Overview on the Dosimetry

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- LhARA dose range
- Dosimetry for FLASH hadron beams
- Charged based dosimeter
- Chemical Dosimeters
- Passive Luminescent dosimeters
- Active Luminescent dosimeters
- Calorimeters
- Gas jet profile monitor
- Summary

LhARA Laser-hybrid Accelerator for Radiobiological Applications

JetDose

The LhARA dose range

LhARA targets FLASH modality.

- Instrument review is focussed on the FLASH dose rates

Critical parameters for selecting dosimeter:

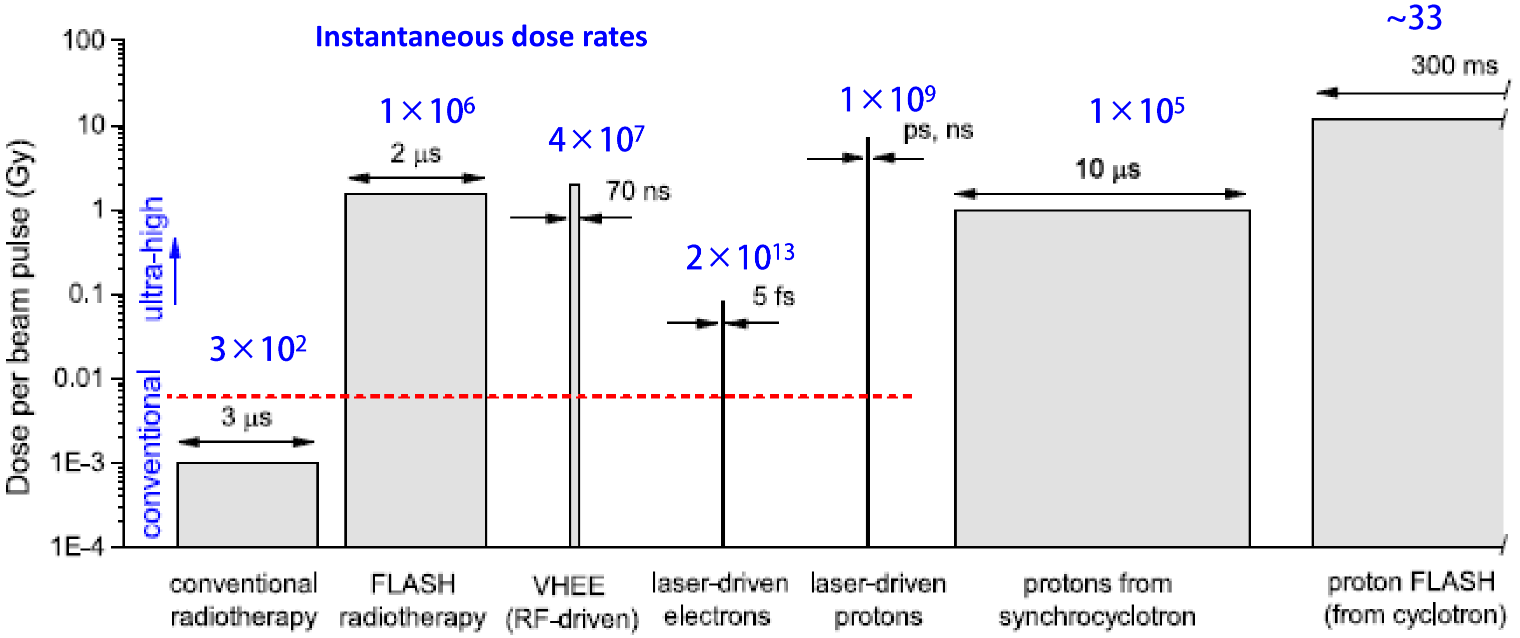
- Per pulse/bunch dose information.
- Dose profile information.
- Online- (within 100 ms.)

Dosimetry is categorised by their operating principle.

LhARA design baseline Report CCAP-TN-11 Issue 1

	Proton			Carbon	
Kinetic Energy	12	15	127	33.4	MeV/u
Bunch Length	7	7	41.5	75.2	ns
Dose per pulse	7.1	12.8	15.6	73.0	Gy
Instantaneous dose rate	1.0×10^9	1.8×10^9	3.8×10^8	9.7×10^8	Gy/s
Average Dose rate (10Hz)	71	128	156	730	Gy/s
Beam profile	square: 3.5 cm × 3.5 cm				LE in-vitro
Beam profile	ϕ 1-3 cm uniform dose / ϕ 1 mm spot				HE in-vitro + in-vivo

Instantaneous dose rates



UHD pulse project (Physica Medica 80 (2020) 134–150)

Dosimetry for FLASH hadron beams

Accelerators

Year	Radiation Type	Machine	Energy (MeV)	Avg. Dose Rate (Gy/s)	Dose per Pulse (Gy/pulse)	Pulse Repetition Rate (Hz)	Field Size	Dosimetry Method
2018	Proton [3]	IBA Isochronous Cyclotron (France)	138-198	40	N/A	106.14 MHz (Quasi-continuous)	1.2 cm @ 90%	Cylindrical IC, EBT3 RCF
2019	Proton [4]	Varian Isochronous Cyclotron (USA)	245	40	N/A	Quasi-continuous	1 by 3 cm	Not Provided
2020	Proton [5]	IBA Isochronous Cyclotron (USA)	230	80	N/A	106.14 MHz (Quasi-continuous)	2 cm FWHM	Plane Parallel IC
2020	Proton [6]	Mevion Synchrocyclotron (USA)	70	100-200	0.16-0.32 (8-16×10^3 Gy/s)	648	1.2 cm FWHM (5mm @ 90% isodose)	Plane Parallel IC, FC, MC Simulation, RCF
2020	Proton [7]	IBA Isochronous Cyclotron (USA)	227.5	130	N/A	106 MHz (Quasi-continuous)	1.6 by 1.2 cm Ellipse	Plane Parallel IC, FC, MC Simulation, EBT3 RCF
2021	Proton [8]	Mevion Synchrocyclotron (USA)	60	120-160	0.22 (9.3×10^3 Gy/s inst.)	750	Dia. 1.1 cm FWHM (5mm @ 90% isodose)	IC, FC, MC Simulation, EBT-XD RCF
2021	Proton [9]	Research Isochronous Cyclotron (Germany)	68	75	N/A	20 MHz	Dia. 1.3 cm	IC, RC
2021	Proton [10]	COMET Isochronous Cyclotron (Switzerland)	170-250	9000 (for a single spot)	N/A	72.85 MHz	2.3-5 mm (16 by 1.2 cm by scanning)	FC
2021	Helium Ion [11]	Synchrotron (Germany)	145.74 MeV/u	185	N/A	Quasi-continuous	1 cm^2 (by spot scanning)	Parallel-plate IC
2021	Carbon Ion [12]	Synchrotron (Germany)	280 MeV/u	70	N/A	Quasi-continuous	1 cm^2 (by spot scanning)	IC, EBT3 RCF

