The Abdus Salam
International Centre
for Theoretical Physics

2495-04

Joint ICTP-IAEA Workshop on Nuclear Data for Analytical Applications

21 - 25 October 2013

Stopping Power and Range of Ions in Matter

M. Kokkoris
Department of Physics
National Technical University of Athens
Athens
Greece

IAEA TRAINING COURSE

Stopping Power and Range of Ions in Matter

M. Kokkoris

Department of Physics, National Technical University of Athens,
Zografou Campus 157 80, Athens, Greece

Basic physics concepts include:

- **Energy loss of charged particles in matter**
- **Interaction of charged particles with target nuclei**

The problem of energy loss

- **How does an energetic charged particle (a point charge) lose energy to the quantized electron plasma of a solid (inelastic energy loss)?**

- **How do you incorporate into this interaction simultaneous distortion of the electron plasma caused by the particle (target polarization)?**

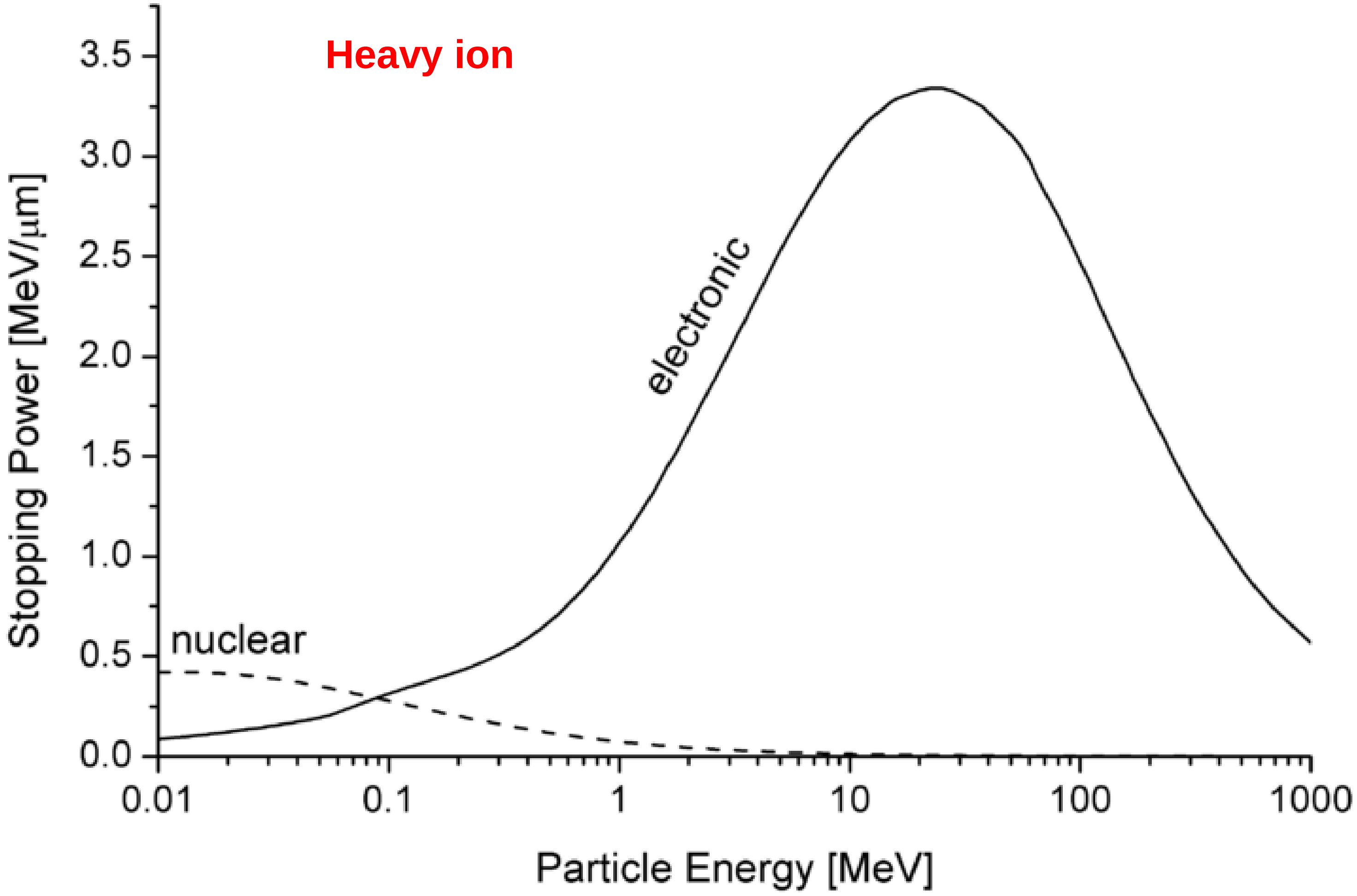
- **How can you extend the point charge-plasma interaction to that for a finite moving atom in a plasma?**

- **How do you estimate the degree of ionization of the moving atom and describe its electrons when it is both ionized and within an electron plasma?**

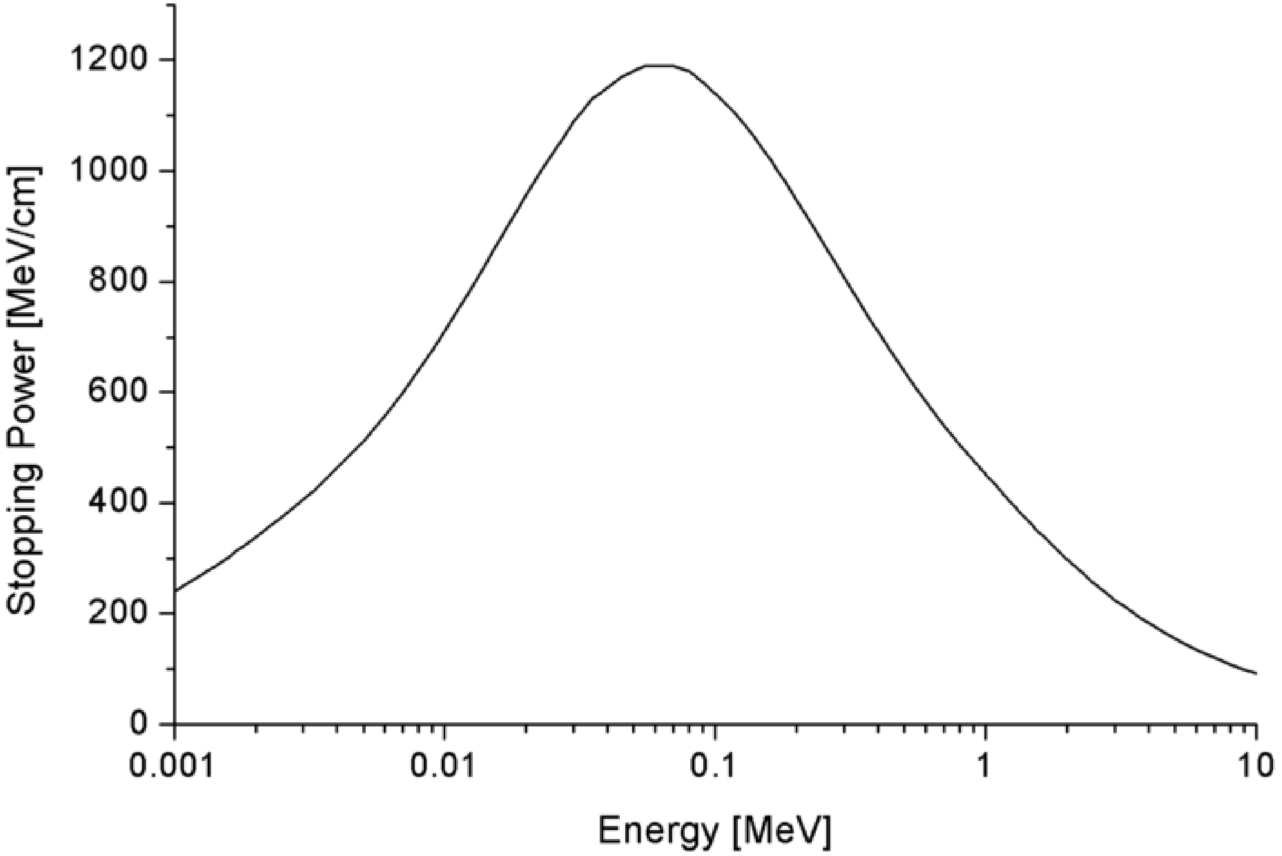
- **How do you calculate the screened Coulomb scattering of the moving atom with each heavy target nucleus it passes?**

- **How do you include relativistic corrections to all of the above?**

Bohr (1915)! ⟶ **(binary collisions and energy transfer to harmonic oscillators)**

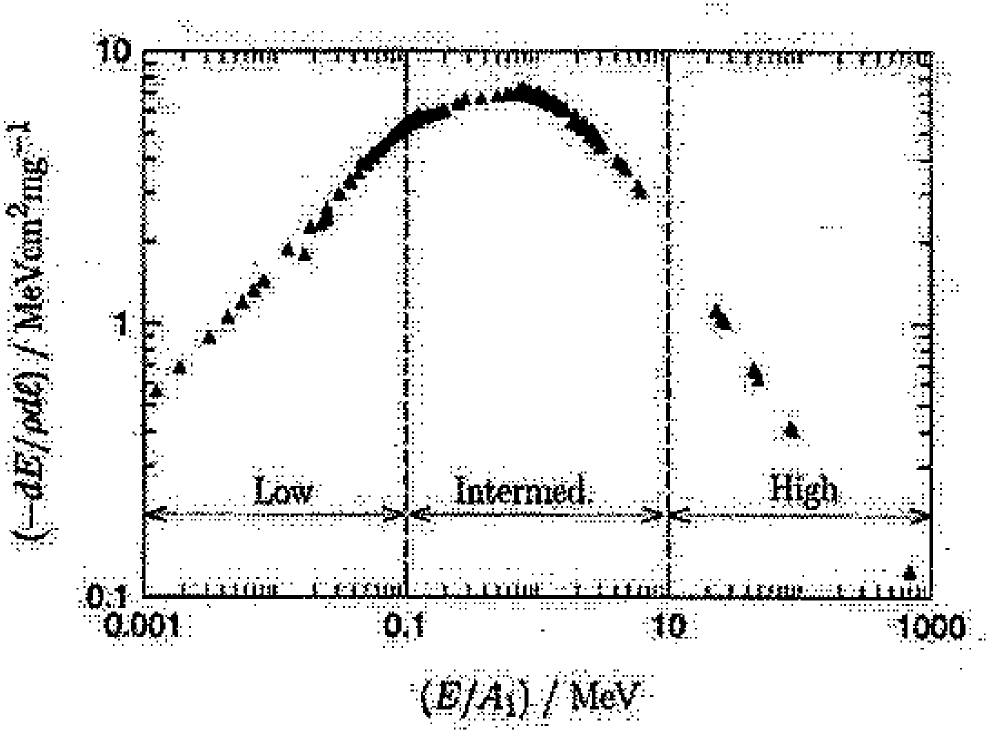

Heavy ion
Stopping Power [MeV/μm]
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
electronic
nuclear
0.01
0.1
1
10
100
1000
Particle Energy [MeV]

