Physique des Interactions
Ioniques et Moléculaires

Negative ion surface production in H_2/D_2 plasmas

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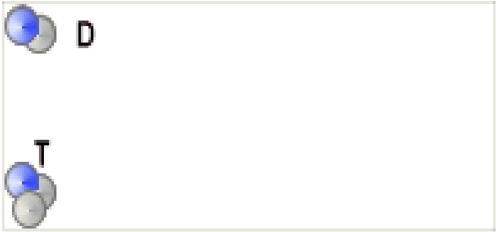
PROJET FINANCÉ PAR L'ANR - PROJECT FUNDED BY THE ANR

Aix*Marseille université

MAIN AIM OF THE STUDY

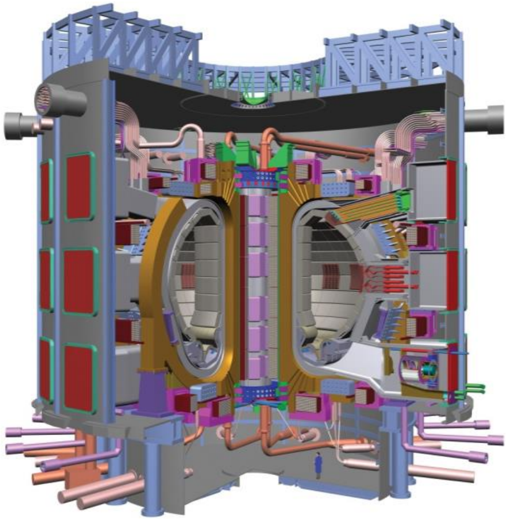
- **Controlled thermonuclear fusion is one of the most promising future energy sources**



RELATION WITH THERMONUCLEAR FUSION

- **Controlled thermonuclear fusion is one of the most promising future energy sources**

- **ITER is the world's largest experimental tokamak nuclear fusion reactor being built at the south of France**



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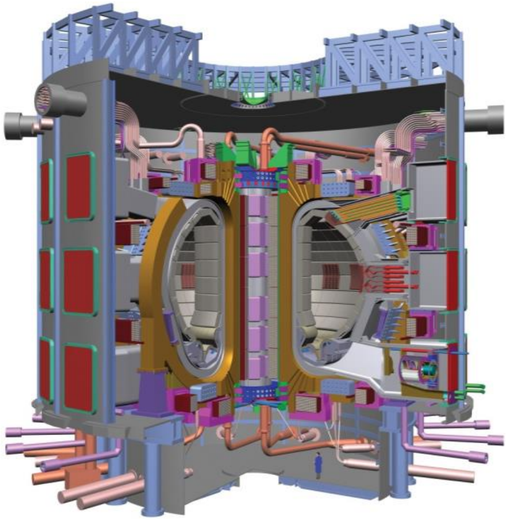

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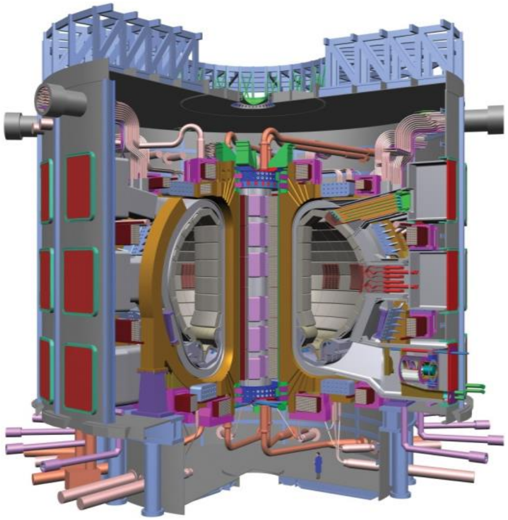
- **required electron temperature: 10 – 20 keV (~10^8 °C)**
- **only 1 keV can be achieved with Ohmic heating**

RELATION WITH THERMONUCLEAR FUSION

- Controlled thermonuclear fusion is one of the most promising future energy sources



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→ **one needs additional heating methods!**

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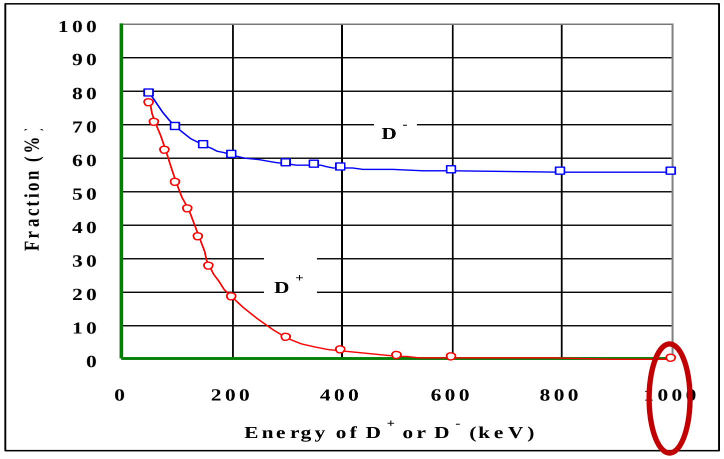
Neutrals of 1 MeV are needed to heat the ITER plasma core and ignite the fusion reactions

Why to use NI ?

Ion neutralization



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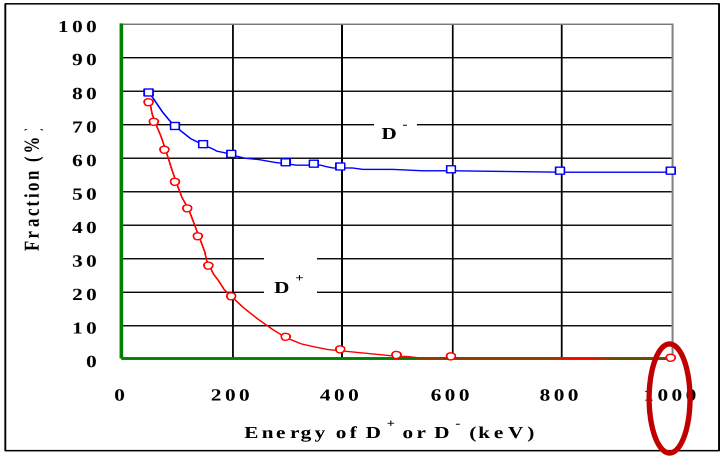
At such an energy:
D^+ → 0%
D^- → 56%
of neutralisation efficiency

Why to use NI ?

Ion neutralization



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At such an energy:

D$^+$ → 0%

D$^-$ → 56%

of neutralisation efficiency

Necessary D$^-$ current: ~ 50 A (250 A·m^{-2})

- ① Neutral beam injectors for fusion
  - we need negative-ions ?

- ② Negative-ion sources for fusion
- How can we produce negative-ions ?
  - Interaction with surfaces
  - ITER

- ③DEMO: New concepts in negative-ion sources?

Production of negative-ions in H_2 plasmas

- **Negative ions can be formed in plasmas:**

* In the plasma bulk (**volume production**)

* At the surfaces in interaction with the plasma (**surface production**).

Surface production

- Negative ions can also be created on surfaces:
  - H_x^+ + surface → H^-
  - H + surface → H^-
  - …

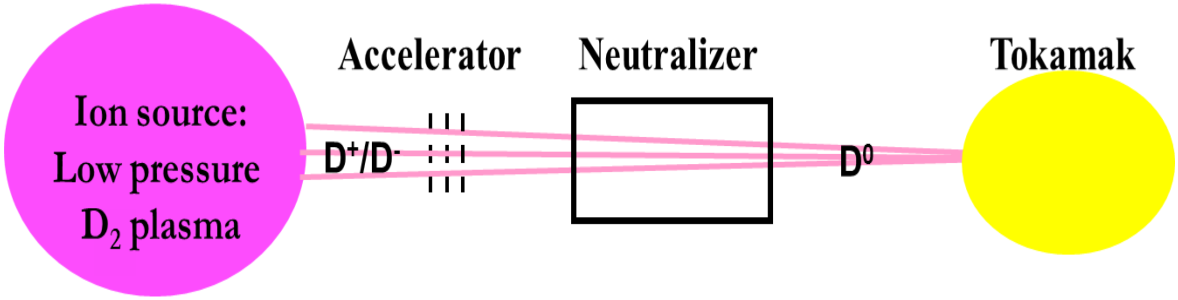
- This process is called **« Surface ionization »**

- What is the origin of surface ionization ?

How a particle can capture an electron from the surface ?

NBI for ITER

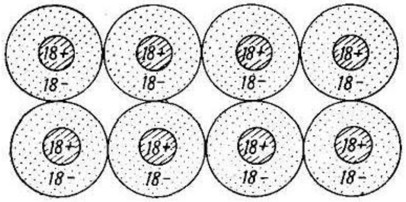
NBI - neutral beam injection



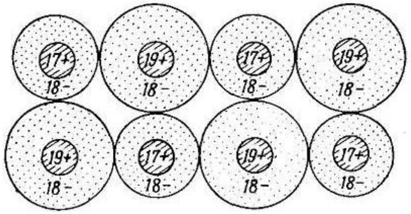
ELEMENTS OF SURFACE PHYSICS

- **WHAT ARE THE MAIN PHYSICAL PARAMETERS THAT WE HAVE TO TAKE INTO ACCOUNT IN THE CHARGE EXCHANGE AT SURFACES?**

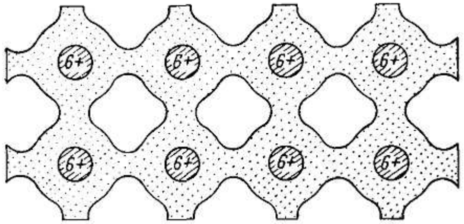
Remind



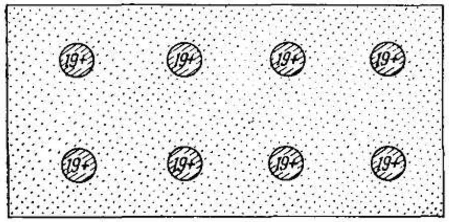
Argon Crystal. Molecular
(Flucuating dipole) Bonds.
No transfer of charge.



Potassium Chloride (KCl). Ionic Crystal.
An electron is transferred from the
K to the Cl to make K+ and Cl-
which then attract each other



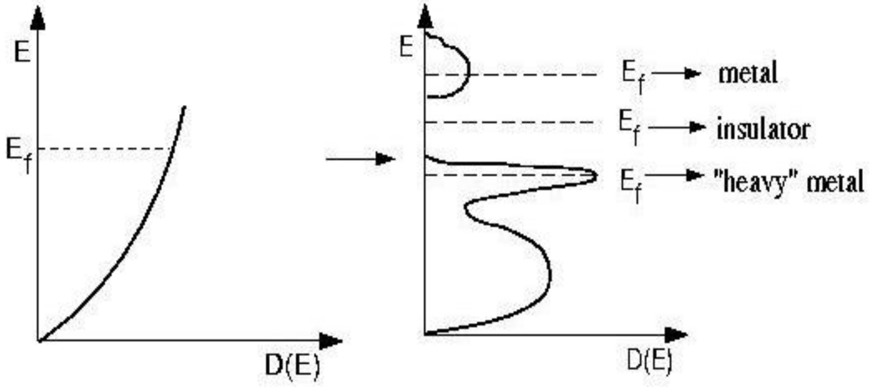
Carbon Crystal (Covalent Bonds). Each
Atom shares electrons with its neighbors.



Metallic bonding in Potassium. Electrons
are completely delocalized into an
electron gas which holds together the ions.

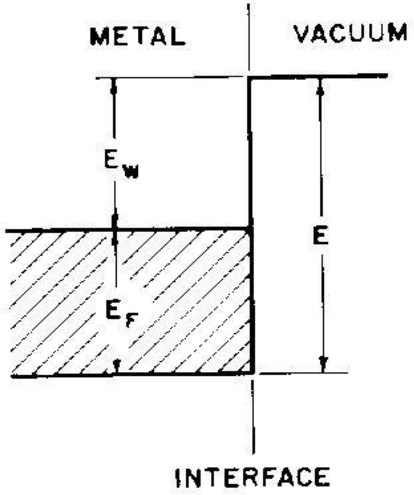
Electronic Density of States

$$D(\varepsilon) = \frac{2}{(2\pi)^d} \int d\mathbf{k}\ \delta\left(\varepsilon - \varepsilon(\mathbf{k})\right) \rightarrow D(\varepsilon) = \frac{2}{(2\pi)^d} \sum_n \int_{B.Z.} d\mathbf{k}\ \delta\left(\varepsilon - \varepsilon_n(\mathbf{k})\right)$$

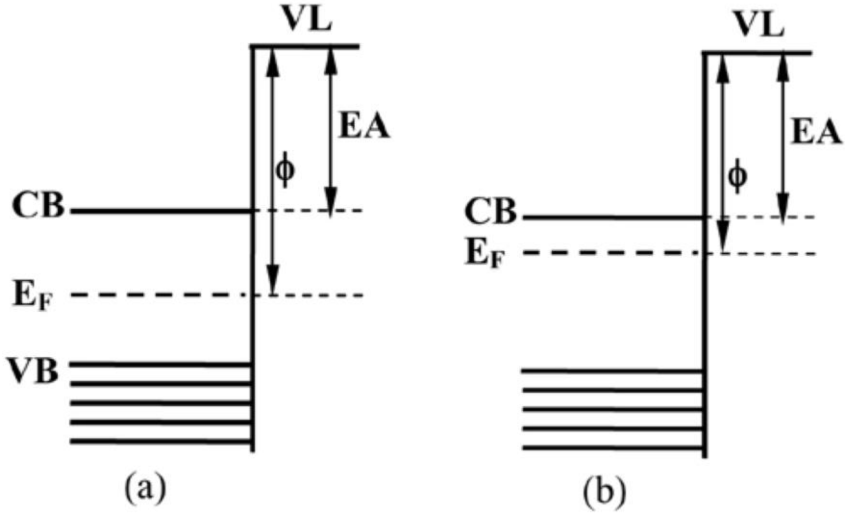


Work function, electroaffinty

Work function: Energy between the Fermi level and the vacuum.
For the semiconductors or insulators it‘s better to take into account the energy between the lower part of the conduction band and the vacuum, ie the electro affinity.



Work function
metal

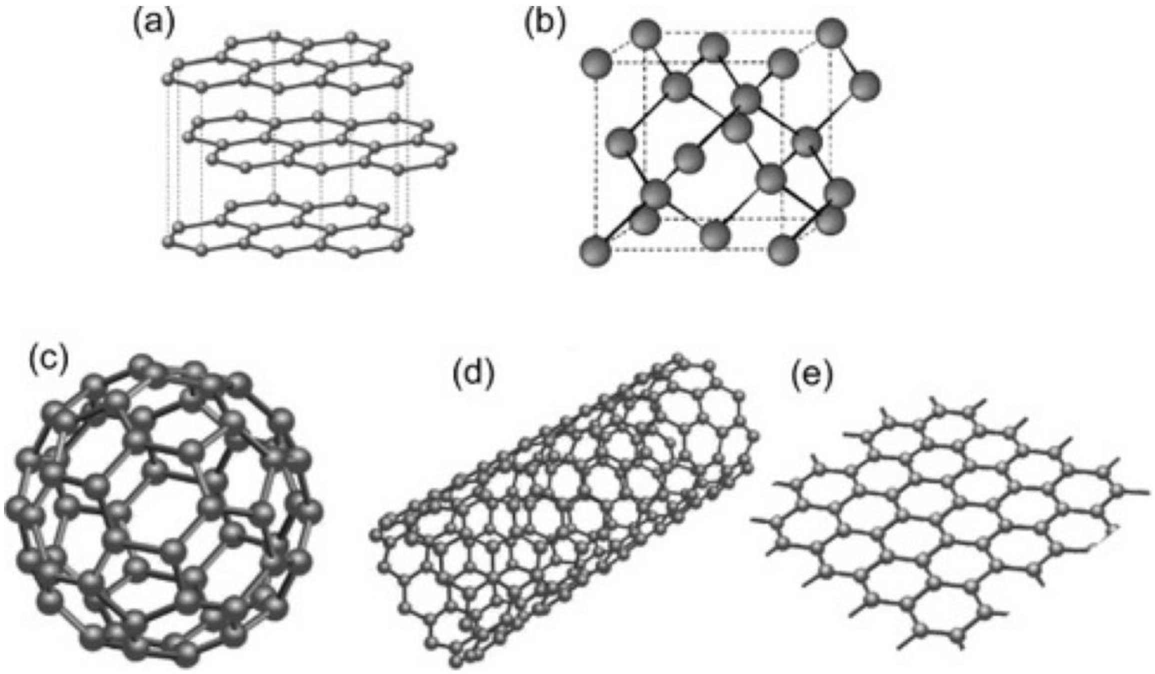


Work function /electro affinity
semiconductor/insulator

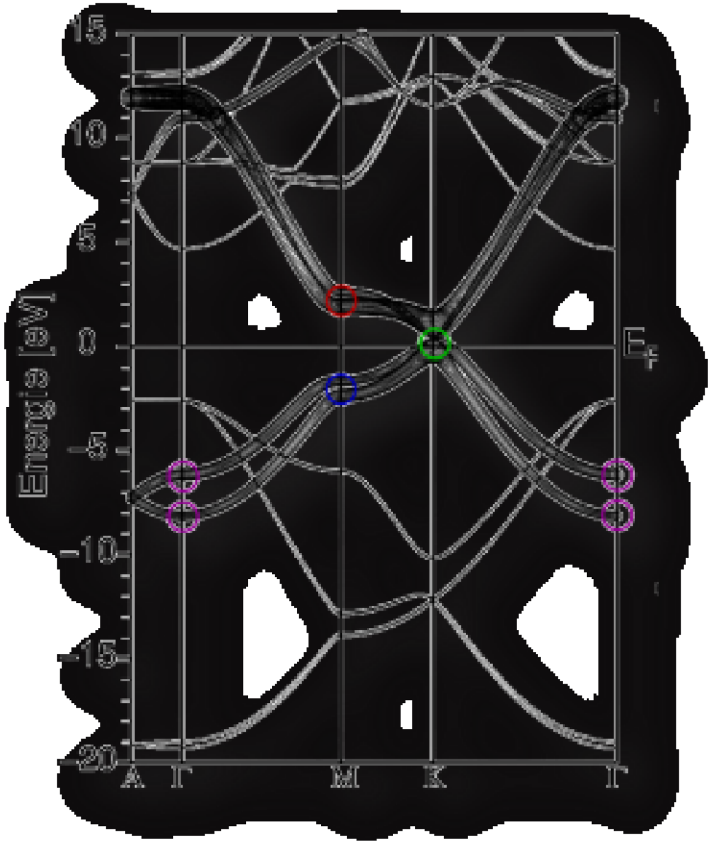
Element	Φ (eV)	Element	Φ (eV)	Element	Φ (eV)
Ag		Cu		Si	
Ag(100)	4.64	Cu(100)	4.59	Ru	4.71
Ag(110)	4.52	Cu(110)	4.48	Ta	4.25
Ag(111)	4.74	Cu(111)	4.98	Ta(100)	4.15
Ba	2.52	Ir(110)	5.42	Ta(110)	4.80
C	5.0	Ir(111)	5.76	Ta(111)	4.00
Ce	2.9	K	2.30	Ti	4.33
Cr	4.5	LaB_6	2.66	W	4.55
Cs	2.14	Mo	4.60	Zr	4.05

