Monte Carlo calculated correction factors for a proton calorimeter in clinical proton beams

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Quantity of interest in clinical proton beams is **absorbed dose to water** but...

... to date, no primary standards laboratory has a proton or ion beam

Use of an ionization chamber calibrated in a $^{60}$Co beam → **beam quality correction factor**

Uncertainties (at 95% CL) on the reference dosimetry of 4.6% for proton beams (ref TRS-398).

TRS 398 → **to calibrate chambers in a similar beam to that which is being used therapeutically.**

**New UK code of practice**

- to facilitate calibration in proton beams primarily for scanned (but also for scattered beam) delivery modes
- to deliver an *uncertainty* on reference dosimetry for protons of approximately 2% (at 95% CL)
- it will utilise a **primary standard graphite calorimeter** that is robust and **portable enough to be used in the end-user facility**
Formalism based on the new CoP

- Water and graphite calorimeters have been developed & demonstrated in p beams
- **Graphite calorimetry** at NPL

\[
D_g = \left( \frac{E_{\text{rad, core}}}{m_{\text{core}}} \right) \cdot k_{\text{imp}} \cdot k_{\text{non-g}} \cdot k_{\text{gap}} \cdot k_{\text{vol}}
\]

- **\(k_{\text{imp}}\)** → differences in specific heat due to core impurities
- **\(k_{\text{non-g}}\)** → presence of non-graphite materials
- **\(k_{\text{gap}}\)** → for presence of vacuum gaps
- **\(k_{\text{vol}}\)** → dose averaged over the whole core to that at the centre

- Aim: determine \(k_{\text{non-g}}, k_{\text{gap}}\) and \(k_{\text{vol}}\) with Monte Carlo simulations for:
  - monoenergetic pencil beams
  - reference clinical SOBP beams (scanning/passive)
How do we calculate $k_{\text{non}-g}$, $k_{\text{gap}}$ and $k_{\text{vol}}$?

- Default modular physics list:
  - Hadronic: QGSP_BIC_HP (Binary Cascade)
  - EM: emstandard_opt4
  - ICRU90 material definitions
  - Production cuts 0.05mm

- Scoring/tracking:
  - Total dose deposited per event
  - Standard deviation $\rightarrow$ SDOM
Correction factors for mono energetic protons

- **3 cm beam diam & 2.0 g/cm² BU:** $k_{\text{gap}}$ up to $1.008$ (230 MeV)
- **Large beam diam (LSCPE),** $k_{\text{gap}}$ within 0.1% of unity for all the energies

- Various disk thickness investigated
- $k_{\text{vol}} \sim 0.997$ at 60 MeV up to $\sim 1.003$ at 230 MeV
Clinical relevant SOBPs

- According to the new UK Code of Practice (*still in draft*), reference dosimetry has to be carried out in a primary STV (Standard Test Volume) centred at 15 cm depth in water (box $10 \times 10 \times 10 \text{ cm}^3$) and further measurements have to be performed in two secondary STVs, respectively centred at 10 cm and 25 cm.

\[ \left[ \begin{array}{c} \sum_{i=1}^{N} \frac{w_i D_{i1} + w_i D_{i2} + \ldots + w_i D_{iN}}{D_{i0}} = 100\% \end{array} \right] \]

- Solution of the equation system $\rightarrow$ weights
- Compromise between number of peaks and complexity in solving equations!

Matlab script for weight calculation
Correction factors for the primary STV (centred at 15 cm)

Reciprocity theorem

<table>
<thead>
<tr>
<th>$k_{\text{non-g}}$</th>
<th>$k_{\text{gap}}$</th>
<th>$k_{\text{vol}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.9988 \pm 0.0006$</td>
<td>$1.0006 \pm 0.0004$</td>
<td>$0.9991 \pm 0.0008$</td>
</tr>
</tbody>
</table>

- 34 peaks in total $\Rightarrow$ uniformity within $0.2\%$
- Weights converted to Nb of evts per peak in TOPAS

$k_{\text{non-g}}$, $k_{\text{gap}}$ and $k_{\text{vol}}$ corrections within $0.1\%$ of unity for the STV-15
Correction factors for the secondary STVs (centred at 10 and 25 cm)

<table>
<thead>
<tr>
<th>STV-10</th>
<th>STV-25</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>k_{non-g}</strong></td>
<td><strong>k_{gap}</strong></td>
</tr>
<tr>
<td>0.9983 ± 0.0006</td>
<td>1.0008 ± 0.0005</td>
</tr>
</tbody>
</table>

62 peaks in total: uniformity within 0.2%

25 peaks in total: uniformity within 0.2%
Uncertainties for STV (for ripple effect)

\[
\sum_{i=1}^{N} w_i D_{i1} + w_i D_{i2} + \ldots + w_i D_{iN} = 99.3\% = 1, 2, \ldots, N
\]

\[
\begin{align*}
\text{STV-15 data-driven} & \\
k_{\text{non-g}} & k_{\text{gap}} & k_{\text{vol}} \\
0.9984 \pm 0.0005 & 1.0002 \pm 0.0004 & 0.9997 \pm 0.0009 \\
\end{align*}
\]

original STV-15

\[
\begin{align*}
\text{k_{non-g}} & \text{ k_{gap}} & \text{k_{vol}} \\
0.9988 \pm 0.0006 & 1.0006 \pm 0.0004 & 0.9991 \pm 0.0008 \\
\end{align*}
\]
Correction factors for a passive beamline (CCC)

- Passive beam line for eye melanoma treatment with 62 MeV proton beams at the Clatterbridge Cancer Centre

### Correction Factors

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_{\text{non-g}}$</td>
<td>$0.9998 \pm 0.0008$</td>
</tr>
<tr>
<td>$k_{\text{gap}}$</td>
<td>$1.0000 \pm 0.0005$</td>
</tr>
<tr>
<td>$k_{\text{vol}}$</td>
<td>$0.974 \pm 0.001$</td>
</tr>
</tbody>
</table>

### Uncertainties (ripple effect)

- $k_{\text{non-g}}$: $0.9998 \pm 0.0009$
- $k_{\text{gap}}$: $1.0003 \pm 0.0007$
- $k_{\text{vol}}$: $0.974 \pm 0.001$
**Summary**

- Overview of the **formalism** for determining absorbed dose to water in proton beams based on a new UK code of practice using a **portable primary standard graphite calorimeter**.
- Description of methods for determining the $k_{\text{non-g}}$, $k_{\text{gap}}$ and $k_{\text{vol}}$ corrections with TOPAS (Geant4) for mono-energetic and clinical relevant beams.
- Description of a robust and versatile method for weight calculations:
  - Simulating an ideal SOBP with uniformity < 0.2%
  - Realistically reproducing fluctuations in the modulation region (ripple effect on corrections)

For mono-energetic beams (LSCPE):
- $k_{\text{non-g}}$ and $k_{\text{gap}}$ within 0.1% of unity
- $k_{\text{vol}}$ varies from -0.3% less than unity at 60 MeV to +0.3% above unity at 230 MeV

For the primary and secondary STVs:
- $k_{\text{non-g}}$, $k_{\text{gap}}$ and $k_{\text{vol}}$ were found to be within 0.1% for the primary STV
- no significant variations for all the three different STVs within the statistical uncertainties
- no significant variations due to ripple effect within the statistical uncertainties

For CCC passive beams:
- $k_{\text{non-g}}$ and $k_{\text{gap}}$ within 0.1% of unity $k_{\text{vol}} = 0.974 \pm 0.001$
Thank you