BERKELEY LAB Lawrence Berkeley National Laboratory

U.S. DEPARTMENT OF ENERGY

Electronics for a Future Large-Scale ^{76}Ge-based Experiment

Alan Poon [with a lot of help and contributions from members of CDEX, GERDA and MAJORANA]

Outline

- Specifications
- Technical issues
  - Cables and interconnects
  - Low noise performance in large array
- Future development

Specifications (Detectors/Signals)

- “Basic” requirements:
  - Energy resolution : < 4 keV @ $Q_{\beta\beta}$=2039 keV
  - Energy range : < ~10 MeV

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  - Energy resolution : < 4 keV @ $Q_{\beta\beta}$=2039 keV
  - Energy range : < ~10 MeV

- Both operating ^{76}Ge experiments with PPC detectors have achieved these, are there other problems?
  - Radiopurity
  - Renew design for NG ^{76}Ge experiment
  - Robustness

Specifications (ex: MAJORANA DEMONSTRATOR)

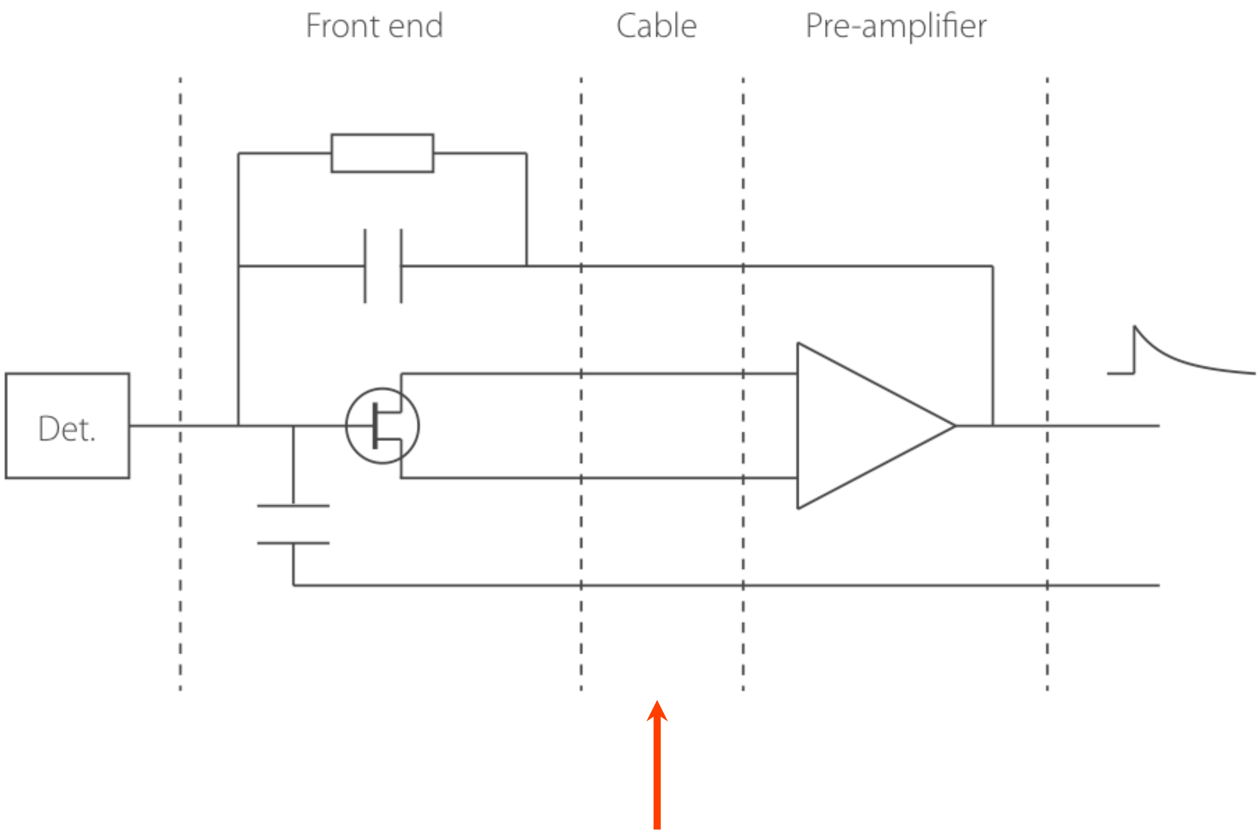
Front-end Preamplifier	
Low-Energy Threshold	Goal is <1 keV
Energy range	Up to10 MeV
Electronic noise	Goal is <300 eV FWHM
Location	Integrated into detector mount
Crystal to preamp lead length	< 30 cm (LMFE) or 1 m (preamp)
Bandwidth	> 25 MHz
Heat load	40 mW/channel
Mass	0.3 g/circuit/channel
Substrate type	Silica or sapphire substrate

To maximize the physics capabilities, it is desirable to trigger below 1 keV:

- for tagging the 1-keV L-shell line from ^{68}Ge in $0\nu\beta\beta$ program
- for a rich low-energy physics program

Signal readout in Ge detectors

- Typical scheme (move hot components far away):



Issue: The cable length is of the order of 1-2 m now,
but may be much longer in a large scale 76Ge experiment

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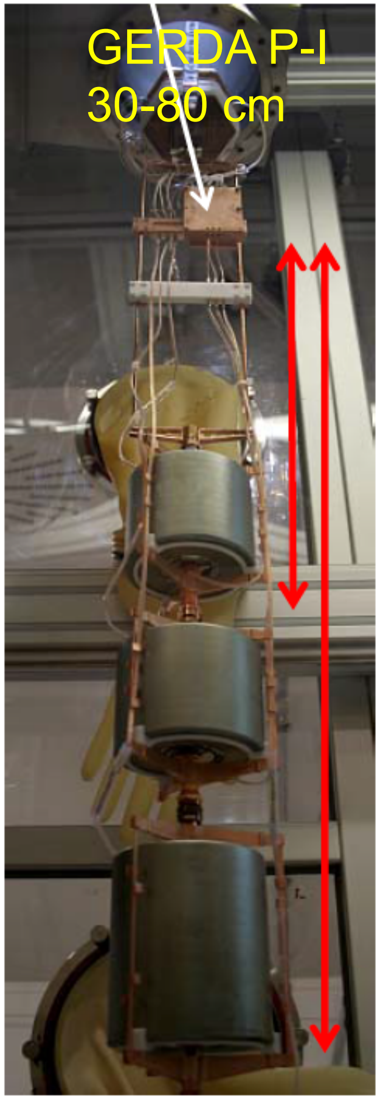
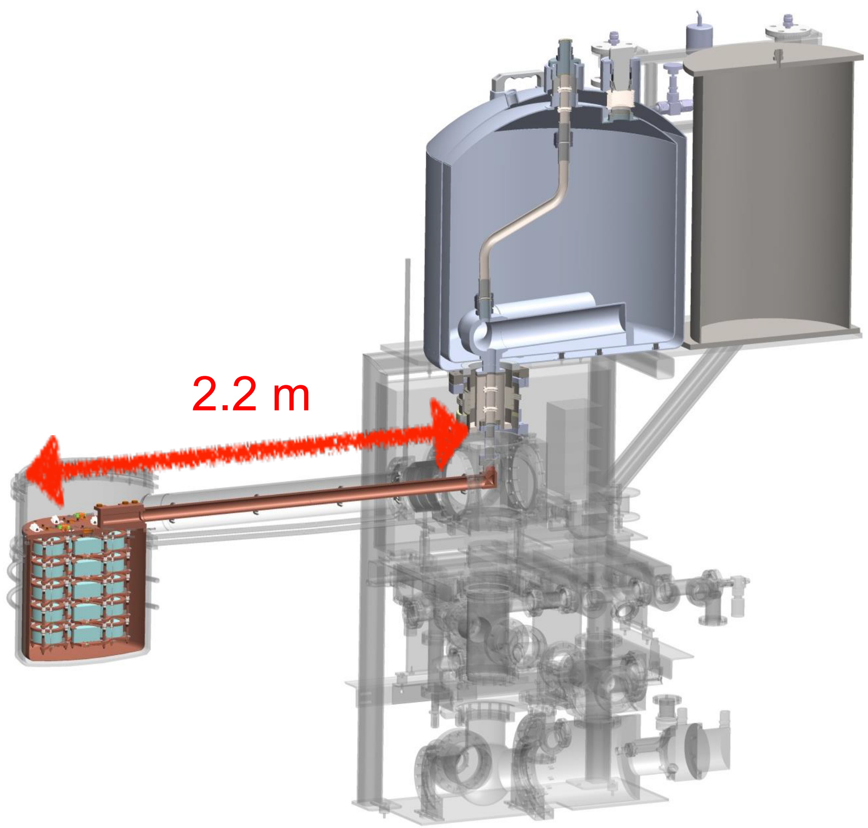
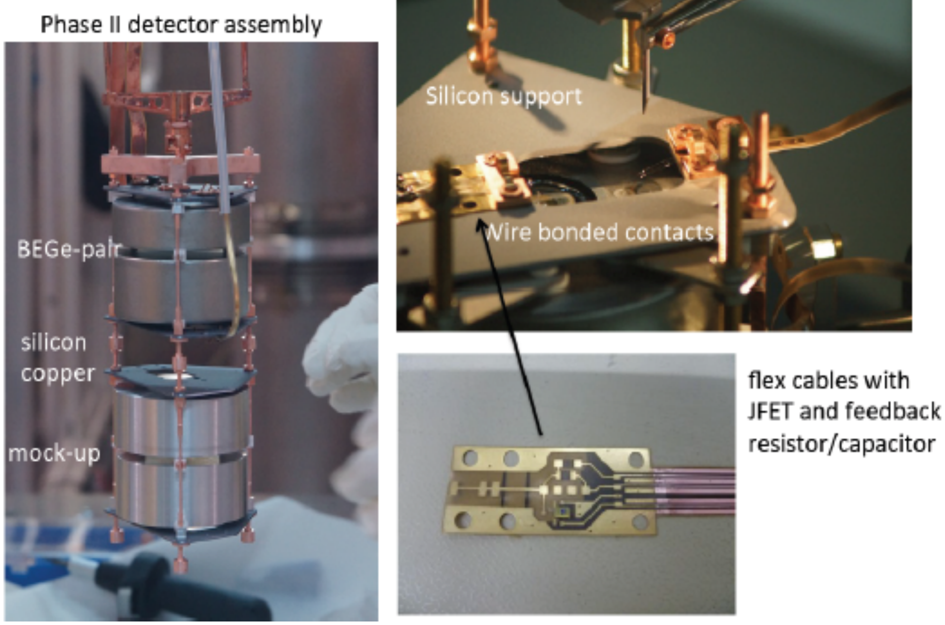




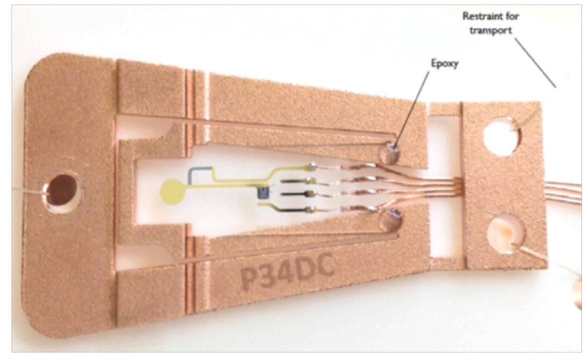
MAJORANA

Signal readout in Ge detectors

- Materials close to the detectors as clean as possible:



GERDA



MAJORANA

Radiopurity of typical electronics components

500 MΩ SMD resistor

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

Cattadori, LRT 2015

Compare: MJD low-mass front-end ~600 nBq Th / ~90 nBq U

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Signal readout in Ge detectors

- We (GERDA & MAJORANA) thought cables and interconnects would be easy

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  We were too optimistic.

