RPC experience: Belle, BaBar and BESIII

Survey of RPC in running and future experiments

Table 1. RPC characteristics in running and future collider experiments

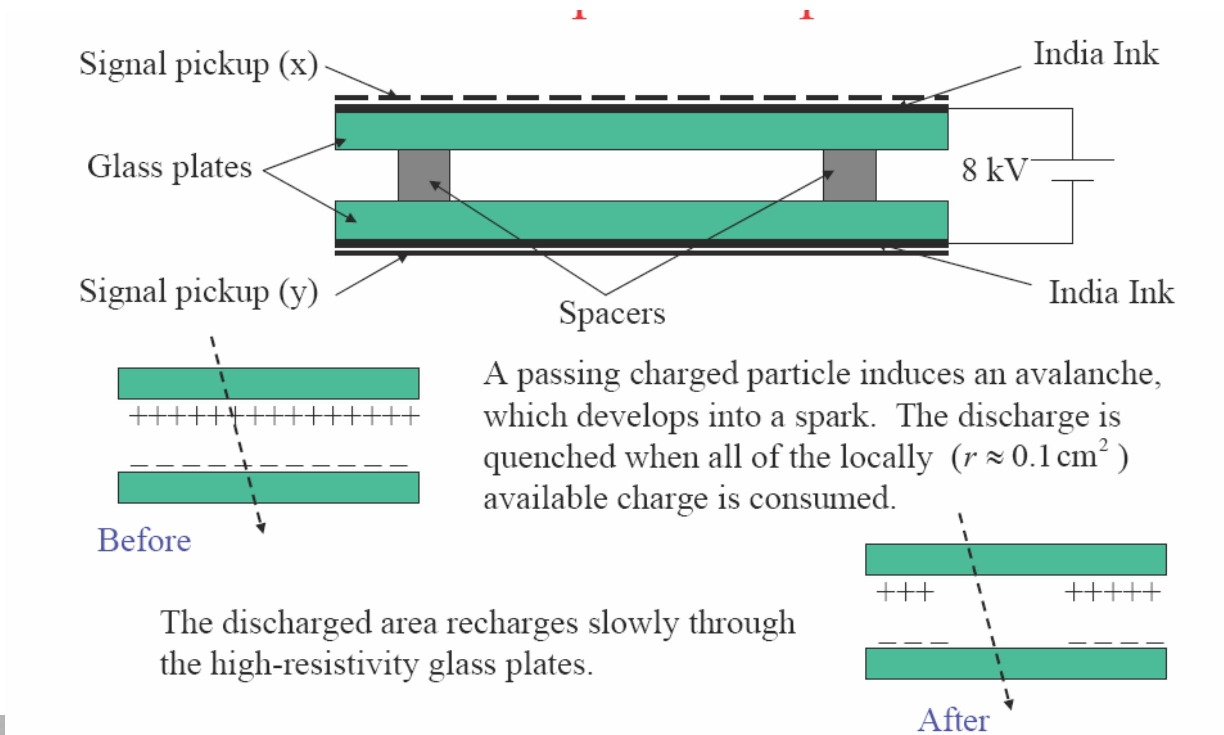
experiment	operating mode	# gaps	gap width (mm)	electrodes material, $\rho\,(\Omega\,\mathrm{cm})$	gas mixture (%)	readout
BaBar	streamer	1	2	oiled bak., $10^{11} \div 10^{12}$	$60\,\mathrm{Ar} + 35\,\mathrm{C_2H_2F_4} + 5\,\mathrm{C_4H_{10}}$	strips xy
Belle	streamer	2	2	glass, $10^{12} \div 10^{13}$	$30\,\mathrm{Ar} + 62\,\mathrm{C_2H_2F_4} + 8\,\mathrm{C_4H_{10}}$	strips xy
ALICE TRI	streamer	1	2	oiled bak., $\approx 3 \times 10^{9}$	$51\,\mathrm{Ar} + 41\,\mathrm{C_2H_2F_4} + 7\,\mathrm{C_4H_{10}} + 1\,\mathrm{SF_6}$	strips xy
ATLAS	prop.	1	2	oiled bak., $\approx 10^{10}$	$96.7\,\mathrm{C_2H_2F_4} + 3\,\mathrm{C_4H_{10}} + 0.3\,\mathrm{SF_6}$	strips xy
CMS	prop.	2	2	oiled bak., $\approx 10^{10}$	$96\,\mathrm{C_2H_2F_4} + 3.5\,\mathrm{C_4H_{10}} + 0.5\,\mathrm{SF_6}$	strips x
STAR	prop.	5	0.22	glass, $\approx 10^{13}$	$95\,\mathrm{C_2H_2F_4} + 5\,\mathrm{C_4H_{10}}$	pads
ALICE TOF	prop.	10	0.25	glass, $10^{12} \div 10^{13}$	$90\,\mathrm{C_2H_2F_4} + 5\,\mathrm{C_4H_{10}} + 5\,\mathrm{SF_6}$	pads

What missing from this table: The following experiments are also building large RPC system,
The OPERA experiment at Gran Saso; YBJ-ARGO at Yangbajing International Cosmic Ray Observatory in China; BESIII at BEPC, Beijing.

Cited from "**Resistive plate chambers in running and future experiments"**
G. Bruno, CERN, Geneva, Switzerland, Eur Phys J C **33**, s01, s1032–s1034 (2004)

Experience of BELLE glass RPC

Belle's glass RPC is a good example of glass RPC's application in high energy physics experiment. (all the following slides about Belle are from D. Marlow's talk at NuMI Off-axisWorkshop and Eiichi Nakano's talk at IEEE, 2003)



2 mm thick glass,
2mm gas gap

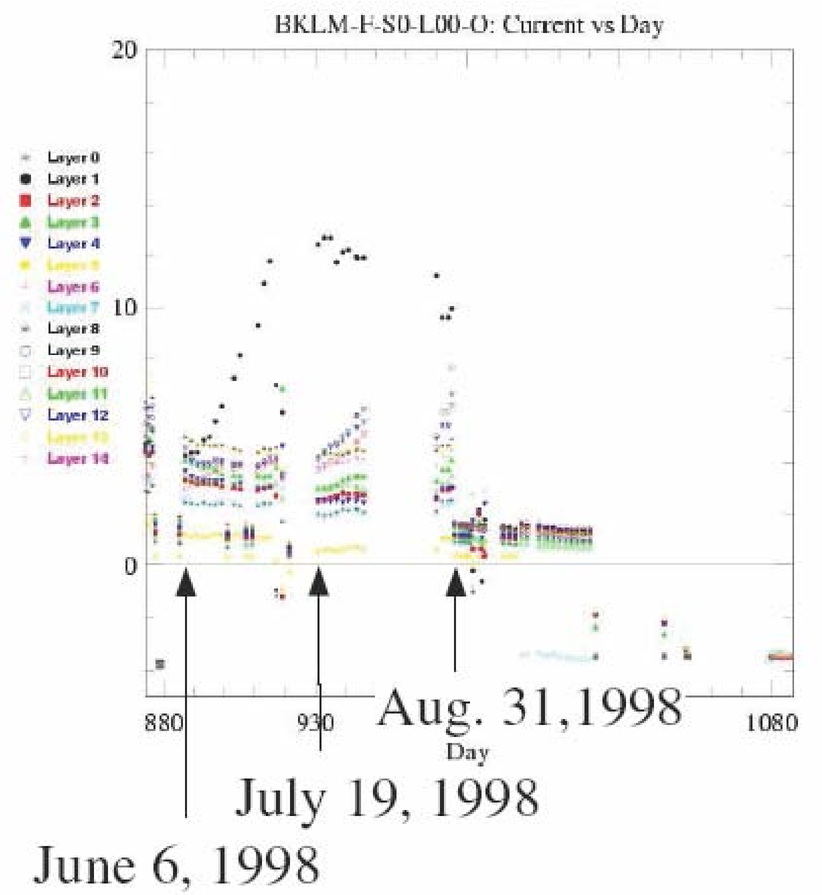
Bulk resistance
~7x10^{12} Ω•cm

Belle RPC's problem

In Summer 1998, the first signs of trouble showed up shortly after installation and looked something like the plot to the right. The current from a chamber would "suddenly" show a dramatic increase.

Many RPCs showed a dramatic loss of efficiency.

