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PNNL Rad QIS

Ben Loer On behalf of PNNL QIS



PNNL is operated by Battelle for the U.S. Department of Energy



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Sources of ionizing radiation

- External sources
 - Gammas
 - Cosmic ray secondaries (muons)
- Most mass of the fridge is:
 - Copper, gold plating
 - Aluminum (radiation shields)
 - Steel (Vacuum flange)
 - Mumetal (magnetic shielding)

Low Radioactivity Moderate or Variable Radioactivity High Radioactivity/Rate

Most high radioactivity materials are very small mass BUT Many of them are very close to the devices

- Packaging and readout: Silicon chips
 - Wirebonds
 - Indium (bump bonds)
 - Epoxy, varnish
 - FR4, ceramics(PCBs)
 - BeCudelectrical connectors
 - Copper





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Assay of critical components

• Qubits (ICP-MS)

- Fabricated at MIT-Lincoln Labs, each chip 2.5x5x0.3 mm
- 3 replicates measured, only 1 above detection limit
- Not significantly any dirtier than pure silicon

Sample	$\frac{232}{2}$ Th (mBq/kg)	²³⁸ U (mBq/kg)	Ref.
Qubits	0.0065 ± 0.0012	0.014 ± 0.003	This w
Silicon	< 0.0073	< 0.011	[38]
OFHC Cu	0.0001–0.01	0.001-0.05	[39–4



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Assay of critical components



• Qubits (ICP-MS)

- Cryogenic SMA connector and semirigid coax cable (ICP-MS)
 - Only metal parts digested (e.g. not PTFE dielectric)
 - Cables fairly clean, connectors dirty (likely BeCu)



			total sample	measured	mass fraction	²³² Th		²³⁸ U		
PNNL ID	Description		mass [g]	mass [g]	measured	milliBq/kg	± inst	milliBq/kg	± inst	
					normalize	ed to metal ma	ss			
2023-10-01	coax	r1	2.9040	2.6336	0.907	1430	20	21000	2000	
	connector metal	r2	2.8953	2.6432	0.913	2240	140	25000	2000	
[]						Γ		I		
			total	mossured	fraction	²³² Th		²³⁸ U		
PNNL ID	Description		mass [g]	mass [g]	measured	milliBq/kg ± inst		milliBq/kg	± inst	
		r1	0.1429	0.1056	0.739	<0.130		<0.39		
2023-10-02	coax cable metal	r2	0.1872	0.1334	0.713	<0.152		<0.42		
		r3	0.1552	0.1111	0.716	<0.16		<0.49		

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Assay of critical components



- Qubits (ICP-MS)
- Cryogenic SMA connector and semirigid coax cable (ICP-MS)
- Low loss ceramic PCB substrates Rogers TMM10 and RO4350B (HPGe)

Sample	Mass	⁴⁰ K	²⁰⁸ Tl	²¹² Pb	²¹⁴ Bi	²¹⁴ Pb	²²⁶ Ra
TMM10	200 g	17.3(9)	1.51(6)	5.5(3)	28.9(4)	25.4(8)	29(2)
RO4350B	30 g	9.1(8)	4.9(2)	15.1(9)	-	11.2(4)	8(4)

²¹⁰Pb

11(2)



