Measurement of the muon Electric Dipole Moment

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- Sensitivity
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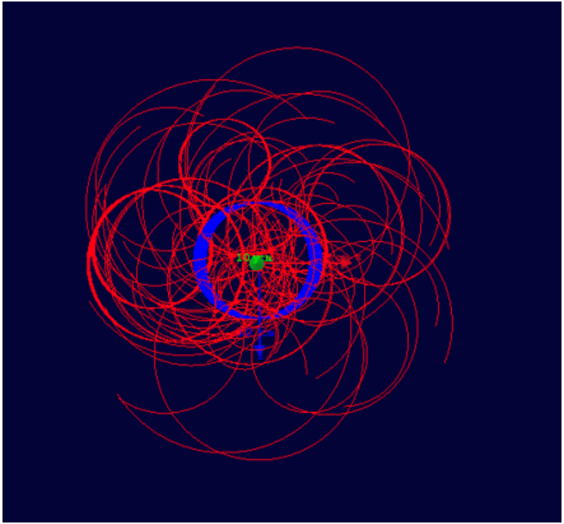
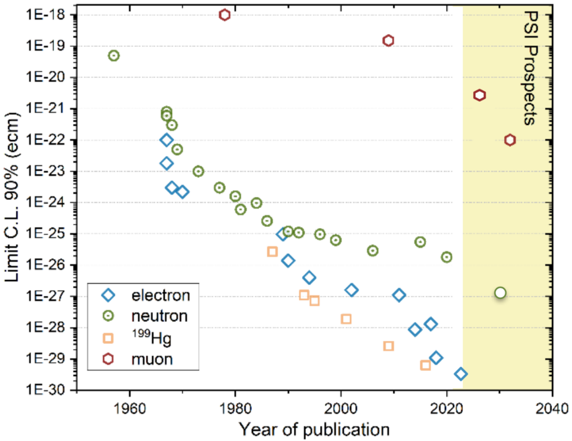
- Systematic effects
- Status (one example)
- Milestones and schedule

→ Some detail in the backup
  - Choice of the magnet
  - Magnetic pulse
  - Injection
  - ...

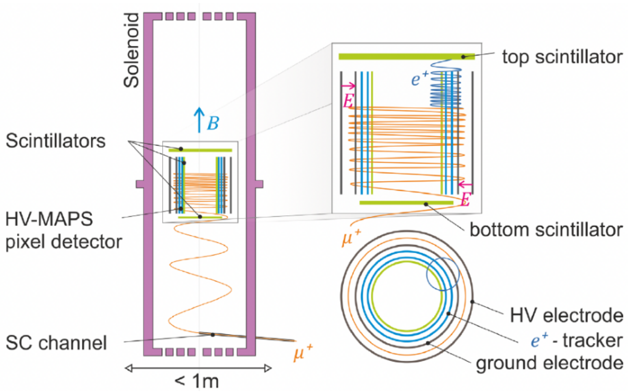


- Cornerstone of the SM is the delicate balance of symmetries and their breaking
- The known CP violation is insufficient to explain the matter-antimatter asymmetry
- EDM violate T and, invoking the CPT-theorem, also CP $\rightarrow$ BSM probes
- BSM hints suggest a flavor structure beyond minimal flavor violation (MFV)
  - In MFV a simple scaling by the ratio m_e/m_μ is predicted for the EDM



- 95% polarized μ^+ beam
- Superconducting shielded injection
- Muon *kicked* in a 'virtual' storage ring
  Achtung! Spiral injection needed
- Thin electrodes to freeze the spin
- Positron tracking after the decay
- 'Up-down' asymmetry is the observable
- g-2 direct limit[a] $d_\mu < 1.8 \times 10^{-19}\,\mathrm{e\,cm}$
  - Stronger indirect limit through d_e
- Aim is $6 \times 10^{-23}\,\mathrm{e\,cm}$ using *frozen spin*

[a] Bennett et al.,PRD80(2009)052008



Frozen-spin technique

- MDM and EDM describe the interaction of the spin with EM fields: $\hat{H} = -\mu\hat{\boldsymbol{\sigma}} \cdot \boldsymbol{B} - d\hat{\boldsymbol{\sigma}} \cdot \boldsymbol{E}$
- Thomas-BMT equation gives the precession of the spin

$$\boldsymbol{\Omega} = \boldsymbol{\Omega}_0 - \boldsymbol{\Omega}_c = \underbrace{\frac{q}{m}\left[a\boldsymbol{B} - \cancel{\frac{a\gamma}{\gamma+1}(\boldsymbol{\beta}\cdot\boldsymbol{B})\boldsymbol{\beta}} - \left(a + \frac{1}{1-\gamma^2}\right)\frac{\boldsymbol{\beta}\times\boldsymbol{E}}{c}\right]}_{\text{Anomalous procession, } \omega_a = \omega_L - \omega_c}$$

$$+ \underbrace{\frac{\eta q}{2m}\left[\boldsymbol{\beta}\times\boldsymbol{B} + \frac{\boldsymbol{E}}{c} - \cancel{\frac{\gamma c}{\gamma+1}(\boldsymbol{\beta}\cdot\boldsymbol{E}\boldsymbol{\beta})}\right]}_{\text{Interaction of EDM and relativistic } \boldsymbol{E},\ \omega_a}$$

