# Experience with Resistive Plate Chambers at BaBar

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# Outline

- RPC
  - General concepts, many incarnations.
  - Very active R&D, accurate ageing studies.
- BaBar muon and neutral hadron detector (IFR)
- BaBar RPC
  - 1999-2000: **Original** version, many problems…
  - 2000-2001 some R&D, improved RPCs (tested in situ **Nov2000**)
  - Forward Endcap **upgrade 2002**.
  - Experience with data-taking (Run3: 2002-2003; Run4: 2003-now).

# Resistive Plate Chambers

A dream: "*Build a **cheap** detector with good timing and position resolution for large surfaces*"

- A constant uniform E field between two parallel electrode plates with gas.
  - ***Particle generates a discharge***
- Electrode made of high bulk resistivity material
  - ***Self-controlled discharge, localized dead region***
- Gas mix with high absorption coeff for UV light
  - ***No secondary discharge***

*R. Santonico and R. Cardarelli, **NIM** 187(1981) 377*

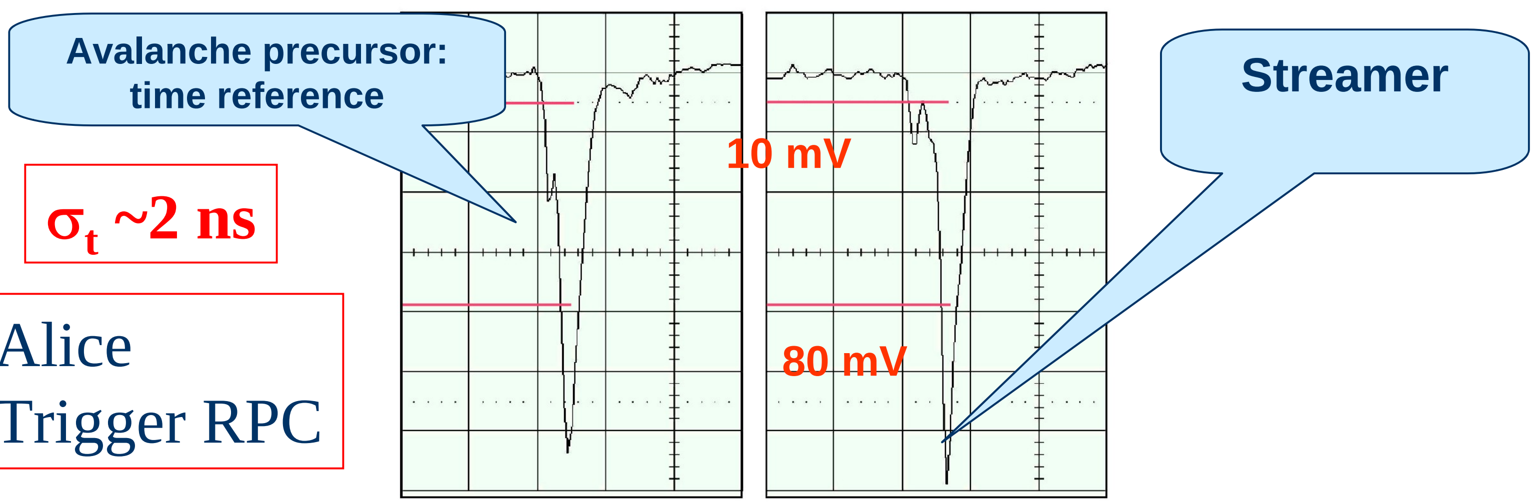
# The basic principles

- *Streamer* mode
  - Large charge (100-1000pC): no signal amplification needed
  - Rate limitation ( 10 Hz/cm2)
- *Avalanche* mode
  - Small charge (1-10pc)
  - Worse S/N ratio
  - **higher** rate capability

*Ageing proportional to integrated charge* $\boldsymbol{Q_{int}}$

$\sigma_t$ ~2 ns

Alice
Trigger RPC



# RPC as muon detectors

**Freons**: *electronegative*! Suppress streamer formation
**Hydrocarbur gas**: *absorb photons* from discharge

Gas mixture
$C_2H_2F_4$ (96.5- a)%, i- $C_2H_4$ 3.5%, $SF_6$ a % (a ~1%)

*Avalanche mode*

*CMS trigger RPC*

| | |
|---|---|
| Time Resolution | $\leq$ 3 ns |
| Efficiency | $\geq$ 95 % |
| Rate Capability | $\geq$ 1 kHz/cm$^2$ |
| Intrinsic Noise Rate | $\leq$ 15 Hz/cm$^2$ |
| Streamer Probability | $\leq$ 10 % |
| HV Plateau | $\geq$ 300 V |

Bakelite electrodes: $\rho_V \sim 8\ 10^{10}\ \Omega \cdot \mathrm{cm}$

# Very active field

**_RPC 2003 VII Workshop_**
http://clrwww.in2p3.fr/RPC2003/

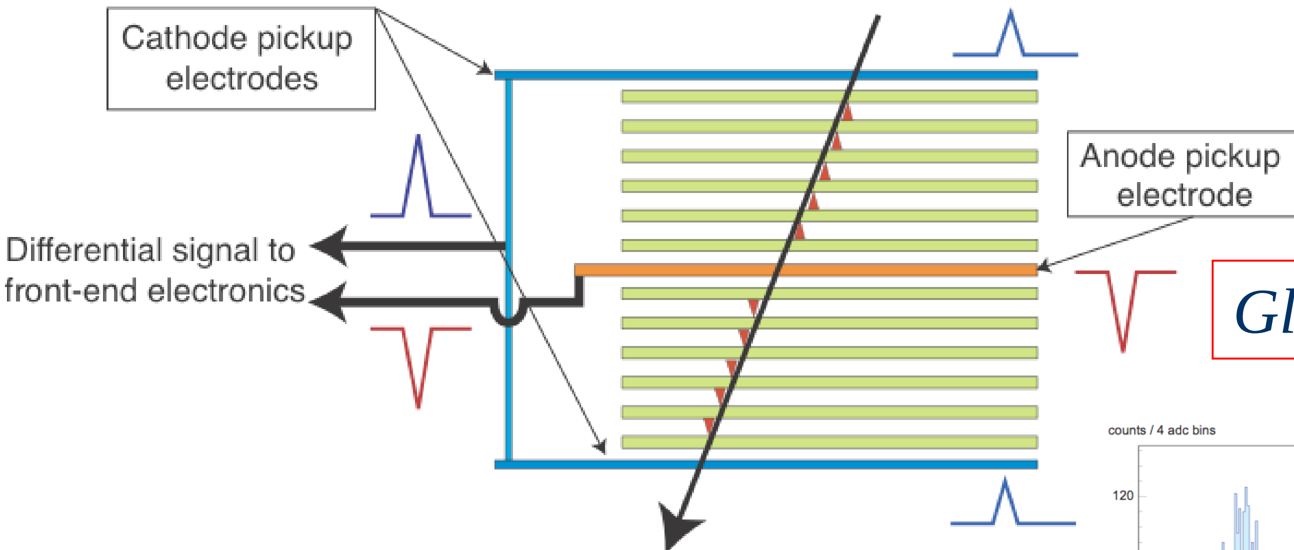
Sessions:

- Trigger
  - BaBar,Belle, Argo, Alice, CMS (endcap/barrel), Opera, HARP
- Montecarlo Simulation
  - avalanche
- Timing device
  - Star,Alice TOF,…
- Ageing studies
  - ALICE TOF, Atlas, LHCb,CMS, glass RPC, bakelite resistivity
- New applications
  - Digital HADCal, Imaging RPC, RPC as neutron detector, neutrino detector for NuMi Off-axis exp.
- Dedicated electronics
  - Alice TOF TDC, NINO amplifier,…
- Large scale production and testbeam studies
  - Atlas,Opera(BaBar),CMS

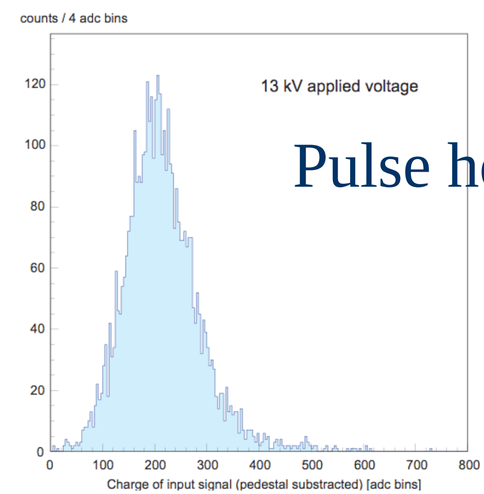
# ALICE TimeOfFlight detector

ALICE-TOF has 10 gas gaps, each of 250 micron width

Built in the form of strips, each with an active area of 120 x 7 $cm^2$, readout by 96 pads (each 2.5 x 3.5 $cm^2$)




*Glass electrode*



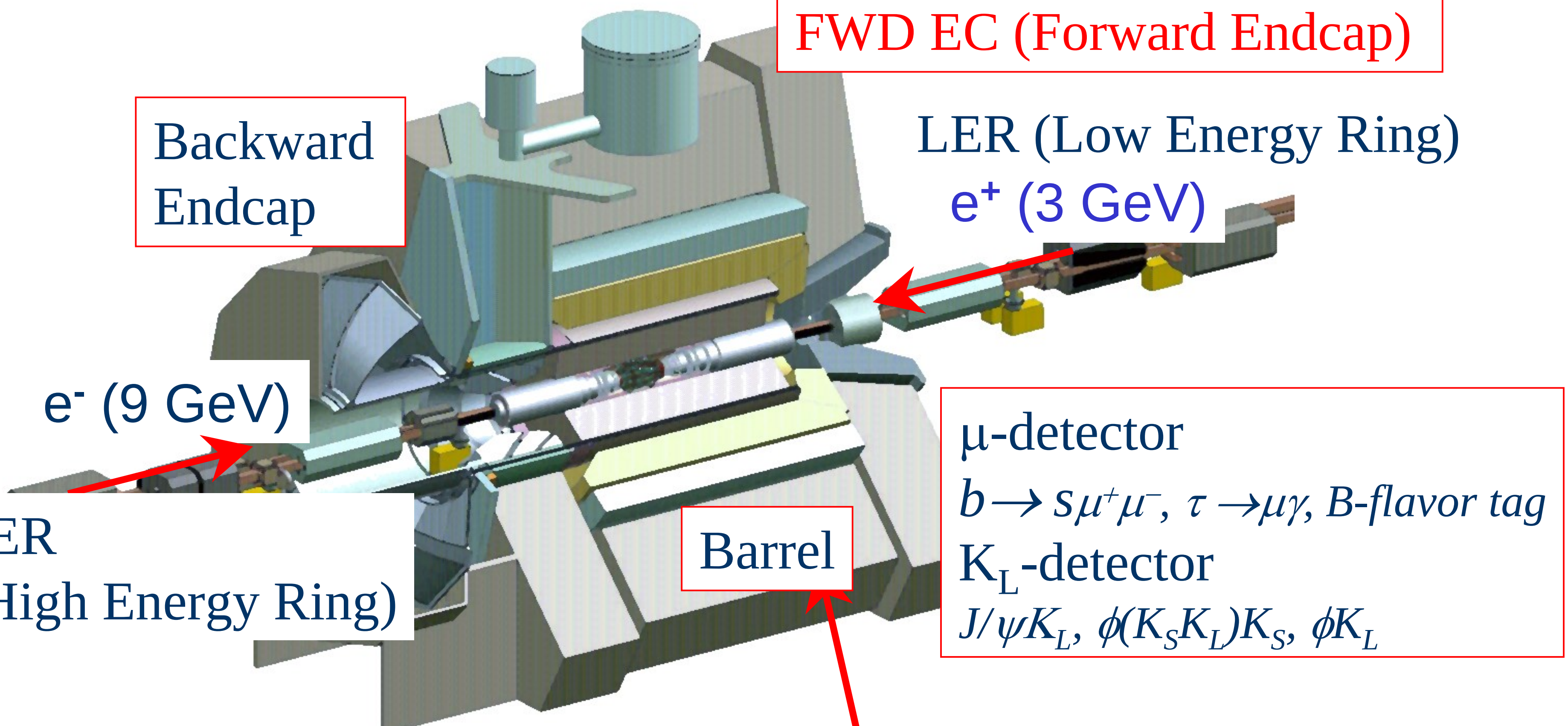

Pulse heigth

Timing depends on individual gap

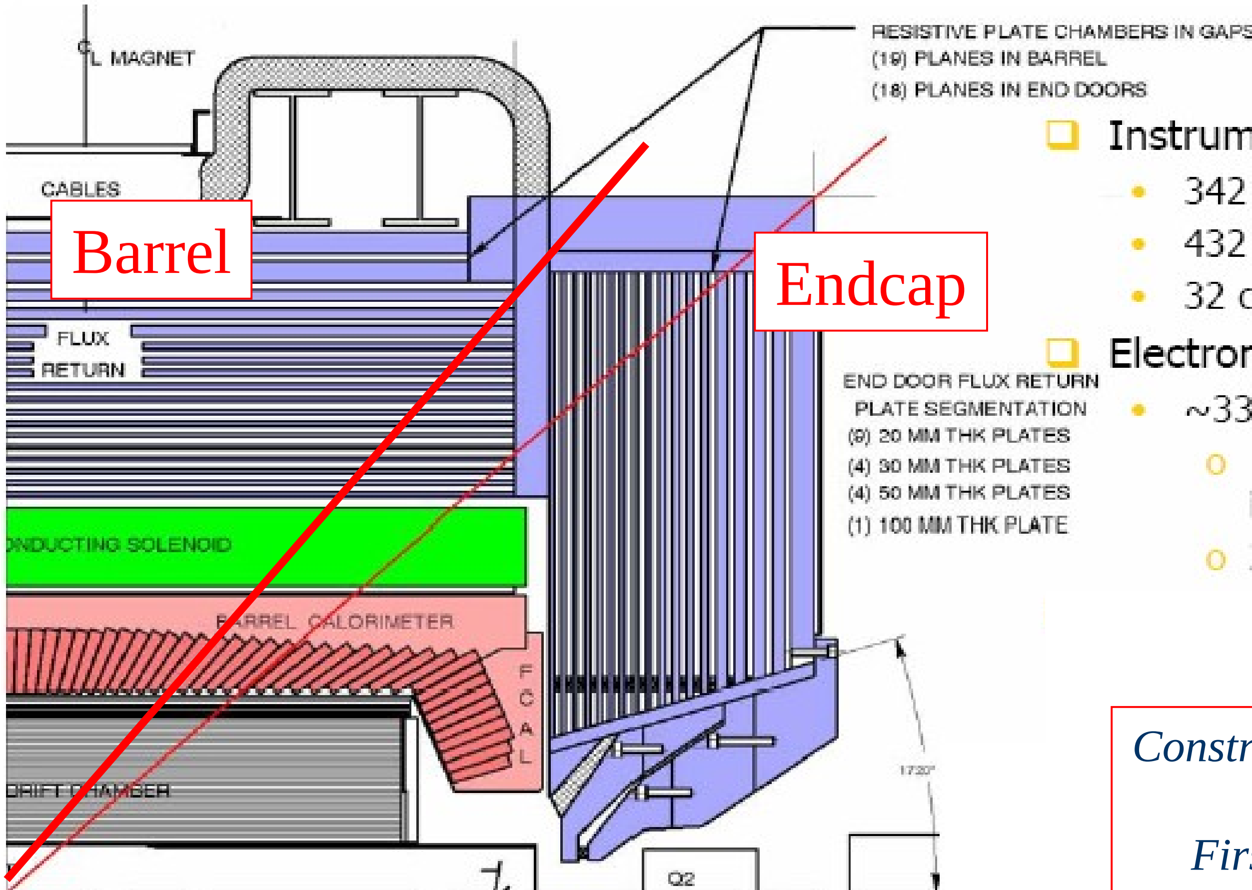
Efficiency depends on total gas gap (10x250 $\mu$m)

$\sigma_t \sim 40$ ps

# The BaBar detector



# BaBar IFR



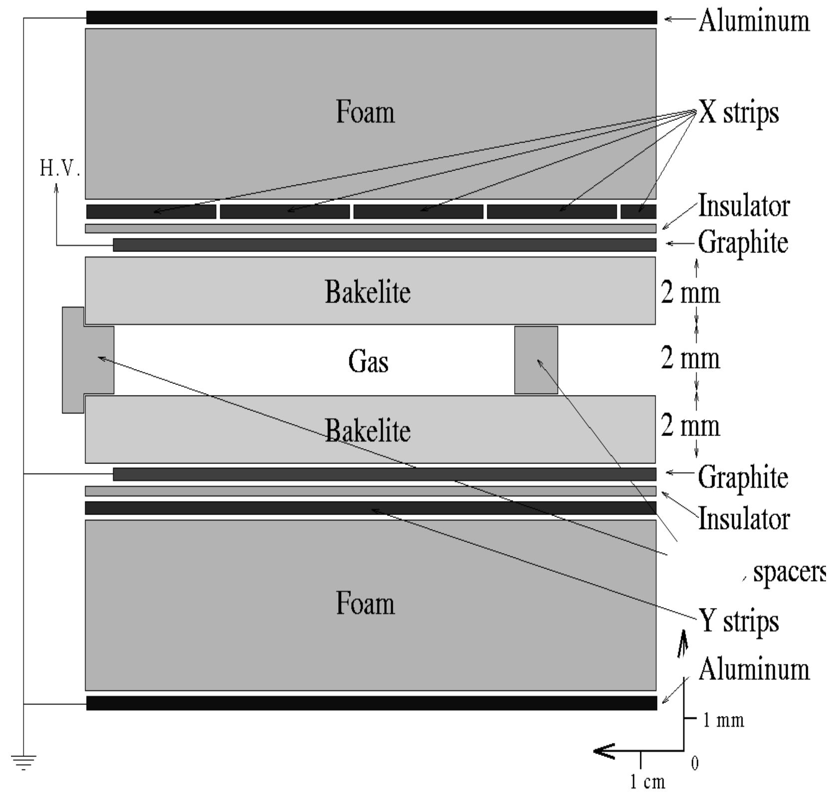

- Instrumented Flux Return
  - 342 barrel RPCs
  - 432 endcap RPCs
  - 32 cylindrical RPCs
- Electronics
  - ~3300 Front end cards
    - 16 strips/FEC digital info. (30 mV threshold)
    - 2 Fast out/FEC

