GMINUS2 Experiment: status update

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INFN Istituto Nazionale di Fisica Nucleare

Overview

- Introduction and theory
- Latest updates from Fermilab
- Italian contribution
- Ongoing work in Napoli
- Closing remarks

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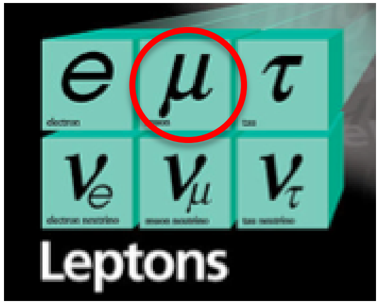
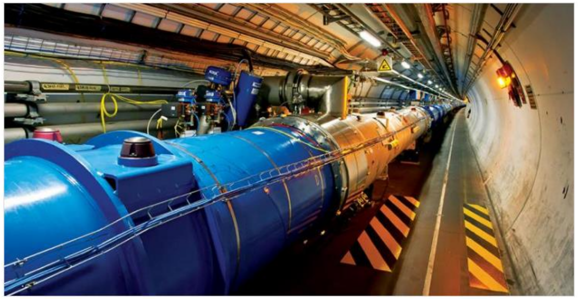
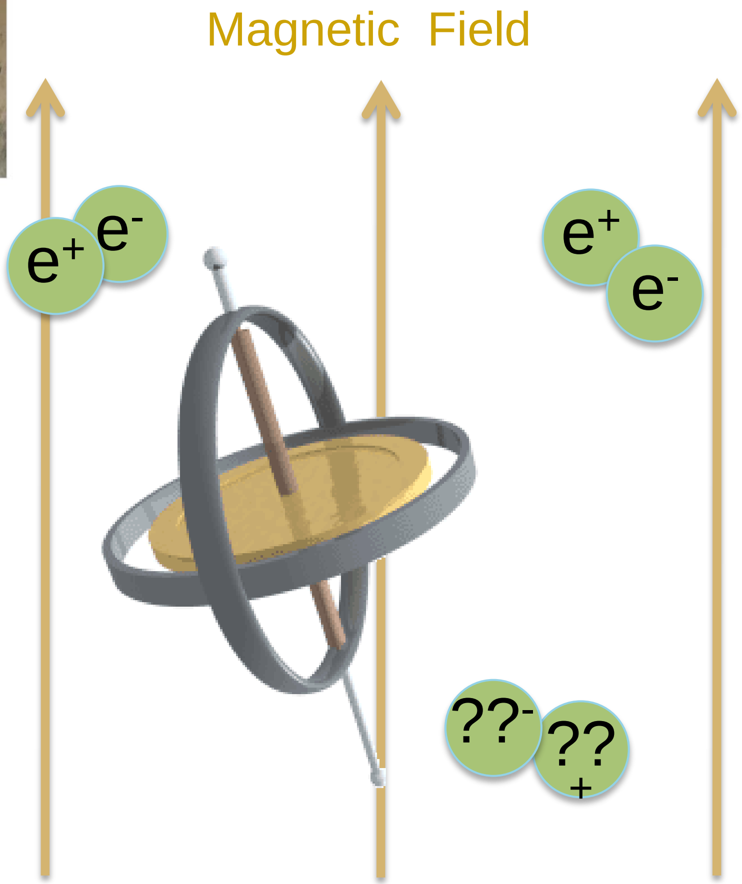
Experiment Background: High intensity frontier




The Large Hadron Collider is the world's largest and most powerful particle accelerator (Image: CERN)

Does particle behavior match Standard Model predictions?

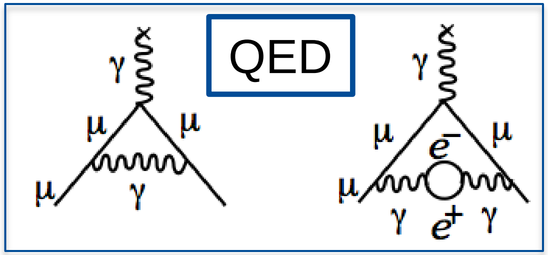
- Probe GeV or TeV?
- Mass?
- Production rates?
- Decay rates?
- Interactions with other particles or fields (e.g. magnetic moment)



Experiment Background: Magnetic moment

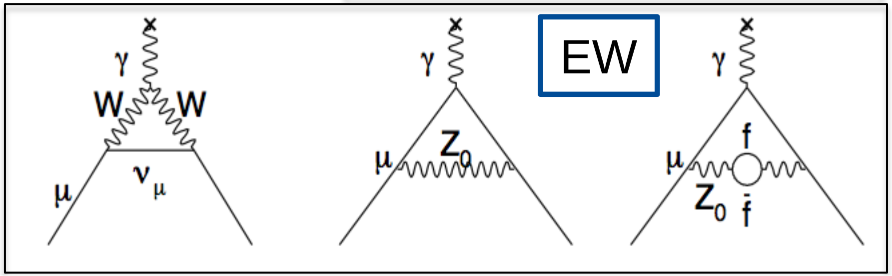
$$\vec{\mu} = g\,\frac{q}{2m}\,\vec{S}$$

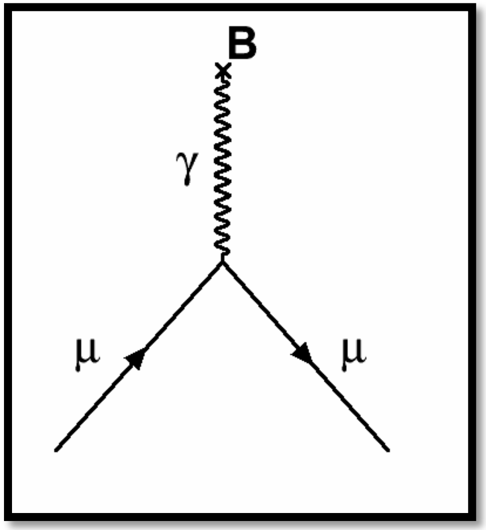
$$a = \frac{g-2}{2}$$

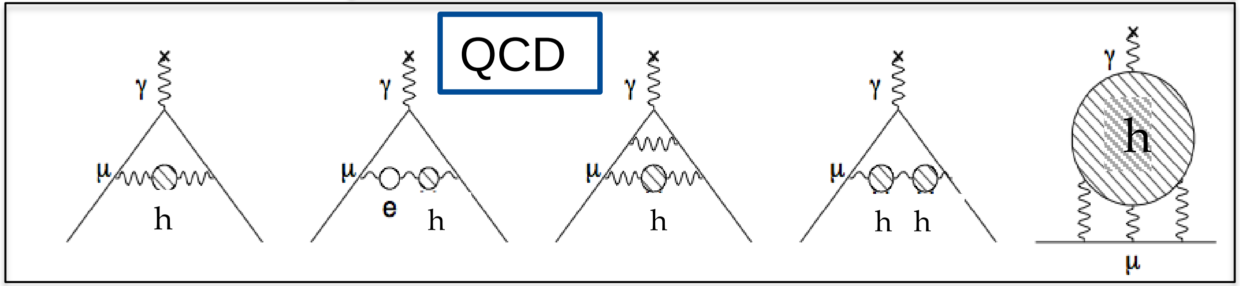


- Dirac theory: a charged, spin ½ elementary point particle has

$$g \equiv 2$$







$$a_m^{SM} = (g_m^{SM}-2)/2 = a_m^{QED} + a_m^{EW} + a_m^{QCD}$$

Experiment Background: Testing the anomalous magnetic moment

$$a_\mu^{\text{Expt.}} - a_\mu^{\text{SM}} = (260 \pm 78) \text{ x } 10^{-11} \quad (3.3\ \sigma)$$

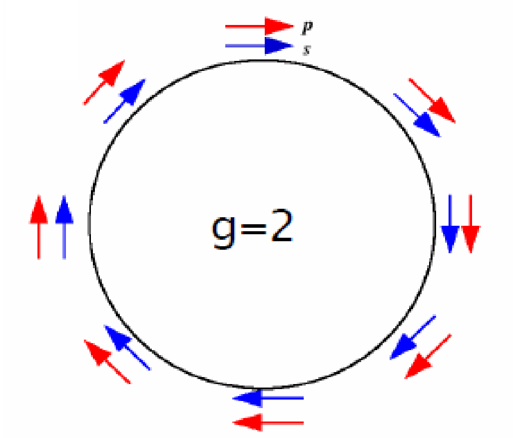
$$a_\mu^{\text{Expt.}} = a_\mu^{\text{SM}} + a_\mu^{\text{New Physics}}$$

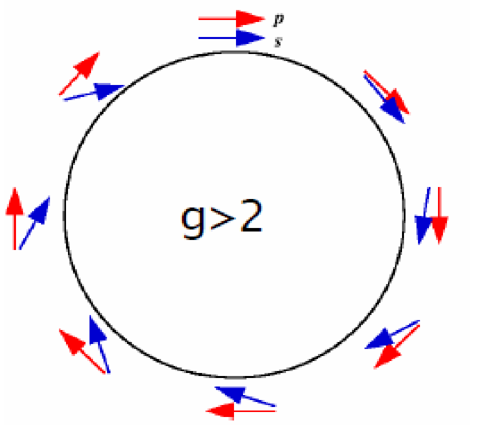
- **E-821 at BNL**
  - Latest measurement of the anomalous magnetic moment of a muon had a **3.3σ discrepancy** from SM
  - Uncertainty mainly in QCD prediction

- **E-989 at Fermilab**
  - More than 21 times the amount of statistics than predecessor E-821
  - δa_μ^{exp} = .54 ppm to .14 ppm improvement
  - Reduced pion contamination, segmented detectors and an improved storage ring kicker

Experiment Background: Muons in a storage ring

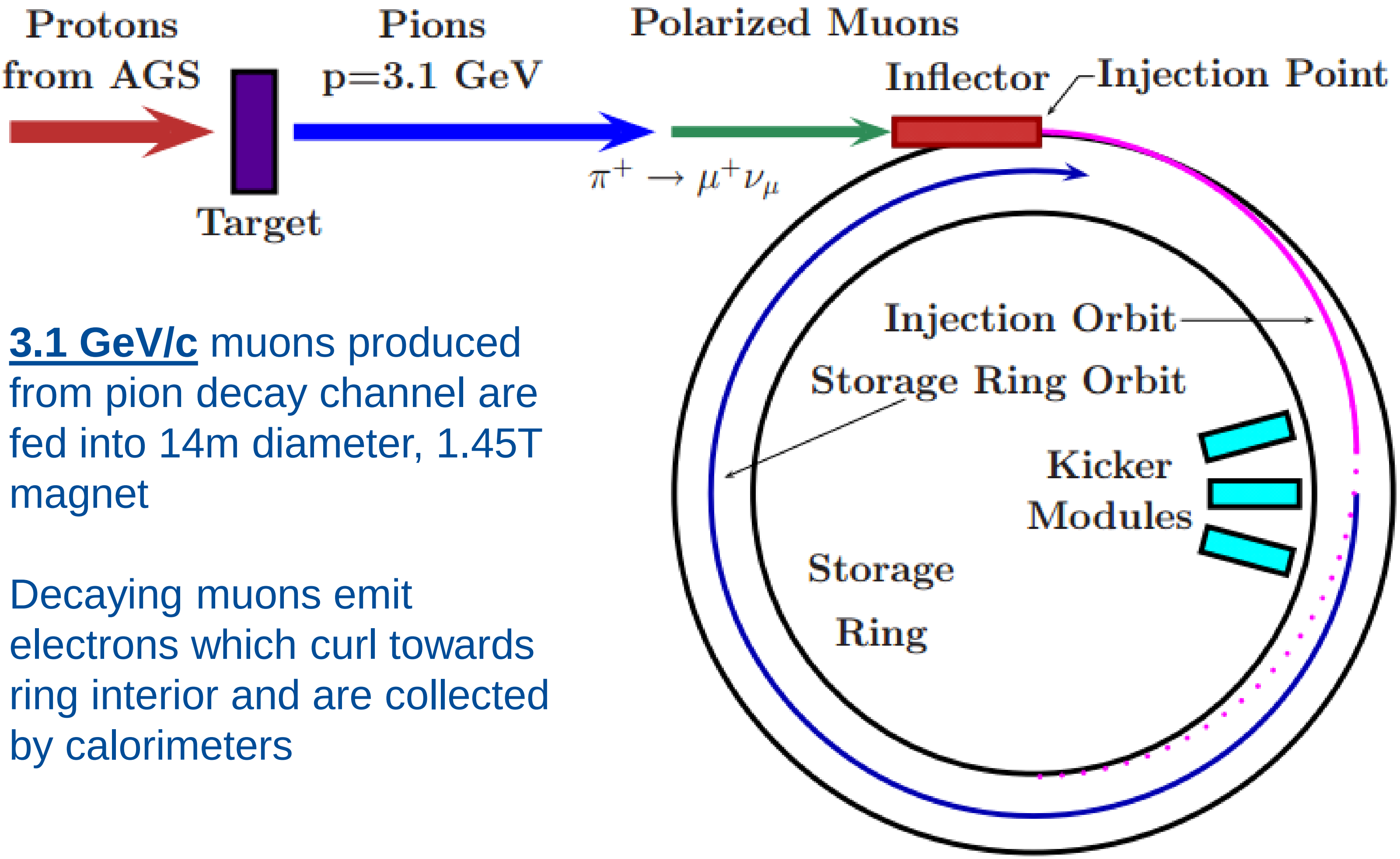
1. Start with polarized muon beam (from pion decay)
2. Cyclotron frequency: $w_c = \frac{e}{m\, g} B$
3. Spin precession frequency: $w_S = \frac{e}{m\, g} B\,(1 + g\, a_m)$





