Calorimetry For Ultra-High-Dose-Rate Very High Energy Electron Beams

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Background

• Monte Carlo treatment planning studies have shown that Very High Energy Electrons (VHEEs) can provide a more conformal dose distributions and reduced integral and organ-at-risk doses (C. DesRosiers 1999, Schuler et al. 2017, Bazalova-Carter et al. 2015).

• VHEEs can also be electromagnetically scanned and focused, reducing excess irradiation of surrounding healthy tissue (K. Kokurewicz et al. 2019).

Bazalova-Carter et al. 2015
VHEE Dose Distribution in Water

• Along the central axis, depth of maximum dose for 20 MeV clinical beam is approximately 1 cm.

• 180 MeV VHEE beam delivers maximum dose at around 5 cm.

• Reduction in lateral scattering and divergence at higher energies.
Calorimeter Experimental Setup

- Absolute graphite calorimeter designed by the NPL for IMRT radiation.
- Core is cylindrical with diameter 7mm and length 7mm.
- Calorimeter placed inside custom PMMA phantom next to ionisation chamber.
- Vacuum created inside calorimeter body and housing.
CLEAR facility provided quasi-monoenergetic electron beam at approx. constant 200 MeV with energy spread between 0.25% and 6.5% (Gamba et al. 2017).

- Circular field with $x$ and $y \sigma$ of approximately 5 mm.
- Instantaneous dose rates investigated ranged between $5 \times 10^6$ Gy/s and $3.1 \times 10^8$ Gy/s.
- Pulse widths ranged between 666ps and 133.2ns.
The dose to the calorimeter is calculated by measuring the temperature rise when exposed to ionising radiation:

\[ D_{g,\text{cal}} = \frac{E_{\text{dep}}}{m_{\text{core}}} = c_g \Delta T \]

The dose-to-water is calculated as follows:

\[ D_{w,\text{cal}} = D_{g,\text{cal}} C_{g,w} k_{\text{gap}} k_{\text{imp}} k_{\text{non-g}} k_{\text{vol}} \]

At present for this work \( k_{\text{vol}}, k_{\text{imp}}, k_{\text{non-g}} \) are all taken to be unity.
Calorimeter volume was scaled to WET along the beam direction.

Diameter of core increased from 7mm to 11.04mm.

PMMA phantom build-up was also scaled to WET.

Dose scored again in WET calorimeter core.

\[ C_{g,w} = 1.103 \text{ with } 0.063 \text{ % relative uncertainty.} \]
Measured Dose

- As expected, dose-to-water per-pulse increases with increasing charge-per-pulse of beam.
- Trend is close to linear across charge-per-pulse range.
- Charge-per-pulse ranged from ~0.05nC/pulse to 11nC/pulse.
- Dose-per-pulse measured was between 0.03Gy/pulse and ~5.27Gy/pulse.

\[
R^2 = 0.98
\]
Ion Recombination

- Significant ion recombination was found when comparing calorimeter dose with that of ionisation chamber.

\[ k_s = \frac{D_{w,cal}}{M N_{D,w,Q_0} k_{TP} k_{elec}} \]

- Large ion recombination effects in secondary standard ion chamber leads to underestimations in the measured dose.
- Collection efficiency of chamber was found to be as low as 4% in some beam configurations.

Recombination factor, \( k_s \), as a function of dose-per-pulse. \( k_{s,abs} \) was found to increase close-to-linearly with dose-per-pulse.
Conclusions and Outlook

• This work aims to develop a traceable dosimetry protocol for high dose-rate VHEEs which could be applied to future VHEE radiotherapy development.

• Monte Carlo calorimeter correction factors have been determined and the dose-to-water inferred from the calorimeter measurements.

• Dose-to-water was found to increase linearly with charge-per-pulse in the beam ranging from 0.03Gy/pulse to 5.27Gy/pulse.

• When comparing calorimeter dose to that of an ion chamber, significant ion recombination was found.
The National Physical Laboratory is operated by NPL Management Ltd, a wholly-owned company of the Department for Business, Energy and Industrial Strategy (BEIS).

Thank You!

This project 18HLT04 UHDpulse has received funding from the EMPIR programme co-financed by the Participating States and from the European Union’s Horizon 2020 research and innovation programme.