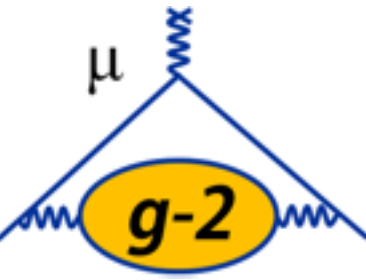


The Commissioning Run Update of The Muon $g-2$ Experiment at Fermilab

Ran Hong
(Muon $g-2$ collaboration)
Argonne National Laboratory



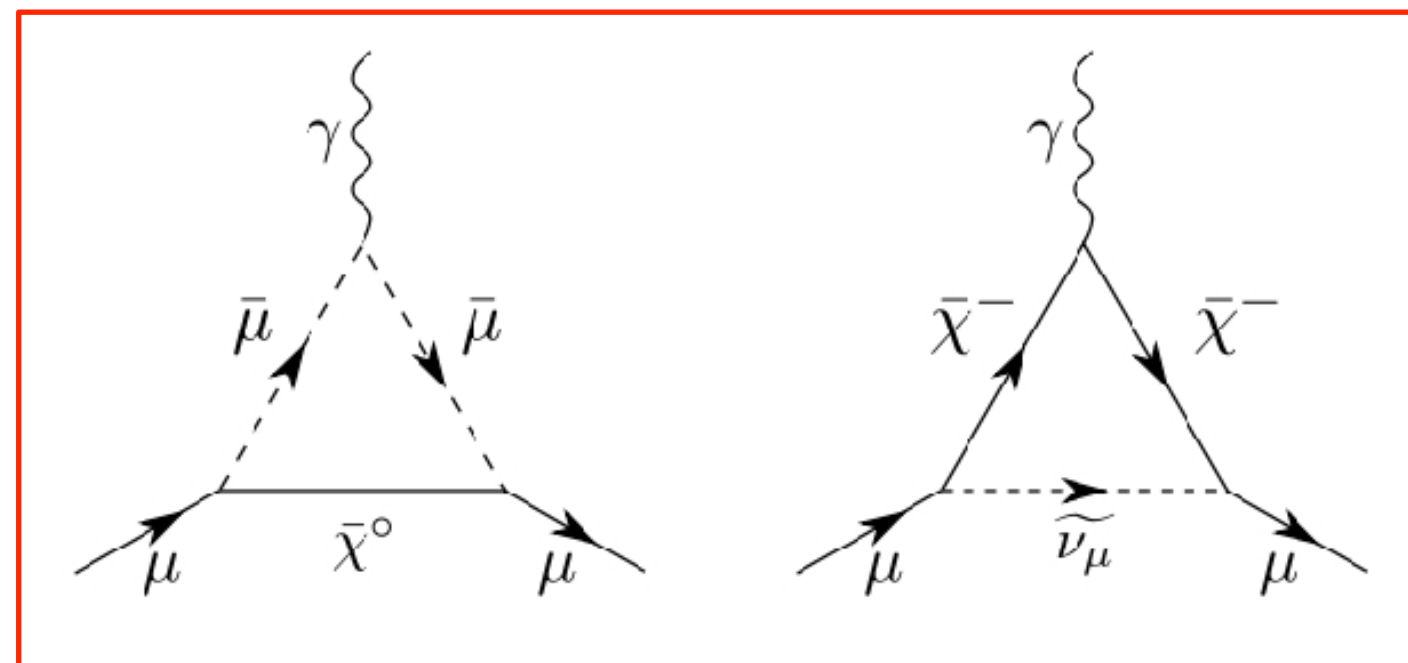
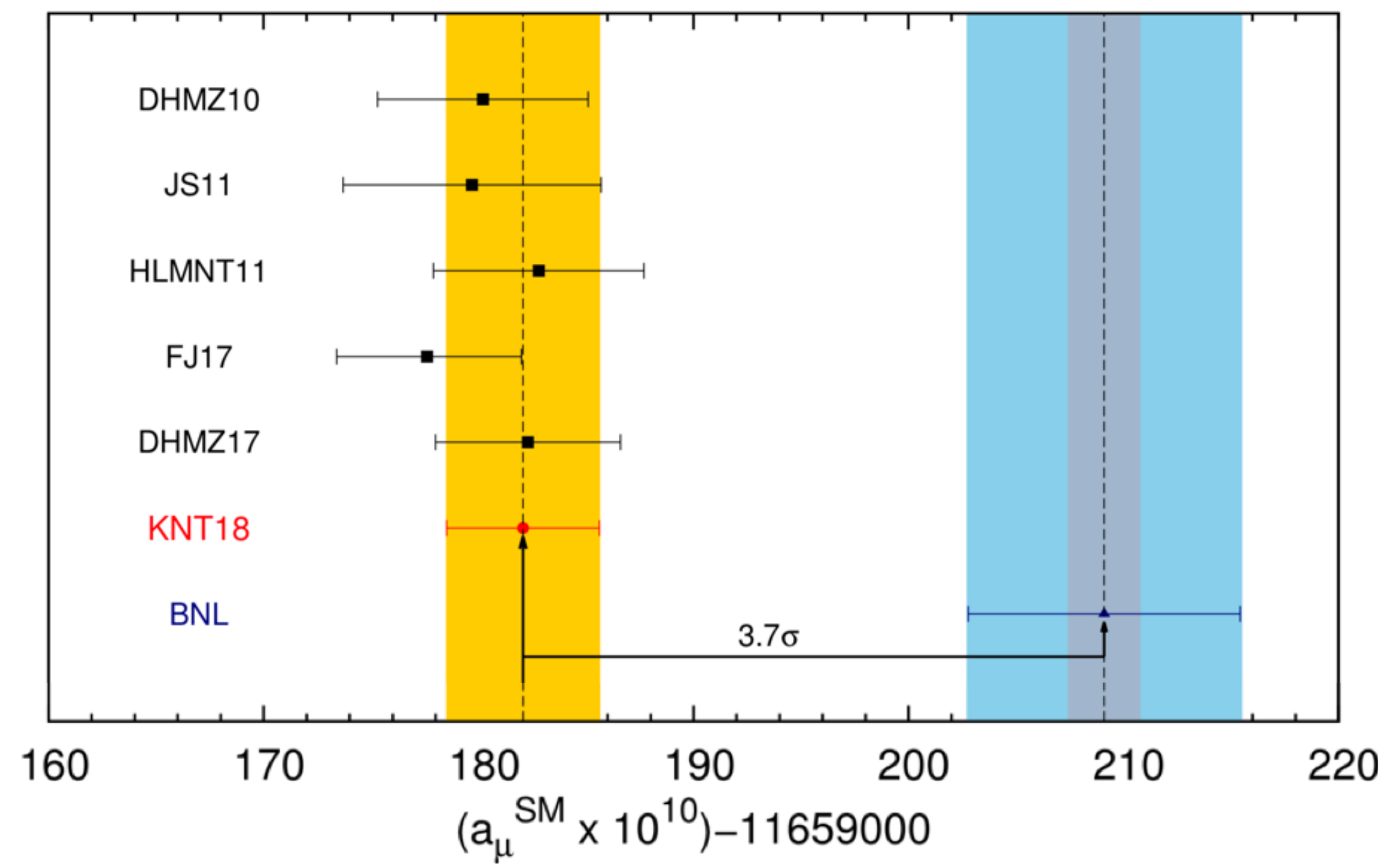
- **Introduction**
- **Experiment Construction and Commissioning Status**
- **Experiment Progress**
- **Summary**

Introduction: Muon g-2 and BSM Physics



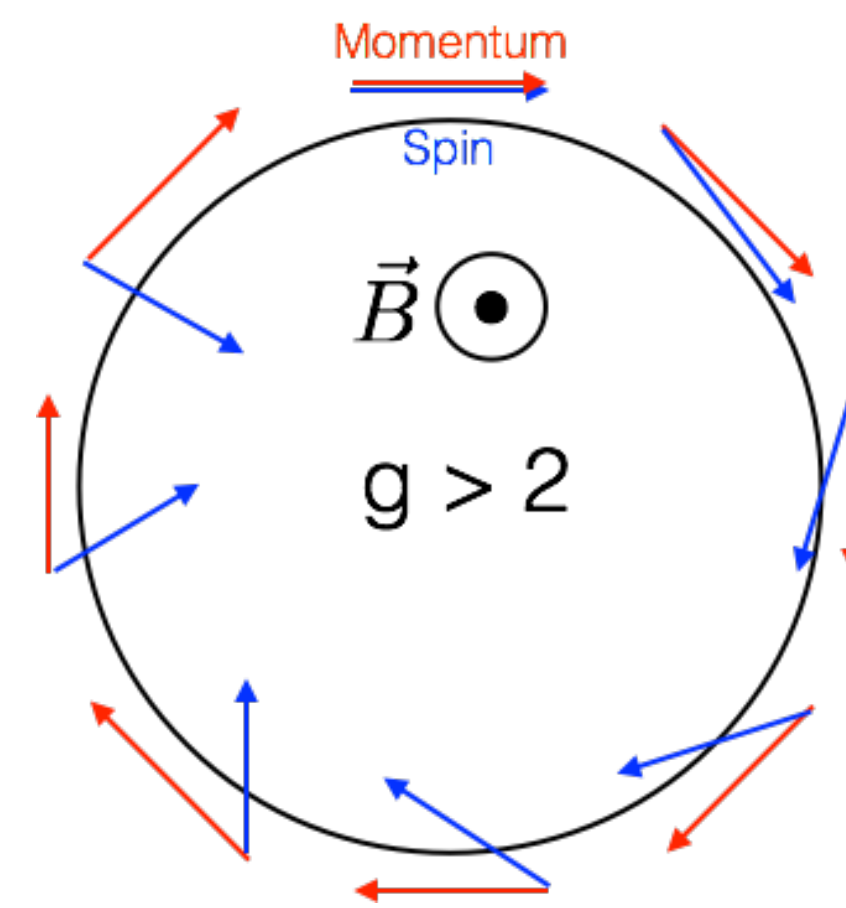
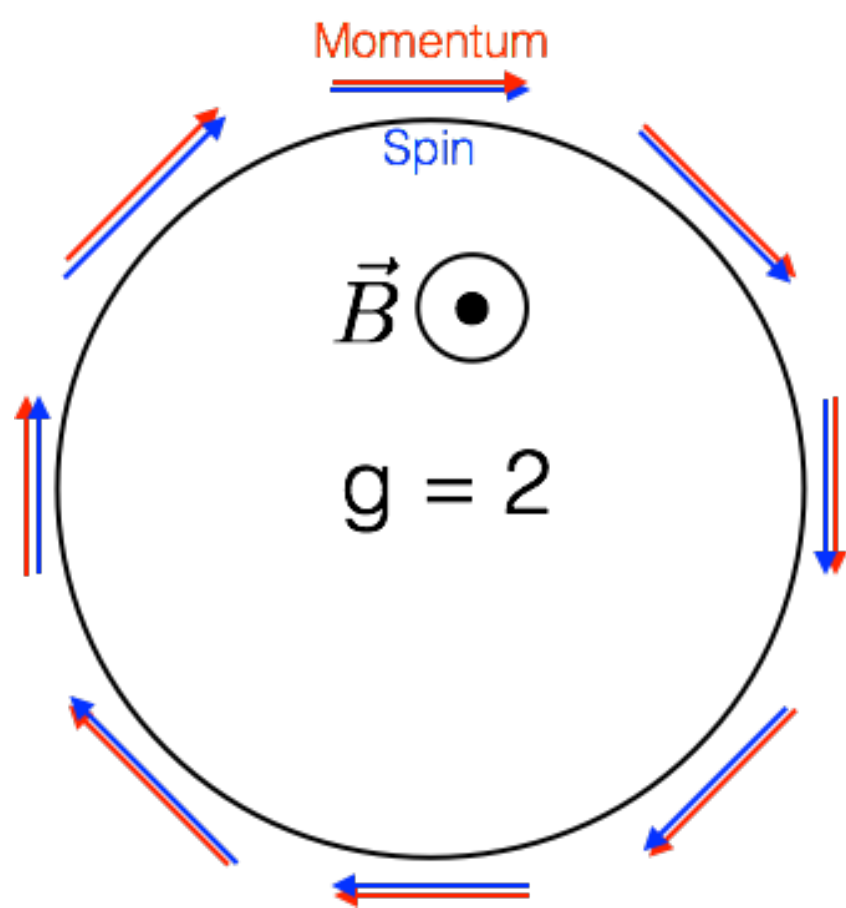
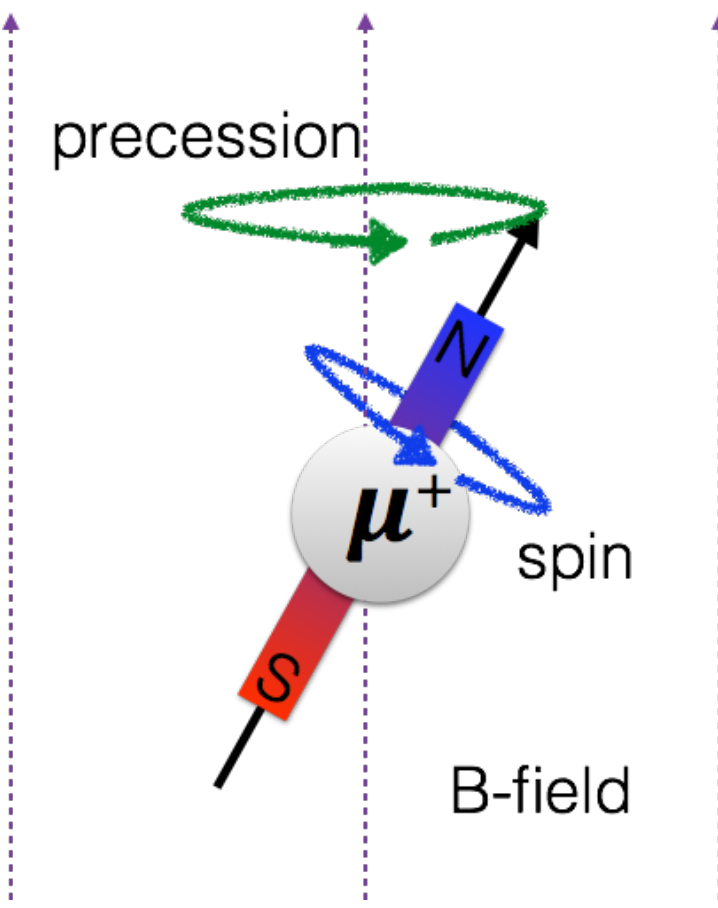
Keshavarzi, Nomura, Teubner arXiv: 1902.02995

- ▶ **Issues in modern particle physics:**
 - ▶ Naturalness of Higgs mass
 - ▶ What is the dark matter made of?
 - ▶ Baryon asymmetry
 - ▶ Unification of fundamental interactions
- ▶ **The measured muon anomalous magnetic moment disagrees with the SM prediction**
- ▶ **What can the new muon g-2 experiment tell us?**
 - ▶ Whether the hint of new physics is true?
 - ▶ If true: energy scale/interaction strength of new interactions
 - ▶ If not true: limits of energy or interaction strength of new interactions



Diagrams of super-symmetrical particle exchanging

Introduction: Brief description of the New Measurement

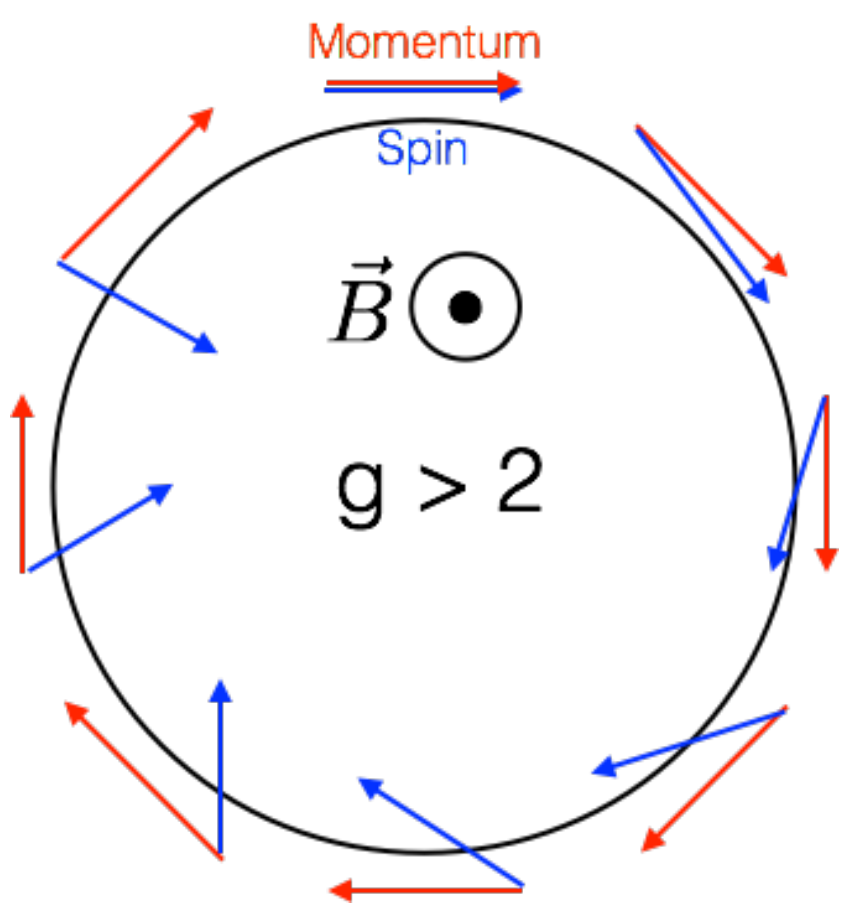
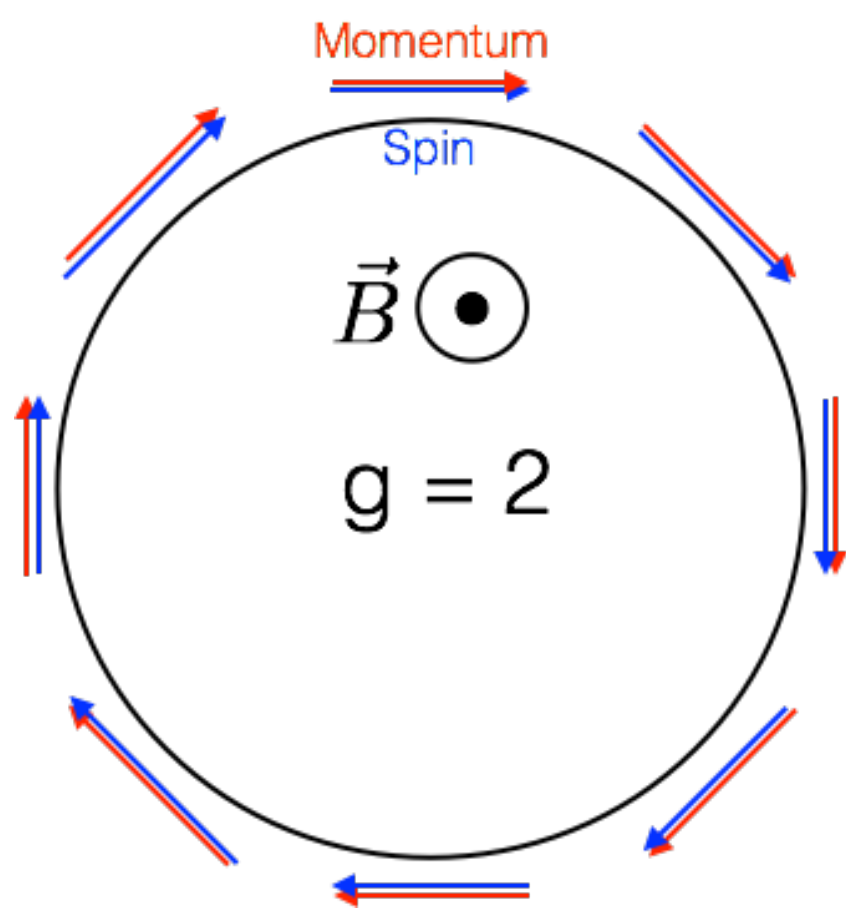
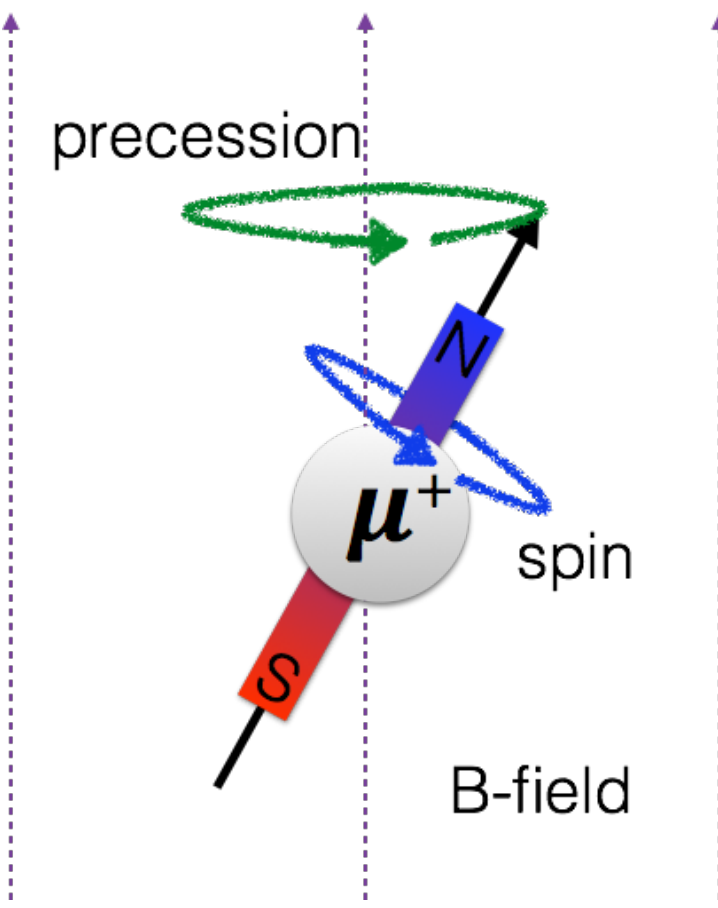
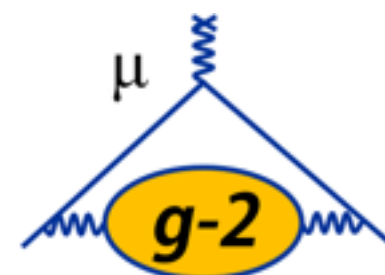


$$\vec{\mu} = g \frac{q}{2m} \vec{s}$$

$$a_\mu = \frac{g_\mu - 2}{2}$$

$$a_\mu(\text{Exp}) = -\frac{m\omega_a}{eB}$$

Introduction: Brief description of the New Measurement



$$\vec{\mu} = g \frac{q}{2m} \vec{S}$$

$$a_\mu = \frac{g_\mu - 2}{2}$$

$$a_\mu(\text{Exp}) = -\frac{m\omega_a}{eB}$$

ω_a Improvement: 180 ppb -> 70 ppb

$$a_\mu(\text{Exp}) = \frac{g_e \omega_a m_\mu \mu_p}{2 \tilde{\omega}_p m_e \mu_e}$$