Protons in Aluminum



Bethe-Bloch Equation (after 20 years) was based on three assumptions:

1) The ion is fully stripped (> 1 MeV/nucleon)
2) The ion moves faster than the target (orbital) electrons
3) The ion is much heavier than the target electrons

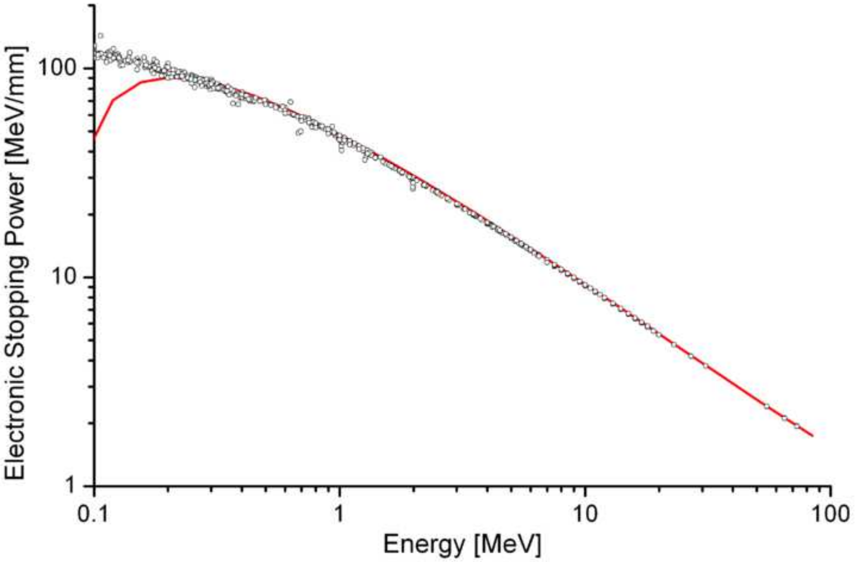


IAEA TRAINING COURSE

The relativistic version of the Bethe-Block formula (1932):

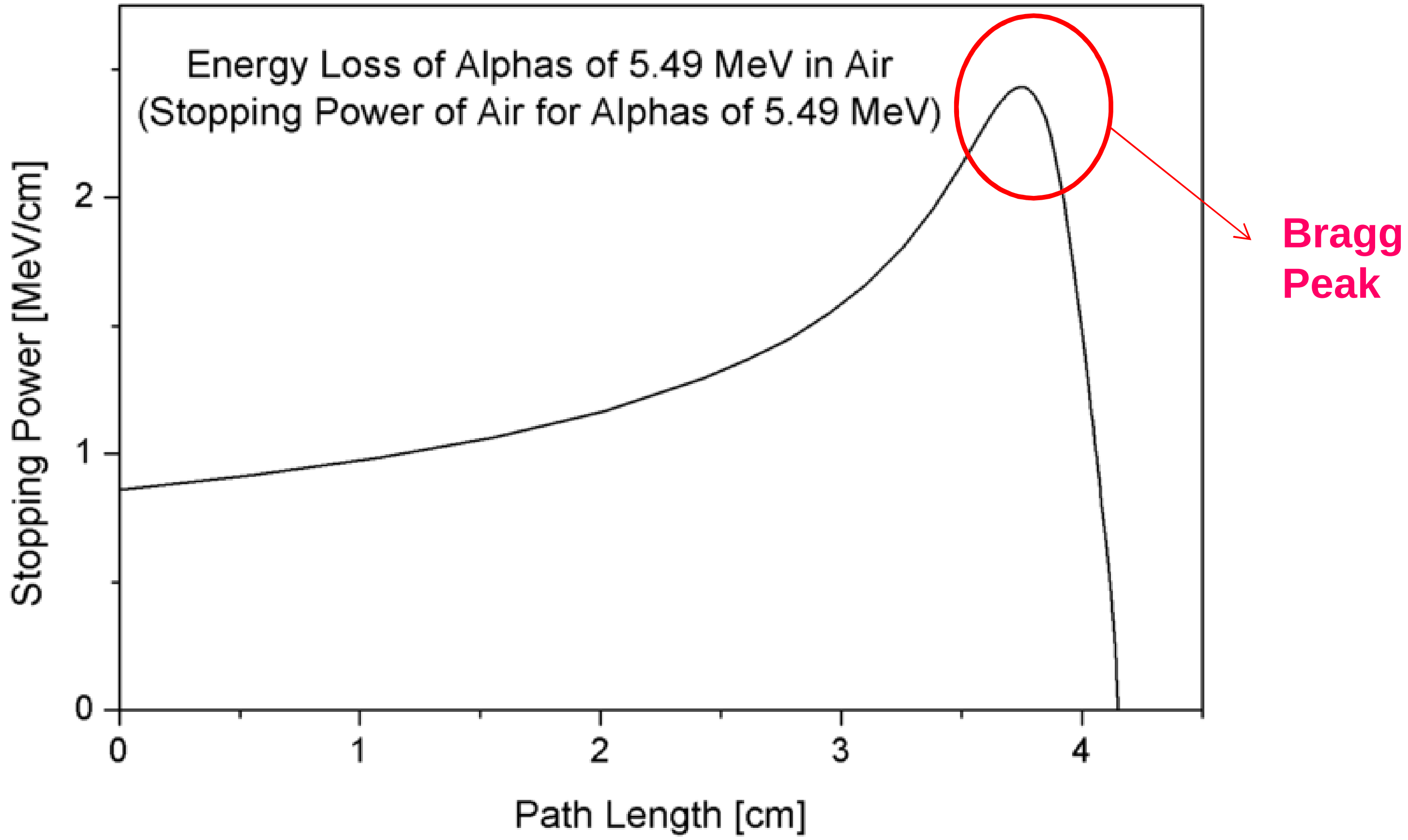
$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e c^2\beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$$

β	**= *v / c***
v	**velocity of the particle**
E	**energy of the particle**
x	**distance travelled by the particle**
c	**speed of light**
ze	**particle charge**
e	**charge of the electron**
m_e	**rest mass of the electron**
n	**electron density of the target**
I	**mean excitation potential of the target**

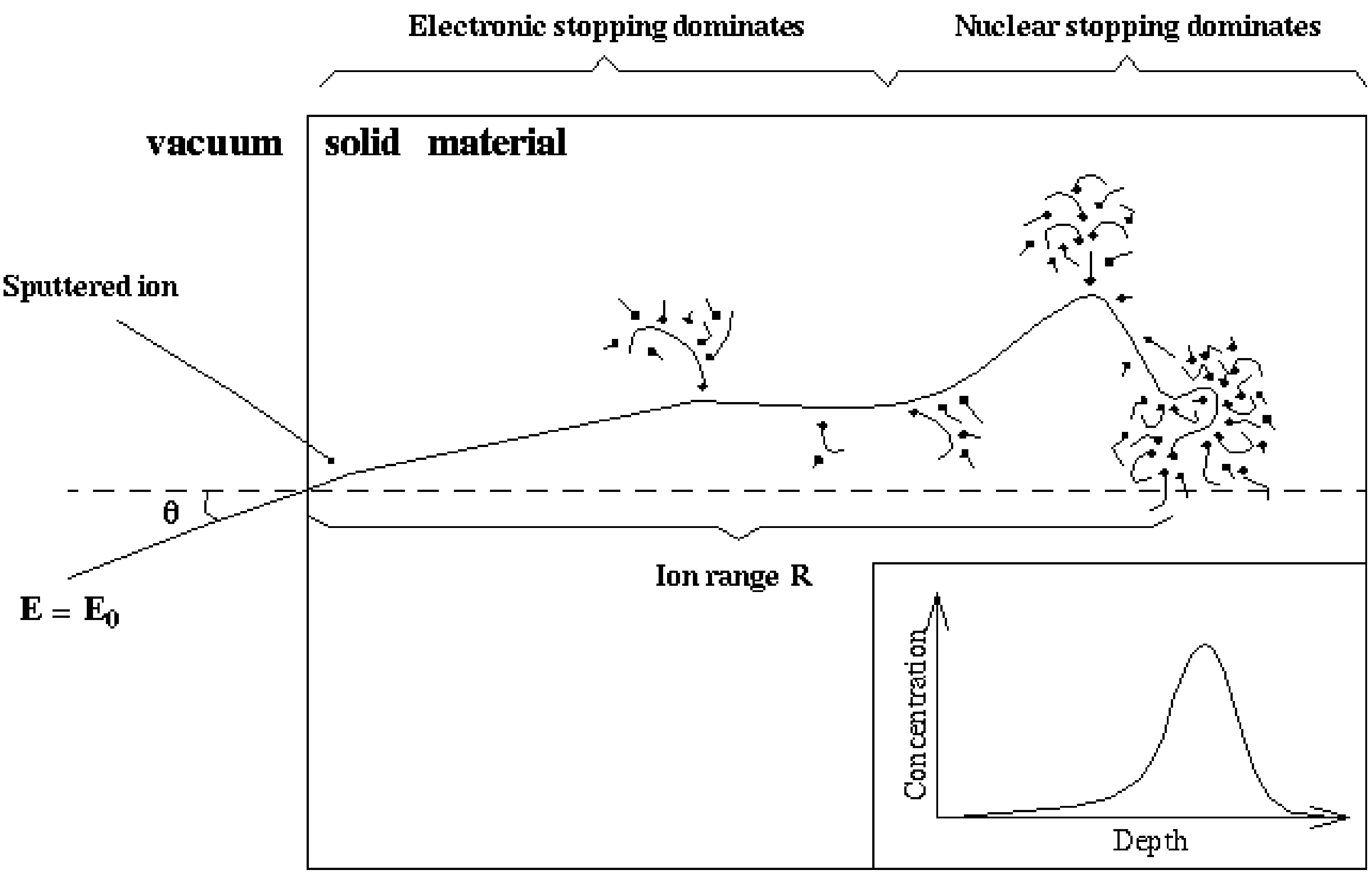


Corrections to the Bethe-Bloch formula:

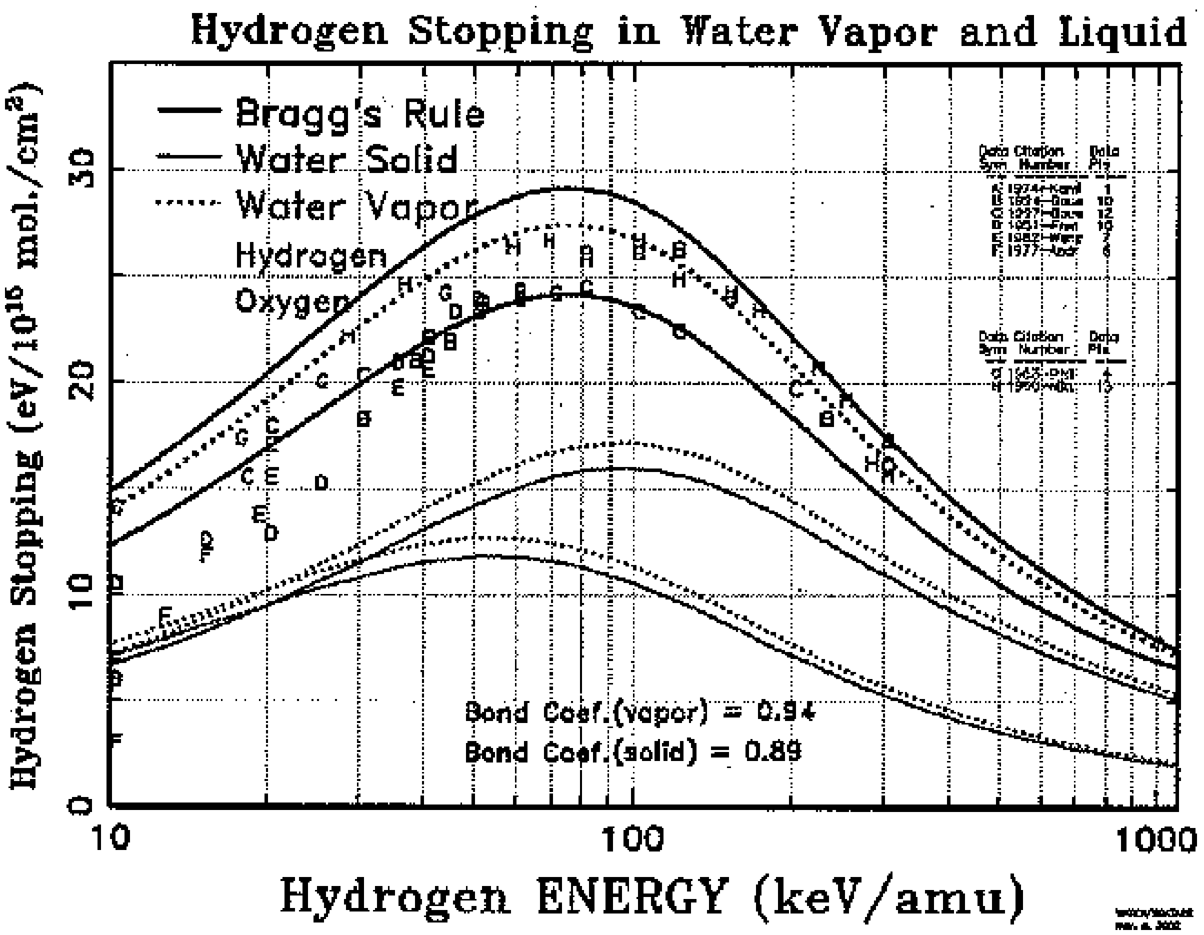
- Difference between positive and negative ions, equally charged, with the same energy and velocity, in the same medium (Barkas effect)
- Difference in the Z2 dependence of the stopping power (e.g. 1 MeV protons vs. 4 MeV α=particles
- The density effect (3-7% at high energies)
- Gas vs. solid targets: Channeling perturbations
- Shell corrections (6%)

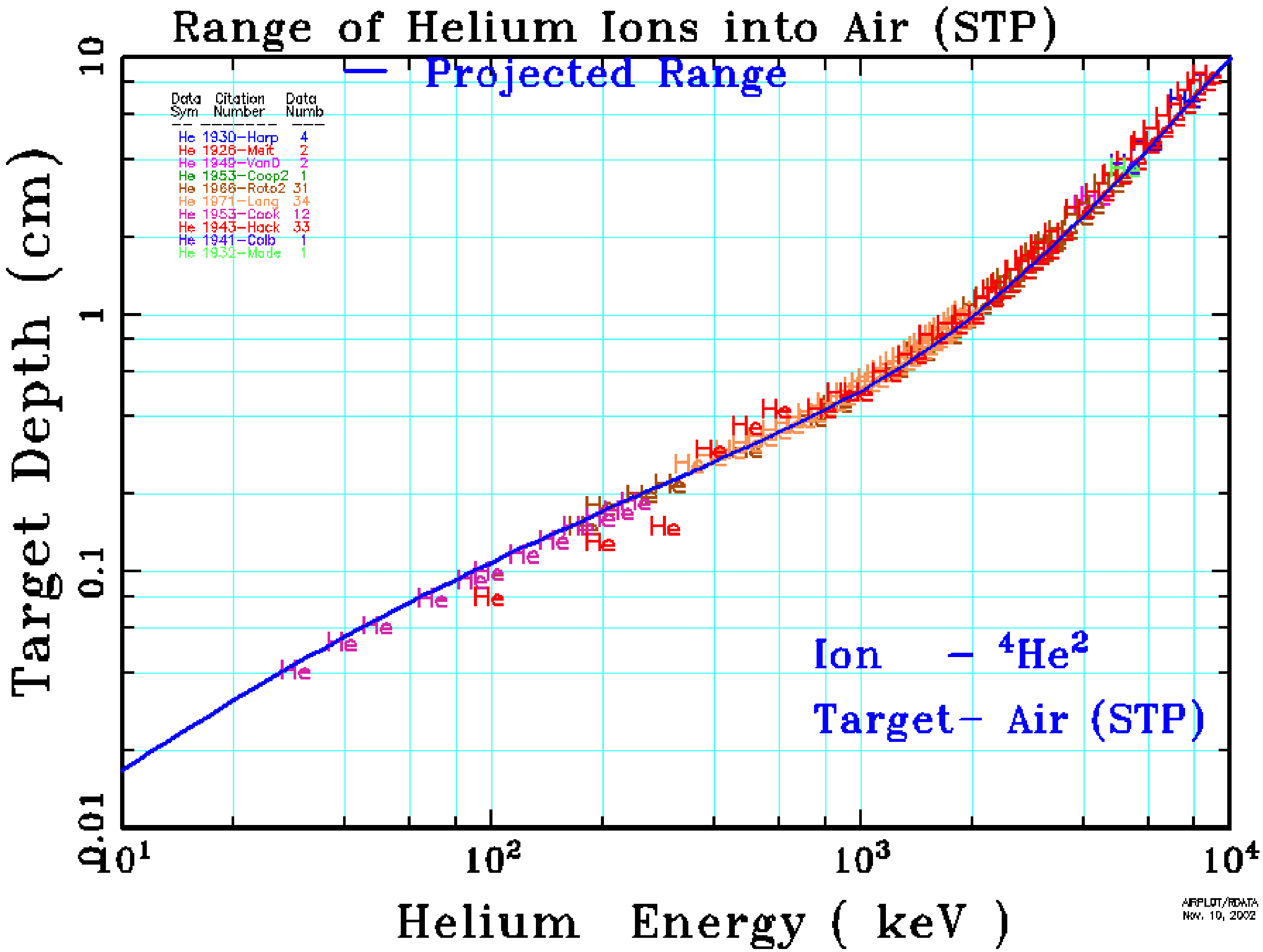

Energy Loss of Alphas of 5.49 MeV in Air
(Stopping Power of Air for Alphas of 5.49 MeV)
Stopping Power [MeV/cm]
0
1
2
0
1
2
3
4
Path Length [cm]
Bragg
Peak

IAEA TRAINING COURSE

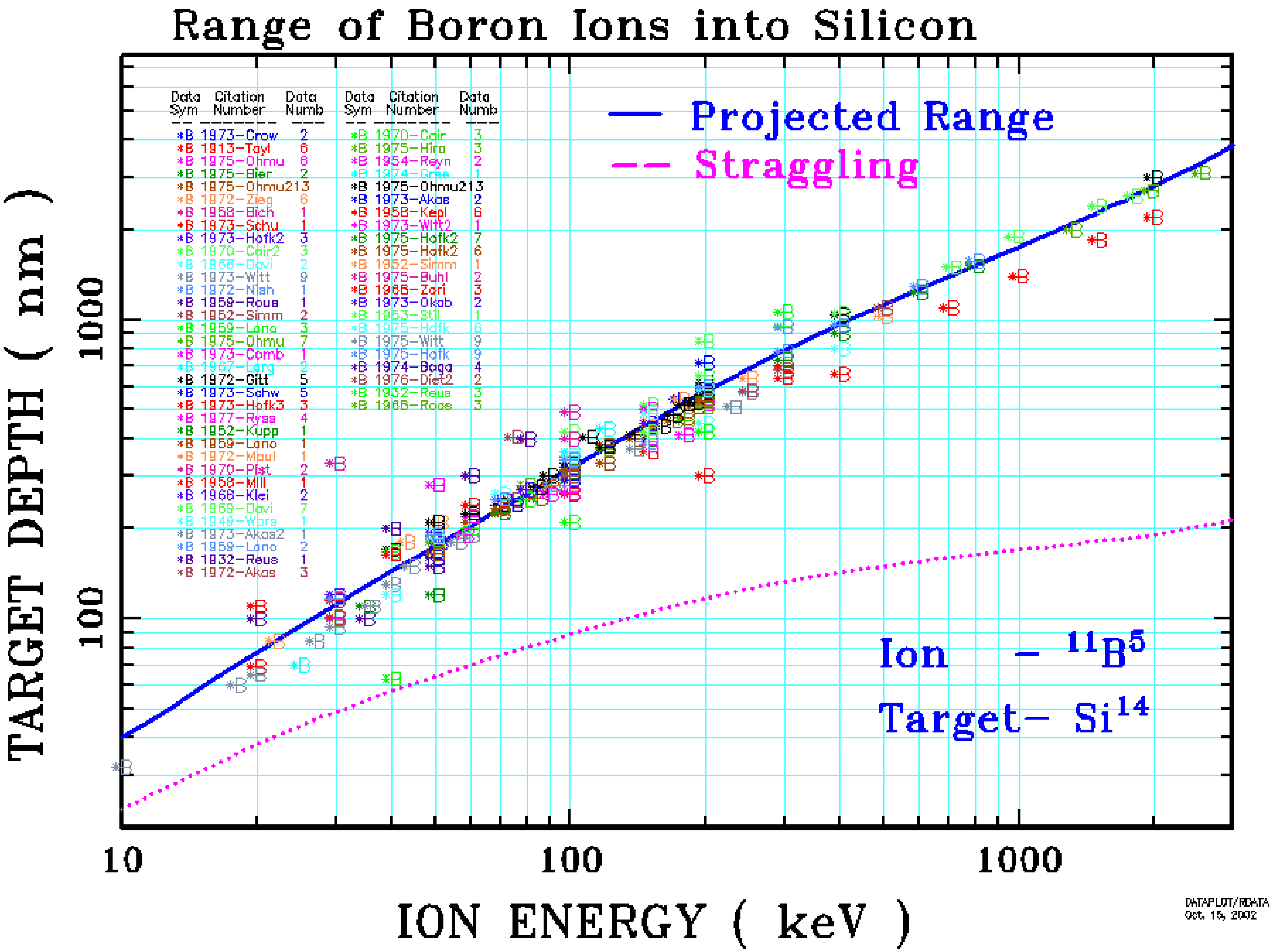


What is happening in the case of compounds?

