Using plastic scintillators to disentangle antiprotons annihilations from positron and positronium annihilations in AEgIS

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JAGIELLONIAN UNIVERSITY
IN KRAKÓW

3rd Jagiellonian Symposium on Fundamental and Applied Subatomic Physics

23-28 June 2019
Collegium Maius
Europe/Warsaw timezone

OVERVIEW

AEgIS

Antimatter Experiment Gravity Intereferometry & Spectroscopy

main goals:

Produce Antihydrogen by means of a charge exchange reaction

Measure its gravitational acceleration on Earth

Test the validity of fundamental principles with antihydrogen : WEP, CPT

The Weak Equivalence Principle (WEP) is Cornerstone of Einstein Theory of General Relativity

$$m_i = m_g$$

AEgIS

Antimatter Experiment Gravity Intereferometry & Spectroscopy

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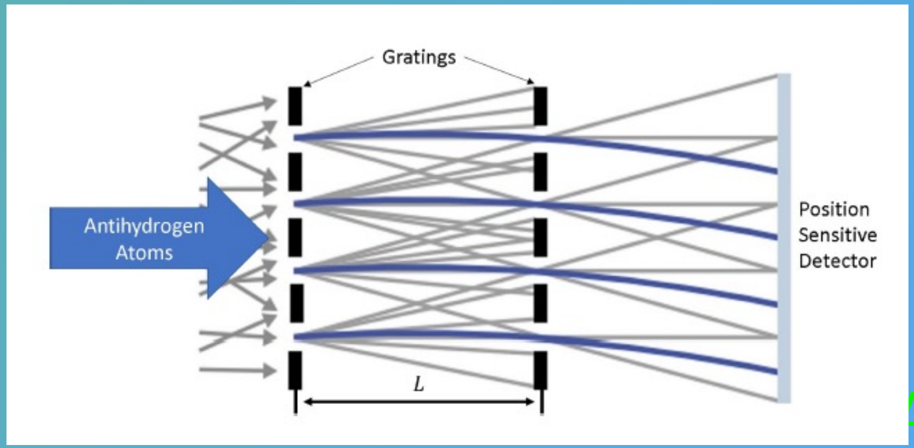
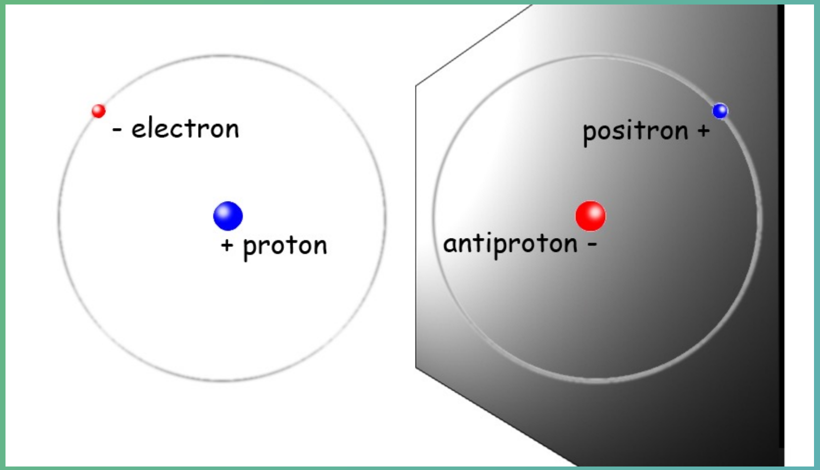
Test the validity of fundamental principles with antihydrogen : WEP, CPT

Proof of principle of tiny vertical force measurement with the grating system with antiprotons in:
"A moiré deflectometer for antimatter"
Nature Comm. 5, 4538 (2014) AEgIS Collaboration



Why Antihydrogen?

Antihydrogen is a neutral system formed by antiproton and by an anti-electron (also called positron)



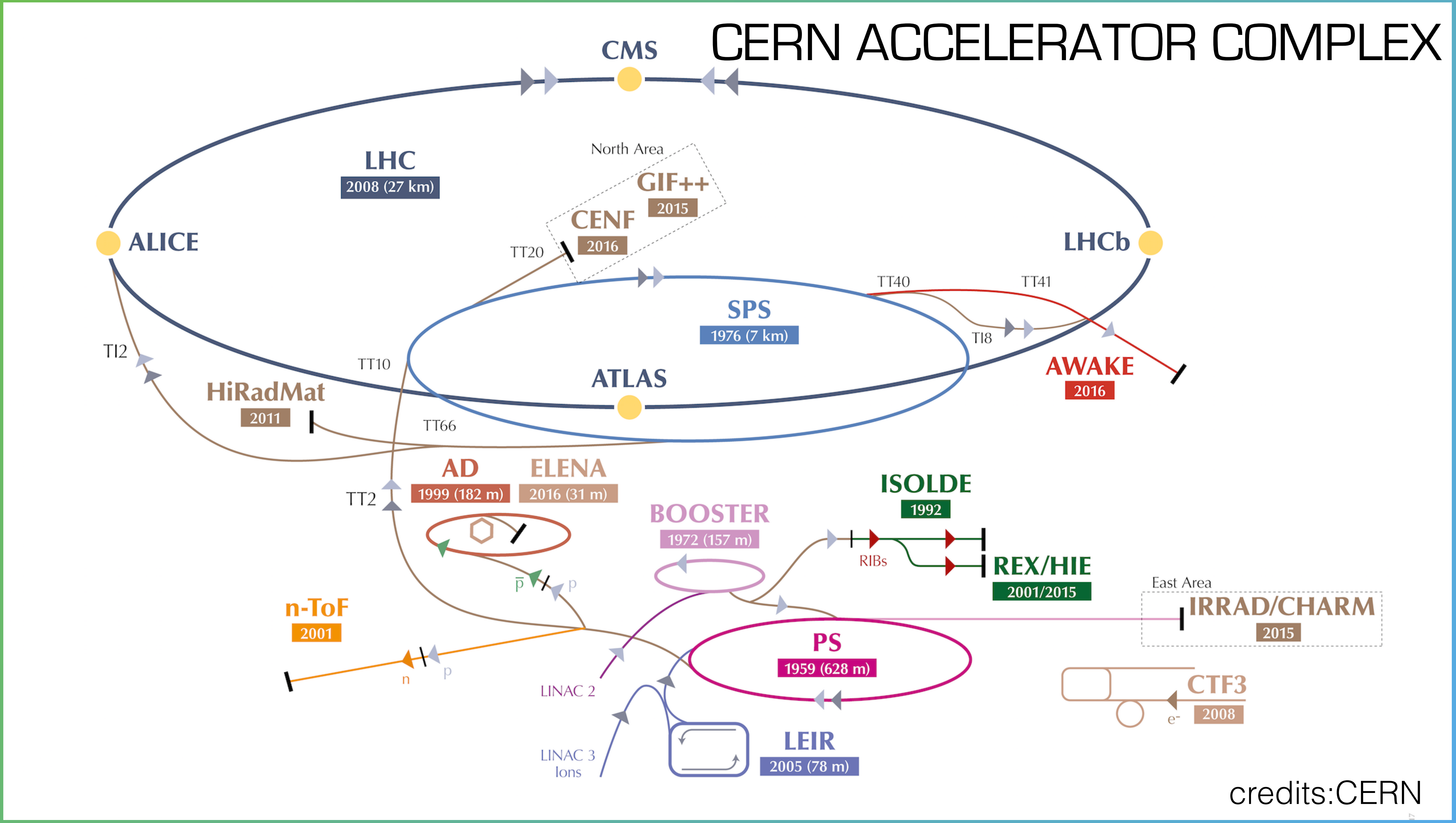
It is the simplest antimatter atom!

Short Antihydrogen history

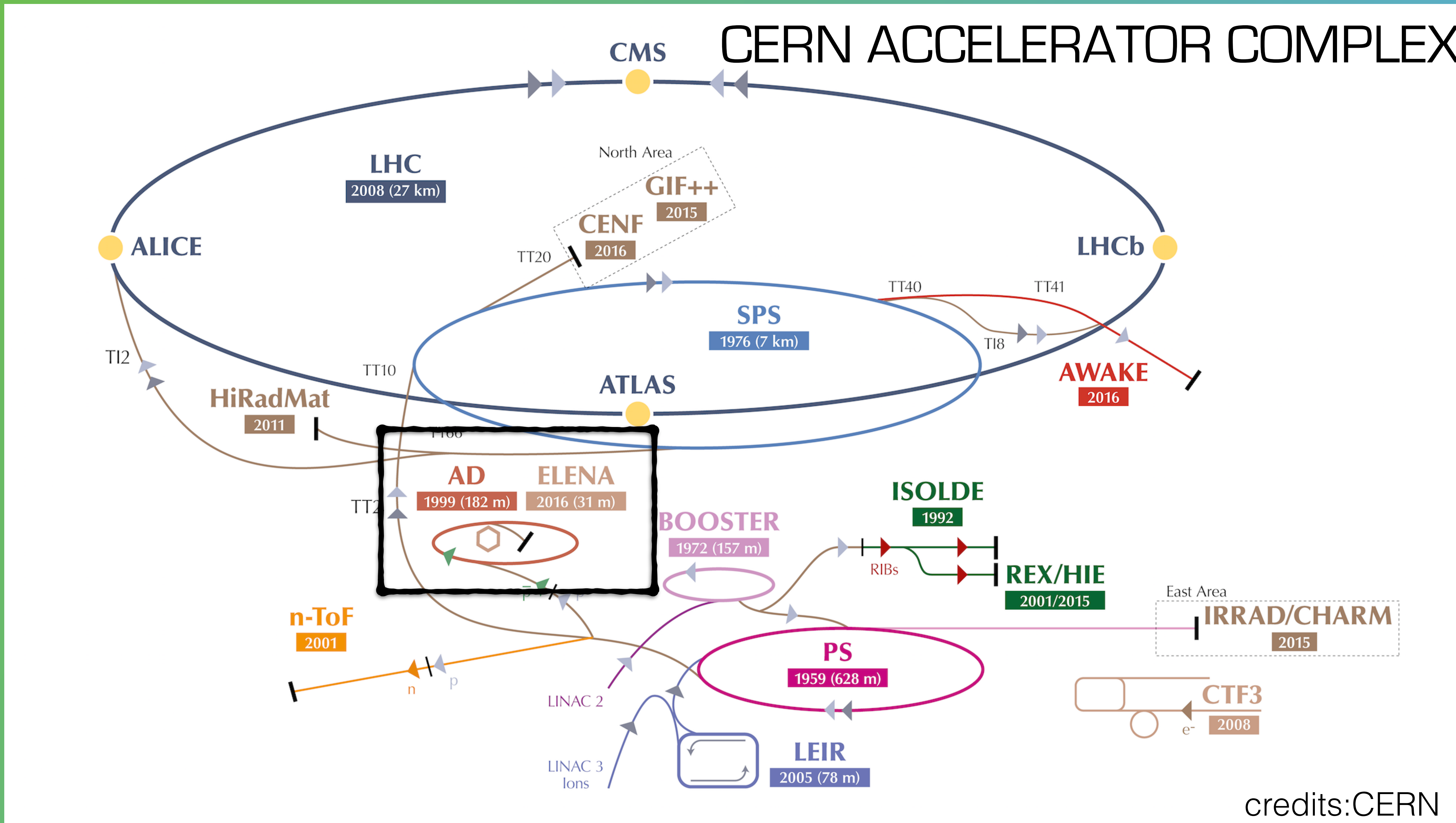
1995 : CERN and FERMILAB: first antihydrogen atoms produced (around 10 in total, but with relativistic velocities)
1999 : the AD (Antiproton Decelerator) starts being in operation at CERN: the main goal is to produce "trappable" antiprotons for **cold** (~tens of K) antihydrogen production
2002 : ATHENA at the CERN AD (and later ATRAP) produces **milions of antihydrogen atoms.**
Since 2006: several experiments are taking data (ALPHA, ATRAP, ASACUSA, AEGIS), or are in preparation (GBAR) to study antihydrogen properties

Antihydrogen can be currently produced only at CERN

“trappable” Antiprotons today



"trappable" Antiprotons today



AD: antiprotons delivered with 5 MeV
ELENA (under test now): antiprotons delivered with 100 keV

Differently from other experiments that just make trapped antiprotons recombine with positrons

$$\overline{p} + \ e^+ \ \rightarrow \overline{H}^*$$

AEgIS aims at producing antihydrogen through a charge exchange reaction:

$$\overline{p} + (Ps)^* \rightarrow \overline{H}^* + e^-$$

Rydberg positronium

First proposed with Rydberg Ps by M. Charlton, PHYSICS LETTERS A 143, 3, 143-146 (1990)

Same charge exchange reaction with a similar technique based on Rydberg cesium performed by ATRAP: C. Storry et al., Phys. Rev. Lett. 93 (2004) 263401

$$\bar{p} + (Ps)^* \rightarrow \overline{H}^* + e^-$$

Rydberg positronium

D. Krasnicky et al. PHYSICAL REVIEW A 94, 022714 (2016)

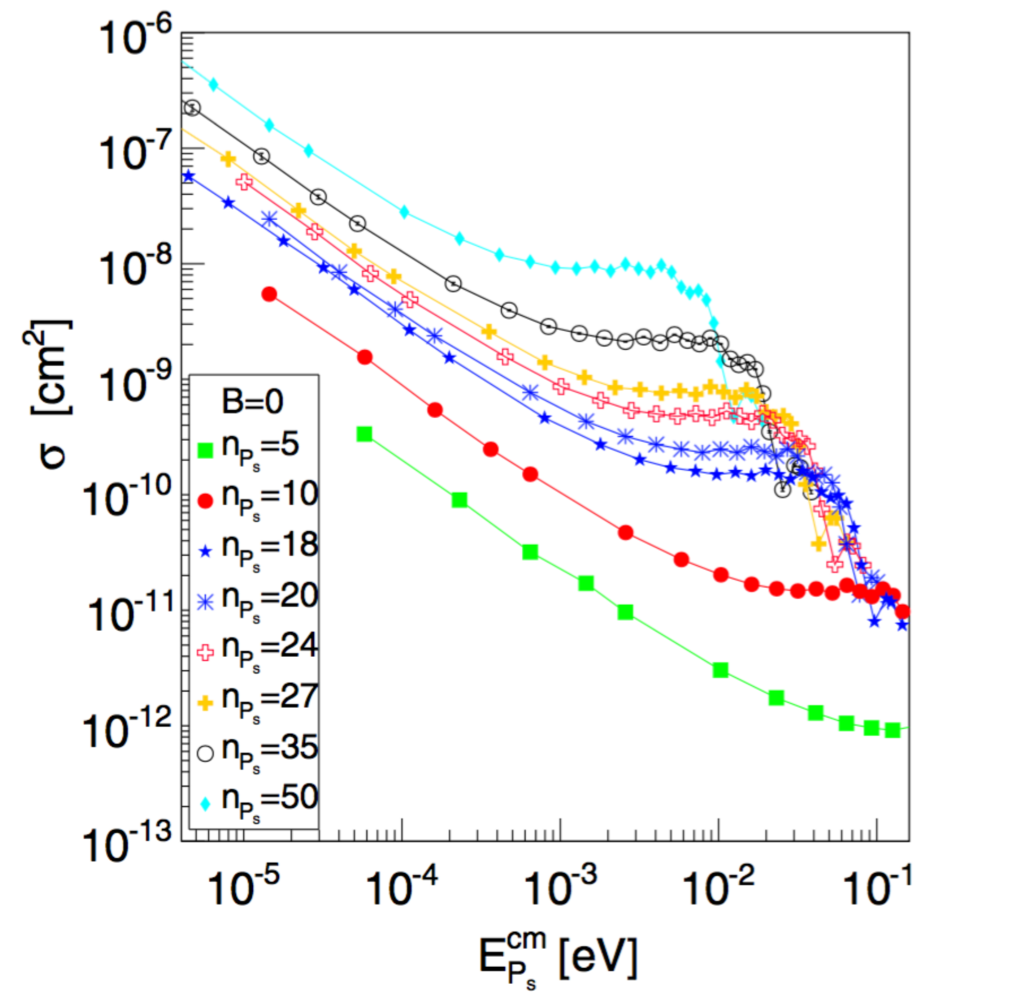


FIG. 3. Charge-exchange cross section σ as a function of the P_s center-of-mass energy. The plot shows the same points of Fig. 2. The lines simply connect the points to help the graphical interpretation.

