Selected Topics on FE Electronics for the GERDA Phase II Ge detector readout

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INFN MiB

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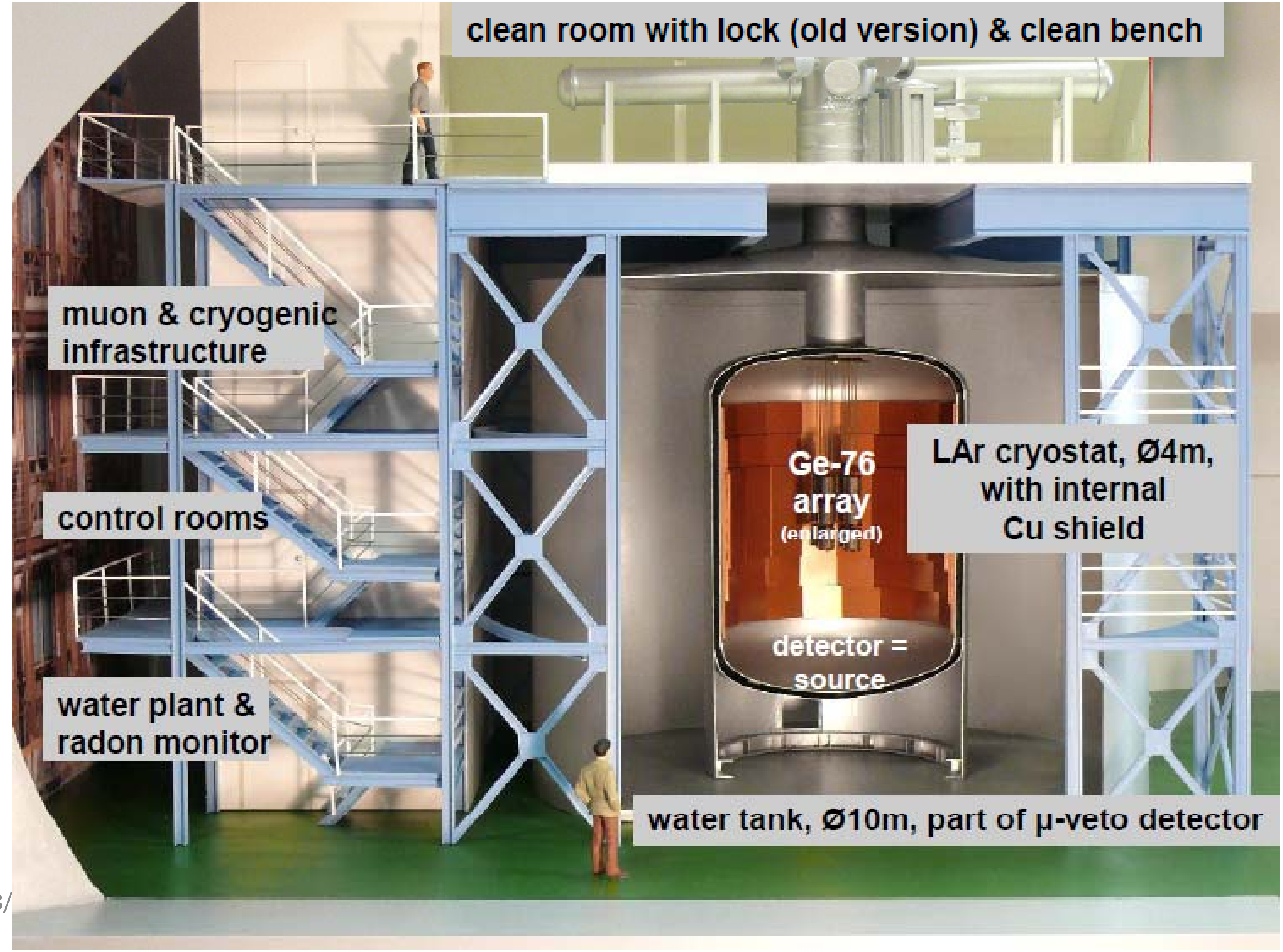
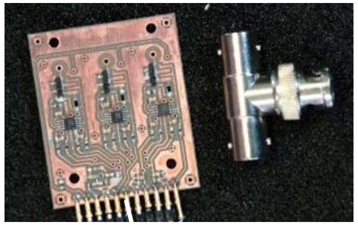
Outline

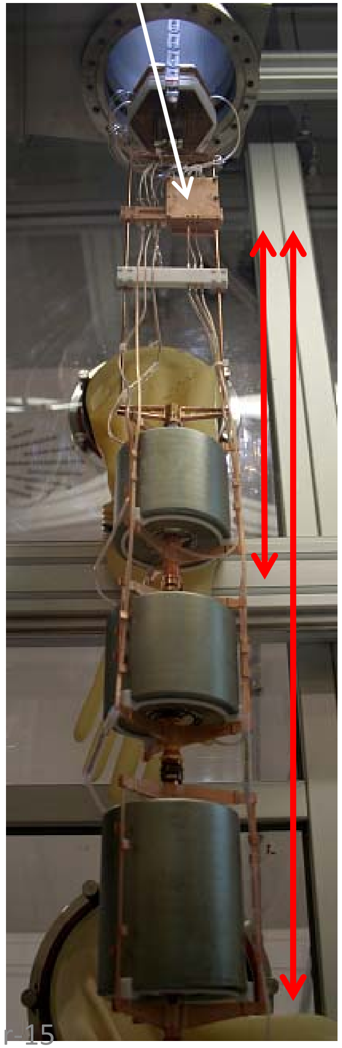
- GERDA experiment.
- GERDA II vs GERDA I FE architecture
- The Substrates
- Signal and HV Lines
  - Front End and HV Ribbon Cables
  - JFETs
  - Feedback Resistors
- Results achieved in GERDA commissioning runs
- Parylene coating
- Background Budget
- Conclusions

All the measurements presented in this talk have been performed by the LNGS ICPMS and γ-ray screening teams. With their highly professional work, they provides unvaluable informations about material contaminations, allowing to proceed in the selection of materials for the setup construction.

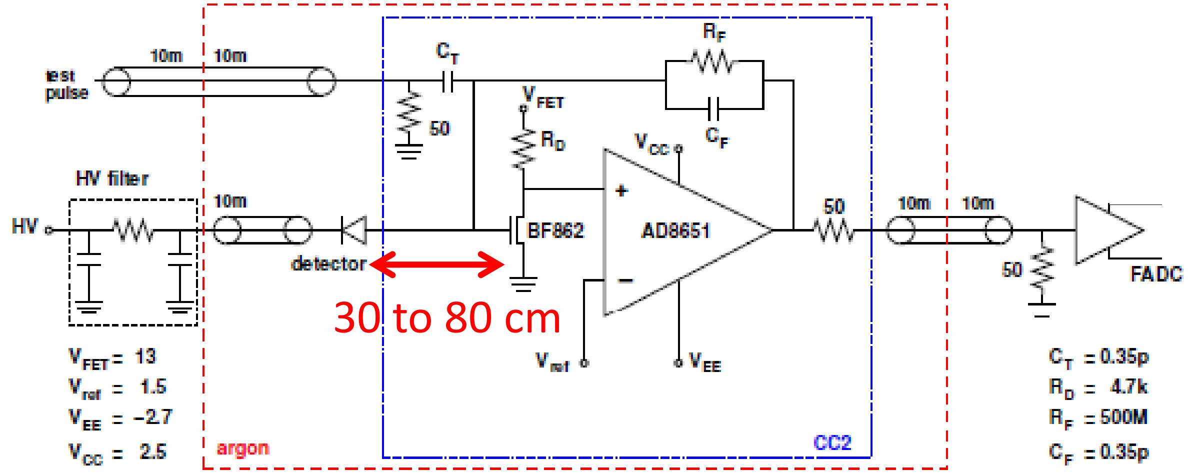
GERDA @ LNGS: Searches of $0\nu\beta\beta$ of ^{76}Ge







GERDA Phase I



- **30 to 80 cm from detector readout electrode to CSA input**
- **Detector HV and readout contacts: spring loaded**
  - Because of activity issues FE device (JFET NPX-BF862) and CSA both **Located at about 30 to 80 cm above top detector**
  - Unshielded OFHC Cu strip to connect Detector to CSA input
  - C_{Det} ~ 30 pf
  - **150 uBq Th-232 for 3 channels**
  - **Microphonics (LF) and HF noise. Variable in time.**
  - **Resolution and PSD suffered**

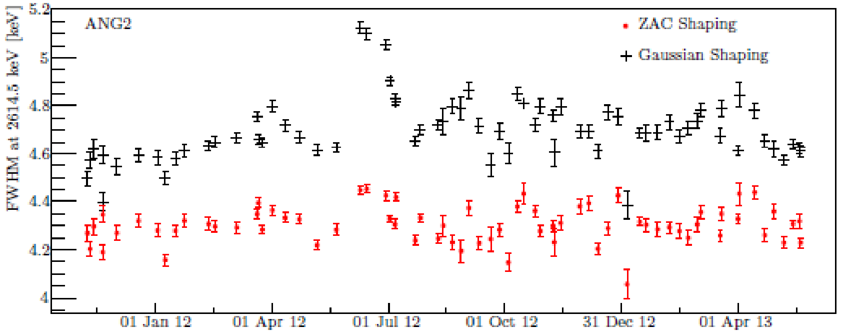


Fig. 10 FWHM of the ^{208}Tl FEP for ANG2 during Phase I.

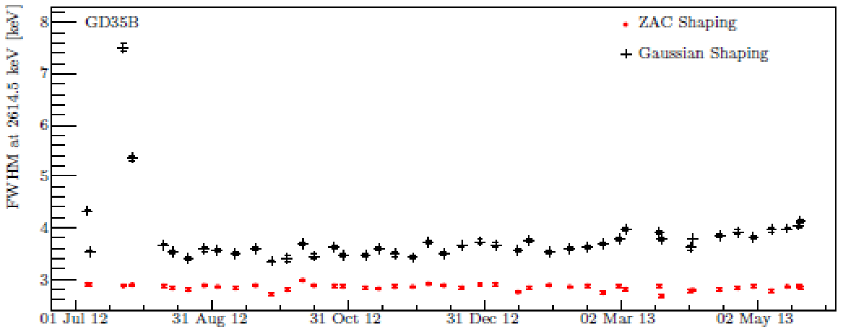


Fig. 11 FWHM of the ^{208}Tl FEP for GD35B during Phase I.

Table 3 Average FWHM over the complete Phase I period. The improvement is computed as the difference between the FWHM for the pseudo-Gaussian and that for the ZAC filter, weighted by the detector exposure. Only the statistical uncertainty due to the peak fit is quoted.

Detector	FWHM at ^{208}Tl FEP [keV] Gaussian	ZAC	Improvement [keV]
ANG2	4.712(3)	4.314(3)	0.398(4)
ANG3	4.658(3)	4.390(3)	0.268(4)
ANG4	4.458(3)	4.151(3)	0.307(4)
ANG5	4.323(3)	4.022(3)	0.301(4)
RG1	4.595(4)	4.365(4)	0.230(6)
RG2	5.036(5)	4.707(4)	0.329(6)
GD32B	2.816(4)	2.699(3)	0.117(5)
GD32C	2.833(3)	2.702(3)	0.131(4)
GD32D	2.959(4)	2.807(3)	0.152(5)
GD35B	3.700(5)	2.836(3)	0.864(6)

Detector Performances improvement by tailored DSP

- **Filtering with an improved filter, tailored for each detector→ Improved 10% FWHM both for Coax and BEGE & stability of reconstructed energy calibration**

arXive: 1502.04392

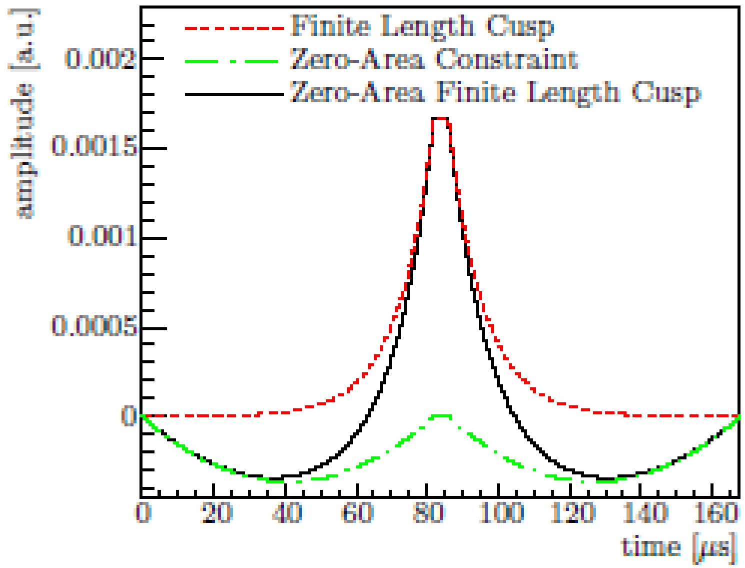
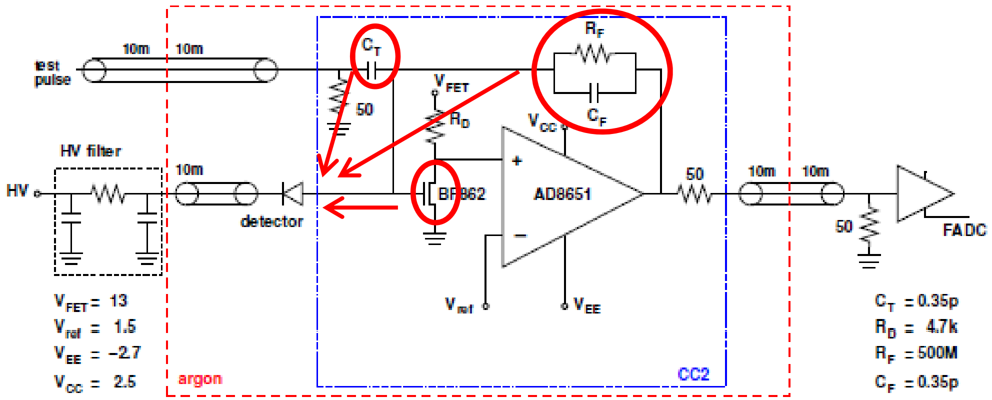


Fig. 5 The ZAC filter (black) is composed by the finite-length cusp (red dashed) from which two parabolas are subtracted on the cusp sides (green dash-dotted).