Work function for different materials

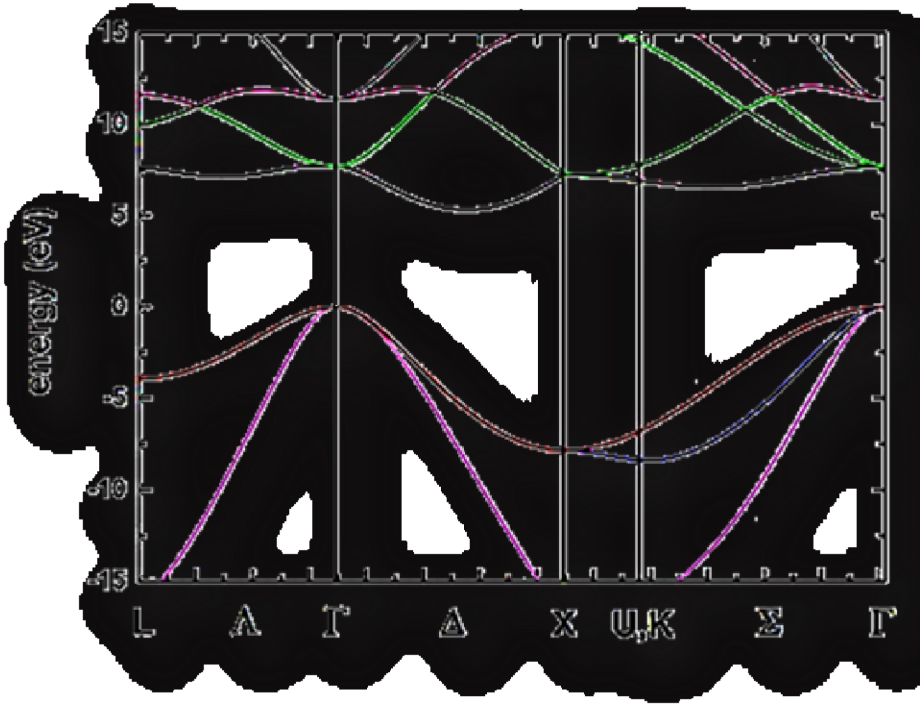
Example: Carbon



a) Graphite, b) diamond, c) fullerene, d) nanotube, e) graphene


15
10
5
0
-5
-10
-15
-20
Energie [eV]
E_F
A
Γ
M
K
Γ

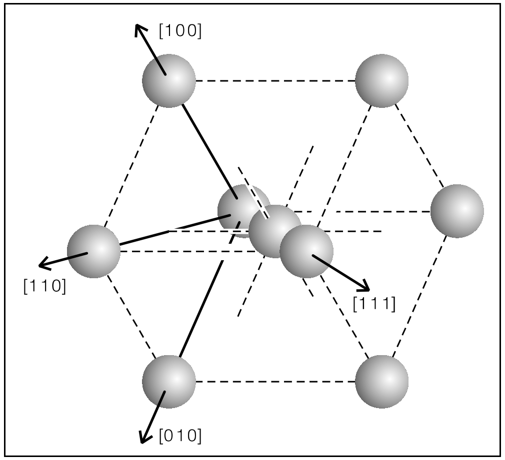
(a)


15
10
5
0
-5
-10
-15
energy (eV)
L
Λ
Γ
Δ
X
U,K
Σ
Γ

(b)

Tungsten W

- Atomic number: 74
- Atomic mass: 183
- Melting temperature : 3422°C



BCC structure

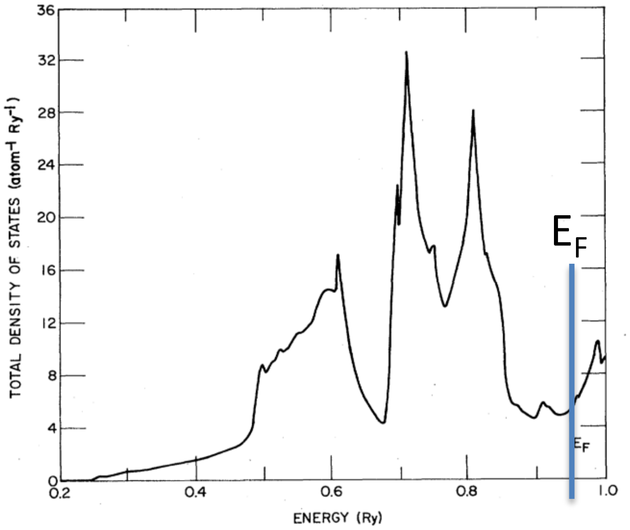


FIG. 2. Density of states of bcc tungsten for $a = 5.95$ a.u. (in states/Ry atom).

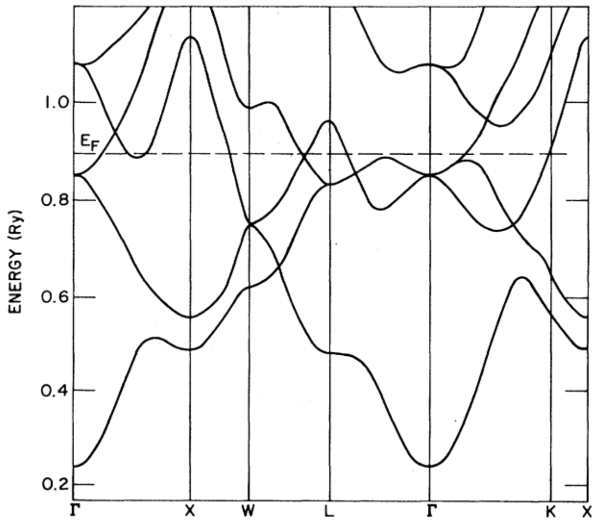


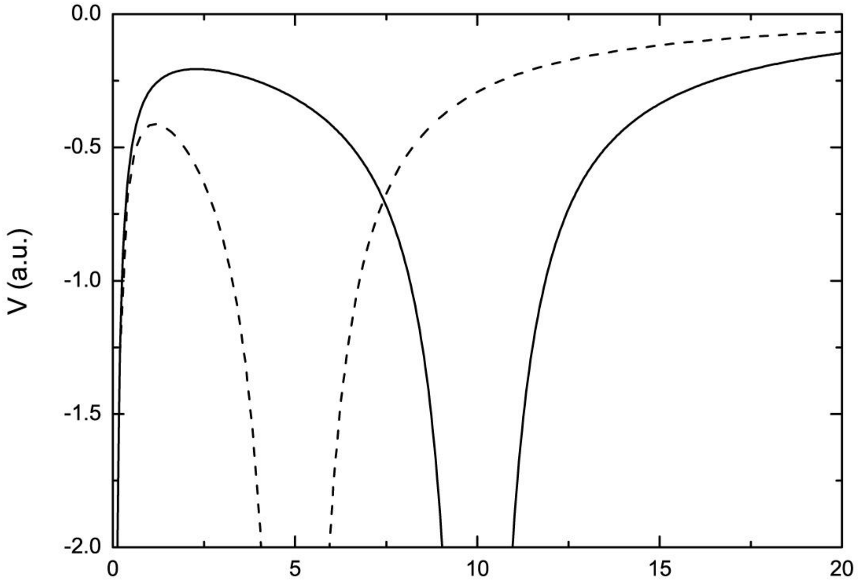
FIG. 4. Electron energy band structure of fcc tungsten for $a = 7.55$ a.u.

H.J.F Jansen, A.J Freeman, Phys.Rev. B vol.30
n°2 July 1984

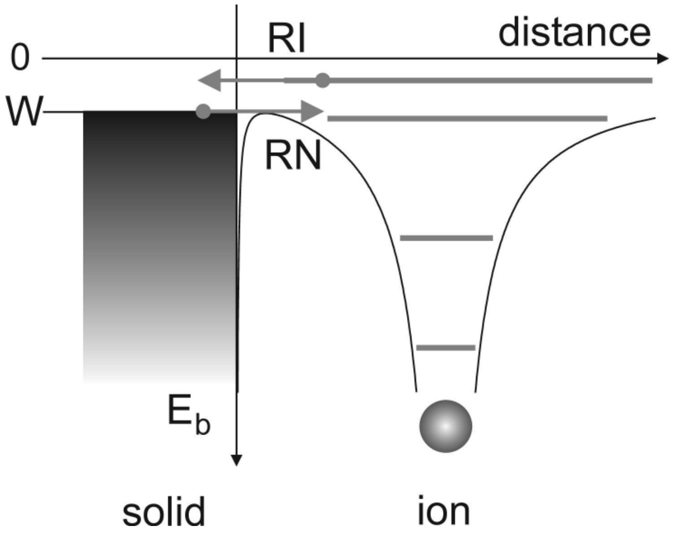
INCIDENT PARTICLE

- Incident particle
- H (D) ions
- Solid

Atom (ion)



Atom (or ion) in interaction with a metallic surface



Negative ion emission by metallic surface

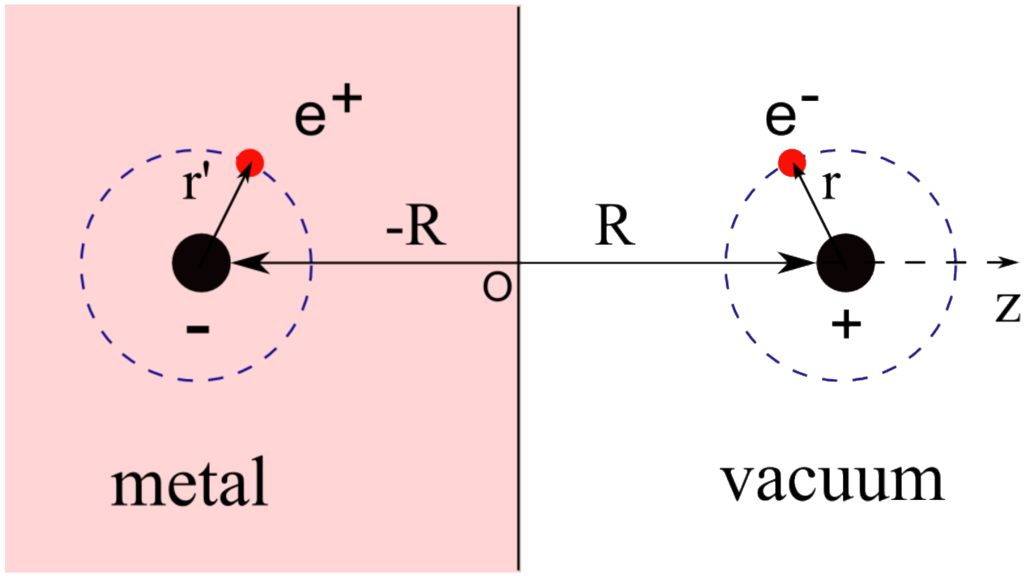
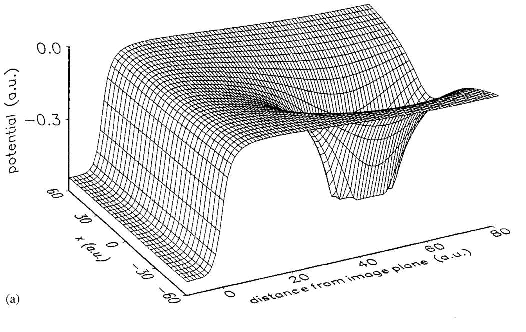
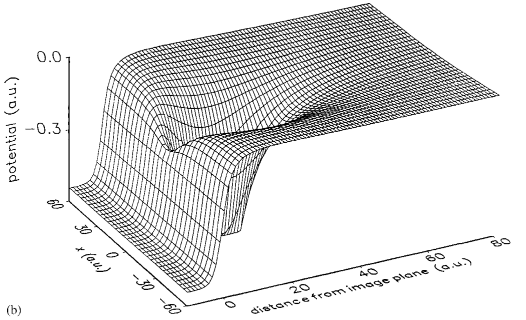


image charge



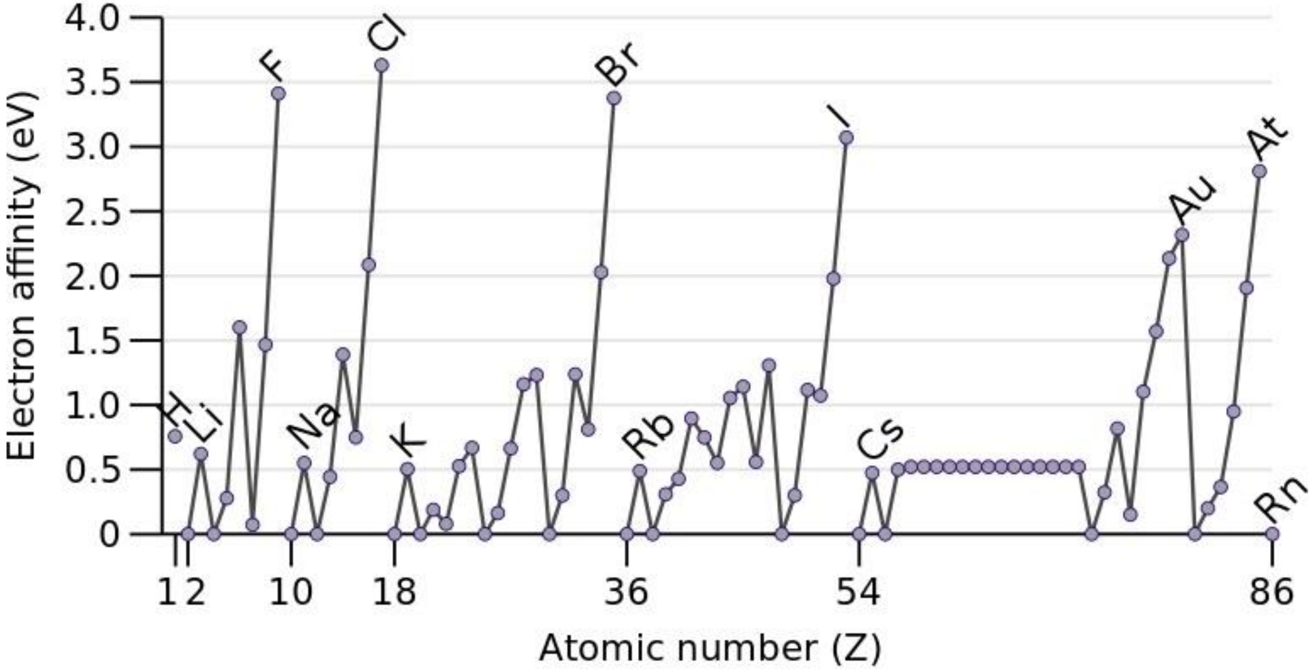
(a)



(b)

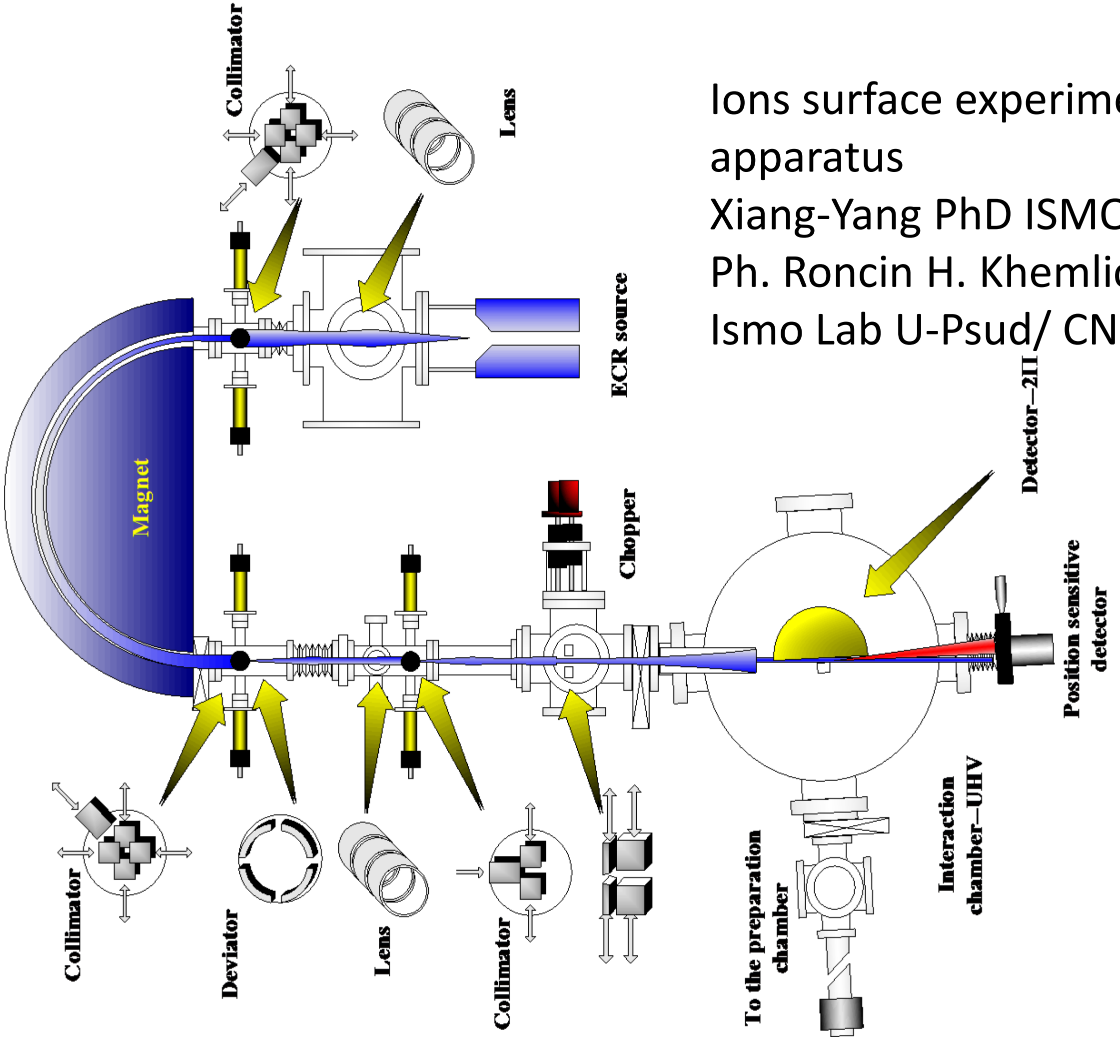
H. Winter: Phys. Reports 367 (2002/387, 582)

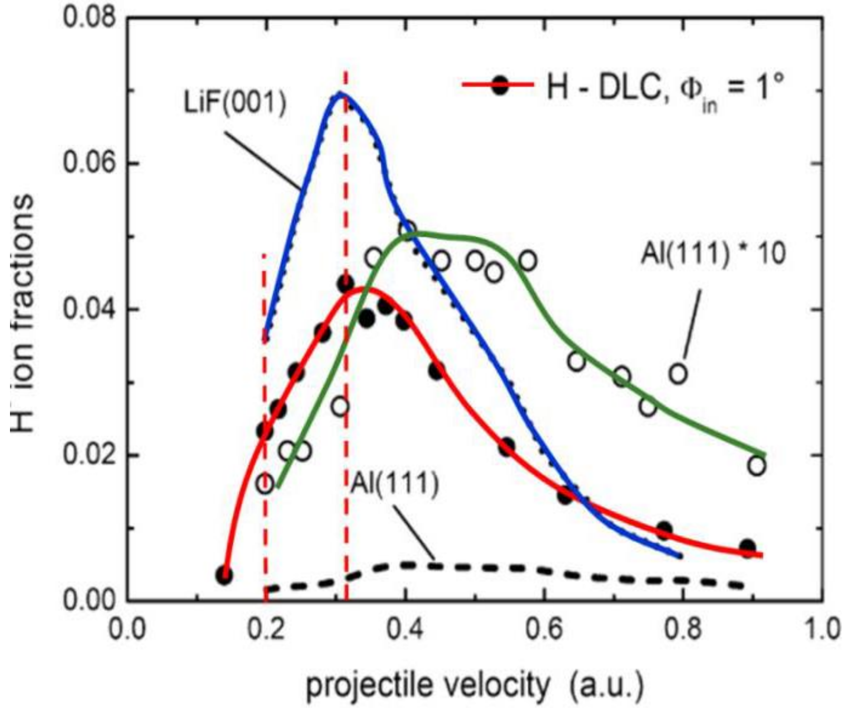
- Electron affinity : energy required to detach the extra electron from a negative ion
  - H^-/D^- are stable negative-ions but:
- The electron affinity is quite low: 0.75 eV



