



After the ELENA installation, ASACUSA will take two dedicated beam lines, LNE05 and LNE06.

CUSP group will use LNE05.

Detail configuration data
(Optics setting, simulation codes, etc..)
are available for CERN users.

Determination of an initial beam dataset

① Design data of ELENA (Layout of ELENA Transfer Lines Version 2.02)

↓ Transfer line configuration, kinetic energy,
horizontal and vertical emittance, momentum spread

② MAD-X, beam optics calculation software distributed by CERN

↓ Phase-space (Twiss) parameters on hand over point of LNE05

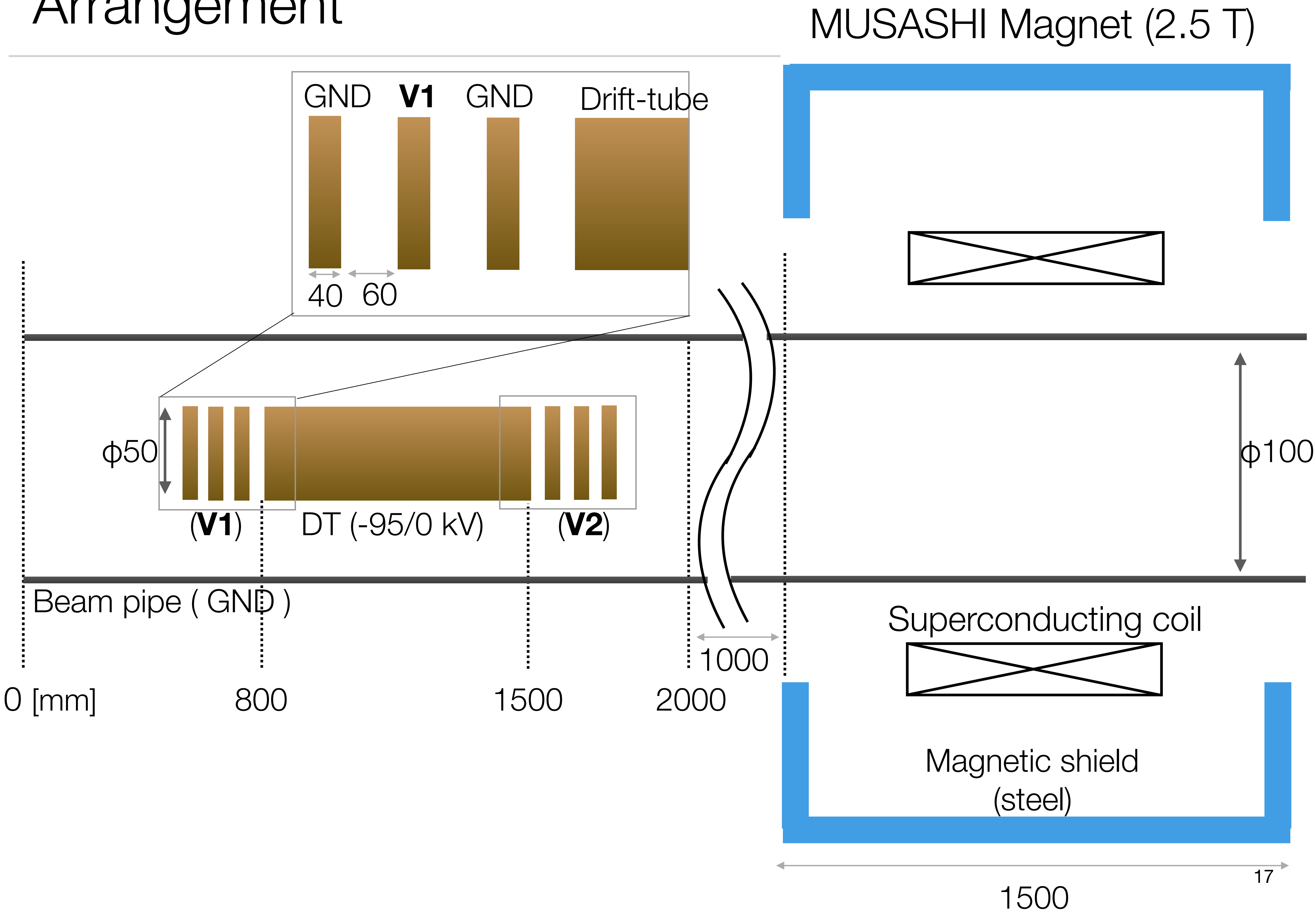
③ ROOT C++ macro. generates each particle data from twiss parameters
: Gaussian random number method is used.

