RISK OF NEUTRON GENERATION WITH IMPLANTATION OF LIGHT IONS

NCCAVS JTG

Recent Studies of Ion Implantation Technology Issues

December 8th, 2022

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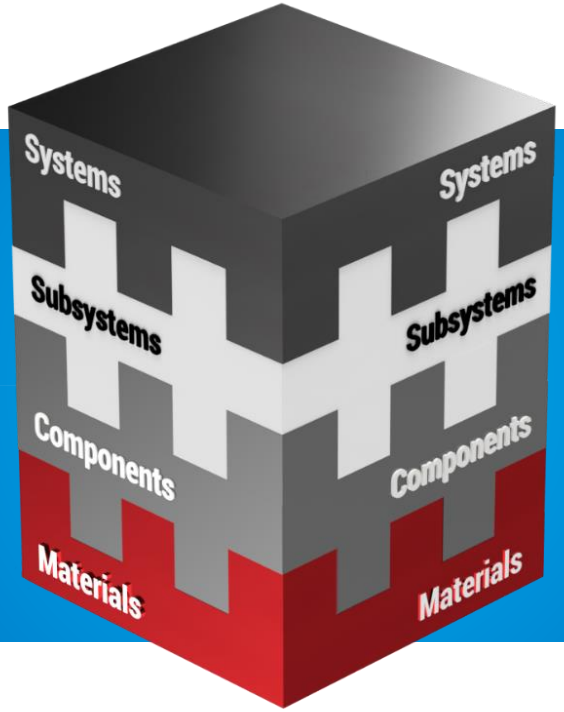
II-VI/COHERENT COMBINATION AT A GLANCE

Innovations that resonate

FY22 Revenue(1) **$4.8B**	**28,000+** Employees(2)
Engineering & Technology **4,500+** Employees(2)	**3,000+** Patents(2)



3 Segments(2)

- Materials
- Networking
- Lasers

4 Markets(2)

- Industrial
- Communications
- Electronics
- Instrumentation

Vertically Integrated Model

Effective September 8, 2022, II-VI Incorporated is now named Coherent Corp. and trades under the ticker symbol COHR.

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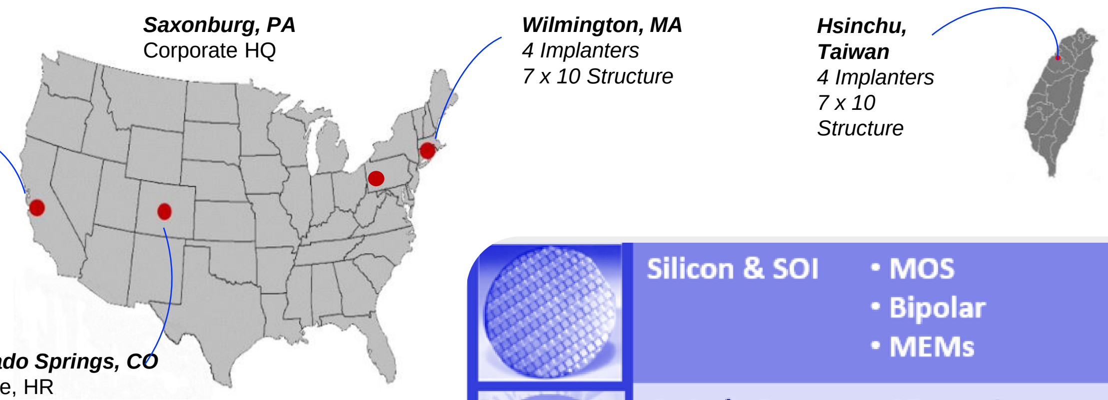
Table of contents

COHERENT ION IMPLANTATION PLATFORM

World's oldest & largest ion implantation foundry

INNOViON → II-VI → COHERENT

CORE → INNOViON



Serving > 200 companies worldwide

- **Compound semiconductor & silicon device manufacturers**
- **> 50 universities & R&D institutions**

1976
Creation of Implant Center & Ion Implant Services

2001
INNOViON is formed via a merger between Implant Center & Ion Implant Services

2012
INNOViON acquires Core Implant Services

2016
Purchase of TSS
Opening of Boston Site

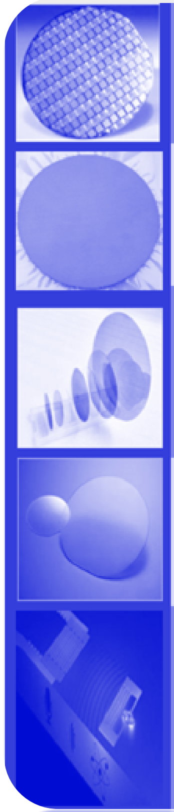
2019
Opening of Hsinchu Taiwan site

2020
Acquisition of Core Systems. Disk Refurbishing

2020
Acquisition by II-VI

2021
Production heated implanter

2022
Taiwan Disk Refurbishing



Silicon & SOI	• MOS • Bipolar • MEMs	• Cleaving • Bonding
GaAs/InP	• 3D sensing • Cellular terminals • Lasers-VCSELs	
SiC	• Power • LED's • IoT & RF & Wi-Fi • Automotive	• MOSFET • Diode
GaN & Diamond	• Infrastructure • Defense & Aero • LED's	• HEMT • HPE • RF
$LiNbO_3/LiTaO_3$ InSb ZnSe	• Optical & acoustic sensors • SAW & BAW filters • Converters	

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COHERENT ION IMPLANTATION PLATFORM