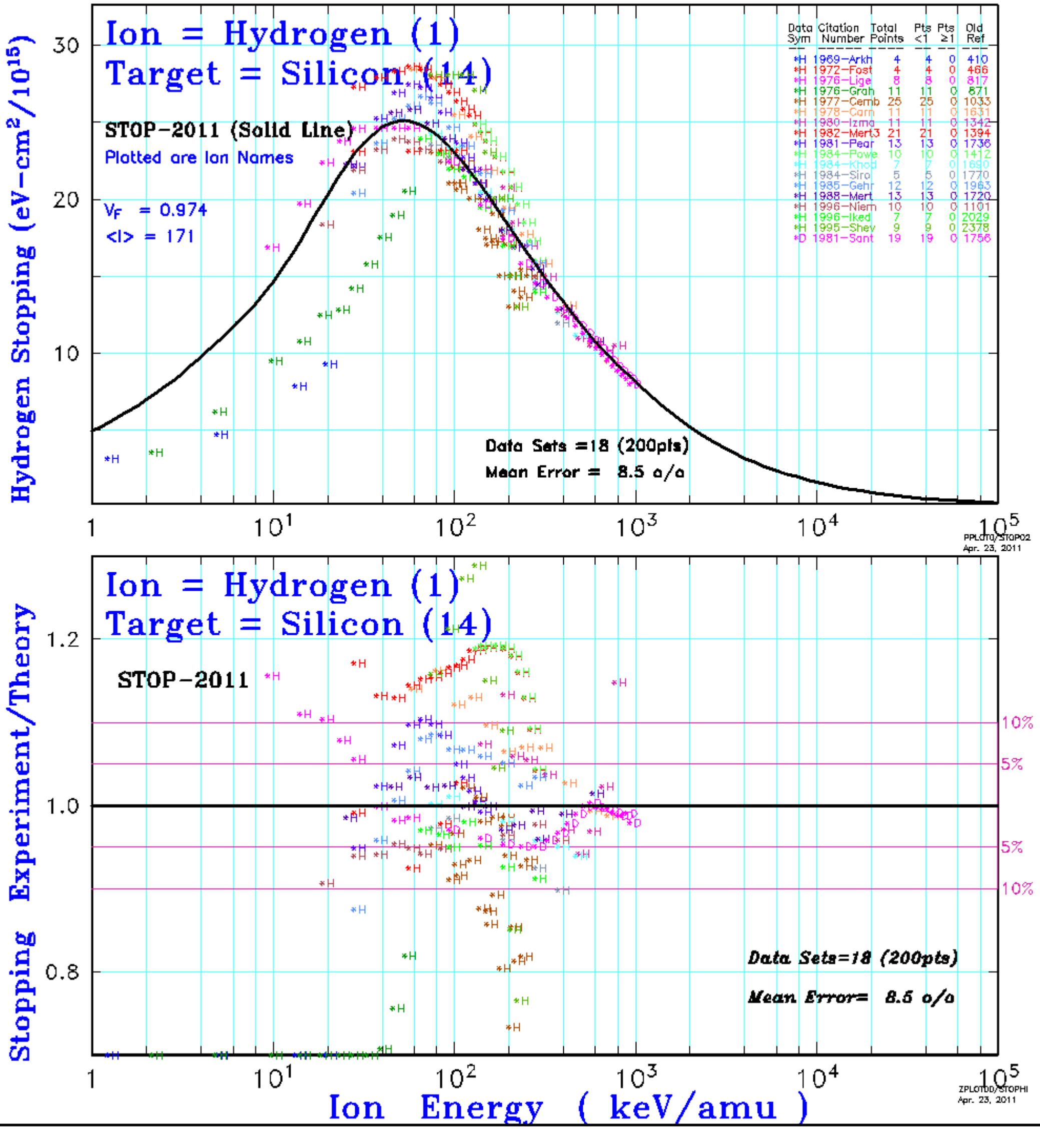



Range of Helium Ions into Air (STP)
— Projected Range
Data Sym Citation Number Data Numb
He 1930–Harp 4
He 1926–Mait 2
He 1949–VanD 2
He 1953–Coop2 1
He 1966–Roto2 31
He 1971–Lang 34
He 1953–Cook 12
He 1943–Hack 33
He 1941–Colb 1
He 1932–Mode 1
Ion – ⁴He²
Target– Air (STP)
Target Depth (cm)
10
1
0.1
0.01
10¹
10²
10³
10⁴
Helium Energy (keV)
AIRPLOT/RDATA
Nov. 10, 2002

IAEA TRAINING COURSE



IAEA TRAINING COURSE



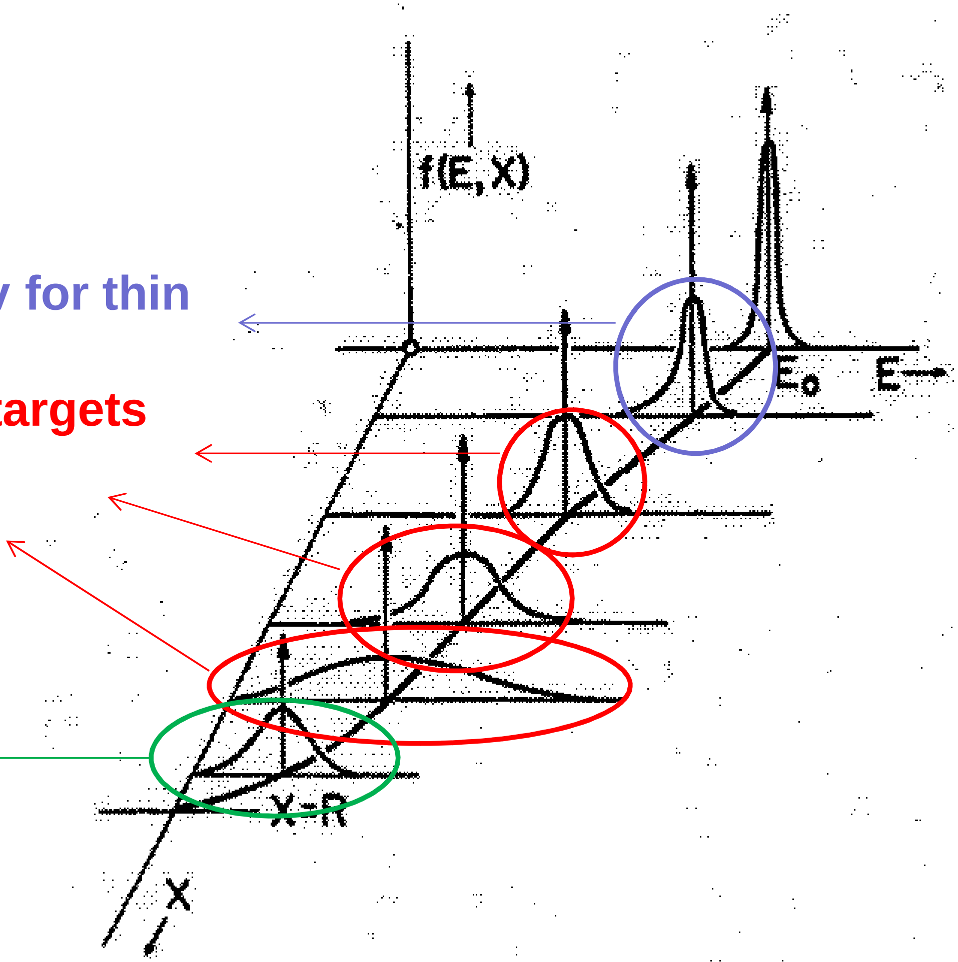
Data Sym	Citation Number	Total Points	Pts <1	Pts ≥1	Old Ref
*H	1969-Arkh	4	4	0	410
*H	1972-Fost	4	4	0	466
*H	1976-Lige	8	8	0	817
*H	1976-Grah	11	11	0	871
*H	1977-Cemb	25	25	0	1033
*H	1978-Carn	11	11	0	1631
*H	1980-Izma	11	11	0	1342
*H	1982-Mert3	21	21	0	1394
*H	1981-Pear	13	13	0	1736
*H	1984-Powe	10	10	0	1412
*H	1984-Khod	7	7	0	1690
*H	1984-Siro	5	5	0	1770
*H	1985-Gehr	12	12	0	1963
*H	1988-Mert	13	13	0	1720
*H	1996-Niem	10	10	0	1101
*H	1996-Iked	7	7	0	2029
*H	1995-Shev	9	9	0	2378
*D	1981-Sant	19	19	0	1756

IAEA TRAINING COURSE

The phenomenon of 'energy straggling'

- Theory of Landau-Vavilov for thin targets (non-Gaussian!)
- Theory of Bohr for thick targets (modified by Chu&Yang)

End of range!



IAEA TRAINING COURSE

A short introduction on the underlying physics:

1. What happens when a MeV-ion interacts with matter?

Conservation of energy and momentum in a head-on elastic collision between a heavy particle of mass M and an electron of mass m yields:

$$\Delta T = T\,(4m/M)$$

For a 5 MeV α-particle → 2.7 keV energy transfer to an electron leading to four conclusions:

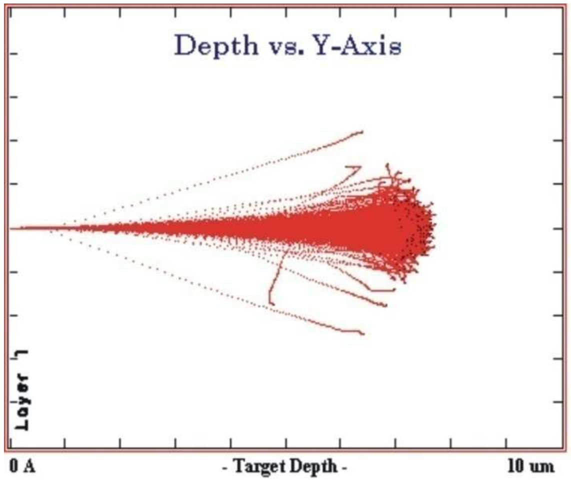
1. It takes many **thousands** of such events before the particle loses all its energy.
2. In a glancing collision the heavy particle is deflected by a **negligible angle**.
3. Since the Coulomb force has infinite range, the particle interacts simultaneously with many electrons and thus **loses energy gradually but continuously along its path**.
4. The energy needed to ionize an atom is ~10 eV. Thus, in the keV range **secondary electrons** are produced.