Beam profile: EBT films
Dose : Ion. Ch.
Current : Far. Cup

Data generated from
F Romano et al., Med Phys. 2022;49:4912–4932.

Charged based dosimeter

Operate by creating ion pairs in known volume and counting them in terms of current to estimated dose

Ionization chambers

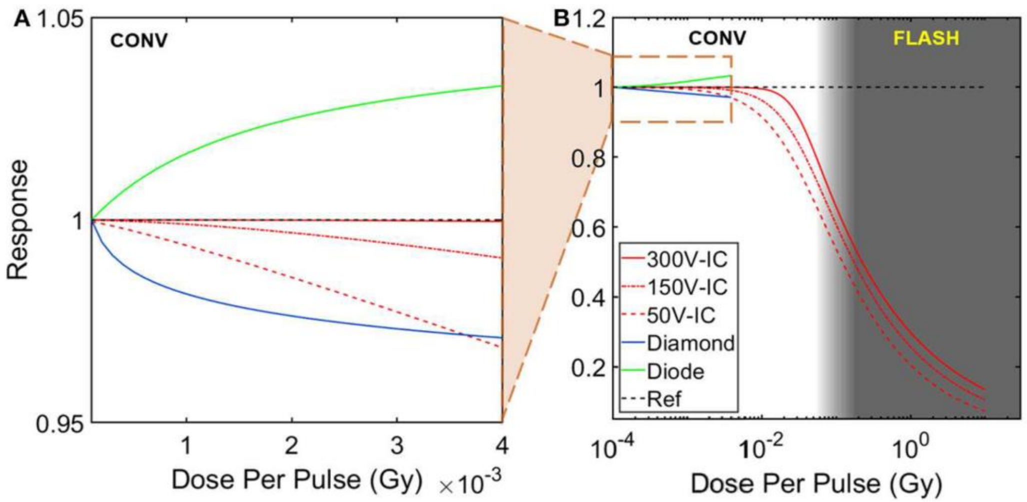
- Generates electron ion pairs in enclosed gas which are collected using electrodes
- Considered best for conventional dosimetry
- µs Resolution (ion-drift velocity)
- Ion recombination >300Gy/s

Direct current measurement
(Faraday cup)

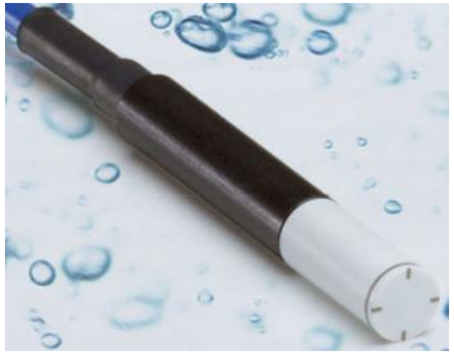
- Beam current measurement
- ns response (electronics)
- Suppression against sputtering
- No beam profile information.

Solid state detectors
(Diodes, MosFets, SST, Diamond)

- Ion-holes pairs are created that constitutes the current.
- Good spatial resolution;
- Real-time by skin mounted
- Recombination Generation (RG) centres saturates at high dose rate
- Radiation damage
- Profiling requires spot scanning/array



Ashraf MR, *Front. Phys.* 8:328, 2020, doi: 10.3389/fphy.2020.00328



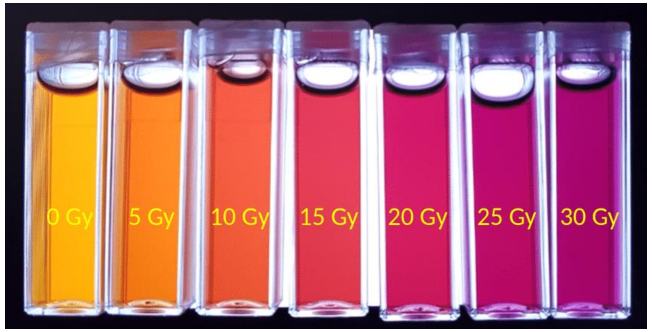
PTW microDiamond

Chemical Dosimeters

Chemical (sensitive) medium undergoes structural changes upon irradiation.