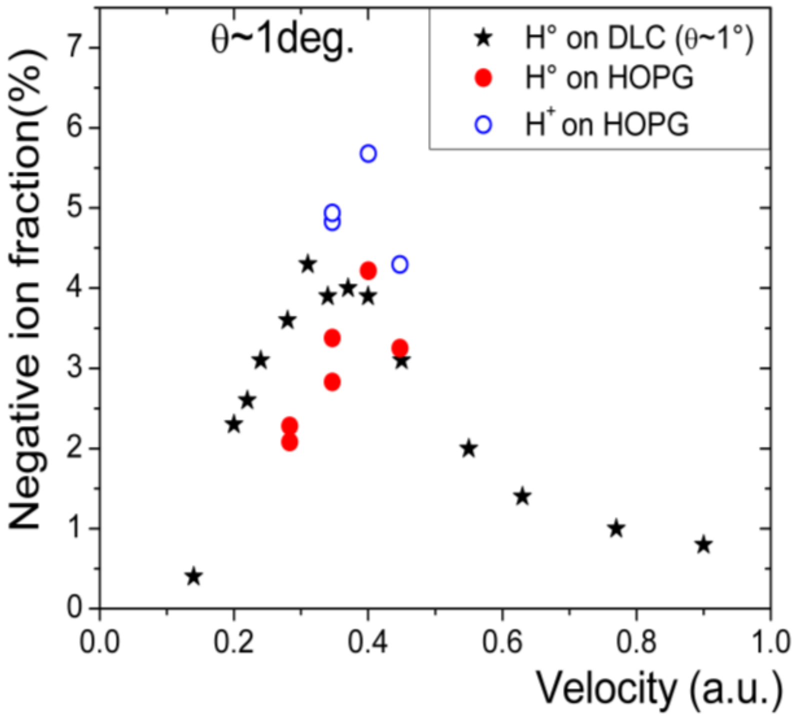
Ions surface experimental apparatus

Xiang-Yang PhD ISMO 2013
Ph. Roncin H. Khemliche,
Ismo Lab U-Psud/ CNRS





Negative H^- formation for different materials (Xiang-Yang PhD)



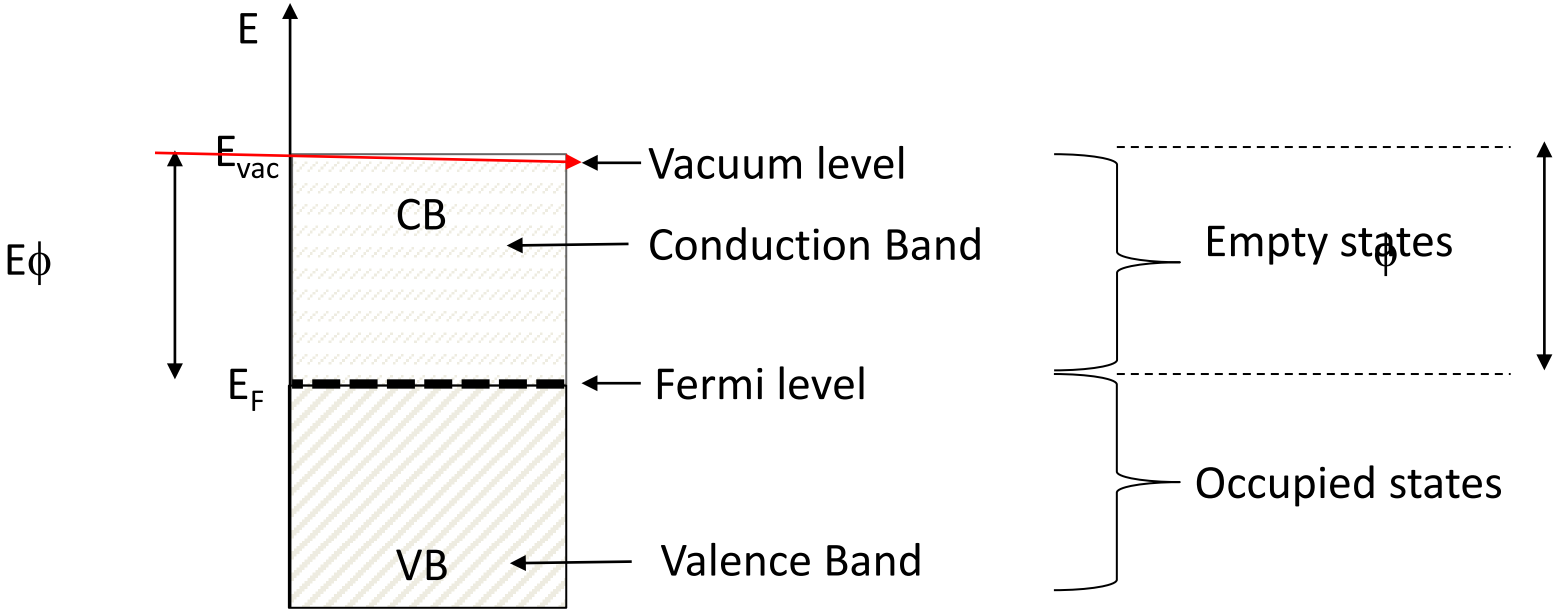
Negative H^- formation different C- materials
(Xiang-Yang PhD)

References

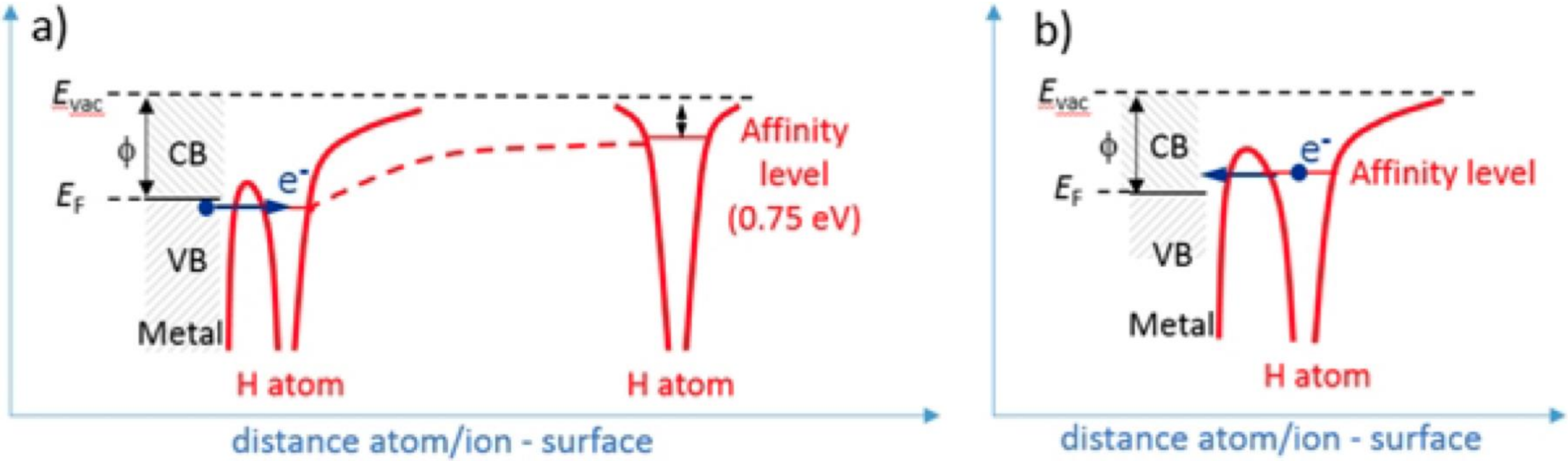
- H. Winter: Phys. Reports 367 (2002/387,582)
- J.A. Scheer et al. Nuclear Instruments and methods in Physics research: B 230 (2005) 330-339.
- Yang Xiang : PhD 2013, Interactions d’atomes et d’ion H^+ dans la création d’ions négatifs.

Surface production mechanisms
Metallic surface

Work function = Minimum energy required to extract an electron from the metal ~ 4-5 eV for most metals

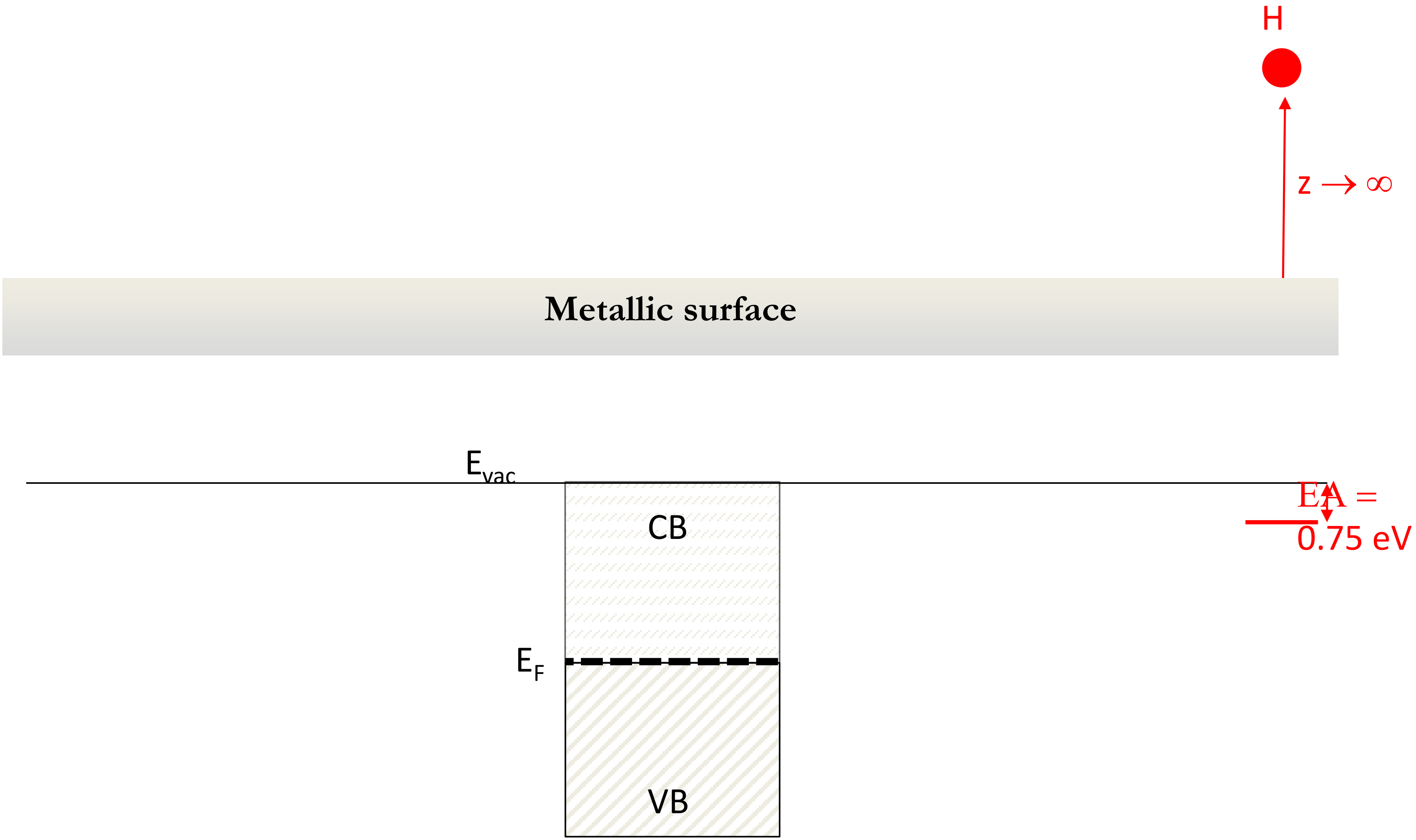


Electron binding energy diagram in a metal

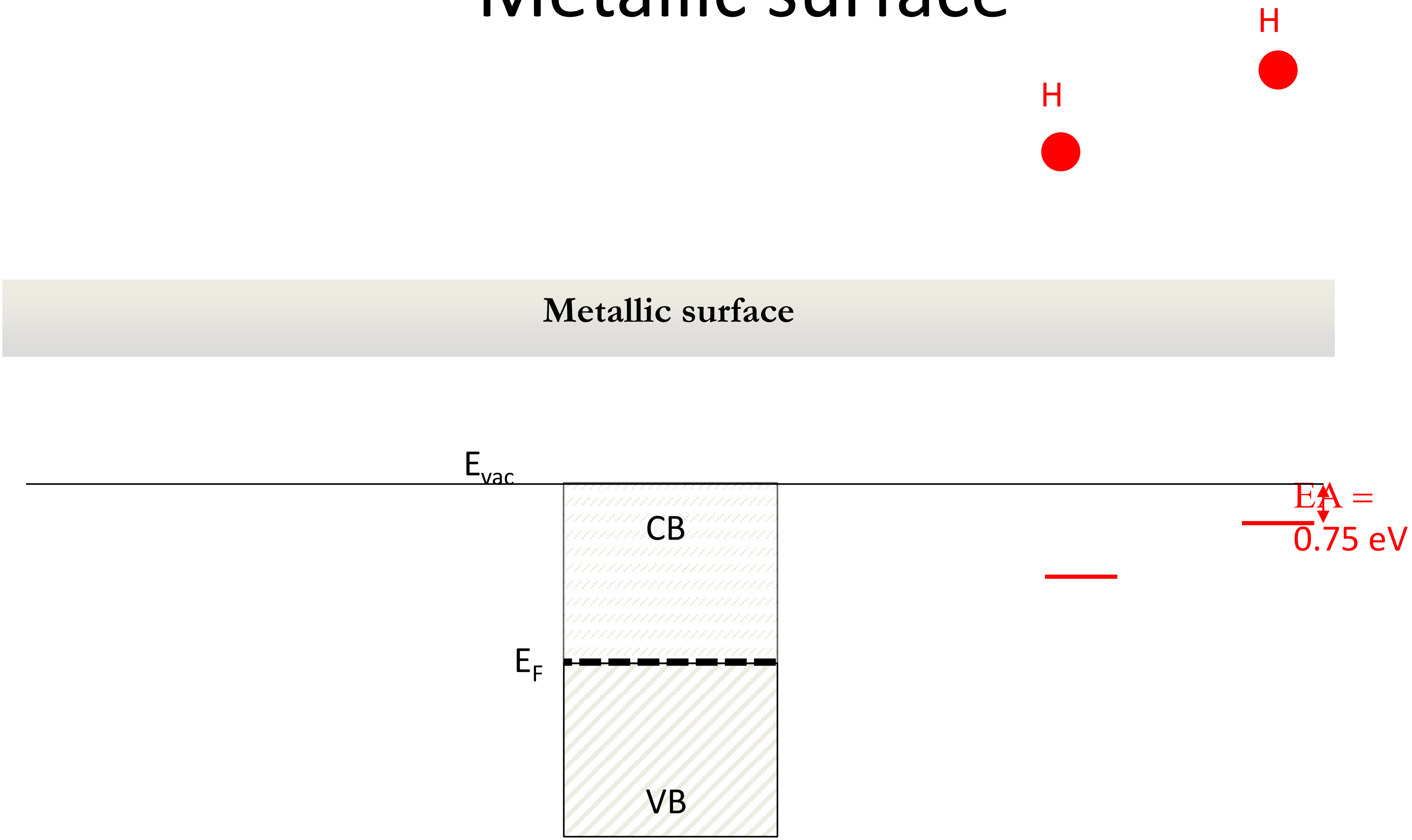


Gilles Cartry et al 2017 New J. Phys.

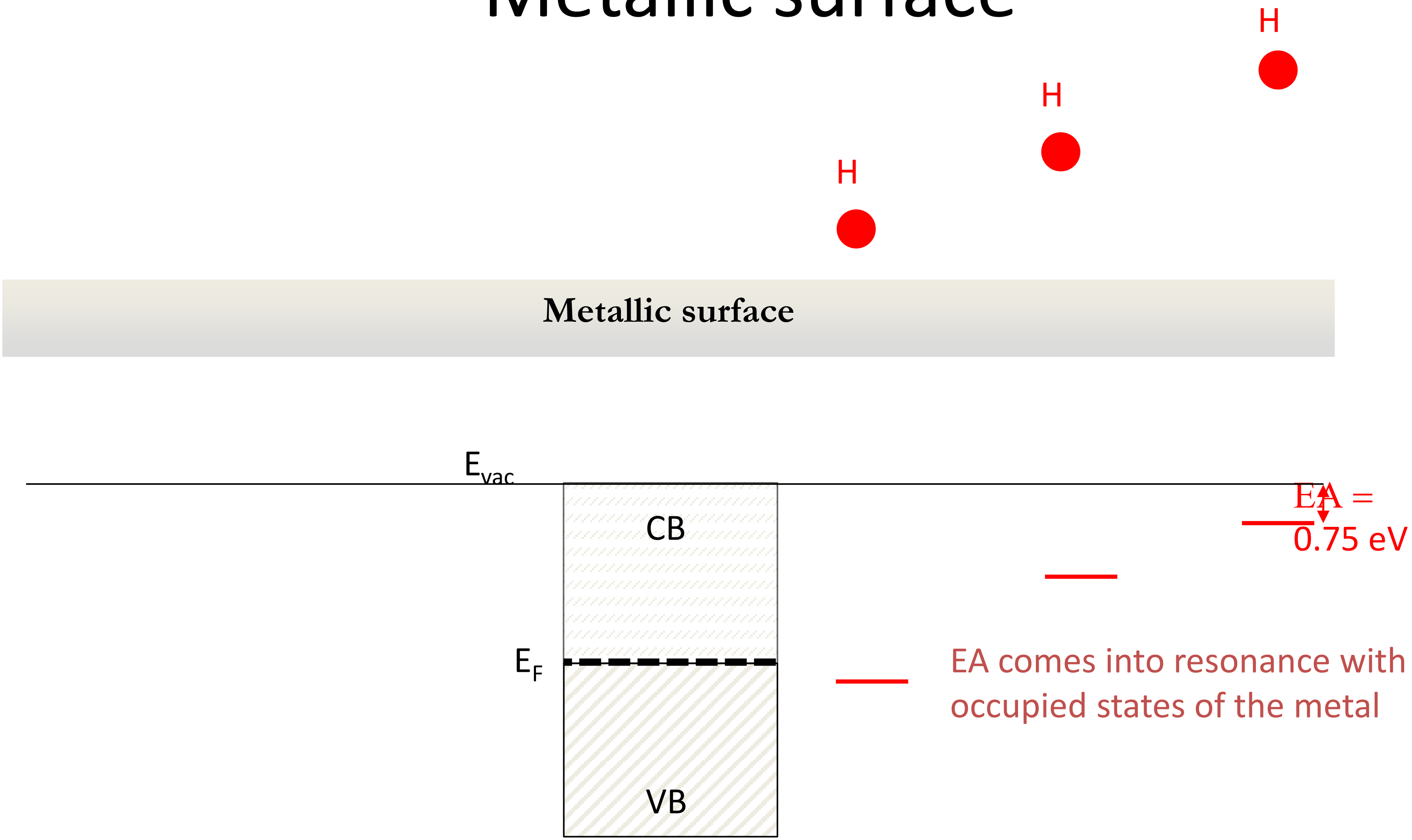
Surface production mechanisms
Metallic surface