Signal readout in Ge detectors

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We were too optimistic.

"I have to say a lot of people have been asking this question. No, really. A lot of people come up to me, and they ask me. They say, 'What about the cables?' And I tell them, look, we know what cables are. We've had almost five years of all kinds of cable work you can imagine. Oh, my God, I can't believe it.…I'll tell you. First of all the cables. By the way, I love cables. It's probably my favorite topic…So, we're gonna be the best on cables, believe me." [modified from Takei's mocking of Trump]

- Radiopurity
- Signal dispersion
- Robustness of connectivity

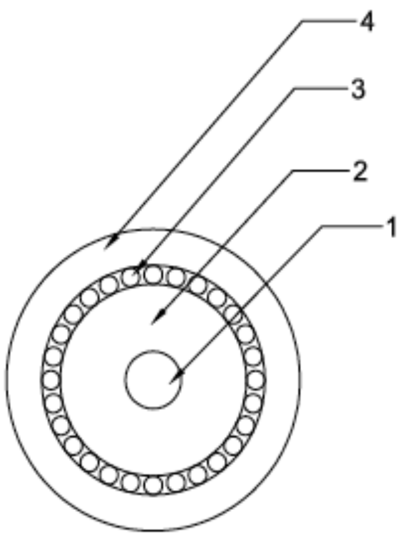
Signal readout in Ge detectors

- Cables are an integral part to the whole readout design. Different approaches in GERDA and MAJORANA

GERDA flex cables

Signal readout in Ge detectors

- Cables are an integral part to the whole readout design. Different approaches in GERDA and MAJORANA



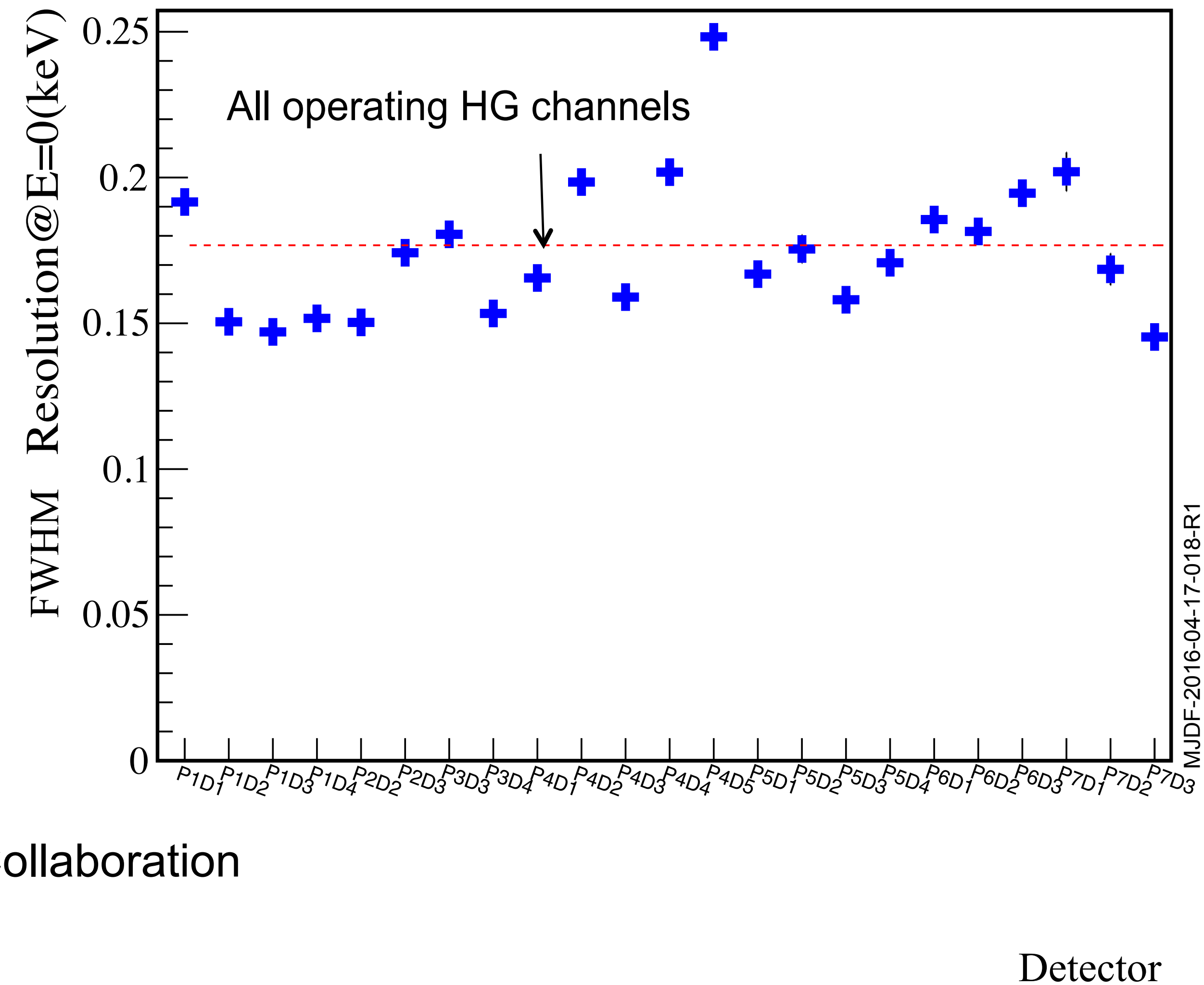
		Material	Signal	HV
1	central conductor	Bare Cu	0.0762 mm ϕ	0.152 mm ϕ
2	inner dielectric	FEP / PFA	0.254 mm ϕ	0.77 mm ϕ
3	helical shield	Bare Cu	AWG50	AWG50
4	jacket	FEP / PFA	0.4 mm ϕ	1.2 mm ϕ
Linear mass density			0.4 g/m	3 g/m

<0.085 c/t-y-ROI

MAJORANA coaxial cables

Low Noise Performance in MAJORANA

Data Set 0 resolution by detector at 0 keV
All operating high gain channels



MAJORANA Collaboration

Signal readout in Ge detectors

- Words of wisdom [Carla Cattadori]

My personal suggestion

GERDA

- Final noise achieved heavily **depends** from cable routing, detector arrangement, signal references etc.→ low noise features of CSA&JFETs could be irrelevant w.r.t. to additional noise introduced by above listed items

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Goals – Future Development

- Reduce “external” amplification electronics
- Reduce cable count
- Reduce cable interconnects (feedthroughs and connectors)

while

- Improving current background of FEE
- Improving robustness of interconnects
- Improving or maintaining low-noise characteristics

Goals – Future Development

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- Reduce cable count
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CMOS-based ASIC readout

+ can operate at lower temperature
+ will maintain low-noise performance

while

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- Improving robustness of interconnects
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Detector R&D as well

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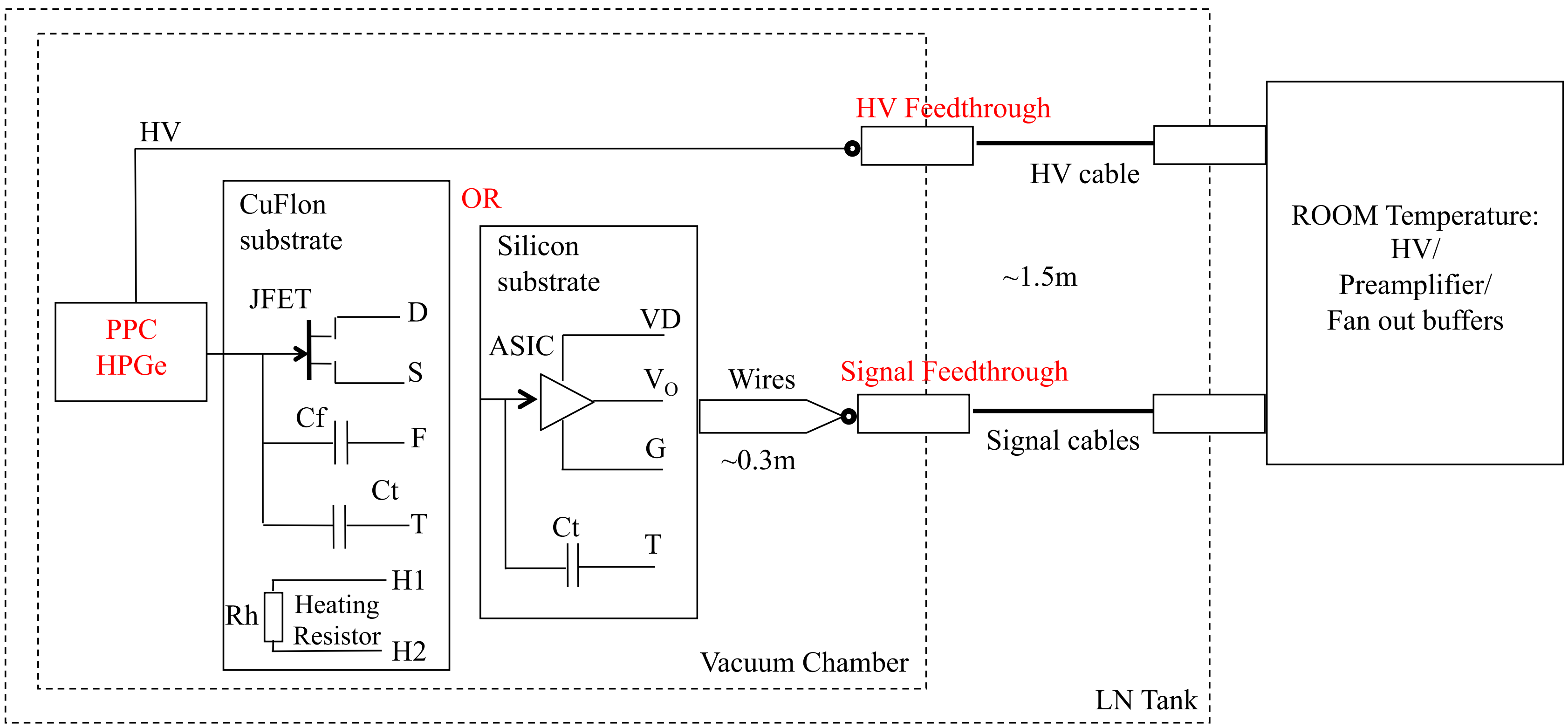
Material and fabrication R&D