*Constructed at General Tecnica (1996-1997)*
*First version: taking data since BaBar first day (1999)*

*40% B decay muons within $0.3<\theta<1.$ rad*

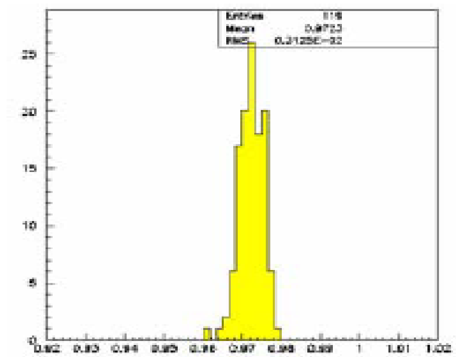
# BaBar Resistive Plate Chambers

- RPC operated in streamer mode.
  - Single gap counter
    - 2 mm gas gap
      polycarbonate spacer
    - Bakelite electrode
      - $\rho_V$ = 3-12 $10^{11}$ Ωcm
    - Linseed oil/n-pentane (70/30)
      - Multiple coating
    - Graphite paint
      - $\rho_S$ = 100 KΩ/□
  - Gas mix
    - 45% Ar, Iso 4.8%, **$C_2H_2F_4$ 50.2%**
    - ~1vol/day (then 3vol/day)
  - Electronics read-out
    - 40 mV threshold



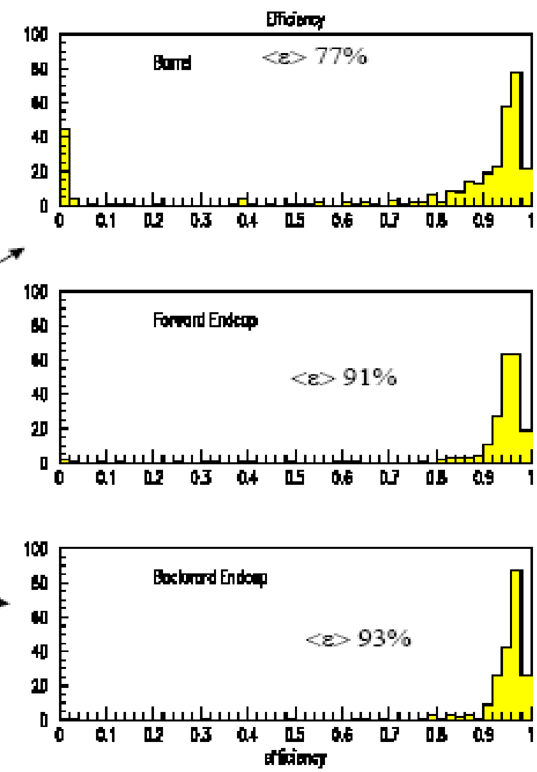

**Cosmic rate 0.1 Hz/cm$^2$**
**Max rate ~ 5-10 Hz/cm$^2$**

# Summer sunny summer…



- RPCs were tested at Frascati prior to shipment to SLAC

- At SLAC RPCs assembled into chambers ( 2 or 3 RPCs with common readout strips and single gas path)
- Inserted into BaBar steel
- First beam May 99
  - Heating from electronics & ambient hall raise BaBar steel to 29-34°
  - Some barrel RPCs disconnected
  - $\langle I \rangle \approx 70$ -210 $\mu$A barrel ~70 Endcap
  - Cooling system being prototyped




***RPC rapidly losing efficiency!!!***

# Linseed oil troubles.

"It is a mixture of the glycerides of linolenic, linoleic, oleic, stearic, and palmitic acids with high degree of unsaturation of its fatty acid radicals."

R-COOH ≡ Fatty Acid ≡

## Linseed Oil

- Test RPCs were subjected to a heating cycle at 36° C in a test stand.
- Permanent changes in both current and efficiency were seen
- Large oil drops spanning the 2 mm gap were found.

- Have not been able to remove any barrel RPCs

*Local spikes!!!*

# Gluey, lower resistivity

***Removed in Nov2000***

## Forward Endcap Photos

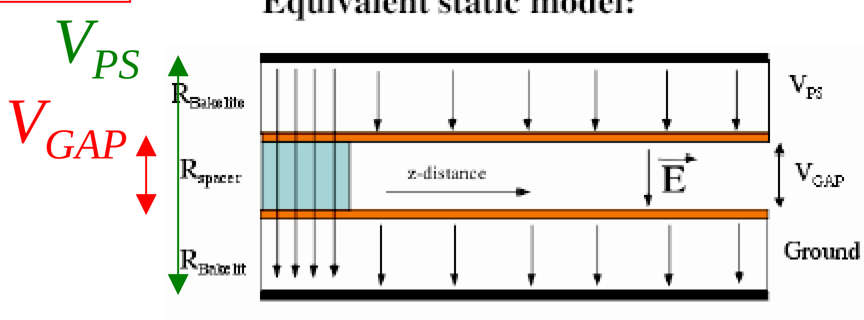
# Voltage divider effect

## BaBar RPC chamber simple Ohmic model

J. Va'vra, http://www.slac.stanford.edu/~jjv/activity/babar_rpc_my_summary.pdf and http://www.slac.stanford.edu/~jjv/activity/babar_rpc_my_summary_1.pdf

J.Va'vra

Equivalent static model:




- **Lexan button:**
  $\rho_V \sim 1.7\times10^{11}\ \Omega$ cm
- **Bakelite:**
  $\rho_V \sim 2.5\times10^{11}\ \Omega$ cm
- **Equivalent resistance:**
  $R_{Bakelite} = \rho_V\ (t_{gap}/Area)\ \sim 5\times10^{8}\ \Omega$
  $R_{Lexan\ button} = \rho_V\ (t_{gap}\ /\ Area) \sim 3.4\times10^{11}\ \Omega$.
- **For these conditions:**
  $V_{GAP} = V_{PS} / (1 + 2R_{Bakelite} / R_{Lexan\ spacer}) \sim V_{PS}$
- **To satisfy $V_{GAP} \sim V_{PS}$, we must have:**
  $R_{Lexan\ spacer} >> R_{Bakelite}$.
- **For example, a factor of 60 increase in $R_{Bakelite}$ gives:**
  $V_{GAP} \sim 0.85 \times V_{PS}$.

5

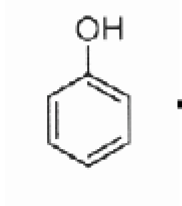
If (*locally/globally*) $\rho_V$ increases

or

If current too high (*high rate*) $\rightarrow V_{GAP} = V_{PS} - R_{bakelite} I_{dark}$

***$V_{GAP}$ below streamer threshold!!!***

# No life without water

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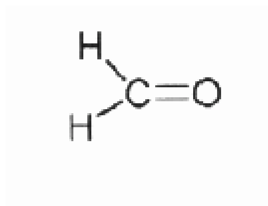


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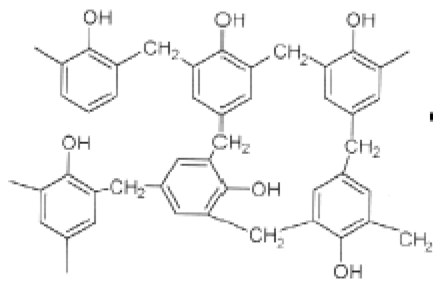
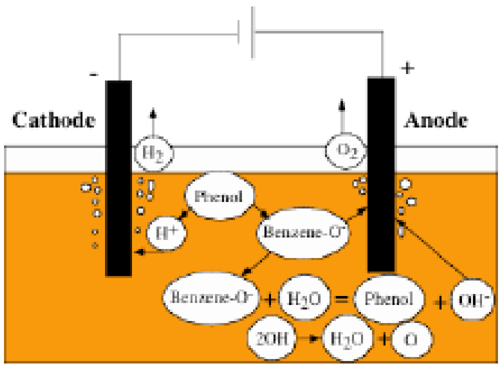
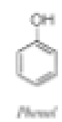



+ $H_2O$

**Phenol** **Formaldehyde**

- **Bakelite**




Phenol ≡ Benzene-OH ≡ 


**Benzene-OH + field -> Benzene-O$^-$ + H$^+$**

**Benzene-O$^-$ + $H_2O$ -> Benzene-OH + OH$^-$**

**OH$^-$ delivers the charge at anode**

**2OH -> $H_2O$ + $O_2$ at anode**

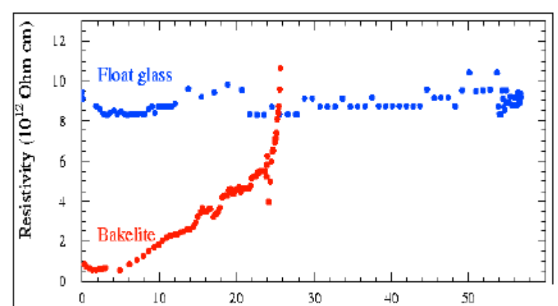
*Similar model for linseed oil, fatty acids and water*

**Model of conductivity:**

**A current in the Bakelite is modulated by a presence of water and Phenol impurities.**

***Charge flowing through the detector depletes it of water!***

A. Tonazzo, IEEE 2002




60

$Q_{int}$ [mC/cm$^2$]

# Graphite vaporization: a dead end…

***$O_2$ to the anode***

**Graphite oxidizes ("burns") and produces $CO_2$ gas.**

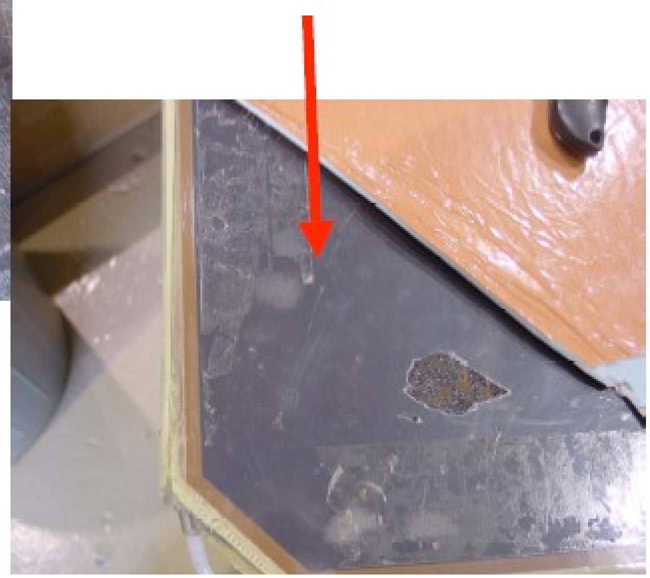
*Nominal graphite $\rho_S$ ~ 100kΩ/□*
*Cathode side: 120kΩ/□*
*Anode side: **> 100MΩ/□***

**Graphite was repainted on a small section and connected to HV**

**Efficiency was restored proving that the inner gap was working**

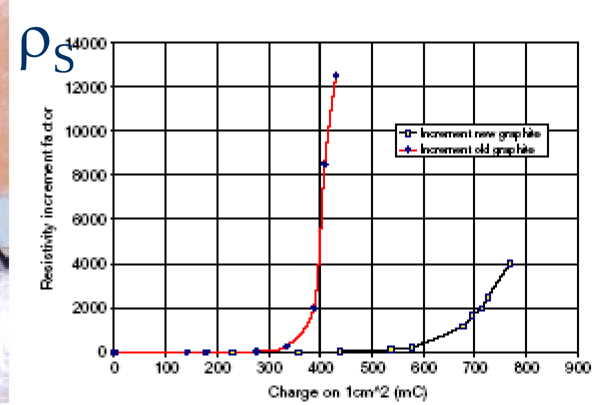
*Permanent damage*

Vaporized graphite



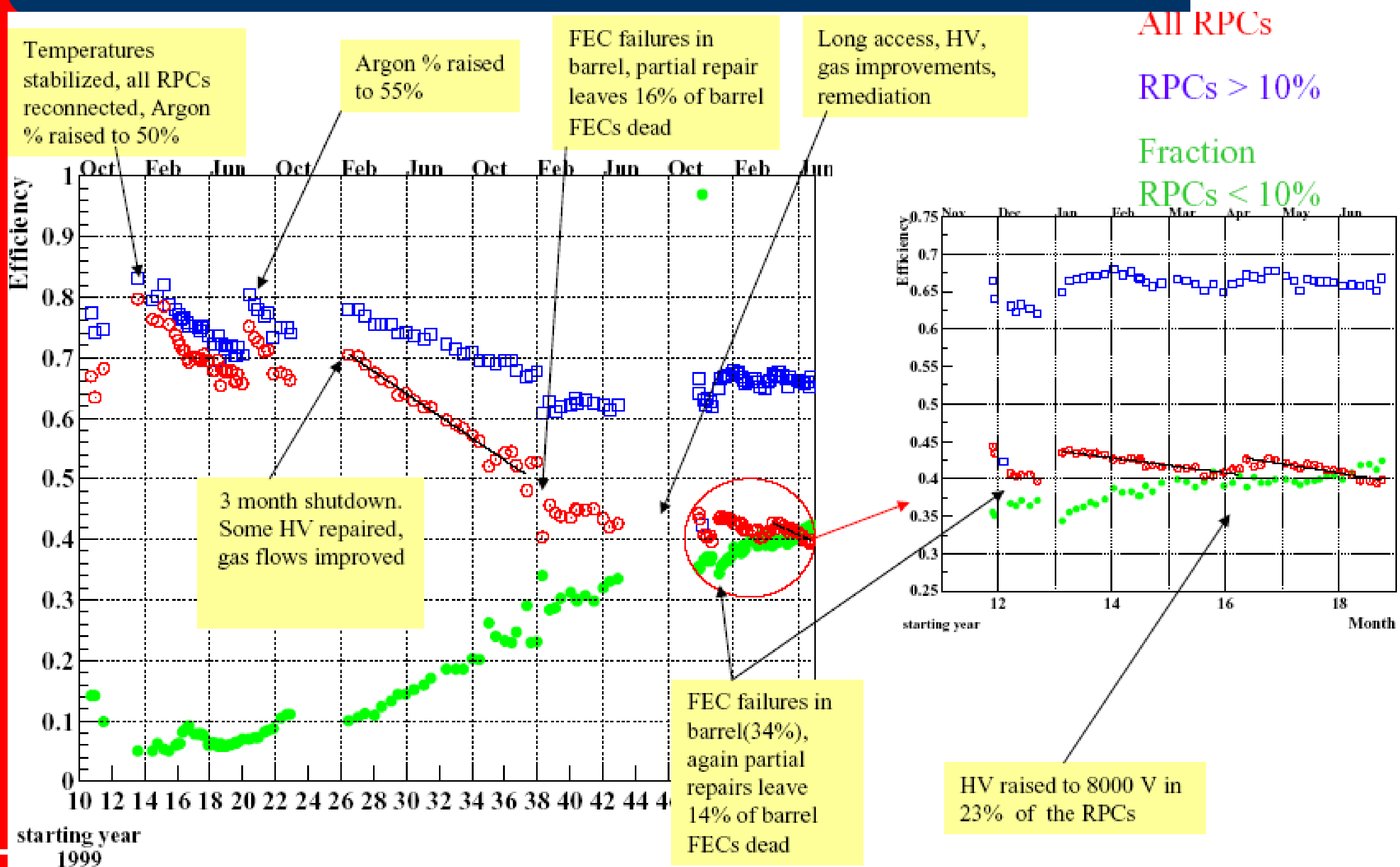
Good graphite

***Threshold effect after 0.2-0.6C/cm²***



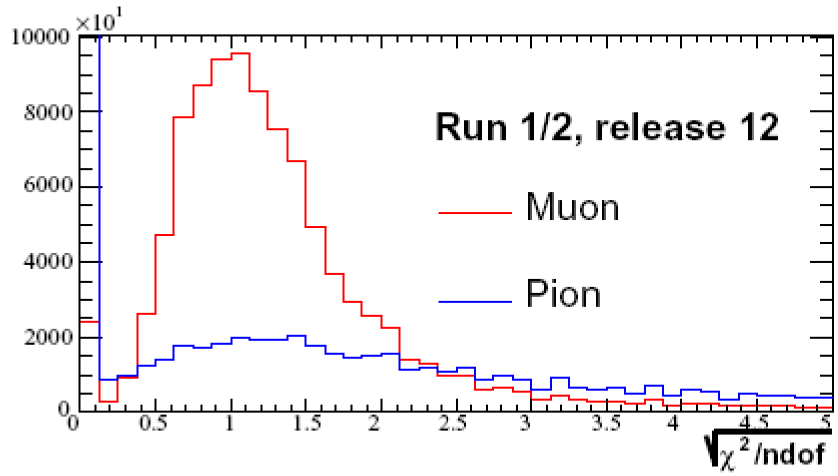

Aielli et al.

