U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND – ARMY RESEARCH LABORATORY

CLUSTER SUB AREA: Energy Science

Radioisotope Power Sources – Technology and Applications

Maximizing Beta Interactions in Textured Energy Converters

Marc Litz, Randy Tompkins, Steve Kelley, Iain Kierzewski, Claude Pullen

Project Type: nuclide energy conversion, Network C3I

Collaborators and Institutions: SUNY, ORNL, Widetronix

POC: Marc Litz, marc.s.litz.civ@mail.mil

Funding Type: [6.1/6.2]

Project Size: Small

Duration: FY16-FY22

OBJECTIVE AND CONTEXT

Objective

- Maximize power density for sensors and communications electronics through use of energy dense isotopes and textured wide bandgap semiconductors for decades of persistent sensing (IoBT) and communications (SatCom)

Goal: 10mW/cm^3
1. Increased Endurance
2. Weight reduction
3. Volume reduction

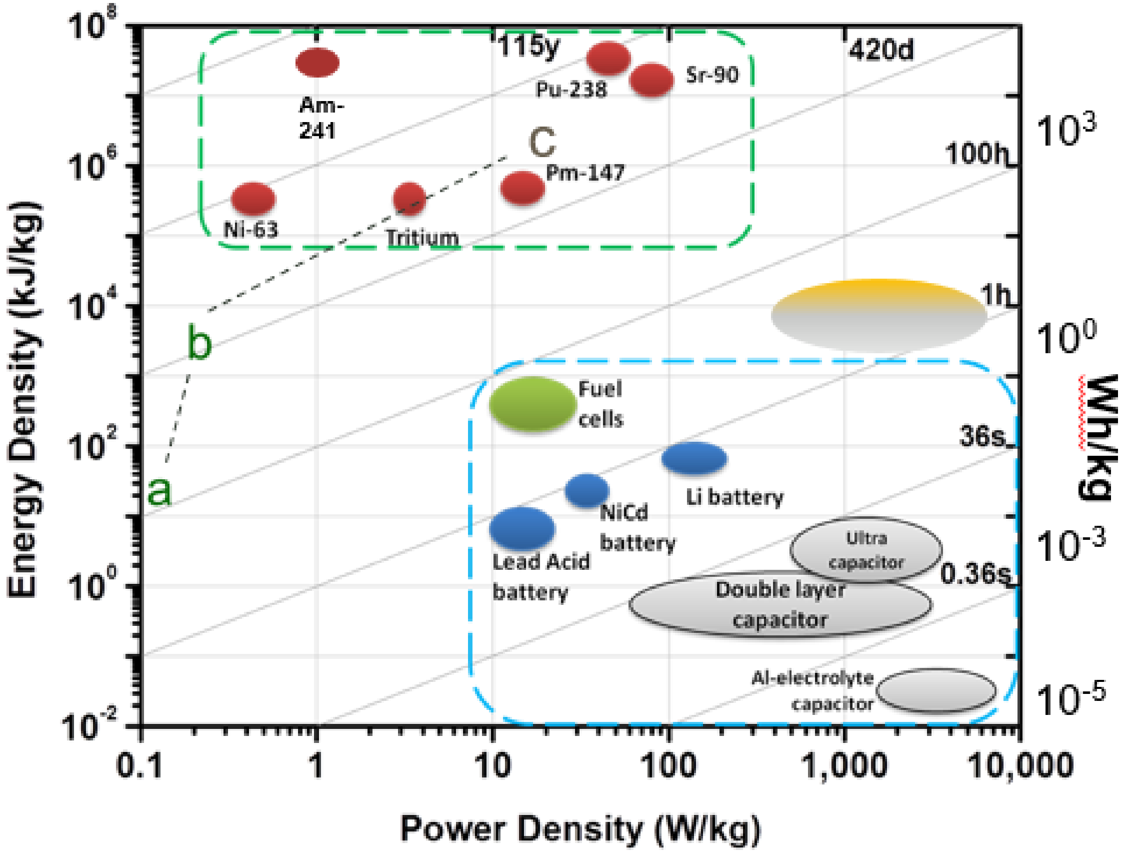
Vision

- 45min max flight time
- 150g battery pack (VC20)
- 24.4 Wh
- extended flight (perching) 30yr
- 80g
- 45 kWh, 12h recharge

- 6 month operation
- 50mW$_{avg}$
- 180 Wh
- 20 year operation
- *7200 kWh*

- Li battery lasts 2 mnth
- 1 kg 800cc
- 50mW RI PS
- 5-year operation
- 50 g 40cc

- 15kJ/day
- Thin film battery 1day
- 1mW RI PS recharger
- 5-year operation
- 20mm^3

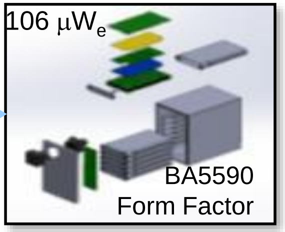


Challenges

- Material Radiation Tolerance limits power density
  - device dependent, defect dependent, RI configuration, etc
- Isotope logistics
  - licensing, safety approval, handling, shipping

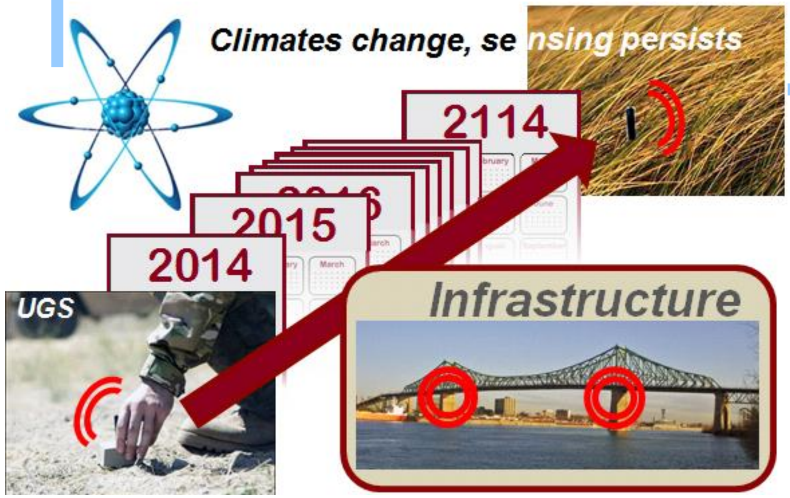
Review papers
[1] Prelas M et al. Nuclear Batteries and Radioisotopes. Switzerland: Springer Int Pub; 2016.
[2] Olsen, et al., Betavoltaic Power Sources, Physics Today 65(12), 35 (2012);
[3] Spencer, Alam, High power direct energy conversion, Appl. Phys. Rev. 6, 031305 (2019)

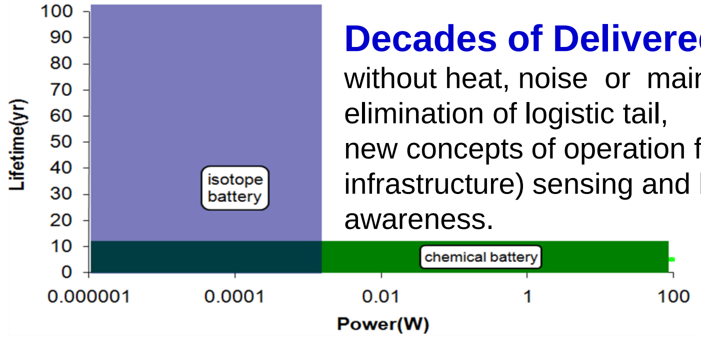
Army Challenges
Sensor and Comms Power
Delivery for Decades



Isotope batteries
Pros: Decades of life, ultra-energetic materials
Cons: Low power, low TRL, high cost

Army Tritium Logistics
Used in compass, fire control azimuth, gunsights, collimators

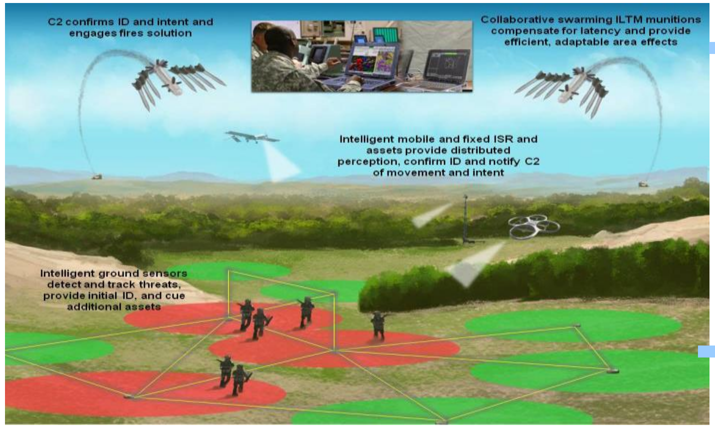




Decades of Delivered Power
without heat, noise or maintenance.
elimination of logistic tail,
new concepts of operation for (lifetime of infrastructure) sensing and battlefield awareness.

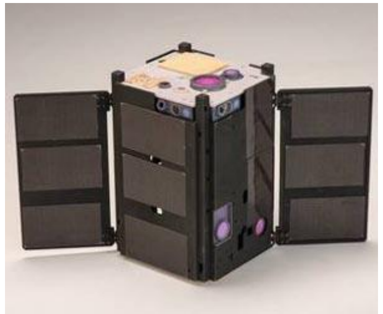
Missile Health Maintenance

Ultra-Low Power Health Monitoring
Health monitoring systems require, extremely low power sensors, and extremely low power analog and digital signal processing to achieve more than 10 years of operation. **PEO-AV SBIR**

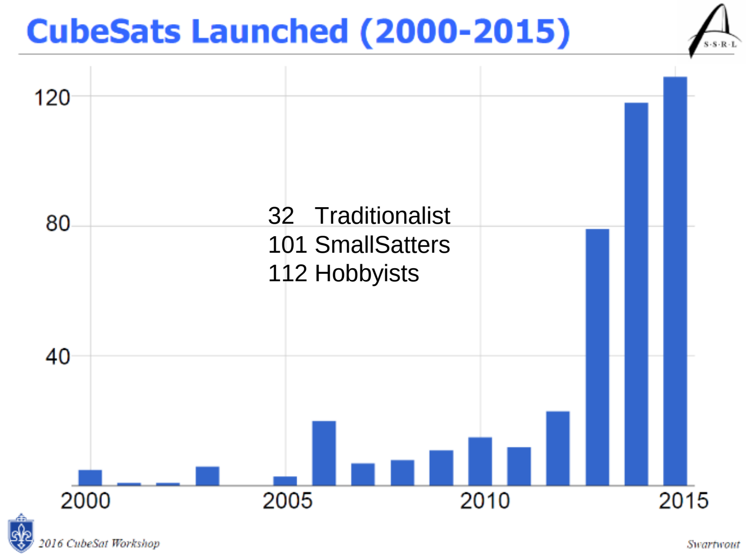


Battlefield Situational Awareness
Anti-Personnel Landmine Alternatives
- detection and positive identification of enemy combatants before engagement
- intelligent sensors/networks, **power sources**, swarming munitions as basis for innovative disruptive capabilities

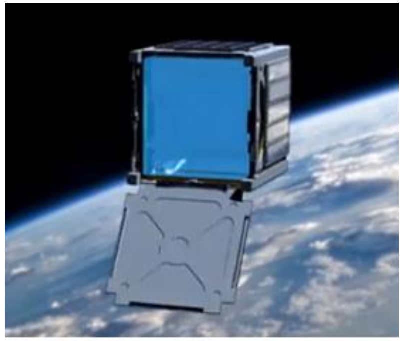
Unattended Sensors and Communications Nodes in LEO



Optical Communications and Sensor Demonstration (OCSD) Spacecraft Configuration. OCSD differs from other space-based laser communication systems because a compact laser is hard-mounted to the spacecraft body. 2015



Michael Swartwout, “CubeSats and Mission Success: A Look at the Numbers,” 2016 CubeSat Developers’ Workshop, 20 April 2016



CACTUS 1 [Capitol Technology University]

CACTUS-1 is a university technology demonstrator of cost saving comms and scientific data gathering instrument.. Aerogel medium trapping micrometeorites and spacecraft hotspot communicating through Iridium. 2015

isotope	A1	A2	τ	SpAct	Act required	α/β-energy
	Ci	Ci	yr	Ci/g	Ci	keV (avg)
^{3}H	1100	1100	12.5	9621	2963.5	5.7
^{63}Ni	1100	810	99	57	949.0	17.8
^{90}Sr	8.1	8.1	28.8	140	14.9	1130
^{147}Pm	1100	54	2.6	930	272.4	62
^{241}Am	270	0.027	432.6	3.43	3.1	5486
					*assume η	
					10%	

A1 – special package (sealed or evaluated)
A2 – normal package
Packaged in instrument ~A2/100 (49CFR173.433)

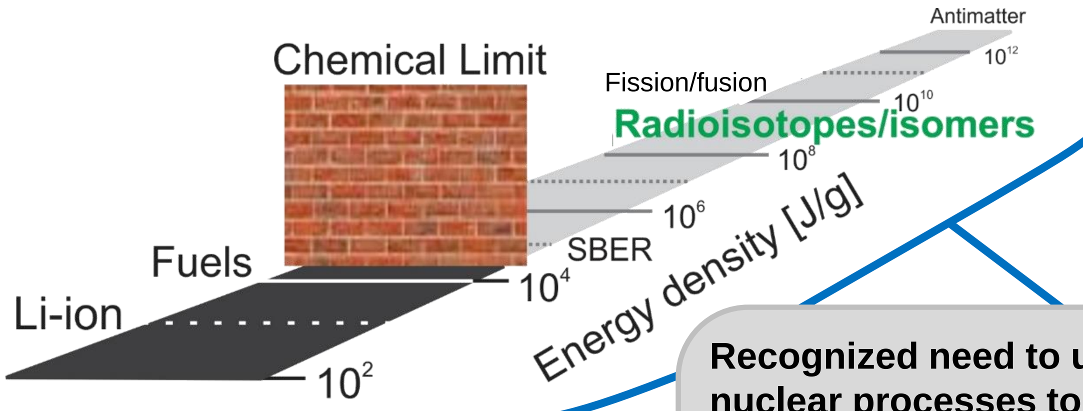
Goal:
10mW in 10cc

10mW*2.5yr=90AA
=150kWhr

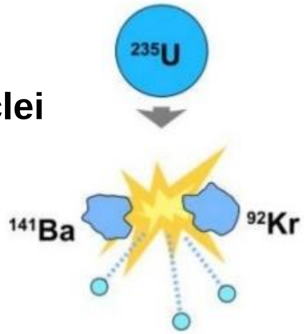
Sources of Space Debris.

