The Muon g-2 Experiment at Fermilab: measuring the magnetic field

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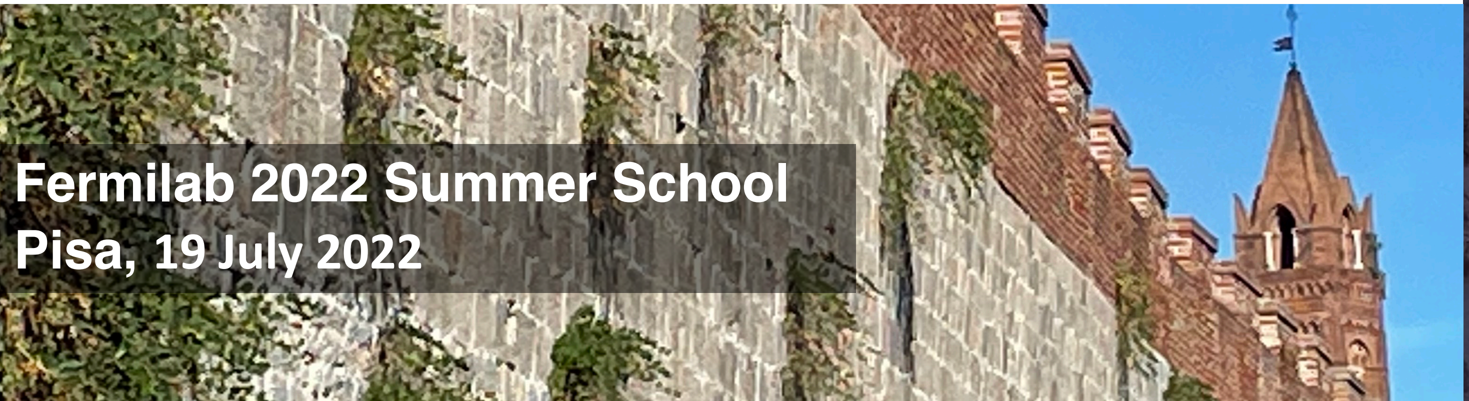
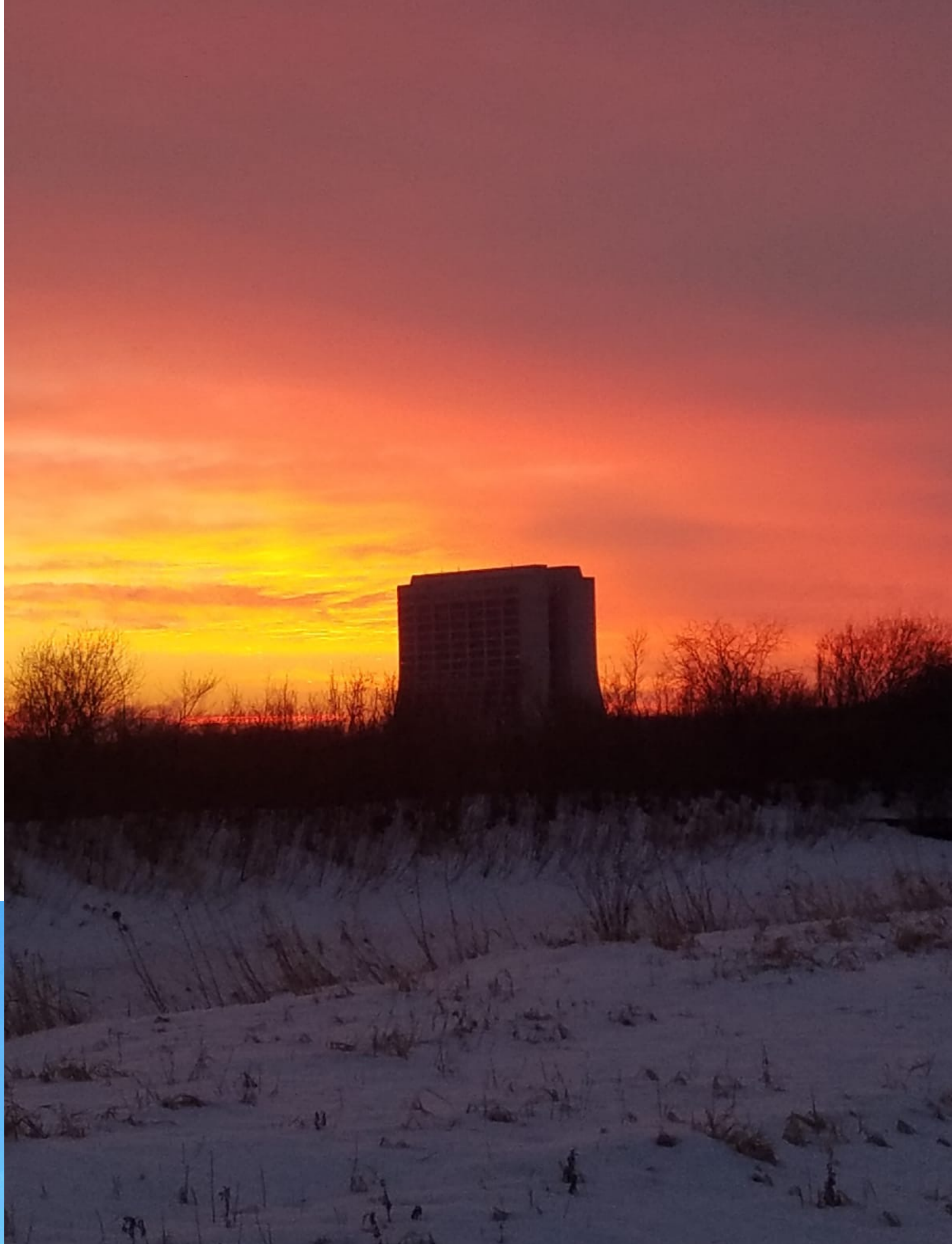




Fermilab Muon g-2 Experiment

Muon anomaly is determined with:

$$a_\mu = \boxed{\frac{\omega_a}{\tilde{\omega}'_p(T_r)}} \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

ratio of frequencies (R_μ) measured by us

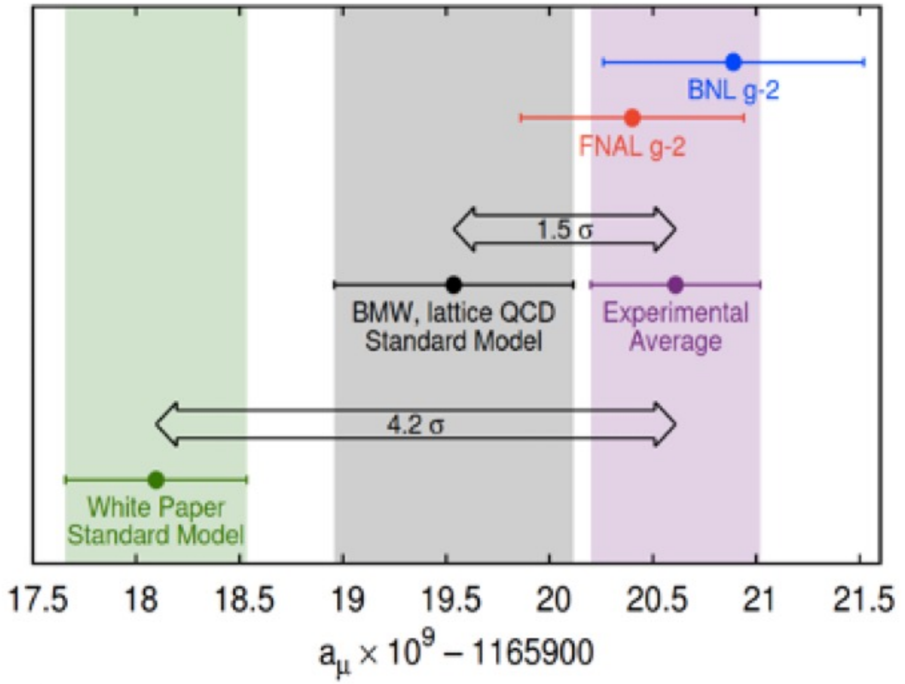
fundamental factors (combined uncertainty 25 ppb):

$\mu'_p(T_r)/\mu_e(H)$ from [Metrologia **13**, 179 (1977)]

$\mu_e(H)/\mu_e$ from [Rev. Mod. Phys. **88** 035009 (2016)]

m_μ/m_e from [Phys. Rev. Lett. **82**, 711 (1999)]

$g_e/2$ from [Phys. Rev. A **83** 052122 (2011)]