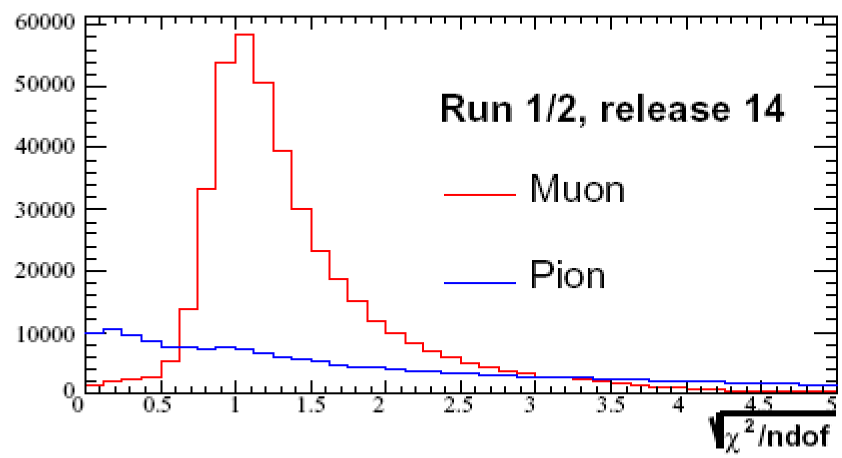
# Barrel declining efficiency



# Muon identification algorithm

– Improved tracking through the IFR with a KalmanFilter-based algorithm
  - Takes into account properly multiple scattering and position resolution



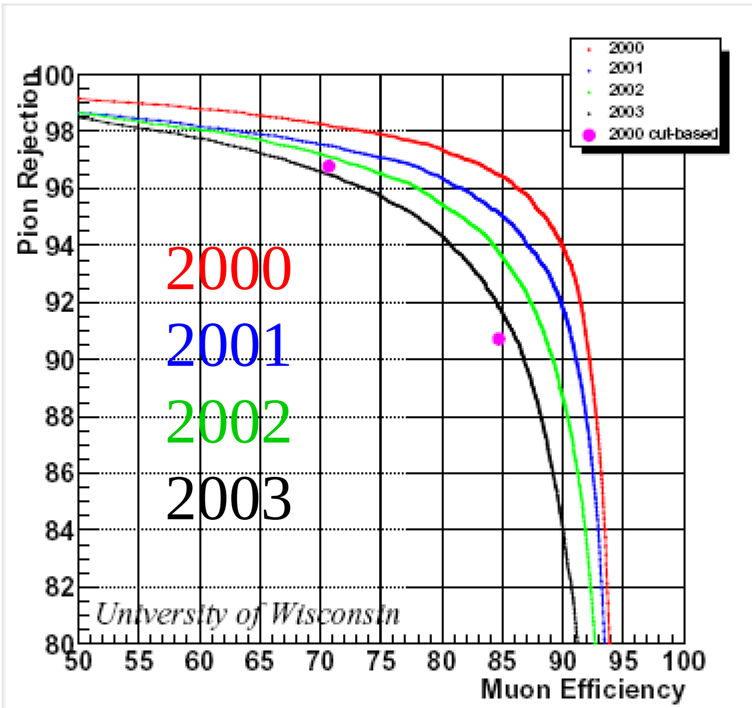

*Neural Network technique to use all the available information* ($\lambda_{expected}$, $\lambda_{measured}$, *track continuity)*

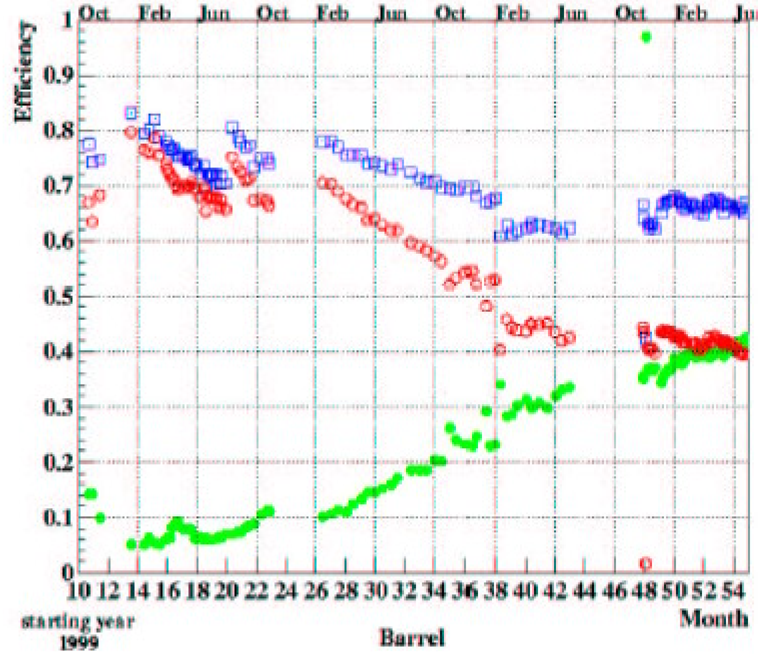
# Barrel declining eff vs μID

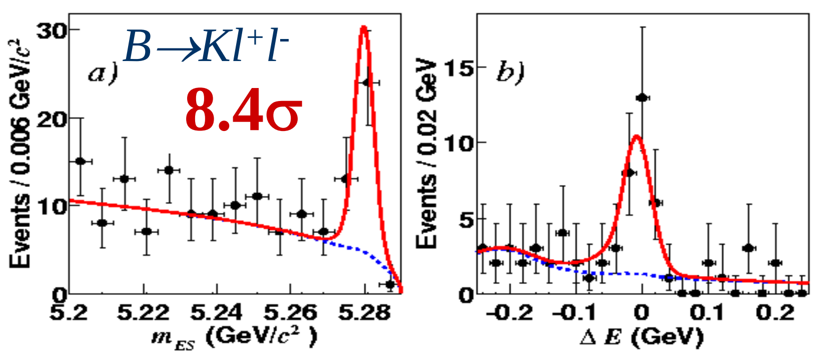
All RPCs

RPCs > 10%

Fraction RPCs < 10%




*Despite declining RPC eff, physics with $\mu$ is possible*

# Original production problems

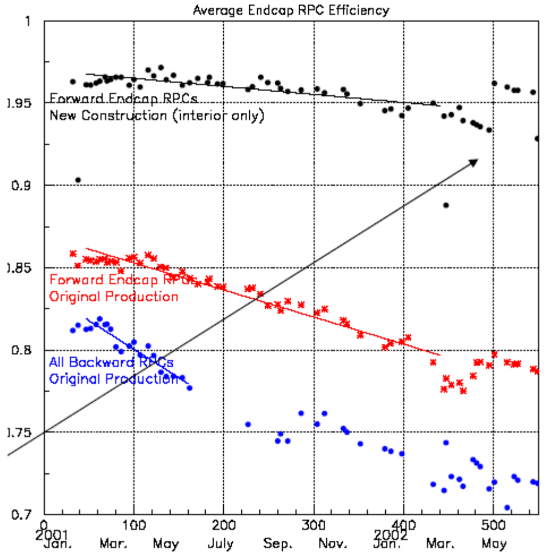
- **Original RPCs exhibit many failure modes**
  - Nearly all RPCs show a slow decline in efficiency (linseed oil, debrii?)
  - Many also suffer a complete efficiency loss in several months (graphite?)
  - Correlated with position in gas chain -barrel
    - 1 <eff> = 55%
    - 2 <eff> = 43%
    - 3 <eff> = 30%
    - 47% of barrel chambers leak, efficiency ~8% lower than above
- **No practical remediation of damaged chambers possible**

*Barrel layers:*
*3 RPC module, gas flow from fwd to bwd (1 to 3)*

# R&D during 2000

– In Nov 2000 24 new modules installed in FWD EC as test in situ.
  - Made with a new oiling procedure
    - – Single coating, linseed oil/n-pentane 40/60

*Declining efficiency*




*Raised HV working point*

– Chemical analysis of linseed oil from damaged RPC:
  - – **Phthalates** (from PVC tubes used in gap coating)
  - – They prevent polymerization of linseed oil.

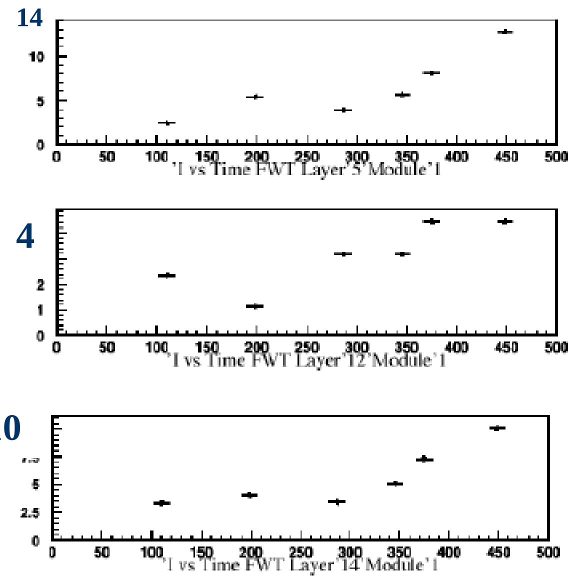
– ***Need to review procedures at production stage***

*In 2001 decision to replace the entire Forward Endcap*

# Nov 2000 RPC

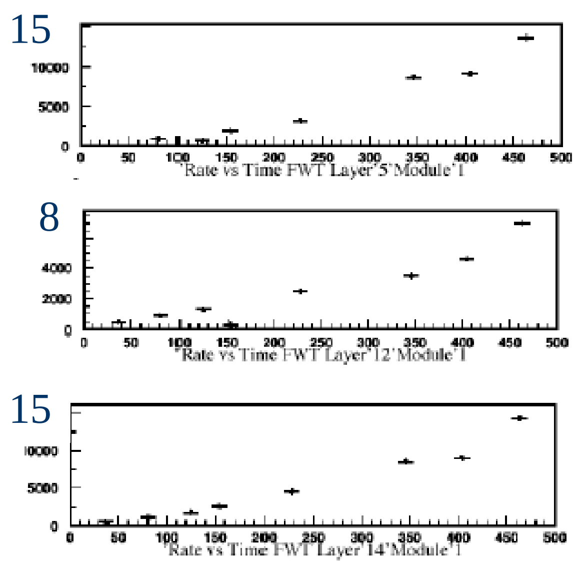
Bulk current (I @ 5.0kV) Single rate with cosmics

μA




*Days since Nov 2000*

kHz

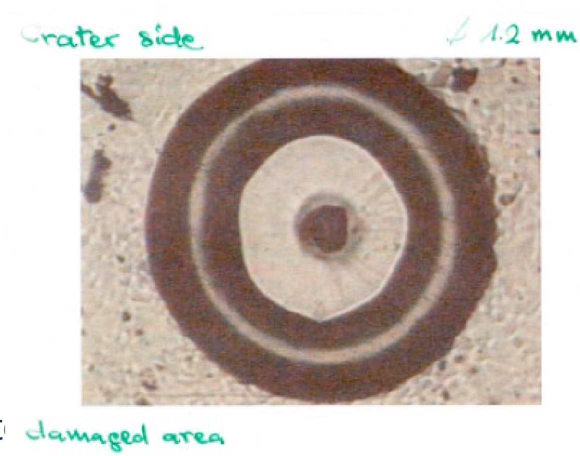



*Days since Nov 2000*

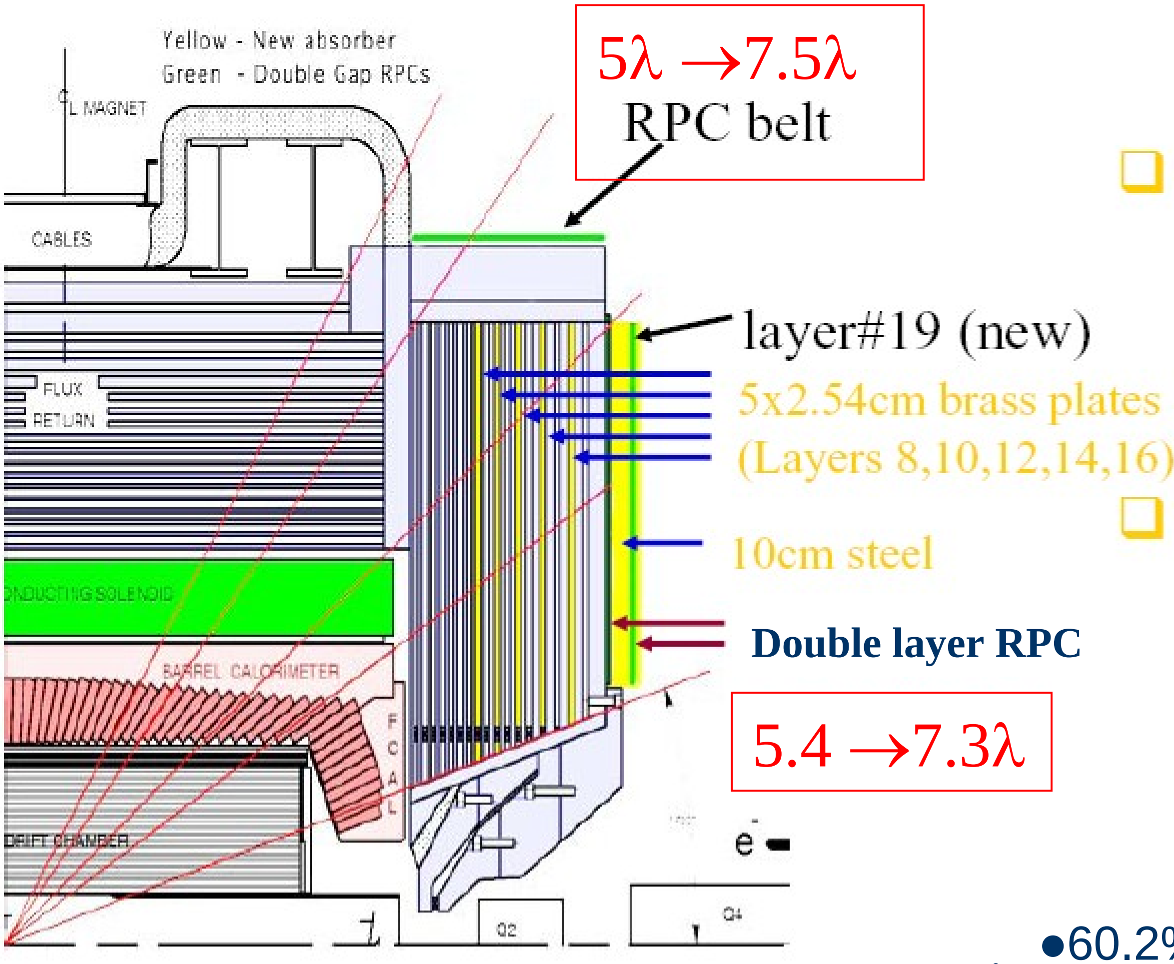
Ageing effects increasing with $Q_{int}$

*Total $Q_{int}$*
*15-75mC/cm$^2$*
*(2 dead RPCs)*

*In test-stand debris and impurities found close to local discharge point.*
***Better QA in production!***



# Forward Endcap 2002 upgrade




- Upgrade in 2002
  - Added additional absorber
  - Double Layers
  - Replaced all RPCs
- New RPCs
  - Molded gas inlets
  - Thinner linseed oil
  - Improved graphite coating
  - Stringent QC/QA

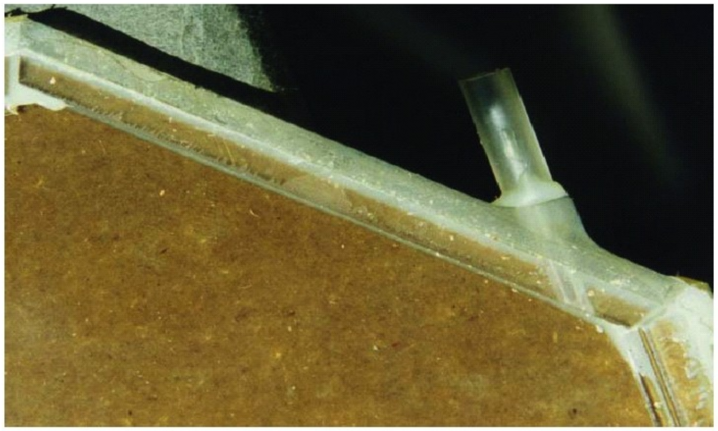
***Gas mix***

- 60.2% Ar, Iso 4.8%, $C_2H_2F_4$ 35%
- 3-4 vol/day

$V_{PS}$ = 6.7 kV

# QA/QC at General Technica

- *Checks during assembly*
  - Clean assembly room
  - Clean bakelite slabs, graphite painting, sampling graphite resistivity
  - Spacer gluing (temperature and humidity monitored)
- *Linseed oil mixture*
  - Periodic chemical analysis, sampling polymerization on sacrificial chambers (12 gaps)
- *Gas tightness test*
  - Digital first bubble test
- *Unglued spacer identification*
  - Manual push test



***Gas inlet made by a corner piece***

# Checking spacers…

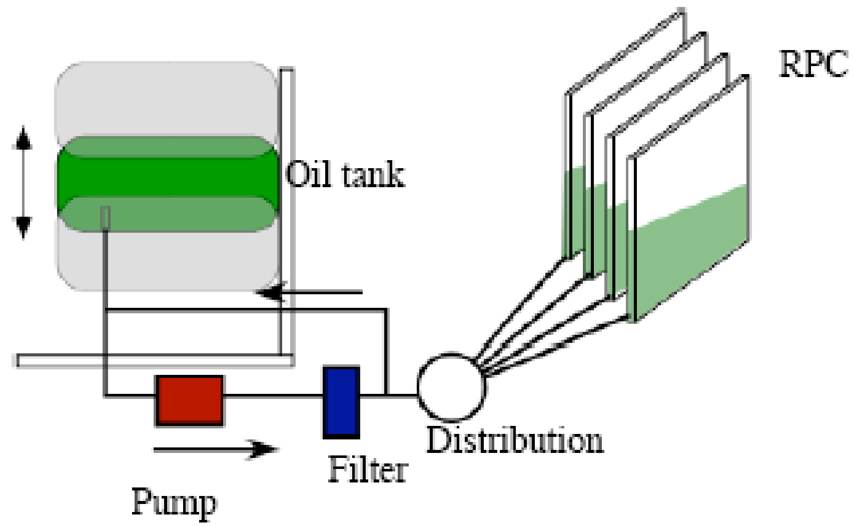
*Sample spacer glued at the same time as all the gap spacers.*

*Trying to remove it..*

Wait before moving assembled gap!