- Taking $\boldsymbol{p} \perp \boldsymbol{B} \perp \boldsymbol{E}$ the equation is simplified
- Anomalous precession term can be set to zero taking $a\boldsymbol{B} = \left(a - \frac{1}{\gamma^2-1}\right)\frac{\boldsymbol{\beta}\times\boldsymbol{E}}{c}$

Frozen-spin technique

- If $\eta = 0$ the angle between p and spin is unchanged $\rightarrow$ 'frozen'
- In the presence of an EDM the change in polarization follows

$$\frac{\mathrm{d}\mathbf{\Pi}}{\mathrm{d}t} = \boldsymbol{\omega}_e \times \mathbf{\Pi} = \frac{2d_\mu}{\hbar}(\beta c \times \boldsymbol{B} + \boldsymbol{E}_f) \times \mathbf{\Pi}$$

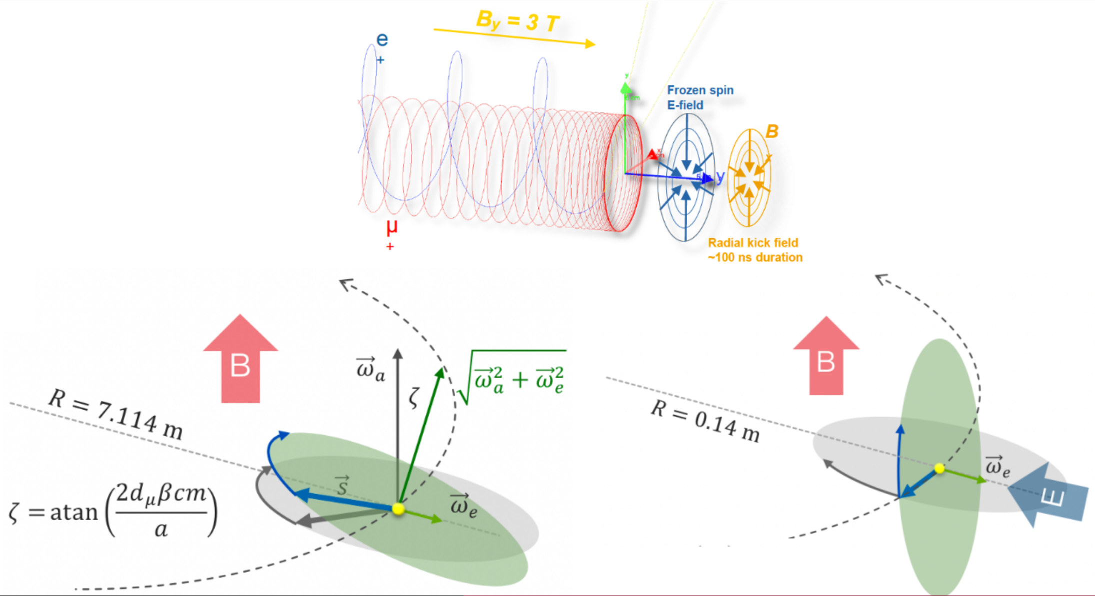
- The net result is a vertical build-up of the polarization $\rightarrow$ Direction of the positrons

$$|\mathbf{\Pi}(t)| = P(t) = P_0 \sin(\omega_e t) \approx P_0 \omega_e t \approx 2P_0 \frac{d_\mu}{\hbar} \frac{E_f}{a\gamma^2} t$$

Bring home message

Choosing an orthogonal $\boldsymbol{p} \perp \boldsymbol{B} \perp \boldsymbol{E}$ and the adequate $\boldsymbol{B}$, $\boldsymbol{E}$ fields the existence of EDM translates in a *time-dependent up-down* polarization which translates in an asymmetry in positrons direction

