Secondary Neutron Production in Proton Radiotherapy using Monte Carlo Techniques

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Overview

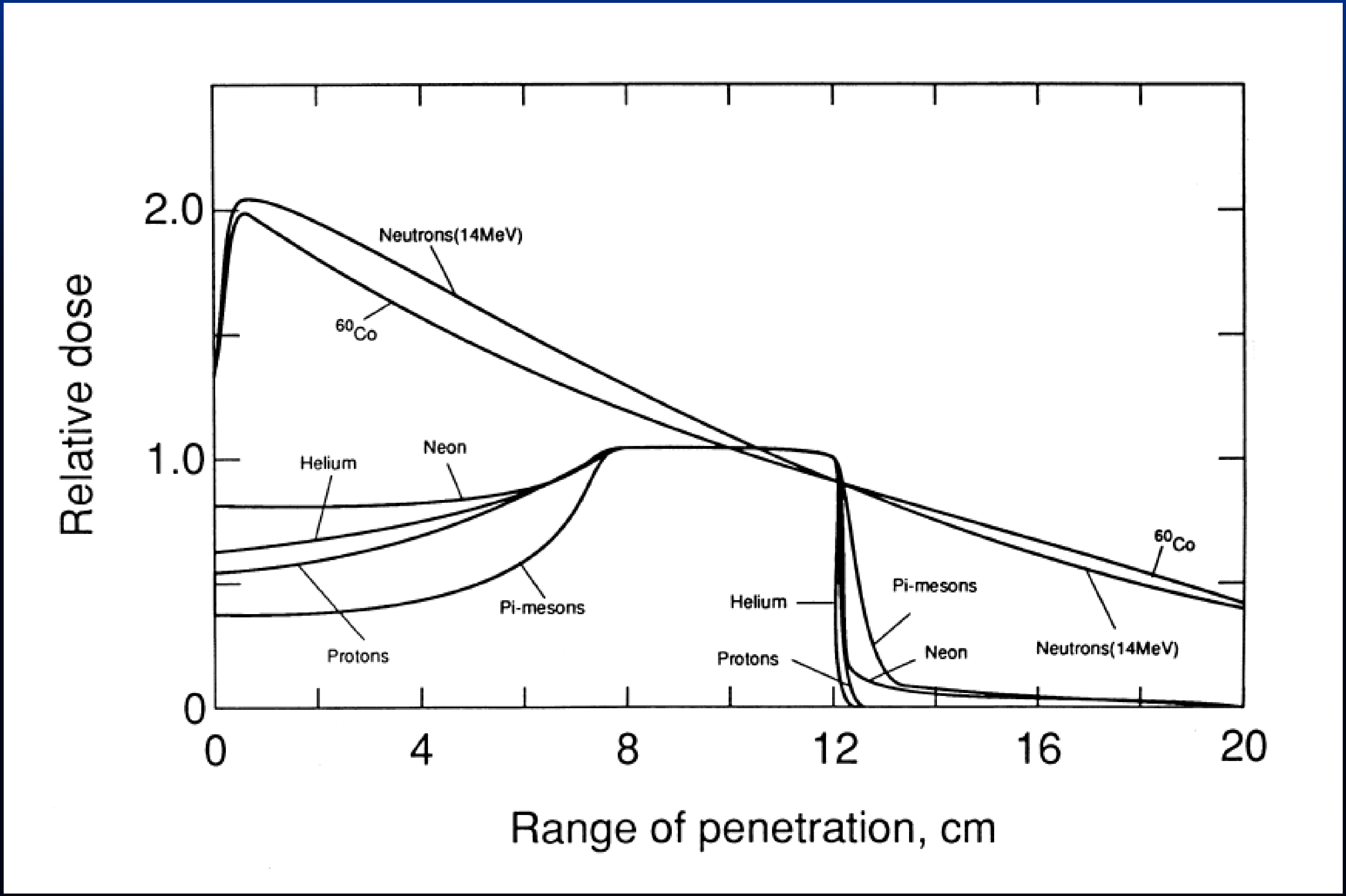
- **Objective:** To evaluate differences in nuclear physics models of the Geant4 Monte Carlo Toolkit and compare results to MCNPX