A versatile portfolio of capabilities

Energy single + (keV)	Wafer Diameter (mm)	Primary Species (with other available on demand)																	Dose Range	Max Tilt Angle
High Energy																				
10 - 1000	50 - 150	H	He	B	P	BF2	As			Si		Ar	C	N	O	Ga	Be	Al	E11 – E17	90˚ (4”) & 60˚ (6”)
Standard Energy																				
1 - 250	50 - 300	H	He	B	P	BF2	As	In	Sb	Si	Ge	Ar	C	N	O			Al	E10 – E17	90˚ (4”) & 60˚ (6”)
Specialty																				
1 - 210	Various	Most elements. Contact us for details. LN Cooled & heated capability on demand																	E8 – E16	0˚ - 90˚
Heated																				
5 - 335	(50 -) 150	H	He	B	P	BF2						Ar	C	N	O			Al	E10 – E16	45˚

✓ Newly added heated implantation reinforcing an already comprehensive portfolio of ion implantation capabilities

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COHERENT ION IMPLANTATION PLATFORM

Extensive elemental capabilities

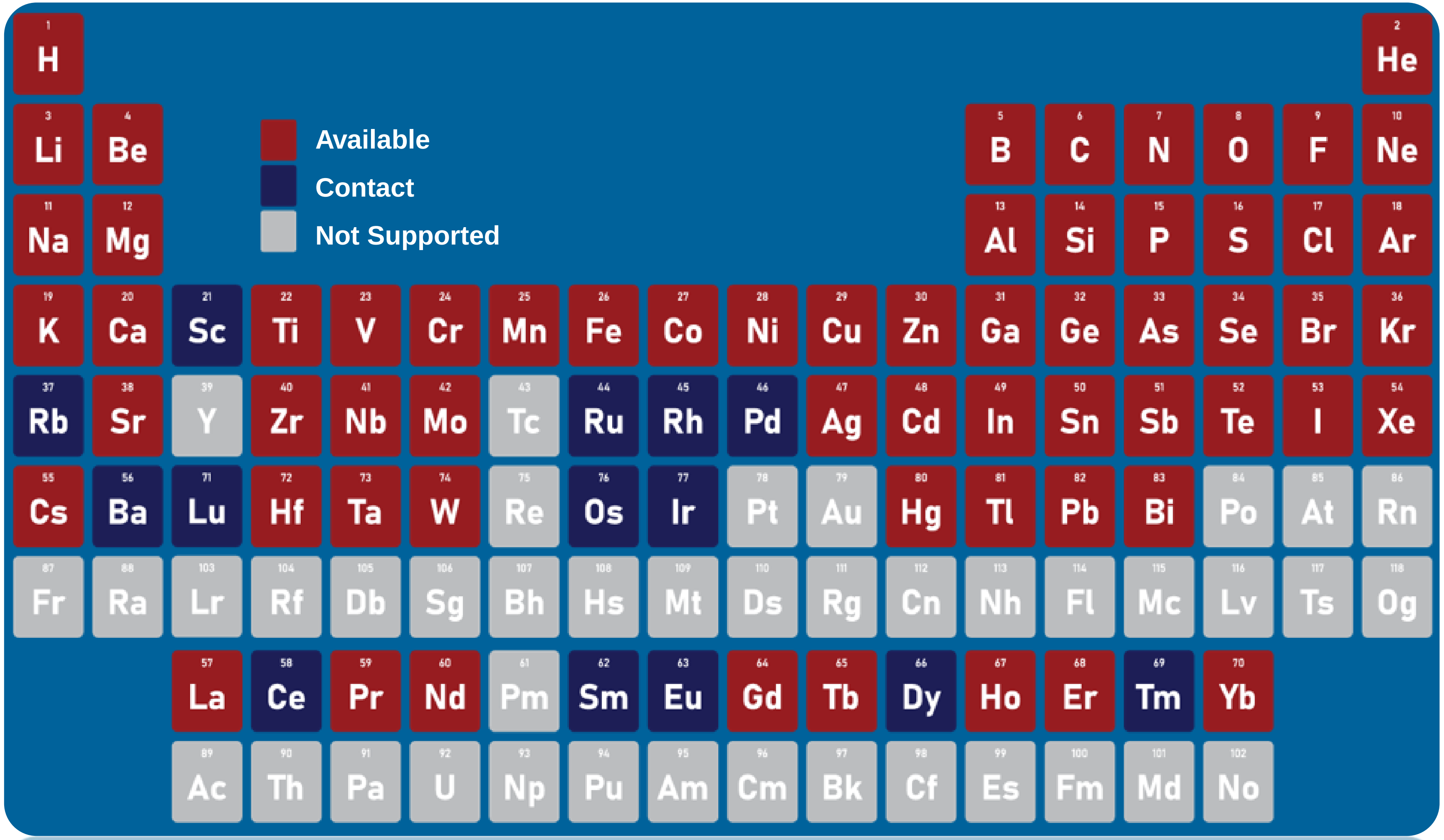
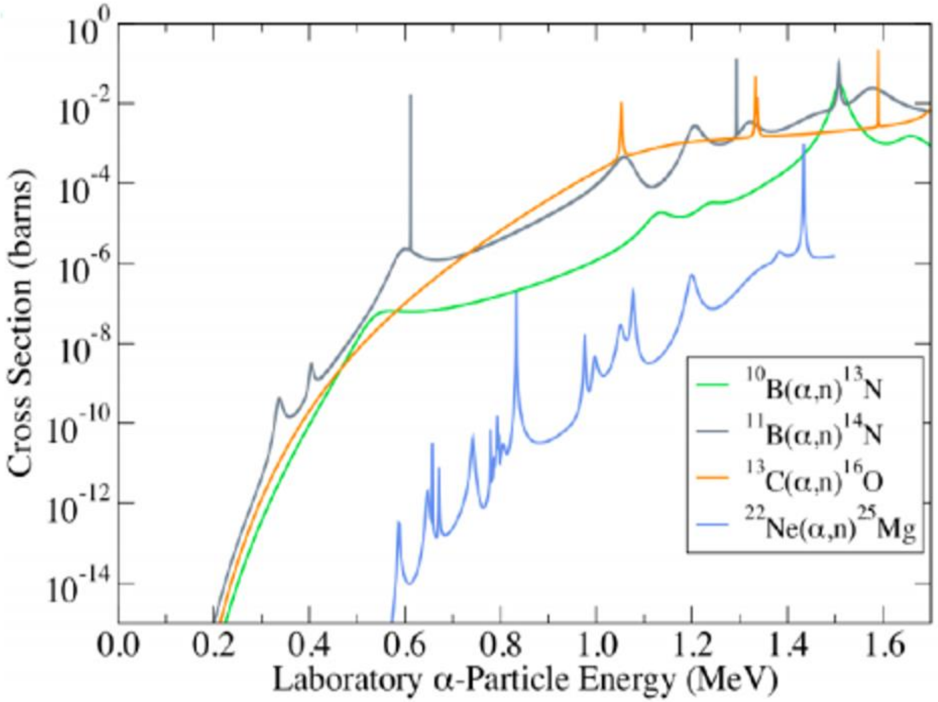