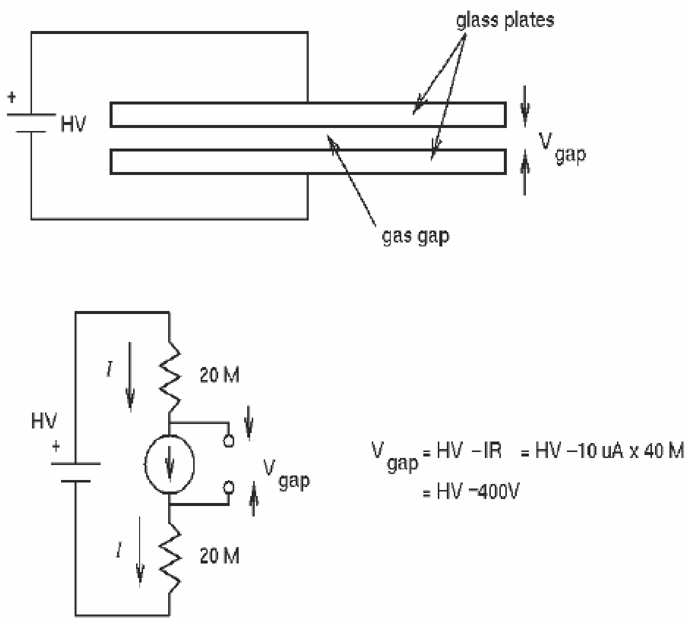
Turn off HV to check the problem.



RPC Spiral ‘o Death

• High current is a serious problem in glass RPCs: High dark currents induce a significant IR voltage drop across the glass plates, which lowers the voltage across the gap, causing the chamber to slide off the efficiency plateau.
• Increasing the applied voltage doesn’t help, since it merely results in increased dark current.

Dan Marlow calls it the classic “RPC Death Spiral”.



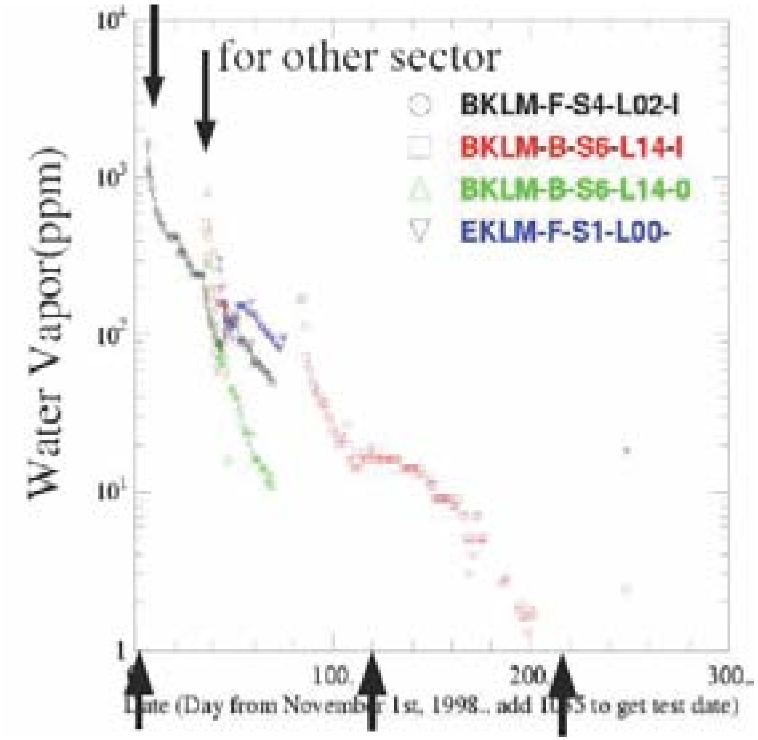
Dx & Rx

- After several weeks of study they determined that the problem was due to high levels of water vapor in the gas. The water was coming in through plastic (Polyflow) tubing.
- The solution was (conceptually) simple:

  Replace the plastic feed lines with copper.

Dry out the system

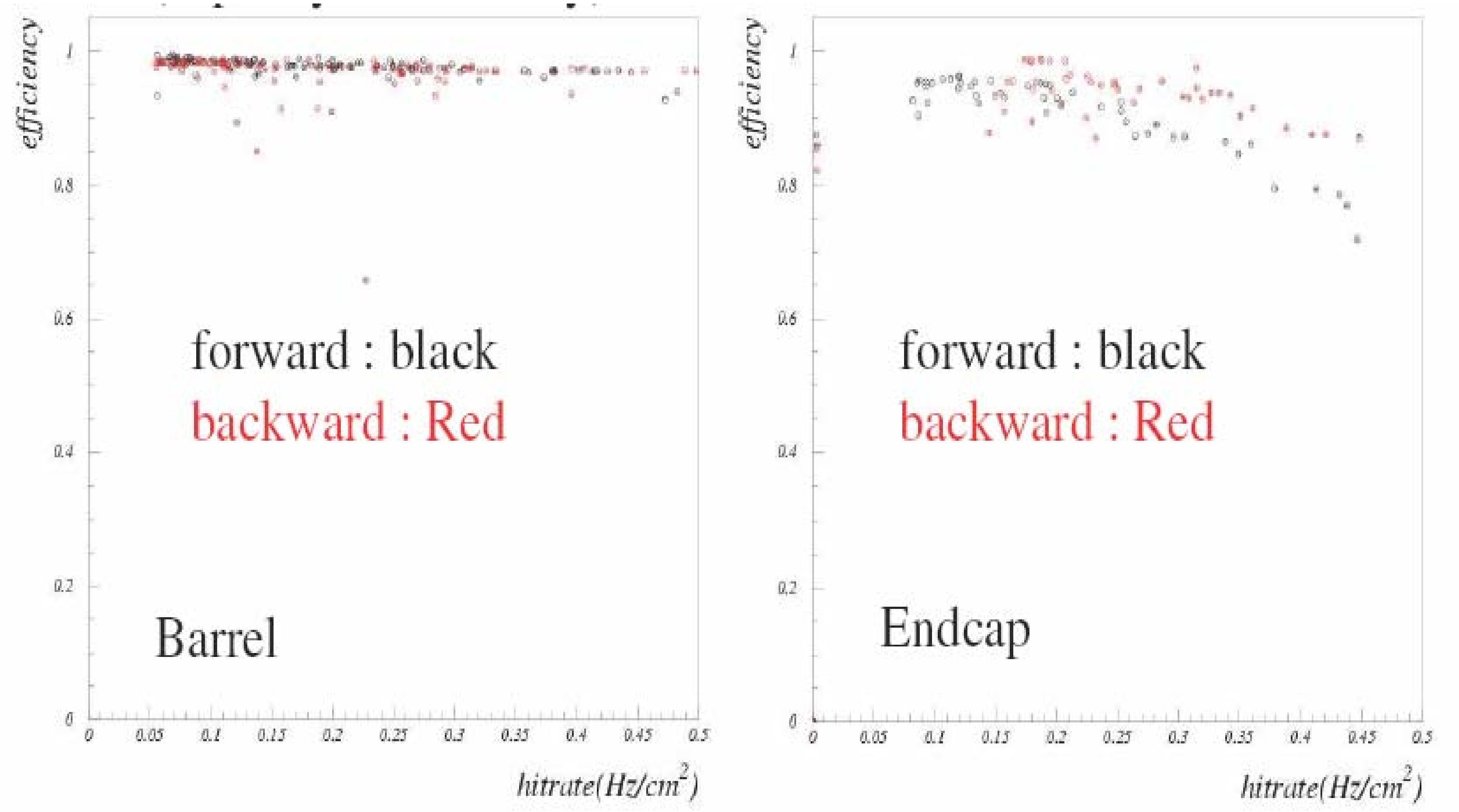
Replace gas tubing for barrel sector



11/1/1998 2/1999 6/1999

- Water vapor at RPC out was decreased to <100 ppm in Feb., 1999.
- More than 3 month before KEKB commissioning (June, 1999)

Rate limitation: Efficiency vs. hit rate



… Rate limitation

At present, hit rate
- Barrel ~ 0.1 Hz/cm2
- Endcap 0.1~0.3 Hz/cm2 slope is larger than Barrel

Higher hit rate -> lower efficiency
- Barrel looks safe for higher hit rate;
- Endcap has problem at higher hit rate

At SupperKEKB hit rate will be
- Barrel ~ 2 Hz/cm2
- Endcap 2~6 Hz/cm2
- Efficiency will be: Barrel ~90 %; Endcap <50 %

Solutions
- Make a new detector;
- Add more shielding to cut down the background;
- New gas mix to reduce the streamer charge;
- Switch to avalanche operation.