Frikie dosimeter

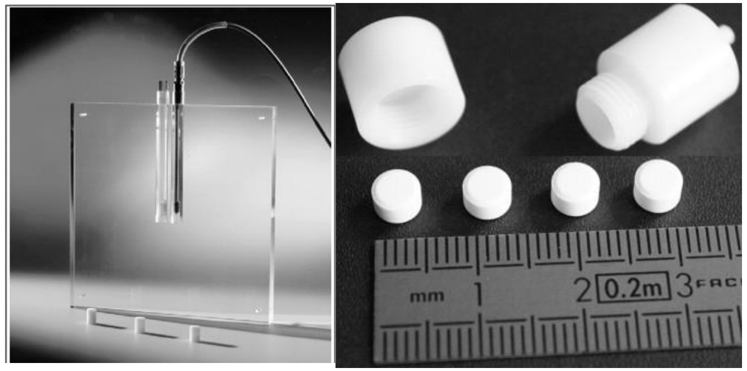
- water-based solution
- Irradiation changes optical density of the material (ferrous-ferric ions)
- Read out using spectrophotometer
- Temperature dependence,
- Max absorbed dose is limited by Oxygen that can be used up (400 Gy)
- At high dose rate decrease in sensitivity at due to ion diffusion and instability of radiation induced species



Marrale M et al.,2021, 7(2):74. https://doi.org/10.3390/gels7020074

Alanine dosimeter

- Pellet forms (5 mm dia. 2.5 mm thick), binder (paraffin wax)
- Alanine forms stable radical whose concentration is proportional to dose.
- Linear response upto 1.5×10^{5}Gy/s (e-beam)
- Accuracy 3% upto 1 kGy/s
- Demonstrated dose rate independence upto 10^{10} Gy/s (e-beam)
- Offline readout (electron paramagnetic resonance (EPR) spectrometer)
- Readout device are not small and cheap.
- Accuracy 0.1% (depends spectrometer and environmental condition)

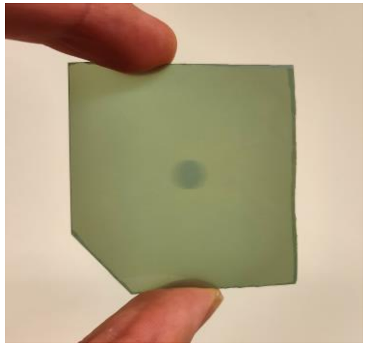


Sharpe, P. H. G. and J. P. Sephton. “Alanine dosimetry at NPL - the development of a mailed reference dosimetry service at radiotherapy dose levels.” (1998).

Chemical Dosimeters (cont..)

Radiographic films

- Polymeric films darken during irradiation due to polymerization.
- Grafchromic (EBT3,EBT-XD) and Orthochromic (OC-1)
- Stackable for 3D dose distribution., 3D gels

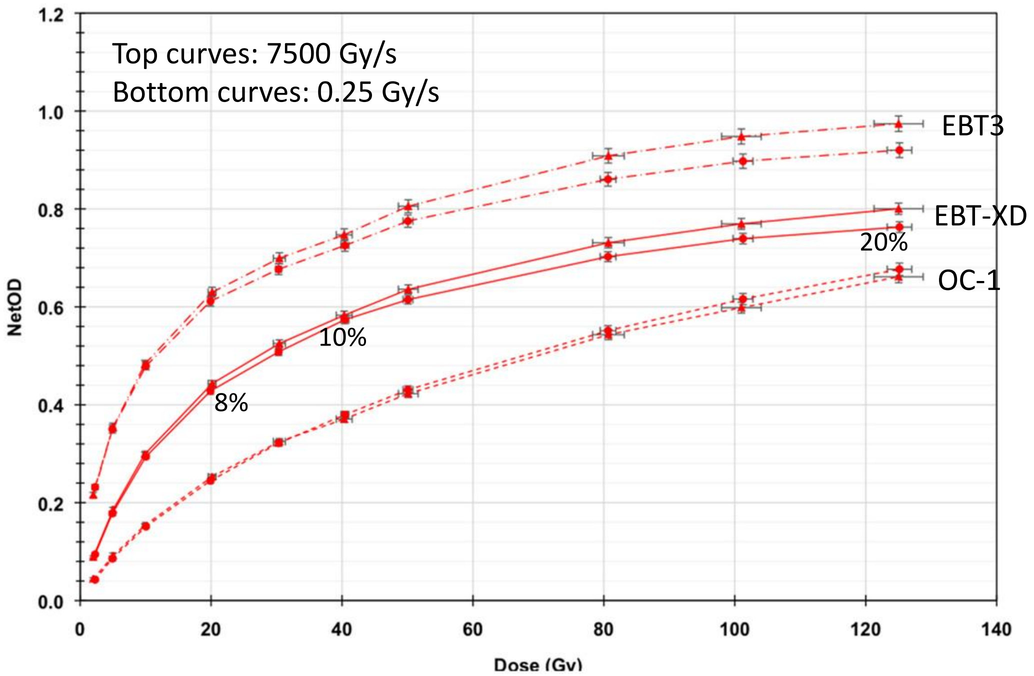


Electron beam (20MeV, 5ps)

- Dose rate independent up to 15 × 10^9 Gy/s.

Proton beam (UHDR , 68 MeV, 7500 Gy/s)

- Under-response: >10-35 MeV, >10Gy.
- Overestimate by 11% (40Gy), >20% at saturation
- Diffusion of irradiated species: dose distribution differs
- Real-time readout complication: pre-exposure polarization.
- Post irradiation stability



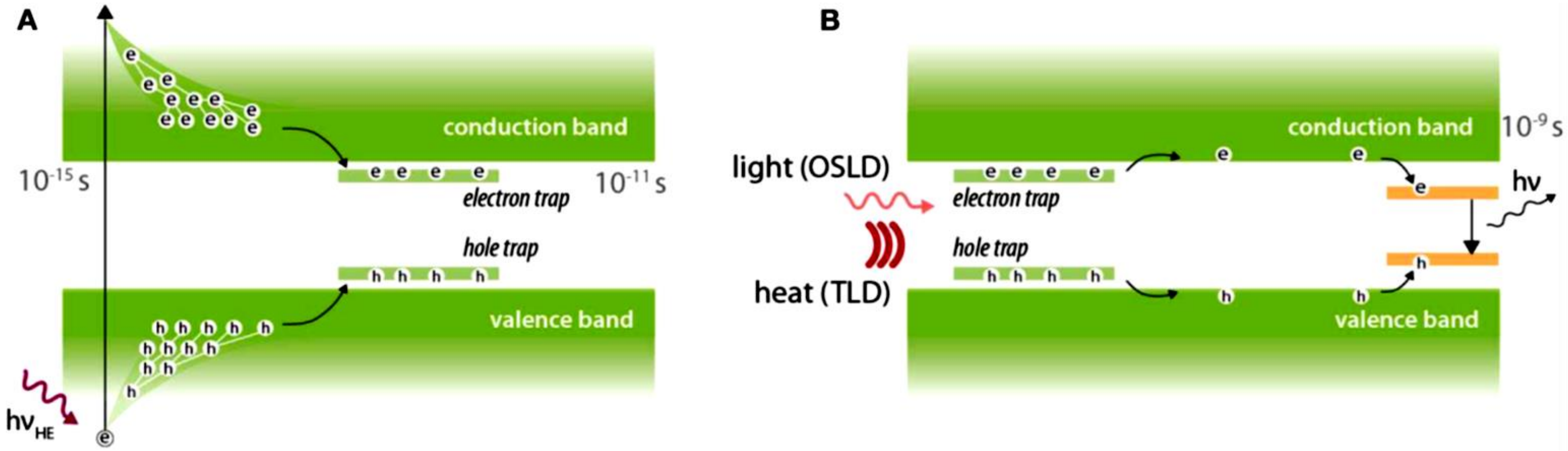
Villoing et al. Med Phy, 2022, 49(4), 2732-2745. doi: 10.1002/mp.15526.