GERDA PHASE II

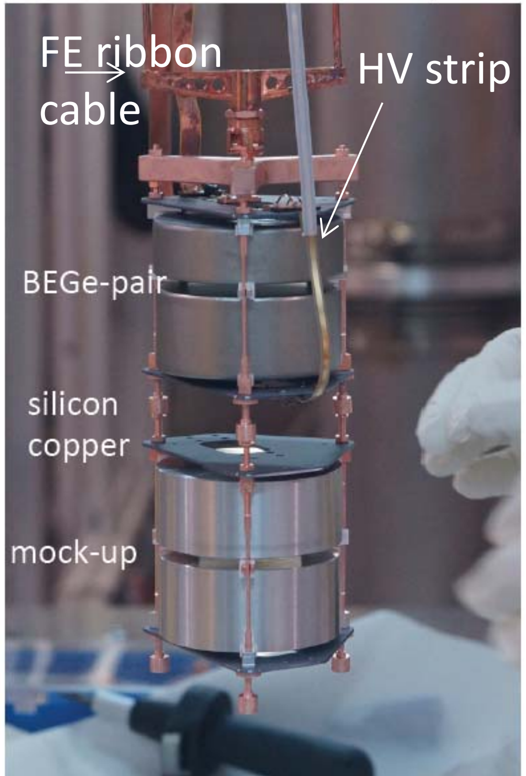
Aim: Reduce disturbances, microphonics, noise due to (variable) extracapacitance etc.

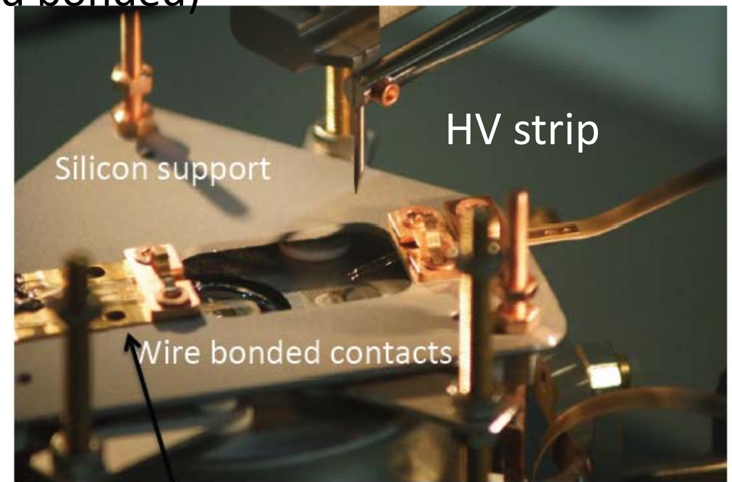
- **Both Detector Contacts wire bonded**
- FE devices moved at detector site
- JFET changed to better match C_{det} (BEGe)
- JFET in die (die attach and bonded)

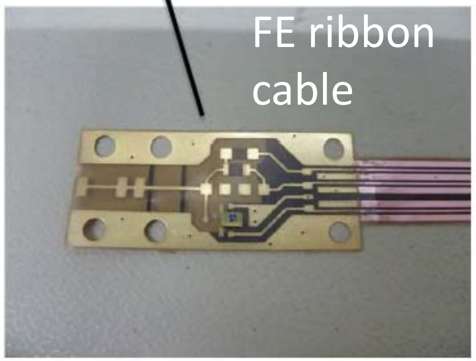


More stringent radioactivity issues!

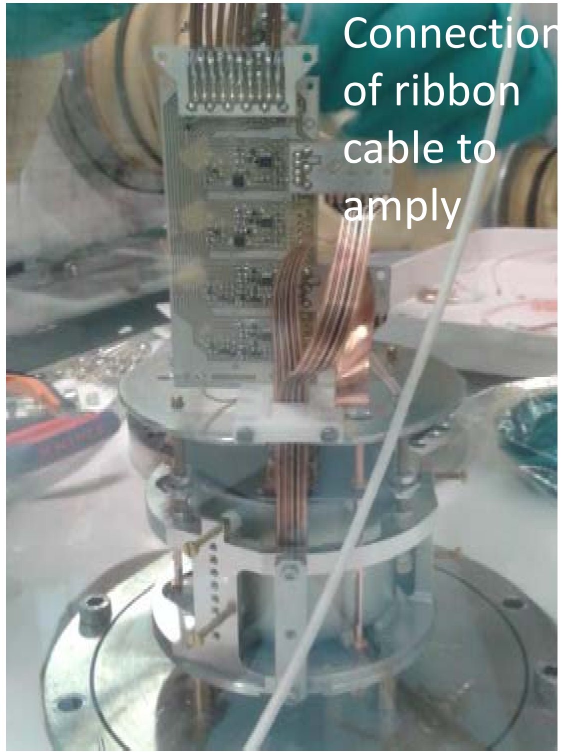
Phase II detector assembly





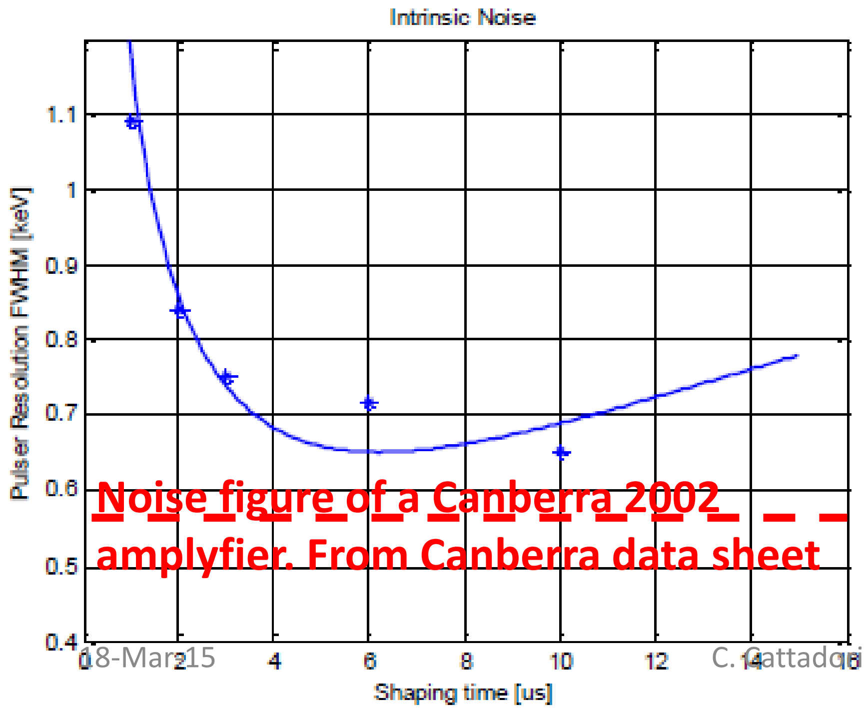


flex cables with JFET and feedback resistor/capacitor

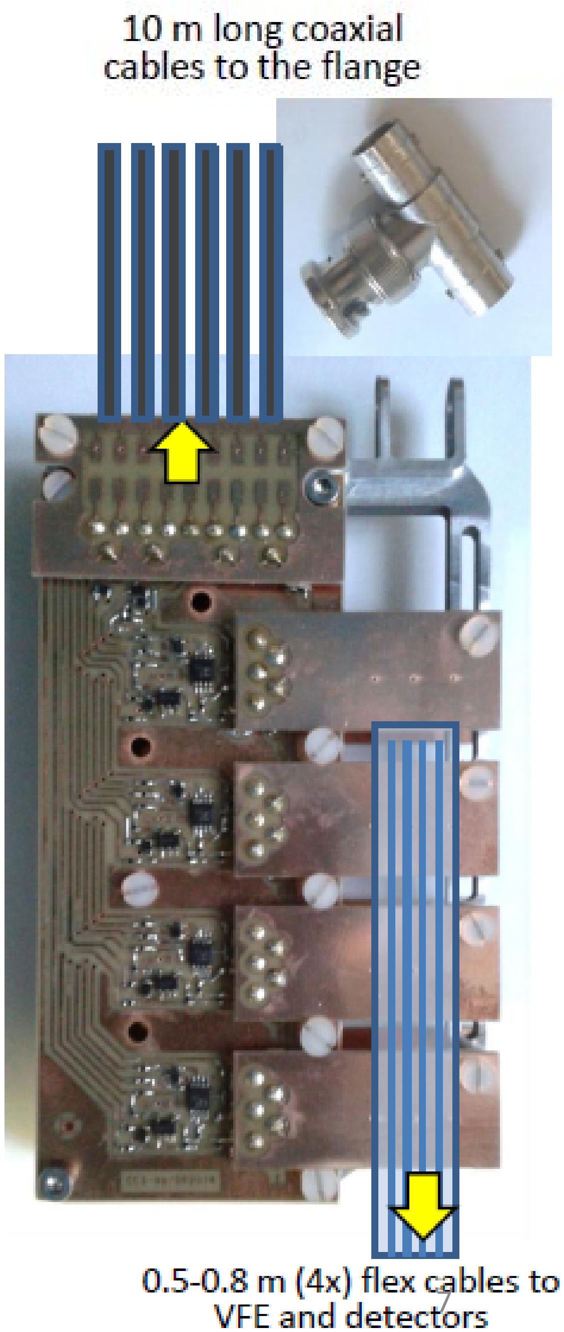


GERDA CC3 preamplifier

- 4 channel cryogenic charge sensitive preamplifier
- Extremely radio-pure electronics (<50 uBeq/ch)
- < 0.7 keV FWHM energy resolution (BEGe detectors)
- up to 80 cm long Cuflon VFE flex cables
- < 100 ns rise time (depending on VFE cable length)
- 15 MeV dynamic range
- < 70 mW power consumption/ch



CC3 + adapters to coaxial and VFE cables (prototype aluminum holder)



Substrate of all the GERDA electronic circuits in LAr

CRANE. Polyflon
a Crane Co. Company

Polyflon Company
One Willard Road • Norwalk, CT 06851 USA
Phone: 203-840-7555 • Fax: 203-840-7565
email: info@polyflon.com • www.polyflon.com

CuFlon® Microwave Substrates

Polyflon has taken advantage of the qualities of PTFE and coupled them with a proprietary plating process to produce a microwave substrate whose loss performance cannot be equaled by any other substrate available at this time.

PTFE has unique electrical and physical properties: low loss tangent and dissipation factor, very low dielectric constant, high volume and surface resistivity, high chemical inertness, and almost zero water absorption.

Features and Benefits	• Ultra Low Loss	• Very Low Dk	• Isotropic Properties
Typical Applications	• High Power Amplifier	• NRM/MRI Coils	• Couplers

Property	Value	Units	Direction	Frequency	Test Method/Condition
Dielectric Constant	2.05 +/- .05	-	Z	18 GHz	IPC-TM-650
Dissipation Factor	0.00045	-	Z	18 GHz	IPC-TM-650
Dielectric Strength (0.020")	1000	V/mil	Z	-	ASTM D 149
Volume Resistivity	10^{16}	ohm • cm	Z	-	ASTM D 257
Maximum Temperature	225	°C	-	-	Short Duration
Thermal Conductivity	0.25	W/m/°C	Z	-	ASTM C 518
Specific Gravity	2.15	-	-	-	ASTM D 792
Thermal Expansion	129	ppm/°C	X	-	ASTM E 831
(Unclad Dielectric)	129	ppm/°C	Y	-	ASTM E 831
	129	ppm/°C	Z	-	ASTM E 831
Water Absorption	<.01	%	-	-	ASTM D 570
Copper Peel (Average)	6-8	lbs/in	-	-	
Operating Temperature	-55 to 175	°C	-	-	
RoHS Compliant	Yes	Compliance Statement Available Upon Request			

GERDA has adopted Cuflon as PCB substrate for the

- Ge CSA PCBs
- PMT Voltage divider PCBs
- SiPM mountings

Cuflon **Pros**:

✓ **OK ε_r, cyogenic features and radiopurity**

✓ **Available in thicknesses down to 2 "mils (50 um)**

Cuflon **Cons**:

❖ **Available in panels of limited size→ not suited to make long circuits**

❖ **Metalization of vias during the PCB manufacturing process is an issue**

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ELSEVIER

Comparison of inductively coupled mass spectrometry and ultra low-level gamma-ray spectroscopy for ultra low background material selection

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Sample	^{40}K (mBq kg^{-1})	^{232}Th (mBq kg^{-1})	^{238}U (mBq kg^{-1})
PEN			
γ-spectroscopy	510±20	136±3	242±3 (^{226}Ra) 236±68 (^{234m}Pa)
ICP-MS	370±50	110±10	200±30
KAPTON® HN DuPont			
γ-spectroscopy	<5.4	1.4±0.7	14±1 (^{226}Ra) <27 (^{234m}Pa)
ICP-MS	7±3	0.65±0.08	17±2
COOL CAT 2 Austrian Aerospace			
γ-spectroscopy	154±32	1.9±0.5	<1.4 (^{226}Ra) <25 (^{234m}Pa)
ICP-MS	135±4	0.50±0.02	1.43±0.09
NAC-2 Air Liquide			
γ-spectroscopy	81±19	5.0±2.0	22±2 (^{226}Ra) <70 (^{234m}Pa)
ICP-MS	86–4/+5	7.2±0.3	23.6±0.9
CuFlon®			
γ-spectroscopy	48±15	<1.9	<0.84 (^{226}Ra) <132 (^{234m}Pa)
ICP-MS	6–2/+9	0.28–0.03/+0.04	0.36–0.04/+0.07

The uncertainties are given with one standard deviation.