Table of contents

NEUTRON GENERATION WITH LIGHT IONS

Background

Ion	Target	Reactions	Threshold energy (keV)	
Hydrogen **$^{1}H+$ / p**	^{2}D - deuterium	$^{2}D(p,n)2p$	?	-
	^{11}B - boron	$^{11}B(p,n)^{11}C$	< 1000	a)
Deuterium **$^{2}D+$**	^{2}D - deuterium	$^{2}D(d,n)^{3}He$	0	b)
	^{9}Be - beryllium	$^{9}Be(d,n)^{10}B$	< 250	c)
	^{10}B - boron	$^{10}B(d,n)^{11}C$	10	a)
	^{10}B - boron	$^{10}B(d,p)^{11}B$	200	d)
	^{11}B - boron	$^{11}B(d,n)^{12}C$	200	d)
	^{12}C - carbon	$^{12}C(d,n)^{13}N$	330	e)
Helium ions **$^{4}He+$ / $^{4}He++$ / α**	^{9}Be - beryllium	$^{9}Be(\alpha,n)^{12}C$	0	f)
	^{10}B - boron	$^{10}B(\alpha,n)^{13}N$	0	f)
	^{11}B - boron	$^{11}B(\alpha,n)^{14}N$	0	f)
	^{13}C - carbon	$^{13}C(\alpha,n)^{16}O$	0	f)



- **B(11)** is noted **^{11}B** as **11** is the AMU
- **α** refers to the particle **$^{4}He++$** (and $^{4}He+$)
- **$^{11}B(\alpha,n)^{14}N$** reaction is **$^{11}B + {}^{4}He{+}{+} \rightarrow {}^{1}n + {}^{14}N$**

Target + accel ion → outgoing particle + product

- Deuterium, H_2+ & Helium ions are the riskiest ions to implant
- Threshold energies within broad range and high energy implanter capabilities
- Absorbed ions on the strike parts in the tool represent potential target for subsequent light ions

a) M. Firouzbakht, D. Schlyer and A. Wolf, "Yield Measurements for the 11B(p,n)11C and the 10B(d,n)11C Nuclear Reactions," *Nuclear Medicine & Biology*, vol. 25, pp. 161-164, 1998
b) N. Jarmie, "Low-Energy Nuclear Fusion Data and Their Relation to Magnetic and Laser Fusion", Los Alamitos Laboratory, Master Thesis
c) Zhang S-J. et al., "Measurements of neutron energy spectra of 9Be(d,n)10B reaction with a thick beryllium target", *Chin.Phys.C* 45 (2021) 2, 024002.
d) W. Burke, J. Risser and G. Phillips, "Angular Distributions and Excitation Curves for the B10(d,p)B11 and the B10(d, n) and B11(d,n) Reactions below 2-MeV Bombarding Energy," *Physical Review*, vol. 93, no. 1, pp. 188-192, 1954
e) V.K. Basenko et al., "Carbon target as neutron source from 12C(d,n)13N and D(d,n)3He reactions", March 2018 Nuclear Physics and Atomic Energy 19(1):80-83
f) G. Vlaskin and Y. Khomiakov, "Calculation of Neutron Production Rates and Spectra from Compounds of Actinides and Light Elements," *EPJ Web of Conferences*, vol. 153, p. 07033, 2017.