ADVANTAGES

- Large cross section $\sigma \propto (n_{Ps})^4$
- Narrow and well defined band of final states ($n_H \approx \sqrt{2} \times n_{Ps}$, with a rms of few units)

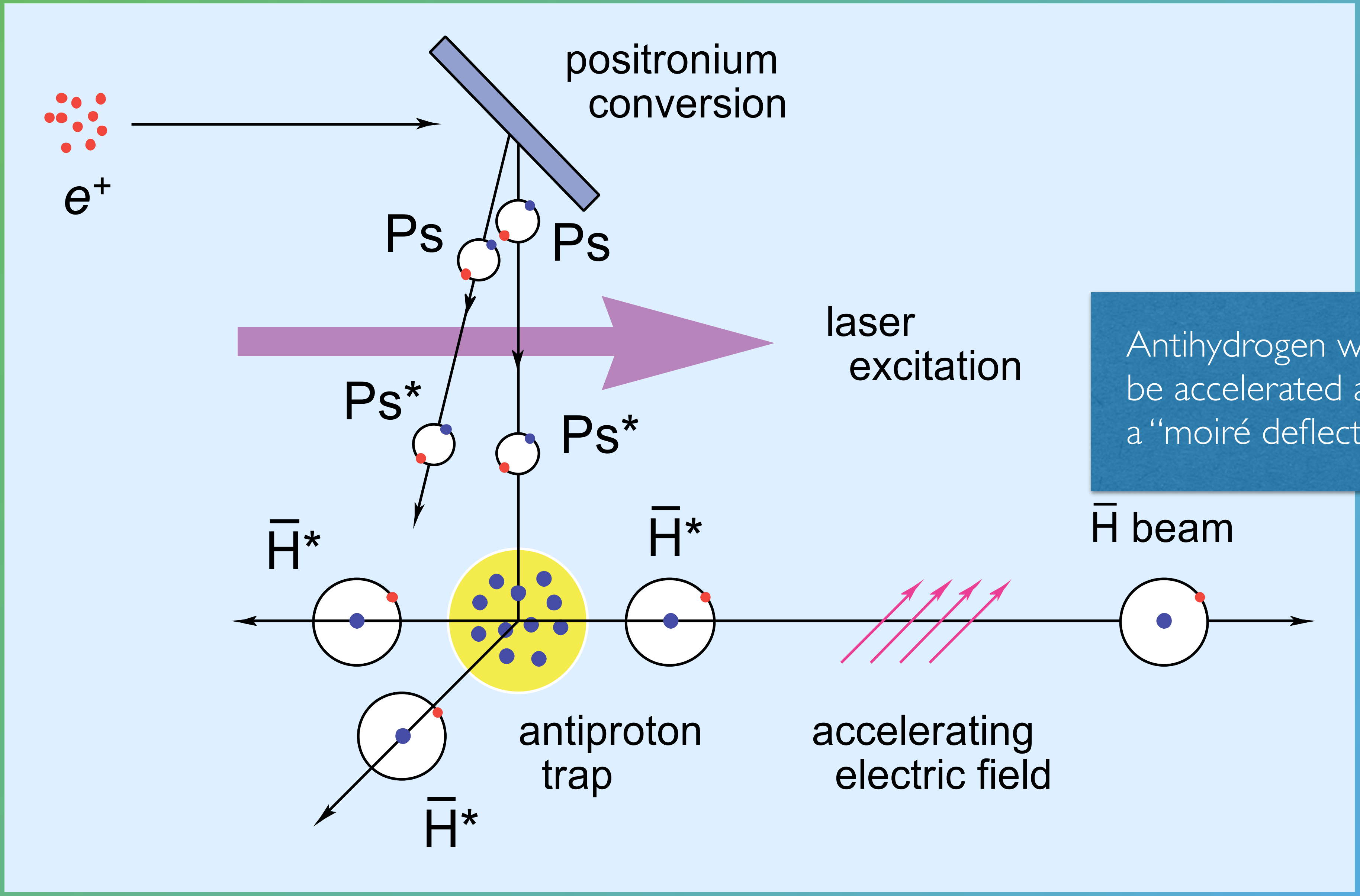
AEgIS Method

Capture of antiprotons from the CERN-AD
Cooling of the trapped antiprotons

Positronium (e^+e^-) production by e^+ on SiO_2
Ps laser excitation to Rydberg state

Interaction of Ps* with the antiproton cloud

$$\bar{p} + (Ps)^* \rightarrow \overline{H}^* + e^-$$



Antihydrogen will eventually be accelerated and fly toward a "moiré deflectometer"

Positronium

$$e^+ + e^- \longrightarrow Ps \longrightarrow (Ps)^*$$

Positronium [o-Ps] is produced through a nanoporous silica converter where a bunch of ~10^7 positrons are launched together

Mariazzi et al. Phys. Rev. Lett. 104, 243401 (2010)

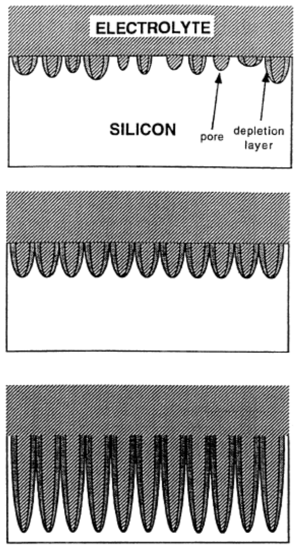
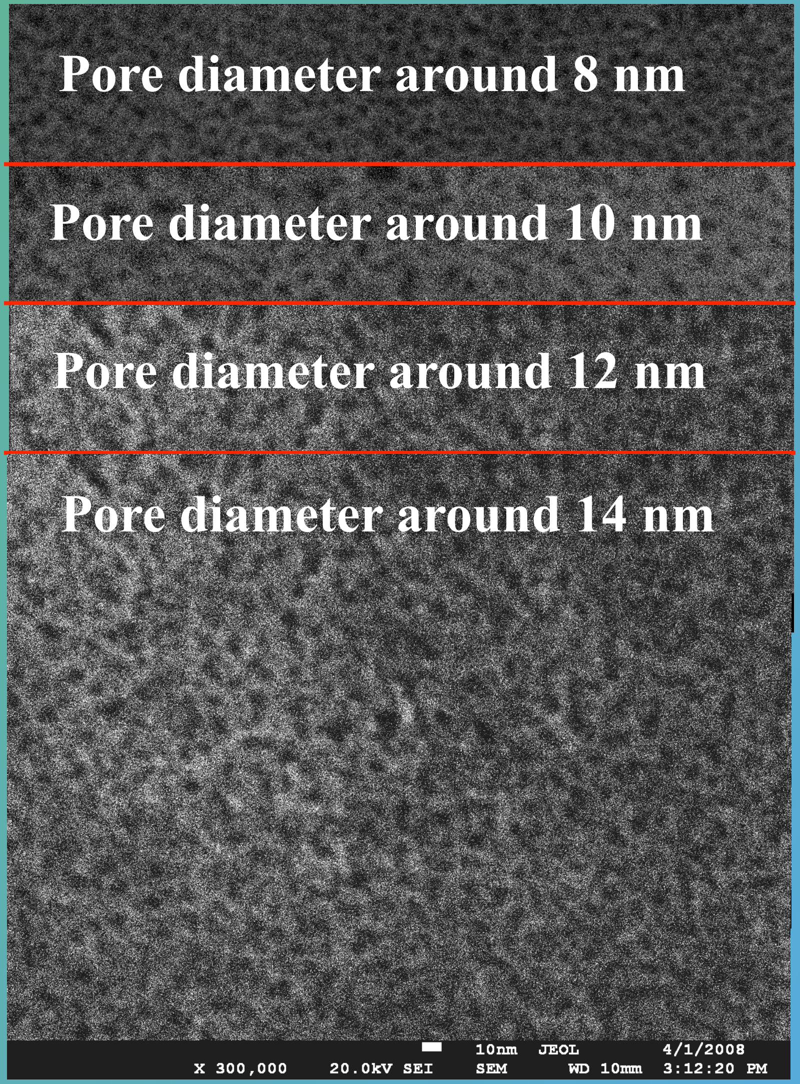


Fig. 6. Mechanism of pore formation in PS. Random pore initiation on the Si surface (top panel), formation of depletion layers and directional growth of pores (middle panel) and dissolution advance only at the pore tips (bottom panel).

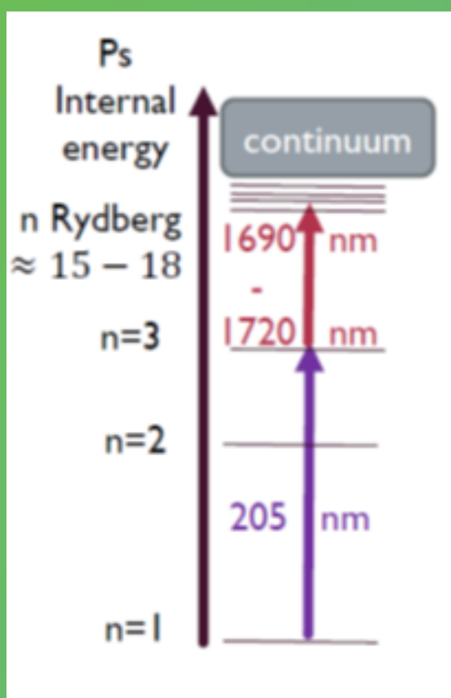


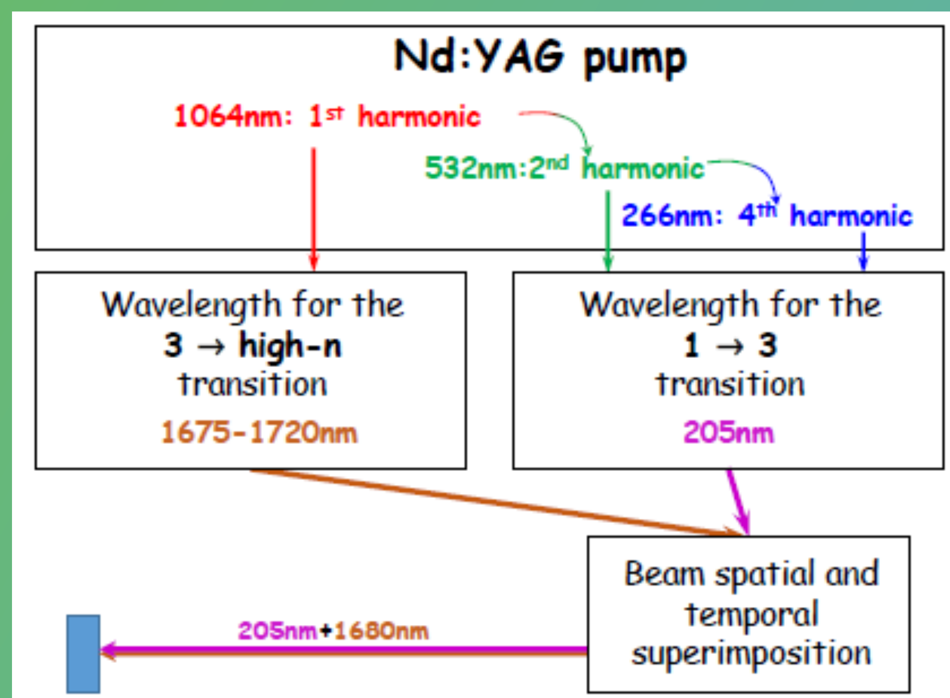
See Roberto Brusa's talk

Positronium

$$e^+ + e^- \longrightarrow Ps \longrightarrow (Ps)^*$$

2 steps Positronium laser excitation



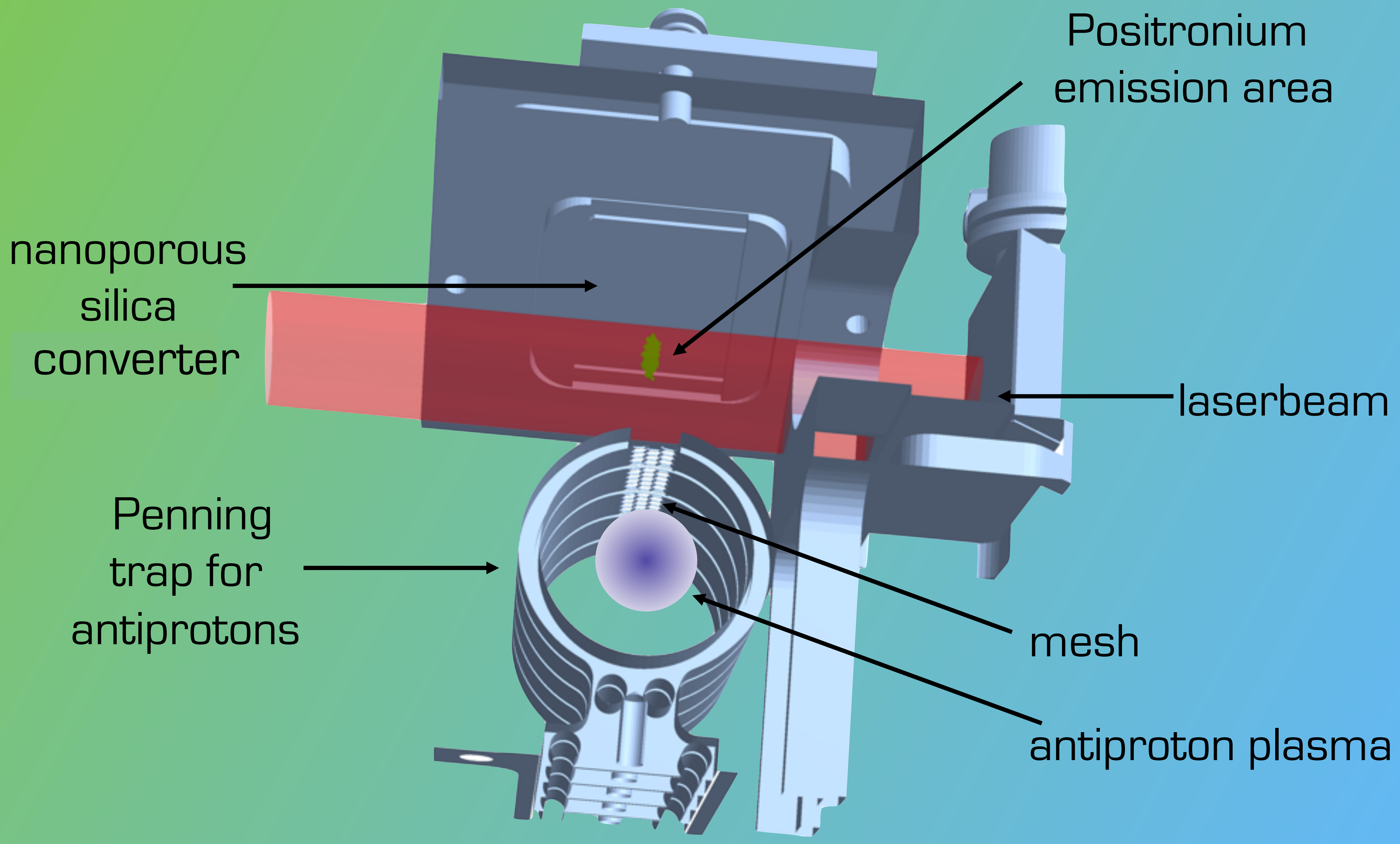


UV 205.047 nm	IR 1680-1715 nm
1.5 ns	5 ns (2 ns delay with respect to UV)
3mm FWHM	3.5 mm FWHM
90 μJ	1 mJ

Already demonstrated by us in the e⁺ test setup

"Laser excitation of the n=3 level of positronium for antihydrogen production"
Phys. Rev. A 94 (2016) 012507 AEgIS Collaboration