Paolo

ω_a: muon anomalous precession frequency

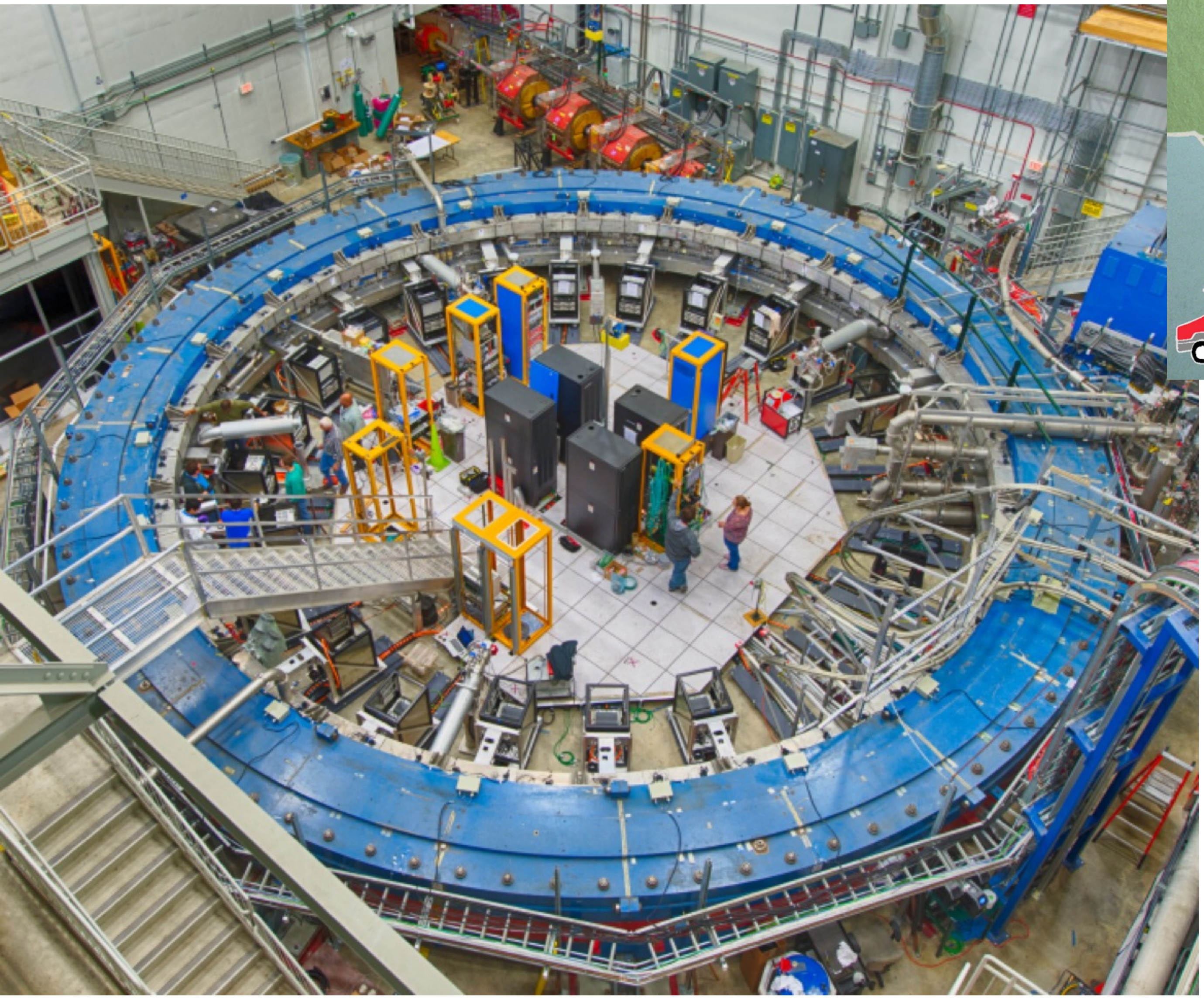
Lorenzo ed Elia

$\tilde{\omega}'_p(T_r)$: magnetic field B in terms of (shielded) proton precession frequency **and** weighted by the muon distribution

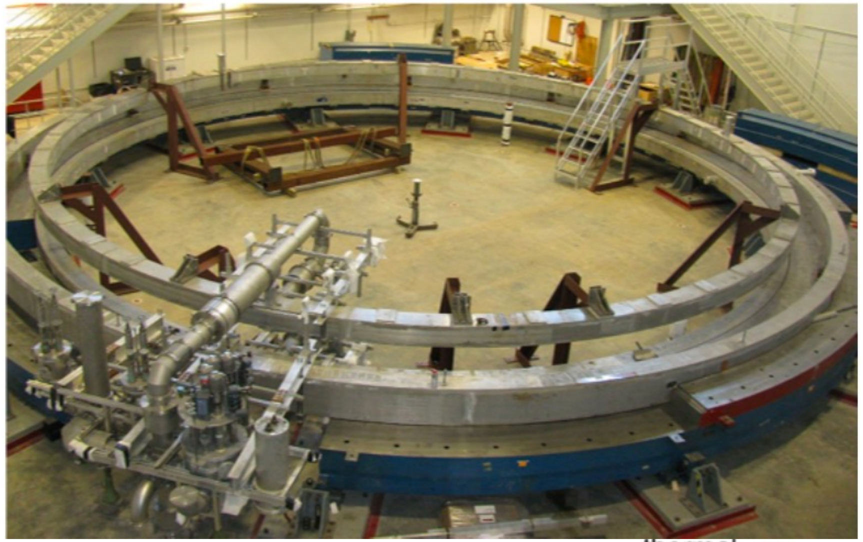
(shielded = measured in a spherical water sample at the reference temperature T_r = 34.7 °C)

In questo talk

The Muon g-2 Storage Ring

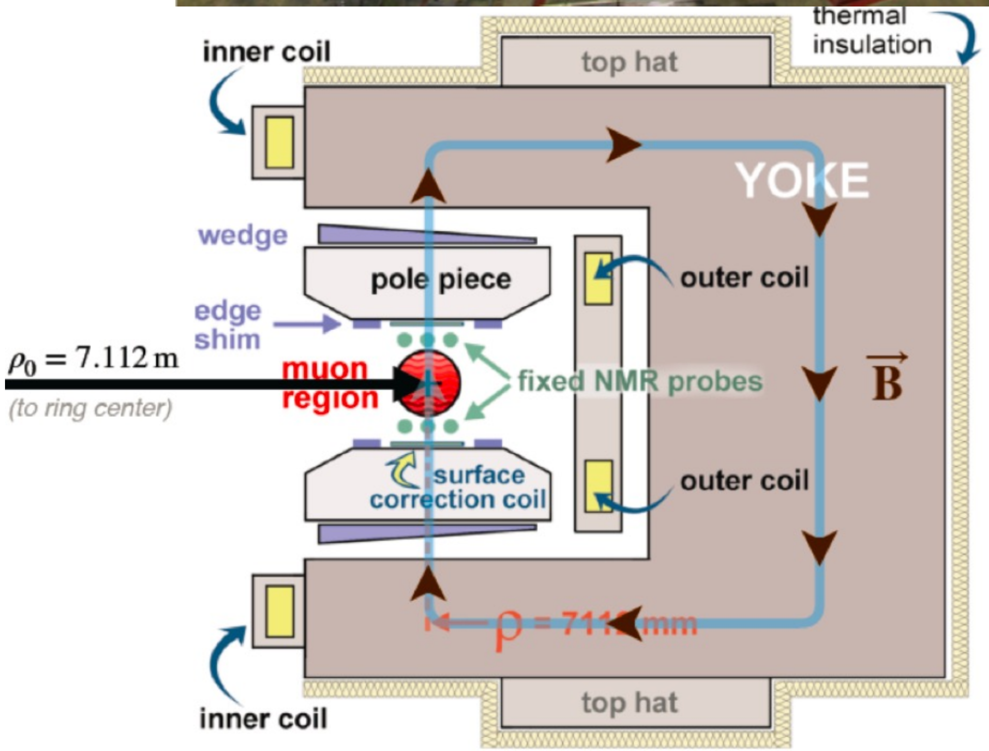


The Muon g-2 Superconducting C shaped magnet



Provides 1.45T vertical and uniform B field:

- **12 iron Yokes**: open on the inside to allow positrons from muon decay to reach the detectors and excited by superconducting coils made of Niobium-Titanium in a Copper matrix
- **72 low-carbon steel poles**: to minimize impurities
- **144 Edge shims**: local sextupole field minimized by changing edge shim thickness
- **864 Steel wedges**: allowed for angle adjustment (compensate quadrupole component) and radial adjustment (shim local dipole field)
- **Surface correction coil**: help to reduce non-uniformities on field higher moment



Fermilab: ~15 ppm RMS (~75 ppm peak-to-peak)
BNL E821: ~35 ppm RMS (~200 ppm peak-to-peak

Achieved ~3x better field uniformity than at BNL

We measure the ratio of two frequency!

f_{clock} : blinded clock
ω_a^{meas} : measured precession frequency

Lorenzo

Elia

C_e : electric field correction
C_p : pitch correction
C_{ml} : muon loss correction
C_{pa} : phase-acceptance correction

ω_a — beam dynamics corrections

$$R_\mu = \left(\frac{\overbrace{f_{clock} \cdot \omega_a^{meas}}^{\omega_a} \cdot \overbrace{(1 + C_e + C_p + C_{ml} + C_{pa})}^{\text{beam dynamics corrections}}}{\underbrace{f_{calib} \cdot \omega'_p(x,y,\phi) \otimes M(x,y,\phi)}_{\tilde{\omega}'_p(T_r)} \cdot \underbrace{(1 + B_k + B_q)}_{\text{field corrections}}} \right)$$