NEEDS, OBJECTIVE, AND CONTEXT

Objective: **Move "beyond fossil fuel" (MG George, Dr. Vettel, LTG Wesley, in press for July 2020 Army Magazine)**



Nuclear Fission: Energy from splitting nuclei



- Established technology – large scale: 500 MW power plants (fixed emplacement)
- Technical challenges to reach "compact modular" scale for transportable power plant
- Develop for base support:
  - SCO RFI 2019
  - INL & LANL designs
    - Funded programs
    - **Not useful for many Army needs, e. g. propulsion**

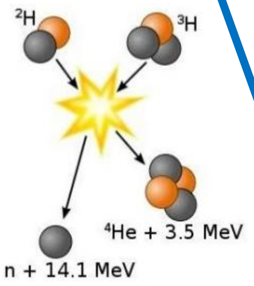
+ multiple support trucks

Recognized need to use nuclear processes to access energy storage far in excess of the chemical limit: 2016 DSB Report; Carroll, in *Innovations in Army Energy & Power* (2018)

Nuclear Fusion:

Energy from fusing nuclei

- "Unregulated": Bombs (and stars)
- "Regulated": Unrealized - tremendous promise, tremendous engineering challenges (see $22B ITER project)
- "Compact" reactor ideas being tested (Lockheed-Martin, others)
- **Very far into the future, unlikely to meet Army needs**



Nuclide Energy:

Energy from radioisotope decays, natural or induced

- Unique ARL scientific expertise and leadership in radioisotope decay energy conversion and experimental physics of induced energy release from long-lived nuclear metastable states (isomers)
- Virtual extended laboratory through extensive collaborations

ARL FOCUS AND LEADERSHIP

APPROACHES

"You say you want a revolution" The Beatles

Standard Radioisotopes

- High energy density (100,000× chemical)
- **Long lifetimes for long mission duration; decades or longer, low power**
  - Research focus on improved energy conversion, isotope loading

$\frac{E\eta}{\tau}$

- Goal: Power output from direct conversion of radioactive decay (beta emission) into electricity
- Lab demos now, fieldable prototypes before 2028
- **Key research:**
  - **Deposition of radioisotopes on textured energy-conversion semiconductors as betavoltaics**
  - **Novel approach ➔ increased radioisotope loading per unit area, increased energy conversion: 8X greater power vs. 2D**

Details: "Maximizing Beta Interactions in Textured Energy Converters", Marc Litz

Nuclide Power FOM

$$P \propto \frac{E\eta}{\tau}$$

Energy content → E

Energy conversion efficiency → η

Energy storage & release lifetime → τ

- **Key research:**
  - **Demonstrate NEEC for other nuclides**
  - **Investigate energy dependence of NEEC during implantation**
  - **Develop theoretical understanding of NEEC**
  - **Search for switching pathways for attractive isomers**

Isomers

- High energy density (100,000× chemical)
- **Multiple lifetimes: long for energy storage, "SWITCH" to shorter for power output when needed**
- Several methods discovered for inducing energy release on demand
- 2018 discovery of "efficient" isomer "switching" via new physical process using atomic electrons (NEEC)

$\frac{E\eta}{\tau}$

LETTER 2/8/2018 nature

Isomer depletion as experimental evidence of nuclear excitation by electron capture

ARL's #1 "Coolest" Advance of 2018

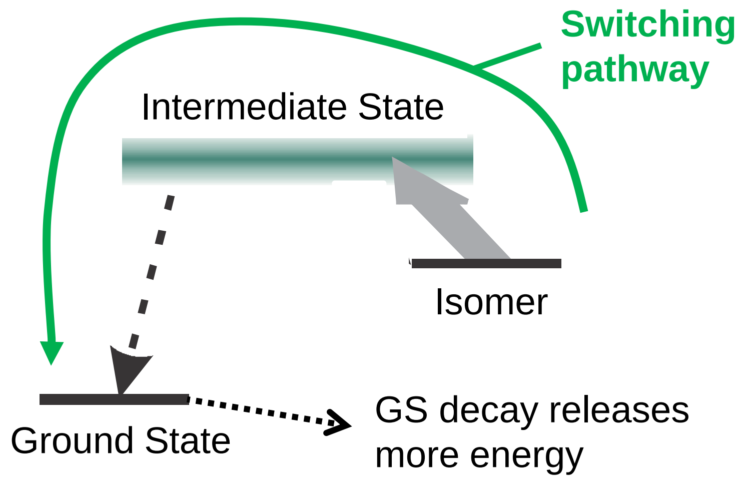
- Goal: Power output from conversion of radioisotope decay heat into electricity or mechanical energy after isomer "switching"
- Discovery phase, deployment past 2030

Details: "First Demonstration of Nuclear Excitation by Electron Capture for Radioisotope Energy Release", Chris Chiara

RESULTS - ISOMERS

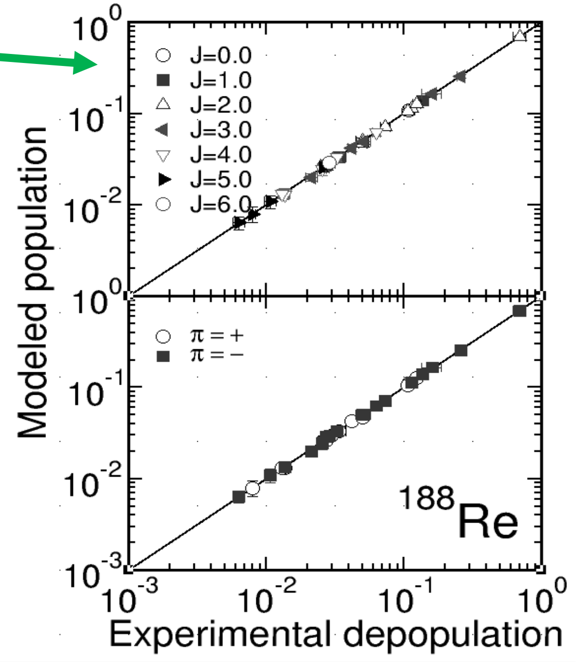
Isomer Switching

- **Twelve isomers with half-lives > 1 year** and shorter-lived ground state [Carroll, in *Innovations in Army Energy and Power* (Materials Science Forum, Millersville, PA, 2018); one additional isomer identified after publication]
- Switching pathway required, starting with excitation of an "**Intermediate State**"
- Nuclear spectroscopic experiments required to identify depletion paths; every nuclide unique

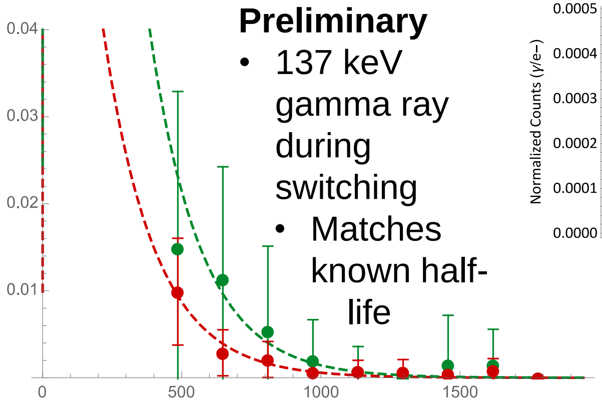


Switching Pathways

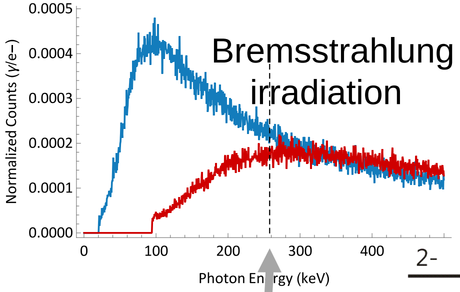
- Experimental search for **^{192}Ir (isomer $T_{1/2}$ = 241 y, ground-state $T_{1/2}$ = 74 days)**; Australian National University/ARL/AFIT collaboration via ITC (part of AFIT PhD project); analysis underway
- Study of **^{188}Re** to develop systematics guide for **^{186}Re (isomer $T_{1/2}$ = 200,000 y, ground-state $T_{1/2}$ = 3.7 days)**; LBNL/Budapest/ARL/AFIT collaboration (part of AFIT PhD project)
- Test of isomer switching for **^{166}Ho (isomer $T_{1/2}$ = 1200 y, ground-state $T_{1/2}$ = 27 h)** using novel photon source: directional, high-energy Bremsstrahlung produced from laser-wakefield-accelerated electrons; UN-L/ARL collaboration (part of UN-L PhD project)

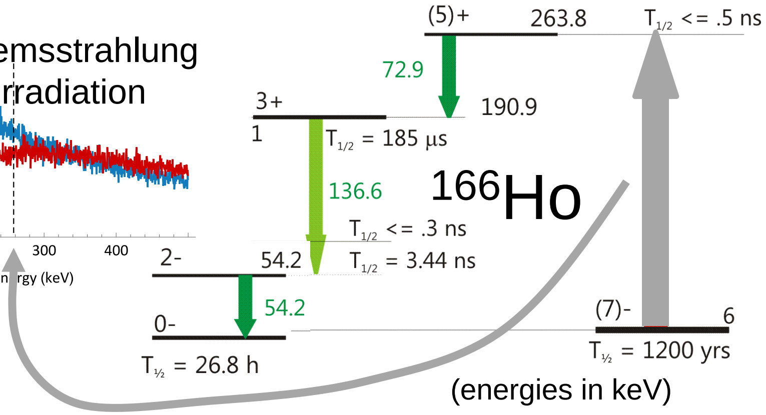


Pre-publication
- Comparison between measured nuclear levels and theory
- Levels excited by thermal neutrons
- In prep for Phys. Rev. C



Preliminary
- 137 keV gamma ray during switching
  - Matches known half-life



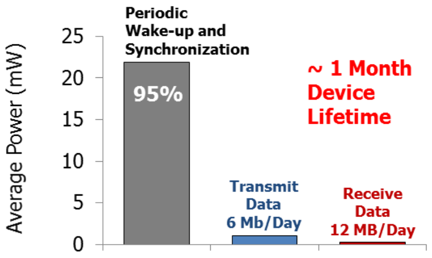
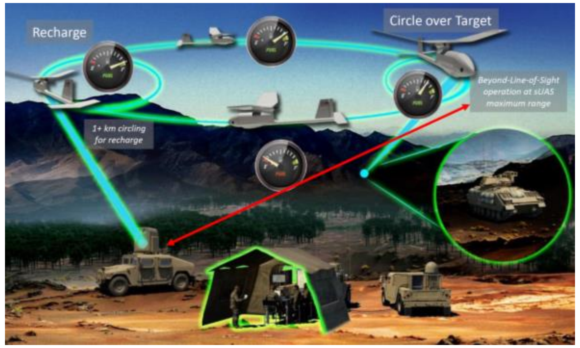


ENERGY EFFICIENT ELECTRONICS PROGRAM OVERVIEW

Army Gaps: Limited energy capacity & general inefficiencies, need extended range and duration; network not expeditionary/mobile; future network → low signature, high QOS, & power savings

Problem: Energy-constrained platforms have limited mission duration due to limited available energy and inefficient electronics

***Program objectives:** provide electronic and photonic technologies enabling efficient use of available energy for increased mission duration, persistence, and endurance*

Soldier	Distributed electronics	UAVs
		
Mission duration	*Long-lived*	*Endurance*

Demand

Comms energy reduction
- *Energy efficient digital backend*
- *Efficient RF front ends*

Hardware for AI

Comms energy reduction
- *RF wake-up radios*
- *UV non-line-of-sight comms devices*

Propulsion (not E3P related)

Light-weight comms
- *Light-weight antennas*

Hardware for AI

Supply

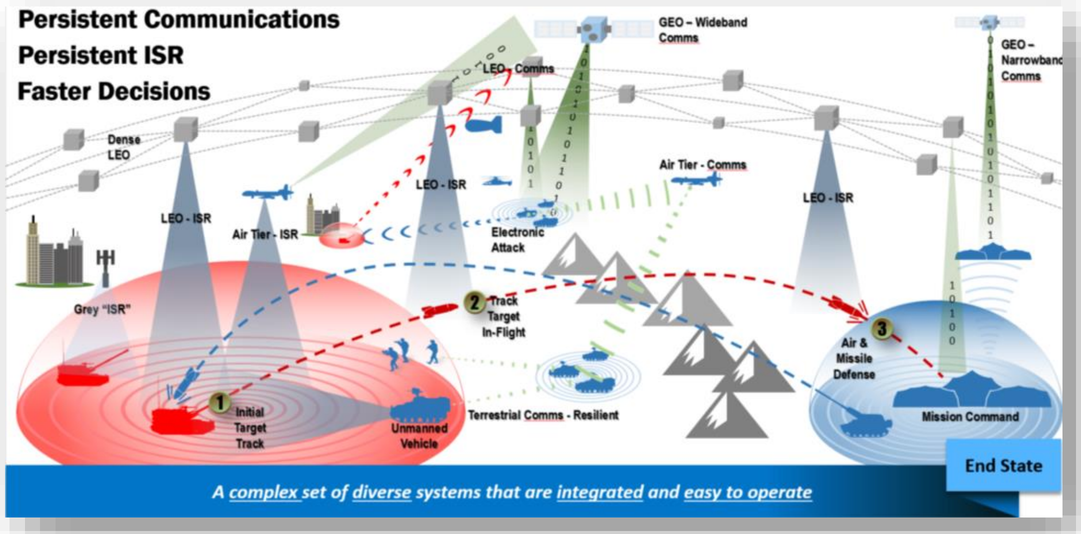
Networked energy
- *Power offloading-rapid recharge*
- *Power offloading-wireless power*

Long-lived power
- *Radioisotope power*

Long-lived power
- *Pyroelectric-based power beaming*
- *Radioisotope power*

WHO CARES?