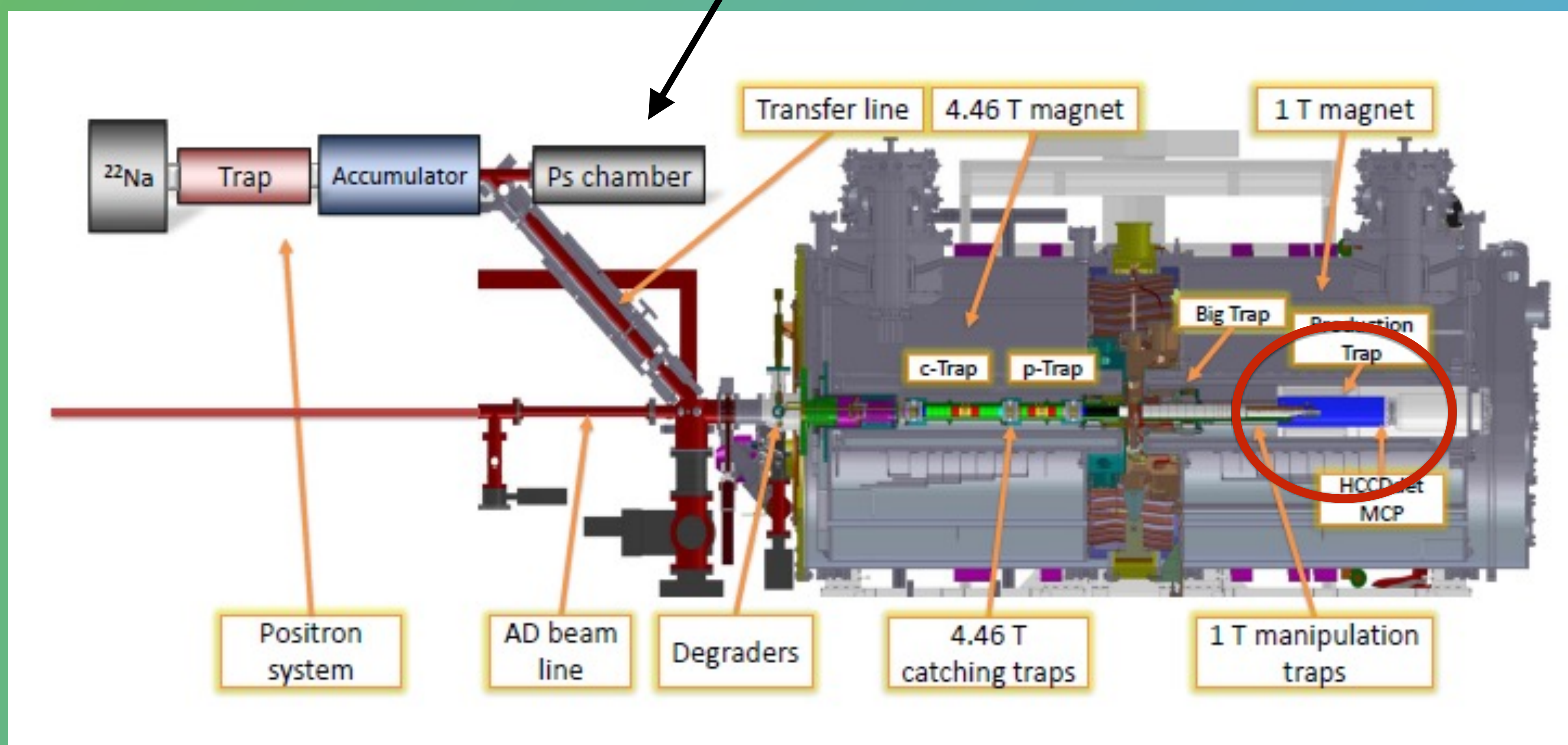
And see again Roberto Brusa's talk

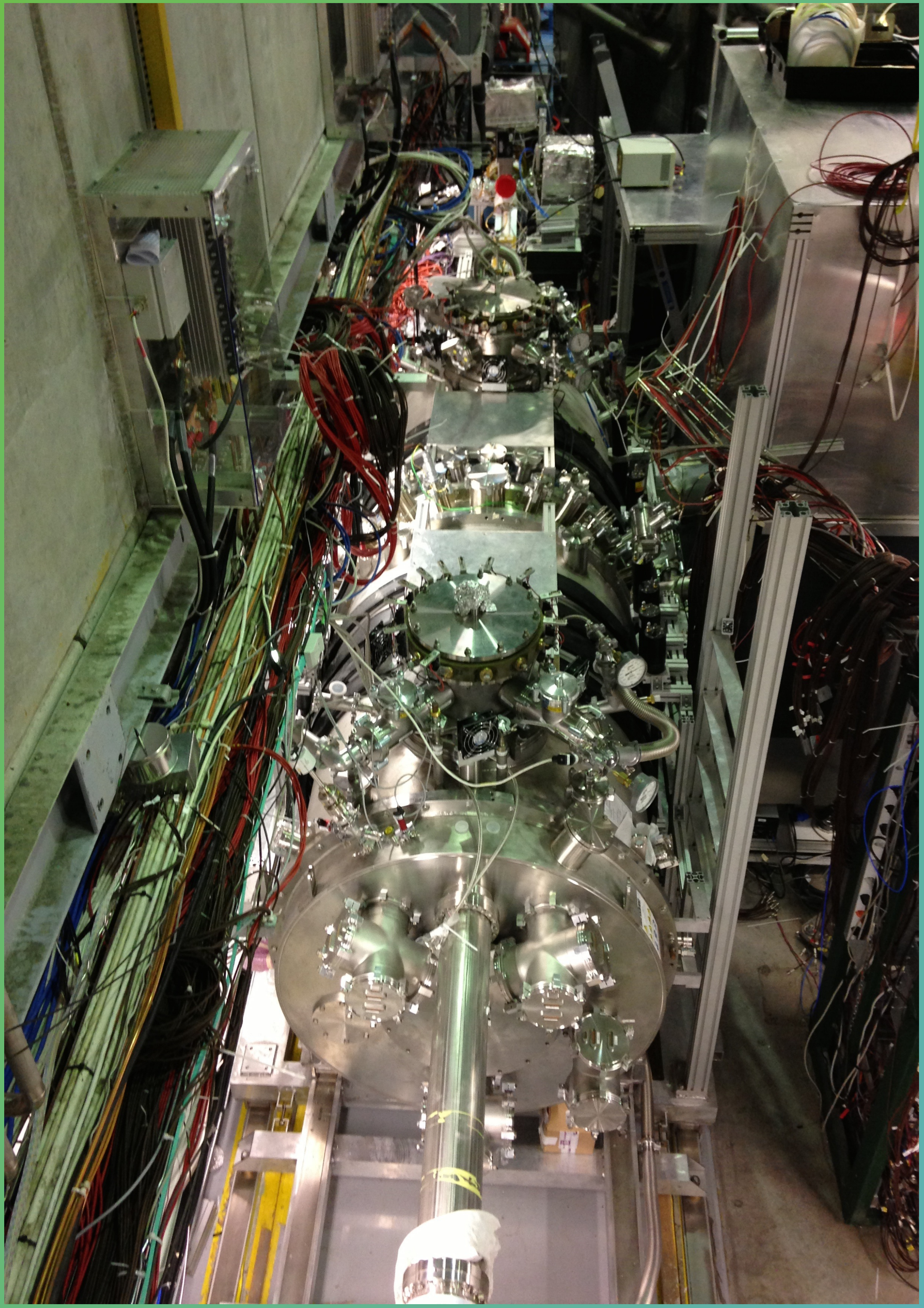

Positronium emission area
nanoporous silica converter
laserbeam
Penning trap for antiprotons
mesh
antiproton plasma

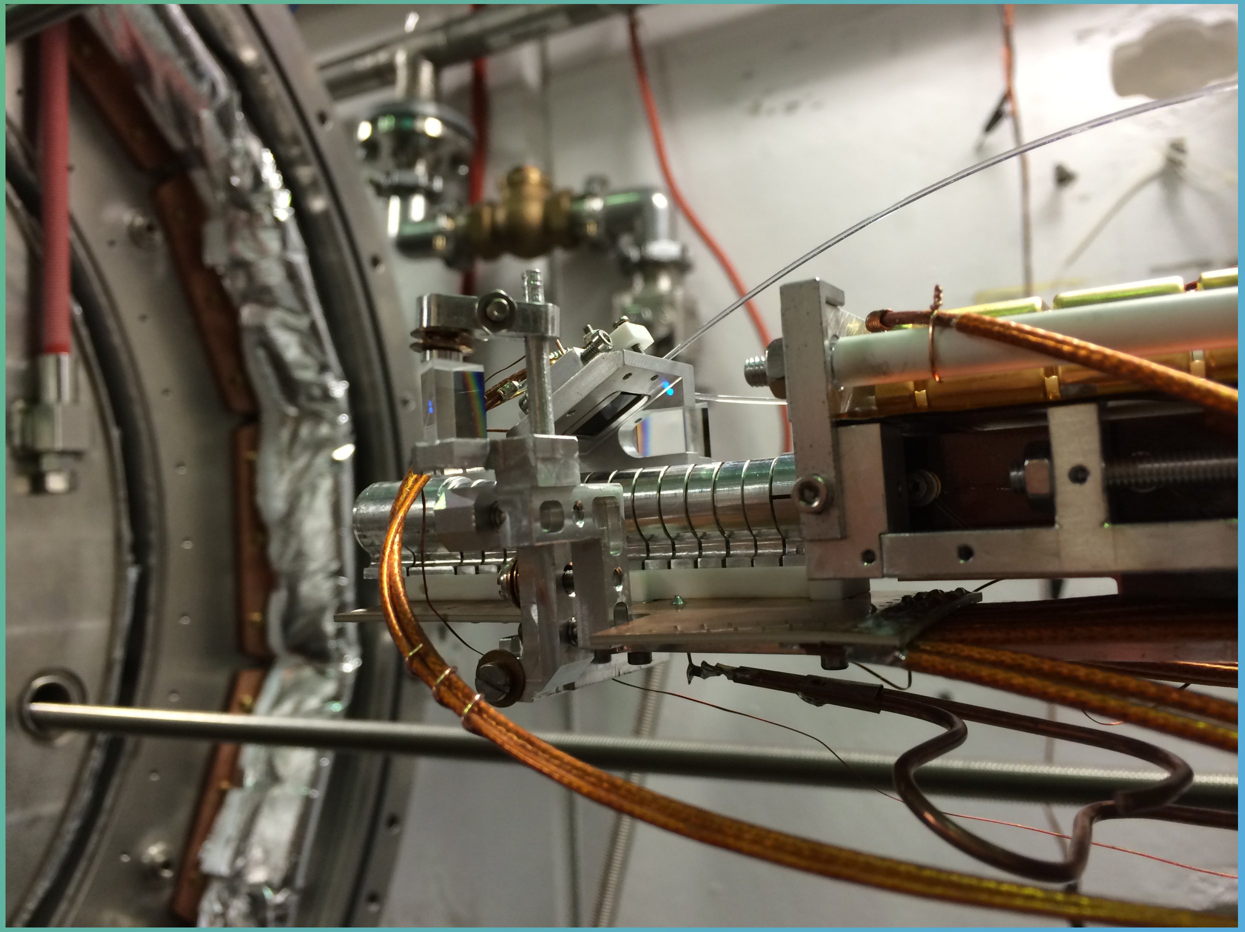
AEgIS Apparatus

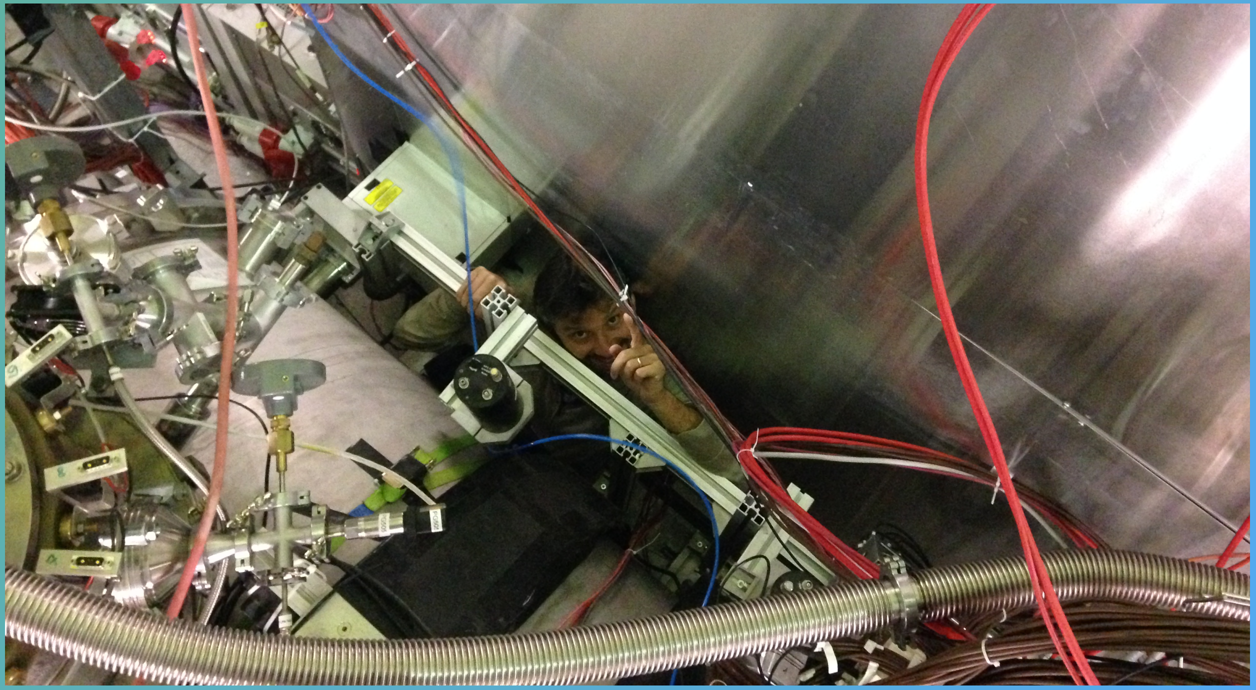
- Accumulator for e+
- Magnetic transfer line for e+
- Superconducting magnetic fields (~5T, 1T)
- Cryogenic traps (105 electrodes)
- antiH detector (scintillating fibers)
- External plastic scintillators
- Internal (MCP+phosphor screen & Faraday cups
  in cryogenic UHV)
- lasers
- Additional detectors
- POSITRON MEASUREMENT setup

Ps test setup
used for measurements with Ps (excitation etc.)