Paolo

$\tilde{\omega}'_p(T_r)$ — In questo talk — field corrections

f_{calib} : absolute magnetic field calibration
$\omega'_p(x,y,\phi)$: field maps
$M(x,y,\phi)$: muon beam distribution

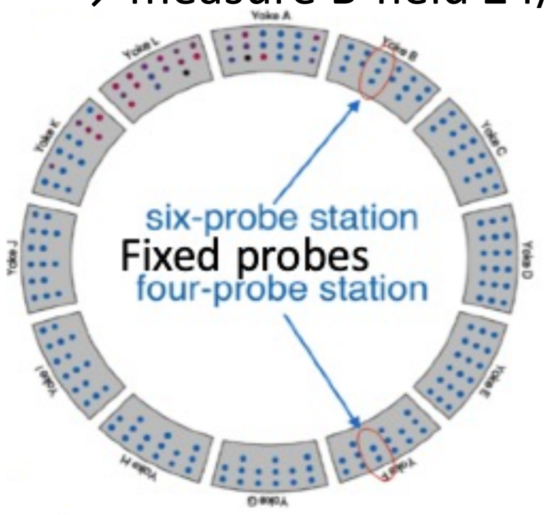
B_k : transient field from eddy current in kicker
B_q : transient field from quad vibration

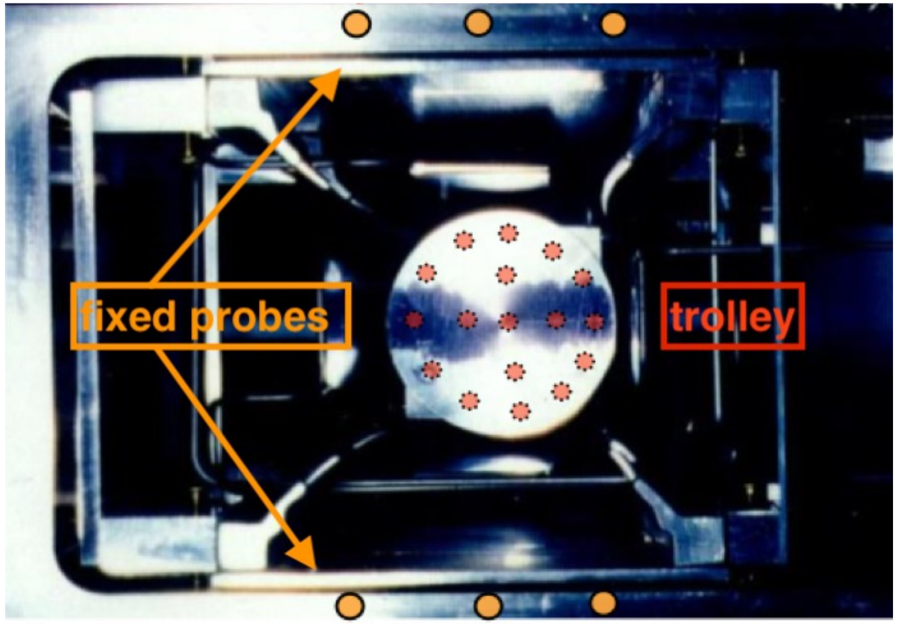
The Field Maps

$$R_\mu = \left(\frac{f_{clock} \cdot \omega_a^{meas} \cdot (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib} \cdot \omega'_p(x, y, \phi) \otimes M(x, y, \phi) \cdot (1 + B_k + B_q)} \right)$$

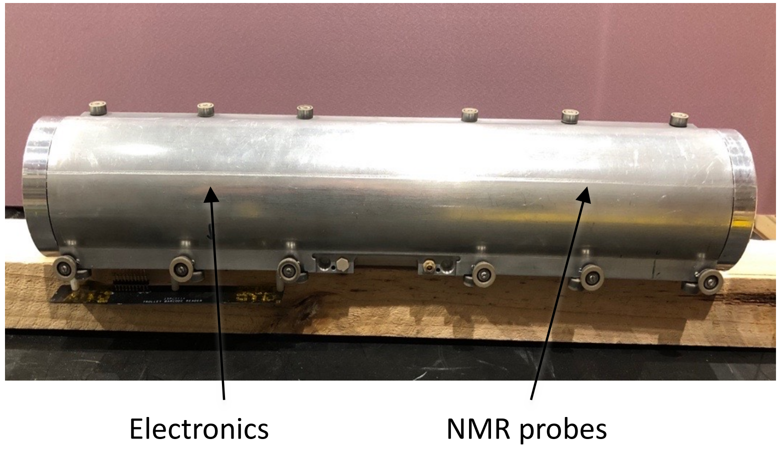
2 types of field probes

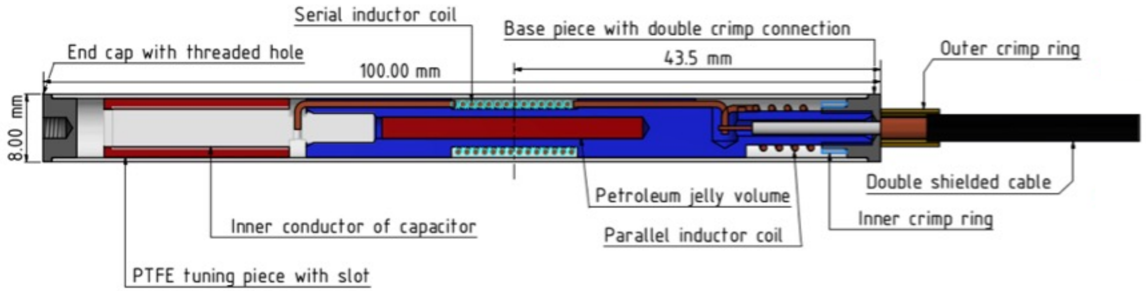
- 378 fixed NMR probes above and below storage region
  → measure B-field 24/7





- Trolley with 17-probe NMR
  → 2D profile of B over the entire azimuth when beam is OFF





Pulsed proton Nuclear Magnetic Resonance (NMR) probes filled with petroleum jelly

The Field Maps

$$R_\mu = \left(\frac{f_{clock} \cdot \omega_a^{meas} \cdot (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib} \cdot \omega'_p(x,y,\phi) \otimes M(x,y,\phi) \cdot (1 + B_k + B_q)} \right)$$

2 types of field probes

- 378 fixed NMR probes above and below storage region
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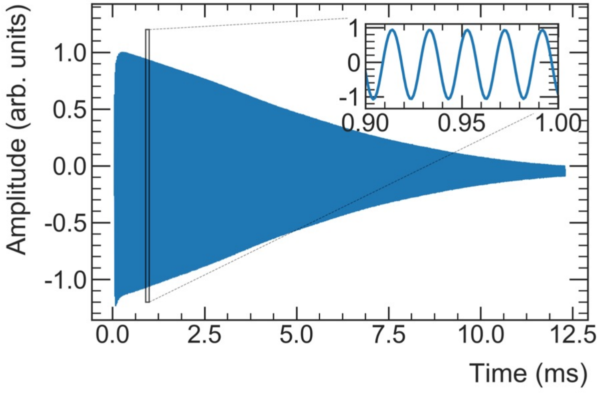
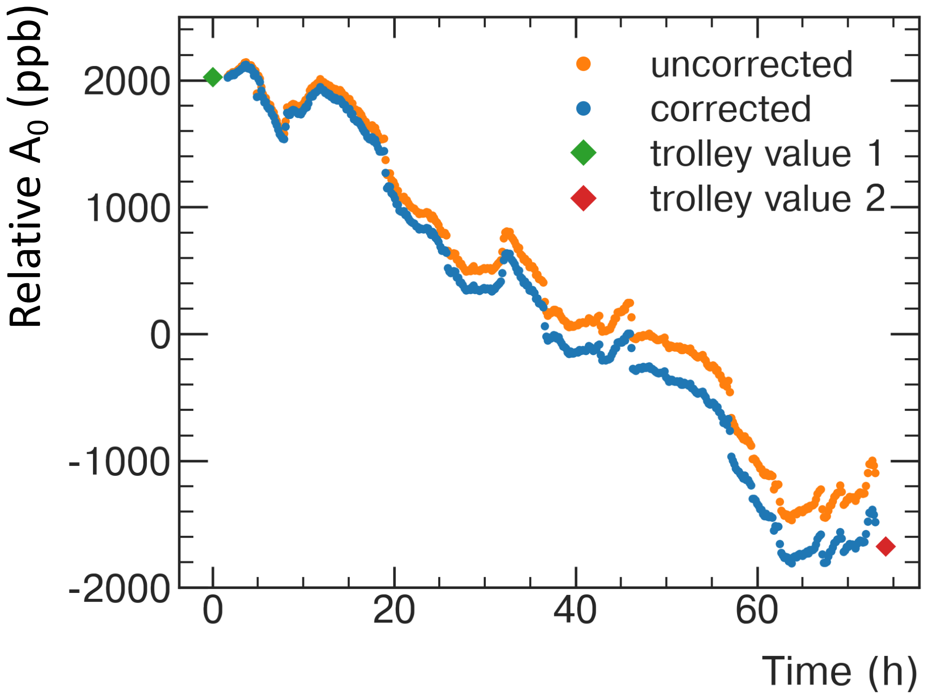