Surface production mechanisms
Metallic surface

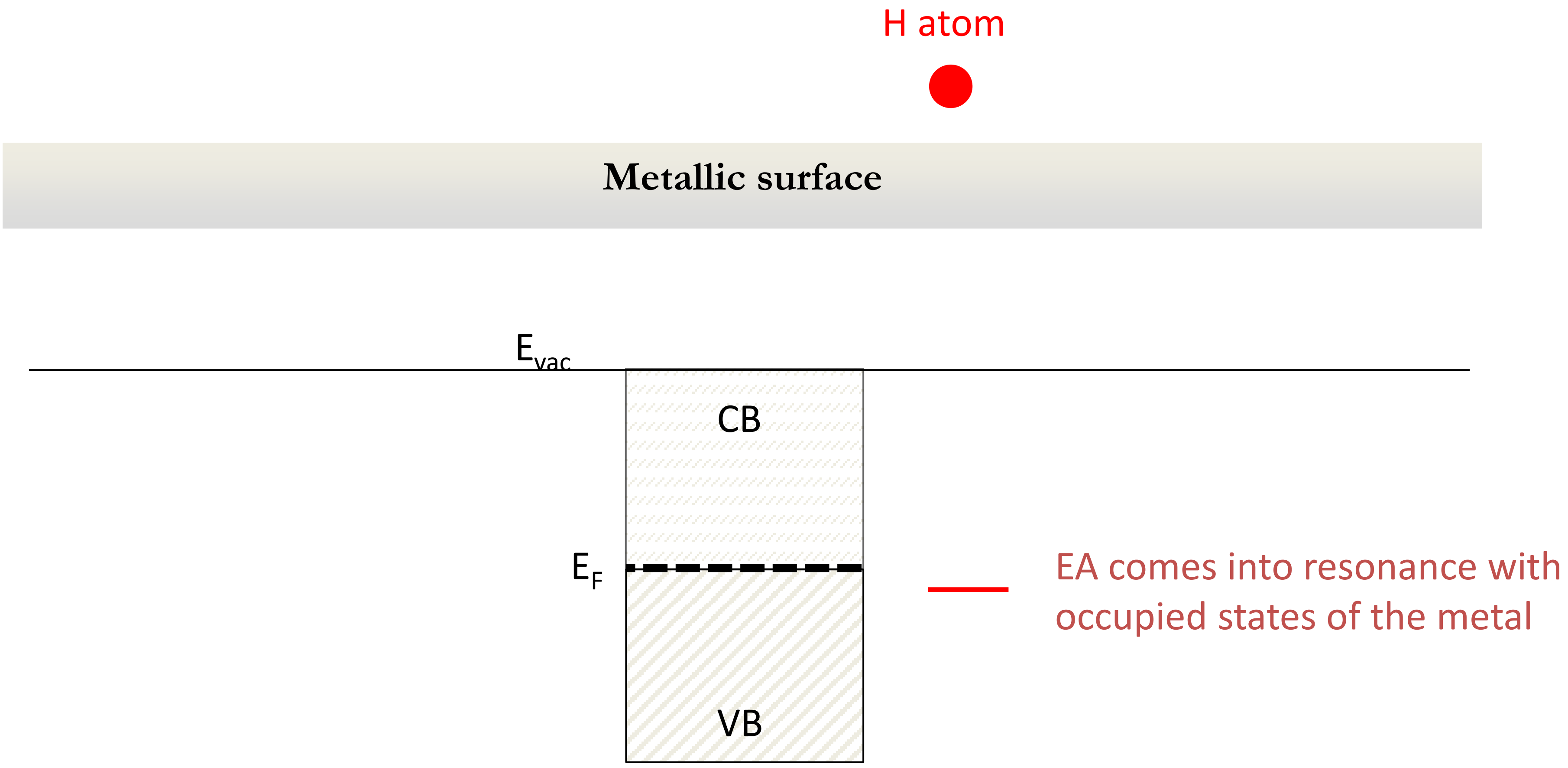


Surface production mechanisms
Metallic surface



EA comes into resonance with occupied states of the metal

Surface production mechanisms
Metallic surface



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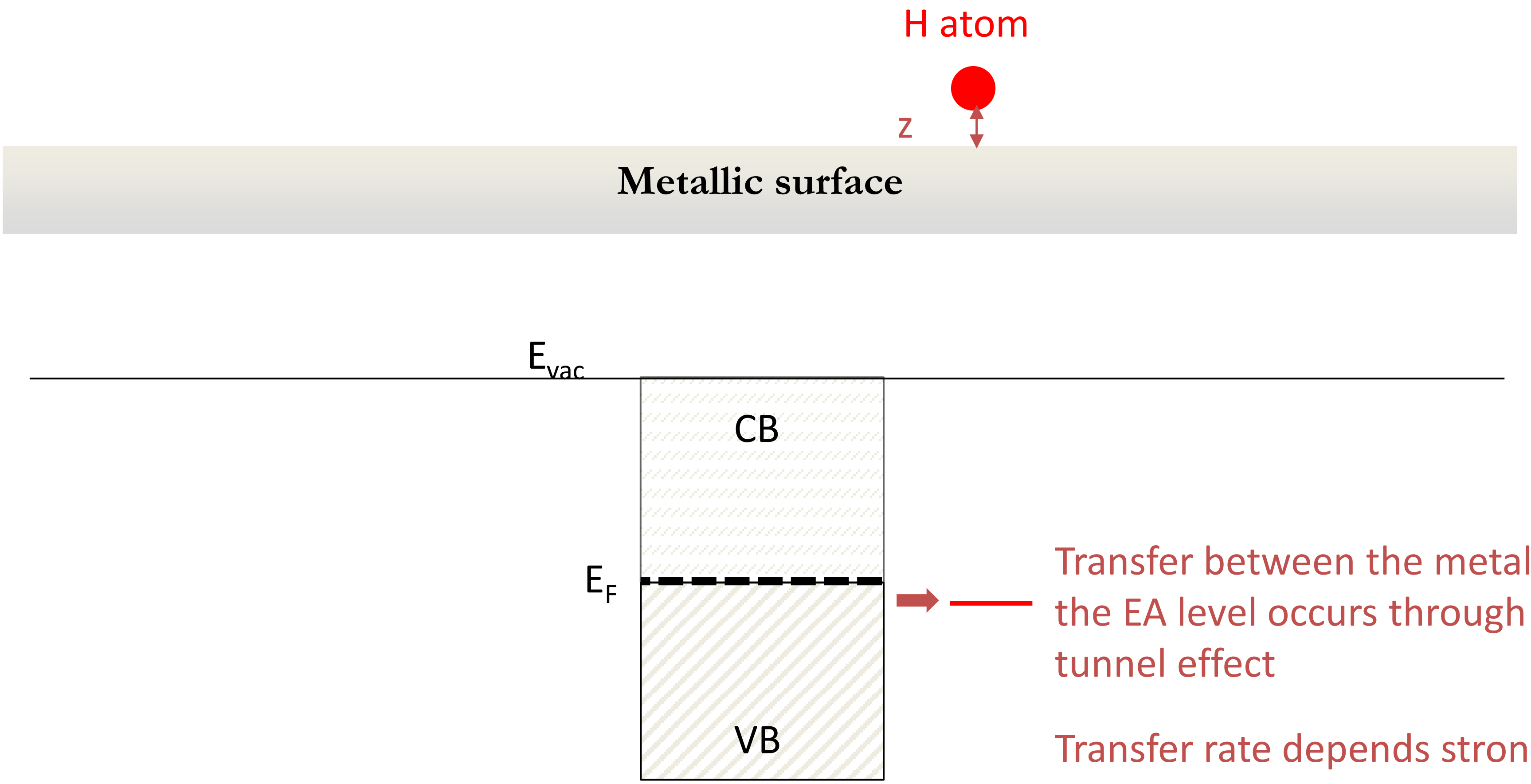
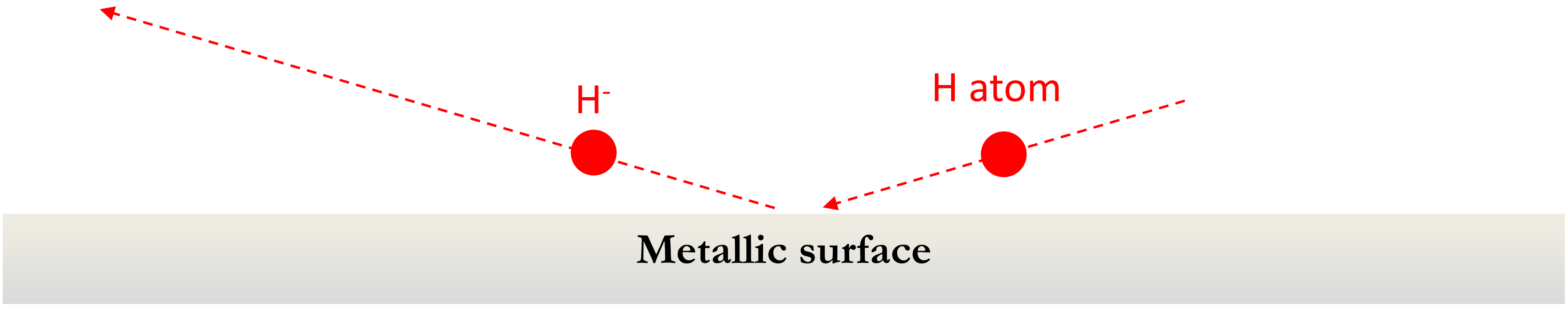
Surface production mechanisms
Metallic surface

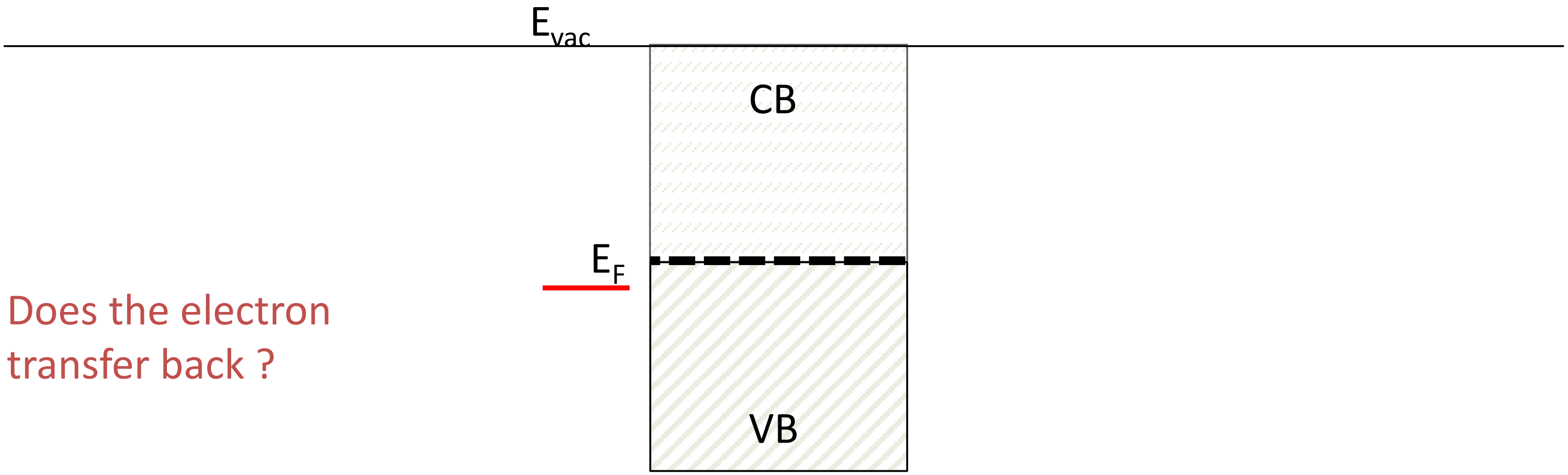


Transfer between the metal and the EA level occurs through tunnel effect

Transfer rate depends strongly on the distance z

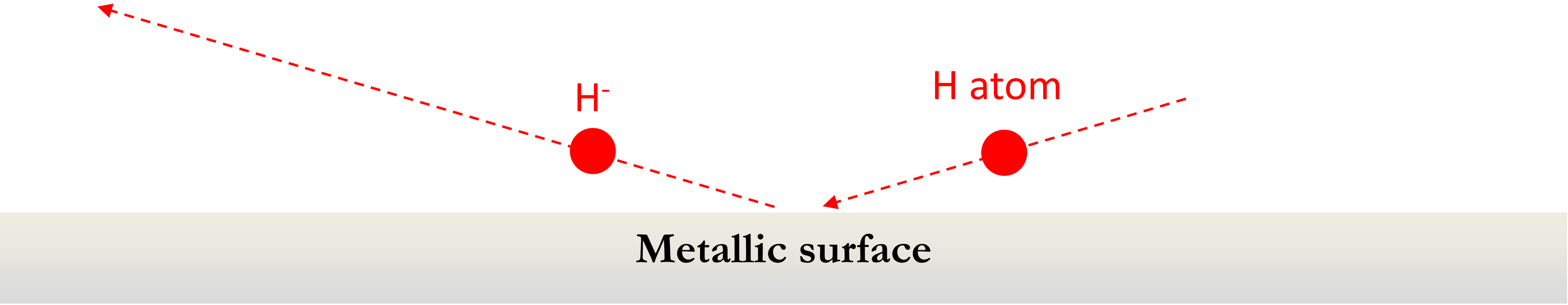
Surface production mechanisms
Metallic surface

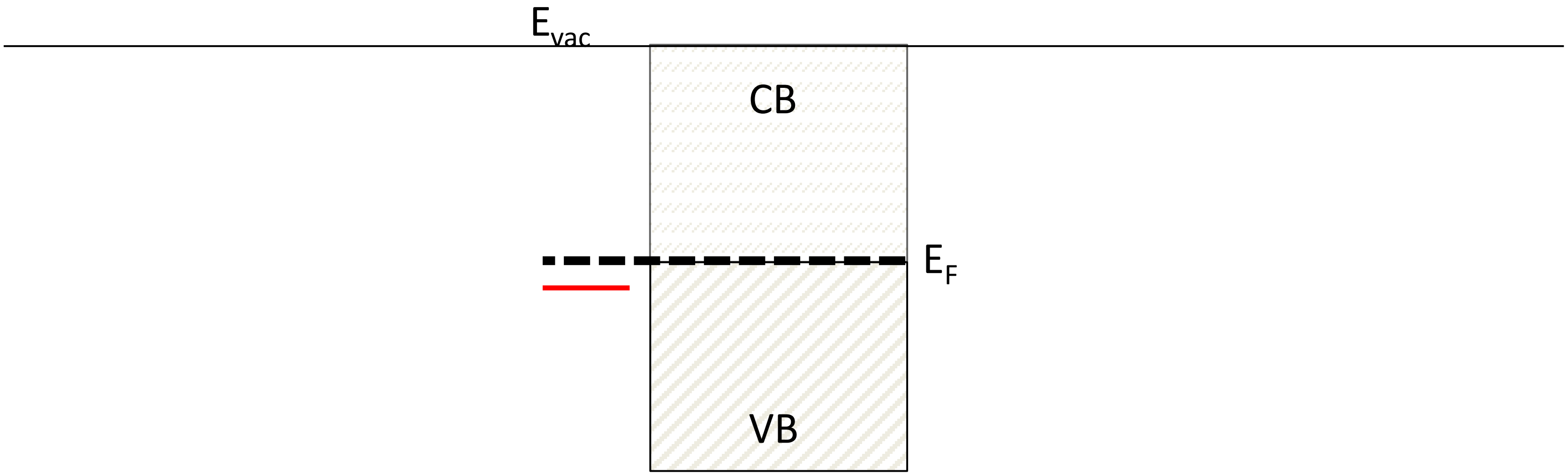




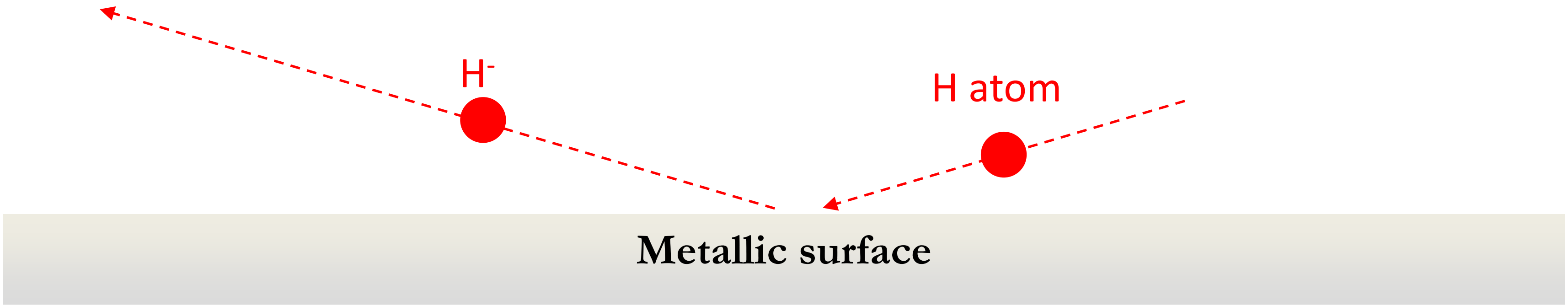
Does the electron transfer back ?

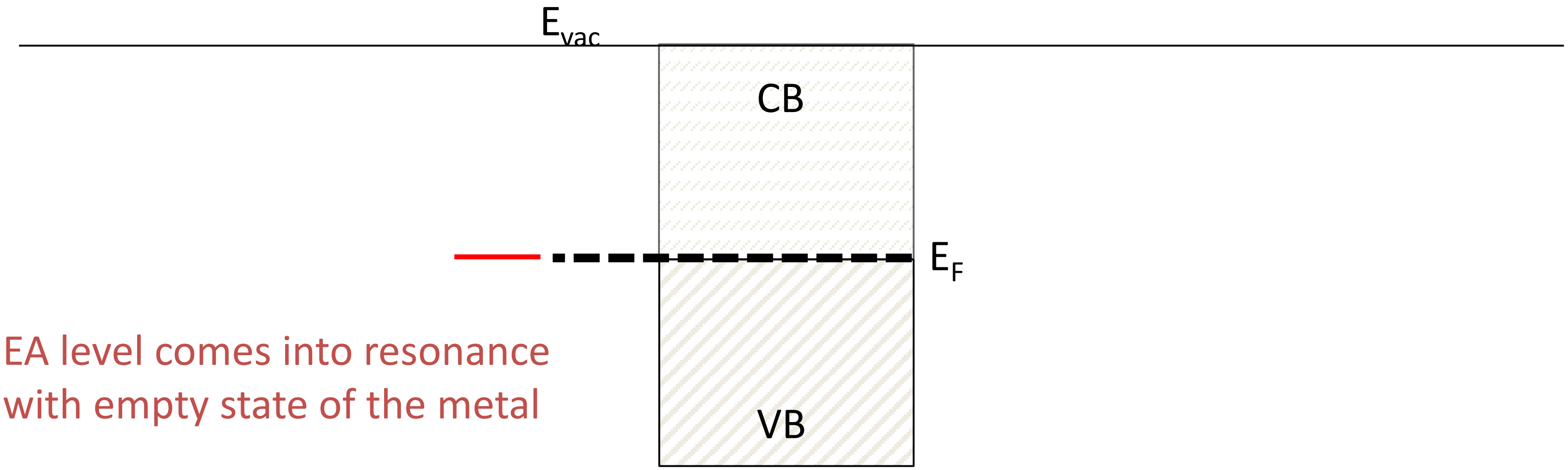
Surface production mechanisms Metallic surface





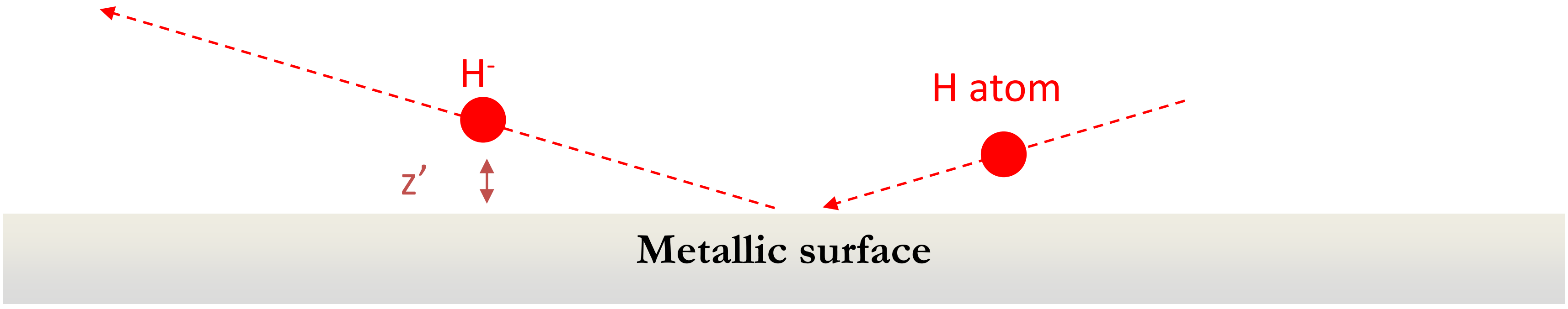
Surface production mechanisms
Metallic surface