CDEX - Current electronics design

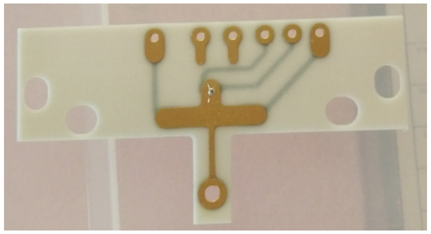
- Readout Scheme



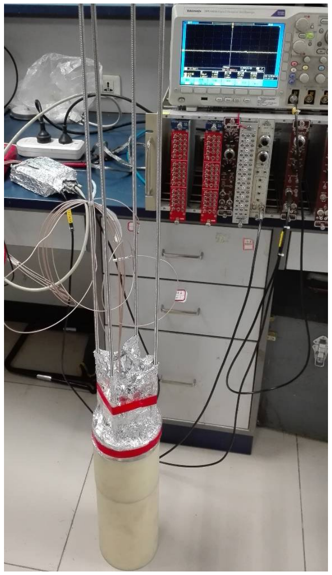
Q. Yue (Tsinghua, CDEX)

CDEX – JFET-based

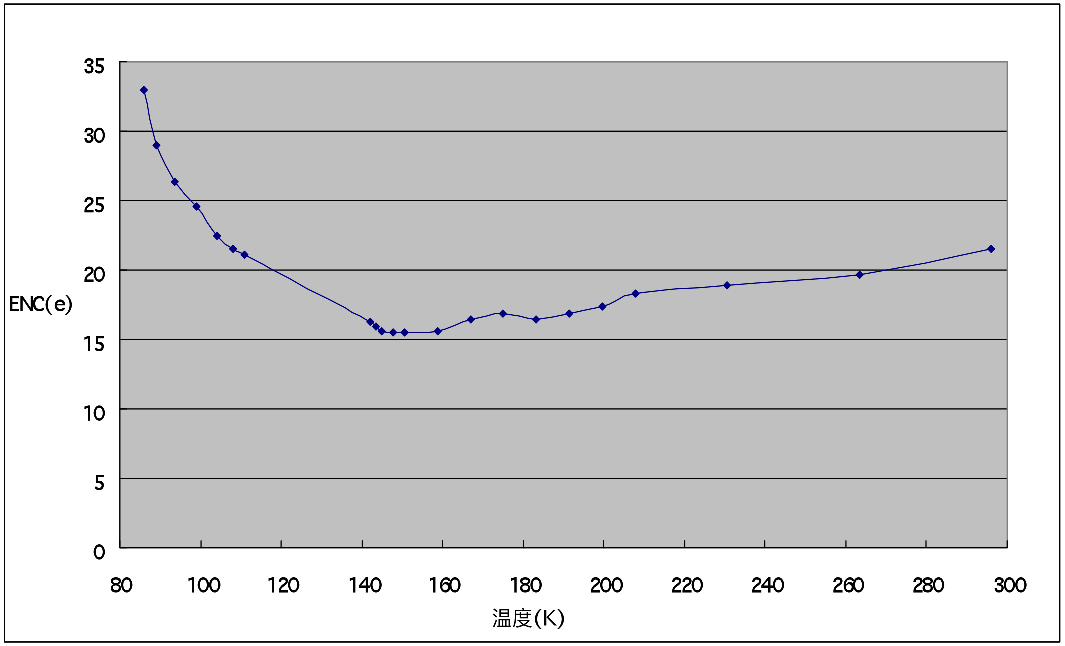
- JFET based readout



JFET bonded on CuFlon substrate



Test Setup

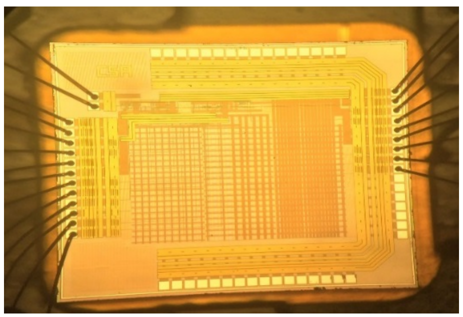


ENC @ Cd=0 vs. Temperature

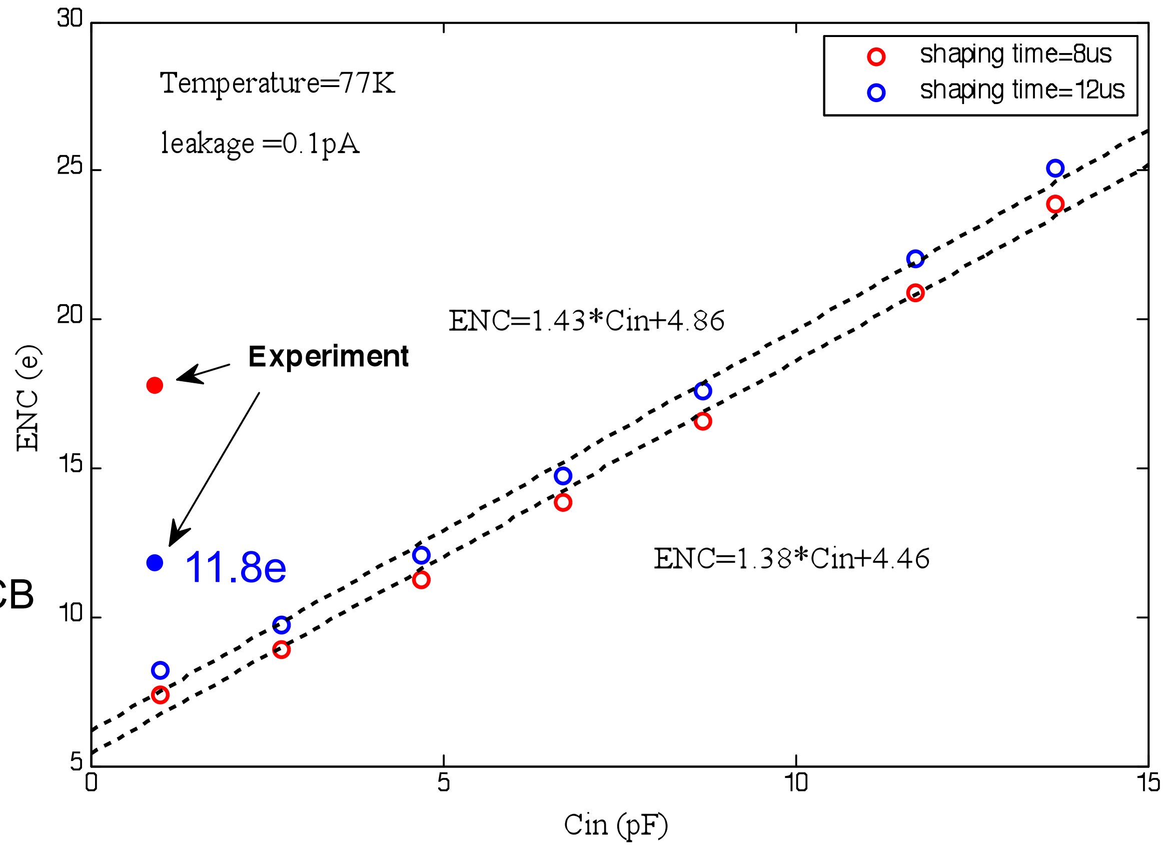
Q. Yue (Tsinghua, CDEX)

CDEX – ASIC Development

- CMOS ASIC based readout



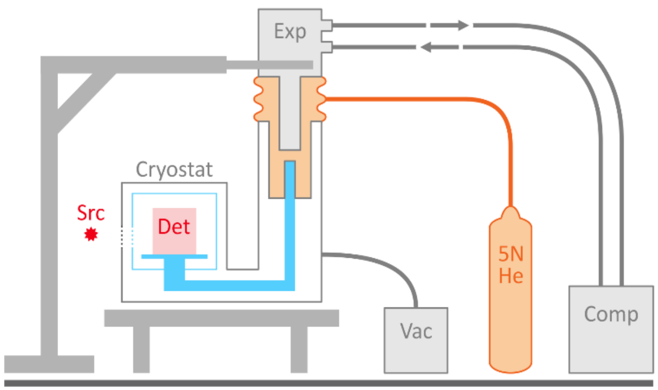
Preamp ASIC bonded on Test PCB

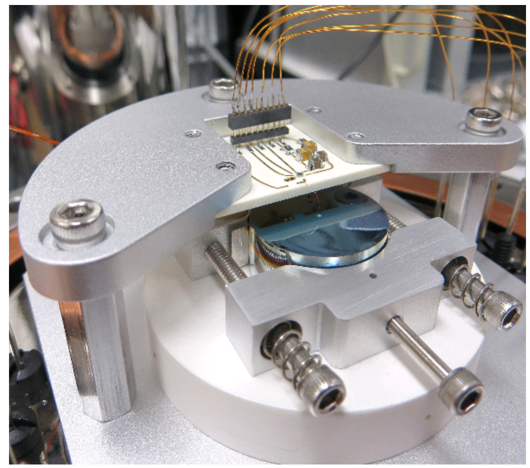


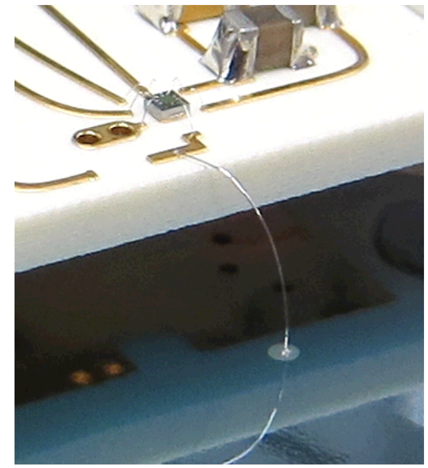
Q. Yue (Tsinghua, CDEX)

Ultra-Low Noise HPGe for Coherent Neutrino Nucleus Scattering

First: Mechanically Cooled, Wirebonded PPC HPGe, with CMOS Front End







Atmospheric Pressure He Gas

Provides ultra-low vibration thermal link using standard GM cycle (10 – 80 K)
→ Eliminates all vibrations

Ultra-Low Capacitance

Smaller point contact (0.26 pF) enabled by wire bonding
→ Ultra-Low Electronic Noise

Preamp-on-a-Chip

CMOS ASIC for SDD
4 electrons-rms noise
→ Better than JFET at low temperatures

Low temperature and **low capacitance** of CMOS and Ge.
Result: lowest noise HPGe detector: **39 eV-FWHM** at 40 K.