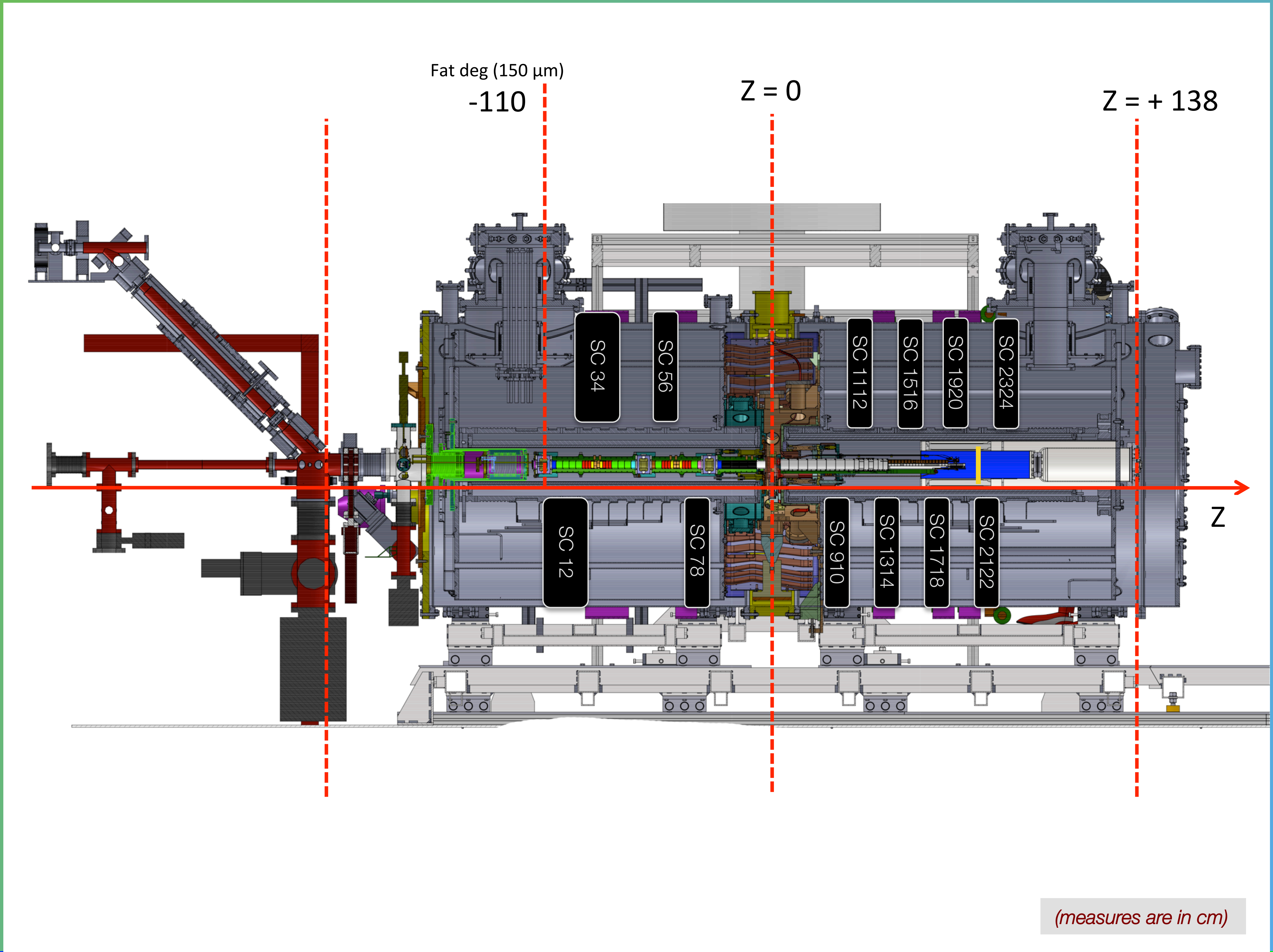




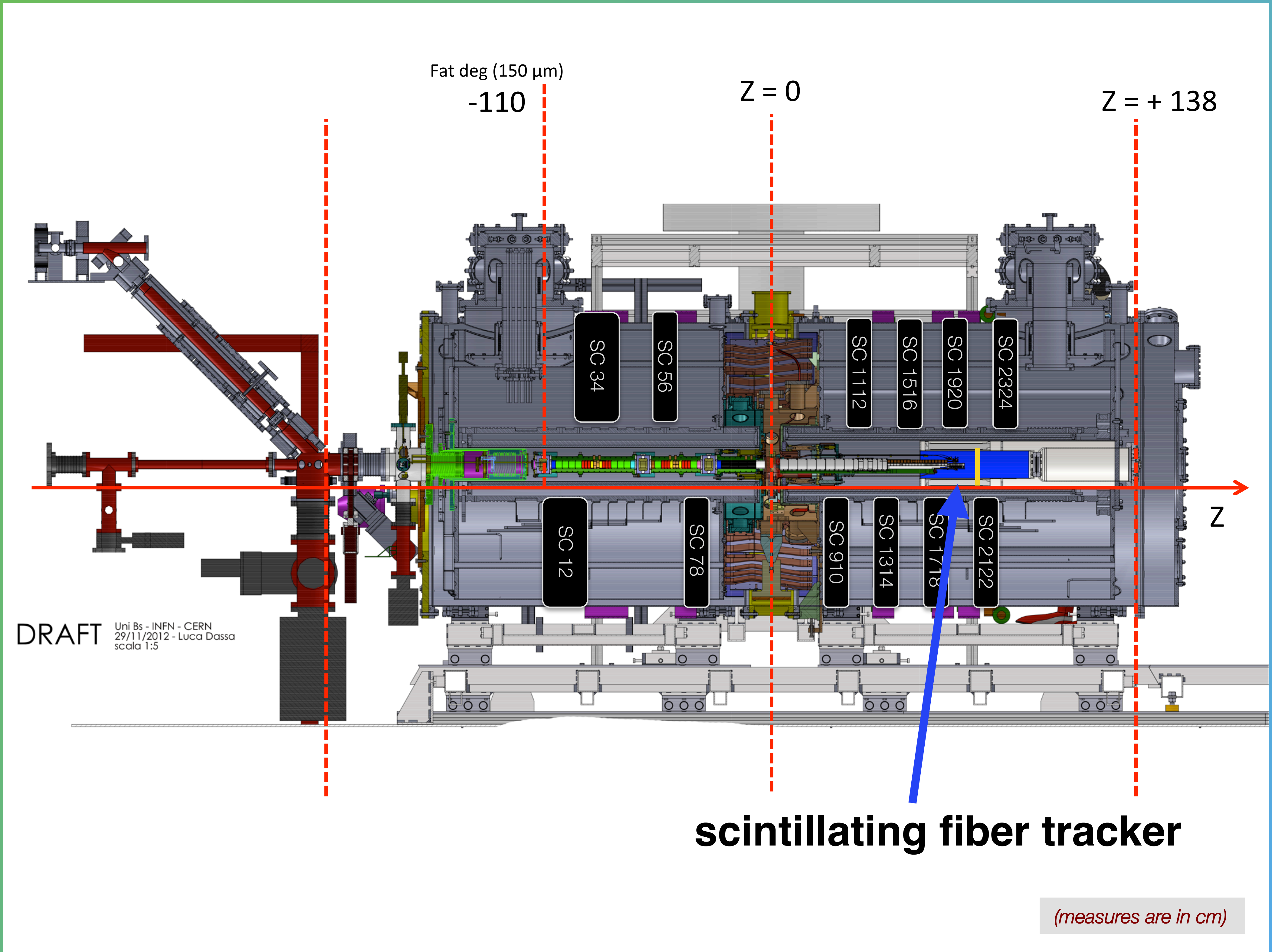




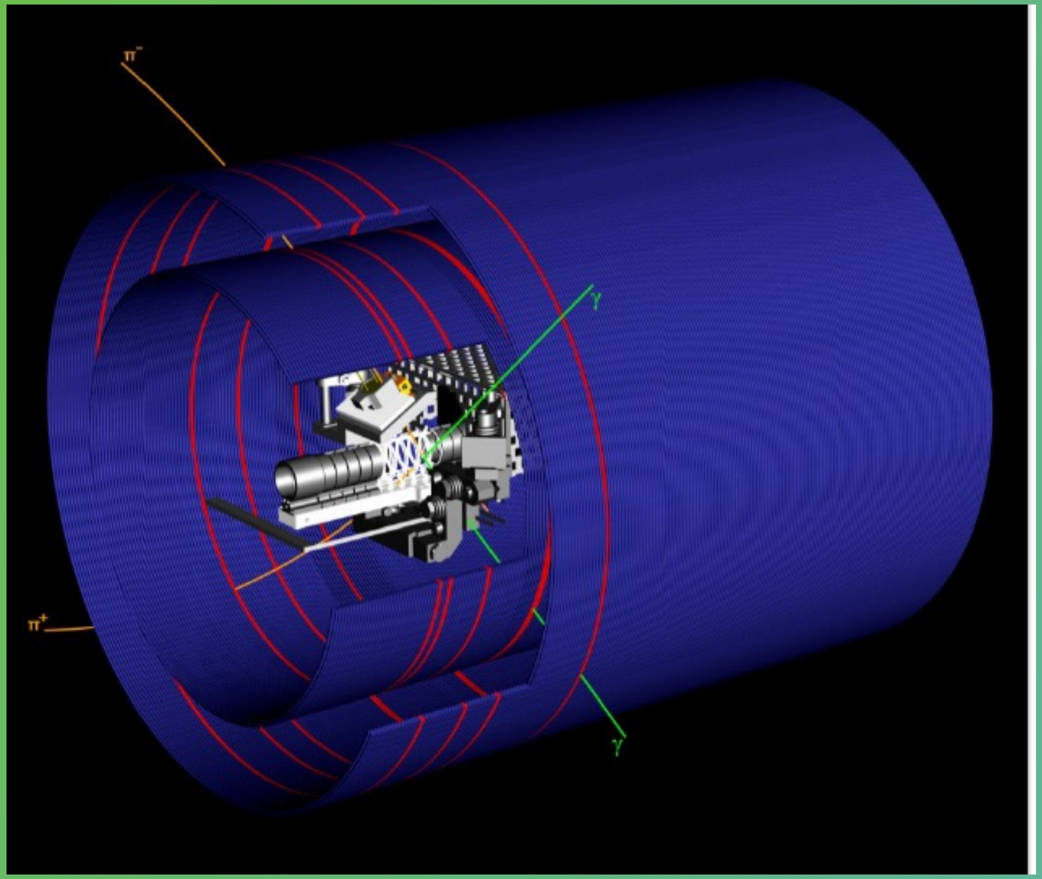
Particle annihilation diagnostic system

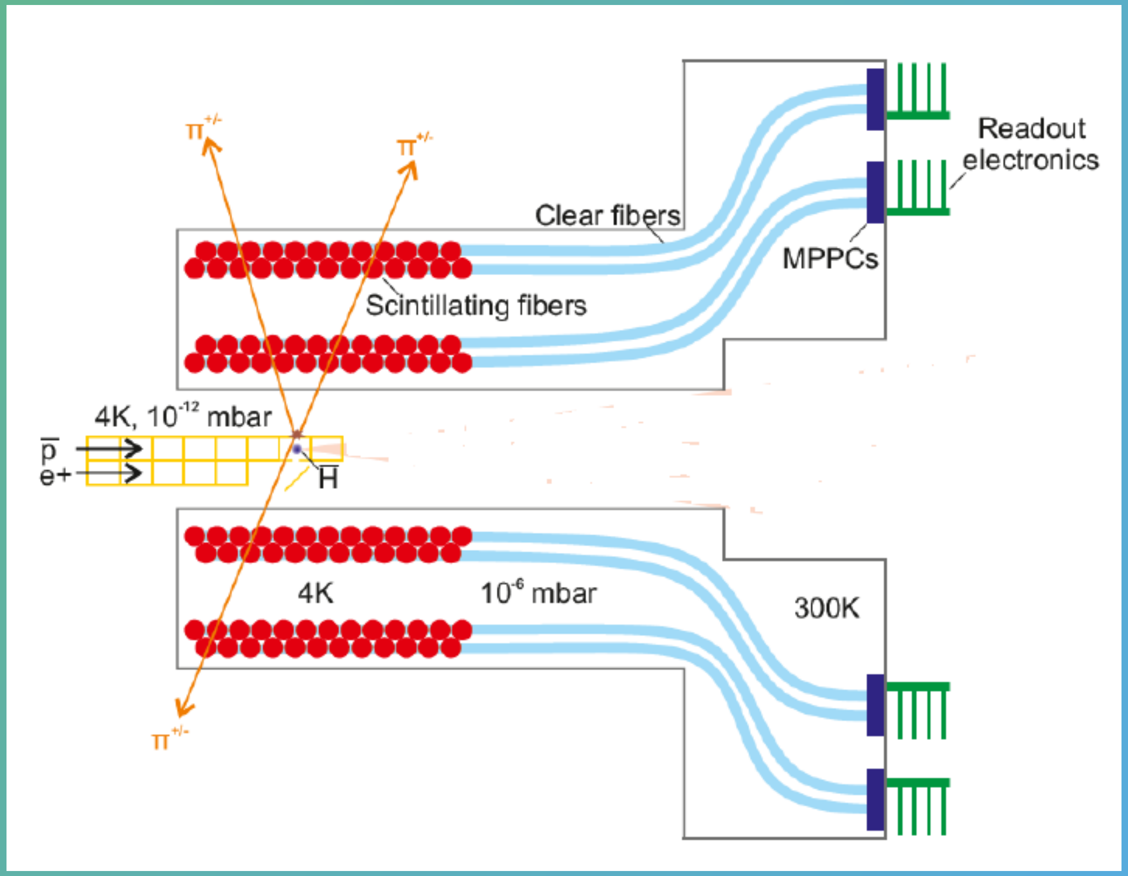


Particle annihilation diagnostic system



Scintillating Fiber Tracker





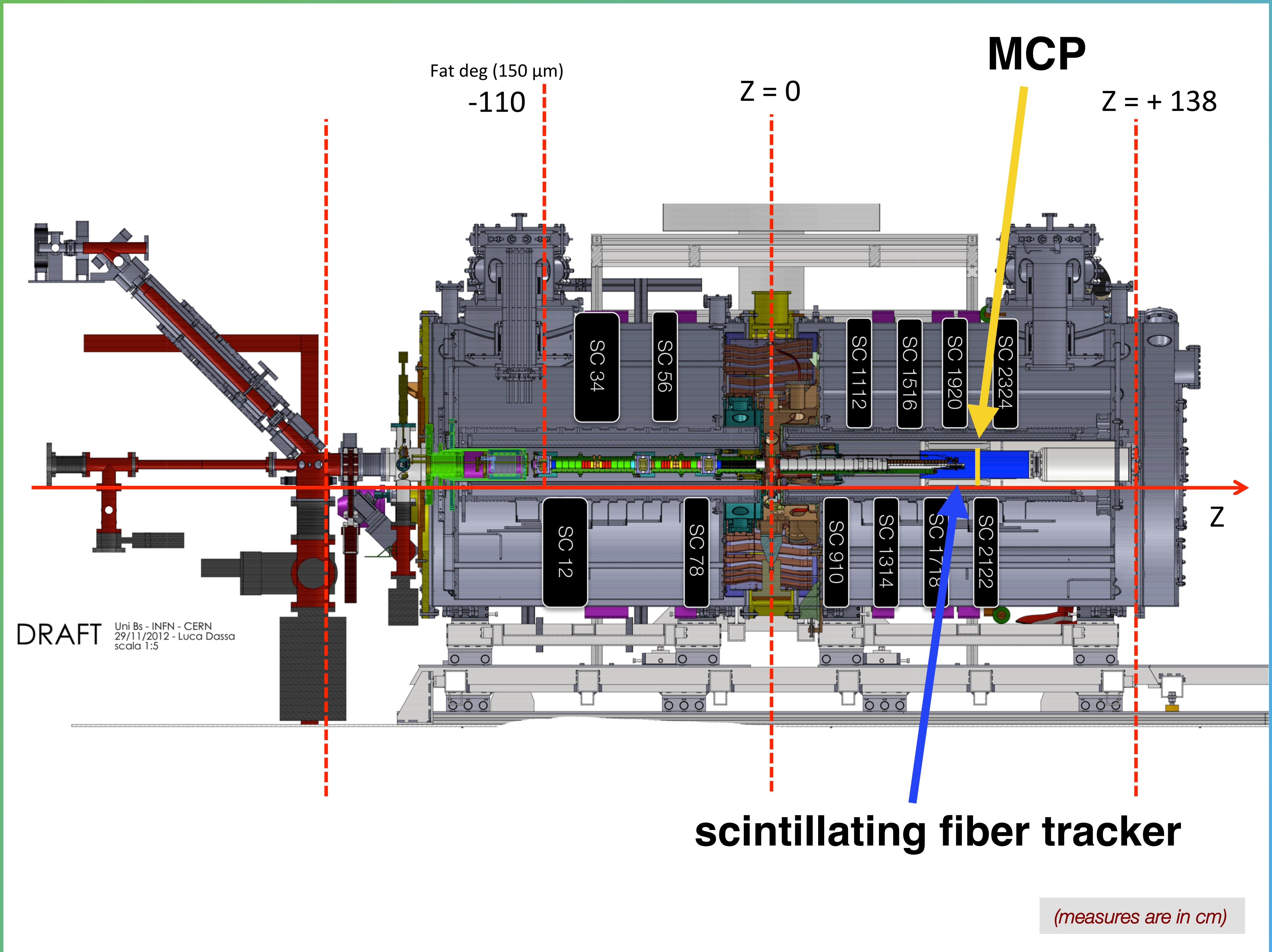
Scintillating fibers at ~4K around the central region

2 cylinders (7 cm and 10 cm radius) , 4 layers, 794 fibers in total

Circular pattern, φ degeneration

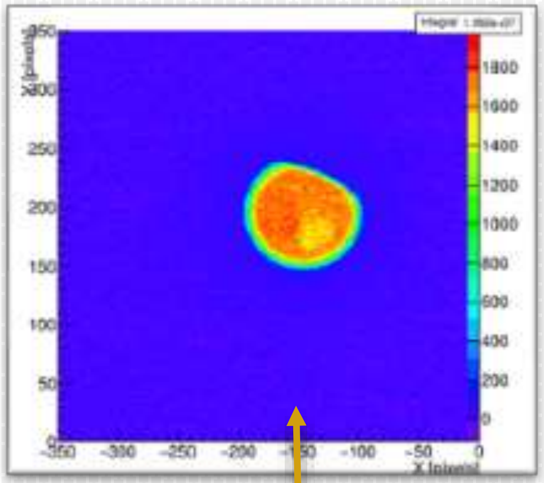
Reading with SiPm matrix: Multiple Pixel Photon Counter
(Hamamatsu MPPC) @ at room temperature

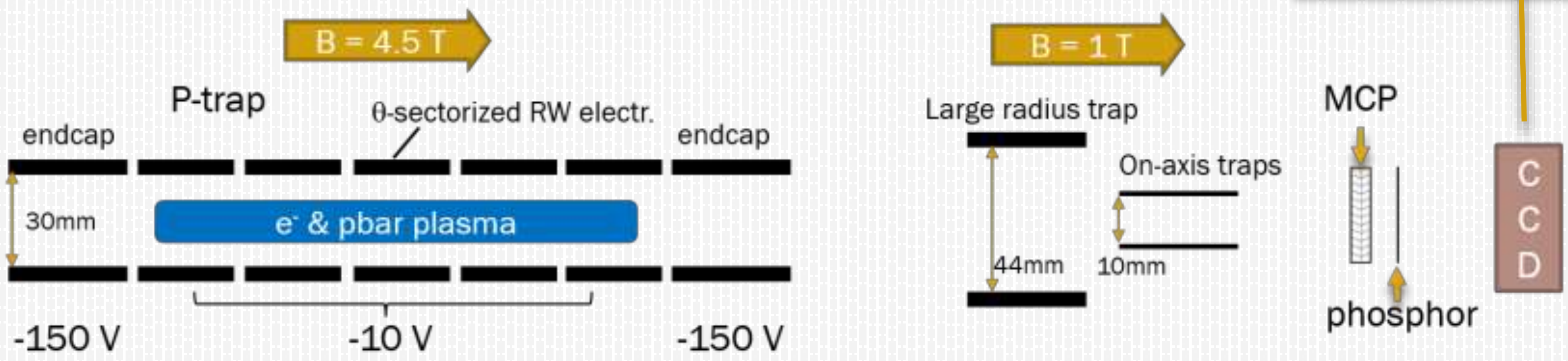
Particle annihilation diagnostic system



TRAPPED PARTICLE IMAGING IN AEGIS - MCP

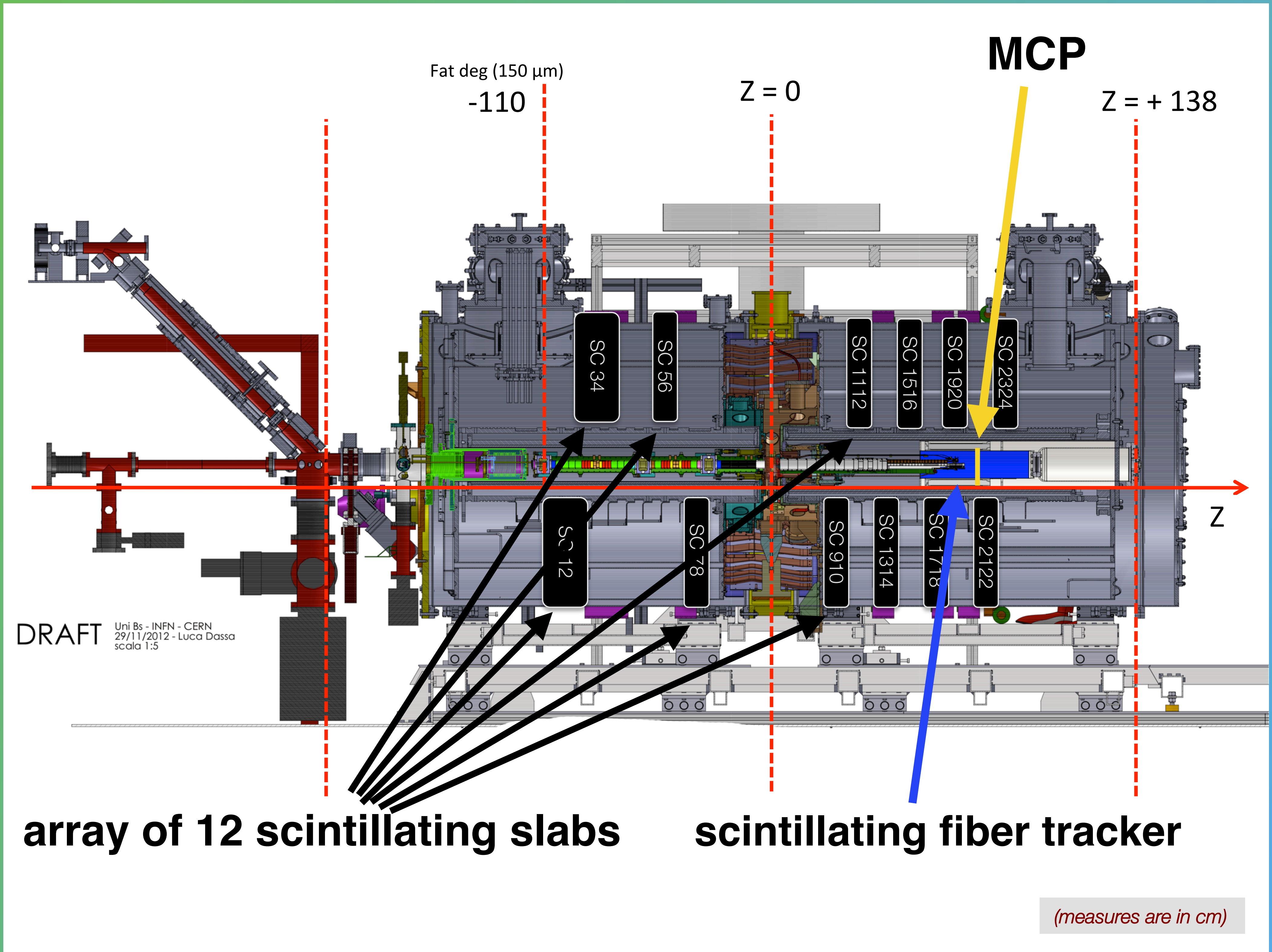
- Electron (and antiproton) imaging with in-vacuum MCP
  - 2-stage chevron Hamamatsu micro-channel plate
  - coupled to a phosphor screen
  - CCD readout
  - MCP & phosphor located in 1T and @ 55K



