



Istituto Nazionale di Fisica Nucleare  
Laboratori Nazionali di Legnaro

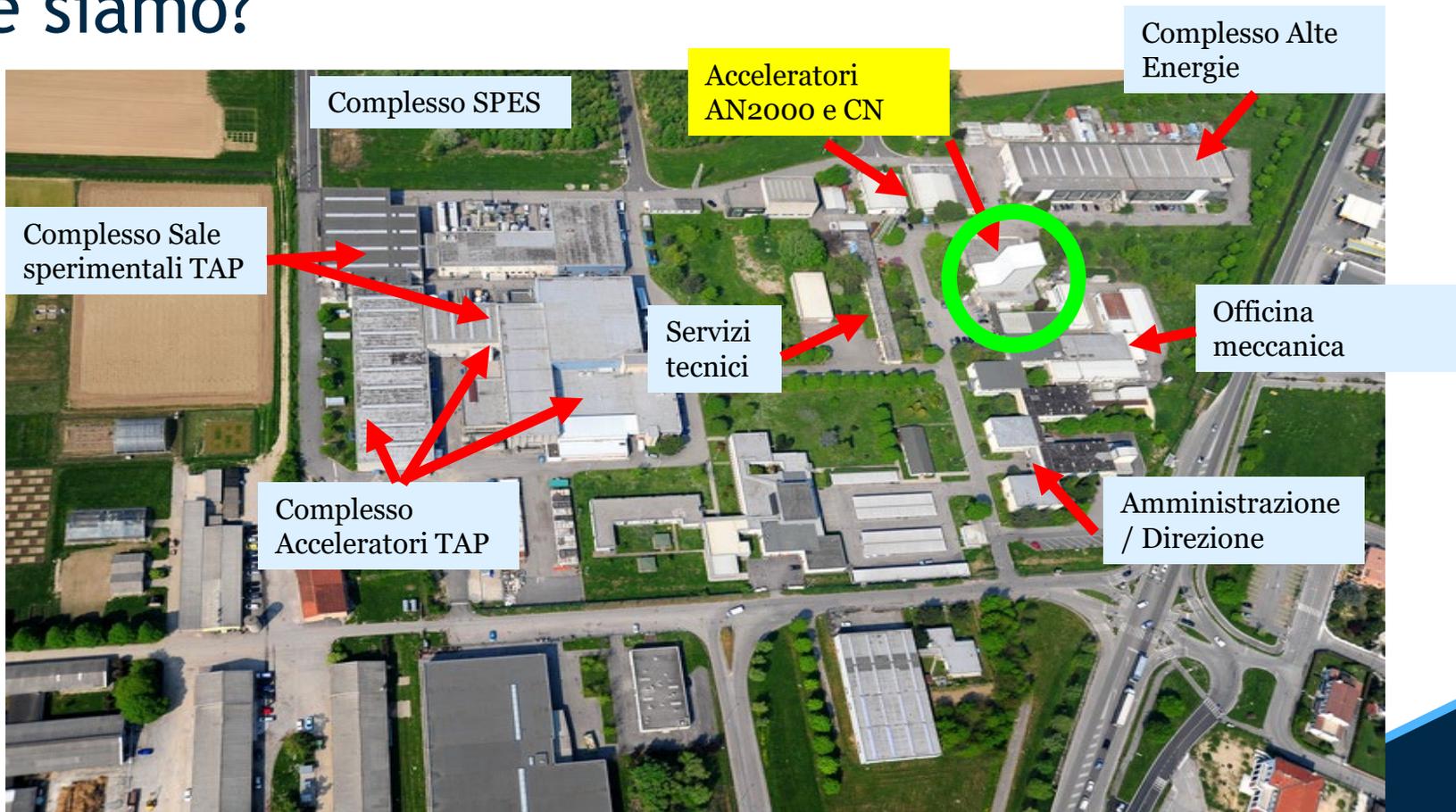
*Programma INFN Docenti 24-25 ottobre 2023*

# **Fisica dei materiali**

Campostrini Matteo, Rigato Valentino,

Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali di Legnaro

# Dove siamo?



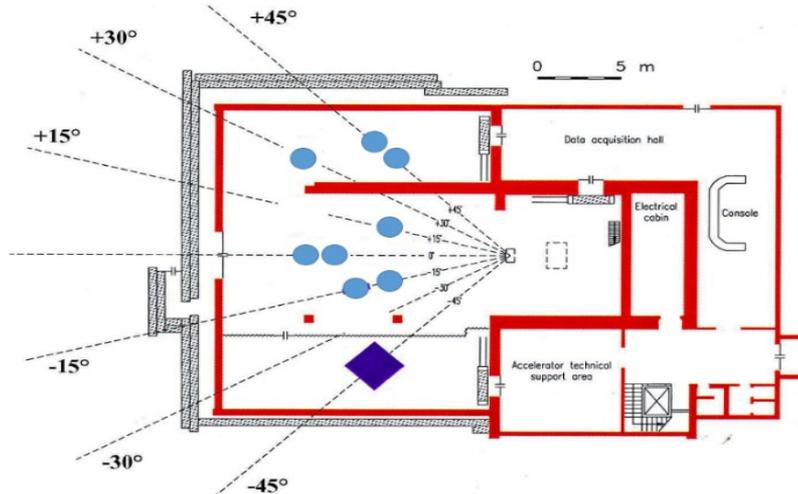
# Dove siamo?

Acceleratore CN: Van De Graaf single end

Energia: 0.8 ÷ 12 MeV

Fasci ionici :  $H^+$ ,  $D^+$ ,  ${}^4He^+$ ,  ${}^4He^{++}$ ,  ${}^3He^{++}$

Beam lines: 7



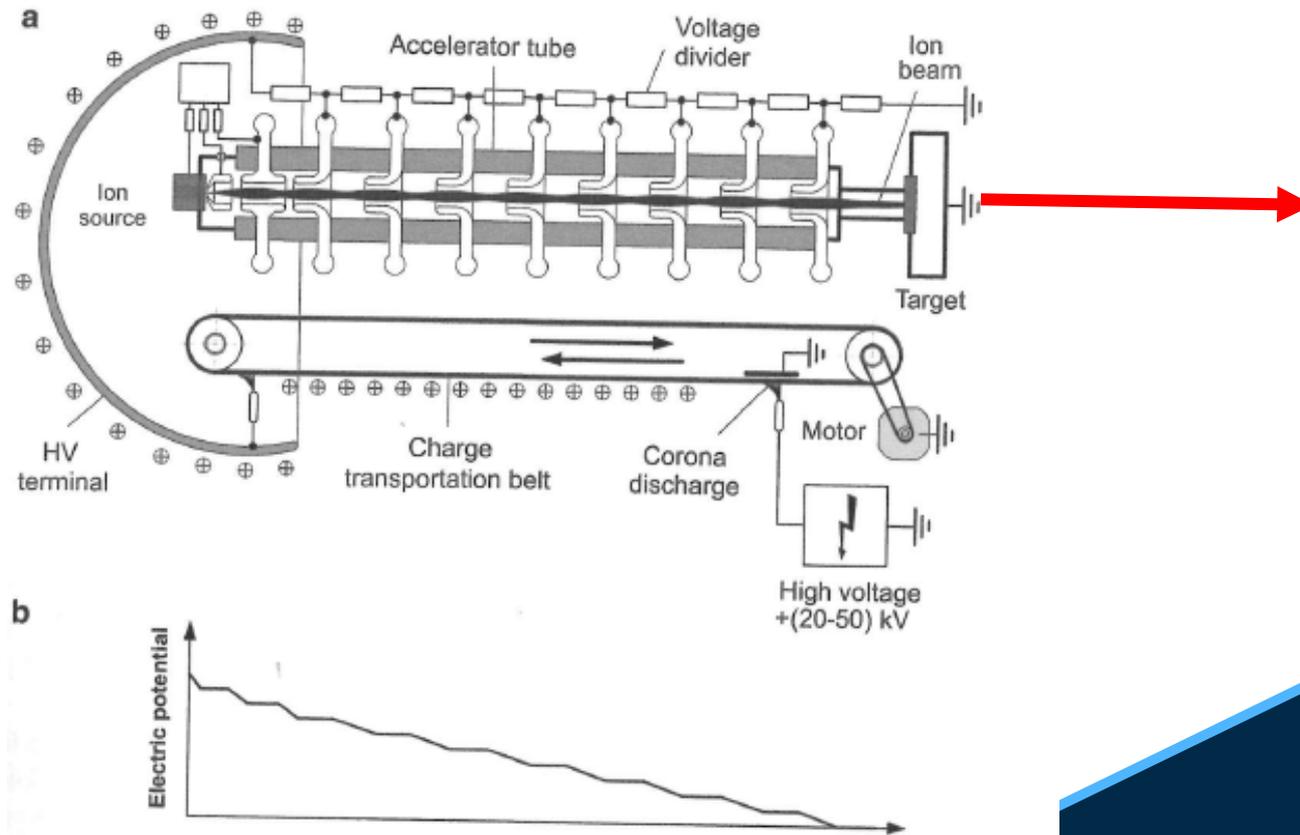
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3.45 Scheme of the Van de Graaff generator (a) and (b) the accelerating potential

# ENERGIA E CAMPI DI APPLICAZIONE DI FASCI IONICI

IONI PESANTI  
Ar, Xe, Kr, Metalli

IONI PESANTI  
C, N - B, P, As...