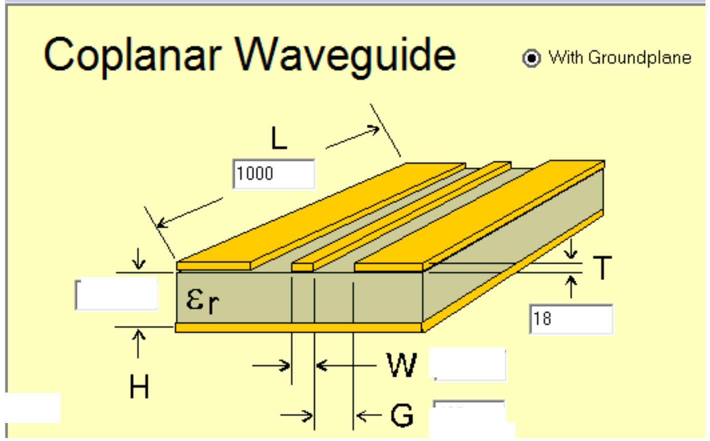
Typical activity values measured for Cuflon material at the ICPMS and STELLA γ-screening facilities @ LNGS

Values can slightly change following substrate thicknesses and Cu/Teflon fraction

Cuflon cleaner than Kapton
factor 15 in Ra-226
factor 40 in U-238

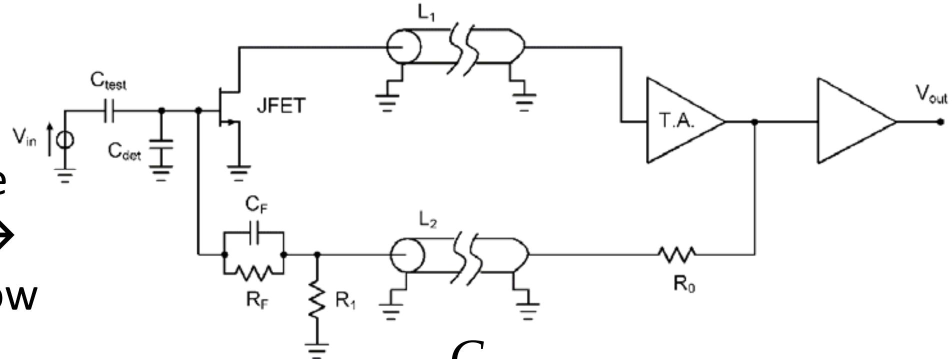
Features of FE Ribbon cables (Coplanar Waveguides)

- Substrates :
  - Cuflon 50-75 um : ε_r=2.1
  - Kapton 50-75 um: ε_r=3.4
- Lengths to connect different detectors to CSA:
  - 48 cm to 80 cm



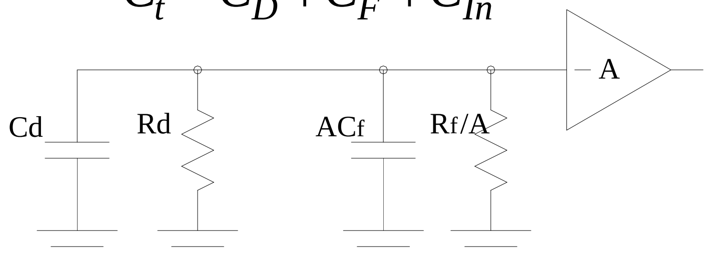
IMPORTANT: Regular waveforms only if

- Impedence properly matched
- Extra C introduced by the long capacitive line compensated at the amplyfier relevant node→
- To preserve pulse rise time keep trace C as low as possible



$$\tau_{RT} \sim C_T \frac{C_{ampnode}}{C_F \times g_m}$$

$$C_t = C_D + C_F + C_{In}$$



	Thick ness	Z_0 [Ohm]	C [pF/m]	v/c %
Kapton	50 um	27	290	59
	75 um	37	180	60
Cuflon	50 um	34	165	73
	75 um	46	102	74

Impact of cable length between the FE devices and the amplifying node in a closed loop CSA

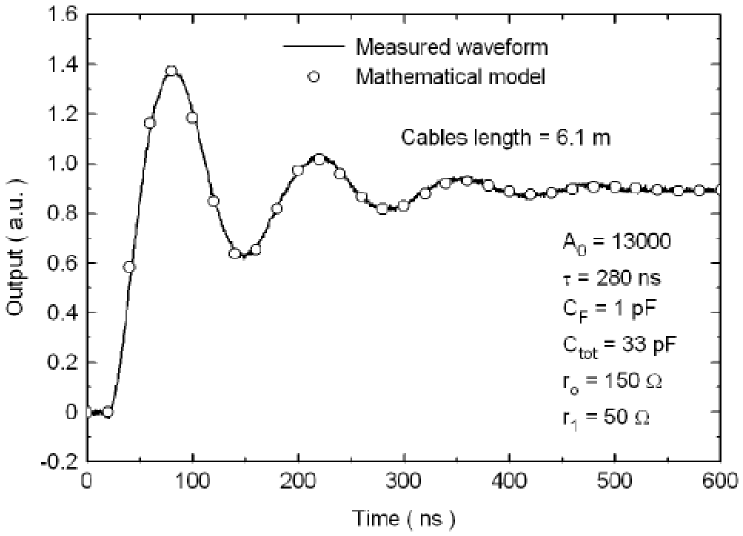
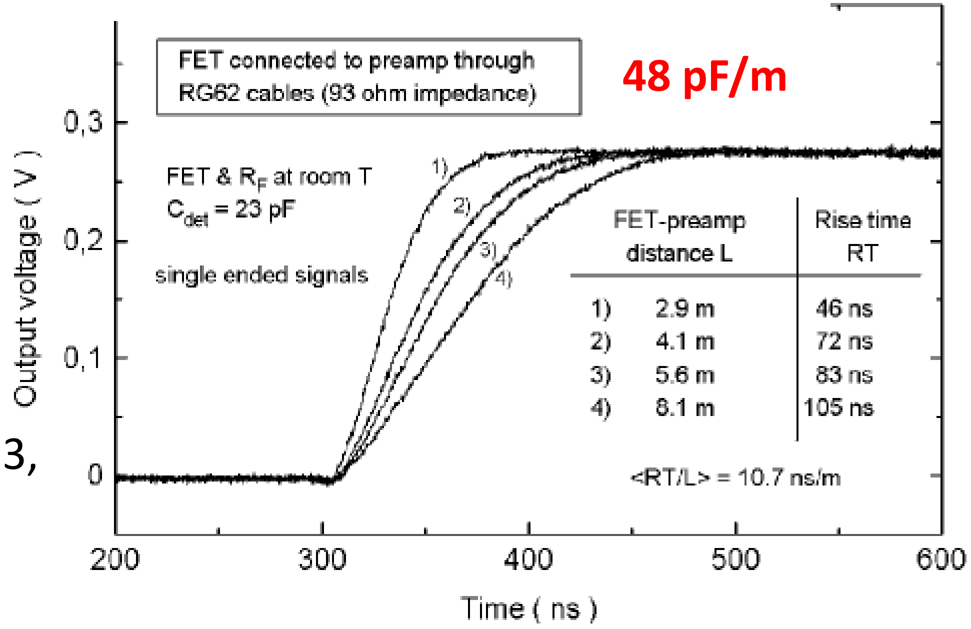


Fig. 2. Comparison between the waveform observed at the circuit output and the mathematical model in the case of a cable total length of 6.1m.

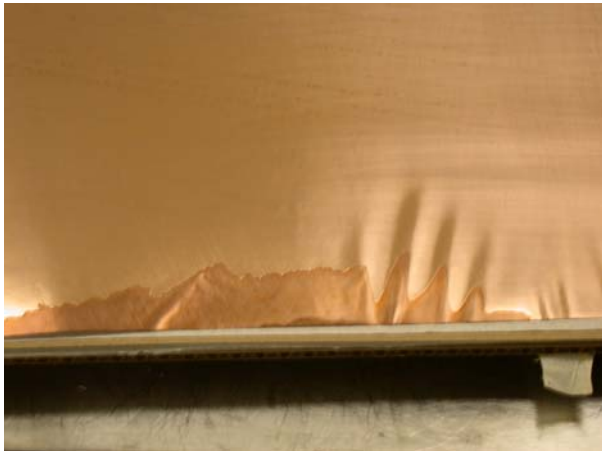


Nuclear Science, IEEE Transactions on , vol.53, no.3, pp.1744,1748, June 2006

Fig. 3. Output signals for different FET-preamp distances when complete compensation is made in order to eliminate any oscillation or overshoot.

Issues related to manufacturing long (up to 80 cm) radiopure flex transmission lines

1° Find raw material radiopure, good ε_r, proper thickness, cryogenic etc.**→Cuflon**
Caveat: Polyflon can produce panels 22" maximal length.
33" panels came in heavily defected and with poor adhesion of Cu to Teflon layer.
2° Find the manufacturer that can produce such long flex circuit by **controlling the radioactivity introduced in the PCB process**



Alternative material for long circuits: DuPont Pyralux

From ICPMS & γ-screening:

• once PCB processed Pyralux and Cuflon have about the same specific activity (confirmed by both ICPMS and γ-screening)

• Kapton has (6 ± 1)mBq/kg of Ra-226, not visible in ICPMS measurements, well visible in γ-screening

PYRALUX

Element	Kapton media	Cu media	Tot Cavo
Unit	ppb	ppb	ppb
Pb	100	1700	1150
Th	0.043	0.196	0.14
U	0.5	0.11	0.245

Tabella 6: contaminazione ridistribuita sull'intero cavo in base alla sua composizione.

CUFLON

Element	Unit	Cable metallic component after lithography (84.6%)	Cable plastic component after lithography (15.4%)	Whole cable
K	ppm	<6	14	2.2<[K]<7.2
Pb	ppb	50	<30	42.3<[Pb]<46.9
Th	ppb	0.08	0.3	0.1
U	ppb	0.2	0.1	0.18

Table 5: measured K, Pb, Th and U contamination in the cable after lithography. The contributions of the different components are first shown separately, then the contamination in the whole sample is calculated. The uncertainty is about 30% of the given values. The given values are blank subtracted.

Impact of PCB process on final FE circuits contaminations

- Once selected the proper raw material →Important not to spoil its radiopurity by PCB process.
- Avoid finishing protective layers (soldermasks etc.)
- Minimize Cu deposition
- **Gold finishing required for bonding (typically <1 um) introduces significant U contaminations. Minimize golded surfaces (in GERDA few mm²/detector)**

				Solfor		Fosfor		Cleaning		PreAu		Micro Etching		Gold		Nickel
39	K	ppb		2000		4900		6100		Saturate		96000		32000000		38000
208	Pb	ppb	<	0,3		0,7		11		28		17		2	<	10
232	Th	ppb	<	0,03		0,05	<	0,03		1		0,04		1,7	<	0,3
238	U	ppb		0,13		22		0,8		5,8		0,81		7,7	<	0,3

			Degrease		Cu activation		Strip per		Micro-etching		Stripper Sn Pb		Sn activator		Micro-etching Sn Pb		Cu solutio		Sn E
K	ppb		4000		13000		16000		Saturato		0		4800		1100		22000		0
Pb	ppb		23		50		350		20		6600		36		11		1900		3800
Th	ppb		0.04		0.1	<	0.3	<	0.03		0.68		0.03		0.04		0.6		0.3
U	ppb		5.4		1.2		1.8		0.86		0.35		1		0.05		1.5		1

Contaminations of FE GERDA circuits manufactured in Cuflon or Kapton substrates

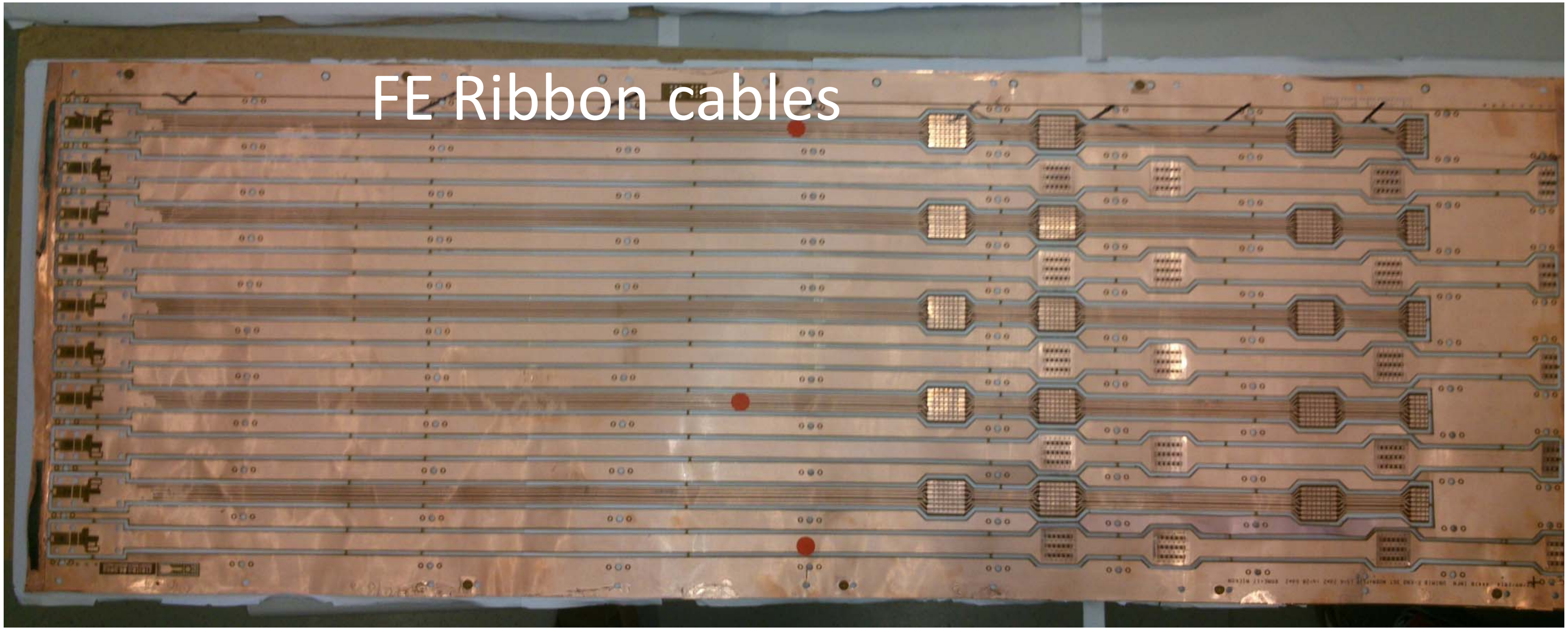
	Signal (Cuflon 3 mils)	HV (Cuflon 10 mils)
Mass of FE circuit	0.5 g/10 cm	0.3 g/10 cm
U-238	1.3 uBq/10 cm	1.0 uBq/10 cm
Ra-226	<0.5 uBq/10 cm	<0.3 g/10 cm
Th-232	0.2 uBq/10 cm	0.2 uBq/10 cm