→ momentum
→ spin

$$\boxed{\omega_a = \omega_S - \omega_C = e/m\, a_\mu\, B}$$



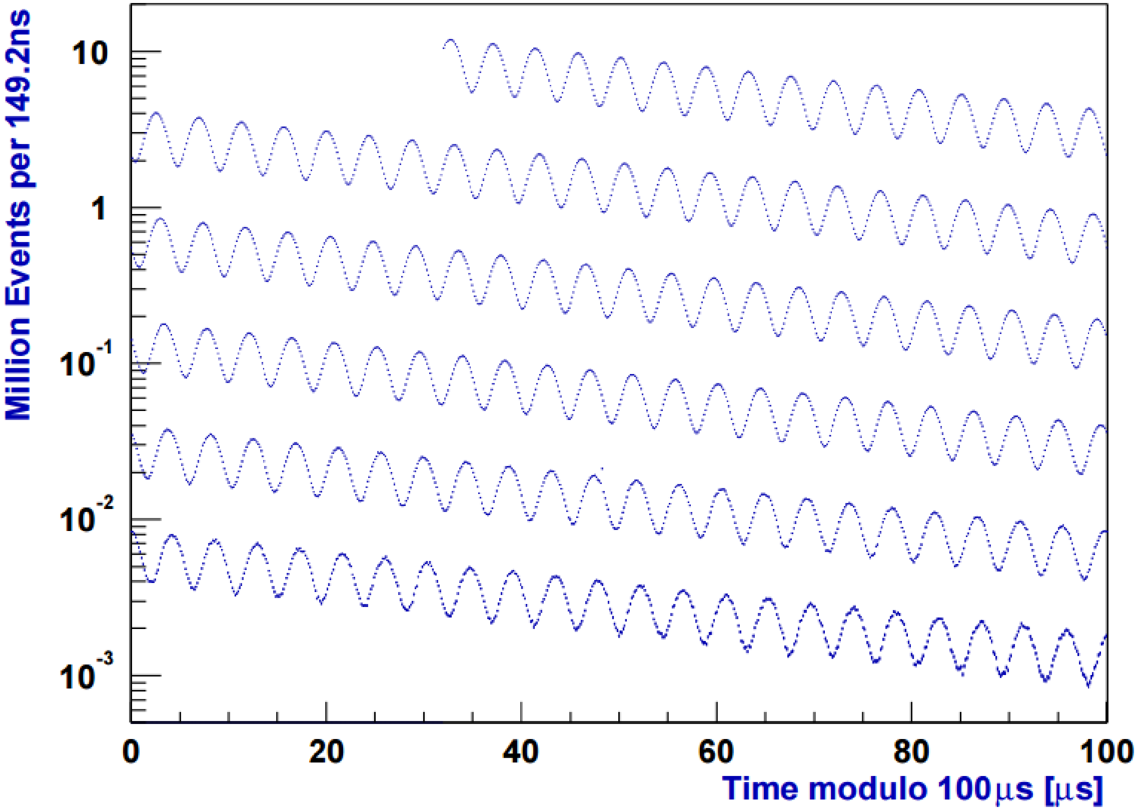
- **3.1 GeV/c** muons produced from pion decay channel are fed into 14m diameter, 1.45T magnet
- Decaying muons emit electrons which curl towards ring interior and are collected by calorimeters

Jegerlehner & Nyffeler, Phys. Rept. 477 (2009) 1-110, arXiv:0902.3360v1

Experiment Background: Muons in a storage ring

$$N(t) = N_0 e^{-t/\tau} \left(1 + Acos(\omega_a t + \phi)\right)$$

τ is the muon lifetime,
A amplitude is determined by the energy cut,
ϕ phase depends on the initial polarization of the muon ensemble.



Time spectrum of decay positrons above 1.8 *GeV/c*^{2}. Modulation is at frequency ω_a which is proportional to a_μ (Courtesy of the E821 collaboration)

Self-analyzing decay:

- Higher energy positrons emitted preferentially in direction of muon spin

Spectrum distortions:

- Pileup, gain stability
- Beam effects, losses

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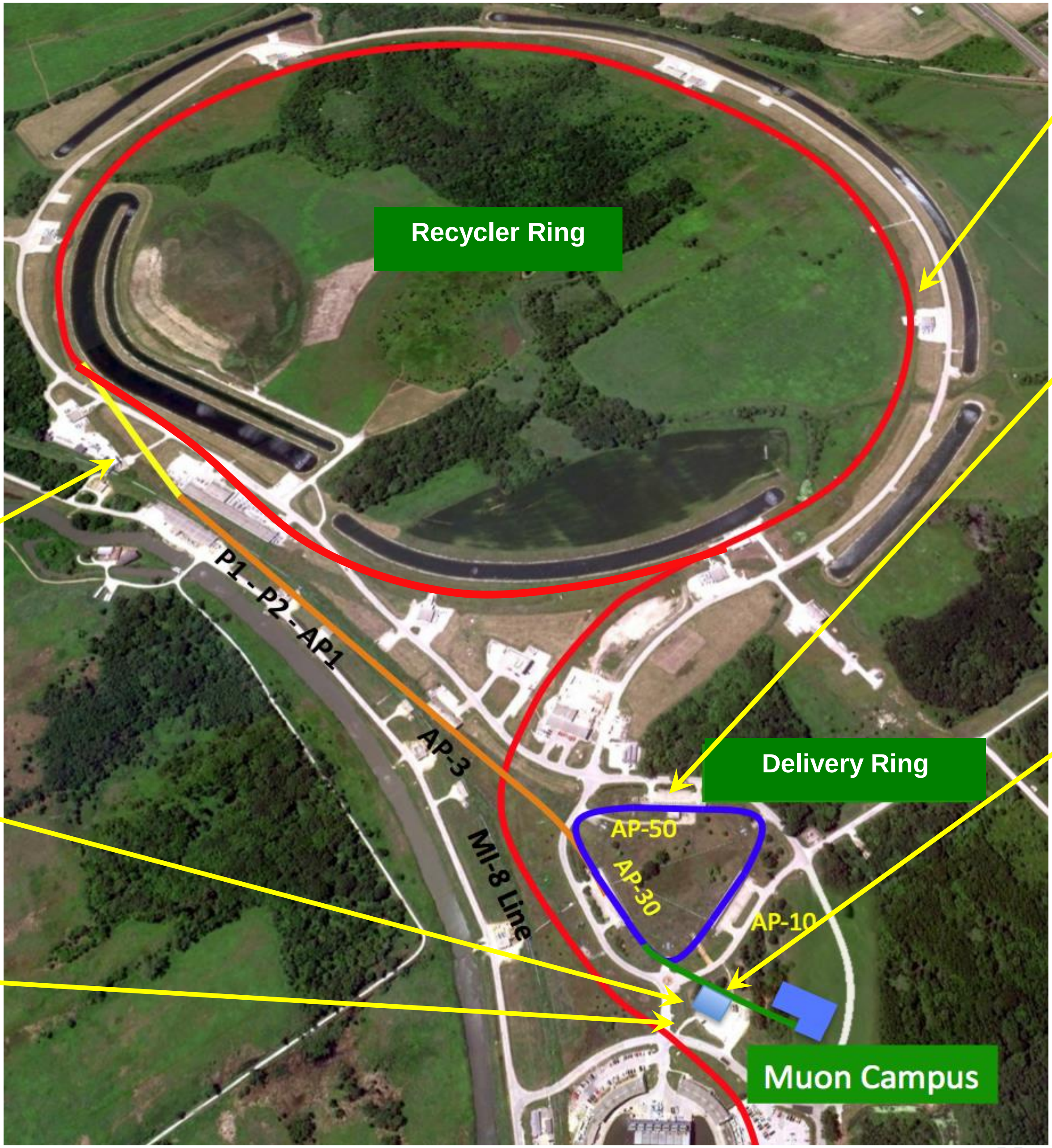
2 Experiments:
Muon g-2 (2016)
Mu2e (2019)



Recycler RF AIP: Adds RF capability to Recycler meeting g-2/Mu2e specifications

Delivery Ring AIP: Modify Delivery Ring to deliver custom beams to the muon experiments

Beamline Enclosure GPP: New tunnel to Muon Campus

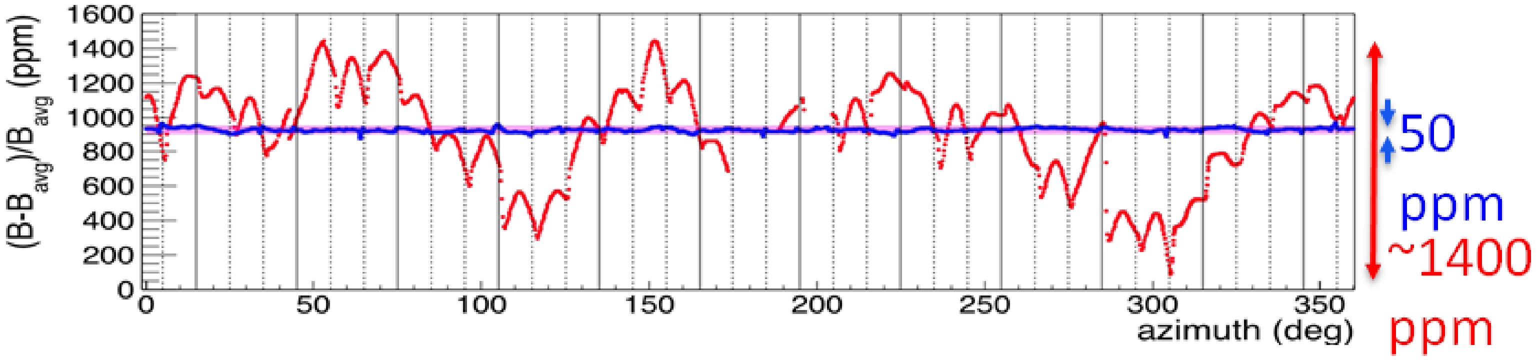
Infrastructure Upgrades: Cooling for A0 compressors, MI-52 building extension, added feeder if needed

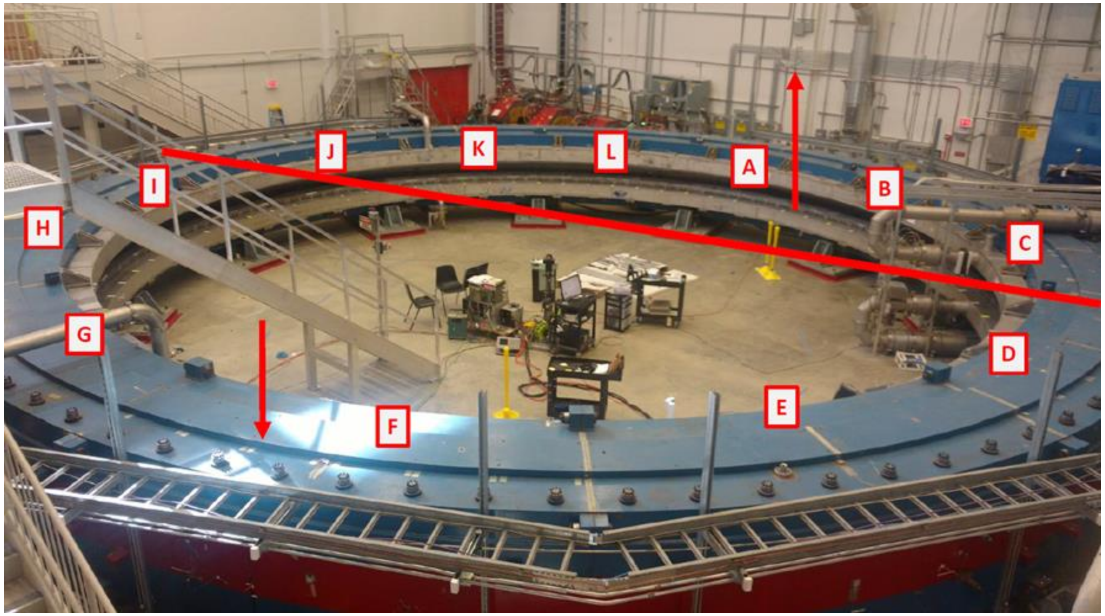
Beam Transport AIP: New connection from Recycler to Delivery Ring, improve apertures

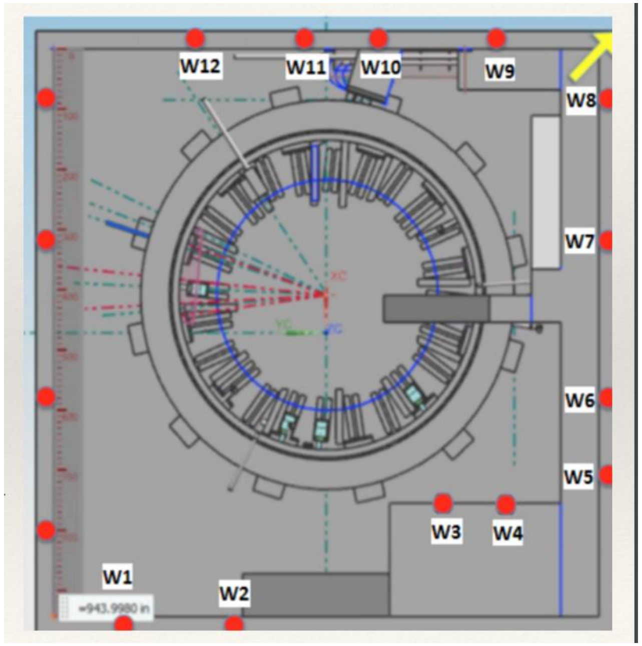
MC-1 Building GPP: Houses cryo plant, power supplies for beams, g-2

