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Heavy Ions: Interaction with matter, synchrotron and synchrocyclotron production and medical applications of particle accelerators in Radiotherapy departments

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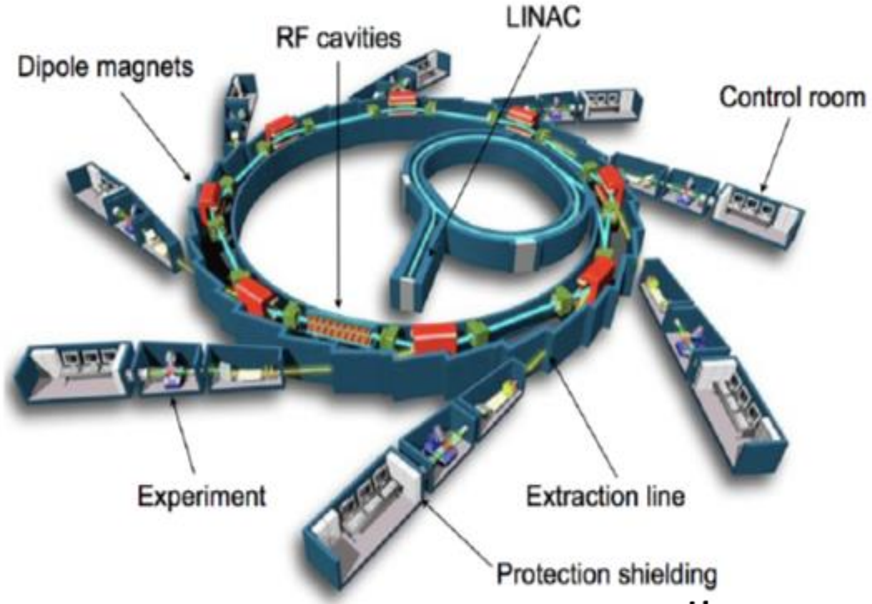
1. Background-Aim