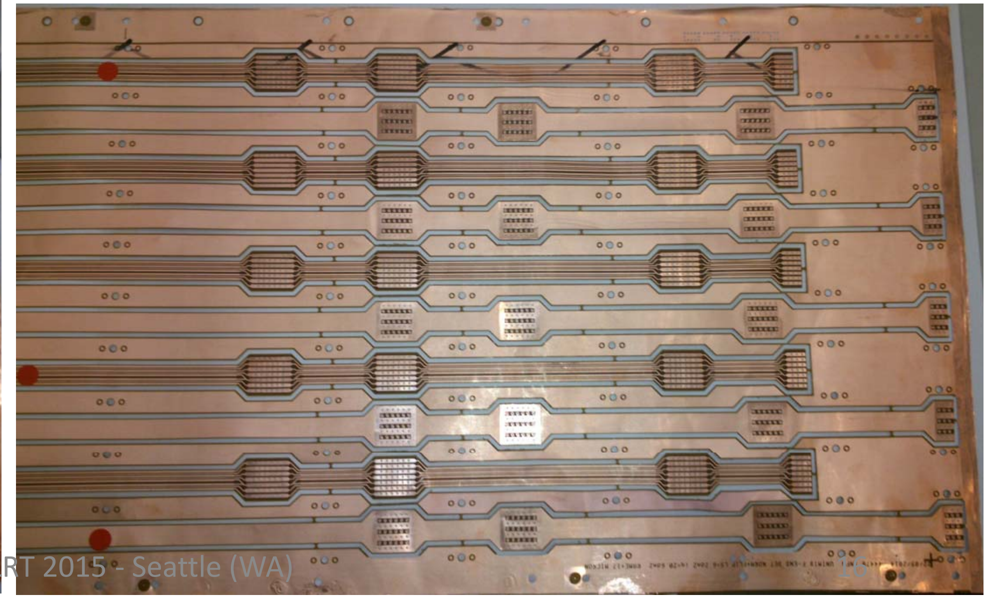
10 cm is the height of one detector couple.

Thanks to its high dielectric strength (6-7 kV/mil) thinner Pyralux substrates can substitute Cuflon (1 kV/mil) for single side HV flexible circuits (or for single trace readout contact for remote FE device)

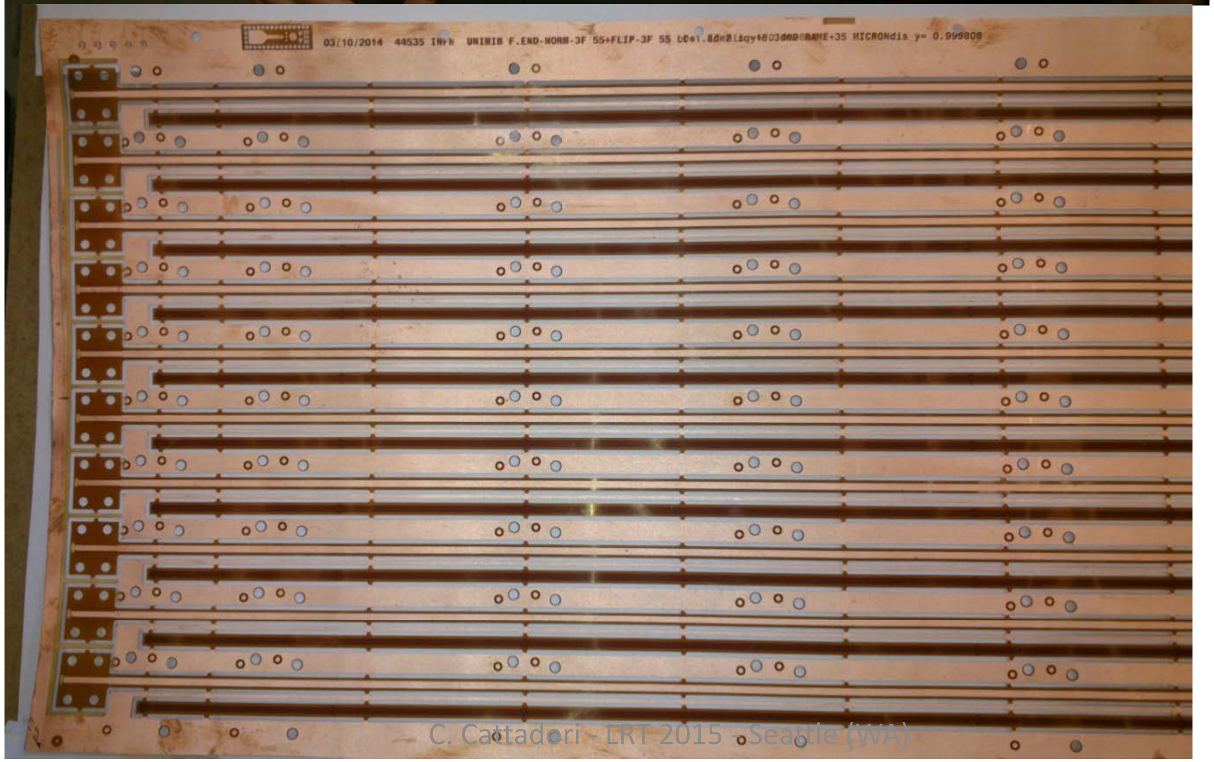
		HV (Pyralux 2 mils)
Mass of FE circuit		0.06 g/10 cm
U-238		0.2 uBq/10 cm
Ra-226		0.36 uBq/10 cm
Th-232		0.034 uBq/10 cm

FE Ribbon cables





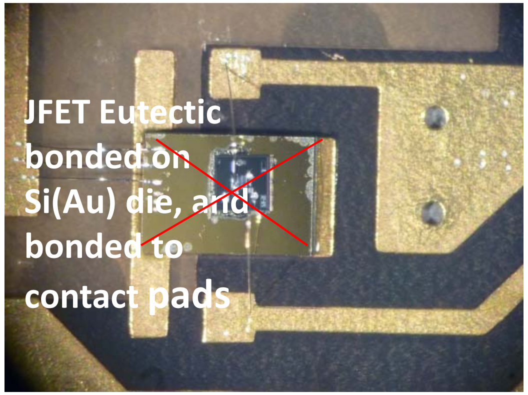
HV-Flex strips

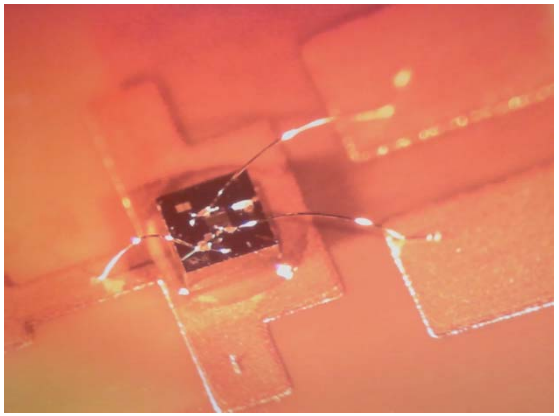


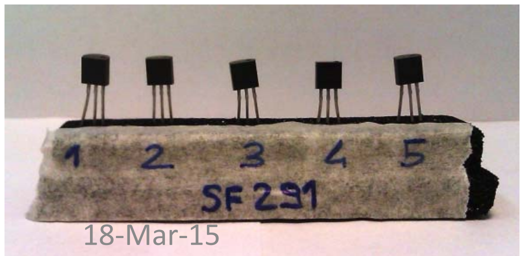
JFETs

So far adopted SF291 as FE JFET

Operated at ~0.5 mA, it has a transconductance of 5 mA/V and the gate voltage is negative





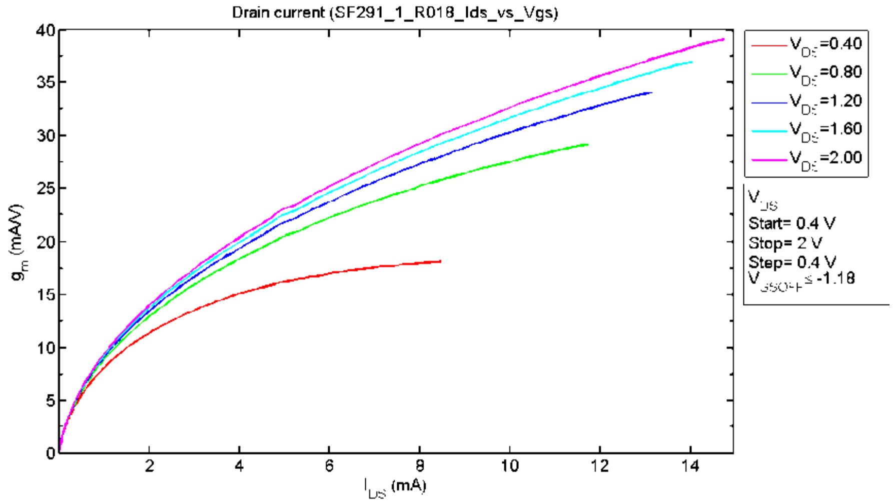


PRO

- ✓ Noise OK
- ✓ g_m OK
- ✓ C_{in} OK
- ✓ Activity OK
- ✓ Comes in die

CONS

- no top gate contact (solved)
- negative V_{GS} → no possible to protect the device by diode reverse pol mounting



		JFET uBq/pc γ-screen	Araldite uBq (5mg)
Th-232	Ra-228	< 2.2	2 x 10^{-3} (30%)
	Th-228	< 4.5	
U-238	Ra-226	1.3 ± 0.4	2 x 10^{-3} (30%)
	Th-234	< 16	
	Pa-234m	< 58	

Feedback R: present choice SMD miniaturized (500 MOhm)

Size	Th-234 [uBq/pc]	Ra-226 [uBq/pc]	Th-228 [uBq/pc]	K-40 [uBq/pc]	Pb-210 [uBq/pc]
0603 0.48 mm^3/pc 1.33 mg	4 ± 2	1.9 ± 0.3	0.6 ± 0.2	10 ± 4	46 ± 5
0402 0.153 mm^3/pc 0.6 mg/pc	2 ± 1	0.7 ± 0.1	0.2 ± 0.1	< 2.6	32 ± 3
BI no veto **BI w. veto**		**4.1E-4** **3.4E-5**	**1.7E-4** **3.4E-7**		

R&D on custom R (0.5-1.0) GOhm:
- **Amorph Ge**
- **TiN**
- **Gold or W**

Deposited on quartz substrates ongoing

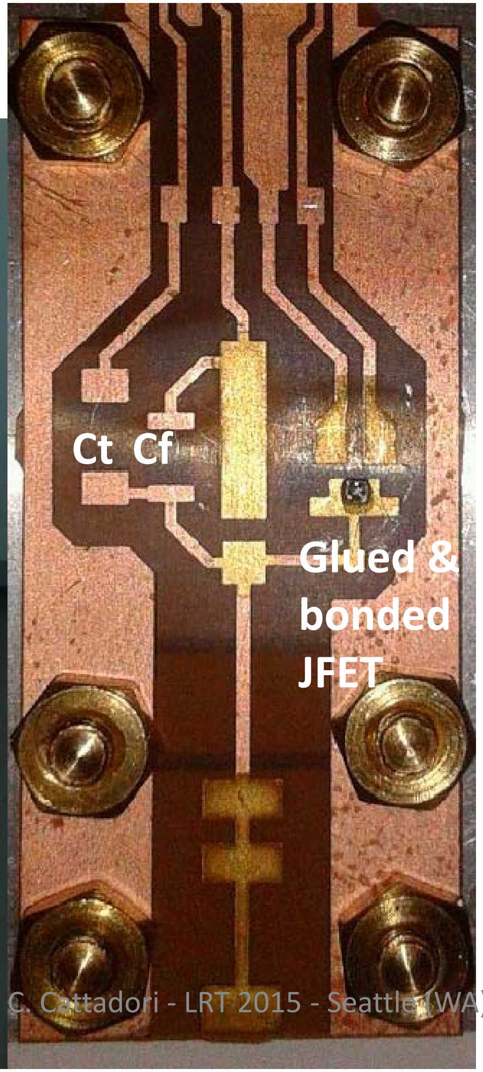
Th & Ra scale with Volume as expected

K lower than expected

Pb-210 doesn't scale with volume → probably from the contact pads

The activity of the R in 0402 size is within the expected activity of the Signal Flex cable

