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STUDY of ECO-FRIENDLY GAS REPLACEMENTS FOR PARTICLE DETECTORS IN HIGH-ENERGY PHYSICS

AGING TEST STATION, PNPI, Gatchina

I. Eco-friendly gas mixtures study:

- Analysis of the gas components
- Longevity resource problem
- Gas mixtures straw-test
- Results for CF3I gas mixtures
- Conclusion

II. CF3I gas mixtures study with CSC prototype:

- CSC prototype
- Test results for 1%, 5% and 10% CF3I containing gas mixtures

  -- N-pentane

III. Si aging recovering method

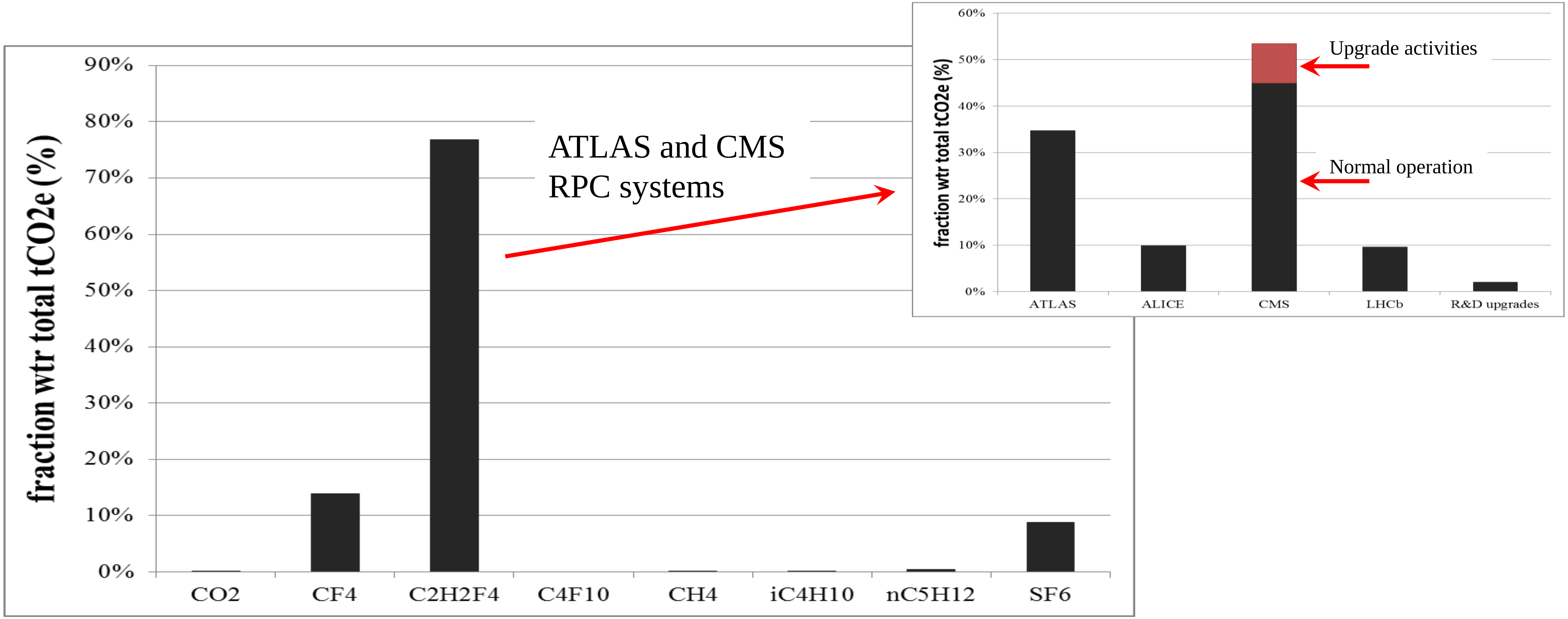
- Short prehistory
- HERMES (DESY) MWPC curing from Si
- ATS straw multiple curing with 80%CF_4+20%CO_2

IV Planning & Outlook

November, 29 2015

Gas emissions from particle detectors

- Operational costs and Greenhouse Gas (GHG) emission
- Total emission: ~127100 tCO_2e
- Main contribution $C_2H_2F_4$(R134a), CF_4, SF_6



I. Исследование новых экологически безопасных газовых смесей
Eco-friendly gas mixtures study:

Экологическая проблема:

•40%Ar+50%CO_2+**10%CF_4**

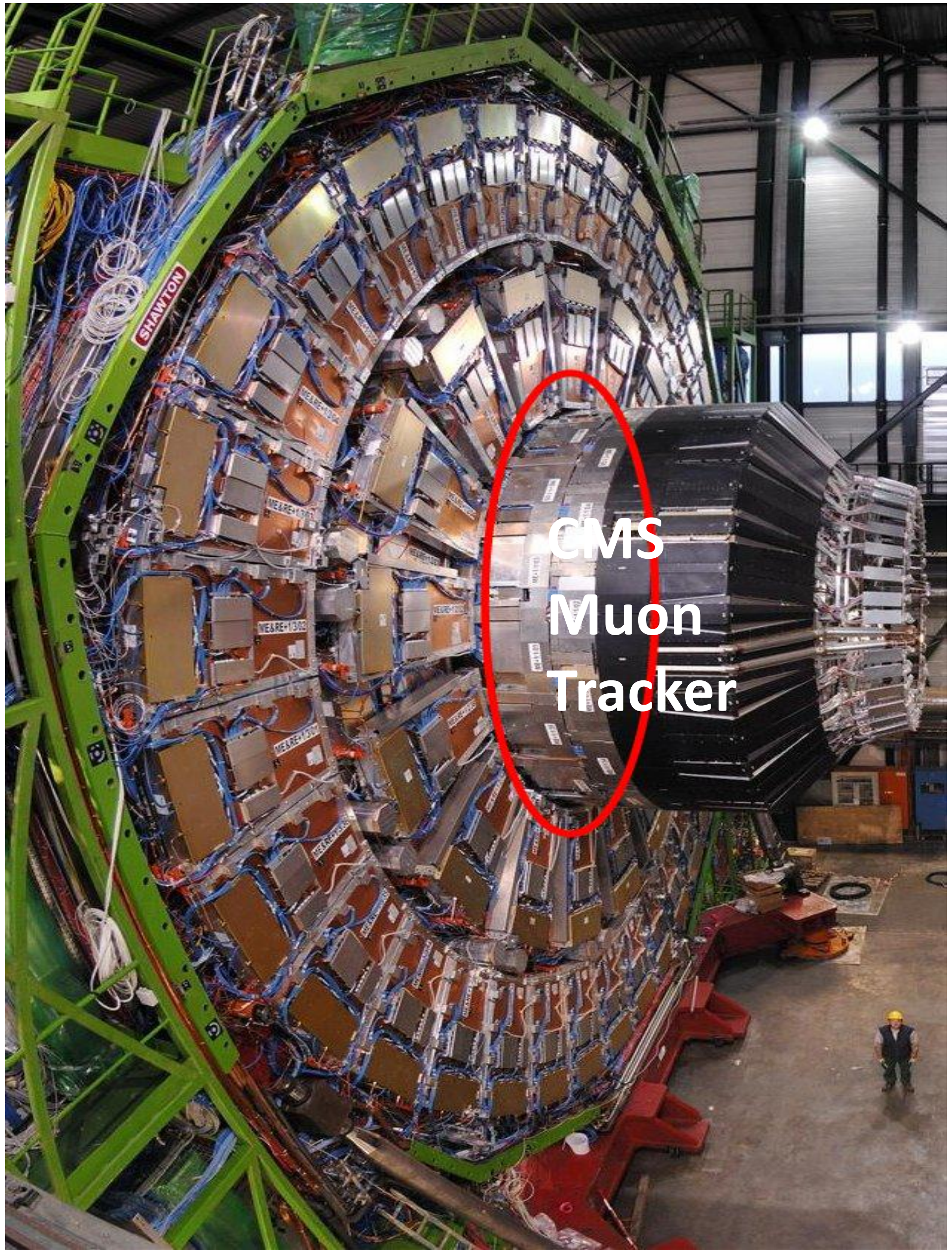
•Общий объем газа, поступающий в камеры CSC 180 m^3 в сутки

•Рециркуляция 90%

•Выброс **CF_4** - 4380 тонн CO_2 в год в GWP единицах
Для сравнения выброс ТЭЦ 11-12 тыс. тонн CO_2 в год

•Время жизни CO_2 в атмосфере 50-200 лет

•Время жизни CF_4 в атмосфере 50 000 лет



1 kg CF_4 в единицах GWP эквивалентен **7390 kg** CO_2

GWP (Global Warming Potential) – единицы воздействия 1 kg CO_2 на атмосферу

Analysis of the gas components

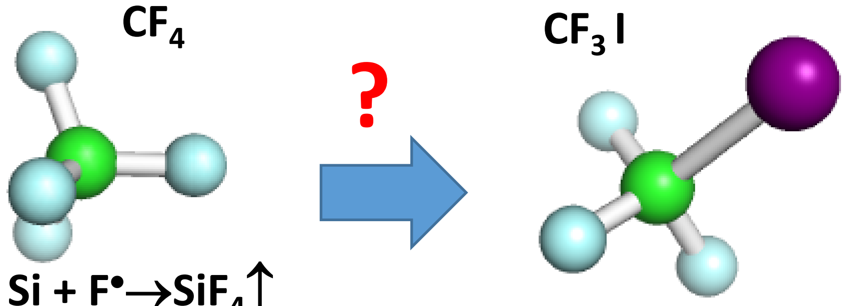
Химическая формула	Индекс	GWP (Global-Warming Potential)	Время жизни в атмосфере, лет
CO_2	R744	1	**50-200**
CF_4	R14	7390	**50 000**
CF_3I	R13I	0.4	<1
C_2F_6	R116	12200	**10 000**
C_3F_8	R218	8830	**7 000**
c-C_4F_8	RC318	10300	**3 000**

В таблице газы, широко применяемые в микроэлектронике для травления кремниевых микросхем все они, обнаружены в атмосфере обладают большим GWP

Только CF_3I не даёт вклада в парниковый эффект:
GWP= 0.4 за 100 лет

Возможность травления Si фтороуглеродами

Рабочий газ	Параметр F/C	Характеристика процесса	
		без ионной бомбардировки (≤15 эВ)	*с ионной бомбардировкой (≥100 эВ)*
CF_4	4	травление	травление
CF_3I	3	травление	травление
C_2F_6	3	нет травления	травление
C_3F_8	2,67	полимеризация	травление
C_2F_4	2	полимеризация	полимеризация

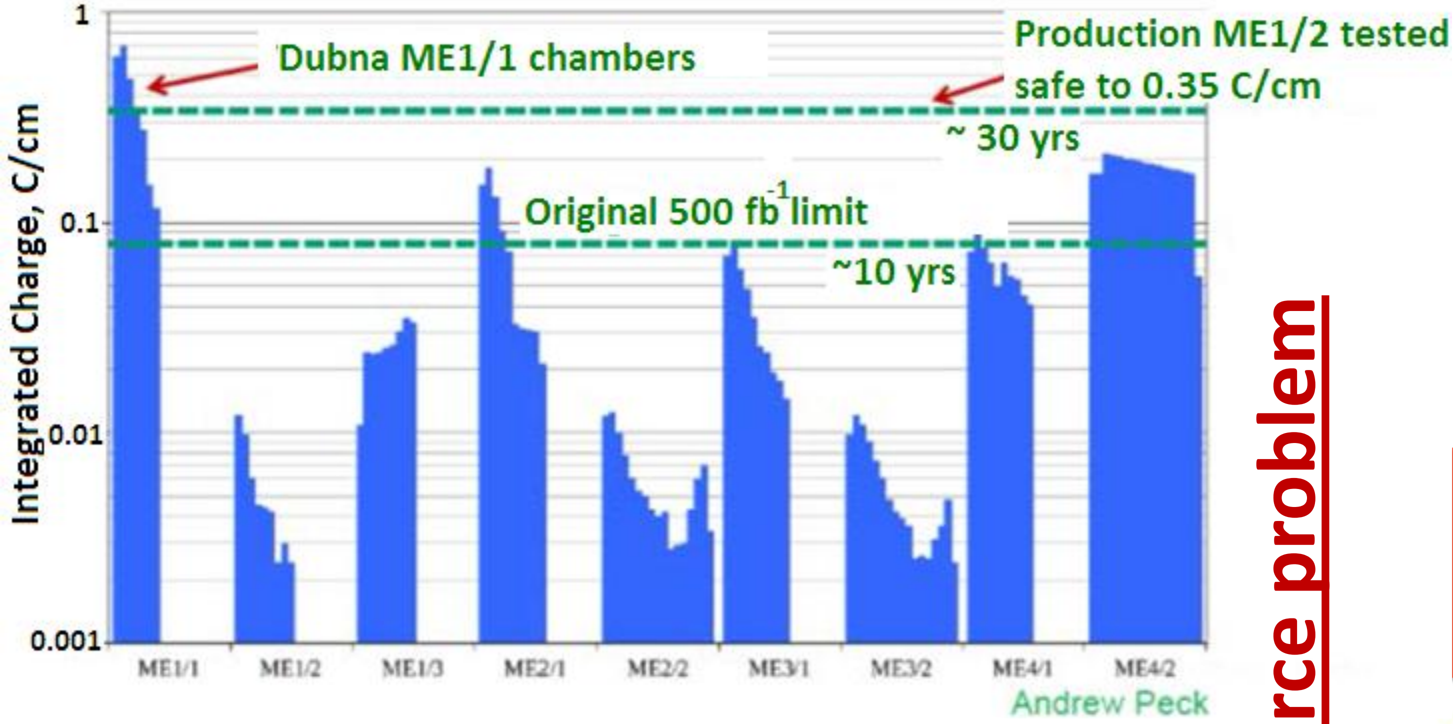


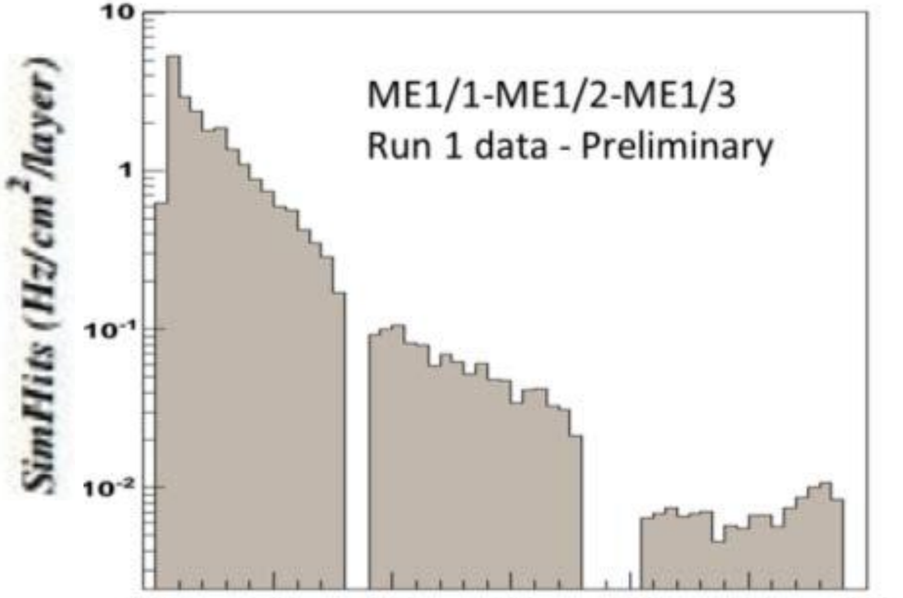
$Si + F^{\bullet} \rightarrow SiF_4\uparrow$

D. Yangd, G. Chend et al. Properties of potential Eco-friendly gas replacements for particle detectors in High-Energy Physics, CERN-OPEN-2015-004, 02 May 2015.

Antti Nuottajärvi, Tarmo Suppula, Plasma Etching and Integration with Nanoprocessing, Ion Beams in Nanoscience and Technology Part of the series Particle Acceleration and Detection pp 251-263, Nanoscience Center, University of Jyväskylä

Григорьев Ф.И. Плазмохимическое и ионно-химическое травление в технологии микроэлектроники: Учебное пособие / Московский государственный институт электроники и математики. М. 2003. 48 с.





Longevity resource problem

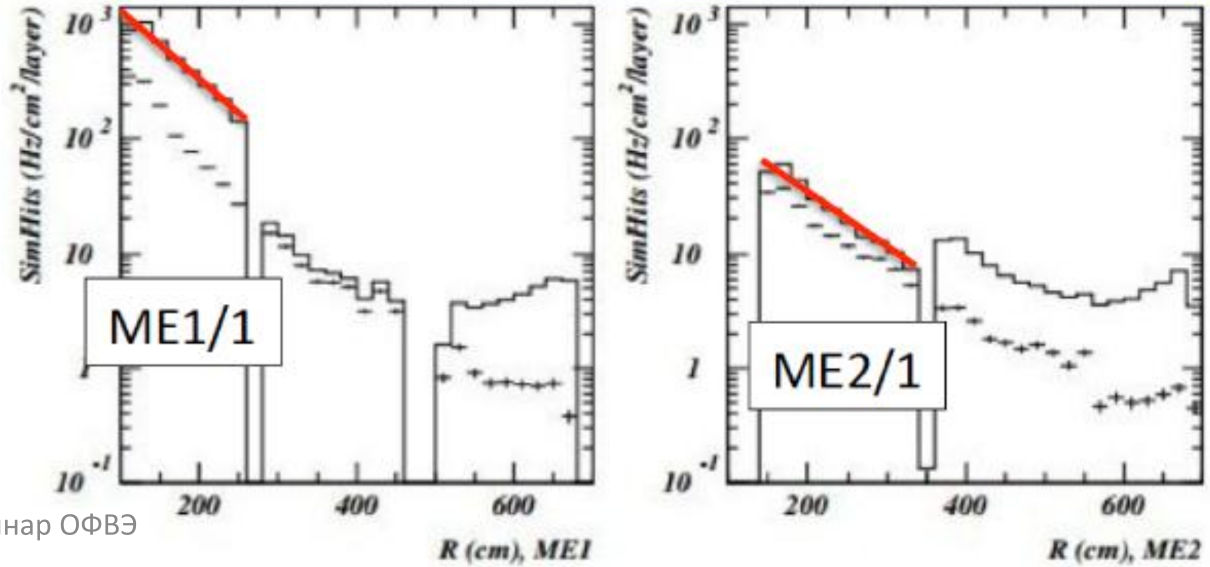
Currents observed in Run 1 and Run 2

- **ME1/1: I ≈ 2 μA per 10^{34} cm^{-2}s^{-1}**
- **ME2/1 (HV#1): I ≈ 5 μA per 10^{34} cm^{-2}s^{-1}**
- Current per lumi is about the same at 8 and 13 TeV

Extrapolation toward HL LHC L = 5×10^{34} cm^{-2}s^{-1}

- **ME1/1: $I_{HL\text{-}LHC}$ ≈ 10-15 μA**
- **ME2/1 (HV#1): $I_{HL\text{-}LHC}$ ≈ 25 μA**

CMS NOTE 2002/007: 14 TeV, 10^{34} cm^{-2}s^{-1}



What is the main origin of background in the CSC?

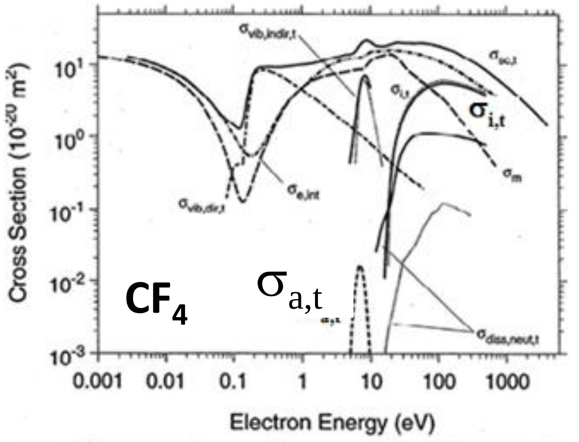
The major source of background radiation in the CMS region away from the beam pipe (R>50cm) comes from neutrons with energies up to few hundred MeV (testing with reactor-n not exhaustive).