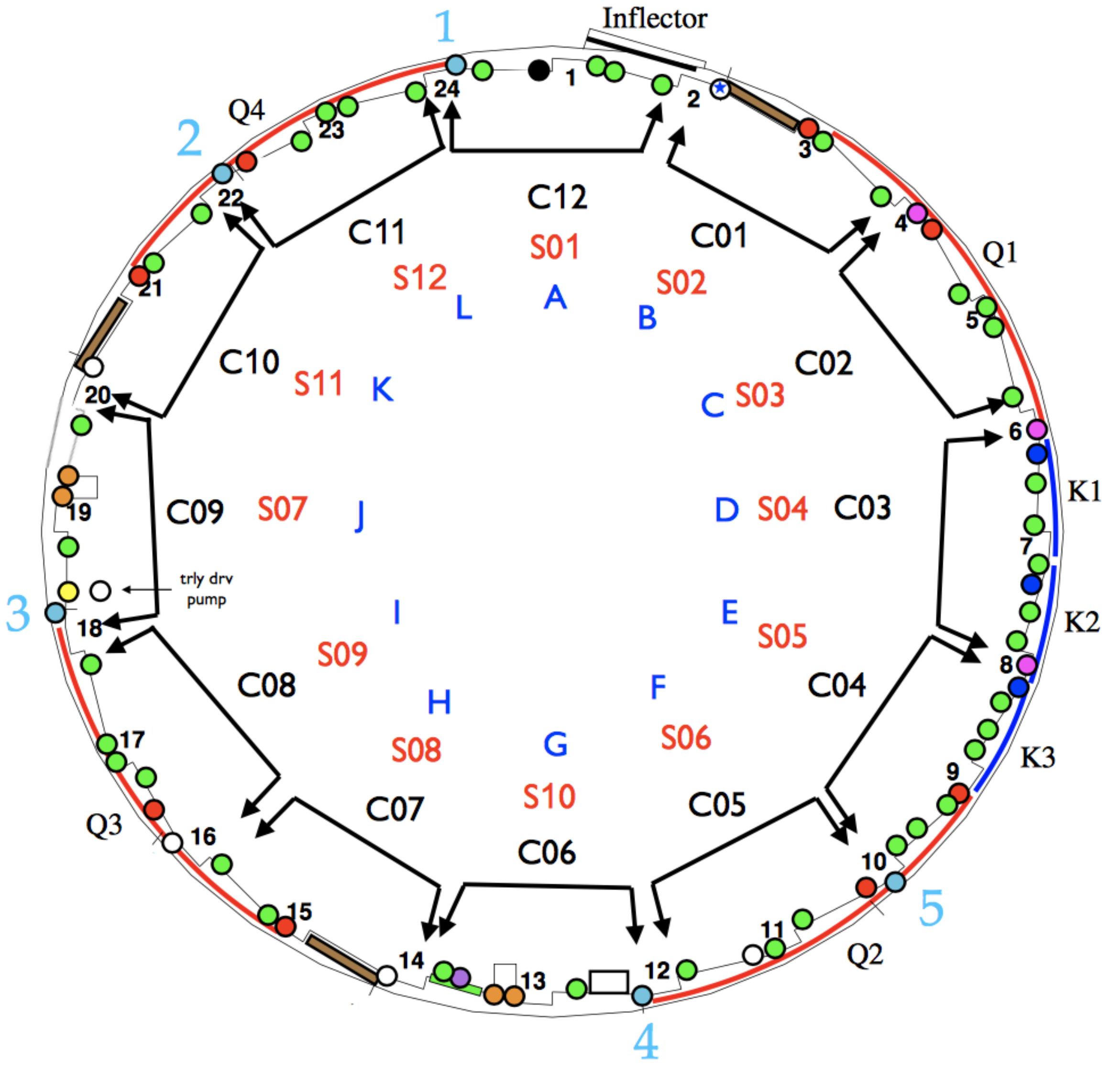
Cryo Plant AIP: Cryogenics to both experimental halls

Oct 2015 →Aug 2016



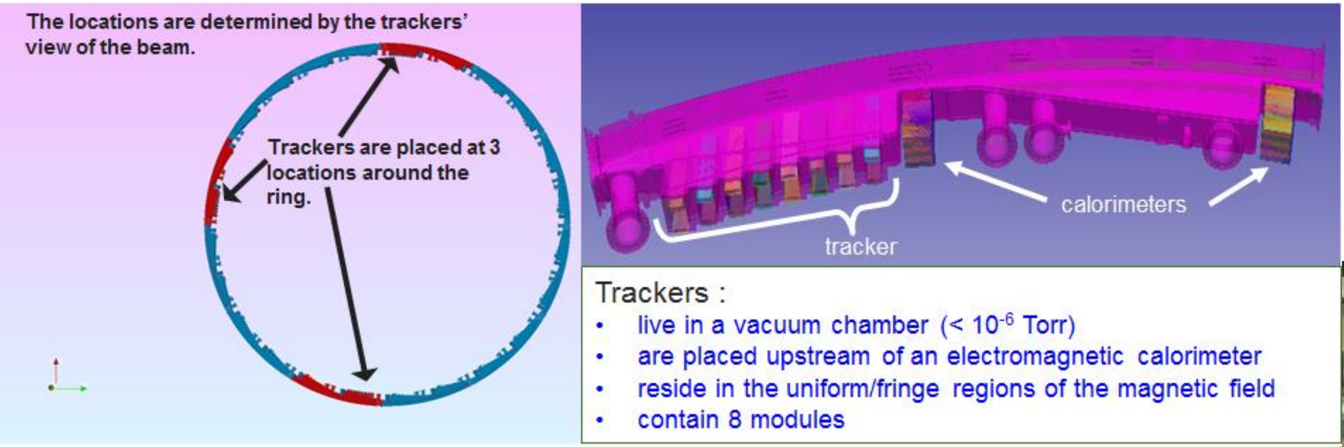






	function	owner
🟢	Unclaimed (chamber)	
🟣	Unclaimed (bellows)	
🔴	Quad HV feedthrough	BNL
🟠	Harp port	Regis
🟡	Trly drive	ANL
▭	Trly garage	ANL
▮	Tracker	FNAL
🔵	Kicker	Cornell
○	Turbo pump	FNAL
🟣	NMR Cal	Amherst
▮	New scallop	
●	Collimator (bellows)	BNL
●	Inflector positioning	FNAL
★	IBMS #3	UW

Experiment Background: Instrumentation Upgrades



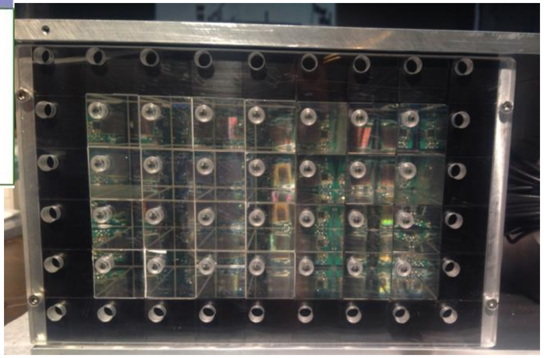
The locations are determined by the trackers' view of the beam.

Trackers are placed at 3 locations around the ring.

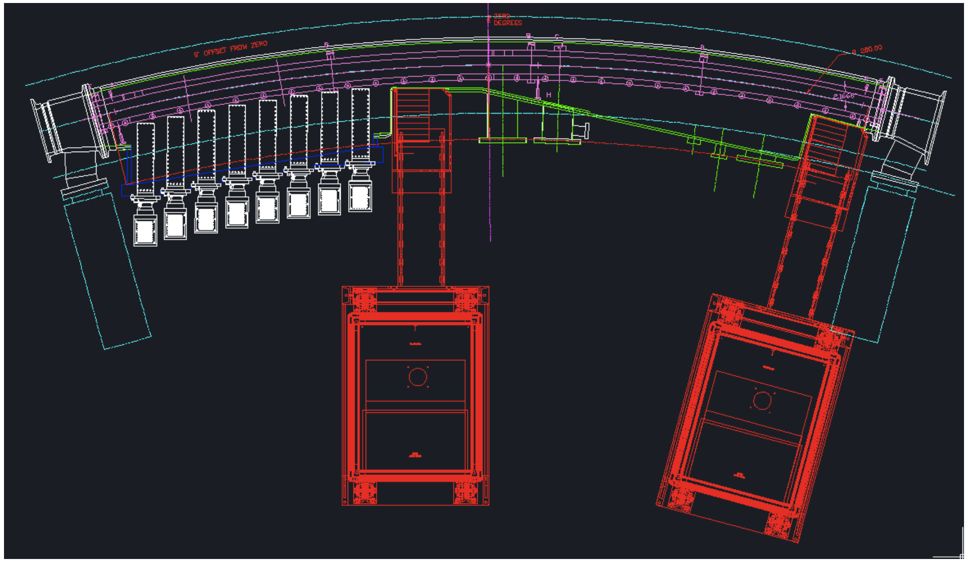
Trackers :

- live in a vacuum chamber (< 10^{-6} Torr)
- are placed upstream of an electromagnetic calorimeter
- reside in the uniform/fringe regions of the magnetic field
- contain 8 modules

Segmented PbF2



Straw tube trackers



- Energy measurement
- Electron arrival time
- Pileup
- Tracking

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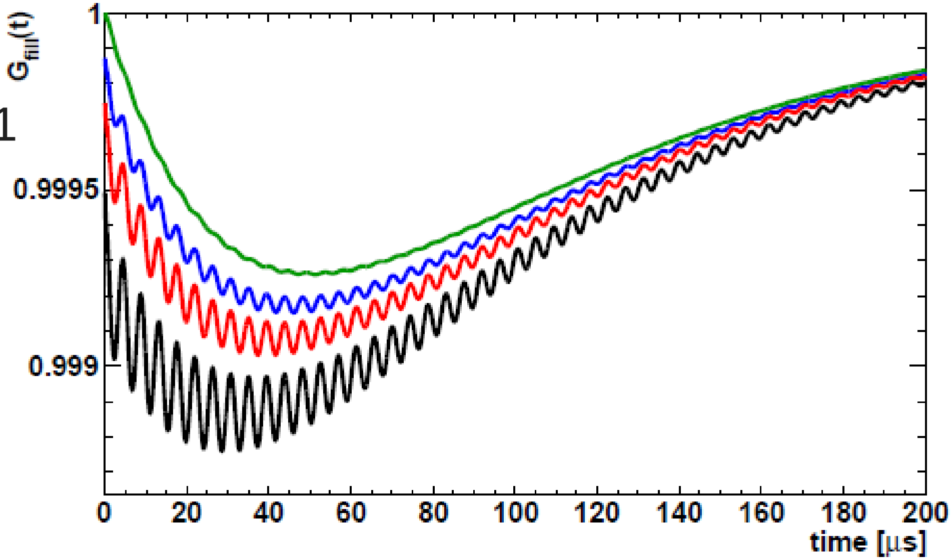
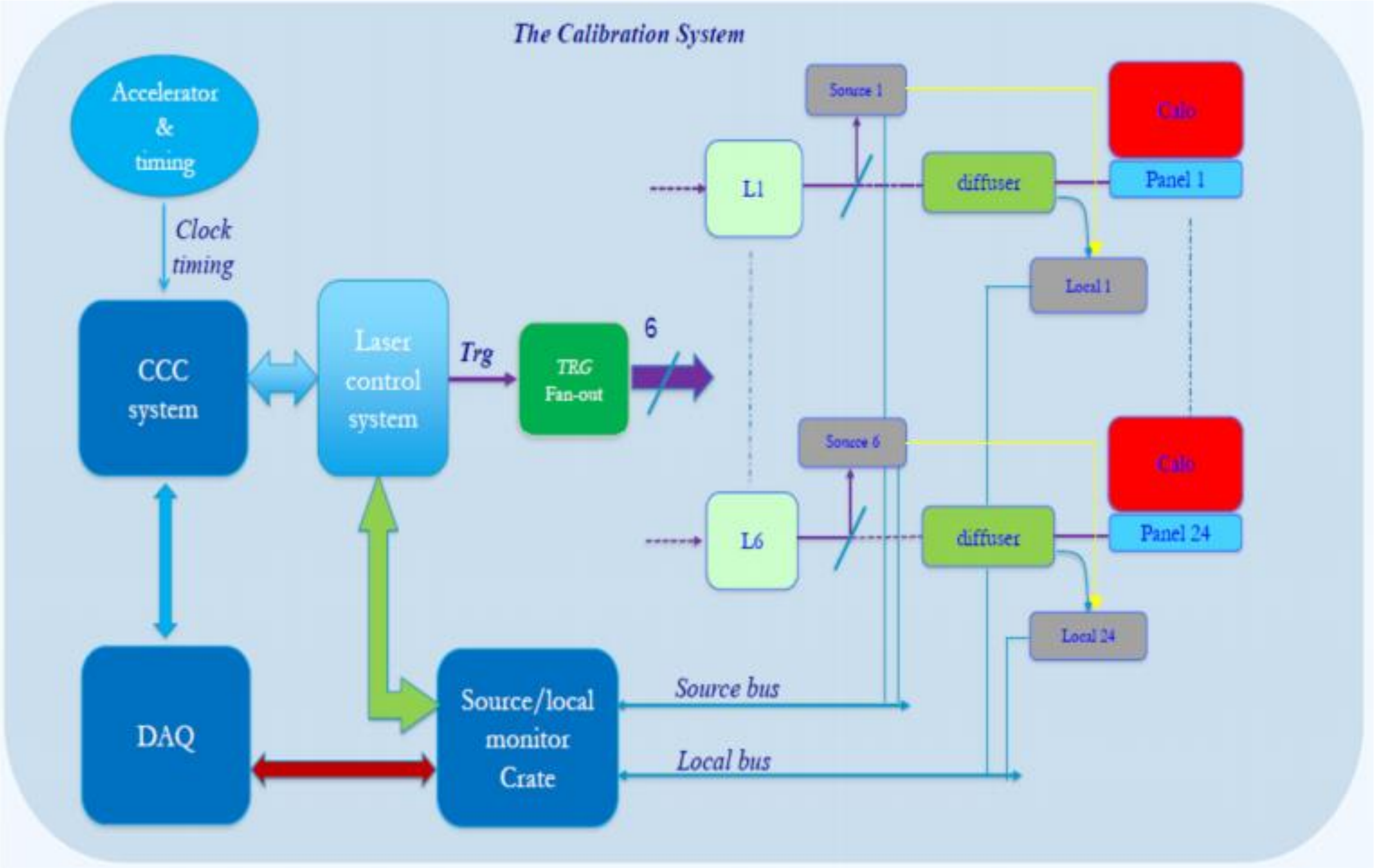
Laser Calibration System: Variable gain