↓ Initial particle dataset

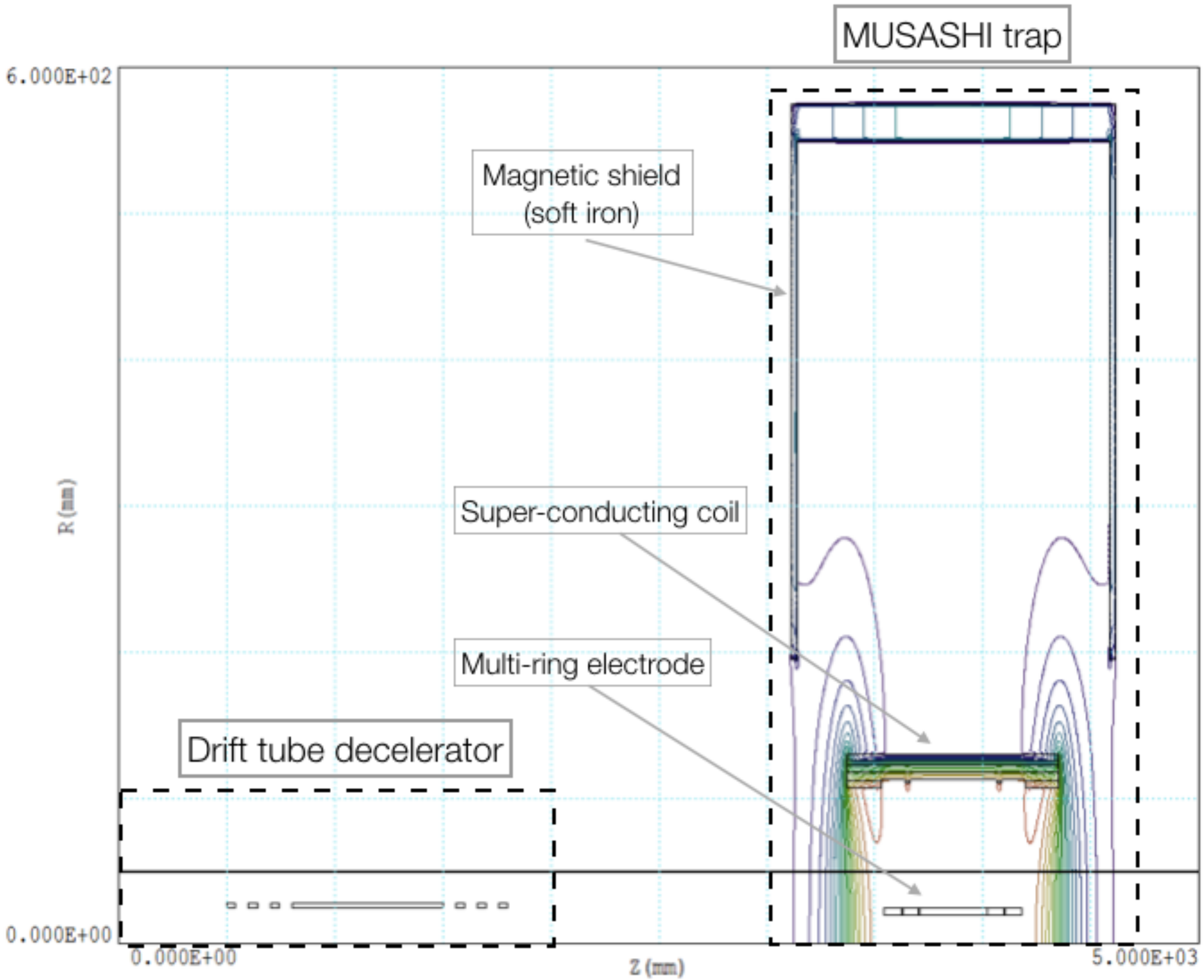
TriComp

④ Result

Arrangement

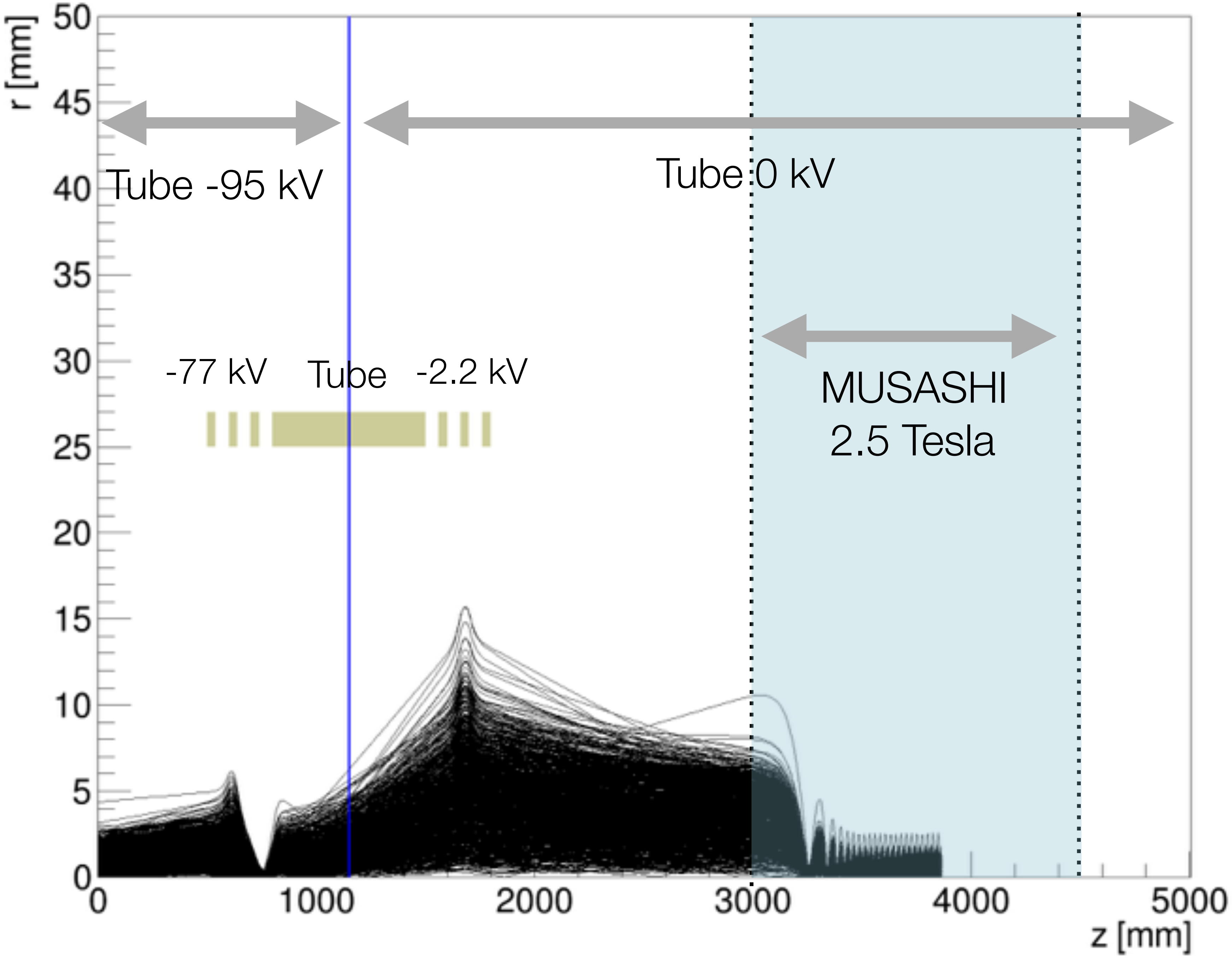


Magnetic field

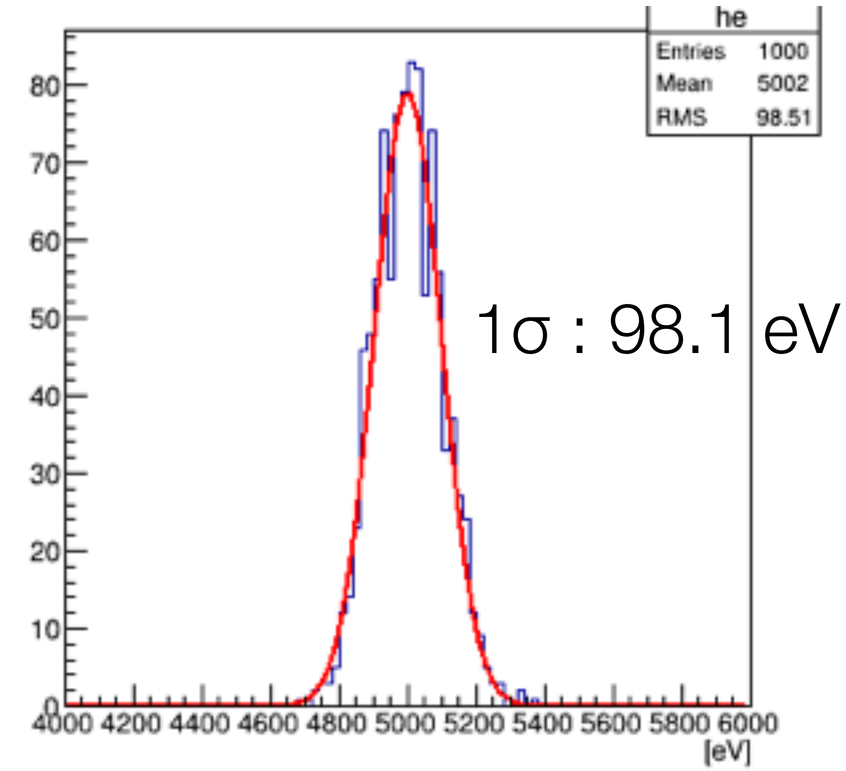


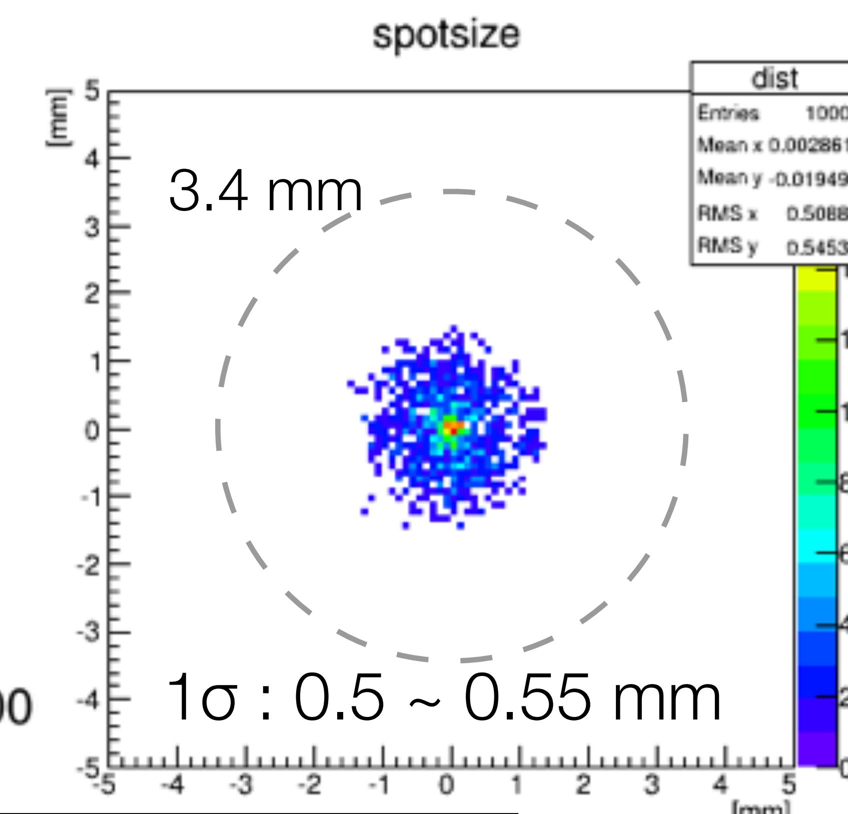
Trajectory calculation

The number of antiprotons is **1000.**



Energy distribution
at the center of MUSASHI





This configuration meets requirements for ASACUSA.

⑤ Comparison with a degrader

Simulation of a degrader foil for ELENA beam

Is the drift tube decelerator really the better choice for ASACUSA?

How much good is the degrader foil designed for ELENA beam?

Simulation code : **TRIM** (TRansport of Ion in Matter)

- A Monte-Carlo simulation package for ion transport in matter.
- Frequently used for a design of degrader foils.
- Barkas effect is not considered.

Configurations of current degrader foil (**110** keV to ~5 keV)

- Two layered biaxially oriented PET (H : 36.36%, C : 45.45 %, O : 18.18%)
- $2 \times 90\ \mu\mathrm{g/cm}^2$ (Total thickness : $1.2\ \mu\mathrm{m}$)
- Roughness : ~ 10 %

Assumptions

- The material of a degrader for simulation

PET (H : 36.36%, C : 45.45 %, O : 18.18%)

(The same material as used for current degrader foil. Metal will be also OK.)

- Roughness

Gauss distribution, (1σ : 10 % of the degrader thickness)

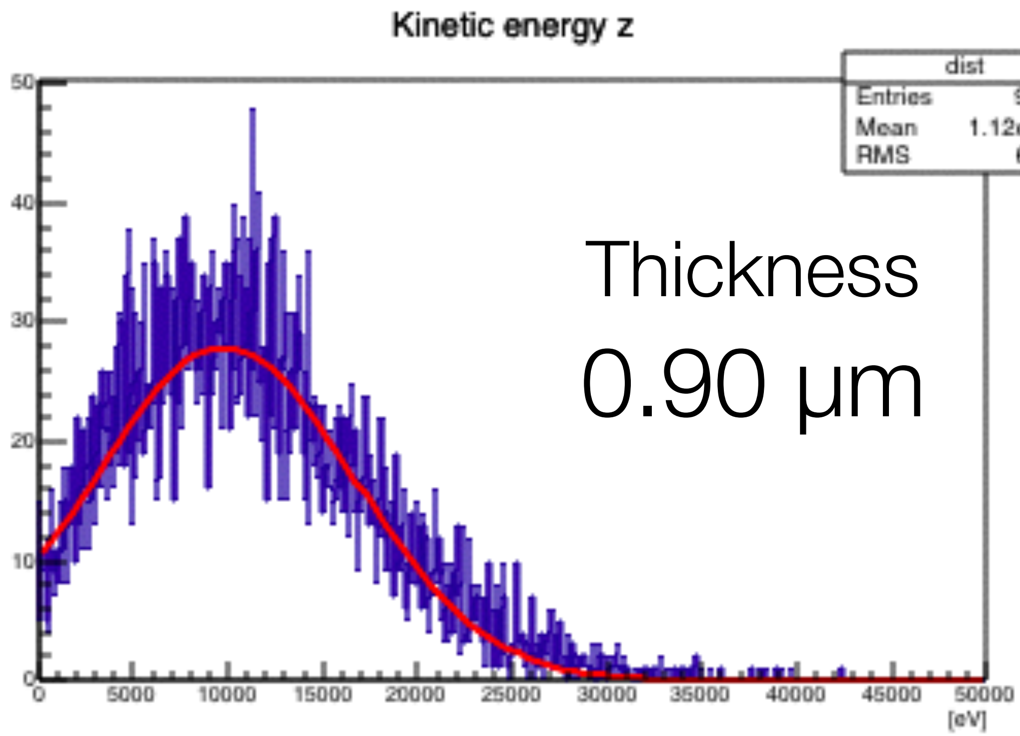
- MUSASHI (Malmberg trap for antiporoton)