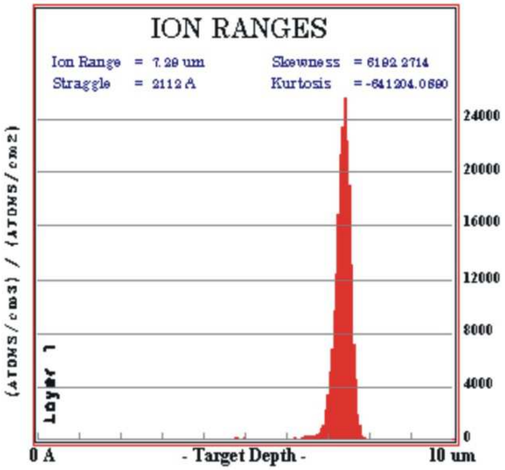
What is happening when the energy falls below the ionization limit???

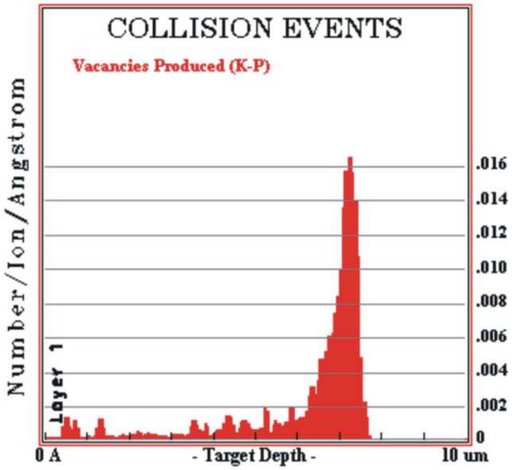
IAEA TRAINING COURSE

A short introduction on the underlying physics:

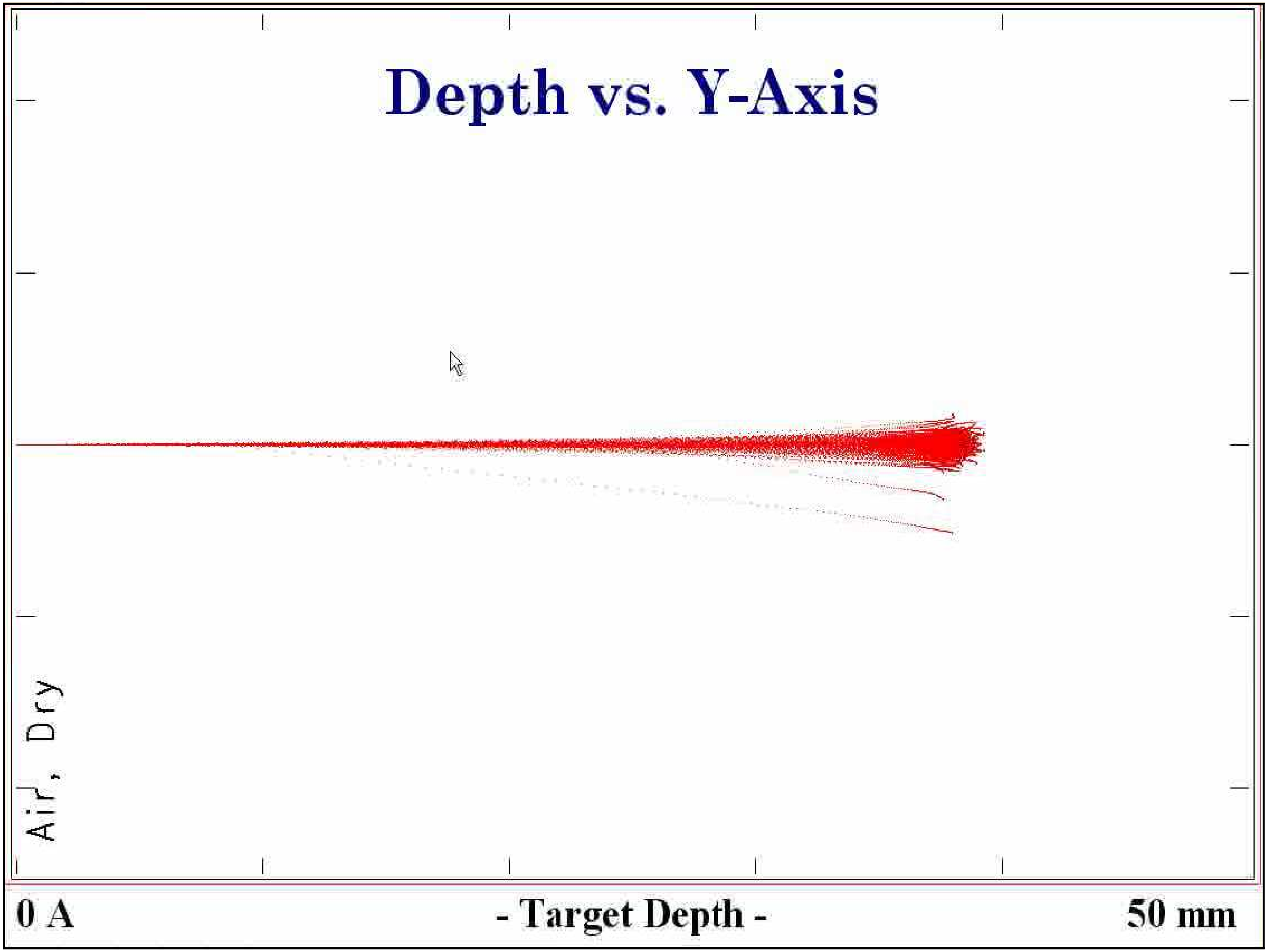
1. What happens when a MeV-ion interacts with matter?







2 MeV α - particles in Silicon at normal incidence, 1000 events:
~99.5 % electronic energy loss (heating)


Depth vs. Y-Axis
Air, Dry
0 A
- Target Depth -
50 mm

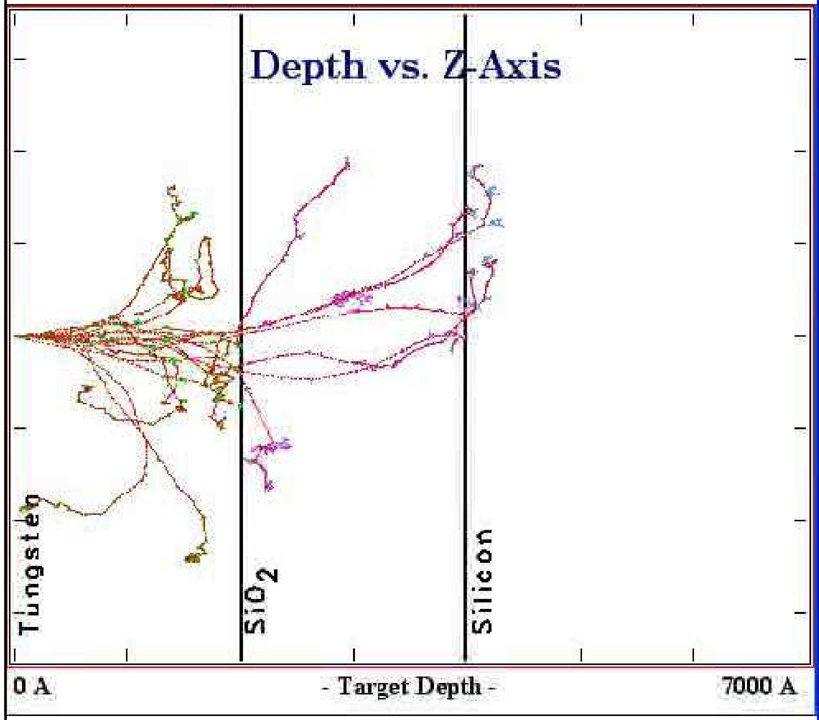
2. What happens when a keV-ion interacts with matter?

1. It starts **capturing electrons** from the medium (its effective charge is reduced).
2. It starts interacting with **nuclei** (or whole atom) rather than with individual electrons.
3. The energy loss is predominantly **'nuclear'** (but excluding any type of nuclear reactions).
4. The trajectory is highly anomalous with **large angle scattering** prevailing (i,e, multiple scattering effect).
5. The recoil nuclei can cause **cascade** events.
6. The damage in the material is **maximized** near/at the end-of-range.
7. The structure of the induced **defects** is usually quite complicated (Frenkel defects, di-interstitial impurities, defect clusters etc.)