Let's try to visualize

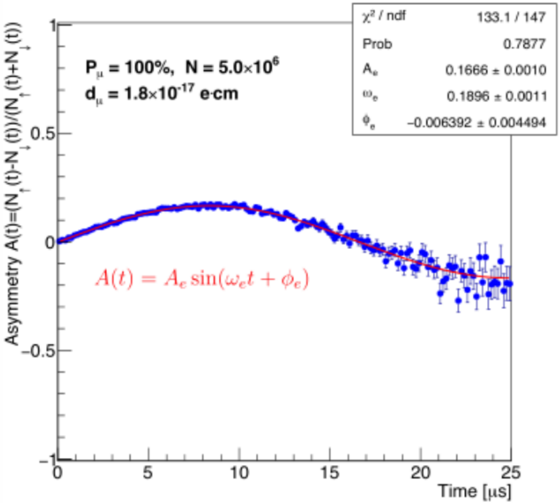


Sensitivity

- From the slope and introducing the mean decay asymmetry A

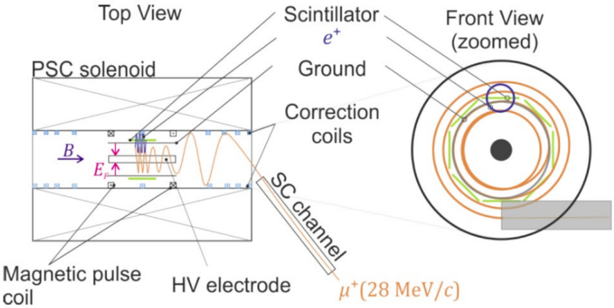
$$\frac{\mathrm{d}P}{\mathrm{d}d_\mu} = \frac{2P_0 E_\mathrm{f} t}{a\hbar\gamma^2} \rightarrow \sigma(d_\mu) = \frac{a\hbar\gamma}{2P_0 E_\mathrm{f}\sqrt{N}\tau_\mu A}$$

- Two scenarios are considered:
  - the first phase will use surface muons with $p \approx 28\,\mathrm{MeV/c}$ from πE1 $\rightarrow \sigma < 3 \times 10^{-21}$
  - the final setup will have higher muon flux and $p = 125\,\mathrm{MeV/c} \rightarrow \sigma < 6 \times 10^{-23}$



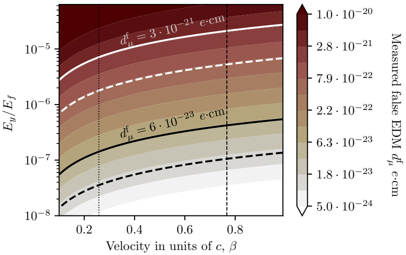
Why a Precursor?

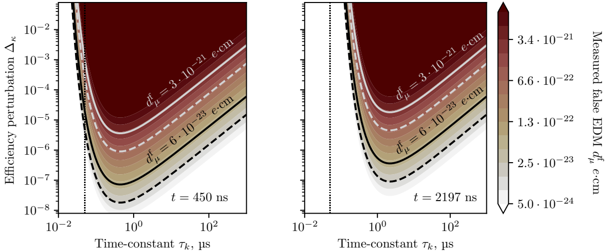
- Challenging experiment → Precursor
- Proof of concept(s):
  - Magnet uniformity
  - **Muon tagging insertion**
  - Injection magnetic shielding
  - Kicker and muon orbit stability
  - **Positron tracking**
  - Fine-tuning with g-2 measurement
  - ...debug
- Develop symmetries in the apparatus to reduce the systematics



Basically we need to demonstrate muons get to the right orbit: insertion and positron tracking

- Many effects lead to a real or apparent precession of the spin around the radial axis
  - Non-zero average longitudinal E-field
  - Presence of time-variable radial B-field
  - Electric field misalignments
  - Resonance between radial and longitudinal E-fields
  - Cyclotron and betatron oscillations beating and/or resonances
  - Early to late variation of of the positron detection efficiency
  - ...
- This requires a detailed study of the Thomas-BMT and crosscheck with the Geant4 spin-tracking package

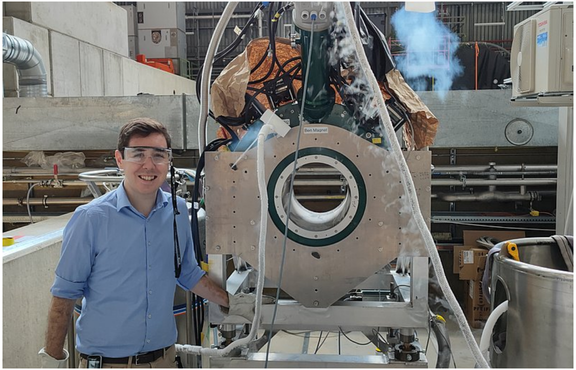




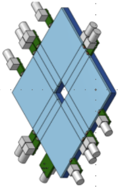
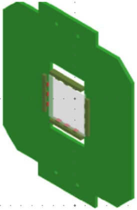
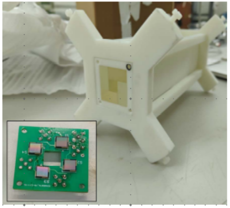
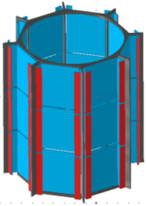
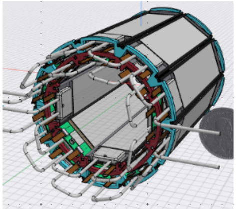
Systematics: summary