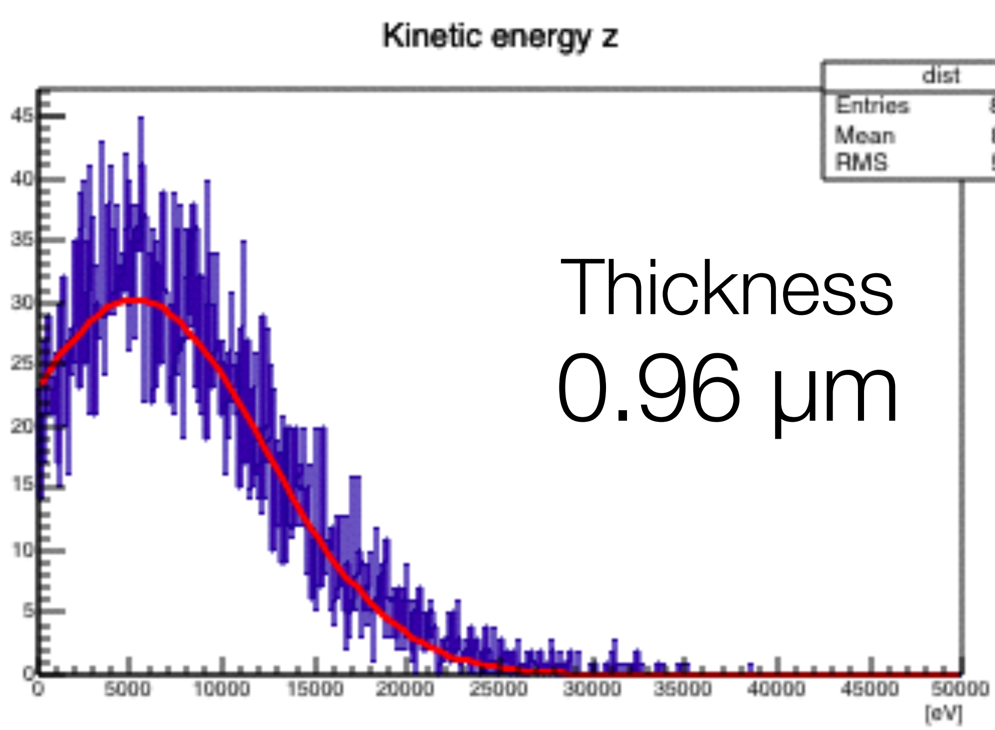
< **12** keV of the axisal kinetic energy can be trapped

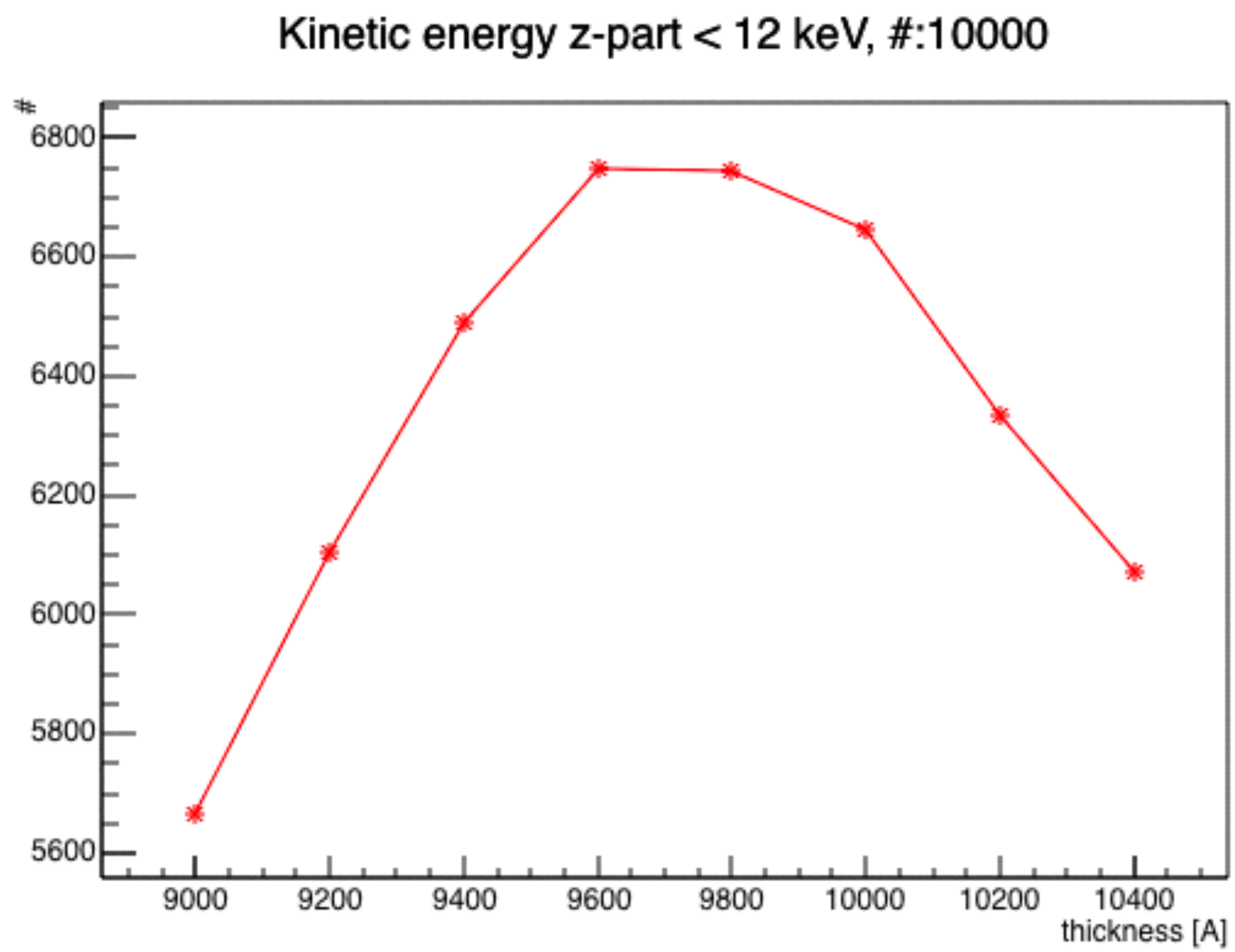
- Initial beam positon, angle distribution

Same condition used for the drift tube trajectory calculations

Energy spread after degrader foil







<u>Maximum</u>

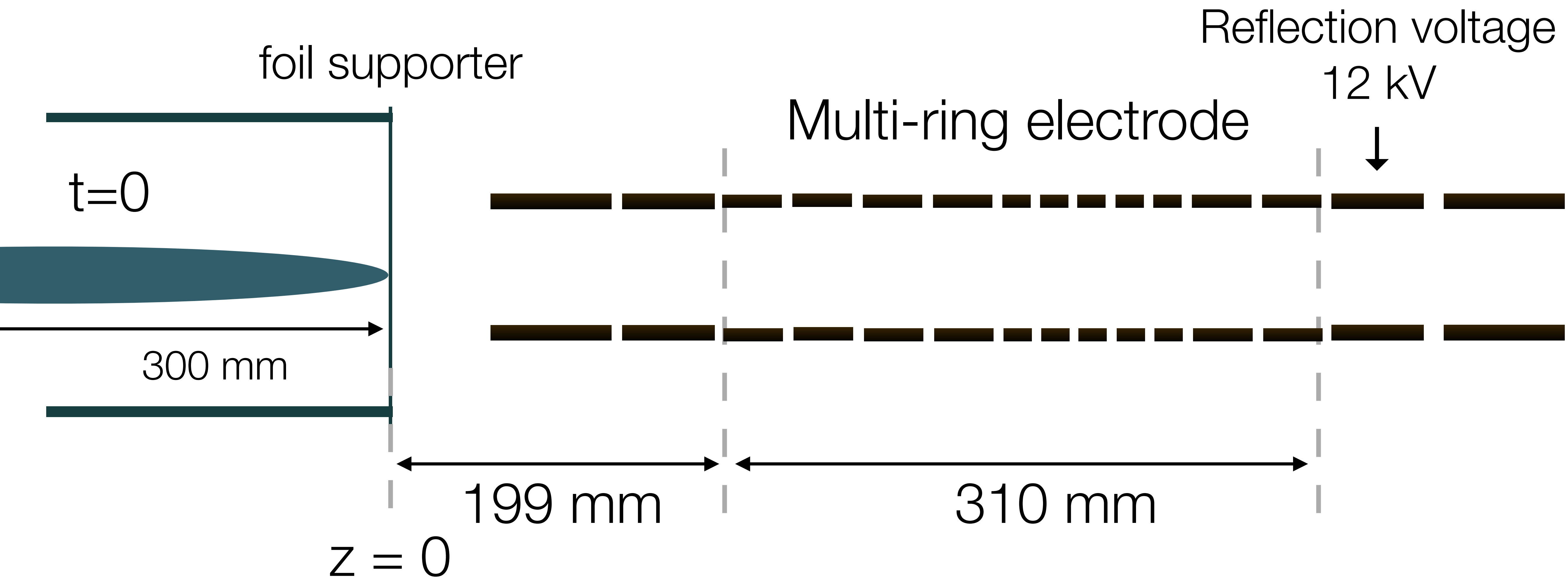
Thickness : 0.96 µm, Efficiency : 67.5 %