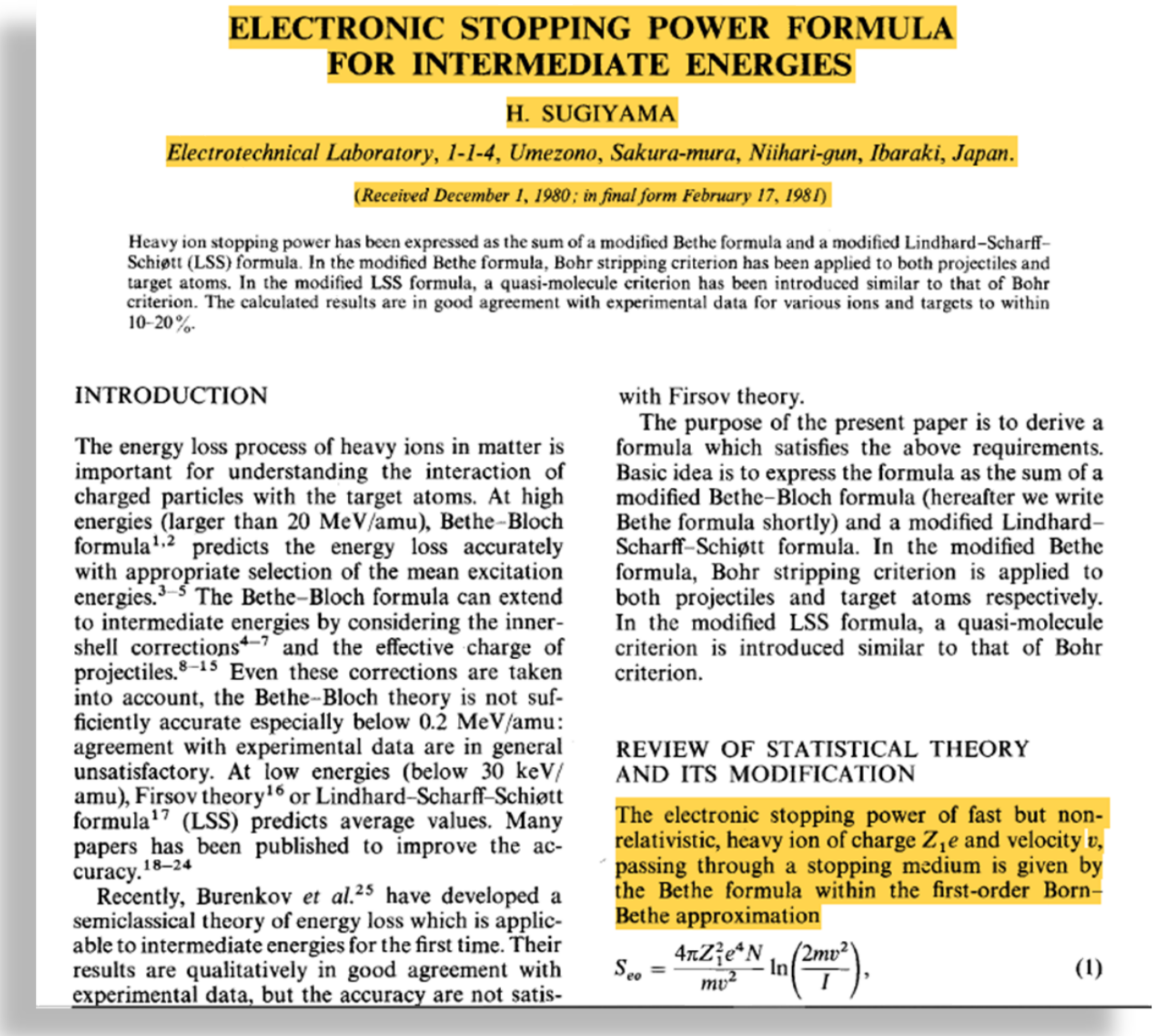
During the past few years Heavy Ion Therapy also known as Hadron Therapy has become an increasingly "hot topic" as it is a promising approach in cancer therapy due to its superior precision in dose delivery compared to more well-known classical radiation therapies such as Photons and Electrons. Hadron Therapy as implied by its name uses the unique properties of heavy ions, i.e. Carbon, to target tumours with higher precision while minimizing damage to surrounding tissues.



The production of Heavy Ions is typically accomplished by particle accelerators, synchrotrons and synchrocyclotrons. Recent research is being conducted and focused on improving treatment planning, understanding the radiobiological effects and developing more compact and cost-effective accelerator designs. This presentation will give a short review into Heavy Ion Therapy. Heavy Ion Production, the particle accelerators, the interaction with matter, their medical applications, the facilities equipped with Heavy Ion accelerators and the recent research that is being done will be discussed.

2. Materials & Methods

Having thoroughly read related bibliography, the necessary information was collected and summarised into the sections to be discussed.



ELECTRONIC STOPPING POWER FORMULA FOR INTERMEDIATE ENERGIES

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Heavy ion stopping power has been expressed as the sum of a modified Bethe formula and a modified Lindhard–Scharff–Schiøtt (LSS) formula. In the modified Bethe formula, Bohr stripping criterion has been applied to both projectiles and target atoms. In the modified LSS formula, a quasi-molecule criterion has been introduced similar to that of Bohr criterion. The calculated results are in good agreement with experimental data for various ions and targets to within 10–20%.

INTRODUCTION

The energy loss process of heavy ions in matter is important for understanding the interaction of charged particles with the target atoms. At high energies (larger than 20 MeV/amu), Bethe–Bloch formula[1,2] predicts the energy loss accurately with appropriate selection of the mean excitation energies.[3–5] The Bethe–Bloch formula can extend to intermediate energies by considering the inner-shell corrections[4–7] and the effective charge of projectiles.[8–15] Even these corrections are taken into account, the Bethe–Bloch theory is not sufficiently accurate especially below 0.2 MeV/amu: agreement with experimental data are in general unsatisfactory. At low energies (below 30 keV/amu), Firsov theory[16] or Lindhard–Scharff–Schiøtt formula[17] (LSS) predicts average values. Many papers has been published to improve the accuracy.[18–24]

Recently, Burenkov *et al.*[25] have developed a semiclassical theory of energy loss which is applicable to intermediate energies for the first time. Their results are qualitatively in good agreement with experimental data, but the accuracy are not satisfactory with Firsov theory.