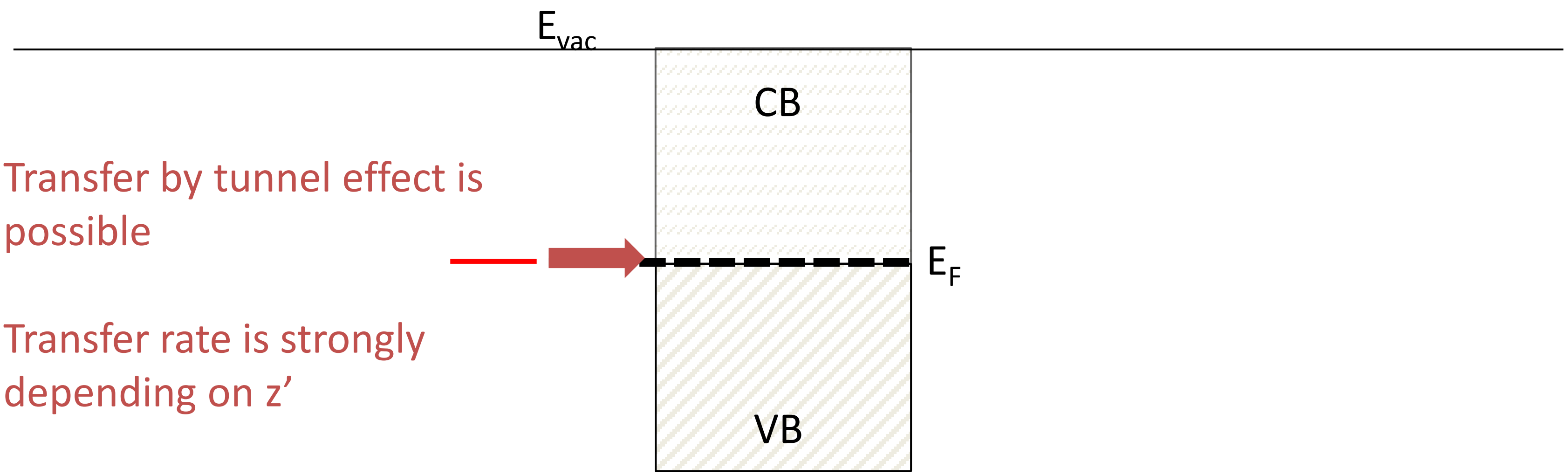




EA level comes into resonance with empty state of the metal

Surface production mechanisms
Metallic surface

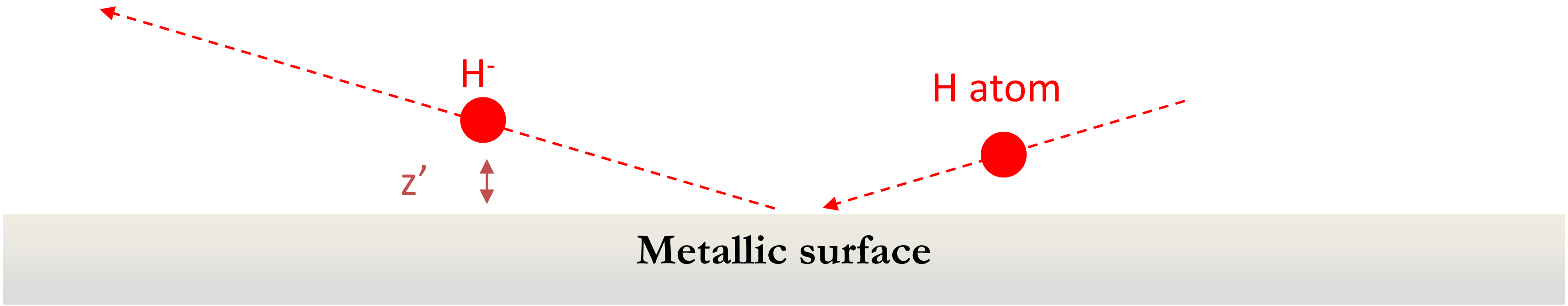


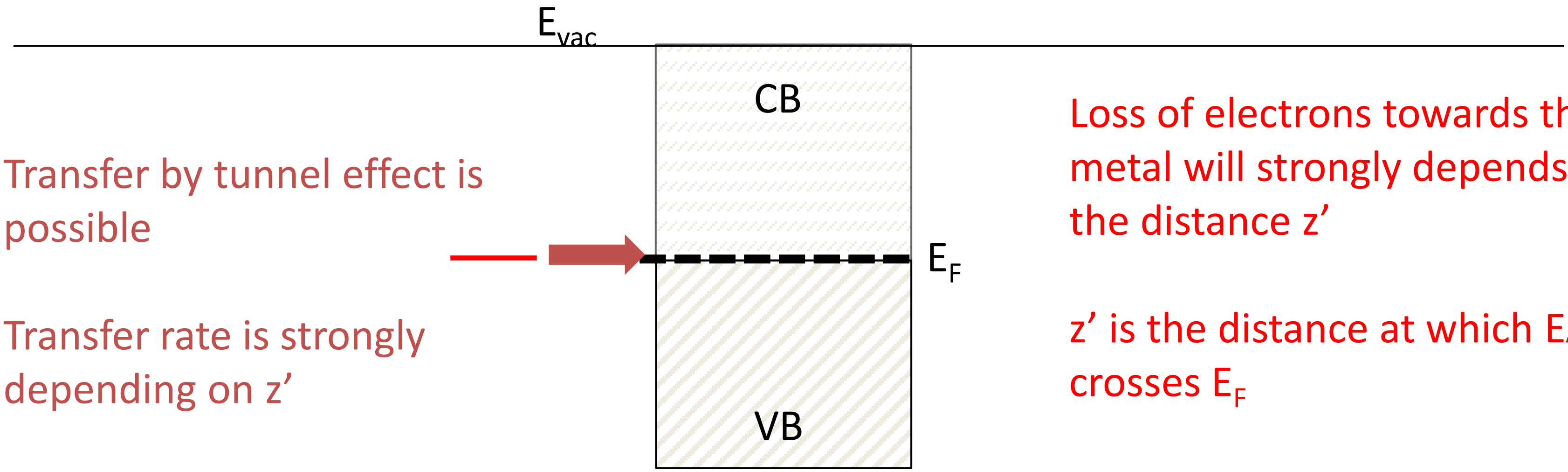


Transfer by tunnel effect is possible

Transfer rate is strongly depending on z'

Surface production mechanisms
Metallic surface





Transfer by tunnel effect is possible

Transfer rate is strongly depending on z’

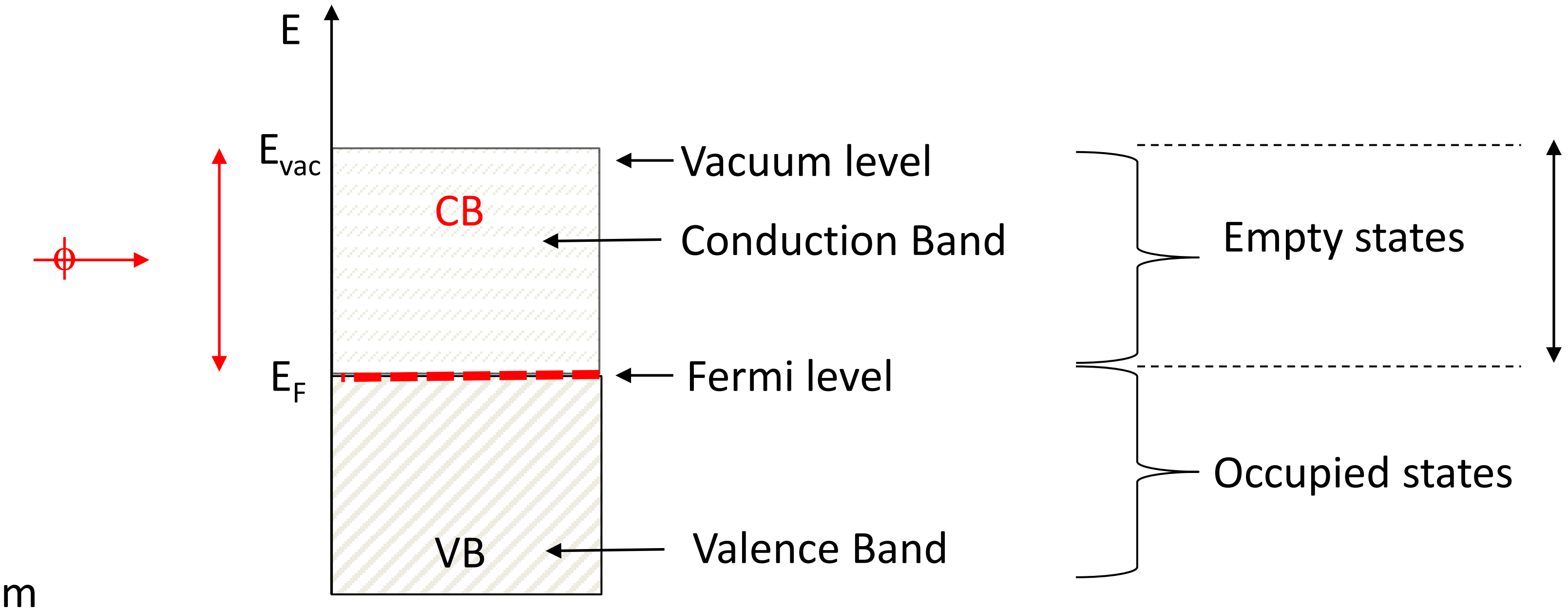
Loss of electrons towards the metal will strongly depends on the distance z’

z’ is the distance at which EA crosses E_F

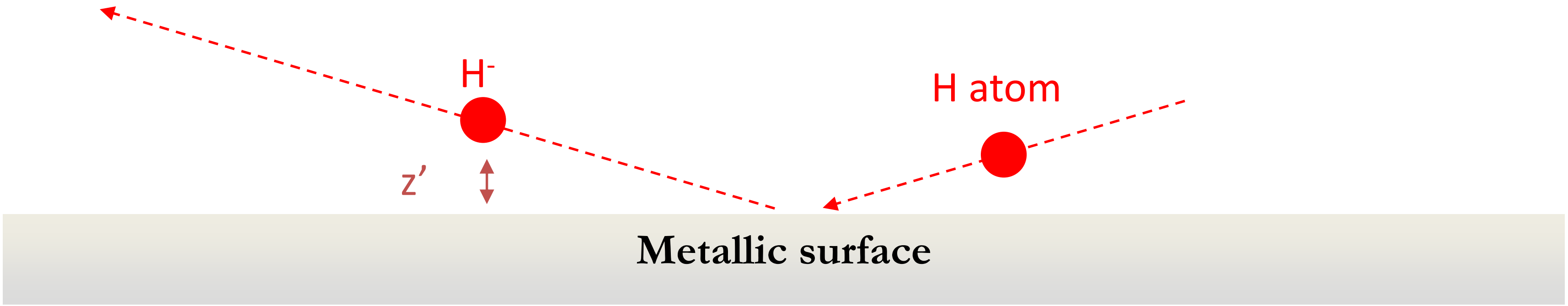
Surface production mechanisms
Metallic surface

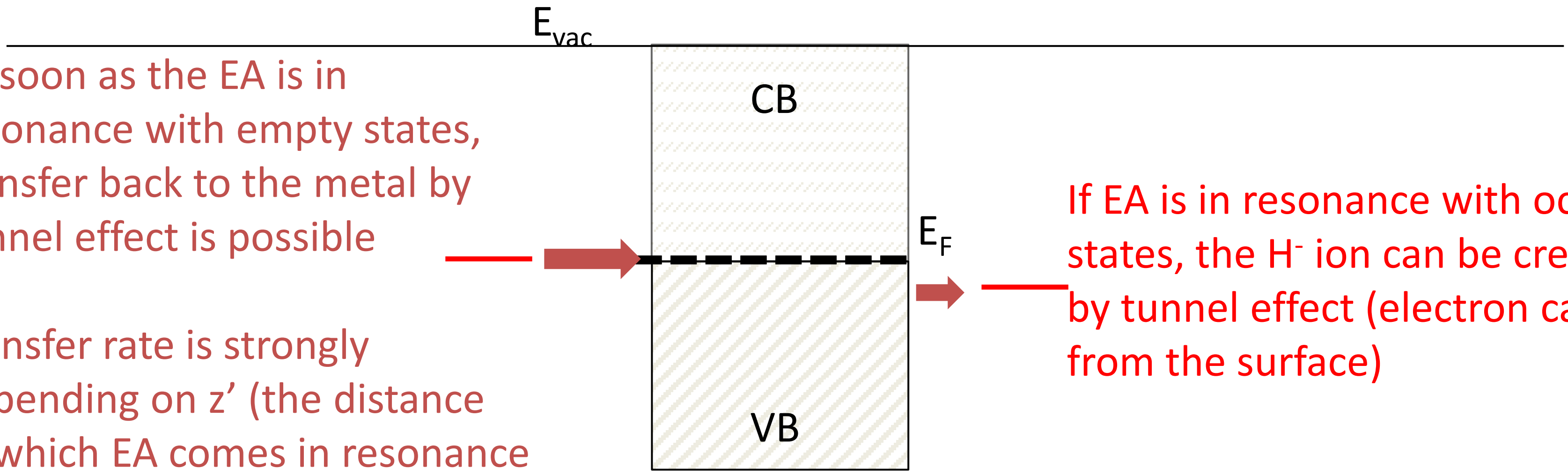
- What is the surface parameter playing the strongest role on the negative-ion yield at metal surface ?

Work function = Minimum energy required to extract an electron from the metal



Surface production mechanisms
Metallic surface



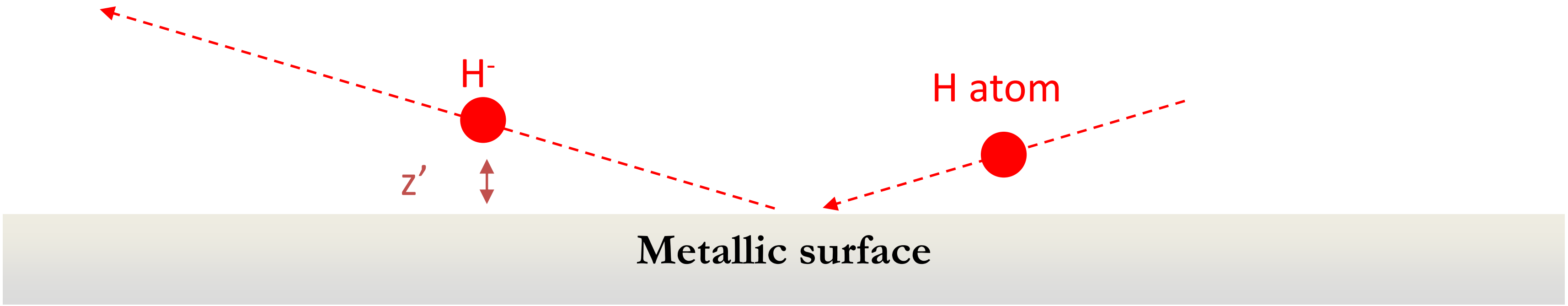


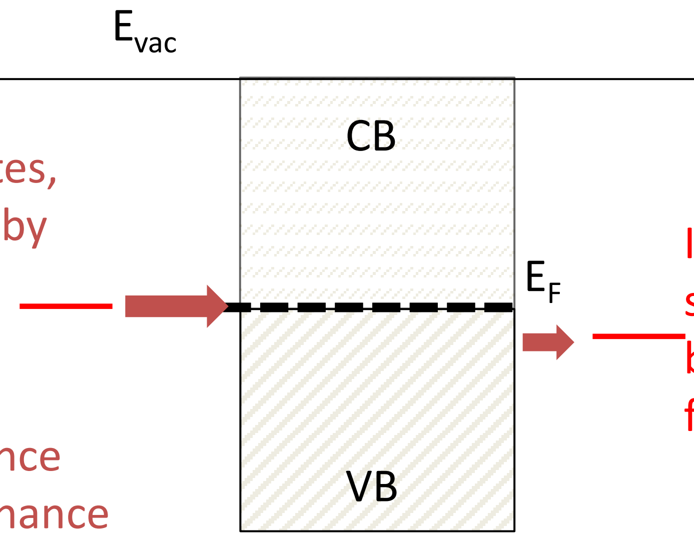
As soon as the EA is in resonance with empty states, transfer back to the metal by tunnel effect is possible

Transfer rate is strongly depending on z' (the distance at which EA comes in resonance with empty states)

If EA is in resonance with occupied states, the H$^-$ ion can be created by tunnel effect (electron capture from the surface)

To increase surface ionization, what is the material parameter we have to play with ?