Passive Luminescent Dosimeter

Adding impurity to certain crystals creates metastable states. Irradiation traps ions depending on the dose received. External stimulation emits light to estimate dose.

TLDs, OSLDs, RPL (persistence , UV excitation)

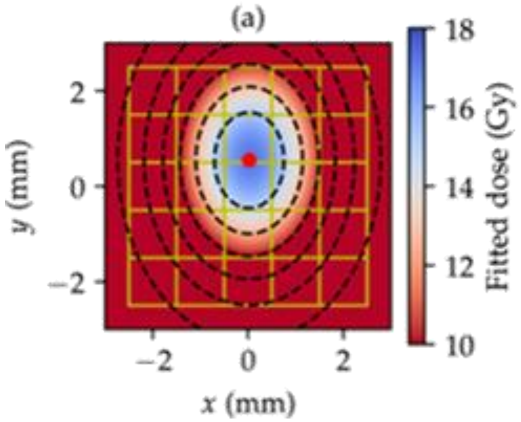
- TLDs (Lif:Mg,Ti / Lif:Mg,Cu,P) are commonly used.
- Principally passive; require readout.
- Accuracy strongly depended on the readout process

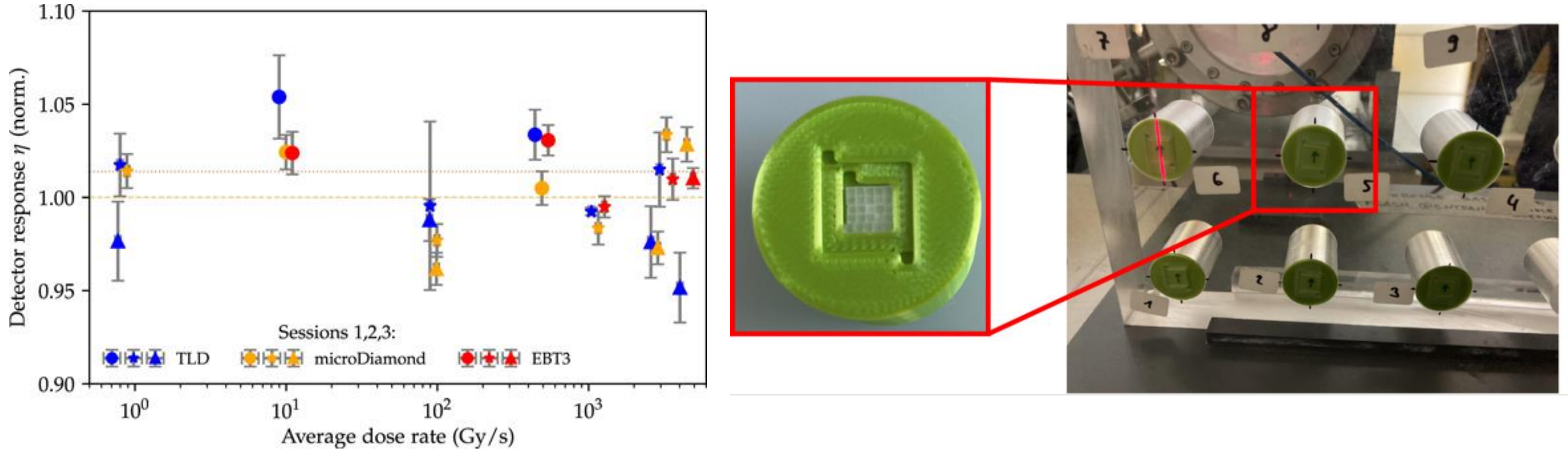


Ashraf et. al., *Front. Phys.* 8:328, 2020, doi: 10.3389/fphy.2020.00328

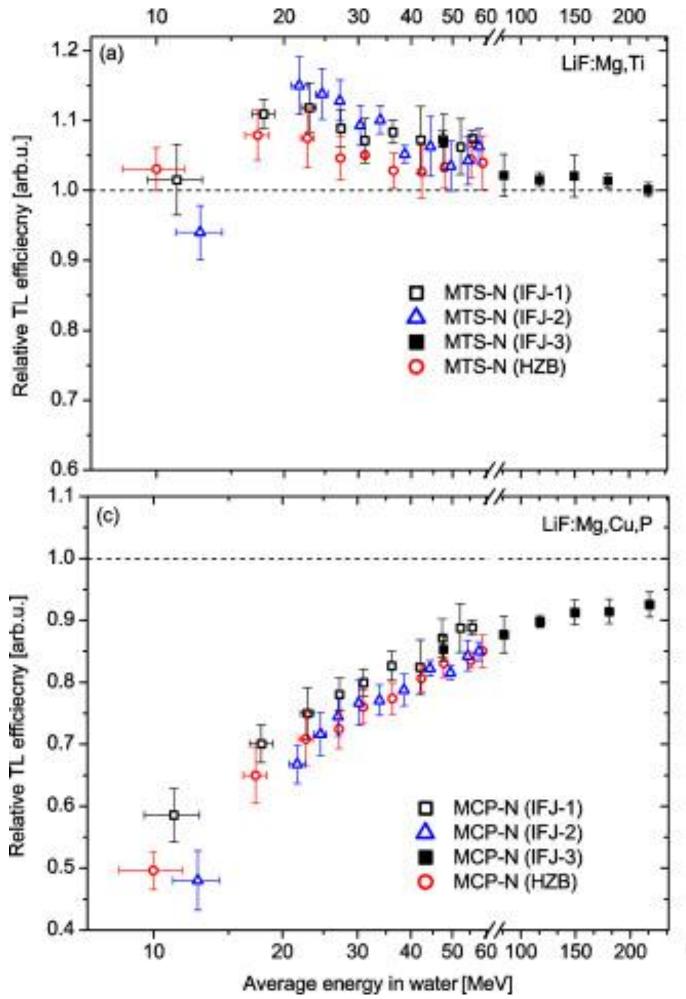
Passive Luminescent Dosimeter (Conti.)

- **TLD (E-beam, 20MeV 5ps)**
  - dose-rate independence up 4×10^{9} Gy/s within 2%
  - Dose accuracy of 3% up to 1050 Gy/s.
- **TLD (P-beam, 10-200MeV)**