The purpose of the present paper is to derive a formula which satisfies the above requirements. Basic idea is to express the formula as the sum of a modified Bethe–Bloch formula (hereafter we write Bethe formula shortly) and a modified Lindhard–Scharff–Schiøtt formula. In the modified Bethe formula, Bohr stripping criterion is applied to both projectiles and target atoms respectively. In the modified LSS formula, a quasi-molecule criterion is introduced similar to that of Bohr criterion.

REVIEW OF STATISTICAL THEORY AND ITS MODIFICATION

The electronic stopping power of fast but non-relativistic, heavy ion of charge Z_1e and velocity v, passing through a stopping medium is given by the Bethe formula within the first-order Born–Bethe approximation

$$S_{eo} = \frac{4\pi Z_1^2 e^4 N}{mv^2} \ln\left(\frac{2mv^2}{I}\right), \qquad (1)$$

Particle Therapy Co-Operative Group

An organisation for those interested in proton, light ion and heavy charged particle radiotherapy

Particle therapy facilities in clinical operation

Information about technical equipment (last update: June 2024).

COUNTRY	WHO, WHERE	PARTICLE	S/C/SC* MAX. ENERGY (MeV)	BEAM DIRECTIONS	START OF TREATMENT
Austria	MedAustron, Wiener Neustadt	p	S 253	2 horiz., 1 vertical fixed beam**, 1 gantry** (under construction)	2016
Austria	MedAustron, Wiener Neustadt	C-ion	S 403/u	2 horiz. and 1 verticalfixed beam**	2019
Belgium	PARTICLE PC, Leuven	p	SC 235	1 gantry**, 1 horiz. fixed beam	2020
China	WPTC, Wanjie, Zi-Bo	p	C 230	2 gantries, 1 fixed beam	2004
China	SPHIC, Shanghai	p	S 250	3 fixed beams**	2014
China	SPHIC, Shanghai	C-ion	S 430/u	3 fixed beams**	2014
China	Heavy-Ion Cancer Treatment Center, Wuwei,Gansu	C-ion	S 400/u	4 fixed beams**	2019
China	Ruijin Hospital, Jiao Tong University, Jiading, Shanghai	p	S 250	1 gantry**, 2 horiz. fixed beams**	2021
China	Hefei Ion Medical Center, Hefei, Anhui	p	C 250	3 gantries**, 1 horiz. fixed beam**	2022
China	Hong Kong Sanatorium & Hospital PTC, Hong Kong	p	S 220	2 gantries**	2023

2. Materials & Methods

GUIDELINES & RECOMMENDATIONS

Heavy charged particle beam therapy and related new radiotherapy technologies: The clinical potential, physics and technical developments required to deliver benefit for patients with cancer

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FLASH and spatially fractionated radiotherapy (SFRT)

Another area of worldwide interest that has the potential to transform radiotherapy is FLASH RT. FLASH is delivered at ultra-high dose rates (normally >40 Gy/s mean dose rate *vs* conventional RT dose rates ~0.16 Gy/s) and in large doses per fraction (so would require fewer fractions). The transformative potential of FLASH RT stems from experimental results obtained across different species (mouse, pig, cat, zebrafish) and various organs (lung, brain, skin, gut) that appear to show that FLASH RT significantly reduces damage to
surrounding the tumour.[25–38] Alth
evidence that FLASH RT delays tum
(over longer time periods) is needed
alent or increased tumour control.[26]

RADIOTHERAPY IN CANCER CARE: FACING THE GLOBAL CHALLENGE

Edited by:
Eduardo Rosenblatt
Eduardo Zubizarreta

IAEA

GSI

GSI Helmholtzzentrum für Schwerionenforschung GmbH

Research at GSI – An Introduction

Scientific research has provided an increasingly comprehensive insight into the structure of matter and of the development of the universe. At the same time, the

3. Results

The physics behind Heavy Ion interactions with matter have been studied by numerous scientists and are not as simple as the interaction of single particles, but the benefits and applications are overwhelming. However, its implementation due to cost and technical challenges present an obstacle.

