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ULGeN: **U**ltra-**L**ow Noise **Ge**rmanium **N**eutrino Detection System

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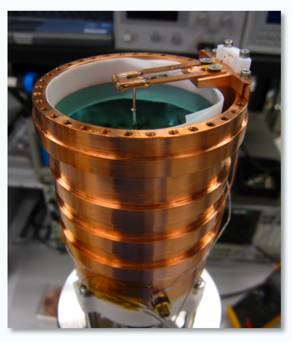
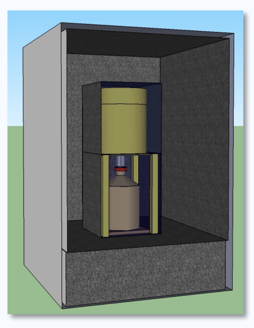
Project Goal

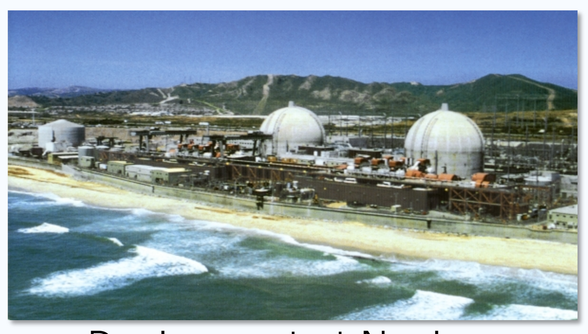
Development, construction, and deployment of the first large-mass High Purity Germanium (HPGe) detector with the required ultra-low electronic noise threshold to demonstrate detection of reactor antineutrinos.



1 pF, 1pA, <100 eV Ge Detector

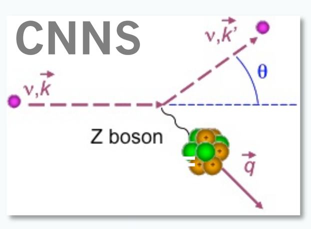


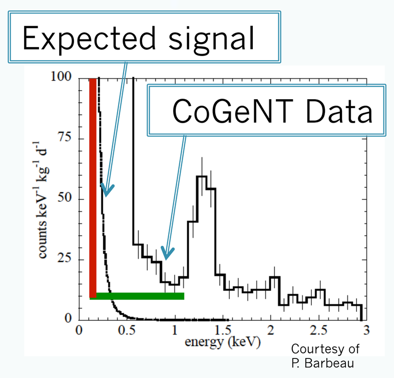
Active / Passive Shielding



Deployment at Nuclear Power Plant (NPP)

Overview





- Reactor Monitoring with HPGe detectors is based on the as-yet undetected Coherent Neutrino-Nucleus Scattering (CNNS)
- Expected CNNS count rate at 25m from reactor core: **5 counts / kg-day in ROI <1 keV**
- Requirement of kg-scale HPGe detector with electronic noise levels so far only achieved with few-gram detectors: **~100 eV electronic threshold**
- Requirement of stringent background reduction and rejection: **<10 bkgnd counts/kg-day in ROI <1 keV**