0.26 ppt

8 ppb

22 ppb

ω_p Improvement: 170 ppb -> 70 ppb

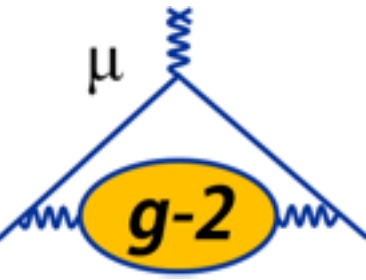
Measure muon anomalous precession frequency:

- Asymmetry in positron emission angular distribution
- Positron energy oscillation in lab frame
- Measure oscillation frequency (ω_a) of the counting rate of positrons above an **energy threshold**

Measure magnetic field:

- Using NMR probes
- Measure proton spin precession frequency (ω_p)
- Average the measured field over the muon distribution

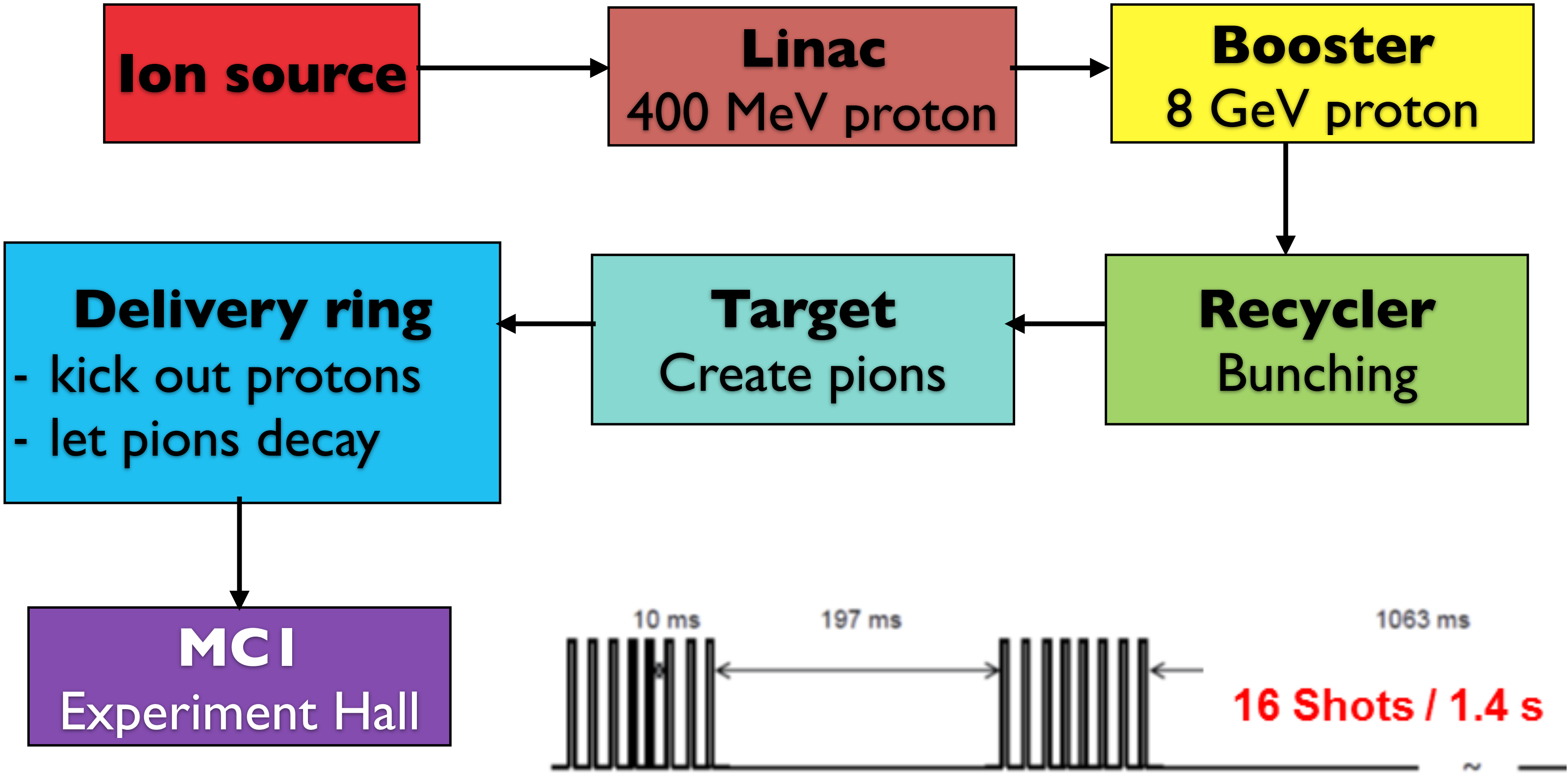
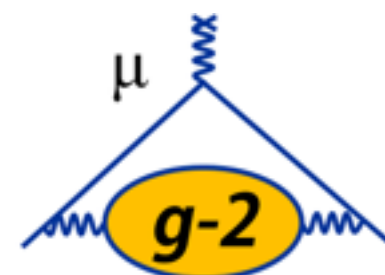
Experiment Construction and Commissioning Status



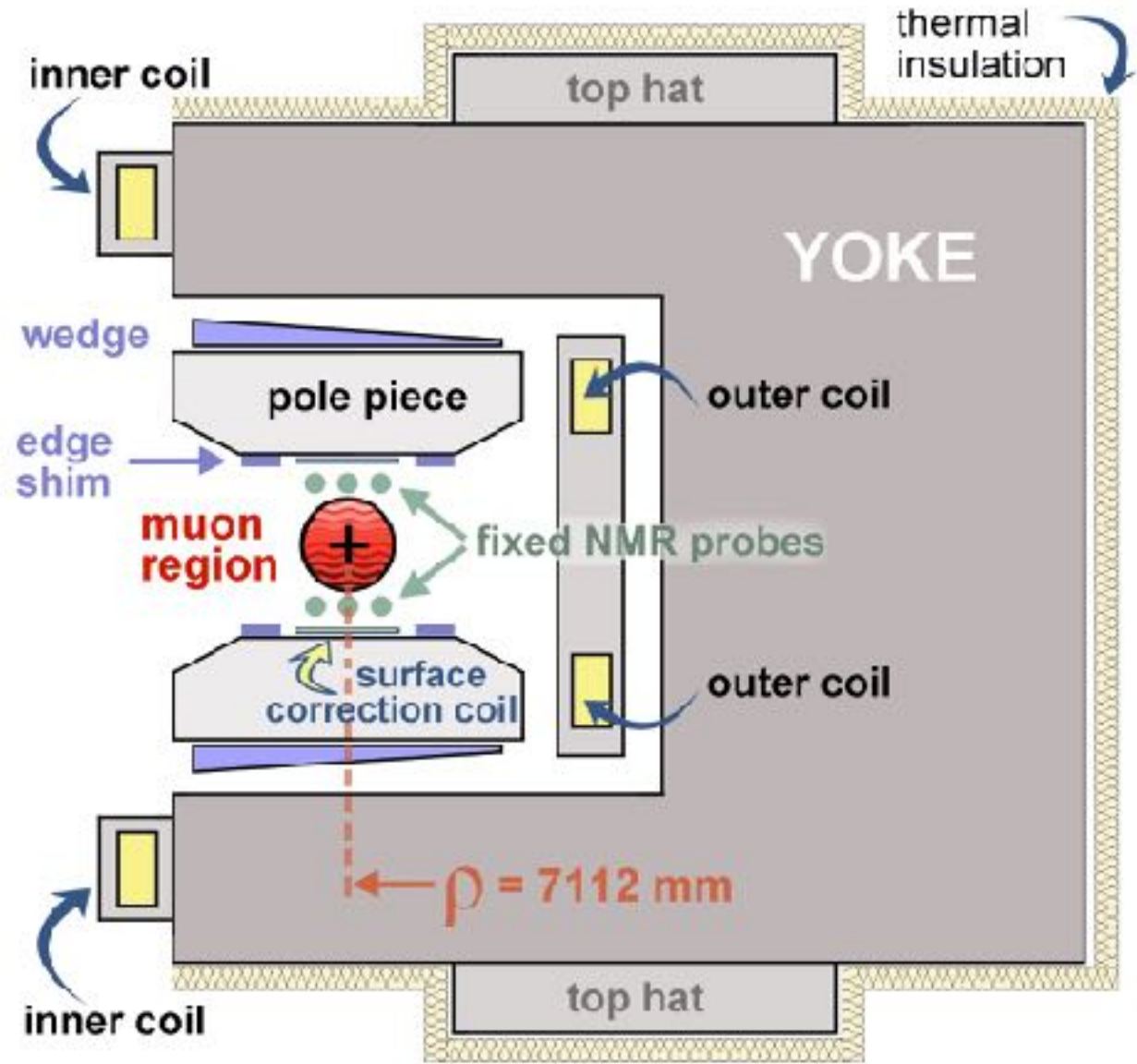
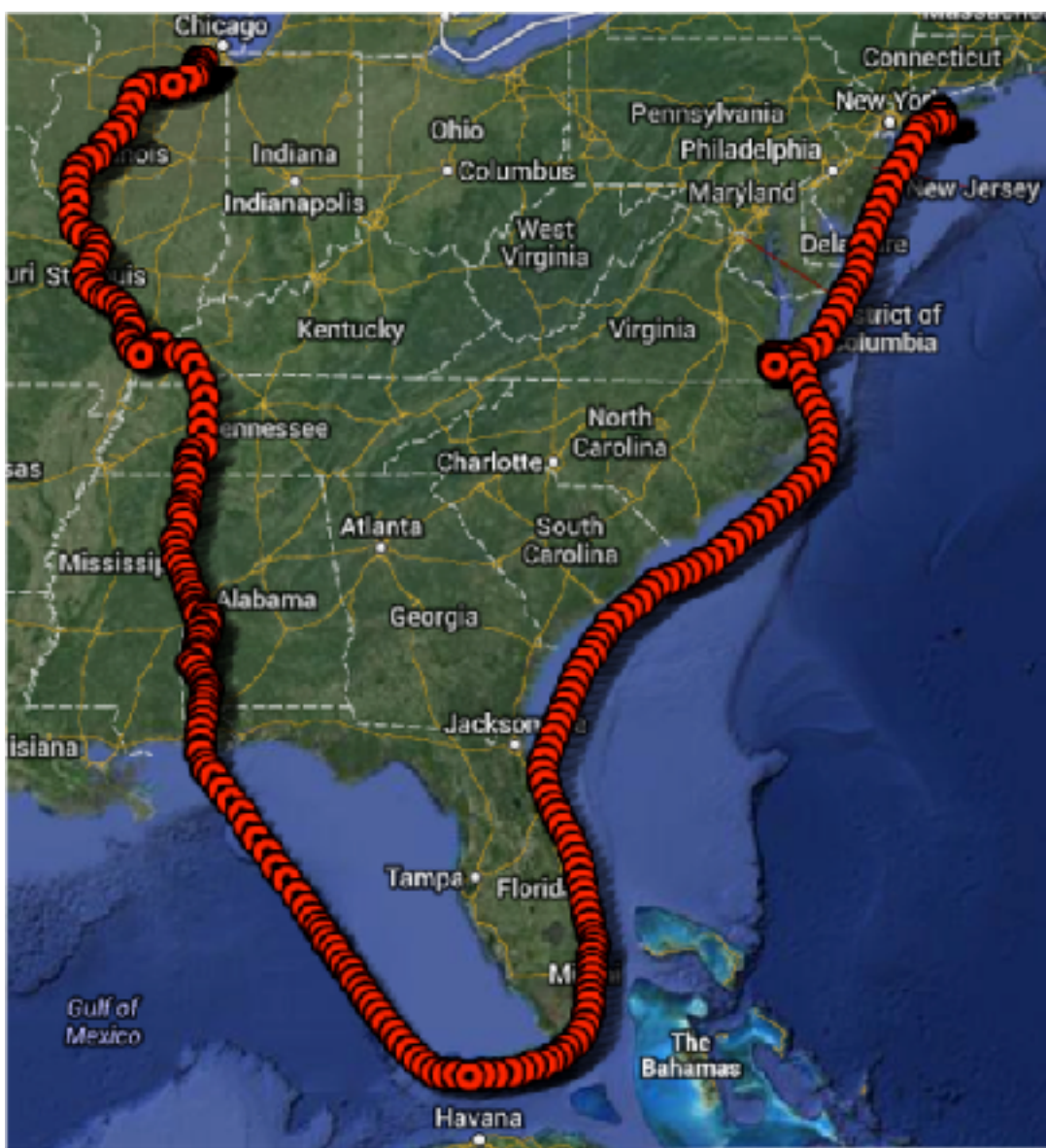
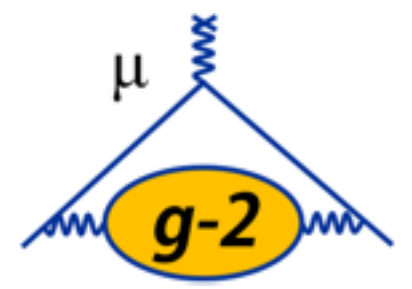
- ▶ **Muon beam line**
- ▶ **Muon storage ring**
- ▶ **Detectors**
- ▶ **Field sensors**



Muon Beam

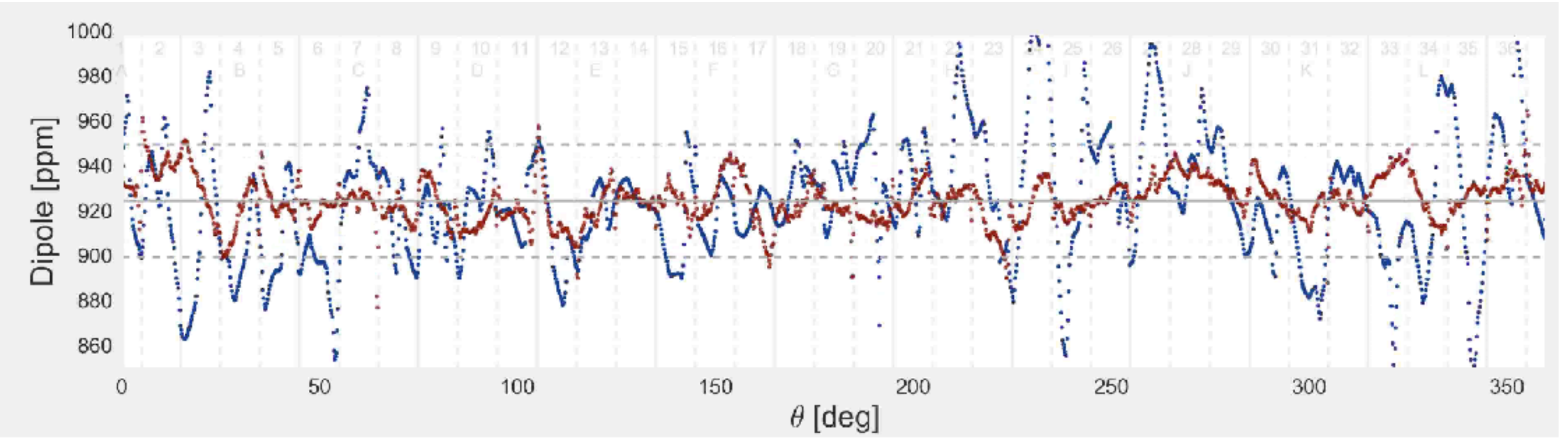


Muon Storage Ring: Magnet



Key :

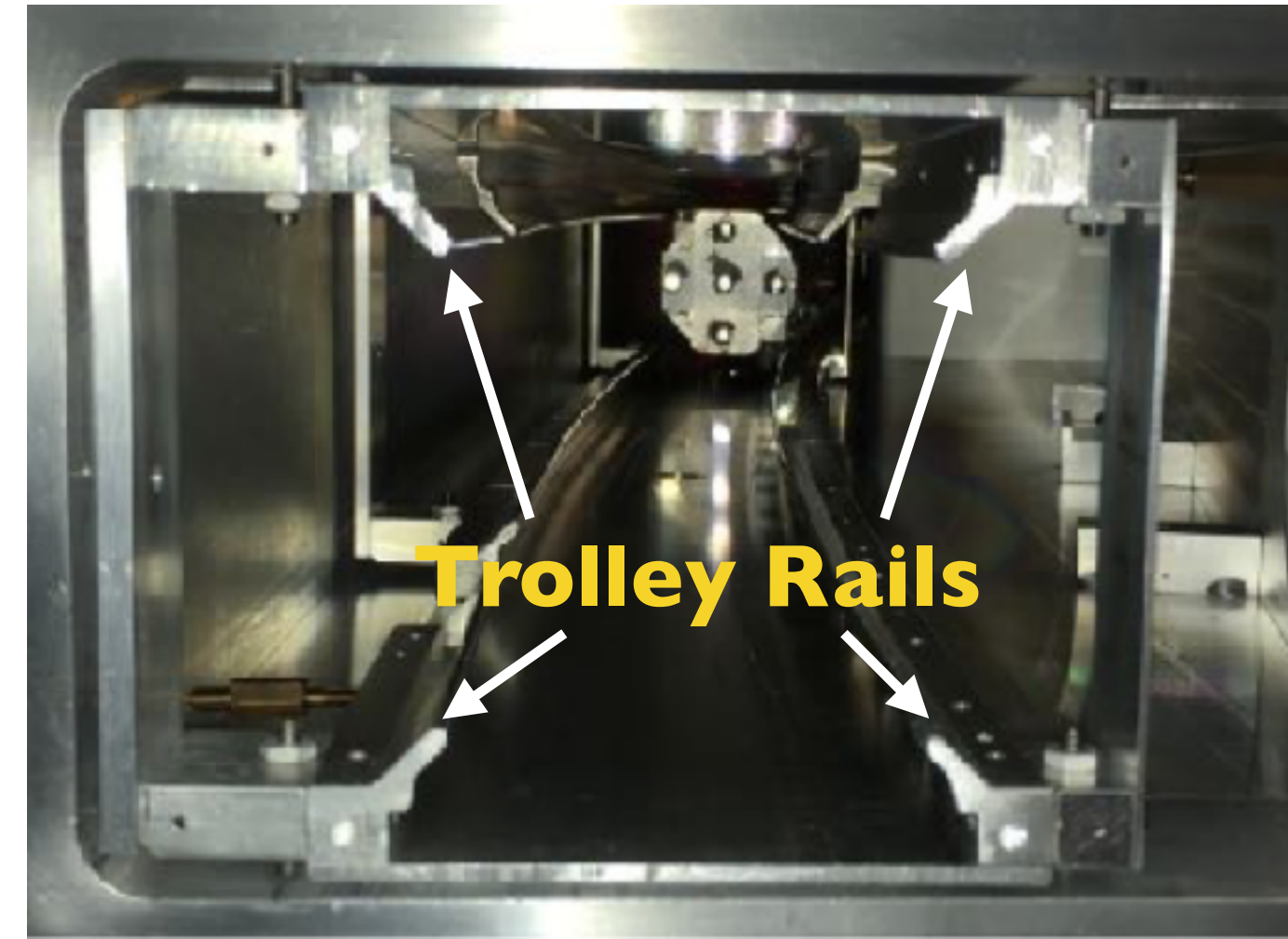
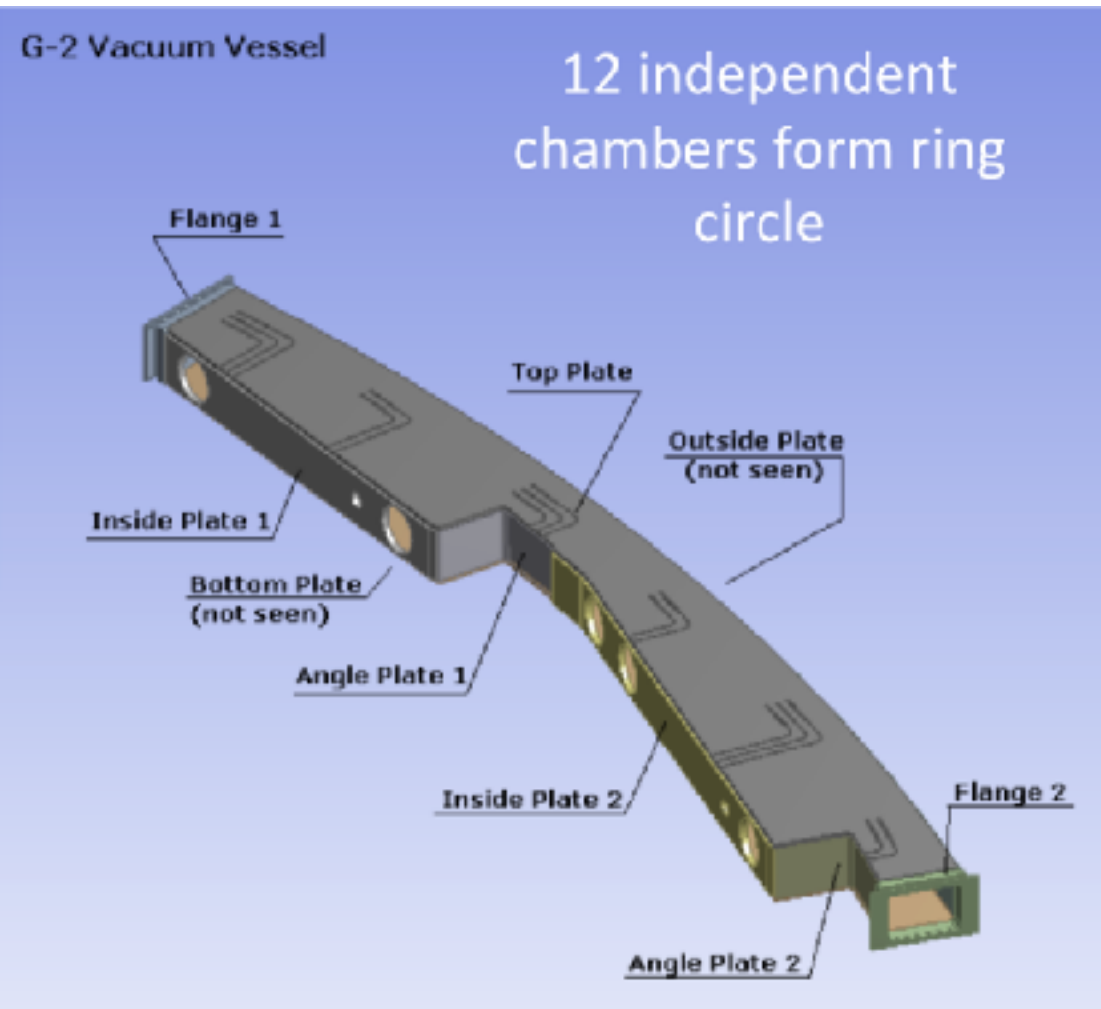
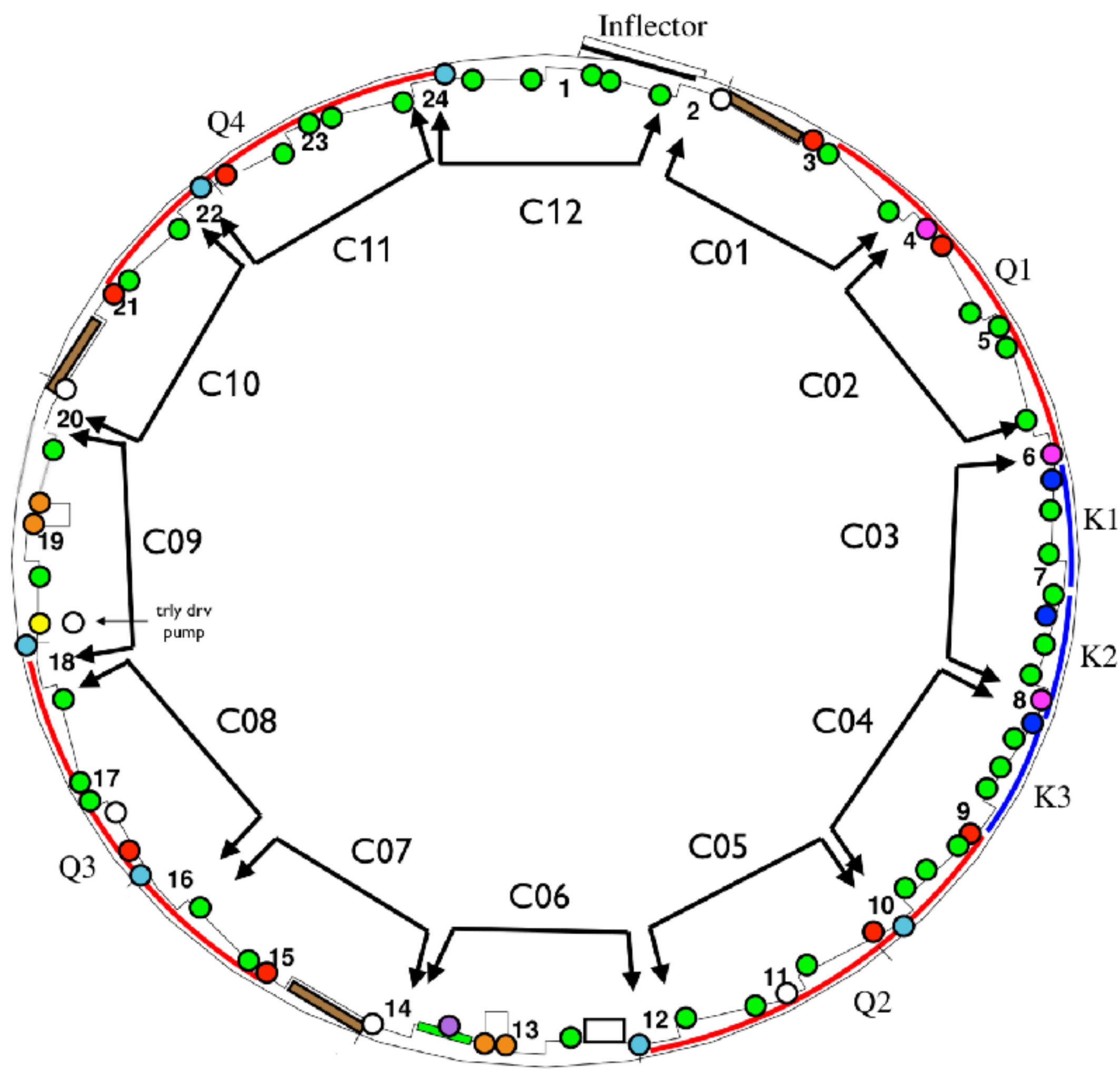
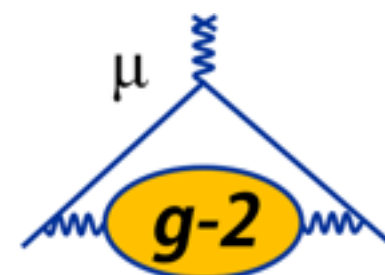
- Transportation: 2015
- Construction: 2015-2016
- Shimming: 2015-2016