  - Dose profile measurement accuracy 12%
  - Dose rate independent up to 4500 Gy/s





S Motta *et al* 2023 *Phys. Med. Biol.* 68 045017



M. Sądel, et al. Radiation Measurements, 82, 2015, 8-13, https://doi.org/10.1016/j.radmeas.2015.07.009.

Active Luminescence Dosimeters

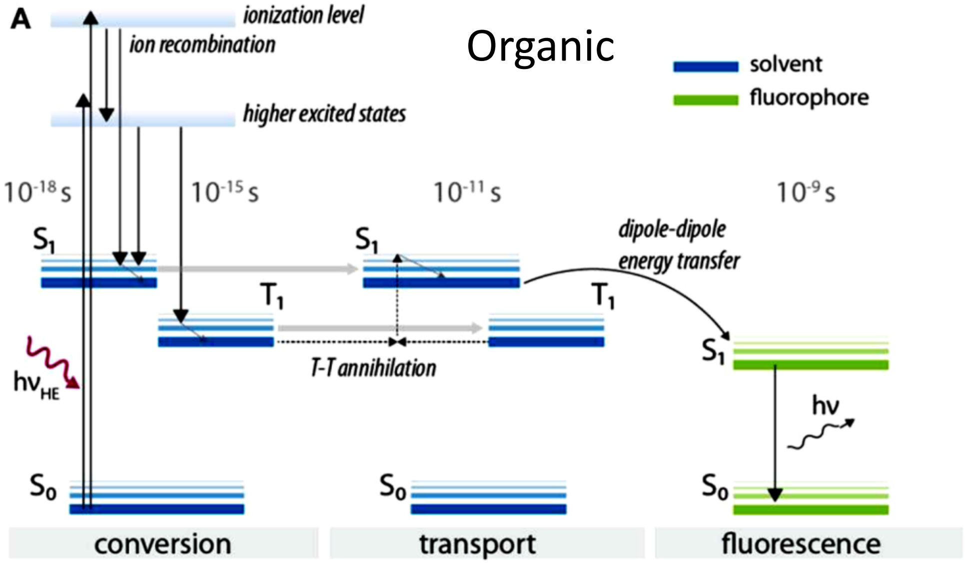
Detectors which emits photons upon irradiation without external stimulation.

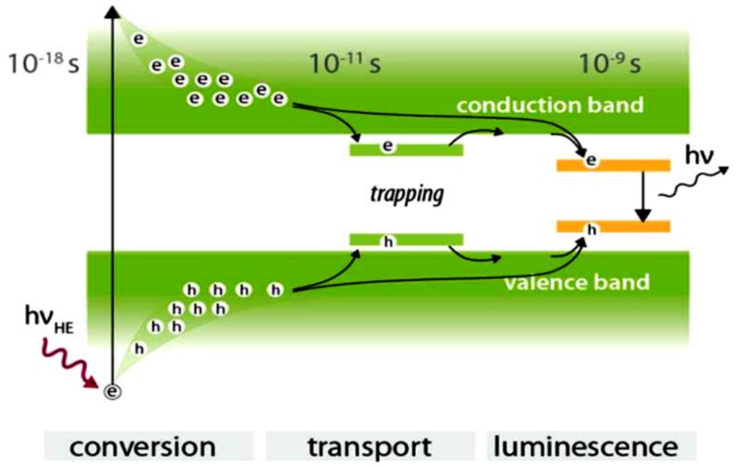
Scintillators

- Scintillation process involves: Conversion transport and Luminescence

- **Organic**: aromatic hydrocompound: excellent tissue equivalence, can be miniaturized.
- **Organic PSD**: organic molecules in solvent, water eq. , energy independence
- **Inorganic:** crystalline materials doped with impurities. High Z materials, non-tissue equivalent.