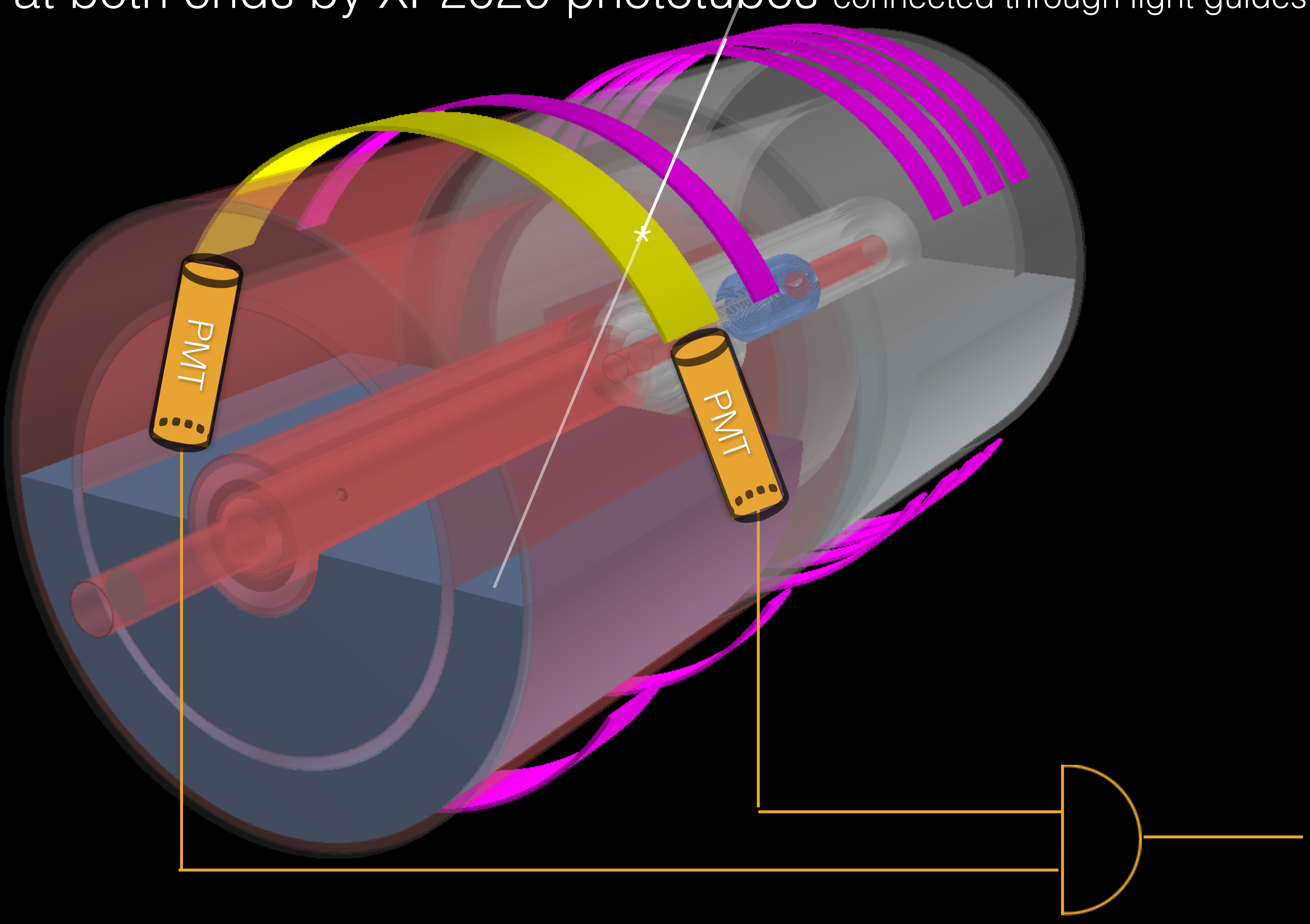


see e.g. "Compression of a mixed antiproton and electron non-neutral plasma to high densities"
S. Aghion et al. Eur. Phys. J. D (2018) 72: 76 (AEgIS Collaboration)

Particle annihilation diagnostic system



array made by 12 slabs of plastic scintillator (EJ200)
read at both ends by XP2020 phototubes connected through light guides



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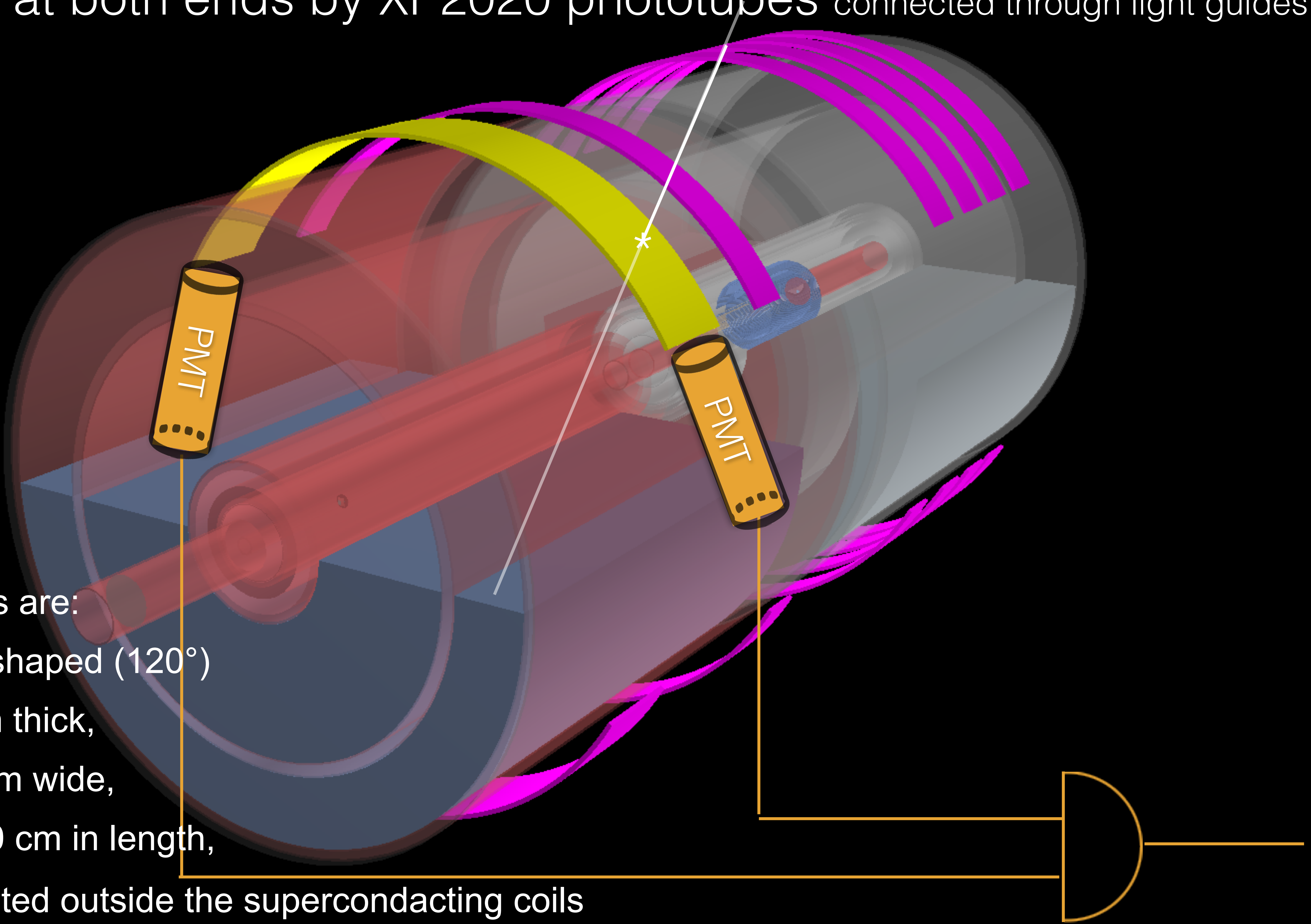


slabs are:

arc-shaped (120°)

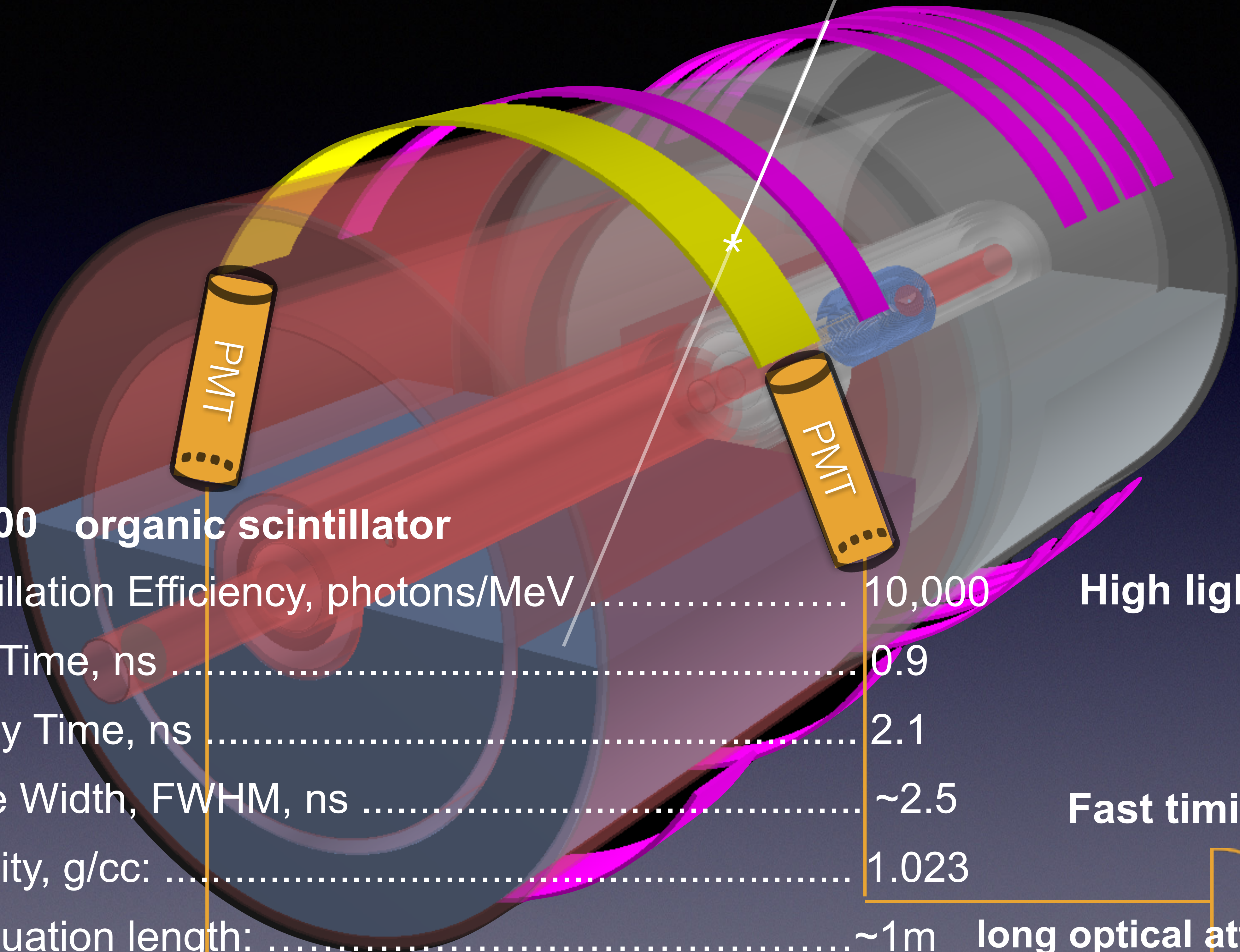
1 cm thick,

10 cm wide,

~150 cm in length,

situated outside the supercondacting coils

array made by 12 slabs of plastic scintillator (EJ200)
read at both ends by XP2020 phototubes connected through light guides



EJ-200 organic scintillator

Scintillation Efficiency, photons/MeV .... 10,000 — **High light yield**

Rise Time, ns 0.9

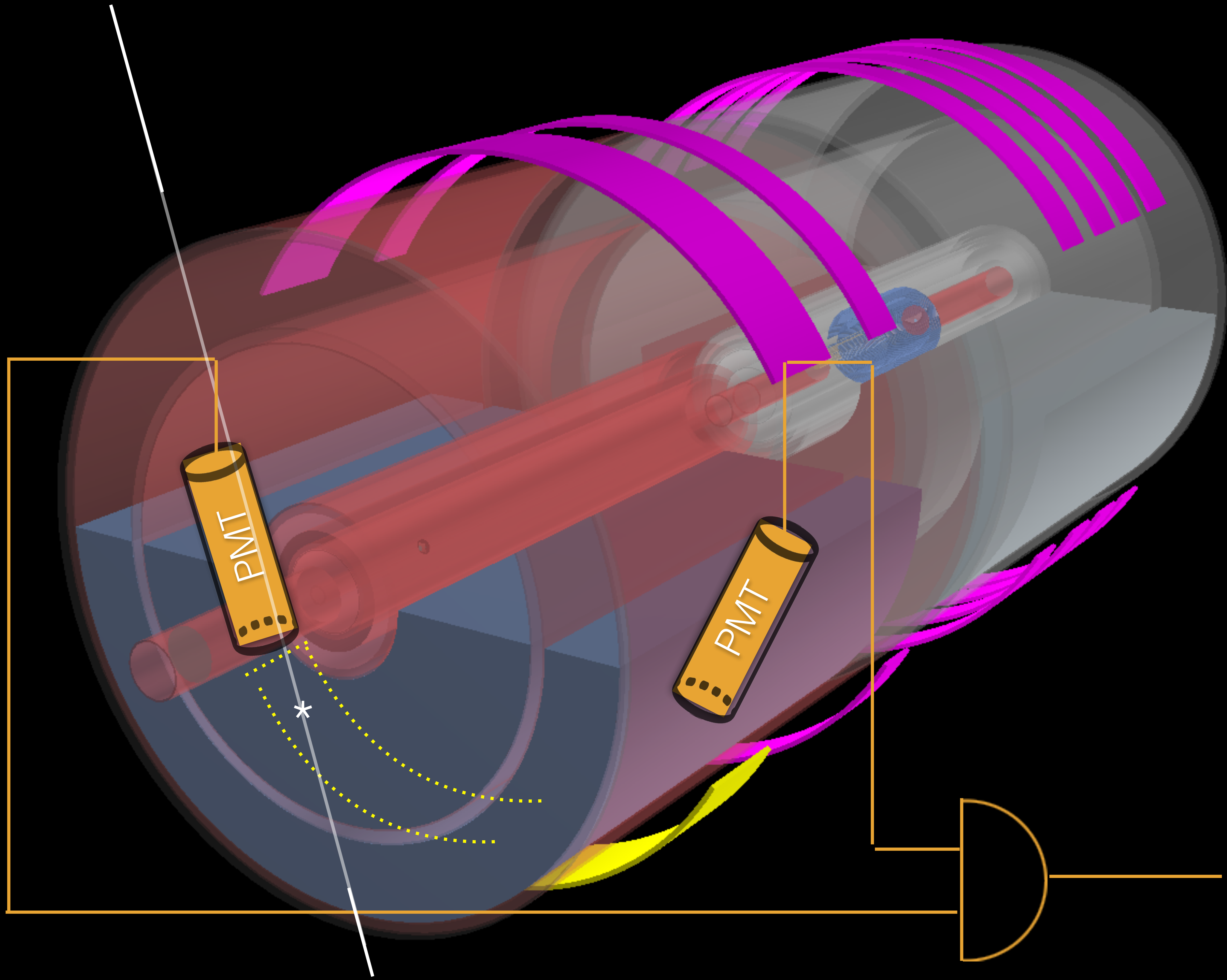
Decay Time, ns 2.1

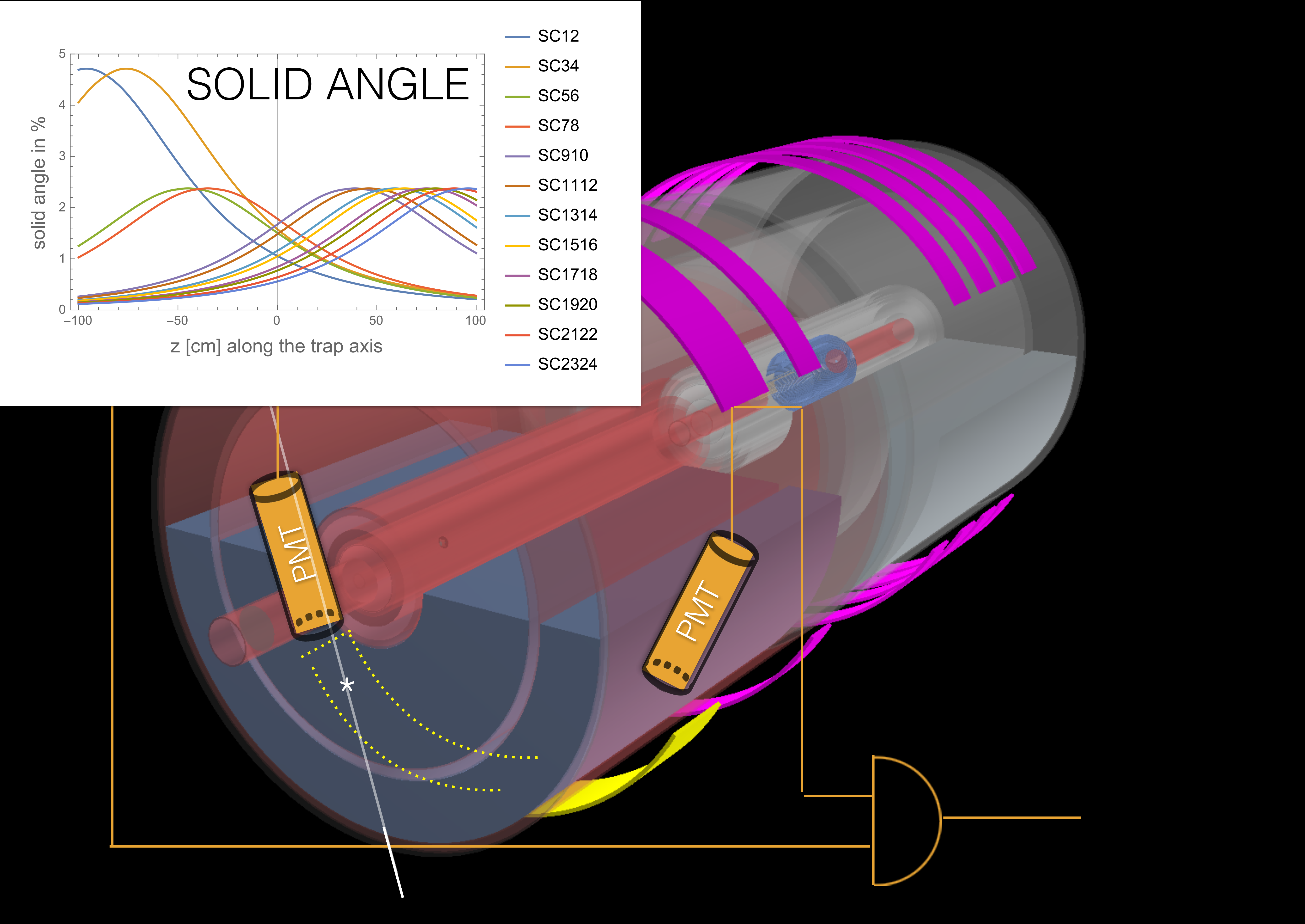
Pulse Width, FWHM, ns .... ~2.5 — **Fast timing**