IONI LEGGERI  
Protoni, He

1eV

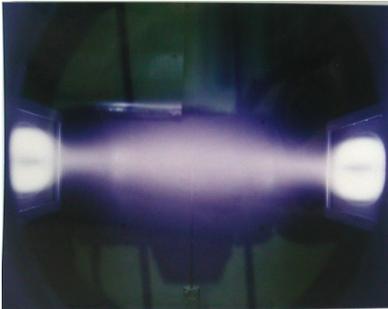
1000eV

1keV

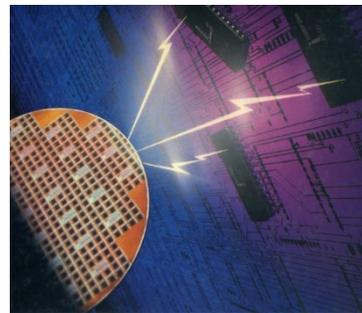
500keV

1MeV

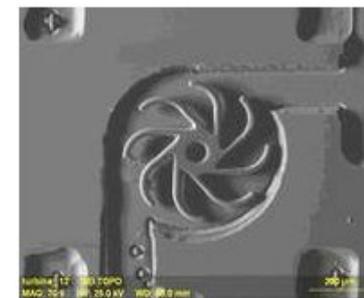
10MeV



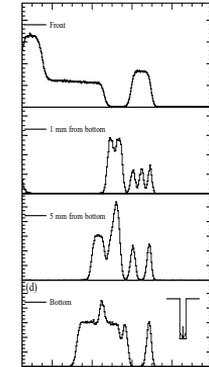
Sintesi di nuovi materiali  
Trattamenti superficiali  
Plasmi a bassa pressione



Impiantazione ionica  
Drogaggio di semiconduttori



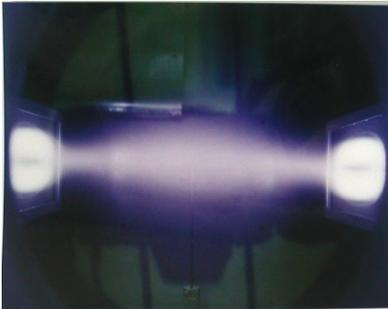
Microanalisi di materiali (RBS, PIXE,  
PIGE, ERD, NRA)  
Microfabbricazione



# ENERGIA E CAMPI DI APPLICAZIONE DI FASCI IONICI

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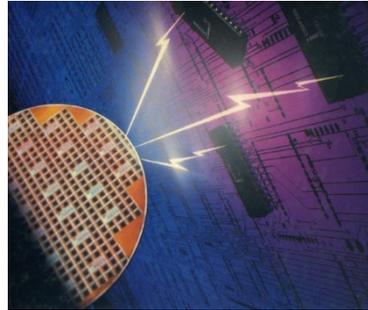
1eV                      1000eV



Sintesi di nuovi materiali  
Trattamenti superficiali  
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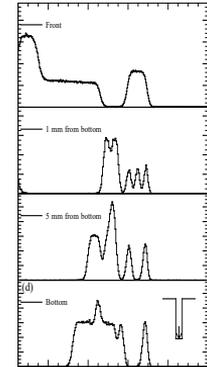
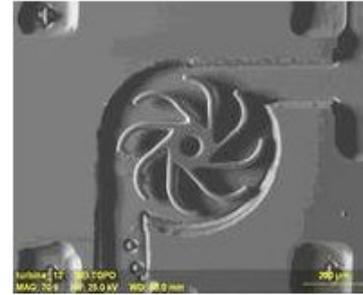
1keV                      500keV



Impiantazione ionica  
Drogaggio di semiconduttori

IONI LEGGERI  
Protoni, He

1MeV                      10MeV



Microanalisi di materiali (RBS, PIXE,  
PIGE, ERD, NRA)  
Microfabbricazione

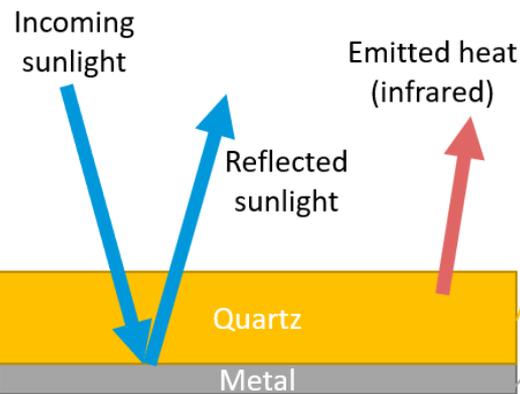
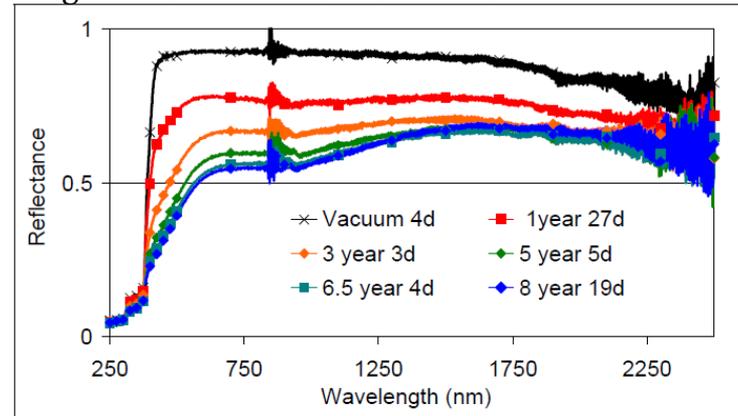
# Attività con fasci ionici al CN

- 1. Irraggiamenti di dispositivi ottici (test accelerati)**
- 2. Irraggiamenti di dispositivi elettronici (SEE e endurance test)**
- 3. Produzione di fasci di neutroni**
  - Esperimenti di fisica nucleare
  - Irraggiamento di dispositivi (microdominria e test su componenti elettronici)
- 4. Sviluppo e caratterizzazione di materiali avanzati**
  - Rivestimenti protettivi e funzionalizzazione superficiali
  - Beni culturali
  - Target per fisica medica
  - Target per fisica nucleare e astrofisica

# Irraggiamenti di dispositivi ottici (test accelerati)



Degradation effect from UV+Proton Irradiation

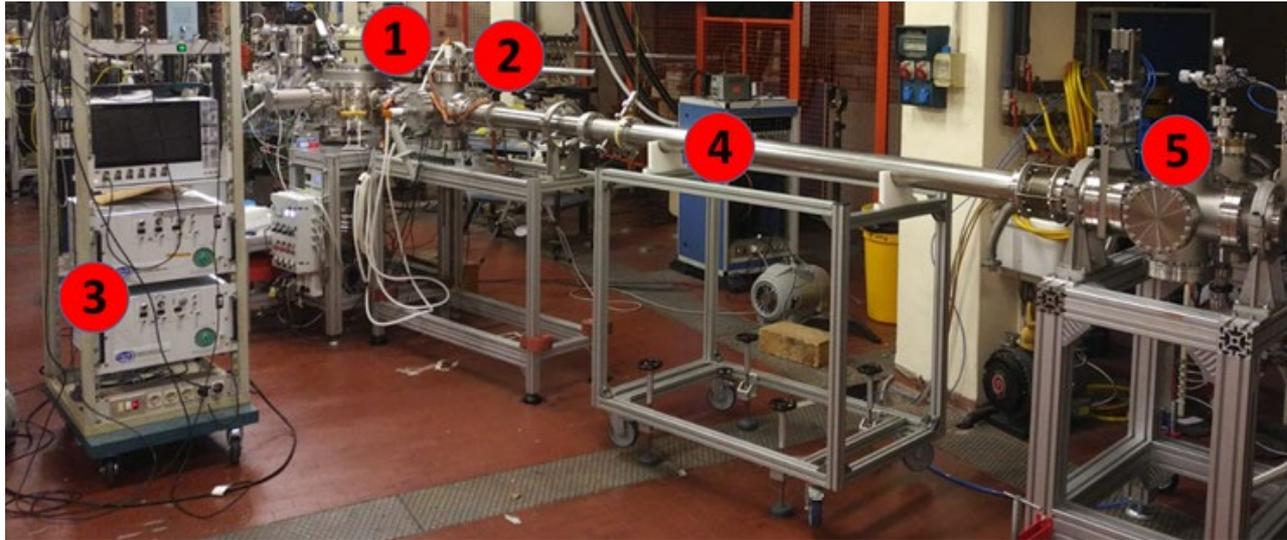


Top layer:  
low absorptivity of  
sunlight (transparent),  
high emissivity of  
infrared radiation.

Back reflector:  
high reflectivity of  
sunlight

Test accelerati su componenti ottici di satelliti geostazionari. Simuliamo l'irraggiamento naturale di flussi di ioni spaziali. L'irraggiamento di qualche ora con fasci ionici corrisponde a 10-15 anni di attività nello spazio

# Irraggiamenti di dispositivi ottici (test accelerati)



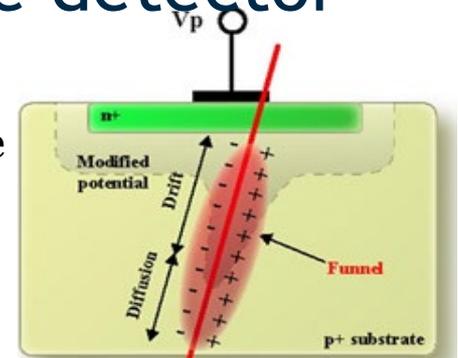
Facility installed at  $-15^\circ$  CN beam line:

- 1) Ion beam collimators with electron suppressors
- 2) X/Y scanning electrodes
- 3) High voltage fast amplifiers
- 4) Drift tube
- 5) Irradiation chamber with sample holder

# Irraggiamenti di dispositivi elettronici e detector

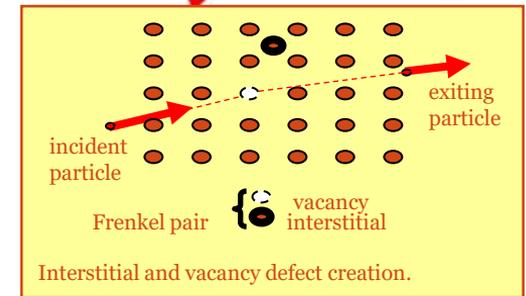
## SEE - Single Event Effects

- Effect due to the passage of a **single** energetic ionizing particle
- Sudden large  $\Delta E_{\text{ionization}}$  deposited in the “wrong” place at the “wrong” time (sensitive junction)



## DDD - Displacement (Bulk) Damage Dose

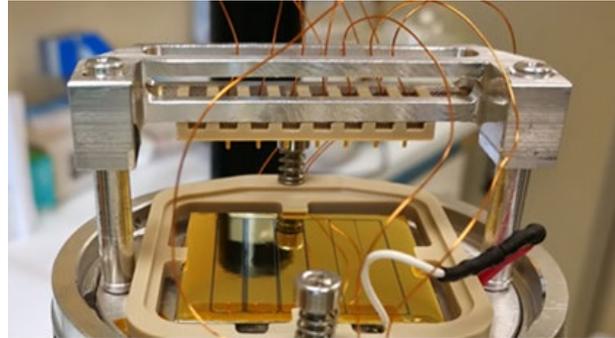
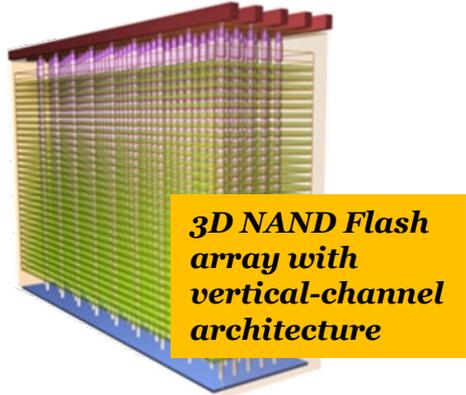
- Non-ionizing  $\Delta E$  transfers to atomic nuclei (Coulomb nuclear interactions).
- Accumulation of displacement damage of lattice