Comments on Belle's RPC: Personal point of view

- Glass RPC is a simpler system: no Linseed oil coating;
- Found the problem long before Belle commissioning;
- Made the right decision to turn off HV immediately and search for the answer to the problem;
- Double gap design, helps to maintain high efficiency;
- The solution was not so complicate that need long time R&D to get;
- The rate limitation is a real challenge to glass RPC.

The story of the BaBar RPC

BaBar RPC's experience has provided several important lessons to Linseed-oiled Bakelite RPC community. Since BaBar RPC group revealed what they discovered in the autopsy of dead RPCs summer, 1999, the aging of RPC becomes the focus of RPC study. So far some of previous black magic are no longer scaring people, but some of them still are.

BaBar RPC chamber – Deterioration & "Remediation"

After years of R&D effort in world RPC community, now we have better understanding to the Bakelite RPC aging. Basically there are three major causes and their solutions:

• Uncured Linseed oil formed stalagmites in the gap —

Sol: Use thinner Linseed oil coating and thoroughly polymerize the oil film before apply HV; Better surface Bakelite, completely abandon the use of Linseed oil coating;

• Vanished graphite coating on the bakelite electrodes after accumulated certain amount of charge through the Bakelite —

Sol: Better technology for making the graphite coating; Switch to the avalanche mode operation;

• Resistivity increase of the Bakelite electrode with the total accumulated charge —

Sol: Add water vapor into the gas mix; Switch to the avalanche.

Autopsy of the bad RPC chambers: Linseed oil stalagmites

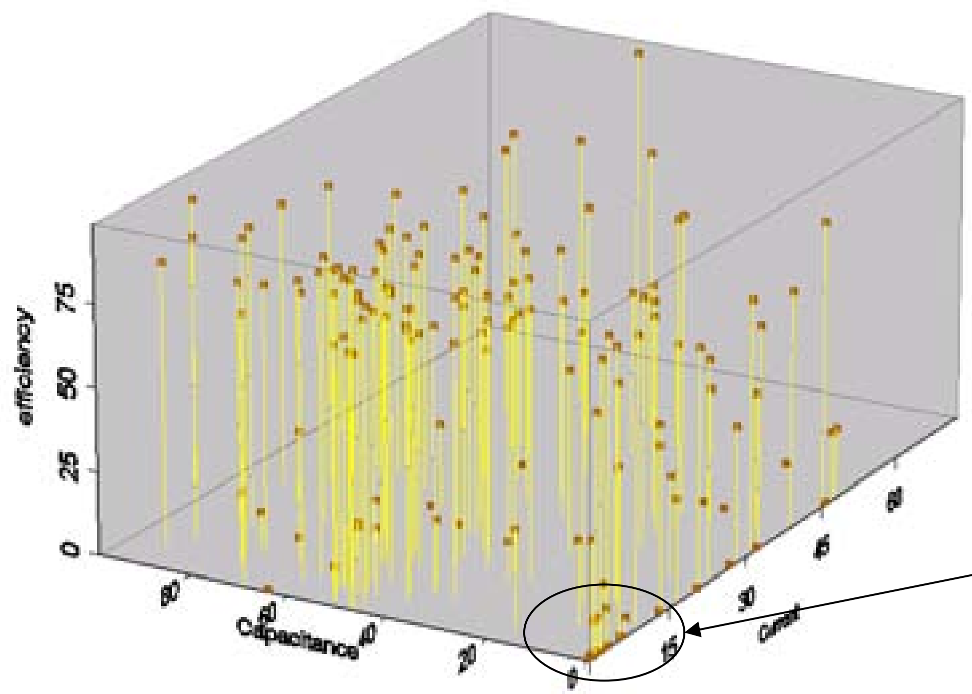
Three basic conditions for forming linseed oil droplets on the inner surfaces of RPC :

- Enough linseed oil existing on the surface, which is the source of the droplets;
- Elevated temperature to soften the oil film, make the oil molecules movable;
- High electric field to help pull the soften oil layer away from the Bakelite sheet. Electric force could be 70 times stronger than the gravity force!

Unfortunately all three conditions were meet for the BaBar RPC chambers in summer 1999 !

Vanishing of the graphite coating

A very interesting capacitance test revealed a surprising fact: If we put three measured values – capacitance, efficiency and dark current – together, made a 3D plot, we noticed at the corner of low efficiency, low dark current and low capacitance gathered number of RPCs. That is very different to our previous experience: lower efficiency always related to high dark current.



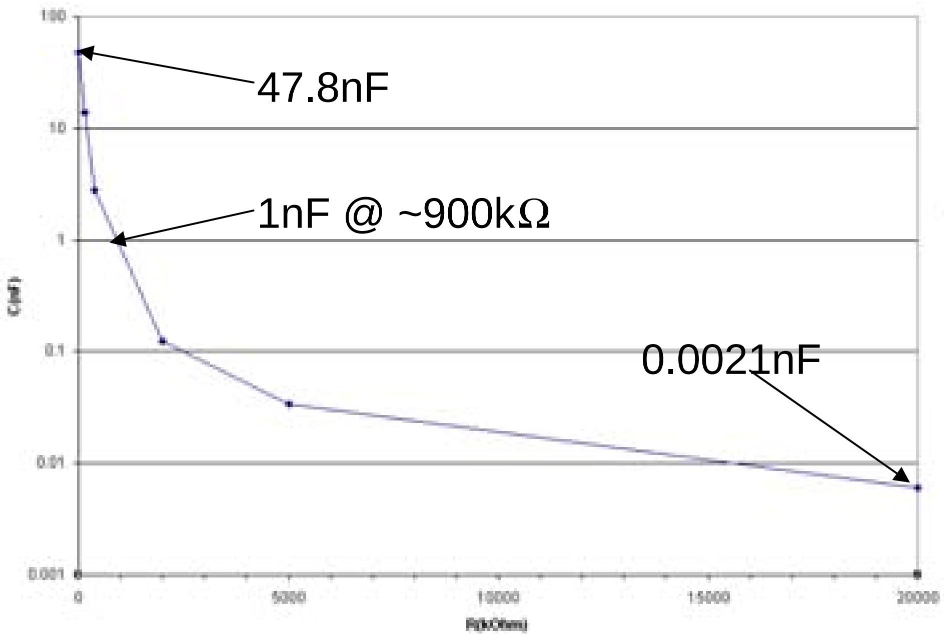
The death certificates for those RPCs point out their common symptoms:

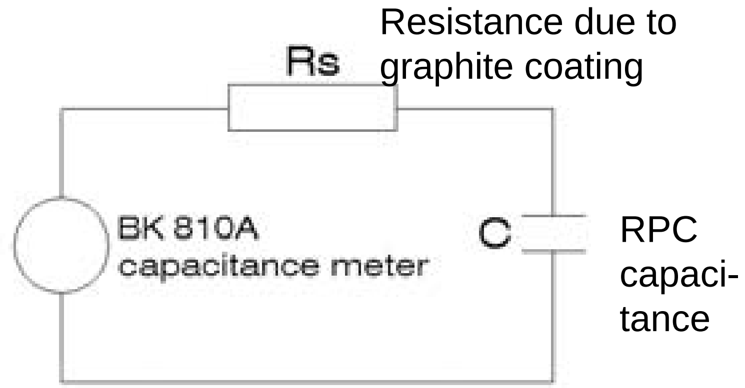
Low capacitance;
Low current; Almost zero efficiency.

What could be wrong for the chambers with very small capacitance reading

The explaination: Graphite paint film developed discontinuity region

Using a simple handheld capacitance meter the resistance of the graphite paint can seriously pervert the capacitance measurement :



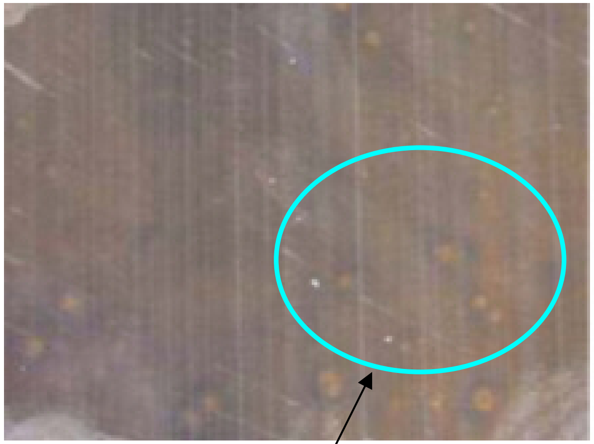


Increase Rs will reduce capacitance reading. A 900kΩ resistor can let a 47.8nF capacitance be read as 1nF with a BK 810A meter!