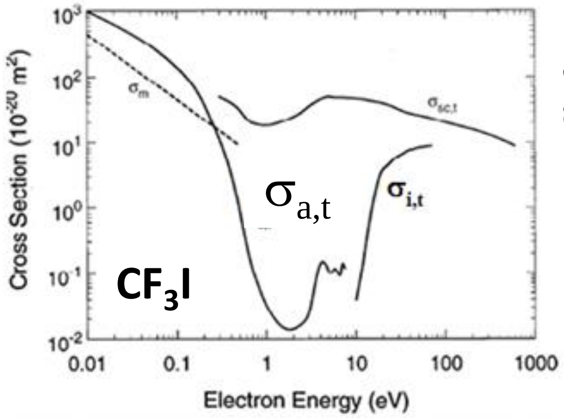
- Background hits in the CSC are mostly generated by Compton electrons produced by 0.1-1 MeV photons irradiated by neutron-capturing nuclei.
- The avalanche total deposited charge is typically 3-4 times larger than that released by minimum ionizing particles (~1pC at the CSC operating voltage of 3.6 KV).

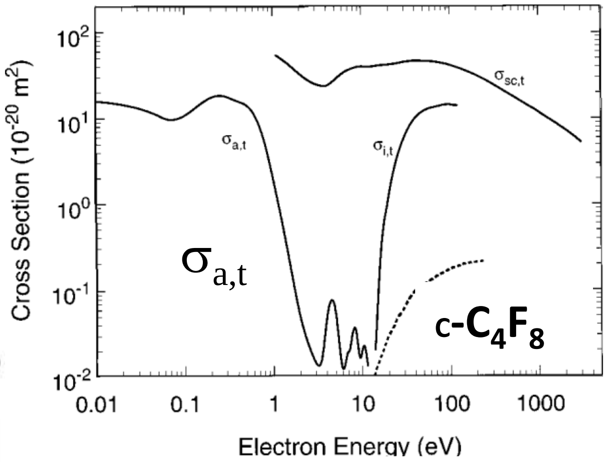
Neutrons (and protons) with energy above 20 MeV are also the major source of malfunctioning (SEU) or incremental damage to electronics components caused by hadronic interactions in the silicon

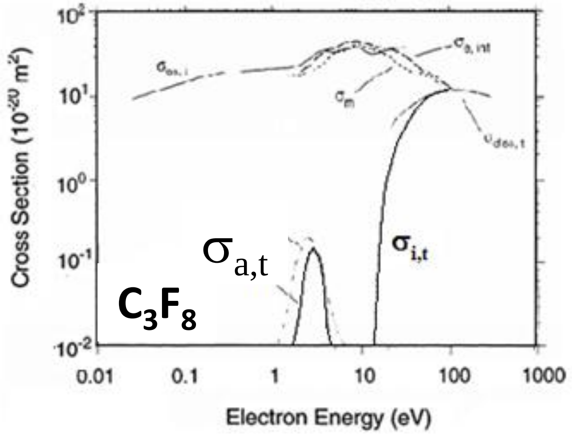
Gas components - candidates for CSC

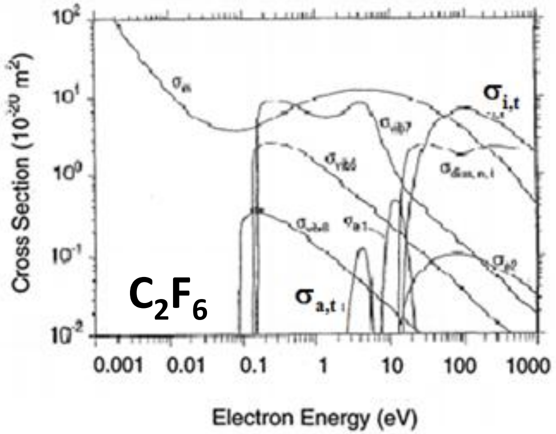
Electron Interactions Cross Section with Plasma Processing Gases











S.R. Hunter , J.G. Carter , L.G. Christophorou ,
Electron motion in the gases CF_4, C_2F_6, C_3F_8, and n-C_4F_{10},
Phys Rev A. 1988 Jul 1; 38(1): 58-69.

From aging point of view:

CF_3I is capable to substitute CF_4 because
$CF_3I + h\nu = {}^\bullet CF_3 + I^-$ ->
Si etching by CF_3I is possible because
the binding energies of C-I (2.4 eV) and C=C (2.8 eV) that is << C-F (5.6 eV)

Daiki Nakayama et al., Highly selective silicon nitride etching to Si and SiO_2 for a gate sidewall spacer using a $CF_3I/O_2/H_2$ neutral beam, Journal of Physics D: Applied Physics

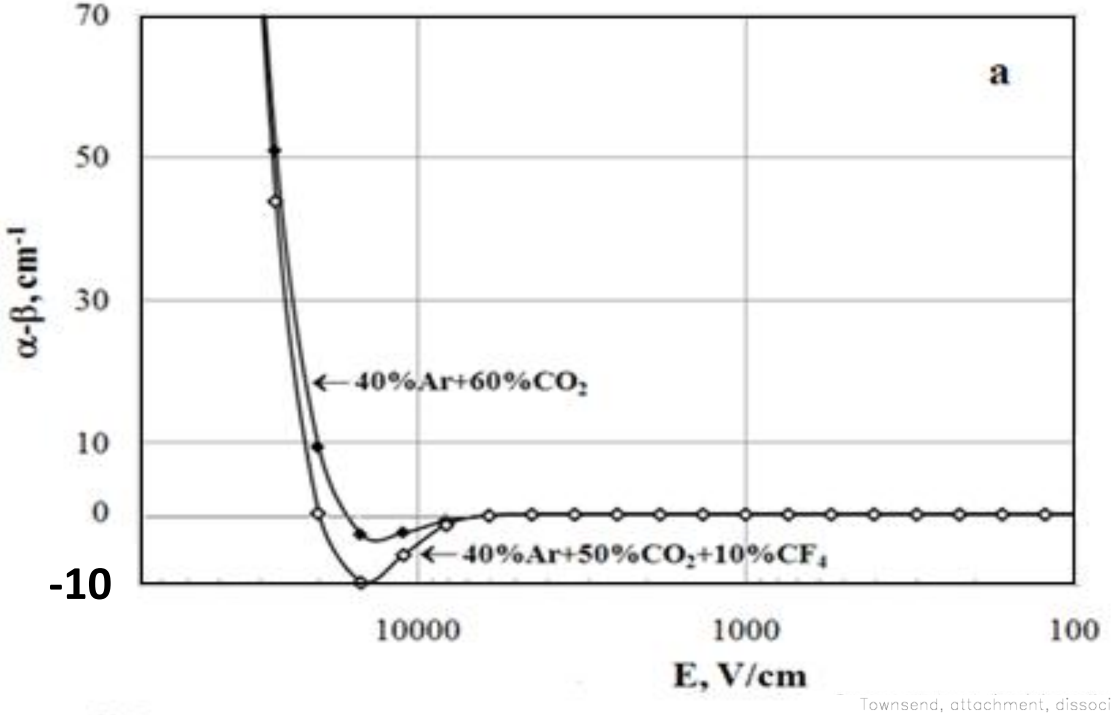
Samukawa, Seiji et al., Environmentally harmonized CF3I plasma for low-damage and highly selective low-k etching, Journal of Applied Physics;Mar2008, Vol. 103 Issue 5, p053310

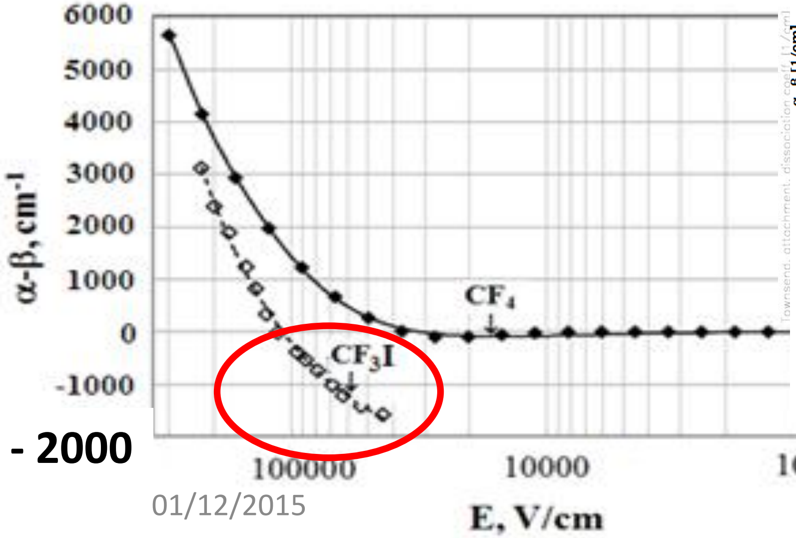
Gas mixture to be studied	-<dE/dx>, Mev·g/cm³	X_o, g/cm²	N_p, cm^{-1}
40%Ar+50%CO_2+10%CF_4	**1.67**	**29.21**	**36.72**
40%Ar+55%CO_2+5%CF_3I	1.667	28.31	45.97
40%Ar+59%CO_2+1%CF_3I	1.67	29.29	36.43
40%Ar+50%CO_2+10%CF_3I	1.64	27.07	57.56

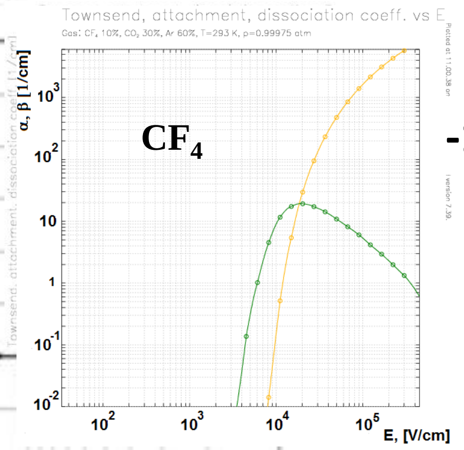
Si etching with CF_3I ➡

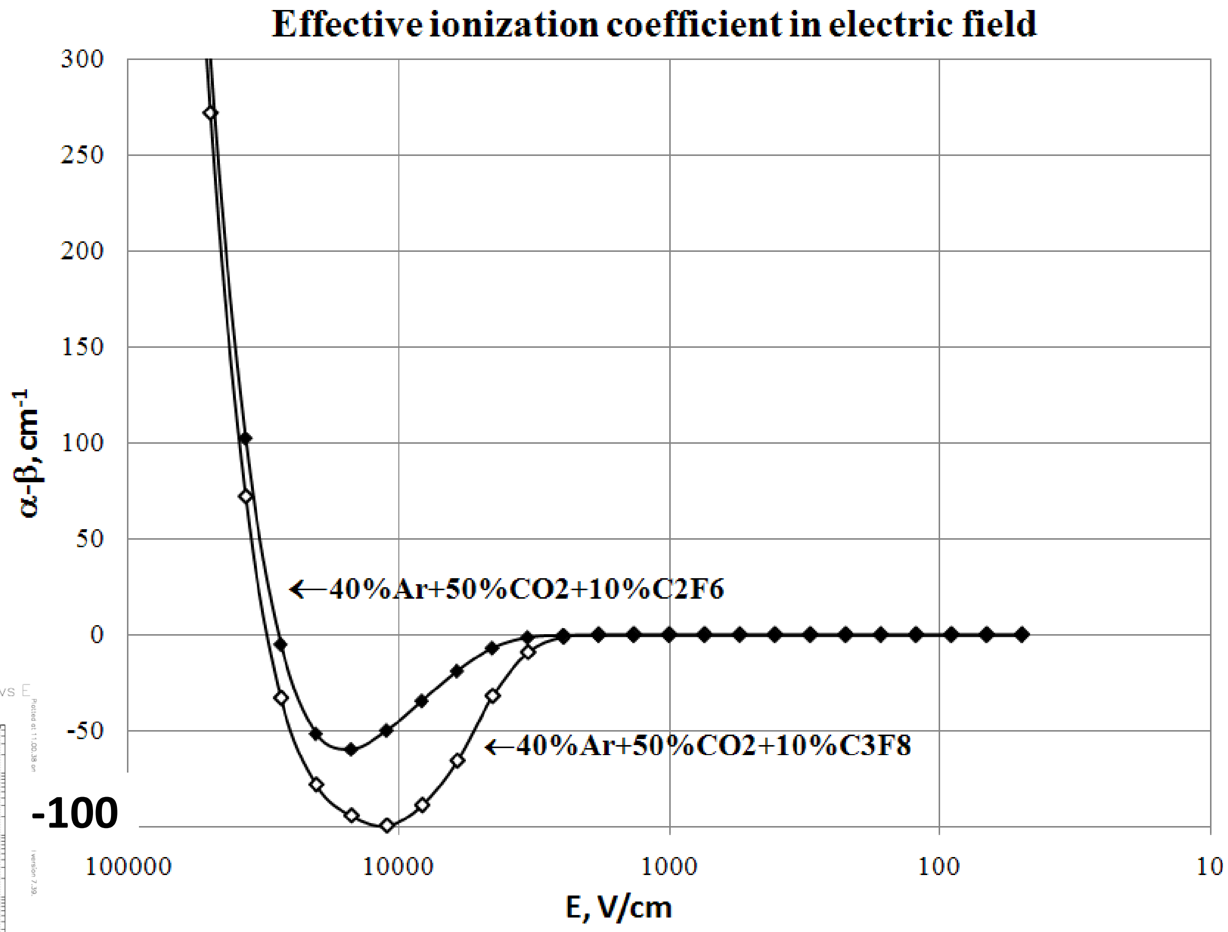
- $\bullet CF_3$(gas) + Si → $\bullet CF_3$(adsorbed) + Si — chemical adsorption
- $\bullet CF_3$(adsorbed) + Si → C(adsorbed) + 3F(adsorbed) + Si — dissociation
- 4F(adsorbed) + Si → SiF_4(adsorbed) — chemical reaction
- SiF_4(adsorbed) → SiF_4(gas) — desorption
- C(adsorbed) + 4F(adsorbed) → CF_4(gas)

GARFIELD simulation of (α–β) – effective ionization and data from publications









Attachment for electrons E ~ 0.01–0.5 eV in CF3I is 200 high than in CF4

Gas components - candidates for CSC

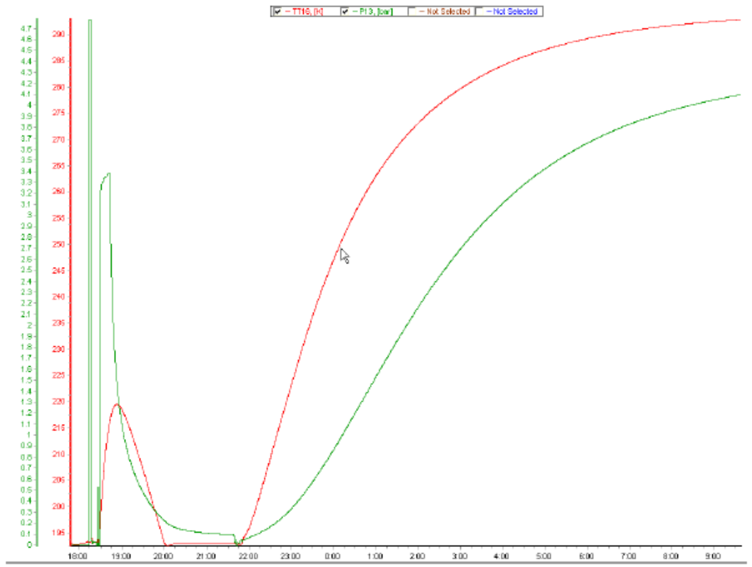
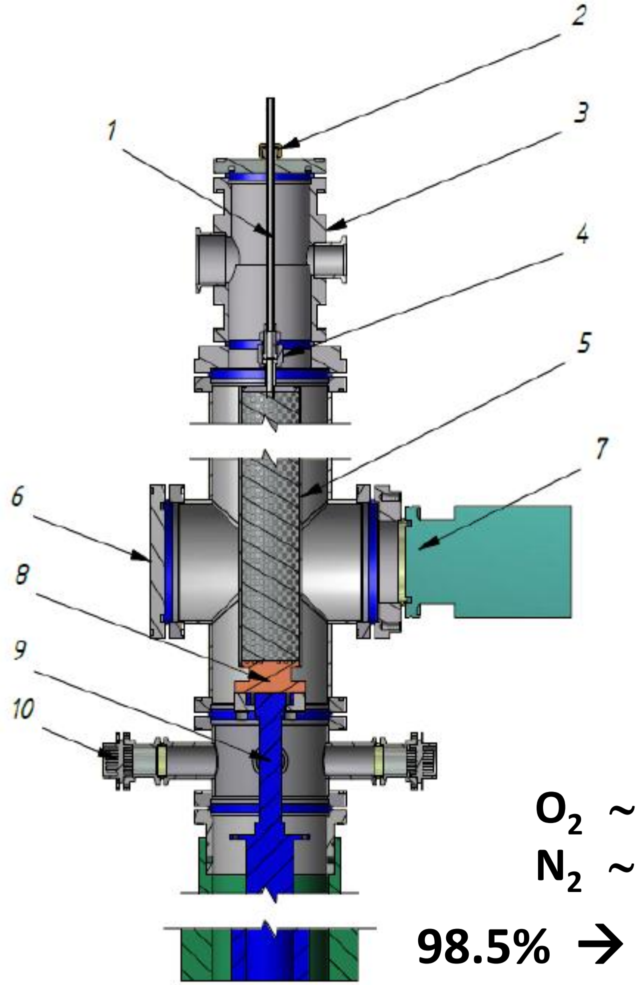


Рис. 4: Графики температуры и давления в системе в процессе очистки. Красный цвет   температура, зеленый   давление

Properties	
Chemical formula	CF_3I
Molar mass	195.91 g/mol
	Colorless odorless gas
Density	2.5485 g/cm^3 at -78.5 °C 2.3608 g/cm^3 at -32.5 °C
Melting point	−110 °C (−166 °F; 163 K)
Boiling point	−22.5 °C (−8.5 °F; 250.7 K)
Solubility in water	Slightly
Vapor pressure	541 kPa