Network CFT



1-N (N=61) relevance in Unified Network Transport:

- Energy-efficient networking and devices (8) → Energy-efficient devices (20)
  - **Stakeholders:** CERDEC STCD Non-Traditional Waveforms (4), potentially PM TR
- Leave-behinds (16, 17, 32) & decoys (36, 37)
  - E3 long-lived comms and radioisotope power
- Satellite communications (2, 3, 5, 13)
  - E3 long-lived radioisotope power for LEOs
- Aerial tier networking (12)
  - E3 far-field wireless

Soldier lethality CFT

Near-term goals:

- Head-borne SA: 1) AI for optimized display; 2) eye, *voice*, & gesture control
  - E3 hardware for AI

Mid-to-long term goals: (Susan Fung June presentation)

- Generating, storing, & distributing squad-level power
- Connecting on-soldier, across squad, to tactical network
- Autonomous assets for squad operations (ground resupply, follow-me robots, E3 power offloading)
  - **Stakeholders:** MCoE & PM Force Projection (PEO CS&CSS) → SMET

Soldier Load = Physical Load + Cognitive Burden

PROGRAM MAPPING

Demand | Supply

Comms energy reduction

6.2

non-RF

UV comms devices
Sampath

**Not directly comms*

*Field Programmable Neural Arrays
Gadfort

RF

Generalized Energy-Efficient Army Radios
Wilson

RF wake-up receiver
Bedair

Efficient Microwave Power Amplifiers
Darwish, Birdwell, Ivanov

6.1

Diamond materials
Birdwell, Ivanov

Topological insulators – ultra-low energy logic and memory
Folkes, Taylor

Lightweight antenna materials
Zaghloul

Networked energy & long-lived power

6.2

Power offloading

High-rate recharge batteries
Read

Near, mid, and far-field wireless
Hanrahan, Tseng

Long-lived power

Radioisotope power sources & electronics
Litz, Thompkins

6.1

Low-leakage & 3D GaN for Betavoltaics
Thompkins, Litz

Pyroelectric materials
Hanrahan

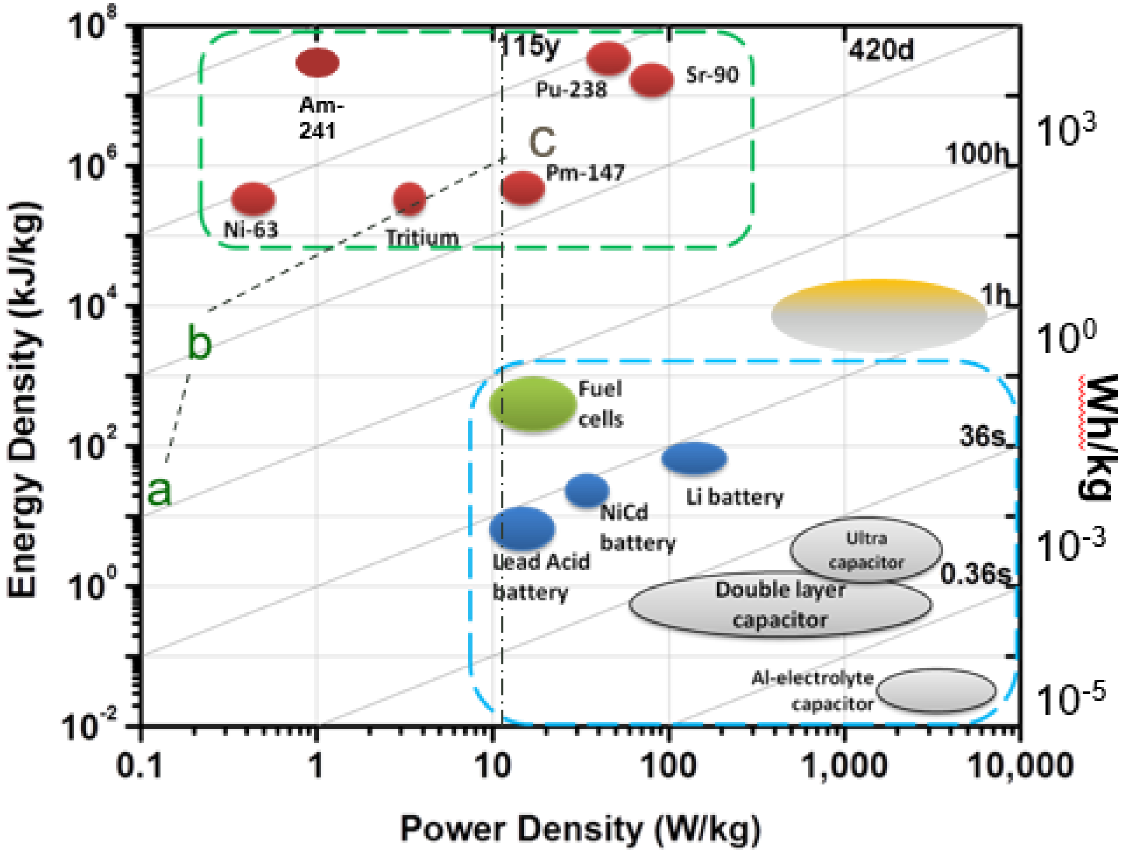
OBJECTIVE/ COMMUNITY CONTEXT

Objective

- Maximize power density for sensors and communications electronics through use of energy dense isotopes and textured wide bandgap semiconductors for decades of persistent sensing (IoBT) and communications (SatCom)
  Goal: 10mW/cm^3

Community Context

- Description of relevant work of others
  - Ti or Mg loaded 3H on textured SiC –Widetronix
  - Radiolytic Water splitting - Infinity
  - Liquid SeS – UMO
  - Medical Radiotracer processes - UMD-ViTrax
  - Isotope-phosphor mix - ORNL-ARL
  - Energy efficient phosphors – Hollerman, ULA
  - 3H loaded Polymer instability – Univ Pitt
- ARL is well positioned (radiation tolerant materials, nuclear scattering, electron beam experiment and modelling, electronics packaging)
  - GaN growth (SUNY-Albany)
  - Widetronix Inc (Textured SiC)
  - ORNL (radio-isotope chemistry and logistics)



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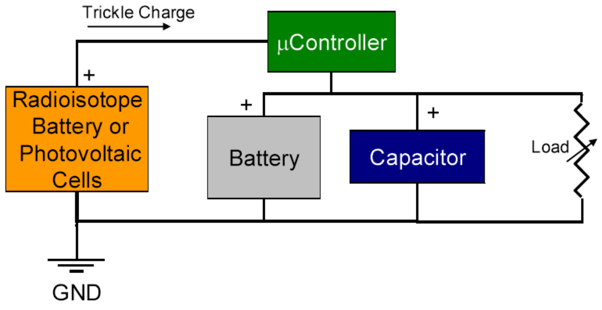
[2] Olsen, et al., Betavoltaic Power Sources, Physics Today 65(12), 35 (2012);
[3] Spencer, Alam, High power direct energy conversion, Appl. Phys. Rev. 6, 031305 (2019)

NON & TECHNOLOGY CONSIDERATIONS

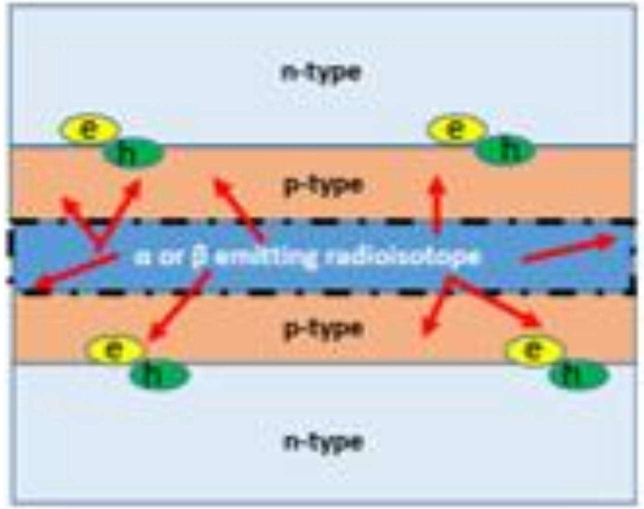
FOR ISOTOPE POWER SOURCE

1. Radioactive Materials
   - Radiation Damage Threshold (E_β <200keV)
   - Half-life (>20yr)
   - Availability, Expense, BioToxicity
2. Energy Conversion from Radiation
   - Direct Energy Conversion (DEC)
     - GaN Geometries
     - SiC Semiconductor Diodes/Etched
   - Indirect Energy Conversion (IDEC)
     - Radioluminescence → photovoltaic conversion
3. Power Management
   - Microprocessor controlled
   - Battery and supercapacitor
   - Interrupt Driven Sleep modes
   - Linked to sensor and functionality
4. Packaging
   - Encapsulation
   - Format (BA5590)
5. Licensing
   - Sealed Src Dev Reg, Army Commodity License, NRC General License
   - meeting DOT regulations

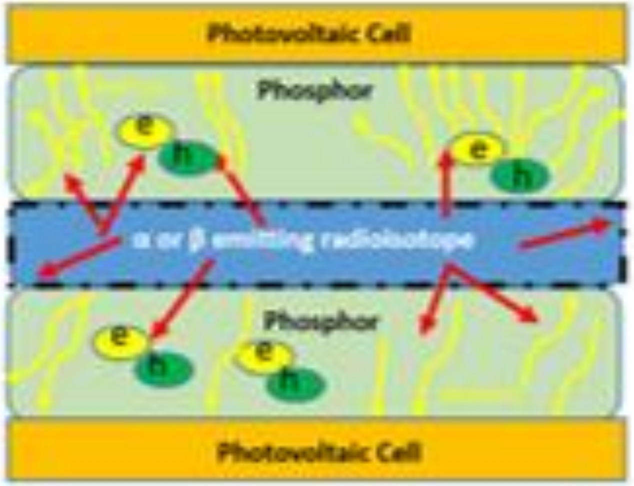
	HalfLife(yr)	E_{avg}(keV)	Ci
^{151}Sm	90	25.3	6.7
^{193}Pt	50	18	9.4
^{63}Ni	101	17	9.9
^{157}Tb	71	16	10.6
^{3}H	12.5	6	28.2
^{121m}Sn	55	3	56.3
^{147} Pm	2.6	63	15



DEC



IDEC



M. Litz, "Isotope Beta Battery Approaches: Technology Review," ARL-TR-7048, Aug 2014
CRC Press, 2002, Polymers, Phosphors, and Voltaics for RI Microbatteries, vol. 1, K. E. Bower, Y. A. Barbanel, Y. G. Shreter and G. W. Bohner, Eds., Boca Raton, FL
M.V.S.Chandrashekhar, C.I. Thomas, Hui Li, M. G. Spencer, and A.Lal, "Demonstration of a 4H SiC betavoltaic cell," Applied Physics Letters 88, 033506, 2006
Olsen, Larry C.; Cabauy, Peter; Elkind, Bret J. Betavoltaic Power Sources. *Phys. Today* **2012**, *65* (12), 35.

Isotope Activity below NRC & DOT Thresholds

*10mW$_e$

isotope	A1	A2	τ	SpAct	Act required	α/β-energy
	Ci	*Ci*	*yr*	*Ci/g*	*Ci*	*keV (avg)*
^{3}H	1100	1100	12.5	9621	2963.5	5.7
^{63}Ni	1100	810	99	57	949.0	17.8
^{147}Pm	1100	54	2.6	930	272.4	62
^{85}Kr	270	270	10.7	390	37.5	450
^{90}Sr	8.1	8.1	28.8	140	14.9	1130
^{241}Am	270	0.027	432.6	3.43	3.1	5486
	A1 – special package (sealed or evaluated) A2 – normal package Packaged in instrument ~A2/100 (49CFR173.433)				*assume η 10%	

Type A quantity – aggregate radioactivity which **does not exceed A1** for special form material or A2 for normal form, (A1 and A2 values are given in § 173.435 or determined with § 173.433)

A1 - the maximum activity of **special form** RI permitted in a Type A package.
*A*2 - the maximum activity of RI material, **other than special form** in a Type A pkg

Special form Class 7 (radioactive) material means either an indispersible solid radioactive material or a sealed capsule containing RI material

No major Logistical Challenges for 10mW power module:
Regulation exists for safe handling and use of several practical RI energy sources

APPROACH/RESEARCH METHODOLOGY

- **ARL internal effort above**

6.1 Comparison of GaN energy conversion (EC) device operating characteristics(OC)

- GaN-on-GaN vs GaN-on-Sapphire P-I-N device materials comparison - leakage
  - complete the fabrication of devices (70% complete)
  - measure OC using ARL EBIC capability

Simulation of energy deposition and transport in WBG materials utilizing

- Monte-Carlo nuclear scattering (MCNPX)
- utilizing finite-element (Silvaco)

Experimental investigation of time dependence (TD) of energy absorption in UWBG SC materials

- utilize 1ns impulse eBm to investigate energy transfer mechanisms and EC(CL, PL, lock-in)

6.1/2 Quantify high fluence degradation and damage in UWB materials (GaN, AlGaN and diamond)

- collaborate with SUNY 100/200keV SEM and UMD 2MeV linac simulating ^{90}Sr
- collaborate with ORNL – application of ^{241}Am for (5MeV α)

6.2 Develop proof-of-principle demonstrations of isotope power sources

- demonstrate first sandwiched device (^{63}Ni on SiC)
- demonstrate 4x4cm^2 array
  (ie PC board design, fabrication process, etc)

- **Integrate with**
  - **GaN pillared growth (ARO-SUNY-Albany)**
  - **SiC textured devices (SBIR-Widetronix)**
  - **ORNL radiochemistry**

Figure 1. EC devices exposed to electron beam in vacuum chamber simulating isotope stimulation.

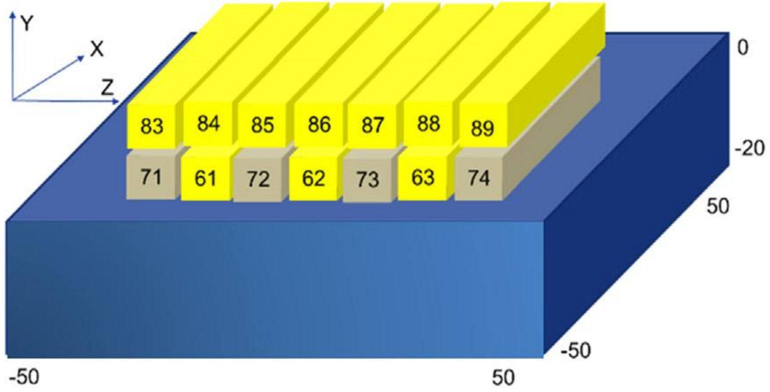


Figure 3. Grooved geometry modelled showing 3.75x increase in energy delivered to EC/cm2 and 5.82x improvement in η_{src}.