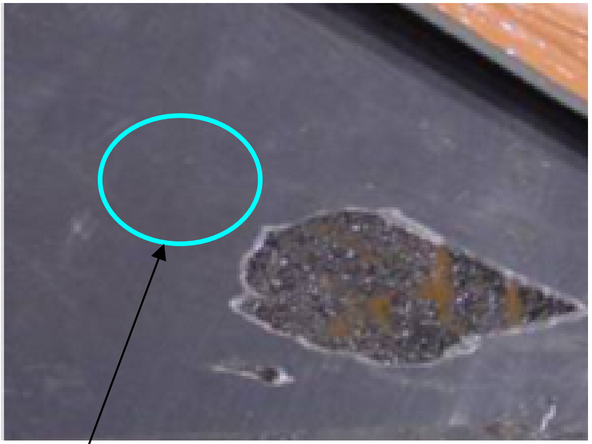
Support evidence of the damaged graphite

Later a strong support evidence from some dead endcap RPCs revealed this failure mode:

(Henry Band)



The anode side graphite film of a dead RPC with low dark current, low capacitance and almost zero efficiency. It shows semitransparent looking, indicates vanished graphite.



New graphite coating should look dark and uniform.

Resistivity increase: adding water vapor

Many RPC groups have found that the resistivity of Bakelite electrode increases with the total accumulated charge flowing through the plate. BaBar new version of endcap RPCs clearly show the efficiency at the gas inlet region is worse than other area. They attribute this effect to the drying process at inlet region being most profound. Add water vapor into the gas mixture to maintain an adequate humidity inside of RPC is therefore advocated.

But the disadvantage is water vapor helps to form hydrofluoric acid, which could cause damage for the inner surface.

> "It should be stressed that a satisfactory understanding of the electrical conduction in RPC electrode plates still remains a central task for the RPC scientific community." (R. Santonico, NIM A533(2004)1)

A prospective good newcomer in RPC family

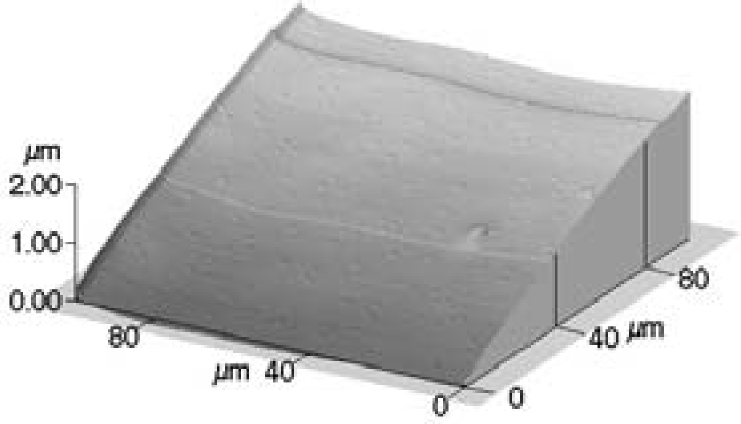
Through several years R&D effort IHEP, Beijing has developed a new material for the RPC electrode. With this new type of Bakelite they can produce RPC w/o Linseed oil coating. The dark current and single's rate can reach the same level as Linseed oil coated RPC.

Study on IHEP's resistive electrode

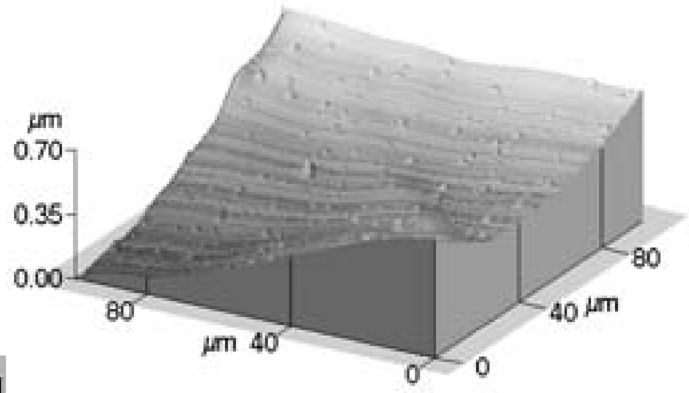
We have studied the morphological feature of IHEP and BaBar Bakelite plates with the atomic force microscope. The surface images show IHEP's sample is about two to three times smoother than BaBar's.