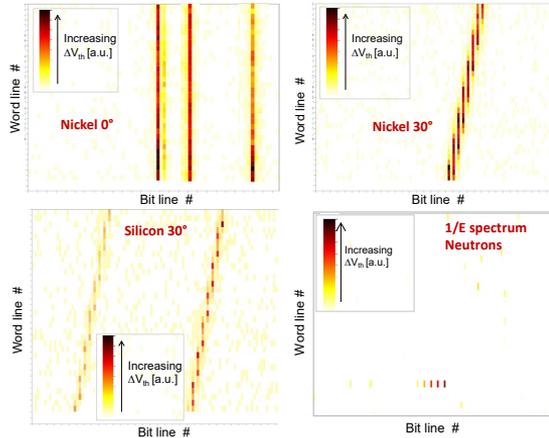
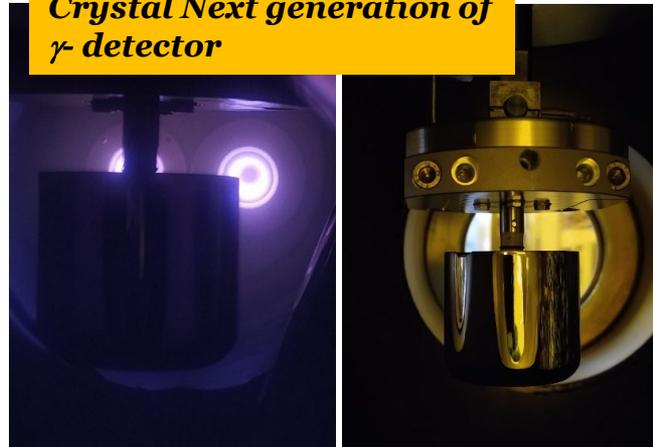
## Endurance test

- Evaluation of life time of the device under ion beam or neutron irradiation

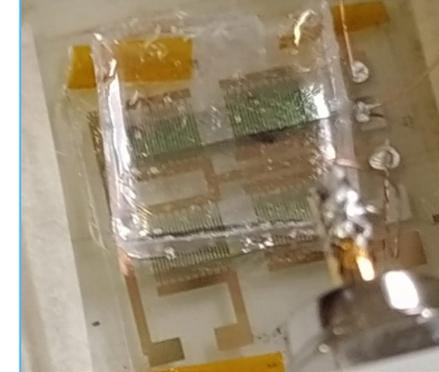
# Irraggiamenti di dispositivi elettronici e detector



**Dopant coating on HPGe Crystal**  
Next generation of  $\gamma$ -detector



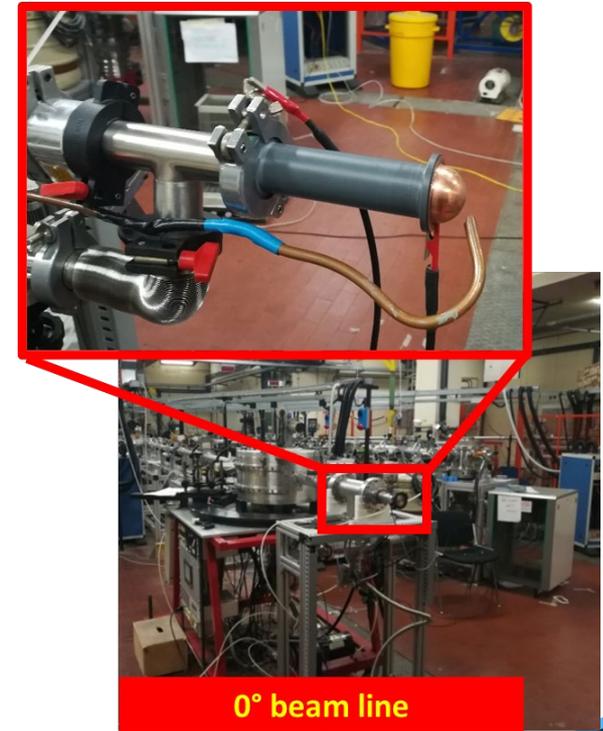
**Dosimeter for medical application**



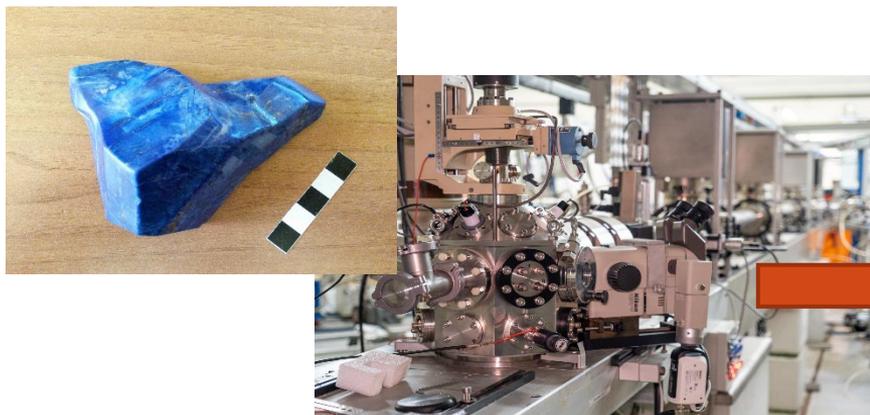
# Produzione di fasci di neutroni

Il fascio di neutroni viene prodotto utilizzando fasci di protoni e deutoni su target di Berilio e Litio

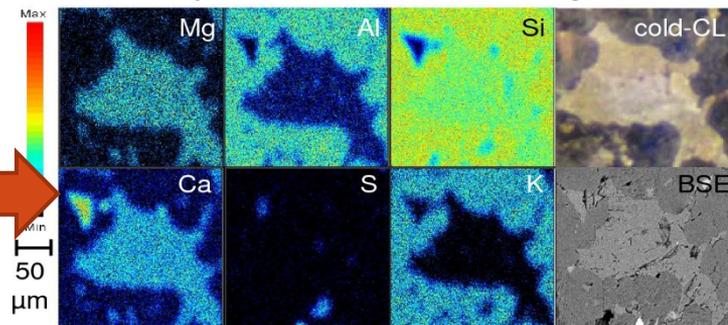
Viene utilizzato principalmente per irraggiamenti di dispositivi elettronici, dosimetri o per studi di fisica nucleare



# Studio di beni culturali



## $\mu$ PIXE analysis

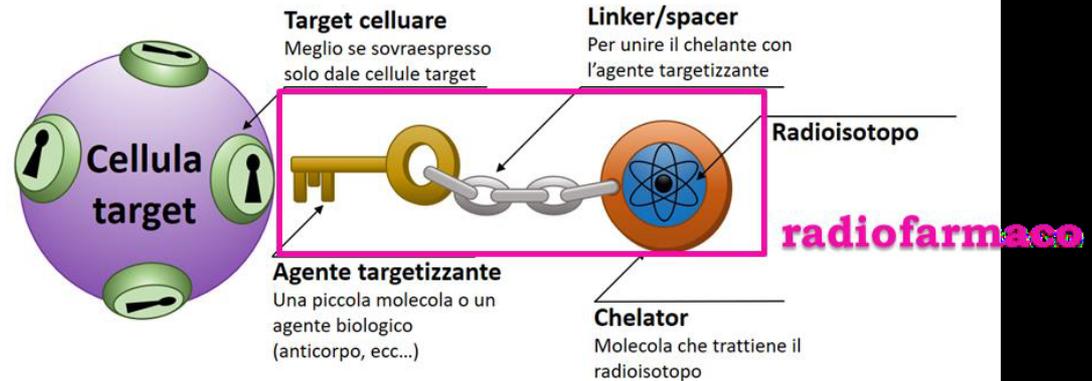
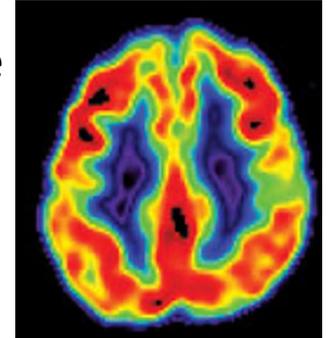


Studio della composizione con particolare attenzione dei contaminanti in traccia di reperti storici per determinare la provenienza, mediante tecnica PIXE  
Attività presso AN2000

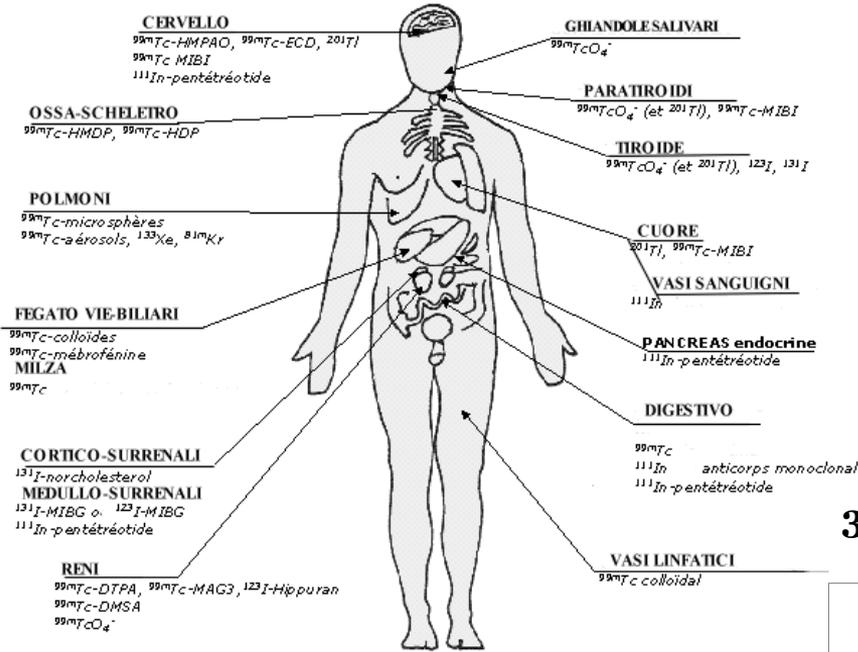
# Fisica Nucleare in Medicina

- Sviluppa nuovi materiali per diagnostica, analisi e terapia in campo della medicina nucleare
- Ottimizza la produzione di nuovi radionuclidi mediante reazioni nucleari tra materiale target e fascio ionico utilizzando acceleratori di particelle