Systematic effect	Constraints	Phase I		Phase II	
		Expected value	Syst. ($\times 10^{-21}$ $e\cdot$cm)	Expected value	Syst. ($\times 10^{-23}$ $e\cdot$cm)
Cone shaped electrodes (longitudinal E-field)	Up-down asymmetry in the electrode shape	$\Delta_R < 30$ µm	0.75	$\Delta_R < 7$ µm	1.5
Electrode local smoothness (longitudinal E-field)	Local longitudinal electrode smoothness	$\delta_R < 3$ µm	0.75	$\delta_R < 0.7$ µm	1.5
Residual B-field from kick	Decay time of kicker field	< 50 ns	$< 10^{-2}$	< 50 ns	0.5
Net current flowing muon orbit area	Wiring of electronics inside the orbit	< 10 mA	$< 10^{-2}$	< 10 mA	0.3
Early-to-late detection efficiency change	Shielding and cooling of detectors	–		–	
Resonant geometrical phase accumulation	Misalignment of central axes	Pitch < 1 mrad Offset < 2 mm	2×10^{-2}	Pitch < 1 mrad Offset < 2 mm	0.15
TOTAL			1.1		2.2

Status



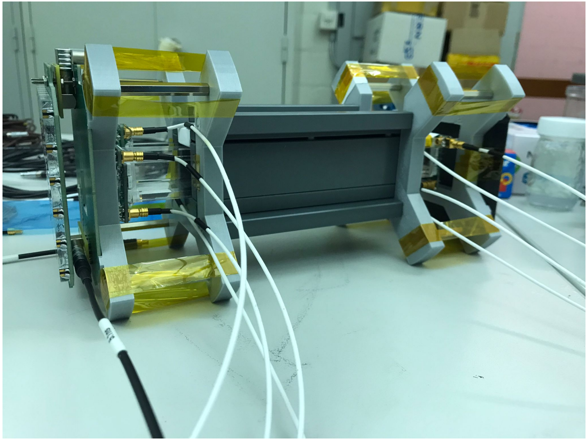
- Many items are still under development
  - Magnet choice
  - Injection channel
  - Magnetic kicker
  - Beam monitoring
  - Entrance trigger
  - Positron tracker
  - . . .
- . . . but we are making a lot of progress!

Entrance

We need something to trigger the magnetic kick

- Thin 'gate' scintillator as trigger and a thicker 'telescope' as veto
- *Geant4* and *musrSim* simulations
- Two prototypes of the 'telescope' with different specs were tested in Oct. 2022



Bring home message

The entrance scintillator is used as trigger but needs to preserve the qualities of the beam

- Thinner than 100 μm
  $\rightarrow$ Reduce multiple scattering
- Read with **and** of 2/4 sides
  $\rightarrow$ Low th. and suppress thermal noise

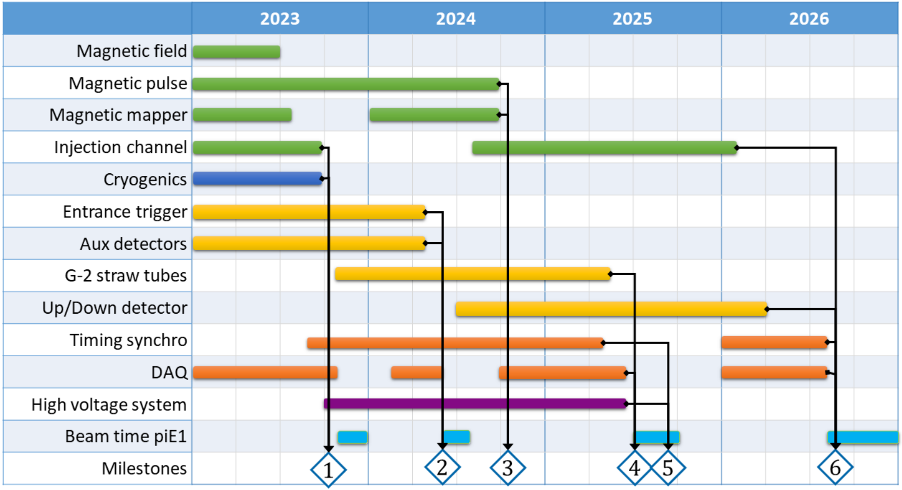
Milestones

- Top-level tasks and milestones:
  - M1 Demonstration of off-axis injection
  - M2 Muon selection and generation of trigger
  - M3 Application of pulsed magnetic field and measurement of eddy-currents
  - M4 Stopping of muons and detection of $(g-2)$-precession
  - M5 Adjust electric field by tuning $(g-2)$-precession to zero
  - M6 Data-taking in muon EDM mode

- Tasks for Phase-II:
  - Conceptional design
  - Technical design
  - Purchasing and production

We plan an engineering run of 100 days, followed by a data production run of 200 days to accomplish a statistical sensitivity of better than $\sigma \leq 6 \times 10^{-23}$