Density, g/cc: 1.023

Attenuation length: ....~1m — **long optical attenuation length**

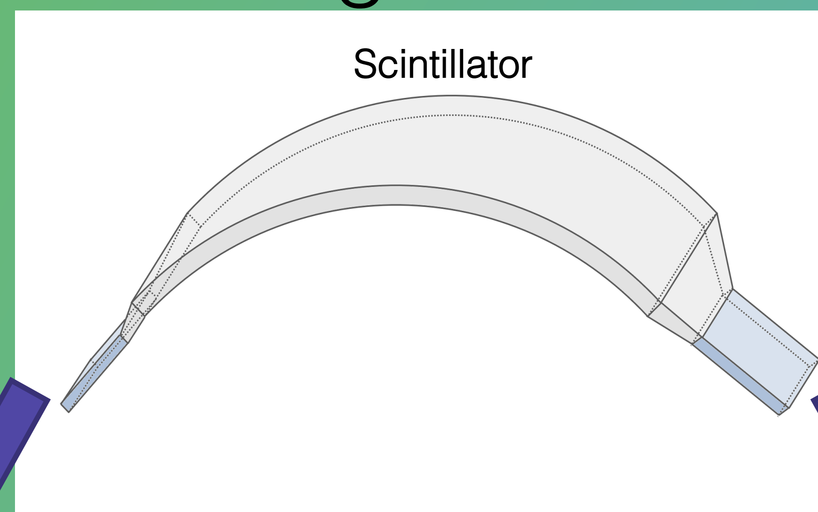
Polymer Base: . Polyvinyltoluene

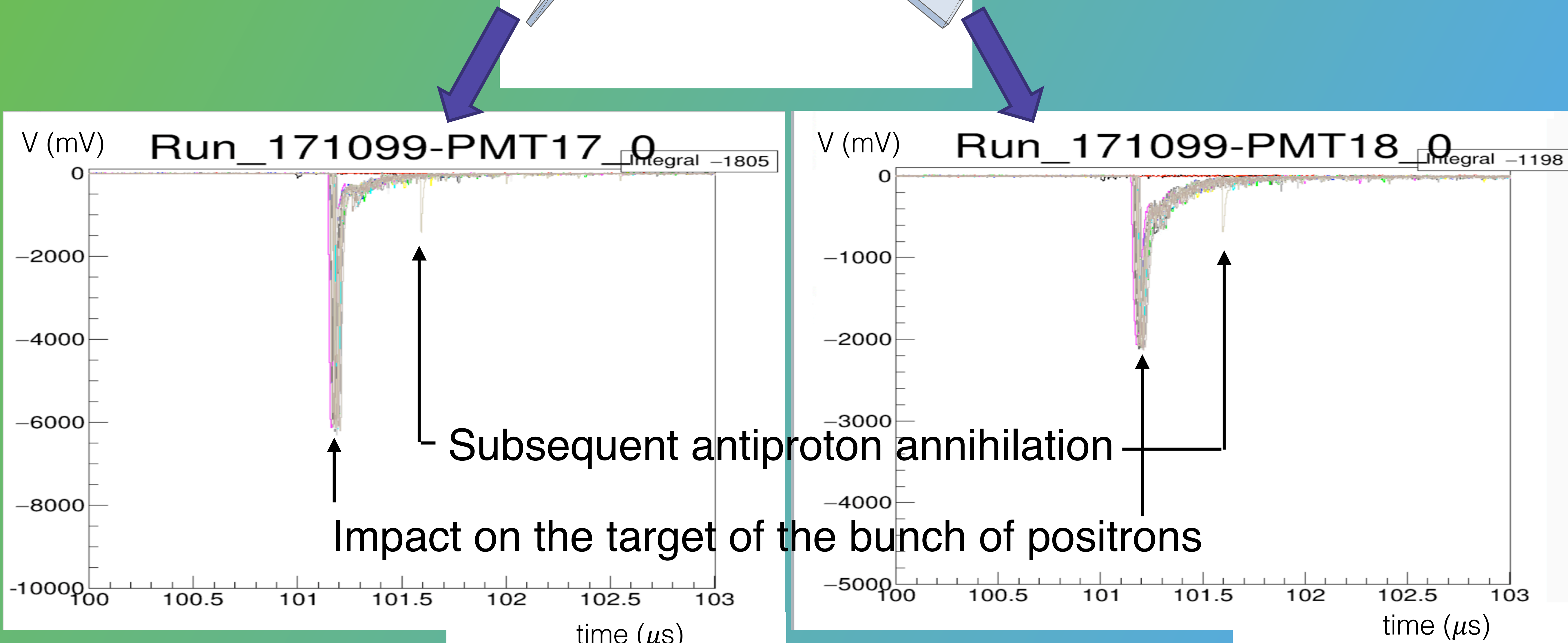

PMT
PMT


SOLID ANGLE
solid angle in %
z [cm] along the trap axis
SC12
SC34
SC56
SC78
SC910
SC1112
SC1314
SC1516
SC1718
SC1920
SC2122
SC2324
PMT
PMT

Goal:

use these slabs to identify signals caused by pbars annihilations (pions) over the background of e+/Ps annihilations



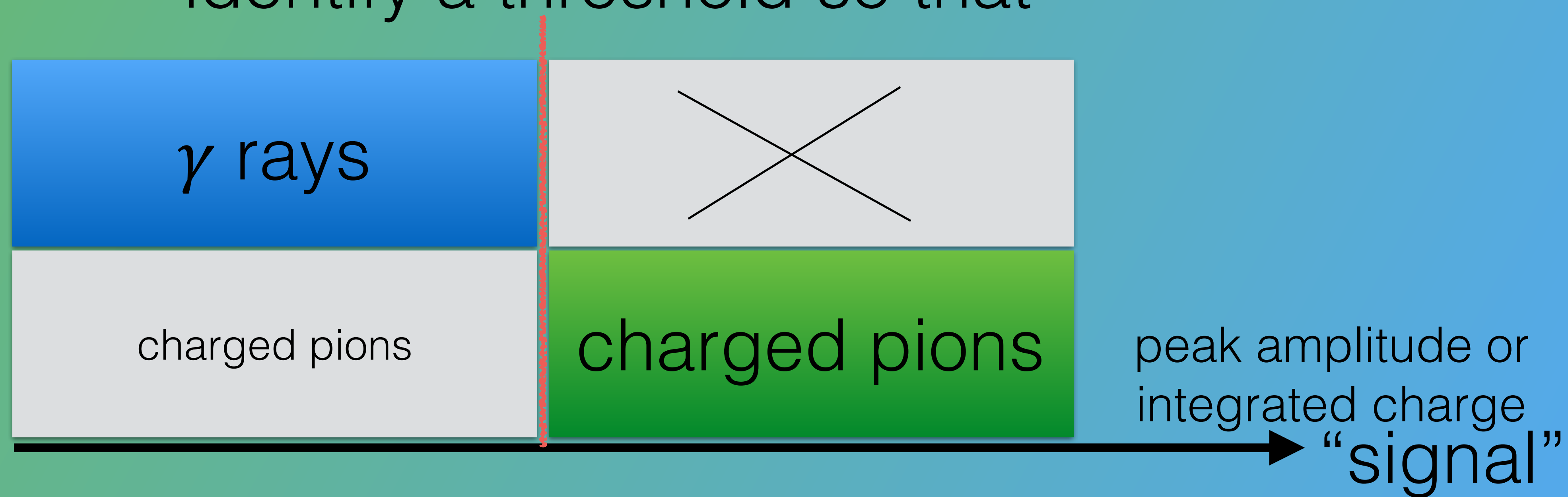


Goal:

use these slabs to identify signals caused by pbars annihilations (pions) over the background of e+/Ps annihilations

Exploit the limited (≦511 keV) energy released by γ rays from e+/Ps single annihilations) → WAVEFORM DIGITISER

identify a threshold so that



Goal:
use these slabs to identify signals caused by pbars annihilations (pions) over the background of e+/Ps annihilations

Exploit the limited (≦511 keV) energy released by γ rays from e+/Ps for single annihilations)

→ WAVEFORM DIGITISER

CAEN V1720 Flash ADC Waveform Digitizer

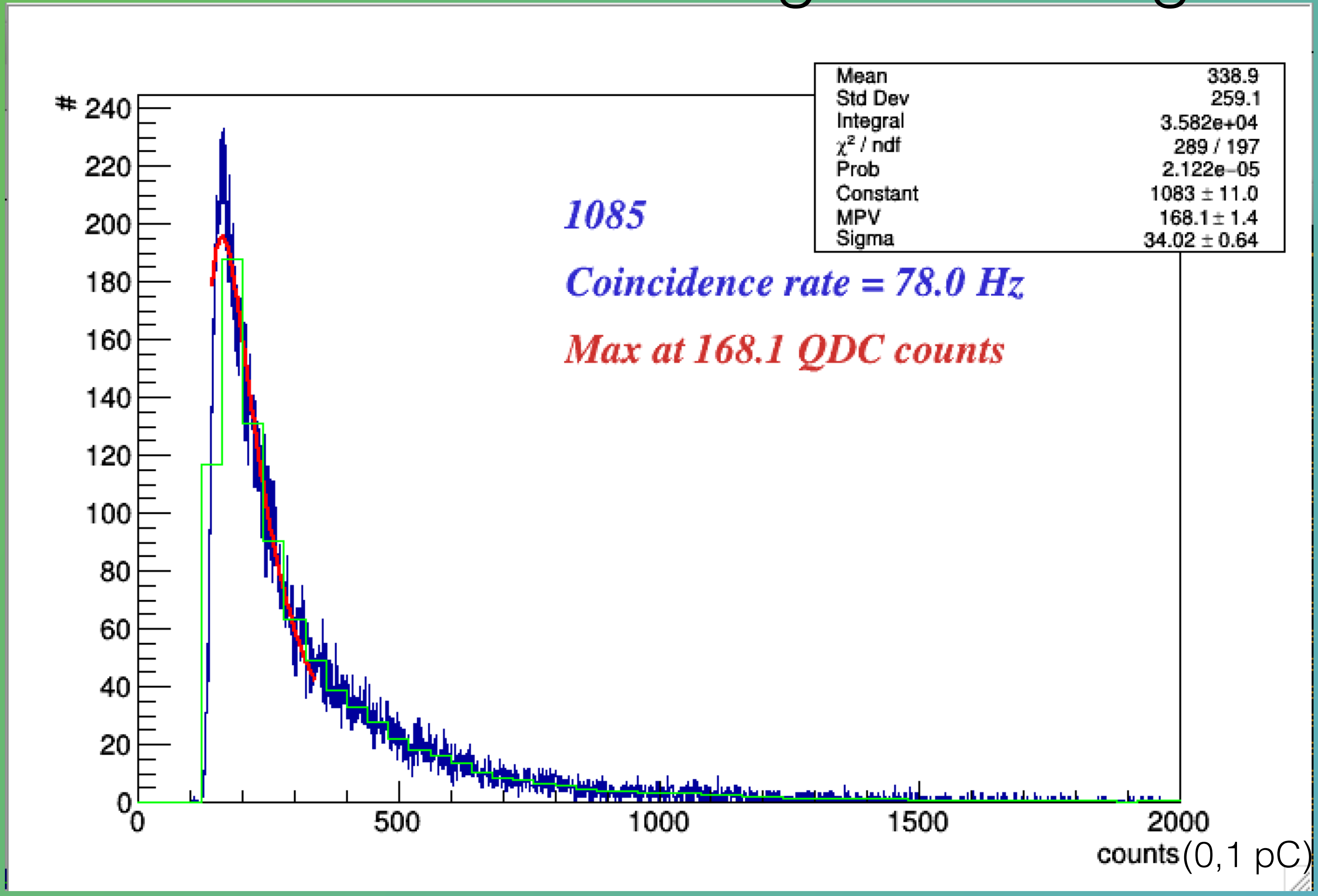
VME module
8 channels
12-bit (resolution = 0,5 mV)
250 MS/s (4 ns /sample)
2 Vpp of input dynamic range
DC offset adjustment
1310720 max data points
(about 5 ms max acquisition time)

First step: calibration with cosmic rays

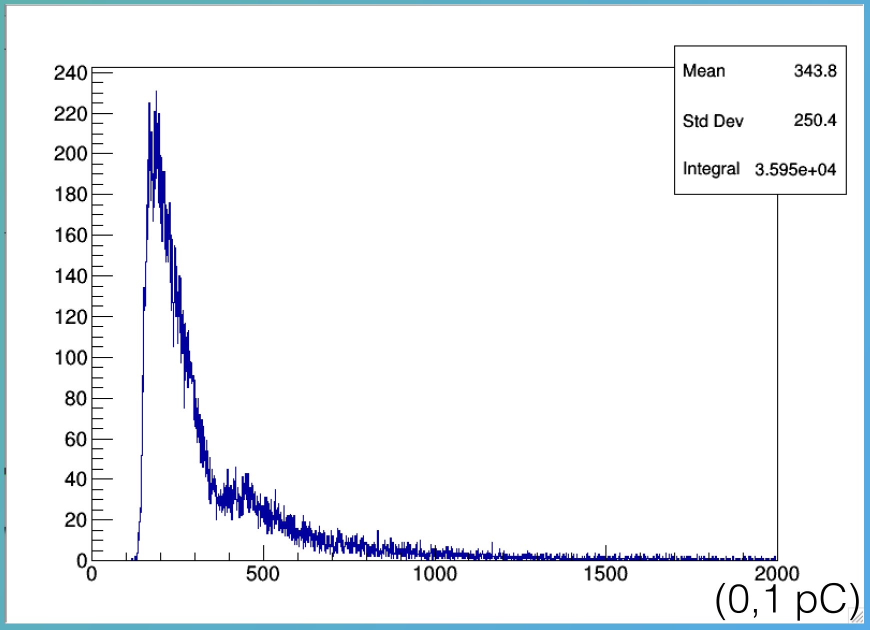
Issues: in the default configuration continuos spectra observed, no evident maximum

Reasons: - strong low-energy room background;
- significant light attenuation inside each slab