O_2 ~ 0.16%
N_2 ~ 0.74%

98.5% → 99.99%

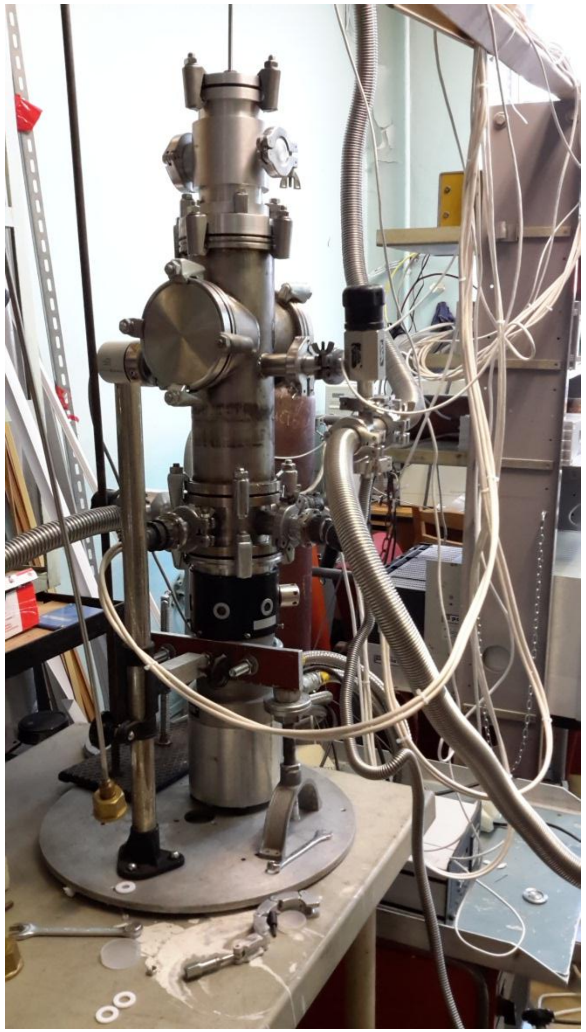
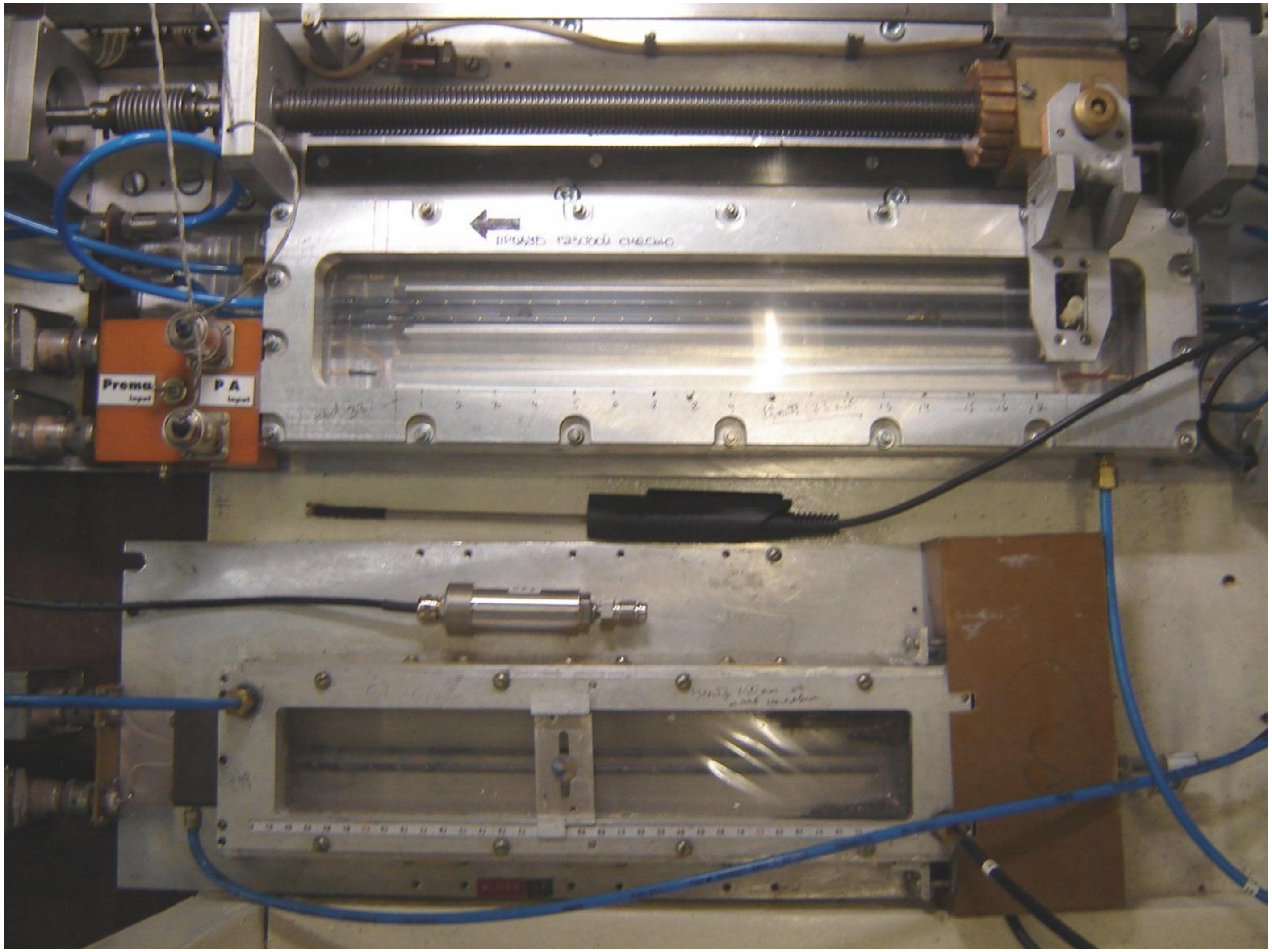


Рис. 2: Схема установки. Внешняя коммутация газовых линий и ряд подробностей опущены. 1) газовая трубка; 2) скользящее уплотнение 3) верхний вакуумный адаптер; 4) криогенное разъемное соединение 5) снабженная внутренней медной сеткой конденсационная ячейка 6) основной вакуумный объем; 7) турбомолекулярный насос; 8) тепловой мост, снабженный нагревателем; 9) головка криогенератора 10) сигнальный разъем

Gas mixtures straw-test set up



Two identical blocks with 2 straws:

1. Test block (top) is irradiated by Sr^{90} with rate 15 MHz per 3.5 cm spot
2. Gas gain monitoring with ^{55}Fe γ-source, $E\gamma$=6 keV
3. Control block (bottom) is not irradiated and used for compensation of the air pressure and temperature influence

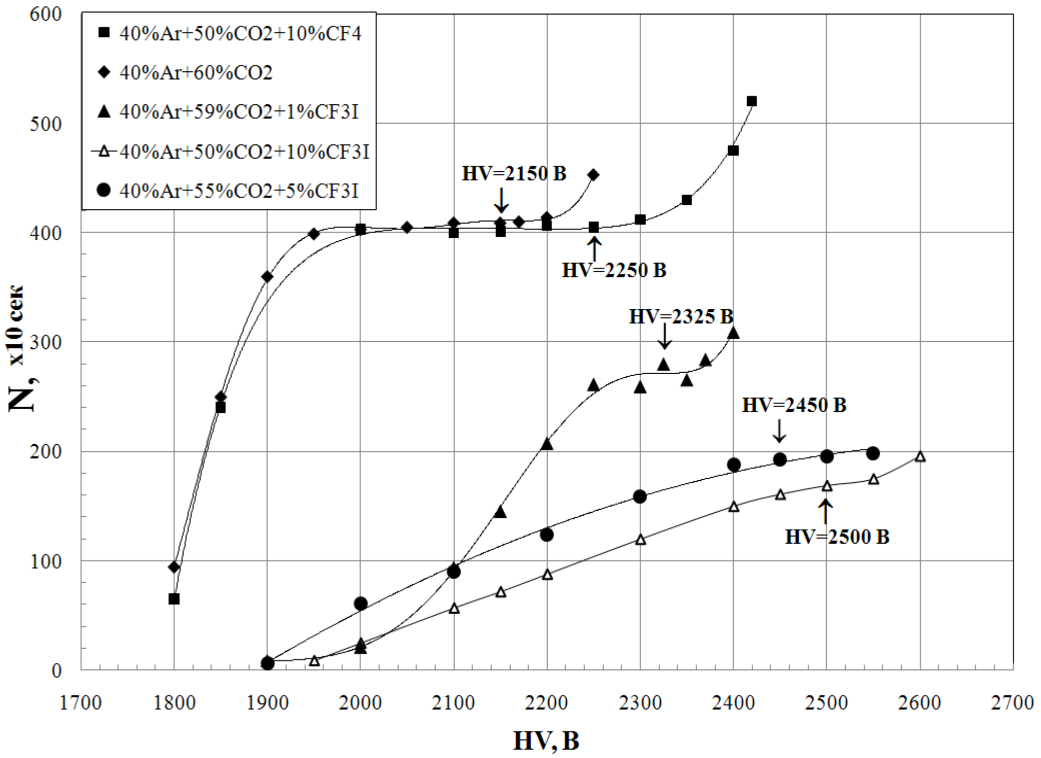
$$\frac{\Delta G}{G} = k\left(\frac{\Delta P}{P} - \frac{\Delta T}{T}\right)$$

- **50 μm W anode wire, 5% weight of Au coating**
- **4 mm straw diameter, 38 mm length**
- **72 μm thickness of the kapton made cathode wall**

Both aging tests and gas mixtures study are available

Gas mixtures straw-test

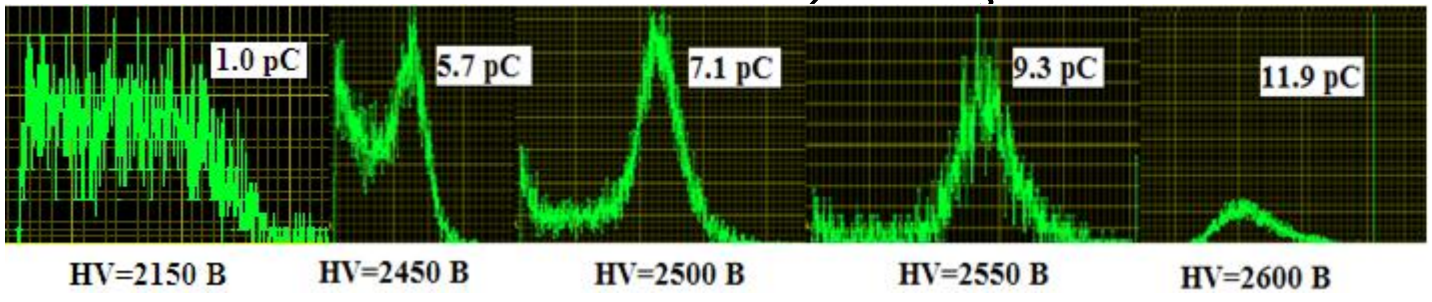
Счетные характеристики от ^{55}Fe



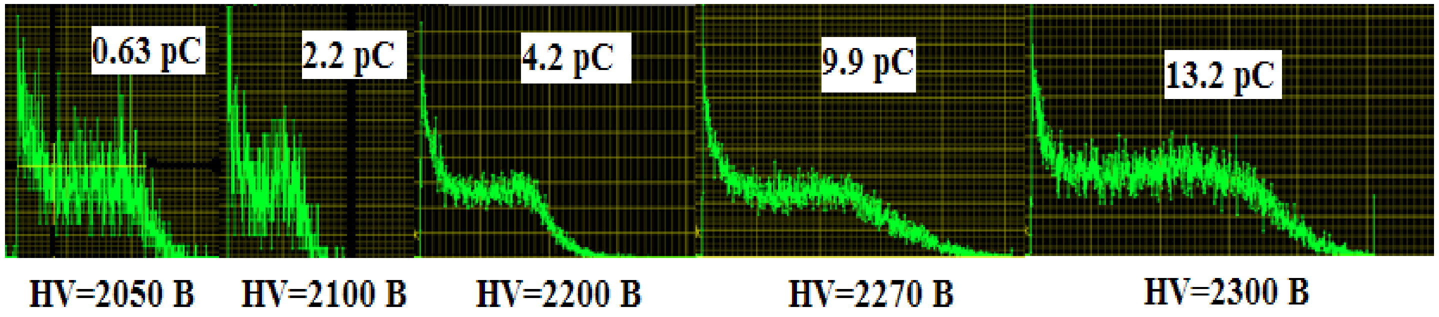
Count rates plateau appears at Limited Streamer mode Q>> 2pC

Амплитудные спектры

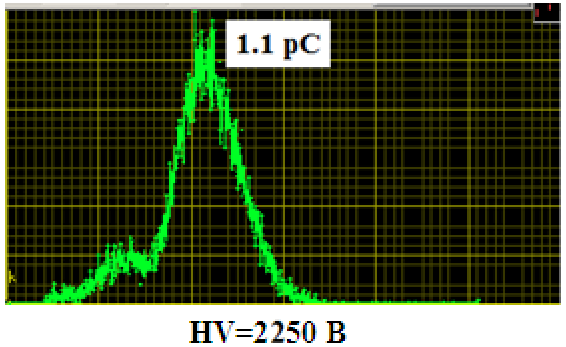
$40\%Ar+50\%CO_2+10\%CF_3I$

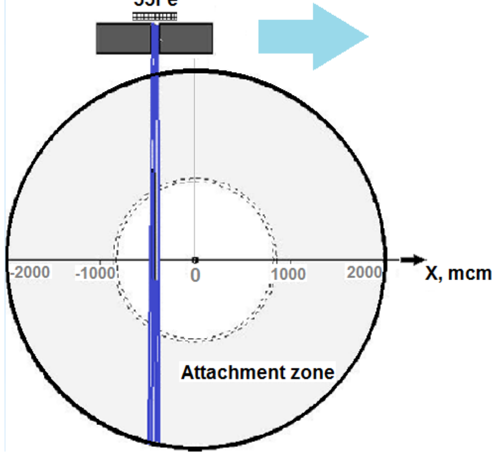


$40\%Ar+59\%CO_2+1\%CF_3I$

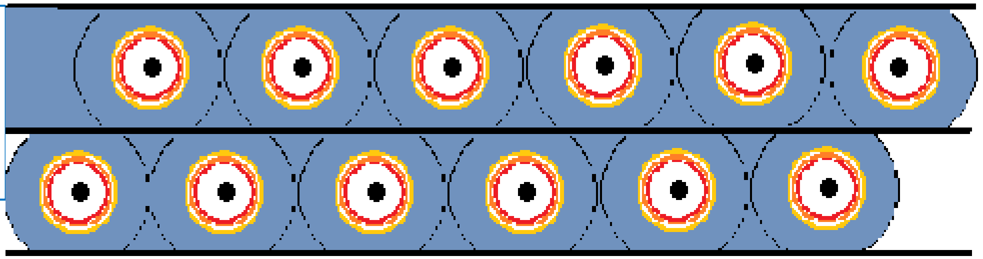


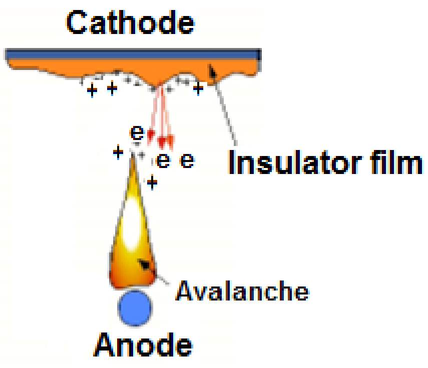
$40\%Ar+50\%CO_2+10\%CF_4$



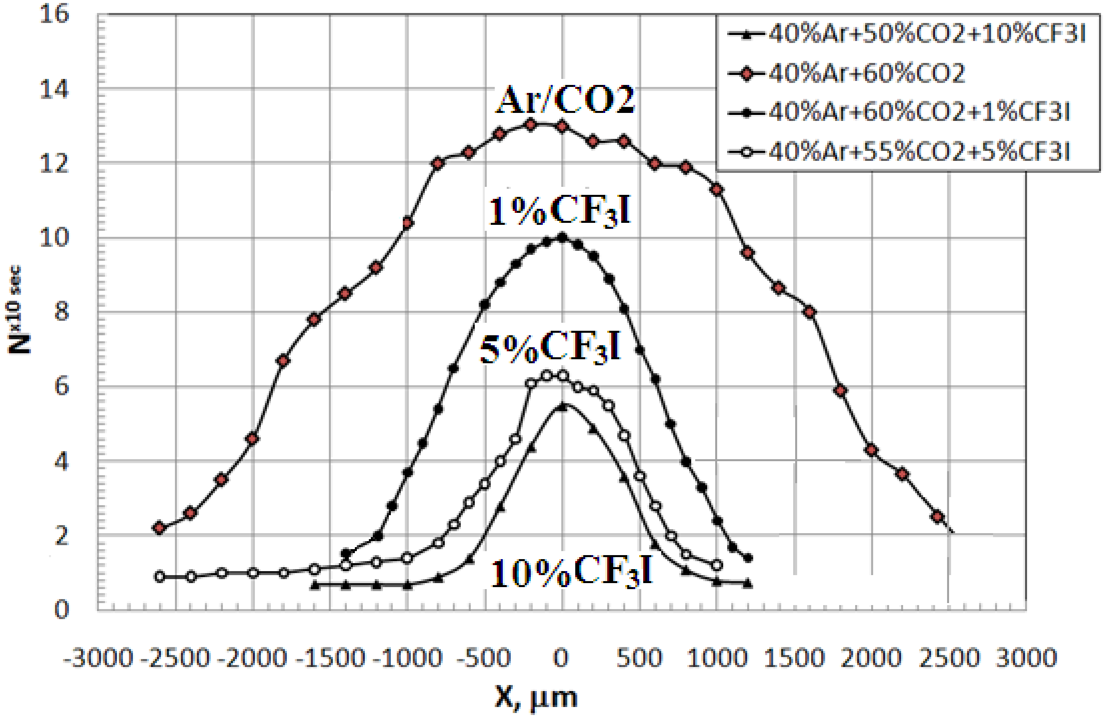


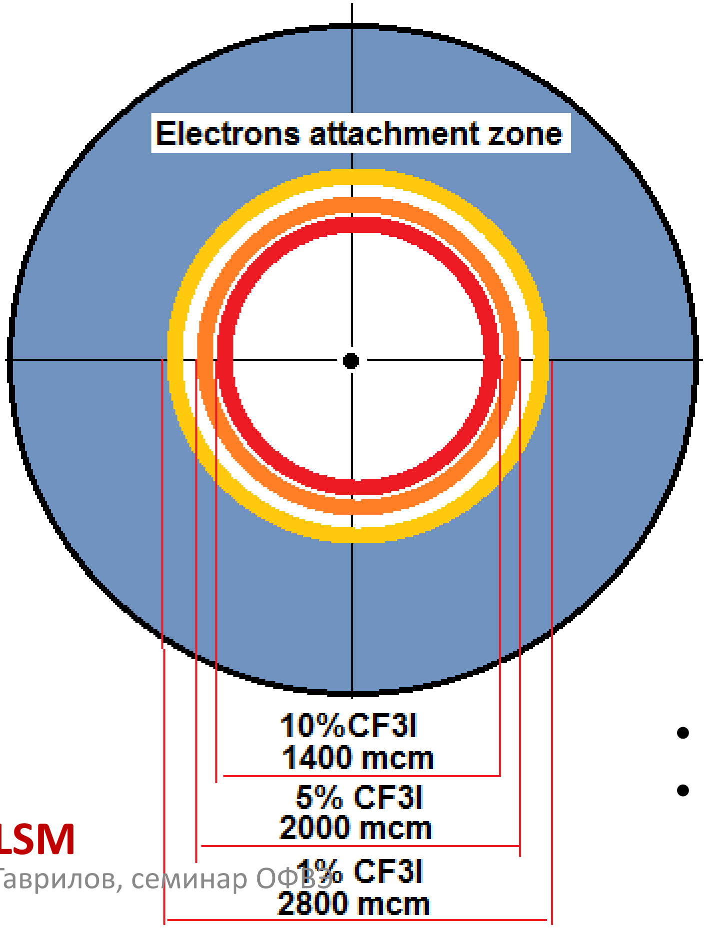
with high angle selectivity, operating in Limited Streamer Mode