‘Short’ term schedule



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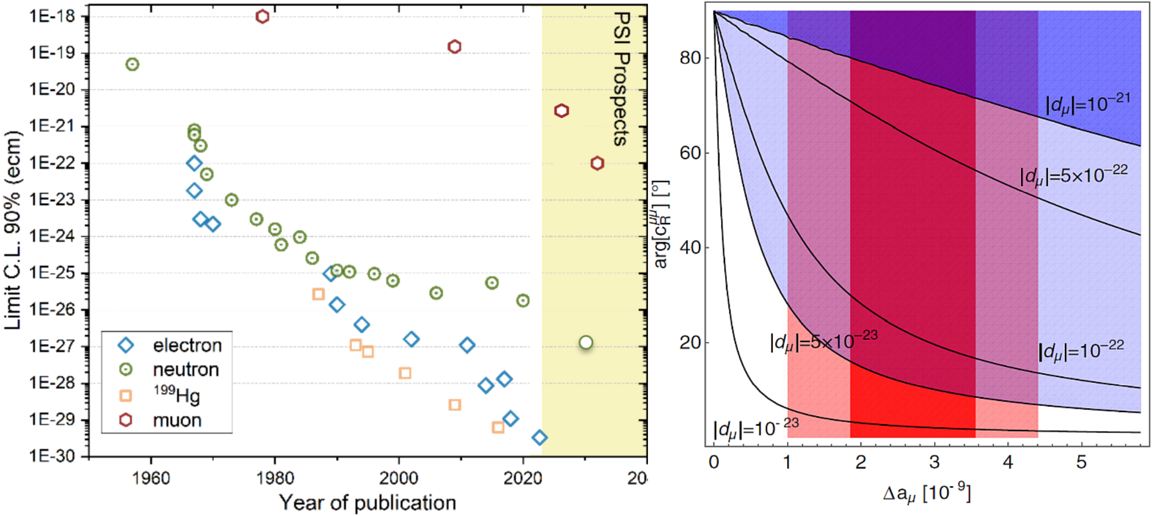
Backup: EDM history and muEDM potential

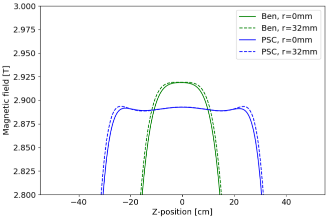


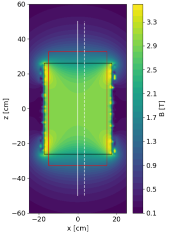
Backup: Sensitivity

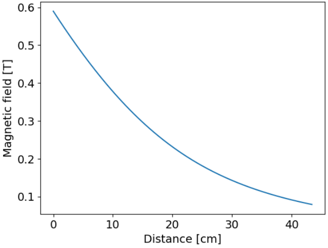
	πE1	μE1
Muon flux (μ^+/s)	4×10^6	1.2×10^8
Channel transmission	0.03	0.005
Injection efficiency	0.017	0.60
Muon storage rate (1/s)	2×10^3	360×10^3
Gamma factor γ	1.04	1.56
e^+ detection rate (1/s)	500	90×10^3
Detections per 200 days	8.64×10^9	1.5×10^{12}
Mean decay asymmetry A	0.3	0.3
Initial polarization P_0	0.95	0.95
Sensitivity in one year ($e{\cdot}$cm)	$<3 \times 10^{-21}$	$< 6 \times 10^{-23}$

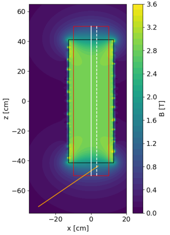
- Injection and stable orbit require deep knowledge of the B field
  - ANSYS simulations
  - B field mapping
  - Lenght/width of the bore
- Strenght and shape of the weakly focusing field is cardinal
- Two options for Phase I

	PSC	Ben
Max B-Field /T	5	4
Persistent mode	yes	no
Solenoid length /mm	1000	650
Bore diameter /mm	200	300
Time trigger to pulse /ns	145	na





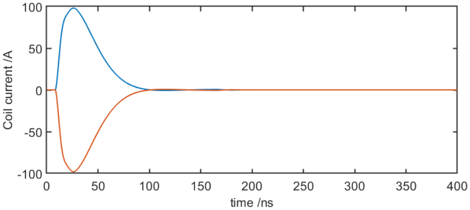


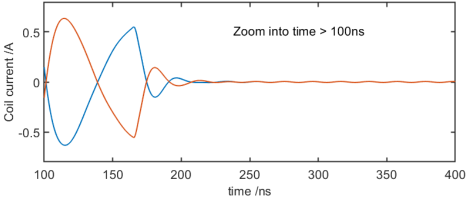


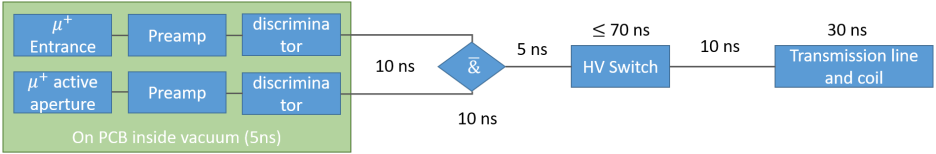
Backup: Magnetic pulse

The muons would spiral through the whole system
→ Magnetic pulse needed to store them

- Quadrupole to balance the longitudinal B created with counterpropagating circular coils
- Triggered by the entrance detector
- Needs to be fast and precise
  - Quick reaction from the trigger
  - Fast rising time
  - Short pulse lenght
  - Pulse ringing 'small as possible'