- Emission occurs in nano second time scale - can be real time,
- Ideal beam profiling monitoring and dose monitoring.
- 3D liquid scintillator for 3D profile.
- Excellent dose linearity 10^2-10^7 Gray/s.
- Precision +-2%
- Needs to be placed in the beam path



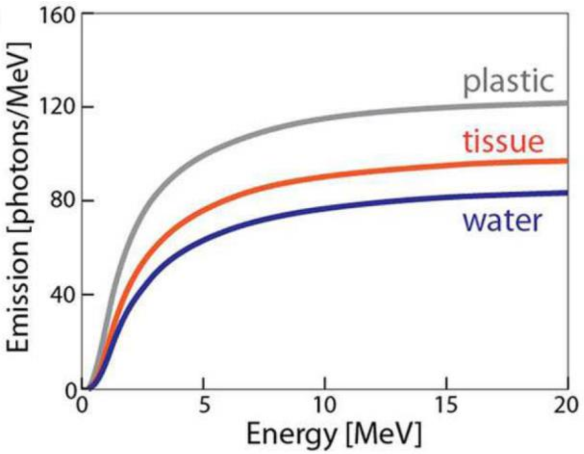


Ashraf et. al., *Front. Phys.* 8:328, 2020, doi: 10.3389/fphy.2020.00328

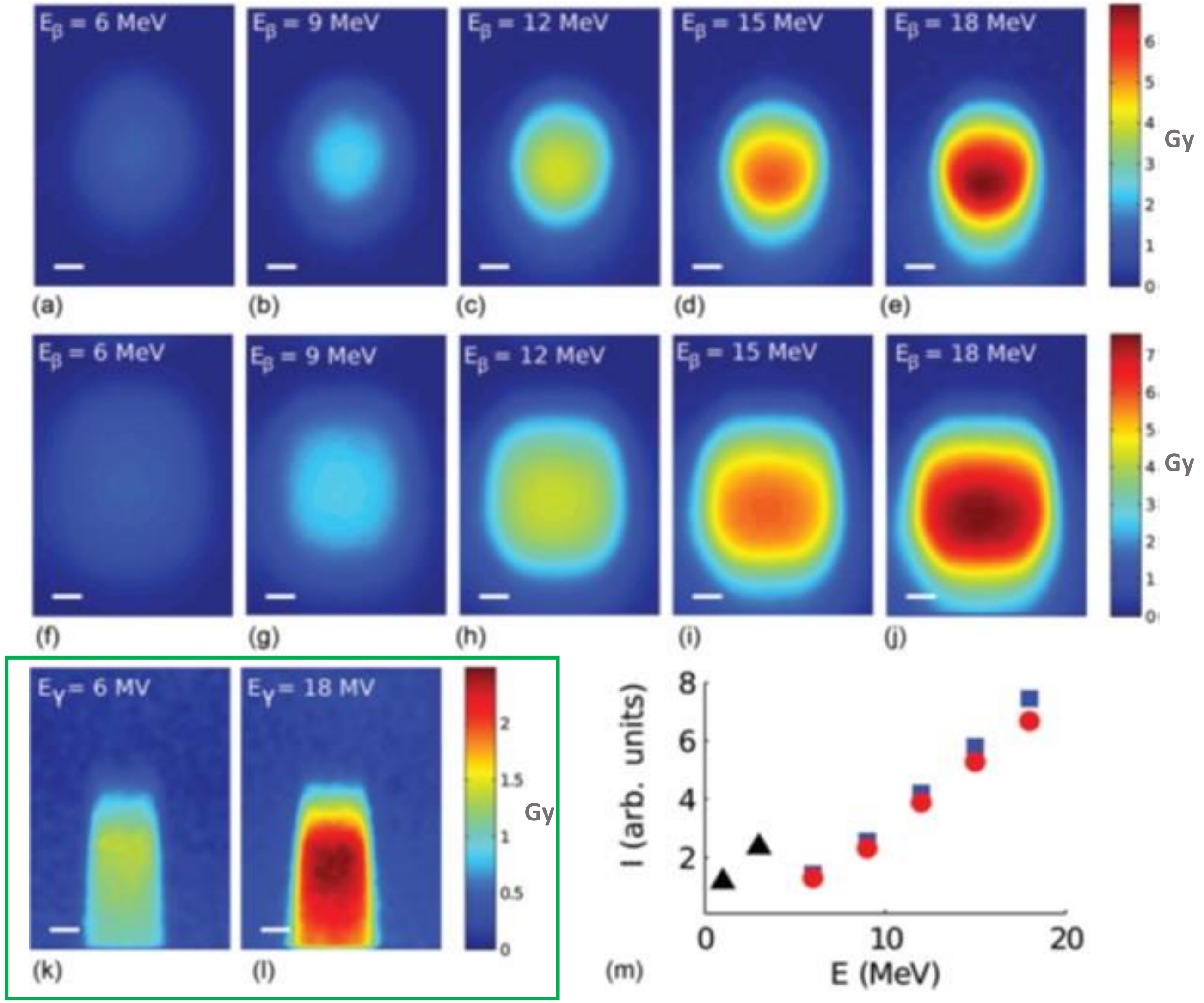
Active Luminescence Dosimeters (conti.)

Cherenkov / Cerenkov

- Emitted when a charged particle moves faster than light through a material. (bluish light)
- Direct information of the dose without any active media.
- Threshold: 264 keV (e), 500MeV (p)