P. Barton (LBNL)

doi:10.1016/j.nima.2015.12.031

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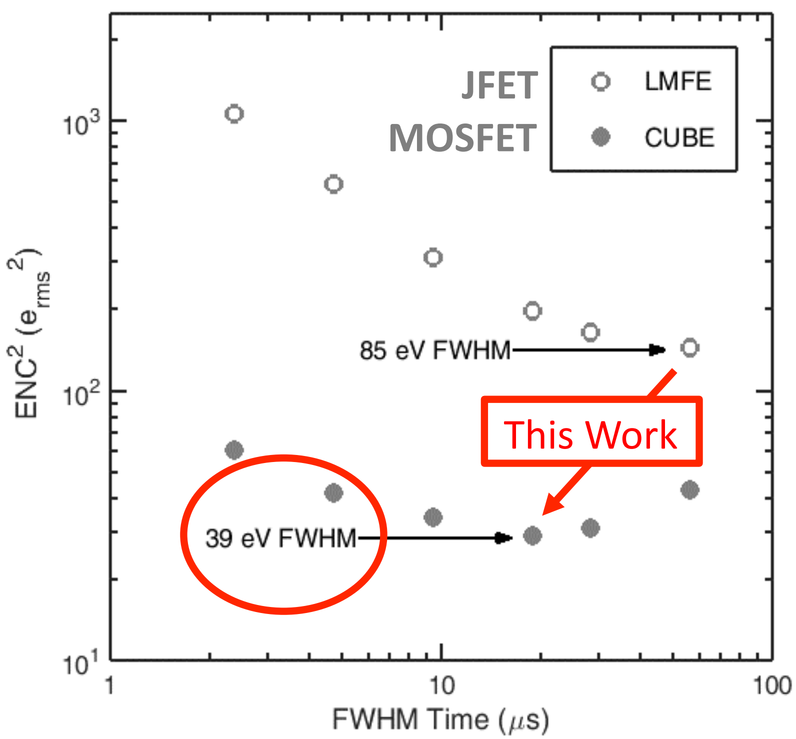
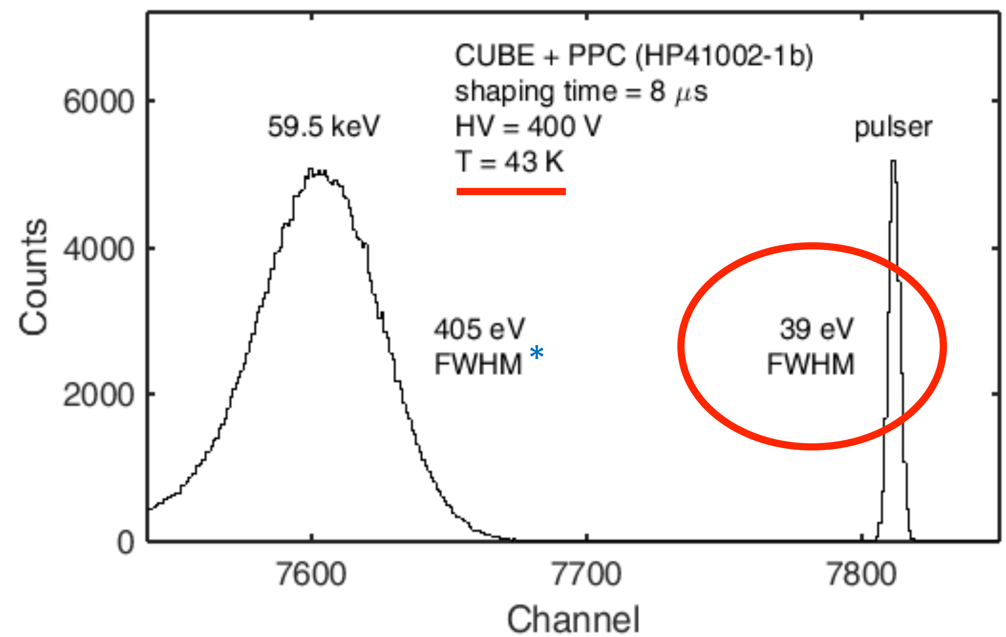
ULGeN – Ultra Low Noise Results

Equivalent Noise Charge



^{241}Am Spectrum with Pulser



* 356 eV-FWHM (Fano limit) at 90 K

All noise components improved by unique combination of **low temperature** and **low capacitance**

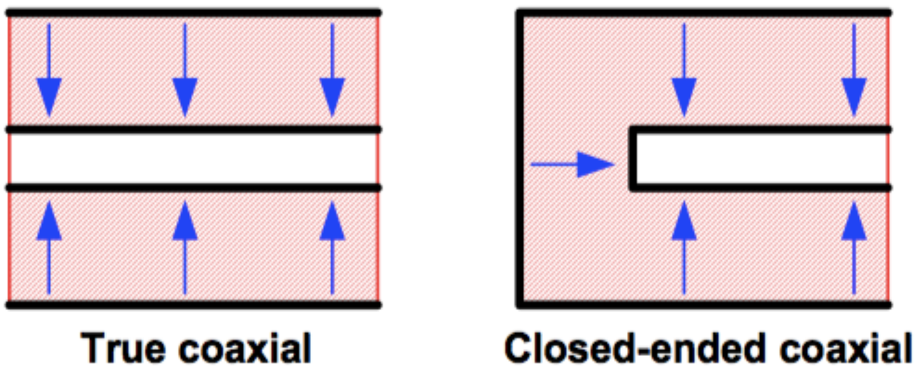
P. Barton (LBNL)

R&D Topics [opinionated version]

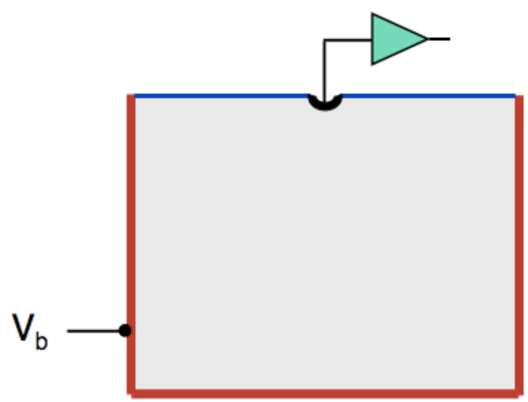
0: Long term R&D of general scientific interests
1: R&D that needs to start now
2: R&D that can start later but completed by PDR
3: R&D that can start later but completed by FDR

Topic	***0***	***1***	***2***	***3***
ASIC Development				
Low-noise ASIC bench test (temperature dep., elec. response)		■		
Low-noise ASIC external component minimization / optimization		■	■	
Low-noise ASIC tweak (optimize dynamic range)		■	■	
Low-noise ASIC operation (if bare) in cryogenic liquid or pressurized gas		■	■	

Detector Capacitance



- $C_{true\,coaxial} = \frac{2\pi\epsilon}{\ln(\frac{r_{outer}}{r_{inner}})}$
- order of ~10s pF



Point-Contact detector

- If the inner electrode is a small hemisphere of radius r,

$$C_{PPC} = 2\pi\epsilon r$$

- ~1 pF possible.
- Intrinsically low-noise detector

IEEE Trans. Nucl. Sci, 36, 926 (1989)
JCAP , 9, 9 (2007)

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R&D Topics – Low C_{det}

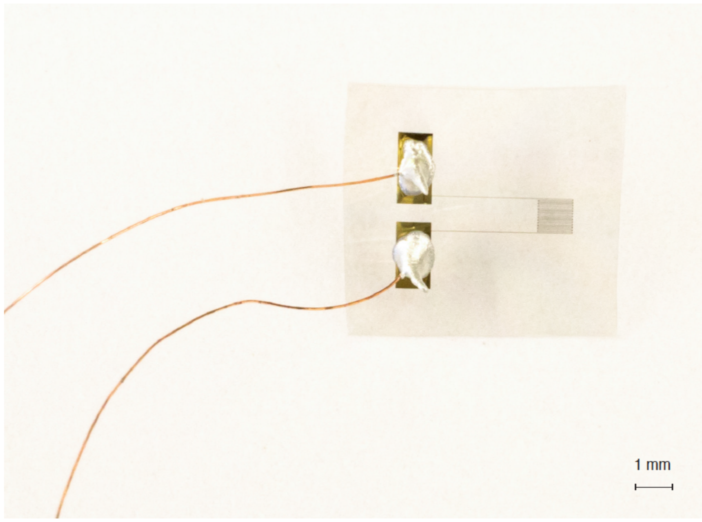
0: Long term R&D of general scientific interests
1: R&D that needs to start now
2: R&D that can start later but completed by PDR
3: R&D that can start later but completed by FDR

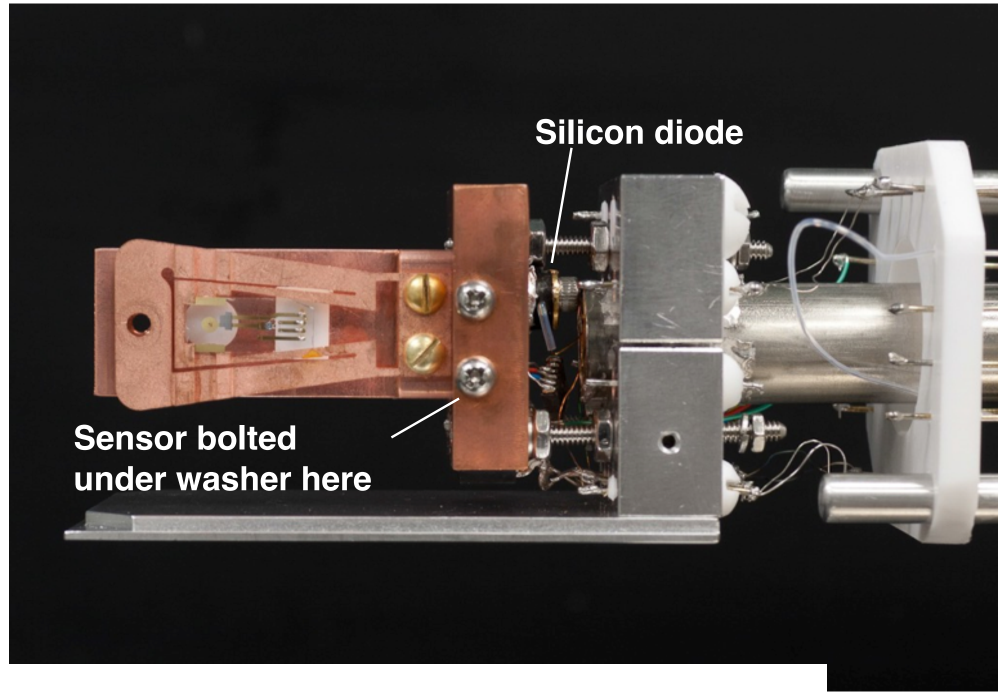
Topic	0	1	2	3
Detector and Mount Design				
Alternate detector design (e.g. 2 readout electrodes)	X	X	X	
Implement larger crystal with low capacitance (< 1 pF)	X	X	X	
Charge collection in small electrode	X	X		
Investigate unknown charge transport	X			
Alpha scanning of surface event dynamics	X	X	X	
Other material (eg. aGe) on N+ contact for low-energy verification	X		X	
Electrode metallization optimization (thickness, materials, patterning)			X	
Optimize HV contact in detector mount design			X	