Comparison of BaBar Bakelite sample w/ and w/o oil

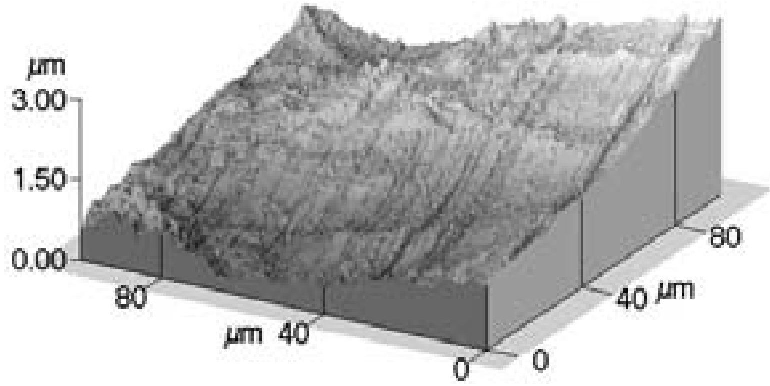
w/ thick Linseed oil coating



w/ thin Linseed oil coating

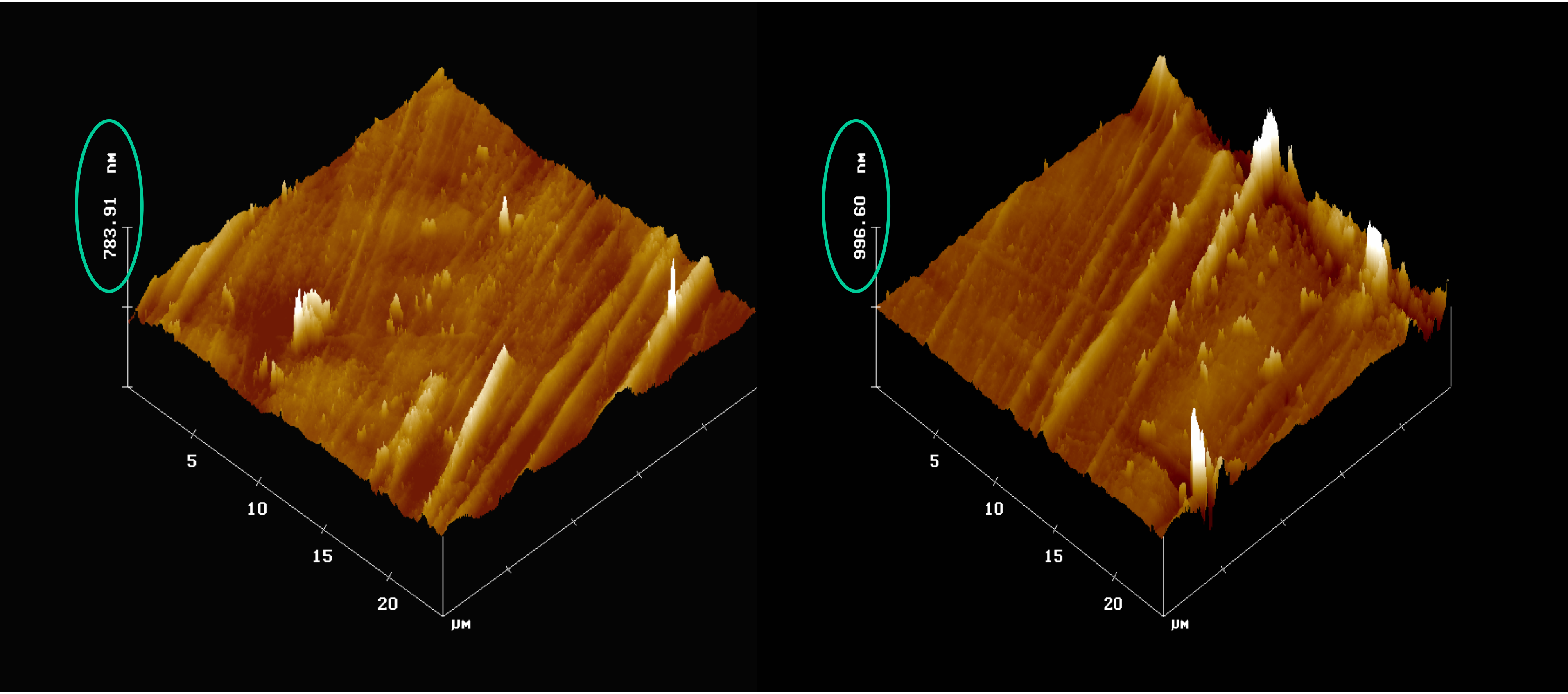


w/o Linseed oil coating



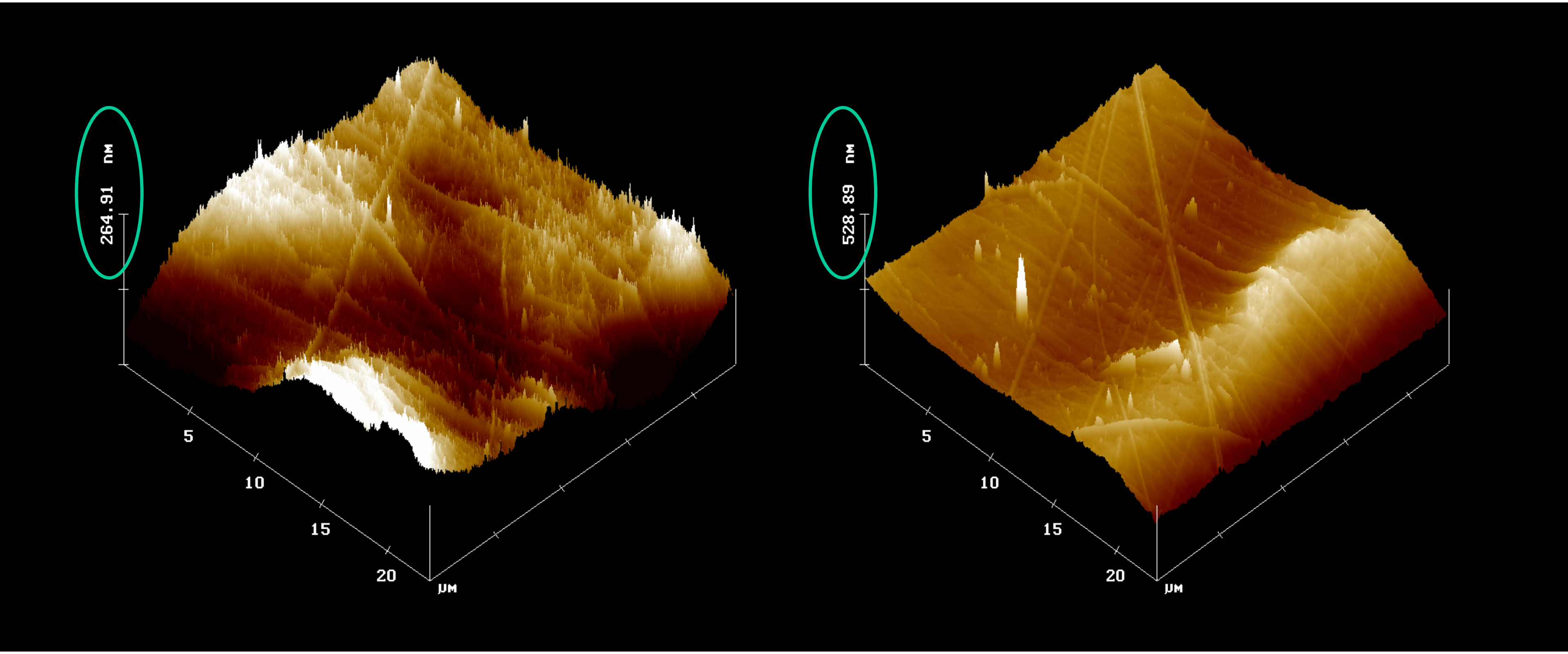
(M. Wu and C. Lu, Dep. Of Physics, Princeton University)

Bare BaBar Bakelite surface w/o Linseed oil coating



Bakelite sample under atomic force microscope

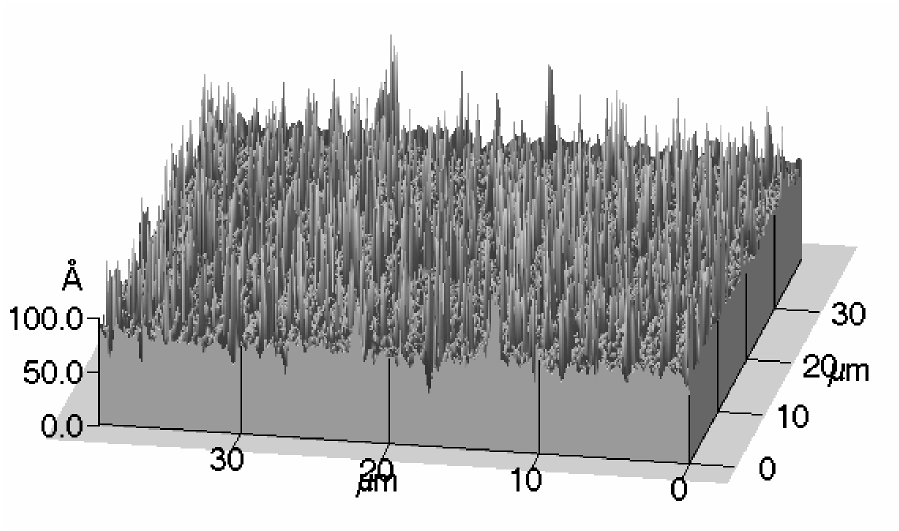
Bare IHEP Bakelite sample w/o Linseed oil coating

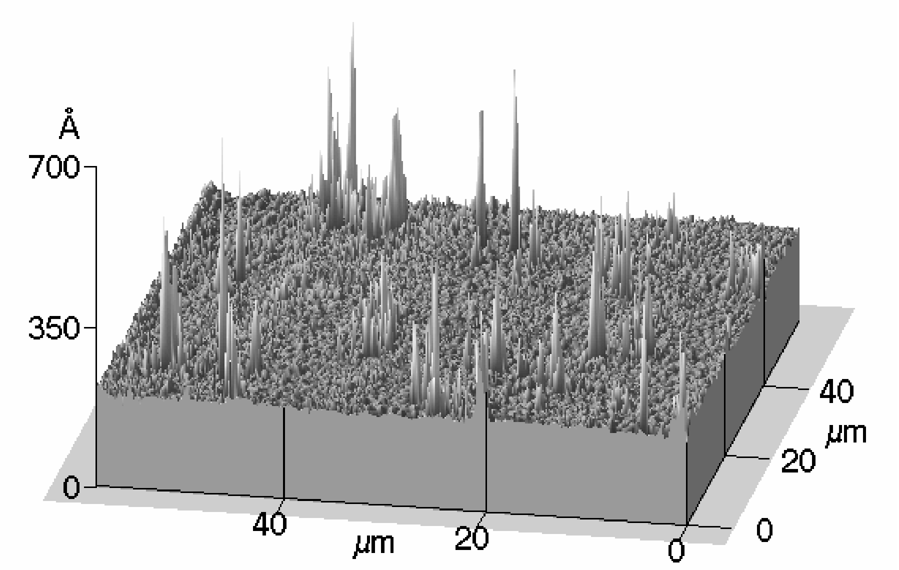


Notice: the vertical scale is 2 – 3 times smaller then previous images.