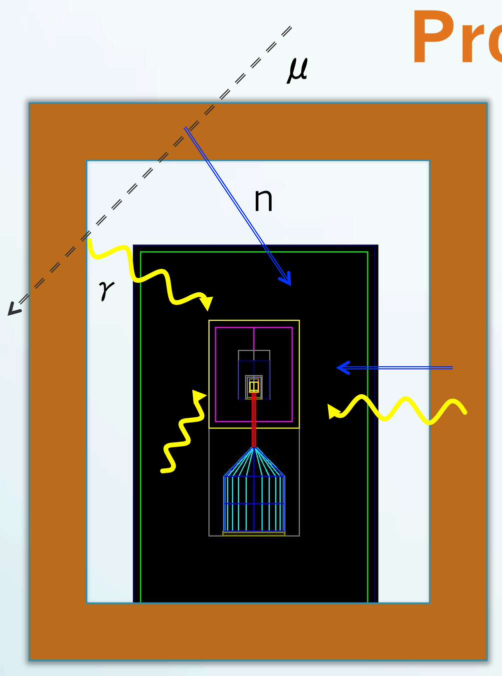
Technical Approach

- Fabrication of 1 kg P-type Point-Contact (PPC) Ge detector, with smaller point contact and decreased surface leakage current
- Optimization of ultra-low mass front-end electronics, based on JFET
- Exploration of alternative front-end, based on CMOS
- Integration of a low-threshold waveform digitizer DAQ
- Specification of shielding / detector materials, from modeling of background and signal

Deliverables

1. Development and characterization of new ultra-low noise CMOS readout.
2. FY13: Development and fabrication of kg-scale and compact, ultra-low noise Ge prototype detection system.
3. FY14: Demonstration of lowest achievable noise with JFET readout and determination of feasibility for CNNS observation at NPP site.
4. FY15: Installation and deployment of prototype detection system at NPP if sufficiently low noise was demonstrated in FY14.

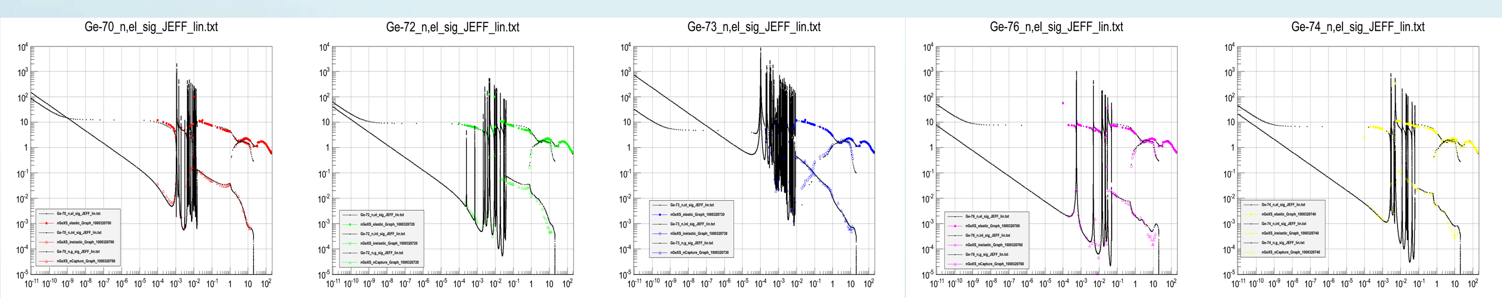
Progress on Background Simulations



Background particle	Process	Background signal
Cosmic secondary n and μ-induced n	Scattering off Ge nucleus	Ge-nucleus recoils
Cosmic secondary n and μ-induced n	Nuclei activation: ^{71}Ge, ^{68}Ga,^{65}Zn, …	Partial energy depositions from X-rays and Auger e-, internal to germanium
Cosmic primary p at sea level	Nuclei activation: ^{73}As, ^{68}Ge, …	
Thermal n	Nuclei activation: ^{71}Ge	
μ-induced γ and radioactivity γ	Forward-peaked Compton scattering	Electron recoils

- **Toy simulation using Geant 4.9.5.p01 to study neutron – Germanium interactions** as a function of neutron energy.
- **Goal 1:** validate neutron interaction rates by comparing G4 and data cross-sections
- **Data to compare:** ENDFB-VII (0 – 20 MeV) and JEFF-3.1(0 – 200 MeV)
- **Plots Below:** n-Ge cross-section (XS in barns) as a function of neutron energy (in MeV) show a 5-10% agreement with ENDFB-VII and <25% with JEFF-3.1

- natural Germanium isotopes: ^{70}Ge, ^{72}Ge, ^{73}Ge, ^{76}Ge, ^{74}Ge
- Elastic XS: filled circles
- Inelastic XS: open circles
- nCapture XS: open triangles