distribution of the integrated charge

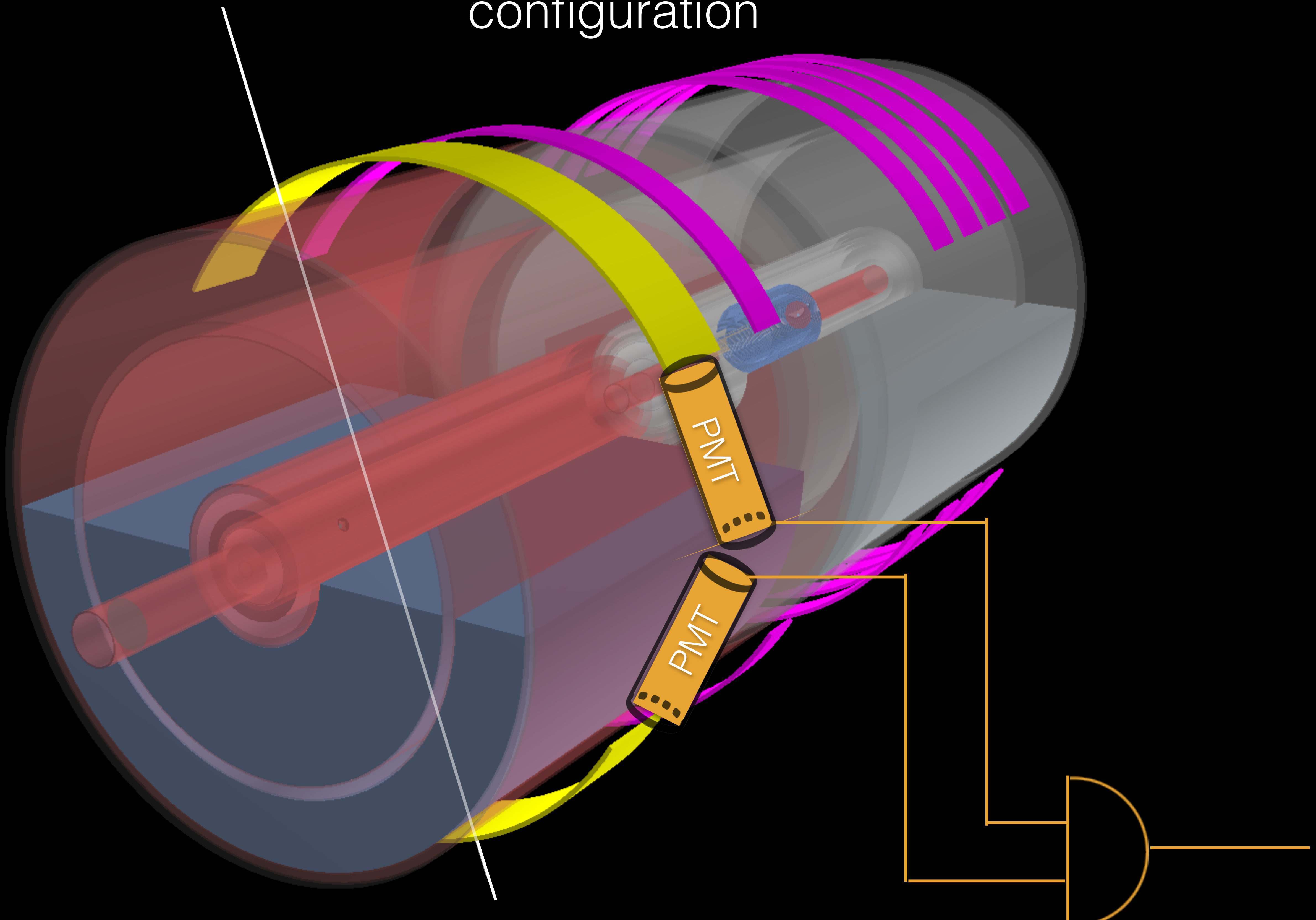


average of the signal of 2 PMTs



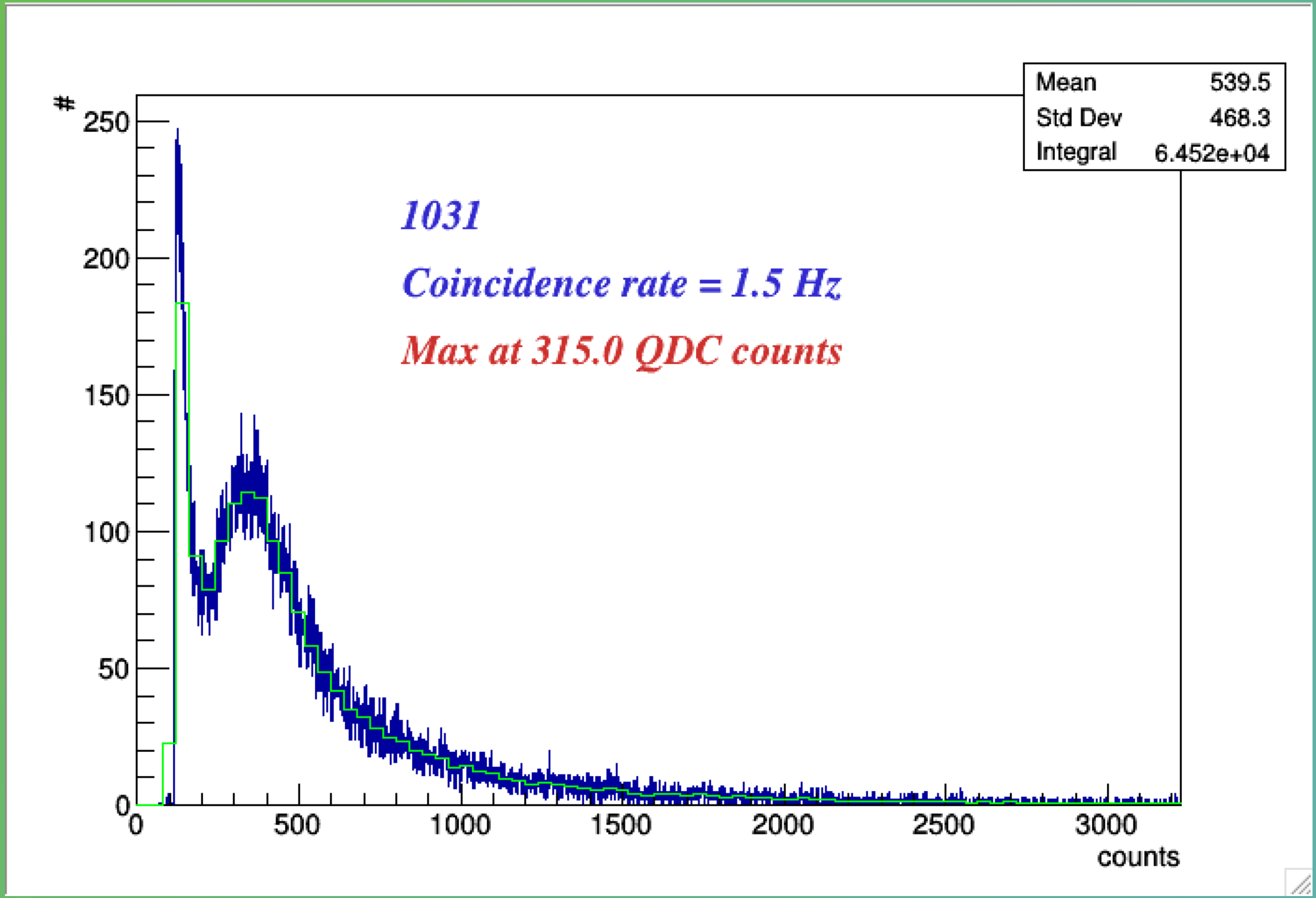
better resolution, but still not enough

Second step: calibration with cosmic rays in a different configuration

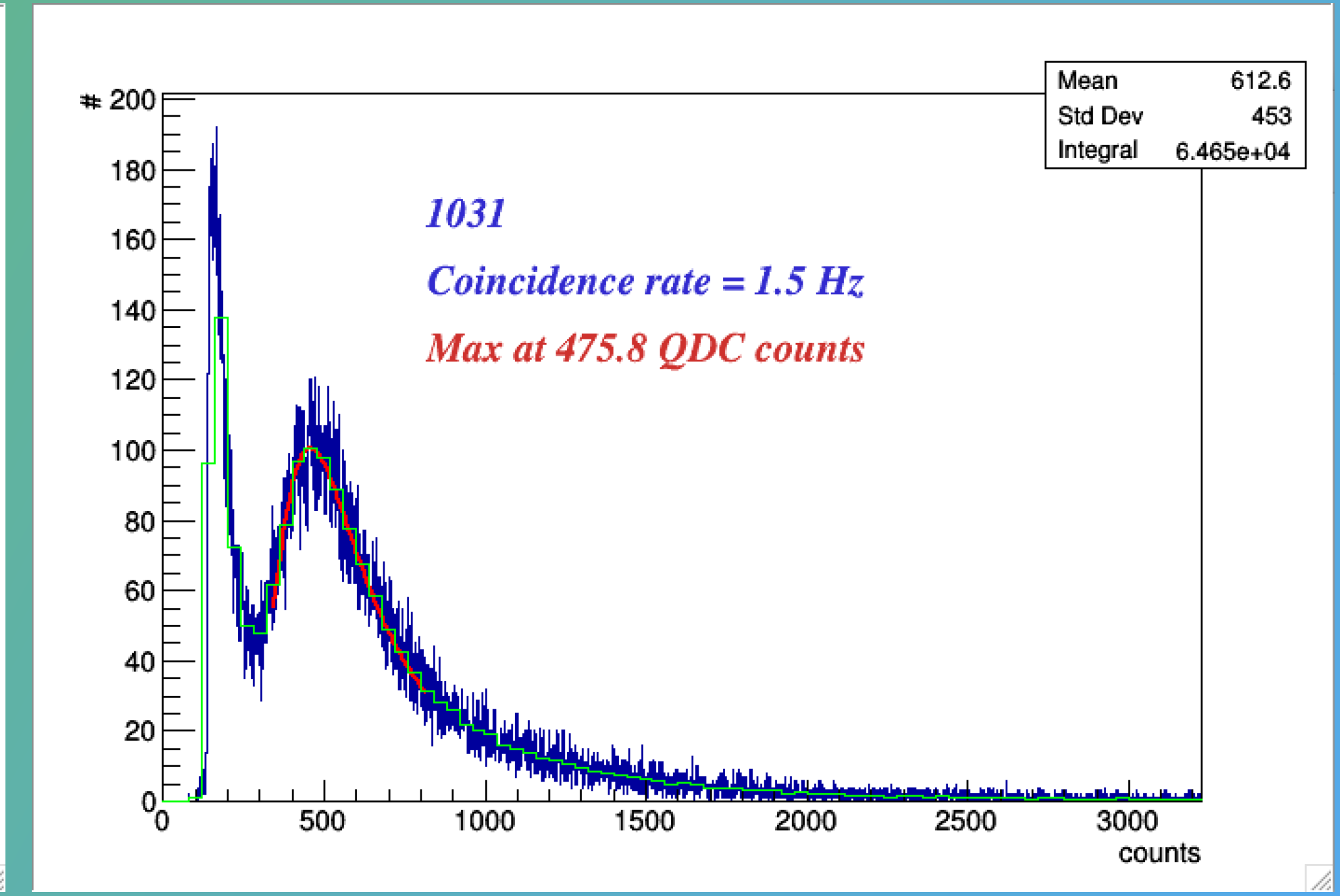


distribution of the integrated charge **in coincidence**

PMT 10

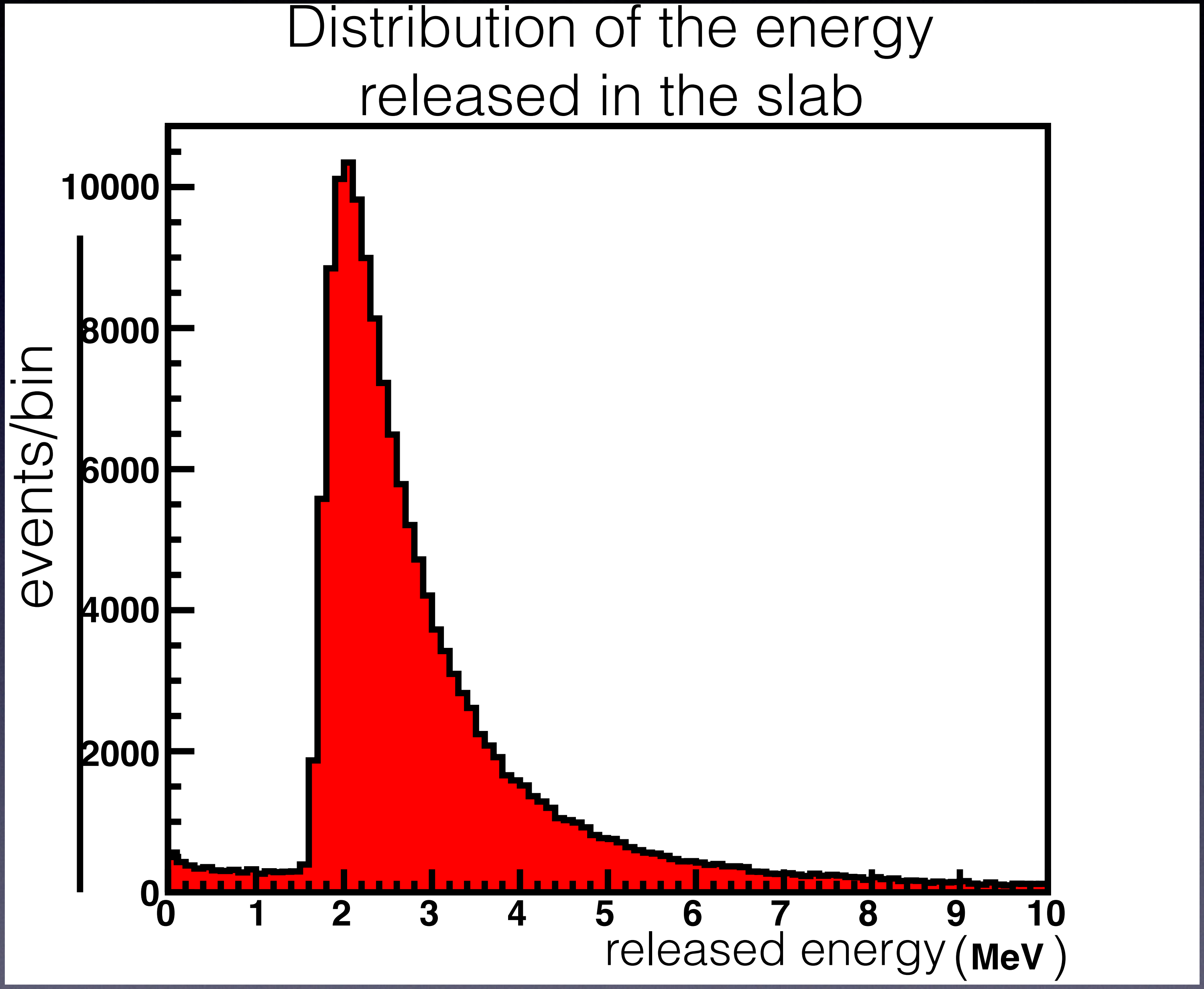


PMT 12



Monte Carlo simulation of cosmic rays

the full apparatus has been implemented in Geant4 via Geant4VMC



Deposited energy ~ 2 MeV/(gr cm^2)

Calibrations were perused to establish a correlation between released energy and signal amplitude

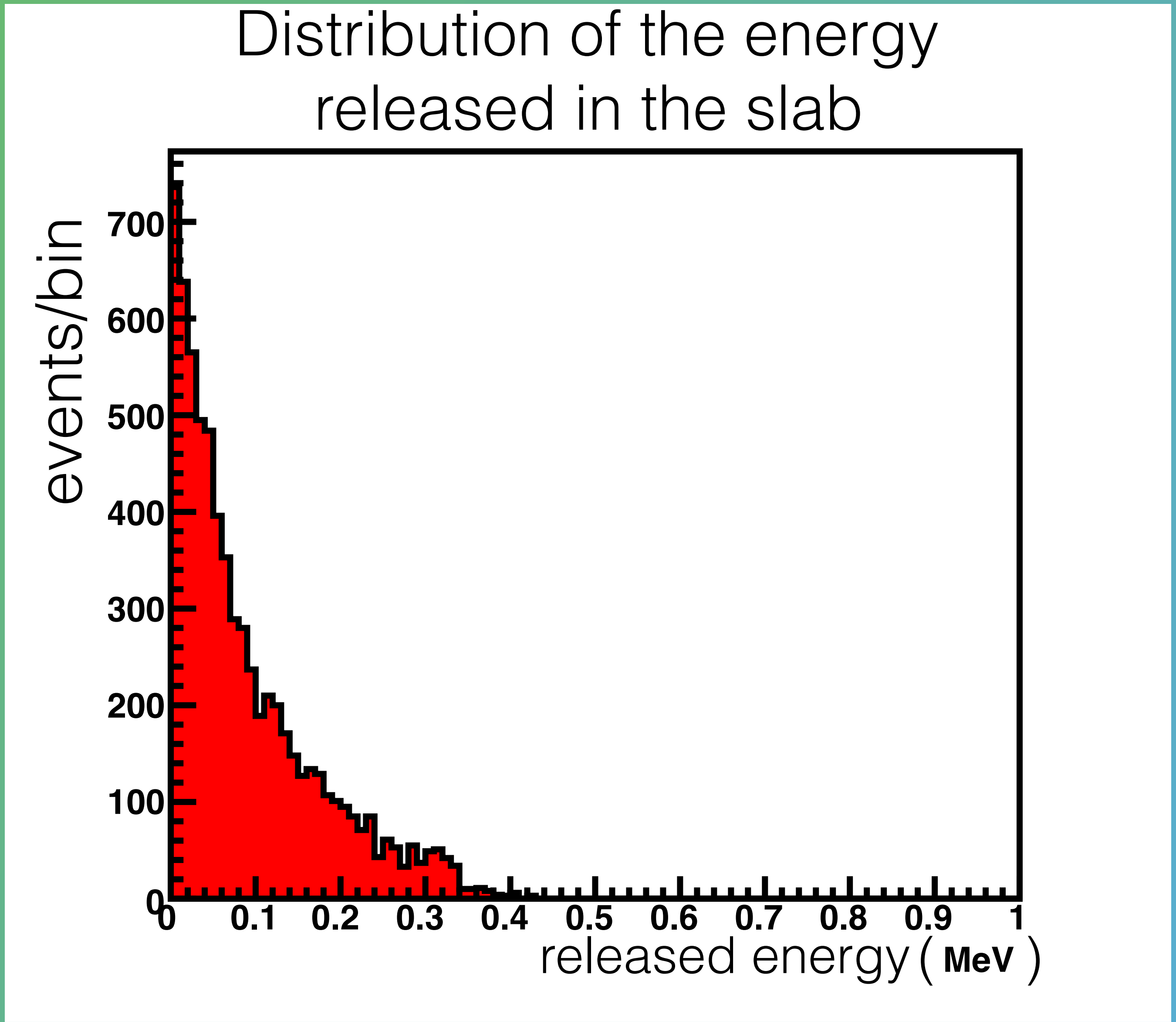
PMT	HV (volt)	QDC channel	cosmic peak position (QDC counts)			calibration constant (pC/MeV)
			uncorrected value	offset subtracted	corrected for QDC channel disuniformity	
1	2300	1	403 ± 3	333 ± 3	320 ± 3	15.9 ± 0.1
2	2300	1	313 ± 3	243 ± 3	233 ± 3	11.6 ± 0.1
3	2300	2	392 ± 3	344 ± 3	358 ± 3	17.8 ± 0.1
4	2300	2	268 ± 2	220 ± 2	229 ± 2	11.4 ± 0.1

Equalise the gain for all the PMTs

All calibration constants were brought to a value around 16 pC/MeV (within ~10%) (by changing the PMT HV)

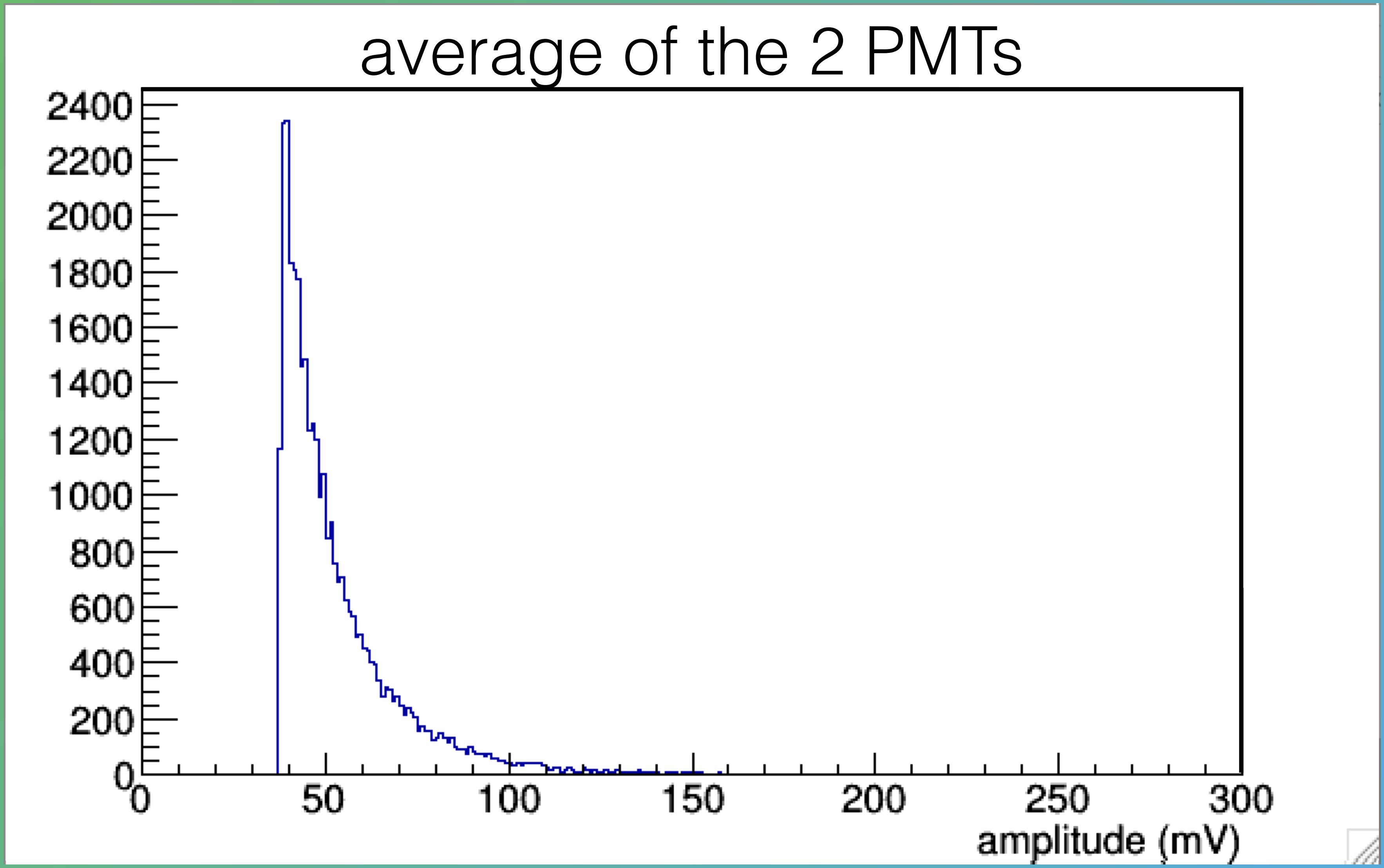
Use the average of the signals of the 2 PMTs connected to the same slab in order to have the best estimation of the energy released in that slab.