E821 (BNL)

E989 (FNAL)

Muon Storage Ring: Vacuum Chamber

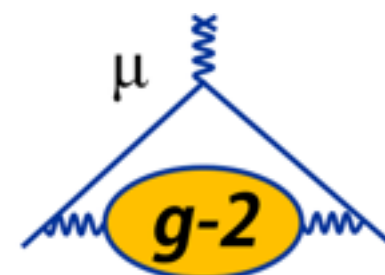


Deformation of the chamber under vacuum



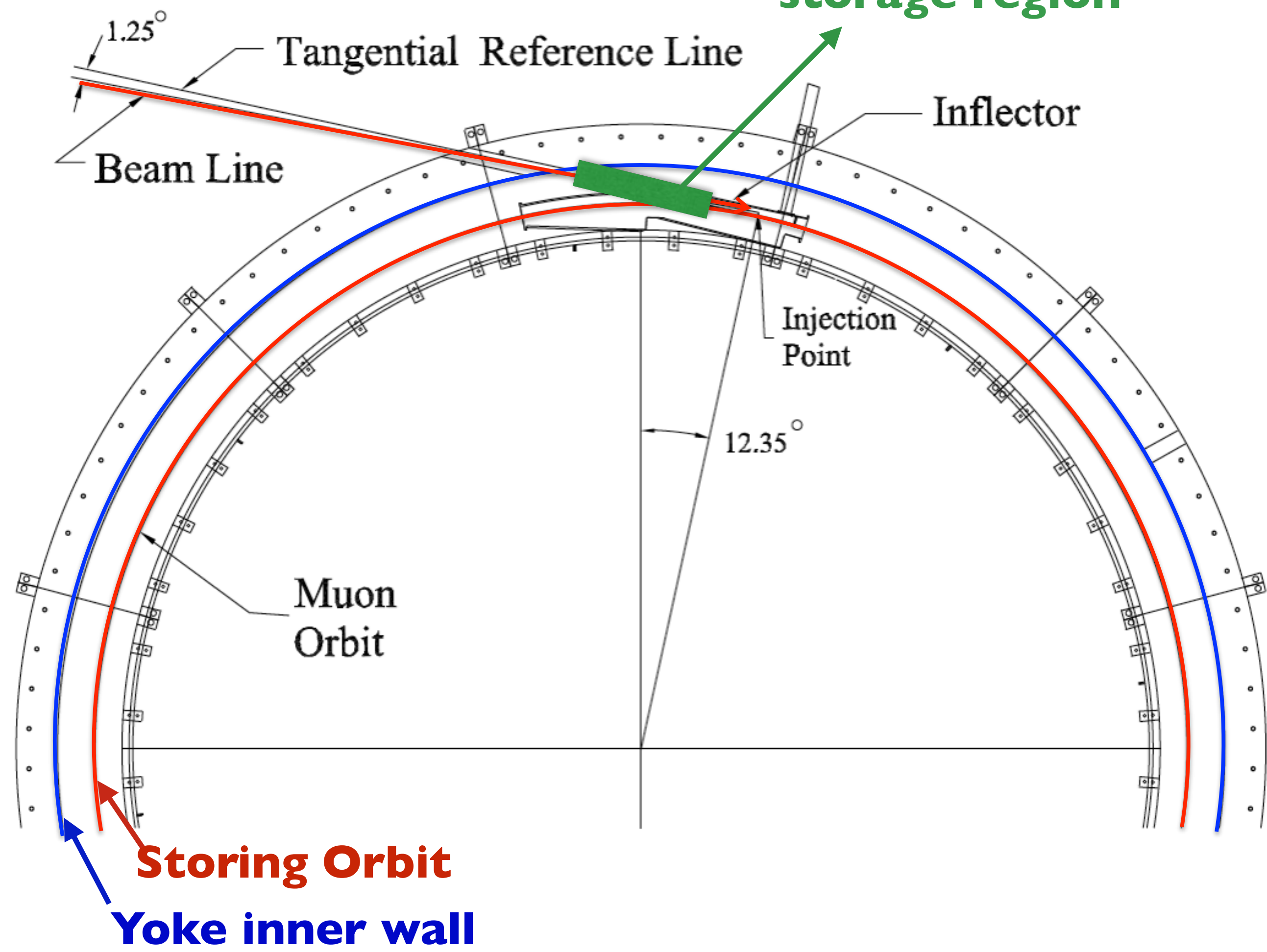
Commissioning:

- Modifying and cleaning: 2016
- Alignment: 2016
- Installation: 2016-2017

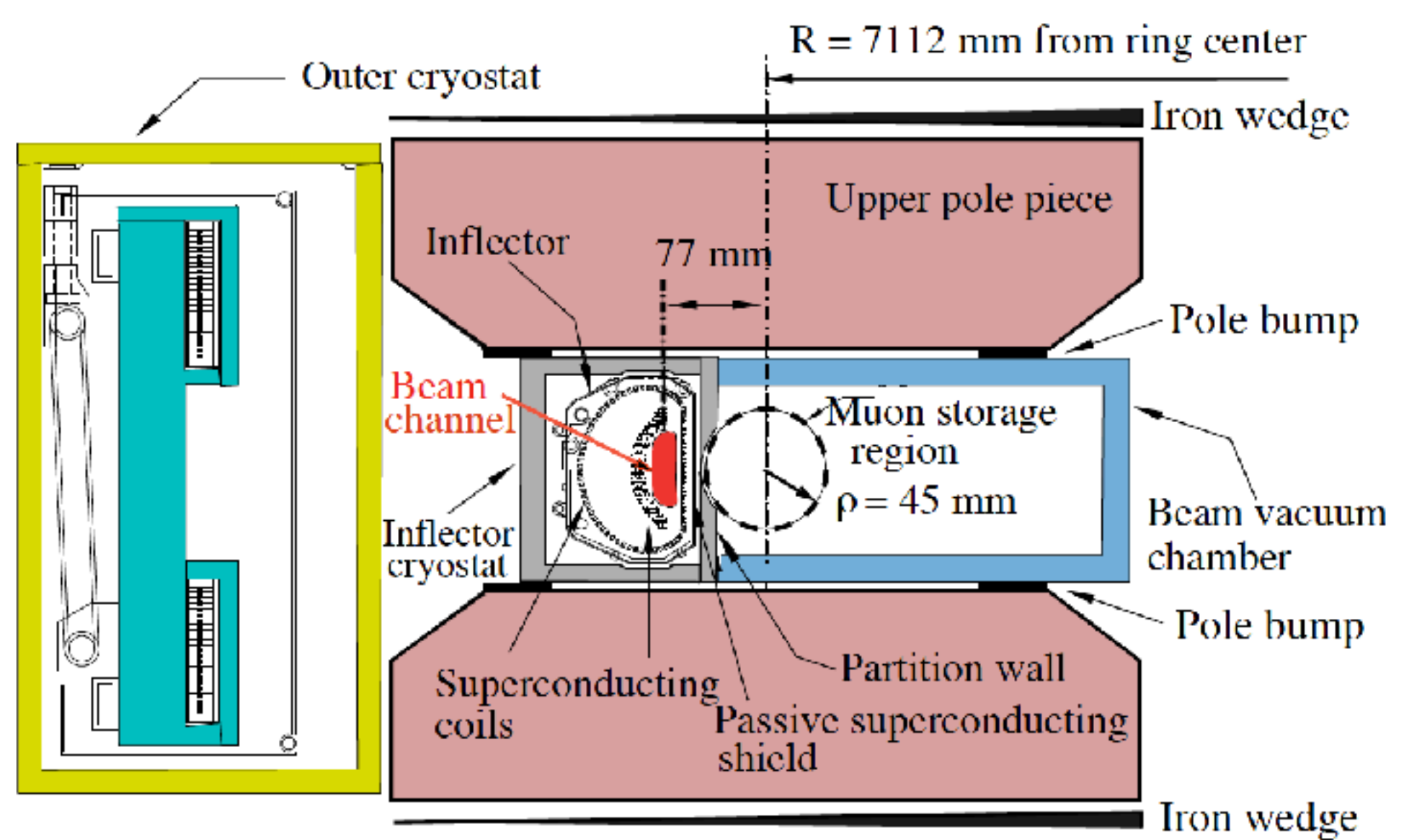


Muon Storage Ring: Inflector

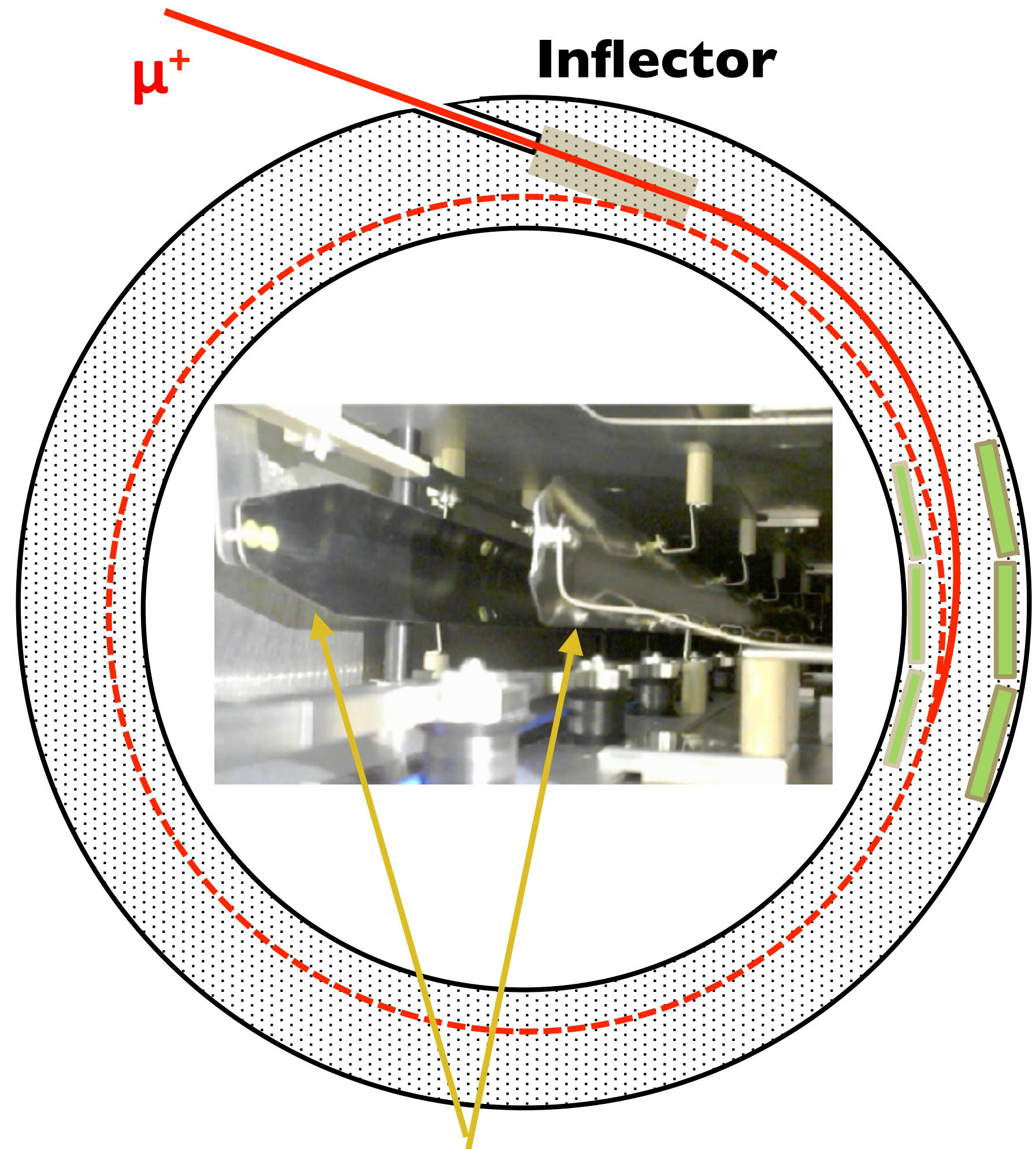
Need to cancel the fringe field before the muons reach the storage region



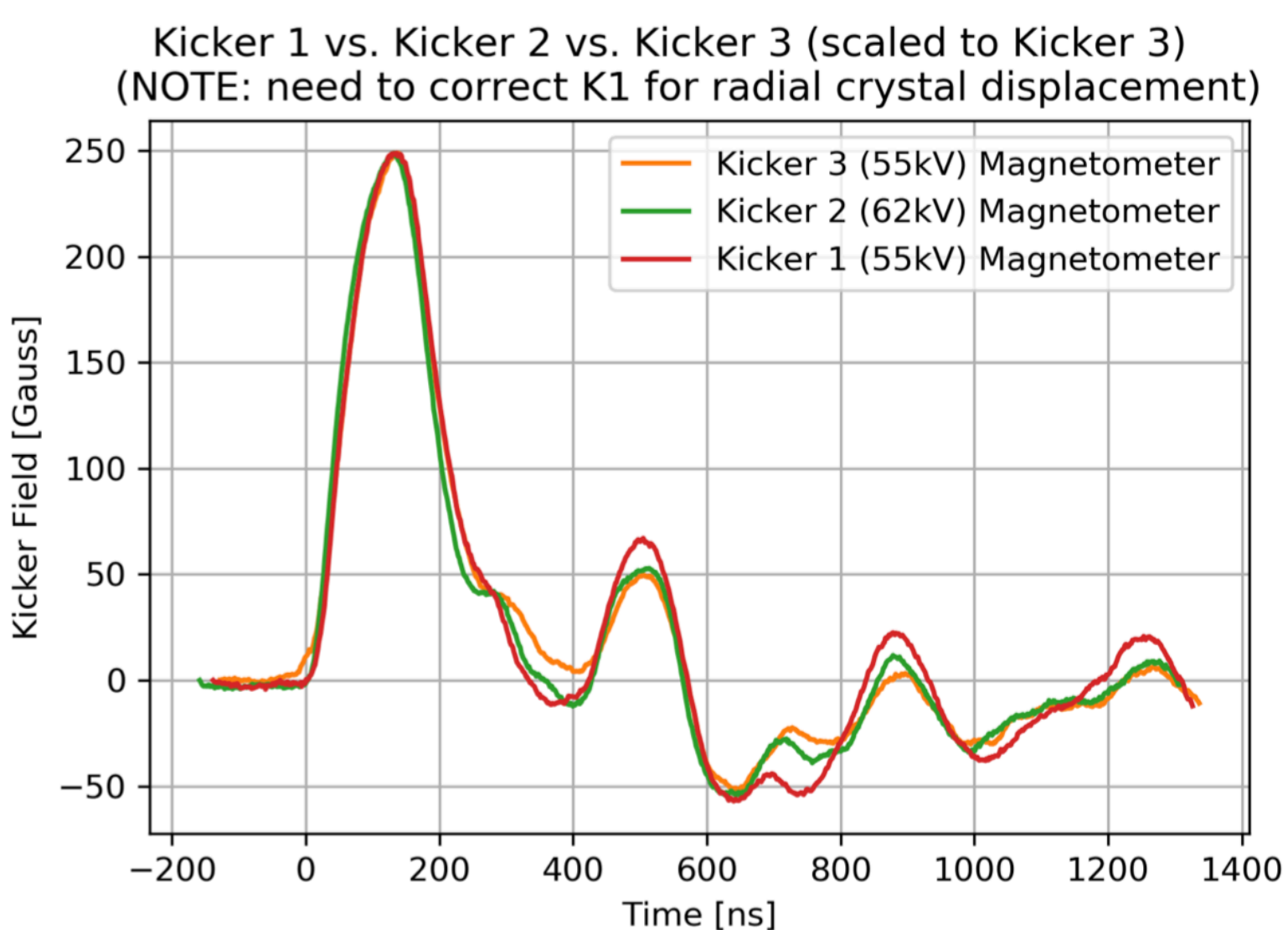
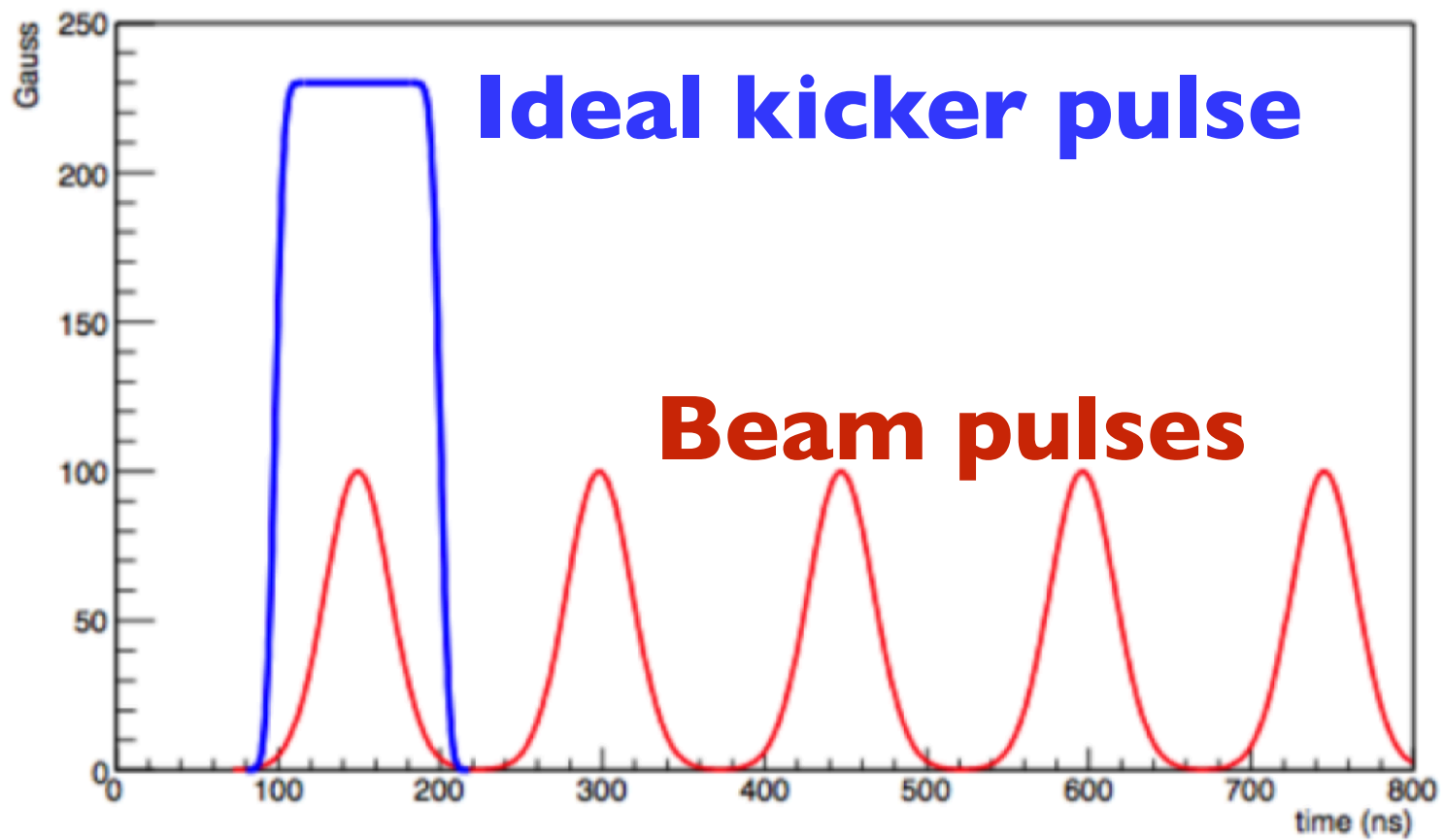
- Commissioning:**
- Installation: Oct 2016
 - Cooled down: Dec 2016