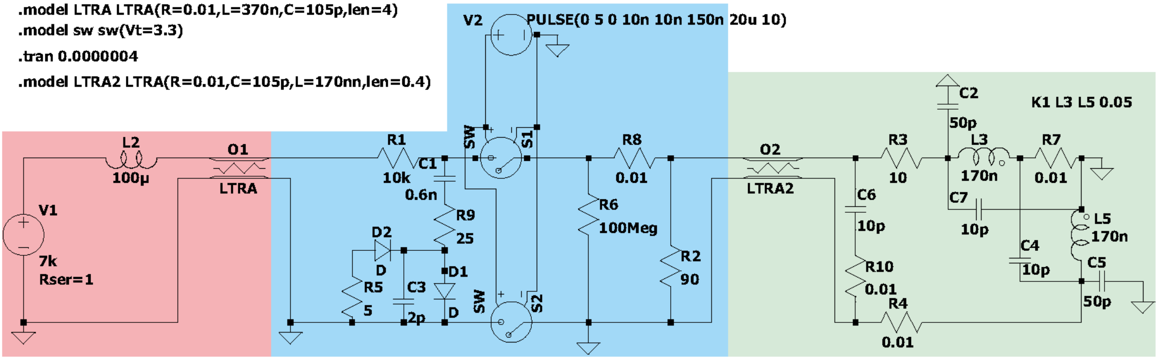




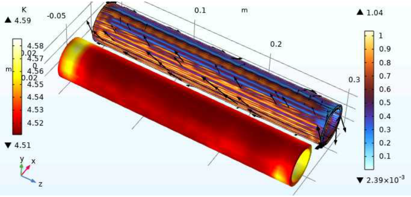


Backup: Magnetic pulse circuit

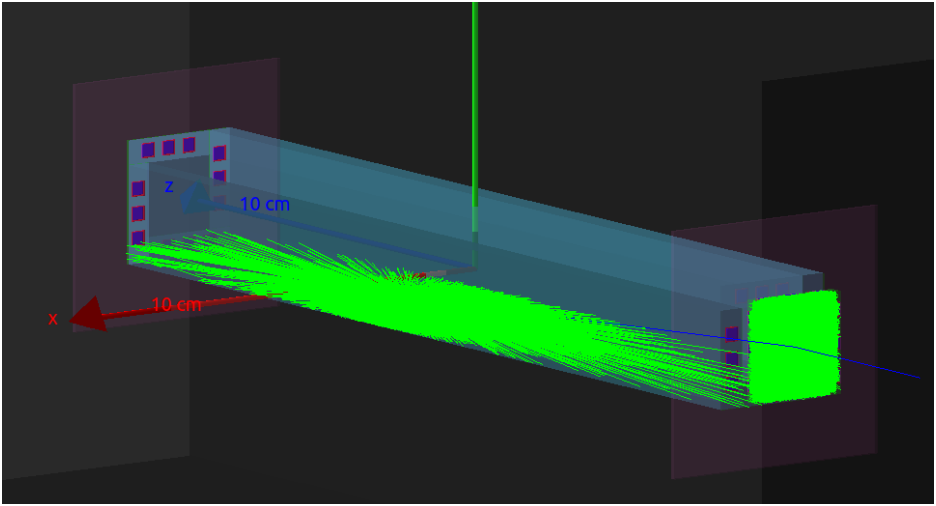
First prototype of the coils was built and is under study
Here a preliminary LTspice design of the pulse circuit



- Superconducting shielding for injection
  - Current induced if $T < T_c$ when ramping the magnet
  - Nb-Ti/Nb/Cu and HTS shielding
  - Simulations and tests are ongoing
- Symmetric injection(s) to cancel/reduce some of the systematics