Final field from interpolation



- Trolley with 17-probe NMR
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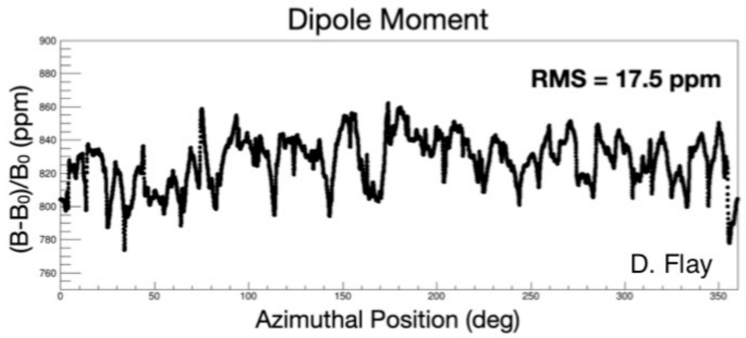
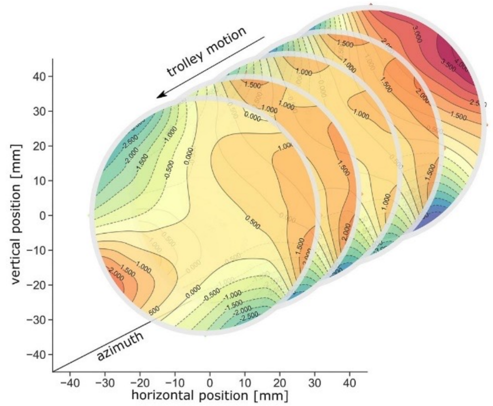
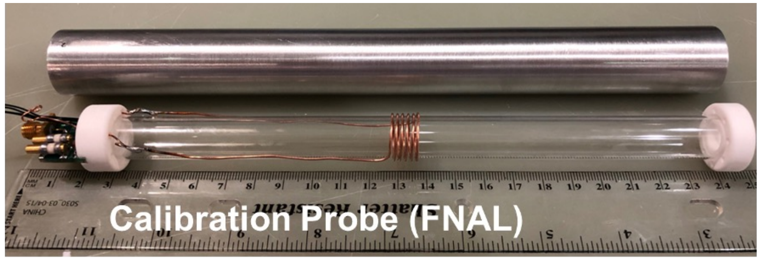




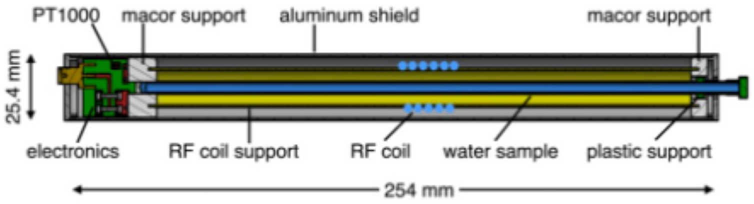
Calibration of the field probes

$$R_\mu = \left(\frac{f_{clock} \cdot \omega_a^{meas} \cdot (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib} \cdot \omega'_p(x,y,\phi) \otimes M(x,y,\phi) \cdot (1 + B_k + B_q)} \right)$$



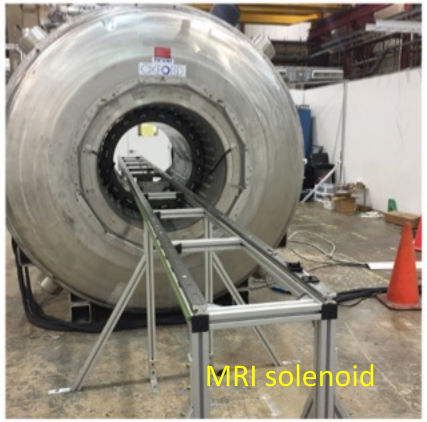
ω_p: free proton precession frequency

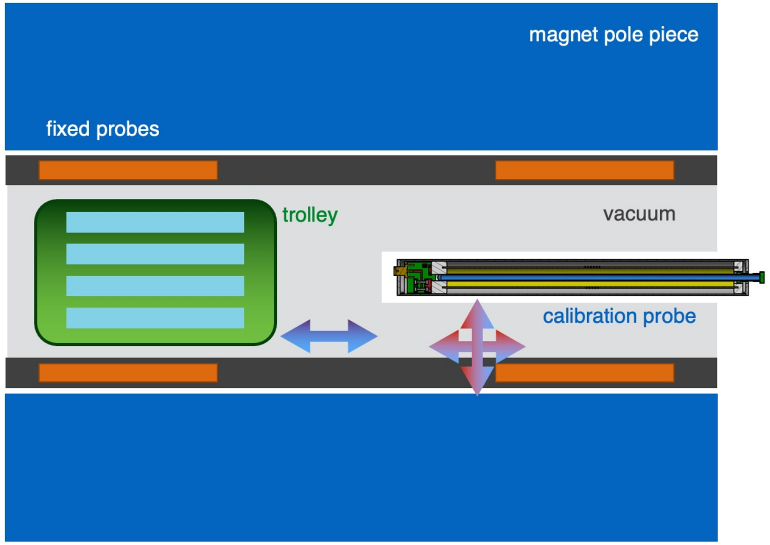
Using proton NMR: $\hbar\omega_p = 2\mu_p B$

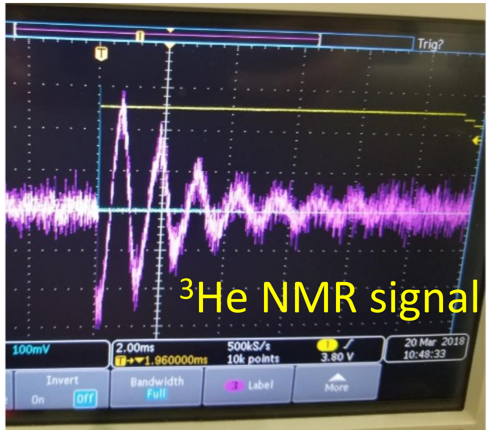


Absolute field calibration:

- NMR probes calibrated using absolute probes
- Absolute probes provide field in terms of proton shielded in a spherical sample of water at an exact temperature: $\omega_p(Tr)$
- Corrections due to sample shape, temp and magnetization from studies in an MRI solenoid
- Trolly probes calibrated inside the ring
- Cross-check provided by a novel ^{3}He NMR probe was developed with different systematics







Convolution

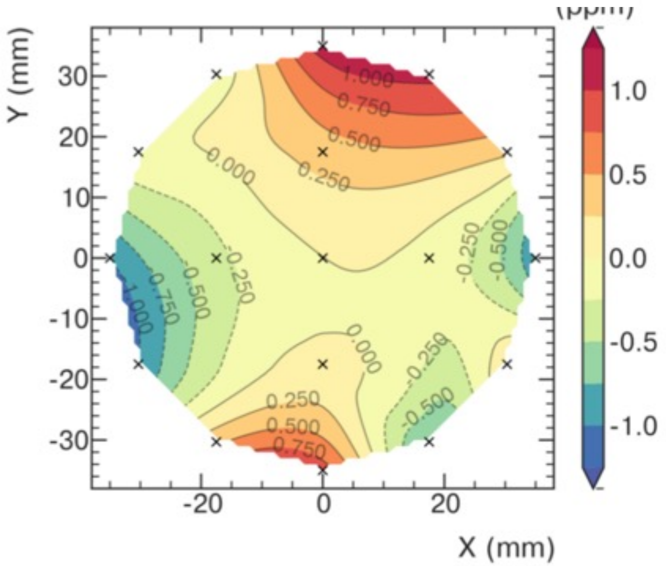
$$R_\mu = \left(\frac{f_{clock} \cdot \omega_a^{meas} \cdot (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib} \cdot \omega'_p(x, y, \phi) \otimes M(x, y, \phi) \cdot (1 + B_k + B_q)} \right)$$

$$\tilde{\omega}_p = \left\langle \frac{\int \omega_p(x, y, \phi)\, M(x, y, \phi)\, \mathrm{d}x\, \mathrm{d}y}{\int M(x, y, \phi)\, \mathrm{d}x\, \mathrm{d}y} \right\rangle$$

Field seen by the muons (tot Run1 unc. 0.56 ppm)

Field maps are weighted by beam distribution

Field from Trolley and fixed probe



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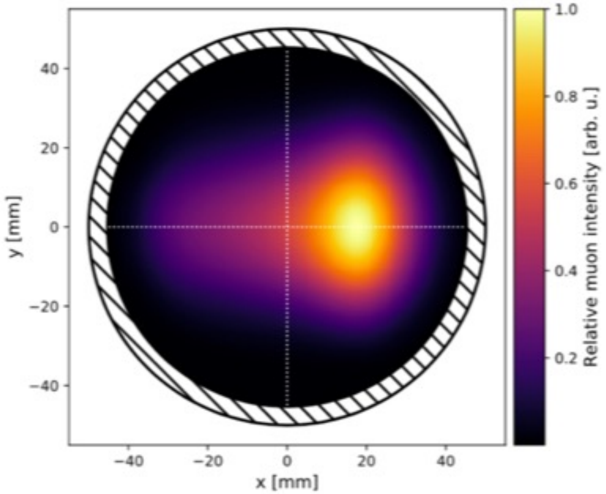
Beam distribution extrapolated from trackers data propagated around the ring with simulations