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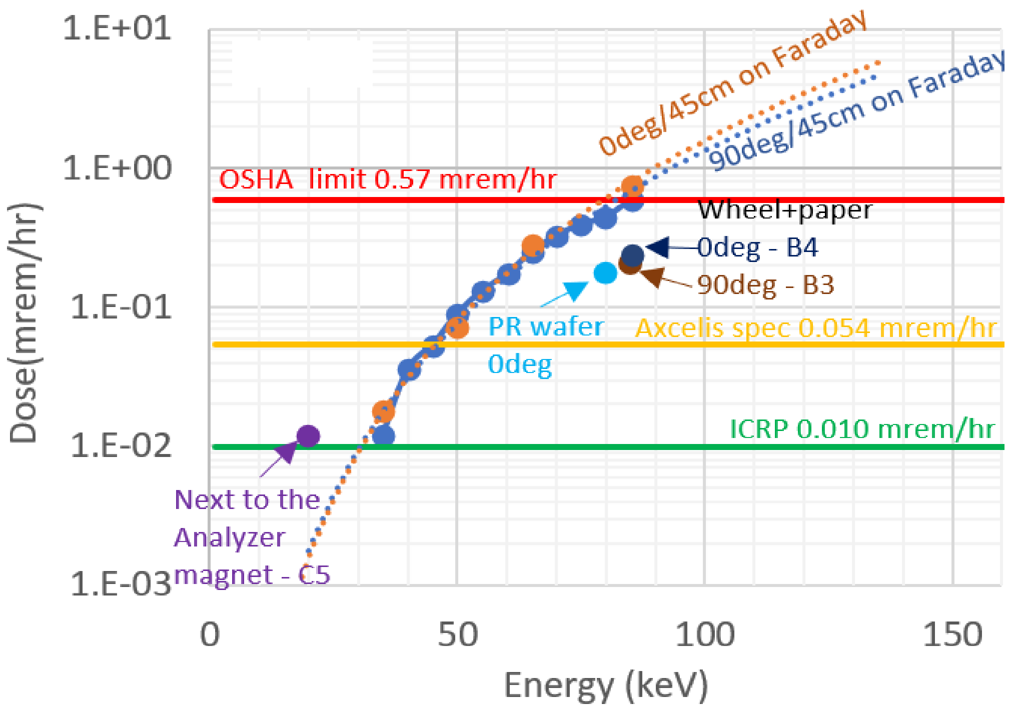
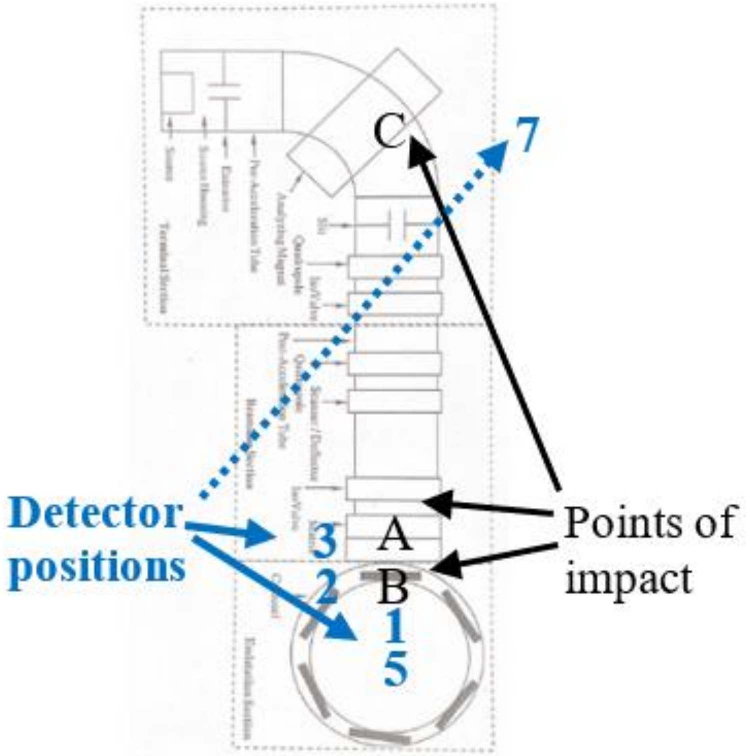
NEUTRON GENERATION WITH LIGHT IONS

Highest neutron yield with deuterium implantation

- **OSHA limit =** **0.57 mrem/hr** - permissible exposure limit for radiation is 5 rem/year (*CFR 1910.1096*)
- **Axcelis spec =** **0.054 mrem/hr**
- **ICRP =** **0.01 mrem/hr** - International Commission on Radiological Protection recommendation is 0.1 rem/year (*ICRP 1990*)





Quasi-exponential increase of neutron generation with energy
- Above ICRP around the tool from 35 keV / 75 uA
- Up to OSHA limit for 85 keV & 100 uA on the Faraday
- Half dose on the wafer with PR or paper.

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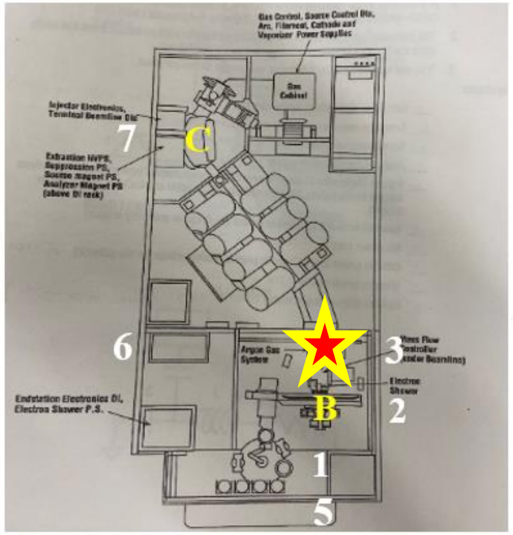
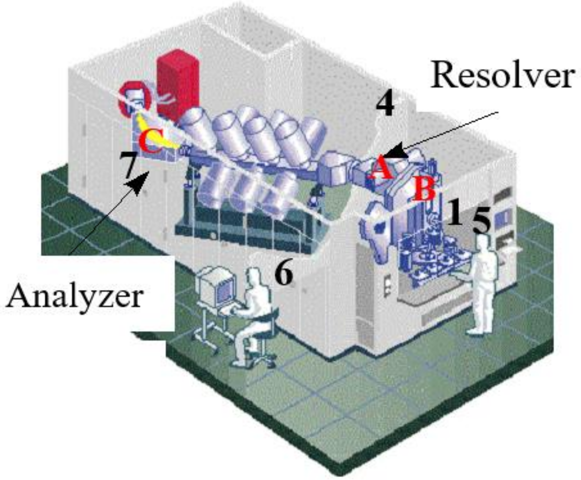
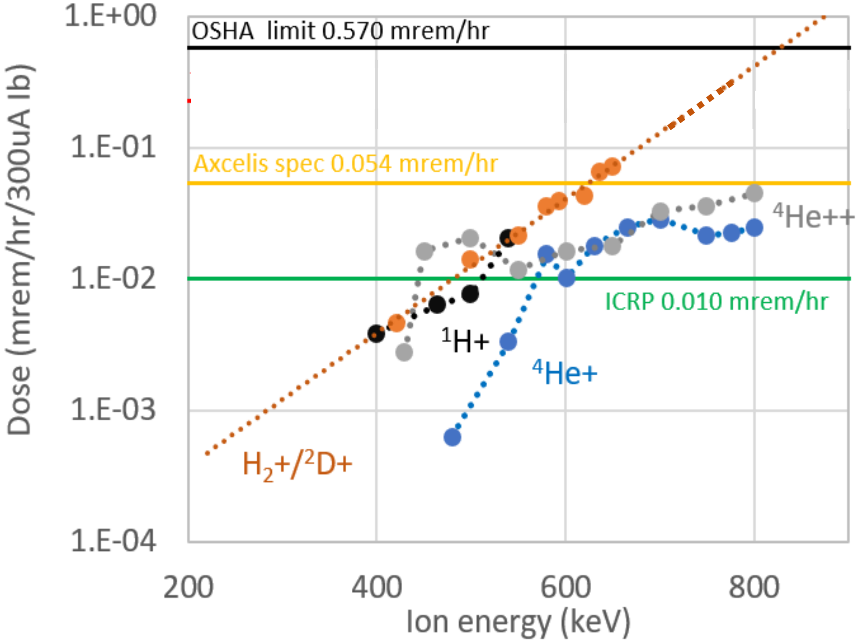
NEUTRON GENERATION WITH LIGHT IONS