Tecniche diagnostiche funzionali  
PET e SPECT



# Fisica Nucleare in Medicina: Caratterizzazione



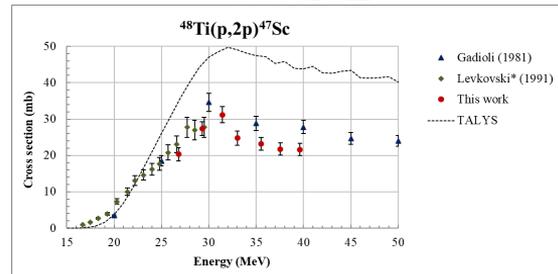
Diversi radiofarmaci per diversi organi

Attività PID, Liliana Mou

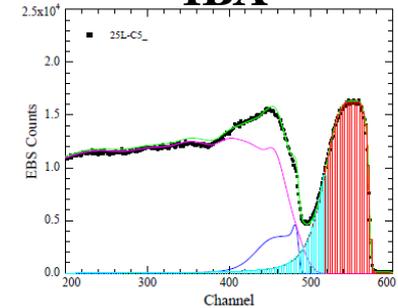
## 1) Produzione del target



## 3) Studio della Nuclear cross section



## 2) Caratterizzazione IBA

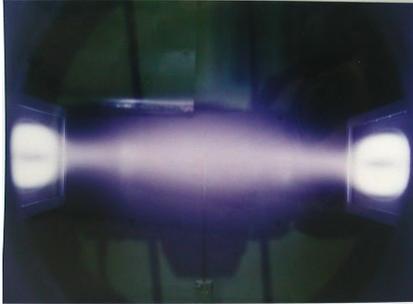


## OBBIETTIVO

Trovare le migliori condizioni di irraggiamento per massimizzare la produzione di radiofarmaci

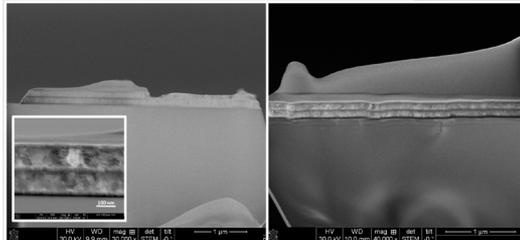
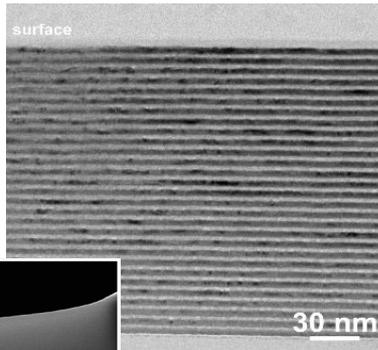
# Sviluppo e caratterizzazione di materiali avanzati

## Synthesis and Process Development



- Plasma Sputtering Deposition
- Plasma Diagnostics
- Ion-solid interaction

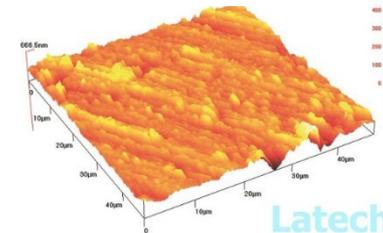
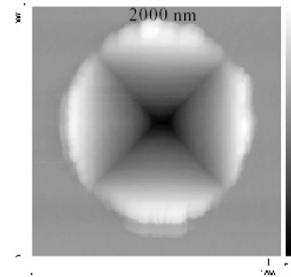
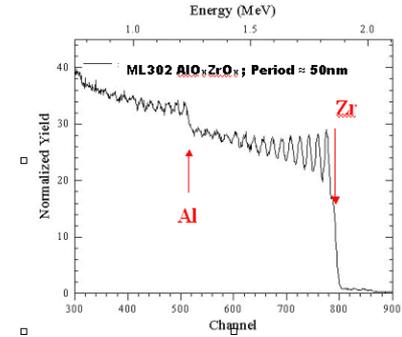
- Low Friction, High Hardness Nanoscaled Materials and Multilayers
- Insulating Oxides
- High Performance



## Characterization of Physical Properties

### Composition

- Ion Beam Analysis (RBS, NRA, ERDA, PIXE)
- Microbeam (Micro-PIXE 2-D trace element analysis)

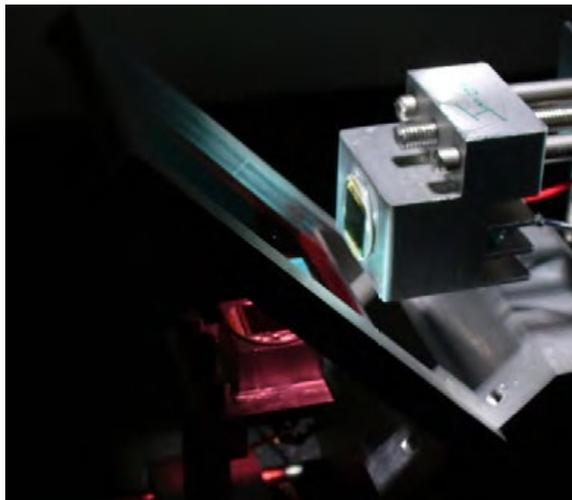


### Morphology, Mechanical prop.

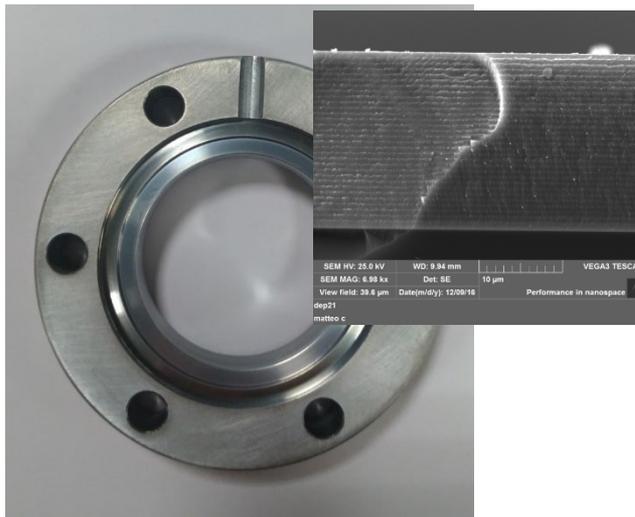
- Nano Hardness, Elastic modulus
- Adhesion (Micro-Scratch)
- Intrinsic Stress
- Atomic Force Microscopy & SEM

# Sviluppo e caratterizzazione di materiali avanzati

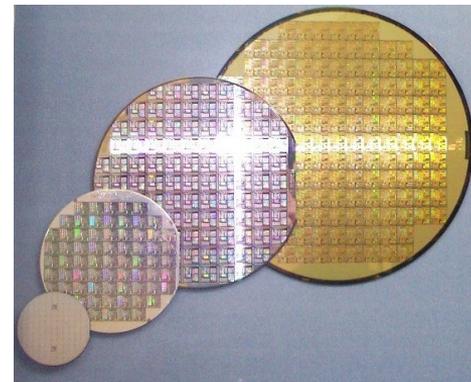
**Funzionalizzazione superficiale:** è la modifica delle proprietà superficiali di un materiale, per ottenere caratteristiche differenti dal materiale massivo di partenza.



Filtri ottici per applicazioni fotovoltaiche (università di Trento)



Rivestimenti di rinforzo per applicazioni Meccaniche in component da vuoto (Aziende del settore)



Realizzazione di component elettronici ultracompati (Aziende del settore)

# Target per fisica nucleare e astrofisica

INFN experiments

LNL Target Service

- Evaporation
- Rolling



ISOL

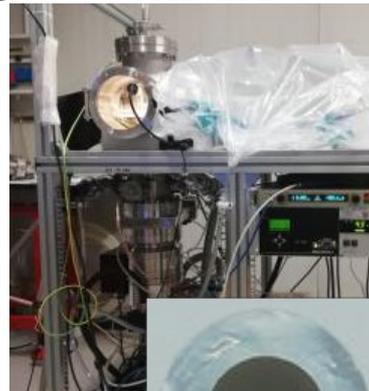
- Sintering
- Additive manufacturing



ISOL target

LARAMED

- SPS
- HIVIPP



Medical and  
nuclear  
applications

SALVIA

- Sputtering



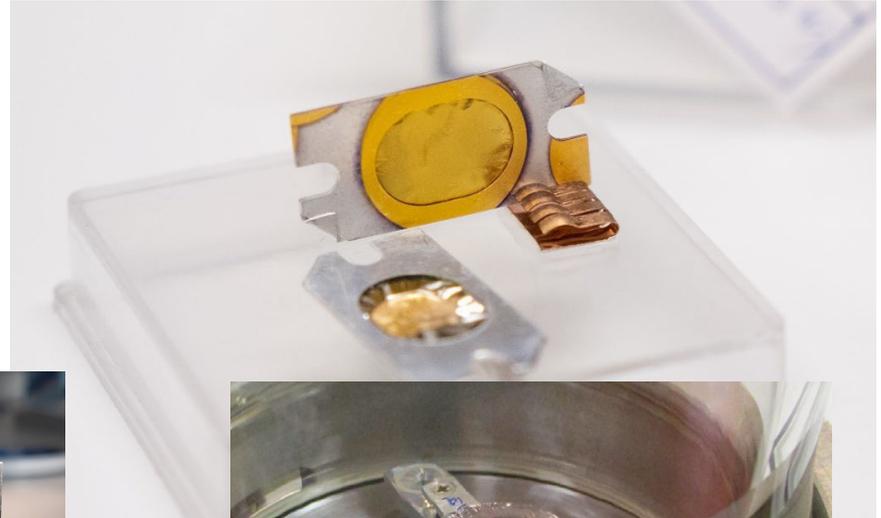
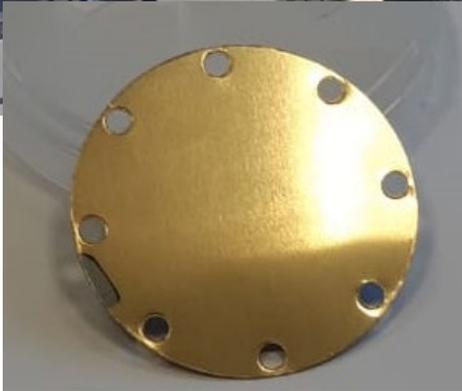
Astrophysics