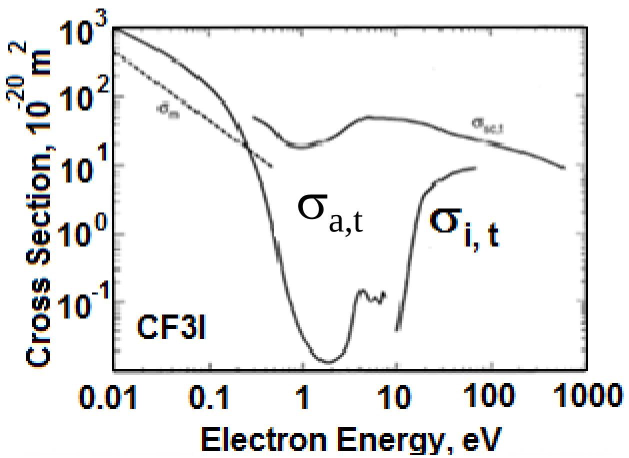




^{55}Fe count rates across straw



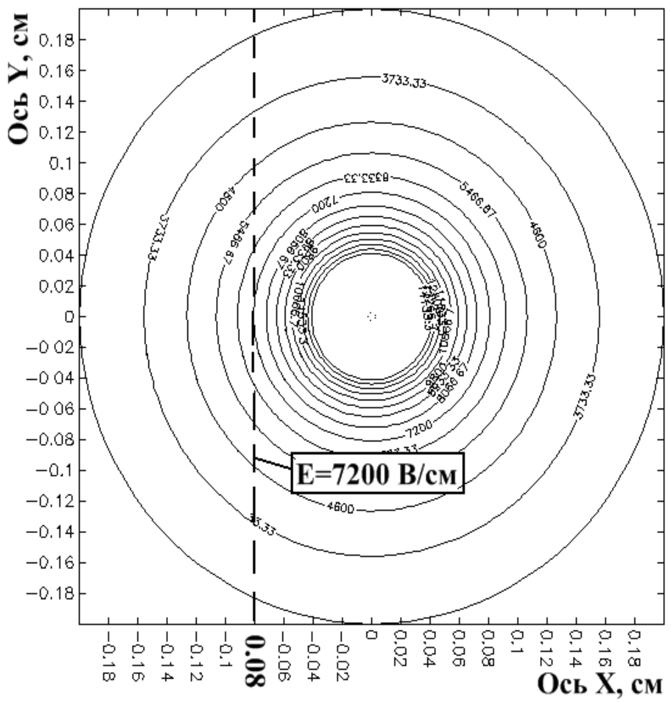


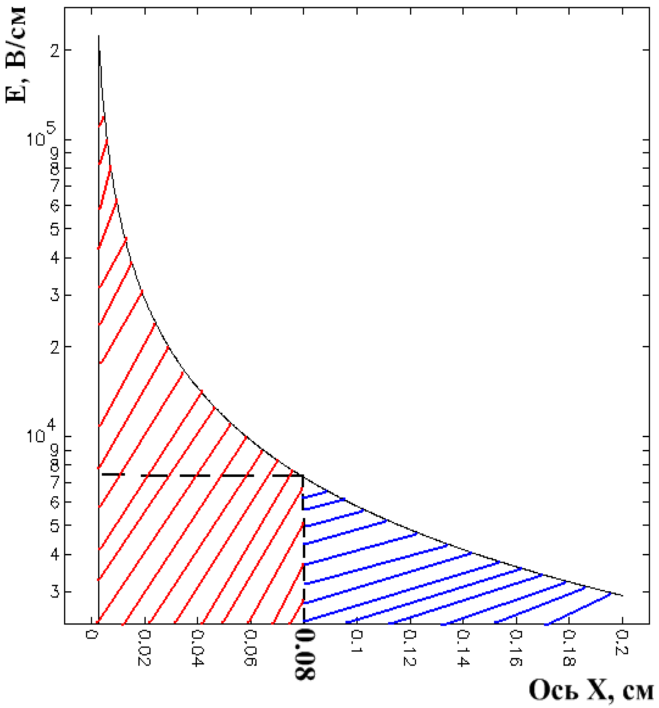


- Malter aging safe detector
- High signal amplitude due to LSM
- High angle resolution

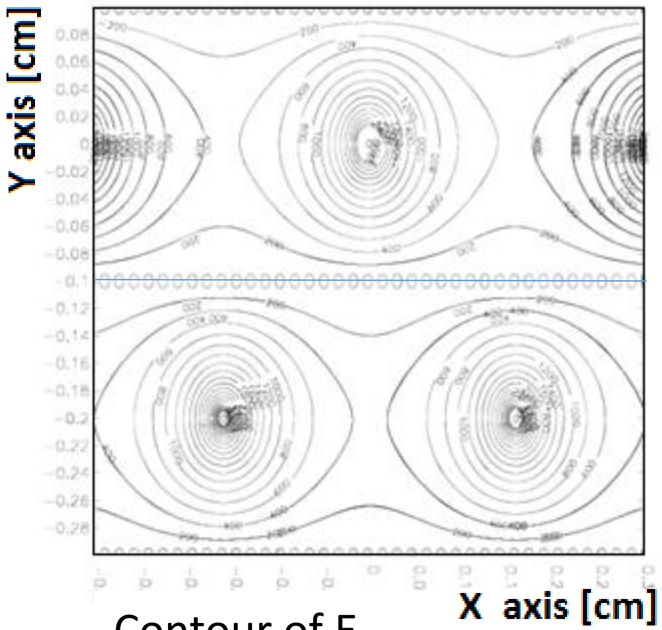
- Low efficiency
- Small efficiency plateau

Probable detector structure

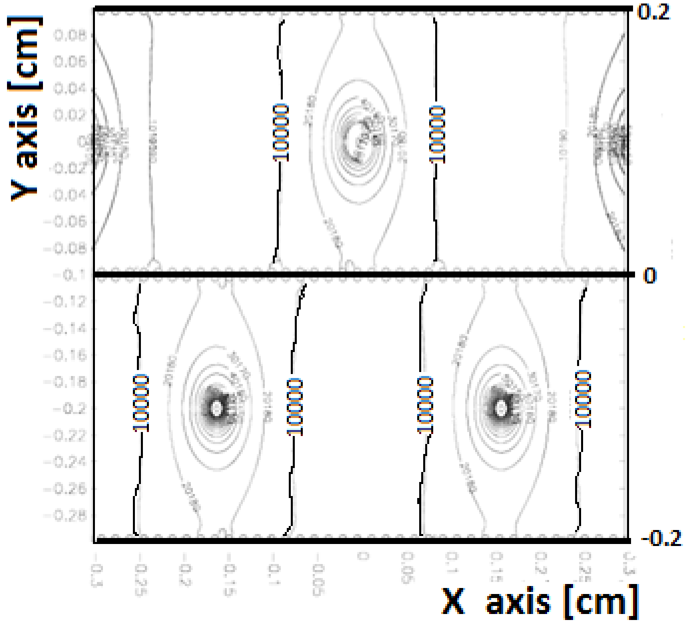




Contour of V



Contour of E



Working gas mixtures with CF3I

PRO - CONS	
10 times high pulses amplitude good for operation at high background	Not good for CSC because of low efficiency
Safe from Malter aging effect, because insensitive to cathode electrons emmision	Short efficiency plateau ~ 100 V
Limited amplification zone in vicinity of the anode wire implies good space resolution	

Outlook

- CF3I concentration < 0.1% with adding methane (to increase plateau) have to be studied
- Searching for new gas components have to be continued

II. CF_3I gas mixtures study with CSC prototype

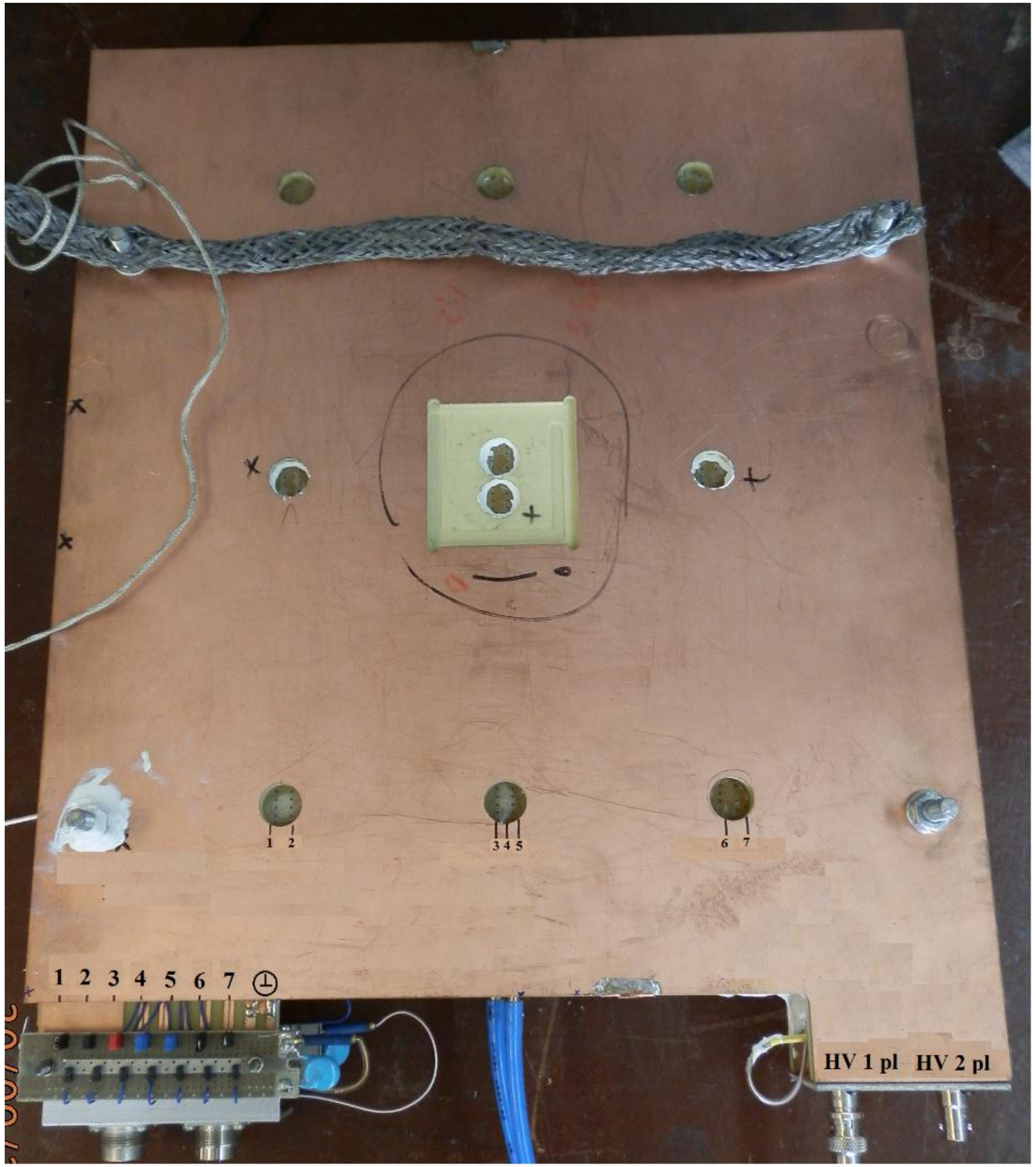
- **2 planes with 7 controlled anode wires in each one**
- **50 μm gold-coated anode wire**
- **300 x 300 mm² sensitive area**
- **S = 3 mm**
- **L = 4.5 mm**
- **Identical geometry, construction materials to CSC**

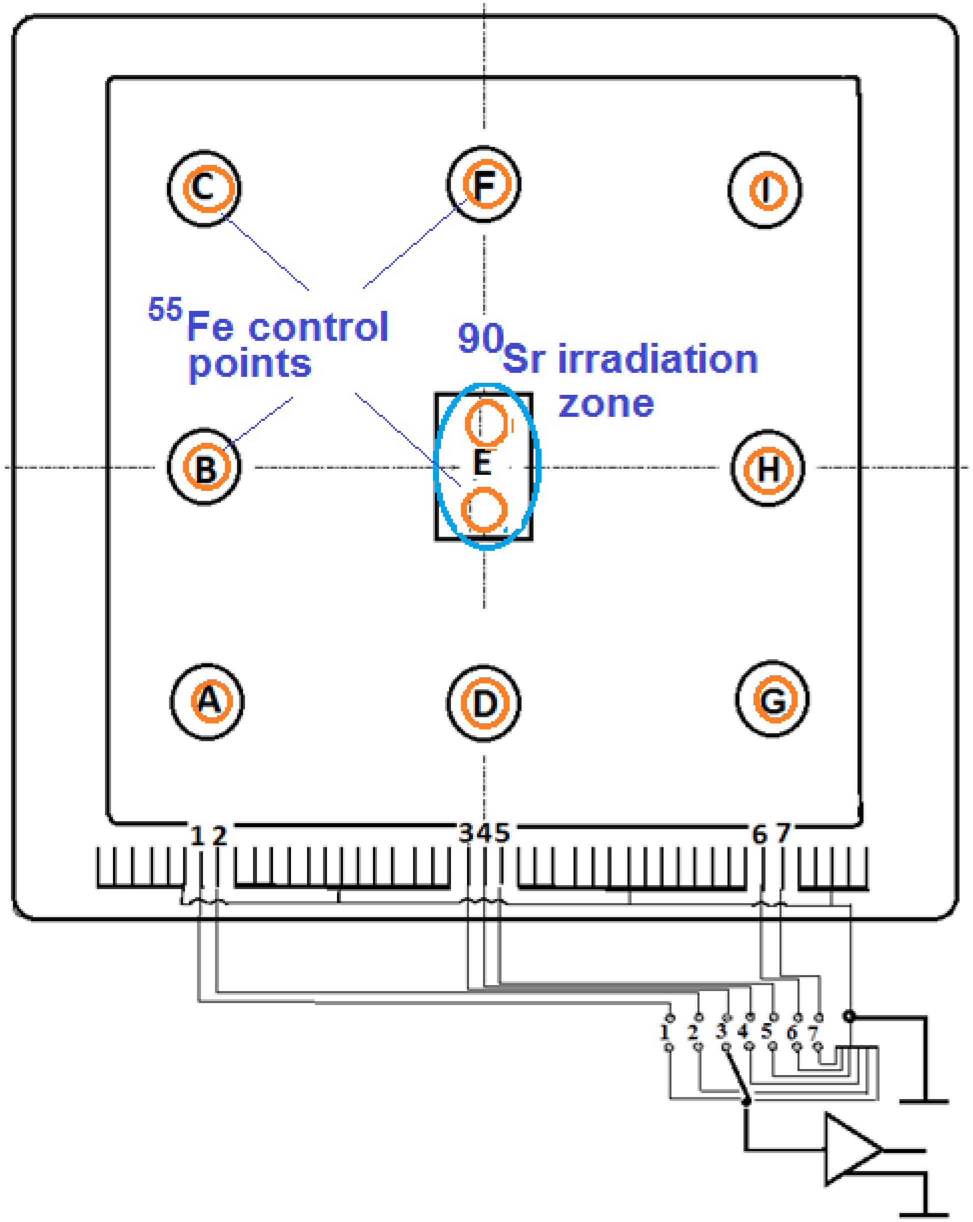
BUT

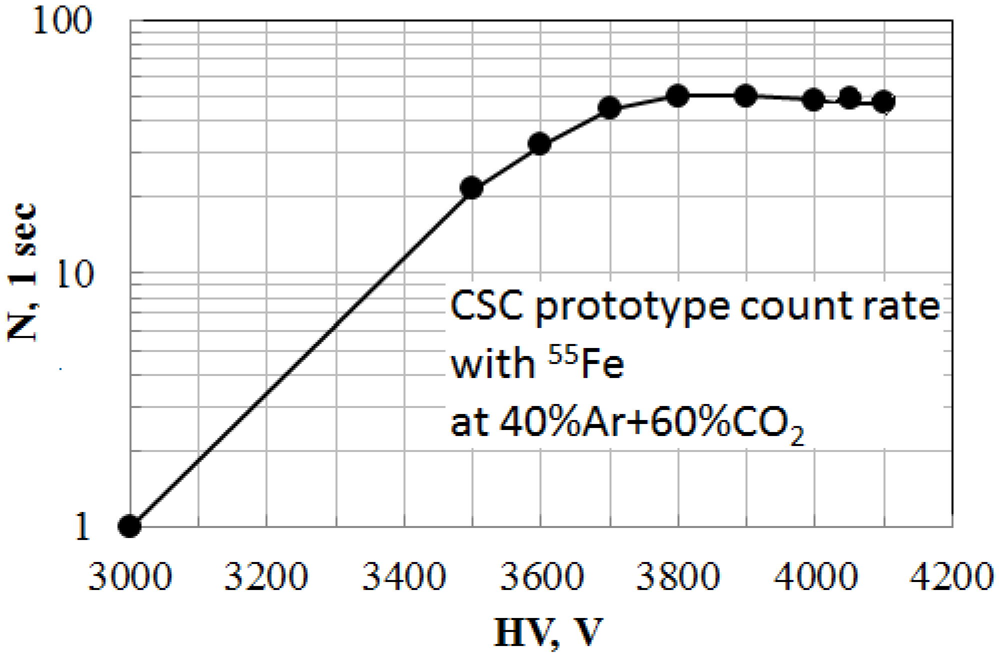
*** No strips, readout from anode wires only**