- **Goal 2:** understand G4 energy depositions due to neutron scatters in ROI = 0.1 – 3 keV
- **Goal 3:** Compare results from several G4 physics lists
- **Motivation:** neutron-Ge scatters producing Ge recoils are the main background source in ROI = 0.1 – 3 keV
- **Table Below**: Probability per event of ionization energy deposition in ROI = 0.1 – 3 keV

	1keV	10keV	100keV	1MeV	10MeV	100MeV
Deposition probability due to all interactions	0.00074	0.396371	0.732646	0.121462	0.081214	0.05697
Deposition probability only due to isotope recoils	0.00074	0.396355	0.732638	0.12145	0.081160	0.05697
Isotope recoils from elastic neutron scatters	0	0.400115	0.740676	0.149263	0.126234	0.07755
Isotope recoils from inelastic neutron scatters	0	0	0.004806	0.038083	0.001819	0.00039
Isotope recoils from neutron Capture	0.00144	0.007495	0.007575	0.000546	0.000206	0.00041

- **Result:** En ~ 10 keV – 1 MeV have higher probability of deposition
- **Result:** Most depositions due to neutron elastic scatters
- **Result:** Validated G4 Underground_HP Physics List
- **In progress:** study of n interaction with shielding materials

Progress on Electronic Noise

Equivalent Noise Charge

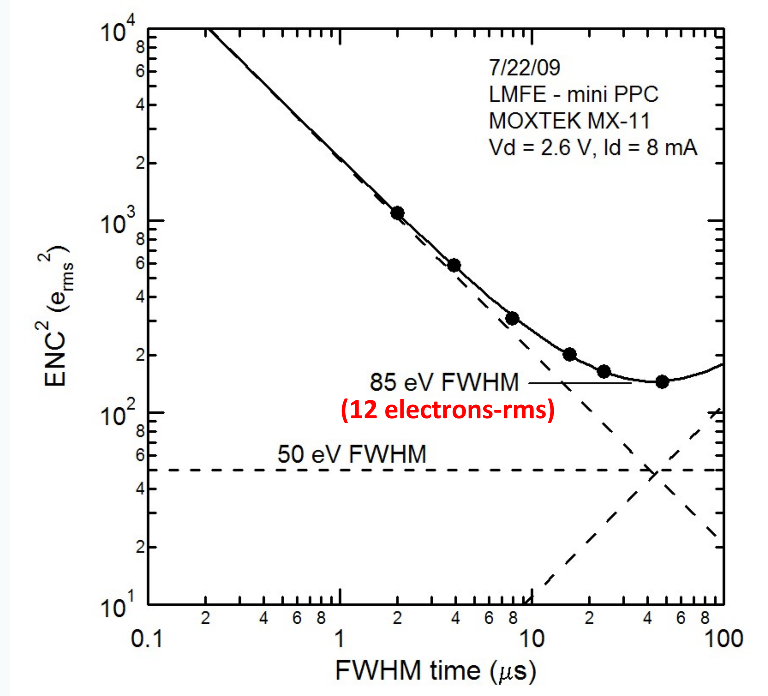
$$ENC^2 = Q_n^2 = \left(\frac{e^2}{8}\right)\left[\left(\frac{4kT}{g_m} + e_{na}^2\right)\frac{C_d^2}{\tau} + 4A_f C_d^2 + \left(2q_e I_d + \frac{4kT}{R_F} + i_{na}^2\right)\tau\right]$$

Voltage (series) | 1/f | Current (parallel)