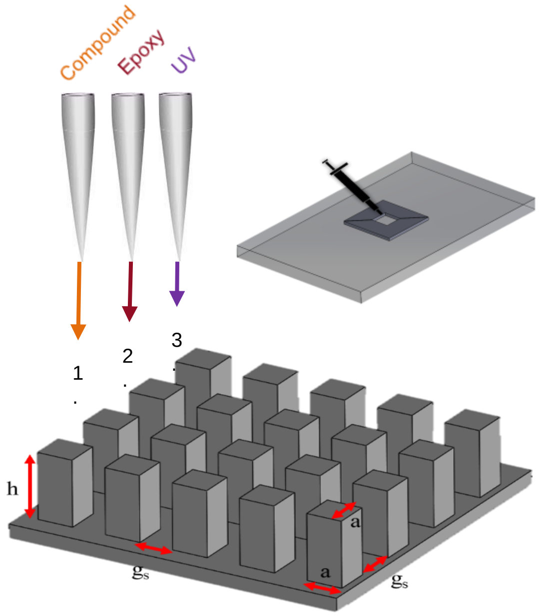
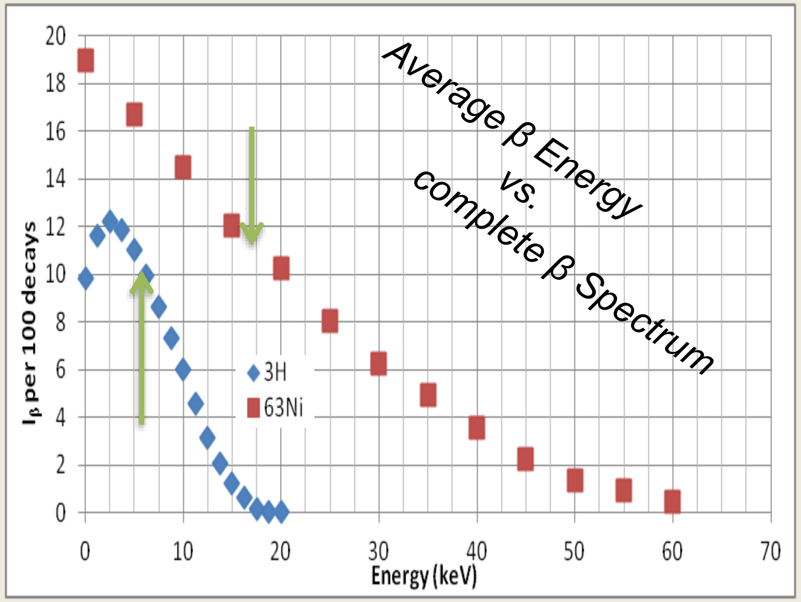
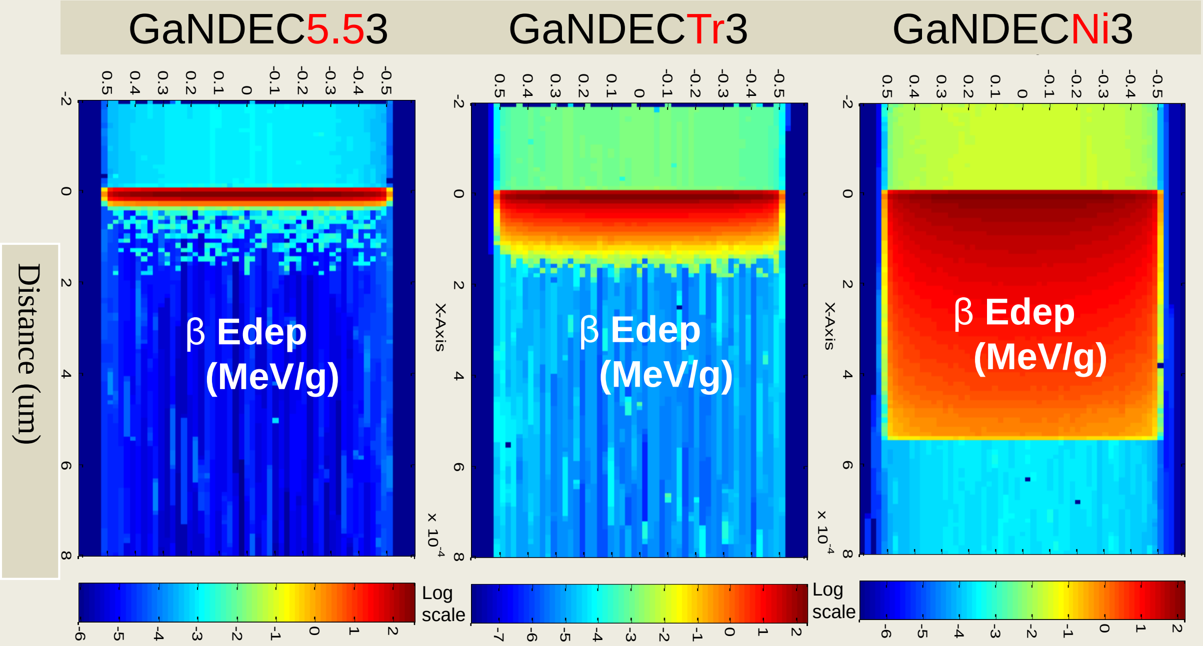


Figure 2. Dispense fuel, Epoxy, and cure with UV LED across BV cell.

Match β Interaction Range in DEC

Not to scale





"Average β" range insufficient to compare well to measured results

^{63}Ni β-spectrum mismatched to GaN interaction region

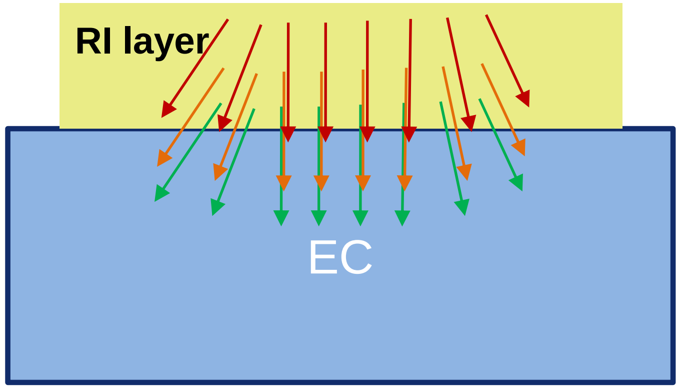
Monoenergetic (Eavg) β inadequate to design efficient energy conversion devices

^{63}Ni β-range in GaN exceeds depletion region depths

Common challenge: range matching

M. Litz, "Monte-Carlo Evaluation of Tritium β-Spectrum Energy Deposition in GaN," ARL-TR-7082, 2014
F.H. Li, X. Gao, Y.L.Yuan, J.S.Yuan, M. Lu, "GaN PIN betavoltaic nuclear batteries," Sci. China Tech. Sci., January (2014), Vol.57, No.1

RESULTS
RI thickness & Range in EC



Vary Liquid-Form Radio-Isotope (LFRI) thickness
1) 90% energy out of layer (η_{src})
2) Efficiency optimized RI layer thickness
3) 90% of maximum RI energy transferable
(as layer thickness increases, RI energy /cm^2 increases)

LFRI characteristics:
- reduced self-attenuation in low-density medium
- Increases effective surface activity
- Uniformly deposit isotope on textured devices

Table 2 Energy from isotope layer deposited on EC materials creates exponential depth profile. The depth (µm) in which 90% of the energy is deposited is shown.

	SiC	GaN	Diamond	ZnS	^{3}H-urea	^{63}NiCl$_2$	^{147}PmCl$_3$	^{35}S(NH$_4$)$_2$	^{90}Sr(NOH$_3$)
^{3}H	0.62	0.23	0.42	1.4	3.4		…	…	…
^{63}Ni	4.4	2.2	3.3	8	…	11.5	…	…	…
^{147}Pm	28.4	14.8	23	40	…	…	42	…	…
^{35}S	18.5	10	15	36	…	…	…	45	…
^{90}Sr	149	130	69.5	231	…	…	…	…	198
g/cc	3.2	6.15	4.5	1.5	.5	1.05	1.55	.99	.99
BG	Indirect	Direct	Indirect	Direct	…	…	…	…	…

Table 3 Isotope activity that can be deposited on planar energy converters (EC) per cm^2 is estimated from MC simulation results and specific activity (ORNL NIDC production values)

Isotope	90% saturated		RI	RI	Activity
	RI layer thickness	RI vol/cm^2	Liquid density	Specific activity	per cm^2
	µm	cc	g/cc	Ci/g	mCi
3H-urea	2	0.0002	1.1	1000	220
NiCl2	15	0.0015	1.5	13	29 *
PmCl3	50	0.005	0.9	211	950 *
Sr(No3)2	250	0.025	0.99	25	619

* Experimentally verified

Modelling and Measurement compare well

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Depletion Region e⁻Xport Modelling

SiC, GaN, AlGaN

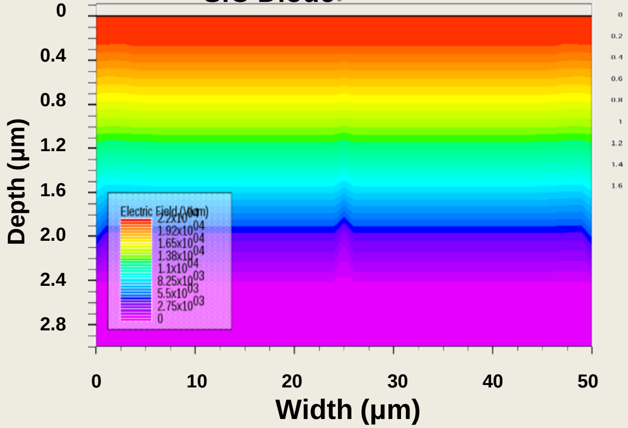
SiC Doping Profile:
700 nm p-type – 1e19 per cm3 p-type doping
10 um intrinsic – 1e14 per cm3 n-type doping
5 um n-type – 1e19 per cm3 n-type doping

GaN Doping Profile:
50 nm p-type – 4e17 per cm3 p-type doping
700 nm intrinsic – 1e16 per cm3 n-type doping
1 um n-type – 1e19 per cm3 n-type doping

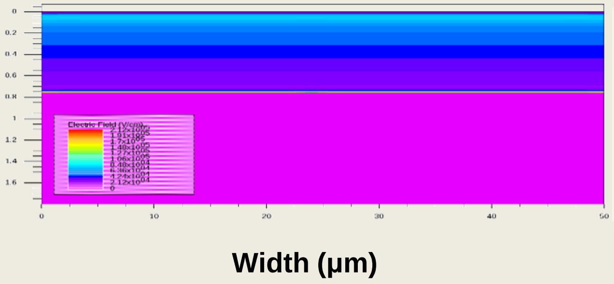
AlGaN Doping Profile:
100 nm p-type – 1e17 per cm3 p-type doping
20 nm p-type graded AlGaN – 1e17 per cm3 p-type doping
600 nm intrinsic – 1e16 per cm3 n-type doping
1.3 um n-type– 5e18 per cm3 n-type doping

	SiC	GaN	AlGaN
Depletion Region:	2 µm	0.75 µm	0.6 µm
Density (g/cc):	3.21	6.15	3.26 – 6.15
E_{dep} 68-90% ^{3}H:	0.2-0.5	0.1-0.3	
68-90% ^{63}Ni:	2.5-5.5	1-2.5	
Max Beta (keV) :	15.5	12.5	9.5

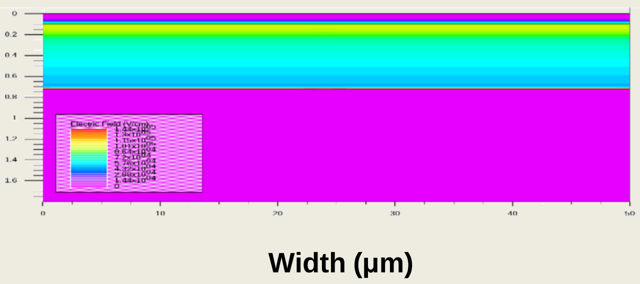
SiC Diode



GaN Diode



AlGaN Diode



i. Charge transport modelling explains experimental results

ii. GaN well matched to ^{3}H by combination of ρ, thickness of depletion region, E_{dep}

E_{dep} GaN

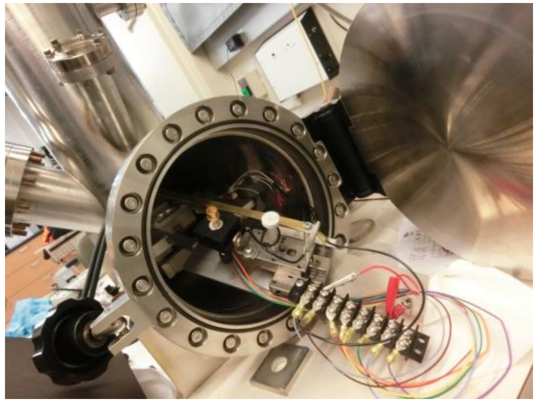
[µm]	68%	90%
^{3}H	0.1	0.3
^{63}Ni	1	2.5
^{147}Pm	9.5	18.6

Unclassified / Approved for Public Release

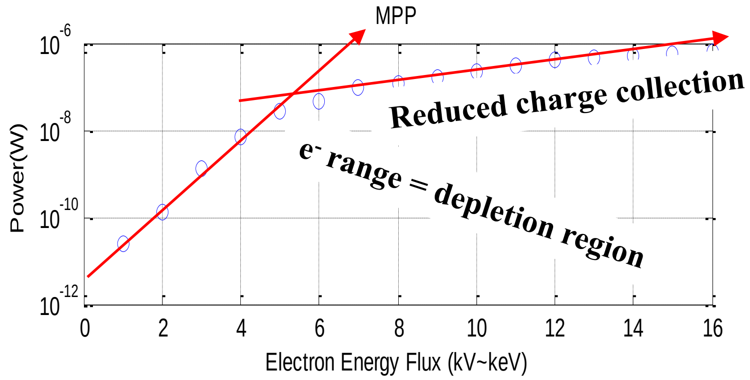
Isotope Simulation Lab

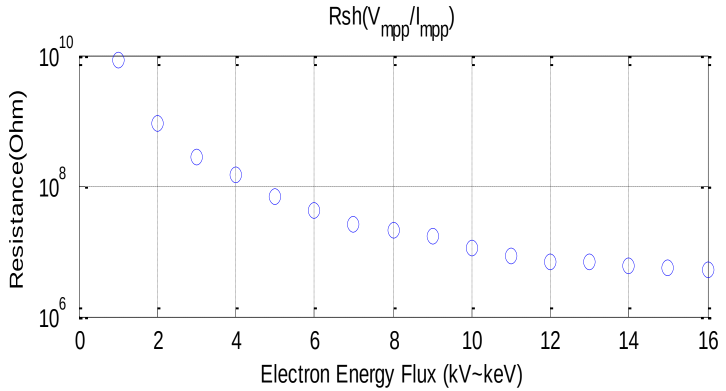
e^-Bm ^{3}H and ^{63}Ni

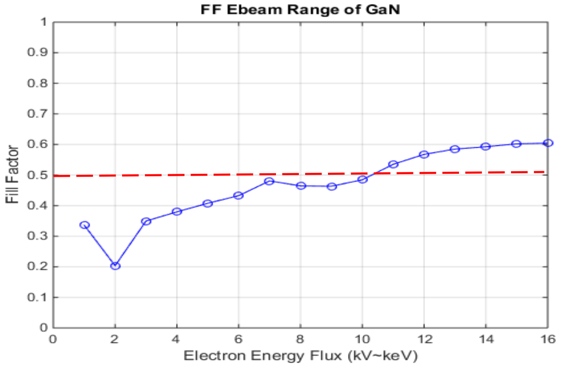
Figure 1. EC devices exposed to electron beam in vacuum chamber simulating isotope stimulation.