Cut : kinetic energy (< 12 keV)

not including the axial length and radial size limitation

Axial length cut

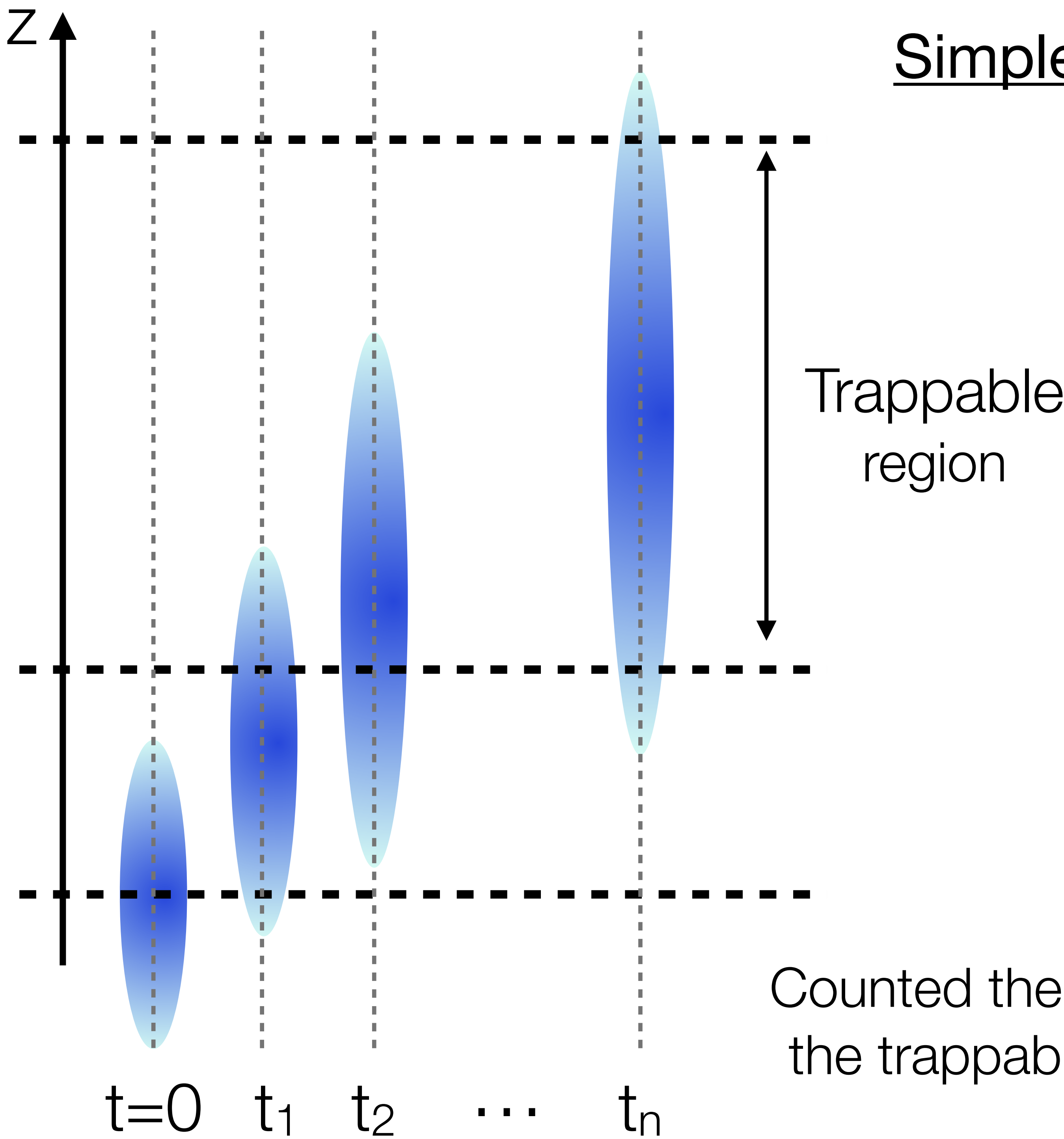
Not all the particles are trapped even if their energy is less than 12keV, because the length of the trap region is finite.



Trappable region : 199 mm < z < 819 mm (199 + 310 × 2)

(× 2 considering the reflection by downstream potential well.)

Axial length cut



<u>Simple estimation of the axial spread</u>

$$z(t) = z(0) + \sqrt{\frac{2K_Z}{m}}t$$

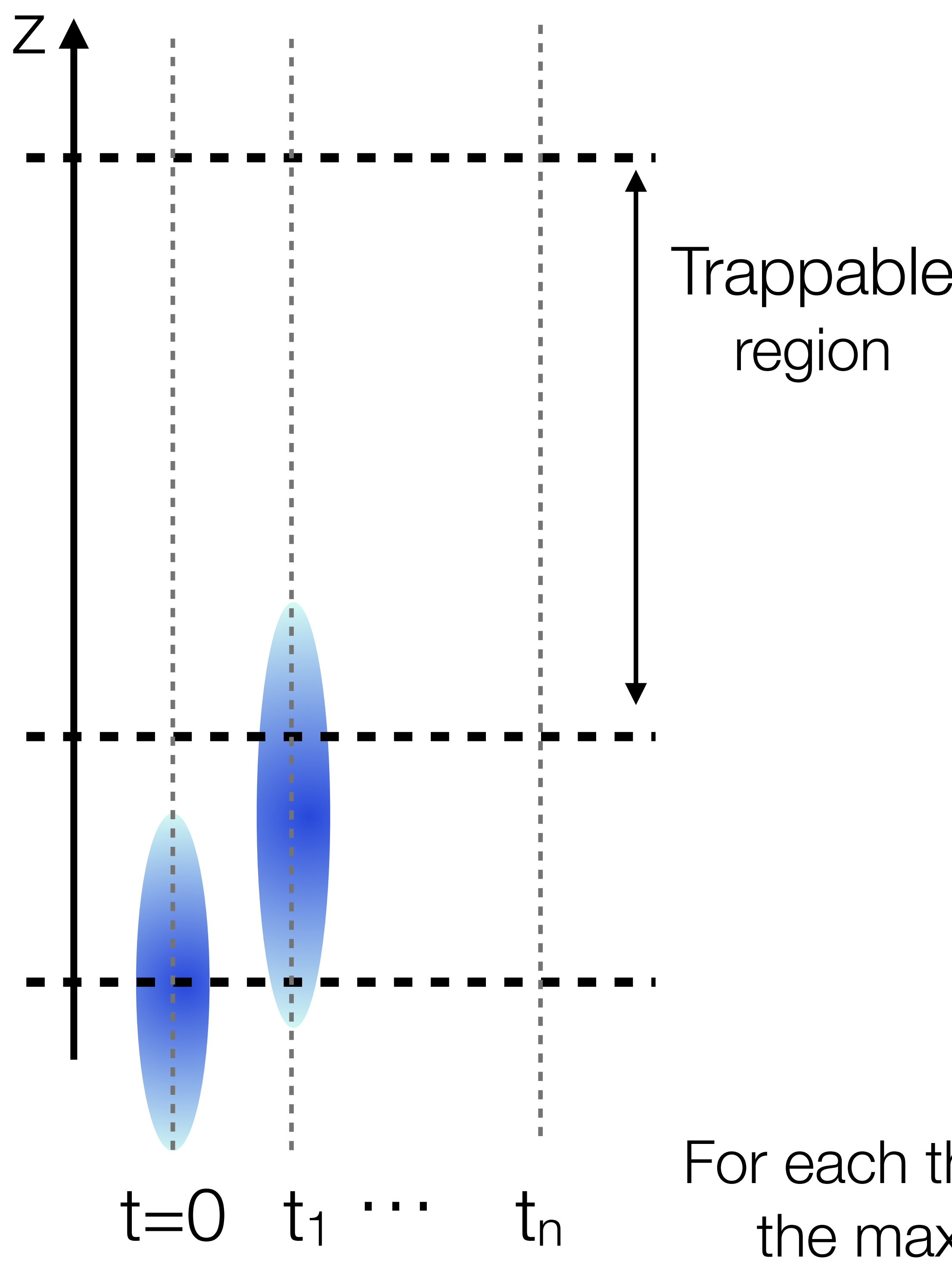
K_Z : Axial kinetic energy after the foil
Obtained from Trim result

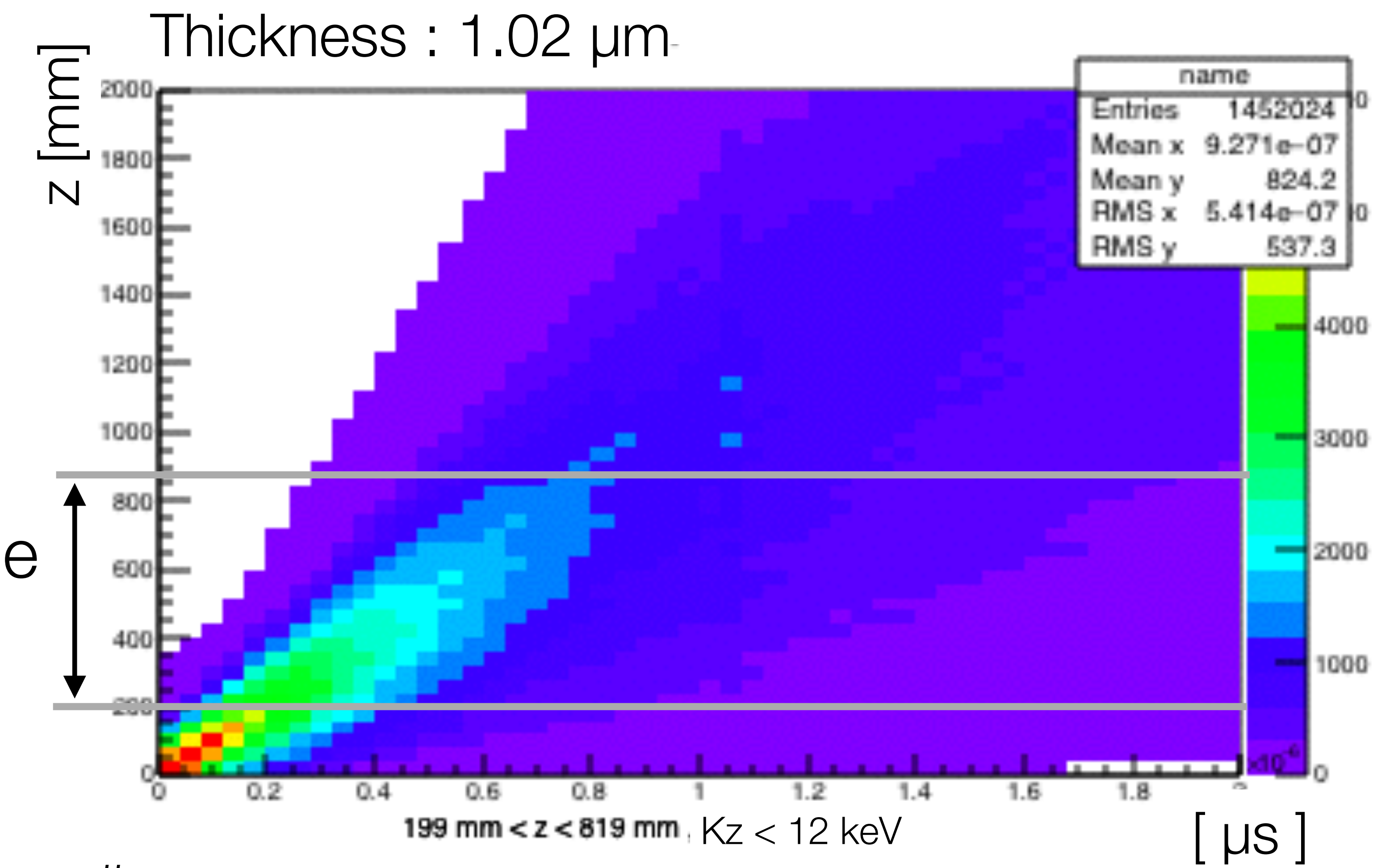
$z(0)$: Initial position
Gauss distribution was generated
(4σ, 300 ns, ~ 300 mm)