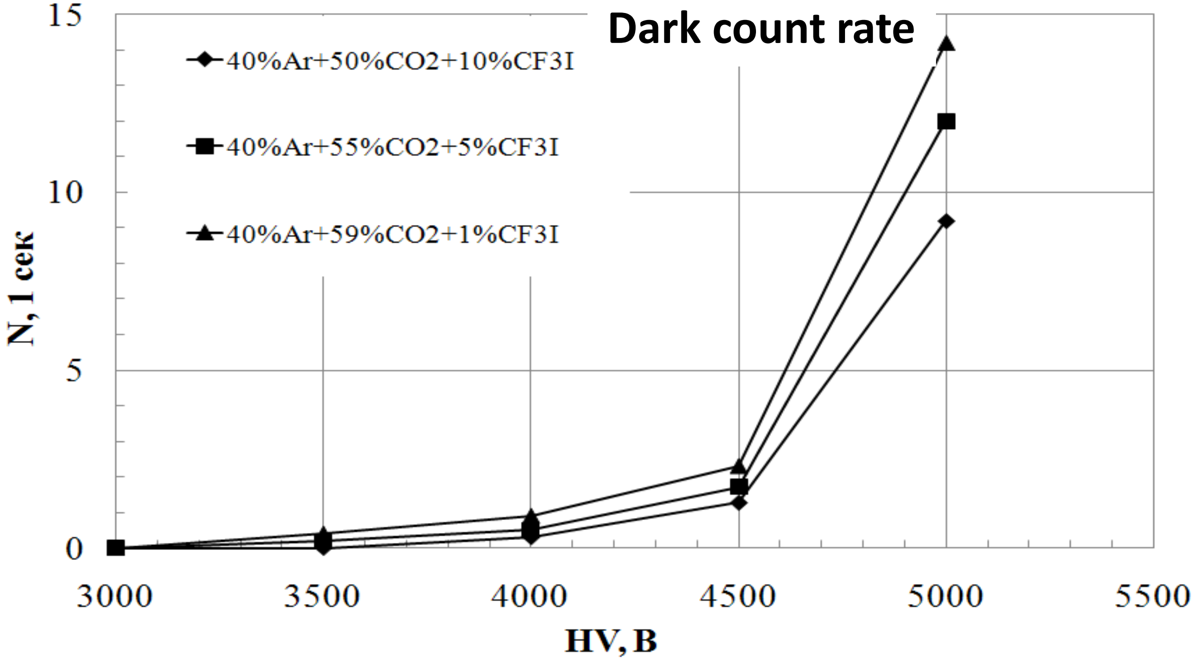
*** - HV applied to the cathode**

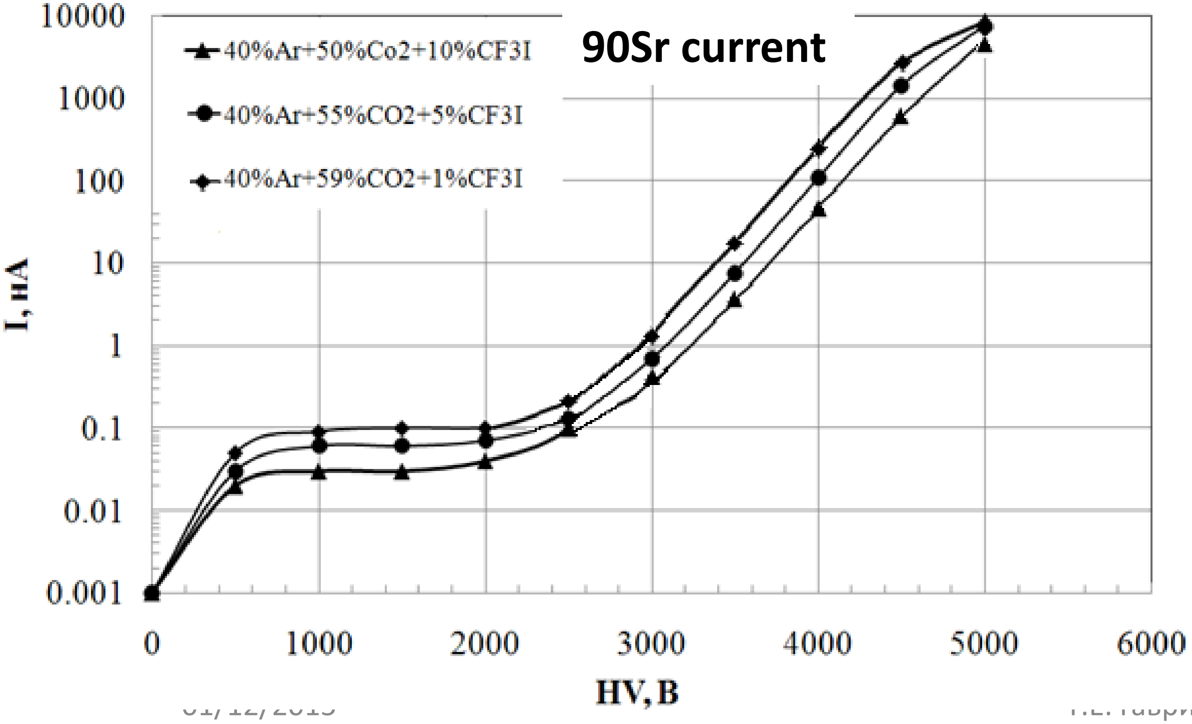
CSC test prototype at ATS in PNPI

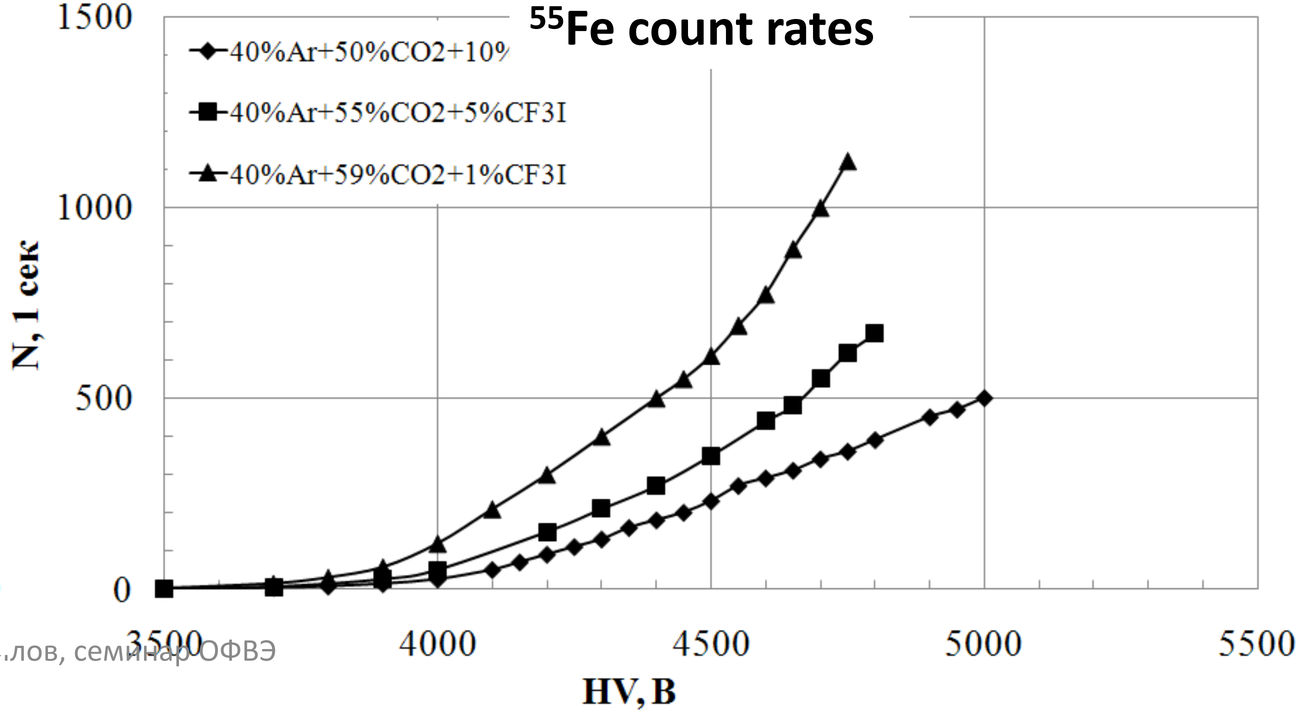





CSC prototype count rate
with ^{55}Fe
at 40%Ar+60%CO_2
N, 1 sec
HV, V
100
10
1
3000
3200
3400
3600
3800
4000
4200

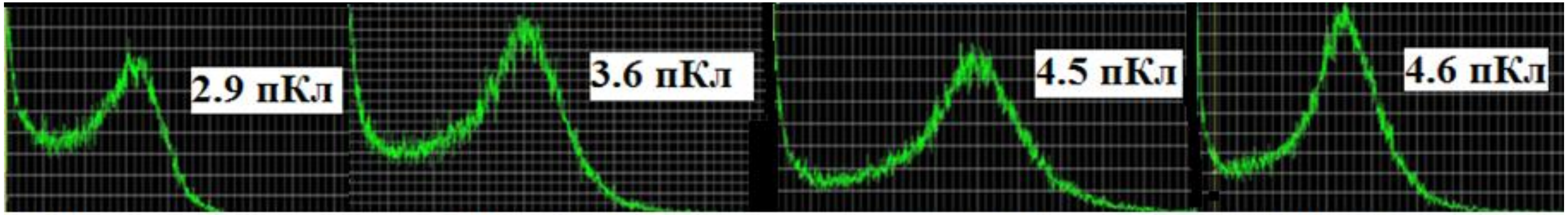

Dark count rate
40%Ar+50%CO2+10%CF3I
40%Ar+55%CO2+5%CF3I
40%Ar+59%CO2+1%CF3I
N, 1 сек
HV, B
15
10
5
0
3000
3500
4000
4500
5000
5500


90Sr current
40%Ar+50%Co2+10%CF3I
40%Ar+55%CO2+5%CF3I
40%Ar+59%CO2+1%CF3I
I, нА
HV, B
10000
1000
100
10
1
0.1
0.01
0.001
0
1000
2000
3000
4000
5000
6000


^{55}Fe count rates
40%Ar+50%CO2+10%
40%Ar+55%CO2+5%CF3I
40%Ar+59%CO2+1%CF3I
N, 1 сек
HV, B
1500
1000
500
0
3500
4000
4500
5000
5500

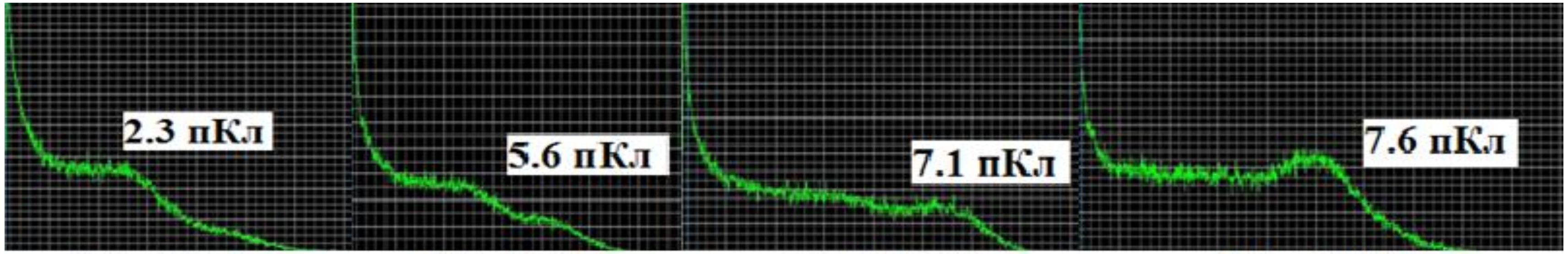
Амплитудные спектры от источника рентгеновских фотонов ^{55}Fe

$40\%Ar+50\%CO_2+10\%CF_3I$



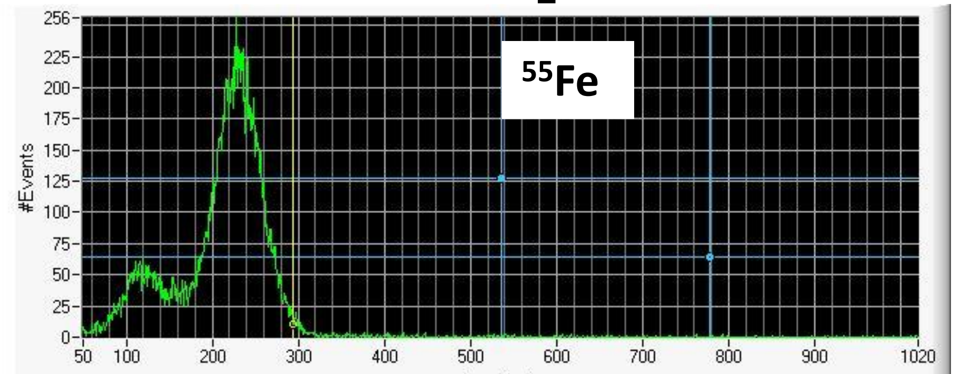
HV=4800 В HV=4850 В HV=4900 В HV=4950 В

$40\%Ar+59\%CO_2+1\%CF_3I$

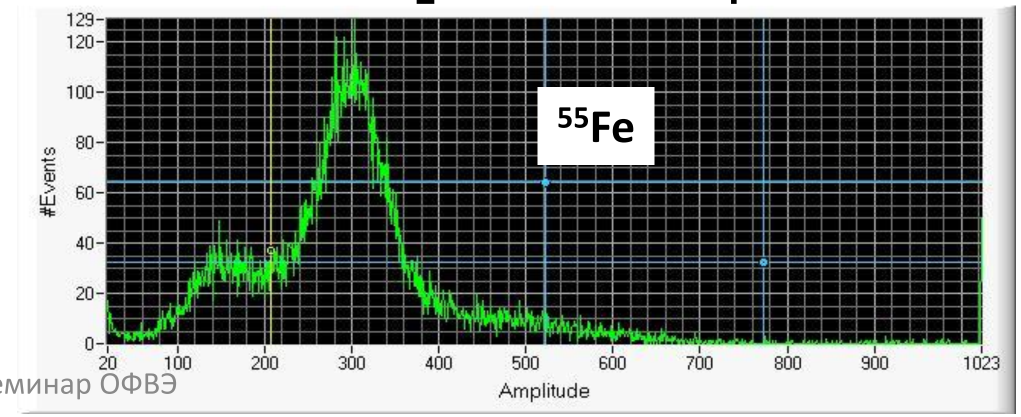


HV=4550 В HV=4600 В HV=4650 В HV=4700 В

$40\%Ar+60\%CO_2$, HV=3650 В



$40\%Ar+50\%CO_2$ +10% CF_4 , HV=4100 В



Возможный кандидат $C(CH_3)_4$ - n - пентан

GWP $_{C(CH3)4}$ **< 15 за 100 лет**

Пентаны — насыщенные ациклические углеводороды класса алканов. Имеют пять атомов углерода в молекуле. Изопентан обладает наркотическим действием. Класс опасности четвёртый

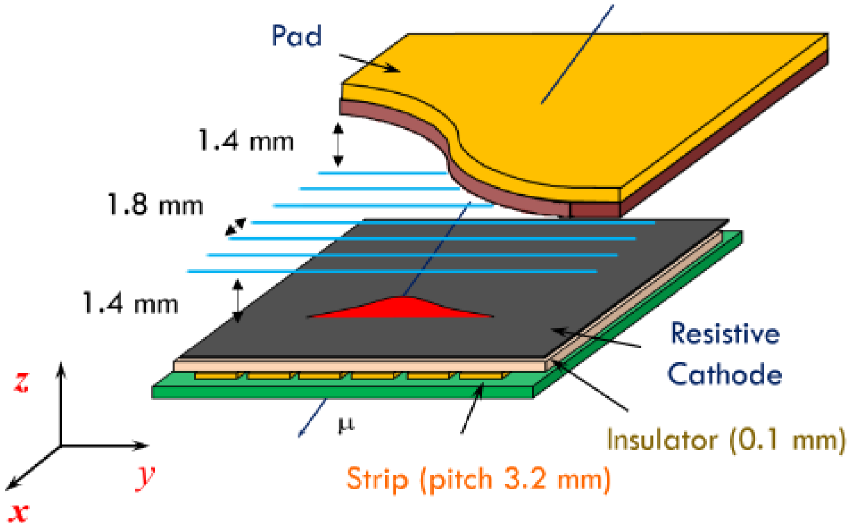
Формула: C_5H_{12}
Температура кипения: 36,1°C
Название ИЮПАК: Pentane
Плотность: 626,00 кг/м^3
Молярная масса: 72,15 г/моль
Температура плавления: -129,8°C
Классификация: Алканы

ATLAS NOTE

June 22, 2015

Simulation Studies of Characteristics and Performance of small-strip, Thin Gap Chambers for the ATLAS New Small Wheel Muon Detector Upgrade

J. Chapman[a], T. Dai[a], E. Diehl[a], H.Feng[a], L. Guan[b,a,*], G. Mikenberg[c], V. Smakhtin[c], J. Yu[a], B. Zhou[a], J. Zhu[a], Z. Zhao[b]



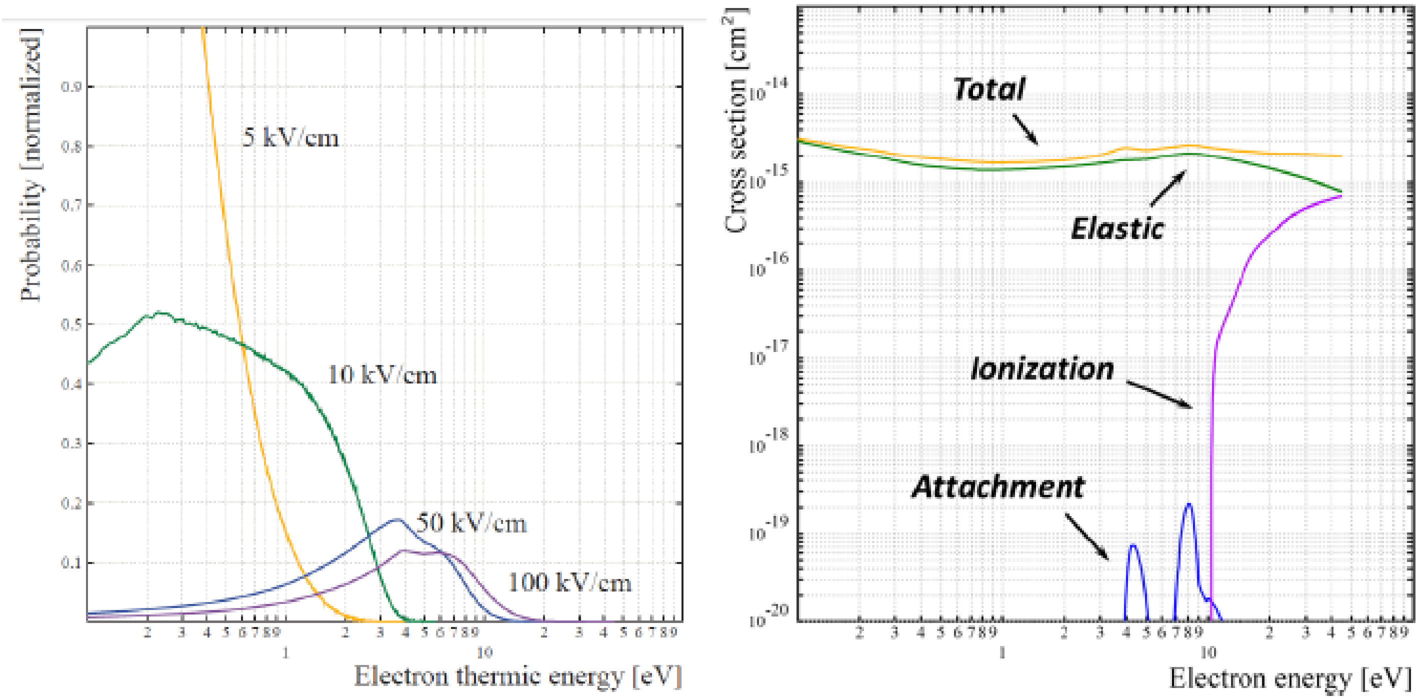


Figure 5: Electron thermal energy distributions in an electric field (a) and various cross-sections for electrons interacting with gas molecules in a CO_2:n-pentane (55:45) mixture (b).

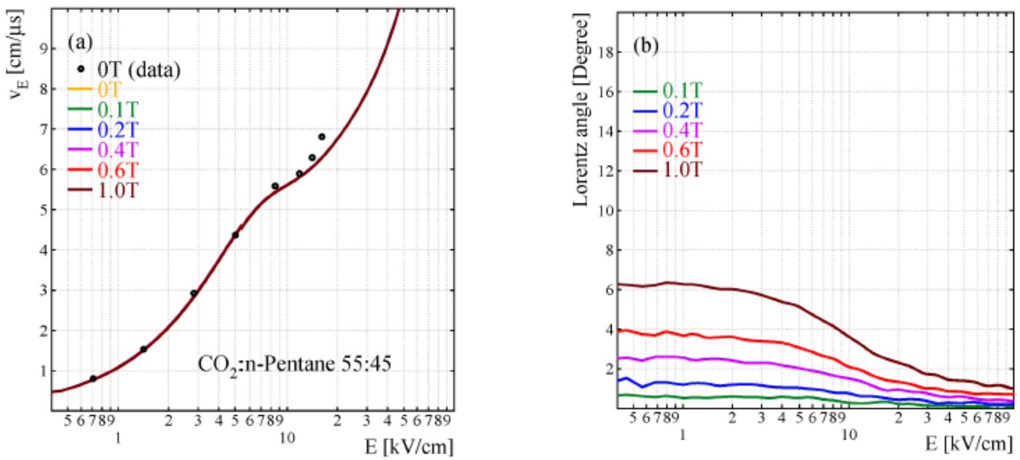
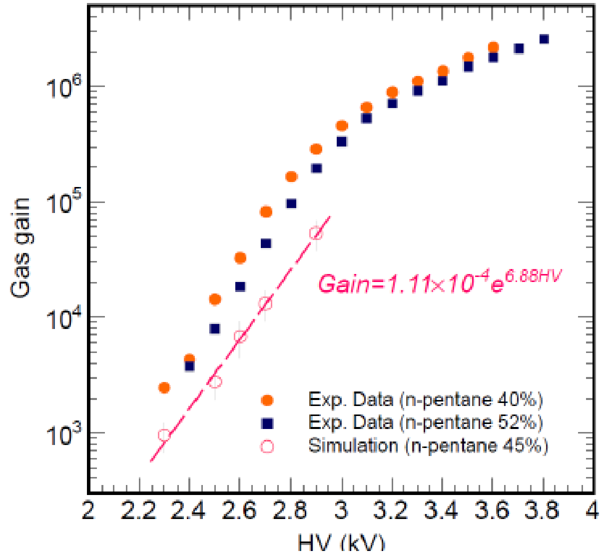
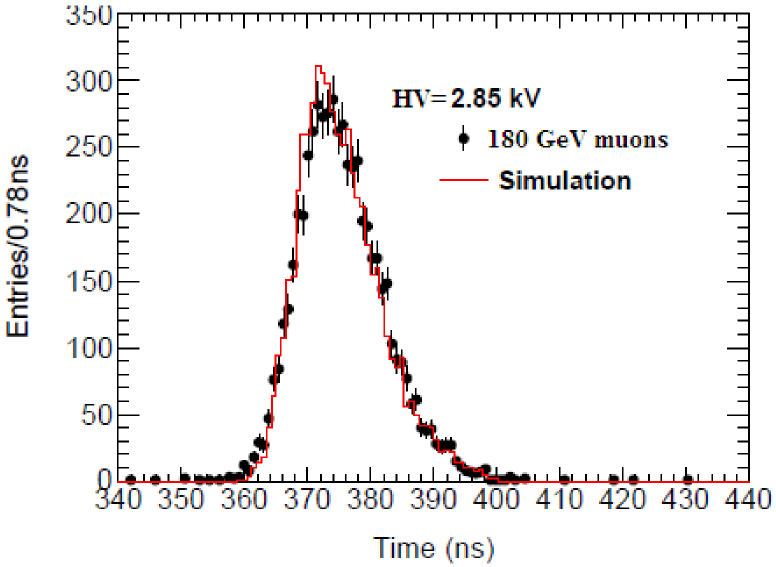


Figure 8: The electron drift velocity (a) and Lorentz angle (b) as a function of the electric field in CO_2:n-pentane (55:45) for several values of an orthogonal magnetic field.