Neutron yield with $^{1}H+$, $H_2+/^{2}D+$, $^{4}He+$ and $^{4}He++$ as a function of energy







- **Measurement realized at hottest location, i.e., next to resolver with impact on resolver**
- **Neutron generation from $^{1}H+$, $H_2+/^{2}D+$, $^{4}He+$ and $^{4}He++$**
  - Stronger reaction from $H_2+/^{2}D+$ → deuterium ions analyzed with AMU 2 - H_2+ ions
  - Exponential increase of radiation exposure with energy
- **All radiation doses are below OSHA & getting close or at OEM limits for this experiment**

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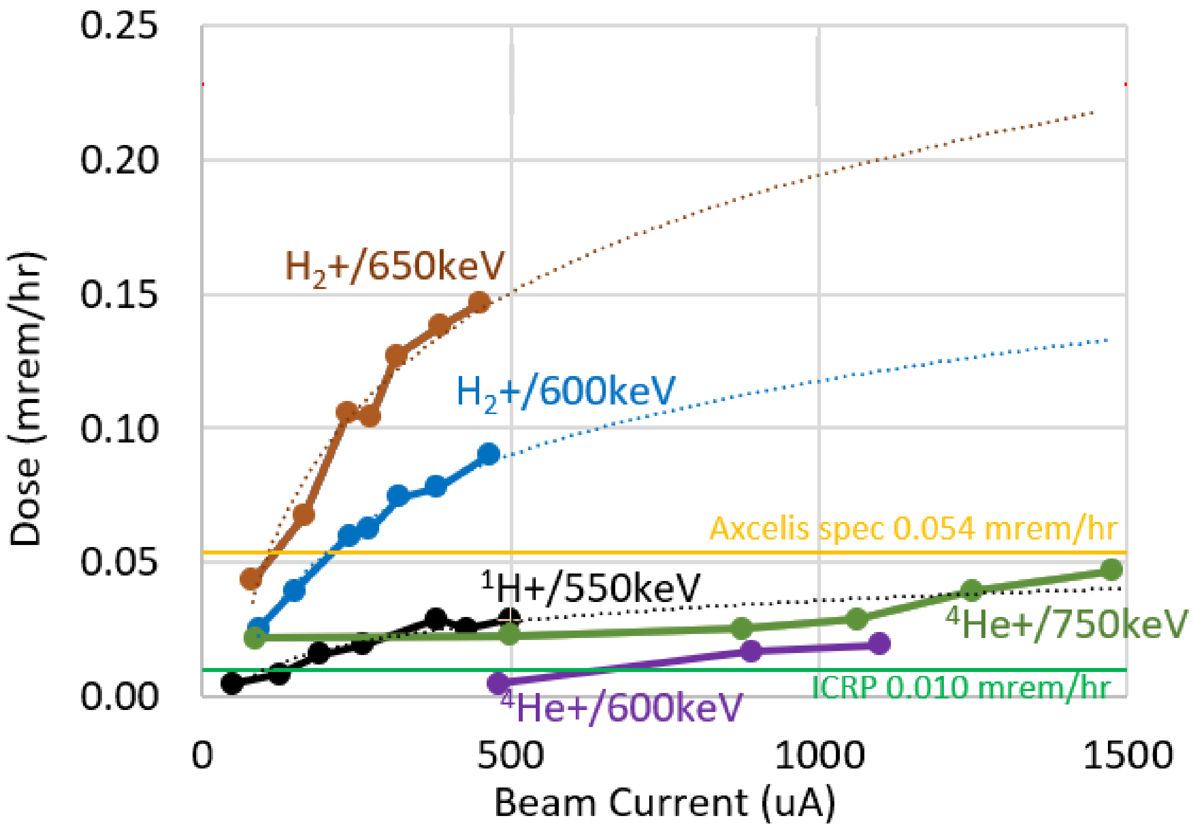
NEUTRON GENERATION WITH LIGHT IONS

Neutron yield with $^1H+$, $H_2+/^2D+$, $^4He+$ and $^4He++$ as a function of beam current