- **Motivation:** Risk of second cancers unknown

"Does it make any sense to spend over $100 million on a proton facility, with the aim to reduce doses to normal tissues, and then to bathe the patient with a total body dose of neutrons …"

Hall, Technol in Ca Res Treat 2007;6:31-34

Pictorial Graph of Comparison with Other Radiation

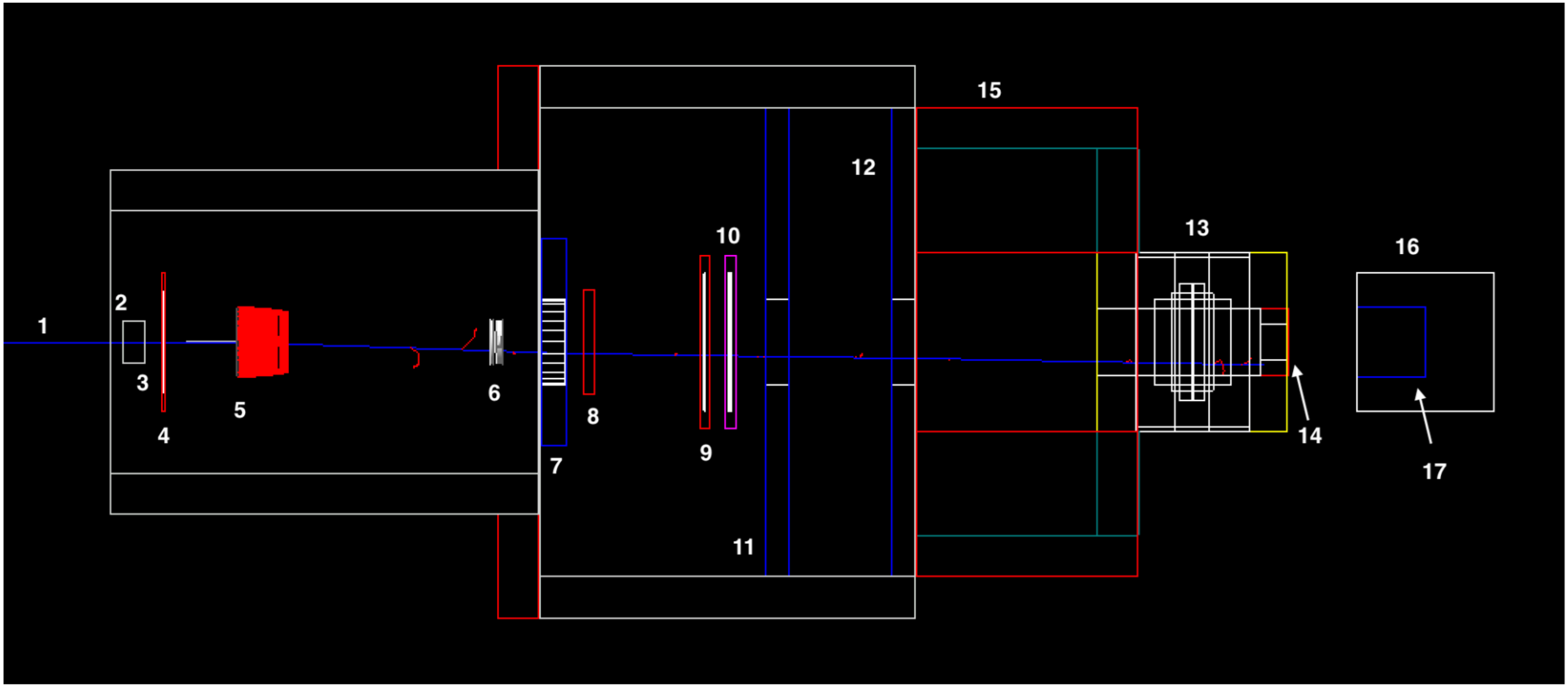


Relevant Physics Mechanisms

- Therapeutic dose
  - Predominated by stopping power, multiple coulomb scattering, and energy straggling
- Stray dose
  - Predominated by nuclear reactions and neutrons
  - described by the underlying nuclear physics interactions