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Building a background model

Radioactivity assays 🔀 Simulated hit efficiencies 🔀 Bill of materials







		Isot	ope conc	entration	ns (mBq/	'kg)			Source location	²³⁸ U	²³² Th	⁴⁰ K	⁶⁰ Co	¹³⁷ Cs	²¹⁰ Pb	Activation
Material	²³⁸ U	²³² Th	⁴⁰ K	⁶⁰ Co	¹³⁷ Cs	²¹⁰ Pb ^{<i>a</i>}	Act. ^b	Ref.				TT:	m . : 1	/ - / - / D -		
copper	0.070	0.021	0.023	0.002	-	40	6.6	[46, 50, 51]				Hite	ficiency, I	/g/s/Bq	115	
lead	0.04	0.005	0.1	-	-	200000	-	[45, 52, 53]	Bump bonds	8.3E+2	6.6E+2	5.4E+1	5.6E+1	6.4E+1	¹¹⁵ In	5.7E+1
steel	130	2.4	10	8.5	0.9	-	-	[46]	Interposer board	7.3E+0	5.2E+0	1.5E+0	3.1E-1	8.3E-1	1.5E+0	4.2E-1
aluminum	66	200	2100	-	-	-	-	[46]	Package	7.3E-2	6.0E-2	1.2E-2	2.1E-2	9.8E-3	8.0E-3	1.4E-2
gold	74	19	150	-	-	-	-	[45, 54]	Package Connector Inside	8.4E-1	5.2E-1	1.8E-1	5.3E-2	7.5E-2		
brass	4.9	3.5	40	-	2.6	40	6.6	[49, 55]	Package Connector Outside	1.4E-2	1.7E-2	9.4E-4	1.4E-2	4.8E-3		
i Kapton	10	20	60	3	-	-	-	[47, 55]	Experiment stage	7.3E-4	1.0E-3	4.5E-5	9.1E-4	2.3E-4	2.5E-6	5.2E-4
Al bonding wire	110	370	100	-	-	-	-	[45]	Experiment shield	2.2E-4	2.8E-4	1.3E-5	2.5E-4	8.1E-5	0.0E+0	1.5E-4
isolator	20	/	2000	-	-	-	-	[30]	Mixing Chamber Stage	1.2E-4	1.6E-4	8.8E-6	1.5E-4	4.4E-5	1.8E-7	8.7E-5
HEMT	1000	890	10000	-	210	-	-	[48]	Cold Plate Stage	1.7E-5	2.3E-5	1.1E-6	2.3E-5	6.8E-6	1.4E-8	1.3E-5
K&L filter	9	23	10000	5	1.9	-	-	[48]	Still Stage	7.3E-6	9.3E-6	5.8E-7	9.5E-6	2.6E-6	4.8E-9	5.4E-6
attenuator	200	52	140	-	13	-	-	[48]	4K Stage	1.6E-6	2.3E-6	1.3E-7	2.7E-6	4.1E-7	0.0E+0	1.5E-6
alumina	5000	66	600	-	-	-	-	[56]	50K Stage	4.6E-7	7.4E-7	2.1E-8	8.2E-7	1.9E-7	3.1E-9	4.4E-7
Rogers TMM10	29000	5500	17000	-	-	-	-	this work	Vacuum Flange	2.6E-7	3.3E-7	1.5E-8	4.0E-7	8.6E-8	0.0E+0	2.3E-7
Rogers RO4350B	11000	15000	9000	-	-	-	-	this work	Still Can	6.0E-5	8.1E-5	4.3E-6	7.4E-5	2.1E-5	7.5E-8	4.4E-5
SMA connector	23000	1800	-	-	-	-	-	this work	4K Can	3.0E-5	3.9E-5	2.1E-6	3.6E-5	1 1E-5	9.7E-9	2.1E-5
coaxial cable	0.4	0.15	-	-	-	-	-	this work	Lower 50K Cor	2.5E.5	2 1E 5	1 0E 6	2.0E 5	0.1E.6	0.7E.0	1.7E-5
qubit chip	0.014	0.0065	-	-	-	-	-	this work	Lower 50K Can	2.5E-5	3.1E-5	1.8E-0	2.9E-5	9.1E-0	9./E-9	1./E-5
Indium	115In.	250000							Upper 50K Can	9.3E-7	1.3E-6	3.6E-8	1.5E-6	4.4E-7	0.0E+0	7.9E-7
	111.	250000							Lower Vacuum Can	1.7E-5	2.3E-5	1.4E-6	2.1E-5	7.6E-6	0.0E+0	1.2E-5
									Upper Vacuum Can	6.3E-7	1.0E-6	8.7E-8	1.1E-6	2.1E-7	0.0E+0	5.7E-7

Component	Material	Mass
		(kg)
Cosmic rays (chip horizontal)		
Cosmic rays (chip vertical)		
Ambient Gammas		
Ceramic PCB interposers		
	alumina	780 mg
	RO4350B	370 mg
	TMM10	550 mg
Coax connectors on package		
inside (line-of-sight)	SMA	10×2.3 g
outside (no line-of-sight)	SMA	10×2.3 g
Bump bonds	indium	20 µg
All other components (itemize	ed below)	
Fridge stages and shields		
MXC stage	Cu	4.6
CP stage	Cu	3.3
Still stage	Cu	5.9
4K stage	Cu	8.7
50K stage	Cu	5.1
Vacuum flange	steel	21
Still can	Cu	6.3
4K can	Al	4.1
50K can	Al	5.7
Vacuum can	Al	21
Gold plating	gold	0.5
Experiment readout		
Wirebonds	Al/Si	$10 \times 0.1 \text{ mg}$
Package	Cu	0.1
Package Fasteners	brass	10×0.3 g
Cryo filters	K&L	10×15 g
Closest coax cable	semirigid	$10 \times 10 \mathrm{cm}$
Coldfinger	Cu	1.8
Inner shield		
	Cu	1
	Al	1
	mumetal	1
MXC DC feedthroughs	BeCu	100 pins
MXC RF feedthroughs	SMA	10×2.3 g
MXC RF attenuators		$10 \times 5 \text{ g}$
MXC isolators		$10 \times 145 \mathrm{g}$
4K HEMT amplifiers		10×17 g







An open-source web application for modeling radioactive backgrounds https://github.com/bloer/bgexplorer

Edit bill of materials and assays in web interface

Editing Model: HPGE Detector Bind simulation data Sample low background HPGE counter Edit Component Components Specifications Nam Search cuBox top Create new: Component Assembly Components Description Description Status Assembly Tree Comment HPGE System 3 Low background shielded HPGE detector detector housing Details of current implementation can Additional Info top lid owner: <Part owner/designer/buver bottom lid partnum: <Part number> M4x1.5 brass screw vendor: <Part vendor> datasheet: <URL for datasheet? sample holde HDPE blocks for placing large samples shield 🤉 copper and lead shielding Query Modifie copper box cuBox top JSON object modifying DB queries cuBox bo cuBox side Categon cuBox_frt cuBox bck M4x1.5 brass screv lead shield dummy component to attach room flux environment Unplaced compo outer radon copper box (single element example) cuBox_right + Add cuBox bck