- **Gain fluctuations**
  - Dangerous "short term" (within 700 μs fill) fluctuations alter energy reconstruction and raise systematic error on ω_a to intolerable levels (>.01 ppm)
- **Calibration approach**
  - Monitor gain (G_{cal}) of all calorimeter elements by exciting and monitoring the entire system periodically with a **common** light source (in principle, can ignore light source fluctuations)
  - Statistical fluctuations in recorded data must be smaller than variations in G_{cal} (<0.1% per hour)



Gain for a fill as shown for various time recovery constants (black shortest time and green largest)

A. Feinberg


The Calibration System
Accelerator & timing
Clock timing
CCC system
Laser control system
Trg
TRG Fan-out
6
L1
L6
Source 1
Source 6
diffuser
diffuser
Calo
Panel 1
Calo
Panel 24
Local 1
Local 24
DAQ
Source/local monitor Crate
Source bus
Local bus

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  - Electronics
  - Lab
  - Analysis
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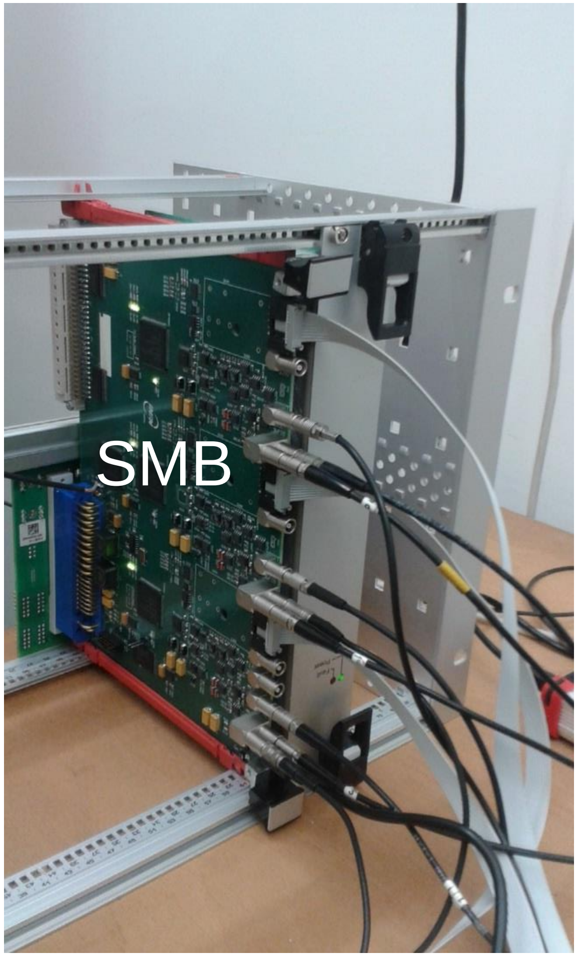
Electronics: Source Monitoring Board (SMB)

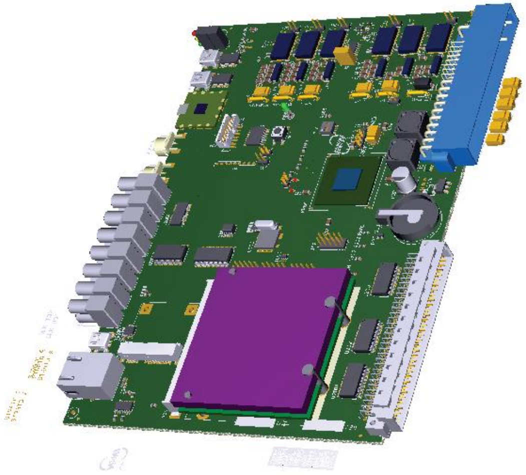


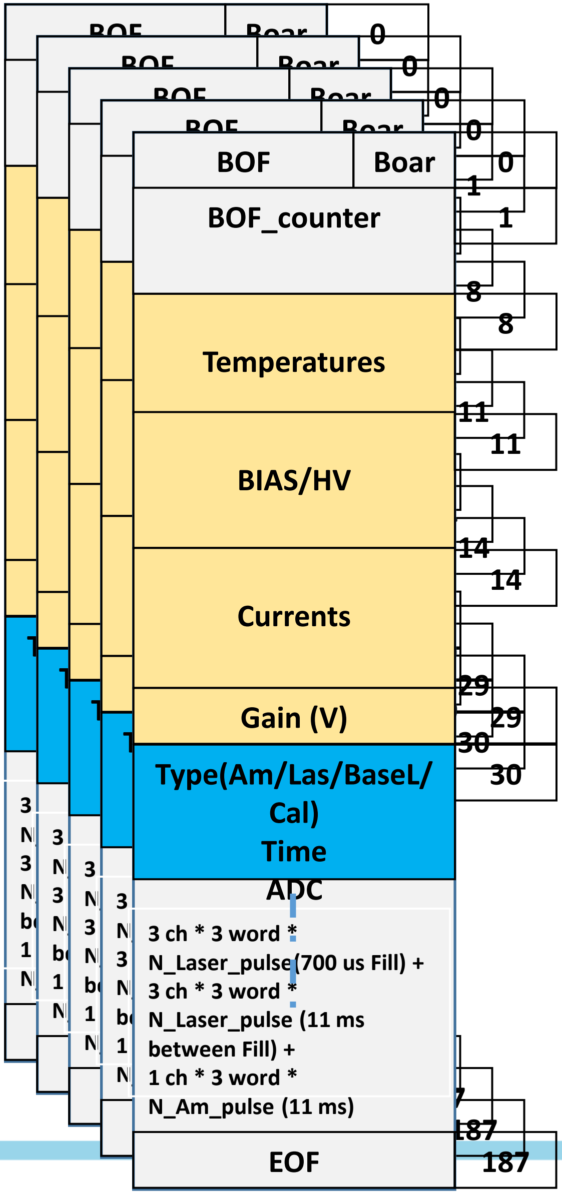
BOF	Boar	0
BOF_counter		1
Temperatures		8
BIAS/HV		11
Currents		14
Gain (V)		29
Type(Am/Las/BaseL/Cal) Time		30
ADC 3 ch * 3 word * N_Laser_pulse (700 us Fill) + 3 ch * 3 word * N_Laser_pulse (11 ms between Fill) + 1 ch * 3 word * N_Am_pulse (11 ms)		
EOF		187

- Monitoring board sends signal to WFD, according to Common mode +/- 0.5 V at 1.9 V.
- Provides the LASER / Monitoring trigger to the WFD / DAQ
- Triggers the asynchronous transfers (Am) to µTCA / WFD
- Opens a time window for digitization to the WFD.
- Digitizes the monitoring signals with a 14-bit ADC and sends the values to the Control Boards which in turns provides the data to the DAQ via TCP / IP protocol.
- Sustains a10 kHz rate
- Digitization is started by the signal of the Laser Control (Start) appropriately timed (programmable delay)
- Provides and monitors bias voltages to the detectors (PIN/PMT)
- Reads the detector currents
- Reads 3 Temp/channel (Tpream, Tboard, Tenvir) - 0.1^{0}C resolution
- Self-calibration of the electronic channel (known pulse to the input)

Many capabilities and flexible design

Electronics: Monitoring Control Board (MCB)





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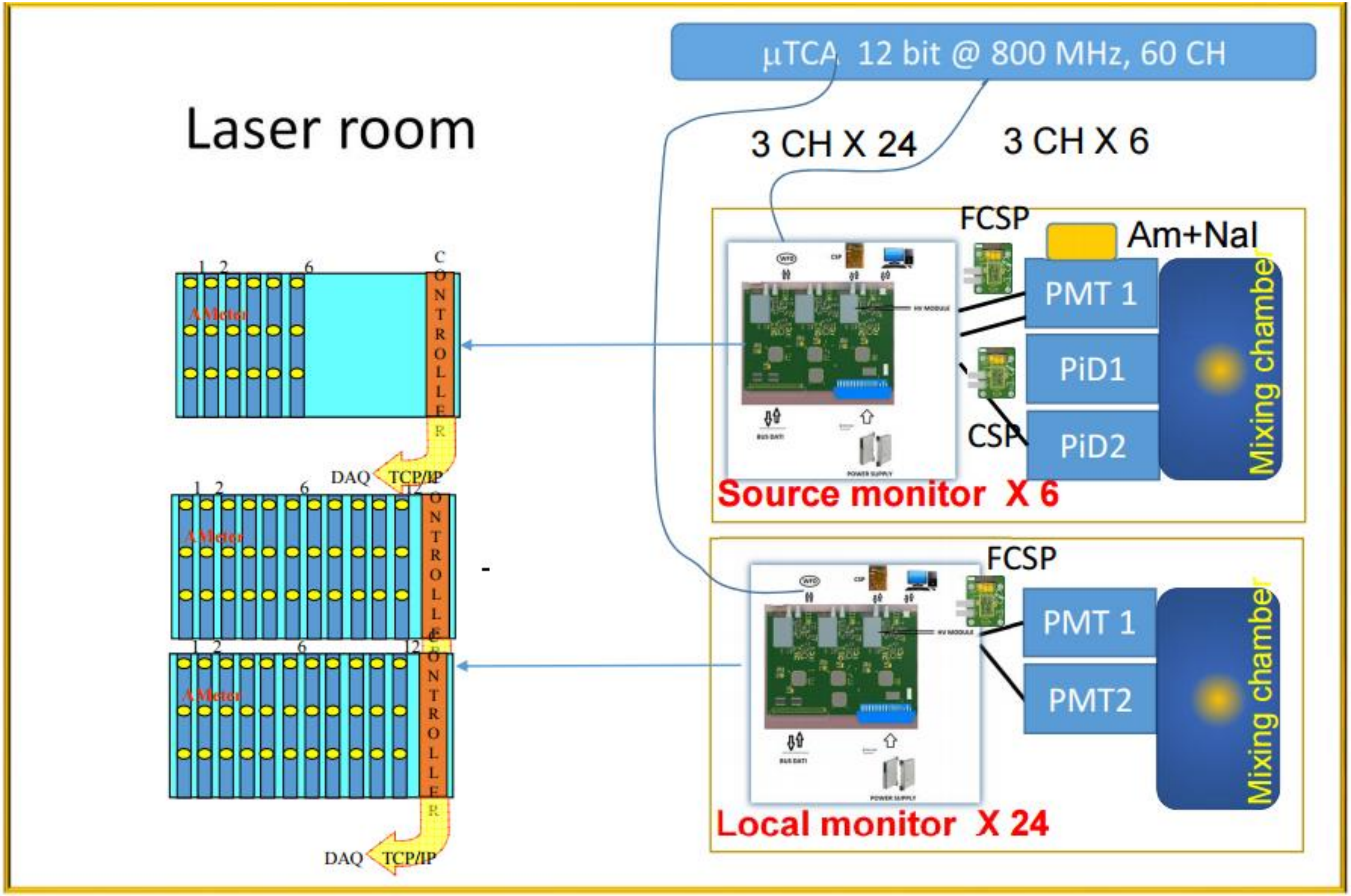
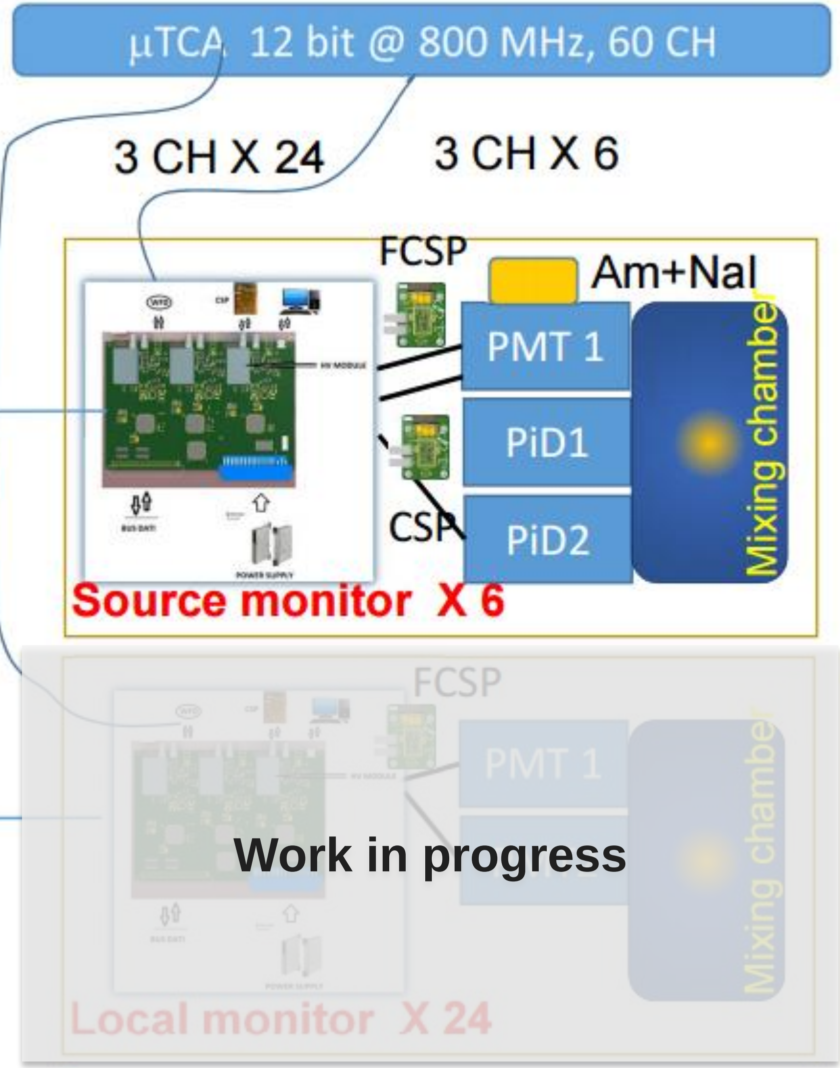
3 ch * 3 word * N_Laser_pulse(700 us Fill) + 3 ch * 3 word * N_Laser_pulse (11 ms between Fill) + 1 ch * 3 word * N_Am_pulse (11 ms)		
EOF		187