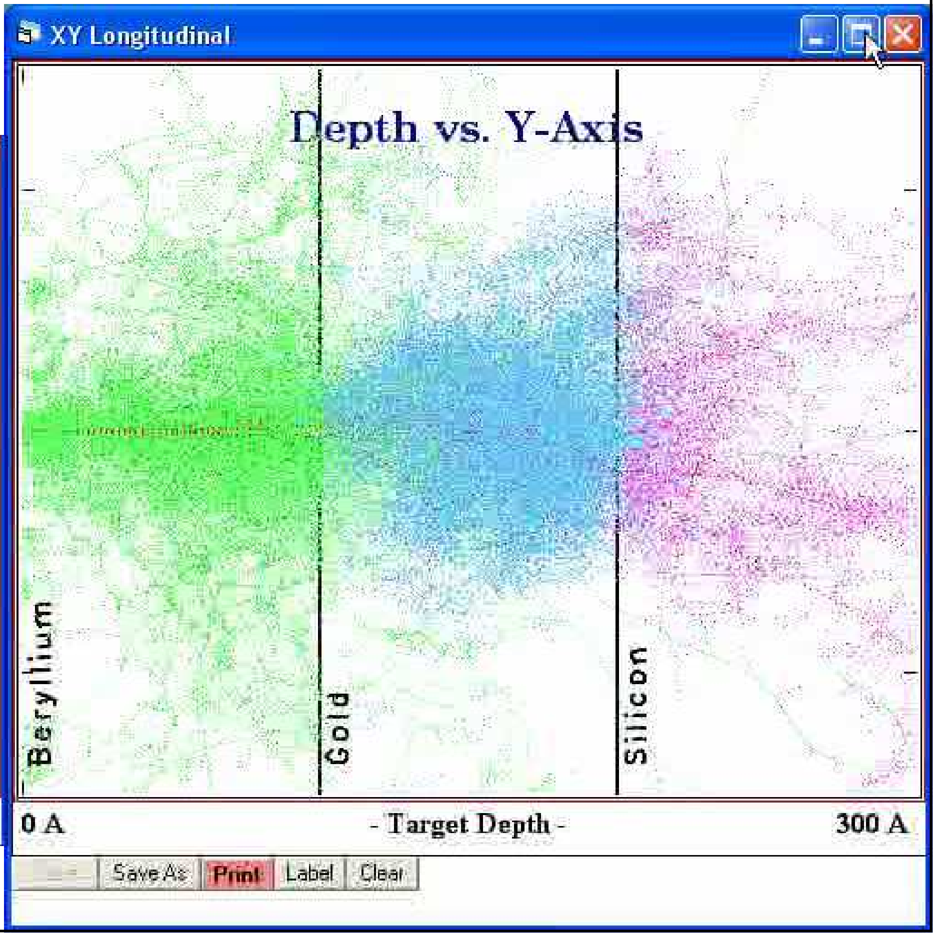
IAEA TRAINING COURSE

2. What happens when a keV-ion interacts with matter?

a) 200 keV B-11 on a thin multilayer structure

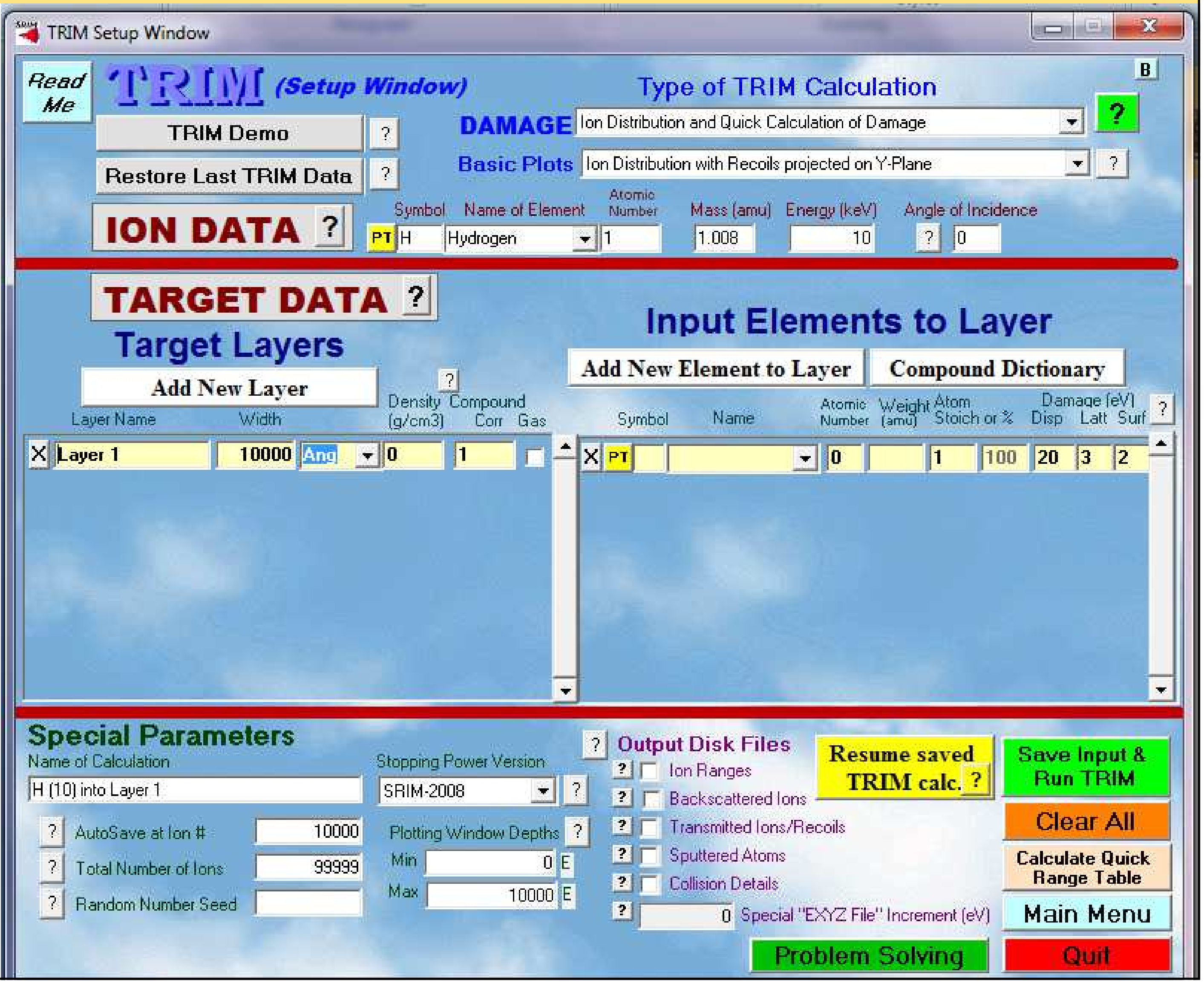


b) 60 keV U-238 on an ultra thin multilayer structure



IAEA TRAINING COURSE

BCA model:
(Binary
Collision
Approximation)
SRIM 2013



Type of TRIM Calculation

DAMAGE: Ion Distribution and Quick Calculation of Damage

Basic Plots: Ion Distribution with Recoils projected on Y-Plane

Symbol	Name of Element	Atomic Number	Mass (amu)	Energy (keV)	Angle of Incidence
PT H	Hydrogen	1	1.008	10	0

	Layer Name	Width		Density (g/cm3)	Compound Corr	Gas
X	Layer 1	10000	Ang	0	1	☐

	Symbol	Name	Atomic Number	Weight (amu)	Atom Stoich	or %	Damage (eV) Disp	Latt	Surf
X	PT		0		1	100	20	3	2

Name of Calculation: H (10) into Layer 1

Stopping Power Version: SRIM-2008

? AutoSave at Ion #: 10000

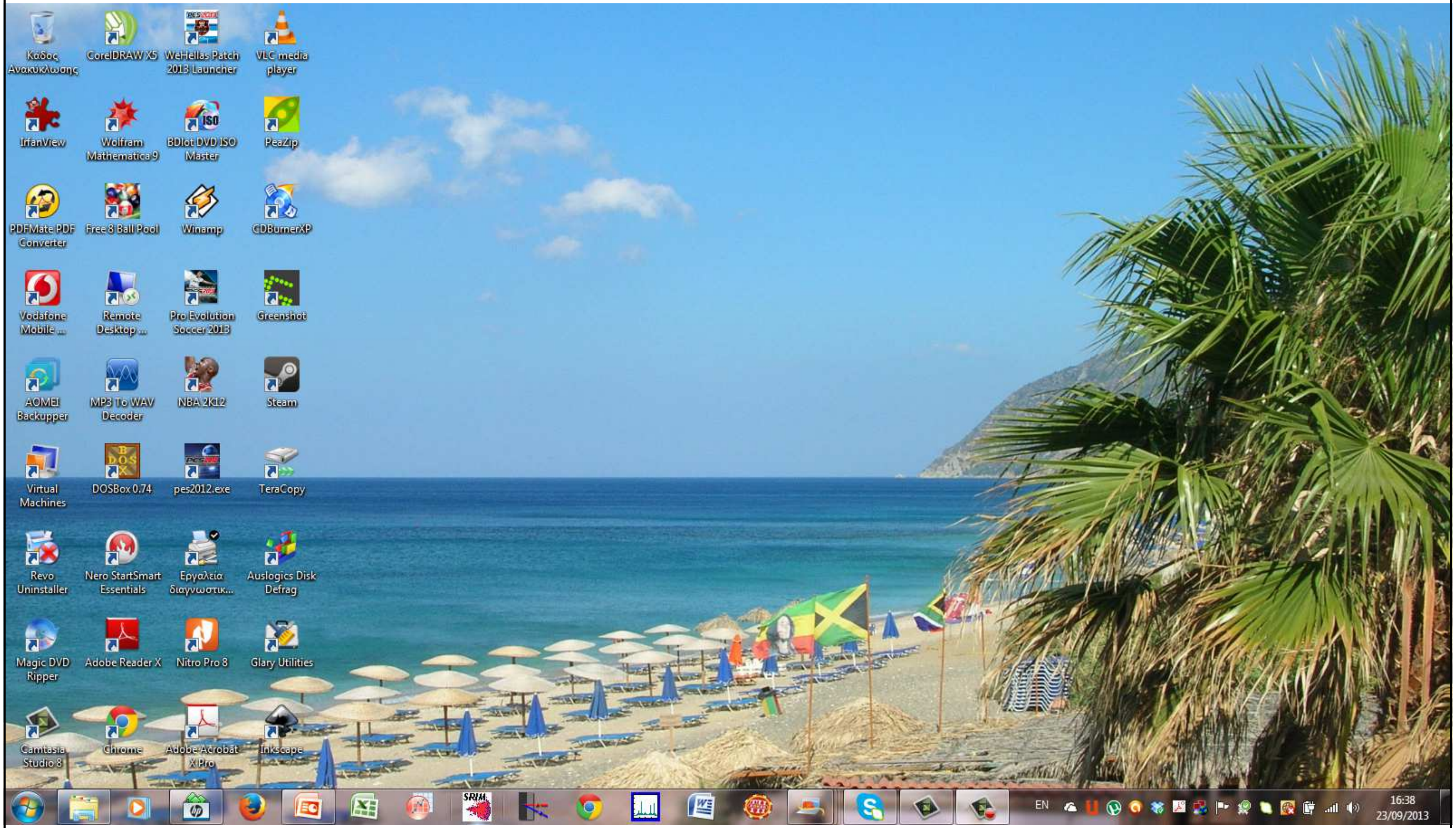
? Total Number of Ions: 99999

? Random Number Seed:

Plotting Window Depths ?
Min: 0 E
Max: 10000 E

? ☐ Ion Ranges
? ☐ Backscattered Ions
? ☐ Transmitted Ions/Recoils
? ☐ Sputtered Atoms
? ☐ Collision Details
? 0 Special "EXYZ File" Increment (eV)

