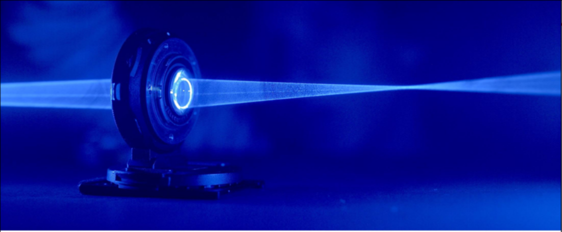

THE UNIVERSITY OF TEXAS MD Anderson Cancer Center
Making Cancer History®

2020 JOINT AAPM | COMP MEETING

Beam Modeling for a Novel Convergent X-ray Treatment Machine

Joint AAPM/COMP Meeting

July 12 2020

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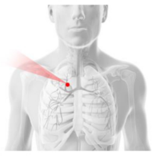
Convergent x-ray beam radiotherapy



CRnR technology utilizes:
- Monochromatic low-energy x-ray beam (e.g.60 KeV)
- Narrow convergent beam
- Concentrated dose build up at the tumor area
- A simple and inexpensive system
- A sharp dose fall-off outside the tumor that enables accurate treatment
- Unmatched accuracy of treatment for shallow lesions (<10 cm)
  - Very small size of the focal spot (0.5 – 3 mm)
  - Position of the focal spot is fixed and determined by the geometry of the lens (no range uncertainty)
  - Treatment planning similar to IMPT (it is easy to produce highly conformal treatments)
- Significantly smaller shielding requirements
- Highly maneuverable device (mounted on a robotic arm)

The Principle of X-ray lens (Elastic Coherent Scattering)

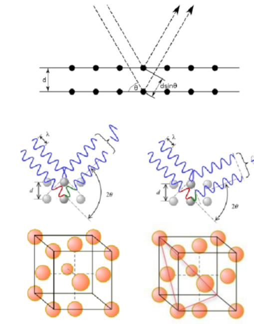
- First theory proposed by father and son Bragg in 1913

$$2d\sin\theta = n\lambda$$

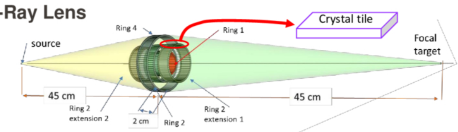
- The interplanar distance d determines the angle of constructive interference

$$d^2 = a^2/(h^2 + k^2 + l^2)$$

- In 3D cubic crystal lattice with lattice constant a there are many possible planes indexed by Miller indices h, k, l
- Aluminum has face centered cubic lattice ($1, 1, 1$ plane shown)

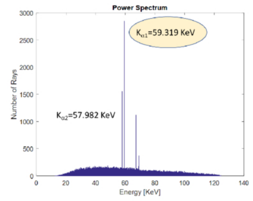


CRnR X-Ray Lens

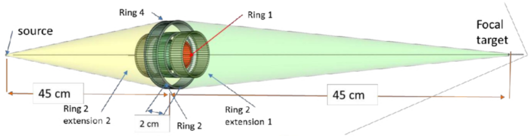


Crystal properties
- High integrated reflectivity
  - Integral of the reflectivity over the angular and energy acceptance of the crystal
- Mosaic structure or curved diffracting planes (CDPs) are the best choice
- Single-Crystal Aluminum ($a = 4.05$ A)

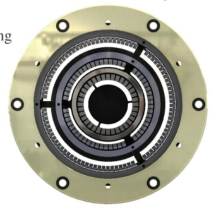
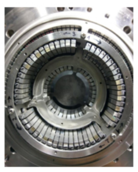
X-ray energy
- Mainly the of K-α_1 of tungsten, 59.3 keV
  - Some of the of the K-α_2, 58.0 keV



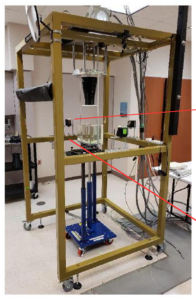
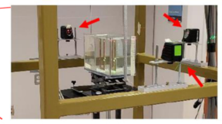
CRnR X-Ray Lens Design



30 – 80 individual tiles per ring

In-water dose measurements – experimental setup

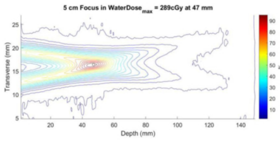



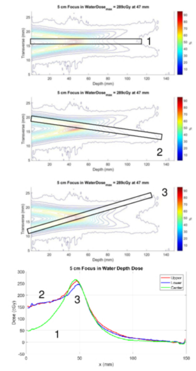
Three self-leveling lasers used to for focal spot alignment highlighted by red arrows.