R&D Topics – PCB, cable and interconnects

Topic	0	1	2	3
PCB, cable and interconnects				
Clean cable design and radioactivity studies				
Connector design and radioactivity studies				
Cable fabrication cleanliness control				
Robust method to strip/prepare cables				
Cable routing and support (compliant materials, reliable force under thermal cycling)				
Establish clean and robust cable attachment to PCB				
Identify low-background epoxies for die attachment				
Identify low-background PCB and trace materials				
PCB fabrication cleanliness control				
PCB design				
Identify clean bypass capacitors				
Cosmogenic activation studies of potential materials for BI target <0.1 (underground prod.?)				
Long-term stability and performance of components and assemblies (e.g. Cable/ASIC assembly)				

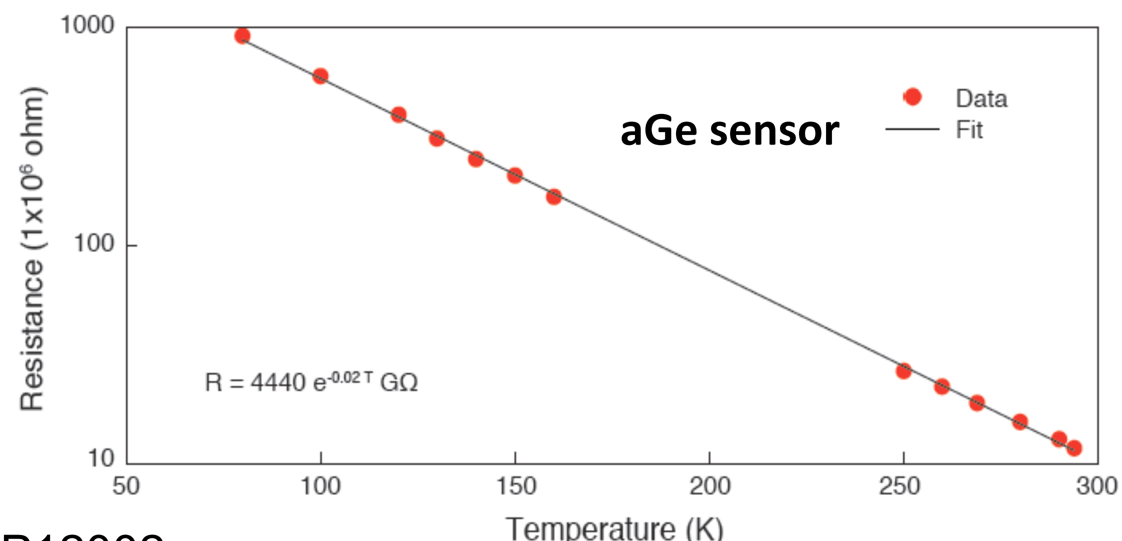
Thermal testing of a flexible temperature sensor





Parylene substrate
Trace by microfab.

Potentially a good way to make clean PCB



JINST 10 (2015) no.12, P12002

R&D Topics – Integration

Topic	0	1	2	3
Detector integration and tests				
Integration of prototype ASIC/PCB/Cable/Interface/Detector				
Full clean ASIC/PCB/Cable/Interface/Detector integration				
Long-term performance/stability test of fully integrated system				
Test multiple detector power / ground scheme (fault tolerant, noise)				
Design and implement pulser system				
Design and implement external buffer and controller				
Design and implement / or specify power supply and filtering				

Summary

- The current generation of JFET-based design is reaching its limit
- Next generation electronics and readout development will tie to detector, cable and connector, cooling and shield designs.
- Lots of work to be done

Backups and other contributions

Additional GERDA contributions from Carla Cattadori

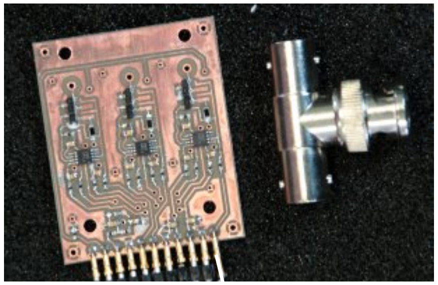
GERDA FE Electronics

C. M. Cattadori INFN MIB

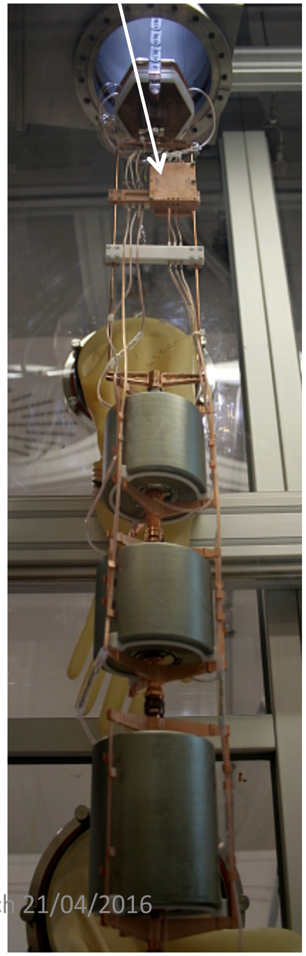
GERDA: FE Electronics

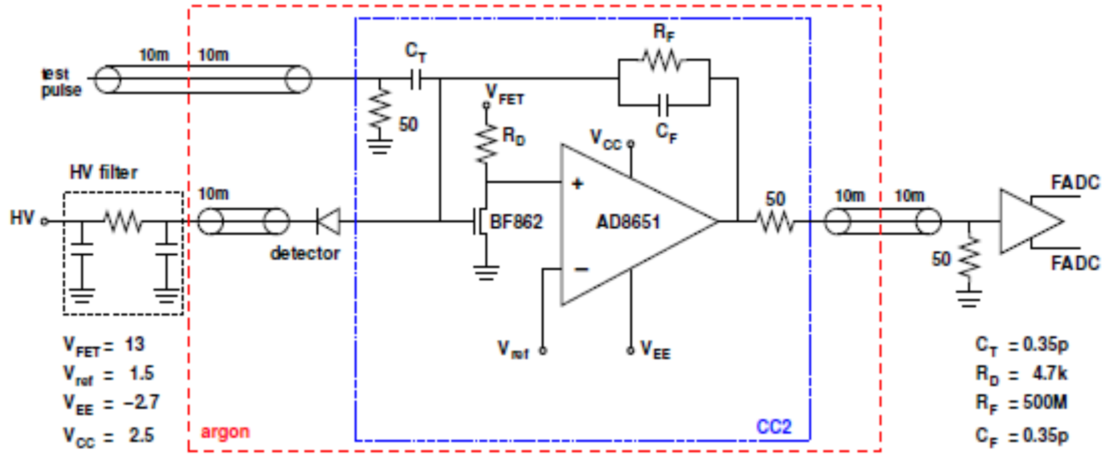
- Fully cryogenic, simple, continuous reset, reliable:

  CSA γ-spectrometry class named CC2 (GERDA-PI), CC3(GERDA- PII)
  - 150 mV/MeV(Ge) → Dynamic Range 8 MeV (PI) -10 MeV (PII) (550 fC input charge)
  - Rise Time (10%-90%) : 70 ns (PI) - 40 ns (PII)
  - Noise Level: (0.7-0.8) keV FWHM @ LN (Both FE and CSA)
  - Power Consumption:
- 3 ch PCB (Phase I) – 4 chs PCBs (PhaseII)
- Accurate selection of SMD components, both for cryogenic performances and radiopurity
- CSA based on the 2 cryogenic Op. Amp. LNT:
  LMH6654 -> Ph. 1   OPA820 -> Ph. 2
- FE Components:
  - JFET: BF862 (Cin=8-10 pF); gm=15 @ Ids=1 mA
  - RF= 500 MOhm (SMD0402), Cf~0.3 pF



GERDA Phase I

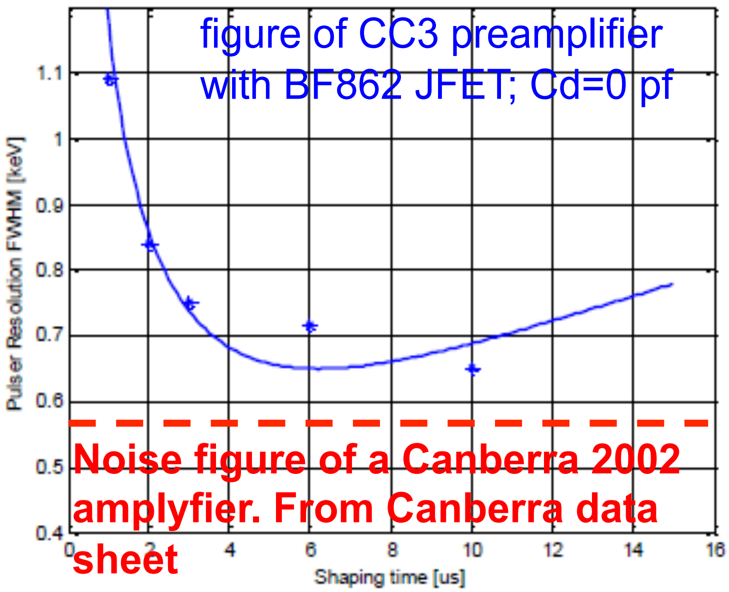




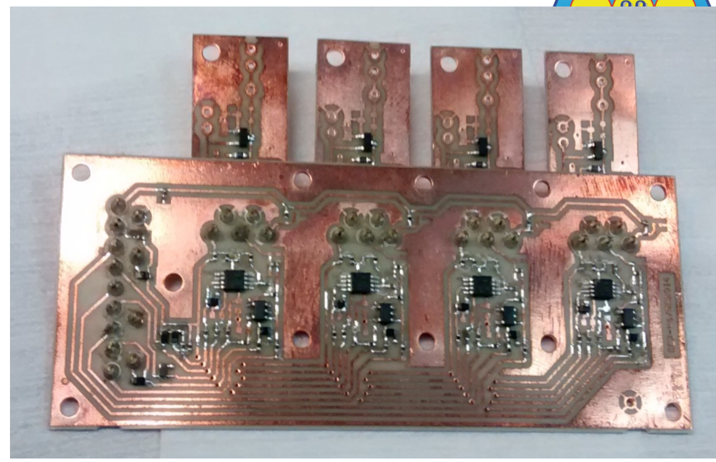
- **200 uBq Th-232 for 3 channels (11 pins-receptacle pairs included)**
- **Located at about 40 cm above top detector**