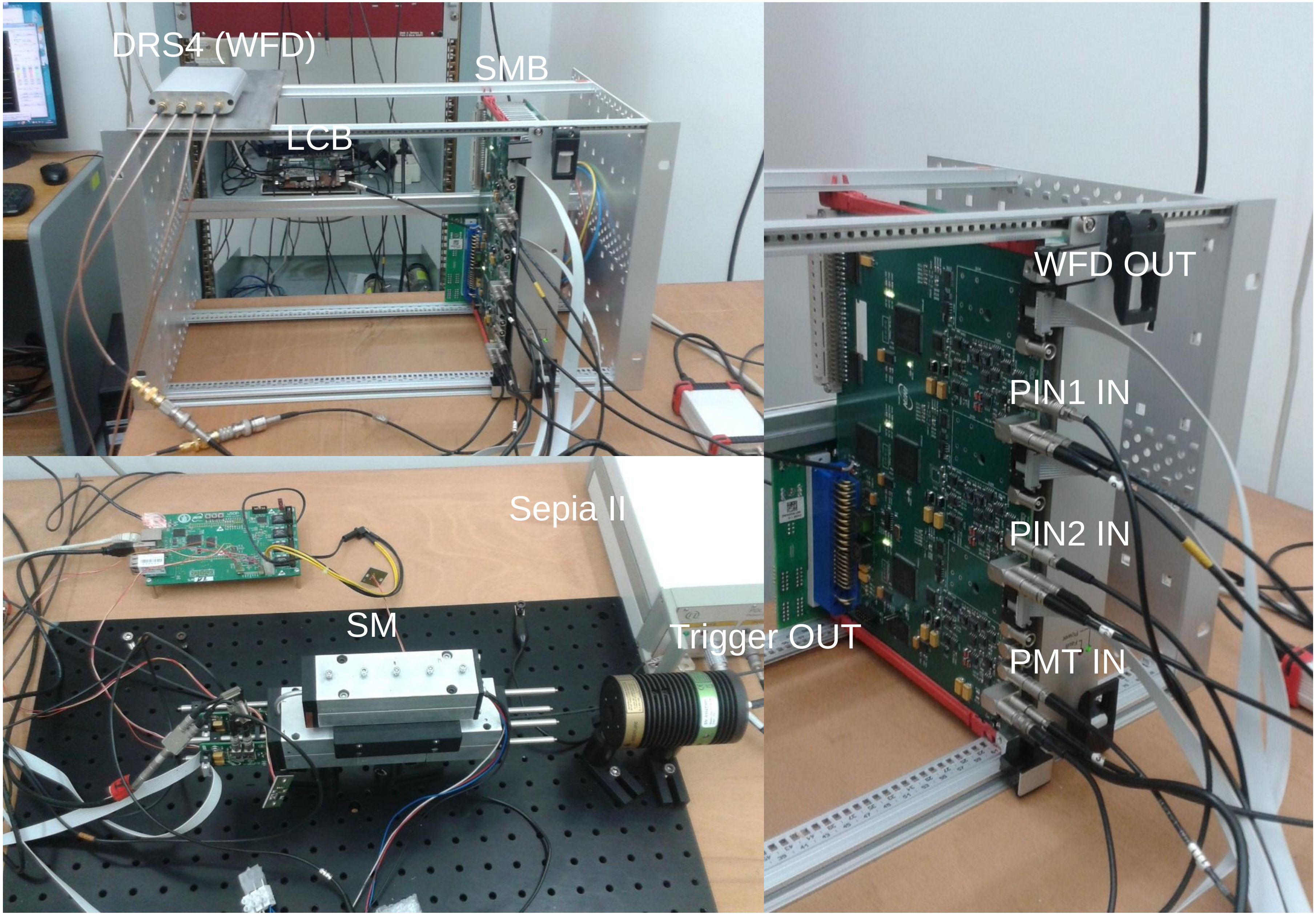
- Frame format of Monitoring Board; each word is 16 bit.
- Throughput: 50-100 kB/s

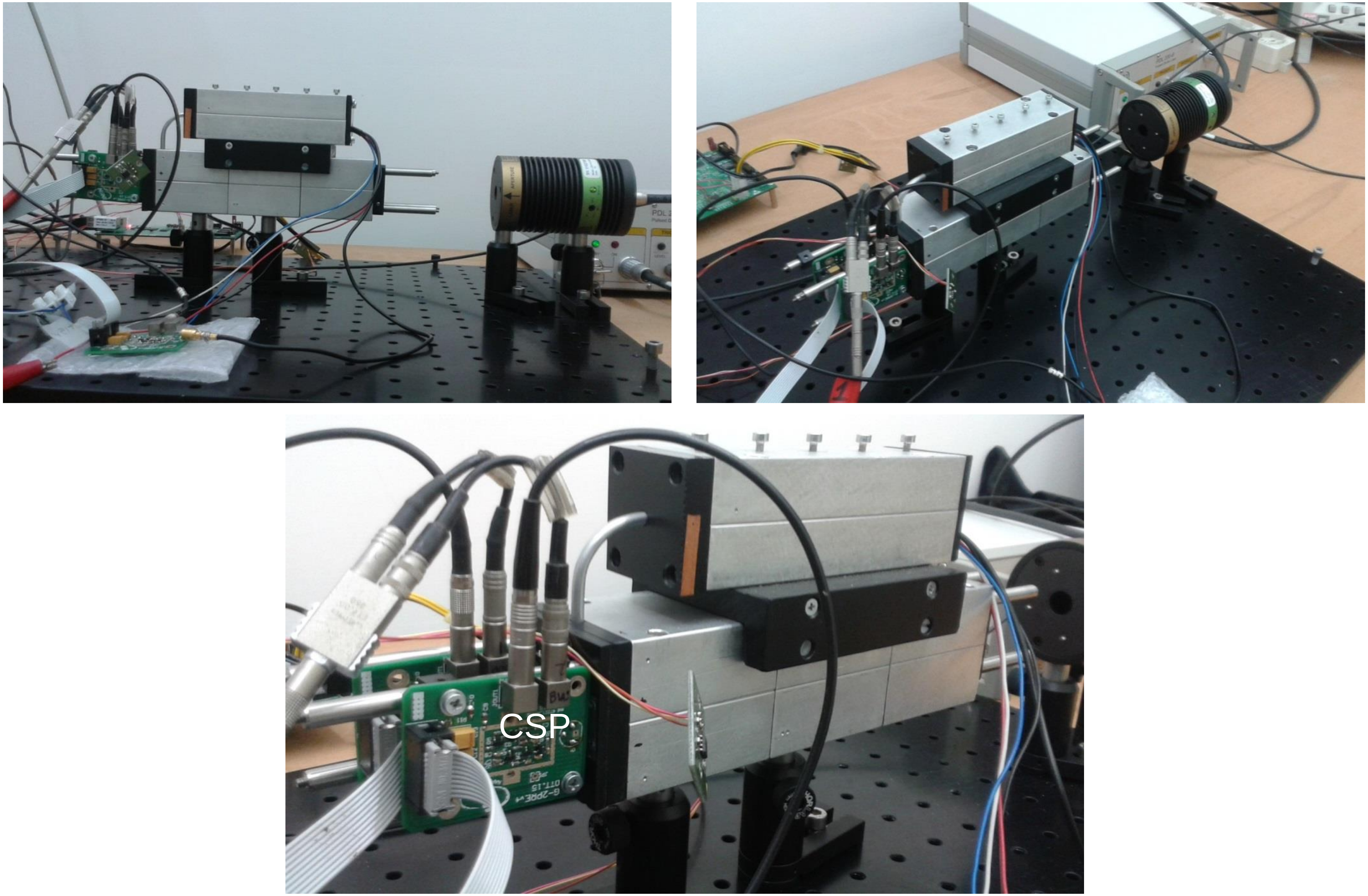

µTCA 12 bit @ 800 MHz, 60 CH
Laser room
3 CH X 24
3 CH X 6
FCSP
Am+NaI
PMT 1
PiD1
PiD2
CSP
Mixing chamber
Source monitor X 6
FCSP
PMT 1
PMT2
Mixing chamber
Local monitor X 24
A Meter
CONTROLLER
DAQ
TCP/IP
HV MODULE
CSP
BUS DATI
POWER SUPPLY

- 10 SMB have been produced and available in Naples (ready to test)
- 2 Controller Board have been produced and available in Naples

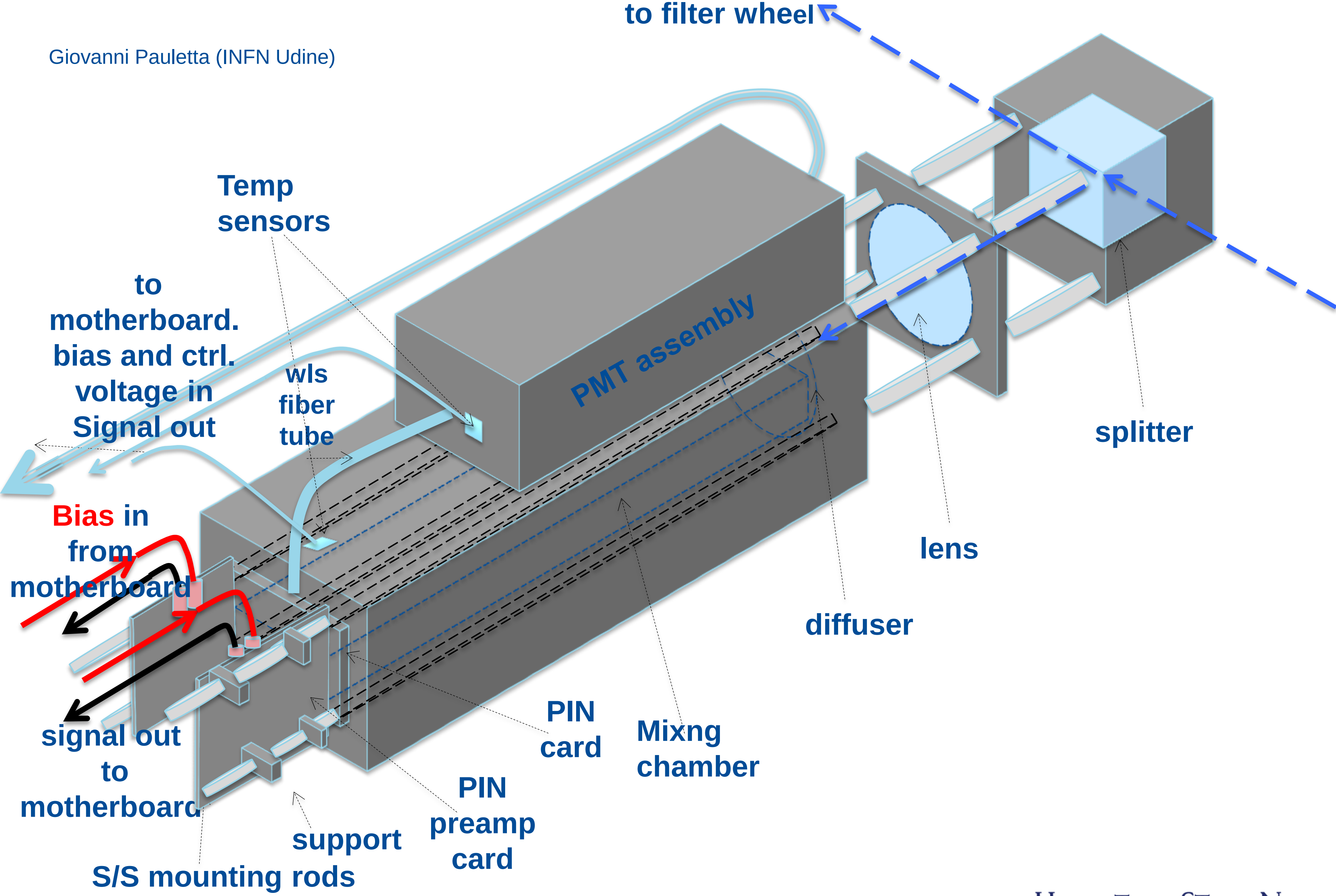


- 1 Crate (full opt: PowerSupply + Fan +…) arrive in early January 2017


DRS4 (WFD)
SMB
LCB
WFD OUT
PIN1 IN
PIN2 IN
PMT IN
Sepia II
SM
Trigger OUT


CSP

Giovanni Pauletta (INFN Udine)



Laser Calibration System: SM detectors

Each Source Monitor detects light using 3 independent detectors, 2 PIN diodes and 1 PMT to observe for eventual beam pointing effects.