Muon Storage Ring: Kicker Magnet



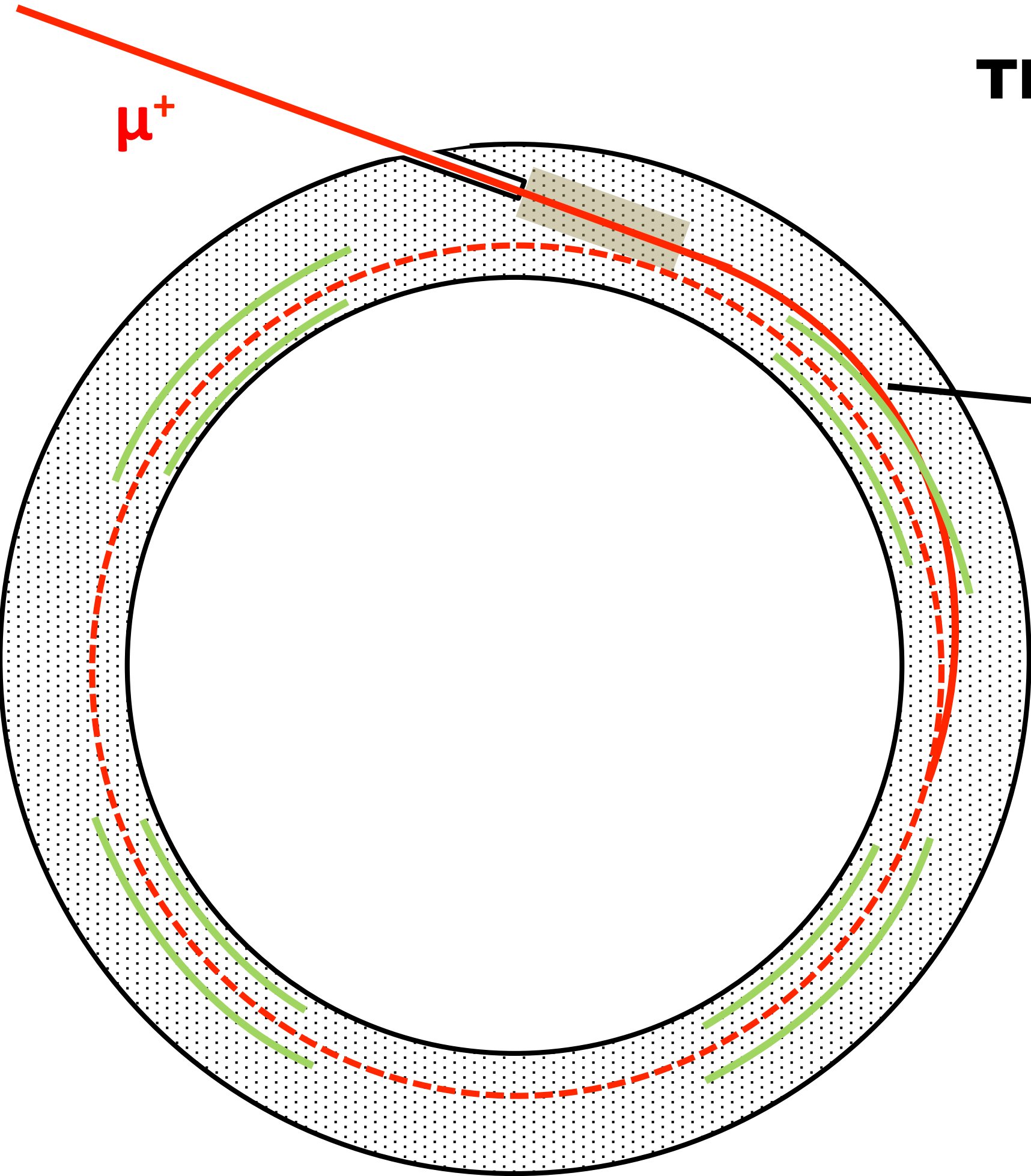
~5000A through the sheets



Measured kicker pulse shapes

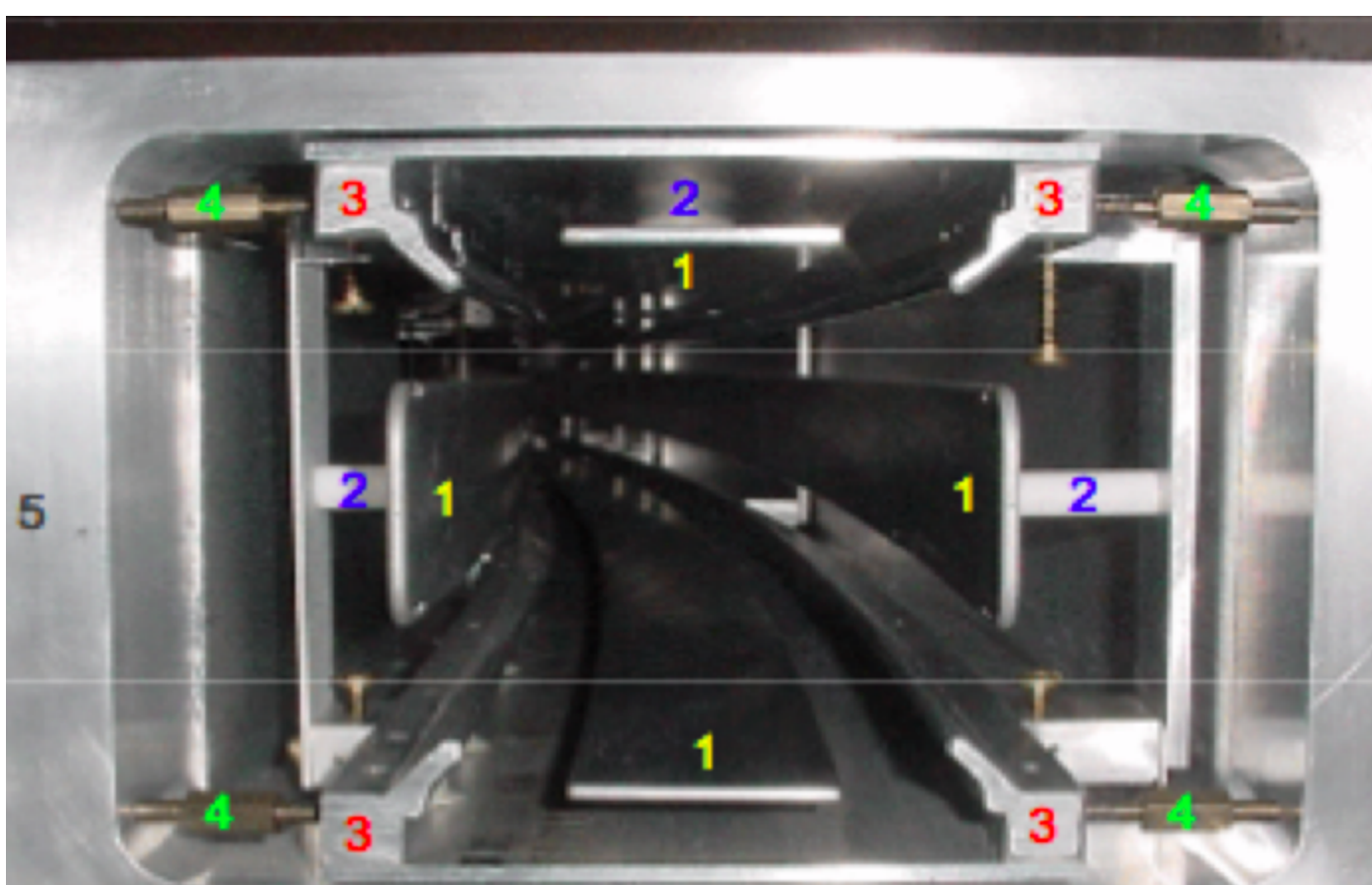
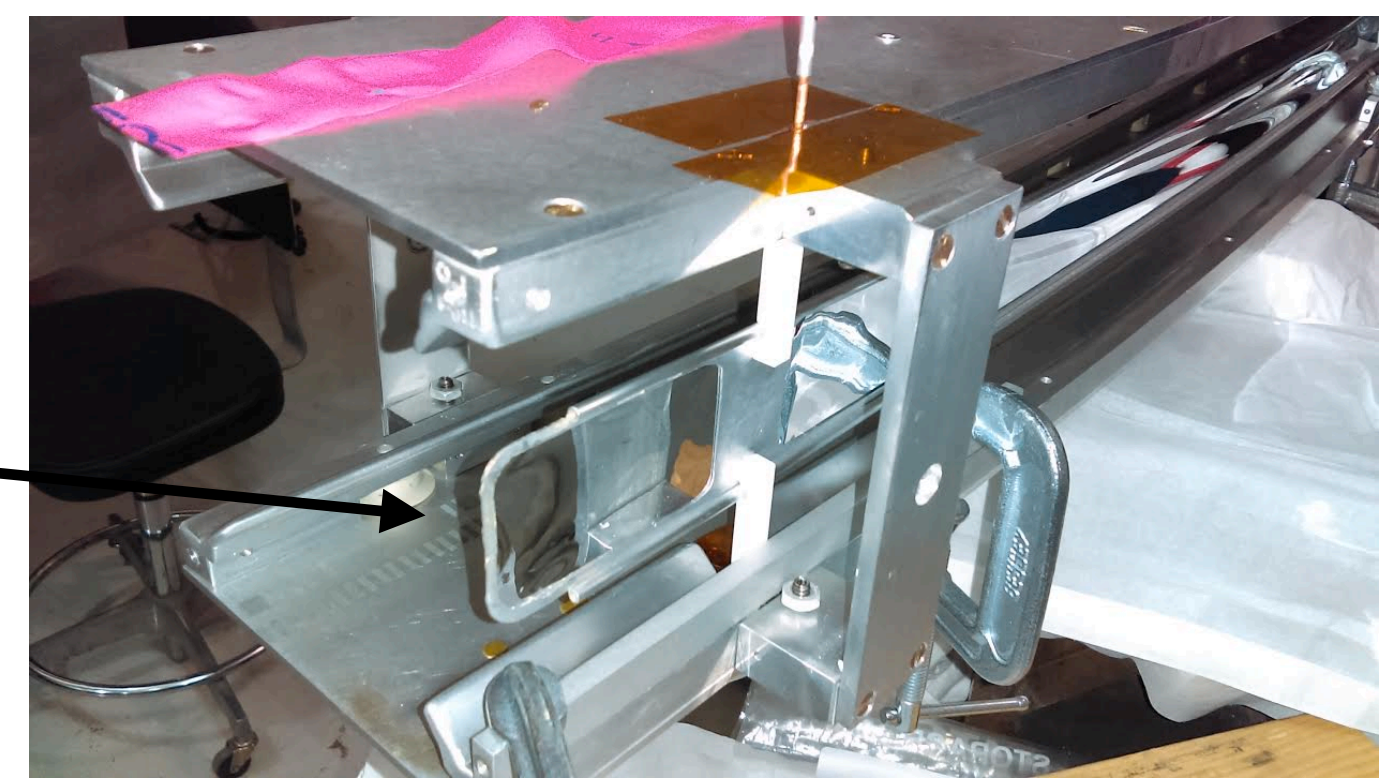
- Commissioning:**
- Installation: Nov 2016 - June 2017
 - Conditioning: Summer 2017
 - Optimization: 2018
 1. Timing optimization
 2. Increasing strength

Muon Storage Ring: Electric Quads



Quadrupole electrodes for beam focusing

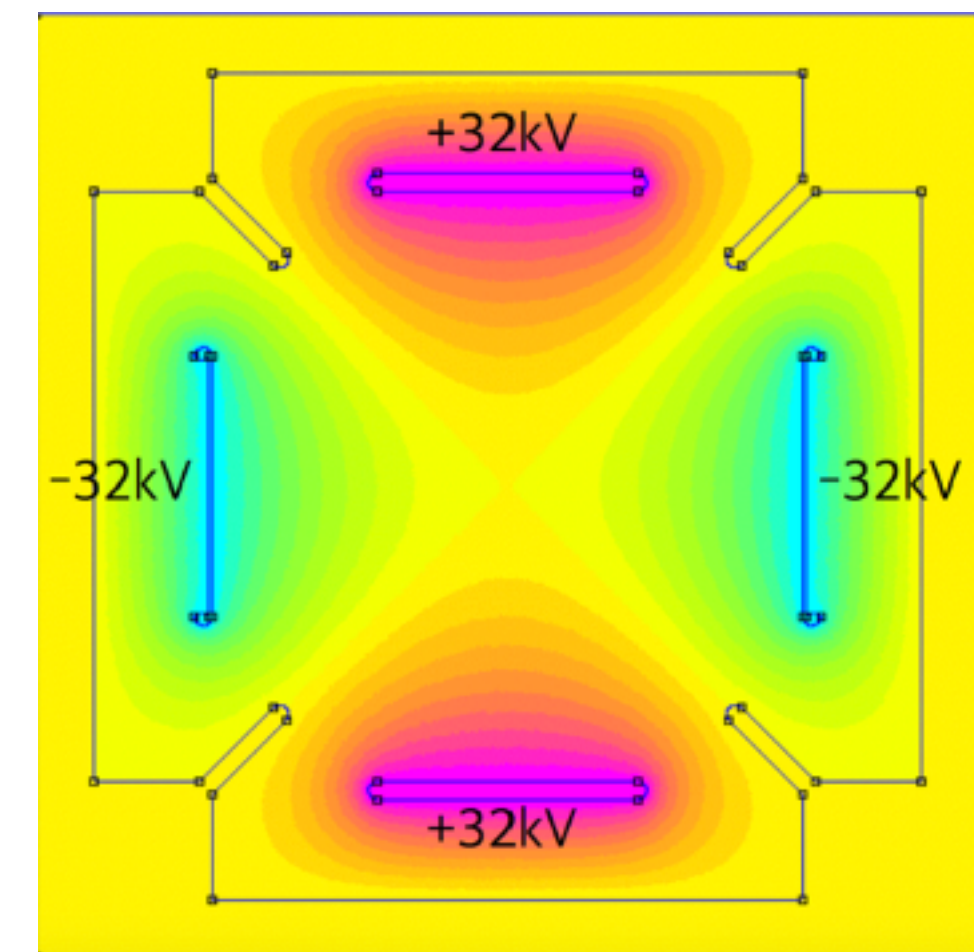
Thin mylar for the outer electrode



1: Quad plates, 2: Stand-offs, 3: Trolley rails, 4: Radial adjustment screws

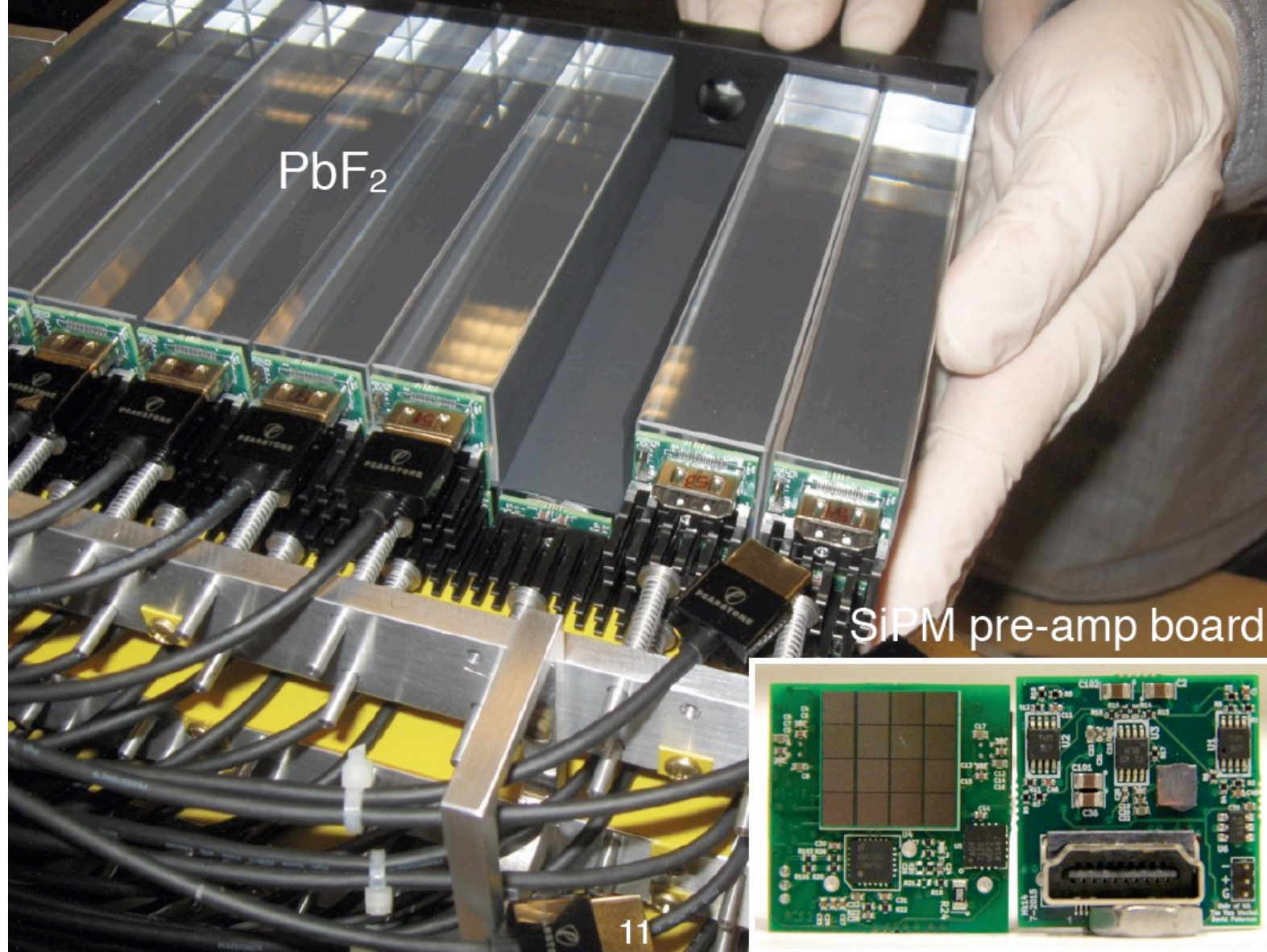
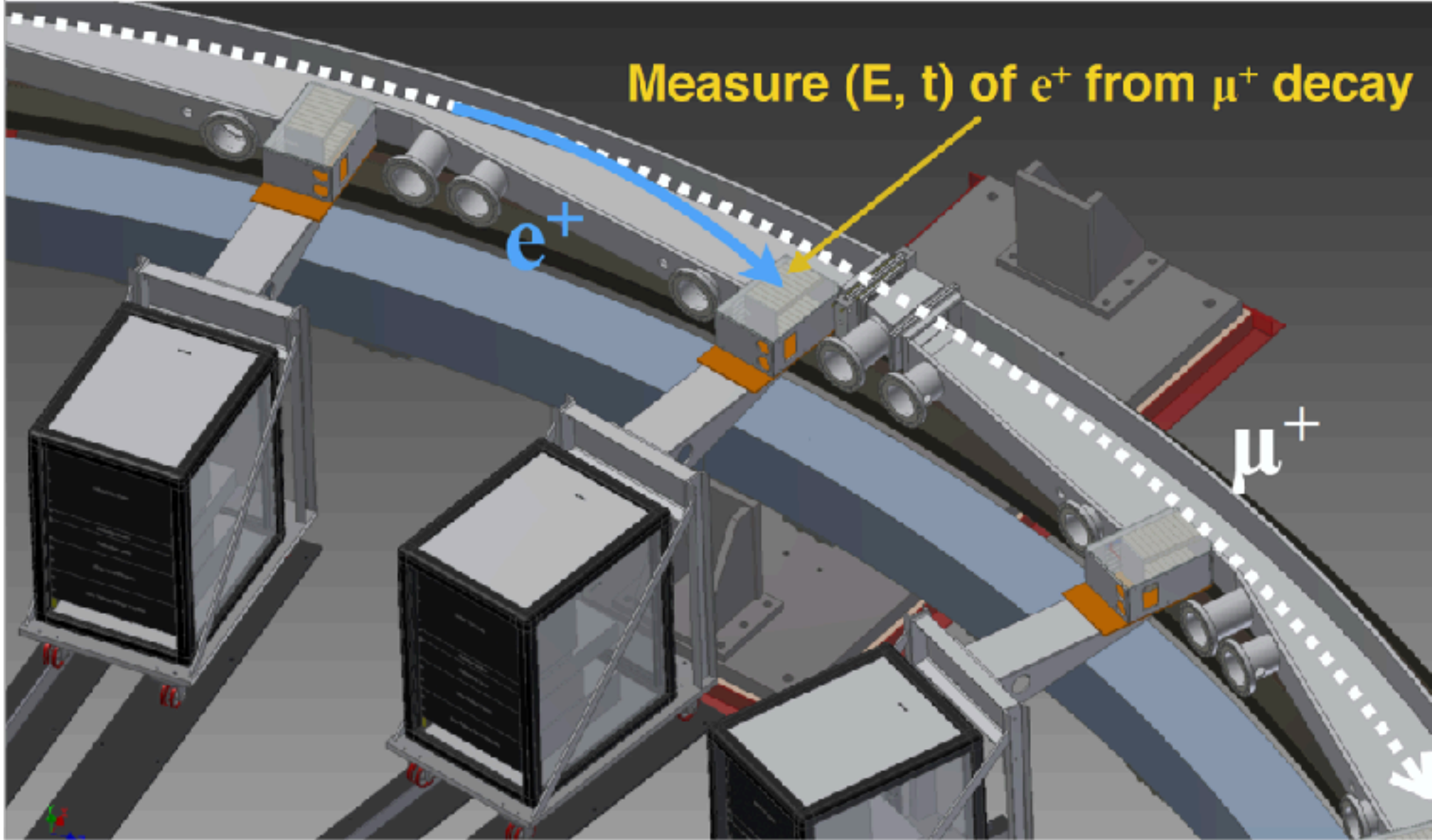
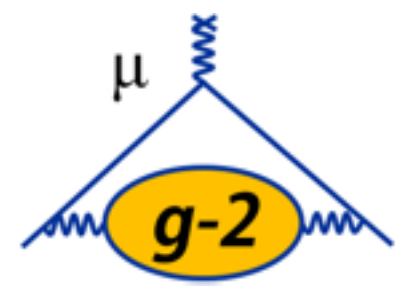
Commissioning:

- Alignment: 2016
- Installation: Early 2017
- Conditioning: June 2017



Field Map (Opera3D)

Detectors: Calorimeters (x24)



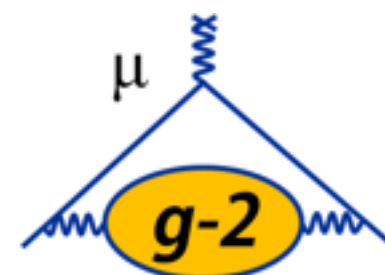
Digitized wave forms for all crystals, template fitting

Upgrades:

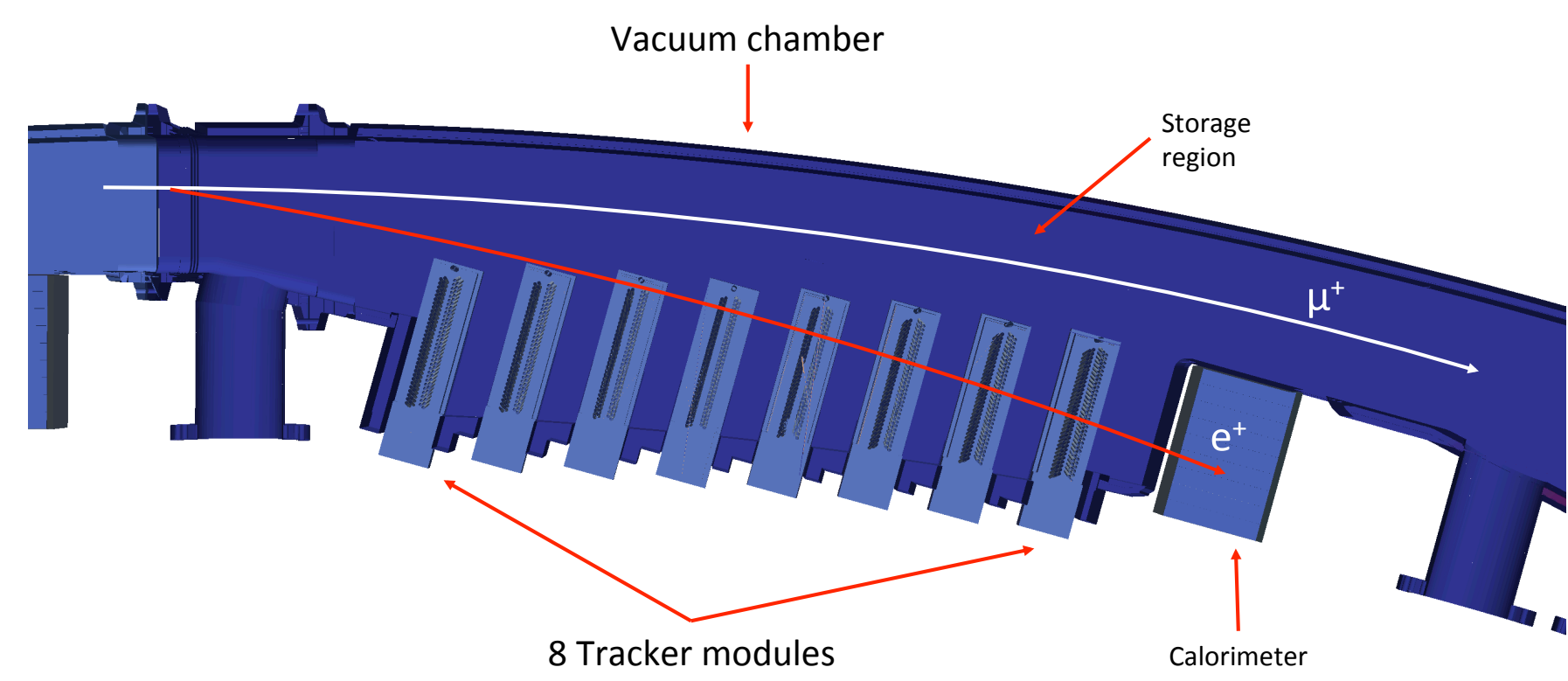
- Pile-up separation: saving digitized waveform and template fitting
- Position sensitivity: read out each crystal
- Gain stability control: Laser calibration system
- Data processing: GPU accelerated pulse finder

Commissioning:

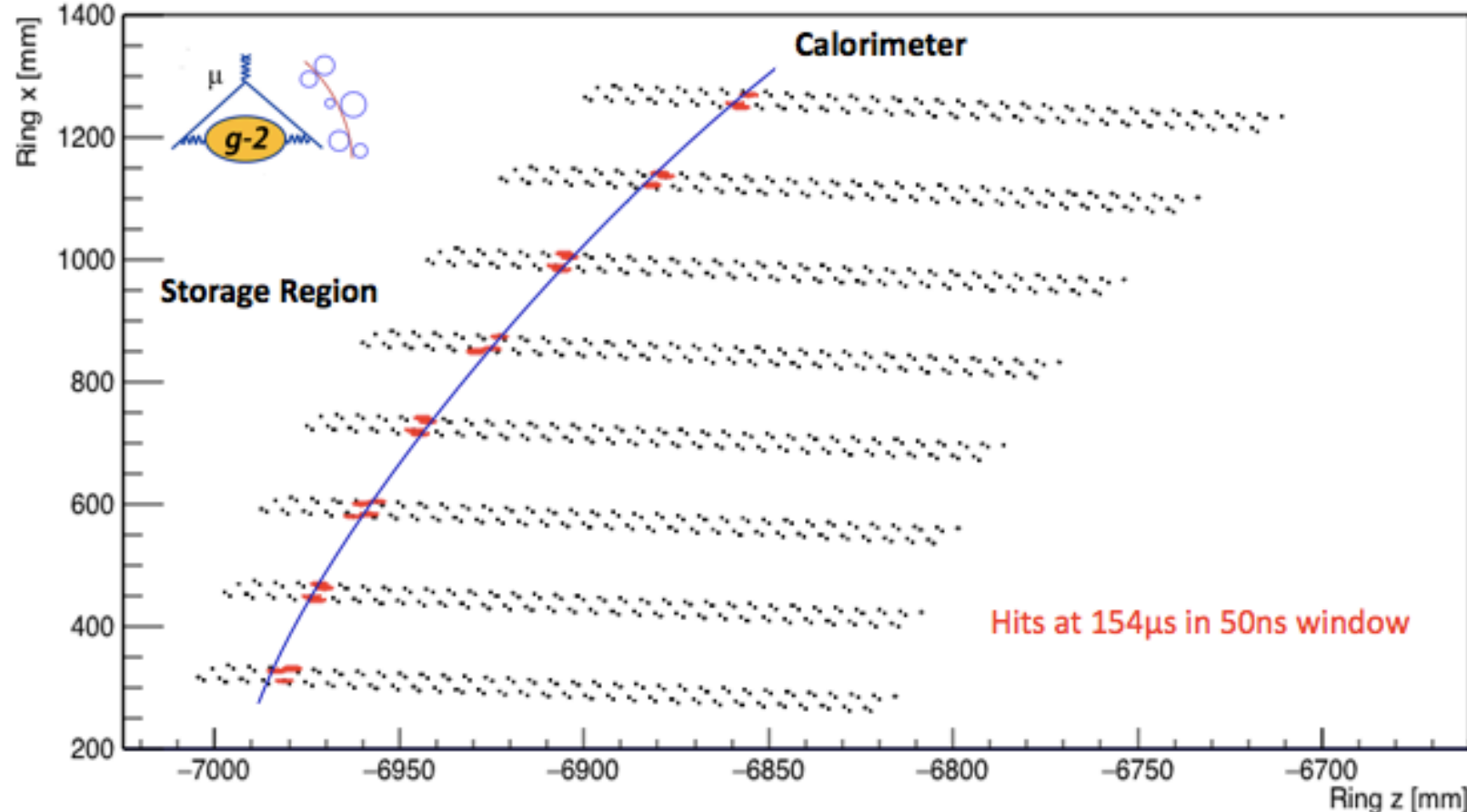
- Fabrication and testing: 2014-2016
- Installation: 2016-2017



Detectors: Straw Trackers (x2)



Track reconstruction

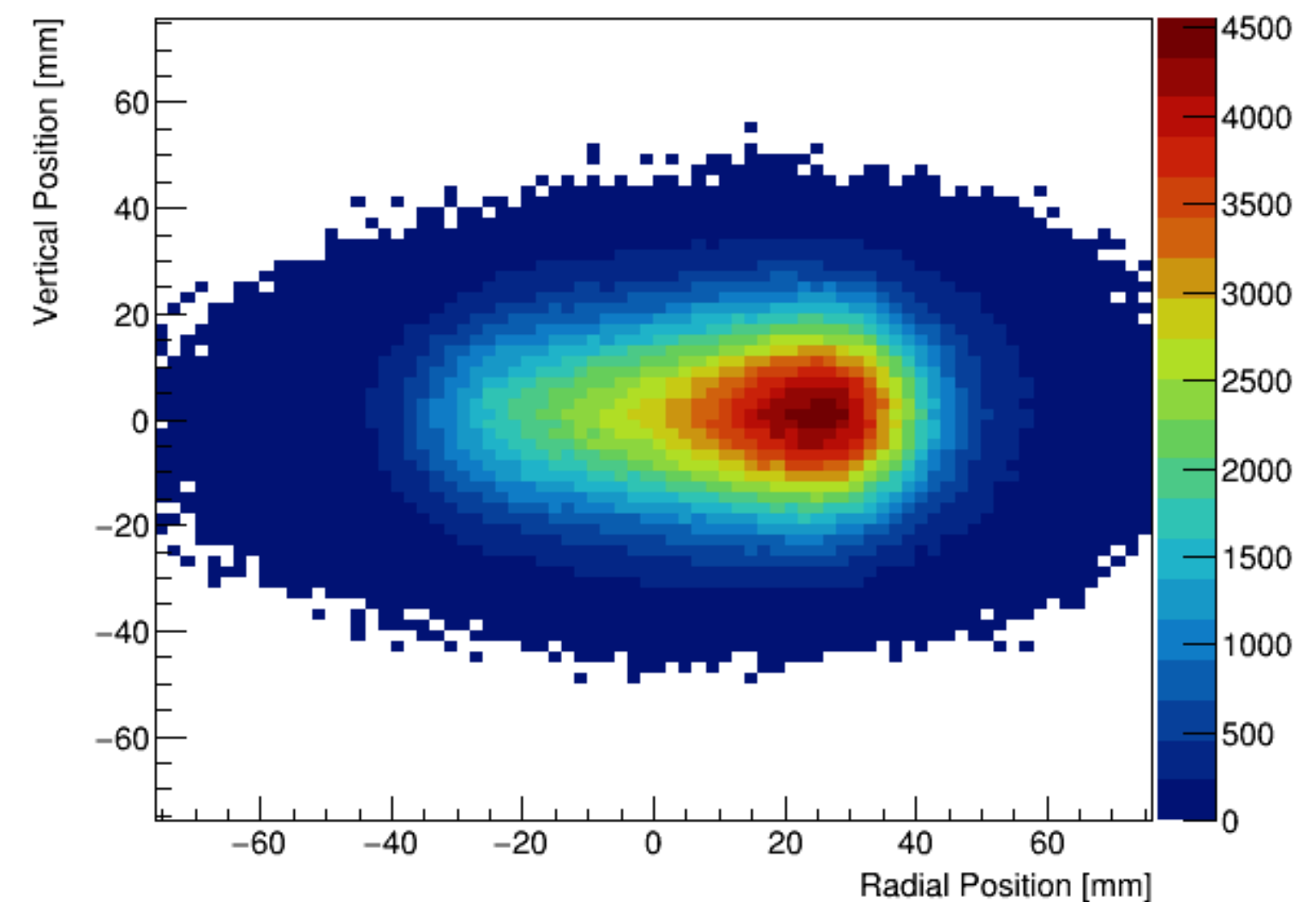


Upgrades:

- In vacuum tracking: better beam position retrieval
- Minimize scattering: Thin straw walls



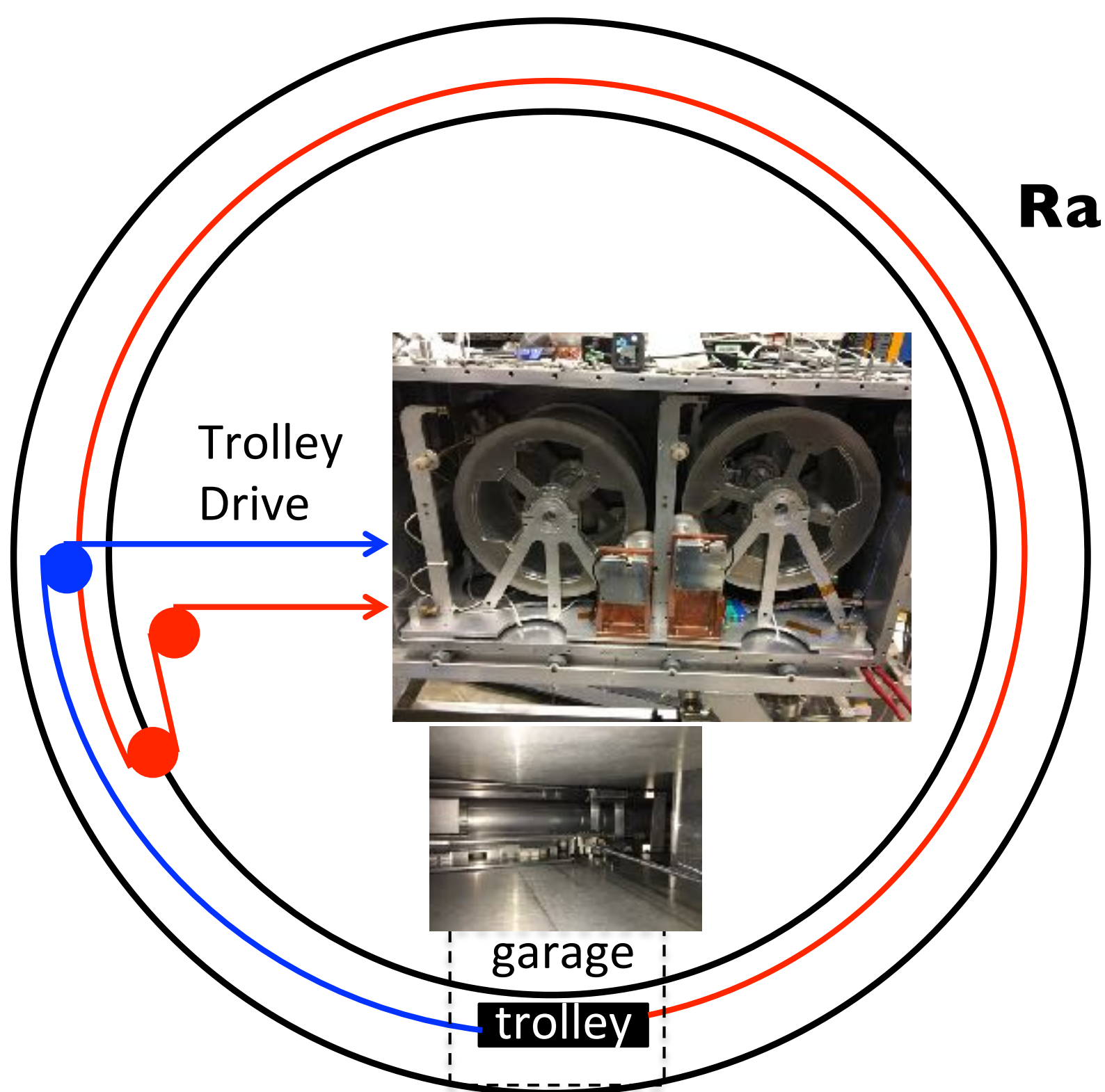
Beam distribution



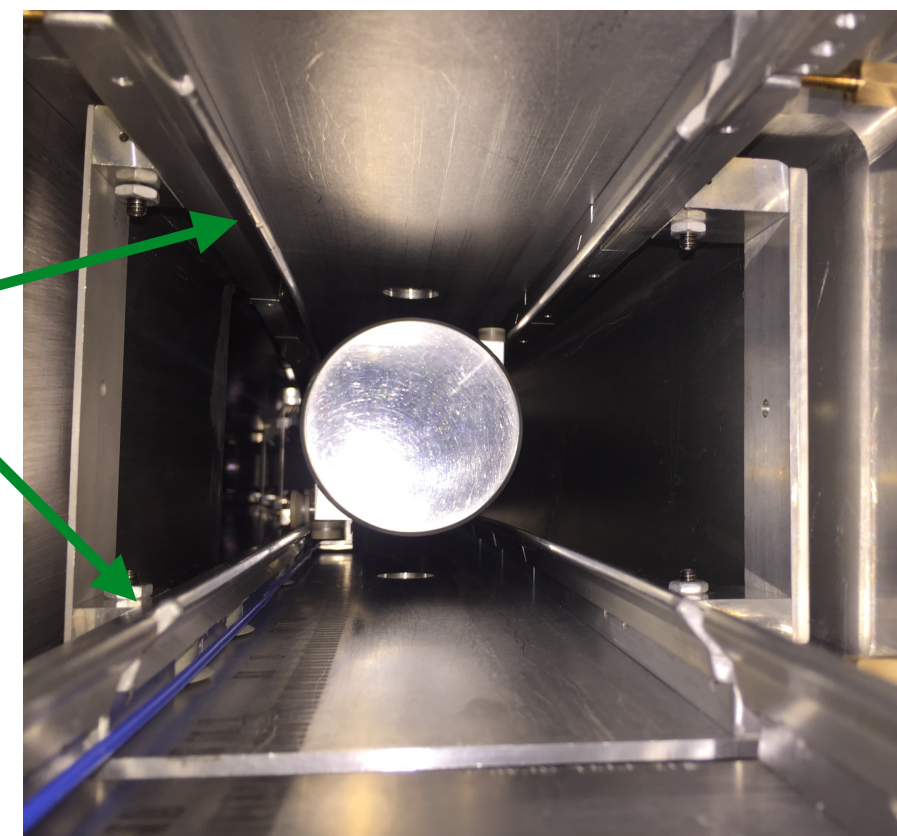
Commissioning:

- Fabrication and testing: ~2016
- Installation
 1. Tracker 1: May 2017
 2. Tracker 2: Dec 2017

Field Sensors: Field Scanning Trolley



Rails

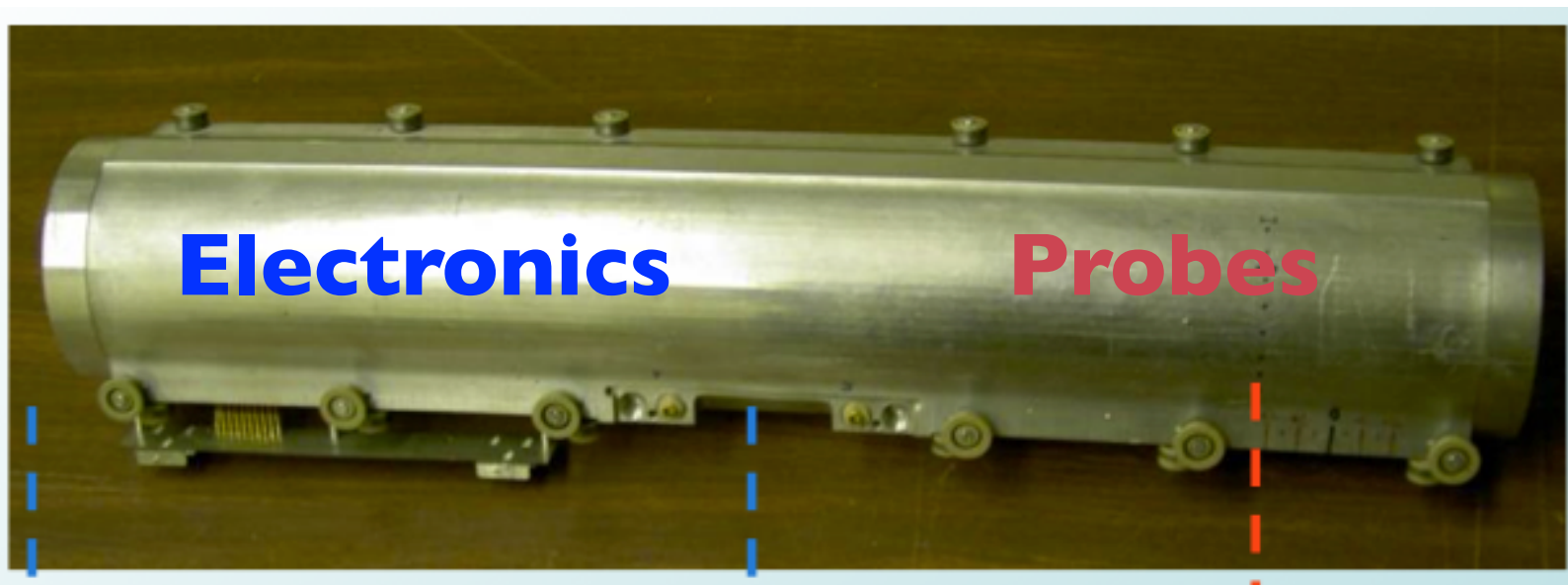


Upgrades:

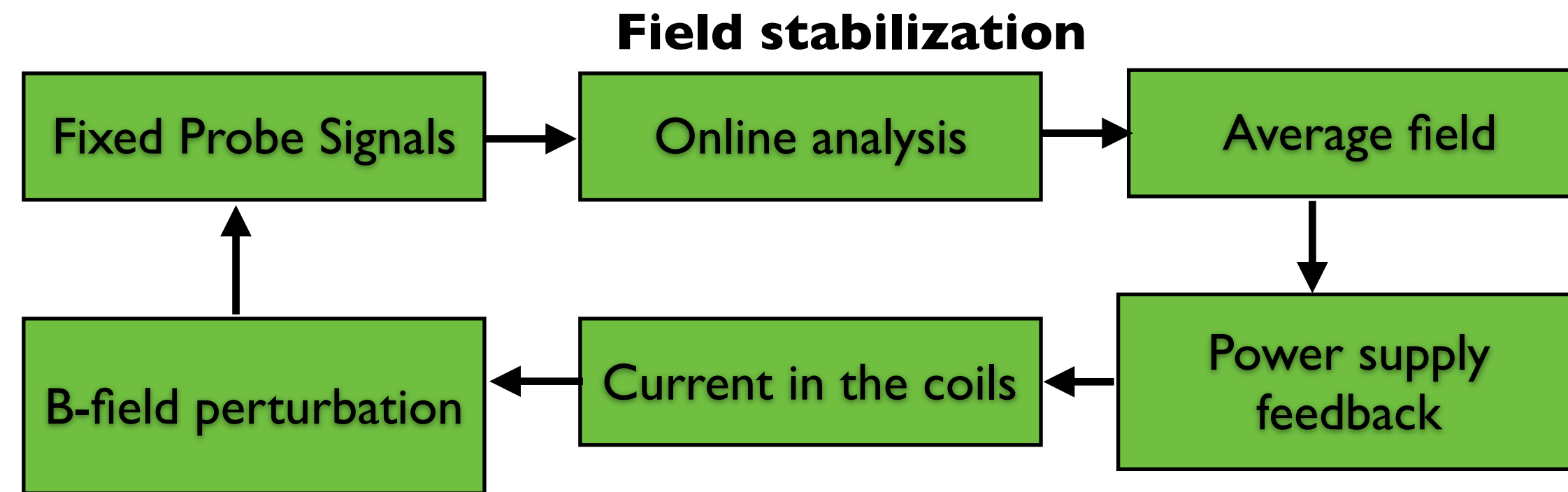
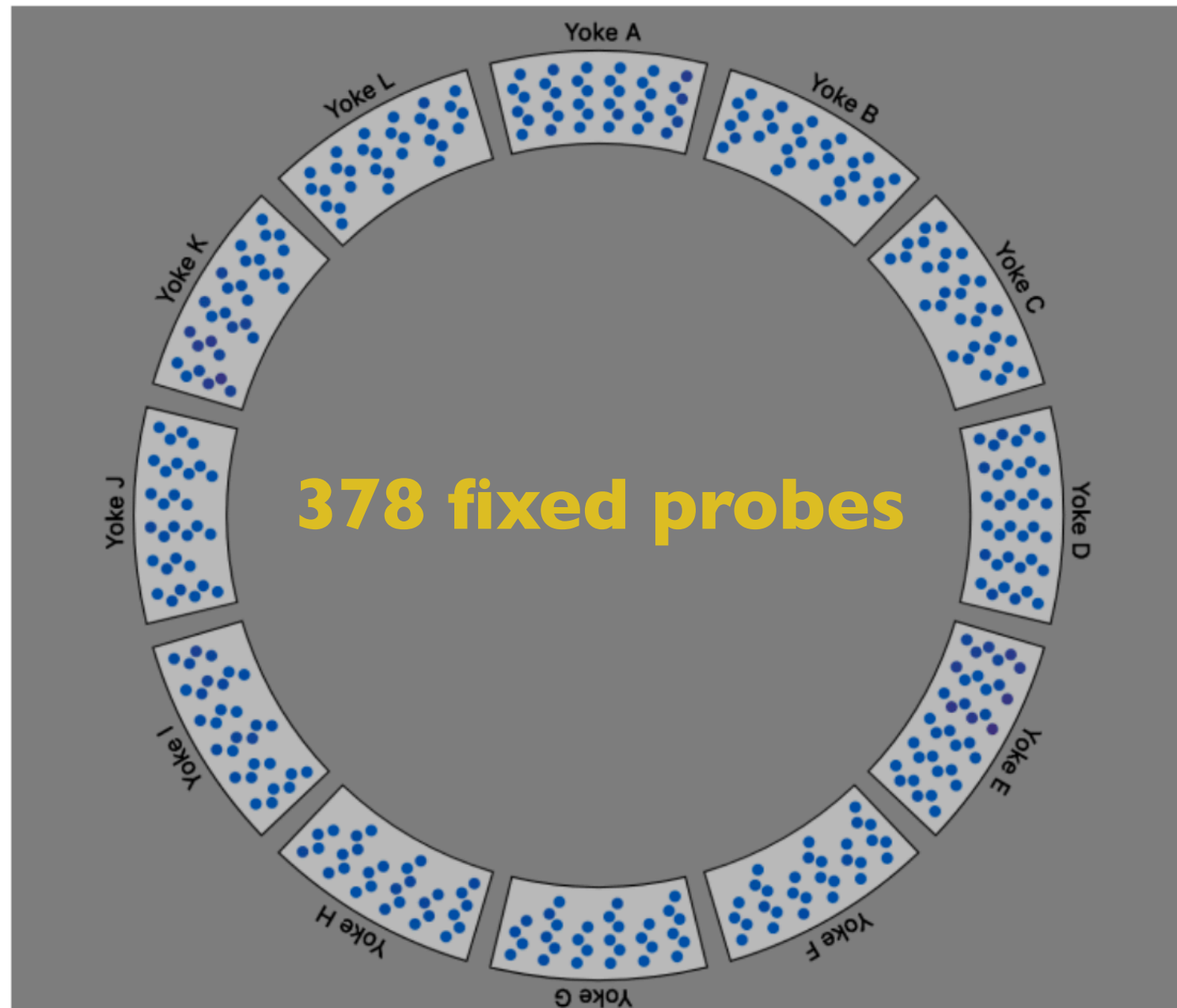
- Automated mechanical motion control
- New probes and electronics: recording fully digitized waveform

Commissioning:

- Design and construction: 2016
- Installation: March 2017
- Resolving interference: March 2017 - March 2018
- Operation and optimization: More automated motion control



Field Sensors: Fixed-Probe Drift Monitors and fluxgates



Upgrades:

- New probes: petroleum jelly (no leak)
- GPU accelerated online analysis: 1.67s per measurement

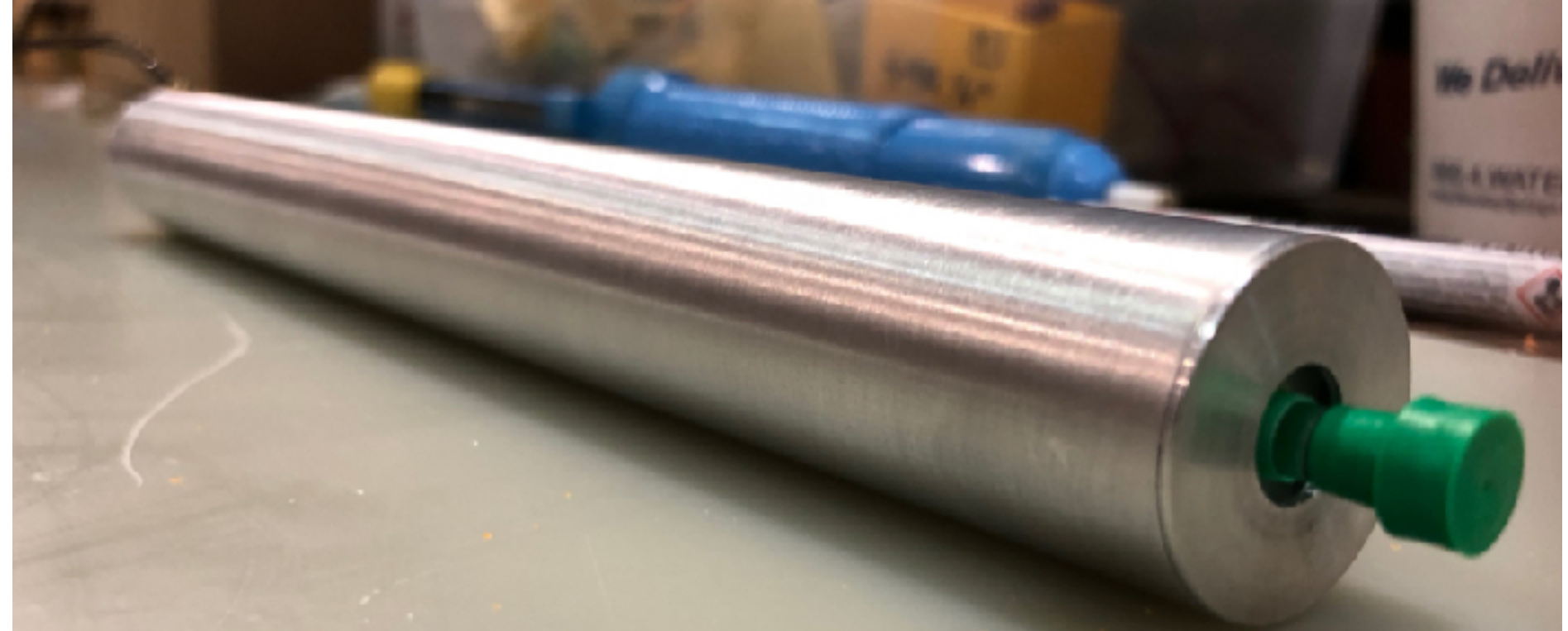
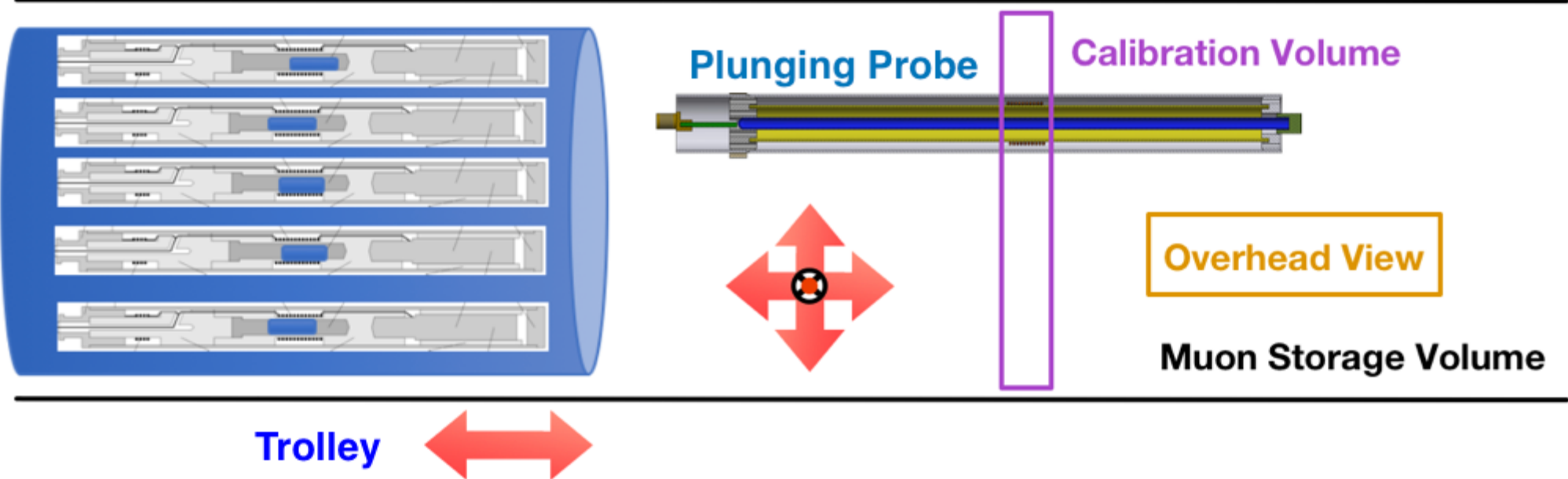
Commissioning:

- Building probes: 2015
- Constructing electronics: 2016-2017
- Installation: 2016-2017

Field Sensors: Calibration Probes

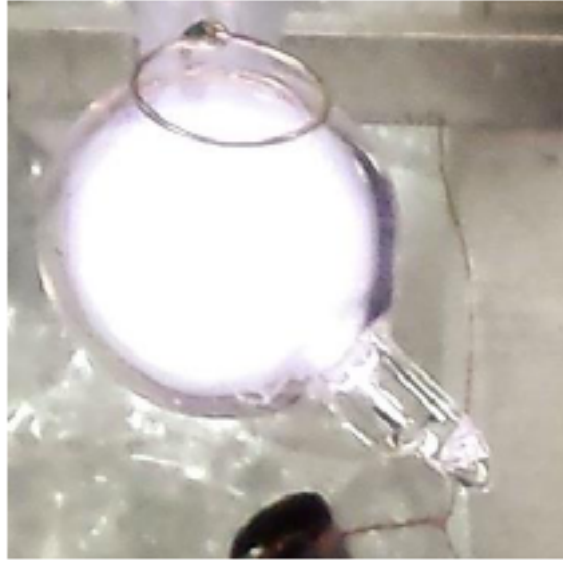


“Plunging” Probe



- Align with each trolley probe in vacuum
- Correct for systematic shifts

³He Probe

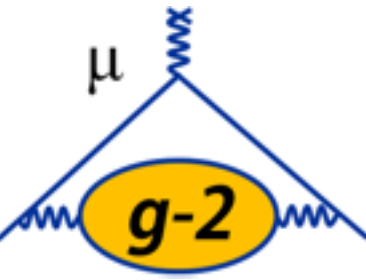


Spherical Water Probe



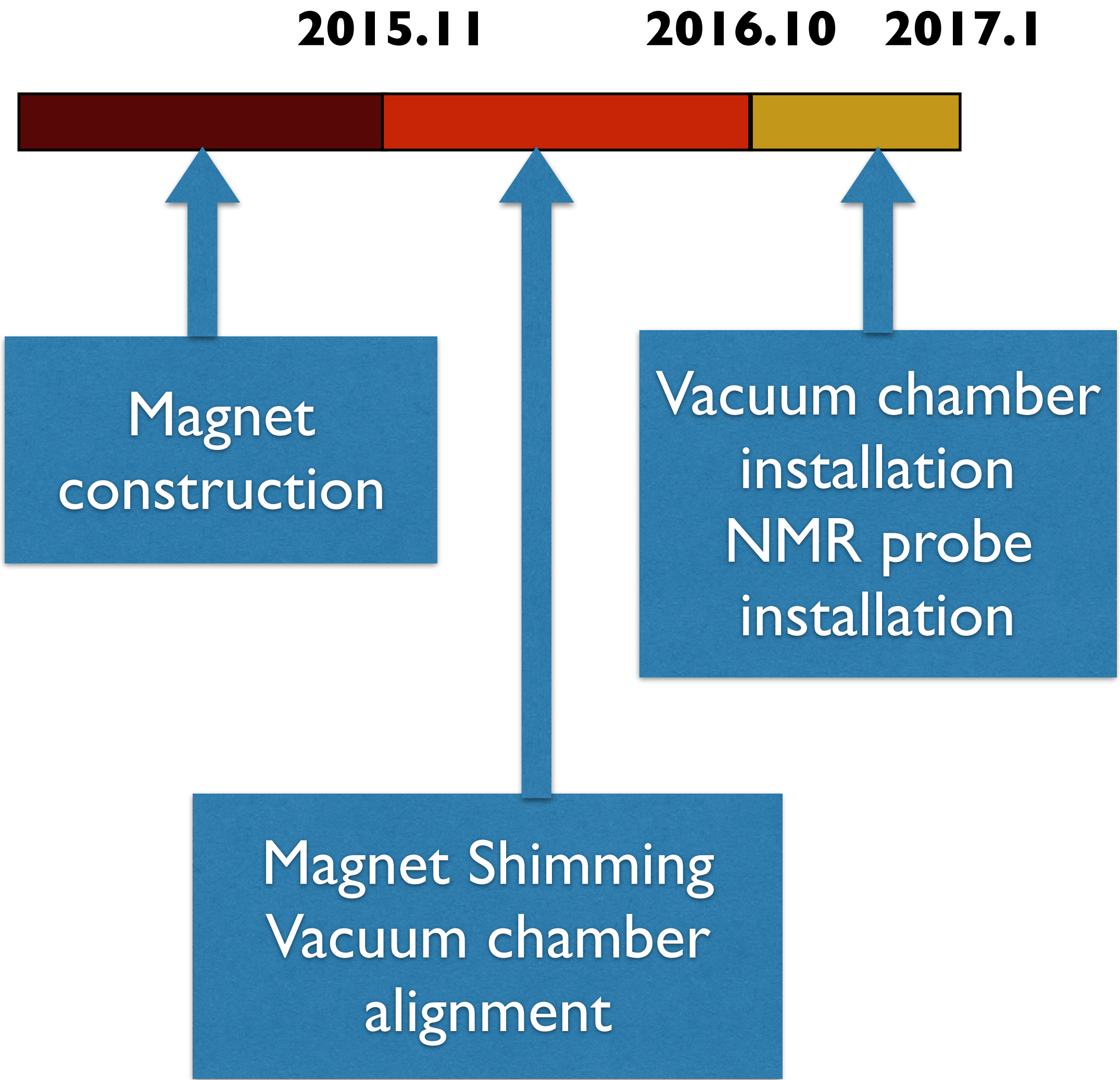
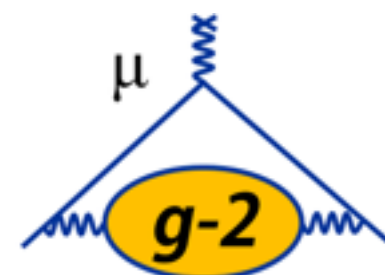
Commissioning:

- Plunging probe assembled and installed: 2018
- Calibration: on-going
- Helium probe and spherical water probe: testing



- ▶ **Review of the progress (2015 ~ 2018)**
- ▶ **Current status**
- ▶ **Upcoming events**
- ▶ **Short-term improvements**

Review of the Progress (2015~2018)





Review of the Progress (2015~2018)