Glass RPC: glass surface

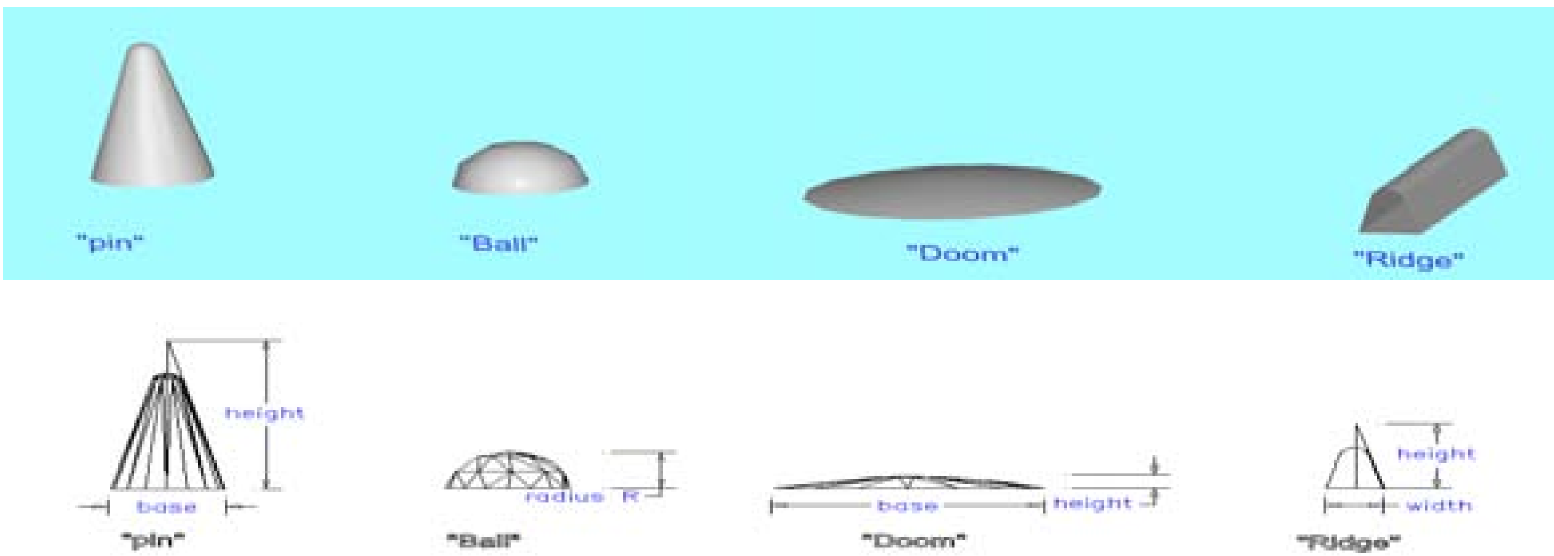
For comparison we also recorded the glass surface morphological image for Belle's RPC:





E-field strength calculation for various imperfection spots

We have calculated four types of surface defects as illustrated bellow: the tips of “pin” and “ridge” have been rounded, R = 0.5μm, the height is the distance from the base to the tip (before being rounded).



Summary of calculation

For 2mm gap, 1000V across the gap:

	"pin"			"ball"		"doom"		"ridge"	
Height (mm)	0.05	0.02	0.005	0.05	0.01	0.2	0.2	0.1	0.01
Base (mm)	0.02	0.008	0.002	0.1	0.02	0.6	1.4	0.04	0.004
Emax (V/m)	6×10^7	1.4×10^7	4×10^6	1.5×10^6	1.5×10^6	8.7×10^5	6.6×10^5	7.6×10^6	2.25×10^6

Few comments on surface defects

- BaBar Bakelite surface is not as smooth as IHEP Bakelite, at least a fact of 2 worse;
- The feature surface morphological structures are:

  pin-like protrude;

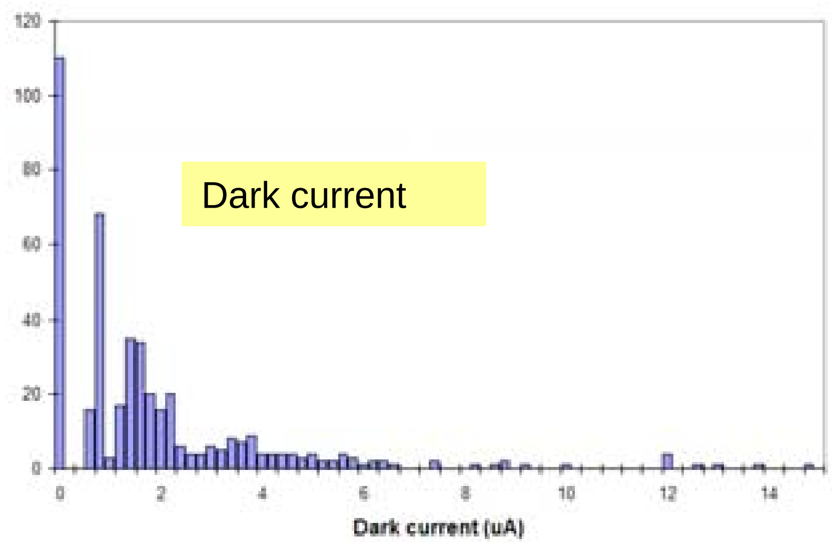
  ridge-like long directional trace;

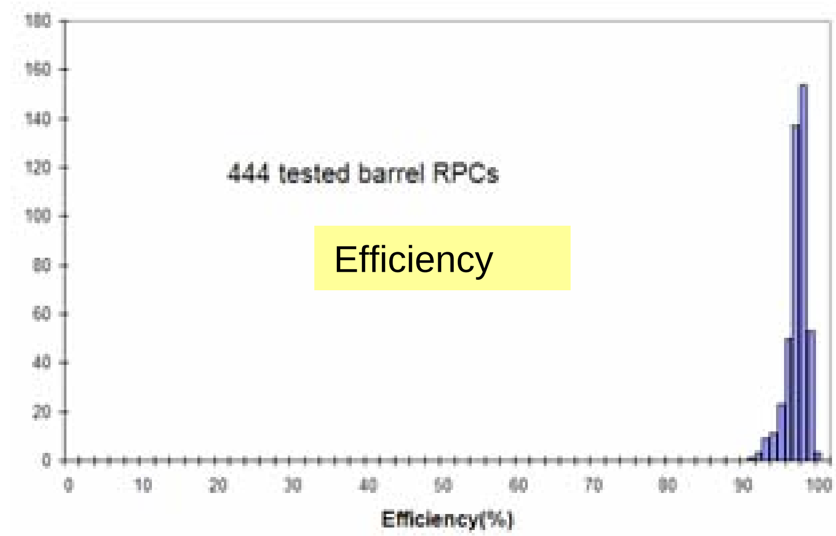
  longer wavelength wave;
- Linseed oil coating covers submicron surface imperfection.

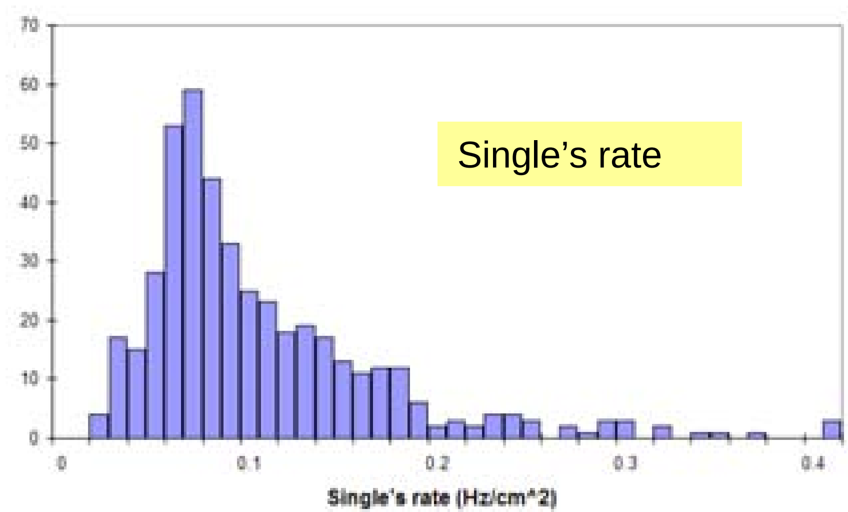
The FEA calculation shows that “pin” is the most serious surface defect in respect of the surface electric field variation. IHEP’s Bakelite surface may have its advantage in this regard, therefore they can abandon the oil coating on the surface.