Heavy Ion Interaction with matter

- **Coulomb interactions with electrons and nuclei (Ionizations and excitations)**
- **In nuclear reactions**
- Emission of electromagnetic radiation (bremsstrahlung)
- By emission of Cherenkov radiation

Charged particles	Heavy Ions
Z<2 , A<4	Z>2 , A>4
Charge invariant	Charge variant (electron loss and capture)

For fast but nonrelativistic heavy ion of charge Z_1e and velocity u → Bethe's formula

$$-\frac{dE}{dx} = \frac{4\pi Z_1^2 e^4 N}{mu^2} \ln\left(\frac{2mu^2}{I}\right)$$

For intermediate energies with Z_1^* being the effective charge of the projectiles → Bohr's electron loss and capture theory

$$-\frac{dE}{dx} = \frac{4\pi Z_1^{*2} e^4 N}{mu^2} Z_2^* \ln\left(\frac{2mu^2}{I^*}\right)$$

For relativistic ion velocities with n_2=charge density, δ the density effect correction of Fermi and $\gamma = \frac{1}{\sqrt{1-\frac{u^2}{c^2}}}$ → LSS formula

$$-\frac{dE}{dx} = \frac{4\pi Z_1^2 e^4}{mu^2} n_2 [\ln\left(\frac{2mu^2}{I}\gamma^2 - \frac{u^2}{c^2} - \frac{\delta}{2}\right)$$

For slow ions with low energies, where α_0 and u_0 being the Bohr's radius and orbital velocity respectively → Firsov's Formula

$$-\frac{dE}{dx} = 8\pi e^2 \alpha_0 N \frac{Z_1 Z_2}{\left(Z_1^{2/3}+Z_2^{2/3}\right)^{2/3}} \left(\frac{u}{u_0}\right)$$

Bohr's theory of electron capture and loss

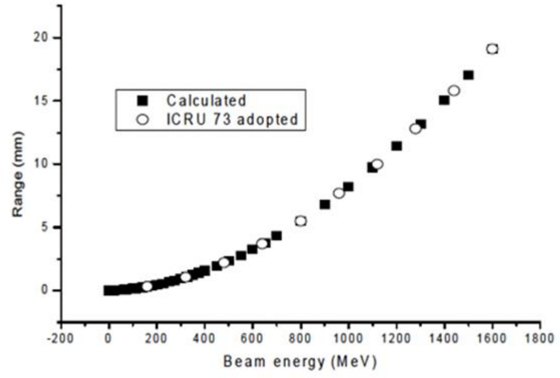
Ion velocity > Orbital electron velocities →
- Low probability of capturing an electron
- High probability of losing an electron

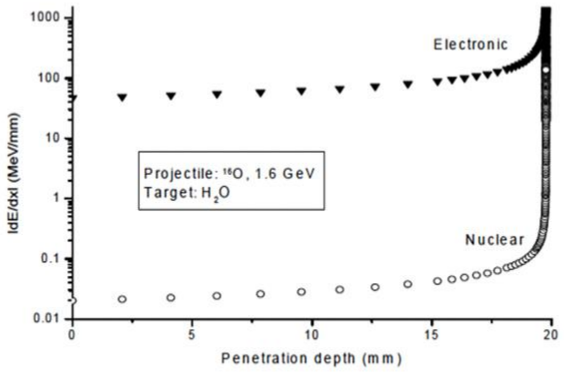
Ion velocity ≈ Orbital electron velocities →
- Probability of capturing an electron ↑
- Probability of losing an electron ↓