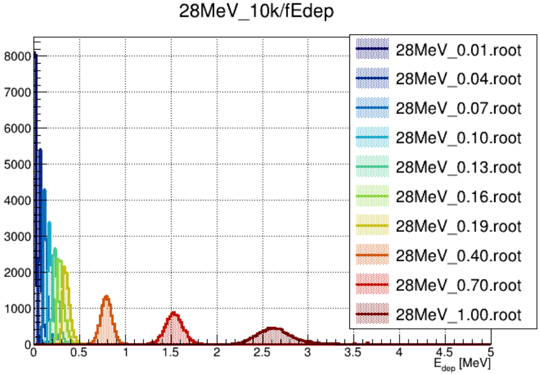


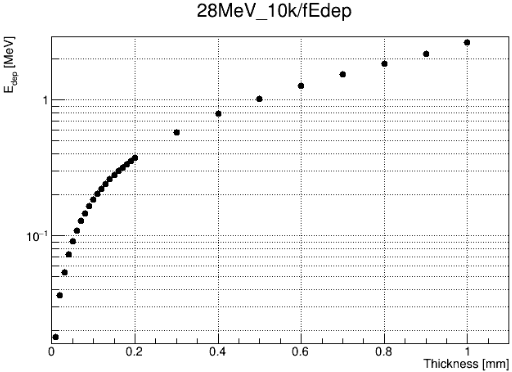
Backup: The insertion system in GEANT4



Backup: The insertion system in GEANT4

- Simulated both momenta varying the thickness of the *gate*

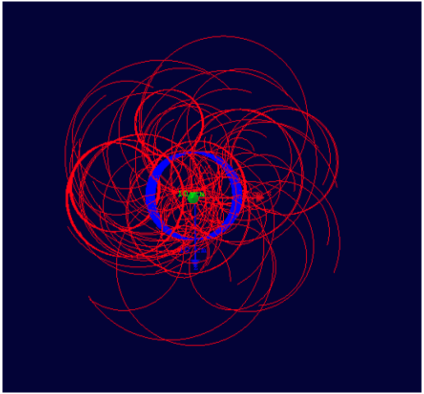




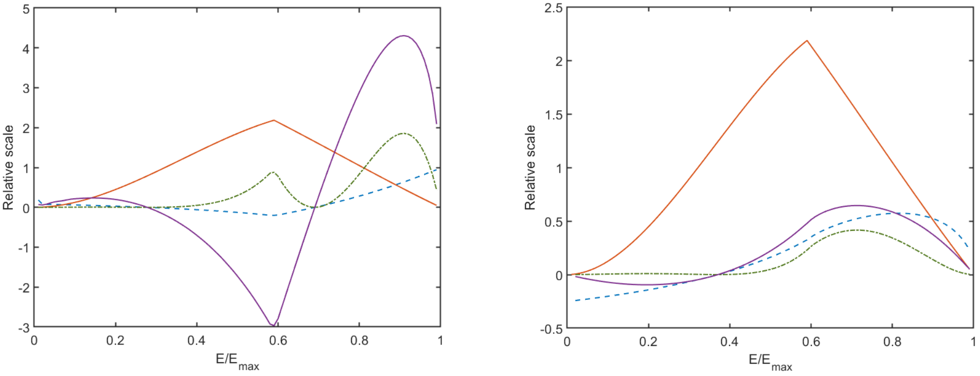
Backup: Positron reconstruction

To assess a stable muon orbit we need to detect and trace back the positrons

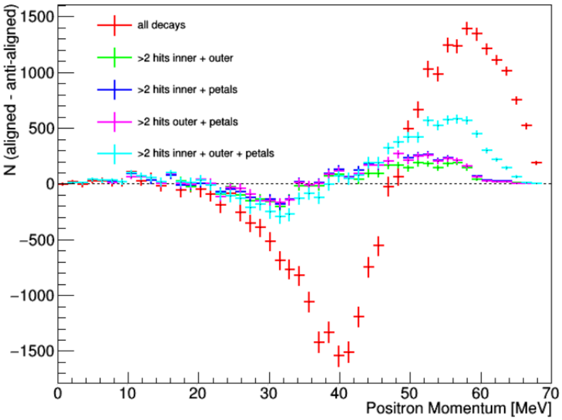
- Slightly ifferent shape of the tracks for the two phases of the experiment
- We are not interested in all the positrons some bring more information than others
- Scintillating transverse fibers for the longitudinal position (up/down spiral) + silicon strip detectors/fibers

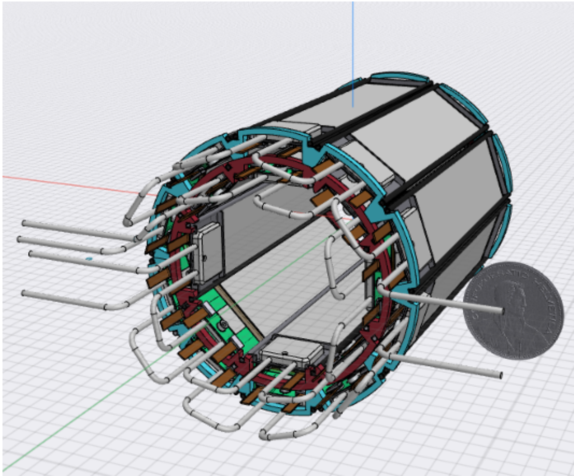


MDM on the left, EDM on the right.
Normalized positron energy spectrum (Red), Asymmetry α (Blue dashed), $\alpha^2 N$ (Green dot-dashed) and $\alpha\sqrt(N)$ (Purple)