- **Measurement realized at hottest location, i.e., next to resolver with impact on resolver**
- **Neutron generation from $^1H+$, $H_2+/^2D+$, $^4He+$ and $^4He++$**
  - Stronger reaction from $H_2+/^2D+$ with deuterium ions analyzed with AMU 2 like H_2+ ions
  - Linear to log increase of radiation exposure with beam current
- **All radiation doses are**
  - Above the ICRP limit
  - Going above to near Axcelis limits for $H_2+/^2D+$ & $^4He+$
  - Below OSHA limit for all

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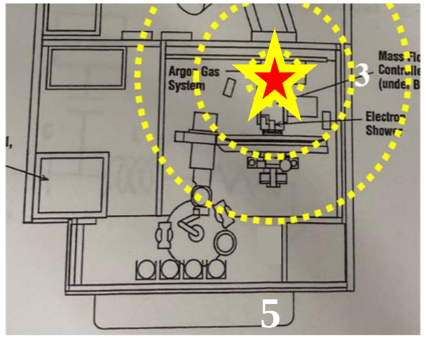
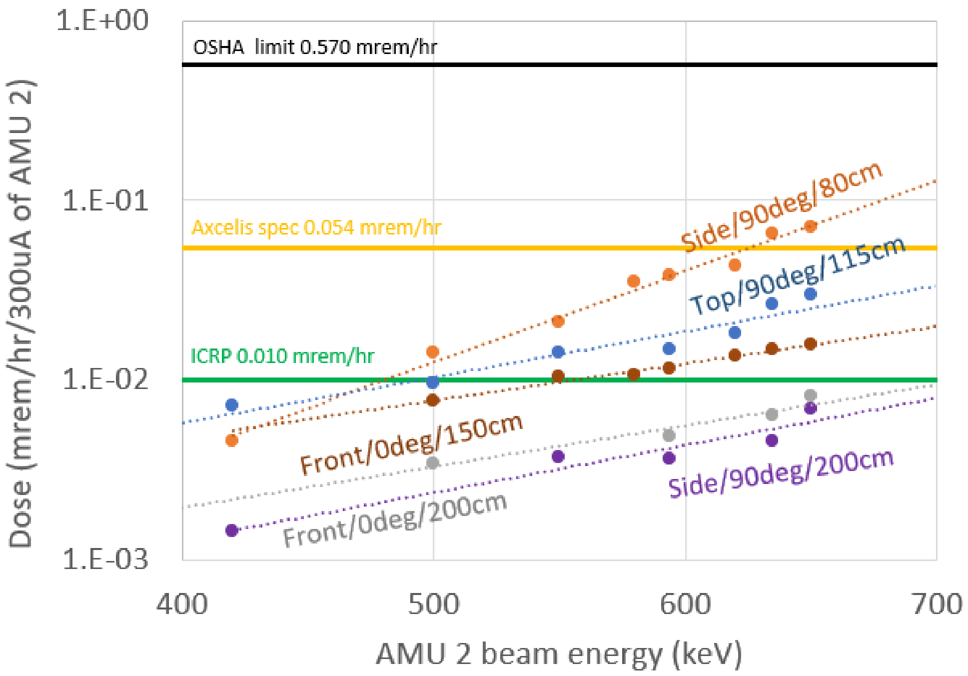
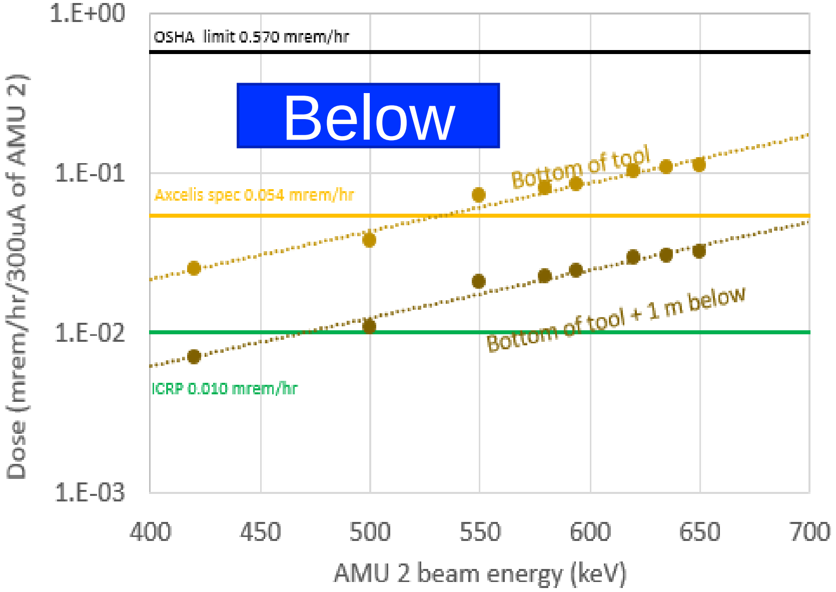
NEUTRON GENERATION WITH LIGHT IONS

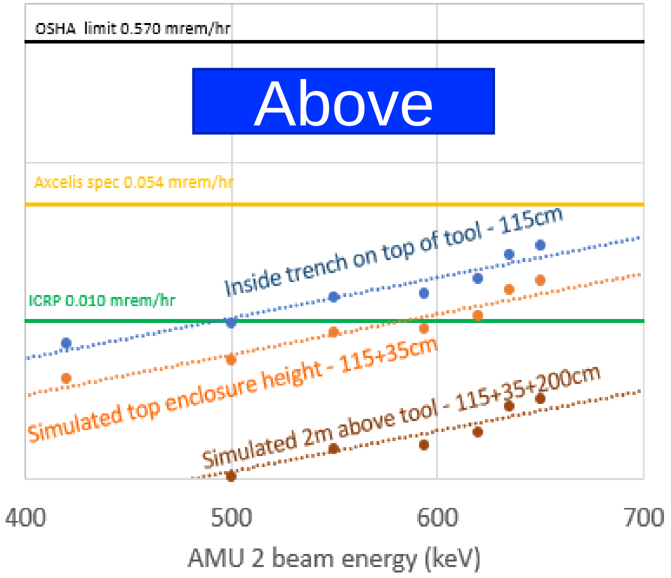
Isotropic neutron yield

H_2+/^{2}D+









- **Isotropic neutron generation**
  - $1/R^2$ decrease with distance
  - Below OEM spec at 1m below tool for these beam current/energies
  - Below OEM spec on top of the tool for these beam current/energies
- **Need to keep this in mind for surrounding floors**