Ion velocity < Orbital electron velocities →
- Probability of capturing an electron ↑↑↑ until neutralized
- Probability of losing an electron ≈ 0

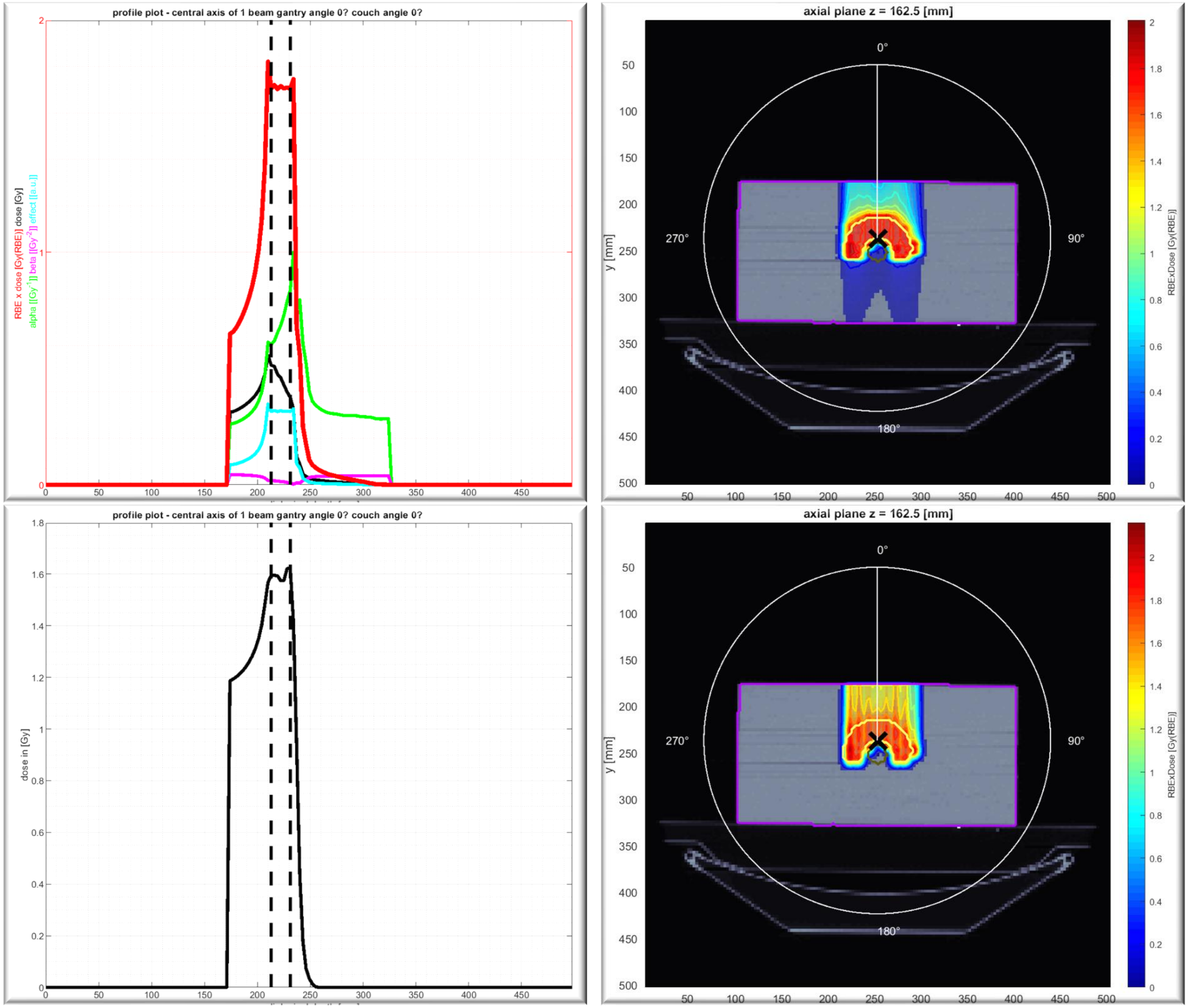
Range (R) = the average distance travelled by a heavy ion before reaching the thermal energy of the medium