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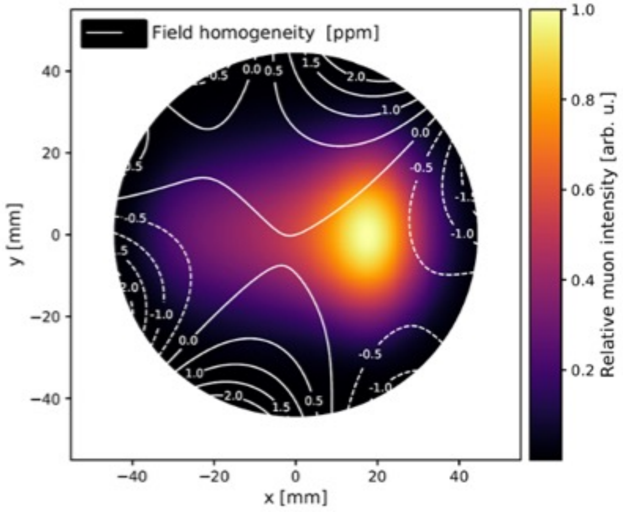
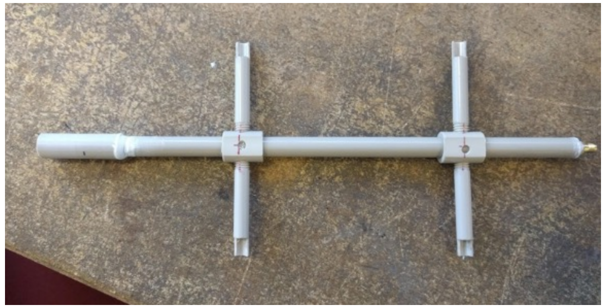
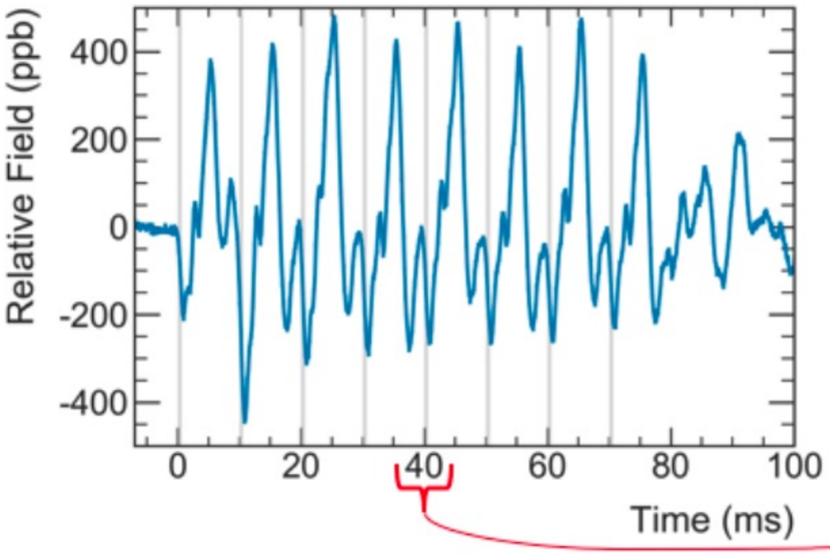


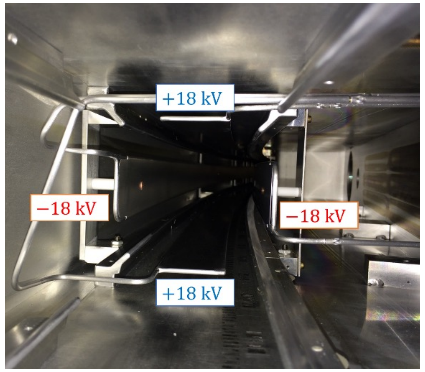
Quads transient field Correction

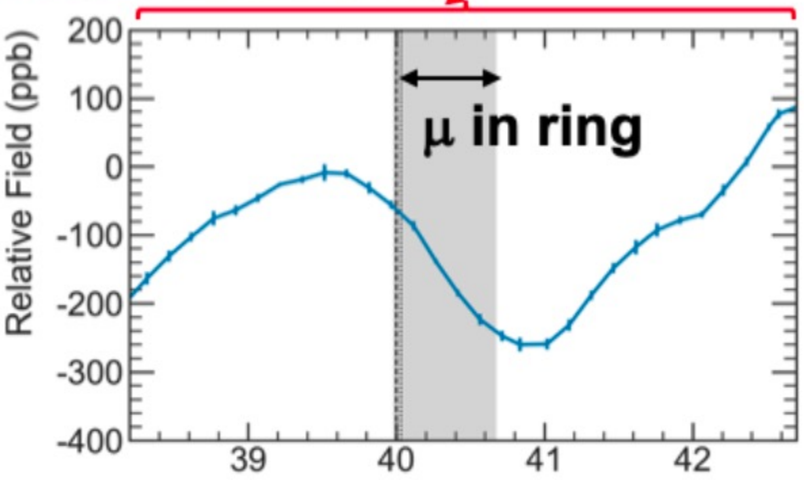
$$R_\mu = \left(\frac{f_{clock} \cdot \omega_a^{meas} \cdot (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib} \cdot \omega'_p(x,y,\phi) \otimes M(x,y,\phi) \cdot (1 + B_k + B_q)} \right)$$

- due to mechanicals vibrations from pulsing the quads
- mapped using special NMR probes









Results for Run1:

$B_q \sim 17ppb \quad \delta_{B_q} \sim 92ppb$

ppb = parti per miliardo (10^9)

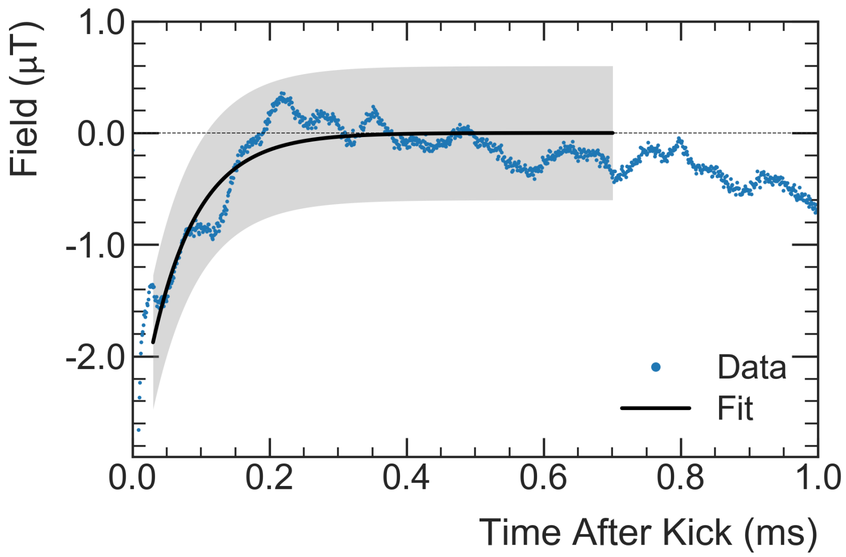
→ δ_{B_q} dominated by incomplete map

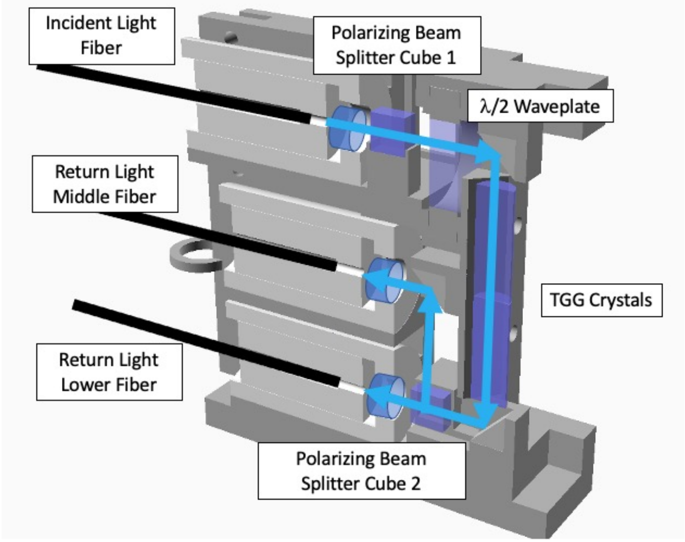
→ expected to be reduced by factor 2 for Run 2 and after

Kicker transient field Correction

$$R_\mu = \left(\frac{f_{clock} \cdot \omega_a^{meas} \cdot (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib} \cdot \omega'_p(x,y,\phi) \otimes M(x,y,\phi) \cdot (1 + B_k + B_q)} \right)$$

- Due to eddy currents indued by the fast magnetic pulses in surrounding materials
- Measured using a magnetometer and cross-checked with second magnetometer





Results for Run1:

$$B_k \sim 30ppb \quad \delta_{B_k} \sim 40ppb$$

ppb = parti per miliardo (10^9)