# Oiling technique

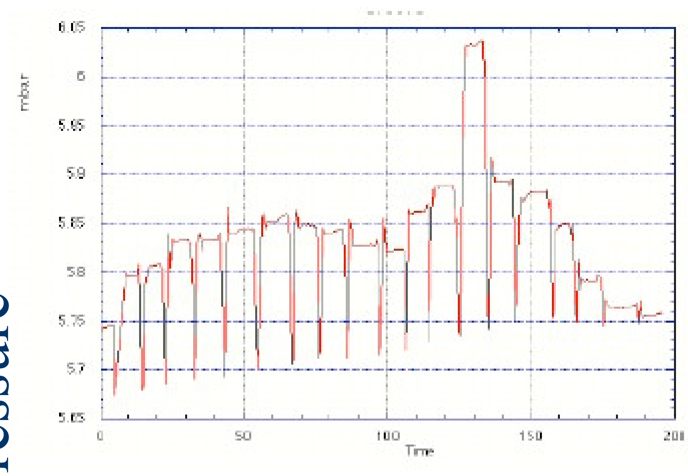
– Single coating
  - Fill a 12-20 gaps raising the tank
  - Slowly lowering the tank (3hours)
  - Filtering oil (remove dust accumulated in draining)

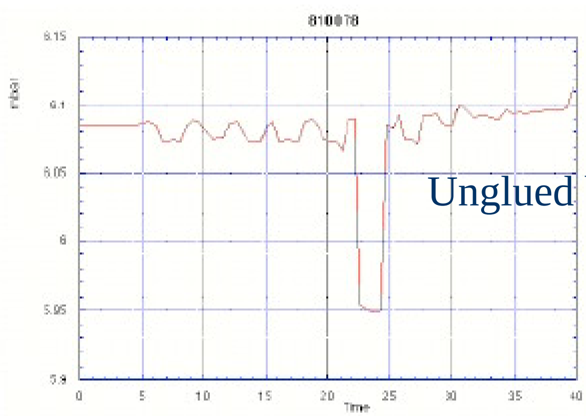



Complete polymerization achieved in 36 hours by flushing air (@40° C)

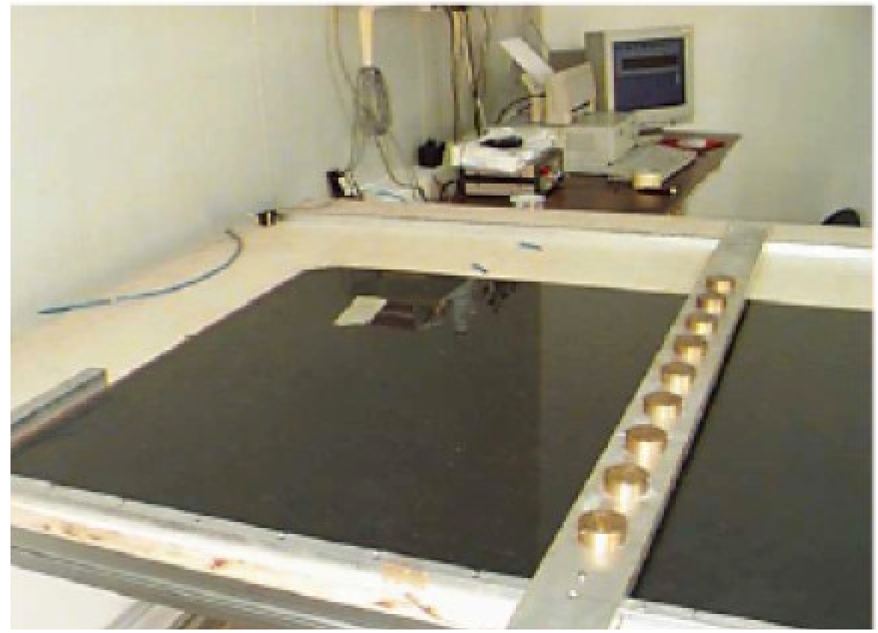
# Leakage and Push

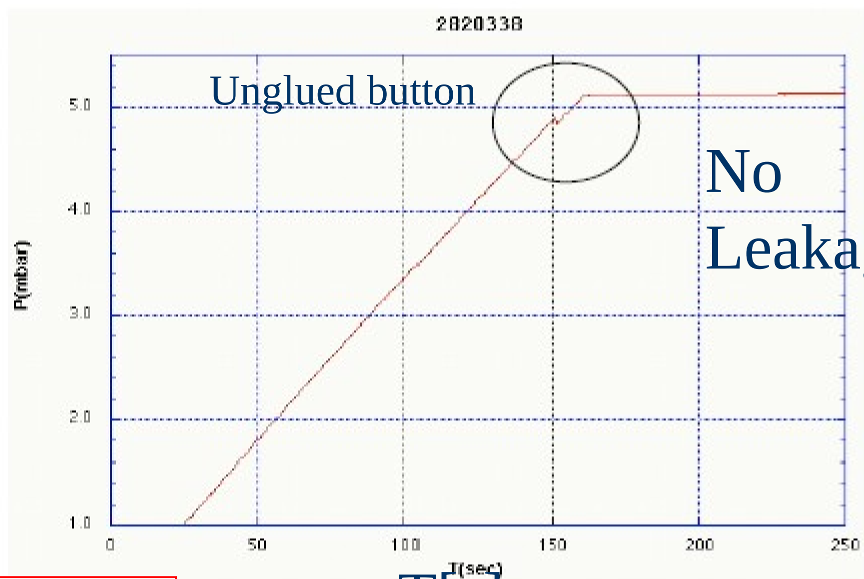
pressure




Unglued button





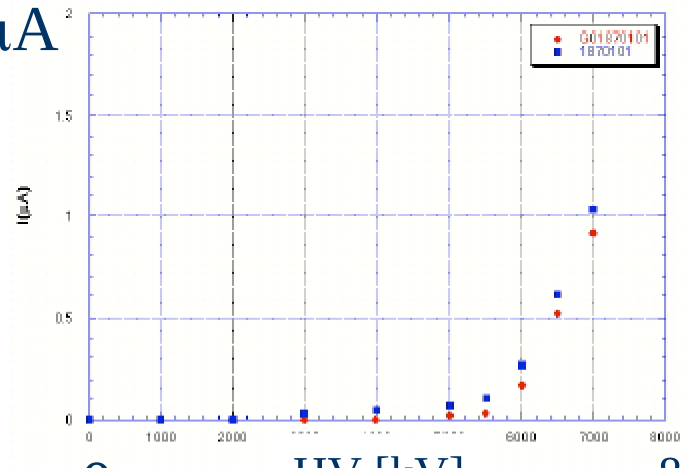

T[s]

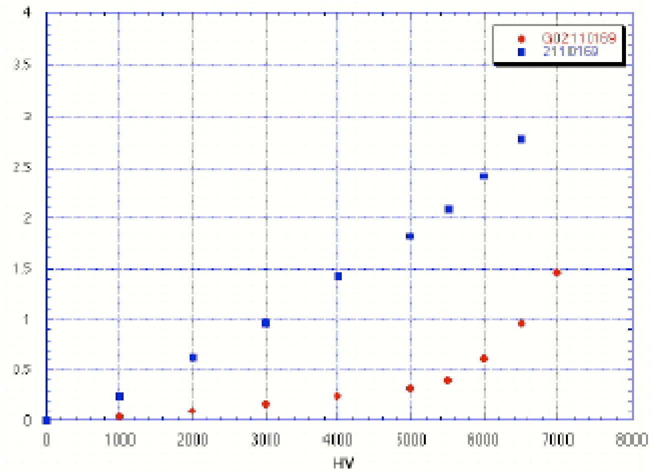
Evidence of unglued buttons

# I vs HV

Good if <2µA @ 7 kV

2 µA




4 µA

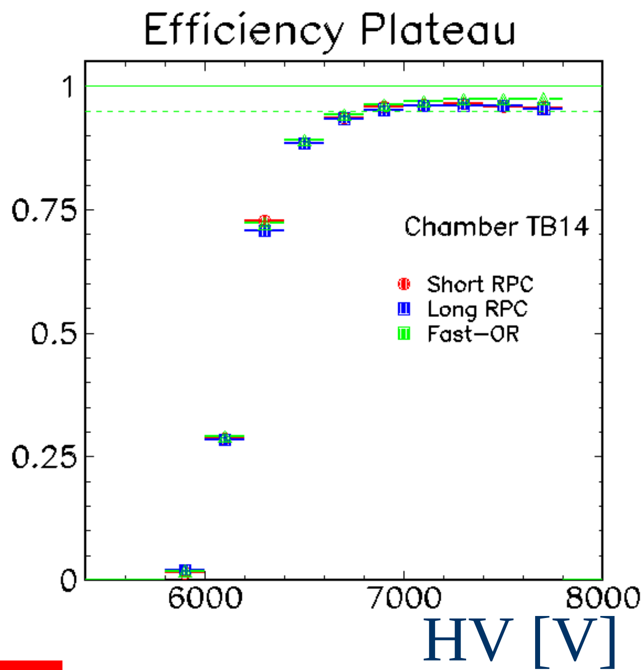
0 HV [kV] 8

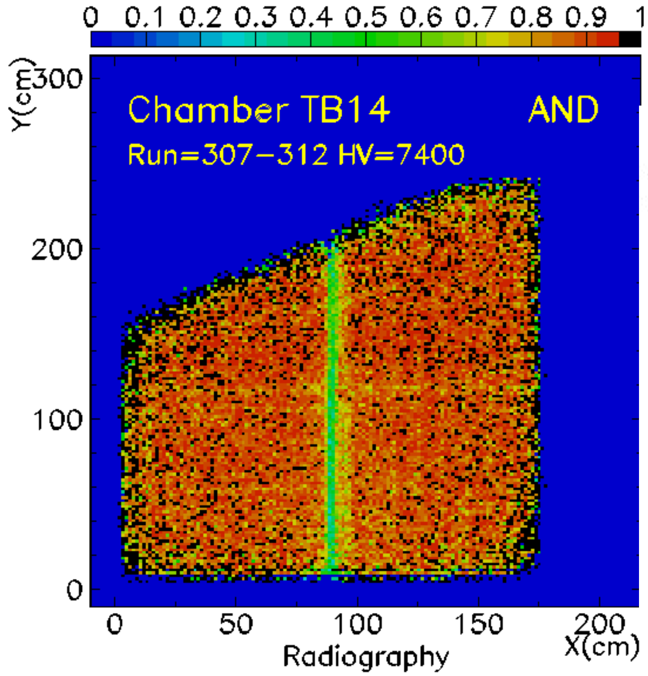
After conditioning

# Cosmic tests

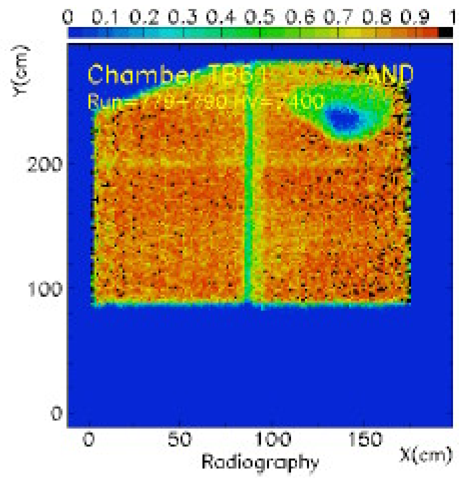
*After complete RPC assembly (strip planes glued)*

- *All the RPC tested with cosmics at GT before shipping*



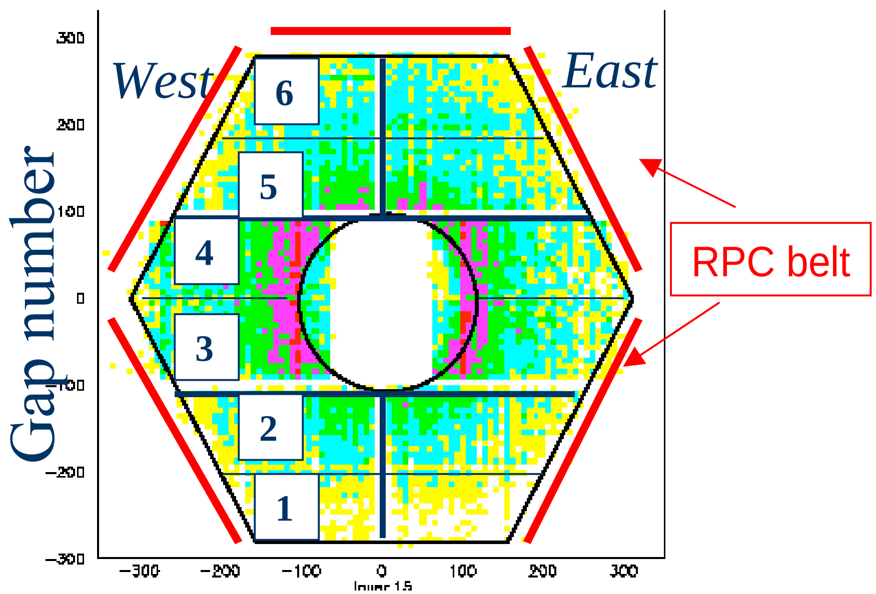

*Popped button!*

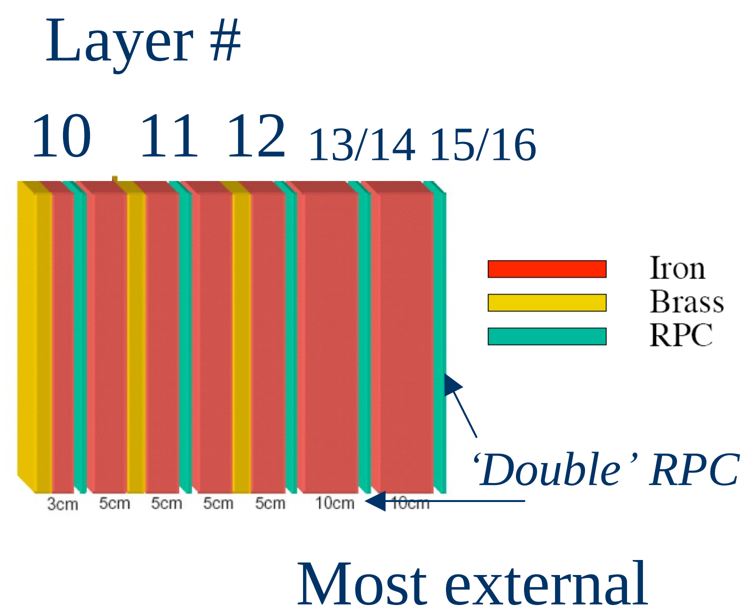



*Gas tightness, efficiency plateau, radiography test at SLAC*
*All RPC >95% efficient with (cosmic) single rate ~0.1Hz/cm2 before installation*

# New BaBar Forward EndCap

- 16 layers * 6 RPC *2 gap =**192 gaps**

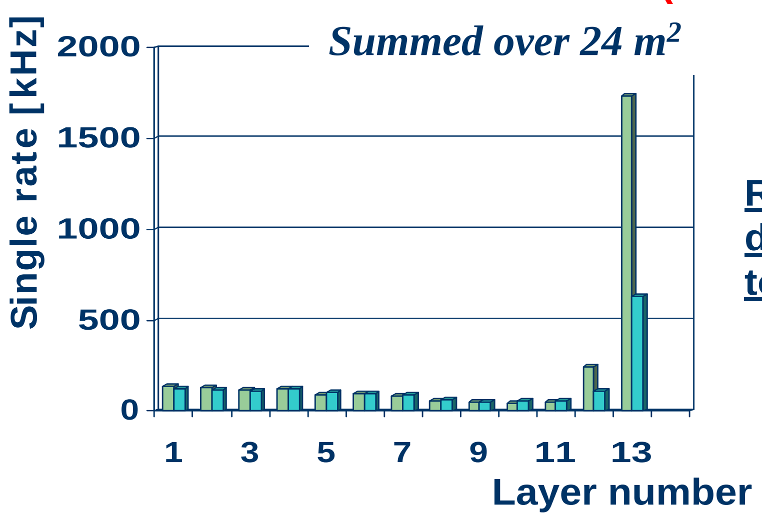


# Operations in BaBar

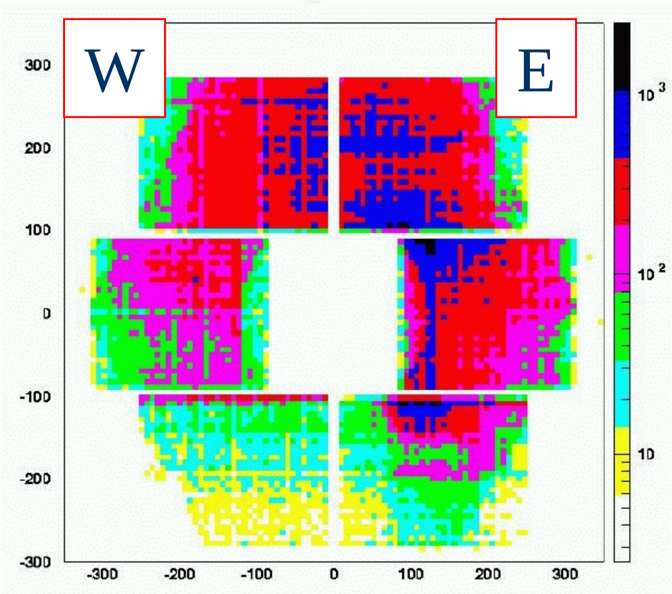
*RPC installed in summer 2002*

- Operated in BaBar in Run3 (since Nov2002)