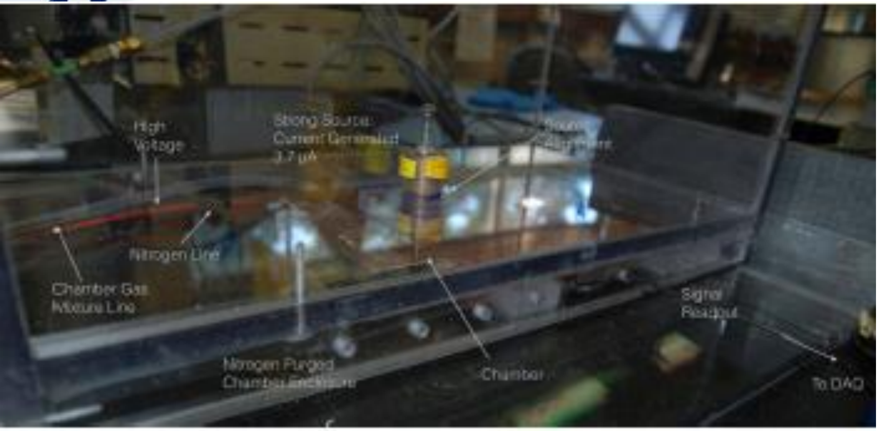


Gas gain as a function of the high voltage.

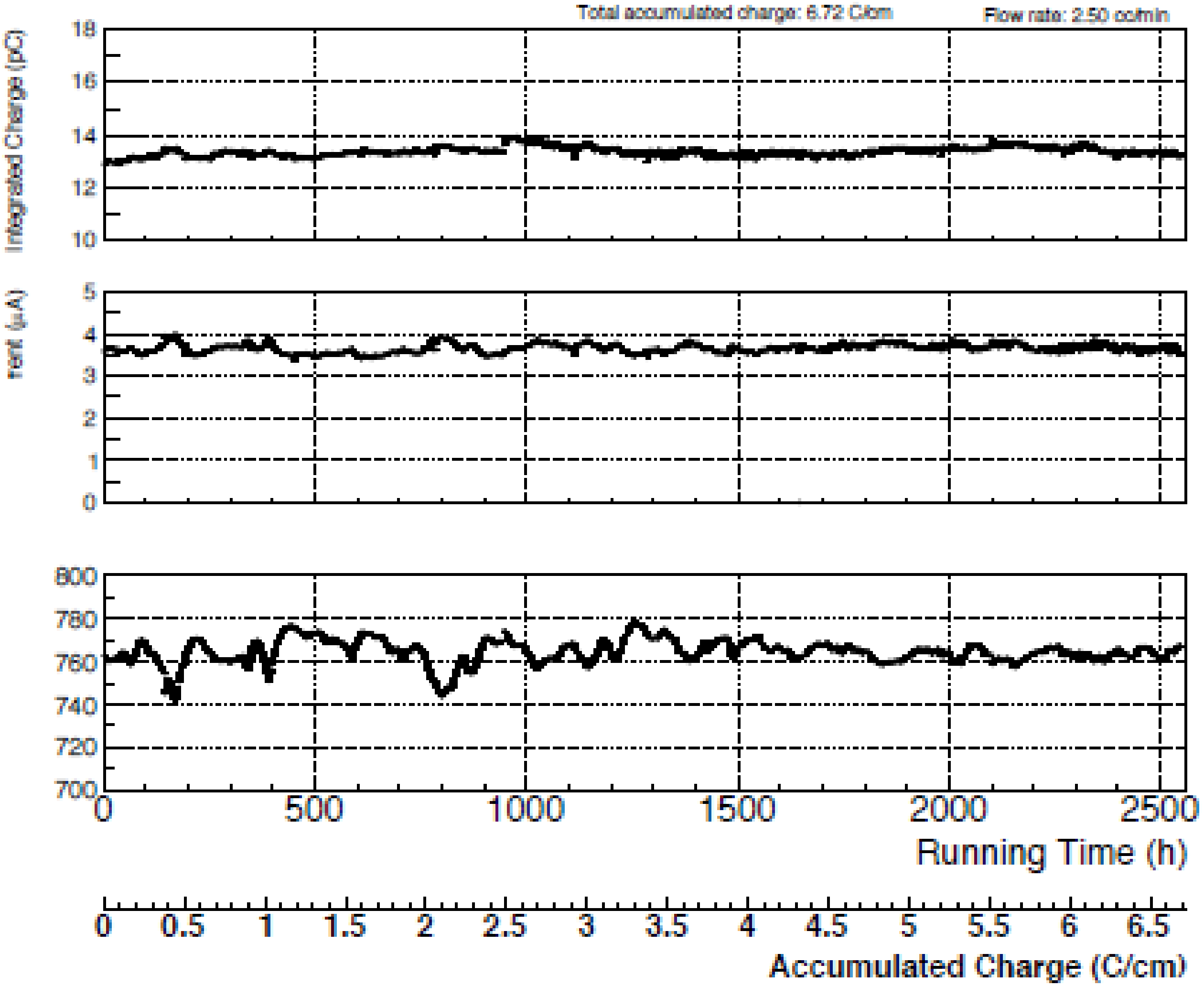


Ageing studies on small Thin Gap Chambers for the New Small Wheel

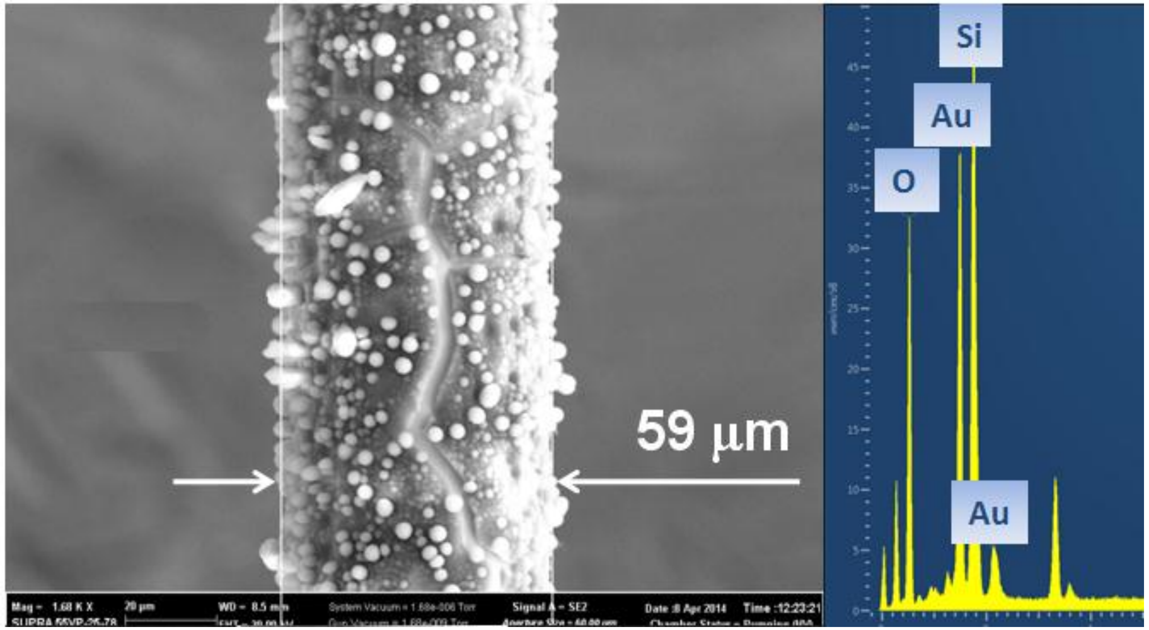
A prototype sTGC chambers measuring 10 cm x 20 cm was used to test the signal quality after *a total accumulated charge of 10 C/cm²*. This is an equivalent radiation dose to that of 150 LHC years.

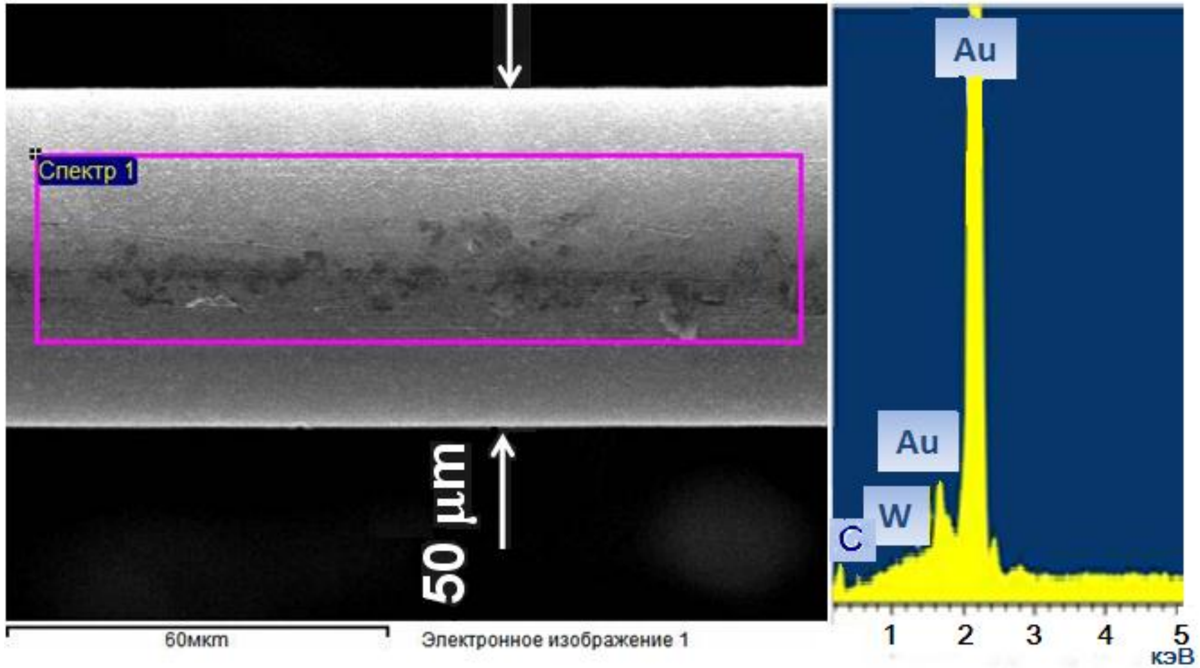


	First 100 hours	Last 100 hours
Flow rate: 2.5 cc/min		
Integrated charge [pC]	13.02 ± 0.82	13.30 ± 0.82
Pressure [Torr]	763	762
Temperature [C]	22	24
Flow rate: 5.0 cc/min		
Integrated charge [pC]	14.70 ± 0.82	14.01 ± 0.82
Pressure [Torr]	762	759
Temperature [C]	26	24
Flow rate: 10.0 cc/min		
Integrated charge [pC]	12.63 ± 0.82	13.11 ± 0.82
Pressure [Torr]	766	765
Temperature [C]	22	25



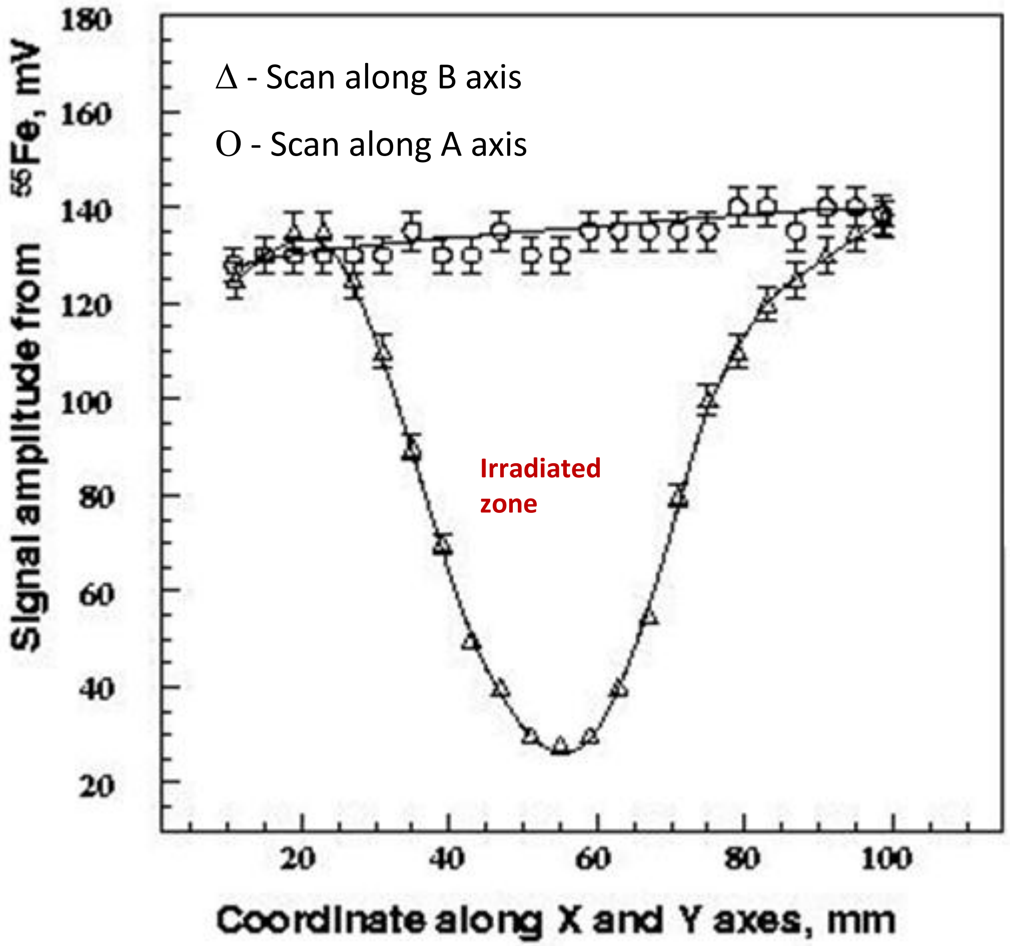
III. Si aging recovering method

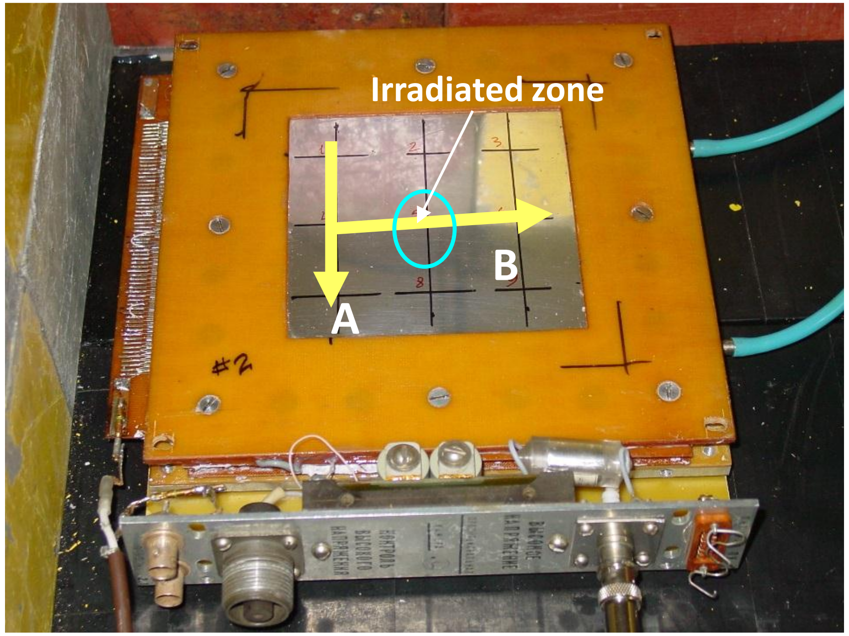




Magnet Chambers (HERMES, DESY) ageing studies

First recovering experience with 80%CF4+20%CO2



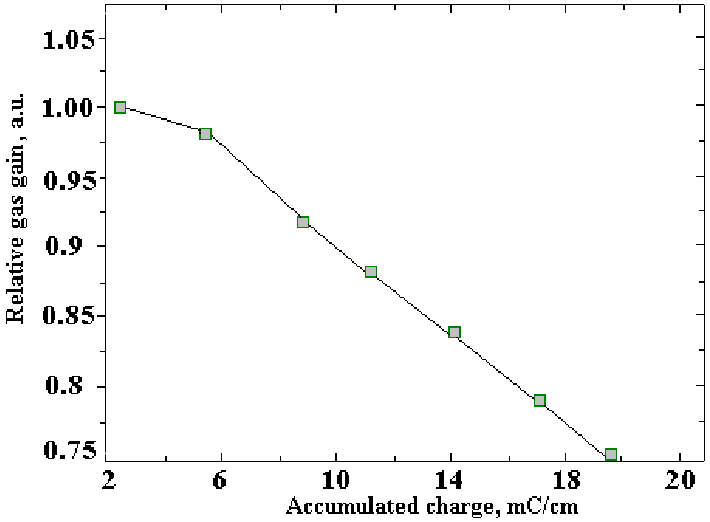


- Gas gain in the irradiated zone drops 4 times at Q_{anode}= 32 mC/cm
- Out of the irradiated zone the gas gain is constant

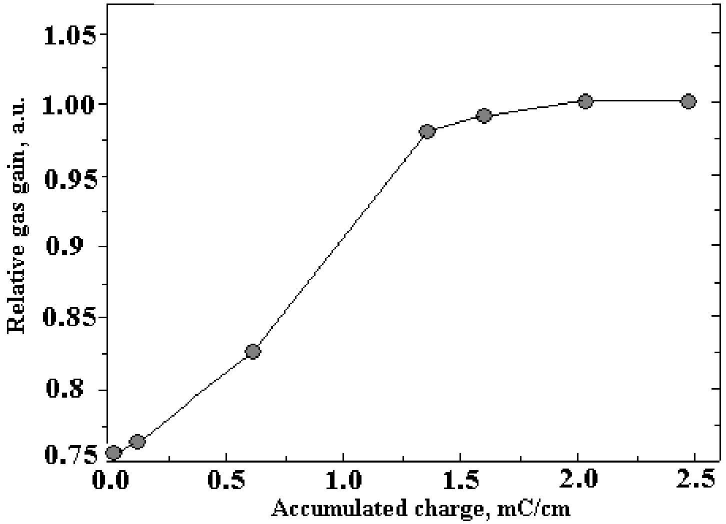
Anode wire 30 mcm

Cleaning of Si, SiO_2 deposits from the anode wire with 80%CF_4+20%CO_2

65%Ar+30%CO_2+5%CF_4

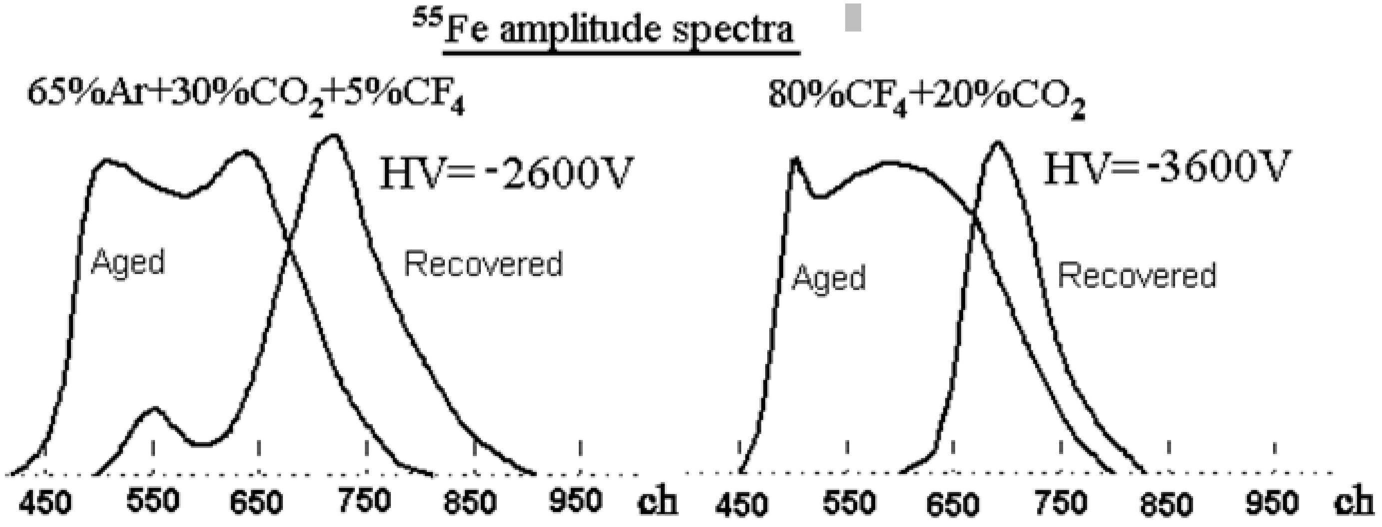


80%CF_4+20%CO_2



- Training with 80%CF_4+20%CO_2 gas mixture at inversed HV = -3400 ÷ -3600 V
- Aged point irradiated with a ^{55}Fe X-ray source (6 keV)

~2μm Si, Si*O_2* *cleaned per 4* h from the wire surface with accumulated charge Q ~ 2 mC/cm !