CRnR experimental setup including x-ray tube, focusing lens, and support cage.

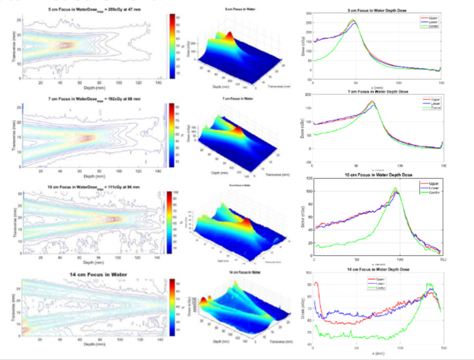
In-Water Measurement Analysis

Isodose curves for focused 60 kV x-rays.





In-Water Measurement



Treatment planning for convergent x-rays

Convergent beam treatment planning requires the following steps:

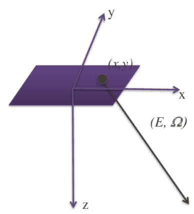
1. Photon source model
2. Dose computation algorithm(s)
   - Monte Carlo
   - Pencil beam or convolution/superposition
3. Patient model
   - Physical and biological models
4. Constrained optimization algorithm

Beam model

The photon source is specified as a 5D flat surface phase space file
- $\Phi(x, y, E, \Omega)$
- z coordinate is constant

The model can be used directly in MC computations and as a energy fluence for treatment planning dose calculations

First step: Energy dependence

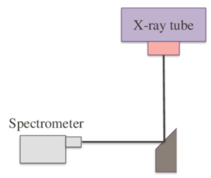


Energy spectrum measurement

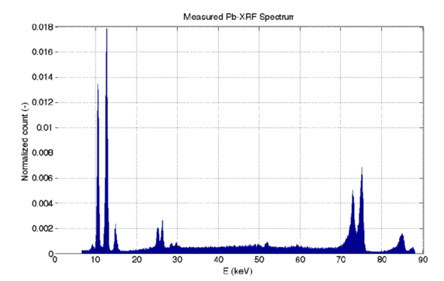
Measurements using Amptek CdTe spectrometer

Measure tube spectrum using beam scattered at 90^0

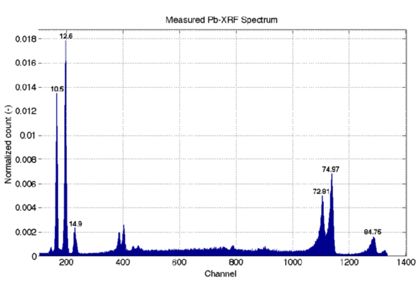
Use Pb-XRF for calibration of the spectrometer
- Thin sheet of lead on top of the graphite block



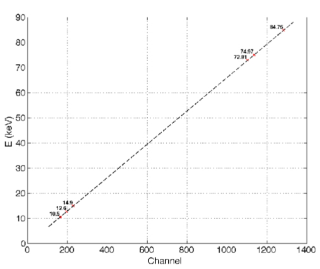
Calibration measurement



Spectral lines selected for calibration



Calibration fit

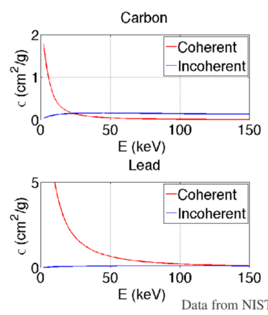


90^0 Compton correction

X-rays scattered at 90^0 have reduced energy if scattering is incoherent

$$h\nu' = \frac{h\nu}{1 + h\nu/511} \quad (\text{keV})$$

For E<150 keV coherent scattering is dominant in lead and incoherent (Compton) scattering is dominant in Carbon