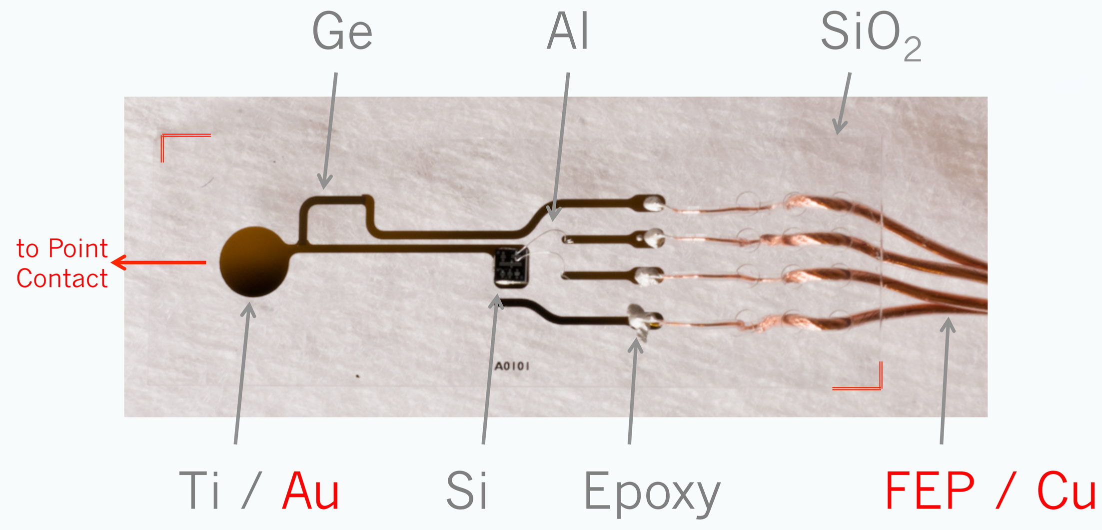
FrontEnd

1 pA ≅ 15 GΩ

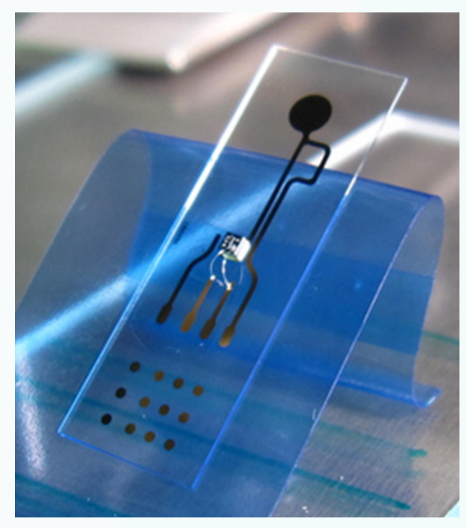
- $e^2/8$ from shaping filter (can affect series / parallel differently)
- T JFET temperature
- g_m JFET transconductance (~gain)
- e_{na}^2 preamp / amp voltage noise
- C_d^2, C_d^2 detector (and other) capacitance
- τ, τ shaping time constant
- A_f fabrication-dependent factor
- I_d detector leakage current
- T feedback resistor temperature
- R_f feedback resistance
- i_{na}^2 preamp / amp current noise



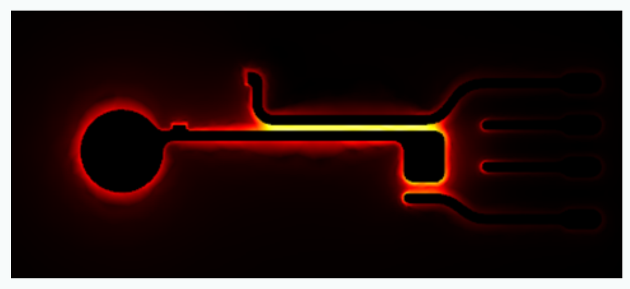
Low-Mass Front End



Projected Background: < 700 nBq (from U + Th)