    → **direct nucleon-nucleon collision processes**

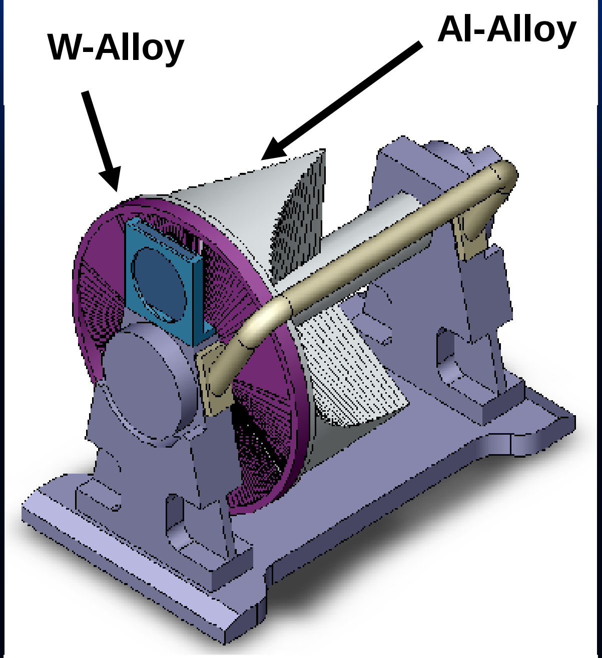
Methods: MC Model of Treatment Head



1. Proton Source
2. Vacuum window
3. Profile monitor
4. Reference monitor
5. RMW
6. Second scatterer
7. Middle base plate
8. Range Shifter blade
9. Subdose monitor
10. Primary Dose Monitor
11. Square pre-collimator
12. Block collimator
13. Medium snout
14. Brass Aperture
15. SS nozzle housing
16. Water phantom
17. Detector

Methods: Range Modulator Wheel (RMW)

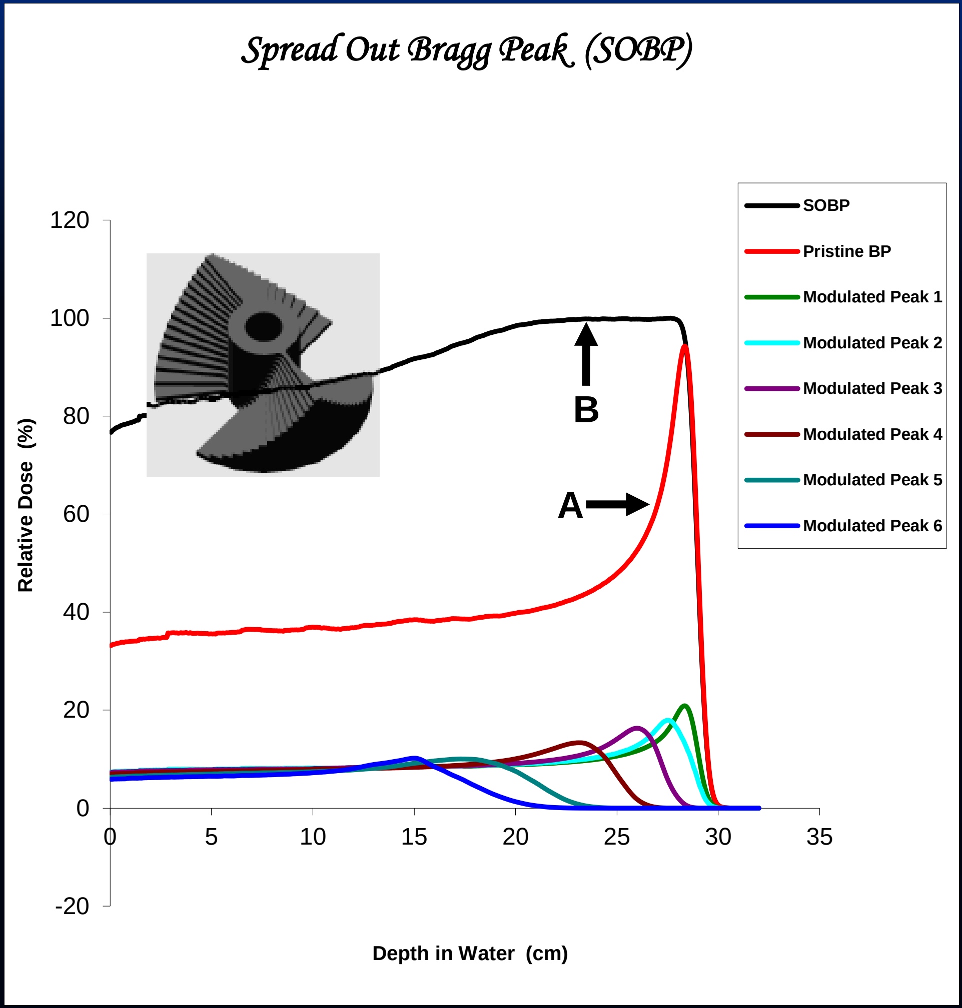
- RMW at PTC-H
  - comprised of W-alloy and Al-alloy
    - W-alloy (first scatterer) → lateral spread of beam
    - Al-alloy blades → beam modulation
  - three-blades
    - opening angles → define beam penetration depth of each B.C.