Nuclear experiments

# Target per fisica nucleare e astrofisica

Sviluppo di materiali per esperimenti di fisica nucleare: **Esempi di Target**



# Target per fisica nucleare e astrofisica

Sviluppo di materiali per esperimenti di fisica nucleare: **Tecniche di caratterizzazione**

Morfologiche:

- SEM (scanning electron microscope)
- AFM (atomic force microprobe)



**COME** sono fatti  
i nostril bersagli

Composizionali:

- IBA (ion beam analysis)
- tecniche nucleari non distruttive



**DA COSA** sono  
fatti i nostril  
bersagli

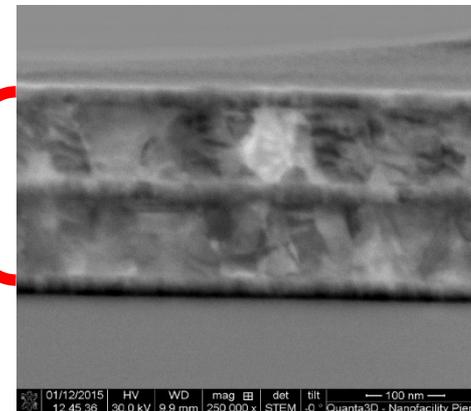
# Target per fisica nucleare e astrofisica

Sviluppo di materiali per esperimenti di fisica nucleare: **Tecniche di caratterizzazione**

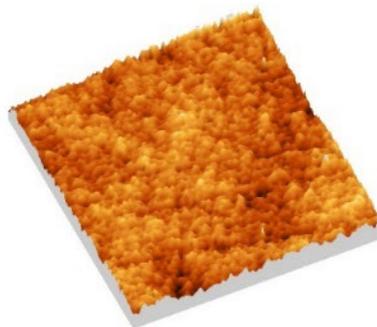
Morfologiche:

- SEM (scanning electron microscope)

Spessore  
120nm



- AFM  
(atomic force microprobe)



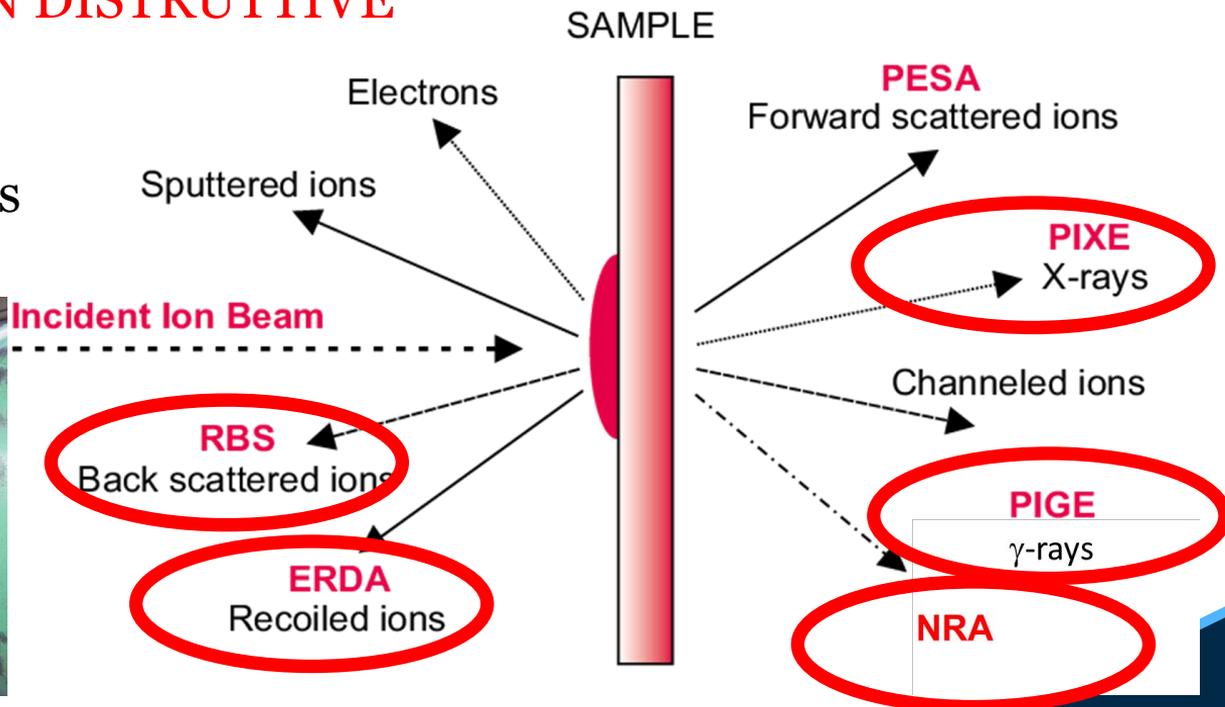
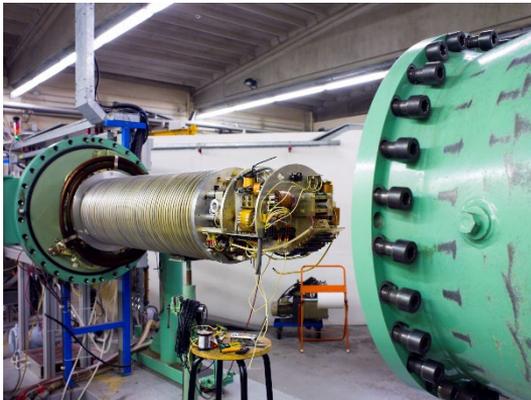
Rugosità  
media <  
2nm

# Target per fisica nucleare e astrofisica

Sviluppo di materiali per esperimenti di fisica nucleare: **Tecniche di caratterizzazione NON DISTRUTTIVE**

Composizionali:

- Ion Beam Analysis

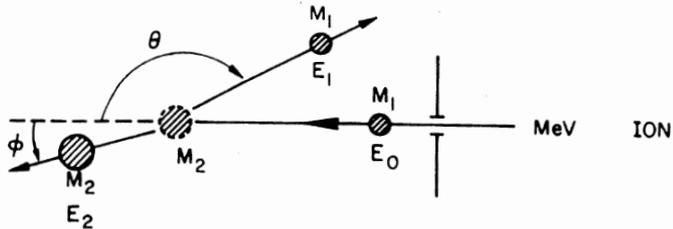


# Target per fisica nucleare e astrofisica

- **PIXE (proton induced X ray emission)** → misura dei raggi X emessi → analisi degli elementi
- **PIGE (particle induced  $\gamma$  ray emission)** → misura dei raggi gamma emessi → analisi di alcuni isotopi leggeri
- **EBS (elastic backscattering spectrometry)** → misura delle particelle del fascio “rimbalzate” all’indietro → analisi composizionale e strutturale
- **IBIL (ion beam induce luminescence)** → misura della radiazione luminosa ultravioletta e visibile → analisi di alcuni legami molecolari
- **NRA (nuclear reaction analysis)** → misura delle particelle prodotte nelle interazioni nucleari → analisi di isotopi

# CENNI TEORICI RUTHERFORD BACK SCATTERING: fattore cinematico K

## KINEMATICS OF ELASTIC COLLISION



Schematic representation of an elastic collision between a projectile of mass  $M_1$  and energy  $E_0$  and a target mass  $M_2$  which is initially at rest. After the collision, the projectile and target mass have energies  $E_1$  and  $E_2$  respectively. The angles  $\theta$  and  $\phi$  are positive as shown.

All quantities refer to a laboratory frame of reference.

For  $M_1 < M_2$ , conservation of energy and momentum, gives:

$$\frac{E_1}{E_0} = \left[ \frac{(M_2^2 - M_1^2 \sin^2 \theta)^{1/2} + M_1 \cos \theta}{M_1 + M_2} \right]^2$$

$$E_1 = K_{M_2} E_0$$

$K_{M_2}$  = kinematic factor

# CENNI TEORICI RUTHERFORD BACK SCATTERING:

## Sezione d'urto

### ELASTIC SCATTERING CROSS SECTION

For the COULOMB INTERACTION, a central force field, the differential scattering cross section of a target atom for scattering an incident particle through an angle  $\theta$  into a differential solid angle  $d\Omega$  centered about  $\theta$ , in the laboratory frame of reference is given by:

$$\frac{d\sigma}{d\Omega} = \left( \frac{Z_1 Z_2 e^2}{2E \sin^2 \theta} \right)^2 \frac{[\cos \theta + (1 - \mu^2 \sin^2 \theta)^{1/2}]^2}{(1 - \mu^2 \sin^2 \theta)^{1/2}}$$

$$\mu = M_1/M_2$$

E = energy of the projectile immediately before scattering

In backscattering spectrometry, the detector solid angle  $\Omega$  is small (about  $10^{-3}$  steradians) so that one defines an average differential scattering cross section:

$$\sigma(E, \theta) = (1/\Omega) \int_{\Omega} (d\sigma/d\Omega) d\Omega$$

# CENNI TEORICI RUTHERFORD BACK SCATTERING:

## Calcolo della dose [atm/cm<sup>2</sup>]

and the scattering angle  $\theta$  is well defined. It is then convenient<sup>†</sup> to introduce the *average differential scattering cross section*  $\sigma$ :

$$\sigma \equiv (1/\Omega) \int_{\Omega} (d\sigma/d\Omega) d\Omega. \quad (2.18)$$

For very small detector angles  $\Omega$ ,  $\sigma \rightarrow d\sigma/d\Omega$ . The average differential scattering cross section is the value ordinarily used in backscattering spectrometry. It is usually called *scattering cross section* in the literature. We follow this convention.

For the experimental condition given in Fig. 2.4, in which a uniform beam impinges at normal incidence on a uniform target that is larger than the area of the beam, the ~~total number of detected particles  $A$~~  can be written from Eq. (2.16) and (2.18) as

$$A = \sigma \Omega \cdot Q \cdot Nt. \quad (2.19)$$

$$\left( \begin{array}{c} \text{number of} \\ \text{detected particles} \end{array} \right) = \sigma \Omega \cdot \left( \begin{array}{c} \text{total number of} \\ \text{incident particles} \end{array} \right) \cdot \left( \begin{array}{c} \text{number of target} \\ \text{atoms per unit area} \end{array} \right).$$

This equation shows that when  $\sigma$  and  $\Omega$  are known and the numbers of incident and detected particles are counted, the number of atoms per unit area in the target,  $Nt$ , can be determined. The ability of backscattering spectrometry to provide quantitative information on the number of atoms present per unit area of a sample stems from Eq. (2.19) and the fact that the average scattering cross section  $\sigma$  of the elements is known quite accurately.