IAEA TRAINING COURSE



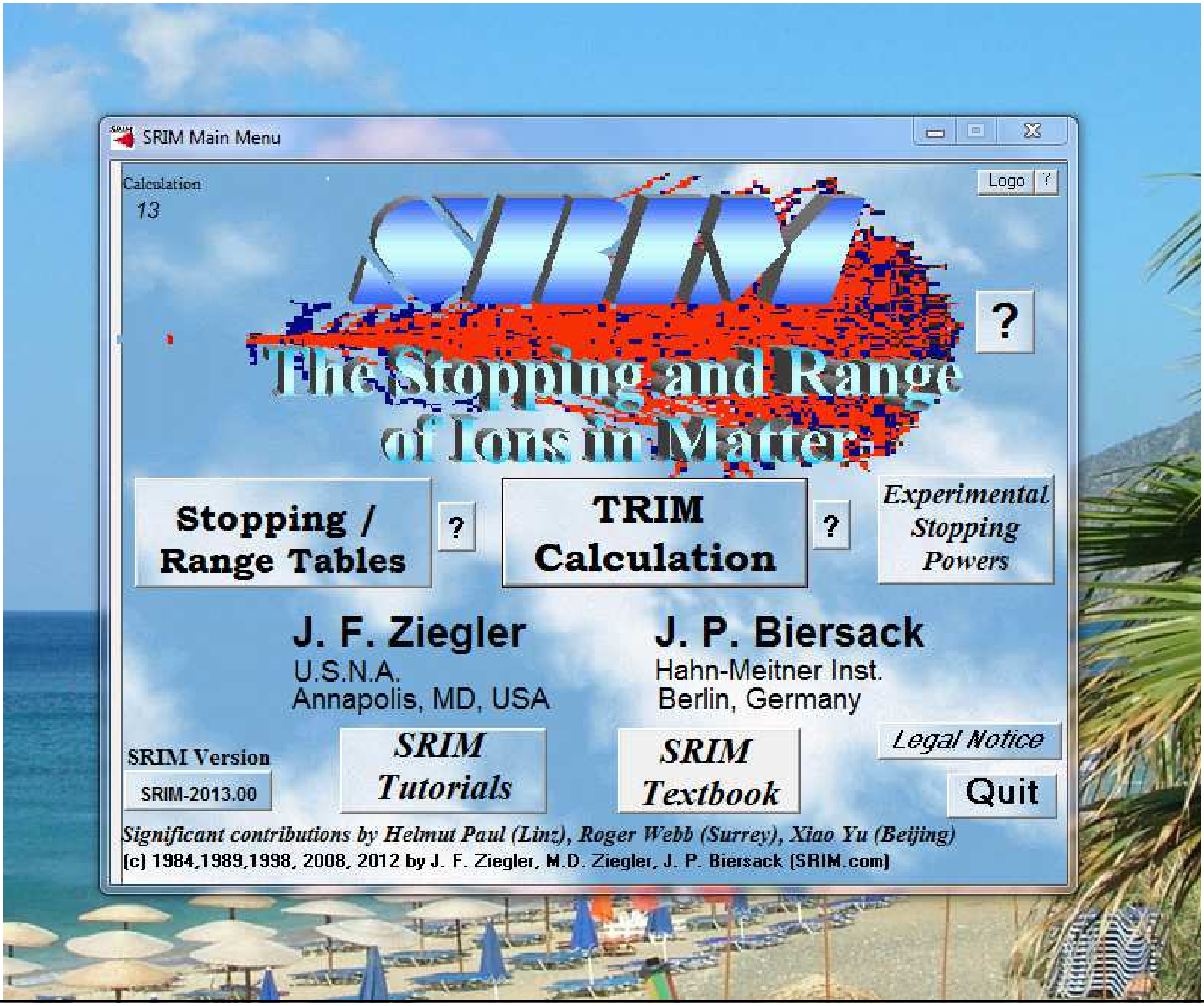
J. F. Ziegler
U.S.N.A.
Annapolis, MD, USA

J. P. Biersack
Hahn-Meitner Inst.
Berlin, Germany

Significant contributions by Helmut Paul (Linz), Roger Webb (Surrey), Xiao Yu (Beijing)

(c) 1984,1989,1998, 2008, 2012 by J. F. Ziegler, M.D. Ziegler, J. P. Biersack (SRIM.com)

SRIM DEMO SIMULATIONS: 1. Low-energy Au ions in Pb



J. F. Ziegler
U.S.N.A.
Annapolis, MD, USA

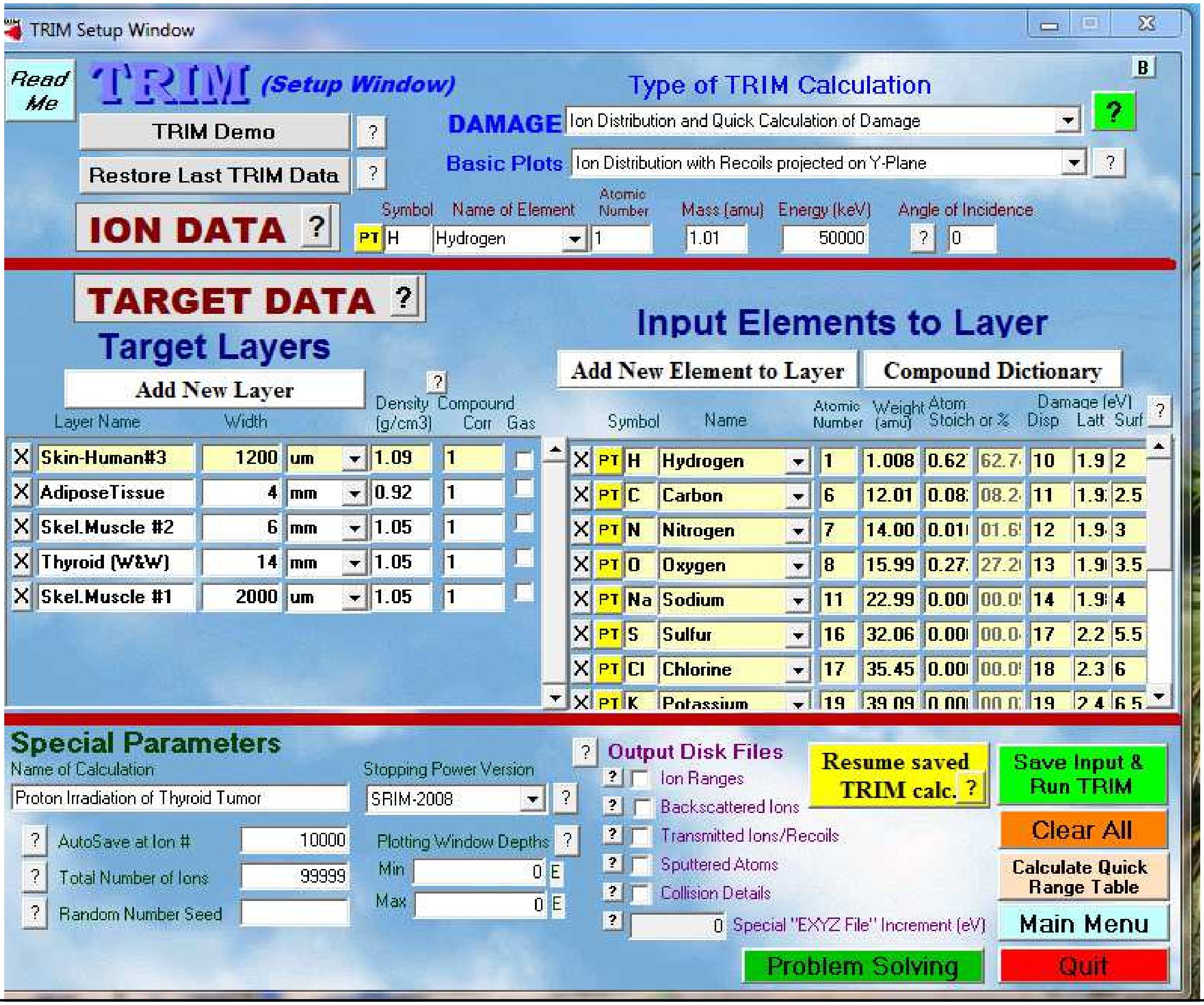
J. P. Biersack
Hahn-Meitner Inst.
Berlin, Germany

Significant contributions by Helmut Paul (Linz), Roger Webb (Surrey), Xiao Yu (Beijing)

(c) 1984,1989,1998, 2008, 2012 by J. F. Ziegler, M.D. Ziegler, J. P. Biersack (SRIM.com)

IAEA TRAINING COURSE

SRIM DEMO SIMULATIONS: 2. High-energy protons in human tissue



Type of TRIM Calculation

DAMAGE: Ion Distribution and Quick Calculation of Damage

Basic Plots: Ion Distribution with Recoils projected on Y-Plane

Symbol	Name of Element	Atomic Number	Mass (amu)	Energy (keV)	Angle of Incidence
H	Hydrogen	1	1.01	50000	0

Target Layers

Layer Name	Width		Density (g/cm3)	Compound Corr	Gas
Skin-Human#3	1200	um	1.09	1	☐
AdiposeTissue	4	mm	0.92	1	☐
Skel.Muscle #2	6	mm	1.05	1	☐
Thyroid (W&W)	14	mm	1.05	1	☐
Skel.Muscle #1	2000	um	1.05	1	☐

Input Elements to Layer

Symbol	Name	Atomic Number	Weight (amu)	Atom Stoich	or %	Damage (eV) Disp	Latt	Surf
H	Hydrogen	1	1.008	0.62	62.7	10	1.9	2
C	Carbon	6	12.01	0.08	08.2	11	1.9	2.5
N	Nitrogen	7	14.00	0.01	01.6	12	1.9	3
O	Oxygen	8	15.99	0.27	27.2	13	1.9	3.5
Na	Sodium	11	22.99	0.00	00.0	14	1.9	4
S	Sulfur	16	32.06	0.00	00.0	17	2.2	5.5
Cl	Chlorine	17	35.45	0.00	00.0	18	2.3	6
K	Potassium	19	39.09	0.00	00.0	19	2.4	6.5