Test of FE flexes at MiB



Signals from GERDA II FE Ribbon Cables & CC3

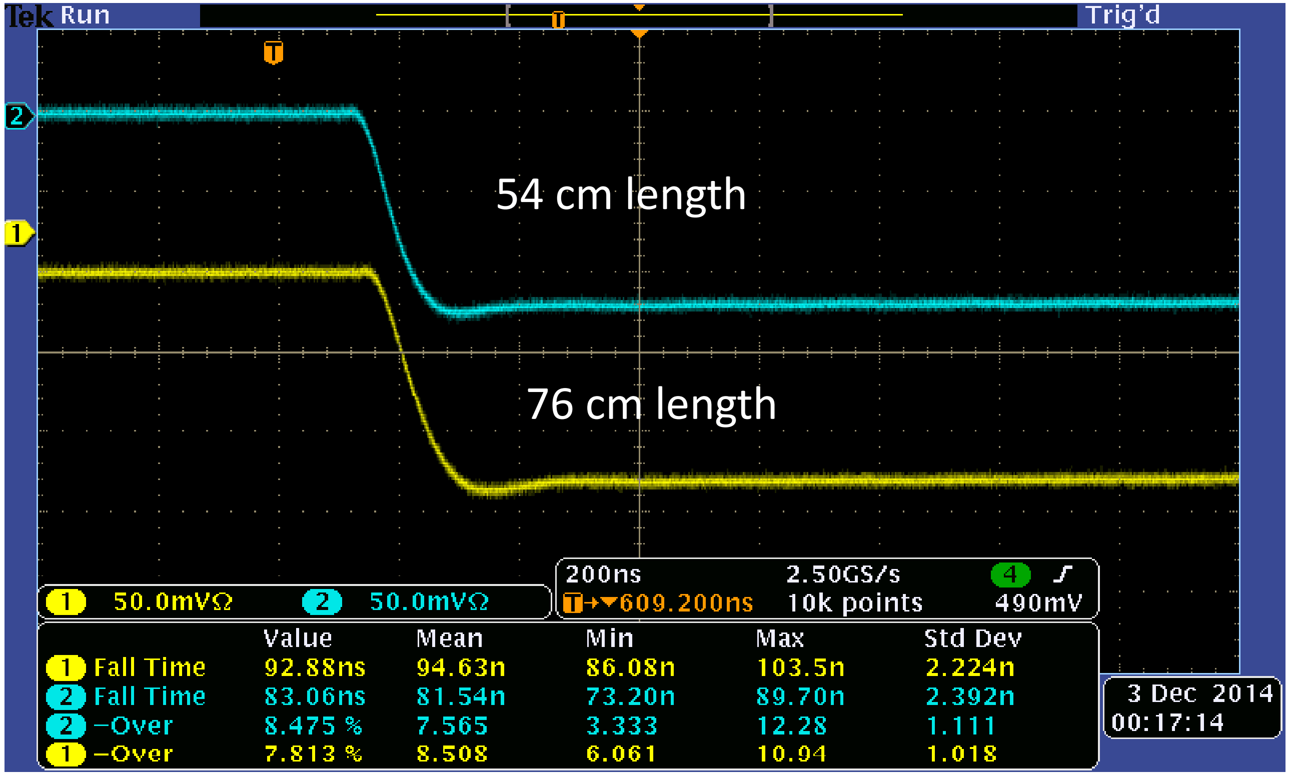
Inserire forma d'onda vera segnale BEGe

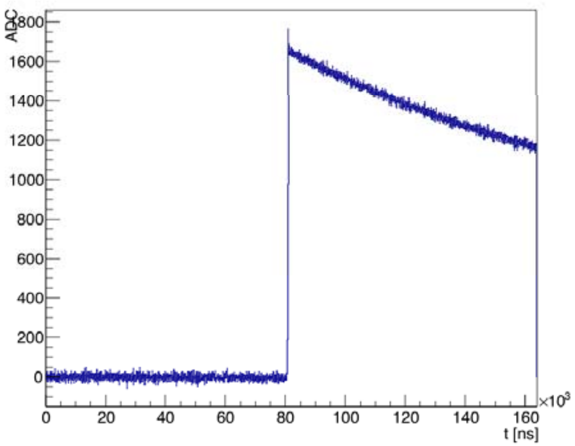
- CC3
- FE Kapton & Cuflon Ribbon cables
- die JFETs
- Rf=500 Mohm SMD (0402 size)