Schematic of RMW

Methods: Spread Out Bragg Peak (SOBP)

- Curve A → Pristine Bragg Curve
  - sharp Bragg peak
- Curve B → SOBP
  - maximum dose uniformity
  - tumor coverage
- Rotating RMW blades sweep through the proton beam → beam modulation
  - shift Bragg curves at depth
  - produces SOBP

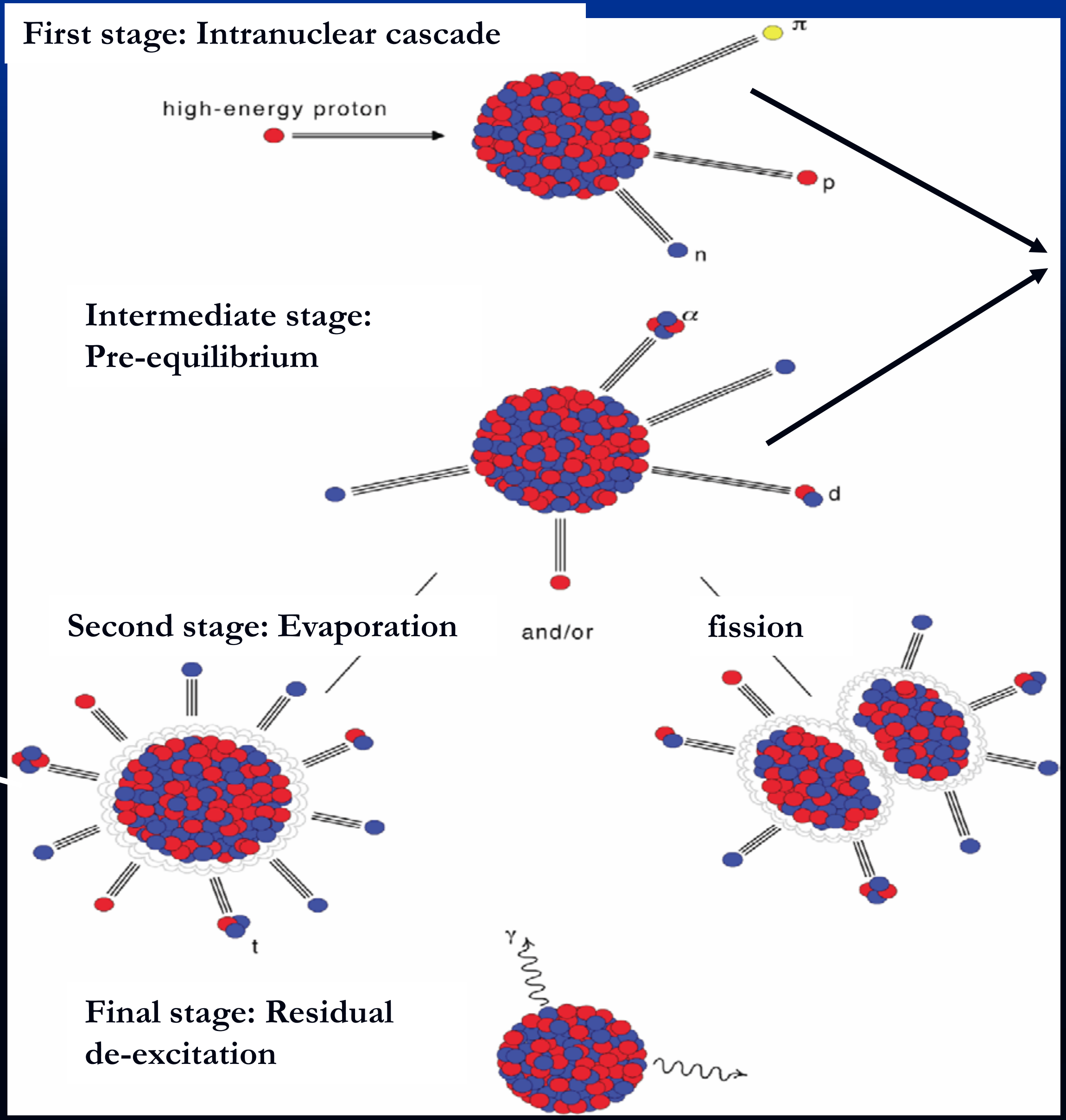


Methods: MC Model of Treatment Head Using TOPAS

Methods: Nuclear Models

- Employ Geant4 Monte Carlo toolkit and also MCNPX to:
  - Calculate therapeutic absorbed
  - Calculate neutron fluence
- Compare results of nuclear physics models
  - **Geant4 Models**
    - **Bertini model (Baseline model)**
    - **Binary Cascade model (BIC)**
    - **Intranuclear Cascade model/ABLA De-excitation model (INCL-ABLA)**
  - **MCNPX Models**
    - **Bertini model (Baseline model)**
    - **Cascade Exciton Model (CEM)**
    - **Liège Intranuclear Cascade Model INCL4**

Methods: Nuclear Reactions of Relevance



Higher Kinetic Energy Particle Emission

Lower Kinetic Energy Particles Emission

Waters, L. 2002 MCNPX User's Manual Version 2.3.0 LA-UR-02-2607

Methods: Secondary Neutron Dosimetric Quantities Calculated

- Total Ambient Neutron Dose Equivalent per source proton: $H^*(10)/p = \Sigma\ (\Phi/p)_i * (H^*(10)/\Phi)_i * \Delta E_i$
  - Following ICRP Publication 74 (1996)

- Therapeutic absorbed dose per proton: D/p
  - Following Zheng et al. (2008)

- **Ambient Neutron Dose Equivalent per Therapeutic absorbed dose:**

  $$\rightarrow\ H^*(10)/D = H^*(10)/p\ /\ D/p$$

  - Following Yan et al (2002)