PIN photodiodes (S1722-02)

- amplified by custom frontend electronics
- High photoefficiency (> 70%)
- Fast – can be shaped according to necessity
- Used to check for fluctuations in laser

PMT (H5783-04)

- amplified by custom frontend electronics
- receives light pulses transmitted from the mixing chamber to the photocathode
- light pulses (~ 5-10 Hz) which are emitted by a weak Am source are situated close to the photocathode to serve as an absolute reference needed to correct for the relatively poor stability (e.g. strong dependence on HV) of PMTs

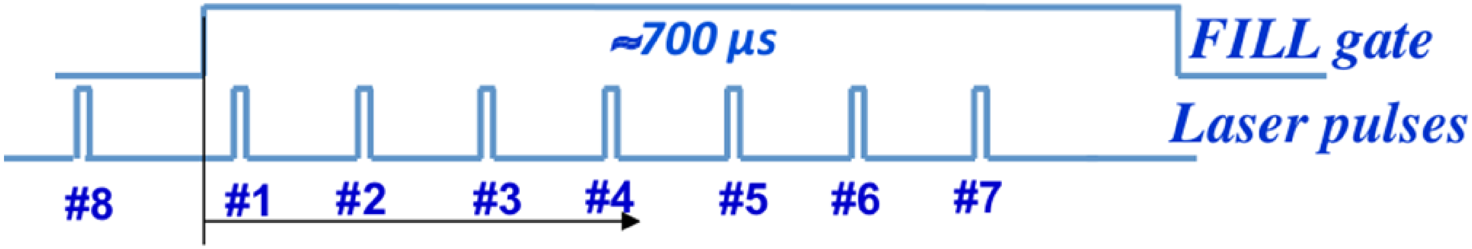
SLAC Runs

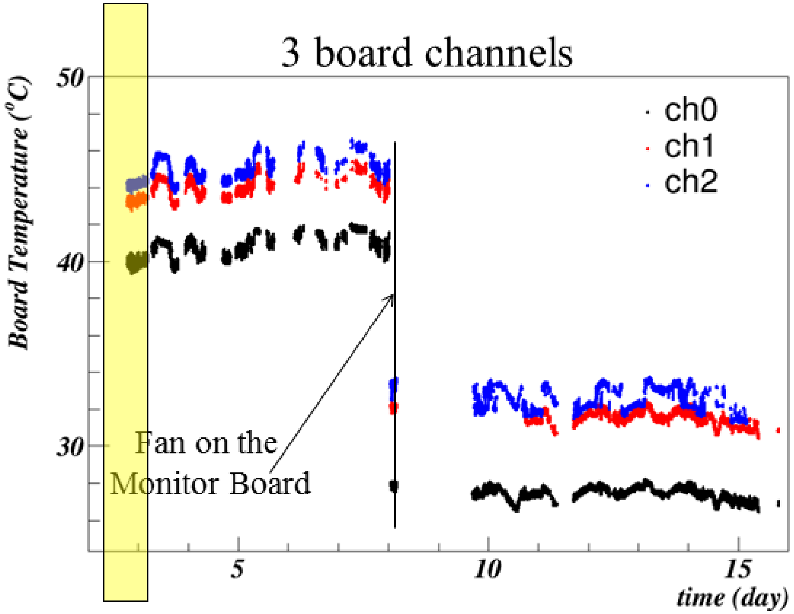
More than 14 days of data acquisition

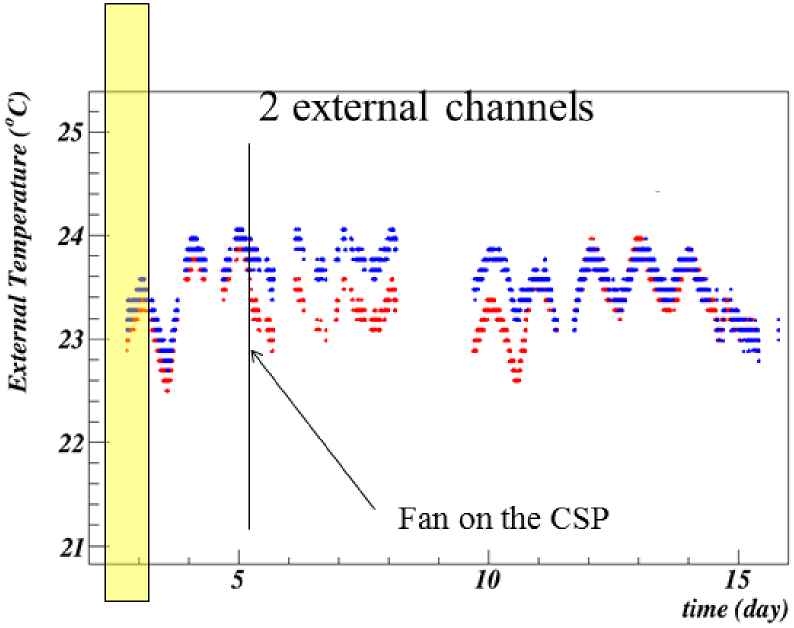
Day (June)	RUN number	Time duration (h)	freq. (kHz)
1	2	6	1 Hz
3	16	10	10
3	17	11	10
4	19	8	10-100
4	22	4	10
4	23	24	10
5	24	10	10-100
5	25	1	100
6	26		
6	27	1	10
6	28	1	10-2.5
6	29	1	20
6	30	1	100
6	31	1	Flight
6	32	1	Flight
6	33	1	Flight
6	34	1	Flight
6	35	10	100
6	36	15	100
7	37	7	100
7	38	2	100
8	39	10	100
9	40	25	100
10	41	40	100 + other
12	42	13	100 + other
12	43	27	100+flight
13	44	19	100
14	45	10	100
15	46	40	100

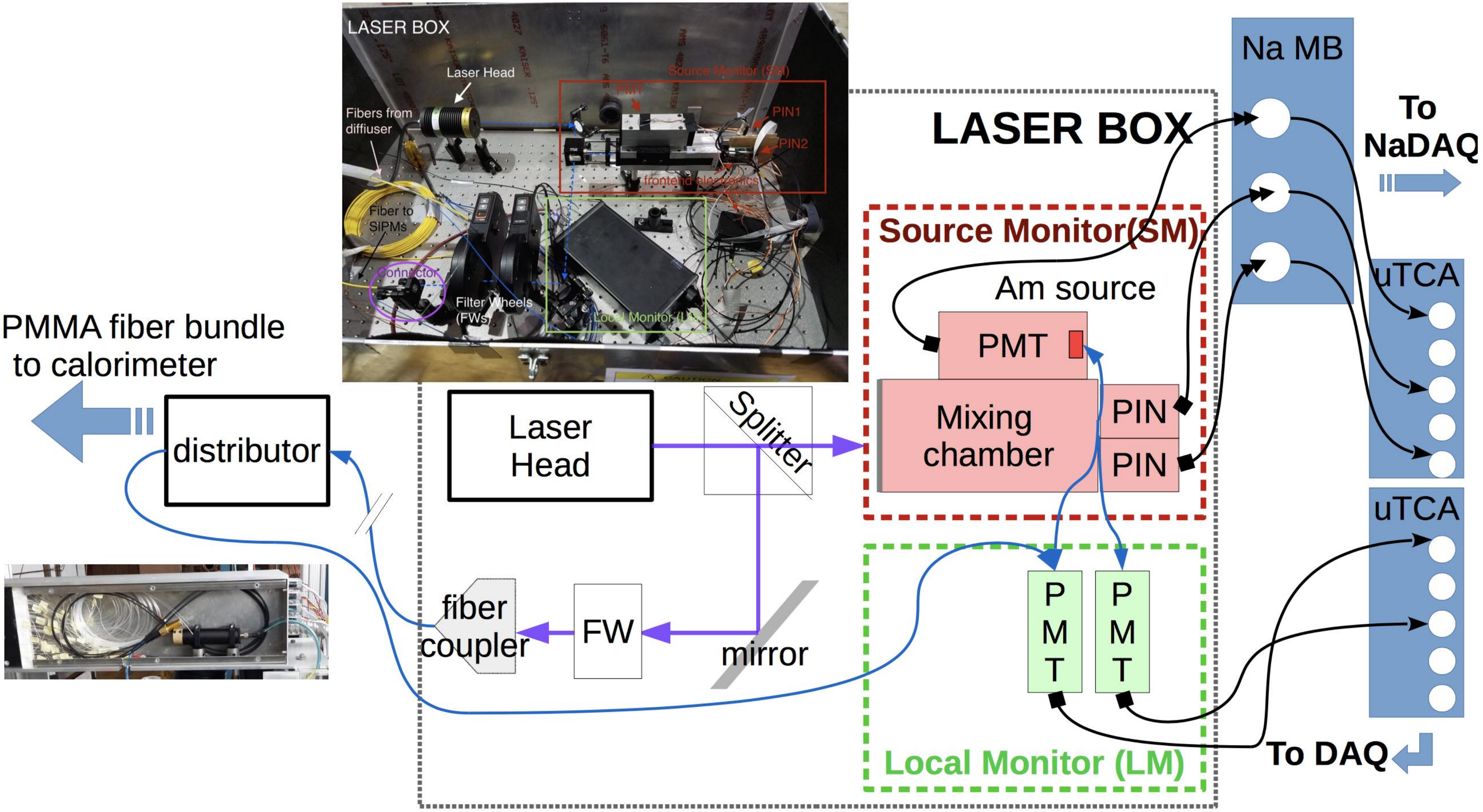
RUN 16 SLAC:

Time duration: 11h freq: 10kHz









LASER BOX

Na MB

To NaDAQ

Source Monitor(SM)

Am source

PMT

Mixing chamber

PIN

PIN

uTCA

uTCA

PMMA fiber bundle to calorimeter

distributor

Laser Head

Splitter

fiber coupler

FW

mirror

PMT

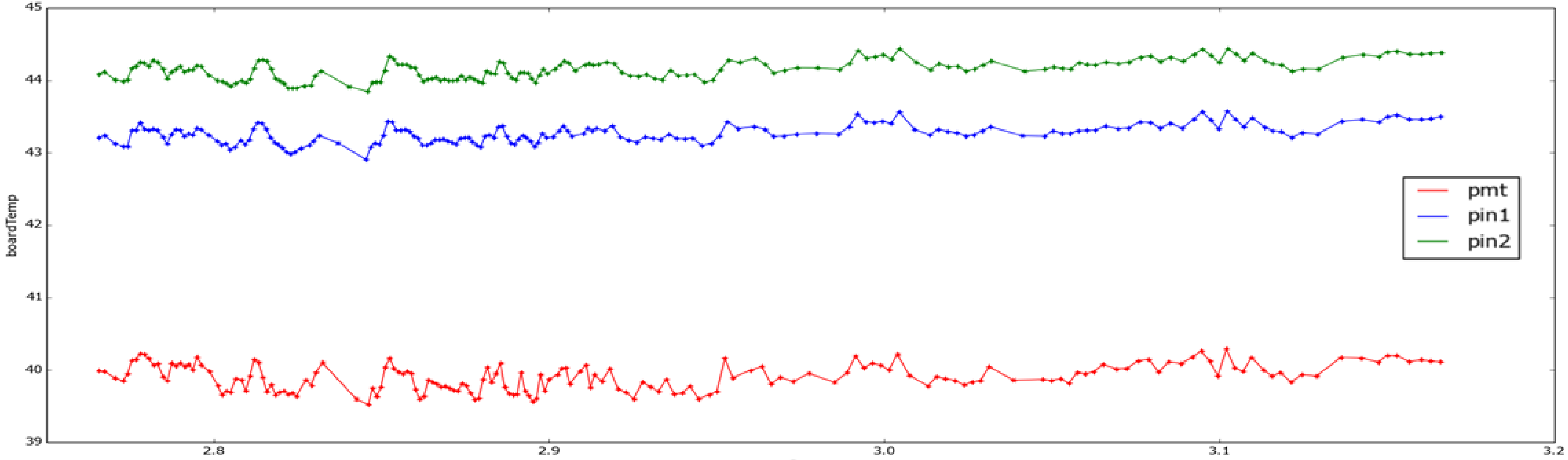
PMT

Local Monitor (LM)