Achieved

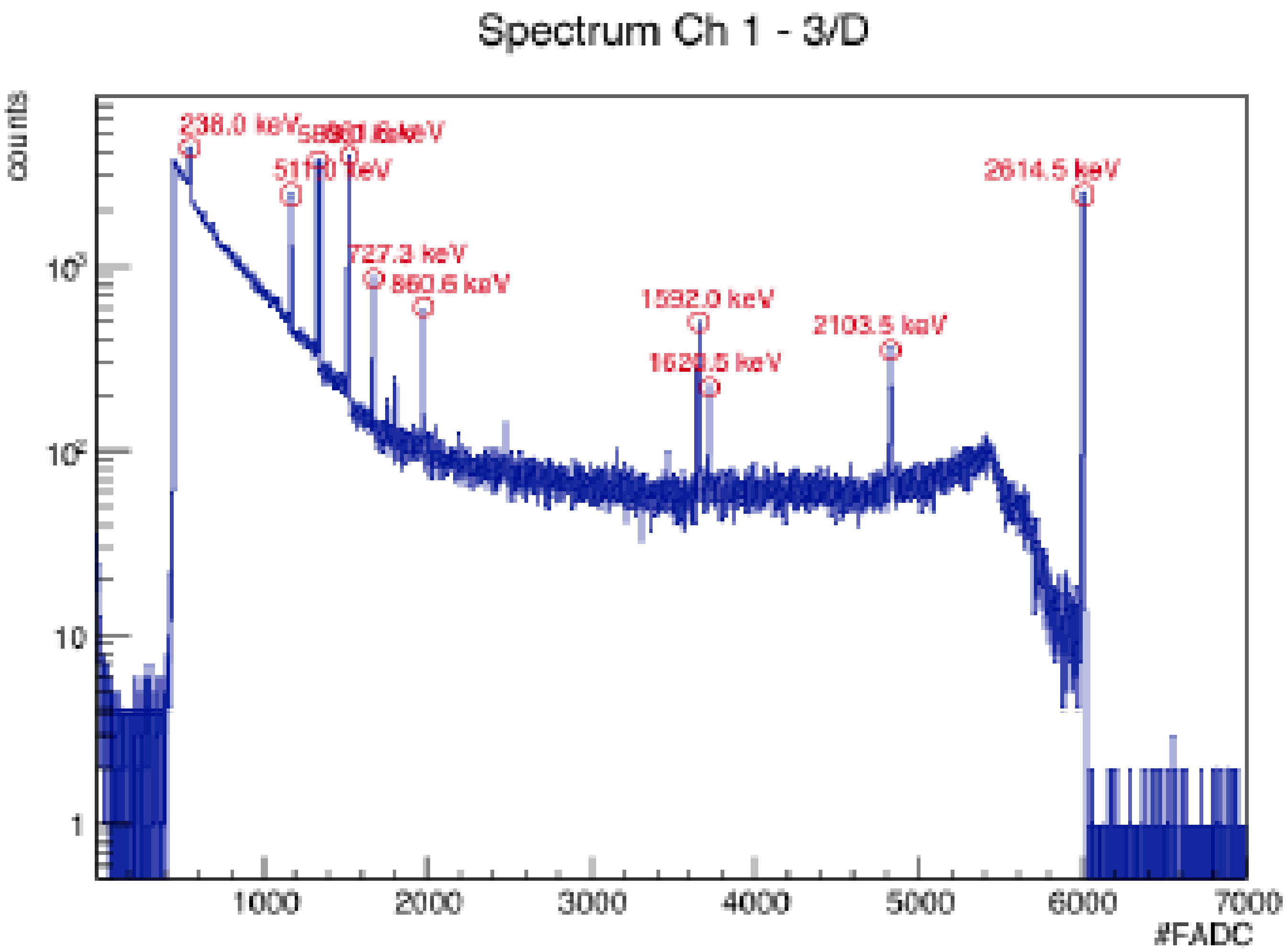
- **RT < 100 ns**

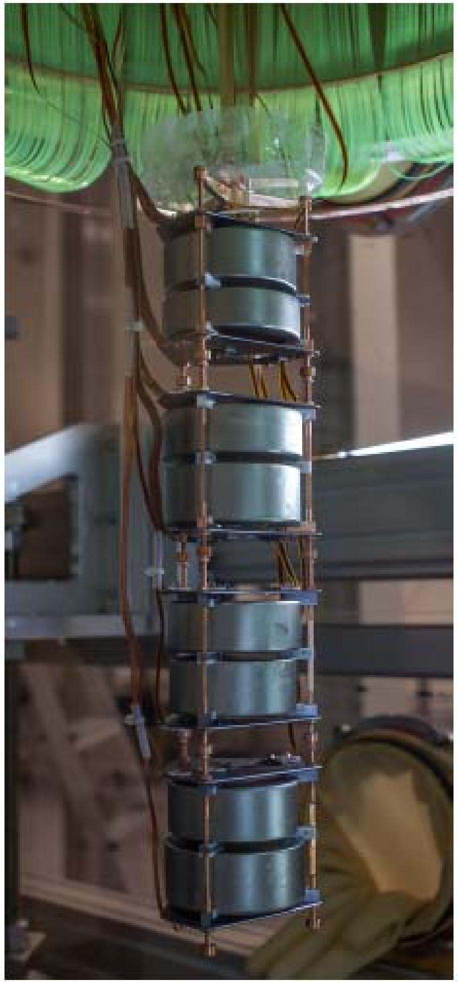
OK for BEGe PSD

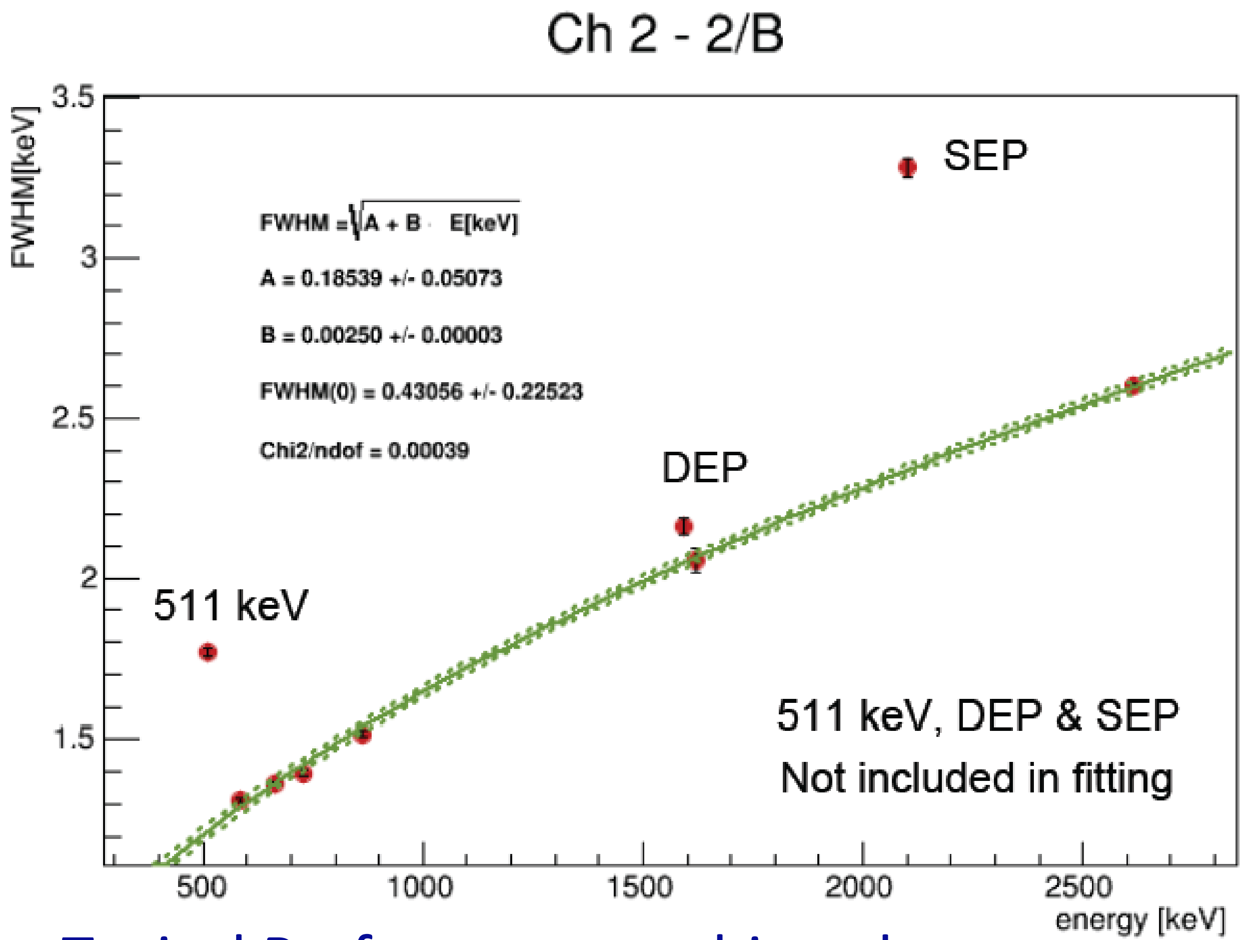


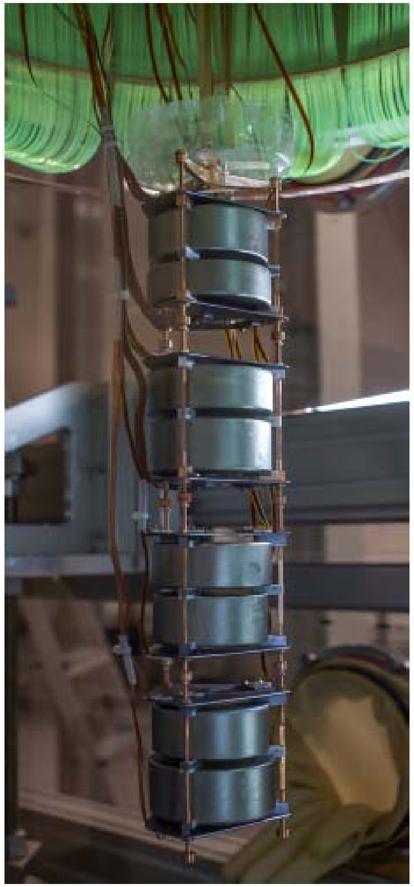


Performances achieved in GERDA Commissioning Run









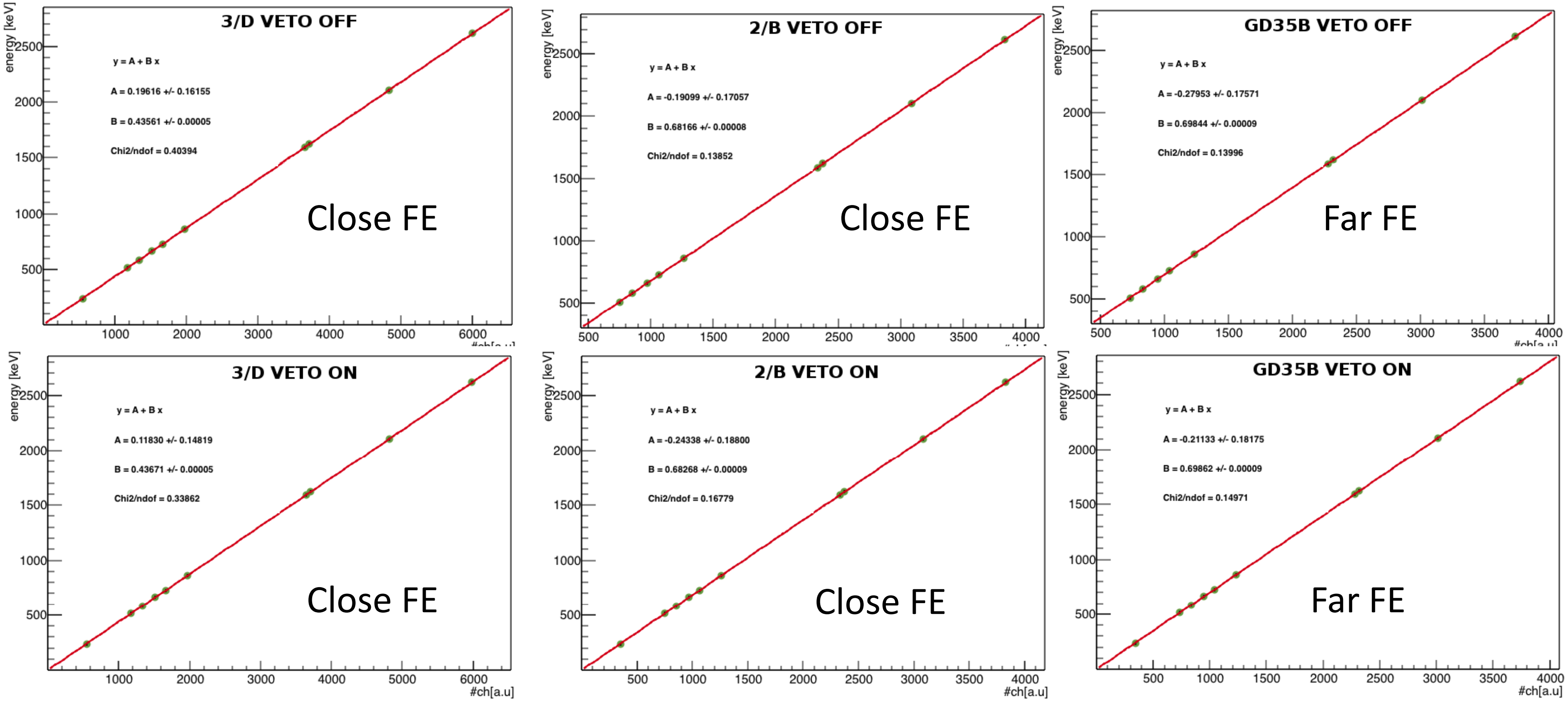
Typical Performances achieved in GERDA Commissioning run

	ZAC		Gaussian	
Detector	FWHM(0) [keV]	B [eV]	FWHM(0) [keV]	B [eV]
2/B	0.43 ± 0.22	2.50 ± 0.03	1.3 ± 0.3	2.3 ± 0.1
GD35B	1.31 ± 0.39	2.61 ± 0.10	1.8 ± 0.3	3.0 ± 0.1

Peak [keV]	Jan 2015 FWHM [keV]	Feb 2014 FWHM [keV]
583	1.76 ± 0.01	1.50(0)
DEP	2.50 ± 0.03	2.14(2)
1620	2.30 ± 0.05	2.12(3)
SEP	3.54 ± 0.05	3.32(3)
2614.5	2.80 ± 0.01	2.71(1)

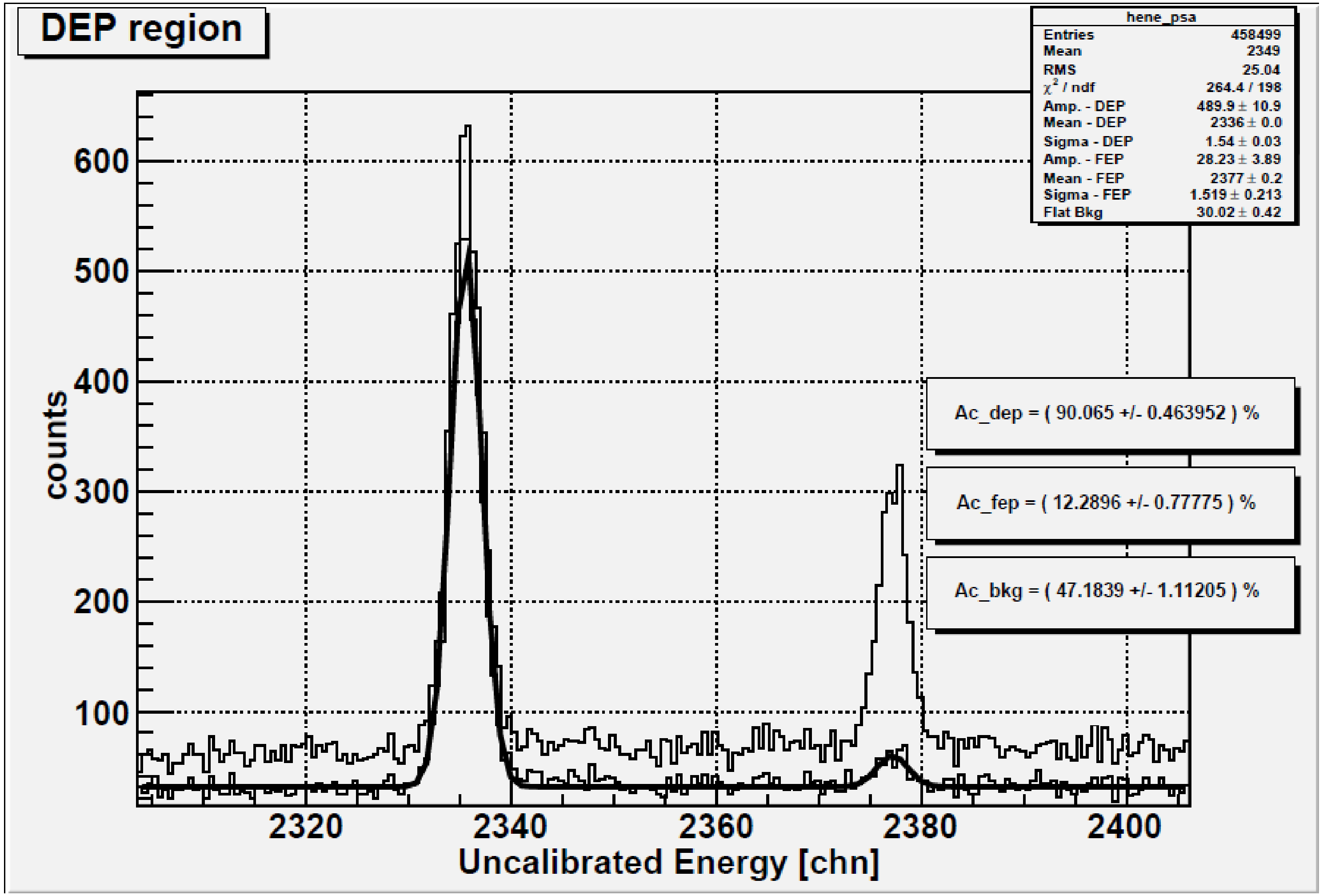
$B_{stat} = 2.35^2 \times 2.96\ eV \times 0.13 = 2.13\ eV$

Linearity of the energy scale in GERDA II Commissioning

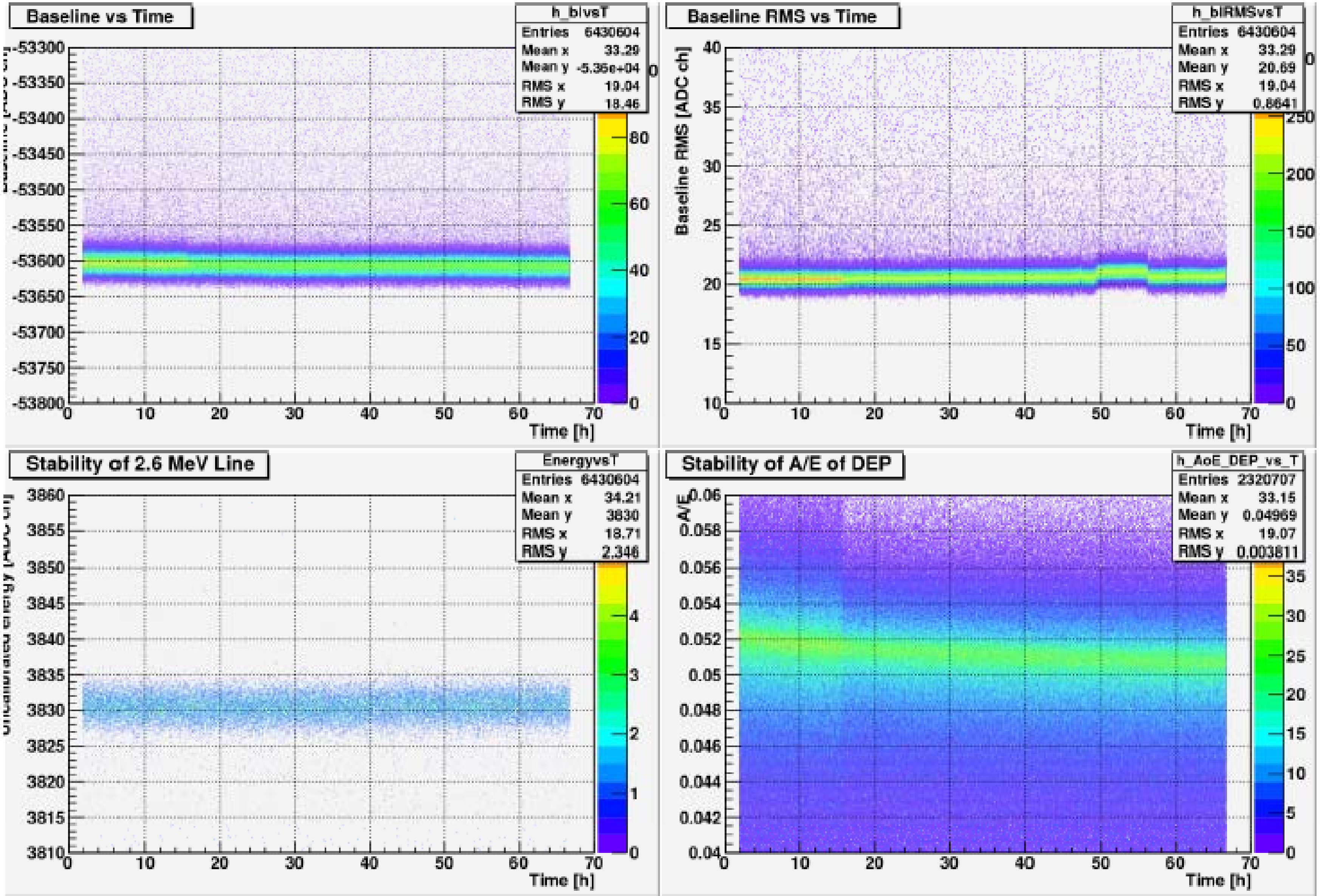


- Linearity during January 2015 commissioning run
- Comparison of VETO ON vs VETO OFF: no visible variation of gain

Typical survival fractions after pulse shape discrimination in GERDA II Commissioning.

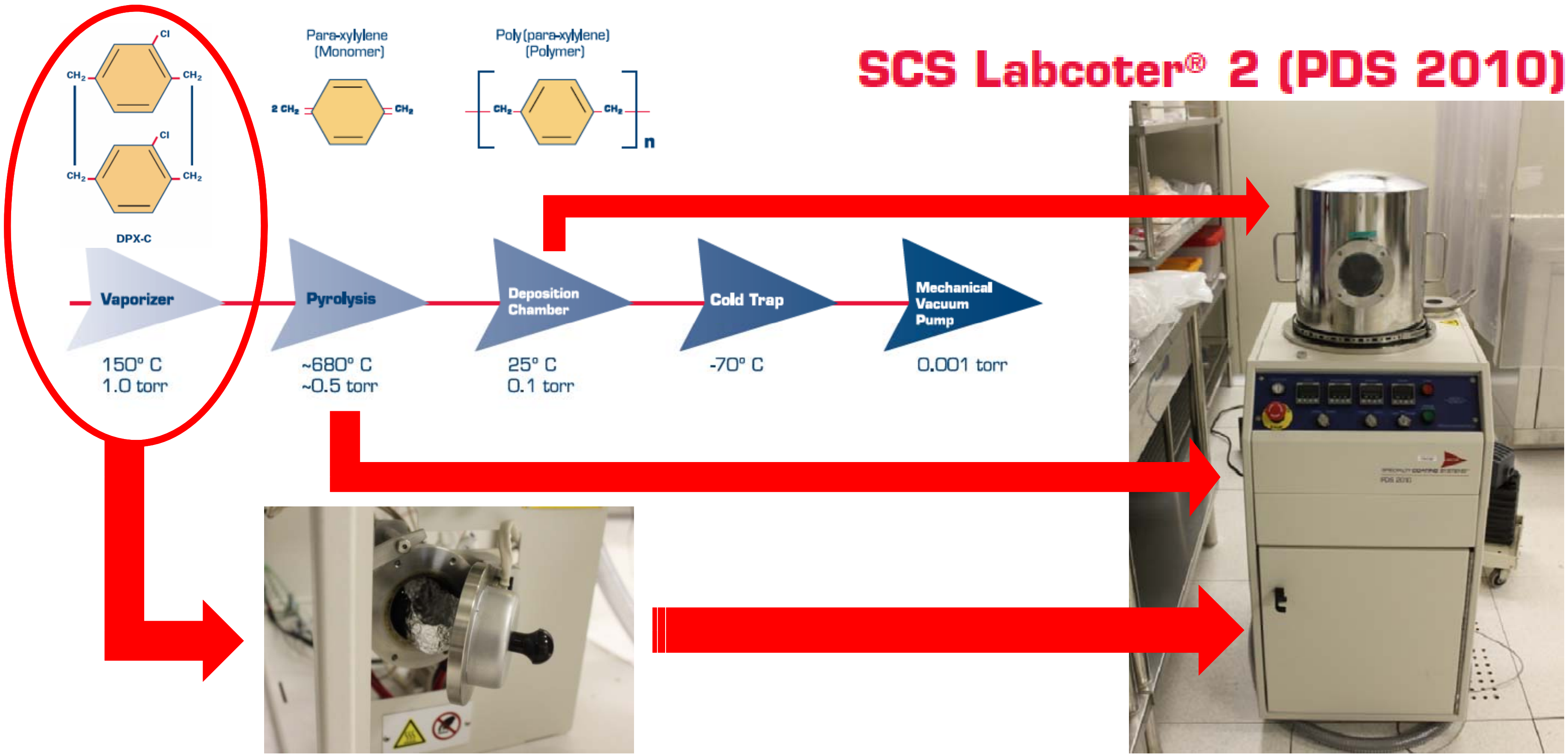


Stability of 2/B from 06.02.2015 - VETO ON



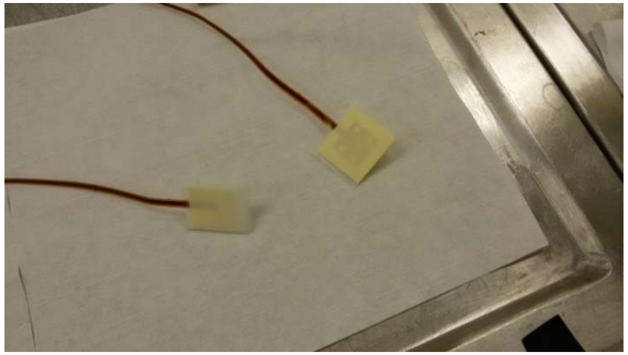
Flex circuit conformal coating: Parylene deposition system available @ LNGS