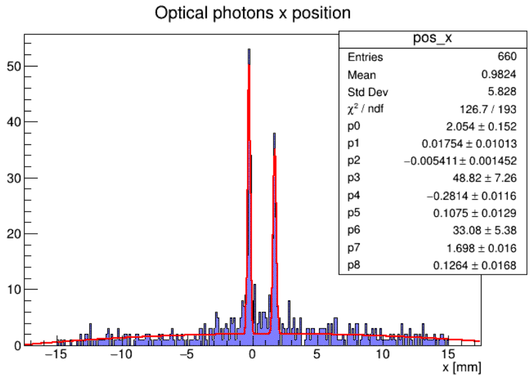


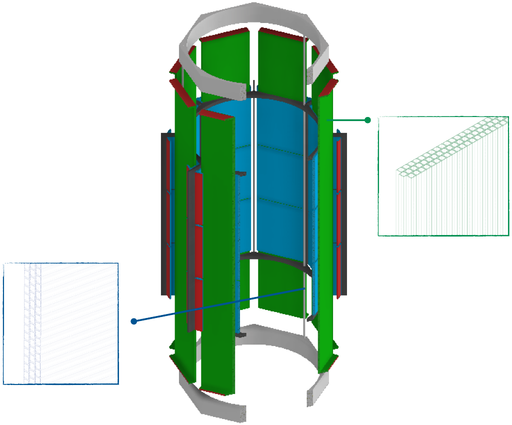
Backup: Tracker

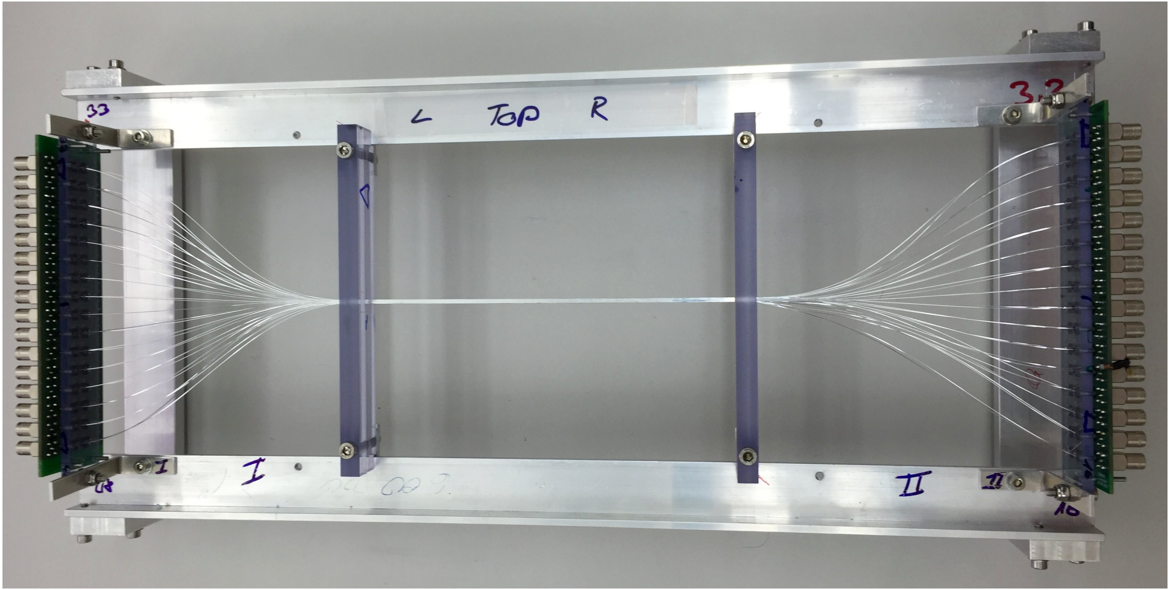




Backup: Tracker



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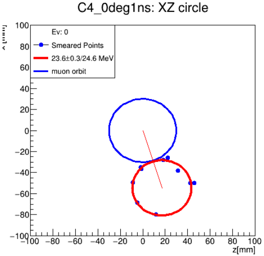
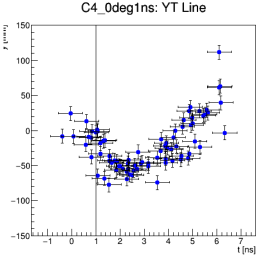
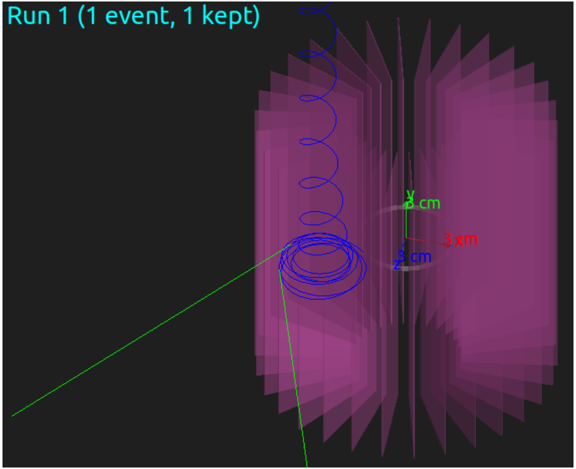
Backup: Positron tracking

- μ^+ orbit's radius $\approx 3\,\text{cm}$ (28 MeV)
- e^+ radius of similar size [25,82] MeV
  - Mainly 'backward' tangent decay due to the beam polarization
- Required resolution $\sim$ mm
- Straw-tubes and/or SciFi scintillator







Backup: 'Long' term schedule