# CENNI TEORICI RUTHERFORD BACK SCATTERING: Straggling e perdita di energia non elastica

## 2.6 ENERGY STRAGGLING

An energetic particle that moves through a medium loses energy via many individual encounters. Such a quantized process is subject to statistical fluctuations. As a result, identical energetic particles, which all have the same initial velocity, do not have exactly the same energy after passing through a thickness  $\Delta x$  of a homogeneous medium. The energy loss  $\Delta E$  is subject to fluctuations. The phenomenon, sketched in Fig. 2.10, is called *energy straggling*. Energy straggling places a finite limit for the precision with which energy losses, and hence depths can be resolved by backscattering spectrometry. The ability to identify masses is also impaired, except for atoms located at the surface of the target. The reason is that the beam energy  $E$  before a collision with a specific mass  $M_2$  at some depth within the target is no more monoenergetic, even if it was so initially, so that the ratio  $E_1/E_0$ , and hence the identification of  $M_2$ , become uncertain as well. For these reasons, it is important to have quantitative information on the magnitude of energy straggling for any given combination of energy, target material, target thickness, and projectile.

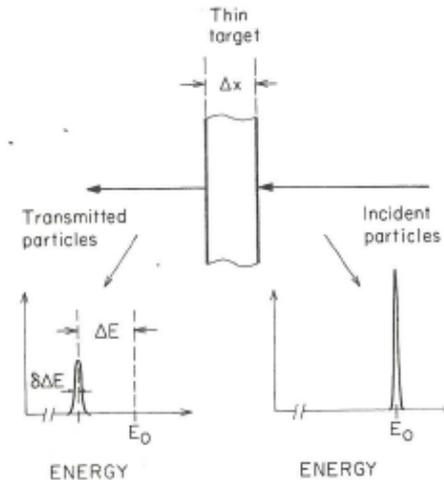


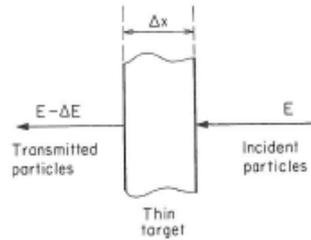
Fig. 2.10 A monoenergetic beam of energy  $E_0$  loses energy  $\Delta E$  in traversing a thin film of thickness  $\Delta x$ . Simultaneously, energy straggling broadens the energy profile.

# CENNI TEORICI RUTHERFORD BACK SCATTERING: Stragglings e perdita di energia non elastica

## 2.4 Energy Loss and Stopping Cross Section

33

Fig. 2.6 Schematic of a transmission experiment to measure the  $\Delta E/\Delta x$  loss of a swift particle in a dense medium.



the target, it slows down and its kinetic energy  $E = \frac{1}{2}M_1v^2$  decreases. The amount of energy  $\Delta E$  lost per distance  $\Delta x$  traversed depends on the identity of the projectile, on the density and composition of the target, and on the velocity itself. The simplest experiment that can be conceived to determine this energy loss is to take a very thin target of thickness  $\Delta x$  and of known composition. A beam of monoenergetic particles is directed at this target (see Fig. 2.6). The energy difference  $\Delta E$  of the particles before and after transmission through the target is measured. The *energy loss* per unit length, also called sometimes the *specific energy loss*, and frequently abbreviated  $dE/dx$  loss, at the energy  $E$  of the incident beam is then defined as

$$\lim_{\Delta x \rightarrow 0} \Delta E/\Delta x \equiv \frac{dE}{dx}(E) \quad (2.25)$$

for that particular particle and energy in that medium. Note that this expression gives an energy loss that is a positive quantity.

## 3.5 Spectrum Height—Elemental Sample

73

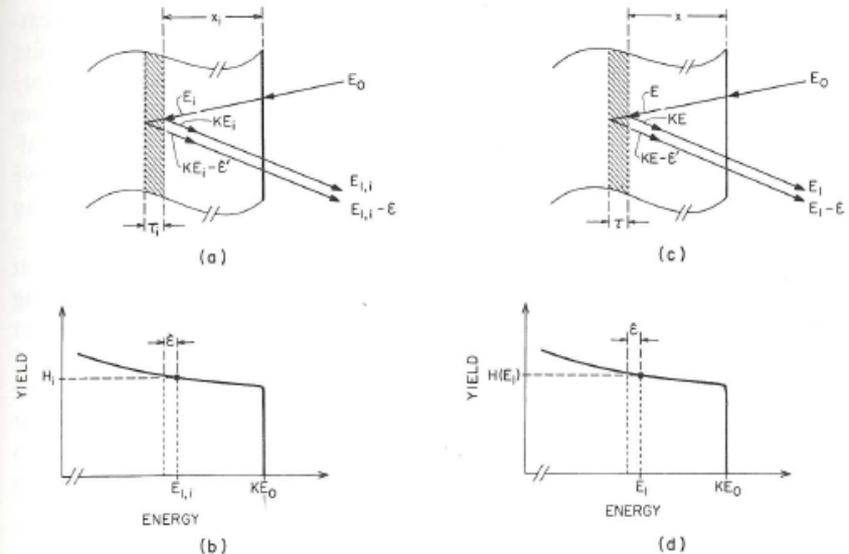
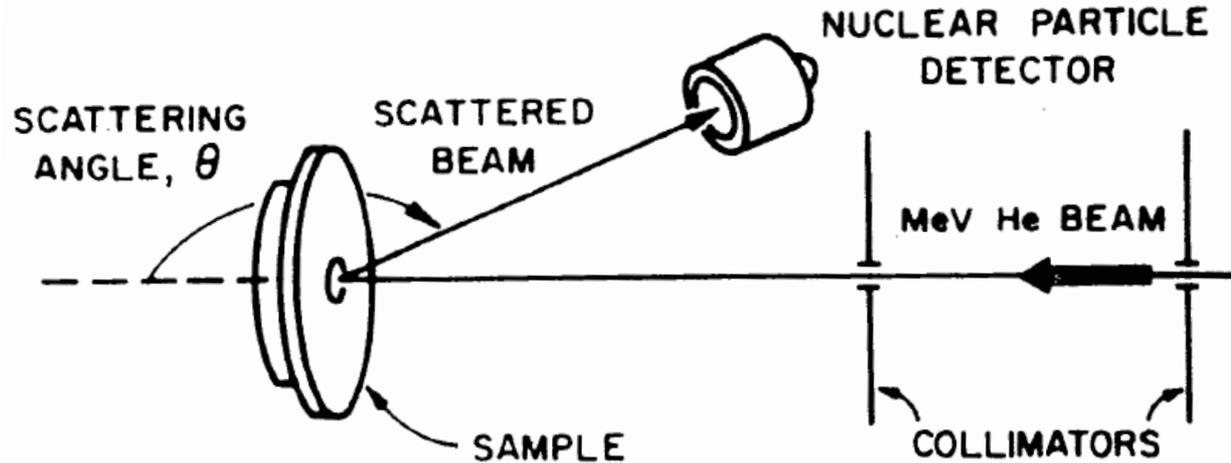


Fig. 3.13 Schematics of and nomenclature for (a) the backscattering process at depth  $x_i$  within a monoisotopic sample in the language of discrete functions, and (b) the resulting spectrum. (c) and (d) give the corresponding schematics and nomenclature in the language of continuous functions.

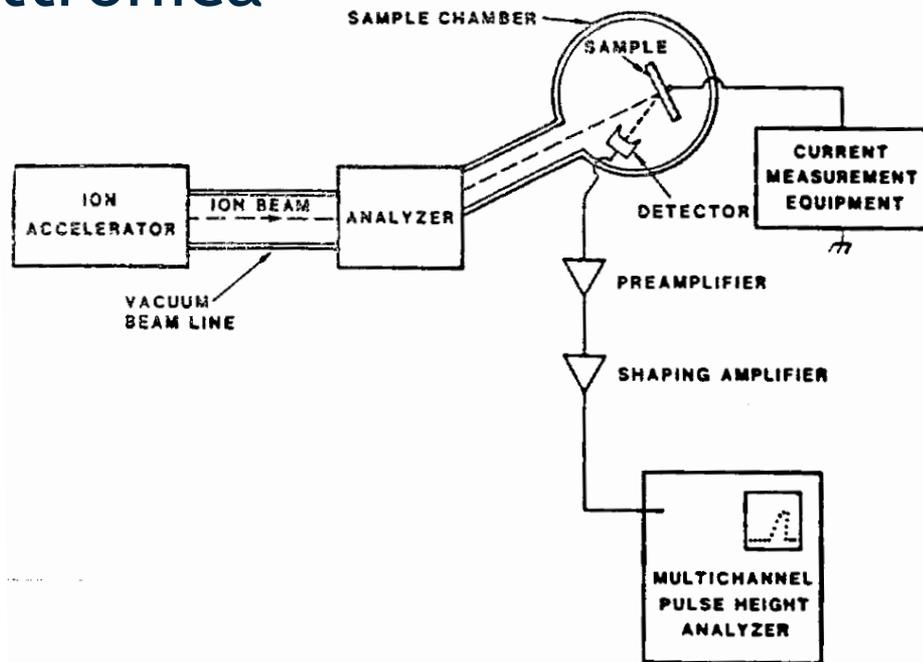
# Strumentazione per generazione segnale: Detector e relativa geometria di scattering



Ion beam: He<sup>+</sup>  
Energy: 3.1MeV  
 $\theta=170^\circ$

# ATTIVITA' SPERIMENTALE

## Strumentazione per acquisizione segnale: catena elettronica



Simplified illustration of the equipment used for RBS.