$$R = \int_0^E \frac{dE}{(\frac{dE}{dx})e + (\frac{dE}{dx})n}$$





3. Results



Carbon Ions

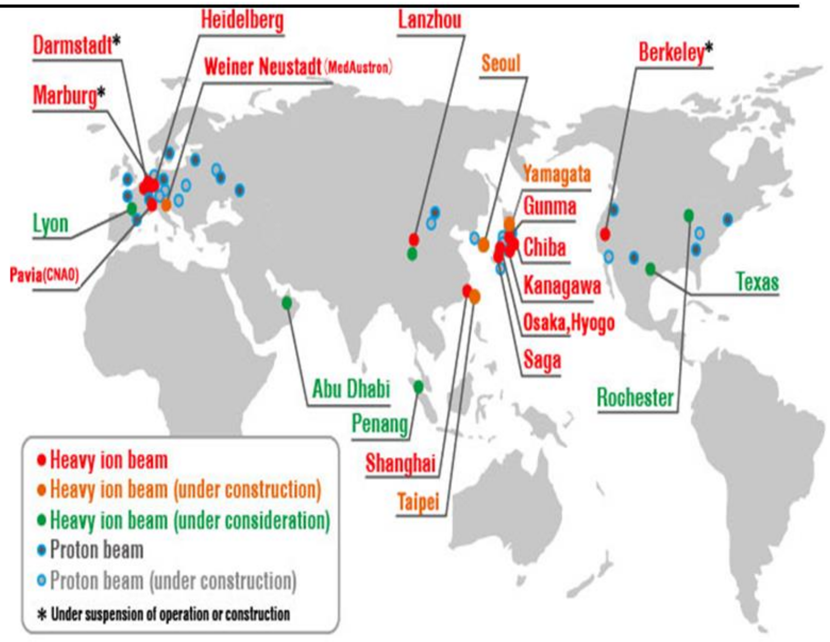
Protons

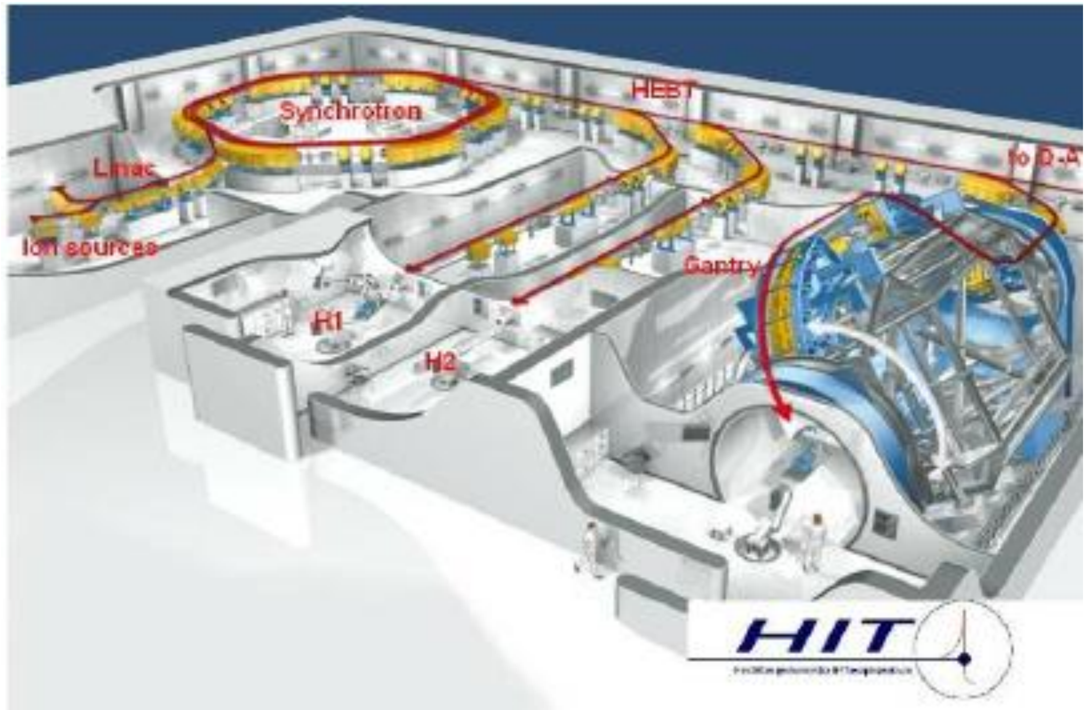
3. Results

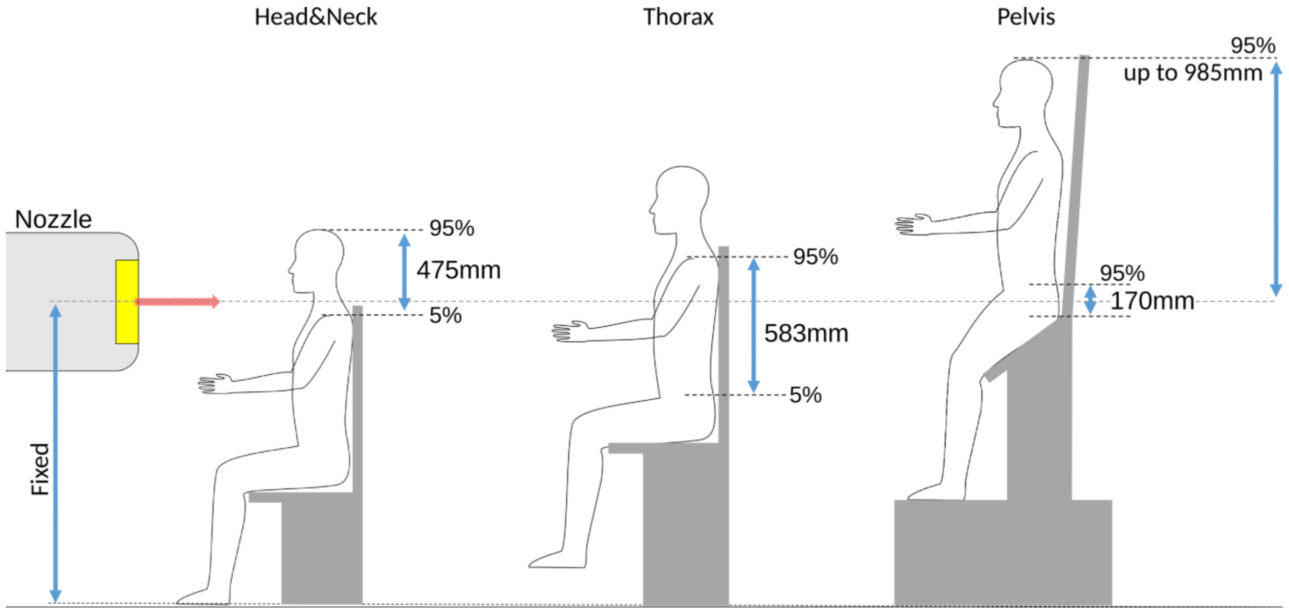
Heavy Ion Facilities

- ➢ 127 Operational.
  - 14 using C-Ions
- ➢ 36 under construction.
  - 5 will be using C-Ions and some He-Ions.
- ➢ 4 In Europe
  - CNAO (Italy)
  - GSI, HIT (Germany)
  - MedAustron (Austria)

\+ ARCHADE (France), SEEIIST (?)