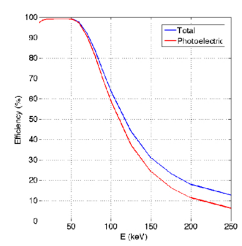
Data from NIST

CdTe Detection Efficiency

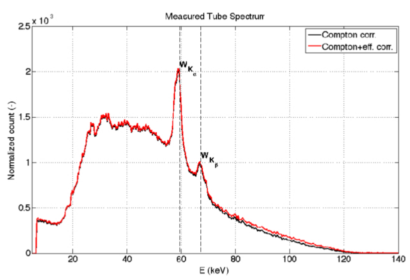
CdTe detector consists of 1 mm CdTe crystal behind 0.1mm Be window

Window dominates low energy response

1 mm CdTe thickness defines high energy response



Measured x-ray tube spectrum

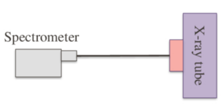


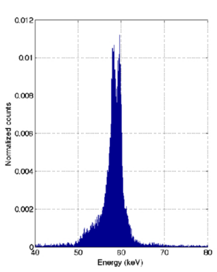
Focal spot spectrum

Direct measurement at the focal spot

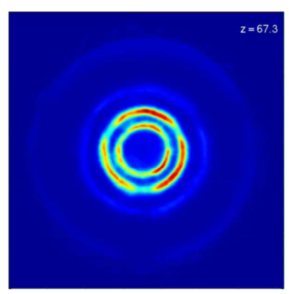
Spectrometer positioned using laser alignment

$K_{\alpha 1}$ peak = 59.3 keV





Measured beam fluence



Beam Model

Assume axial symmetry:

$$\Phi(r, \theta, E, \Omega) = X(r, \theta)\Psi(r, \theta, E, \Omega)$$
$$= R(r)\Theta(r, \theta)\ \Psi(r, \theta, E, \Omega)$$

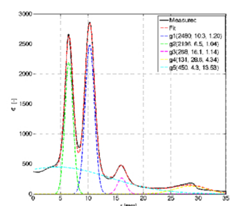
Step 1: Find radial component $R(r)$ using multi-Gaussian fit

$$R(r) = \sum_{i=1}^{5} g_i[A_i, c_i, \sigma_i](r)$$

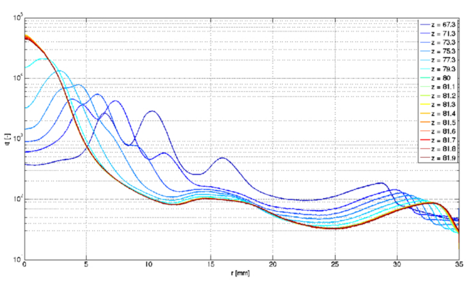
Quality of the fit: $R^2 = 0.998$

Results:
- 3 narrow peaks with $\sigma \approx 1.1$ mm
- Wide peak in the center
  - $\sigma \approx 13.5$ mm

z = 67.3 cm



Radial component



Directional component

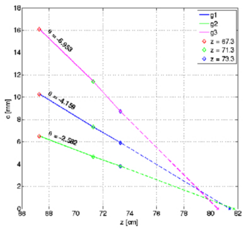
Use 1st three images to get the initial estimate of the directional component $\Psi(r, \theta, E, \Omega)$

The remaining images used for verification and refinement

Tree curves converge for z = 81 cm.

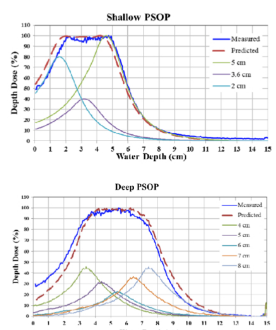
Compute a fit for $\mu = \cos\theta$ as a function of r and z

Miller indices vs. θ:
- (111): 2.5623 (expected)
- (220): 4.1865 (expected)
- (420): 6.6283 (expected)



Photon Spread Out Peak (PSOP)

PSOP designed from 3 focal spots ranging from 2 to 5 cm in depth in water.



PSOP designed from 5 focal spots ranging from 4 to 8 cm in depth in water.

CRnR Collaboration

MDACC Team

Israeli Collaborators

Thank You