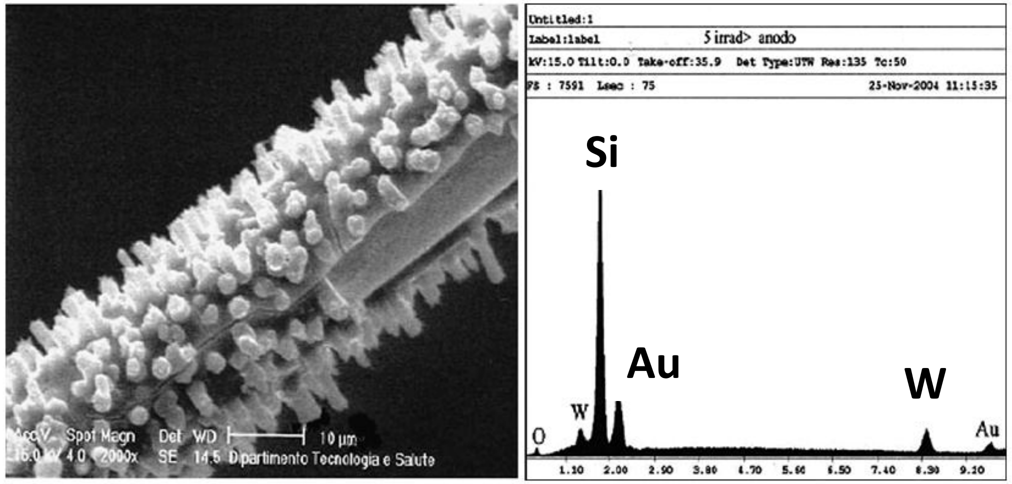
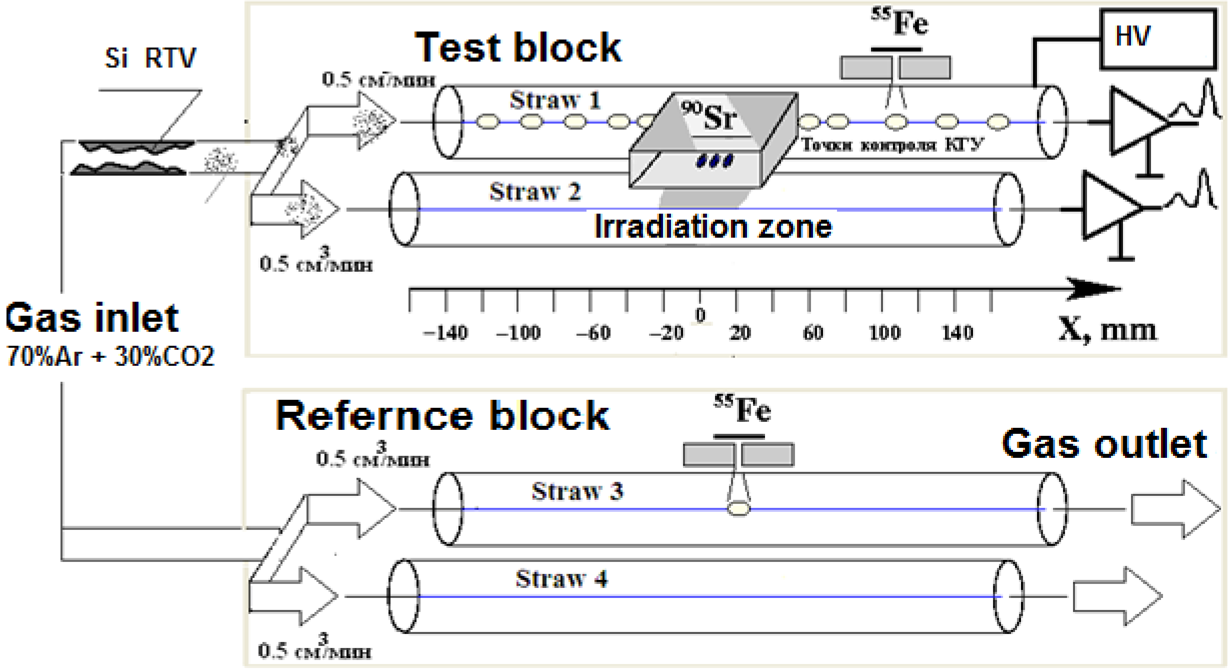


Fig. 11. SEM micrograph of the anode wire irradiated in the fifth test point (see Fig. 6) after accumulation of $Q^{point\ 5}_{anode}$ = 32 mC/cm and XEM spectra of the deposits on the surface.

S. Belostotski, S. Frullani, G. Gavrilov, O. Miklukho, L. Shchipunov, Extension of the operational lifetime of the proportional chambers in the HERMES spectrometer, NIMA 591 (2008) 353–366



Free radicals generation

$e^- + CF_4 \rightarrow CF_2^{\bullet} + 2F^{\bullet} + e^-$

$e^- + CF_4 \rightarrow CF_3^{\bullet} + F^{\bullet} + e^-$

Etching of silicon deposits

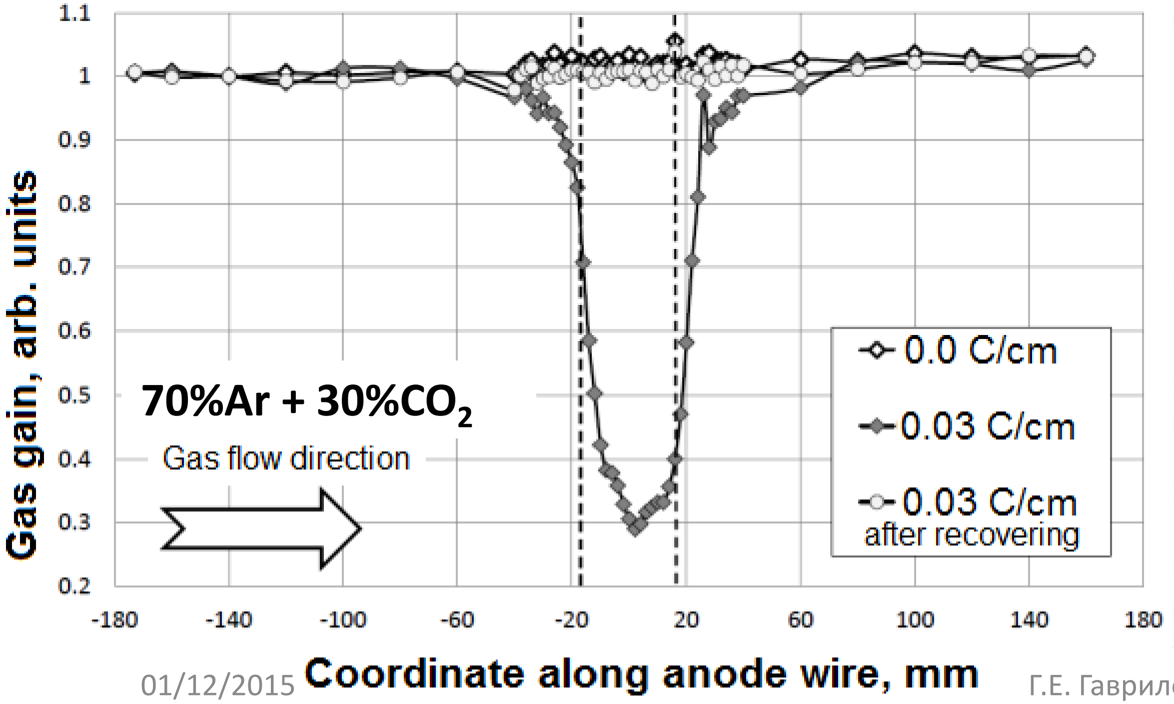
$Si + CF_3^{\cdot} + F^{\cdot} + 2O \rightarrow SiF_4\uparrow + CO_2\uparrow$

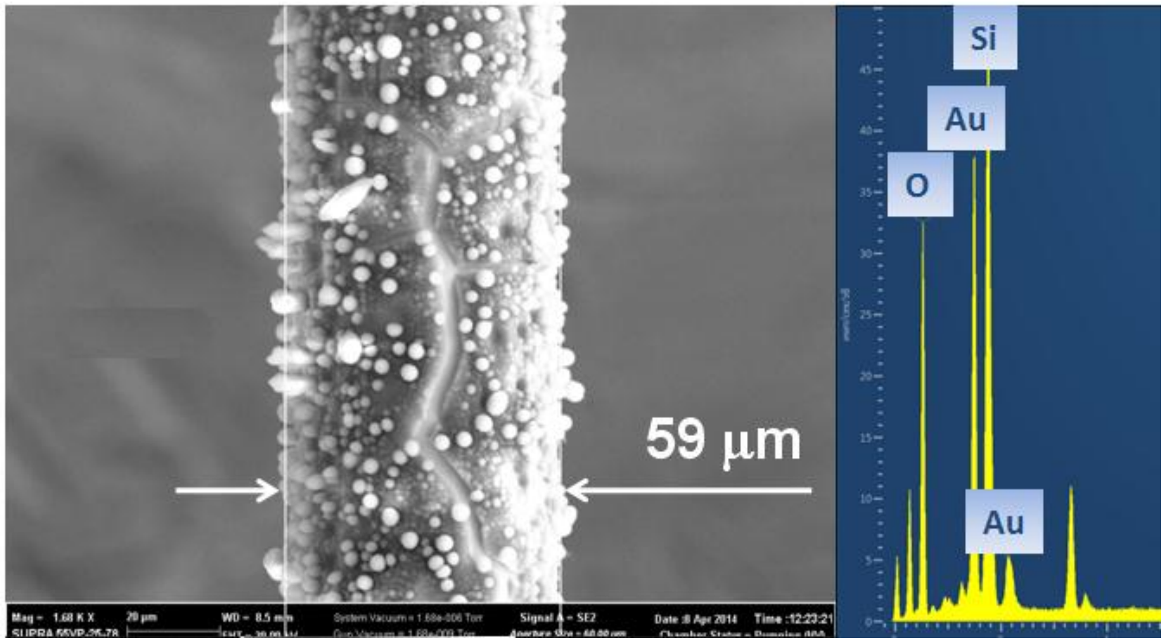
$SiO_2 + 4F^{\cdot} \rightarrow SiF_4\uparrow + O_2\uparrow$

$Si + 4F^{\cdot} \rightarrow SiF_4\uparrow$

$$\frac{d\lambda}{\lambda} = 0.2\frac{\Delta D}{D}$$

$$\frac{dG}{G} = \left[\ln G + \frac{\lambda \cdot \ln 2}{2\pi\varepsilon_0 \cdot \Delta V}\right]\frac{d\lambda}{\lambda} = 59\%$$

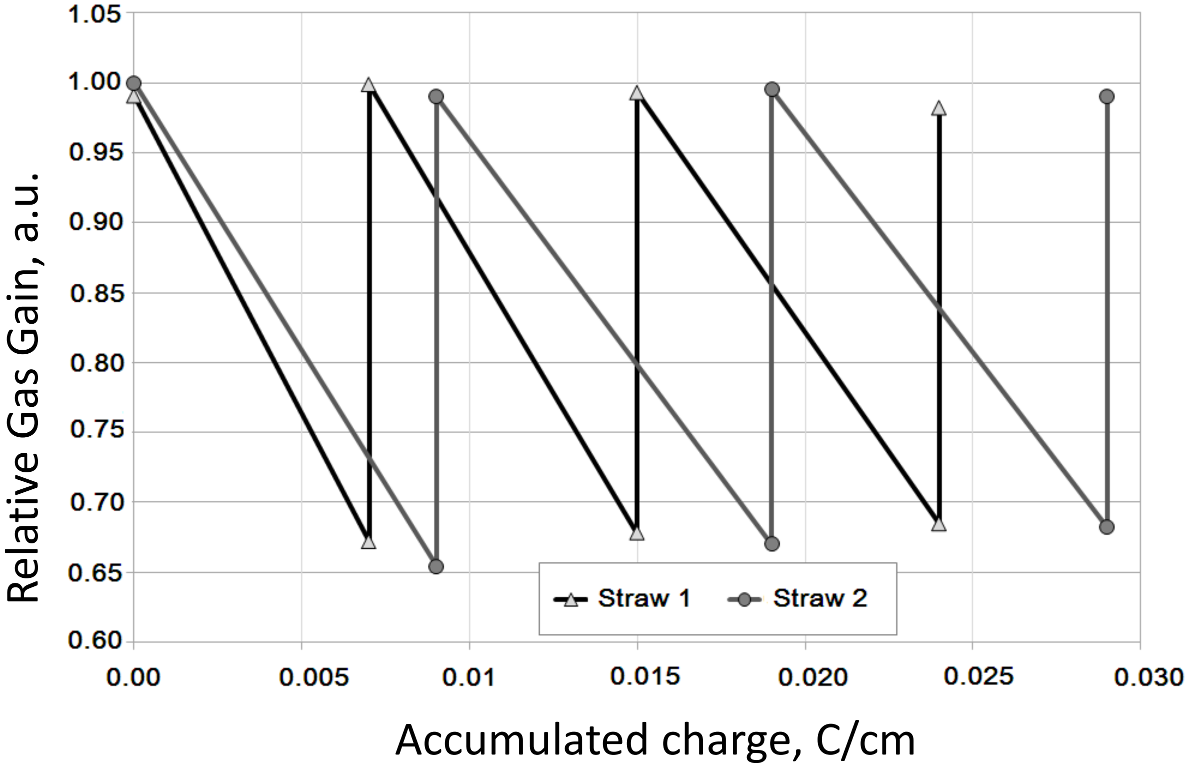


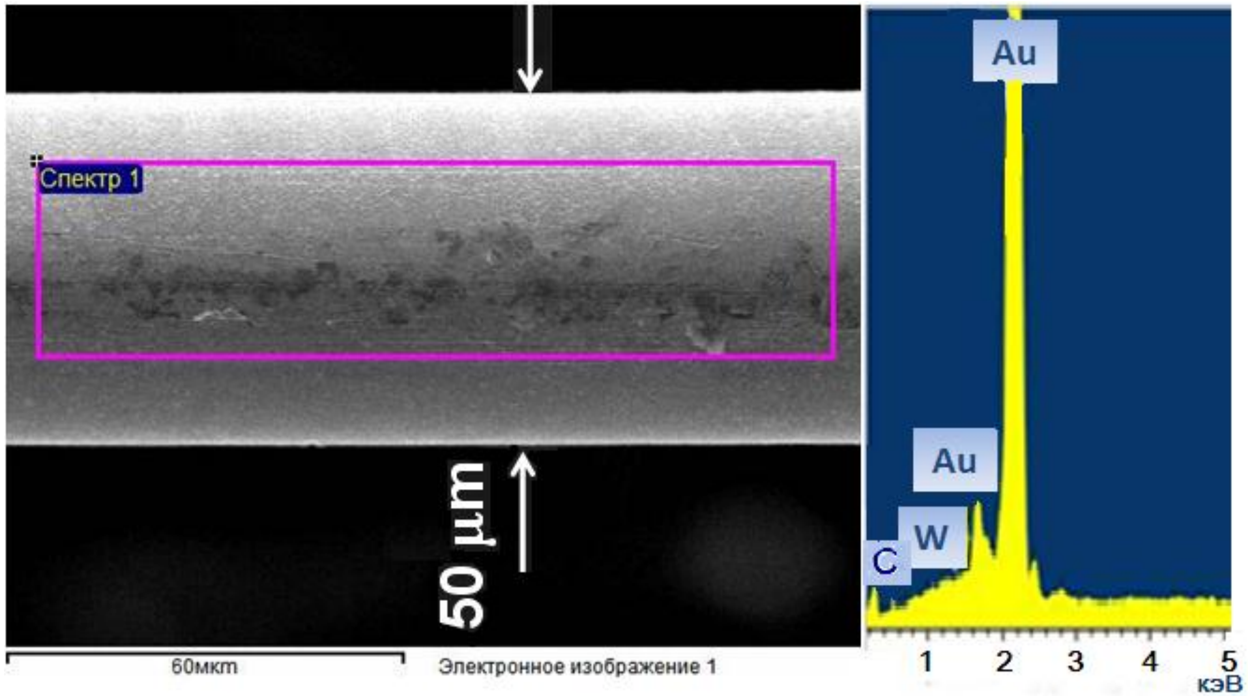


Anode wire 50 mcm

Multiple cleaning of the anode wire with plasma chemistry glow discharge

Straw aging performed with a **60%Ar + 30%CO_2+ 10%CF_4** working gas mixture and limited by ***dG/G* ~33%**
Straw recovering with a **80%CF_4 + 20%CO_2** gas mixture





Multiple cleaning with plasma etching of the silicon compounds on the wire surface leads to complete restoration of the detector performance and few times increases the lifetime.

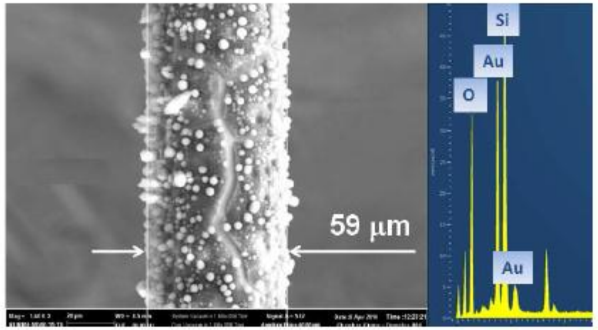
Methods for recovery of aged CSC

Chamber aging and eco-friendly gas mixtures

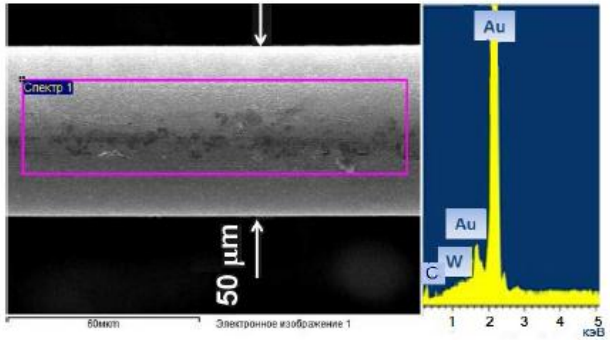
Armando Lanaro (UW)
CSC Coll. Meeting CMS week
Oct 20, 2015

Many thanks to all colleagues providing material and inputs

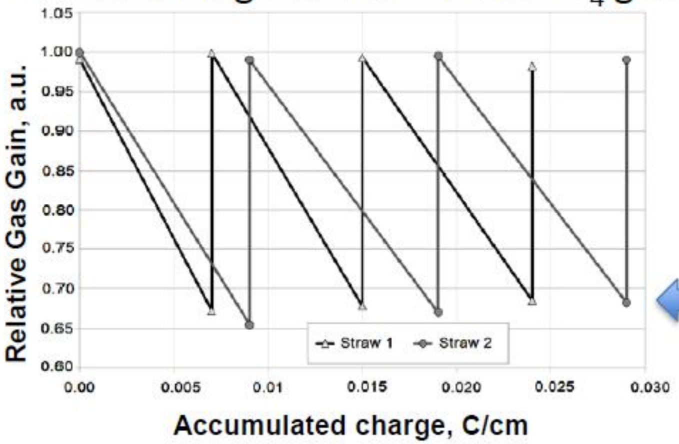
- PNPI collaborators are actively studying this subject (see last week presentation https://indico.cern.ch/event/454874/ by G. Gavrilov)



Cleaning of Si, SiO_2 deposits from the anode wire with 80%CF_4+20%CO_2



- Use of high concentration CF_4 gas mixtures (glow discharge) produces etching of Si



- Aged point irradiated with a ^{55}Fe X-ray source (6 keV)
  - Perform recovery of aged CSC in equipped lab (B904)

Multiple cleaning leads to complete restoration of detector performance

11

Strategy for future

- Preliminary targeting aging tests in PNPI. At ATS with intensive 90Sr local irradiation will be performed studies of alternative gas mixtures.