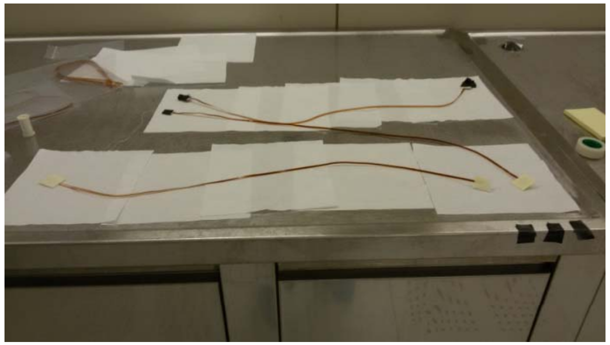
The PDS 2010 transforms Parylene dimer to a gaseous monomer; upon deposition the material polymerizes, at room temperature, onto the substrate. There is no intermediate liquid phase or separate cure cycle. At the vacuum levels employed, all sides of the substrate are uniformly impinged by the gaseous monomer, resulting in a truly conformal coating.

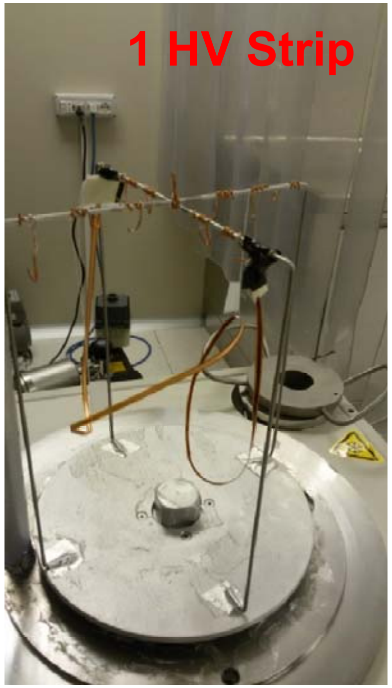


Parylene coating of GERDA flex

1) Masking is necessary to avoid electric contact insulation by parylene deposition.
2) Samples to be coated suspended into the vacuum deposition chamber (30 cm diameter x 30 cm height):







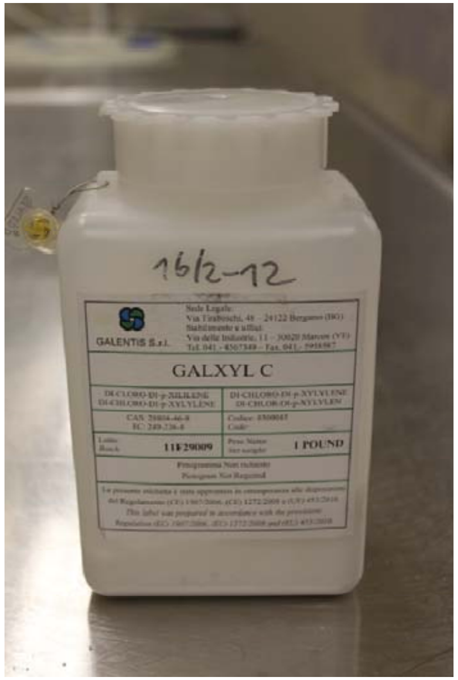
Coating thickness is controlled mainly by the amount of dimer:
≈ 20 g Parylene C for ≈ 30 μm coating in 5 hour deposition

Radiopurity of Parylene C

ICP-MS measurement @ LNGS:

	Th	U	K	Pb
GALXYL C	< 40 ppt (<1.62*10^{-7} Bq/g)	< 20 ppt (<2.45*10^{-7} Bq/g)	< 200 ppb (<26 Bq/g)	< 2 ppb

For example
1 GERDA Ph II unit= 2 BEGEs
4 GERDA Ph II units → 8 signal FLEXs



Estimated contamination due to 8 signal (or HV) cables

^{232}Th: 10 μm coating → <0.132 μBq
50 μm coating → <0.664 μBq

^{238}U: 10 μm coating → <0.2 μBq
50 μm coating → <1 μBq

^{40}K: 10 μm coating → <0.21 μBq
50 μm coating → <0.105 μBq

SUMMARY Activity Budget FE devices & Holders				Th-232				U-238			
	Mass [g]	Method	#	[uBq]	+/-	BI [1E-4]	BI w. veto [E-4]	[uBq]	+/-	BI [1E-4]	BI w. veto [E-4]
SIGNAL Flex Head	3,0E-01	MS	2	2,9E-01	30%	1,20	0,0020	1,6E+00	30%	4,6228	0,3082
Signal Tail	4,9E-01	MS	1	2,4E-01	30%	0,98	0,0017	1,3E+00	30%	3,7753	0,2517
Parylene 10 um	2,6E-02	MS	1	5,1E-03	30%	0,02	0,0000	7,7E-03	30%	0,0223	0,0015
HV Flex	2,5E-01	MS	1	1,2E-01	30%	0,50	0,0008	6,6E-01	30%	1,9262	0,1284
Parylene 50 um	5,2E-02	MS	1	1,0E-02	30%	0,04	0,0001	1,5E-02	30%	0,0445	0,0030
R feedback		GA	2	4,00E-01	50%	1,64	0,0033	1,40E+00	15%	4,0600	0,3383
			2					4,00E+00	50%		
JFET die	5,3E-04	MS	2	3,44E-02	30%	0,14	0,0003	2,6E-02	30%	0,0756	0,0063
	5,3E-04	GA		2,20E+00		9,24	0,0185	1,3E+00	30%	3,7700	0,3142
				4,50E+00		18,90	0,0378	1,6E+01			
Araldite	5,0e-3	MS	1	2,20E-03		0,009		1,80E-03		0,005	
Bronze Springs	1,2	MS	1	2,44E-01	30%	0,56	0,0016	3,0E-01	30%	0,4428	0,0583
PTFE per detector pair	3	GA	1	9,0E-02	4%	0,21	0,0006	7,5E-02	3%	0,1125	0,0148
Si per detector pair	40	GA	1	2,00E+01		46,00	0,1314	1,40E+01		21,0000	2,7632
Cu per detector pair	26	GA	1	5,2E-01		1,20	0,0034	5,2E-01		0,7800	0,1026
mini shroud	17,4	MS	0,25	0,3		0,7	0,0021	0,62		0,9351	0,1230

Limits

Conclusions

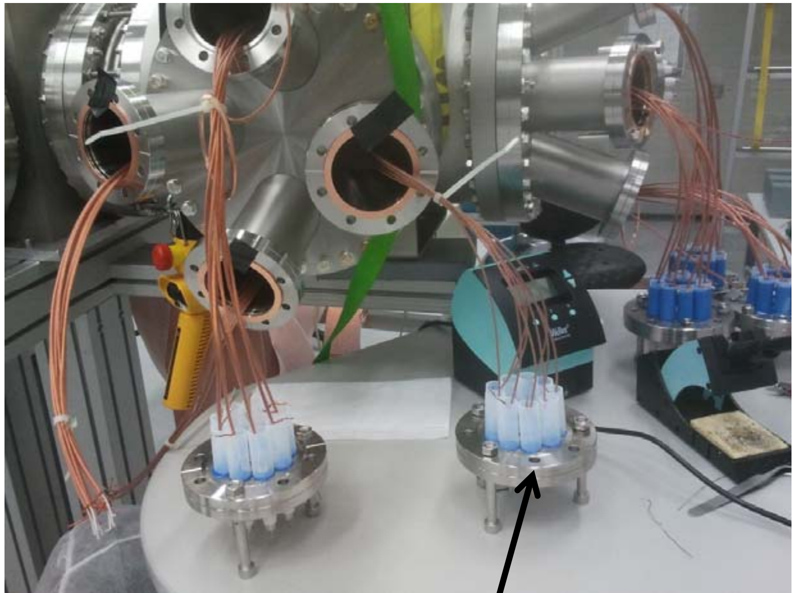
- In the framework of the GERDA setup upgrade to the Phase II, the Ge-FE electronic has been upgraded to better match the Phase II detector features with the aim of preserving the Ge signals (54 fC for 1 MeV released in Ge) from HF and LF disturbances and minimizing the intrinsic noise related to long capacitive lines
- Designed and manufactured flex circuits to contact, by wire bonding the Ge detectors and to act as substrates for the FE devices (JFET in die) and coplanar waveguides
- Results achieved are OK in term of Energy
  - (FWHM < 3 keV @ 2614 keV) and Pulse Shape analysis ,
  - not yet satisfactory in term of reliability of JFET survival fraction→ GERDA PHASE II will start with still far away front end devices
- Huge and systematic effort selecting the FE components (JFETs, SMD Resistors) and qualifying the PCB process has been done in collaboration with the LNGS facilities. This to reach GERDA Phase II design background index of 10^{-3} cts/(keV kg y) at $Q_{\beta\beta}$ (2039 keV).

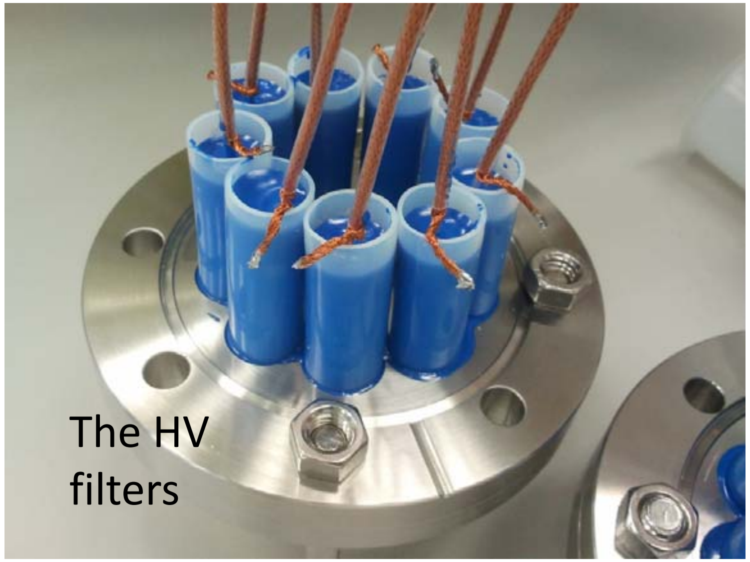
EXTRA SLIDES

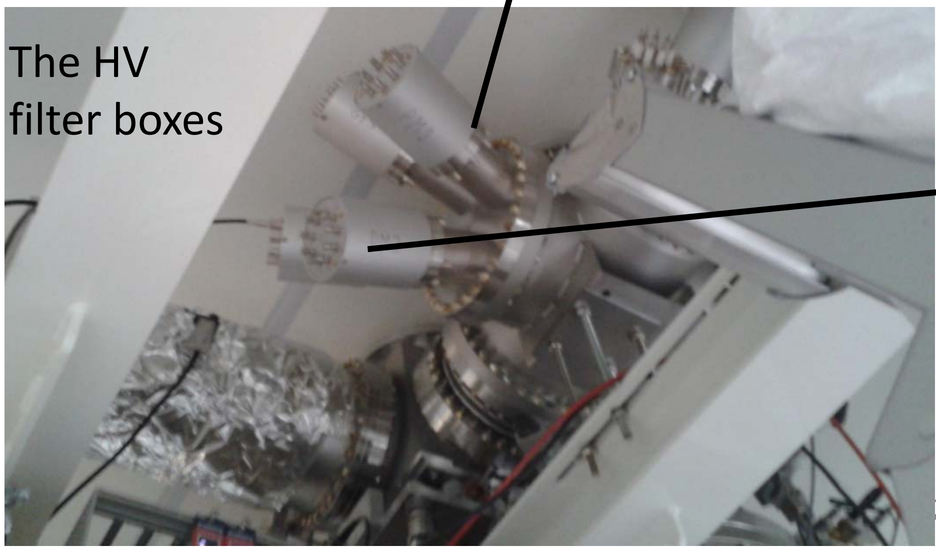
Total activity of last 1 m cable closest to detectors