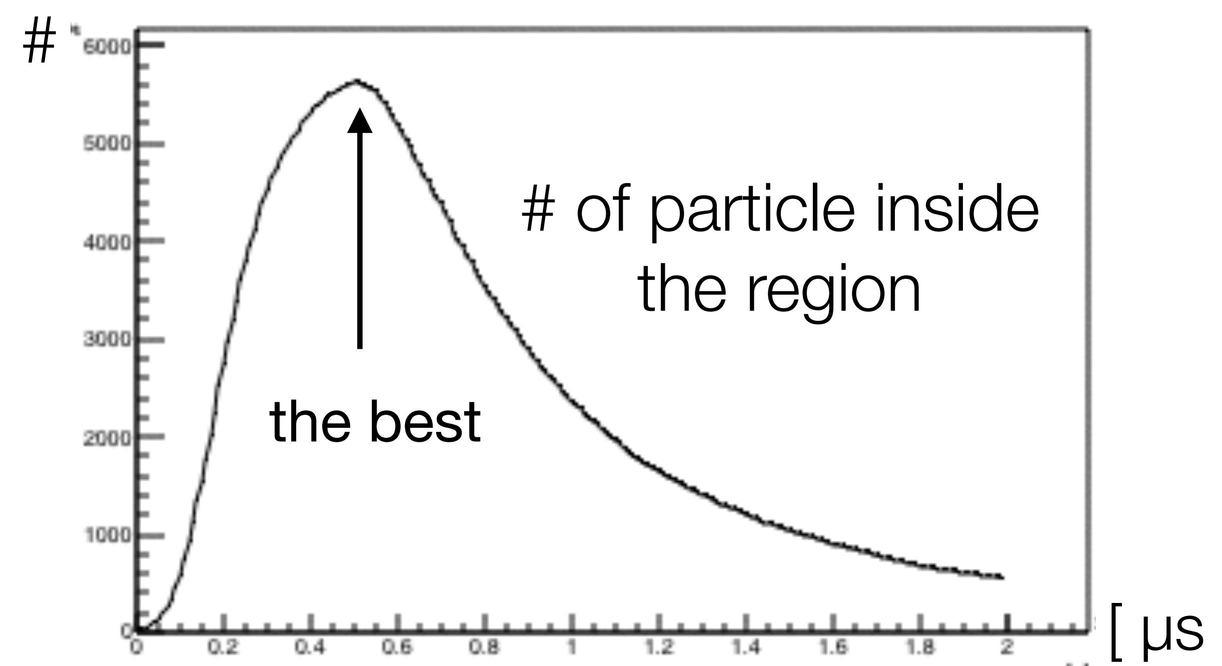
m : (Anti-)Proton mass

Counted the number of particles of < 12 keV, inside the trappable region in each time, each thickness.

Axial length cut

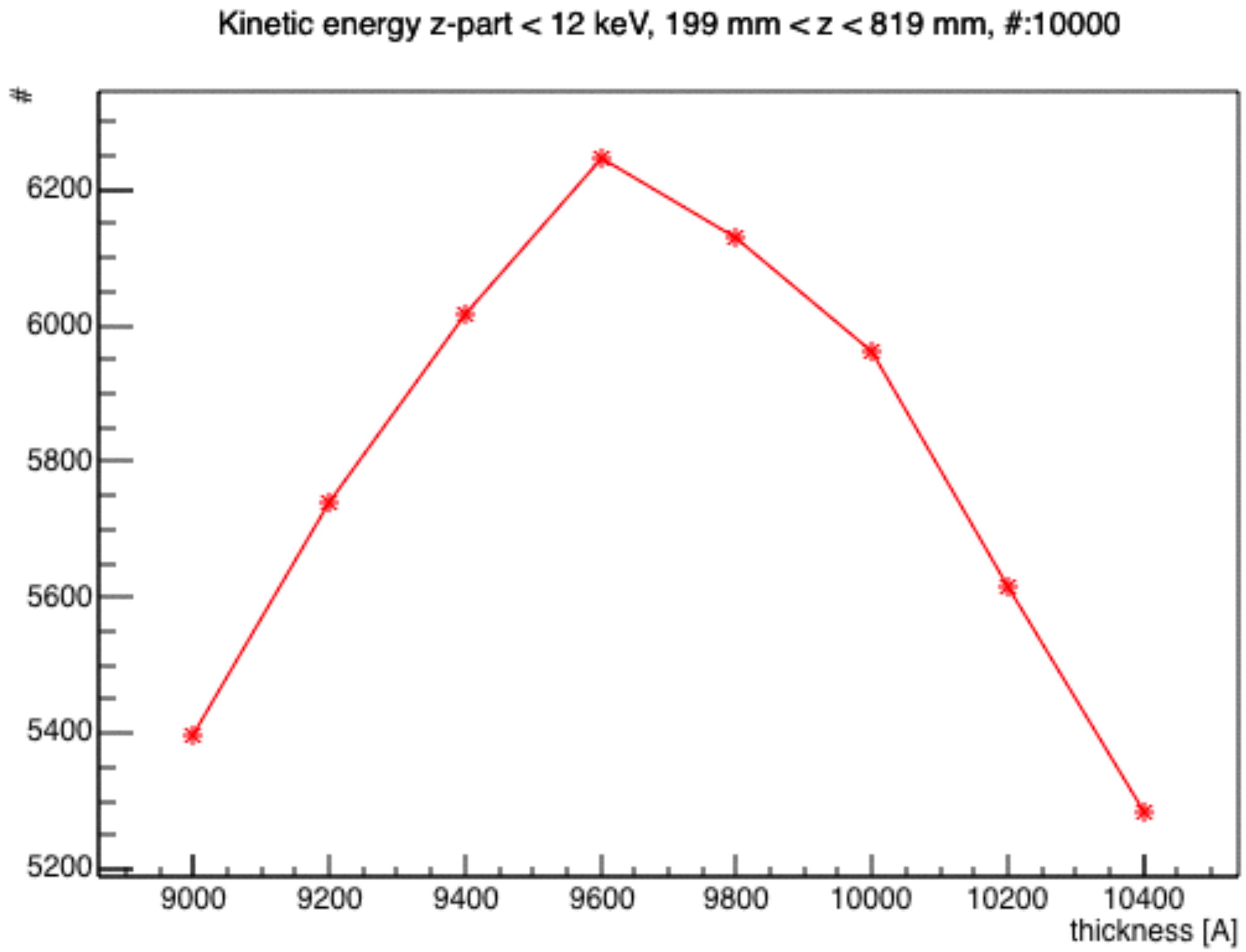




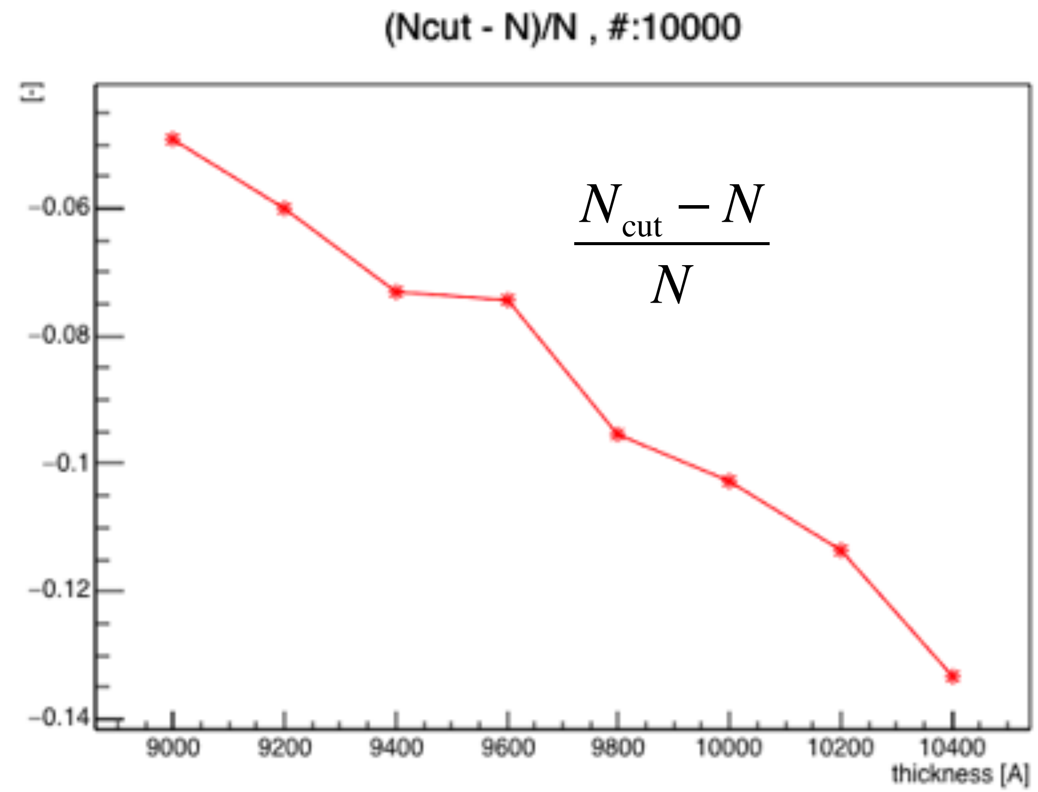


For each thickness, the trap timing is optimized so that the maximum number of particle can be trapped. Then compared with different thickness.

Axial length cut



Difference between with and without axial cut



$$\frac{N_{cut} - N}{N}$$

N : number of particle after the degrader

N_{cut} : number of particle with axial length cut

The thicker foil causes the wider axial length.