CC3 Phase II

Measured Intrinsic Noise figure of CC3 preamplifier with BF862 JFET; Cd=0 pf



Noise figure of a Canberra 2002 amplyfier. From Canberra data sheet



13 x CSA Boards mounted back to back above the Ge strings

Activity Budget: CSA Phase II vs Phase I

	CC3 – completely assembled (4 channels) (Phase II)	CC2 – completely assembled (3 channels) (Phase I)	Improvement/ch	BI [10-3] ckky For 12 PCB; AC prior Veto cut
^{226}Ra	150 μBq/PCB → 38 μBq/ channel	300 μBq/PCB → 100 μBq/ channel	2.6	0.2
^{228}Th	50 μBq/PCB → 13 μBq/ channel	150 μBq/PCB → 50 μBq/ channel	3.8	0.9
^{40}K	800 μBq/PCB → 200 μBq/ channel	1800 μBq/PCB → 600 μBq/ channel	3.0	
^{137}Cs	< 43 μBq/PCB → < 11 μBq/ channel	50 μBq/PCB → 17 μBq/ channel	> 1.5	

	Pyralux 3 mil TECNOMEC (Single trace) 0.5 g/80 cm	Cuflon- HV Haefele (Single trace) 2.7 g/80 cm	Cuflon - signal Haefele (Single Trace) 0.5 g/80 cm	Pyralux 2 mil TECNOMEC (Phase II) 4.0 g/ 80 cm
^{226}Ra	< 2 μBq	(22 +- 5) μBq	(25 +- 5) μBq	(24 +- 4) μBq
^{228}Th	< 3 μBq	< 22 μBq	< 11 μBq	< 22 μBq
^{40}K	(55 +- 15) μBq	(300 +- 80) μBq	(100 +- 50) μBq	< 100 μBq
^{60}Co	< 0.4 μBq	< 6.2 μBq	< 8.5 μBq	< 7.2 μBq
^{137}Cs	< 0.6 μBq	< 6.5 μBq	< 5.0 μBq	< 3.7 μBq

- GERDA PhaseI Cu contact in PTFE pipe:
  4.7 uBq/m (Ra-226) and 2.6 uBq/m (Th-228)
- Pyralux 3 mils can be safely used for HV (DS: 6-7 kV/mil)
- At present both the Cuflon – Signal and the Pyralux 3 mil are deployed in GERDA. If BI requires they will be changed

SUMMARY Activity Budget FE Deployed in GERDA

	[g] Mass	Number/ detector	Position	Th -228 [uBq]	BI [E-3] AC	Ra-226 [uBq]	BI [E-3] kky AC
CC3 Board		1/4	40 cm top	50	1.0	150	0.3
1 Trace FEFC Pyralux	0.4	2	close	<3	<0.9	<2	<0.5
1 Trace FEFC Cuflon 10 mils - HV	2.7	1	close	<23	<7.2	27(5)	5.4(1.1)
1 Trace Cuflon Signal -3 mils	0.5	2	close	<11	<3.6	21(5)	6.0(1.2)

FEFC= Front End Flex Contacts

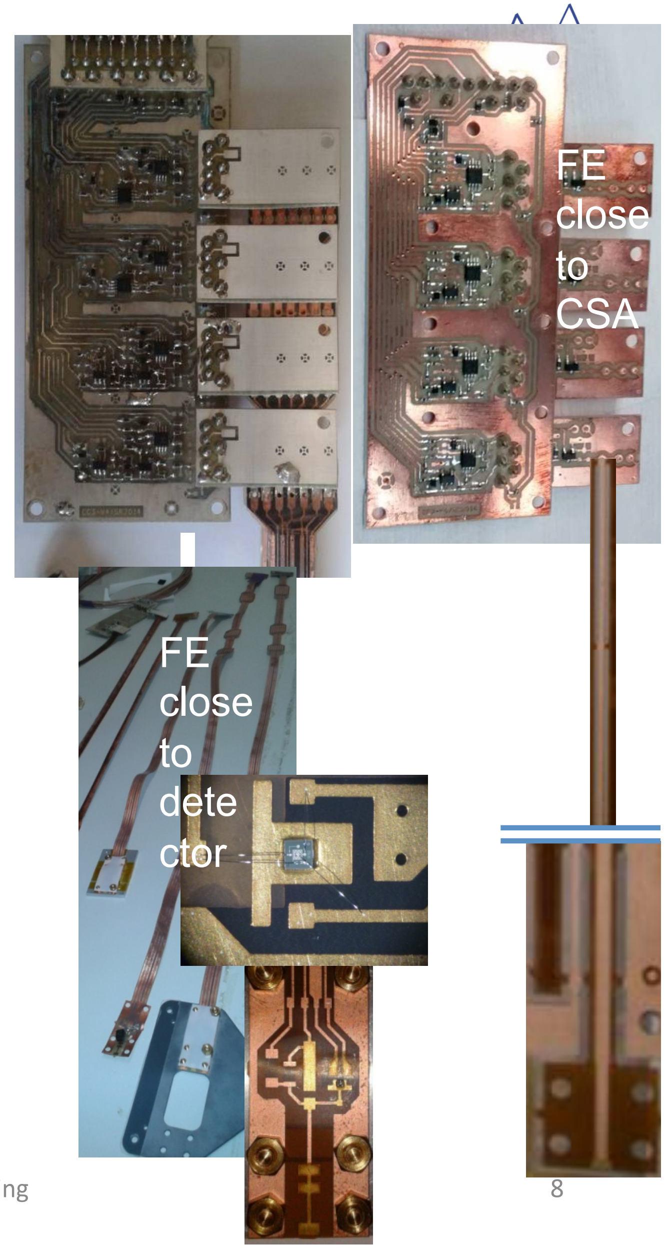
BI evaluated for the full array

FE Electronics

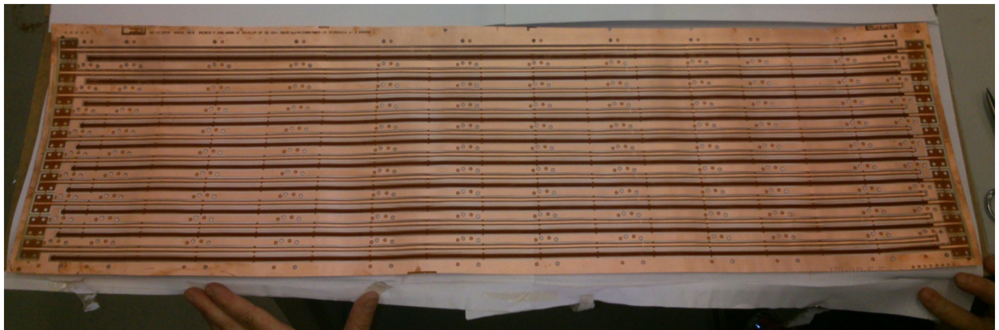
By Changing 3 components, CC3 can be coupled both to

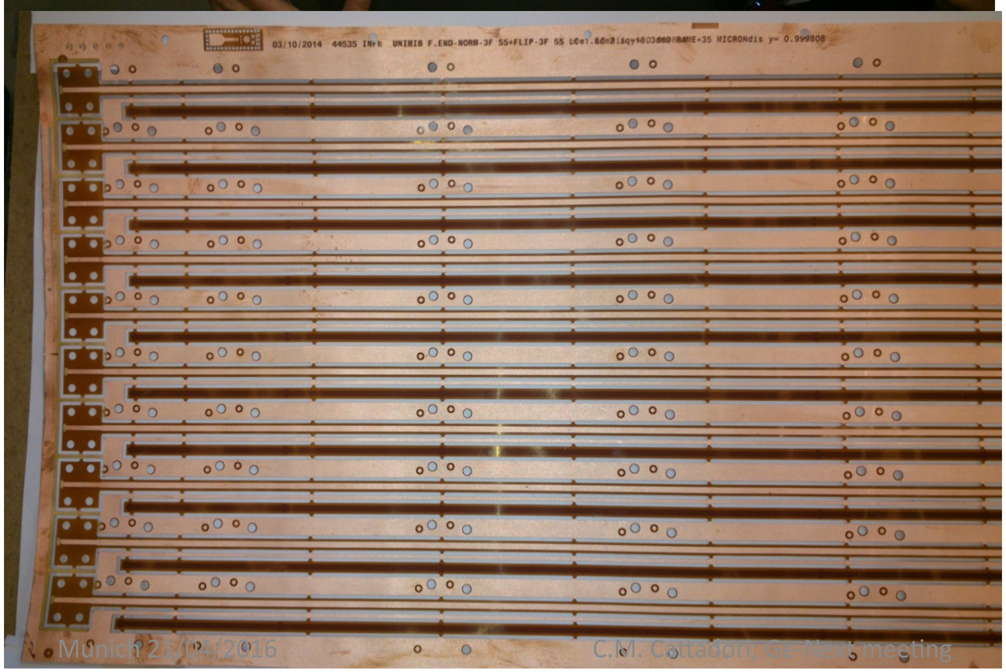
- FE close (to CSA) FE→
  - Unreferenced single contacts from detector to FE for low stray C
  - PRO: Low Mass (0.5 g) → Low Activity, short path and low C at the amplifying node
  - CONS: Signals travel unreferenced over 1 m distance→ microphonics, disturbances pick ups etc.
- FE far (close to detector):
  - PRO: immune from microphonics, disturbances. stray C smaller.
  - CONS: 3 referenced contacts (coaxial, or coplanar waveguide etc.) required. → Larger C at the amplifing node, larger mass (4.0 g/80 cm), Additional Materials close to detector (JFET, Rf, Bonding wires) → Radiopurity,Handling and Reliability issues

  GERDA 3 Traces FEFC for FE close to detector
  - Mass : 4.0 g/80 cm
  - Th-228: <22 μBq → BI (AC) <7.2 10^{-3} ckky
  - Ra-226: 24 (4) μBq → BI (AC) = 6.0(1) 10^{-3} ckky