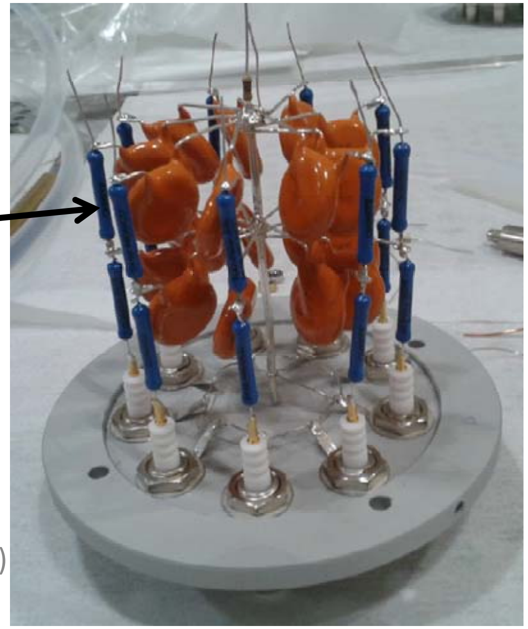
- Assuming 300 cables (100 each type), last 1 m of cable will account for a total activity of 1.5 mBq.
- Rn emanation on the woven bands < detectable limits (10 μBq)
- Thanks to high quality material outgassing 10^{-6} mbar l/sec after 24 pumping time

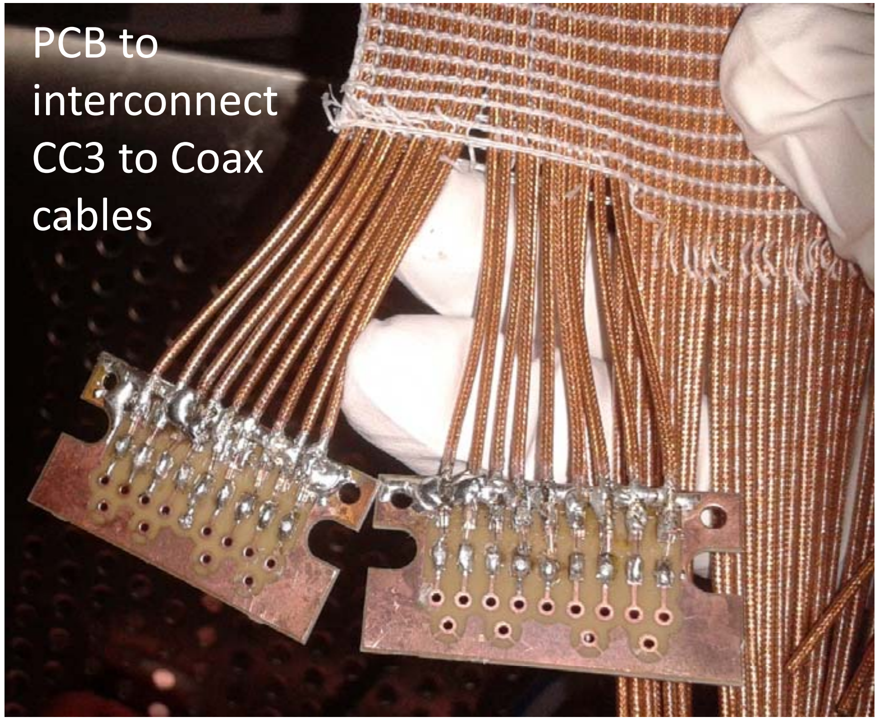
Potting the HV FeedThroughs with Blue Stycast to prevent arch effect of the HV biased surfaces operated in Ar atmosphere

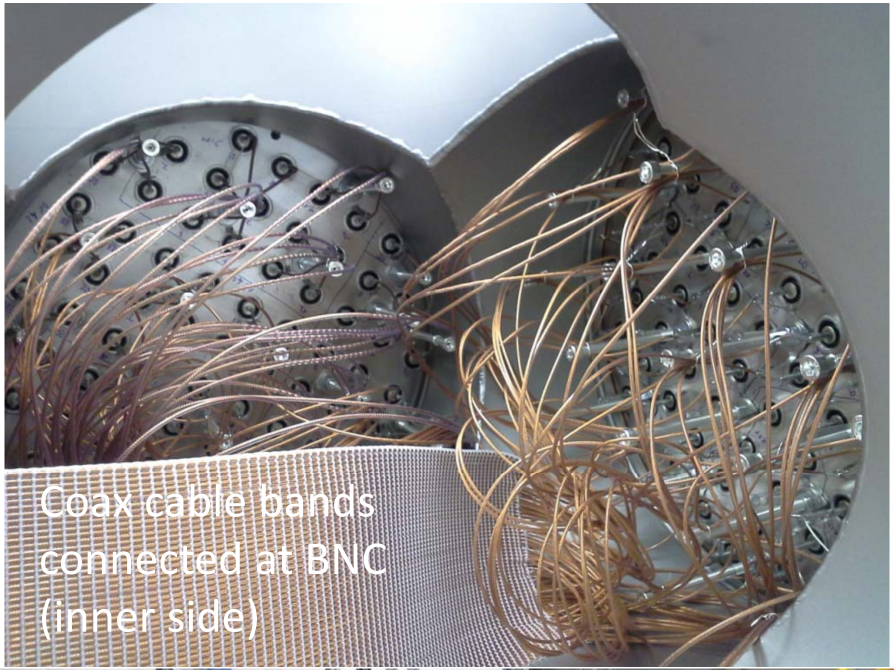


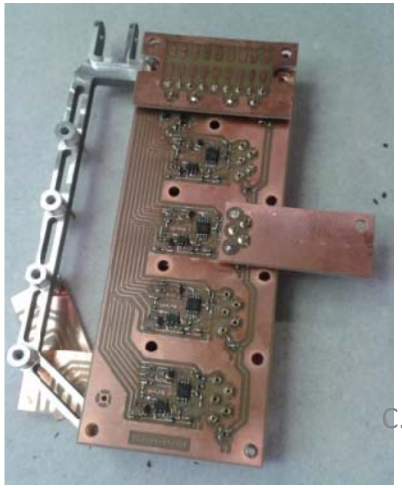


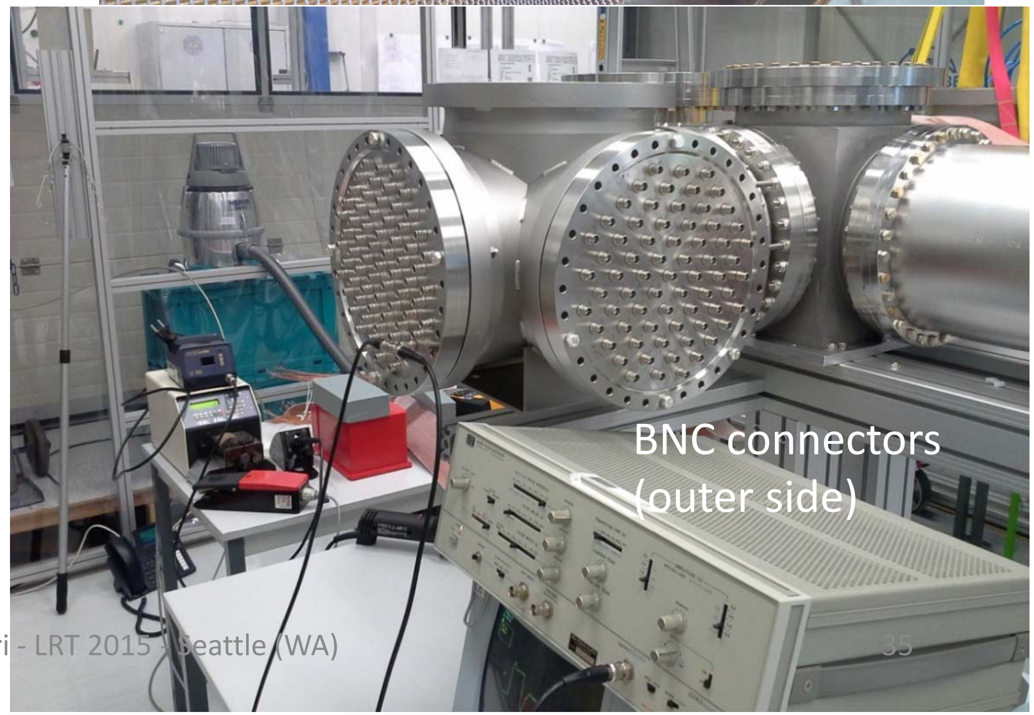




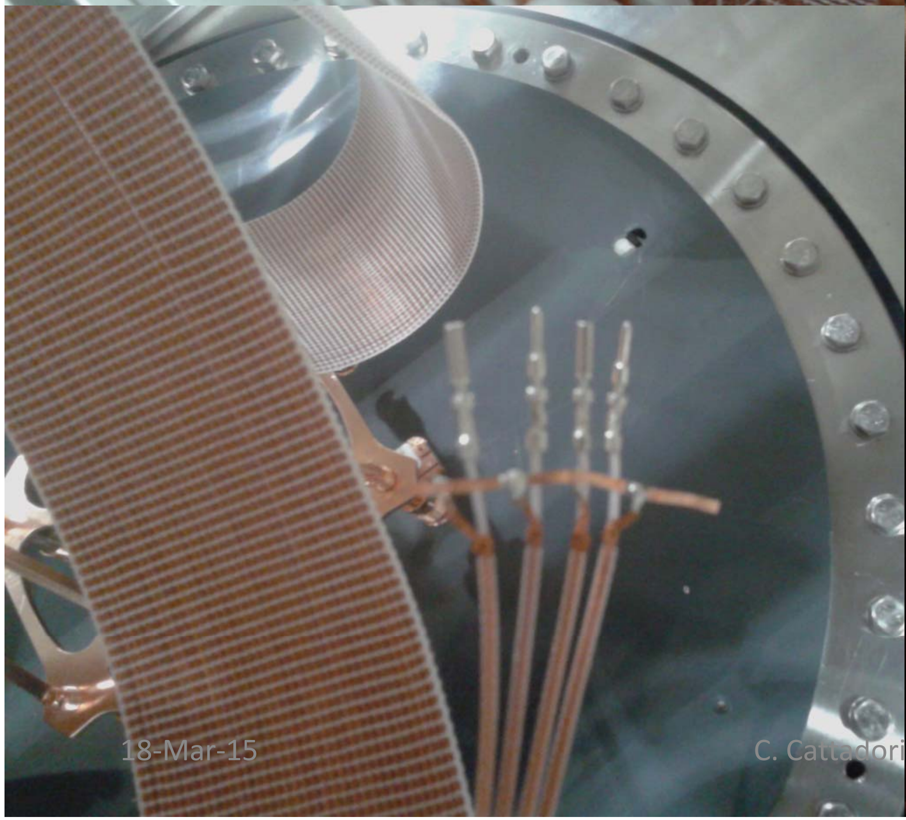

PCB to
interconnect
CC3 to Coax
cables

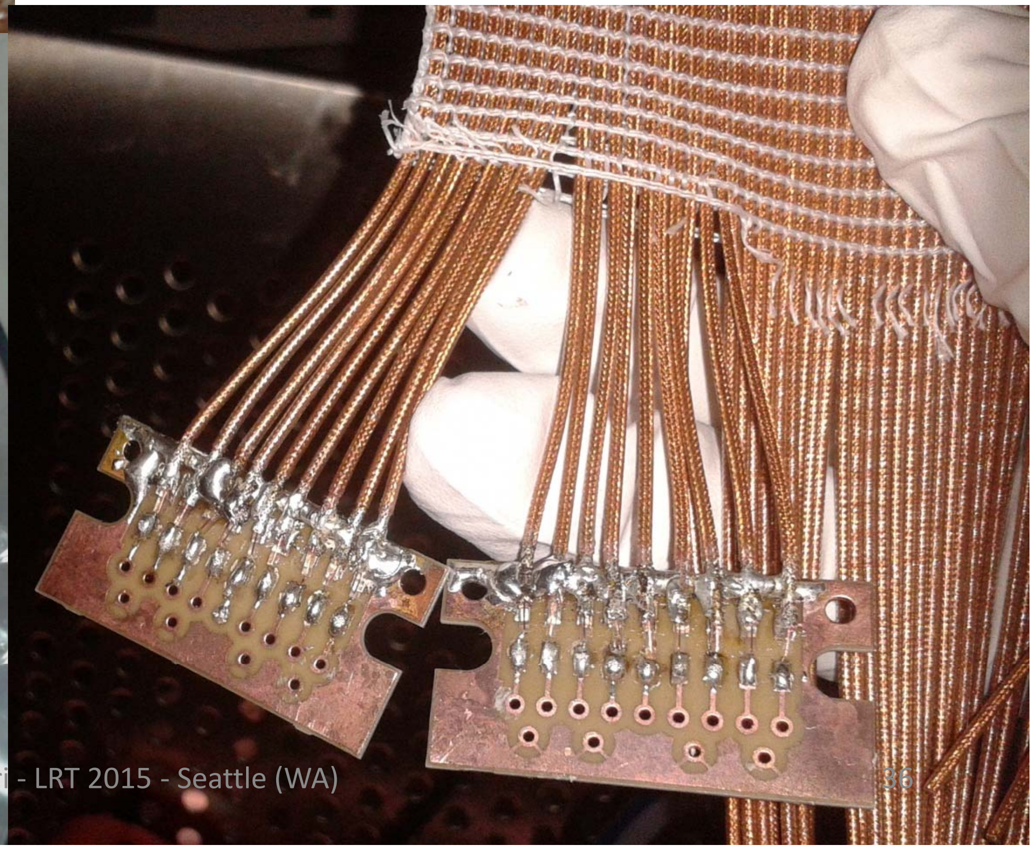

Coax cable bands
connected at BNC
(inner side)




BNC connectors
(outer side)

Signal & HV coaxial cable ends preparation





Data from: GDL Run 14/06/2014

Energy [keV]	FWHM [keV]
238	1.142+/-0.022
538	1.349 +/- 0.016
DEP 1592.5	2.175 +/- 0.027
FEP 1620.6	2.178 +/- 0.074
SEP	3.189 +/- 0.053
FEP 2614.5	2.544 +/- 0.031
Pulser	0.94

- **<u>Optimized modified butterfly (ZAC) filter</u>**
- Fitting function: gaus+gaus + pol0
- FWHM= DEP → (2.175 +/- 0.027) keV
  FEP → (2.178 +/- 0.074) keV

• Cross-Talk: ~ 1% or larger depending on load, gndind etc. : work ongoing