**Rates dominated by top modules**

*Layer 14 hit map*




*Behind 11cm Fe*

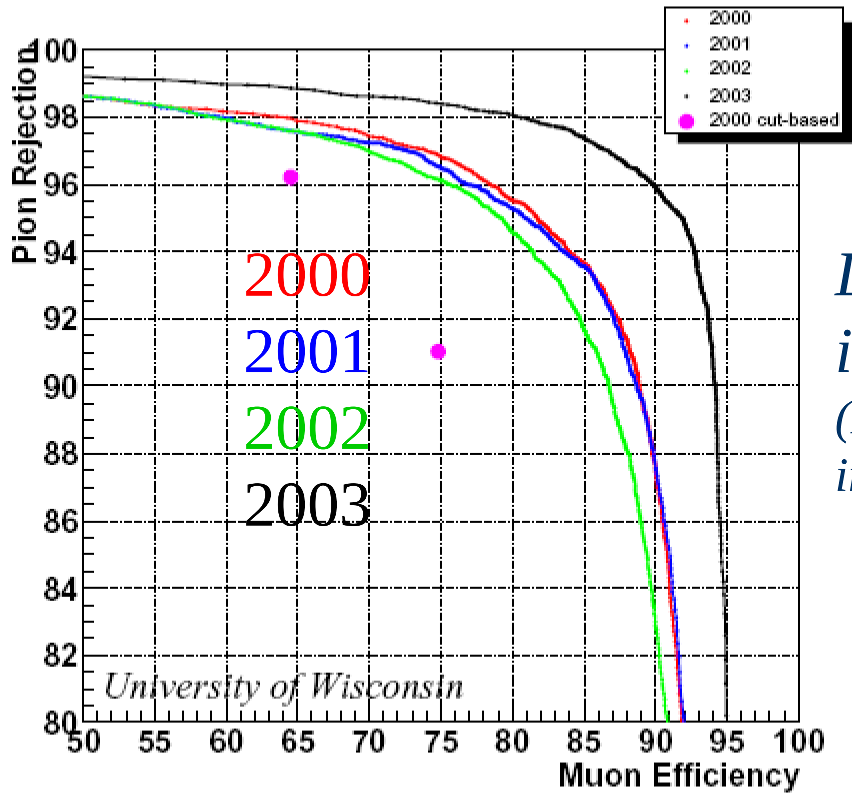
*$10^3$ = 1% occupancy*

Machine background worse than expected

Layer 15/16 not operated routinely

*layer 13/14 average rate ~ 5-10Hz/cm²*

# Improved μID




*Largest effect due to increase in absorber.*

*(Layer15-16 not used, still room for improvement)*

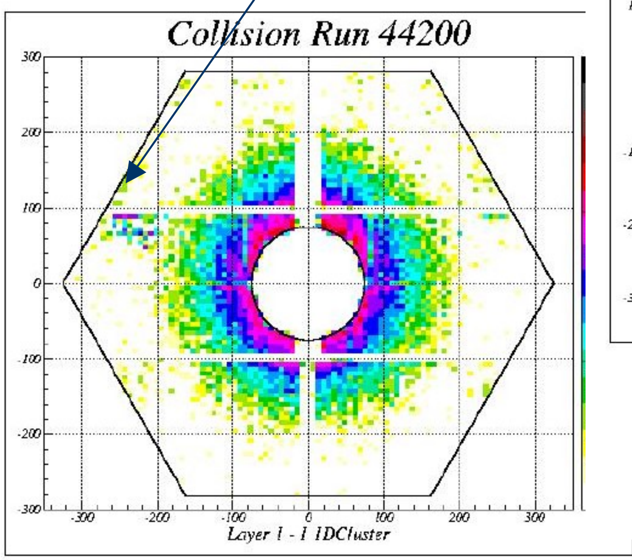
*Data control samples:* $e^+e^- \to \mu\mu\gamma$, *pions from* $\tau \to 3\pi\nu_\tau$

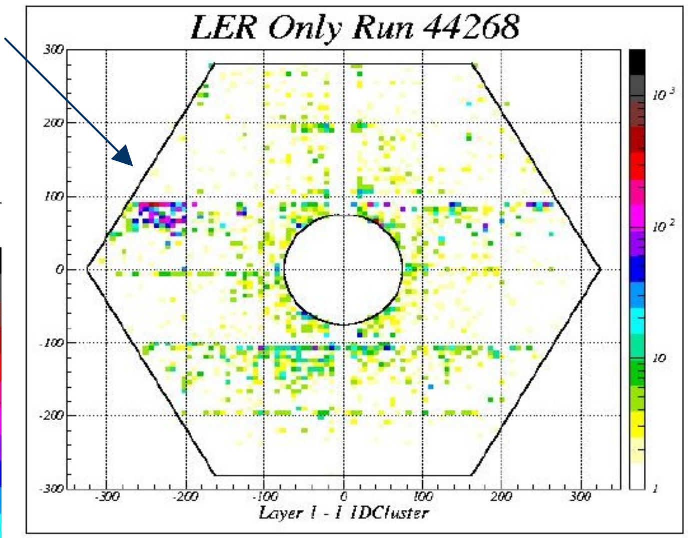
# Occupancy plots (FWD ec Layer 1)

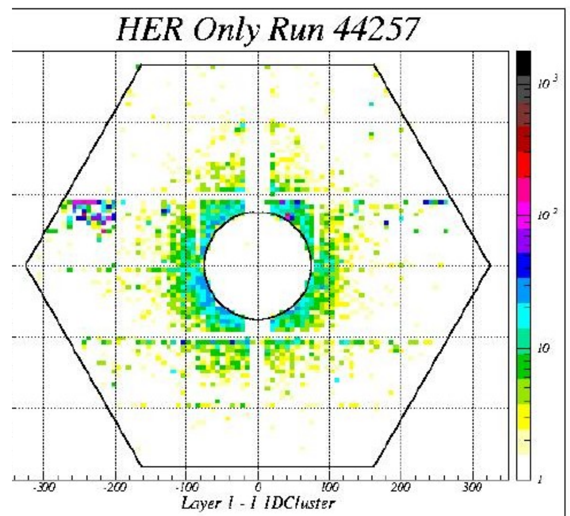
Internal layer (1-12) 0.2-1 Hz/cm$^2$ (middle gaps hotter)

RPC hot spot

*$10^3$ = 1% occupancy*



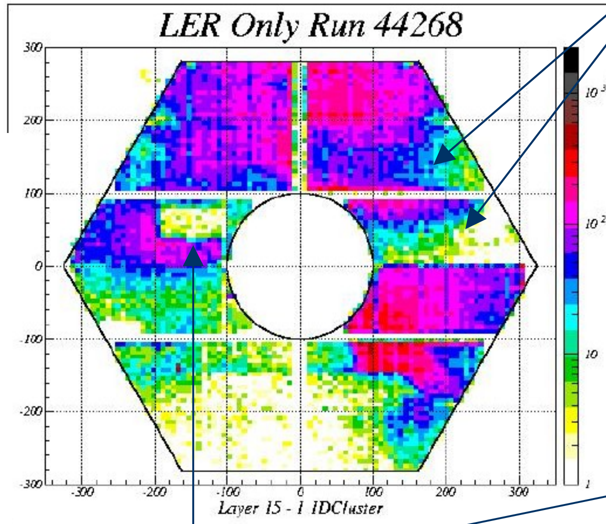



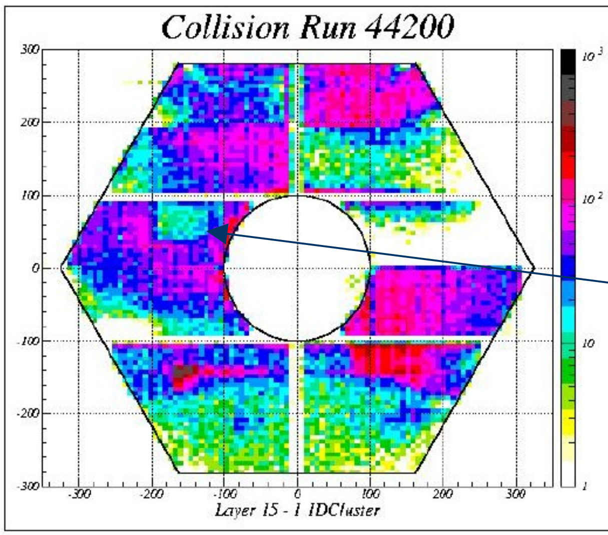

Internal layers background dominated by beam-beam background

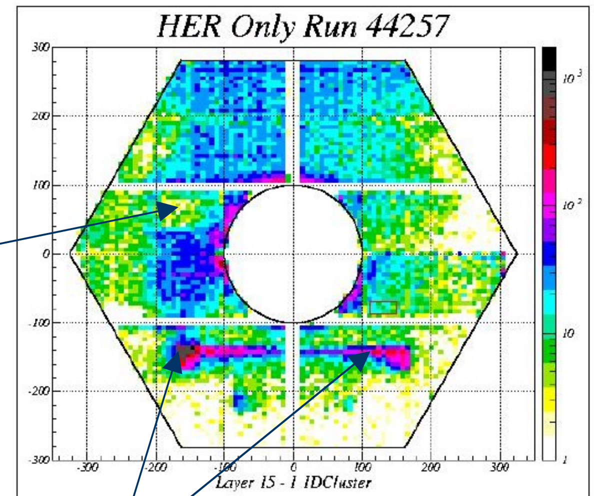
# Occupancy plot (FWD EC Layer 15)

Clearly LER current dominated



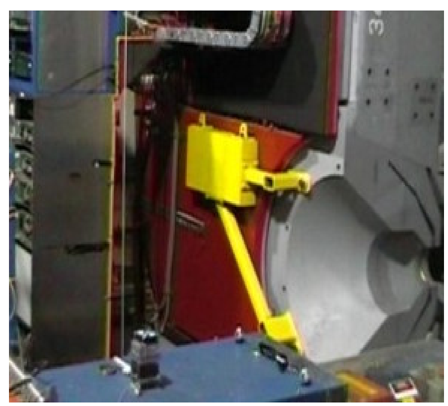

Low efficiency RPCS




Shadow of test shielding steel

Hot spots from HER under cutouts for E.Q. clearance

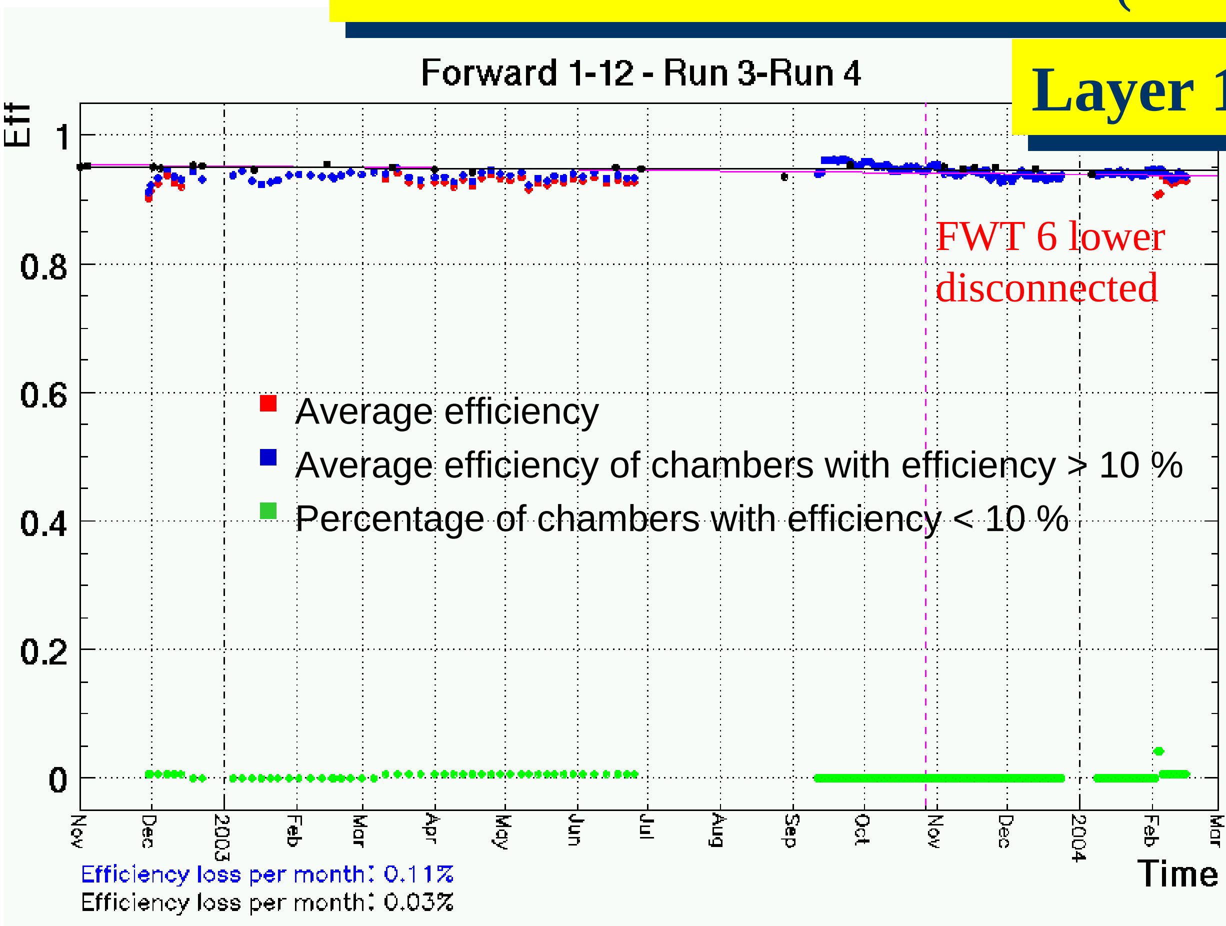


8 inches steel

***Factor 10 less BKG***

# FWD EC efficiency history

*Evaluated with collision data ($e^+e^- \rightarrow \mu^+\mu^-$ events)*




**Layer 1-12**

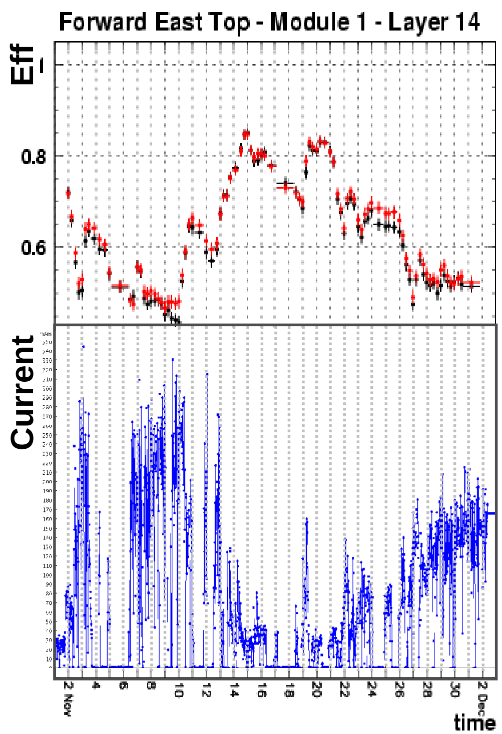
No drop with cosmics (black dots)

Efficiency in Collisions for ***outer layers*** suffers from high background (*voltage divider effect*)

***No substantial decrease since installation***

# Shielding necessary

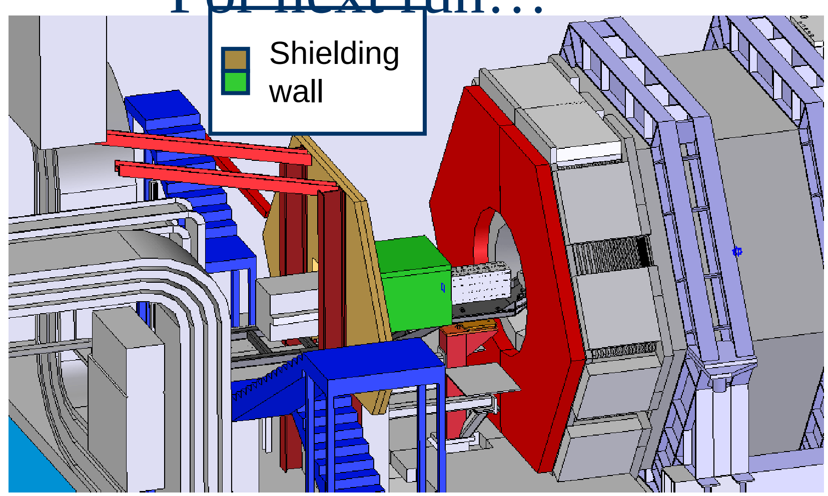
Layer 14




**High rate, low eff.**

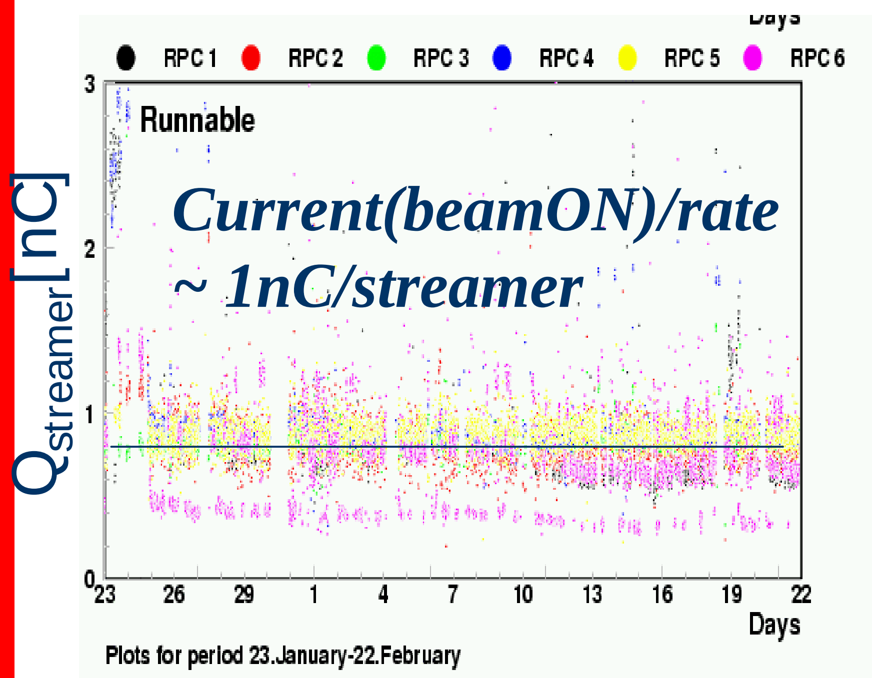
- Based on collision run
  - Eff = .87 @ 1.5 Hz/cm2
  - Eff = .65 @ 9 Hz/cm2
  - **Eff = .50 @ 15 Hz/cm2**