The INFN breadboard magnetometer

- Aiming at few mG sensitivity :
  - Run2/3: **30ppb (5mG)**
  - Run4/5: **10ppb (2mG)**

- Based on Faraday observation that an external magnetic field influences light propagating in materials:

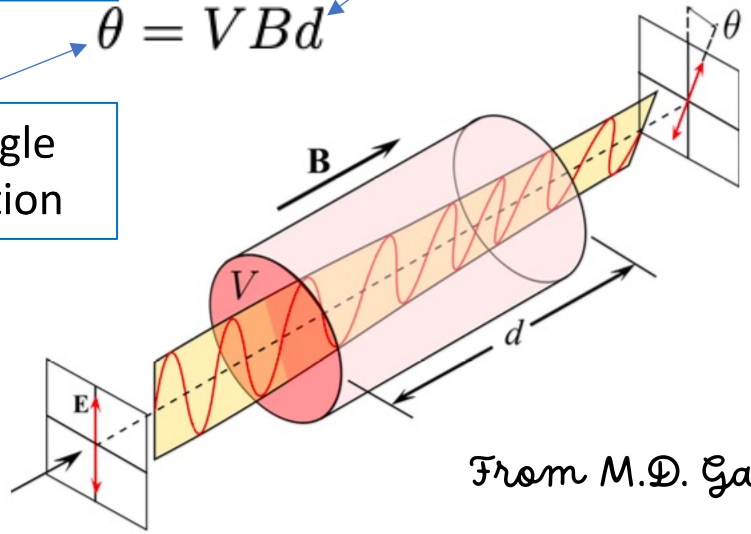
magnetic field // light

Crystal Verdet constant

length of crystal

$$\theta = VBd$$

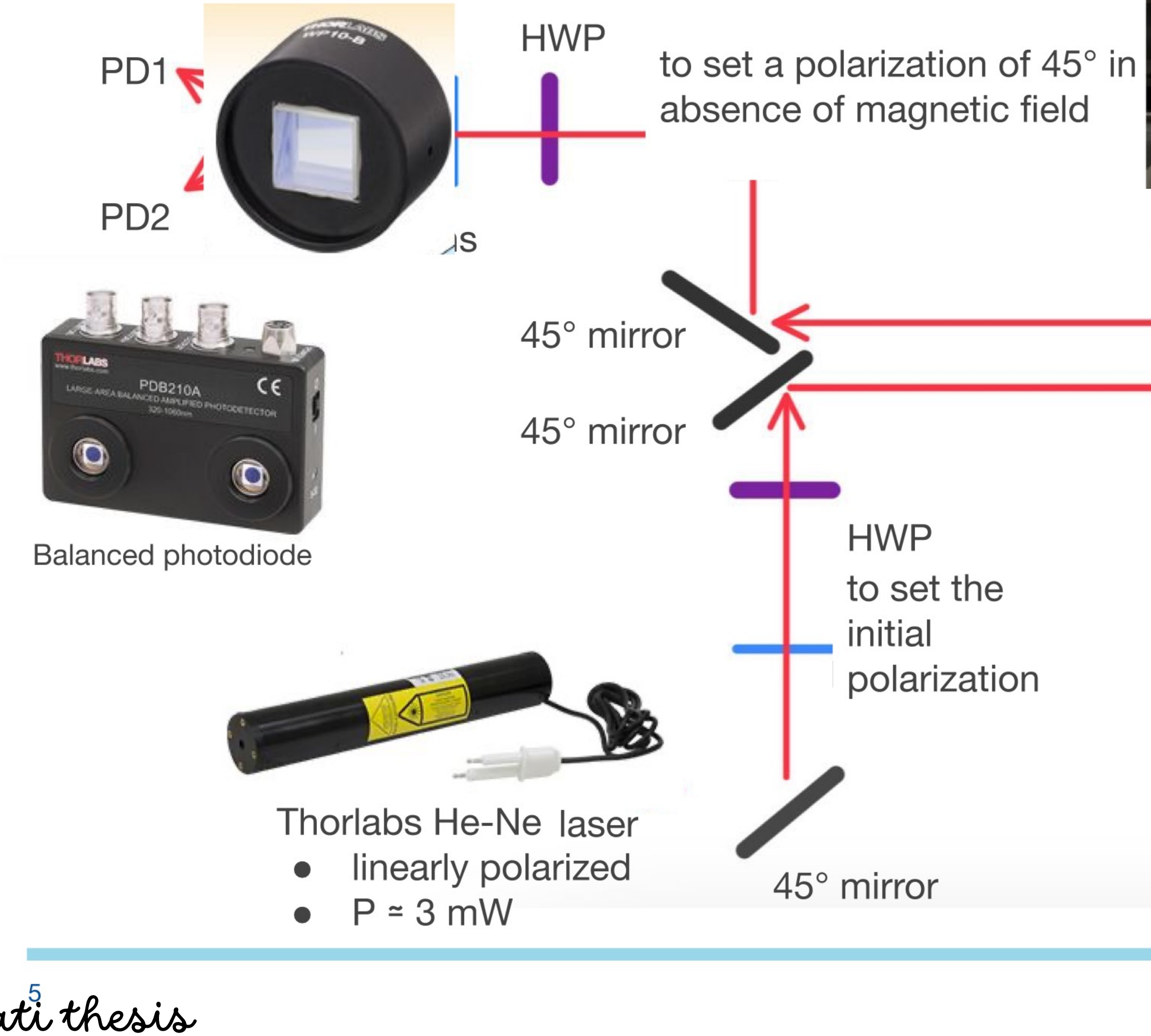
rotation angle of polarization



From M.D. Galati thesis

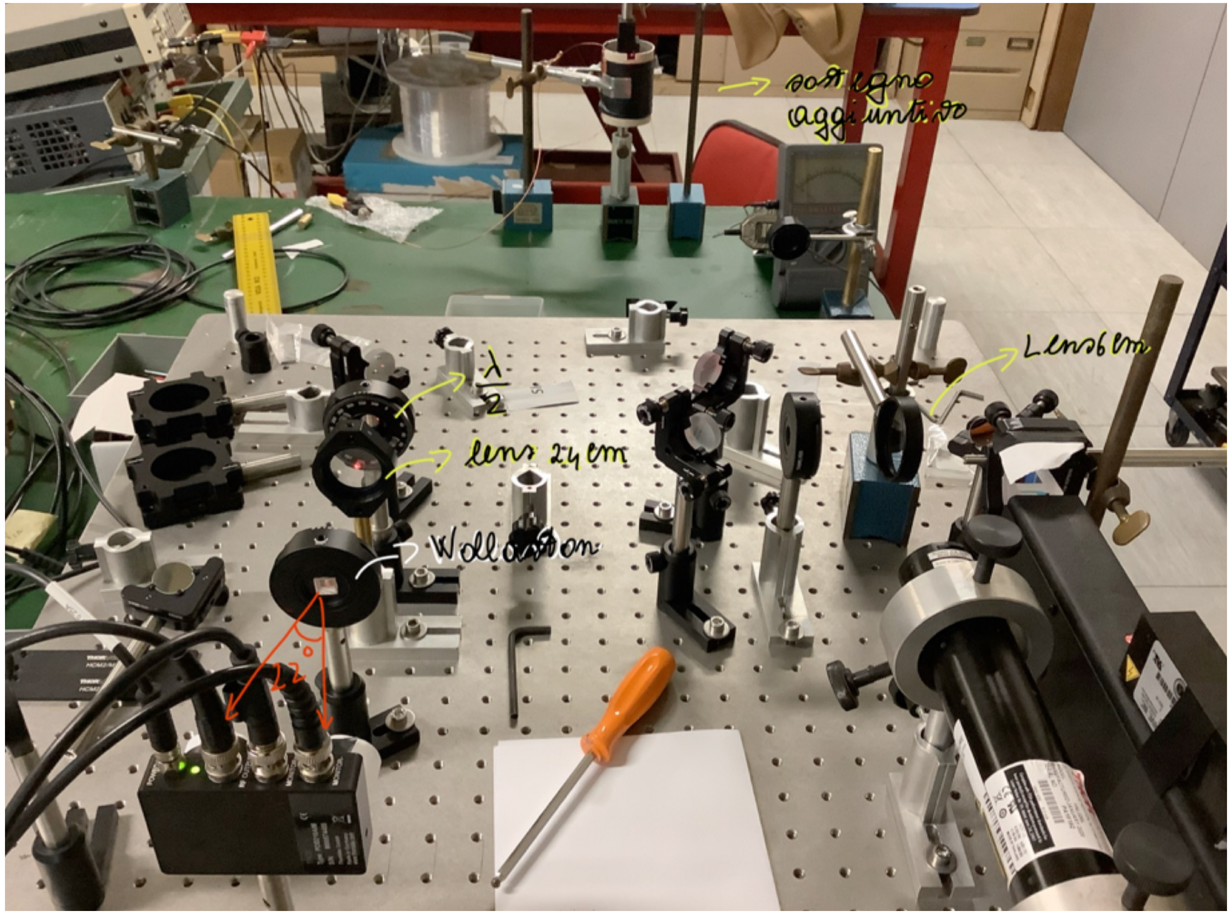
Periscope inside the ring: easily affected by vibrations

Setup scheme (upper view)