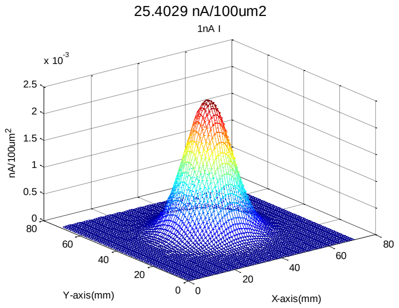


- ❑ **1nA Integrated Current**
- ❑ **1mm FWHM**
- ❑ **2.4 pA/100um^2 @peak**

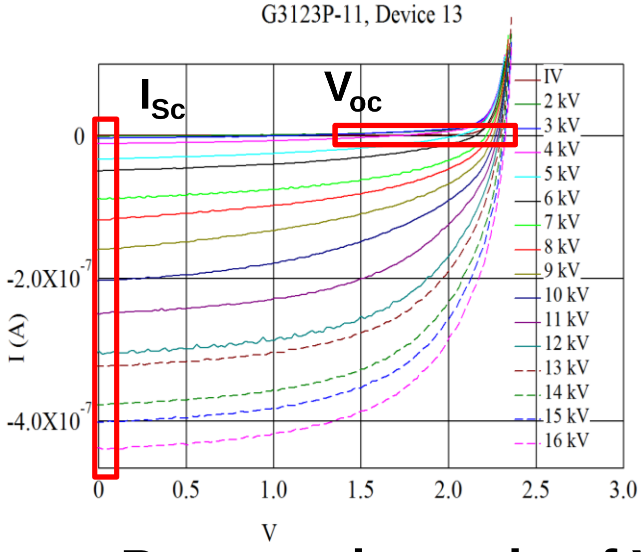


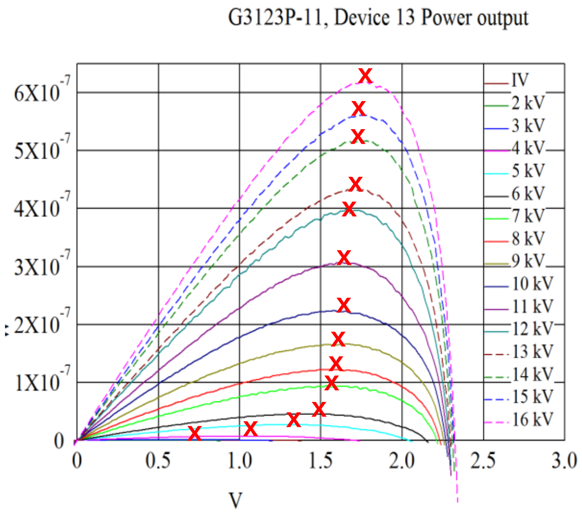






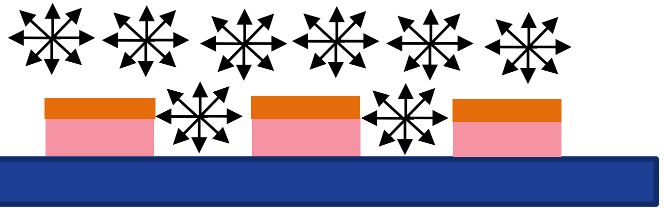
eBm current for 1 atm ^{3}H ~ 0.6nA ~ 0.1Ci/cm^2



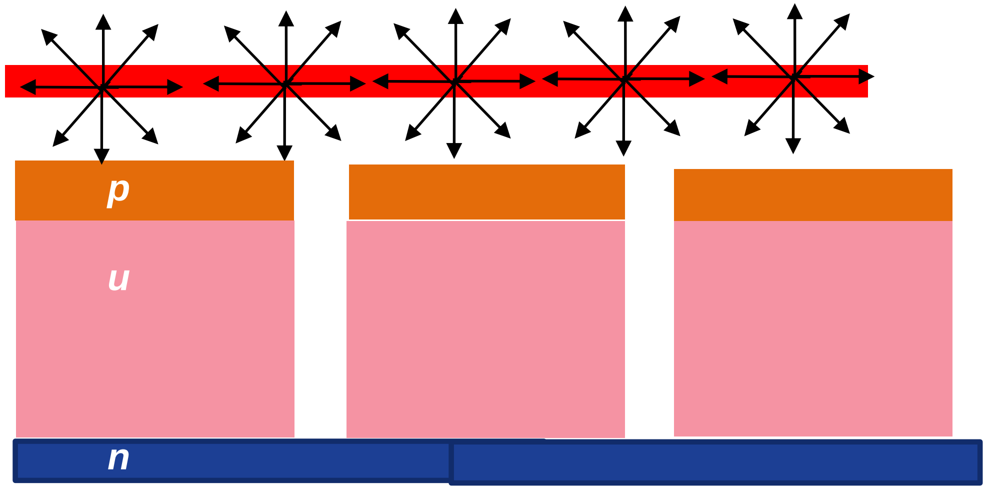


Parametric study of V_{app}

Mesa

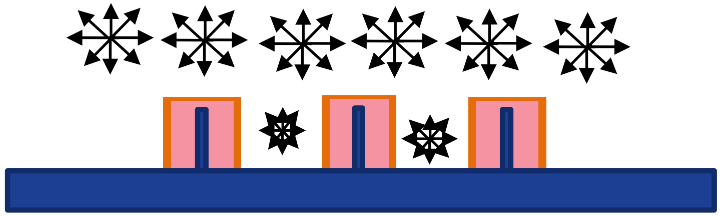


H: 2µm **Diam:** 4µm **Sp:** 2µm
* higher loading

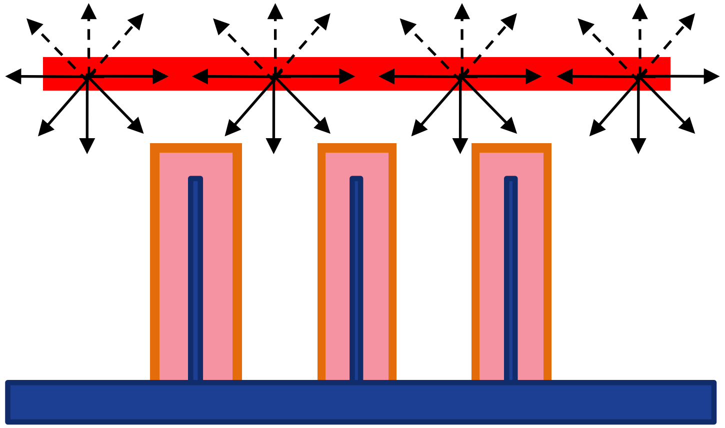


H: 10µm **Diam:** 8µm **Sp:** 2µm

post



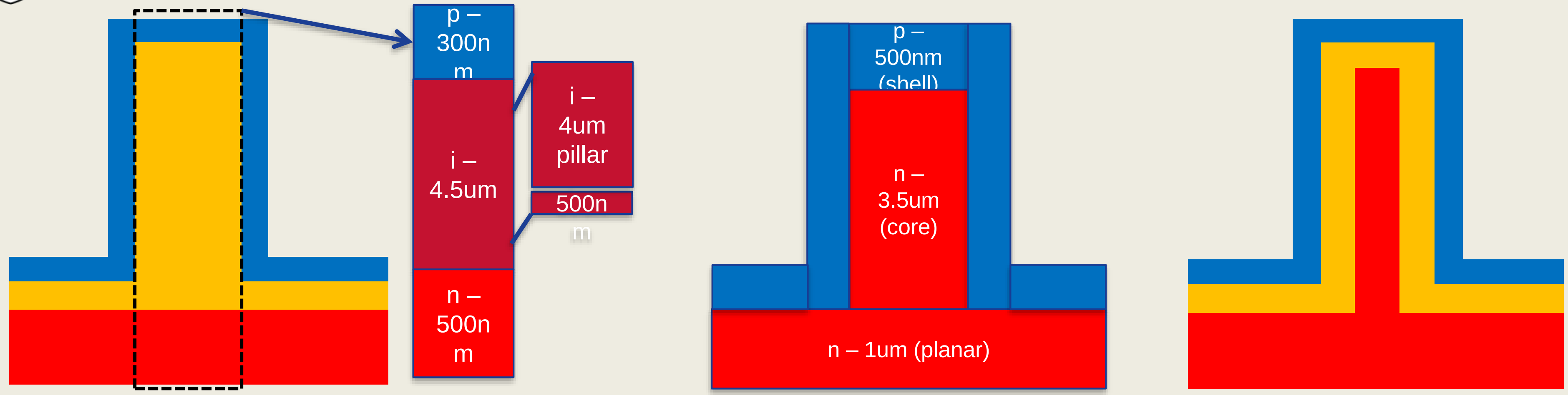
H: 2µm **Diam:** 2µm **Sp:** 2µm



H: 8µm **Diam:** 2µm **Sp:** 2µm

Challenge: contacts

3D Pillared GaN device modelled



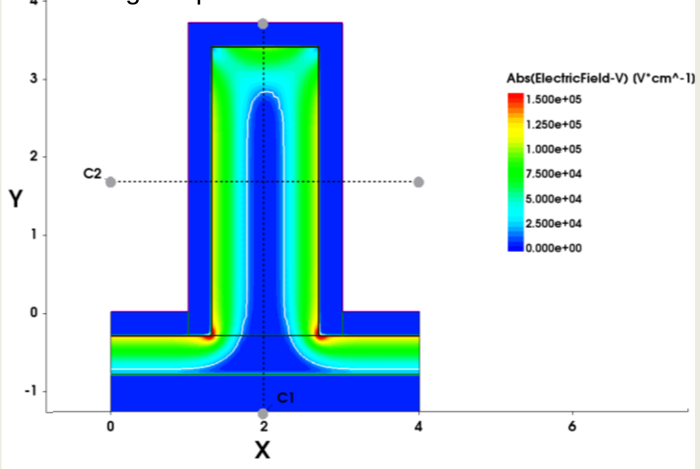
3D-planar

3D PN core-shell

3D PiN core-shell

- ❑ Modelled
- ❑ Grown
- ❑ Detailed electrical characteristics in process
- ❑ Iterations
- ❑ demonstration
  - With Logistically relevant Isotopes
  - Increasing system power density
    - through careful radiation coupling
    - Range matching of energy dense isotopes

At zero bias this structure has an equilibrium depletion region up in to the pillar concentrated along the p-i interface.



SUNY College of Nanoscale Science and Engineering

Discussion

i. Developed textured device produced **8x increase (SiC)** in electrical power
   i. Optimized passivation in grooves leading to low leakage material
ii. Modeling predicted **6x power increase (GaN)** (textured over planar)
iii. Achieved 20µW/cm^2 - **Record power density** to date using ^{63}Ni on SiC
iv. Developed in-house **fabrication procedures** for packaging and encapsulation
   i. Required for robust operation, safety and logistics
v. Developed in-house **growth procedures** for quality GaN PIN diodes
   i. Explored unique **liquid-form RI deposition** achieved 10µW/cm^2
   ii. Pursuing pillared GaN growth techniques
   iii. Evaluated textured SiC devices with useful yield

vi. Success….3D structures modelled, grown, fabricated

….and record power output measured

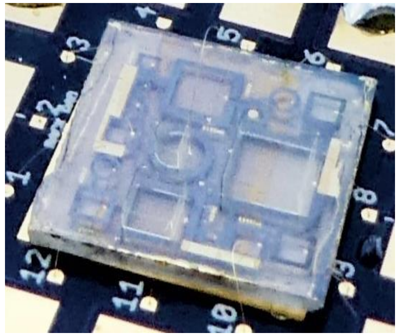


Figure 1. GaN (high radiation tolerance) βV with reservoir for liquid format RI

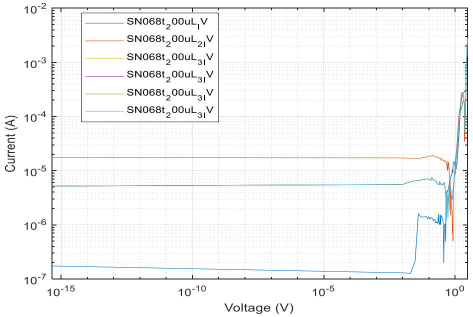


Figure 2. IV curves showing application of liquid form RI increasing I_{sc} and electrical power

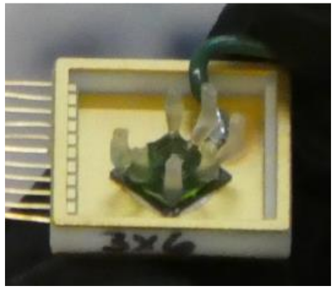


Figure 3. $^{63}NiCl_2$ on SiC EC contained by 1mm PMA reservoir (leaky).

SUNY College of Nanoscale Science and Engineering — Widetronix — Oak Ridge National Laboratory

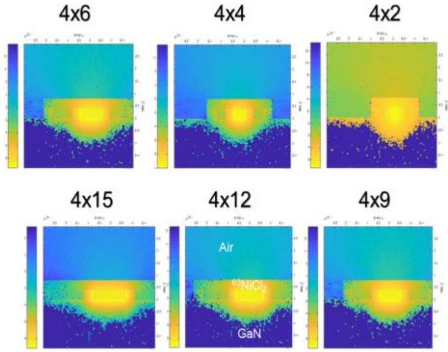


Fig. 10. Example of MCNPX simulation output (energy deposited) for 4 µm mesa while varying isotope filled gap spacing (2–15 µm), i.e. 4(mesa) × 2 (gap spacing).

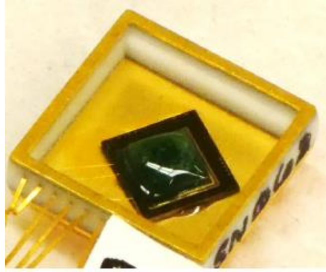


Figure 3. $^{63}NiCl_2$ on textured SiC EC contained by 500µm SU8 reservoir (8µL).