Monte Carlo simulation of positron annihilations

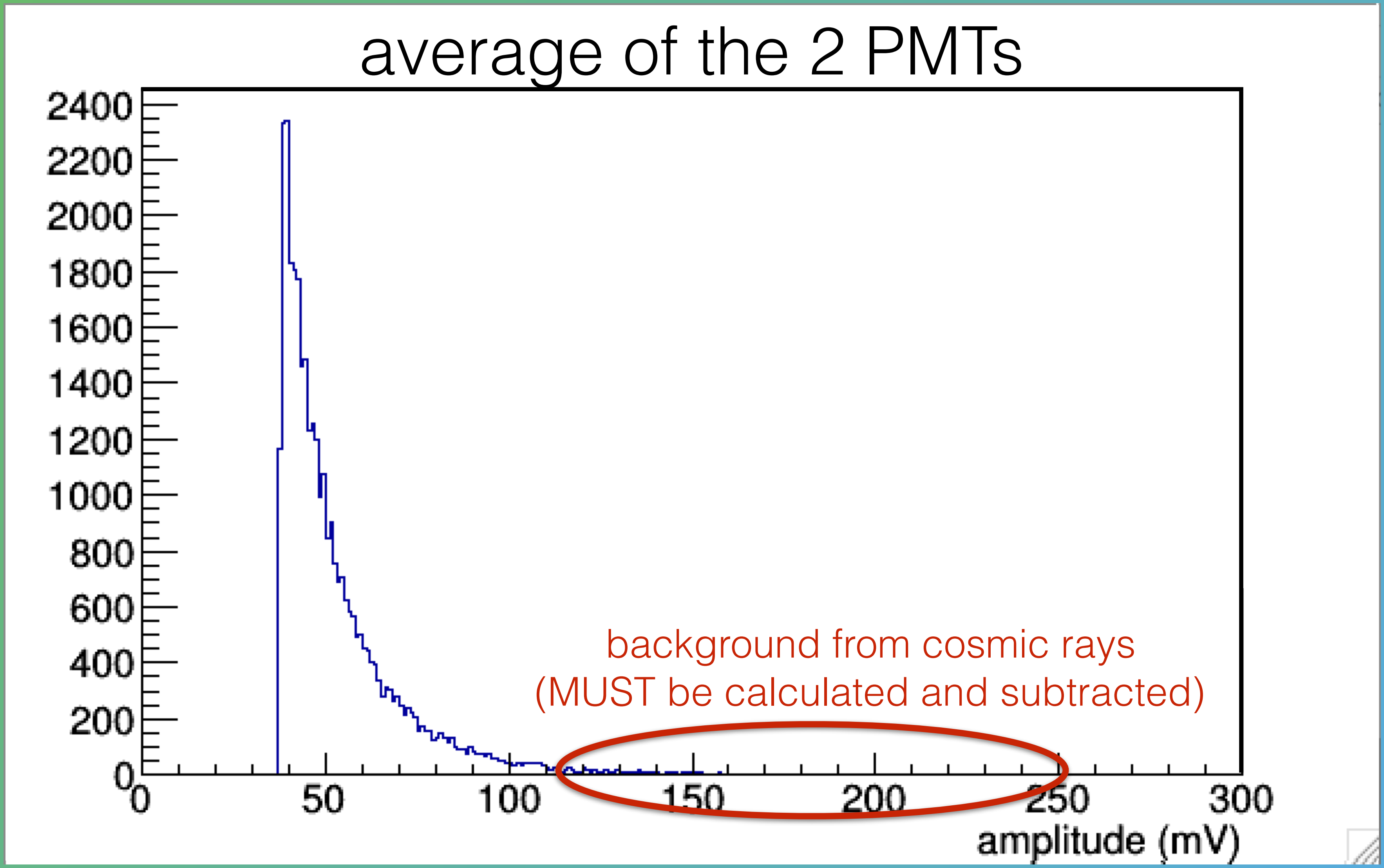


(pay attention to the scale that now is 10 times smaller)

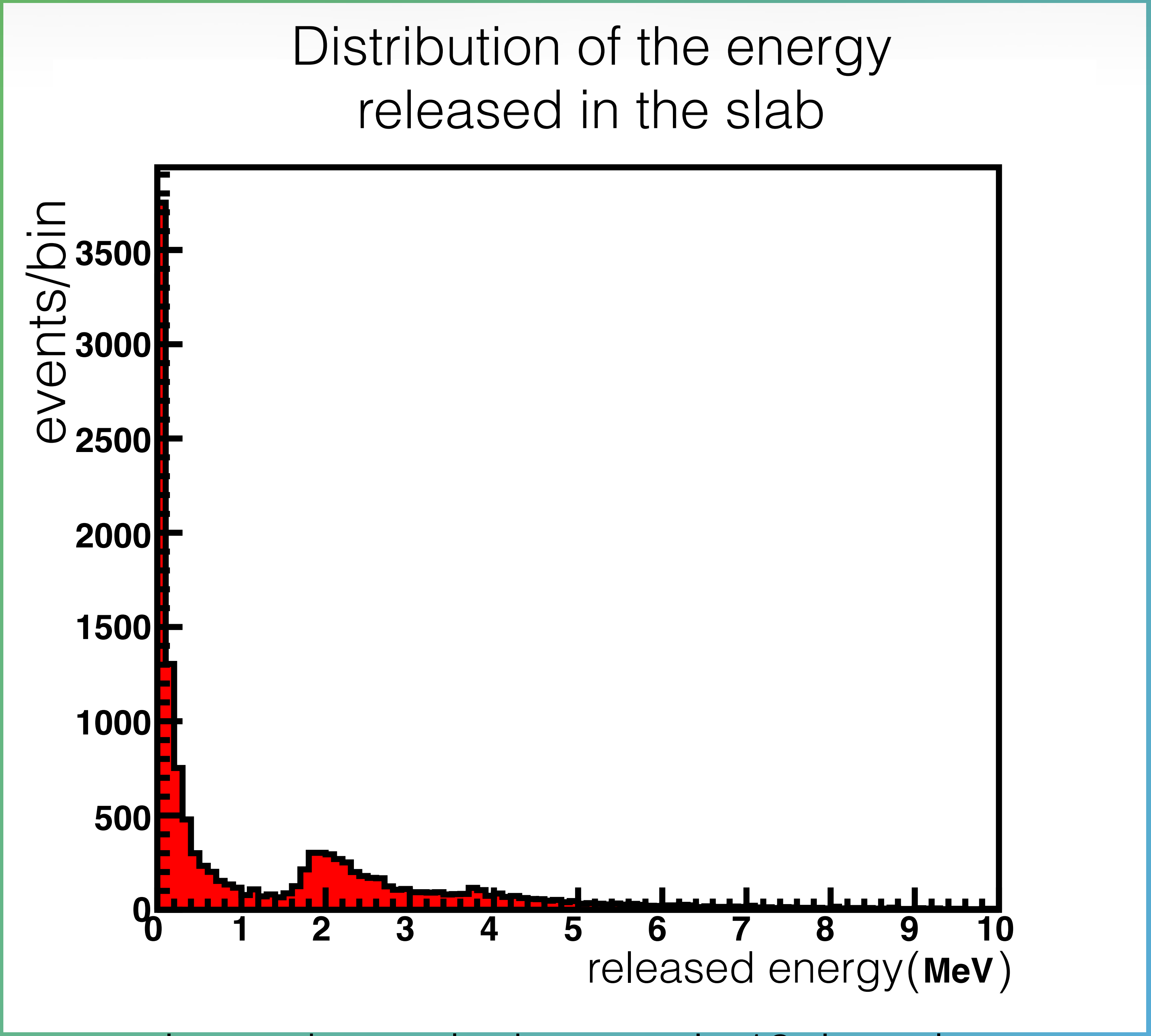
EXPERIMENTAL RESULTS for positron annihilations



EXPERIMENTAL RESULTS for positron annihilations

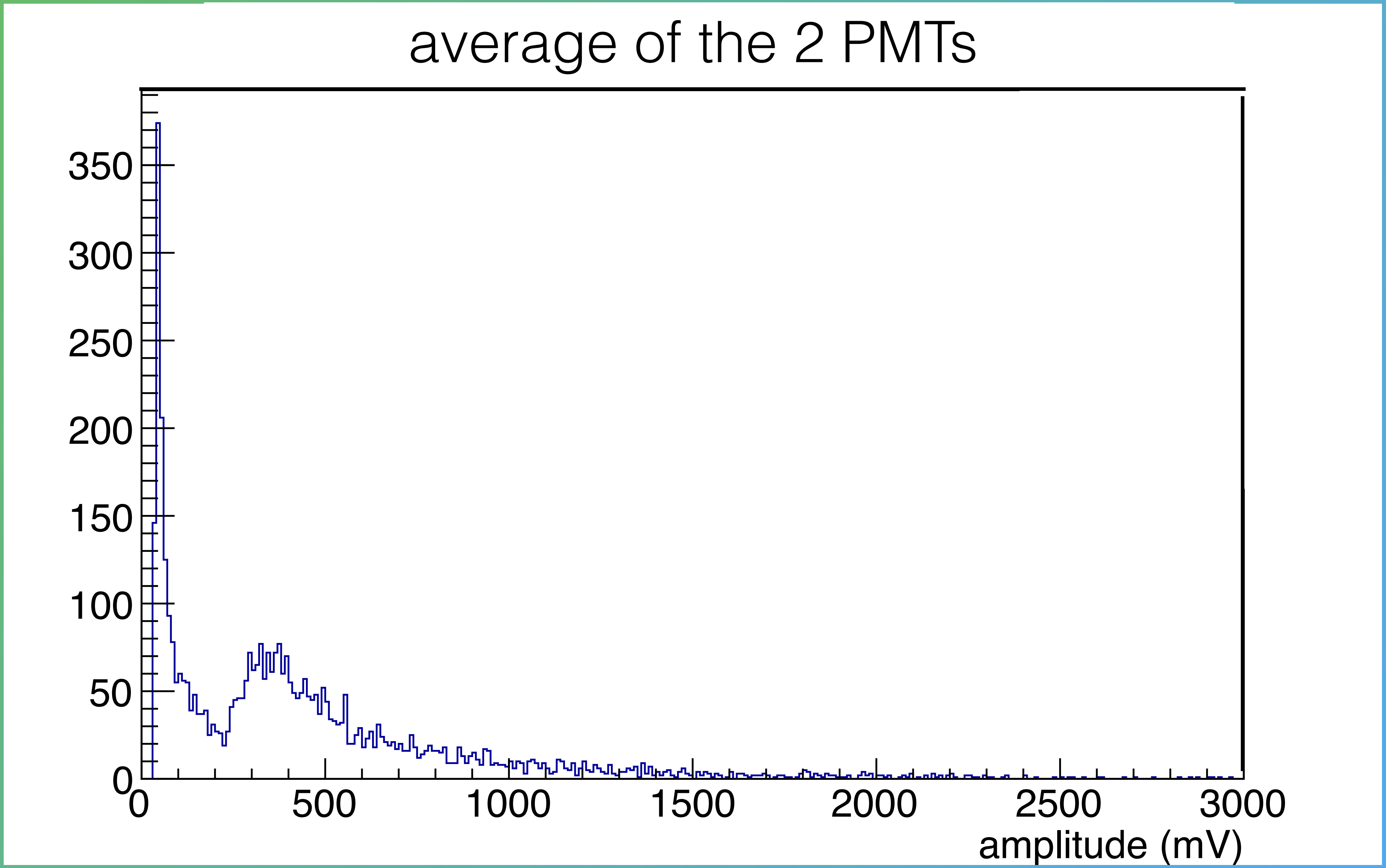


Monte Carlo simulation of antiproton annihilations

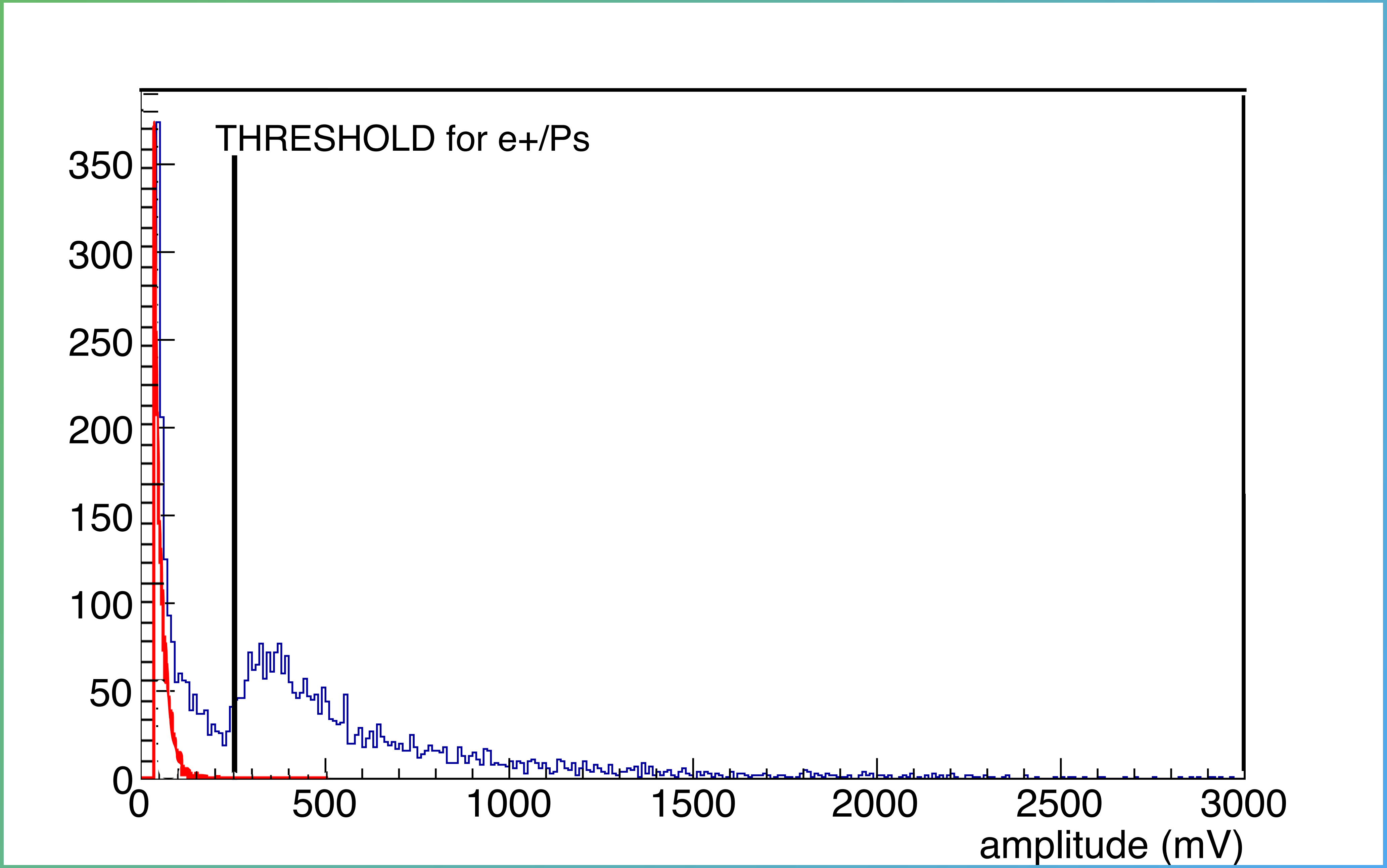


(pay attention to the scale that now is 10 times larger, again)

EXPERIMENTAL RESULTS - peak height for antiproton annihilations



EXPERIMENTAL RESULTS



Conclusions

- We have exploited our array of plastic scintillator slabs in order to identify signals generated by antiproton annihilations (or cosmic rays) and to univocally rule out the possibility that they were caused by positrons (or Ps)

- We have developed a calibration method for the PMTs which is reliable and robust and let us equalise the average gain within ~10%

- Collected data show excellent agreement with Monte Carlo simulations and a good linearity of the response of our detectors

Thank you for your attention!