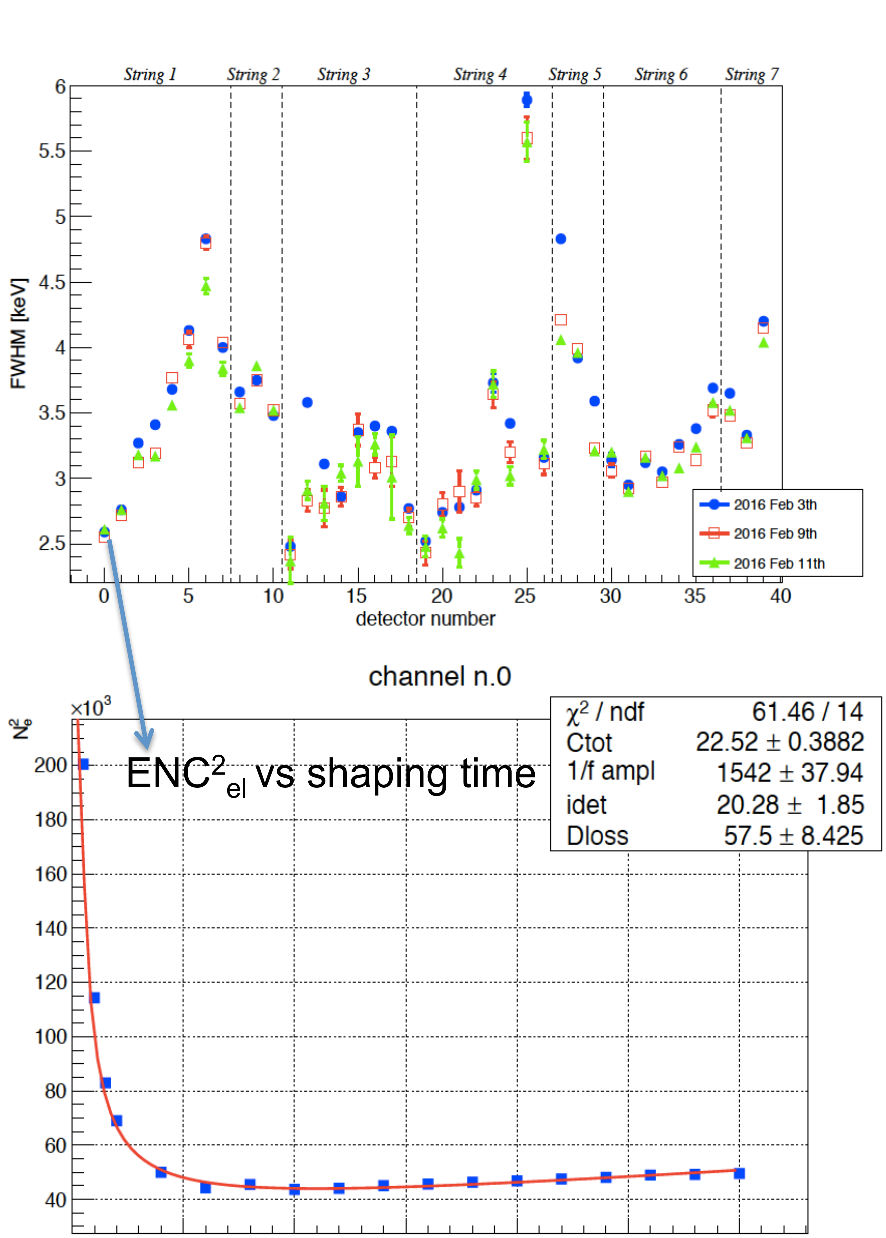


GERDA HV and Signal Front End –Flex Contacts



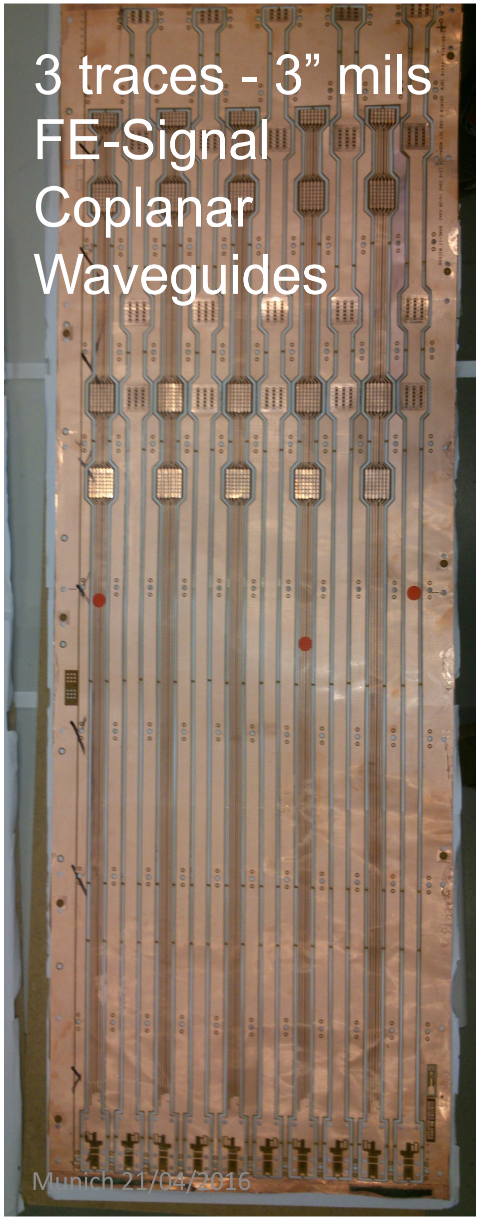


- Produced both in Kapton and Cuflon
- Flex circuits doesn’t require any connection at the detector level (no weak point added)
- PCB Production line monitored for radiopurity
- “Dirty” steps avoided or minimized
- Room for improvement: yes, mass (0.5 g/80 cm in kapton 3 mils) can be reduced (30%) but handling in glove box more difficult



Observed trend of FWHM vs detector position for BEGe detectors

Effective ENC achieved in GERDA – PII with one BEGe detector connected



GERDA Coplanar Waveguides

- They were the FE GERDA reference design untill middle 2014.
- Problems encountered because of high JFET mortality (see next slide).
- JFET radiopurity not negligeable

(^{228}Th: <2.2(1) uBq/pc; ^{226}Ra: 1.3(0.4) uBq/pc)

- Produced both in Kapton and Cuflon
- Flex circuits doesn't require any connection at the detector level (no weak point added)
- PCB Production line monitored for radiopurity
- "Dirty" steps avoided or minimized
- Room for improvement: yes, mass (present value 4.0 g for kapton 3" mils, 80 cm length) can be reduced (~50%)

Next Steps on FE for the Next Ge-exp or GERDA-PhaseII-v2

- Achieve FE the configuration with Components Close to detector
- (FE & detector assembly) connected issues to be solved in a reliable, robust, reproducible way to approach FE devices close to Ge diode as in original GERDA-PII design
  - ❑ High mortality of JFETs (SF291 of SEMEFAB) during the string assembly /diode connections/disconnection operations. This due to specificity of GERDA glove box environment (highly flushed with pure gas N2→ high electrostatics i) in the glove box and high static charge of ii) unbiased Ge diodes
  - ❑ Not negligeable Radioactivity of die JFETS.

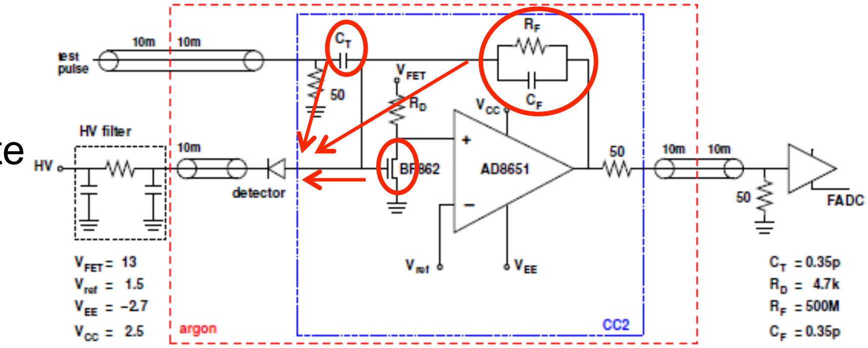
  → JFET Protecting device required → more activity

  - ❑Radioactivity of SMD 500MΩ feedback-R: OK.

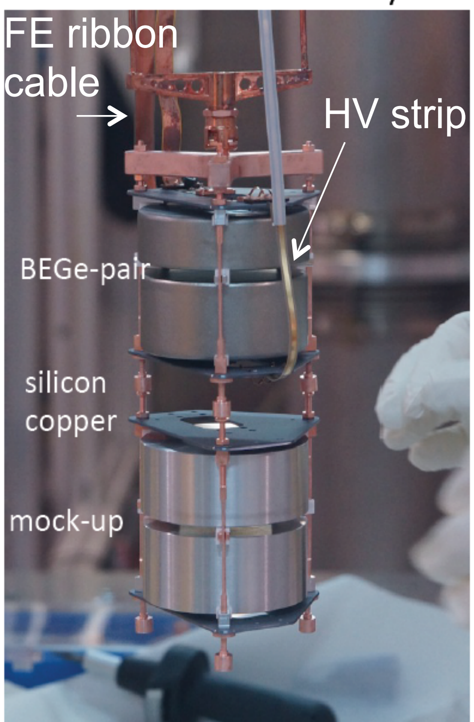
  (^{228}Th: 0.2(1) uBq/pc; ^{226}Ra: 0.7(1) uBq/pc; ^{234}Th: 2(1) uBq/pc)

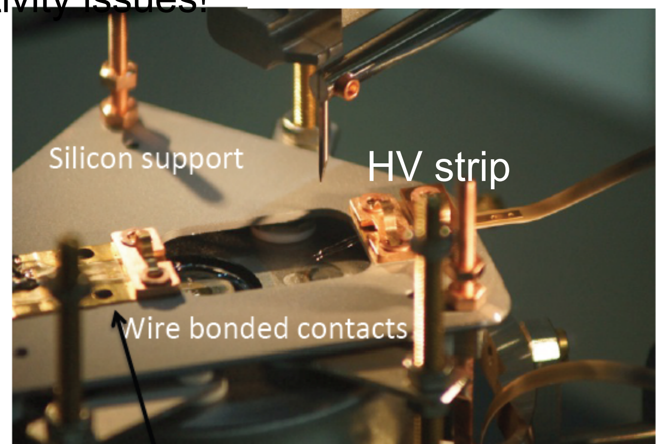
GERDA PHASE II

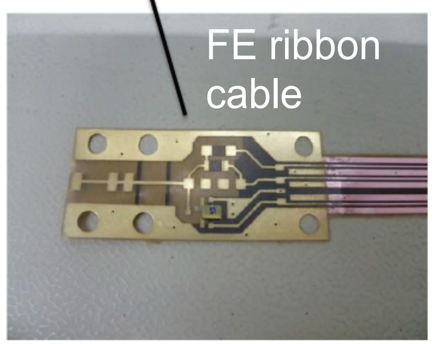
- FE devices moved at the detector site
- JFET changed to better match C_{det} (BEGe)
- JFET in die (die attach and bonded)
- More stringent radioactivity issues!