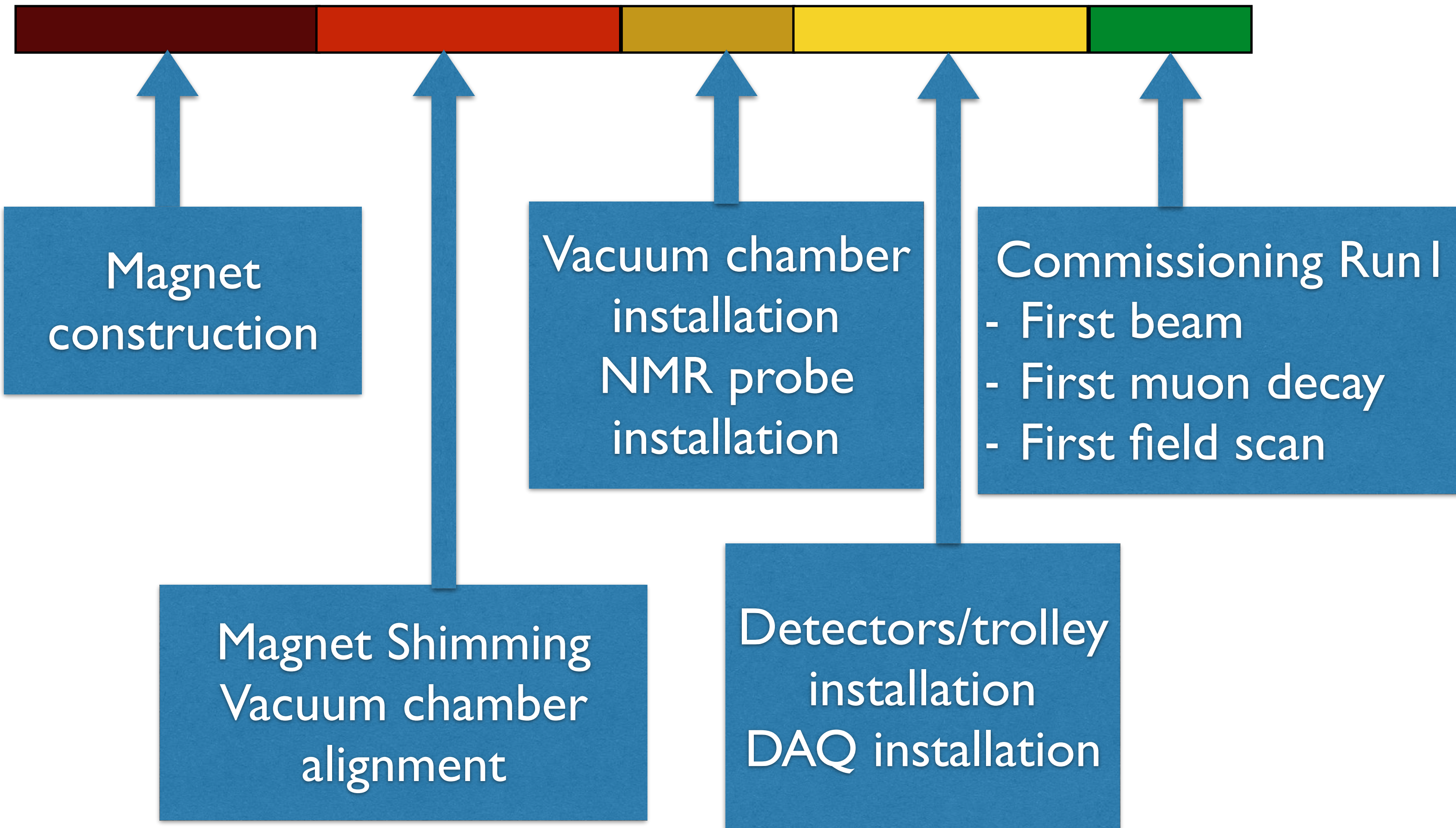
2015.11

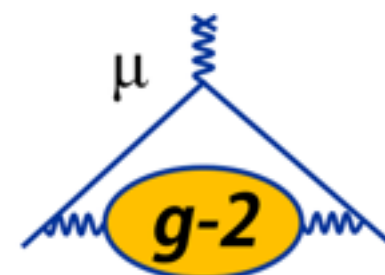
2016.10

2017.1

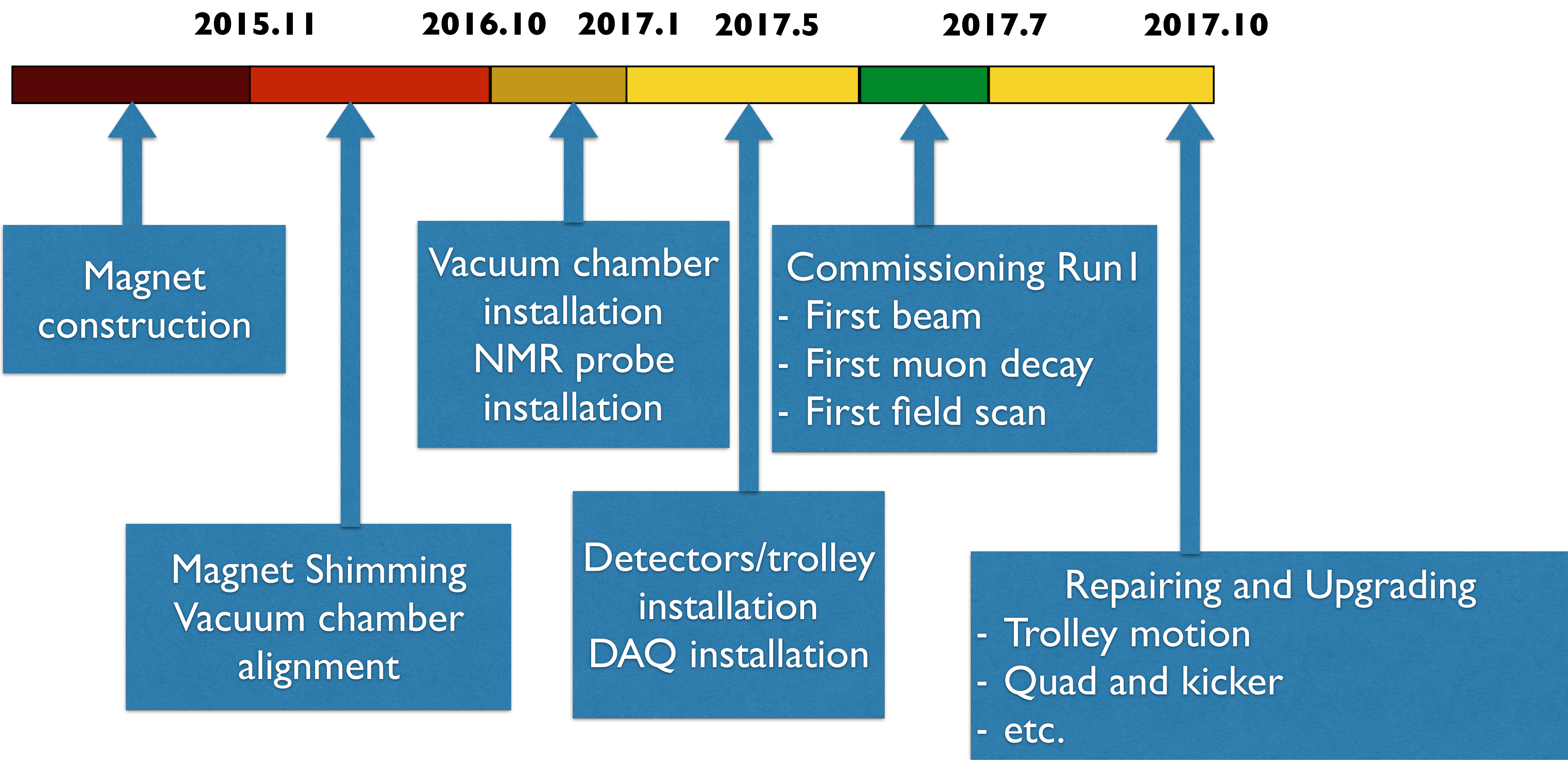
2017.5

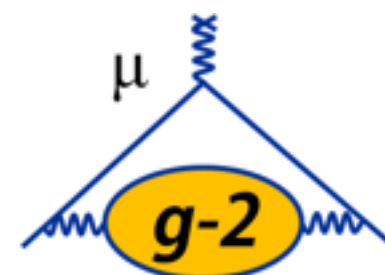
2017.7



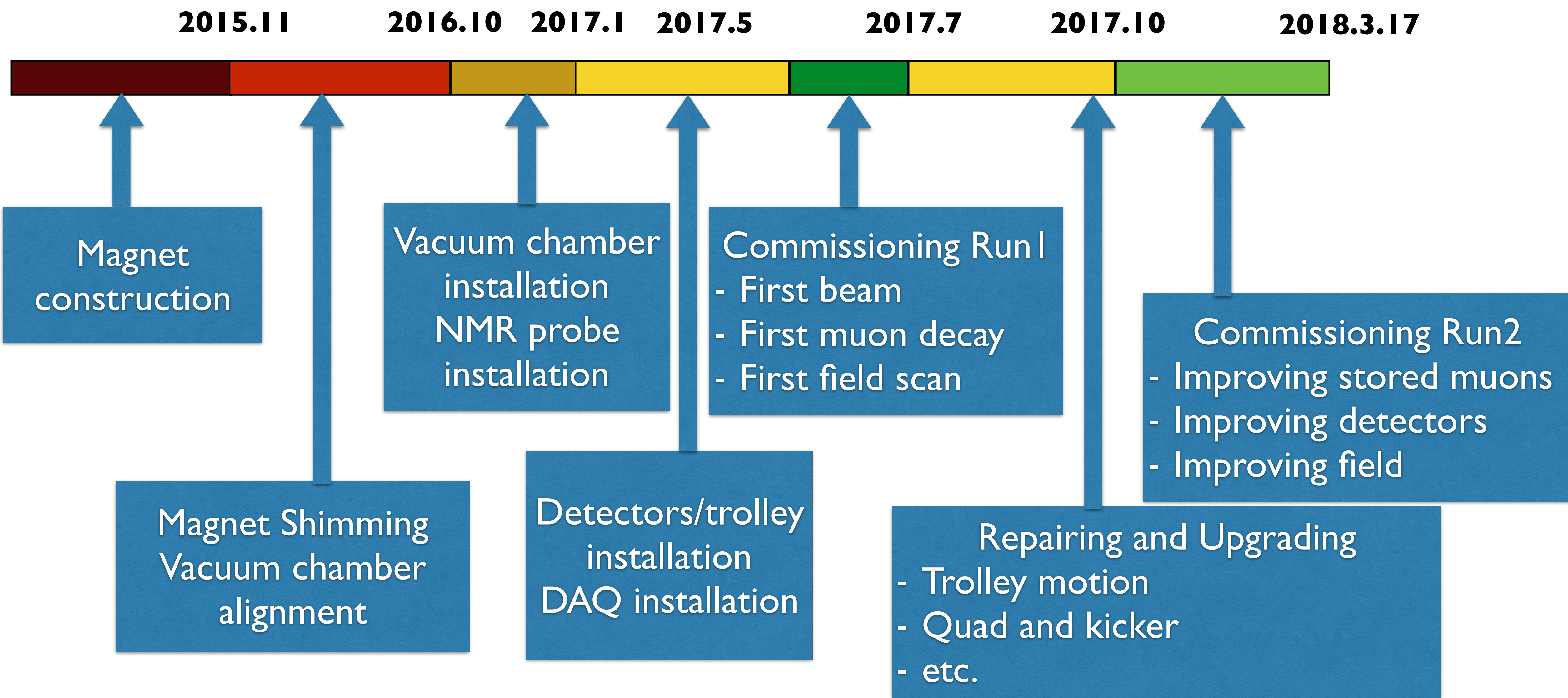


Review of the Progress (2015~2018)

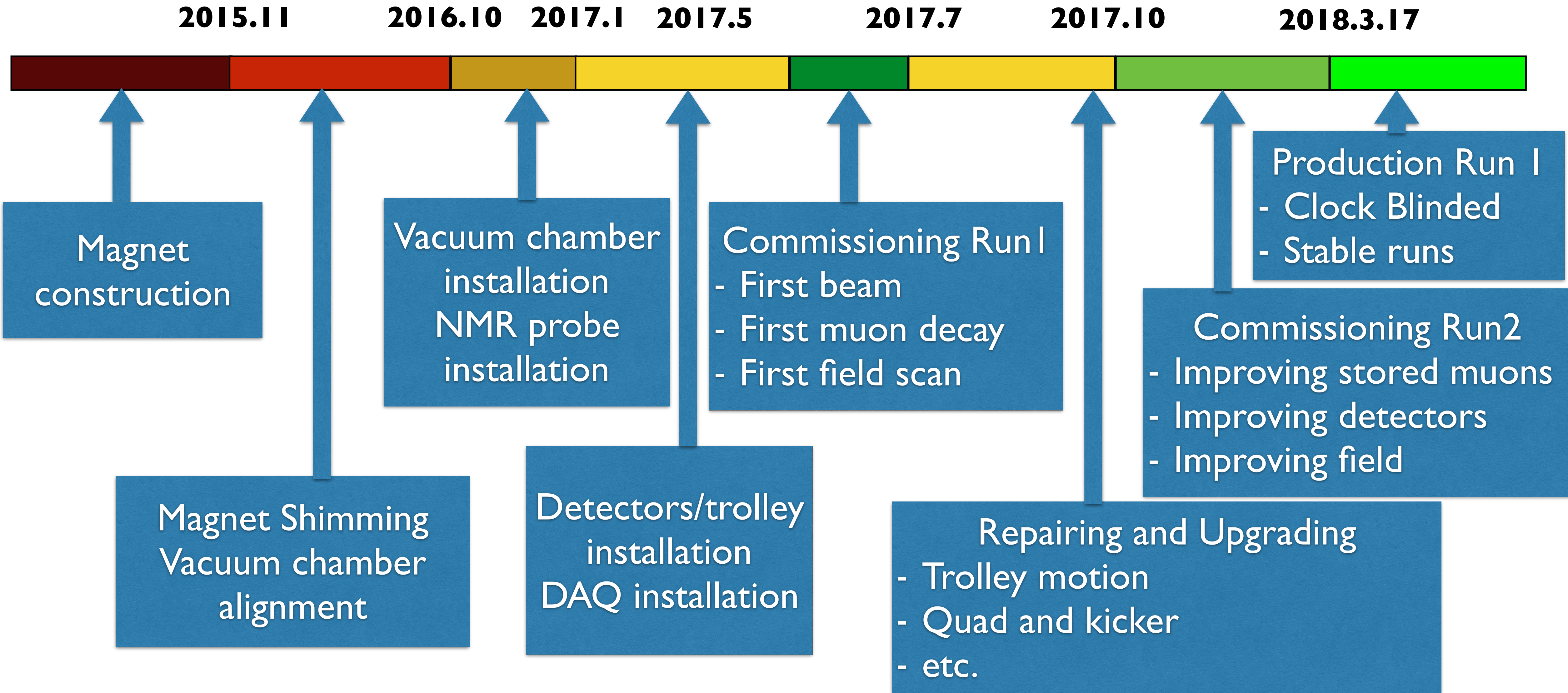
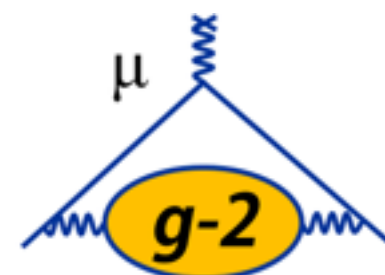




Review of the Progress (2015~2018)

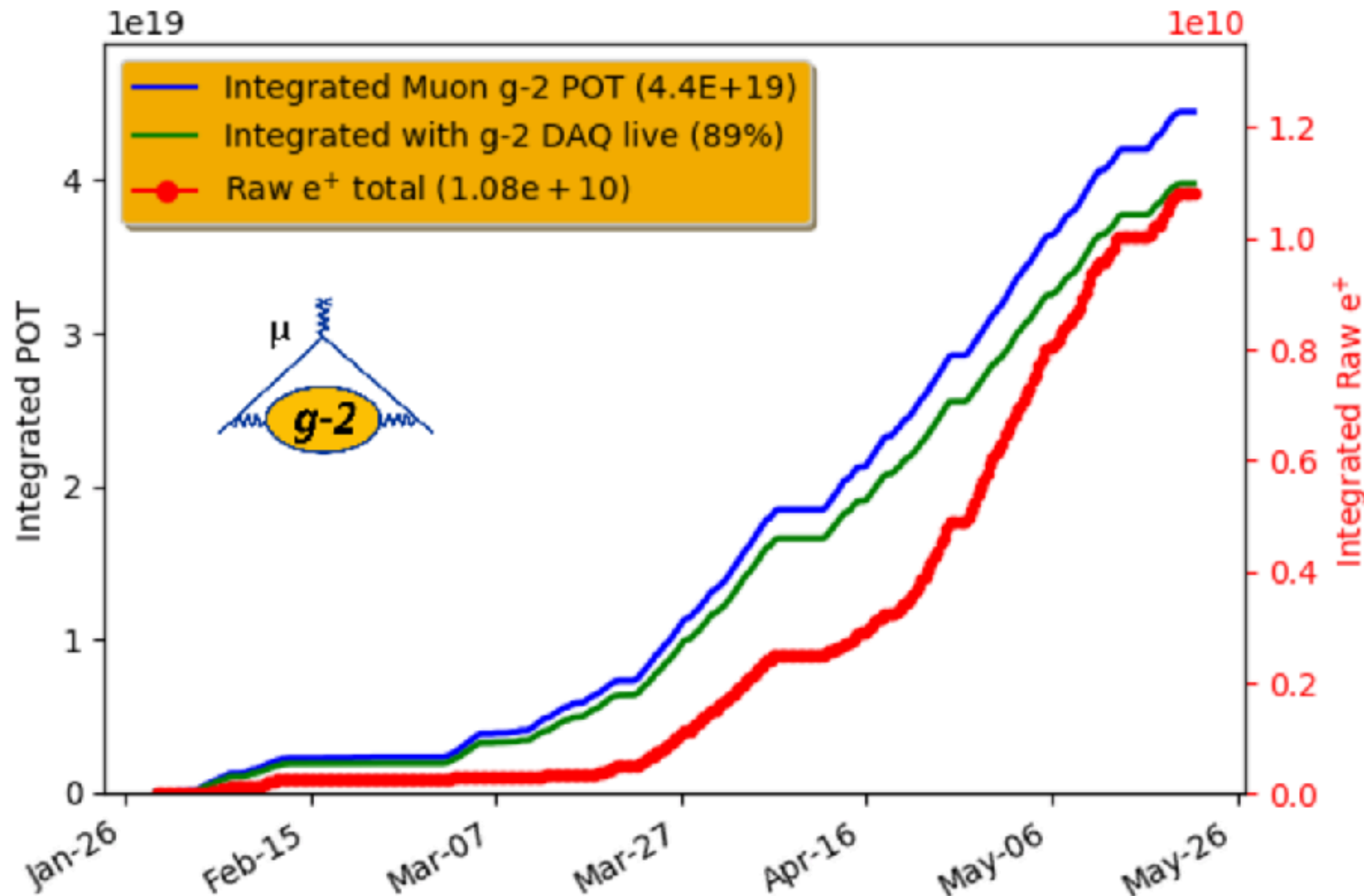


Review of the Progress (2015~2018)





Experiment Progress



Beam Performance:

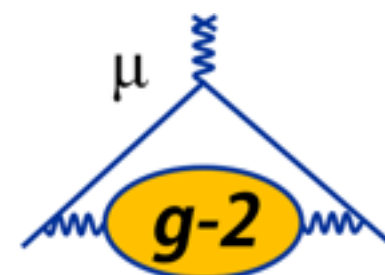
- Quads and kickers experienced several major repairs, but are improved significantly in 2018

Field Performance:

- >30 successful trolley runs (field scans)
- 100% DAQ UP time since 3/17/2018
- Field monitors are ON for all field-up time
- Magnet uptime > 95%

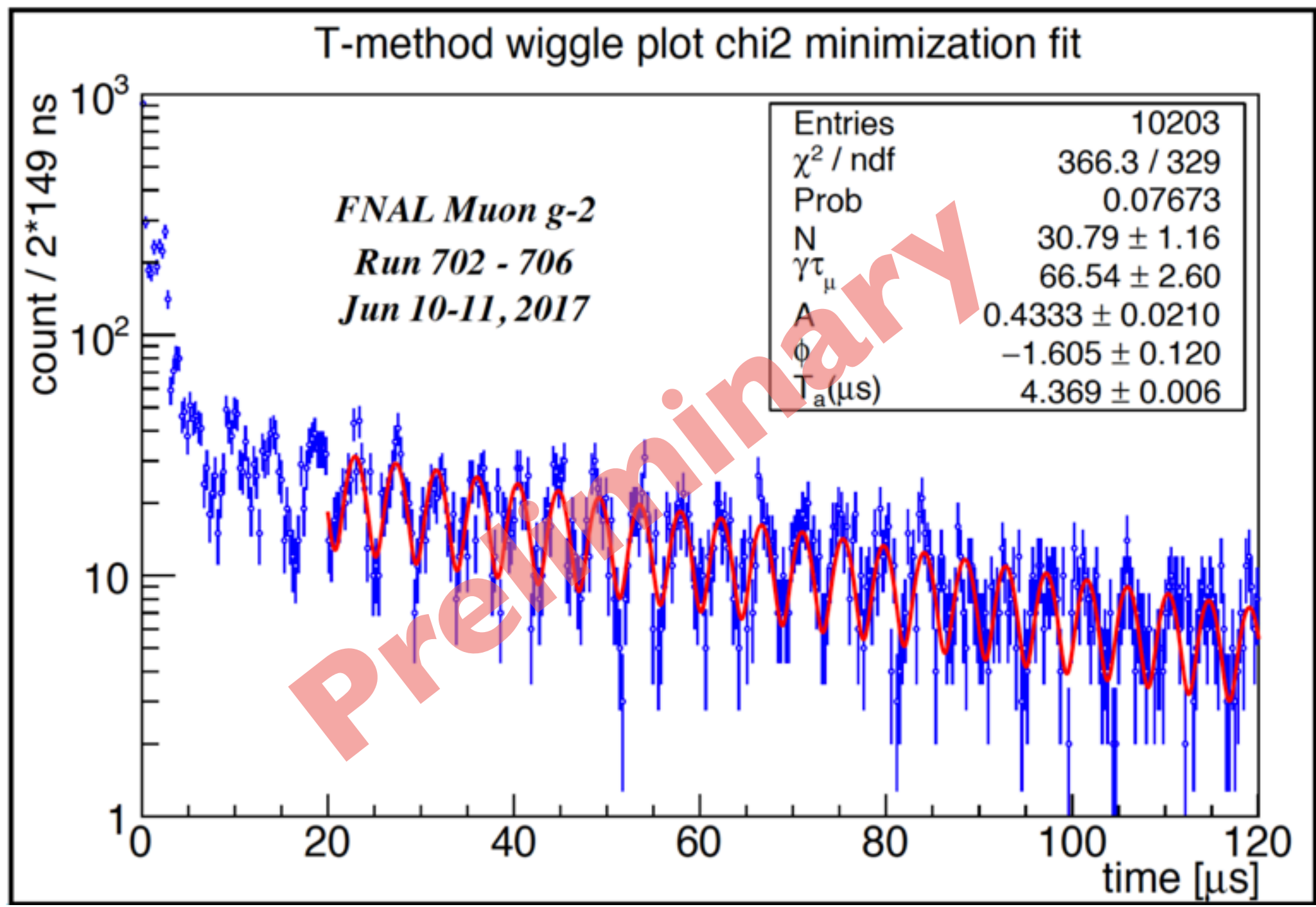
DAQ/Detector Performance:

- DAQ live time ~90%
- Calorimeters and trackers: stable
- Beam Monitors: stable

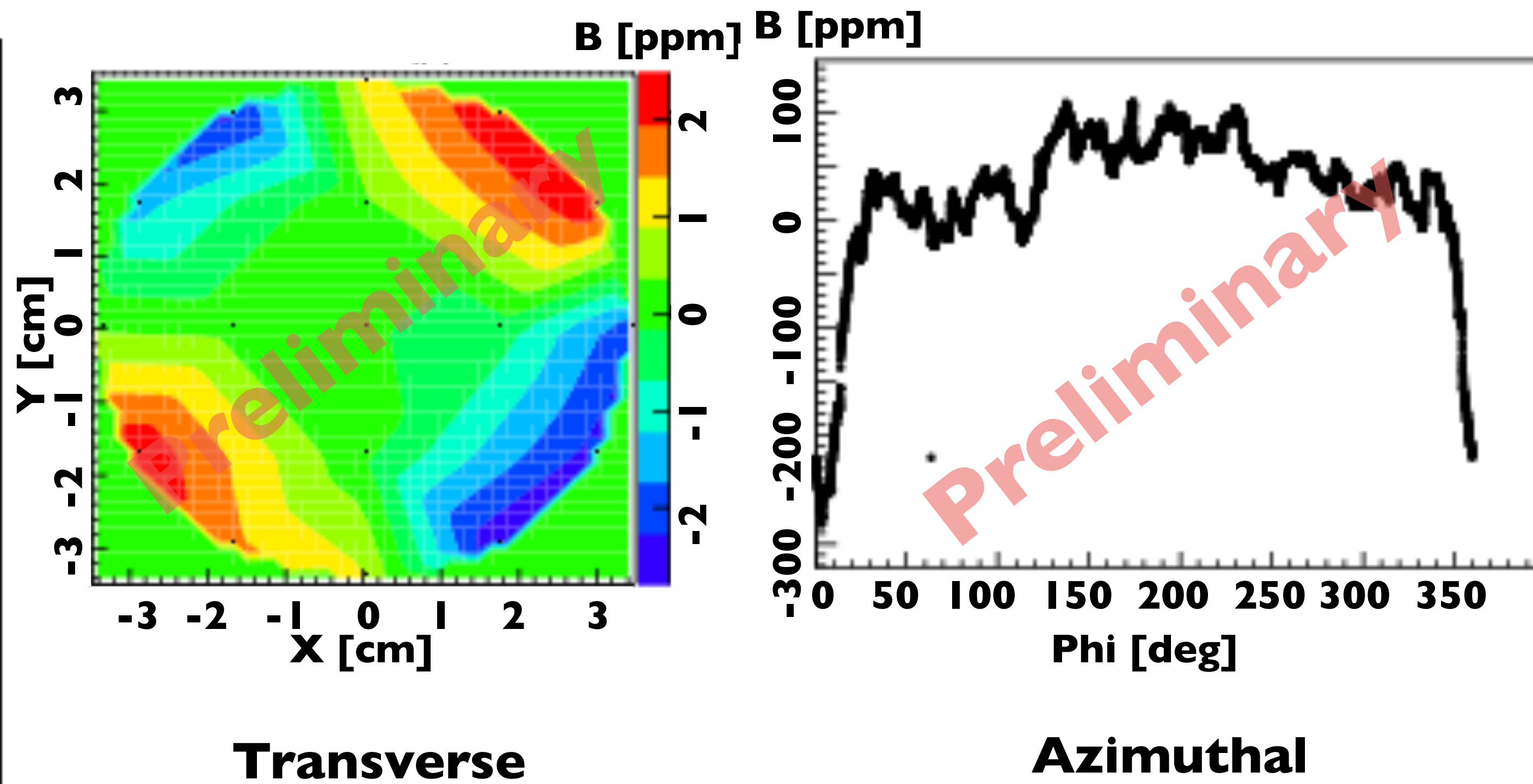


Commissioning Run I, 2017

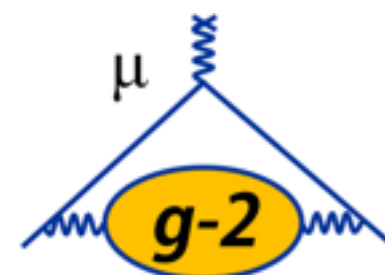
Positron-count oscillation Plot



Field Map (6/15/2017)