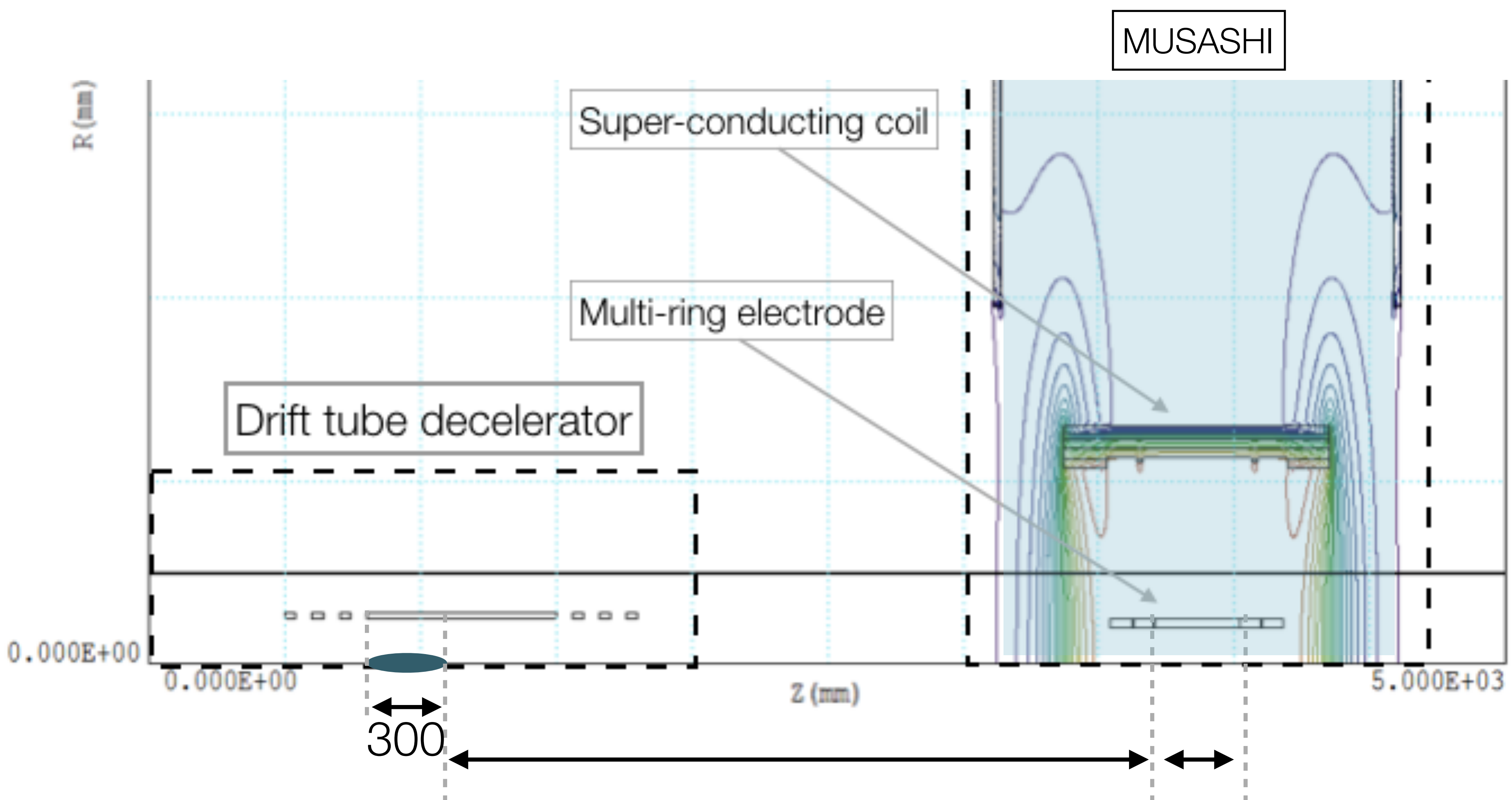
Maximum **Thickness : 0.96 μm, Efficiency : 62.5 %**

Cut : Kinetic energy (< 12 keV), axial length

not including the radial size limitation

Axial length with drift tube deceleration

Simple estimation of the axial spread

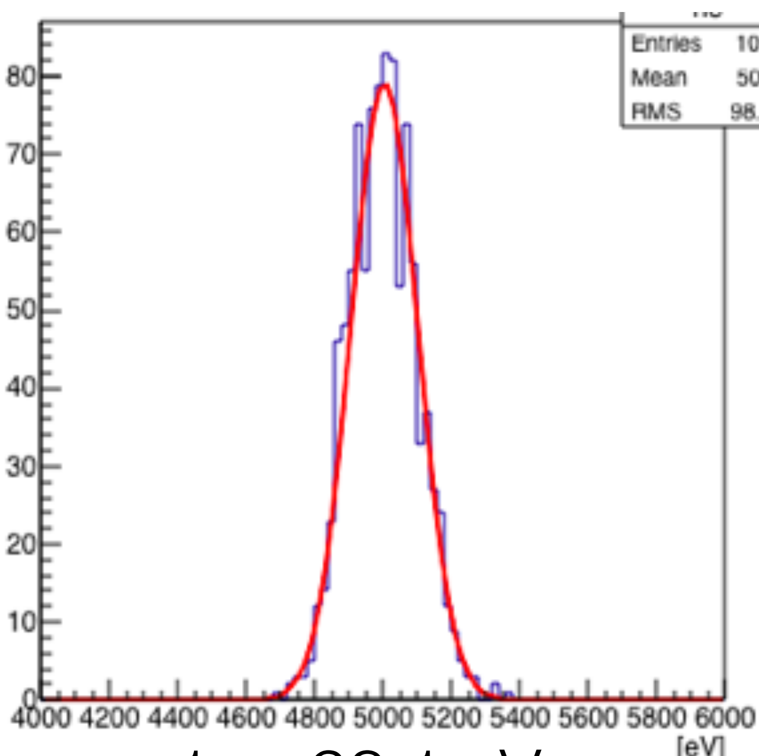


(much longer distance than the degrader's)

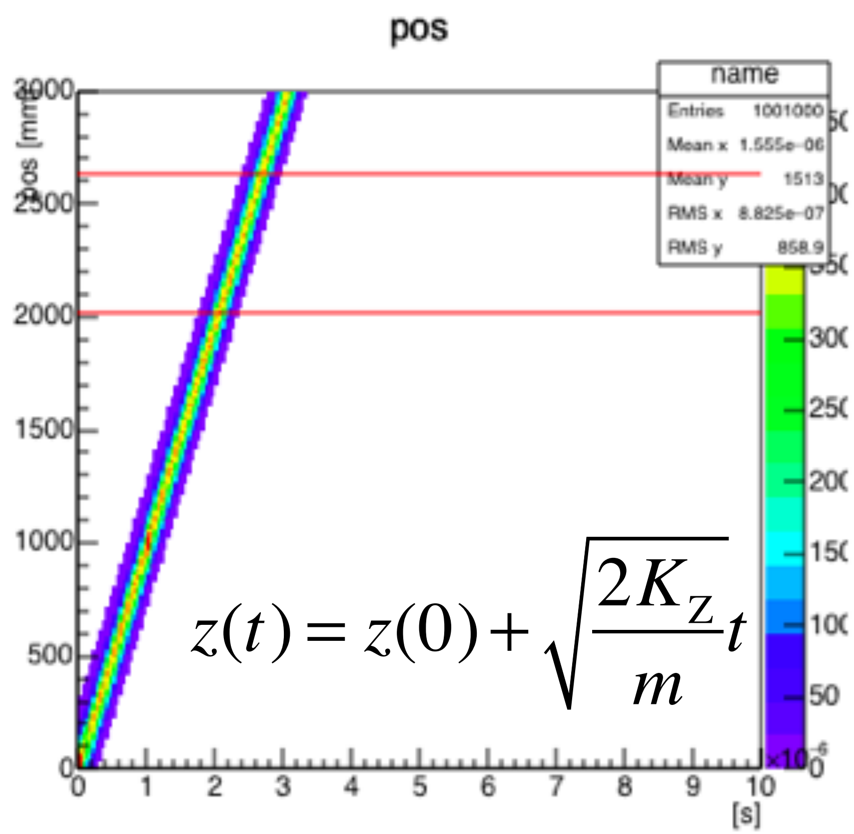
Axial length was estimated by the same way.

Axial length with drift tube deceleration

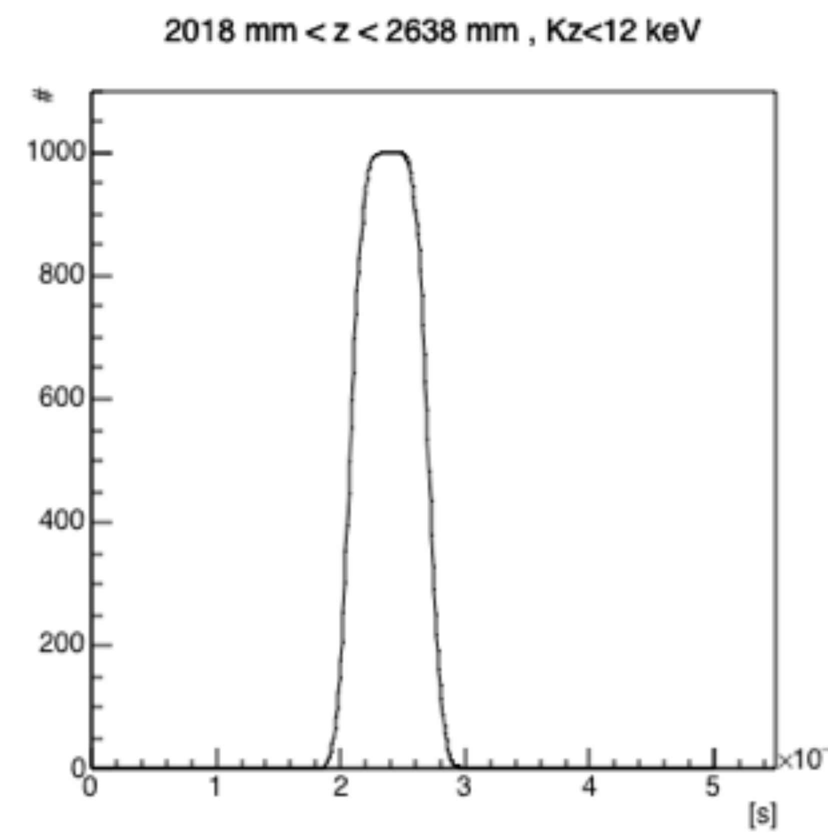
Energy spread after deceleration by drift tube