- Possible: using secondary electron emission?
- Observed for photons

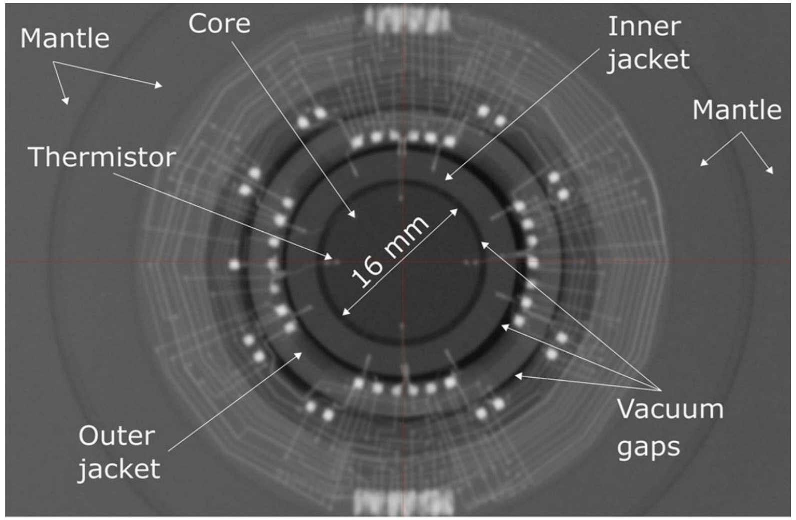


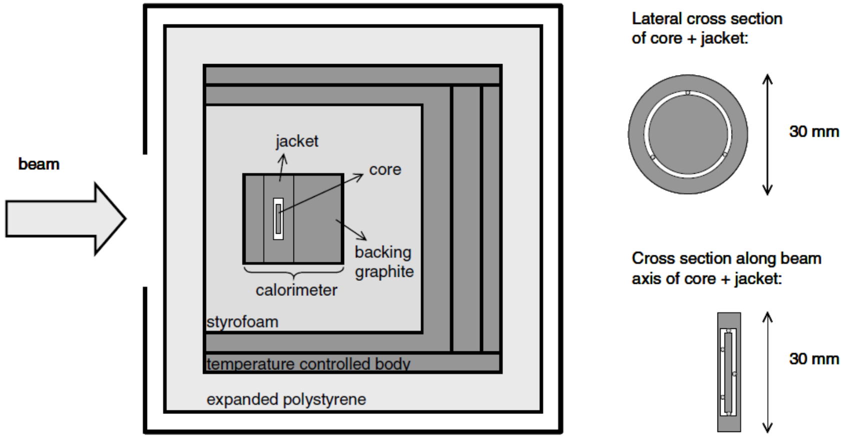
Axelsson et al., Med Phys, 38(7):4127–4132, jul 2011.

Calorimeters

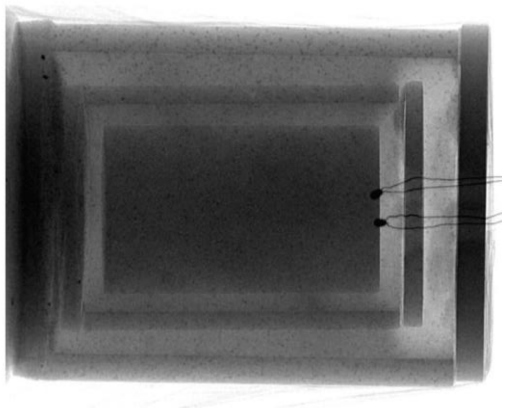
Dose estimated by measurement the heat generated in a medium during irradiation

- Fundamentally independent on the dose rate, energy
- Accuracy depends on the ability to measure minimum temperature rise. (3%)
- Considered best for reference dosimeters in FLASH
- **Graphite calorimeters are being considered as primary standard for FLASH (e-beam)**
- **Principally offline**

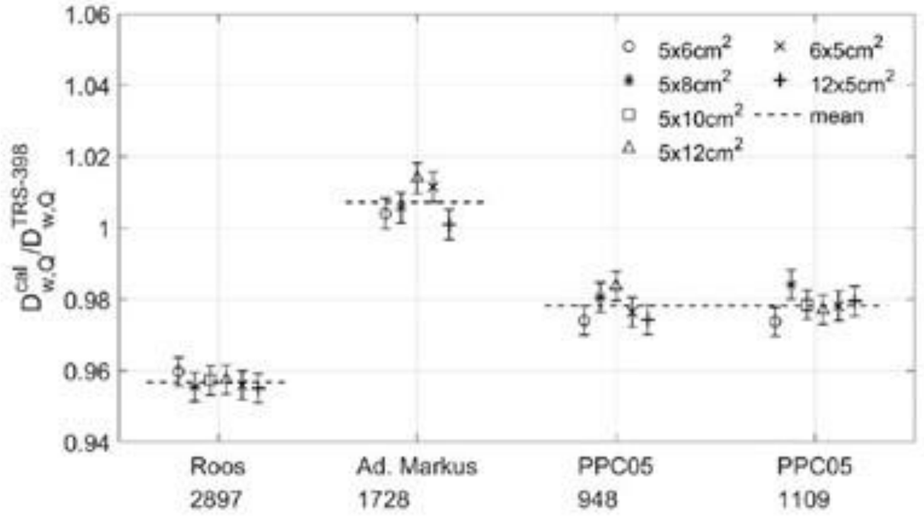




Small-body portable graphite calorimeter (SPGC) ,
62 MeV clinical proton beam, 1.9-2.5% @ 0.25 Gy/s



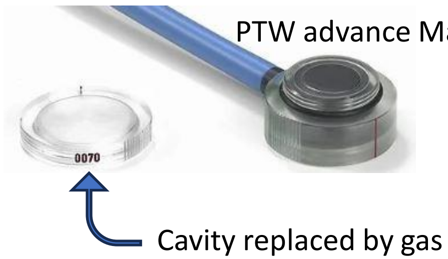
Aerrow: Graphite probe calorimeter (GPC)
1% @ 76 MV photons,