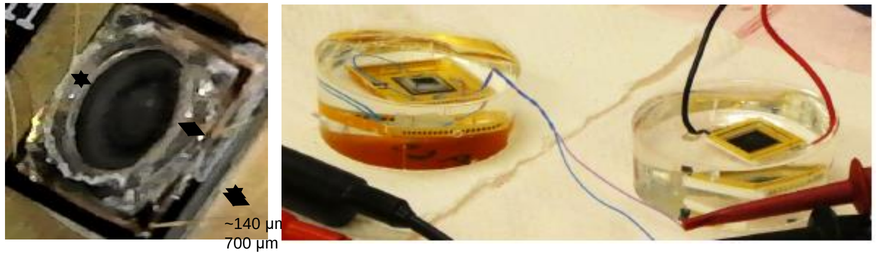


Figure 4.a) ^{147}Pm Liquid format and b) ^{63}Ni on SiC in epoxy generating 2µW electrical, shows progress in packaging maturity

CONCLUSIONS/PATH FORWARD

DEVCOM ARMY RESEARCH LABORATORY

Conclusion

1. Utilized liquid-form-isotopes (LFI) as low-density medium
   - ➢ reduce self-attenuation
   - ➢ Increasing effective surface activity
   - ➢ Uniformly deposit isotope on textured devices
2. Calculated energy deposition (MCNP) from LFI
   - ✓ Parameter study of RI thickness
   - ✓ Parametric study of isotope (^{3}H, ^{63}Ni, ^{147}Pm, ^{90}Sr, ^{241}Am)
   - ✓ Parameter study of RI remainder density
3. Experimentally Measured (record) Isc, Voc, effective surface activity
   - ✓ $^{63}NiCl_2$ on SiC, GaN
   - ✓ $^{147}PmCl_3$ on SiC, GaN
   - ✓ Extrapolated Results show 30mW/42cc (~.5 W/kg, 15GJ/kg) achievable

Increase the SWAP & lifetime of unattended sensors and consumer electronics

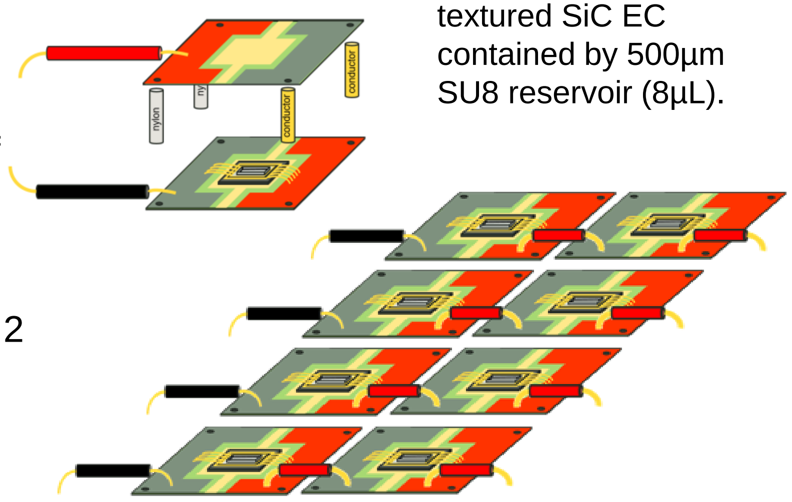


Figure 3.. PC board design for $^{63}NiCl_2$ on textured SiC EC contained by 500µm SU8 reservoir (8µL).

Path Forward

- Investigate control parameters for deposition of liquid form isotope and understand crystallization of remainder for homogeneous layers and optimized coupling of beta emission to energy converter
- Investigate material properties of GaN, AlGaN and Diamond radiation tolerance, defect formation, PIN device degradation and damage
- **Collaborations:** ORNL(radiochemistry), SUNY-Albany(pillared GaN), Widetronix Inc. SBIR Phase 2 (textured SiC), Infinity LLC, SBIR Phase 2 (ionic liquid)
- **What is path forward for current work and timeline to completion (1-2 years)?**
  Higher Energy and Power densities achievable (2 years)
  - ❑ Guided by MC calculations using $^{90}Sr/^{241}Am$ on GaN/Diamond
- **New collaborations:** DKS CRADA, UMO CA, NIOWAVE (2MeV Linac), Chicago State (Diamond damage), Univ AZ (PIN diamond)
- **Transition opportunities: Network CFT, Startup Business(FedTech)**

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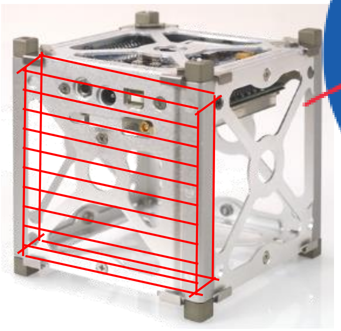
COLLABORATION

DEVCOM ARMY RESEARCH LABORATORY

ARL

OAK RIDGE National Laboratory



NASA

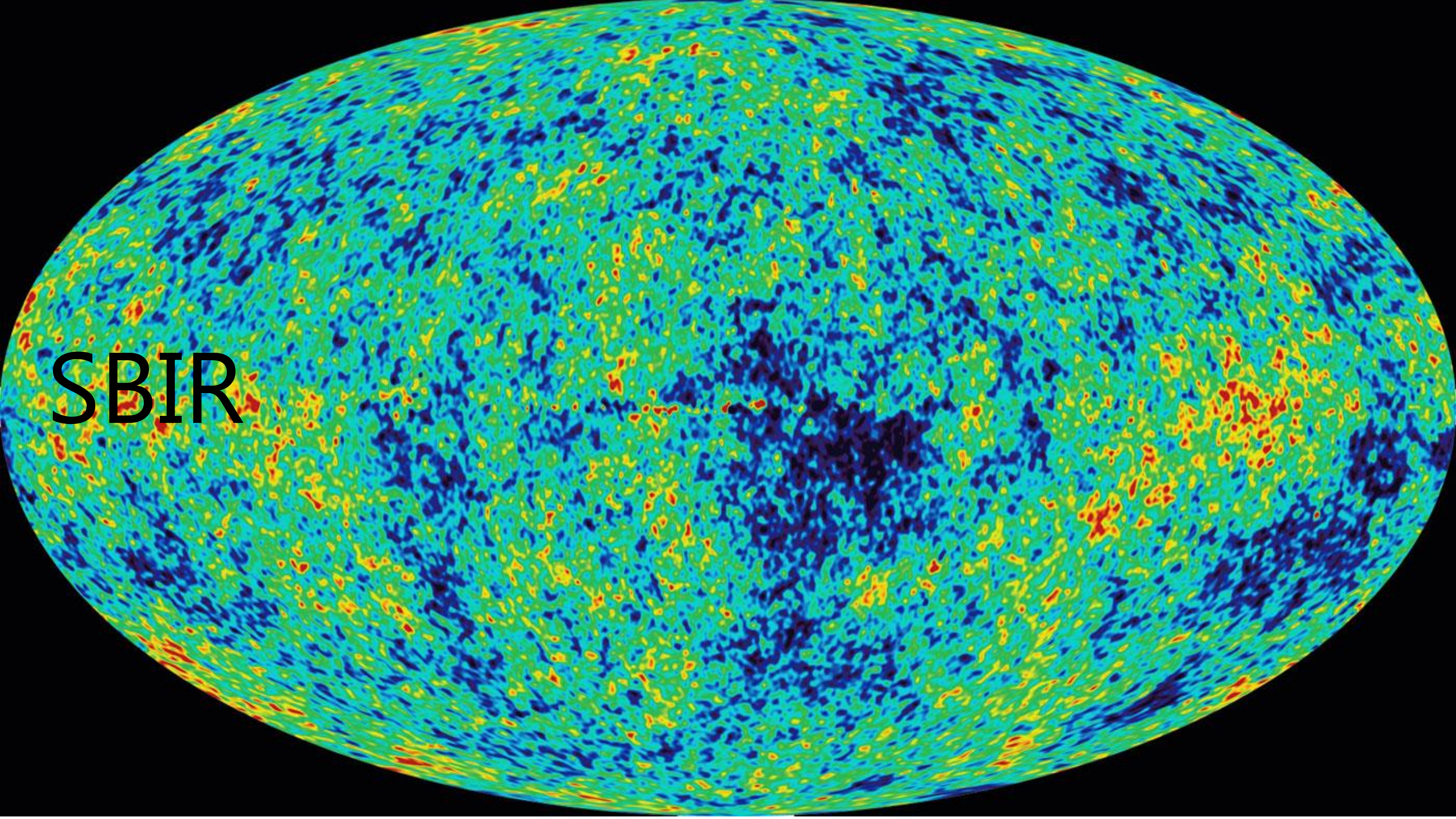
WIDETRONIX

SUNY COLLEGE OF NANOSCALE SCIENCE AND ENGINEERING

TEXAS TECH UNIVERSITY

UNIVERSITY OF MARYLAND

ADROIT MATERIALS


SBIR

WIDETRONIX
W911QX-15-C-0047 PHASE I SBIR

DEVCOM ARMY RESEARCH LABORATORY

Objective

• Develop a radioisotope power source system suitable for long-lived unattended sensors or network communications nodes

Army Impact:

- manufacturable design to fabricate efficient (12%) SiC DEC
- Reduce logistic burden of storing, transporting, distributing expendable materials
- Timely mission command & tactical intelligence to provide situation awareness and communications in all environments
- Compact Power for Dismounted Soldiers

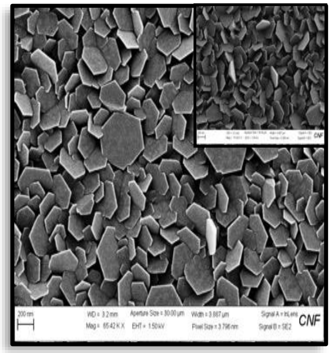
Tasks:

1. Improve beta flux – 10 → 30 mCi/cm^2
2. Increase Die Size - 6 → 12mmx12mm
3. Provide 50mW burst RF Transmission -
4. NRC device Licensing

Challenges:

1. Attenuation from metalized foils
2. Homogeneity, uniformity, material quality
3. Energy storage for higher power
4. Sealed source design

Morphology of deposited Magnesium (Mg)

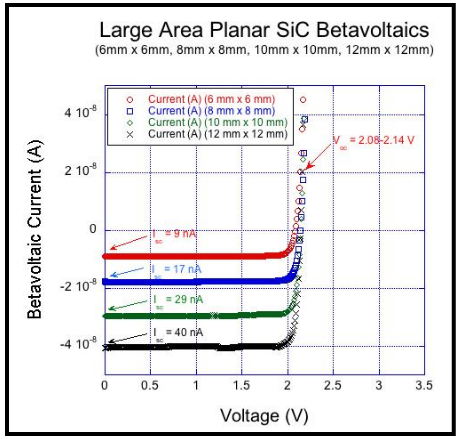


Parameters	Titanium		Magnesium	
	Standard Foil	New Foil	1st Result	Goal
Beta Flux (mCi/cm^2)	15.69	21.7	14.54	30
Current (6x6) mm^2	9.5 nA	14 nA	9.1 nA	18 nA

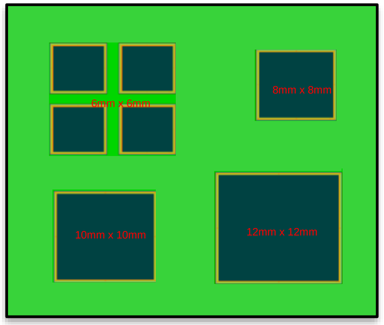
*In partnership with Steve Falbella & Jennifer Ellsworth at LLNL

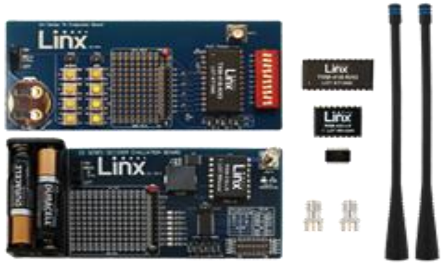
Accomplishments:

1. 20 mCi/cm^2 – larger energy footprint
2. 12mmx12mm die size – mfg efficiency, cost reduction
3. Links xmission hardware - 5 mW power burst for radio transmission using a 1 µW betavoltaic



Increasing die size





Commercial radio load for demonstrated capability of power sourceIncreasing die size

Comments:

- evolutionary - ability to produce volume after PII

INFINITY

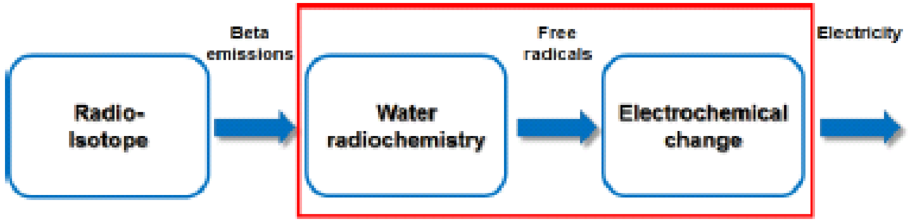
W911QX-15-C-0046 PHASE I SBIR

Objective

• Develop a radioisotope power source system suitable for long-lived unattended sensors or network communications nodes

Army Impact:

- ❖ novel high efficiency (70%) ElectroChem approach to Low power
- ❖ Reduce logistic burden of storing, transporting, distributing expendable materials
- ❖ Timely mission command & tactical intelligence to provide situation awareness and communications in all environments
- ❖ Compact Power for Dismounted Soldiers



Radiolytic electrochemical power converter

Tasks:

1. Gas Evolution
2. Electrode Materials
3. Device Design and Fabrication
4. Power Characterization

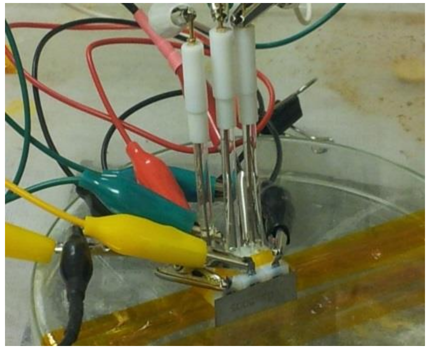
Challenges:

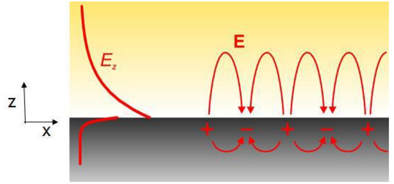
1. Quantify and avoid gas evolution in efficient H splitting process
2. Identify efficiency parameters of plasmonic electrochemistry
3. Match isotope with plasmon splitting energy
4. Quantify fluid degradation over time

BH Kim, JW Kwon, "Plasmon-assisted radiolytic energy conversion in aqueous solutions", Nature Sci Rep 4 : 5249

Accomplishments:

1. reduced gas evolution during process
2. compact recirculating structure fabrication
3. 85% efficiency (?)