Wire bonding of JFET to Au traces on glass



Electric field of feedback capacitor from 3D electrostatic simulations

Current Design Goals

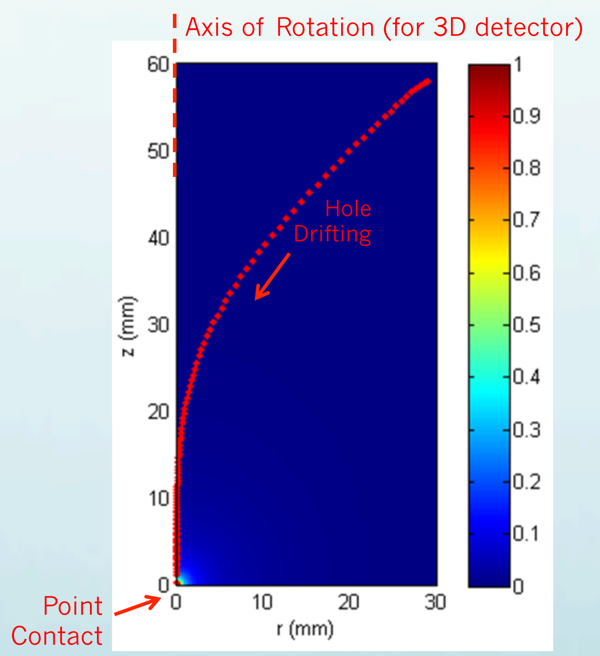
$R_{feedback}$ ~ 50 GOhm
$C_{feedback}$ ~ 50 fF
C_{pulser} ~ 50 fF

Ongoing Tasks

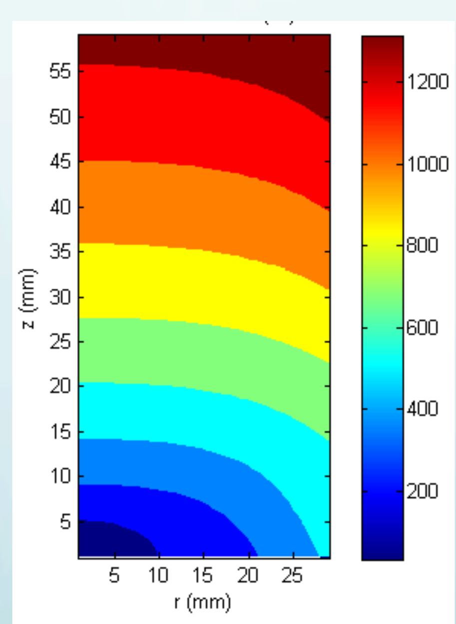
- Optimizing JFET current and temperature
- Balancing feedback resistor and JFET temperatures
- Reprocessing large-volume PPC for lower C_d and lower I_d

Progress on Signal Simulation

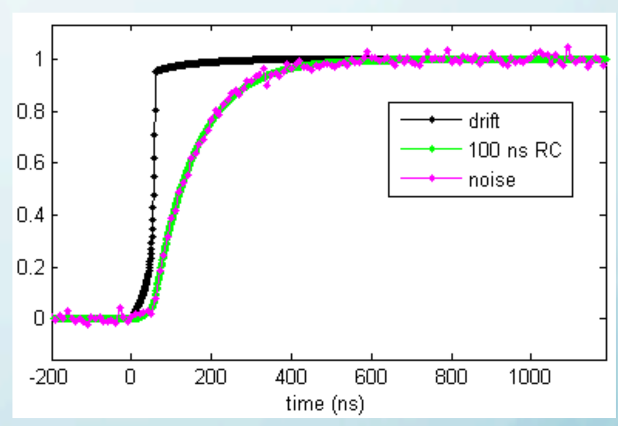
Full 1st order signal simulation package implemented for PPC detectors.



Weighting potential and drift path



Drift times in ns (from creation)



Induced charge and preamplifier response

Adding 2nd order effects:
- Charge trapping
- Dead layer effects

Expected Technical Challenges

- Reduction of electronic noise and energy threshold in kg-scale Ge detectors.
- Mitigation of radiation backgrounds.
- First-time observation of Coherent Neutrino Nucleus Scattering.
- Stable long-term system operation for remote monitoring of reactor status and power.