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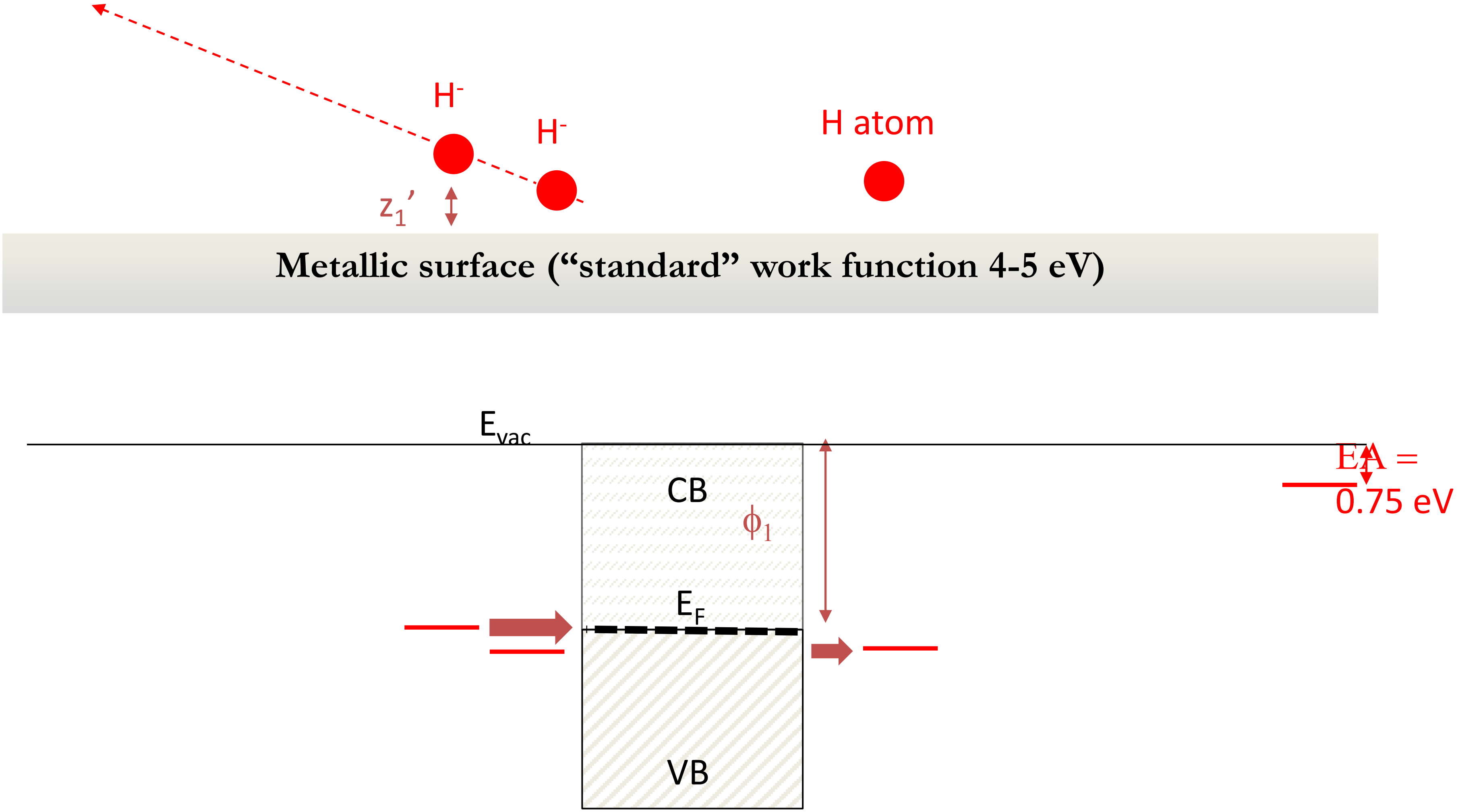
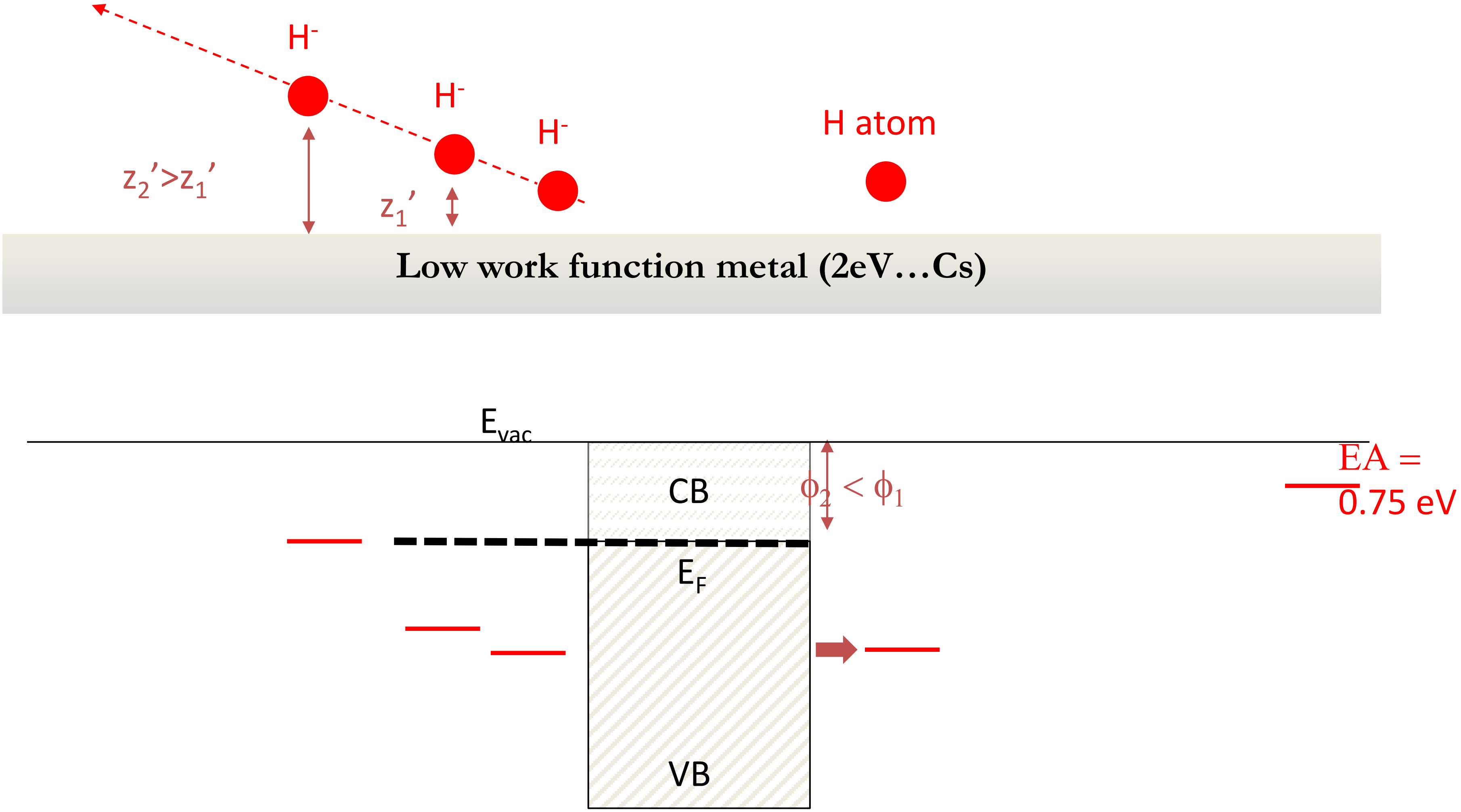
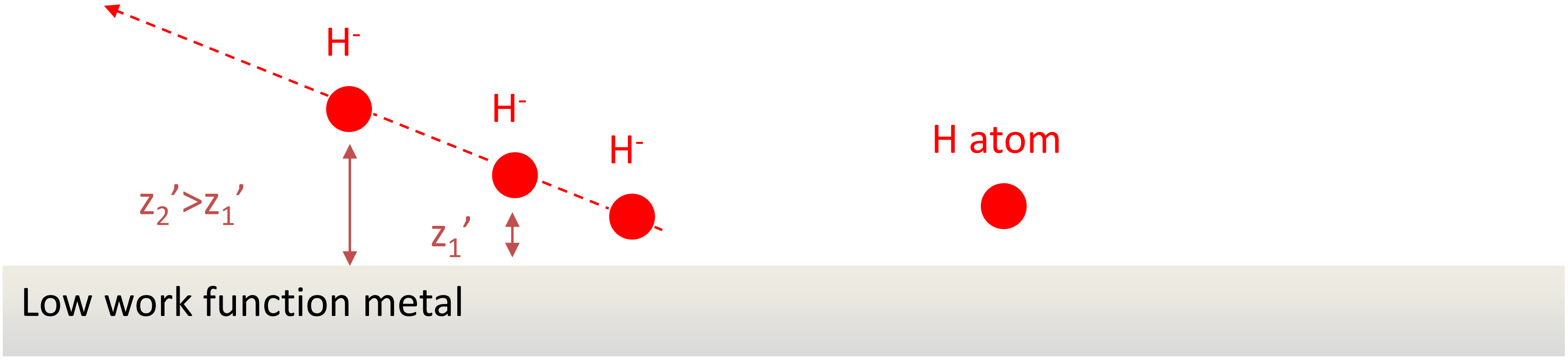
Surface production mechanisms
Metallic surface

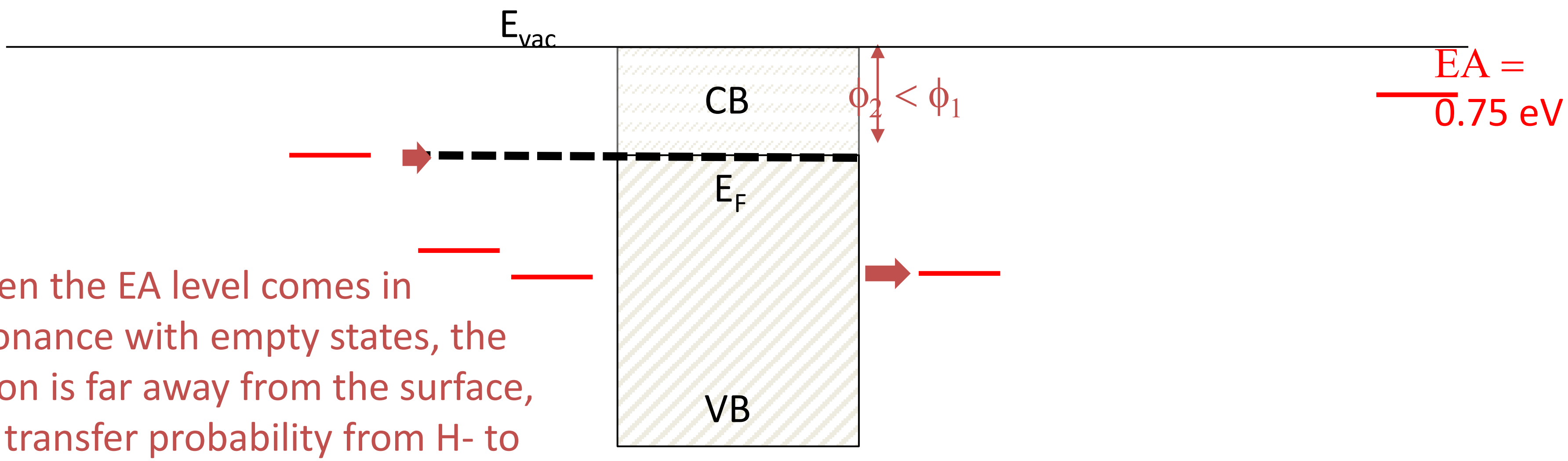


Surface production mechanisms
Metallic surface



Surface production mechanisms
Metallic surface





When the EA level comes in resonance with empty states, the H- ion is far away from the surface, the transfer probability from H- to the metal is low

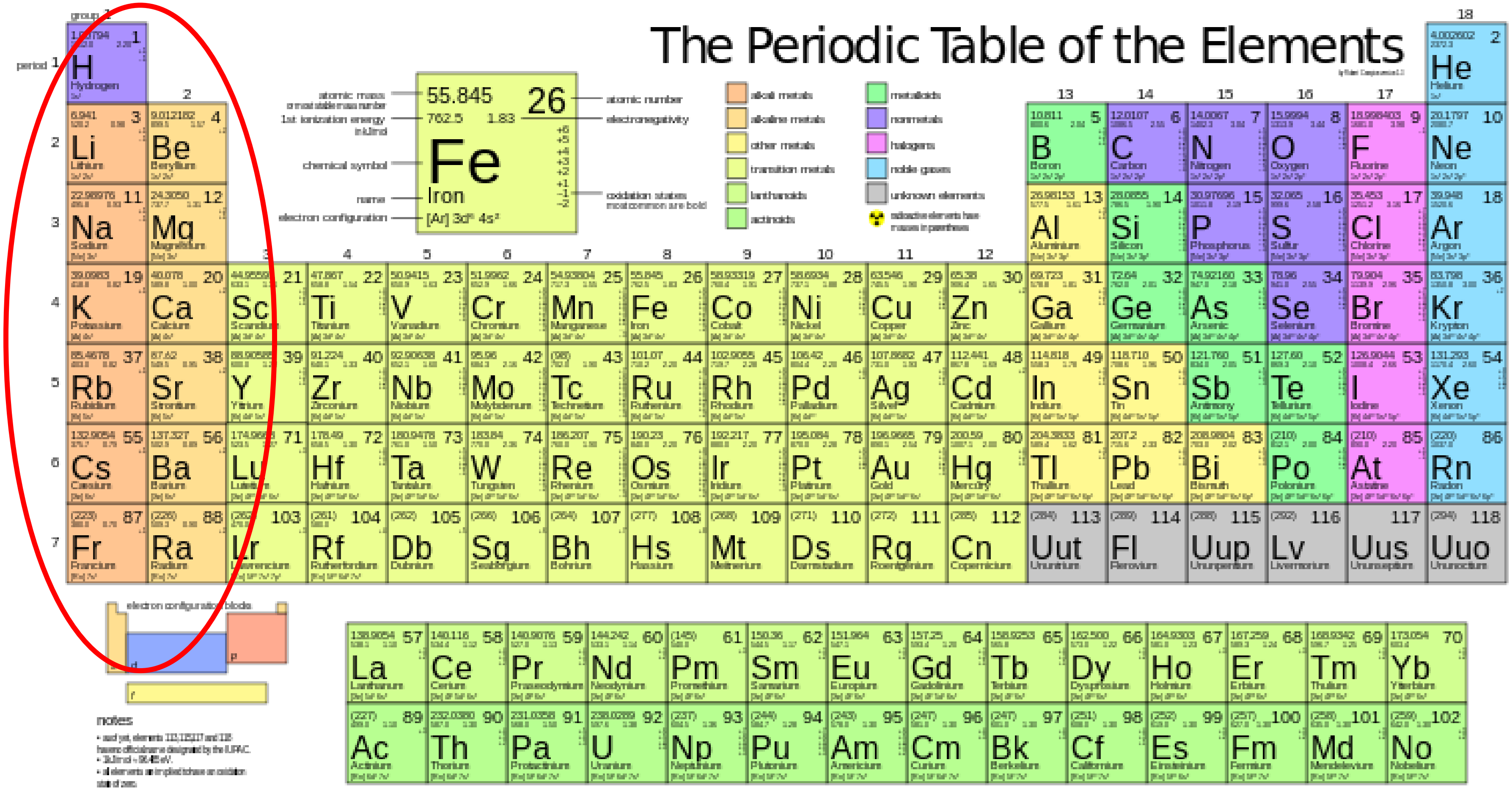
Conclusion on surface production mechanisms at metal surfaces

- Electron capture on a metal is efficient
- Electron loss is usually high

Surface ionization yield is therefore usually low on metals

- Low work function metals can strongly increased the surface ionization yield: capture is easier, loss is lower !

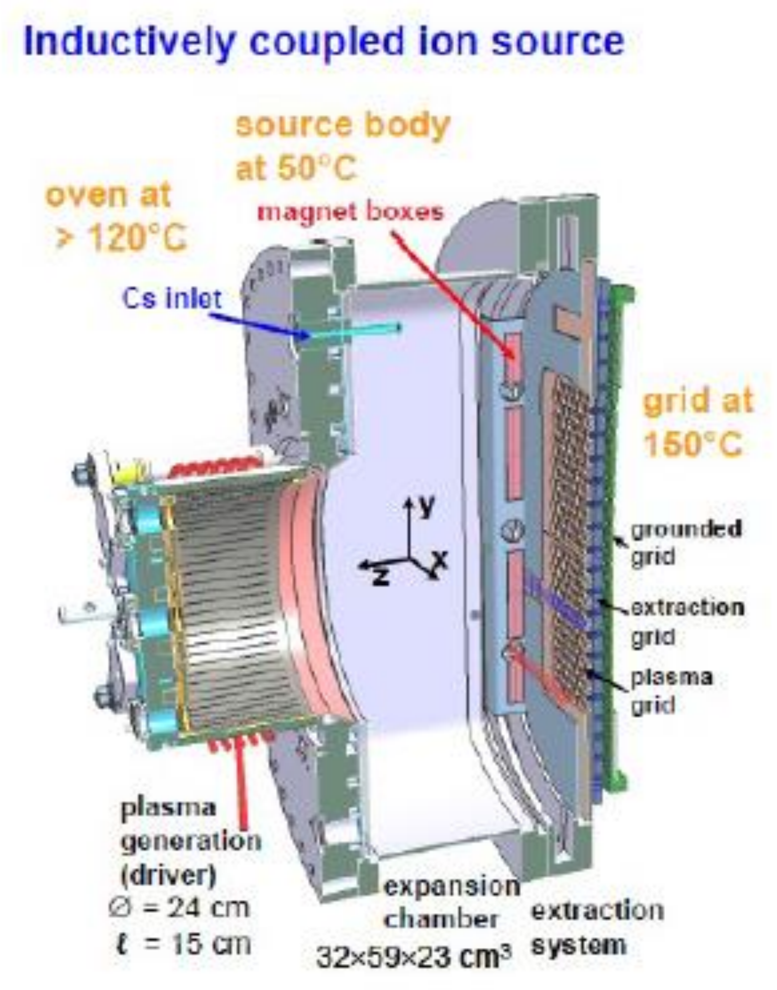
- What are the low work-function metals ?
  - Alkaline and alkaline earth elements

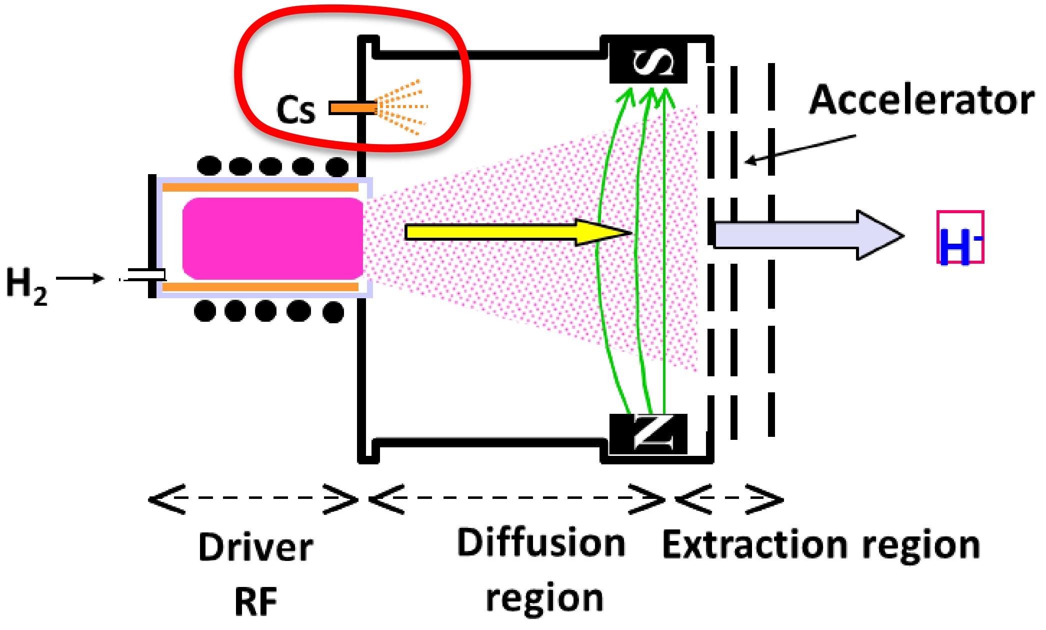


- Cesium (Cs) has the lowest work-function: 2.14 eV
- Barium (Ba) is 2.5-2.7 eV…

Negative-Ion Sources for fusion

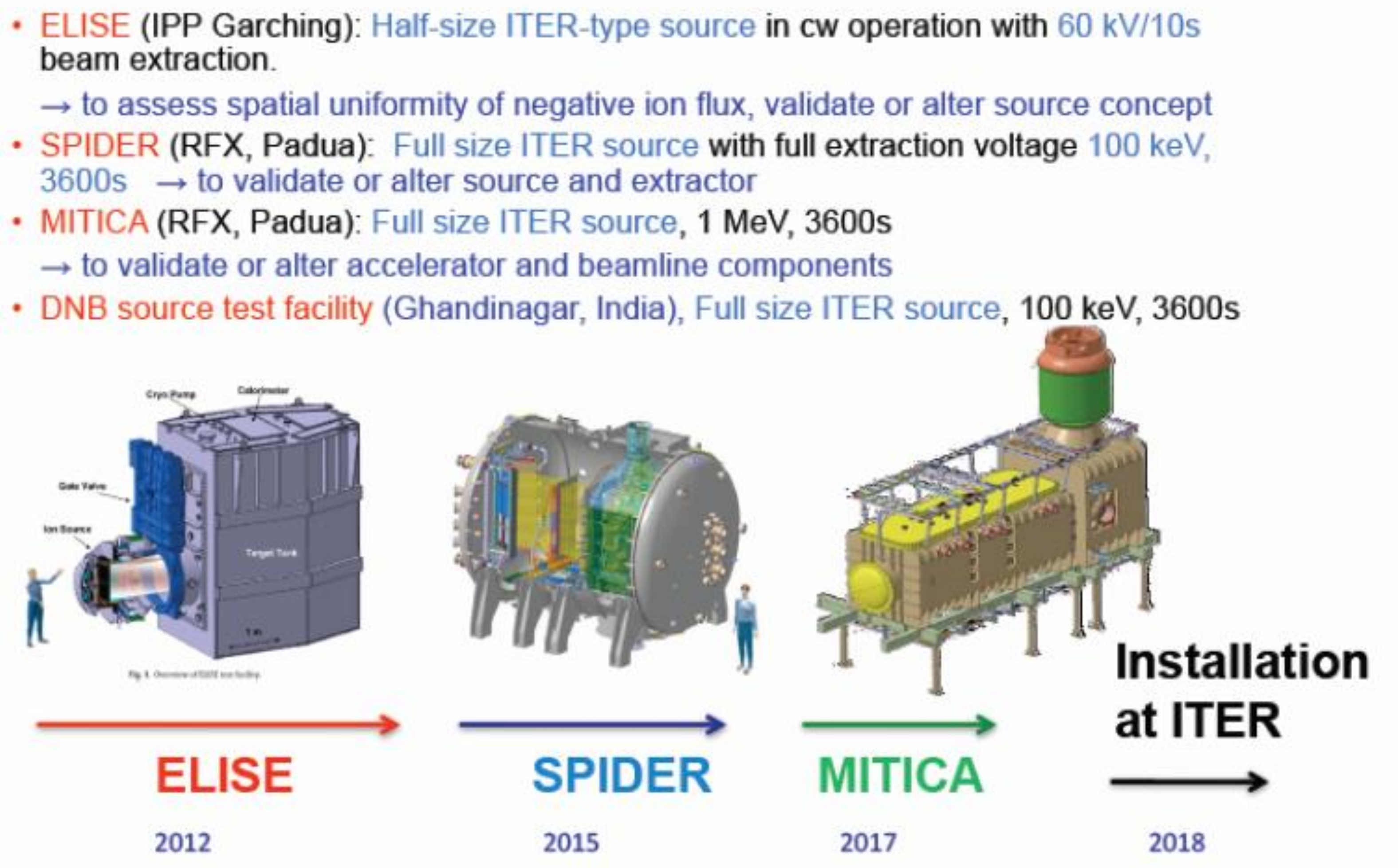
ITER Negative-Ion source (Max Planck Institute)





Next steps

- Batman: first prototype
- MANITU: dedicated to cw operation



- ELISE (IPP Garching): Half-size ITER-type source in cw operation with 60 kV/10s beam extraction.