1σ : 98.1 eV



$$z(t) = z(0) + \sqrt{\frac{2K_Z}{m}}t$$



Efficiency : 100 %

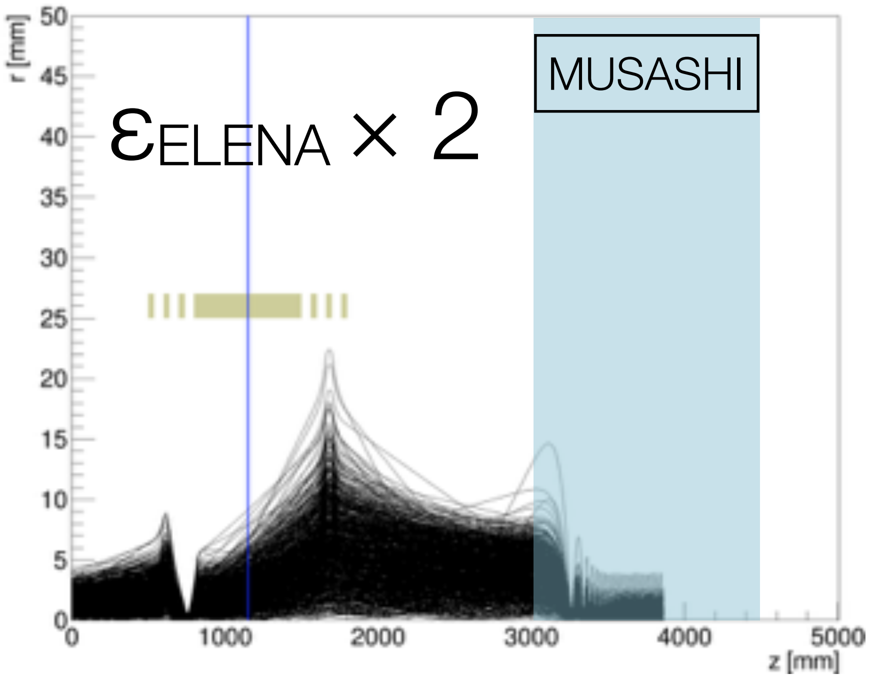
Cut : Kinetic energy (< 12 keV), axial length, (Radial size was ~ 1.0 mm (2σ).)

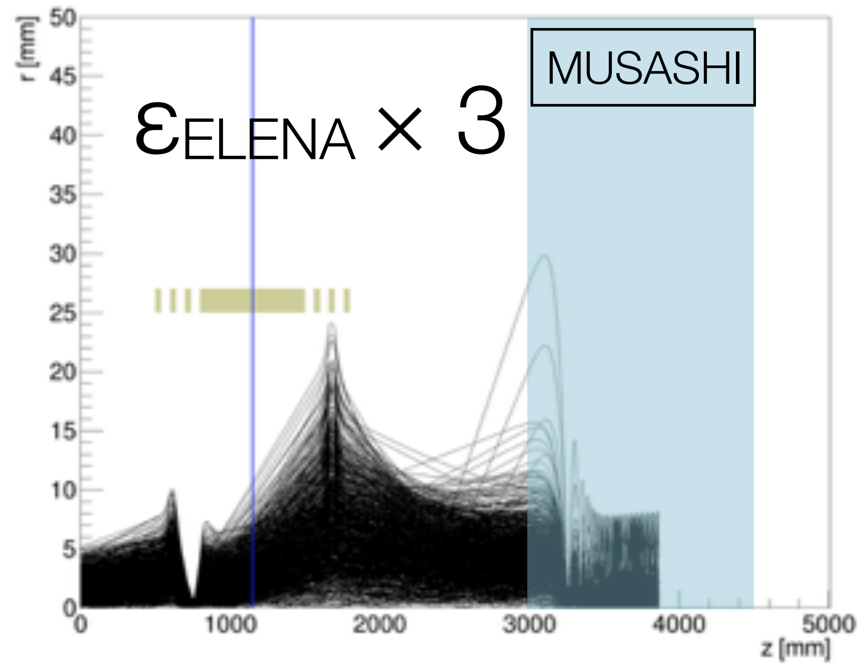
The Drift tube decelerator seems the better choice than the degrader foil

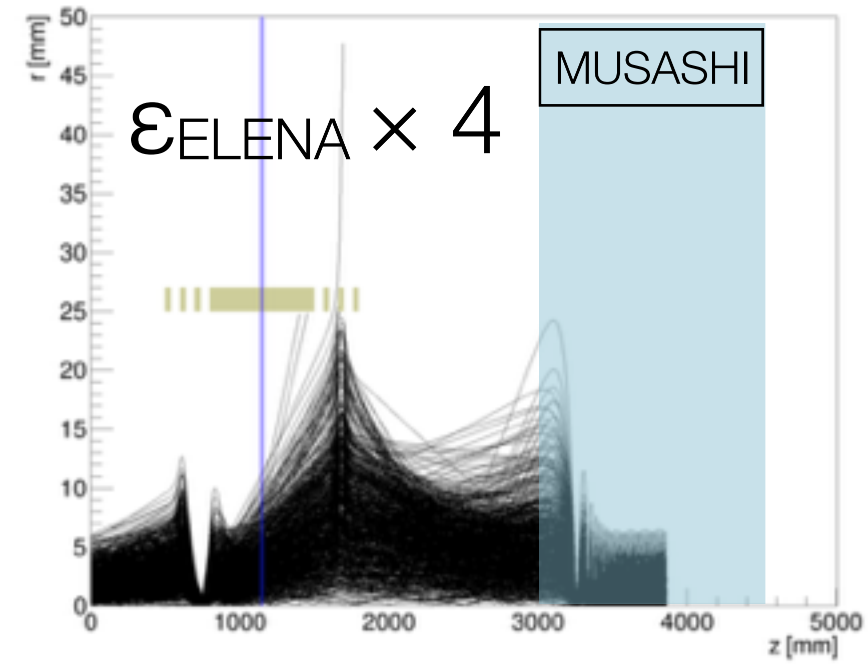
⑥ Deceleration at bad beam condition

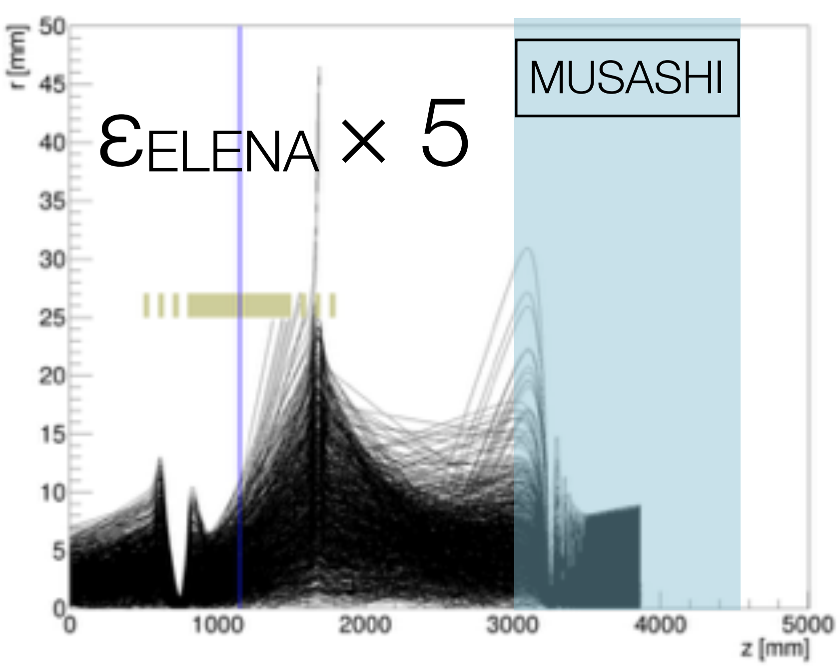
Bad emittance

Increasing of the beam emittance will affect the beam size of antiproton beam.







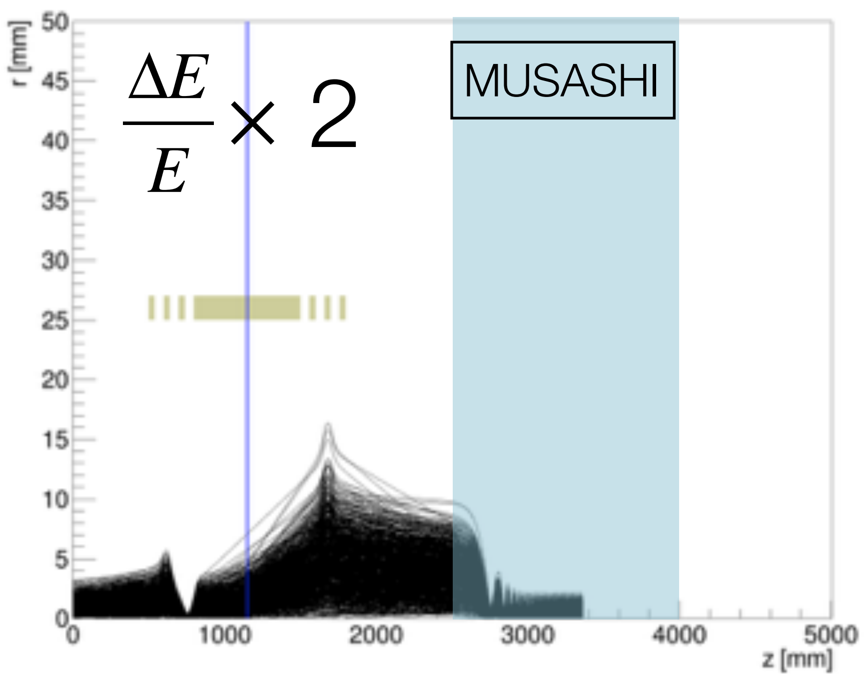


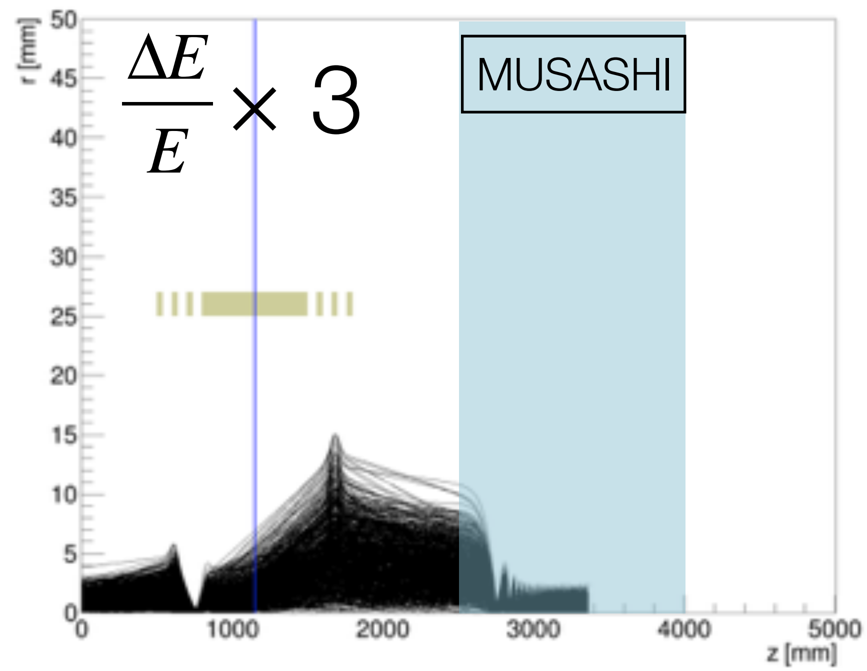
All antiprotons reached to MUSASHI by $\varepsilon_{ELENA} \times 3$.
(The maximum emittance is limited by the size of the tube.)