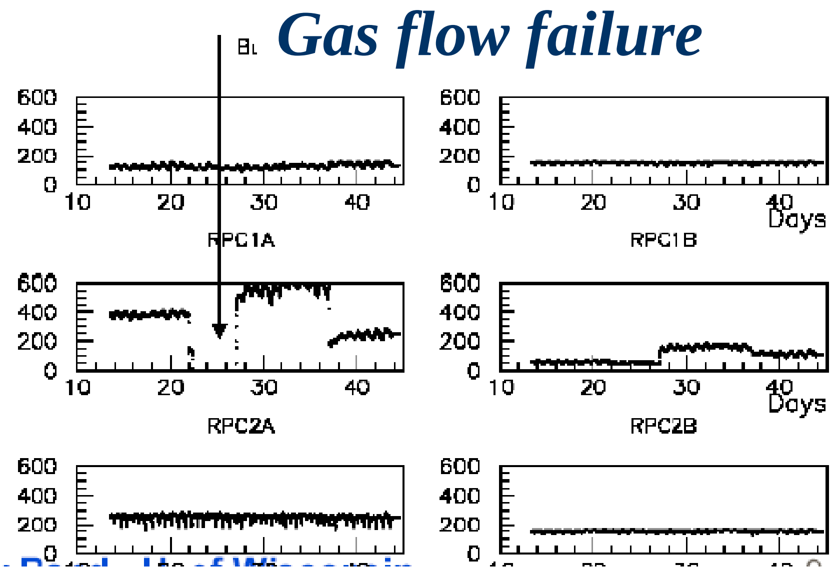
For next run…



# On-line monitoring

– Single rate, current, gas flow continuously monitored

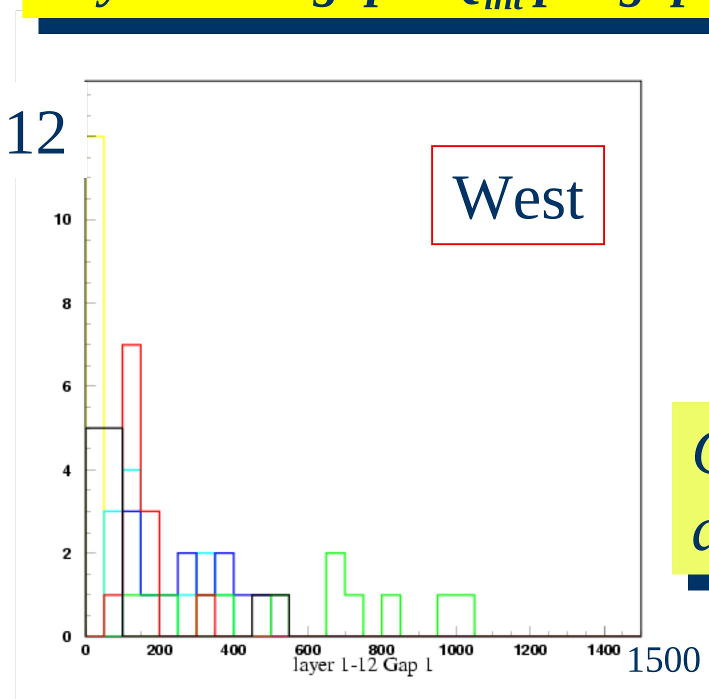



***Ability to spot operational problems and appearance of ageing effects.***

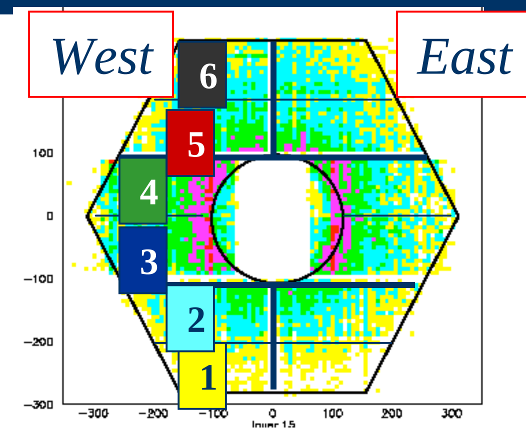
# Integrated charge

***Layers 1-12 gaps: $Q_{int}$ per gap***



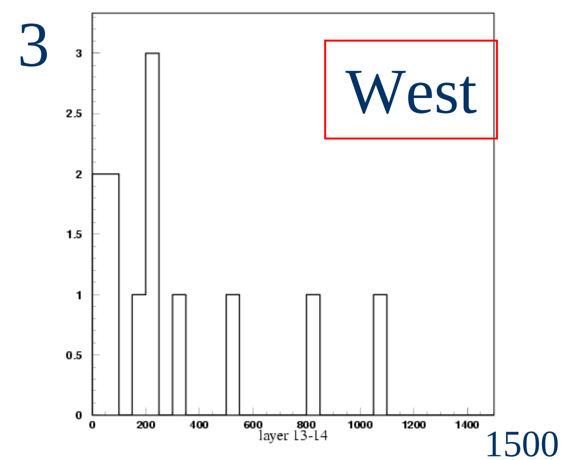

C/gap

$1000C \rightarrow 50mC/cm^2$




*$Q_{int}$*
*at Apr2004*

***Layer 13-14 gaps: $Q_{int}$ per gap***




C/gap



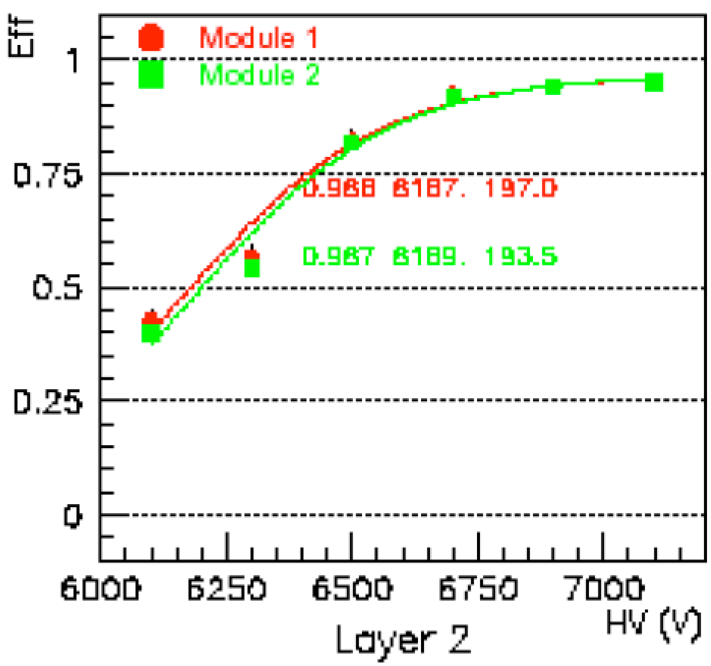

Gianluca Cavoto

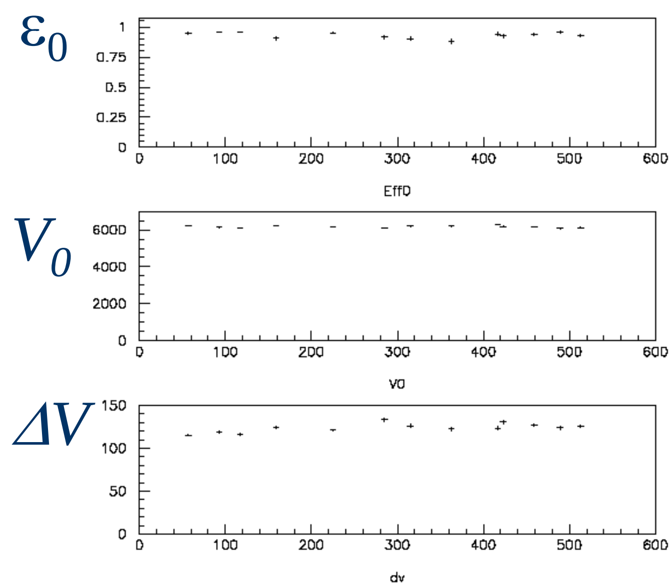
# Plateaux stability

Fit function

$$\varepsilon(V) = \frac{\varepsilon_0}{1 + e^{\frac{V_0 - V}{\Delta V}}}$$

Cosmic data

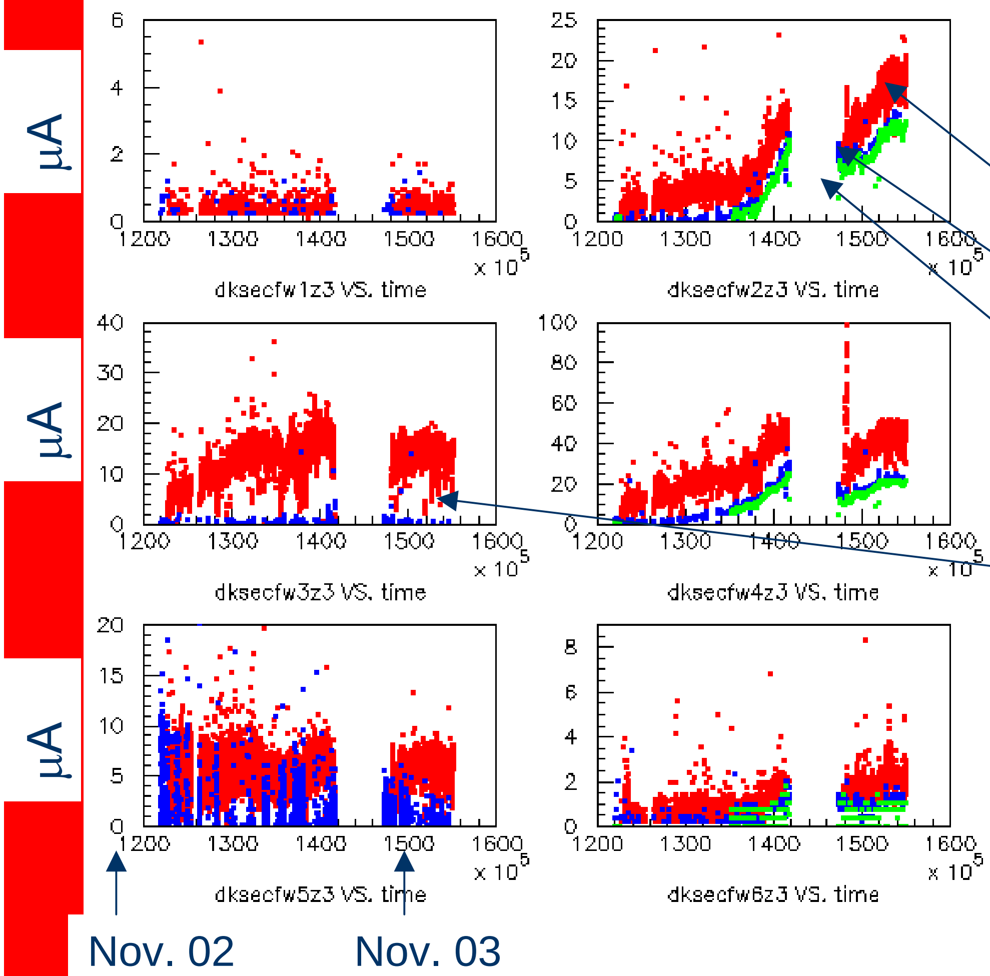



*Days of run (since Nov2002)*

*No visible drift so far…*

# Increased Dark Currents




- The dark currents with cosmics have increased in time for some chambers
  - Collision
  - Cosmic
  - Bulk contribution
- Most of increase is in the bulk current

***Bulk I: I @4.5kV***

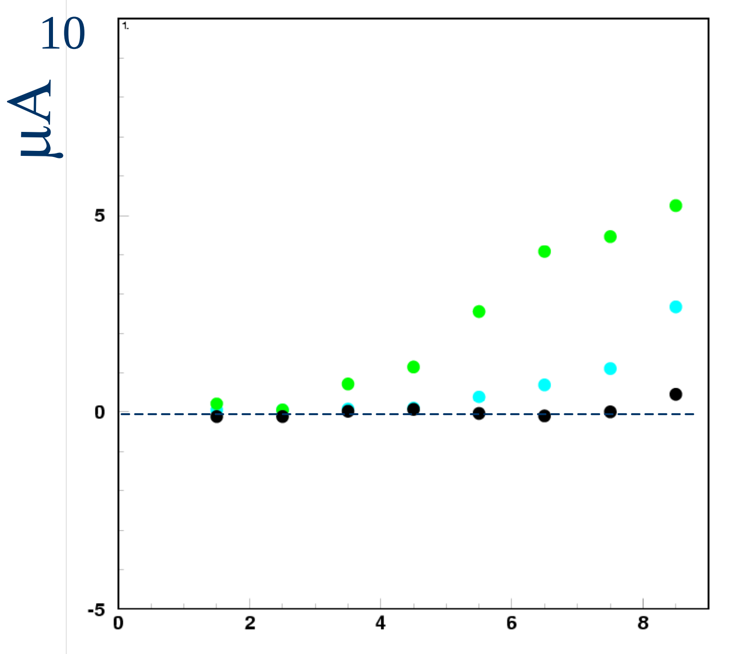
# Polluted gas ?...

Dark currents differences:

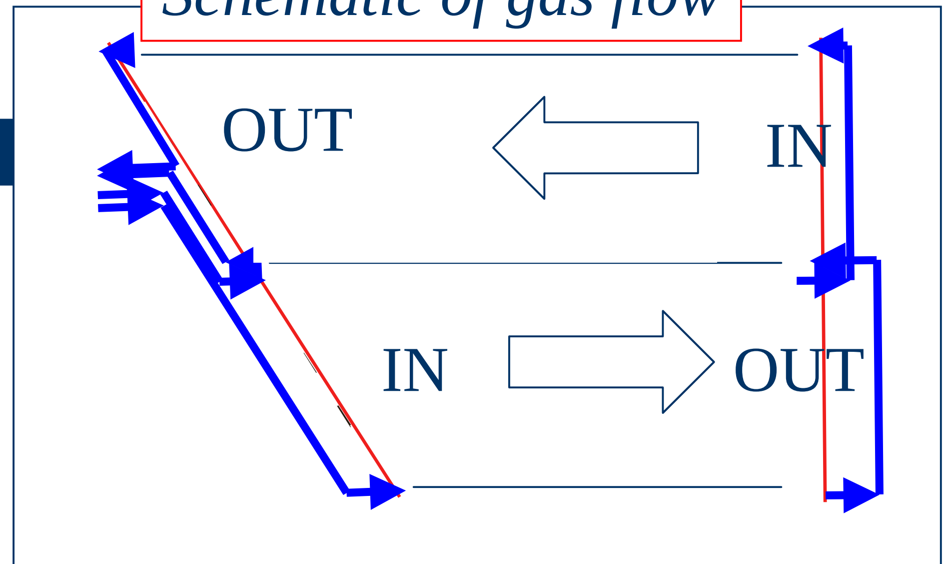
**I(6) – I(5)**

**I(4) – I(3)**

**I(2) – I(1)**




Schematic of gas flow

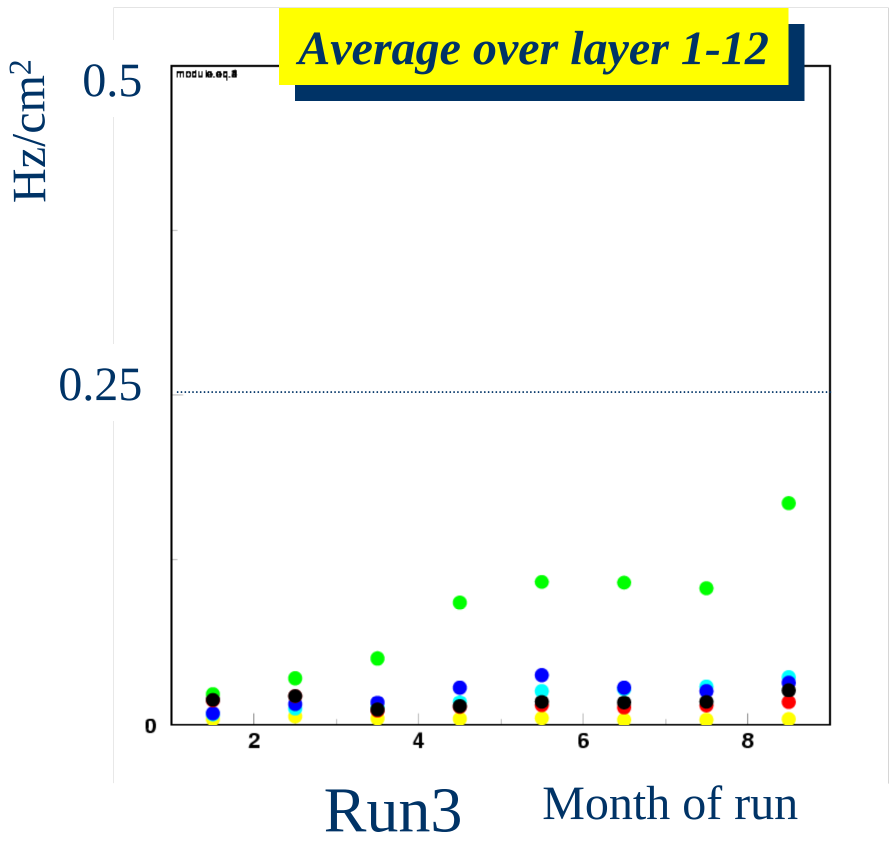


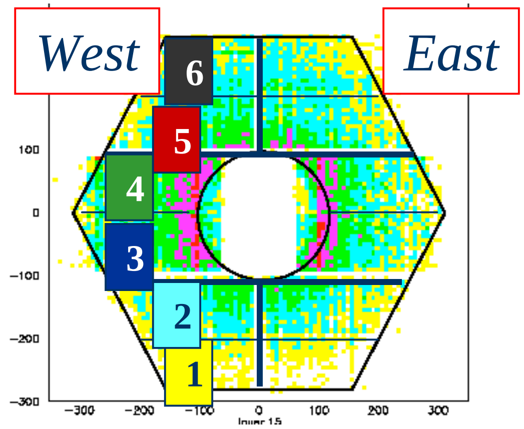

*One single gas circuit for 2 gaps*

*Gas mix in the downstream gap likely to be different*

***In Run4 gas flow raised to 8 vol/day for RPC seeing high background***

# Single rate in cosmics



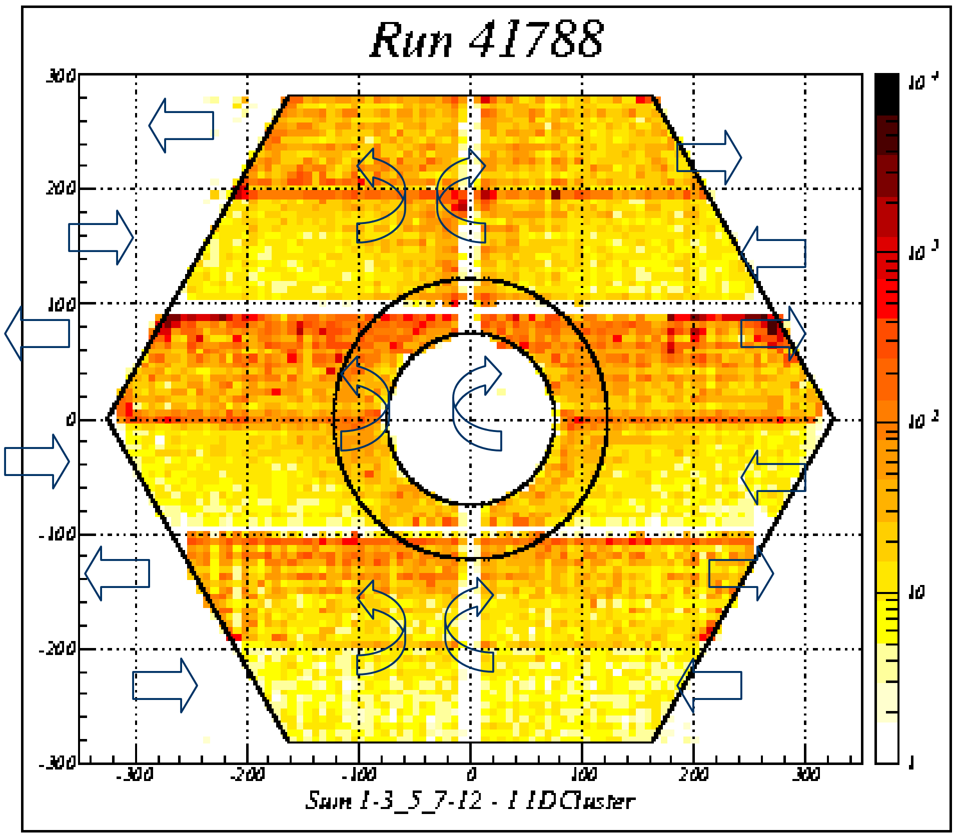

Gap on the horizontal plane show an increase in single rate.

Worrisome…
(no exponential behaviour at least)

# Increased Singles rate

Gas flow

- Summing the 2D occupancy for the inner layers shows that the additional noise occurs in regions of higher background (inner ring) and in the 2nd RPC of the gas chain
- Random hot spots are more likely in the 2nd RPC
- Increase in 2nd RPC larger when downstream of higher background region

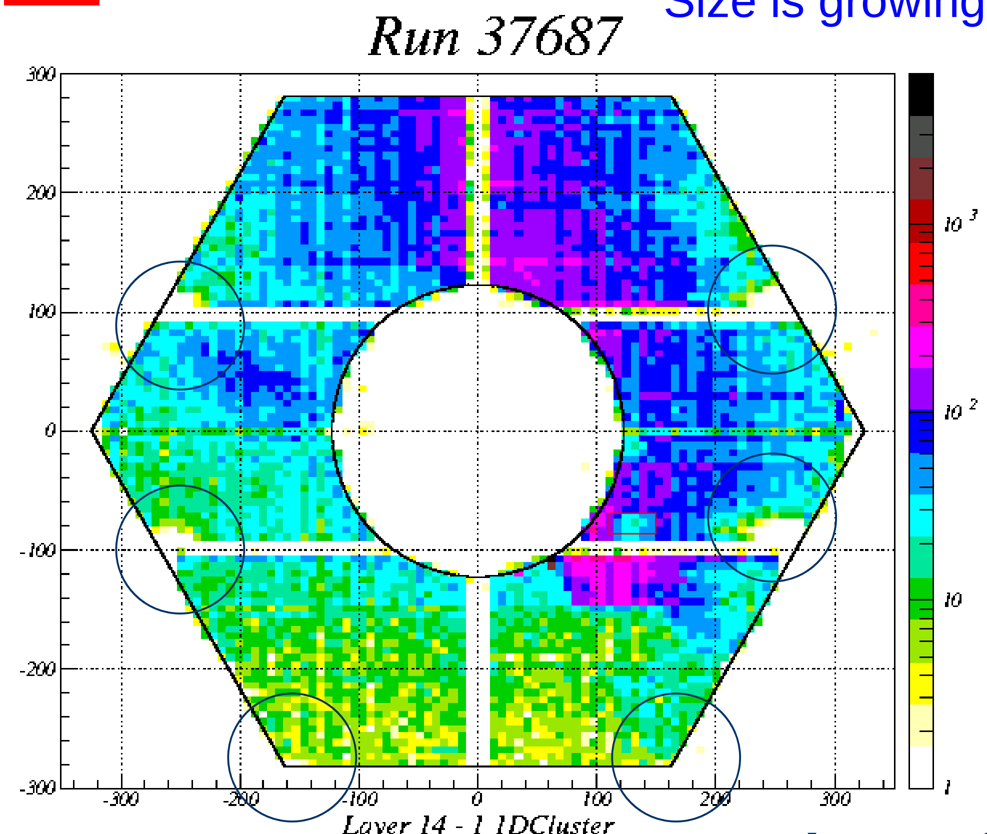


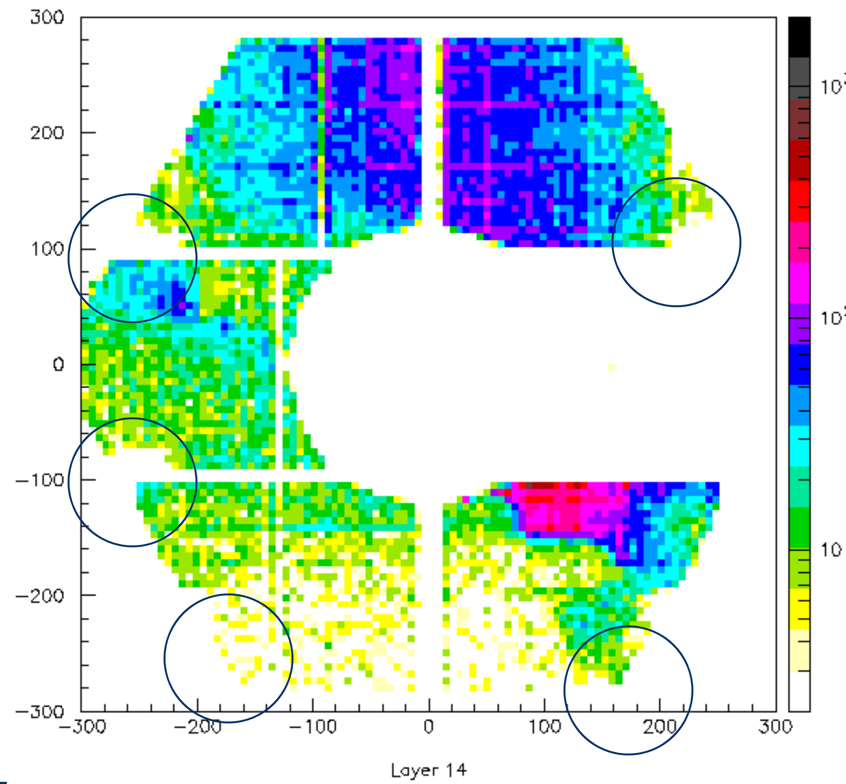
# Evidence of bakelite resistance changes?

Run 3

Noticed that there is a lack of noise hits near the gas inlets. Size is growing in time.

Run 4



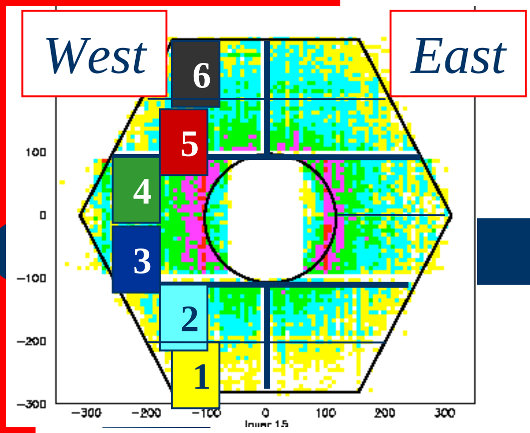




**Layer 14**

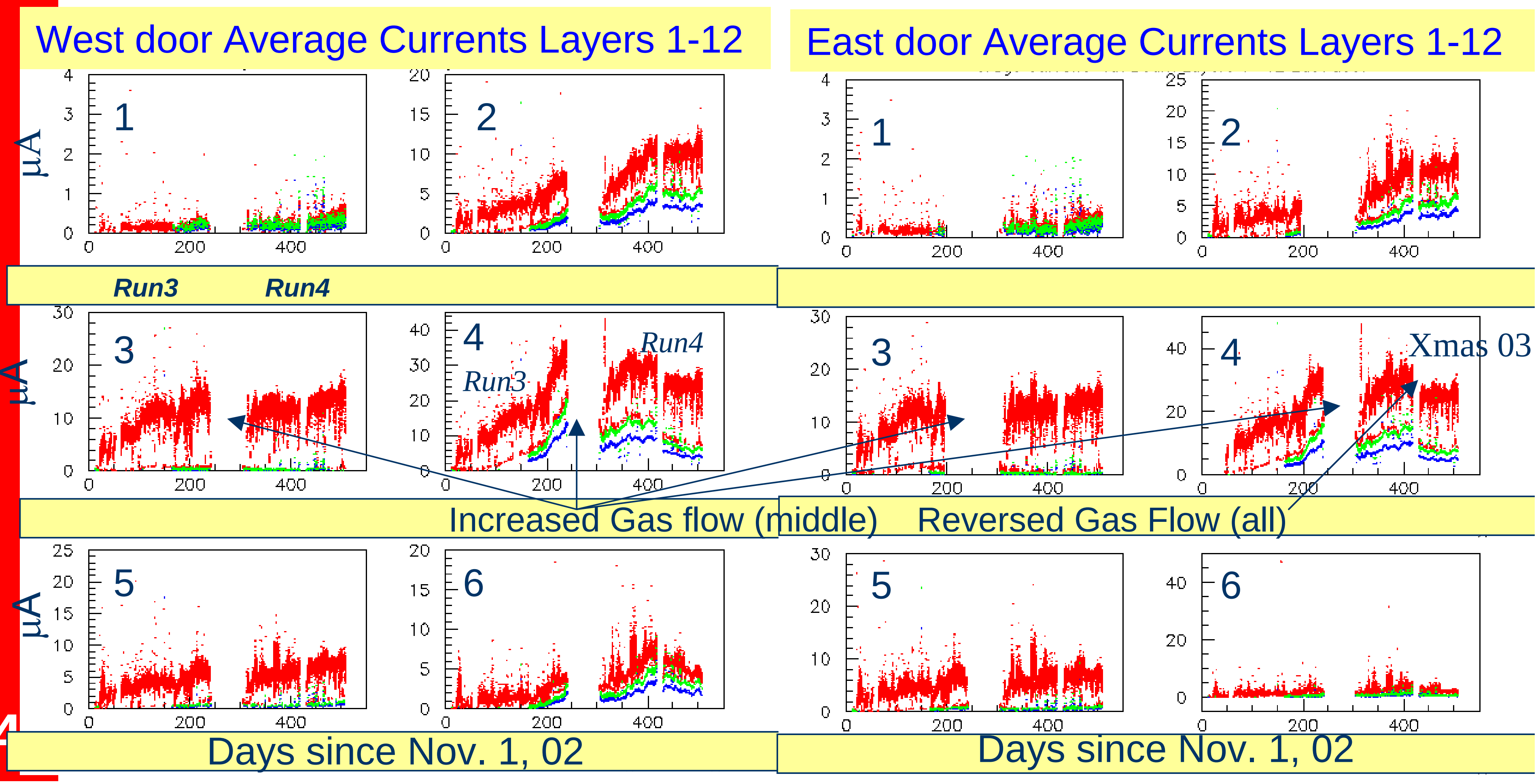
# Recent Operational changes

- Raised gas flows to 8vol/day in middle RPCs after Run 3
- During Christmas 03  shutdown reversed gas flows in all FWD EC RPCs

# RPC current, effects



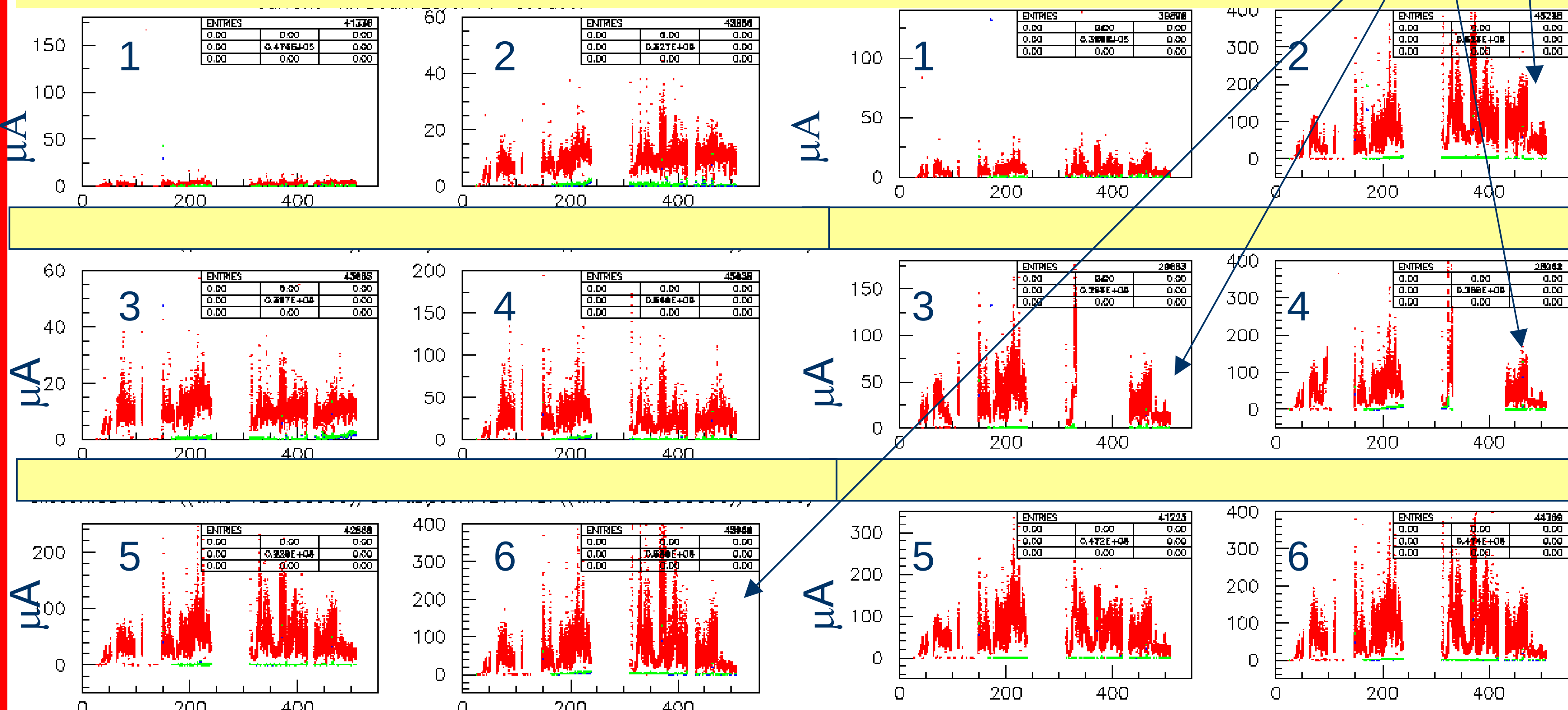

Runnable with Beam  Injectable  Scaled Bulk current



# Layer 14 Backgrounds

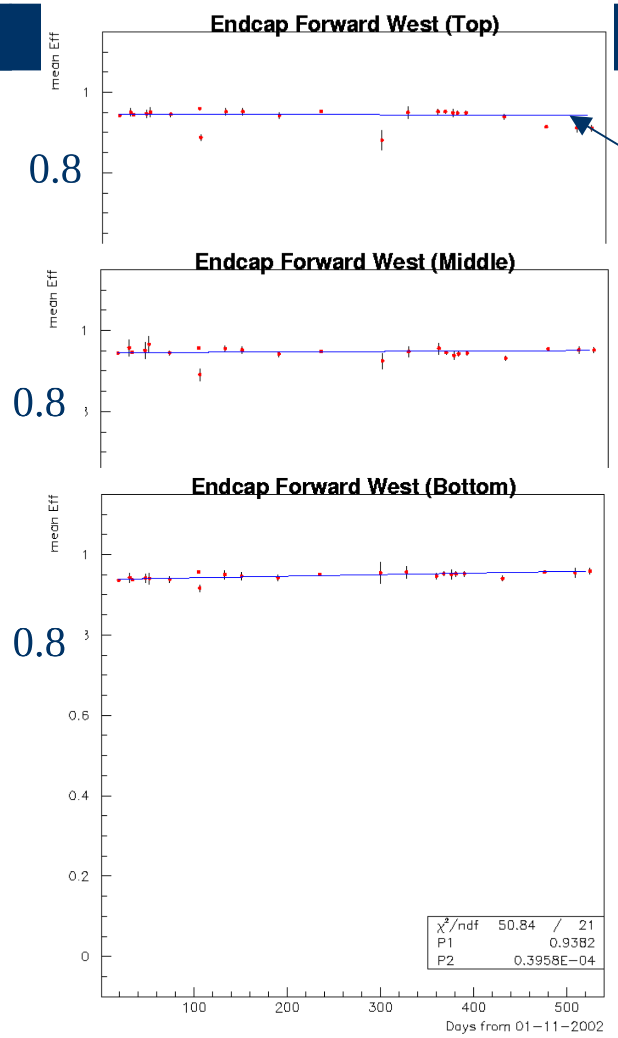
*New mode of PEP operation improved BKG*