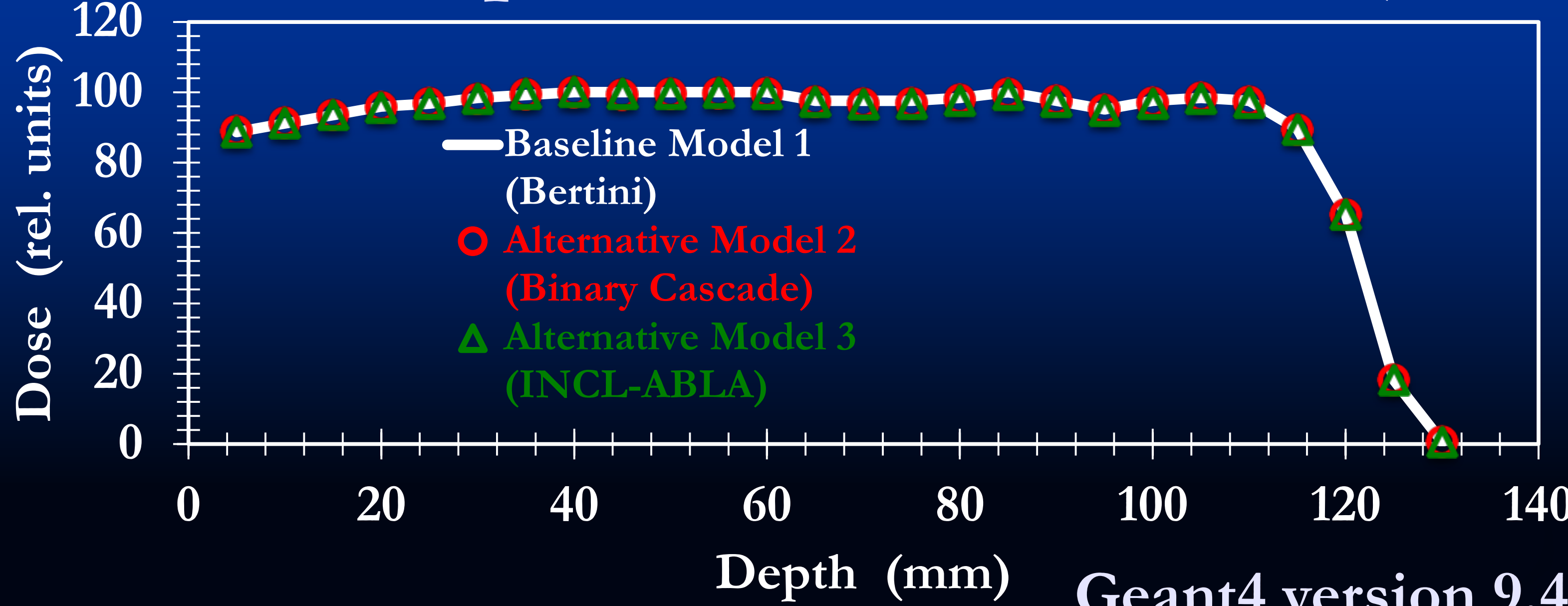
Results

Using three nuclear physics models:

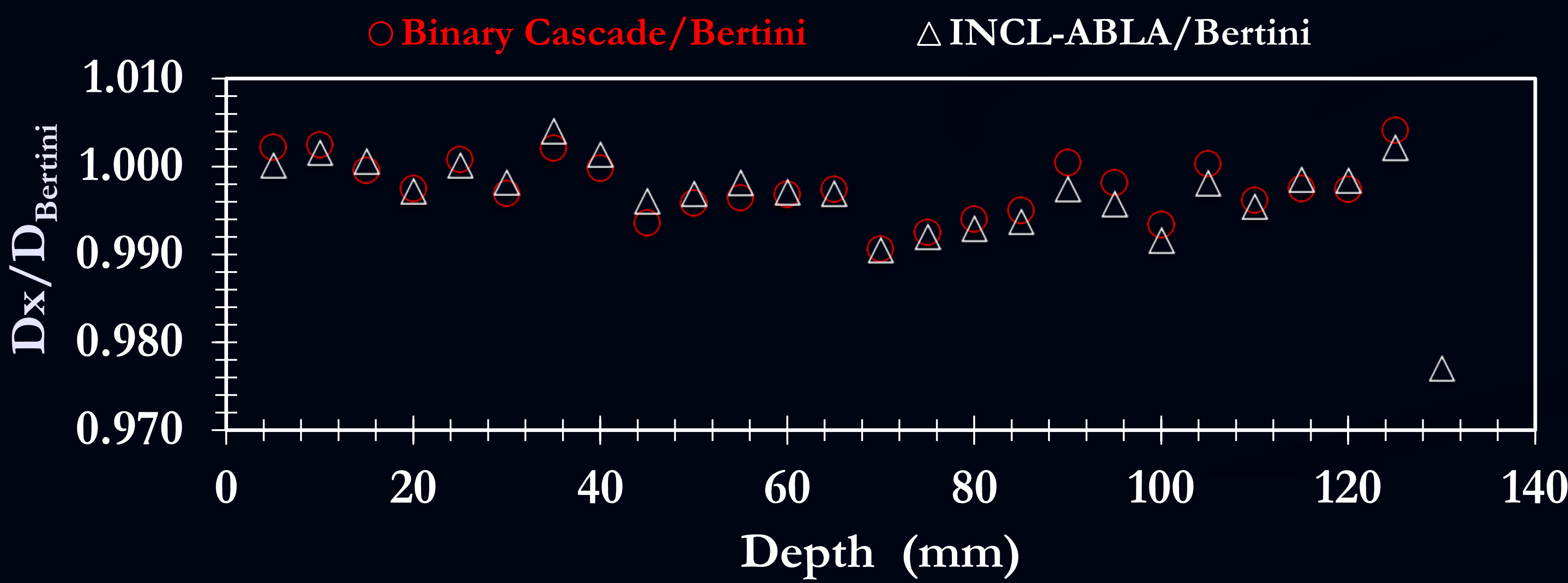
1. **therapeutic absorbed dose in water**