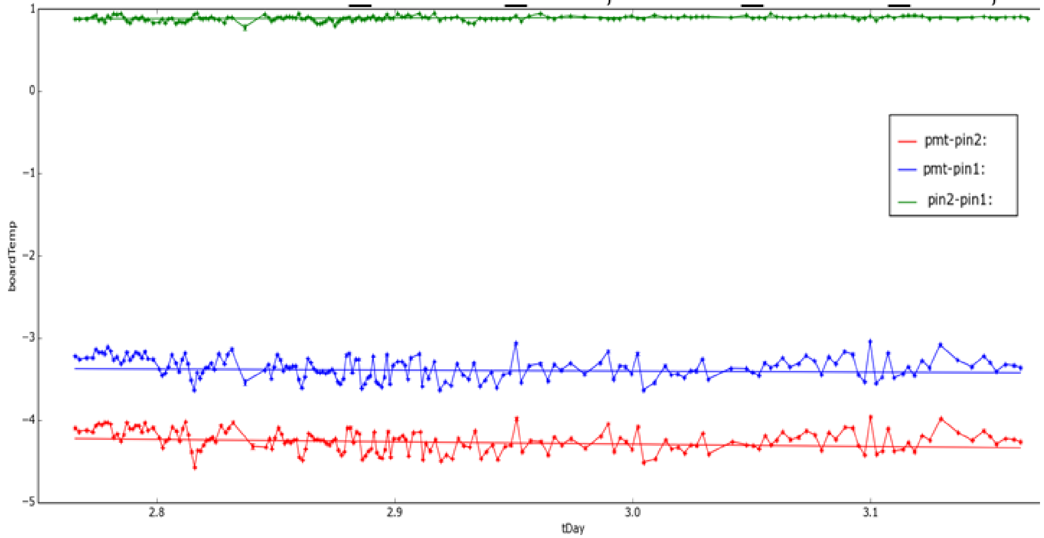
To DAQ

Anna Driutti (INFN Udine)

BoardTemp for PIN1,PIN2 and PMT channels, NtrgBOF=1



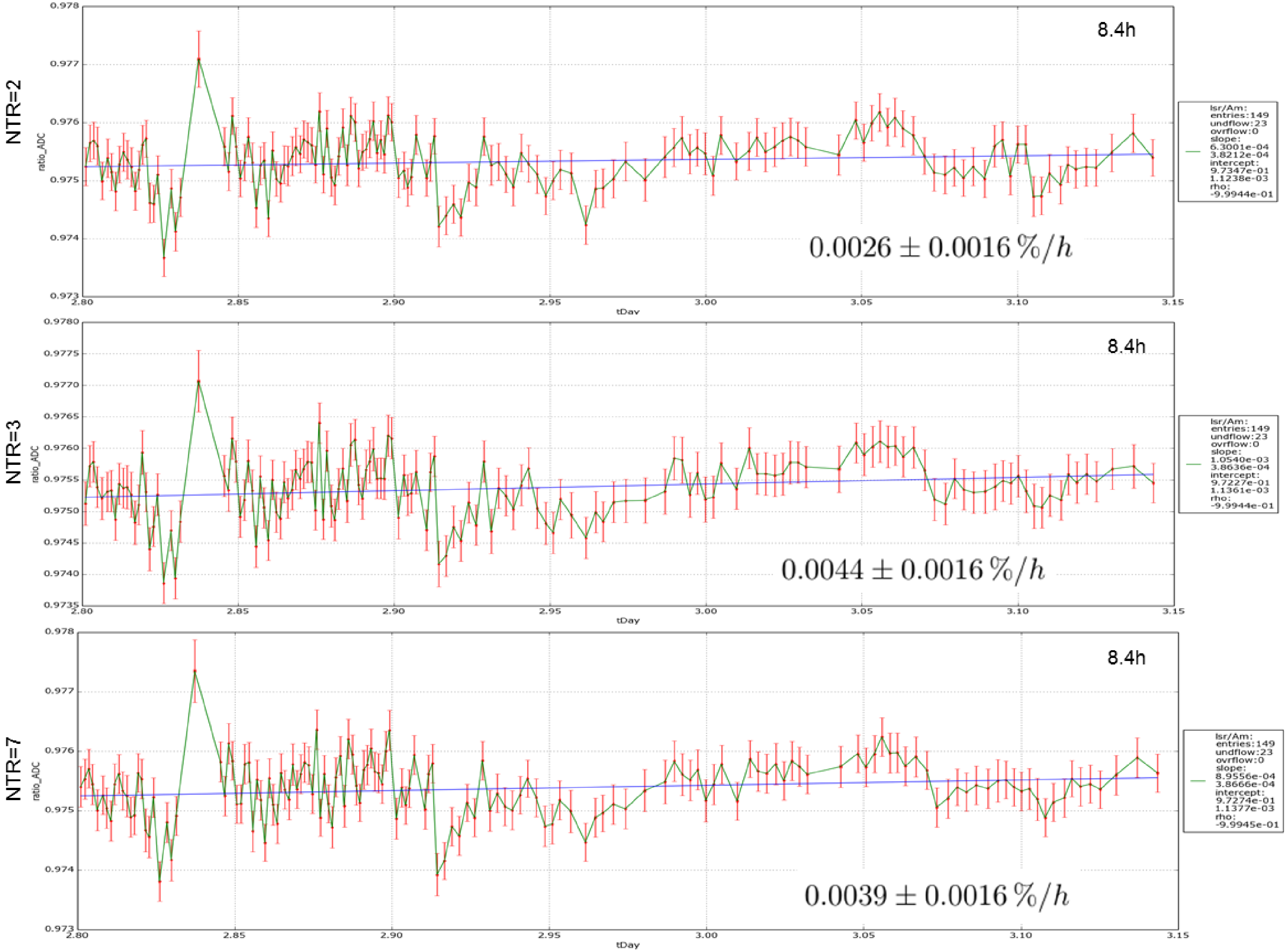
bT_Pin2-bT_Pin1, bT_Pmt-bT_Pin1, bT_Pmt-bT_Pin1:



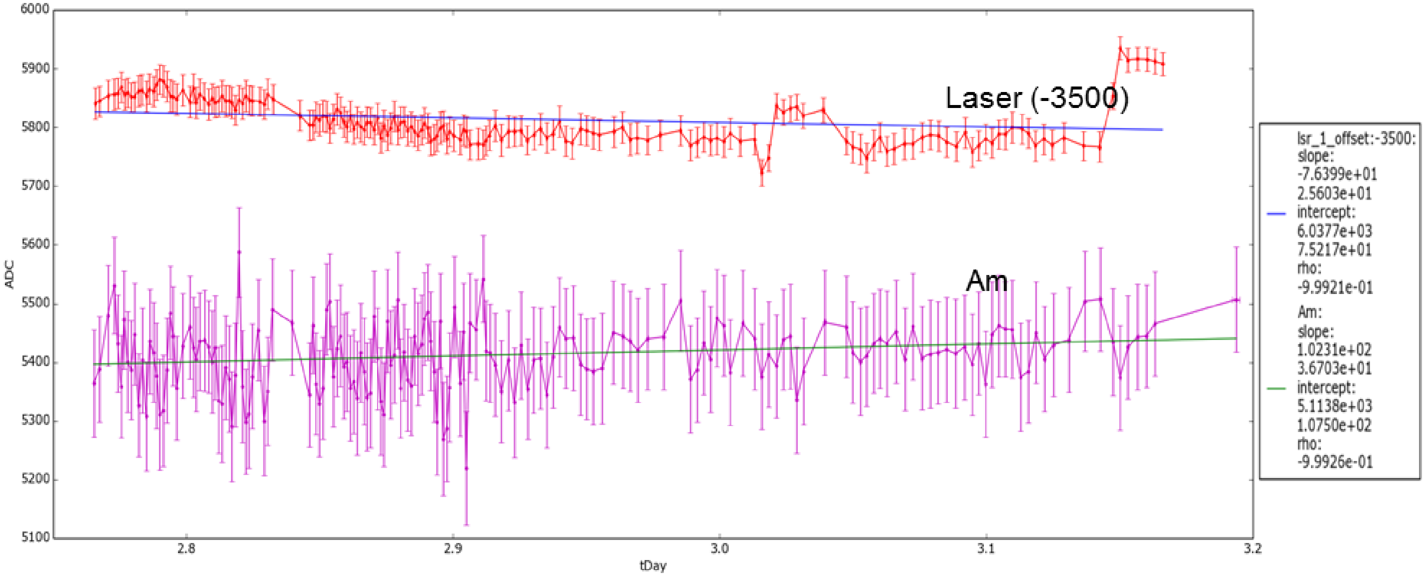
	slope	intercept
PIN2-PIN1	$0.07\pm0.02^\circ\mathrm{C}/\mathrm{day}$	$0.69 \pm 0.06^\circ\mathrm{C}$
PMT-PIN2	$-0.28 \pm 0.1^\circ\mathrm{C}/\mathrm{day}$	$-3.4 \pm 0.3^\circ\mathrm{C}$
PMT-PIN1	$-0.12 \pm 0.1^\circ\mathrm{C}/\mathrm{day}$	$-3.0 \pm 0.3^\circ\mathrm{C}$

NTRG=1	slope	intercept
PIN2-PIN1	$0.07\pm0.02^\circ\mathrm{C}/\mathrm{day}$	$0.69 \pm 0.06^\circ\mathrm{C}$
PMT-PIN2	$-0.28 \pm 0.1^\circ\mathrm{C}/\mathrm{day}$	$-3.4 \pm 0.3^\circ\mathrm{C}$
PMT-PIN1	$-0.12 \pm 0.1^\circ\mathrm{C}/\mathrm{day}$	$-3.0 \pm 0.3^\circ\mathrm{C}$
NTRG=2	slope	intercept
PIN2-PIN1	$0.06\pm0.02^\circ\mathrm{C}/\mathrm{day}$	$0.70 \pm 0.06^\circ\mathrm{C}$
PMT-PIN2	$-0.28 \pm 0.1^\circ\mathrm{C}/\mathrm{day}$	$-3.5 \pm 0.3^\circ\mathrm{C}$
PMT-PIN1	$-0.13 \pm 0.1^\circ\mathrm{C}/\mathrm{day}$	$-3.0 \pm 0.3^\circ\mathrm{C}$
NTRG=5	slope	intercept
PIN2-PIN1	$0.07\pm0.02^\circ\mathrm{C}/\mathrm{day}$	$0.70 \pm 0.06^\circ\mathrm{C}$
PMT-PIN2	$-0.27 \pm 0.1^\circ\mathrm{C}/\mathrm{day}$	$-3.5 \pm 0.2^\circ\mathrm{C}$
PMT-PIN1	$-0.16 \pm 0.1^\circ\mathrm{C}/\mathrm{day}$	$-3.0 \pm 0.3^\circ\mathrm{C}$
NTRG=8	slope	intercept
PIN2-PIN1	$0.07\pm0.02^\circ\mathrm{C}/\mathrm{day}$	$0.70 \pm 0.06^\circ\mathrm{C}$
PMT-PIN2	$-0.26 \pm 0.1^\circ\mathrm{C}/\mathrm{day}$	$-3.5 \pm 0.2^\circ\mathrm{C}$
PMT-PIN1	$-0.15 \pm 0.1^\circ\mathrm{C}/\mathrm{day}$	$-3.0 \pm 0.3^\circ\mathrm{C}$

ADC ratio: PIN1/PIN2



PMT: Laser (ntrg=1), Americio

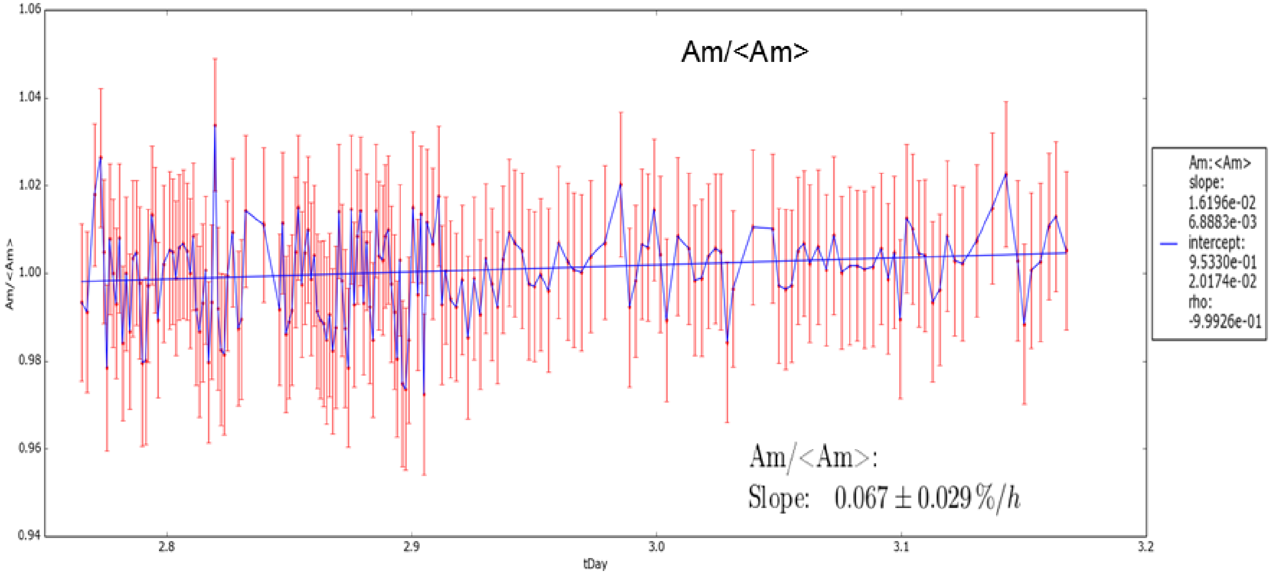


Laser ntrg=1 (-3500):