Surface charge resonance and plasmon-induce electric field distribution at metal and dielectric interface.

Three units in parallel. ^{63}Ni Externally applied through membrane

Materials	Life-time	Energy density (Wh/Kg)
Lead-acid	500–800 cycles	27
Lithium-ion	400-1200 cycles	105
Nickel-Cadmium	2000 cycles	27
Nickel-Metal Hydride	500-1000 cycles	31
Zinc-air	2000 cycles	250
Pu-238	87.7 years (half-life)	2.8×10^7
Ni-63	100 years (half-life)	3.7×10^5
Sr-90	28.79 (half-life)	1.4×10^7

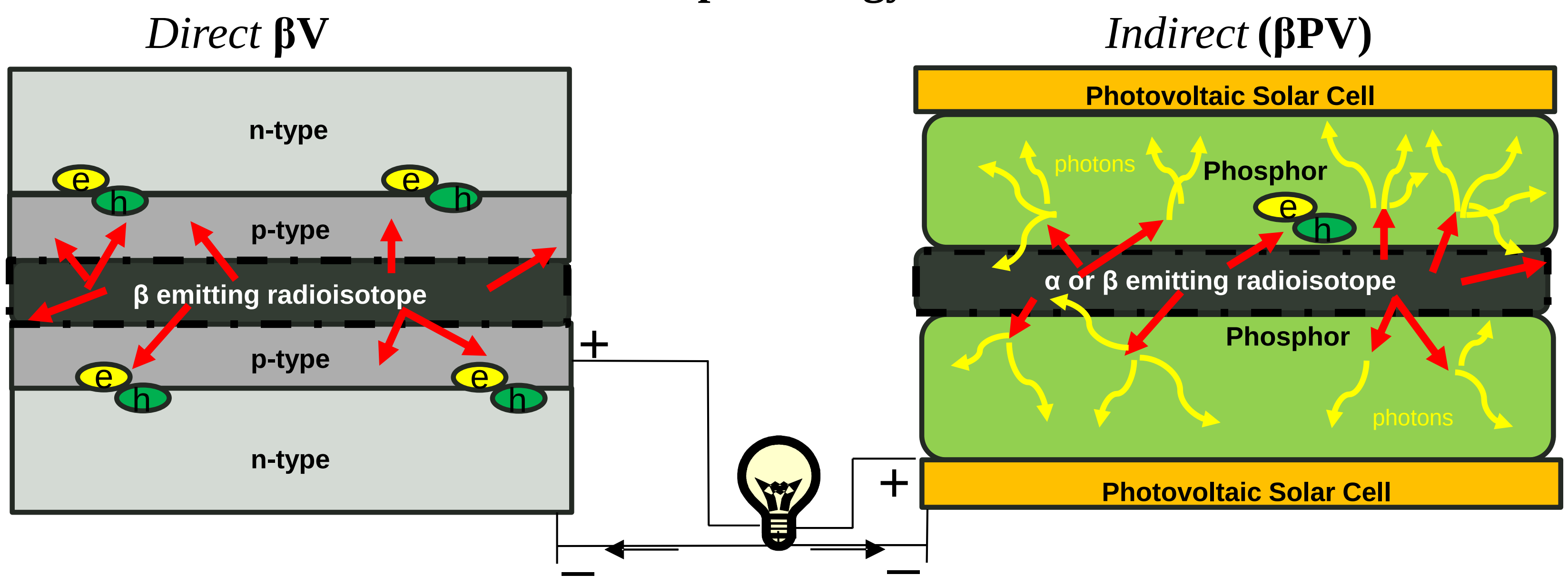
J. Bockris and S. Srinivasan, Fuel Cells: Their Electrochemistry, McGraw–Hill, New York, NY, USA, 1969

Comments:

- ❑ Higher risk-high efficiency payoff – commercially available materials – low-tech fabrication
- ❑ Calculate contribution medium consumption/burn


Backup Materials

Radioisotope Energy Conversion



Advantages:
- WBG voltage (power) output
- direct conversion (single step process)

Disadvantages:
- Fixed depletion region (β range broad)
- Solid w/Crystal bonds (rad tolerance)

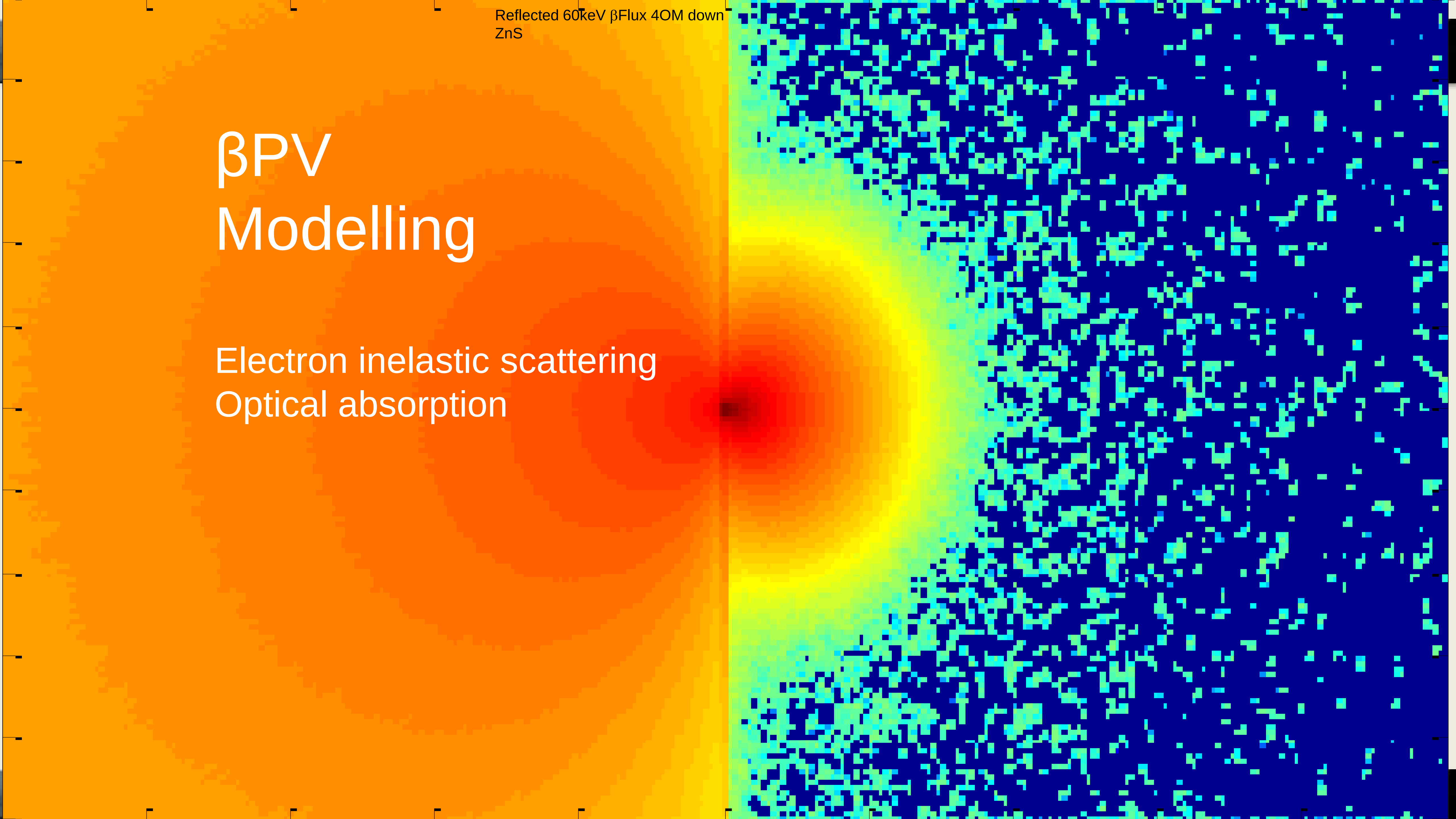
Advantages:
- Commercially available materials
- phosphor self-absorption small
- amorphous protective material/layer

Disadvantages:
- Reduced efficiency (two-step process)

Each p-n junction will produce a voltage related to its built-in field and internal resistance
- Match V_{out} to load by cascading several junctions in series
- Increase I_{out} by adding junctions in parallel or increasing junction area

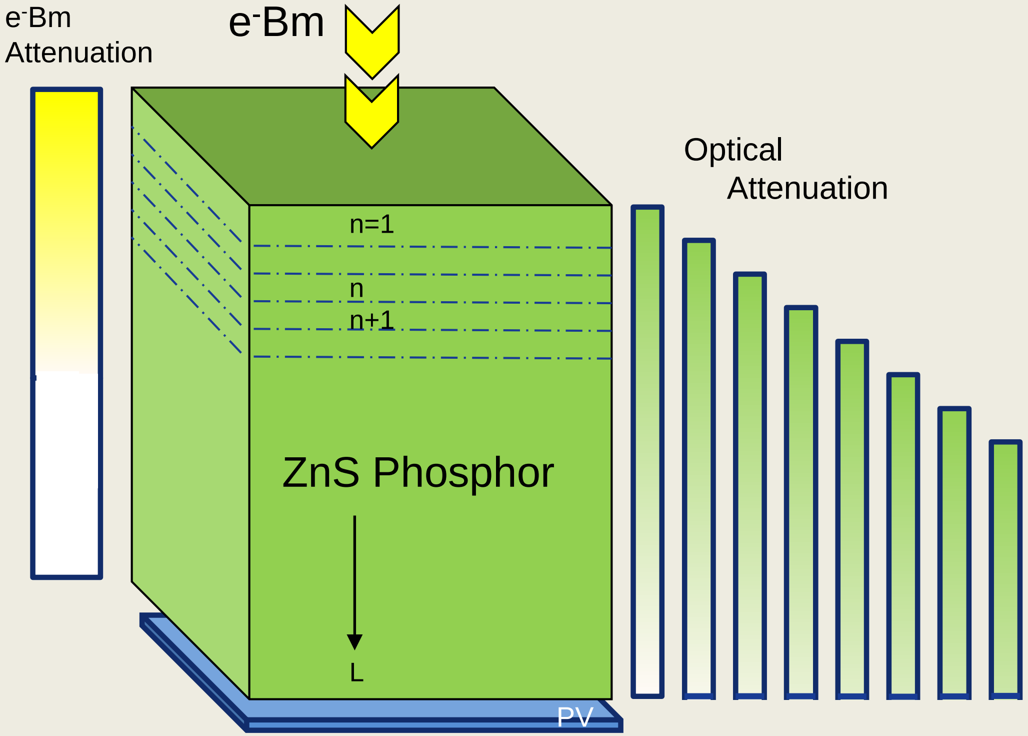
βPV Modelling

Electron inelastic scattering
Optical absorption

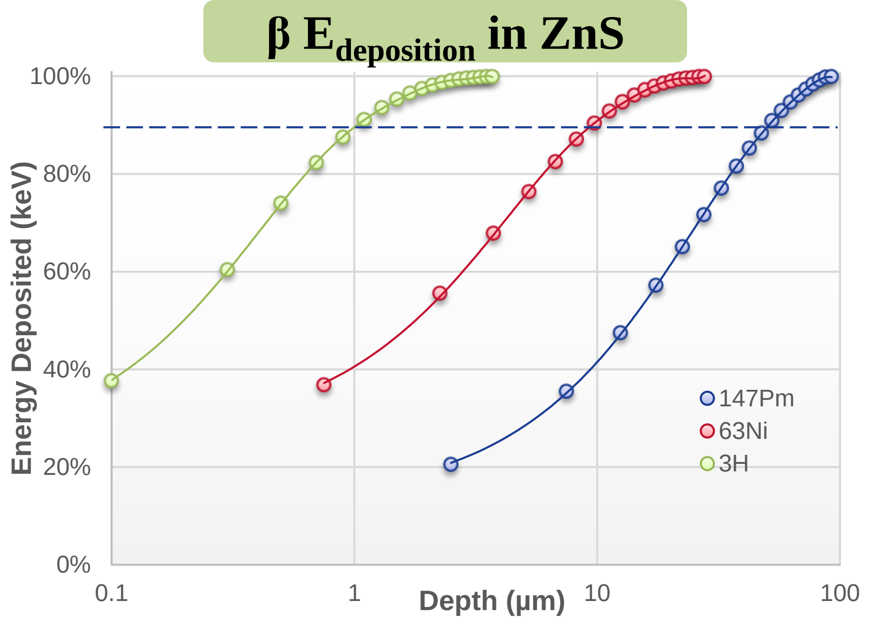


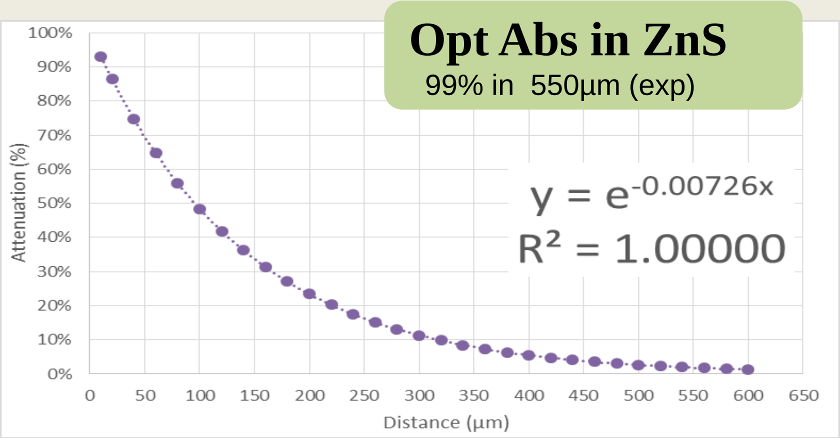
βPV 2D optimization

βRange<<PhotonRange



$$P_{opt}^{total} = \sum_{n=0}^{L} P_{opt}(n) * e^{u(L-n)}$$





* e-Bm E_{dep} stimulates luminescence ~ 10µm
* Optical self absorption *(540nm)* ~200µm