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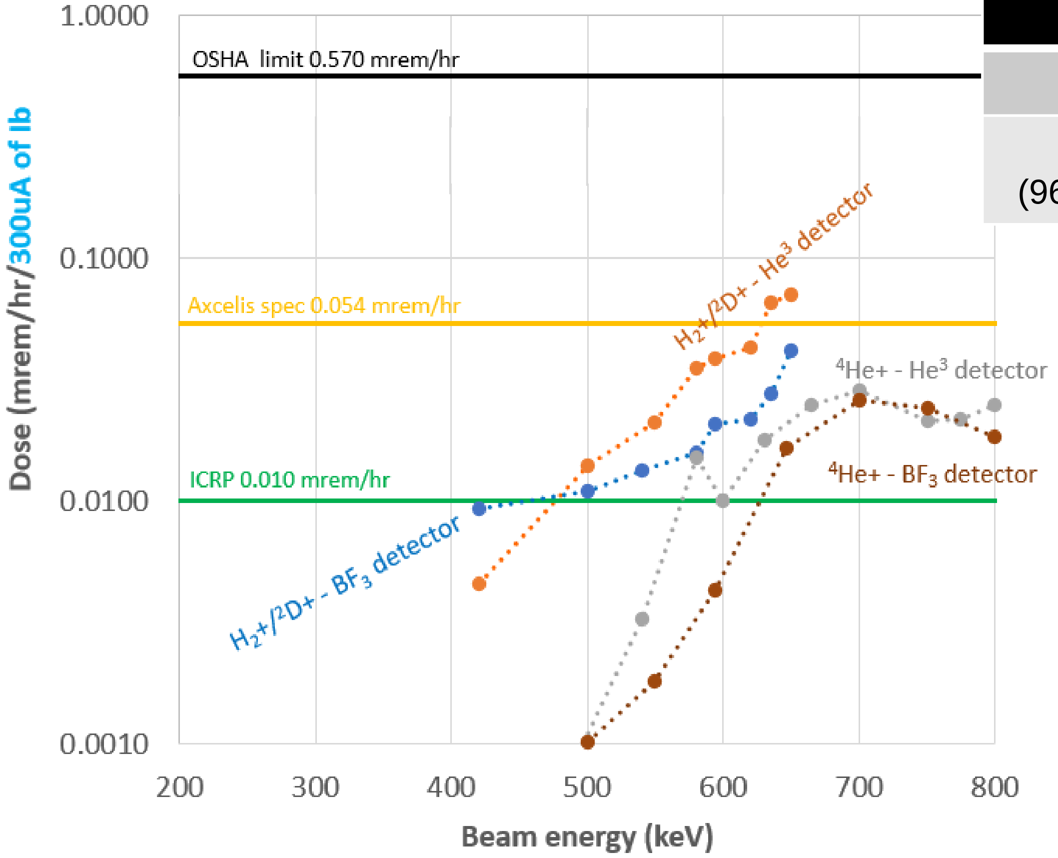
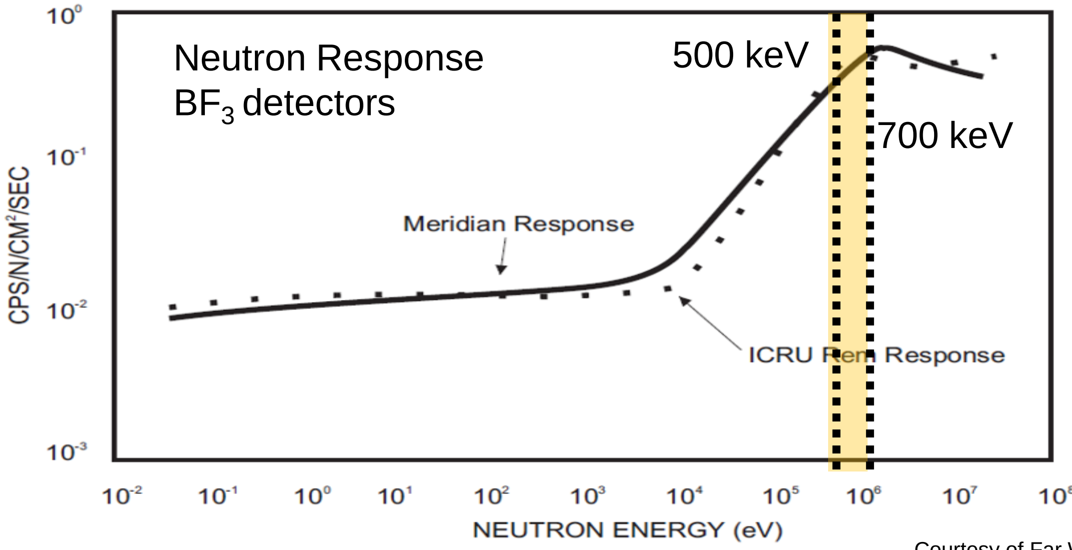
NEUTRON GENERATION WITH LIGHT IONS

Detector sensitivity $^{10}BF_3$ vs. ^3He



Detecting gas	Neutron capture cross section (barns)	Reaction	Sensitivity Cts/mRem	Gamma response (Cs137@1 Rem/hr)
^3He	5333	$n + {}^3He \rightarrow {}^3H + {}^1H + \gamma$ (0.76MeV)	50000	< 1%
BF_3 (96%^{10}B)	3840	$^{10}B + n = {}^7Li + \alpha$ (1.78MeV) $^{10}B + n = {}^7Li^* + \alpha$ (1.47MeV)	12000	< 1%

L. Lakeotes & C. Marianno, "Comparisons in Neutron Detection, as modeled by MCNPX, in Li-6 Glass, HE-3, BF-3, and Borated PVT" National Security Technologies.