Segnale dal  
detector

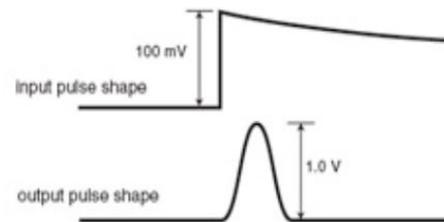
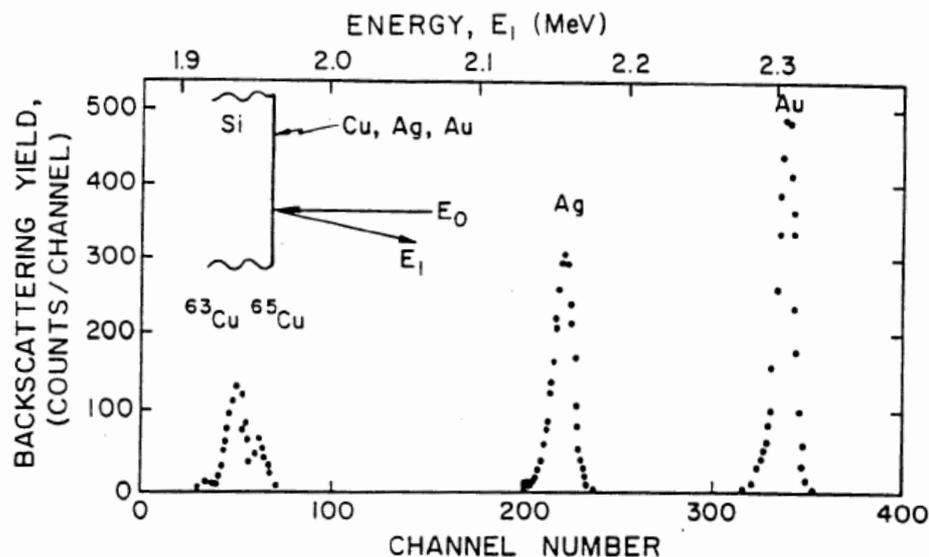


Figure 1. Comparison of sample input and output pulse shapes

Segnale dal  
shaping amplifier

# ATTIVITA' SPERIMENTALE

## Strumentazione per acquisizione segnale: esempio di spettro di film sottile



For a thin target of thickness  $t$  with  $N$  atoms/cm<sup>3</sup>, the YIELD, or the number of detected particles in a detector that subtend a solid angle  $\Omega$  is:

$$Y = \sigma(E, \theta) \Omega Q N t$$

$Q$  = total number of incident particles in the beam

Peak areas scale with  $N$  and (in first approximation) with  $Z_2^2$ .

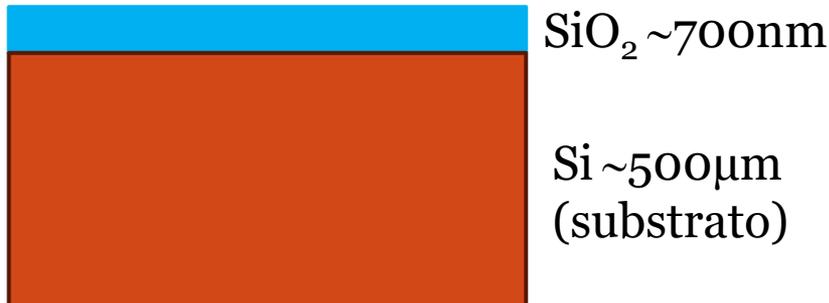
Absolute coverages of a heavy element on a light substrate can be detected down to a limit of about  $10^{-3}$  monolayers.

# ATTIVITA' SPERIMENTALE

Analisi campione noto di SiO<sub>2</sub> depositato su substrato di Si

Obiettivi:

1. Valutare il differente fattore cinematico tra elementi con massa diversa
2. Valutare lo stopping power
3. Osservare l'effetto tra spettro simulato basato su formule teoriche (RBS teorico) e spettro acquisito con risonanza (EBS reale)
4. Valutare diversa sezione d'urto tra elementi con Z diverso

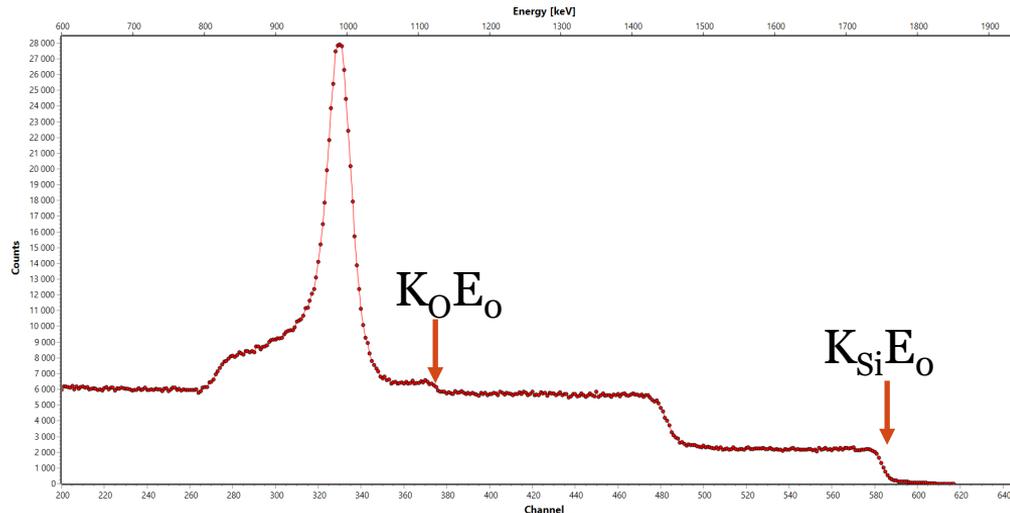


# ATTIVITA' SPERIMENTALE

Analisi campione noto di SiO<sub>2</sub> depositato su substrato di Si

Obiettivi:

- Valutare il differente fattore cinematico tra elementi con massa diversa



$$\frac{E_1}{E_0} = \left[ \frac{(M_2^2 - M_1^2 \sin^2 \theta)^{1/2} + M_1 \cos \theta}{M_1 + M_2} \right]^2$$

$$E_1 = K_{M_2} E_0$$

$K_{M_2}$  = kinematic factor

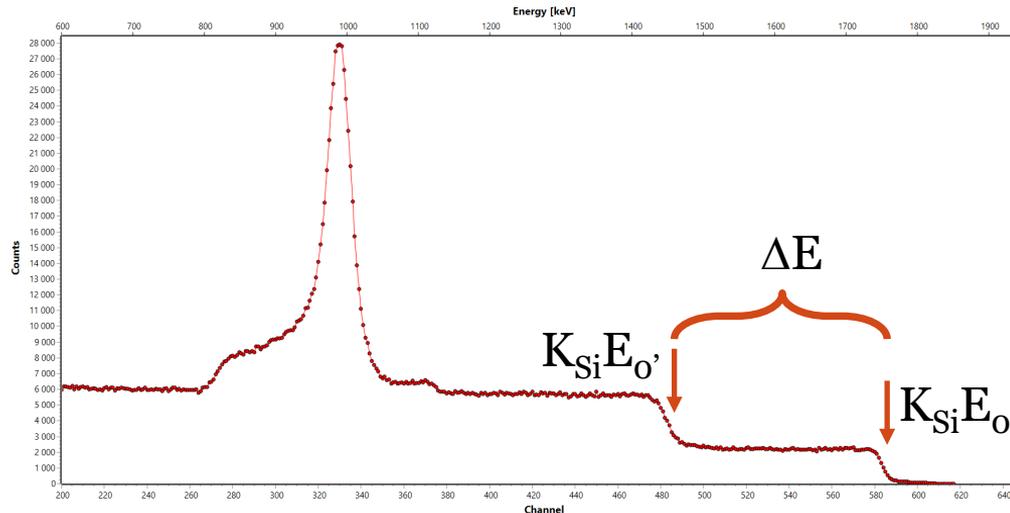
$$K_{Si} > K_O$$

# ATTIVITA' SPERIMENTALE

Analisi campione noto di SiO<sub>2</sub> depositato su substrato di Si

Obiettivi:

- Valutare lo stopping power



$\Delta E$  è dovuto alla perdita di energia dello ione che attraversa il materiale del primo layer (SiO<sub>2</sub>)

Il  $\Delta E$  dipende dallo “stopping power” del materiale e quindi dal “rallentamento” (interazione non elastica) dello ione che interagisce con il “materiale attraversato”.

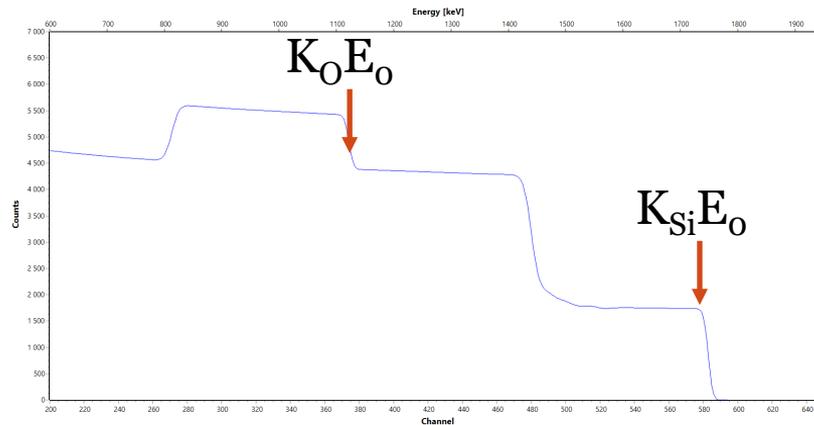
# ATTIVITA' SPERIMENTALE

Analisi campione noto di SiO<sub>2</sub> depositato su substrato di Si

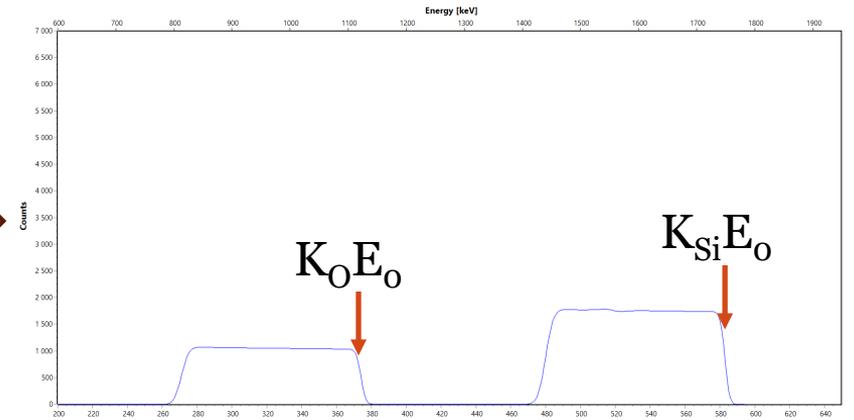
Obiettivi:

- Valutare divisa sezione d'urto tra elementi con Z diverso

Spettro simulato SiO<sub>2</sub>/Si



Spettro simulato SiO<sub>2</sub> (con sottrazione substrato)