- Then at GIF will be tested compact CSC prototypes with recirculation gas system flushed by the tested at ATS gas mixture.

Заключение

1. Все составы исследованных газовых смесей демонстрируют выход на плато счетной характеристики в моде ограниченного стримера. Это продемонстрировано на пропорциональном счётчике straw при работе с прототипом CSC.

2. Большая амплитуда сигнала в области плато – в 4-10 раз большая, чем в обычной пропорциональной моде – позволяет рассмотреть возможность создания нового типа детектора, работающего в моде ограниченного стримера.

3. Наличие зоны сильного прилипания электронов вблизи катодной плоскости делает детектор, работающий с рабочей газовой смесью содержащей CF_3I, безопасным для эффектов вторичной эмиссии электронов с катода, которые возникают в результате старения при длительном облучении.

4. Но. Применение подобных смесей для камер CSC невозможно из-за их низкой эффективности регистрации и необходимости подавать значительно более высокое напряжение.

5. Необходимо изучить возможности разработки новых рабочих газовых смесей с использованием других компонент

IV Planning

1. Aging test of straw (50 μm anode wire) at ATS with the 5% gas mixture.
2. Aging test of the CSC prototype (50 μm anode wire) at ATS with 5% gas mixture.

& Outlook

- Reducing of CF4 content in gas mixture up to 1-2%

This makes shorter the efficiency plateau

To compensate an X component have to be added. It can be CH_4, C_2H_4 and e t c.

- Reducing the CF3I content in the gas mixture up to 0.1 %
- Looking for new gas components

How to cure ageing?

- R.Openshaw, R.S. Henderson et al IEEE Trans. Nucl.. Sci NS-34, 528 (1987) - **training with 80%CF_4+20%iC_4H_{10} glow discharge**
- T. Marshall NIMA 515 (2003), 50 – **“Zap” cleaning by quick current heating (C=1.5μF HV=3500V *l* = 190 cm)**
- M. Kollefrath, V. Paschhoff, M. Spegel et al NIMA419 (1998), 451 – **reversed HV and glow discharge in Ar +O_2 (the current I=0.7÷23 μA/cm cleaned carbon)**
- A.M.Boyarski NIMA515(2003), 190 – **2h of training with He + iC_4H_{10}+ O_2 under ^{55}Fe irradiation cured the Malter effect (29nA/cm)**
- S. Belostotski, S. Frullani, G. Gavrilov… NIMA 591 (2008) 353–366 **4 hours training of HERMES Magnet chamber prototype with 80%CF_4+20%CO_2 with ^{55}Fe irradiation and inversed HV cured anode (~2 mcm Si cleaned from the anode with 20nA/cm glow discharge current)**

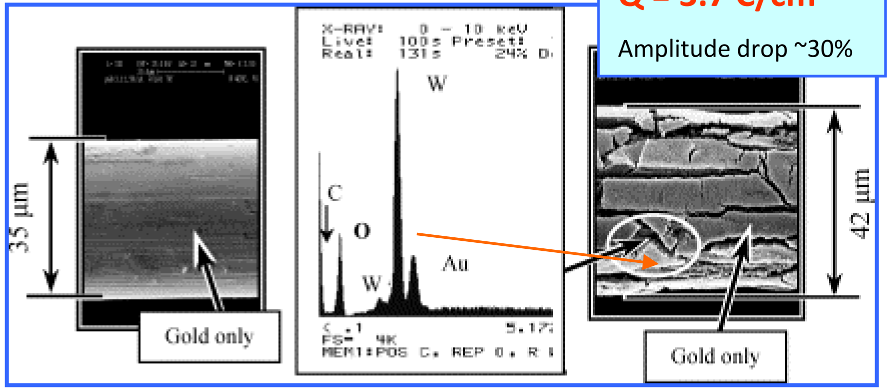
Ageing terms and faces

Backup

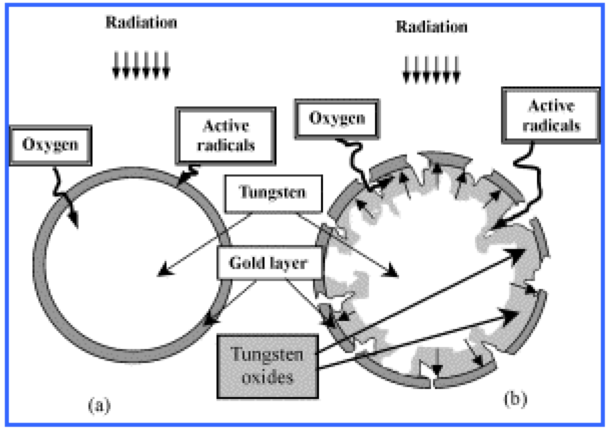
Anode wire swelling effect

Q = 3.7 C/cm

Amplitude drop ~30%

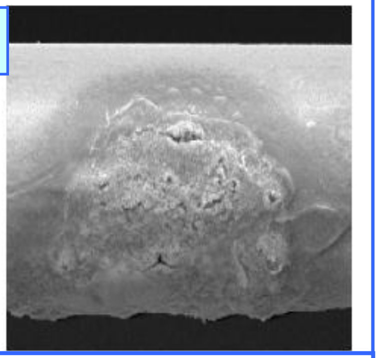


T.Ferguson et al. NIMA 478(2002) 254-258



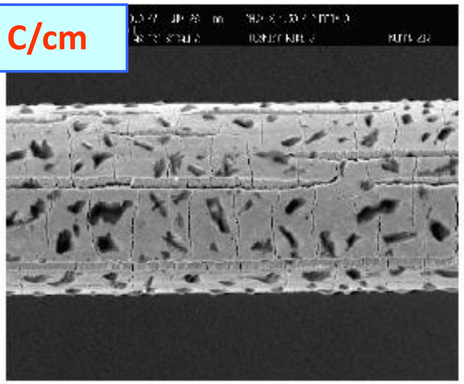
$$
\begin{aligned}
e^- + CO_2 \rightarrow\ & CO^{\bullet} + O^{\bullet} + e^-; \\
\rightarrow\ & CO^{\bullet} + O^-; \\
\rightarrow\ & CO^- + O^{\bullet}; \\
\rightarrow\ & C^{\bullet} + 2O^{\bullet} + e^-; \\
\rightarrow\ & C^{\bullet} + O^{\bullet} + O^-;
\end{aligned}
$$

Q = 2.0 C/cm



Amplitude drop ~3%

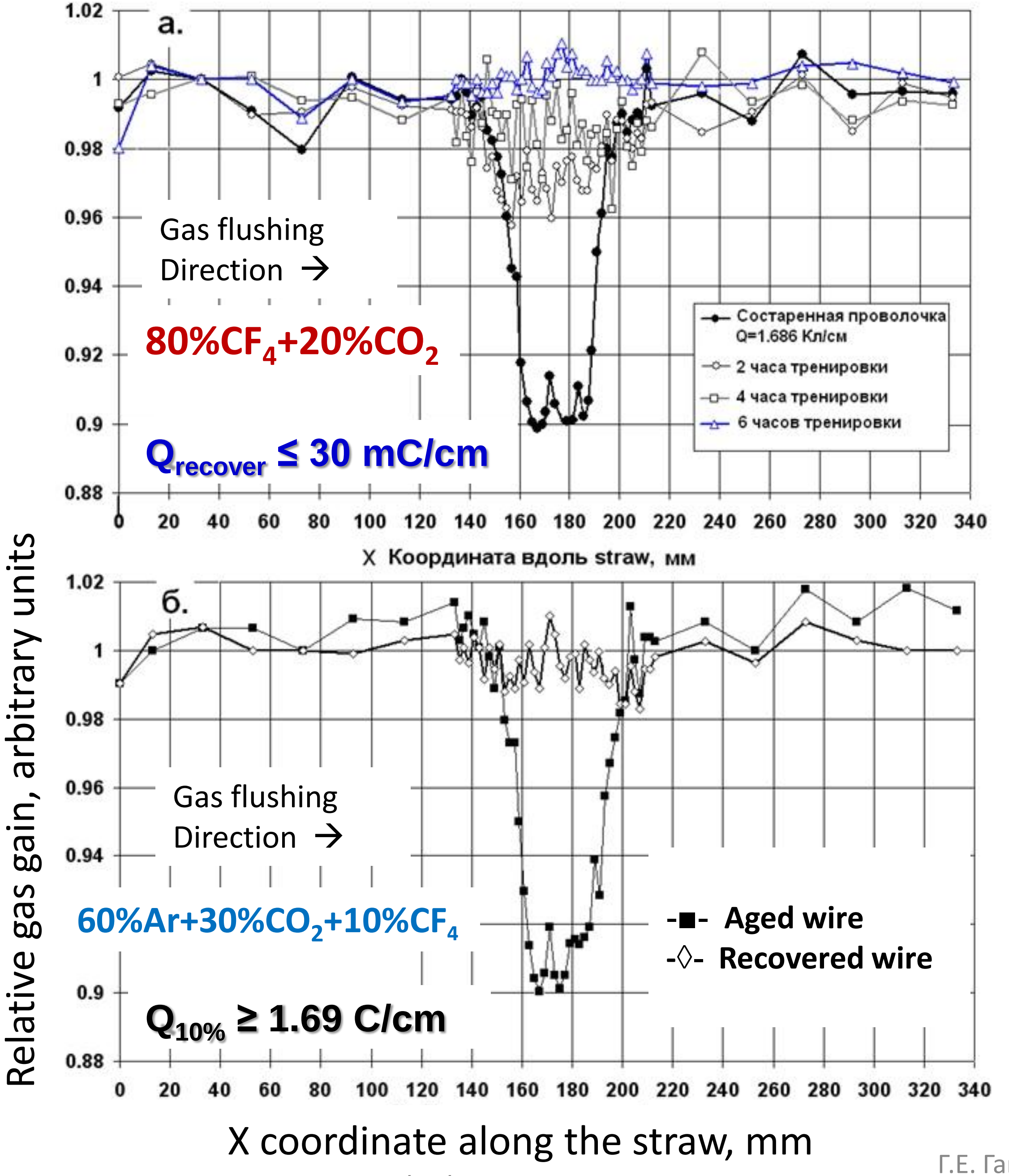
Q = 6.5 C/cm

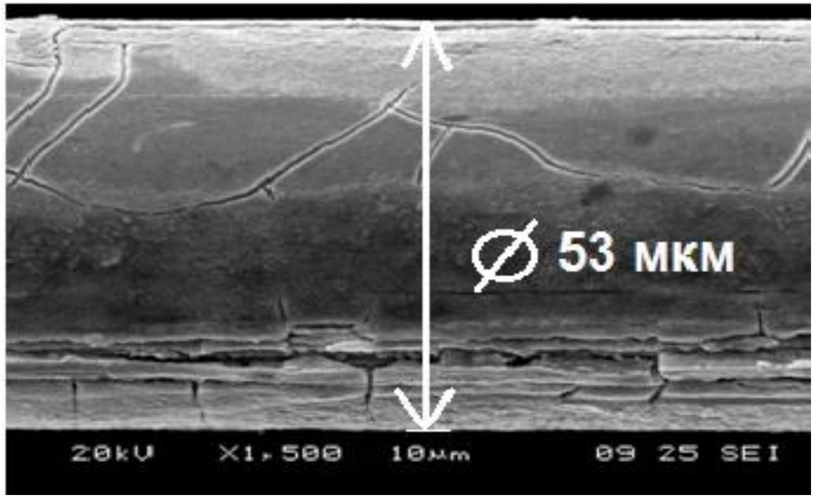


T.Akesson et al. NIMA 515(2003) 166-179

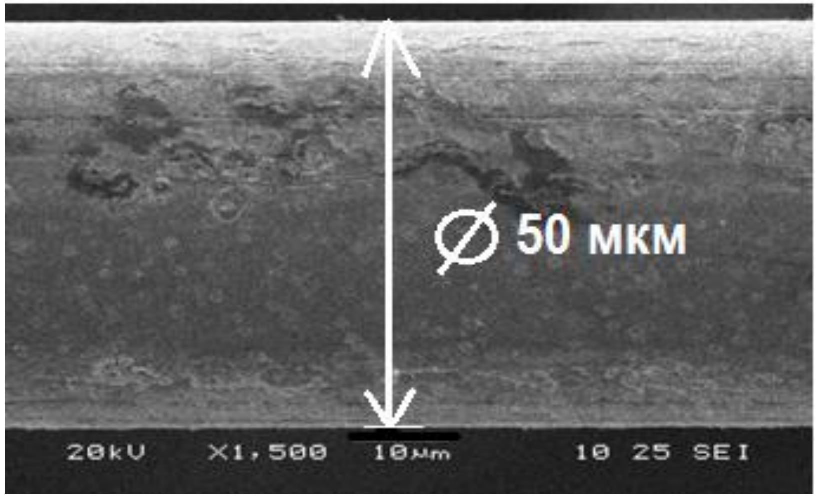
T. Fergusona, G. Gavrilov e t c, Swelling phenomena in anode wires aging under a high accumulated dose, NIMA 515 (2003) 266–277

Curing of the anode wire in the straw from swelling



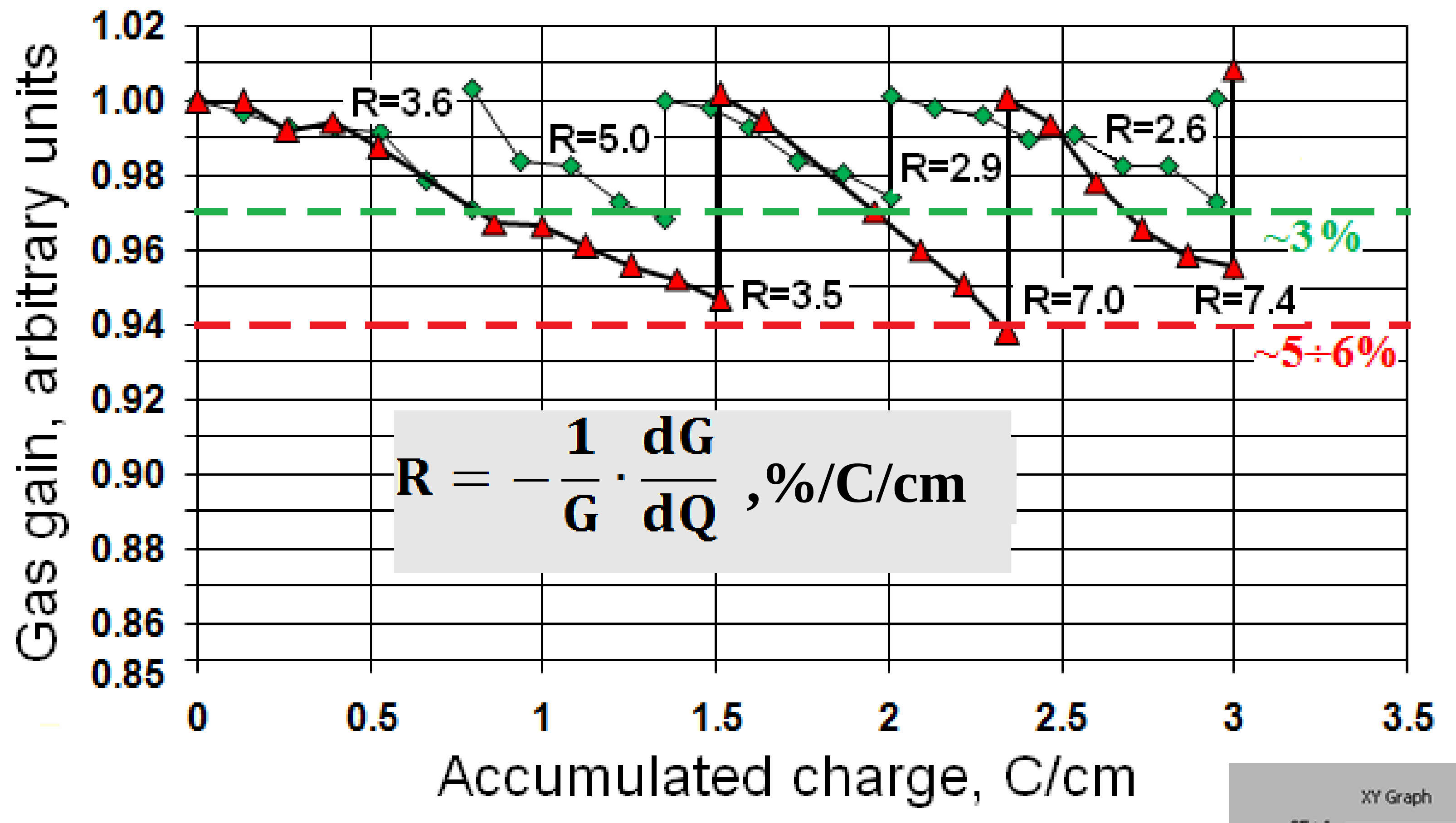


$$\frac{dG}{G} = 10\% \Rightarrow \frac{dG}{G} \leq 1\%$$



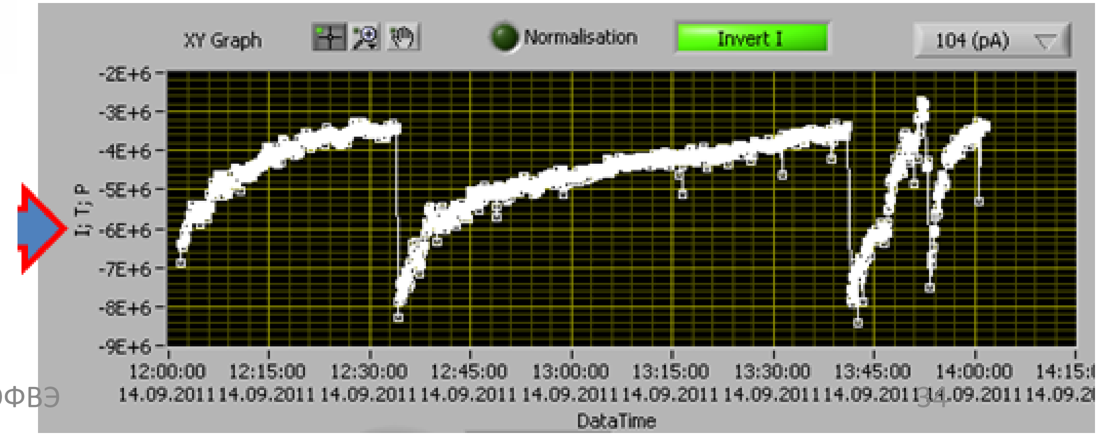
Backup

Multiple recovery test results



Backup

Currents changing during recovering



G.E. Gavrilov, D.A.Aksenov, R.Conti et al., Using an 80%CF4+20%CO2 gas mixture to recover aged anode wires in proportional chambers, NIMA 694 (2012) 167–172

PAST EXPERIENCE

DETECTOR	AGEING EFFECT	SOLUTION
ZEUS Central Tr. 83%Ar+12%CO_2+5%C_2H_6+0.5%C_2H_5OH	**Malter effect (0.1 C/cm)**	**Addition of water 0.1%**
H1 Central Jet Ch. 50%Ar+50%C_2H_6+0.1%H_2O	**Malter effect** **Anode ageing** **(0.01 C/cm in CJC2)**	**5 years with 0.1% water, then changed on 0.8% ethanol**
D0 Drift Tube Ch 90%Ar+4%CO_2+6%CF_4	**Anode ageing**	**Remove outgasing material and clean wires**
CDF Central Tr. 50%Ar+50%C2H6+1%C_2H_5OH	**Anode ageing** **(20 mC/cm)**	**Clean of gas system and gas filtering**

Existing methods of ageing preventing are passive and only delay the process development