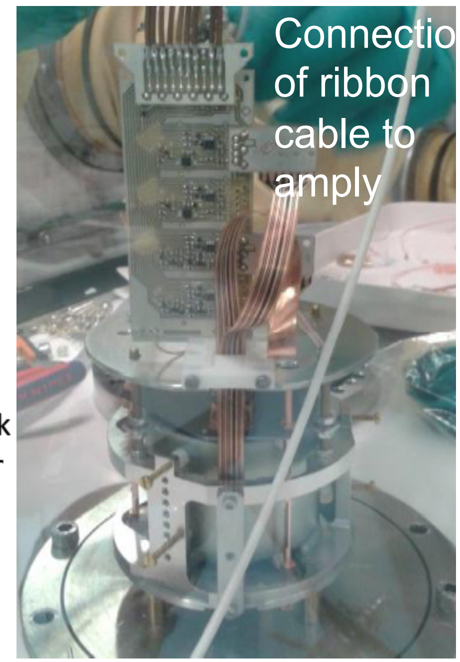
Phase II detector assembly





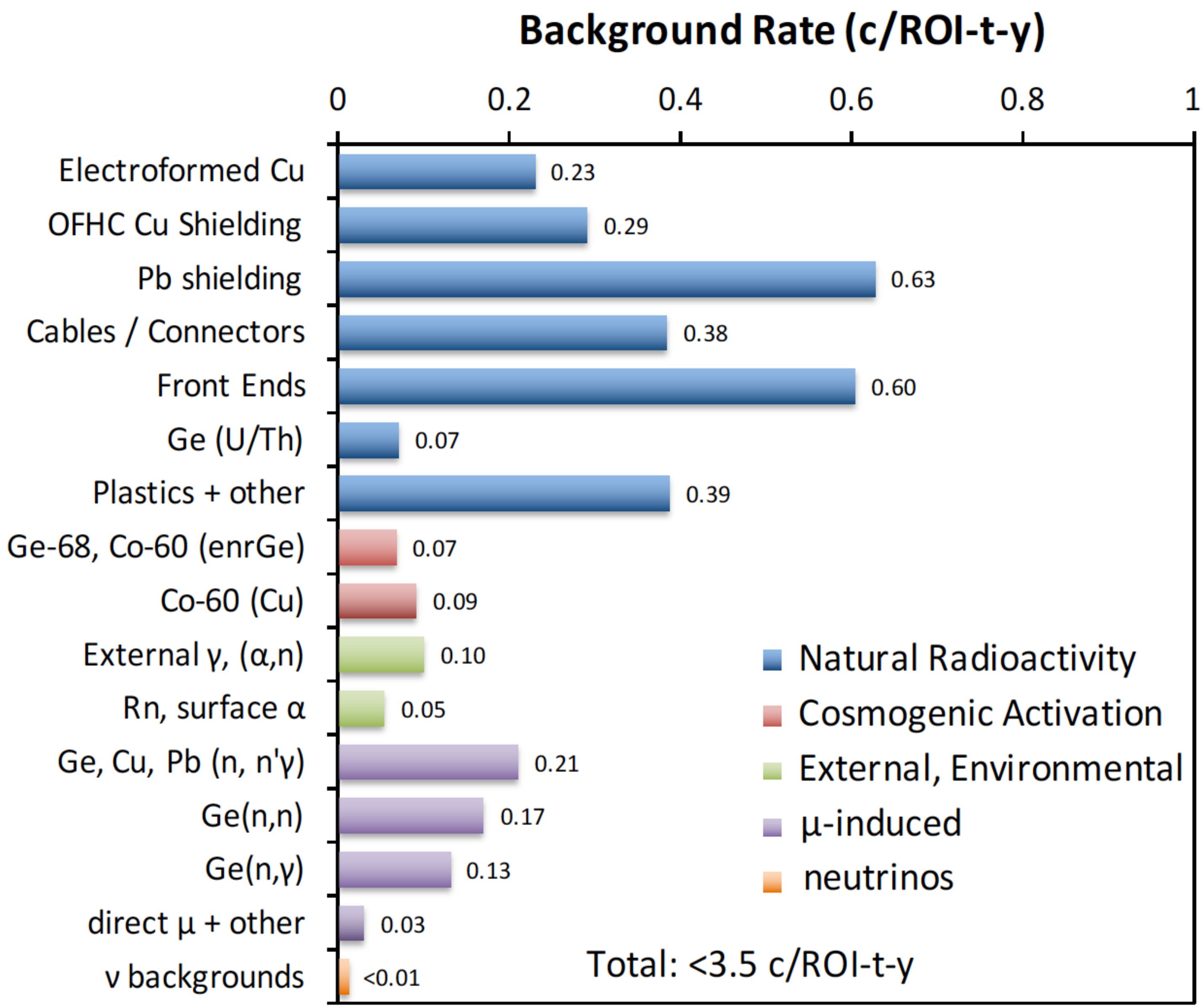


flex cables with JFET and feedback resistor/capacitor



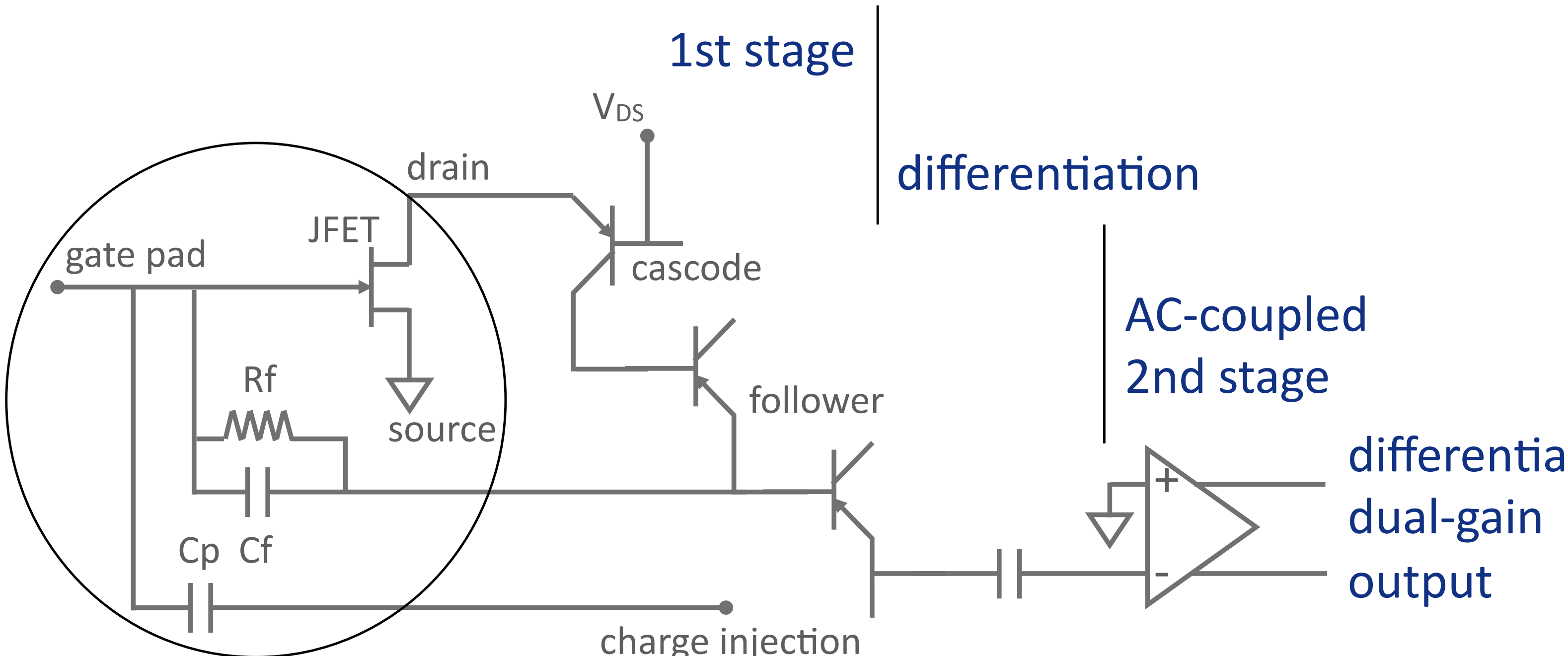
MJ backups

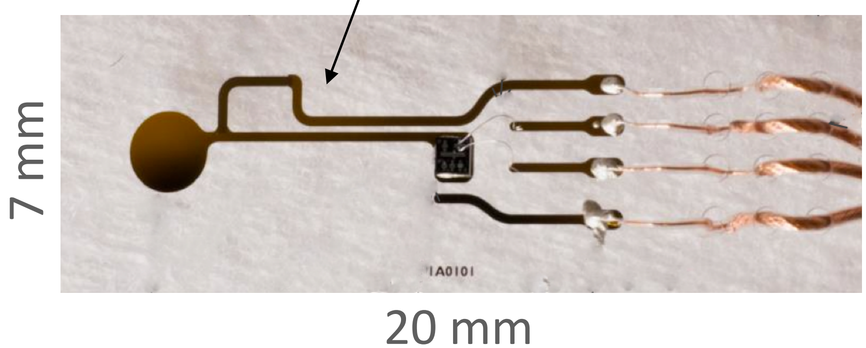
DEMONSTRATOR Background Model



Overview of MJD LMFE-preamp

Resistive feedback charge-sensitive preamplifier:





front-end:

n-channel JFET

Rf ≈ 10 GΩ @ 85K

Cf = 0.17 pF

Cp ≈ Cf

External control (10%) on drain to source current (via V_{DS})

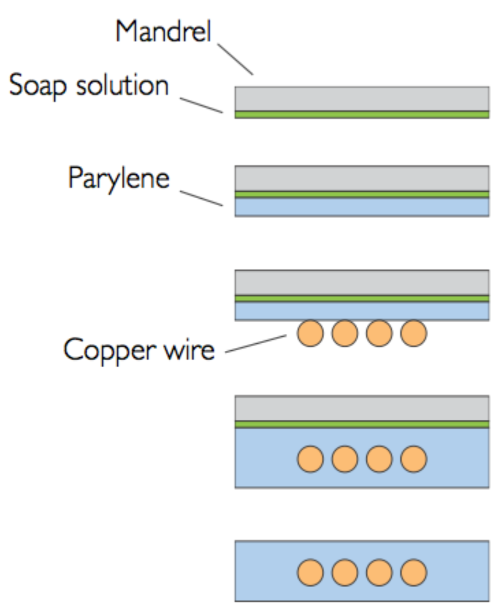
Reduced the component count by using stray capacitance

IEEE Nucl. Sci. Symp. Conf. Rec. 2011, 1976 (2011).

BERKELEY LAB

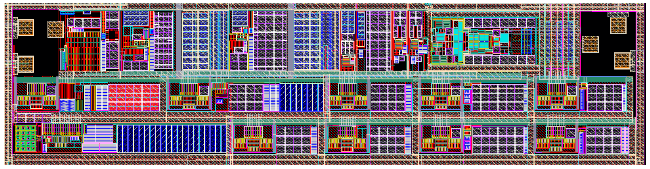
Can we make coaxial cables with parylene?

- MJD tried. Issues:
  - When the thickness of the parylene becomes thick (> ~5 mil), the "film" becomes more rigid. Whiskers begins to form.
  - Hard to do a good ground shield for surface that becomes non-uniform (from cutting the whiskers)



A prototype:
wrapped Cu foil;
heat shrink outside

Lower Noise ASIC Development and Detector Integration



LNC ASIC

Lower Noise ASIC Goals

1. Low Noise, Low Threshold
2. Optimize for 0.1 pF detectors
3. Minimize Cabling
4. Reduce External Components

Developed **improved** preamp-on-a-chip ASIC with BNL:
The "Low-Noise Low-Capacitance" (LNC) Preamplifier

1. Single Power Supply
2. No Reset Signal (internal reset)
3. Only [Power, Ground, In, Out]
4. 50 MHz bandwidth
5. Capable of 27 eV-FWHM (HPGe)

Due from foundry in May.

P. Barton (LBNL)