  → to assess spatial uniformity of negative ion flux, validate or alter source concept
- SPIDER (RFX, Padua): Full size ITER source with full extraction voltage 100 keV, 3600s → to validate or alter source and extractor
- MITICA (RFX, Padua): Full size ITER source, 1 MeV, 3600s

  → to validate or alter accelerator and beamline components
- DNB source test facility (Ghandinagar, India), Full size ITER source, 100 keV, 3600s

Installation at ITER

ELISE 2012 → **SPIDER** 2015 → **MITICA** 2017 → 2018

Eurofusion workprogram

WPHCD: H&CD systems

Description

- H&CD System Engineering

The activities planned for 2014 include: the preparation of an initial CAD configuration model; the definition of design and analysis strategies; the analysis of system requirements and preparation of a draft System Requirement Document (SRD) and of a draft Load Specification (LS) (neutrons, heat loads etc.) including off-normal load conditions which may affect the system itself, or ports and launchers (arcing, VDEs, disruptions etc.).

- NB R&D

The key activities within the work package are: (i) selecting of Cs alternatives and develop source technologies; (ii) investigation of candidate energy recovery solutions and write test specifications; and analysing power supply concepts taking into account energy recovery.

- EC R&D

The activities planned for 2014 are: the design and start of fabrication of a pre-prototype step-tuneable high frequency gyrotron including the analysis of the integrated gyrotron parts; and the analysis and development of candidate high power broadband window solutions.

Why eliminating cesium ?

- Cesium consumption is too high for a fusion power plant (10µg/s)
- Cesium diffusion inside the accelerator may cause breakdowns, parasitic beams…
- Long term operation stability (stable ion beam over very long period) is hard with cesium

- => imply a regular and restrictive maintenance in a nuclear environment

  - Alternative solutions to cesium would be highly valuable !

What are the way of research ?

- A better control of cesium to <u>strongly</u> reduce its use
- Other low work function materials ?
- New ion source design to improve negative-ion yield efficiency without cesium
- New materials enhancing surface production

What are the way of research ?

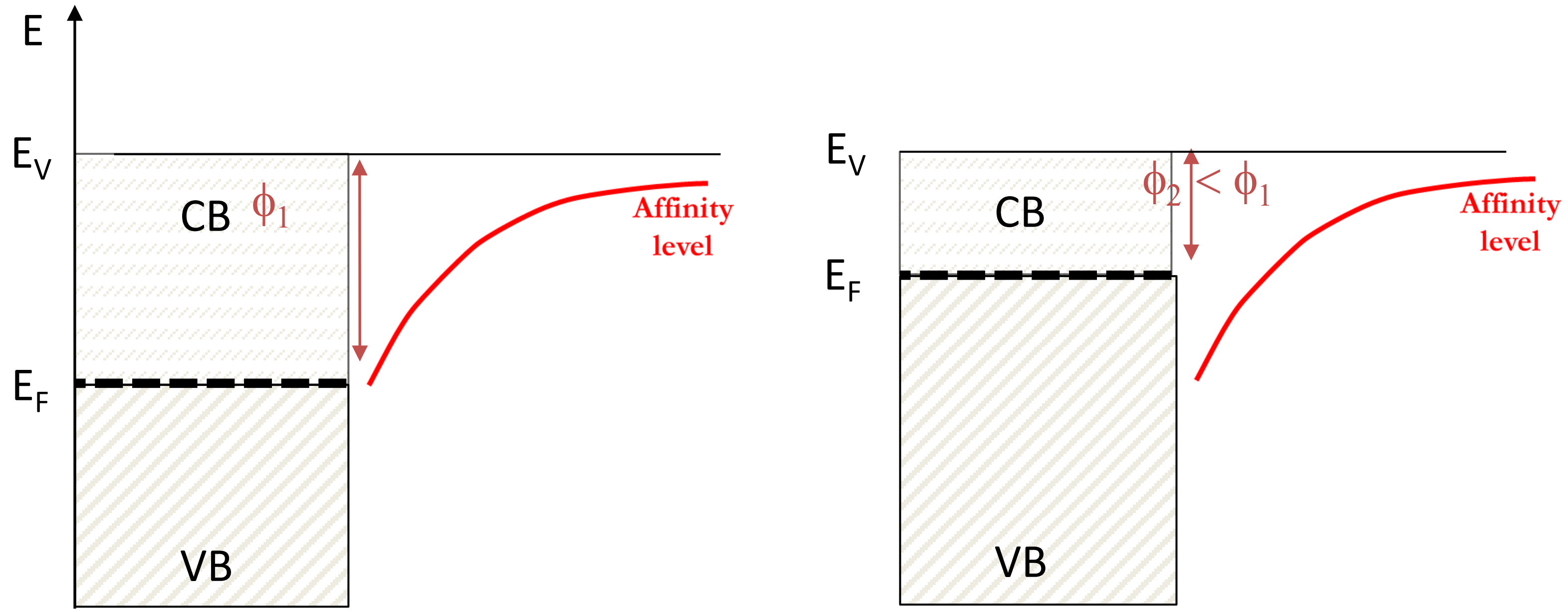
- A better control of cesium to strongly reduce its use

- Other low work function materials ?

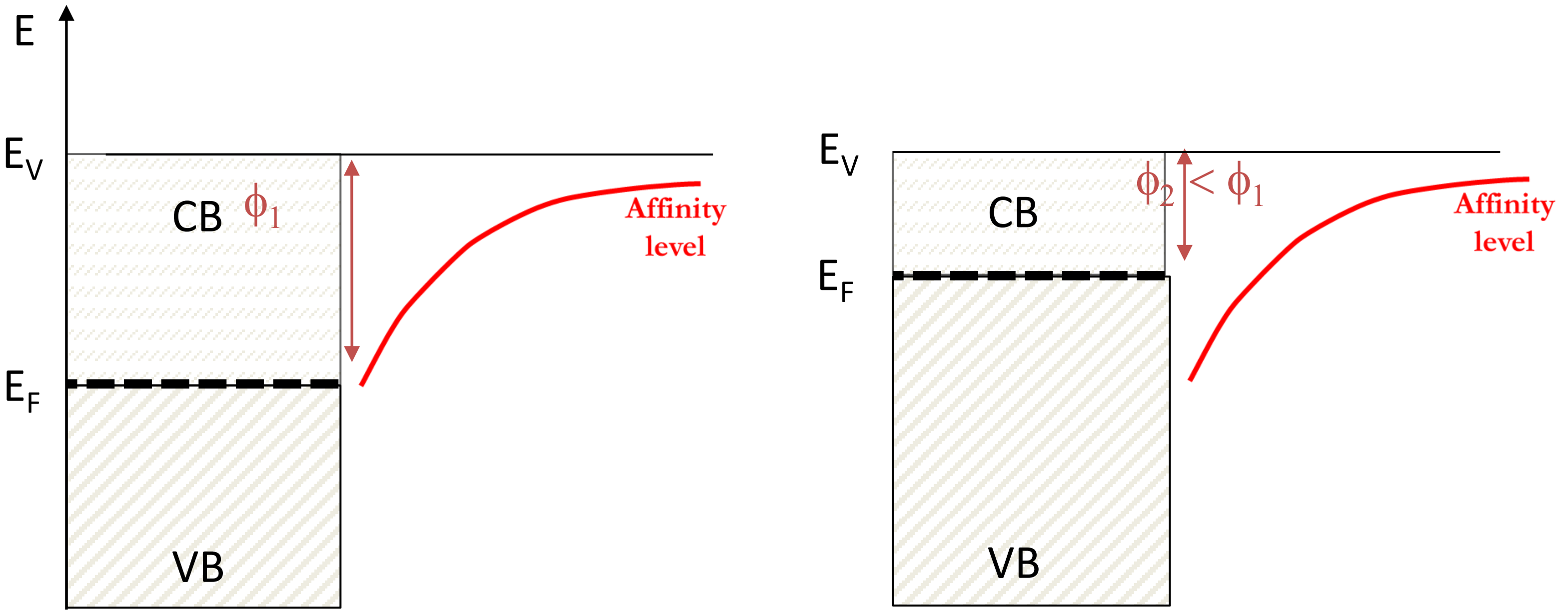
- New ion source design to improve negative-ion yield efficiency without cesium

- New materials enhancing surface production

Negative-ion enhancer materials

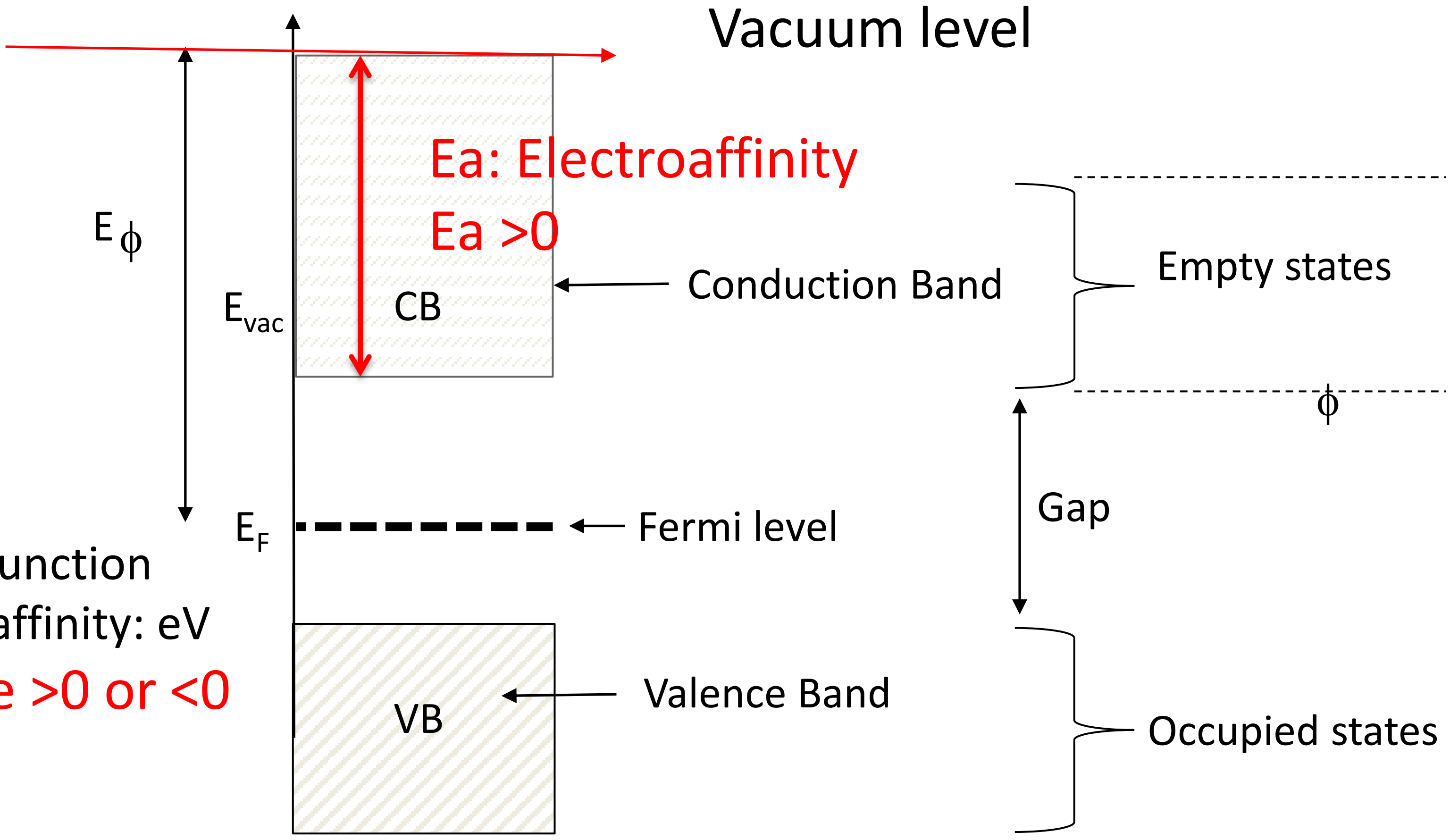


Negative-ion enhancer materials
metallic



What about the insulating materials ?

Electronic structure of insulator



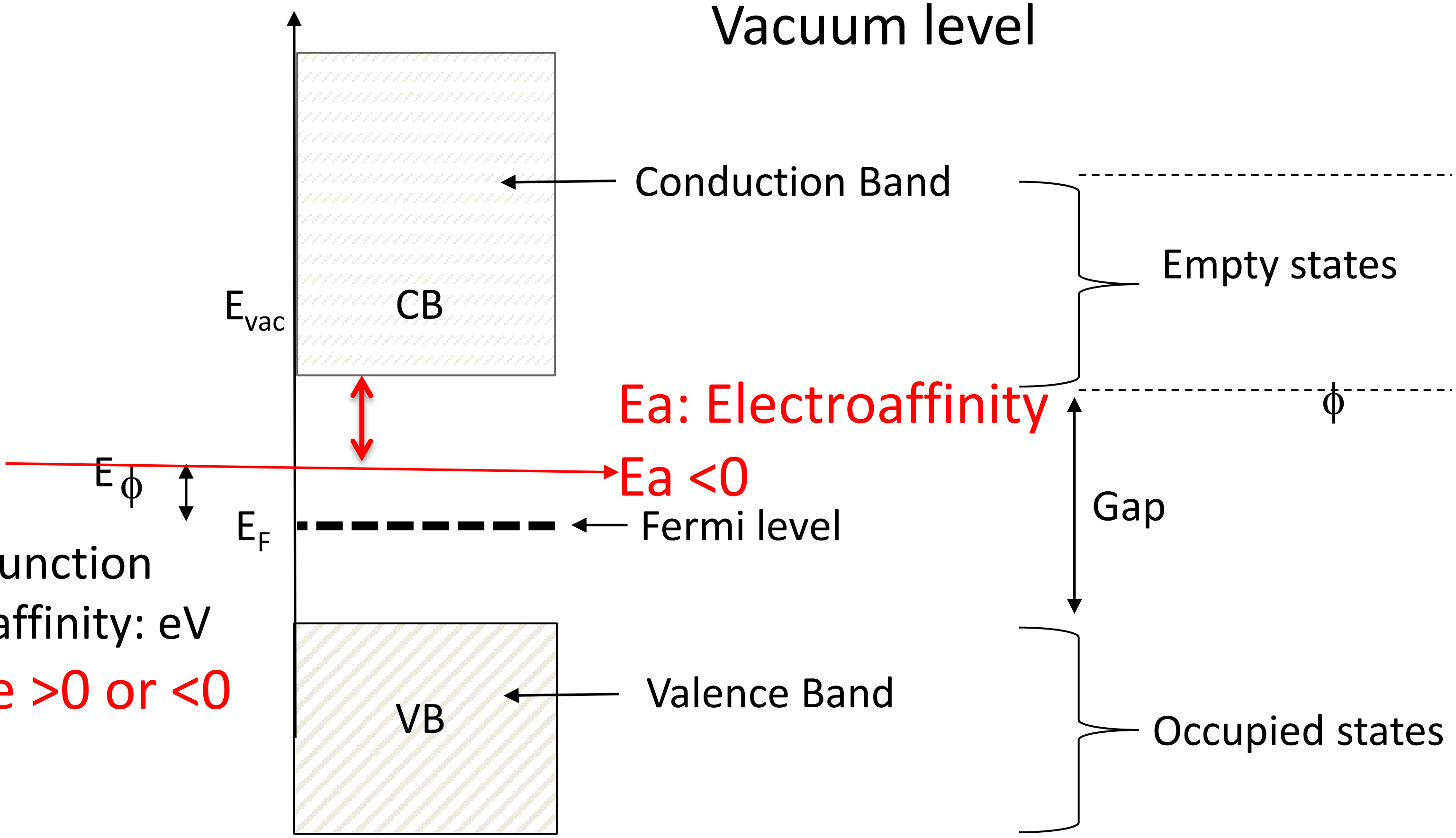
Eϕ: work function

Ea:Electroaffinity: eV

Ea can be >0 or <0

Electron binding energy diagram in an insulator or semiconductor

Electronic structure of insulator



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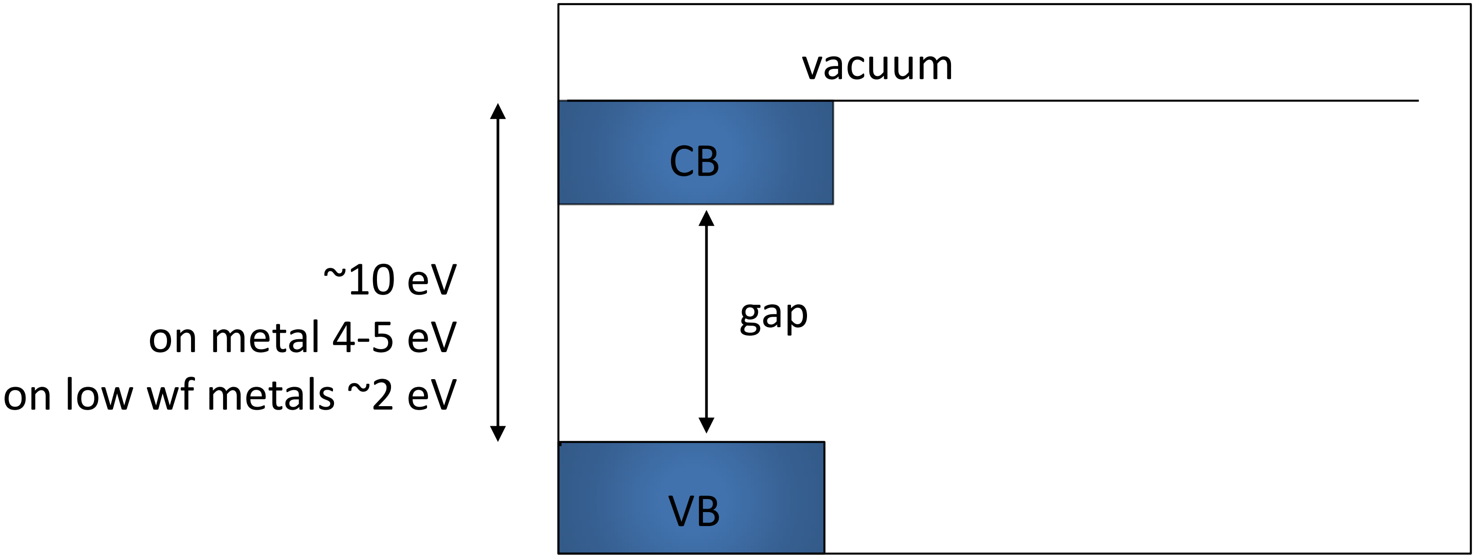
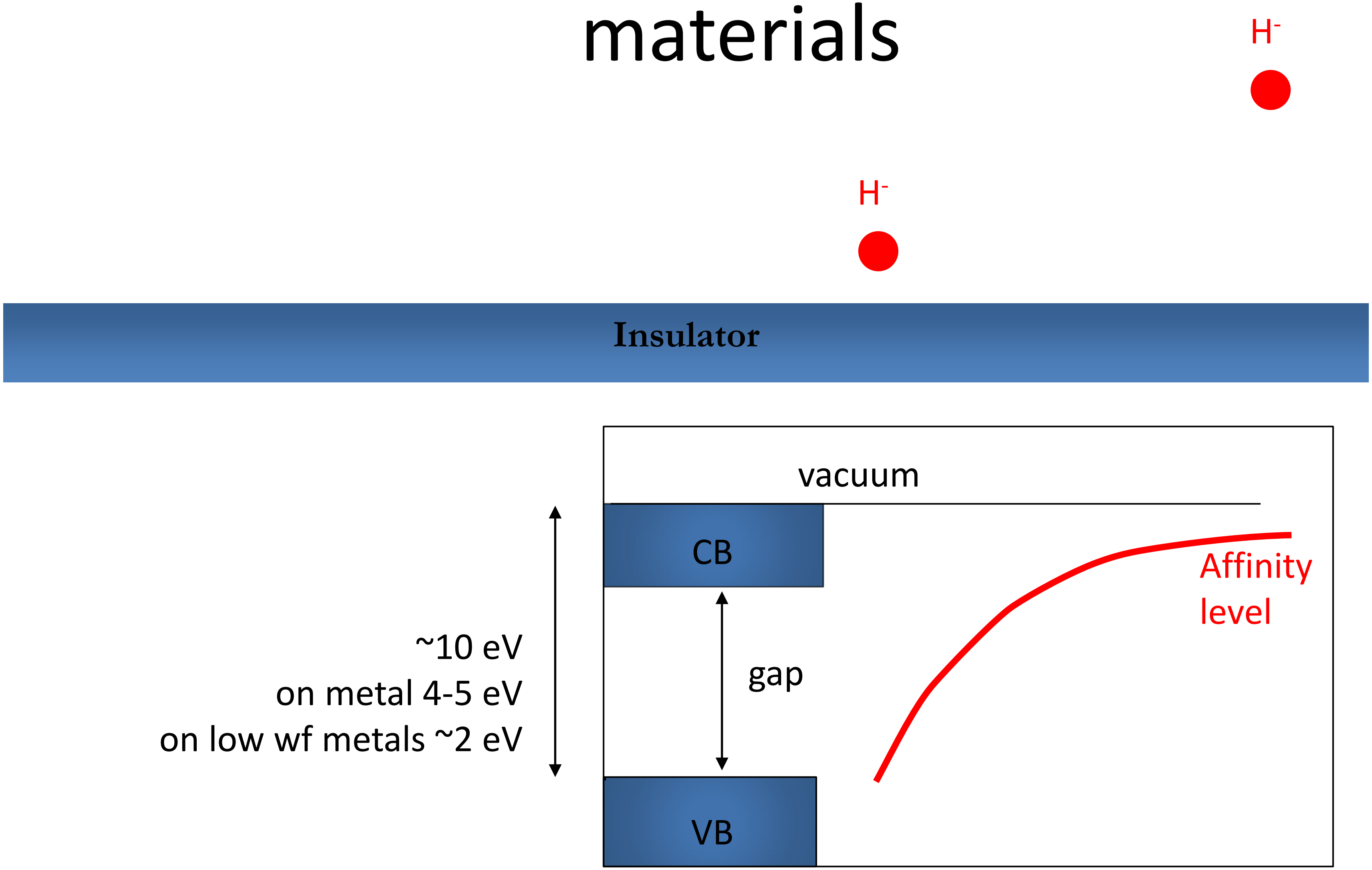
Negative-ion enhancer insulating materials