Special Parameters

Name of Calculation: Proton Irradiation of Thyroid Tumor

Stopping Power Version: SRIM-2008

AutoSave at Ion #: 10000

Total Number of Ions: 99999

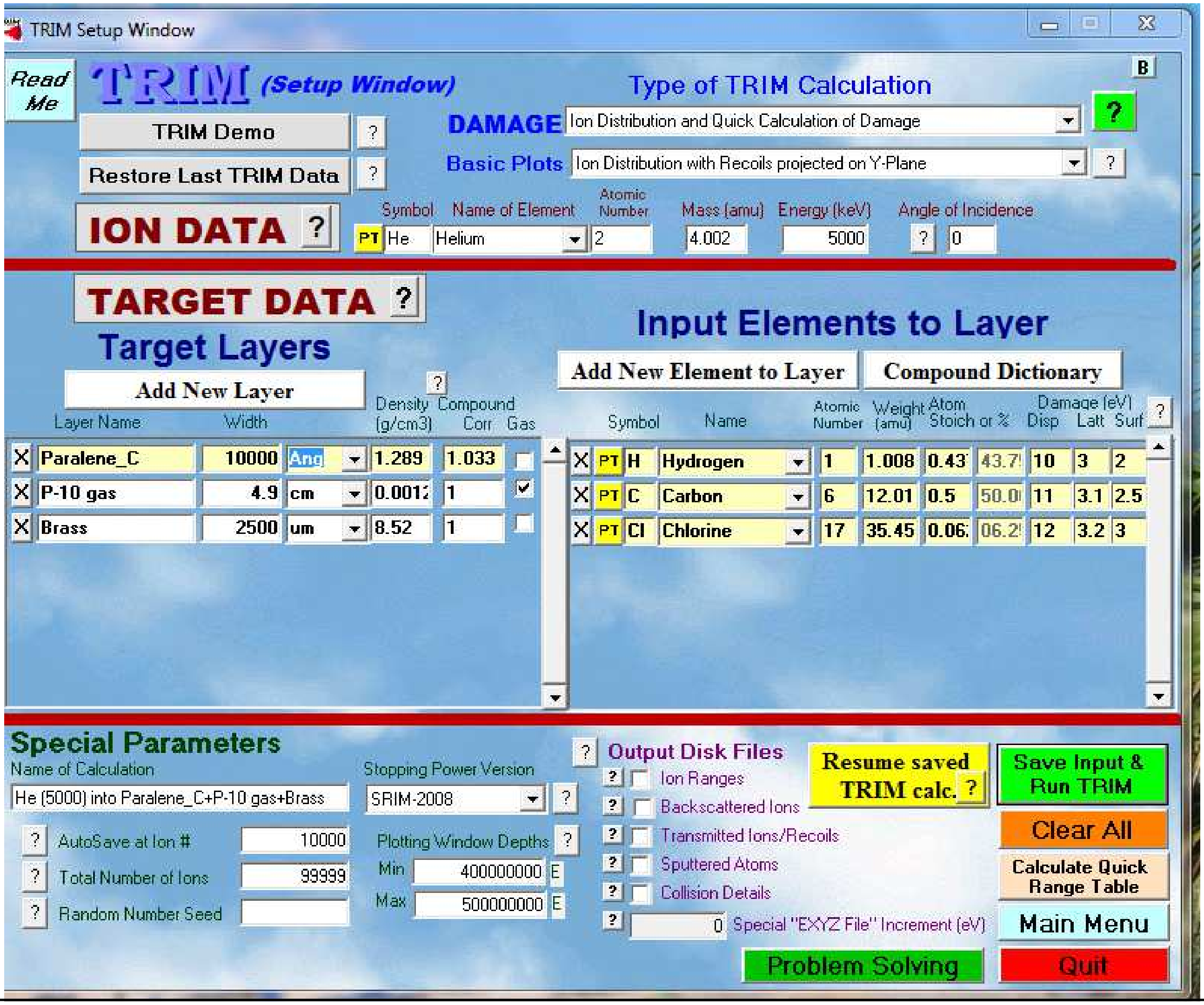
Random Number Seed:

Plotting Window Depths: Min 0 E, Max 0 E

Output Disk Files
- ☐ Ion Ranges
- ☐ Backscattered Ions
- ☐ Transmitted Ions/Recoils
- ☐ Sputtered Atoms
- ☐ Collision Details
- 0 Special "EXYZ File" Increment (eV)

IAEA TRAINING COURSE

SRIM DEMO SIMULATIONS: 3. 5 MeV alpha particles in a gas detector



Type of TRIM Calculation

DAMAGE: Ion Distribution and Quick Calculation of Damage

Basic Plots: Ion Distribution with Recoils projected on Y-Plane

Symbol	Name of Element	Atomic Number	Mass (amu)	Energy (keV)	Angle of Incidence
He	Helium	2	4.002	5000	0

Target Layers

	Layer Name	Width		Density (g/cm3)	Compound Corr	Gas
X	Paralene_C	10000	Ang	1.289	1.033	☐
X	P-10 gas	4.9	cm	0.001	1	☑
X	Brass	2500	um	8.52	1	☐

Input Elements to Layer

		Symbol	Name	Atomic Number	Weight (amu)	Atom Stoich	or %	Damage (eV) Disp	Latt	Surf
X	PT	H	Hydrogen	1	1.008	0.43	43.7	10	3	2
X	PT	C	Carbon	6	12.01	0.5	50.0	11	3.1	2.5
X	PT	Cl	Chlorine	17	35.45	0.06	06.2	12	3.2	3

Special Parameters

Name of Calculation: He (5000) into Paralene_C+P-10 gas+Brass

Stopping Power Version: SRIM-2008

AutoSave at Ion #: 10000

Total Number of Ions: 99999

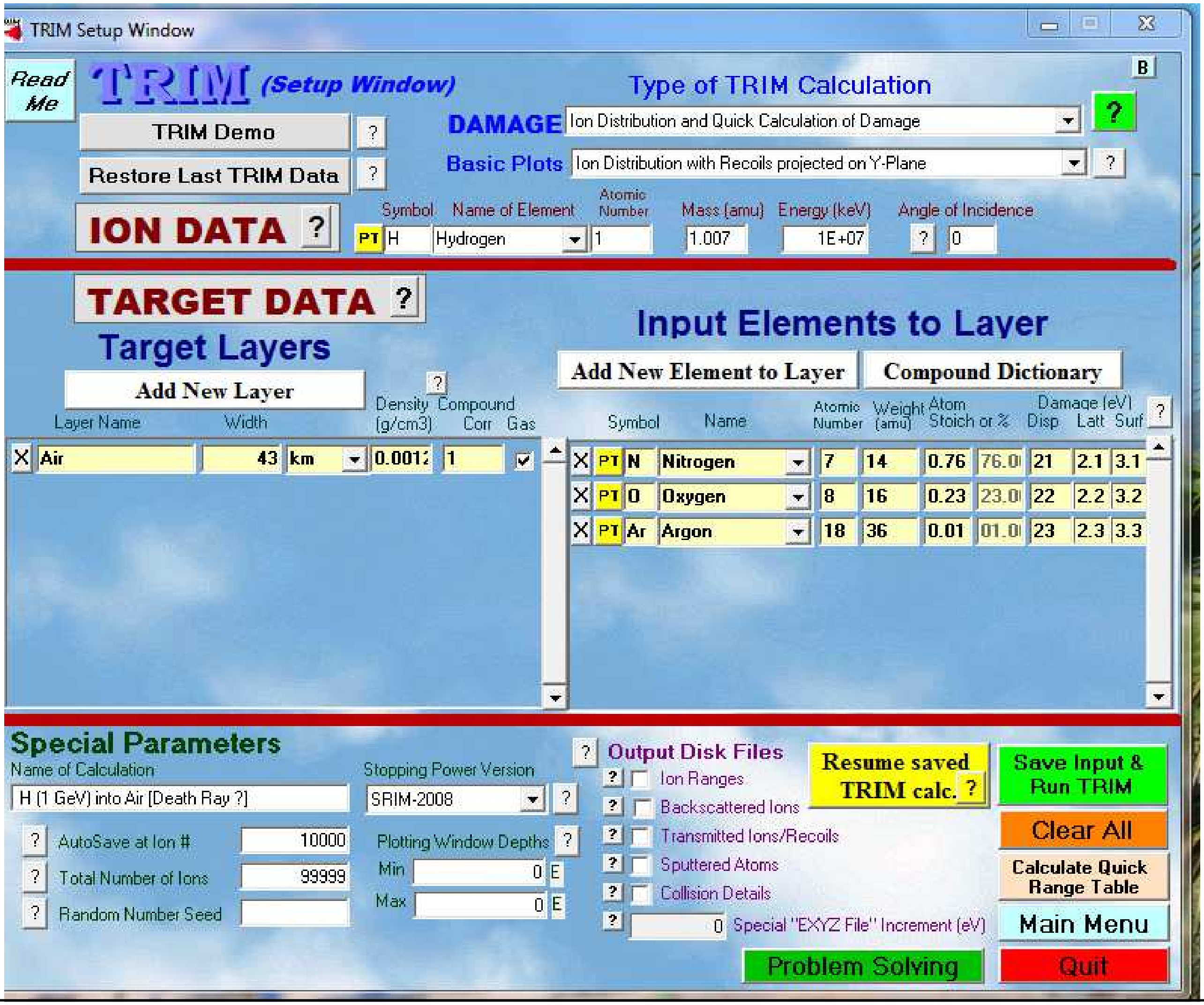
Random Number Seed:

Plotting Window Depths: Min 400000000 E, Max 500000000 E

Output Disk Files
- ☐ Ion Ranges
- ☐ Backscattered Ions
- ☐ Transmitted Ions/Recoils
- ☐ Sputtered Atoms
- ☐ Collision Details

0 Special "EXYZ File" Increment (eV)

SRIM DEMO SIMULATIONS: 4. High-energy cosmic-ray in the atmosphere



Type of TRIM Calculation

DAMAGE: Ion Distribution and Quick Calculation of Damage

Basic Plots: Ion Distribution with Recoils projected on Y-Plane

Symbol	Name of Element	Atomic Number	Mass (amu)	Energy (keV)	Angle of Incidence
H	Hydrogen	1	1.007	1E+07	0

Target Layers

Layer Name	Width		Density (g/cm3)	Compound Corr	Gas
Air	43	km	0.001	1	☑

Input Elements to Layer

Symbol	Name	Atomic Number	Weight (amu)	Atom Stoich or %		Damage (eV) Disp	Latt	Surf
N	Nitrogen	7	14	0.76	76.0	21	2.1	3.1
O	Oxygen	8	16	0.23	23.0	22	2.2	3.2
Ar	Argon	18	36	0.01	01.0	23	2.3	3.3

Special Parameters

Name of Calculation: H (1 GeV) into Air [Death Ray ?]

Stopping Power Version: SRIM-2008

AutoSave at Ion #: 10000

Total Number of Ions: 99999

Random Number Seed:

Plotting Window Depths: Min 0 E, Max 0 E

Output Disk Files

- ☐ Ion Ranges
- ☐ Backscattered Ions
- ☐ Transmitted Ions/Recoils
- ☐ Sputtered Atoms
- ☐ Collision Details
- 0 Special "EXYZ File" Increment (eV)

IAEA TRAINING COURSE

SRIM SIMULATIONS: Comparisons with experimental data

Calculation
15

J. F. Ziegler
U.S.N.A.
Annapolis, MD, USA

J. P. Biersack
Hahn-Meitner Inst.
Berlin, Germany

SRIM Version
SRIM-2013.00

Significant contributions by Helmut Paul (Linz), Roger Webb (Surrey), Xiao Yu (Beijing)

(c) 1984,1989,1998, 2008, 2012 by J. F. Ziegler, M.D. Ziegler, J. P. Biersack (SRIM.com)

PRACTICAL EXERCISES USING SRIM:

1. How thick should a Si SSB detector be (at least), in order to stop and record the full energy of 10 MeV protons?

2. What is the range of α-particles emitted from Po-210 (E=5306 keV) in dry air?

3. A student puts a source of α-particles, typically Po-210 (E=5306 keV) in front of a G-M detector, whose window is made of mica ($KAl_3Si_3O_{12}H_2$, $\rho=2.82$ gr/cm^3). The student discovers that only when the source-detector distance (with dry air in between) is 1.7 cm or less, the detector starts counting. What is the thickness of the thin mica window?