Upload simulation outputs as **JSON** files

Save Other actions-

Dist.

bulk

bulk

surface

surface

Material

copper

Mass 63.4 kg

Volume

0 cm3 Inner Surface

10 cm²

Outer Surface

Querymod

Multiple views for summarizing and drilling down into inputs and results

Component	Gammas, 0.1-5 keV [dru]	Gammas, 3-100 keV [dru]	Gammas, 10-2000 keV [dru]
Total 👻	2.89(9)	60(10)	Interactive Charts
sample holder	0.53(2)	1.77(8)	Gammas, 0.1-5 keV [dru]
detector housing 👻	2.19(9)	8.4(3)	Filter Info
bottom lid	0.111(5)	0.37(2)	55 / 55 (100.0%) records pass all filters. 2.89 / 2.89 dru (100.0%) rate pass all filters
can	1.76(8)	6.8(3)	Active Filters reset all
top lid	0.32(1)	1.23(5)	Component: Material:
shield 👻	0.167(7)	50(10)	Source: Source Category:
lead shield	0.010(2)	50(10)	
copper box 👻	0.157(7)	0.219(9)	
cuBox_bck	0.009(6)	0.015(1)	
cuBox_bot	0.025(2)	0.036(2)	
cuBox_frt	0.030(2)	0.040(3)	
cuBox_side	0.045(3)	0.065(5)	Source
cuBox_top	0.028(2)	0.034(2)	
hinge	0.020(5)	0.029(7)	
		Comment 2 400 loss laboration	

				1123
flaterial	Gammas, 0.1-5 keV [dru]	Gammas, 3-100 keV [dru]	Gammas, 10-2000 ke\	
fotal 👻	2.89(9)	60(10)		
ead	0.010(2)	50(10)		
copper	0.137(5)	0.190(7)		
luminum	2.19(9)	8.4(3)		
IDPE	0.53(2)	1.77(8)		
orass	0.020(5)	0.029(7)		0.011(3)



+ Click a cell to draw the associated spectrum









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Typical Radiation budget

Count rate above threshold



B. Loer, et. al. "Abatement of Ionizing Radiation for Superconducting Quantum Devices." arXiv:2403.01032

RISQ Workshop



Key Takeaways

- Three dominant sources of ionizing radiation events:
 - Cosmic ray secondaries
 - Ambient gammas
 - Line-of-sight "dirty" components (ceramic PCBs, BeCu coax connectors)
- If devices are sensitive to low energy impacts, these sources contribute roughly equally
- If there is a significant threshold effect, line-of-sight alphas are the biggest concern, followed by cosmic rays, and gammas are very subdominant

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Spectrum of pulses recorded in 5x5 mm² Thermal KID microcalorimeter agrees well with predictions. Only Cu and Al have line-of-sight to sensor.



Joseph W. Fowler, et. al. "Spectroscopic measurements and models of energy deposition in the substrate of quantum circuits by natural ionizing radiation." arXiv:2404.10866

RISQ Workshop



Common Gamma Backgrounds

- Environmental gamma and muon rates measured in multiple buildings, laboratories, and institutions with same instrument
- All within factor of ~5



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PNNL Shallow Underground laboratory

- SUL houses clean rooms (class 10,000 and 1,000), world-leading ultra-pure material growth and characterization capability
- 19 m overburden reduces muon flux by 6X, neutron and proton flux by >100X
- Bluefors LD-400 operating for ~1.5 years





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Low Background Cryogenic Facility (LBCF) shield design approach

- Surround dil fridge model floating in space with hermetic lead shield of different thickness
- "Done" when residual gamma rate is below ~10% residual muon rate at 4" thick
- Then add holes for access, framing, seams between sections



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LBCF Shield design

- Reduces gamma rate by ~99.8%
- Automated cage door open/close enables A/B tests for ambient radiation
- Expected completion late Summer 2024



Devices running in the LBCF

- McEwen et. al. observed "catastrophic" error bursts with rate ~1/(10s)
- Estimated radiation dose in LBCF ~5% of "typical" surface lab if care paid to line-of-sight components
- If McEwen error rate is 100% radiation-driven, naïve scaling suggests error burst rate in LBCF would be $\sim 1/(2 \text{ minutes})$

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- Cosmic ray muons dominate at low-to-medium energy
- ²¹⁰Pb in copper housings likely dominates at high energy (~few/year)



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cosmic rays in SUL (chip horizontal): 6.9 keV/s/g



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Summary

- PCBs and BeCu connectors dominate radiation budget if within direct line-ofsight of device, especially at high energy
- Otherwise ambient gammas and cosmic ray muons contribute roughly equally
- Therefore both shielding and overburden are necessary to achieve reduction
- PNNL Low Background Cryogenic Facility achieves 85% reduction in cosmic ray muons, expects 99.8% reduction in internal gammas, total 95% reduction in ionizing radiation event rate for typical chips
- Expected error burst rate ~2 minutes



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Thank you

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