Courtesy of Far West Technology Inc.

- **BF_3 detector loses up to ½ of sensitivity compared to He^3 detector in the range 500 to 700 keV**
  - For $H_2+/{}^2D+$, $^4He+$ and $^1H+$ (not shown here) → <u>less sensitive from smaller cross section</u>
  - Emitted neutrons have an energy range right in a less sensitive part of the detection spectrum

Summary

- **Background**
  - Neutron generating reactions from light ion implants have threshold energies within implanter capabilities
  - $^{2}D+$, H_2+ & He+ ions are the riskiest ions to implant
  - Absorbed ions on the strike parts represents target for subsequent light ions

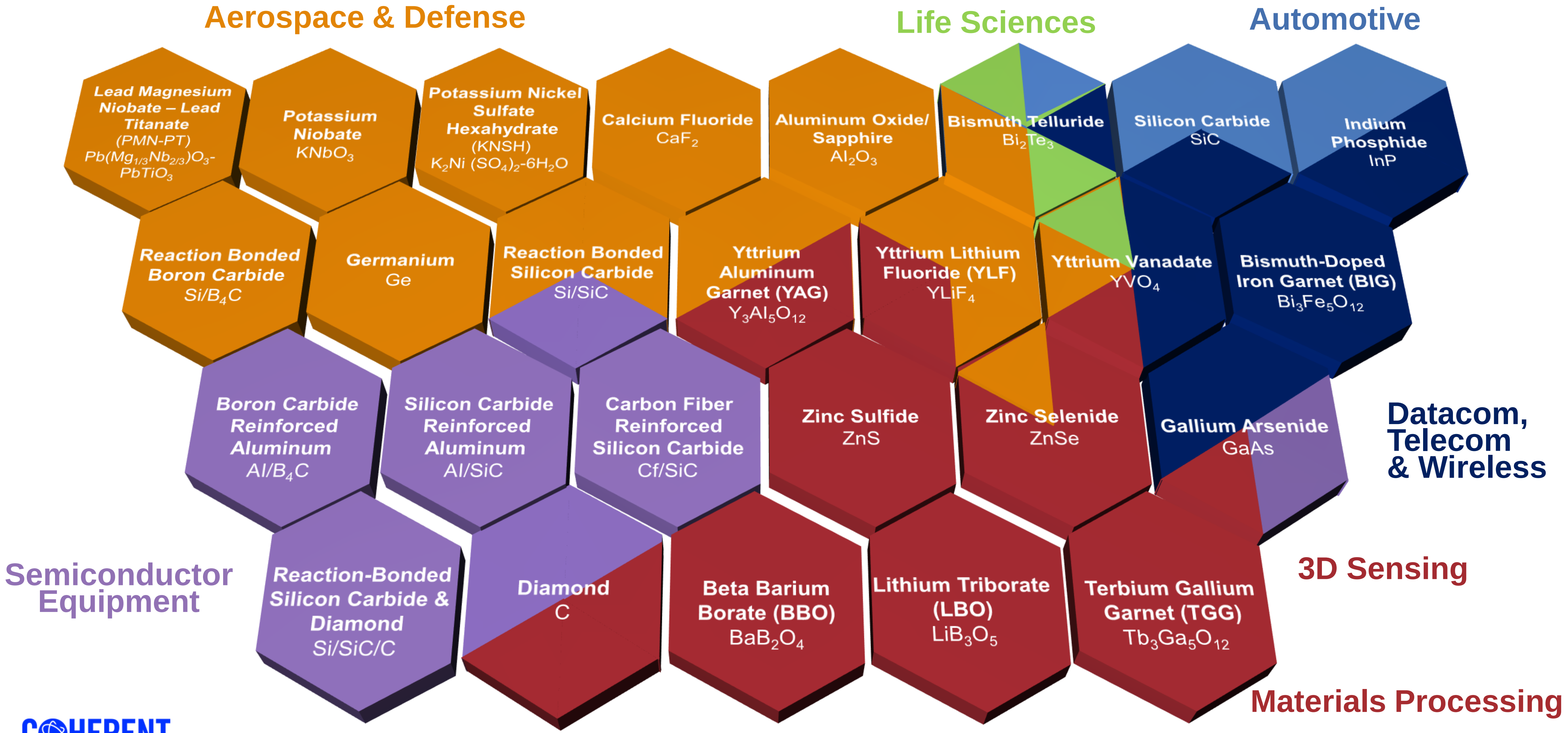
- **Neutron yield with $^{1}H+$, $H_2+/^{2}D+$, $^{4}He+$ and $^{4}He++$**
  - Stronger reaction from $H_2+/^{2}D+$ → deuterium ions analyzed with AMU 2 - H_2+
  - Exponential increase of radiation exposure with energy
  - Linear to log increase of radiation exposure with beam current
  - Radiation levels above the ICRP limit, above to near Axcelis limits for $H_2+/^{2}D+$ & $^{4}He+$ for highest energies & below the OSHA limit (except high energy/current H_2+)

- **Isotropic neutron generation**
  - $1/R^2$ decrease with distance for current implant energies
  - Need to keep in mind of surrounding floors

- **Neutron detector sensitivity**
  - BF_3 detector loses up to ½ of sensitivity compared to He^3 detector in the range 500 to 700 keV

Special care & precautions must be followed for light ion implantation

THANK YOU



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