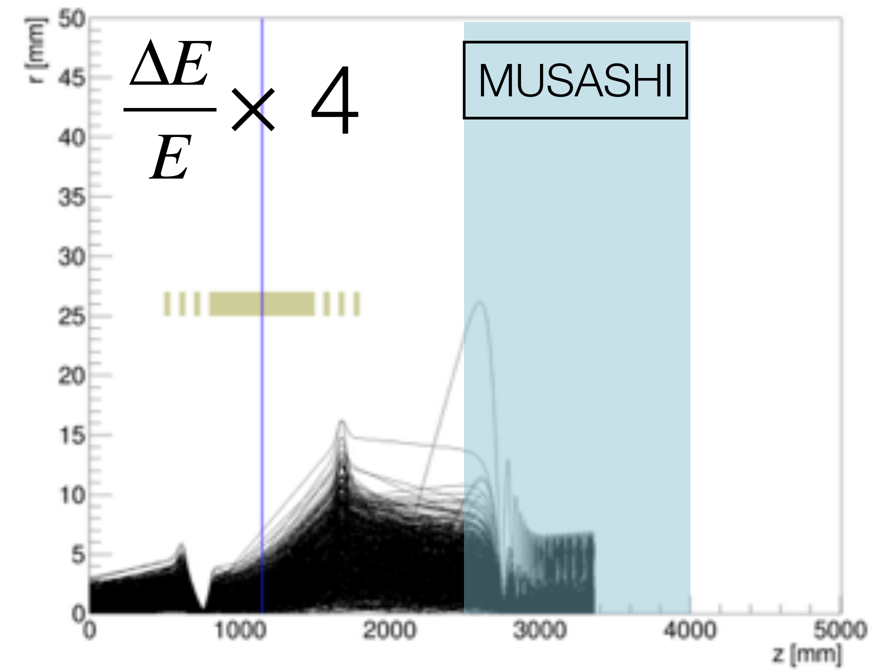
Beam size after the tube gets large as emittance increases.

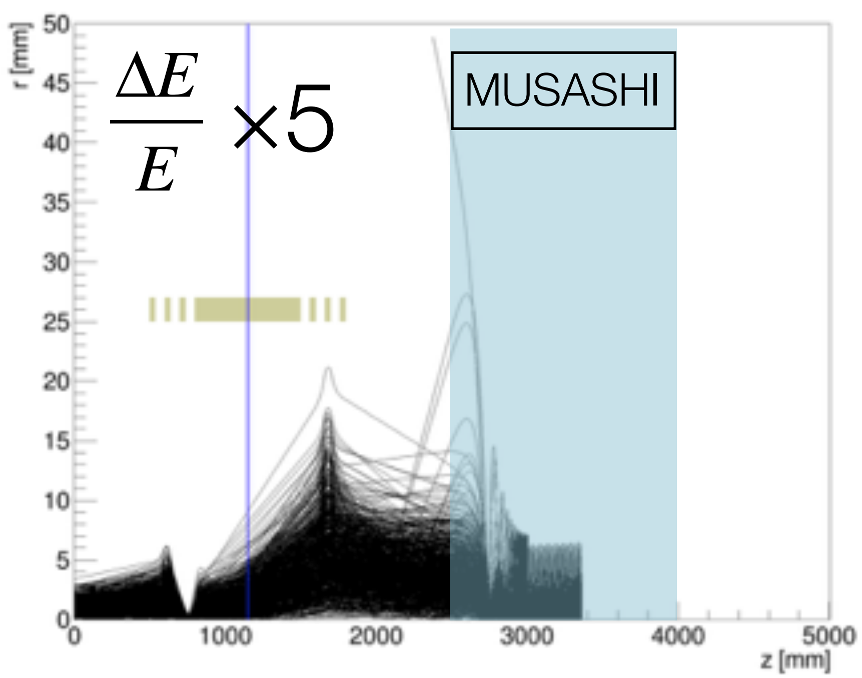
Bad energy spread

Increased energy spread affects the lens focussing.









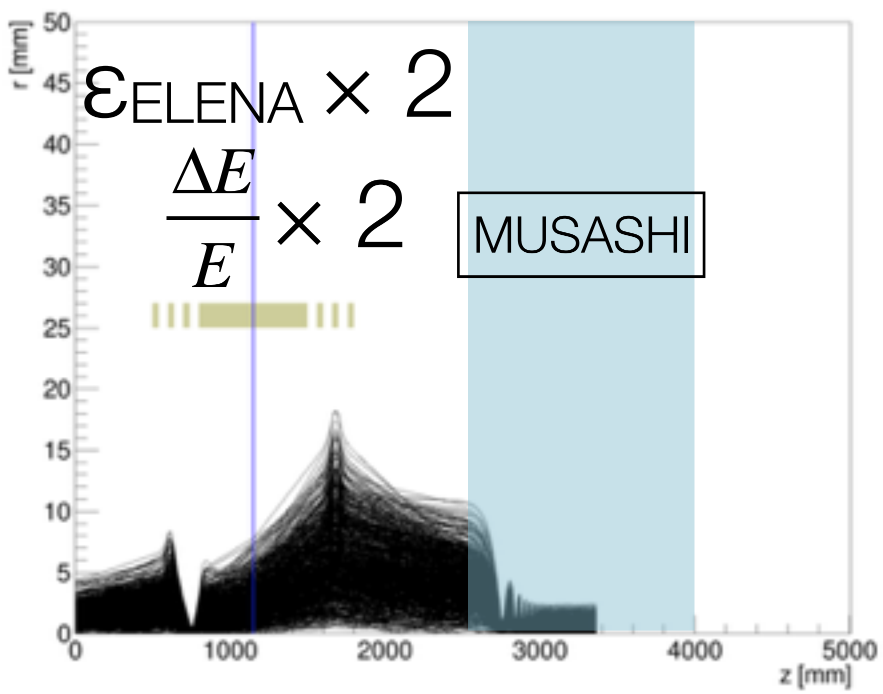
(The drift space after the decelerator is 500 mm.)

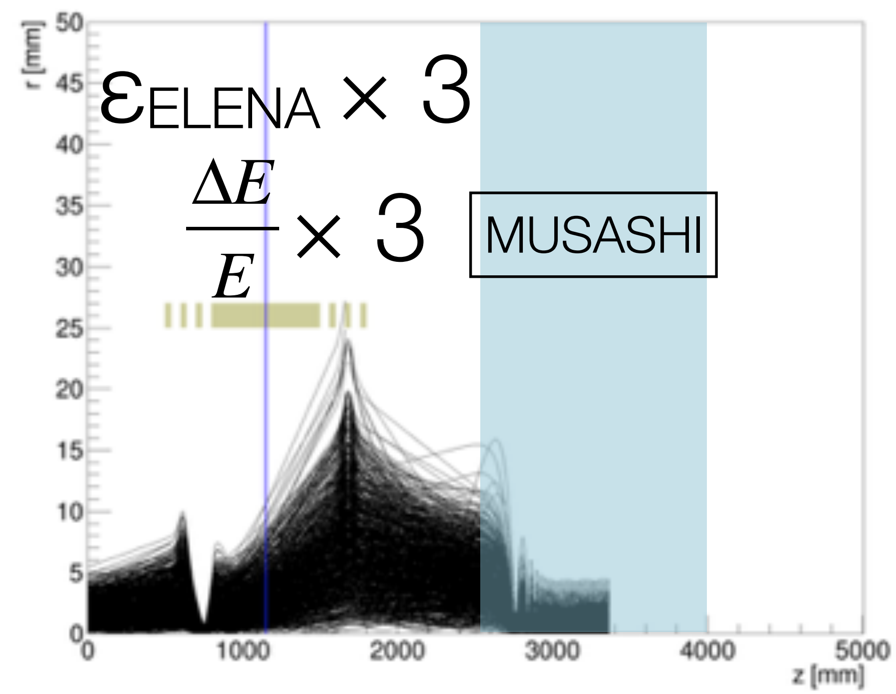
All antiprotons reached to MUSASHI by $\frac{\Delta E}{E} \times 4$.

Beam size after the tube gets large as energy spread increases.

Bad energy spread 2

Both of beam emittance and beam energy spread were increased





$\times$ 2	All antiprotons were reached to MUSASHI trap and inside the radius of the electron cloud, 3.4 mm.
$\times$ 3	997/1000 antiprotons were reached to MUSASHI trap and inside the radius of the electron cloud, 3.4 mm.

The discussed configuration can work even if the emittance and energy spread get worse by a factor of 3.

Conclusion

1. Design of the drift tube decelerator for ASACUSA CUSP group was conducted by using a FEM software. Almost all antiproton expected to be decelerated from 100 keV to 5 keV with no antiproton losses.

2. Simulation of the deceleration by a degrader foil was conducted by using a Monte-Carlo simulation software.

3. Effects of the increased beam emittance and beam energy spread were studied. The discussed configuration can work even if the emittance and energy spread get worse by a factor of 3.

Thank you.