2. **produced neutron spectral fluence in air**

Results: Therapeutic Absorbed Dose (SOBP)



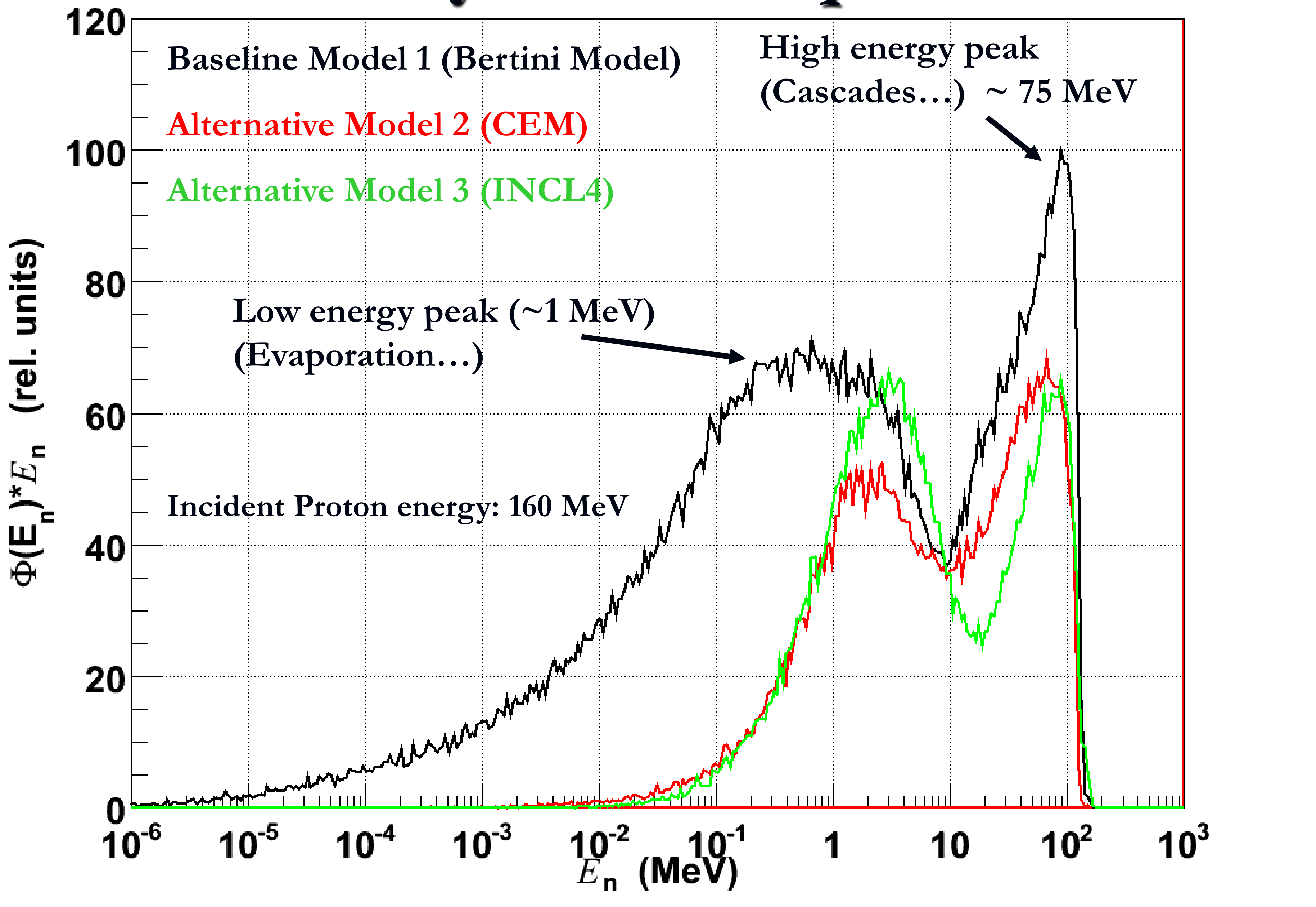
Geant4 version 9.4.p06



Results: Therapeutic Absorbed Dose

	Bertini model 1 (Baseline)	Binary Cascade model 2	INCL-ABLA model 3	$\lvert z_{BC}-z_{Bertini} \rvert$	$\lvert z_{INCL-ABLA}-z_{Bertini} \rvert$
Dose quantities					
	mm	mm	mm	mm	mm
pristine distal 90% dose point	114.0	113.9	113.9	0.1	0.1
pristine distal 80%-20% dose point	4.9	4.9	4.9	0.0	0.0
SOBP distal 90% dose point	114.98	114.97	114.96	0.1	0.1
SOBP proximal 95%-distal 90% width	**92.90**	**93.15**	**92.68**	**0.2**	**0.25**

MCNPX: Stray Neutron Spectral Fluence



Results: $H^*(10)/D$ (SOBP)

	Bertini model 1 (baseline)	CEM model 2	INCL4 model 3	$\lvert H^*(10)/D_{CEM} - H^*(10)/D_{Bertini} \rvert$	$\lvert H^*(10)/D_{INCL4} - H^*(10)/D_{Bertini} \rvert$
receptor location	$H^*(10)/D(X)$ mSv/Gy	$H^*(10)/D(X)$ mSv/Gy	$H^*(10)/D(X)$ mSv/Gy	mSv/Gy	mSv/Gy
At isocenter	**6.92 ± 0.25**	**4.84 ± 0.21**	**4.55 ± 0.20**	**2.08 ± 0.29**	**2.37 ± 0.32**
At 100 cm downstream from isocenter	0.32 ± 0.05	0.21 ± 0.04	0.21 ± 0.04	0.11 ± 0.06	0.11 ± 0.06
At 100 cm lateral to the isocenter	0.44 ± 0.06	0.33 ± 0.05	0.36 ± 0.06	0.11 ± 0.08	0.08 ± 0.08

Summary

- Compared baseline model (Bertini) to two alternative nuclear physics models (Binary Cascade and INCL-ABLA) in Geant4 and (CEM and INCL4) MCNPX
  - in-phantom therapeutic absorbed dose
    - **~ 1 – 2 percent in dose**
    - **< 1 mm at depth**
  - in-air neutron spectral fluence
    - **< factor of 2 at most neutron energies**
  - in-air *H*(10)/D*
    - Bertini (baseline) model in good agreement with **measured data from Tayama et al (2006)**
    - CEM and INCL4 under predict neutron dose w.r.t. Bertini model by **2 mSv/Gy at isocenter (~30% deficit)**
- Simulations are underway in our computational laboratory to finalize calculations of the neutron energy fluence in ICRU sphere using TOPAS for H*(10) estimates

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