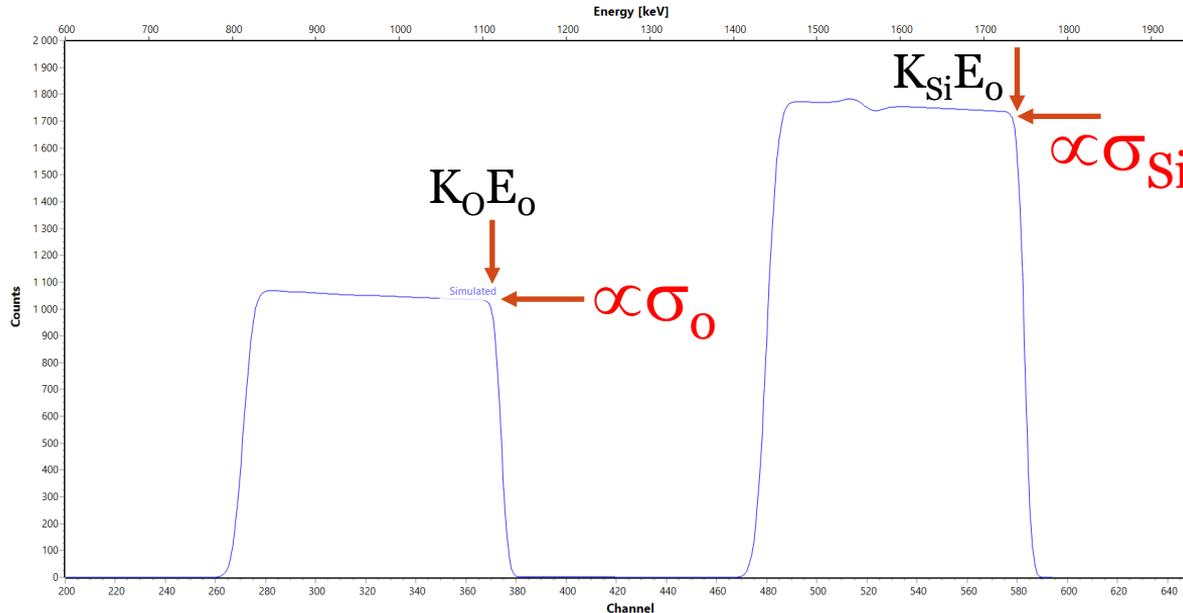


# ATTIVITA' SPERIMENTALE

Analisi campione noto di SiO<sub>2</sub> depositato su substrato di Si

Obiettivi:

- Valutare diversa sezione d'urto tra elementi con Z diverso



Spettro simulato SiO<sub>2</sub> (con sottrazione substrato)

$$\frac{d\sigma}{d\Omega} = \left( \frac{Z_1 Z_2 e^2}{2E \sin^2 \theta} \right)^2 \frac{[\cos \theta + (1 - \mu^2 \sin^2 \theta)^{1/2}]^2}{(1 - \mu^2 \sin^2 \theta)^{1/2}}$$

$$\sigma(E, \theta) = (1/\Omega) \int_{\Omega} (d\sigma/d\Omega) d\Omega$$

$$Z_{Si} > Z_O \rightarrow \sigma_{Si} > \sigma_O \rightarrow A_{Si} > A_O$$

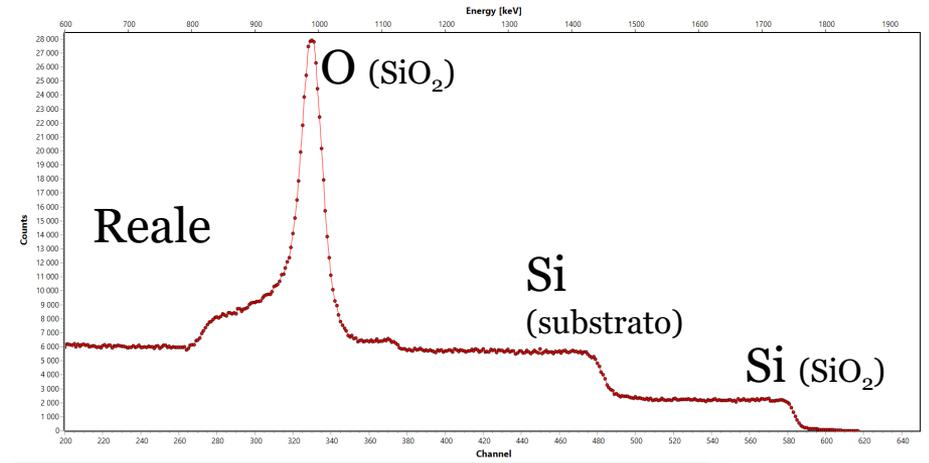
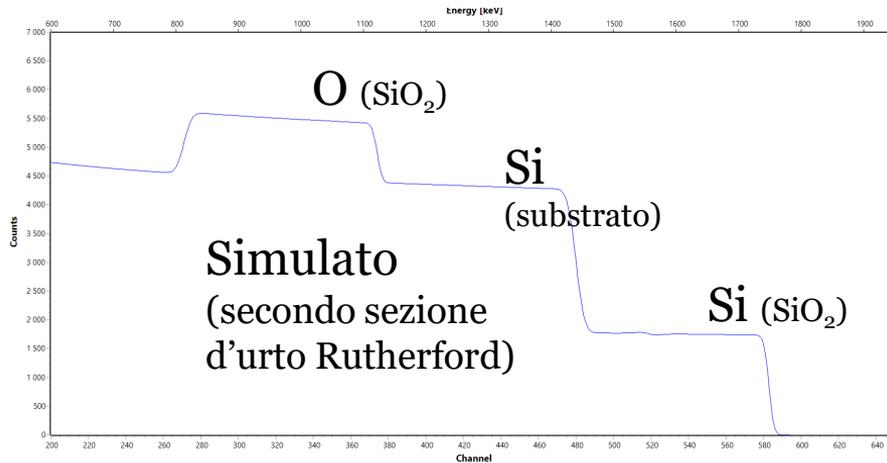
N° atomi O doppio rispetto  
N° atomi Si !!!

# ATTIVITA' SPERIMENTALE

Analisi campione noto di  $\text{SiO}_2$  depositato su substrato di Si

Obiettivi:

Osservare l'effetto tra spettro simulato basato su formule teoriche (RBS teorico) e spettro acquisito con risonanza (EBS reale)



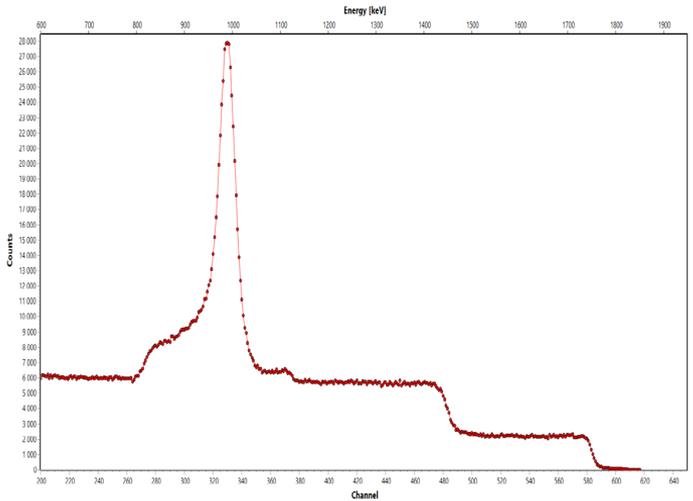
# ATTIVITA' SPERIMENTALE

Analisi campione noto di SiO<sub>2</sub> depositato su substrato di Si

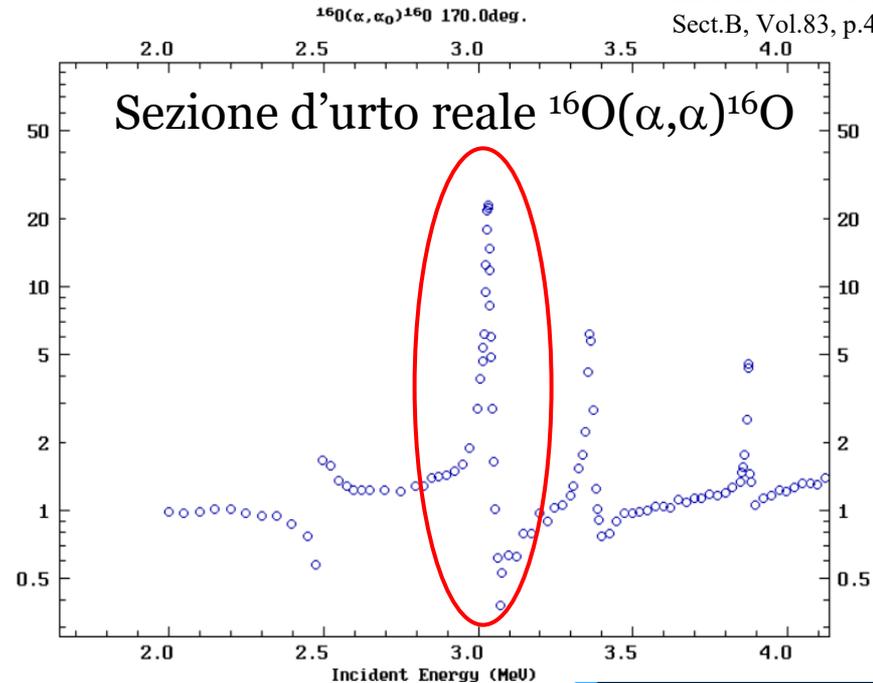
Obiettivi:

Osservare l'effetto tra spettro simulato basato su formule teoriche (RBS teorico) e spettro acquisito con risonanza (EBS reale)

Huan-Sheng Cheng+(1993), Nucl. Instrum. Methods in Physics Res., Sect.B, Vol.83, p.449



Cross section (Ratio to Rutherford)



# CONCLUSIONI

- I fasci ionici sono utilizzati in svariati campi, sia di ricerca che di sviluppo tecnologico
- Le tecniche Ion Beam Analysis sono uno strumento di caratterizzazione indispensabile in diversi settori per lo studio di materiali
- È stato descritto e mostrato un tipico setup sperimentale per la caratterizzazione EBS
- È stato acquisito uno spettro EBS su  $\text{SiO}_2/\text{Si}$  con un fascio di  $\text{He}^+$  di energia 3.1 MeV
- Lo spettro è stato selezionato per motivi didattici in quanto mostra una risonanza e quindi una discrepanza della sezione d'urto teorica a 3.05 MeV [ $^{16}\text{O}(\alpha,\alpha)^{16}\text{O}$ ]

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