Layer 14 West | Layer 14 East



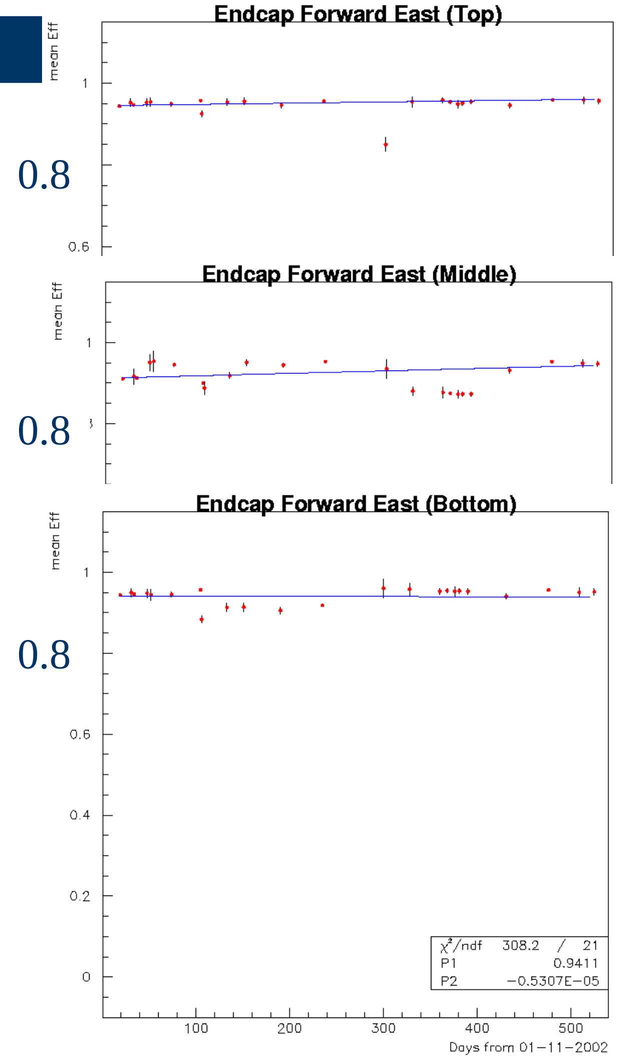

Days since Nov. 1, 02 | Days since Nov. 1, 02

# RPC Efficiency from Cosmics




Loss of FWT
Layer 6 old
2000 era
chamber

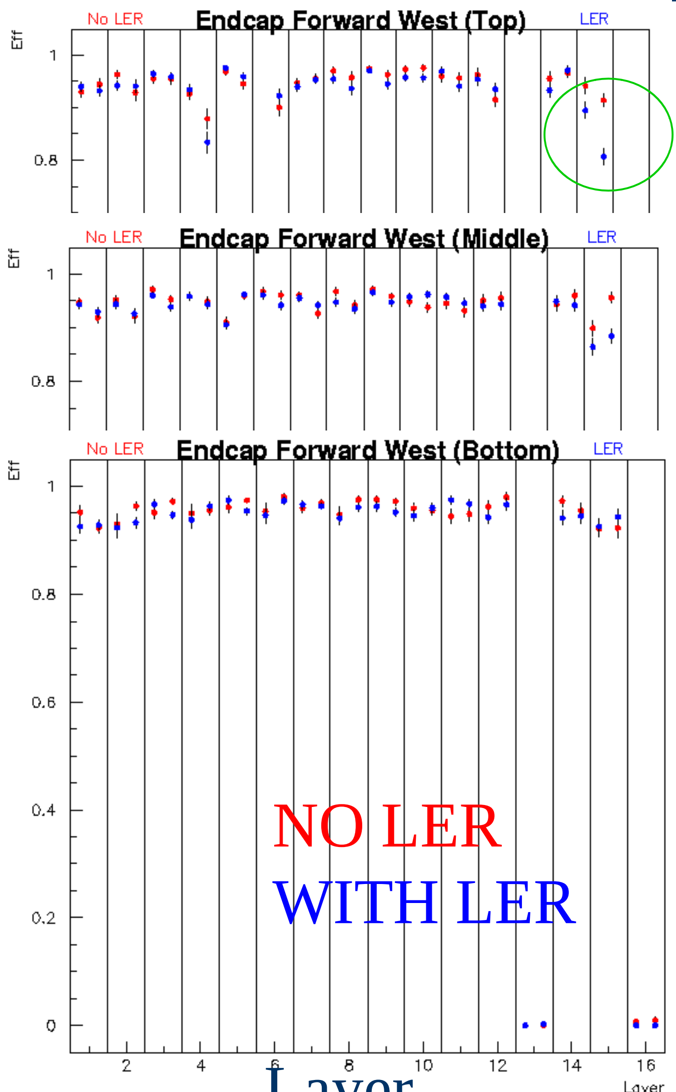
No clear trend visible in Cosmic data



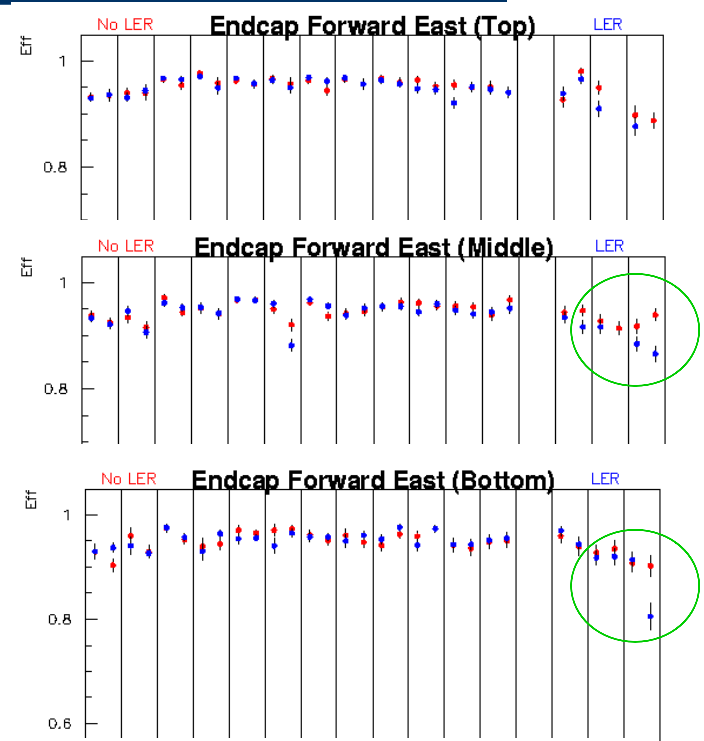

*Days of run (since Nov2002)*

*Days of run (since Nov2002)*

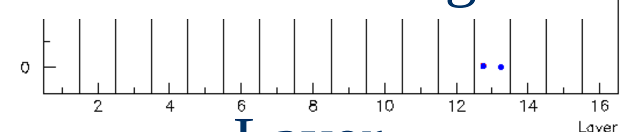
# Cosmic rays with and without LER beam




Layer




High background rate, drop of efficiency in collisions
No instrumental damage.




Layer

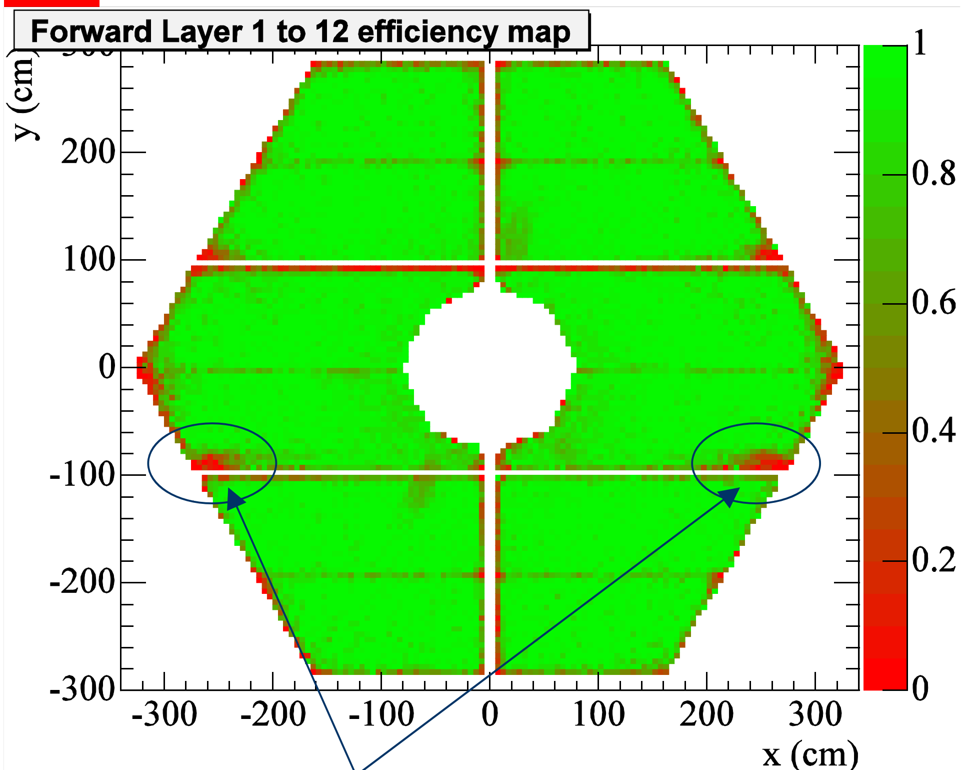
# Radiography of FWD EC with $\mu^+\mu^-$

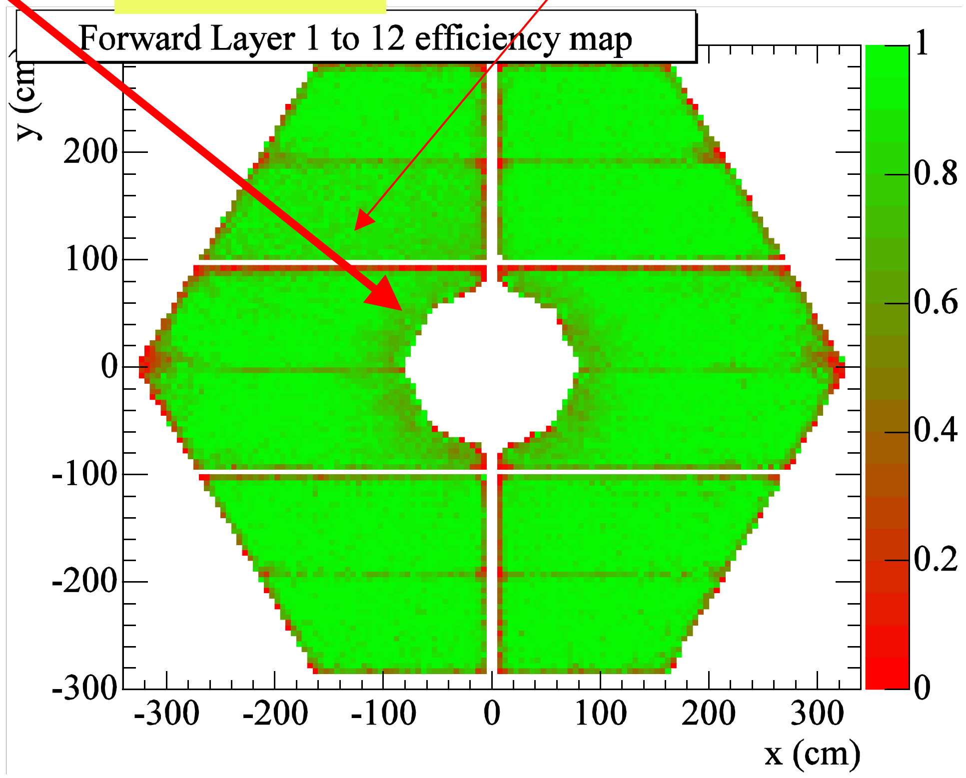
Runs before Xmas03

Less efficient around beamline

Runs after Xmas03

Dead layer 6 (Nov 2000)




Ineff. areas near gas inlets

*First sign of declining efficiency in high $Q_{int}$ regions?*

# Initial Humidity Measurements

- First preliminary measurements
  - Dry Gas in input ~ 0% RH
    - (SLAC average environmental RH ~30%)
  - Gas in output 25-28% for FET14
- We are removing water from the RPCs

Building a system to deliver 30-50% RH gas

Need to be tested carefully in test-stand!

*We could worsen things though!!!*

# Measuring HF production

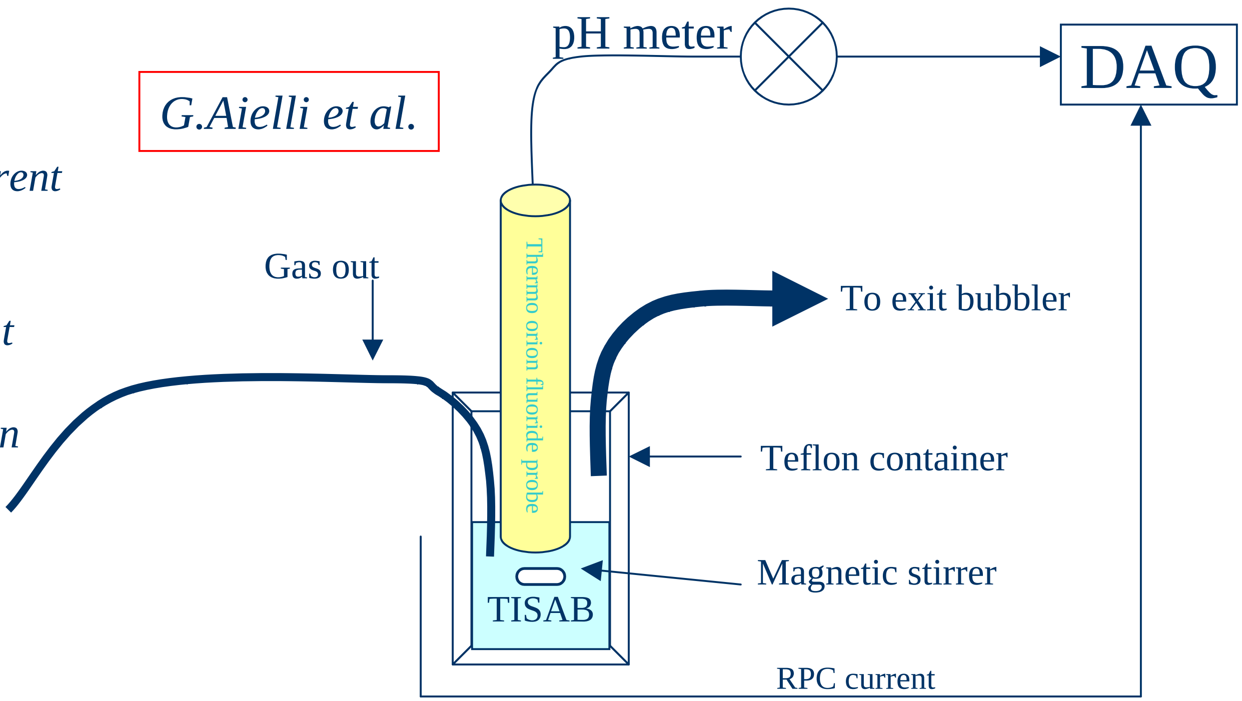
- LHC exp reports production of HF in RPC operated in streamer mode. Believed to be a cause of RPC degradation.

– Want to measure it in exhaust gas line from FWD RPC (layer14)

- Line already installed, buying components for exp'l setup

*They correlate increase in ohmic current with $F^-$ production.*

*And they conclude that More i-C4H10 would Suppress $F^-$ production*



# Conclusions

- RPCs in BaBar have been a troubled life.
  - *Original version RPCs*
    average Barrel RPCs efficiency is now 40% (40% RPCa have zero eff)
    *but $\mu$ID basically preserved*
  - Many failures, some related to bad construction, some to bad operations.
    - *BaBar will replace 2 sextants with LST this summer*.
- 2002 RPCs still in good shape
  - Suffer from high machine background, collision efficiency reduced in few cases.
    - Closely monitoring operational parameters (rate, currents)
  - For few RPC $Q_{int}$ ~50 mC/cm$^2$, more than Nov2000 RPCs but efficiency with cosmics is unchanged (~95%)

  *They won't die for **graphite vaporization** in BaBar's lifespan*

*If properly built and operated, RPCs properly work*