The INFN breadboard magnetometer in Pisa

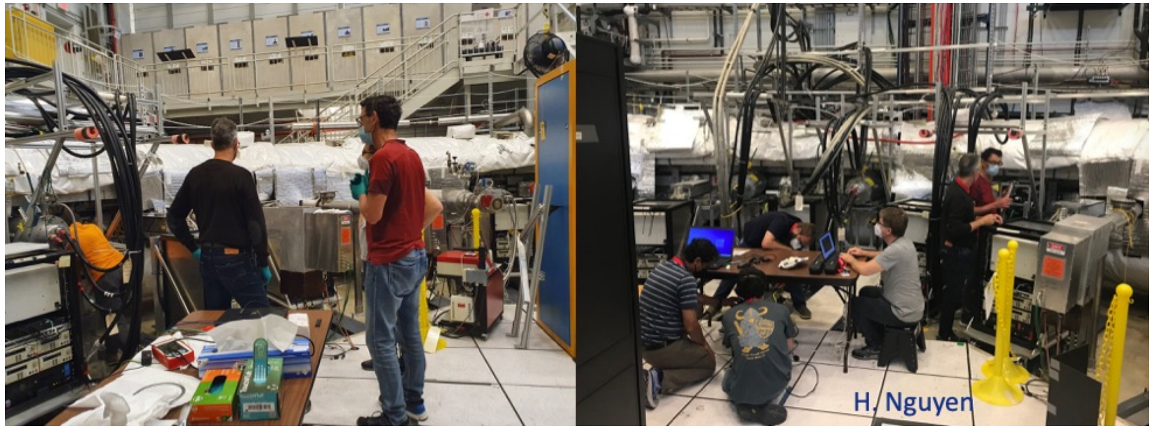
- 2020: Built, charaterized and tested in Pisa

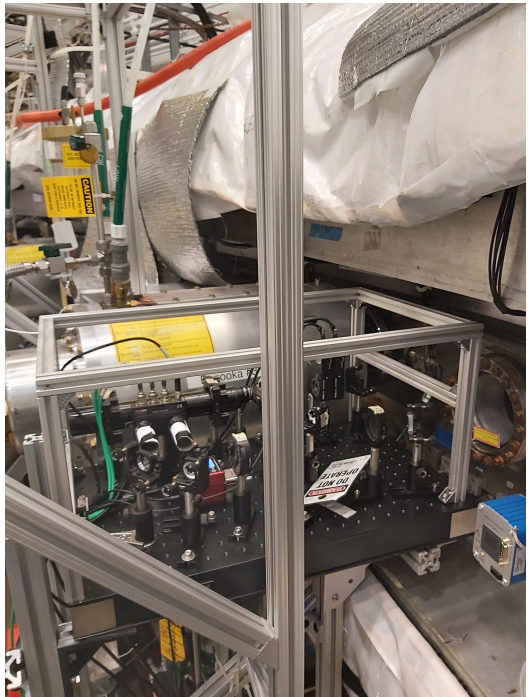


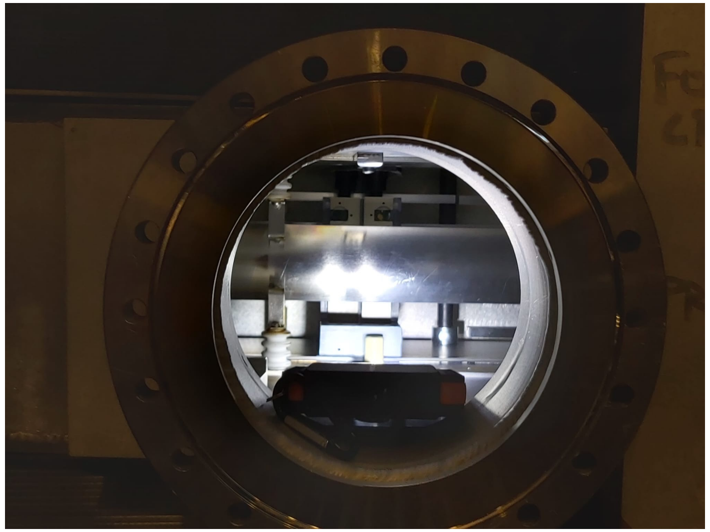
M. Incagli et. al.

The INFN breadboard magnetometer at FNAL

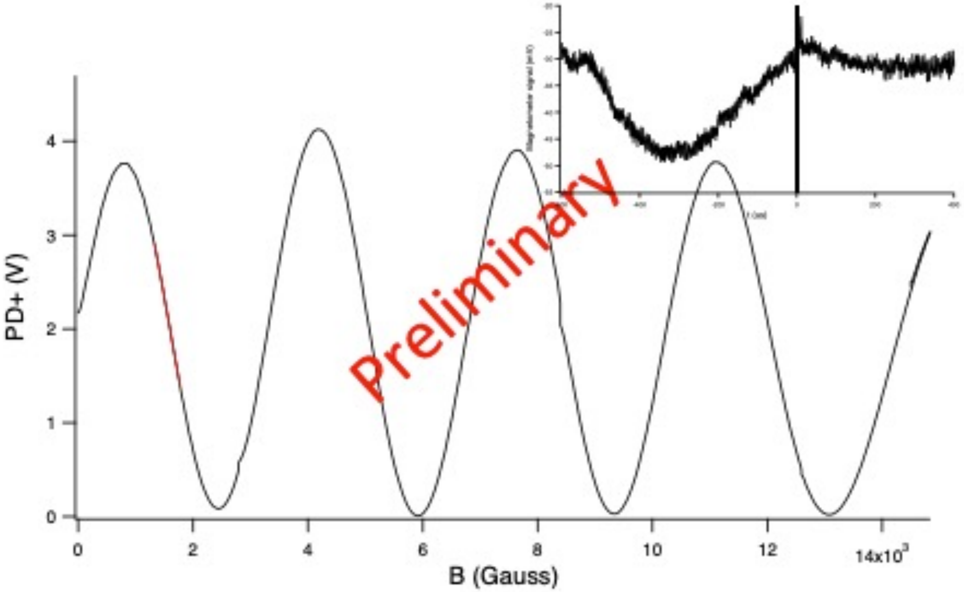
- Summer 2021: Installed and tested with magnet off
- Summer 2022: installed and tested with magnet on (last week) – planned more measurments during the summer shutdown