Slope: $-3.2 \pm 1.1\, adc/h$

Americio:

Slope: $4.3 \pm 1.5\, adc/h$



$Am/\langle Am\rangle$:

Slope: $0.067 \pm 0.029\,\%/h$

$Am/\langle Am\rangle$	
Am Range $[ADC]$	$Am/\langle Am\rangle$ Slope $[\%/h]$
$[650, 8000]$	(0.067 ± 0.029)
$[800, 8000]$	(0.070 ± 0.029)
$[1000, 8000]$	(0.071 ± 0.028)
$[1200, 8000]$	(0.073 ± 0.07)

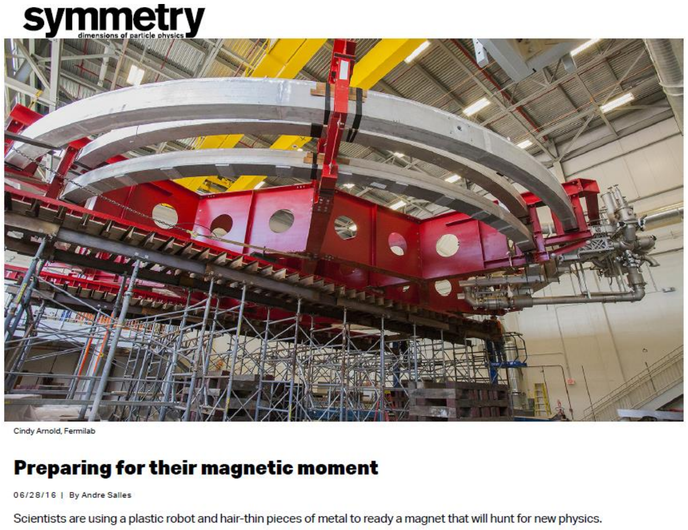
Overview

- Introduction and theory
- Latest updates from Fermilab
- Italian contribution
- Ongoing work in Napoli
- Closing remarks

Closing remarks

- Storage ring is cold and powered
  - Installation of auxiliary ring equipment has commenced
  - Muons expected in 2017

- Laser calibration system will aid in obtaining 0.01 ppm statistical uncertainty
  - Monitoring electronics stable at 10^{-4}/h (time derivative)
  - Laser pulse measured at ~10^{-3} (single pulse resolution)
  - Monitoring equipment is ready for installation
  - Temperature, electronic baseline fluctuations and other factors must still be well understood (frontend electronics)



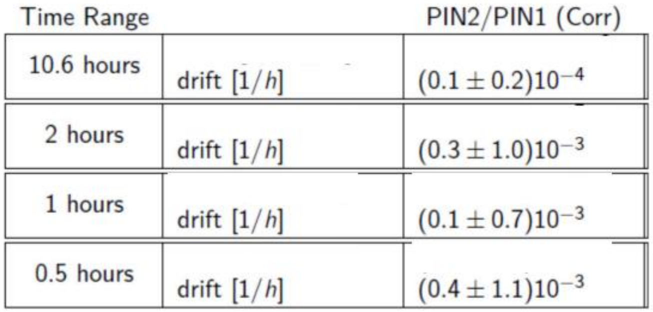
symmetry
dimensions of particle physics

Cindy Arnold, Fermilab

Preparing for their magnetic moment

06/28/16 | By Andre Salles

Scientists are using a plastic robot and hair-thin pieces of metal to ready a magnet that will hunt for new physics.



Time Range		PIN2/PIN1 (Corr)
10.6 hours	drift $[1/h]$	$(0.1 \pm 0.2)10^{-4}$
2 hours	drift $[1/h]$	$(0.3 \pm 1.0)10^{-3}$
1 hours	drift $[1/h]$	$(0.1 \pm 0.7)10^{-3}$
0.5 hours	drift $[1/h]$	$(0.4 \pm 1.1)10^{-3}$

Thank you!

Backup

The magic momentum

Muons can be confined vertically by an electric field quadrupole

However, electric field causes a problem as the relativistic muon will “see” the lab frame electric field as a magnetic field in the muon’s rest frame.

$$\vec{\omega}_a = \frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)(\vec{\beta} \times \enclose{circle}{\vec{E}})\right]$$

Causes dependence of spin frequency on electric field

This is a serious issue there exists no precise method to measure electric fields (i.e. no NMR equivalent for $\vec{E}$)

The magic momentum

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However, electric field causes a problem as the relativistic muon will “see” the lab frame electric field as a magnetic field in the muon’s rest frame.

$$\vec{\omega}_a = \frac{e}{m}\left[a_\mu \vec{B} - \left(\boxed{a_\mu - \frac{1}{\gamma^2 - 1}}\right)(\vec{\beta} \times \vec{E})\right]$$

If coefficient can be made zero, then problem no longer exists

$$\gamma = \sqrt{\frac{1}{a_\mu} + 1}$$

With the correct relativistic enhancement, that is, “magic momentum” $p_\mu = 3.09\ \mathrm{GeV}/c$ the entire coefficient becomes zero.

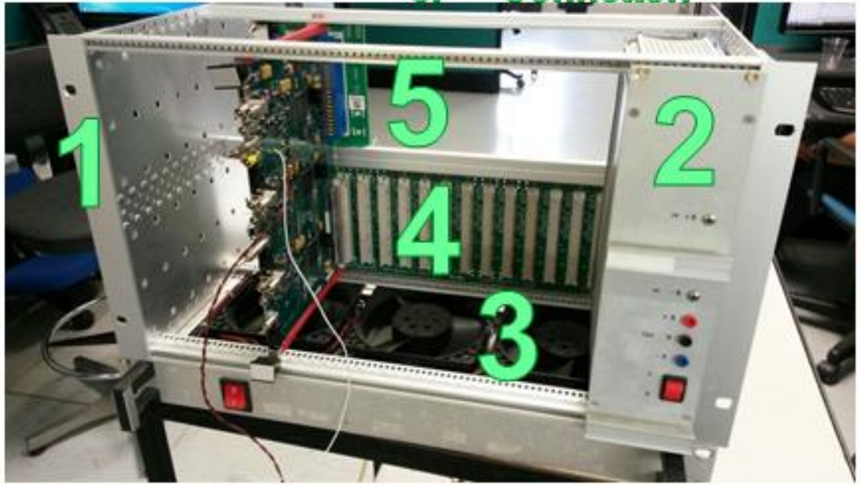
$$a_{\mu}^{QED} = \frac{\alpha}{2\pi} + 0.76\ldots\left(\frac{\alpha}{\pi}\right)^{2} + 24.0\ldots\left(\frac{\alpha}{\pi}\right)^{\overset{\Big\downarrow}{3}} + 131\ \ldots\left(\frac{\alpha}{\pi}\right)^{4} + \overset{\Big\downarrow}{930}\ldots\left(\frac{\alpha}{\pi}\right)^{5}$$

$$i\hbar\frac{\partial\phi}{\partial t} = \left[\frac{(\vec{p})^{2}}{2m} - \frac{e}{2m}\left(\vec{L} + \underset{\Big\uparrow}{2}\vec{S}\right)\cdot\vec{B}\right]\phi$$

Crates

gara da iniziare: 3 crate

1. Chassi
2. Alimentatore
3. Unità ventilazione
4. Backplane trasf dati (VME standard)
5. Backplane alimentazione (custom, disegno completato)
6. Connettori



Laser Calibration System: SM detectors

Each Source Monitor detects light using 3 independent detectors, 2 PIN diodes and 1 PMT to observe for eventual beam pointing effects.

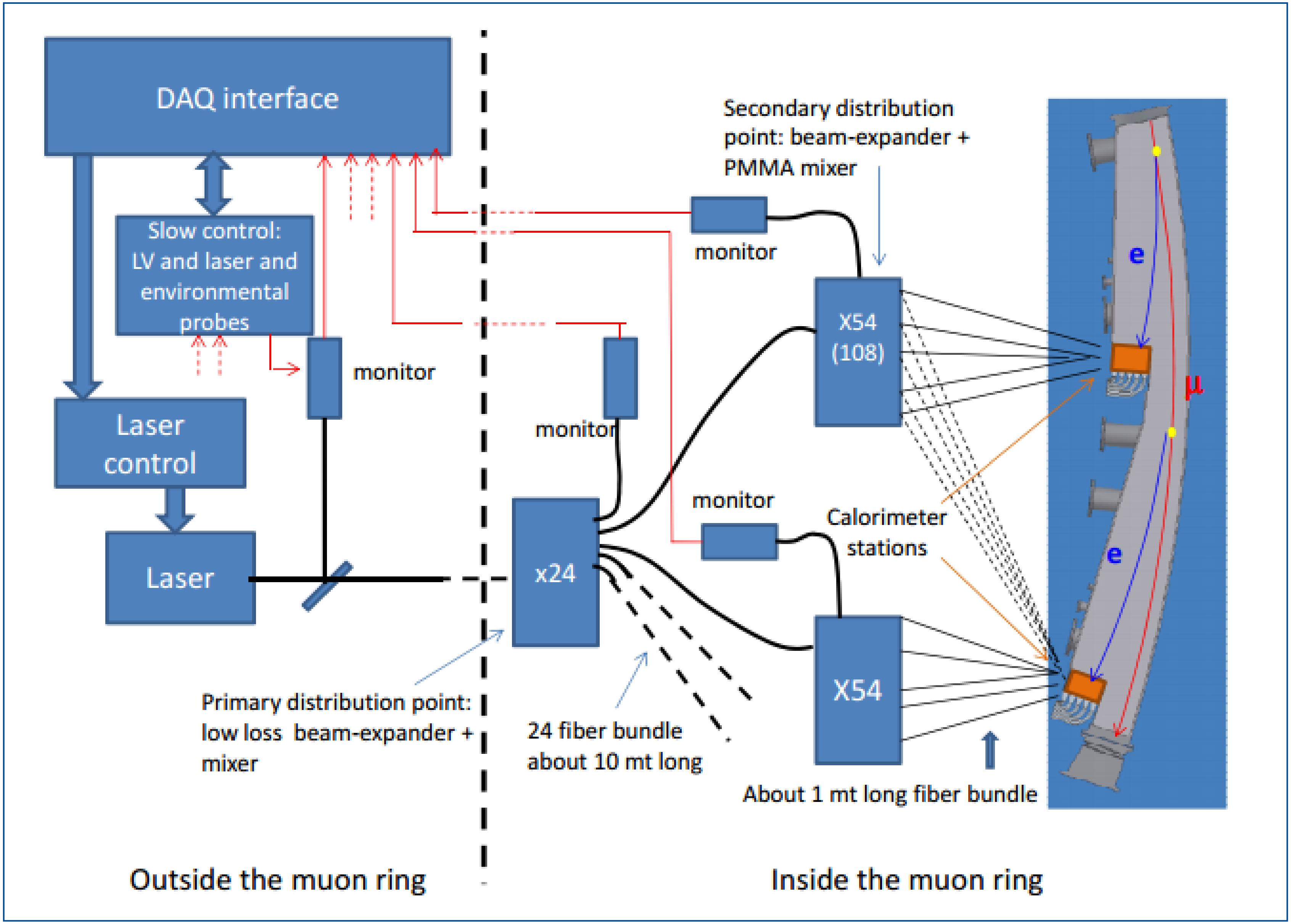
PIN photodiodes (S1722-02)

- amplified by custom frontend electronics
- High photoefficiency (> 70%)
- Fast – can be shaped according to necessity
- Used to check for fluctuations in laser

PMT (H5783-04)

- amplified by custom frontend electronics
- receives light pulses transmitted from the mixing chamber to the photocathode
- light pulses (~ 5-10 Hz) which are emitted by a weak Am source are situated close to the photocathode to serve as an absolute reference needed to correct for the relatively poor stability (e.g. strong dependence on HV) of PMTs

Università degli Studi di Napoli Federico II


DAQ interface
Slow control: LV and laser and environmental probes
Laser control
Laser
monitor
monitor
Secondary distribution point: beam-expander + PMMA mixer
monitor
X54 (108)
monitor
Calorimeter stations
x24
X54
e
μ
e
Primary distribution point: low loss beam-expander + mixer
24 fiber bundle about 10 mt long
About 1 mt long fiber bundle
Outside the muon ring
Inside the muon ring