Performance of IHEP RPCs

So far they have fabricated ~1000 RPCs for BES III, the average area for the endcap RPC is 1.3m^2, barrel RPC 1.4m^2. Maximum RPC they can make is 1.2mx2.4m. The performance statistics of the tested 444 barrel RPCs:



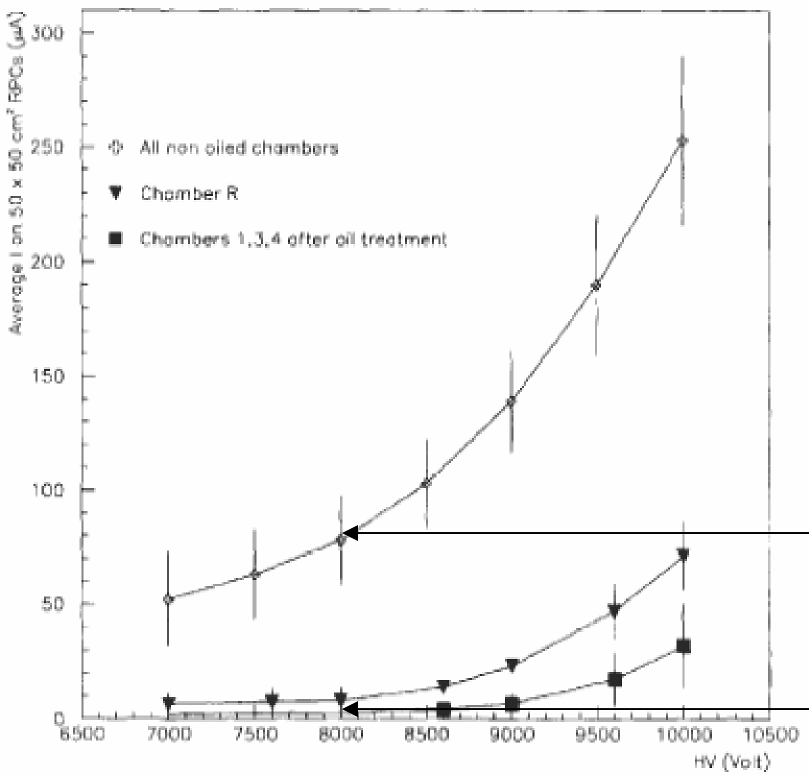




The performance is comparable to BaBar's new version of RPCs with Linseed oil coating.

Comparison to other non-oiled RPC studies

"Effect of the linseed oil surface treatment on the performance of resistive plate chambers", M. Abbrescia et al. NIM A394(1997)13-20



argon/isobutane/
freon 13Bl (48%/48%/4%)
gas mix

Non-oiled RPC, huge dark current

Oiled RPC, dark current much smaller

Fig. 4. Current versus HV averaged on all non-oiled (open cross) and oiled gaps (full square); chamber R behaviour (full triangle) is shown as reference. Error bars correspond to one standard deviation.

… comparison to other non-oiled RPC studies

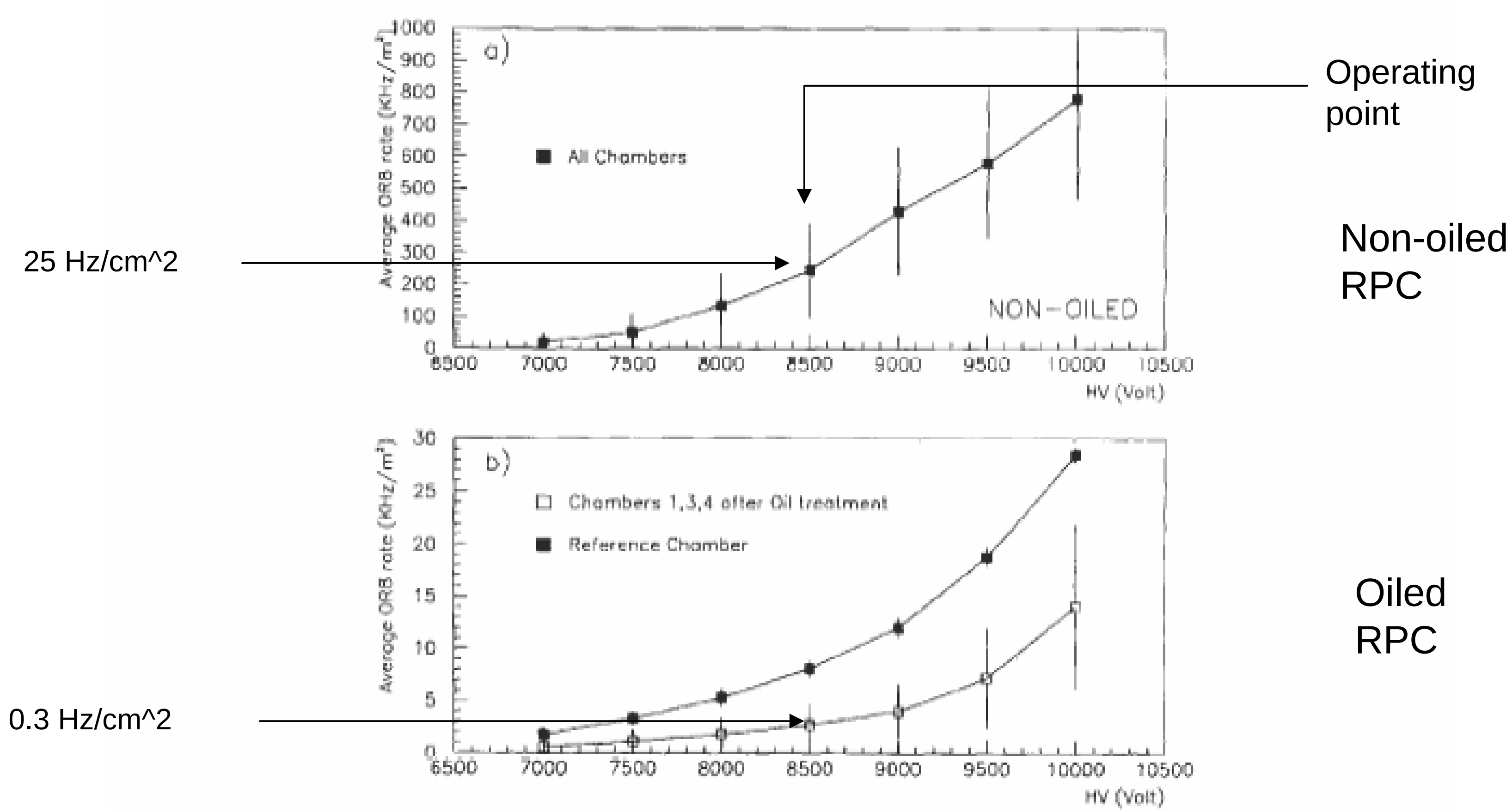


Fig. 5. Average single rate (as explained in the text) versus HV at a fixed discriminating threshold: (a) Non-oiled gaps; threshold −80 mV. (b) Oiled gaps; threshold −50 mV. The chamber R is shown as reference.

… comparison to other non-oiled RPC studies

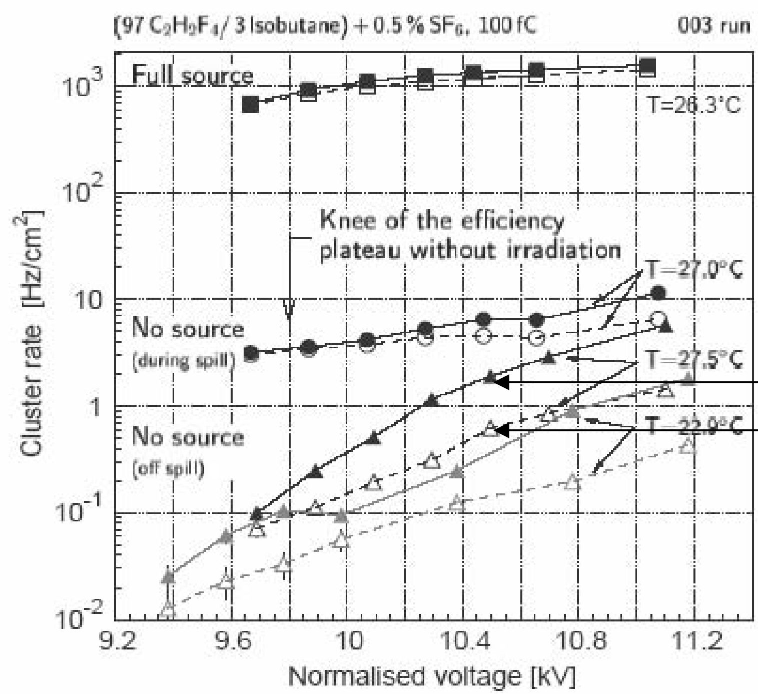


Fig. 5. The measured rate of avalanches as a function of the normalised H.V. for two RPC modules filled with the gas mixture containing 0.5% SF_6. The corresponding irradiation conditions are shown. Solid and dashed lines correspond to the non-oiled and the oiled chamber, respectively.