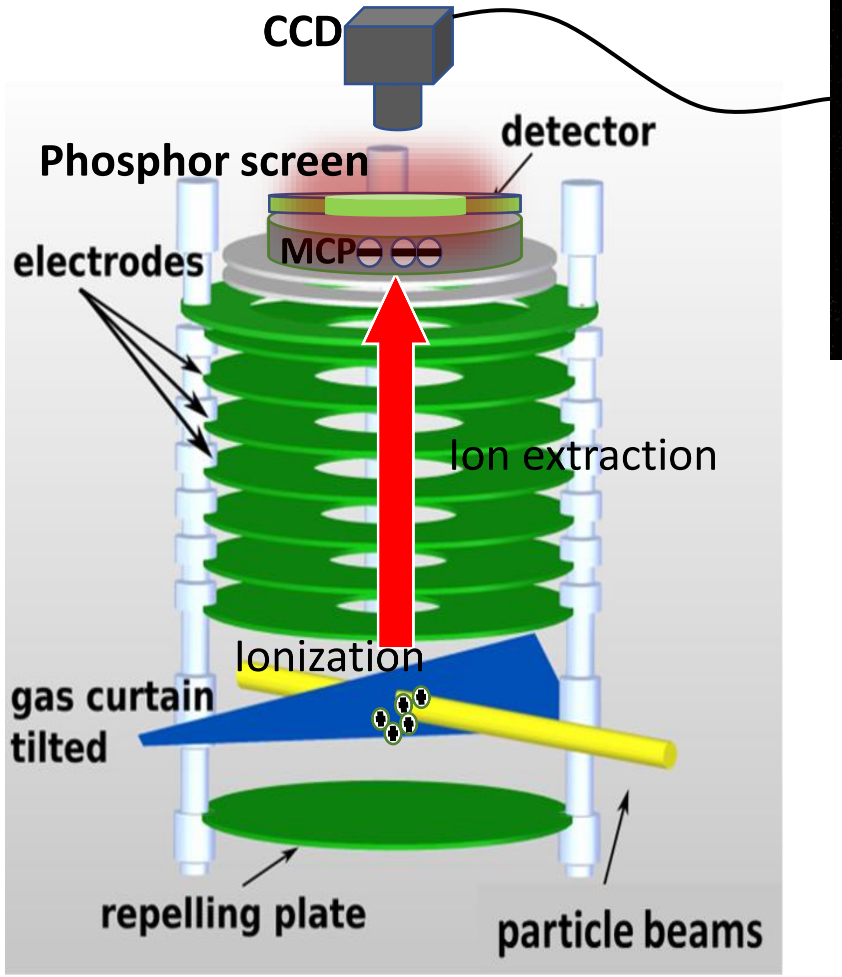
NPL Primary Standard Proton Calorimeter (PSPC)
Accuracy <3% @ 250 MeV (Probeam,USA)

Gas-curtain based profile monitor

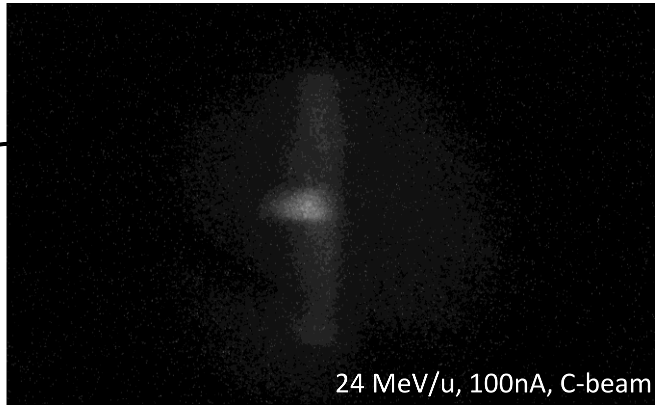
Beam incident on gas curtain creates ionizations/excitations



- Ionization cross-sections is more than excitation. (4π collection)
- **Time resolution**: travel time of charge (~10 µs), detector (10ms)
- **Beam current(dose rate)** principally independent
- **Energy dependency** follows ionization cross-section trend
- **Challenges**:
  - Ion extraction and detection maintaining their separation.
  - Sensitivity



What camera sees



Summary

Selling point (limitations)	Dosimeter	Absolute Dosimetry	FLASH dosimetry	Dose measurement	Spatial resolution	Response time	beam perturbation	Dose-rate dependence	Accuracy	Characteristics
Gold standard → for conventional (non-linarity in FLASH modality)	**Ionization chamber**	Yes	p ,e	1D, 2D scanning	few mm	10-200us	Yes	significant > 1 Gy/pulse >80Gy/s	1% 80Gy/s, 15% at 1050Gy/s , 1% with recombination correction	Ion recombination at High dose rates
	Diodes	N	C, ph	1D, 2D scanning	sub mm	ms	mask	Independent at 0.2 Gy/s	2-5%	Radiation damage at high dose rate, over-response at low dose rate
	MOSFETs	N	ph	1D, 2D scanning	1mm	ms	mask			Temperature dependence
	Diamod Detectors		p,ph,e	1D	1 mm	us	mask	> 1mGy/pulse, 50 mg/s	1% <1mGy/s, 9% for >50 mGy/s	
	Faraday cup	N							up to 1%–2%	Measures total collected charge
	Frikie	D	ph,e	1D	2mm	ns	Yes			High dose rate causes diffusion of radiation induced species.
	Alanine	D	ph,e	1D	5mm	Passive	Yes	independent up to 3^10	<3% upto 1050 Gy/s	Decreased accuracy for doses less than 10 Gy (minimum 2 Gy)
Gold standard → for beam profiling (invasive, offline)	**Radiochromic /Radiographic films**	Yes	p, C, e	2D	<1um	Passive	partially transparent	independent up to 1.5^10	5-20% @ bragg peak , 25-35% for C	Underresponse in high LET field
	Polymet gels			3D	1 um	Passive	Completely			Complex measurement and Complicated readout machinery
	TLD	D	ph, e	1D, 2D array/scan	1 mm	Passive	mask	independent up to ~10^8	2% for ~10^9 Gy/s with corrections, ~15% without corrections	Energy dependence, time consuming, LET dependence
	OSLD	D	ph	1D, 2D array/scan	1 mm	Passive	mask	Independent up to ~10^9 Gy/s)	3-5%	Energy dependence, time consuming, LET dependence
Profile (invasive) →	**Scintillators**	D	e, p	1D, 2D-film	1 mm	ns	partially transparent	Independent up to ~10^7 Gy/s	2% up to ~10^7 Gy/s	Real-time readout, water-equivalence, energy independence, dose-linearity and resistance to radiation damage,
	Chernkov	D(e)	e, Ph	1D, 2D, 3D	1 mm	ps	partially transparent (energy)			Only applied to electron or Photon beams
Calibration standard for FLASH modality (invasive, offline) →	**Caloriemeters**	Yes	p, e, ph				Completely	principally independent	<1%	Bulky, not easy to use, correction factors, time consuming
Minimally invasive → (weak signal, non-abs)	**Gass jet (in development)**	Potentially	p, C	2D (profile)	sub-mm		mostly transperent	principally independent	NA	Principally dose-rate independent, transparent to beam

Thank you