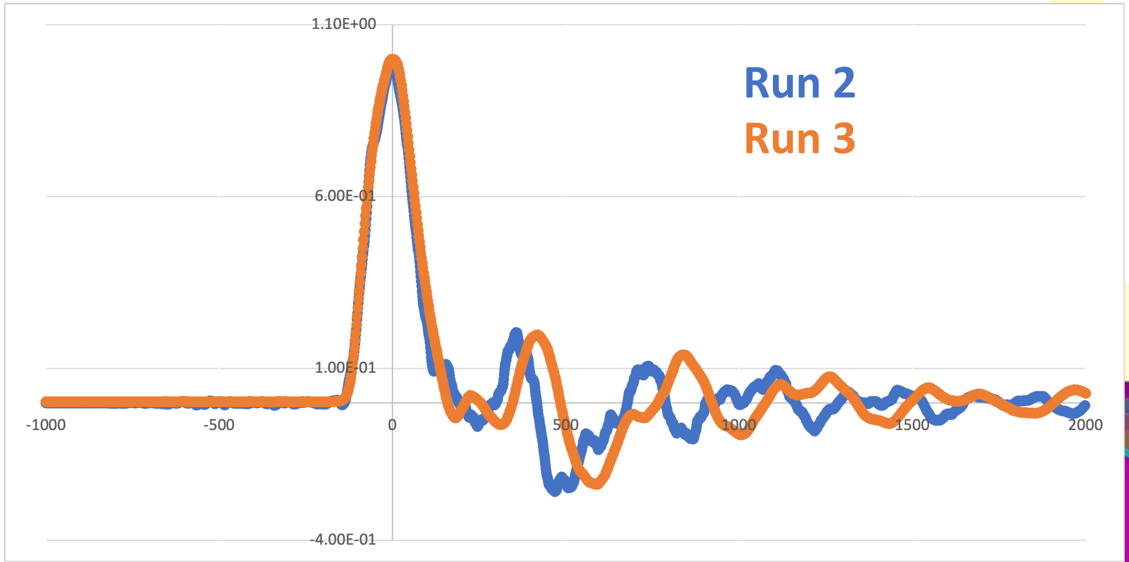
A. Gioiosa

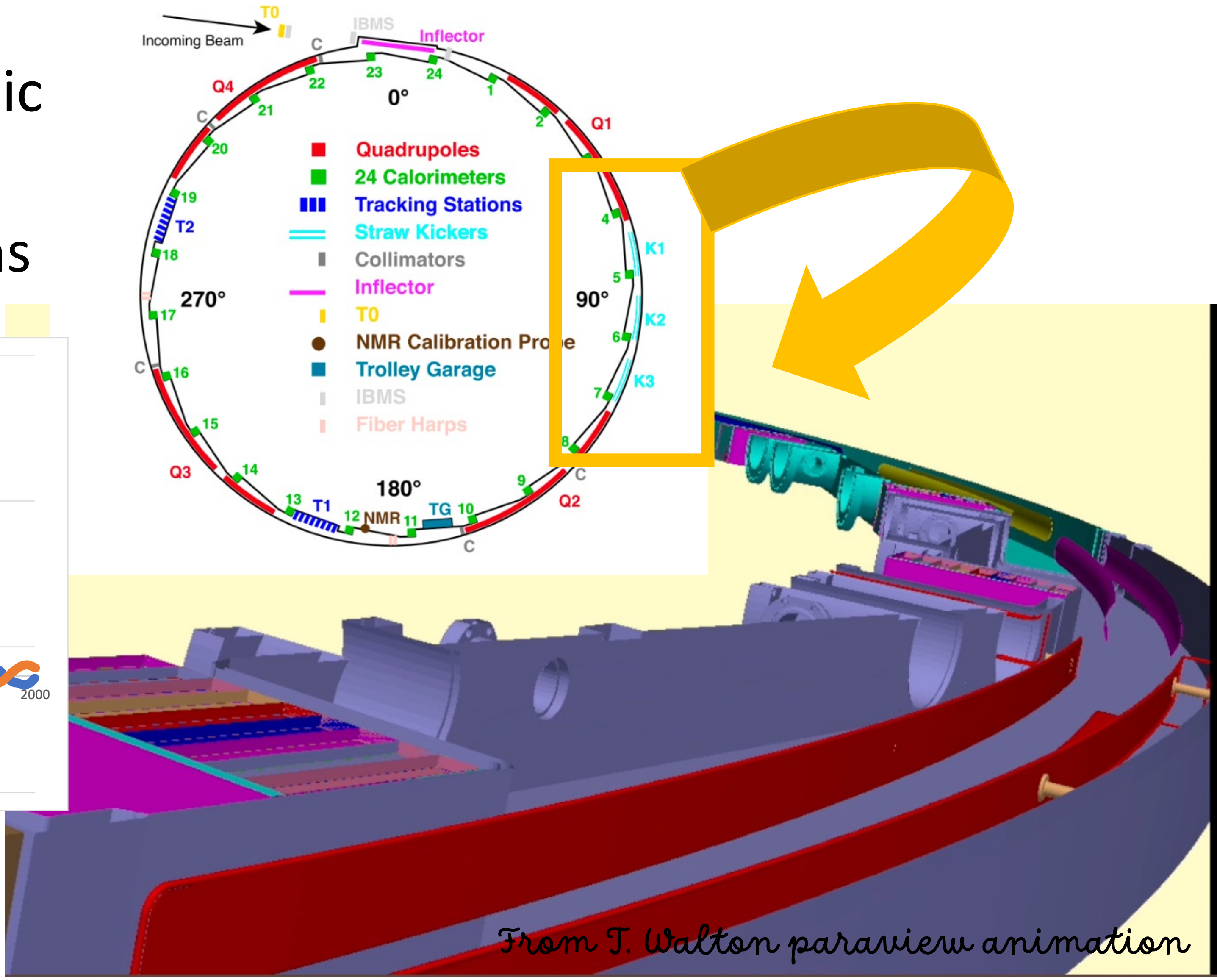


M. Sorbara (OPS meeting)

Magnetometer: not only for systematics!

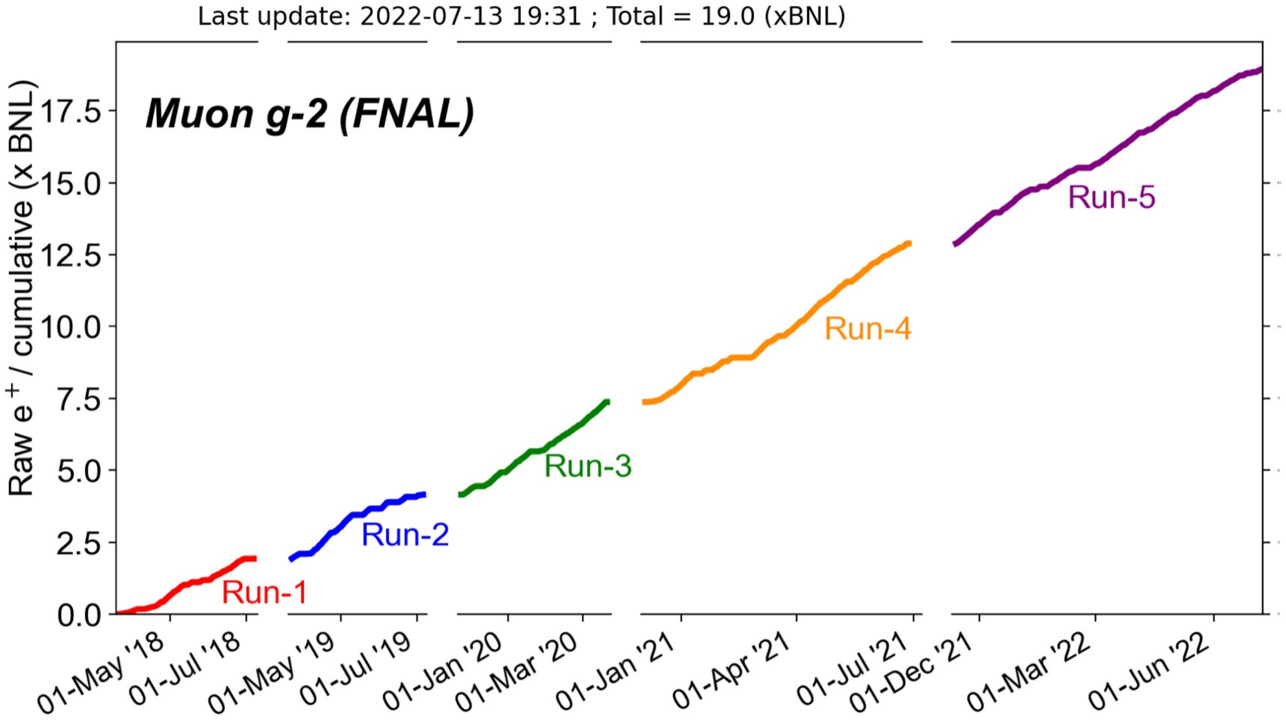
- Using a fast diode it is possible to measure the shape of the magnetic pulse of the kickers
- Input for the Muon g-2 simulations





What's next?

Analysis of data fromRun 2-5



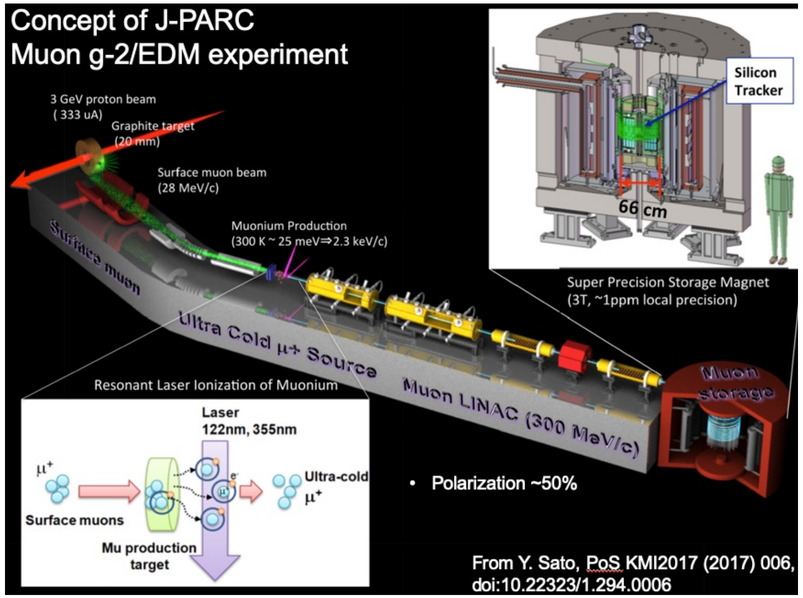
Run-2 and **Run-3** analysis are ongoing:

-> reduce combined exp. error by 2 times

Run-4 + **Run-5** (ended beginning of July)

-> stat. uncert. down to 100 ppb in total

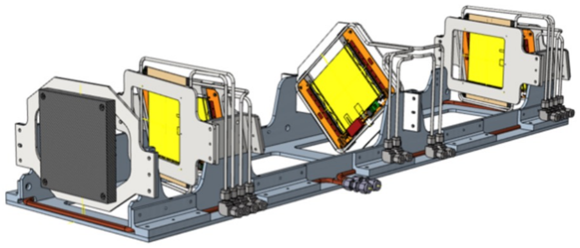
Muon g-2 experiment at J-PARC

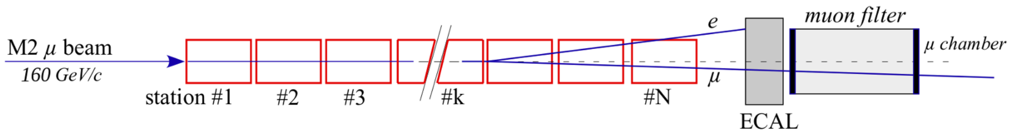


MUonE experiment at CERN

$$a_\mu^{HLO} = \frac{\alpha_0}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]$$

(spacelike approach)






Thank you!