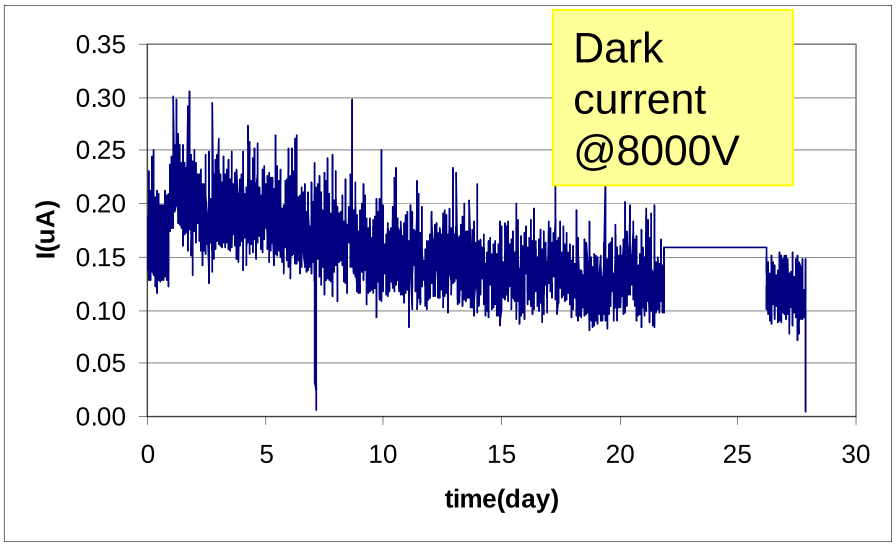
Operation of low-noise single-gap RPC modules exposed to
ionisation rates up to 1 kHz/cm^2
M. Cwiok et al.
NIM A533(2004)27

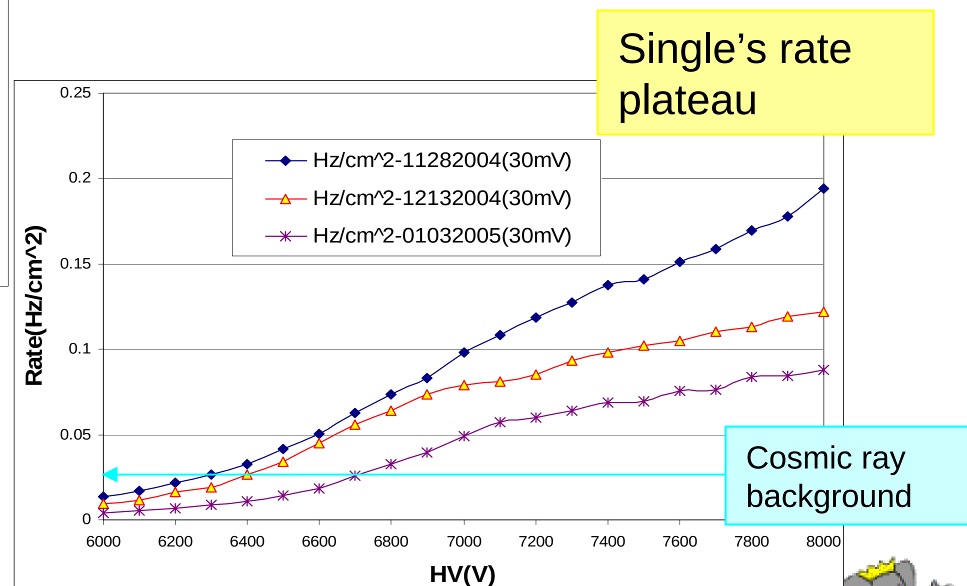
Non-oiled RPC, ~2Hz/cm^2

Oiled RPC, ~0.6Hz/cm^2

Test IHEP RPC prototype at Princeton

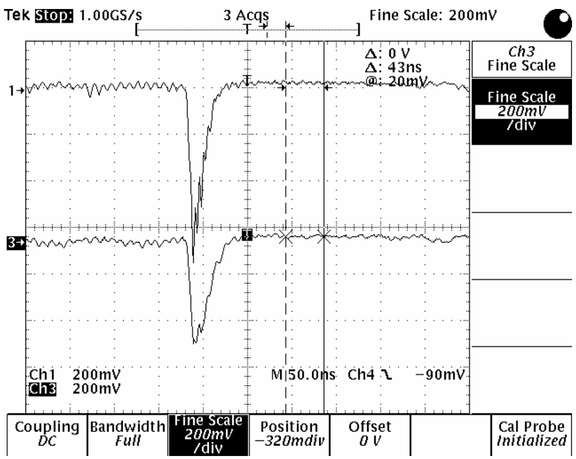
Three small prototypes (50x50cm^2) from IHEP. In streamer mode the dark current and single's rate plateau look very nice.

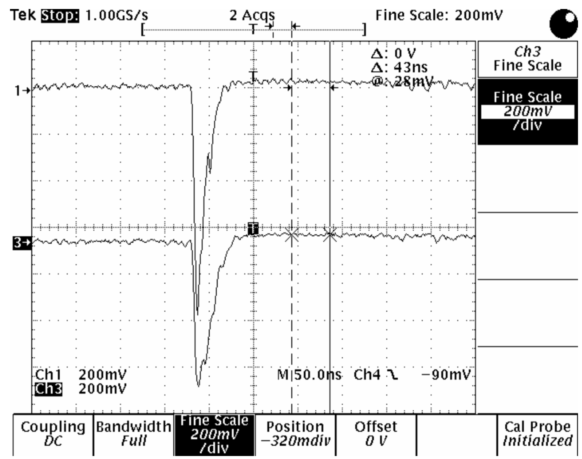


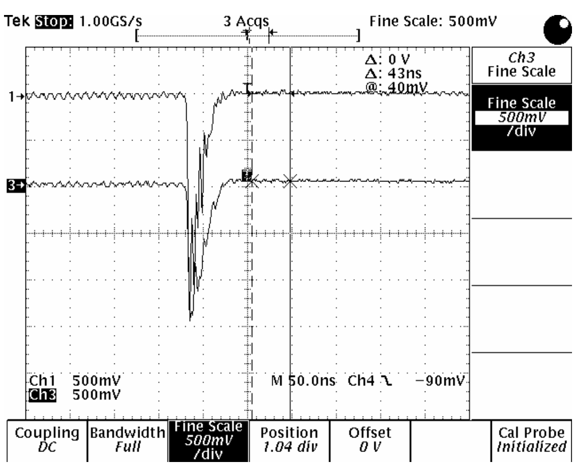


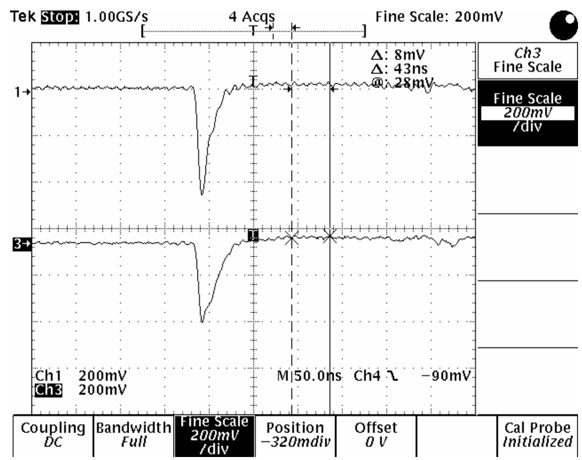
Avalanche signal of IHEP prototype

The avalanche signal is so small, it is not possible to see the signal on the scope w/o amplification. We use an ORTEC linear amplifier VT120 (amplification x200) to look at the RPC signal:









The vertical scale is 200mV, since amplification is 200, so the equivalent vertical scale is 1mV/div.

Time scale is 50ns/div.

Gas mix: R134A/Isobutane (95/5) with 1% of SF6.

HV = 10600V.

More R&Ds are needed for IHEP's RPC

IHEP is installing RPCs into BES III. It will take one year to finish the whole detector installation. So far about 20 prototypes have been under HV for more than 2 years, no deterioration has been found. But the following very important issues are waiting for more careful and systematic R&D:

- Stability of Bakelite resistivity, humidity dependence;
- Performance of lower resistivity Bakelite RPC in high background environment;
- Toughness of the Bakelite surface against the HF acid attack;
- Systematic aging study;
- Detailed performance study in avalanche mode.

Conclusion

• Experience of BaBar and Belle RPC has provided valuable expertise on manufacturing and maintaining a large RPC system;

• RPC technology has made good progress in recent years, mainly due to the R&D efforts of CMS, ATALAS and ALICE at LHC;

• RPC technology has various options to offer for different experimental circumstances;

• New type of RPC developed by IHEP, Beijing might be a good candidate for ILC muon detector and hadron calorimeter. But still have a lot of R&D ahead of us to verify its longevity.