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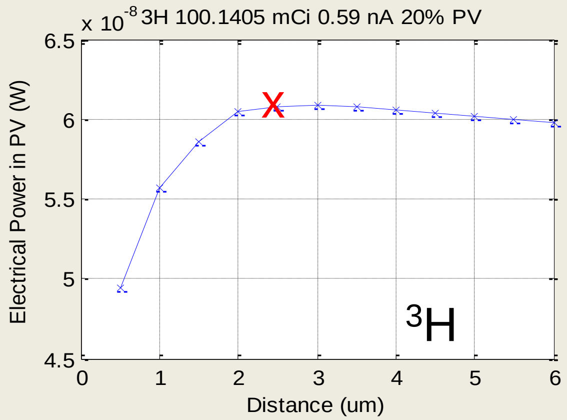
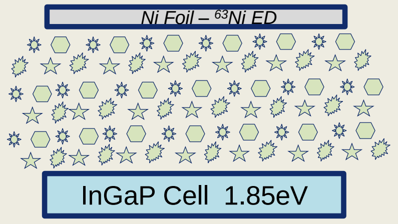
βPV 2D optimization

^{3}H, ^{63}Ni, ^{147}Pm



ZnS Thickness Optimization Algorithm for 2D Foil Geometry

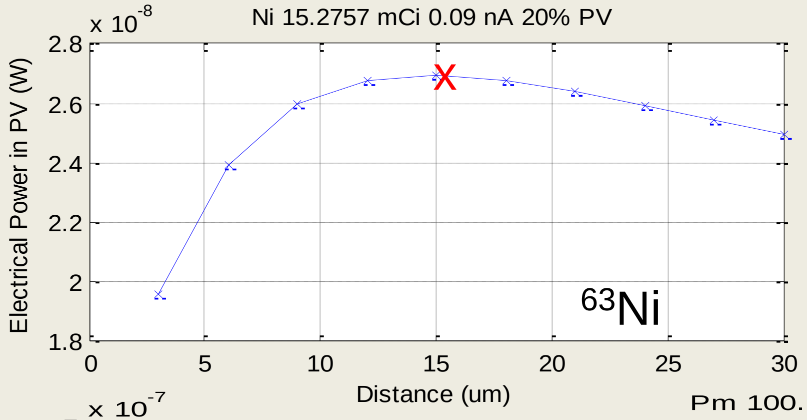


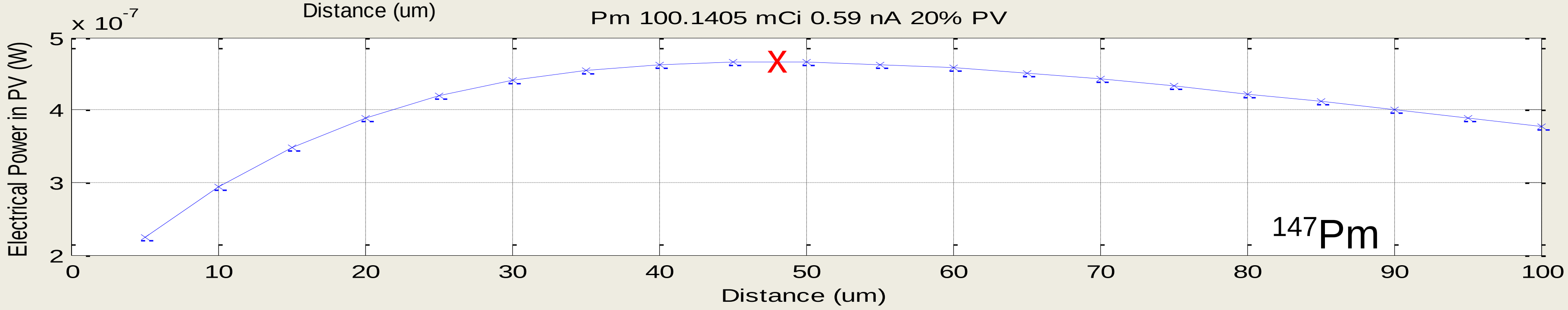
* limited by Edep

	µm	$\mu W_e/cm^2$	mCi/cm^2	η_{power}	*100cm²* ***µW***
^{147}Pm	48	0.459	100	1.25%	460
^{63}Ni	15	0.025	15	1.76%	27
^{3}H	3	0.033	50	1.86%	6

* optimized thickness of ZnS based on Edep and ATTNopt

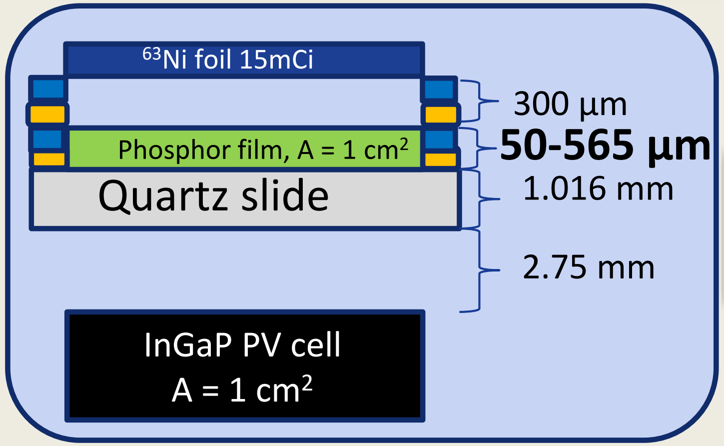
* By MatLab algorithm optimizeRI4 – convolution of β-range and optical attenuation range





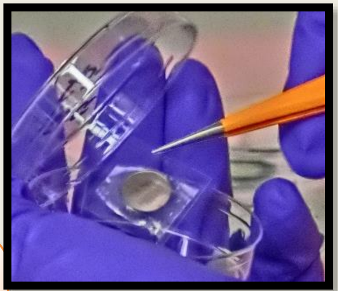
2D ^{63}Ni β-PV cell – ORNL Experiment

15 mCi ^{63}Ni foil / ZnS:Cu,Al / InGaP PV cell

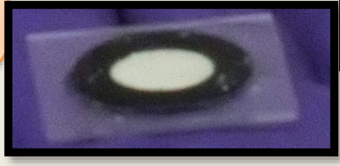


W_{opt} = 10.2 nW_{opt}/cm^2

W_{opt}/W_{nuc} = 0.72%



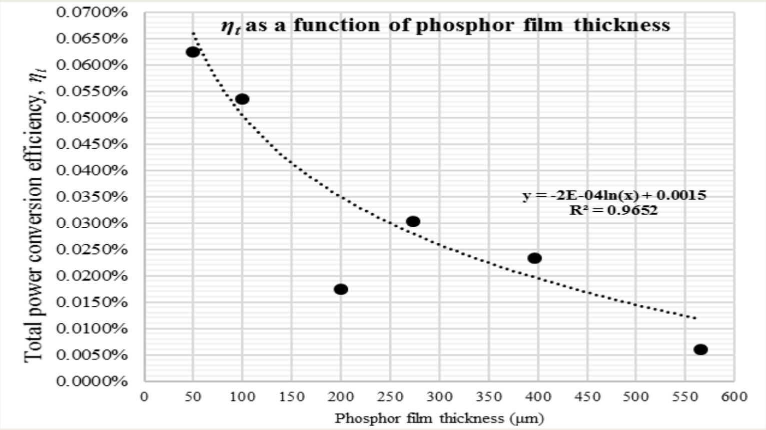
^{63}Ni foil



ZnS:Cu,Al film

Light-tight enclosure

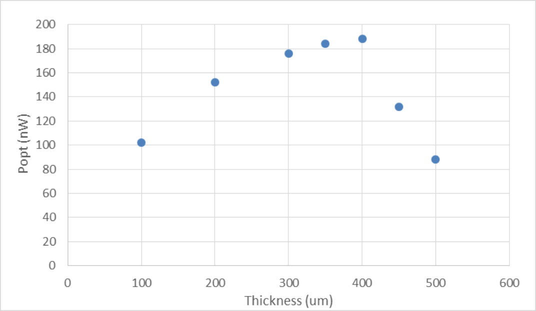
Highest reported β-PV efficiency $\eta_t = \eta_{opt}\, \eta_{PV}$ because InGaP response matched to ZnS optical emission (525nm)



Description	η_t	References
AlGaAs PV **^{238}Pu/ZnS:Cu**	0.11%	Sychov et al. (2008)
InGaP/GaAs/Ge PV **^{147}Pm/ZnS:Cu**	0.035% 0.045%	Zhi-Heng Xi et al. (2014) & Hong et al. (2014)
InGaP/GaAs/Ge PV **^{63}Ni/ZnS:Cu**	0.045%	Zhi-Heng Xi et al. (2014)

Russo et al., "A beta-photovoltaic cell nuclear battery using volumetric configuration: ^{63}Ni solution/ZnS:Cu,Al/InGaP," *Applied Radiation and Isotopes*, 2017. (2nd *review*)

3D Interaction Space



* 400um optimized thickness
  Matching β range and
  Photon attenuation range

Optimized ZnS Thickness for 3D loaded Geometry

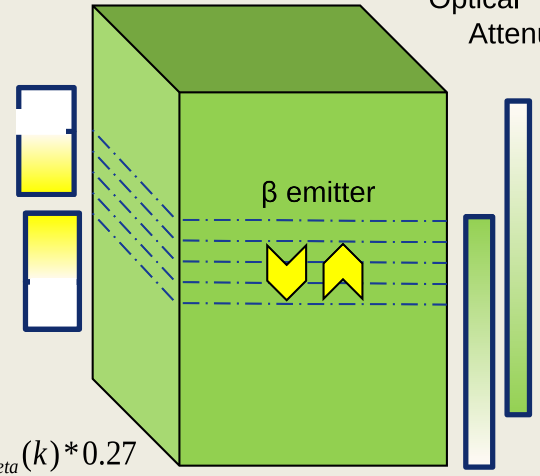
* limited by AttnOpt

* *By MatLab algorithm optimizeVOL*

	15mCi 63Ni		
ZnS			
thick			5014
film	each side	x2	eff
um	nW	nW	
100	51	102	2.03%
200	76	152	3.03%
300	88	176	3.51%
350	92	184	3.67%
400	94	188	3.75%
450	66	132	2.63%
500	44	88	1.76%

* 400um optimized thickness
- 50nW electrical output represent a doubling from 2D foil
- Now examine limitis of loading

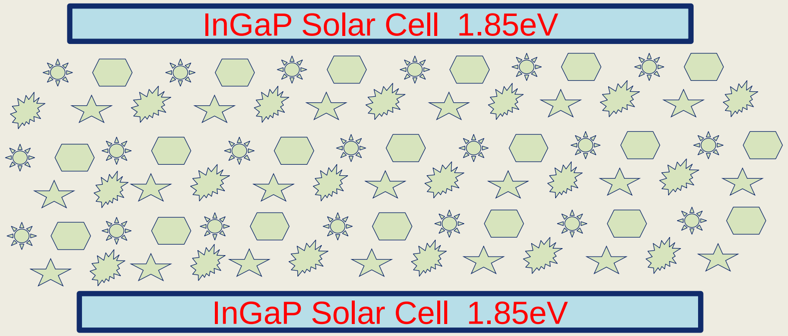
β << Photon Range



$$P_{opt} = \sum_{k=0}^{L} P_{beta}(k) * 0.27$$

$$P_{opt}^{total} = \sum_{n=0}^{L} P_{opt}(n) * a^{L-n}$$

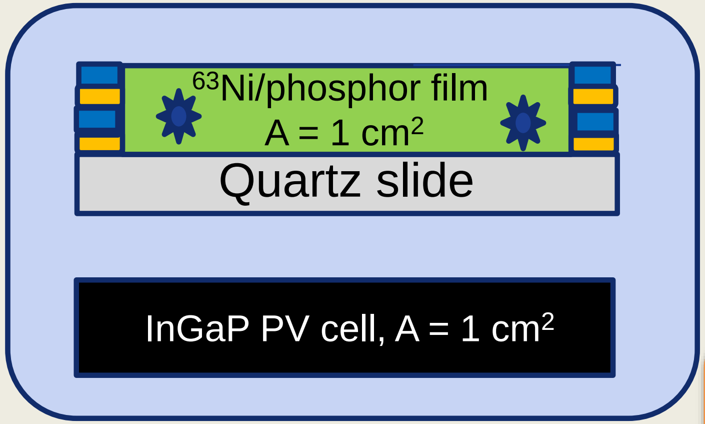
* e-Bm Edep stimulates luminesence



Unclassified / Approved for Public Release

3D ^{63}Ni βPV cell - experimental result

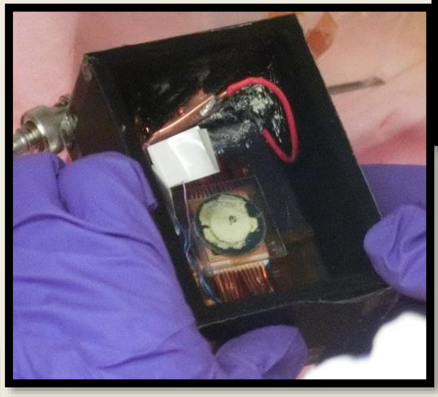
^{63}Ni solution in ZnS on InGaP PV cell



AstroScope Night Vision image of glowing phosphor samples

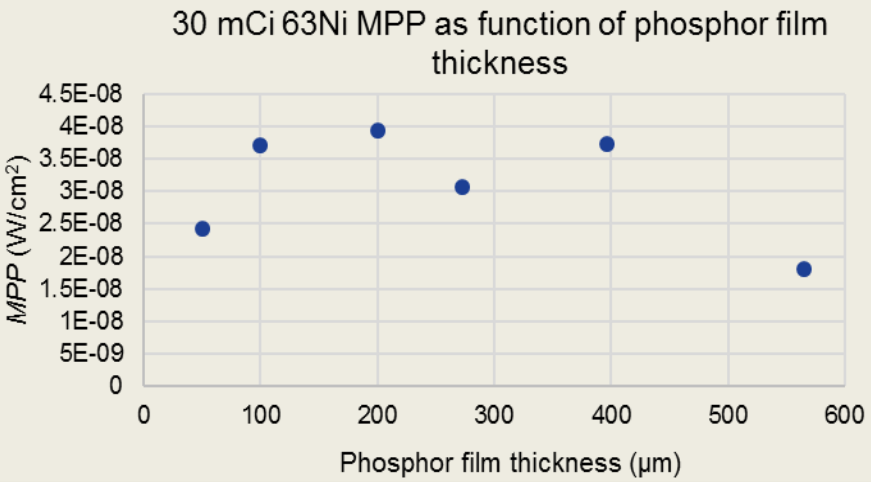
Phosphor sample after ^{63}Ni solution integration

^{63}Ni/phosphor film placed on top of InGaP PV cell in Light-tight enclosure



W_{opt} = 267.8 nW_e/cm^2

W_{opt}/W_{nuc} = 18.9%



✓ 3D βPV **20x** greater W_e than 2D βPV

….more activity can be loaded than deposited on foil