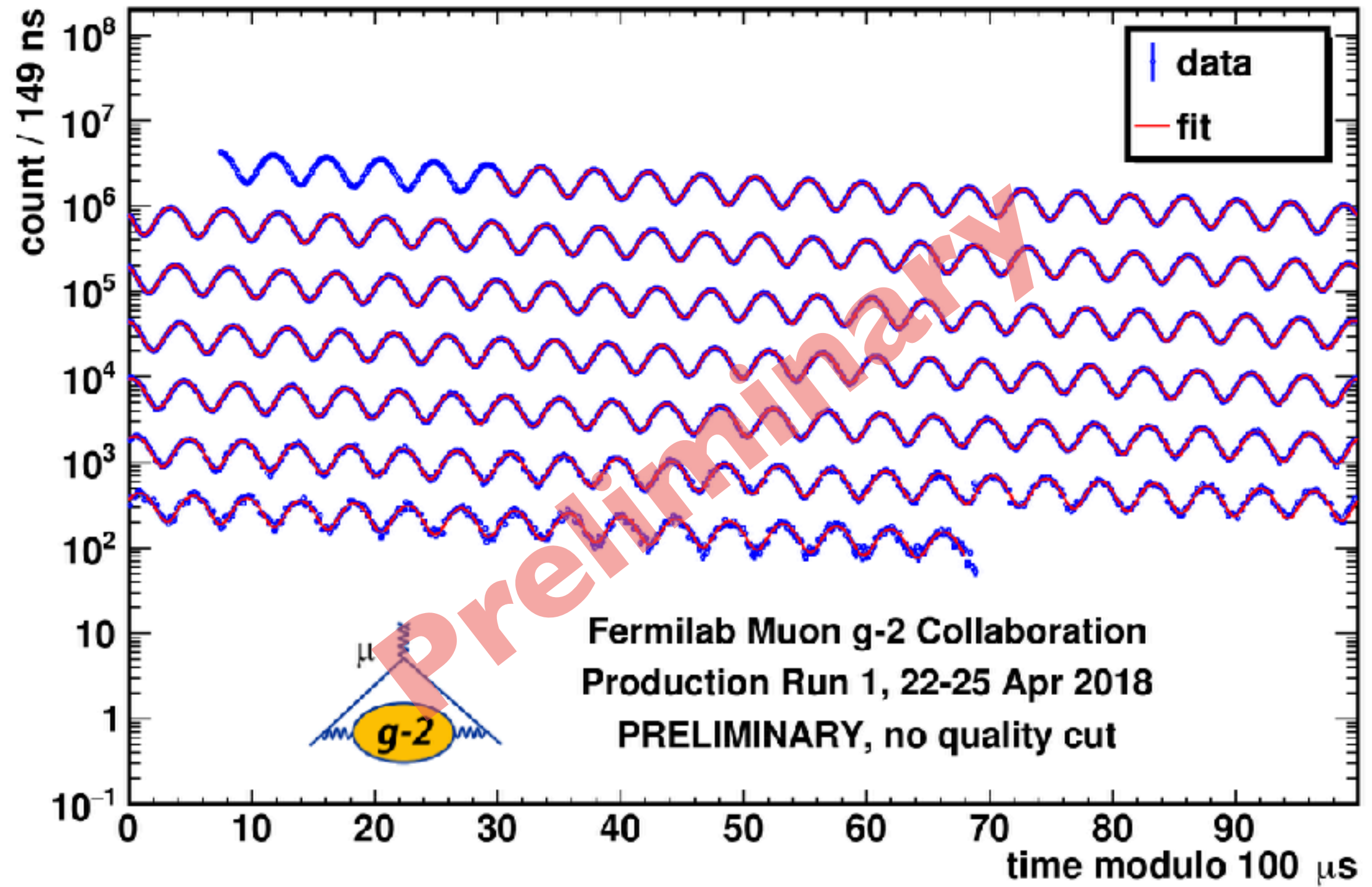


Current Status

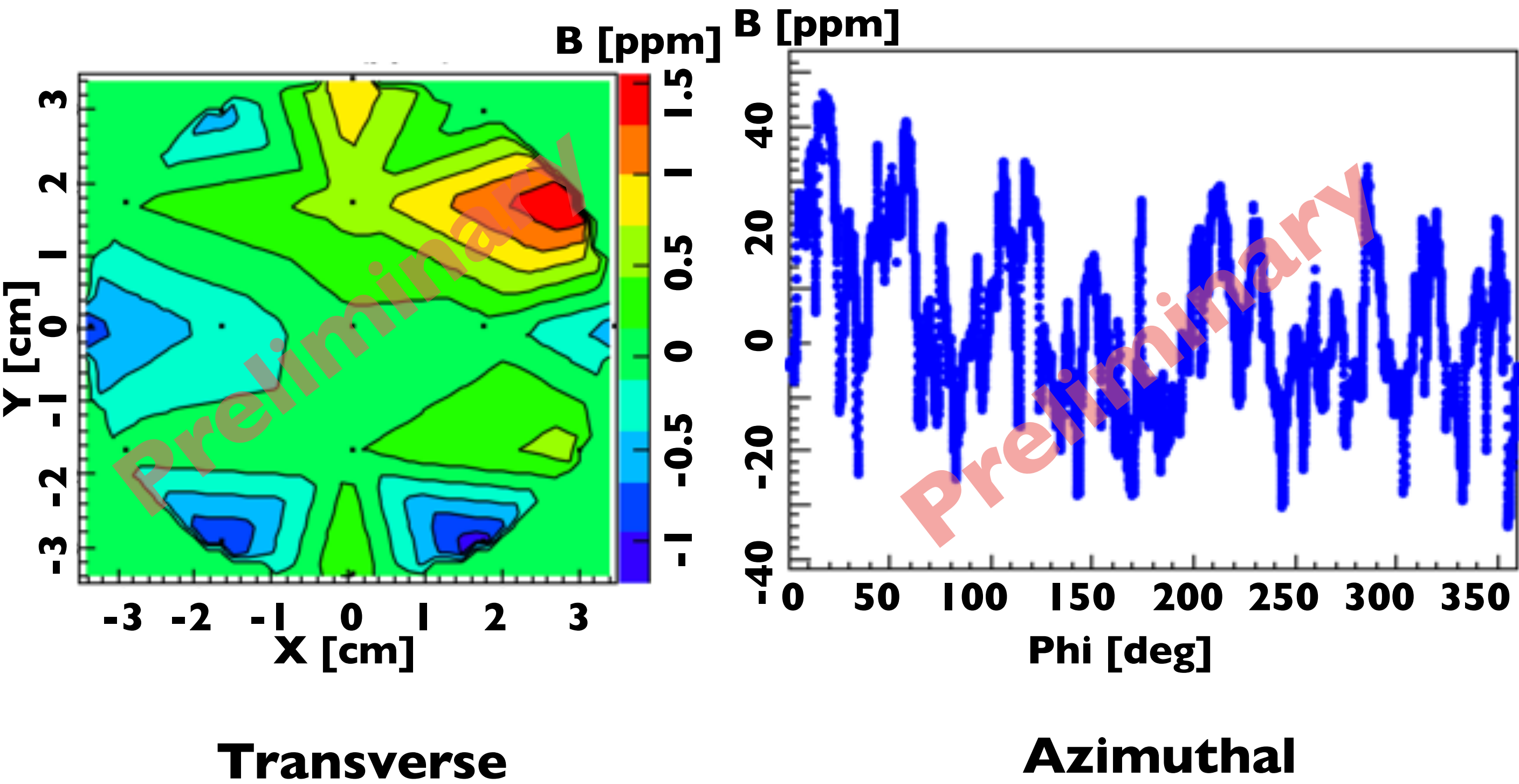


Production Run I, 2018

Positron-count oscillation Plot



Field Map (5/16/2018)



Upcoming Events



- ▶ **End of Run 1: July 7th 2018**
- ▶ **Analysis**
 - ▶ **Full analysis of Run 1: Summer-2019**
- ▶ **Start of Run 2: October 2018**



Short-term Improvements



▸ Kicker

- [Improve kicker strength, shape and width](#): more stored muons and less beam oscillation

▸ Inflector

- [Install new inflector with open ends](#) to improve stored muons by 30%

▸ Quads

- [Ramp up to higher voltages](#): improve storage and reduce beam oscillation

▸ Vacuum

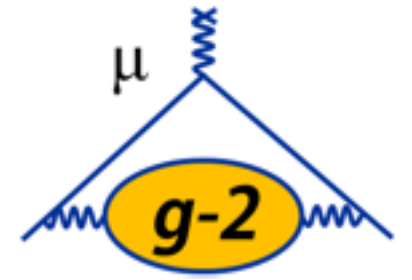
- [Activate cryogenic pumps](#) for better quad performance

▸ Field

- [Install thermal insulation](#) to improve field stability
- [Calibrations](#): cross-calibrating plunging probe, spherical probe and the helium probe
- [External trigger for fixed-probe readouts](#): read when muon comes



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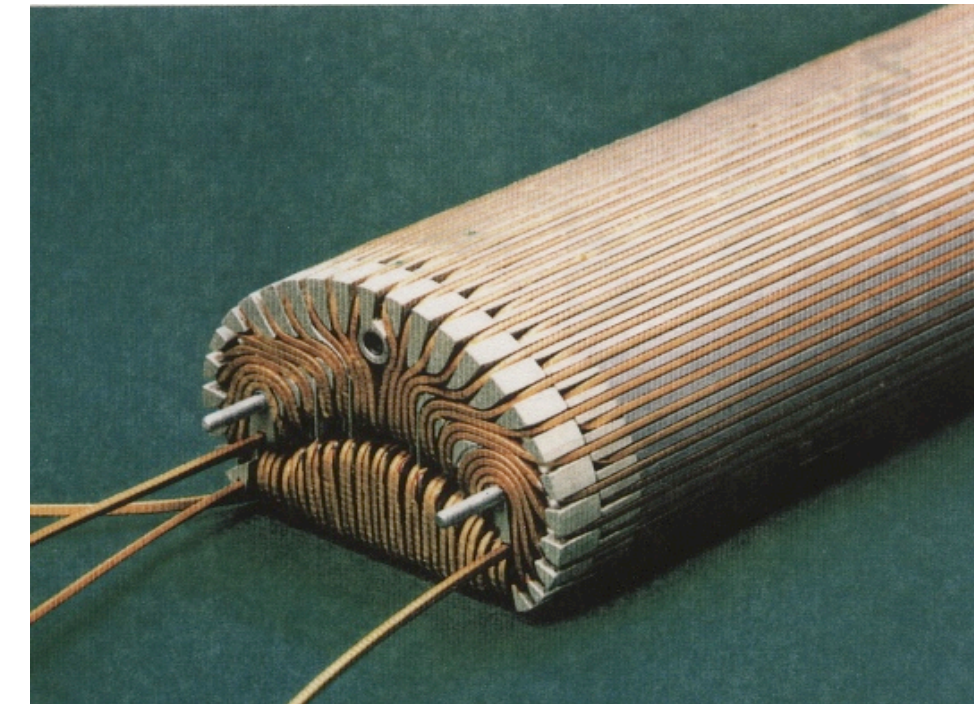
▸ Vacuum

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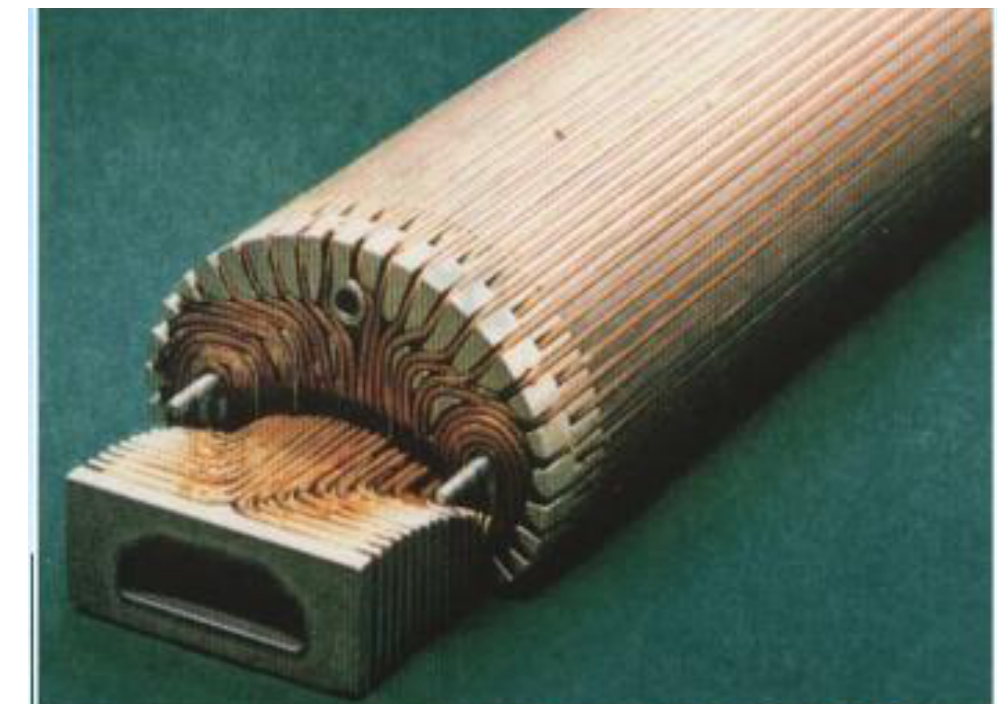
▸ Field

- [Install thermal insulation](#) to improve field stability
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Close-end inflector



Open-end inflector





Short-term Improvements

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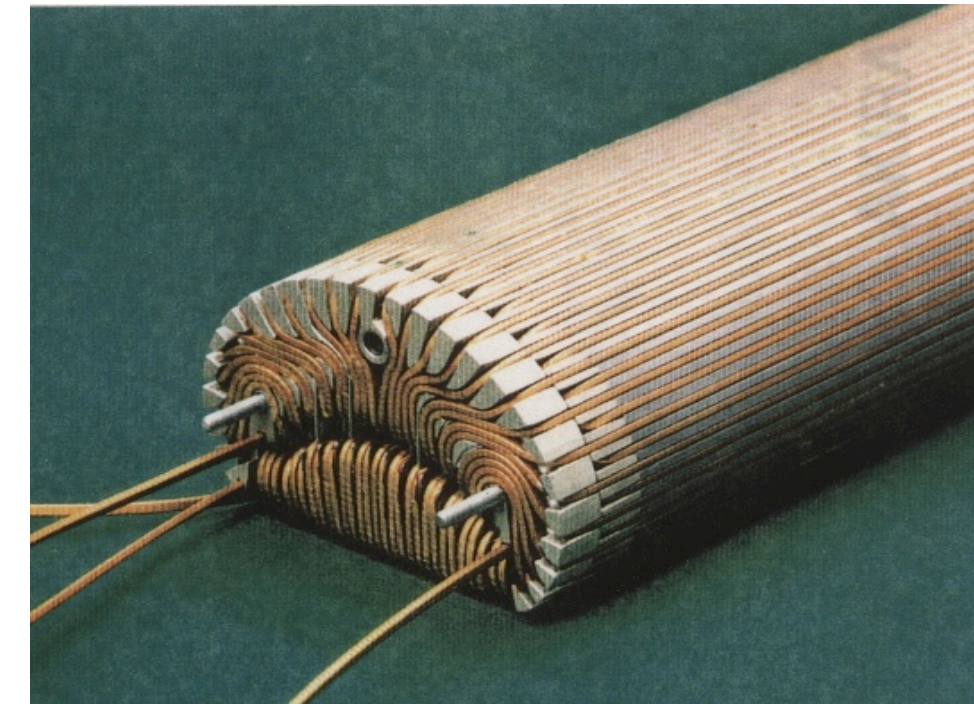
▸ Vacuum

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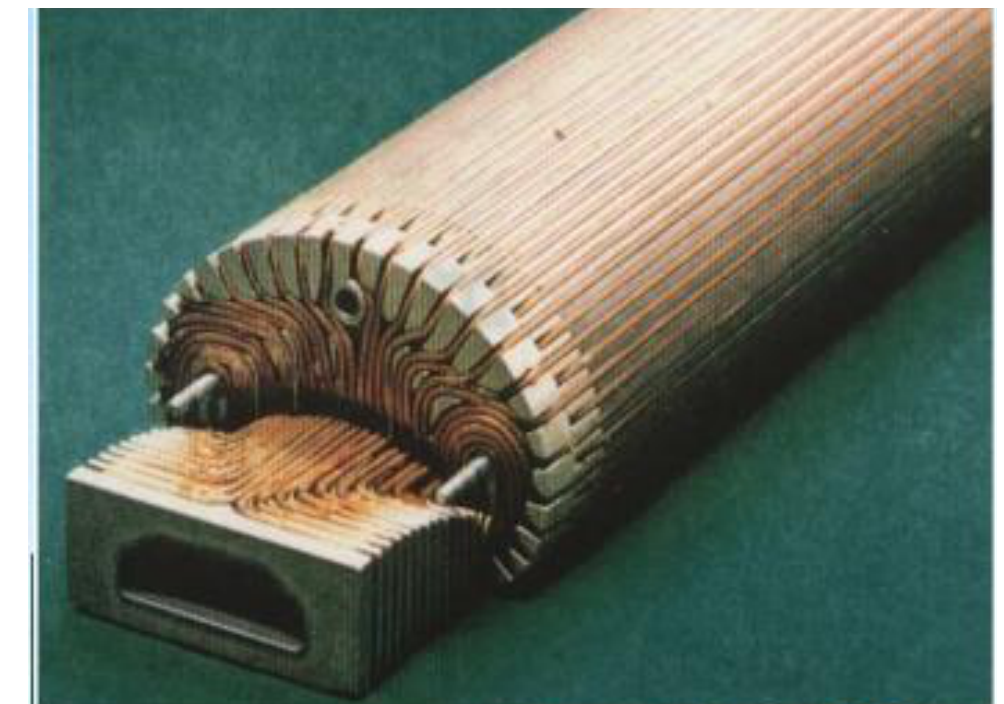
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Close-end inflector

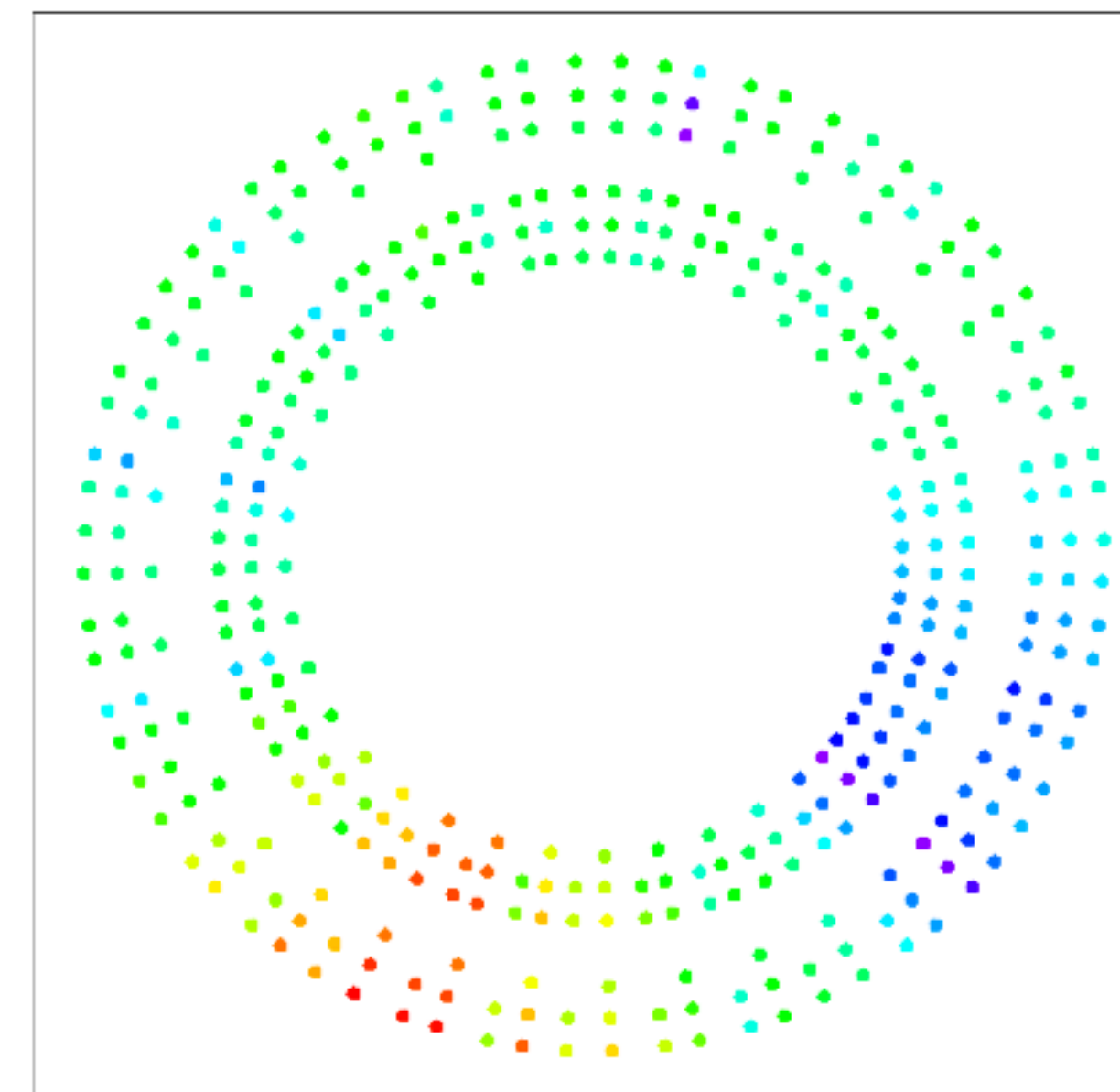


Open-end inflector



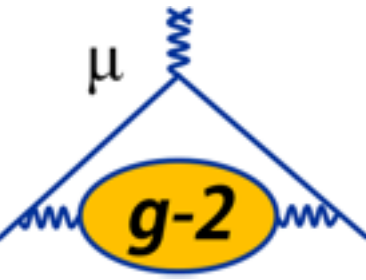
Field drift differences across the ring

11:00 - 13:00 May 28th 2018



● **-2.1 ppm**

● **1.2 ppm**



- ▶ **The Muon g-2 experiment is commissioned!**
- ▶ **Number of decay e^+ detected: 1.08×10^{10}**
- ▶ **More improvement in summer 2018**
- ▶ **Run 2 will start in October**
- ▶ **Expect the run 1 result in 2019**

Thanks for your attention!