Applications

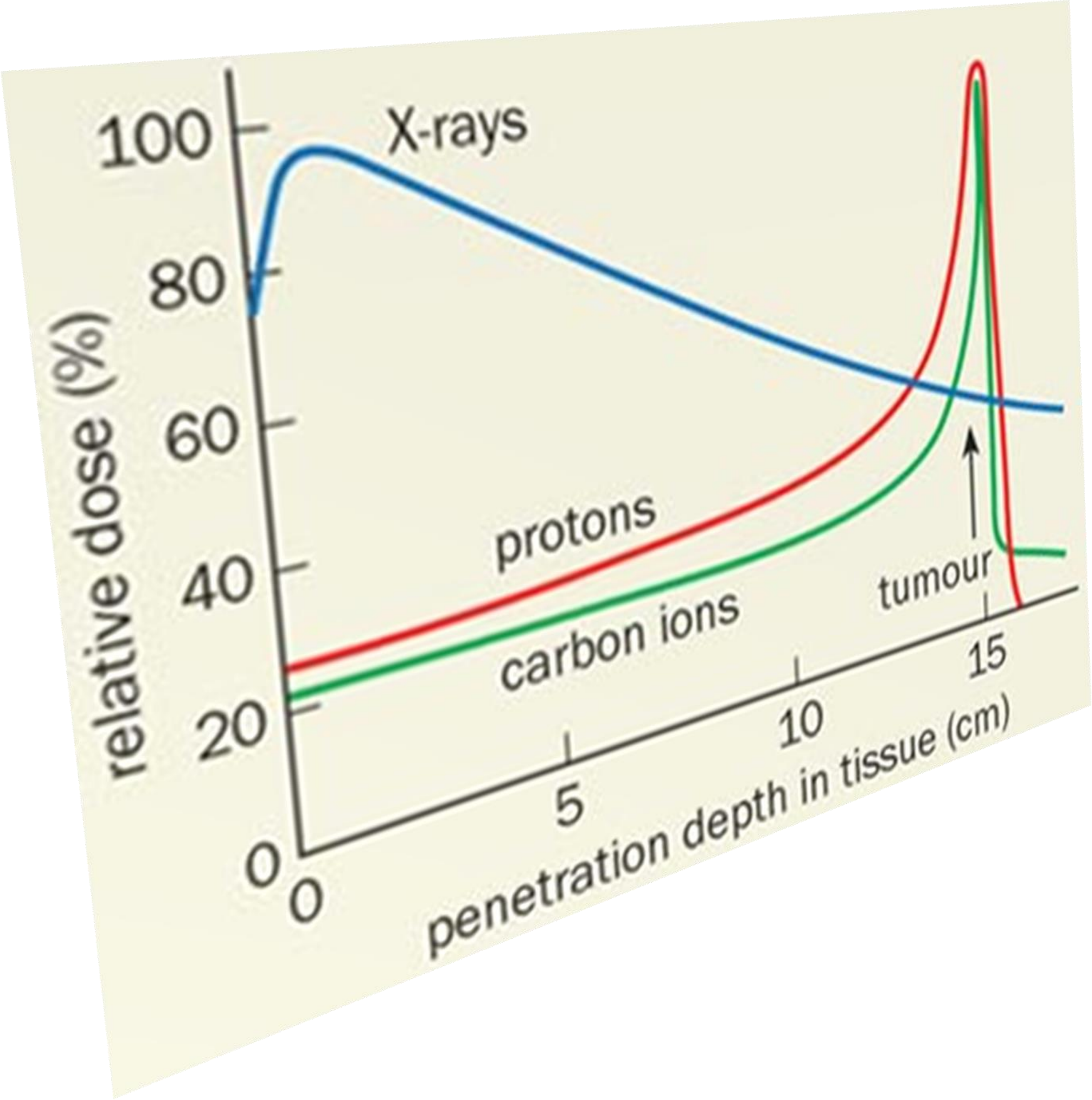
- ***Radiotherapy, Radioisotope Production***
- Nuclear, Particle, Atomic Physics
- Solid State Physics
- Astronomical, Cosmology studies
- Plant breeding

Research

- FLASH therapy
- Sitting position radiotherapy
- He-Ions research
- Heavier Ions

4. Conclusions

The applications and benefits are many and promising, unfortunately until new compact and cost-effective designs come to light its applications in the medical field will be suppressed.



- Better Bragg peak (better dose distribution)
- Less risk for healthy tissue (especially when tumour is close to important organs)

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