Insulator



Negative-ion enhancer insulating materials



H^-

H^-

Insulator

vacuum

CB

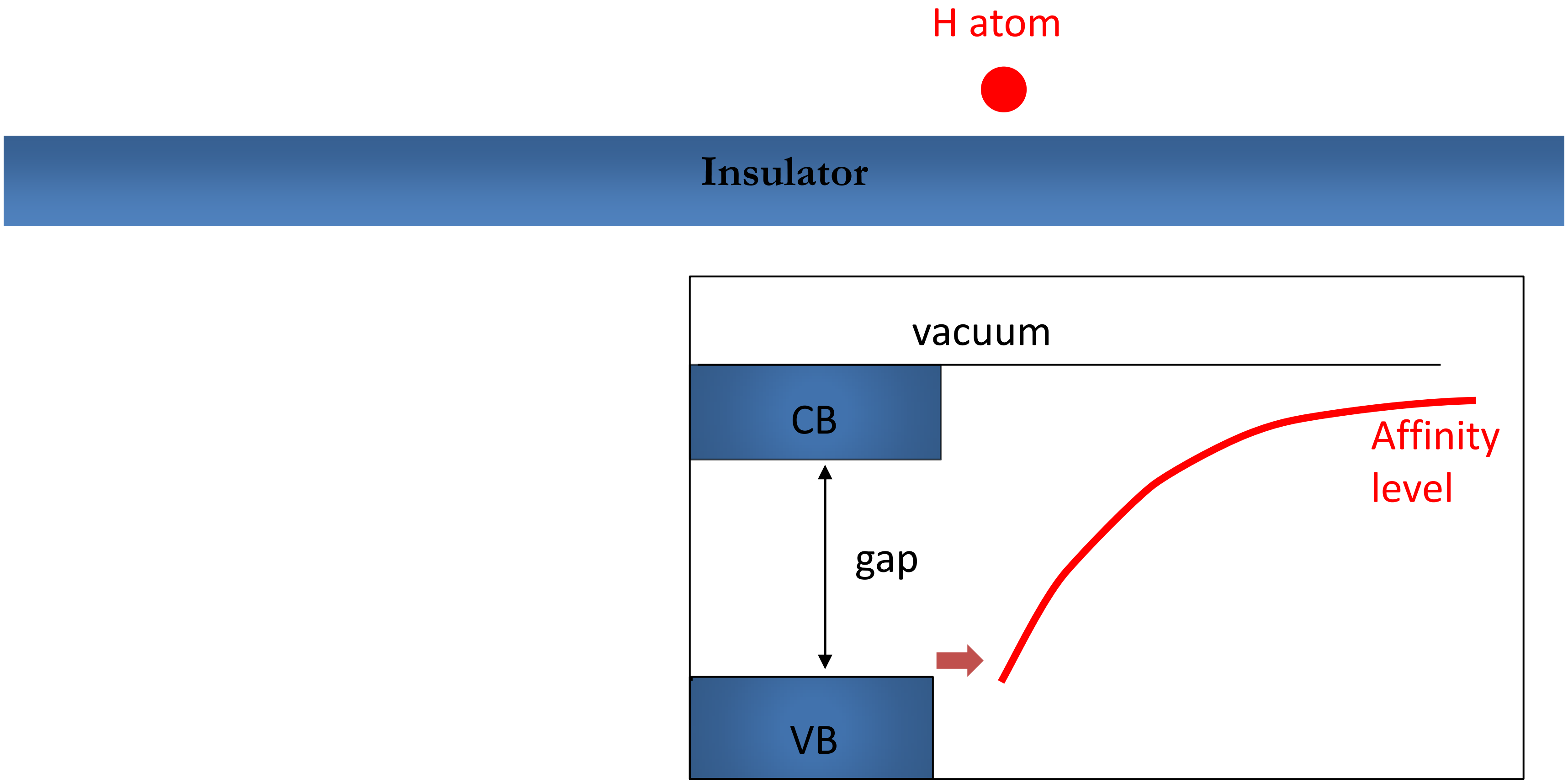
gap

VB

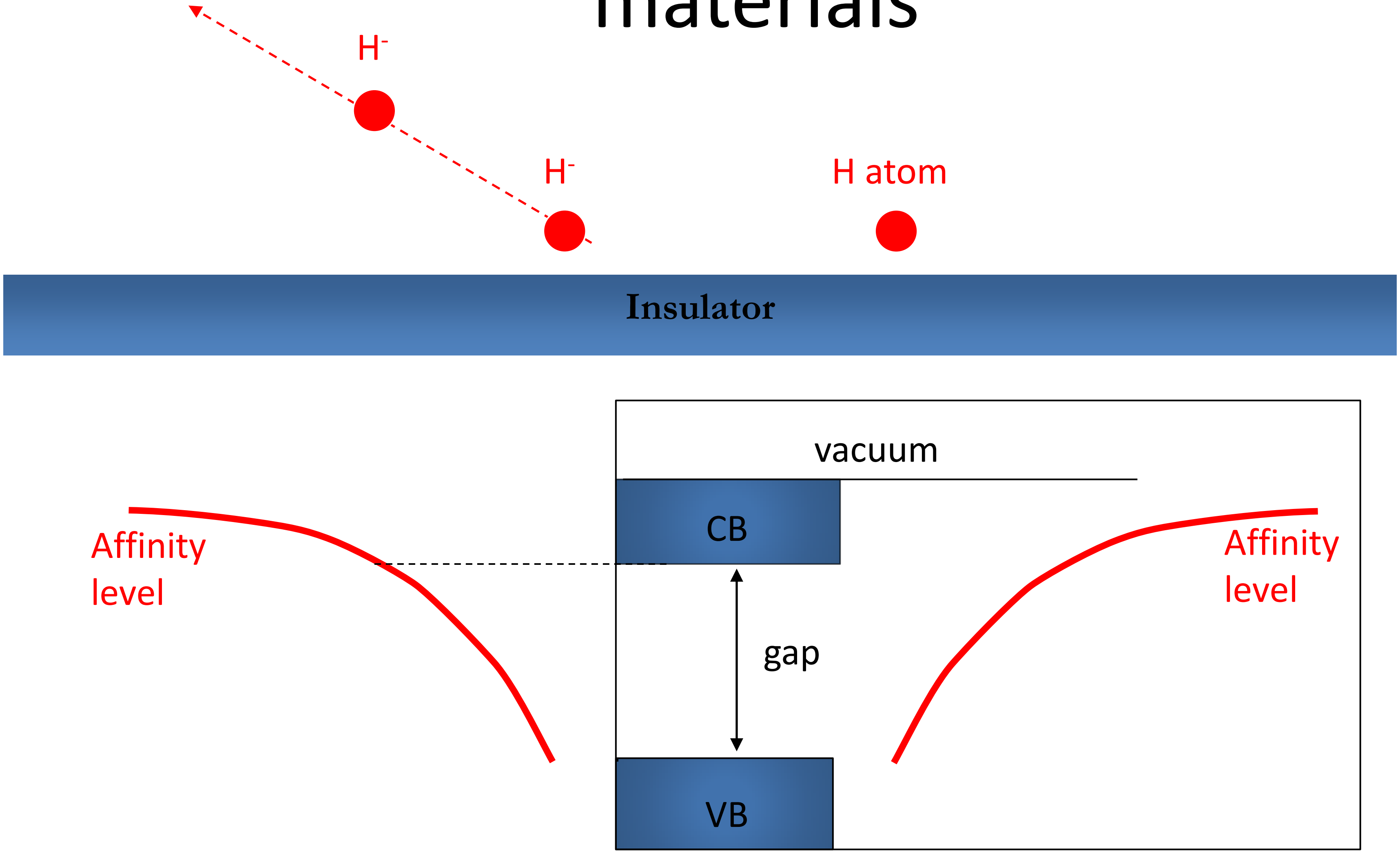
Affinity level

~10 eV
on metal 4-5 eV
on low wf metals ~2 eV

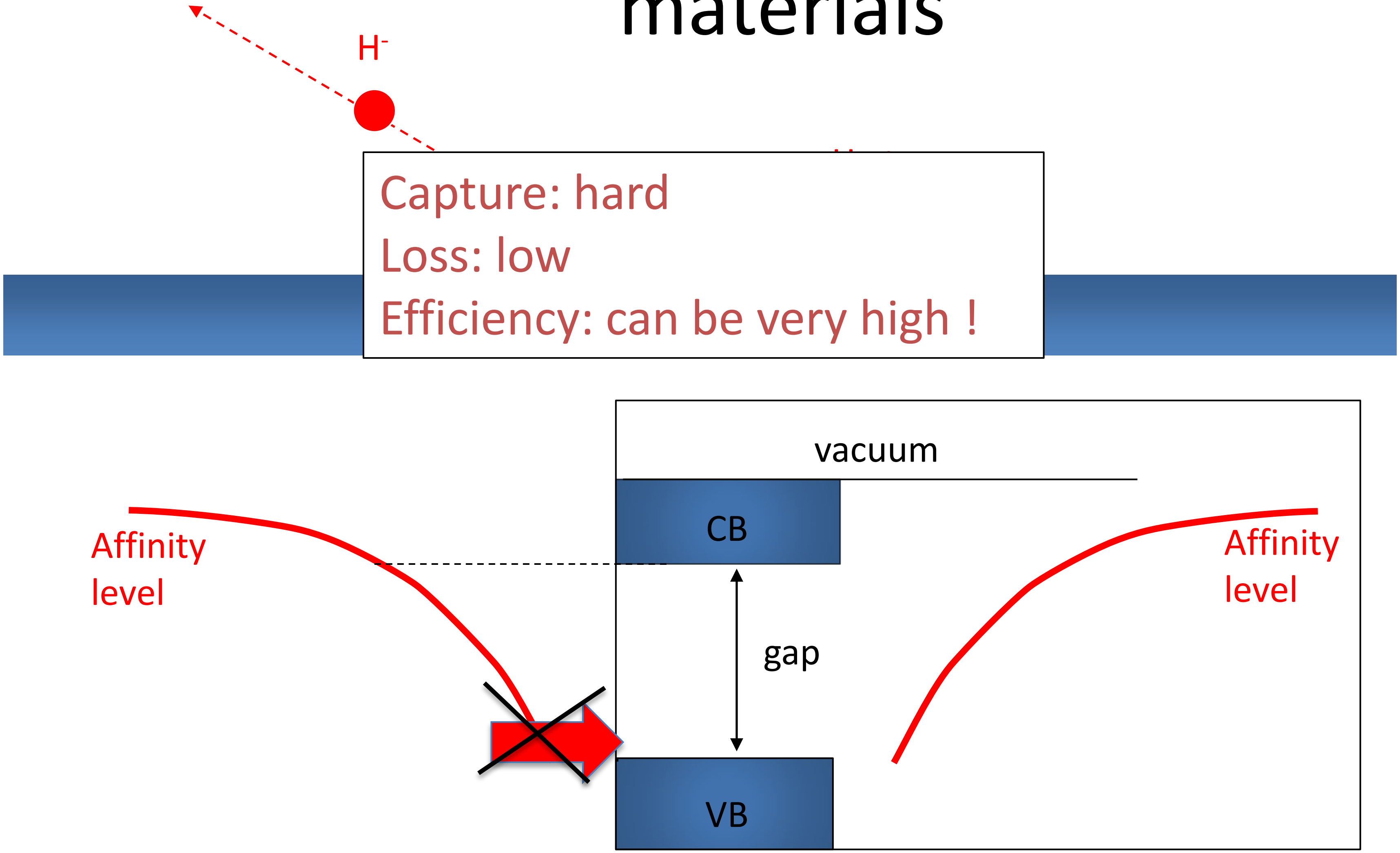
Negative-ion enhancer materials



Negative-ion enhancer insulating materials



Negative-ion enhancer insulating materials

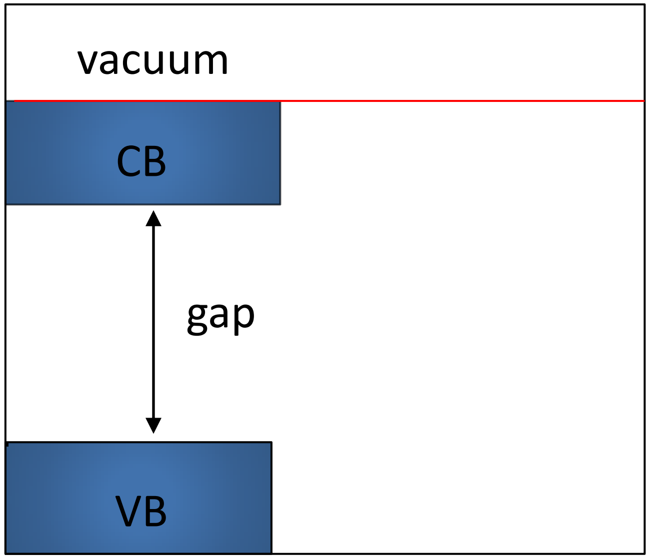


Capture: hard

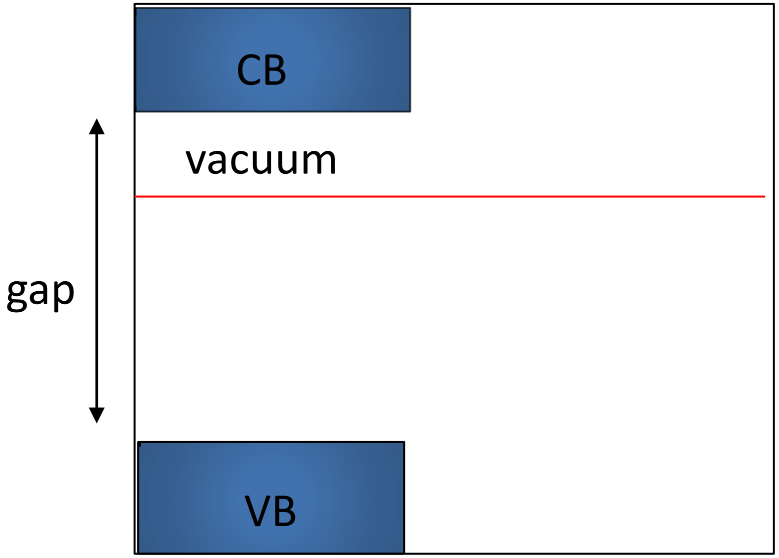
Loss: low

Efficiency: can be very high !

Negative-ion enhancer materials

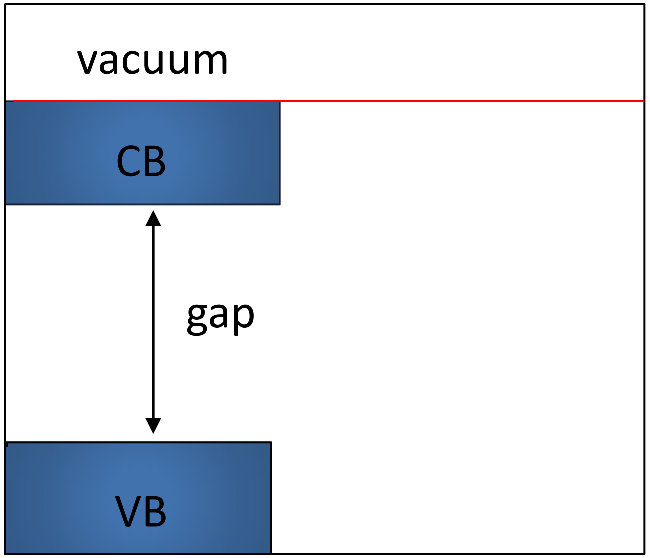


Insulators



Materials with conduction band above the vacuum level

Negative-ion enhancer materials



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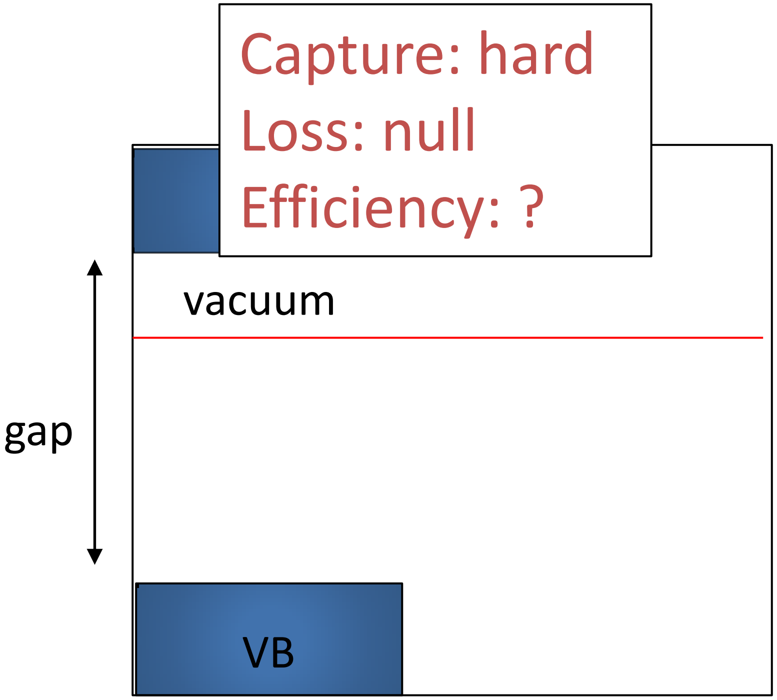
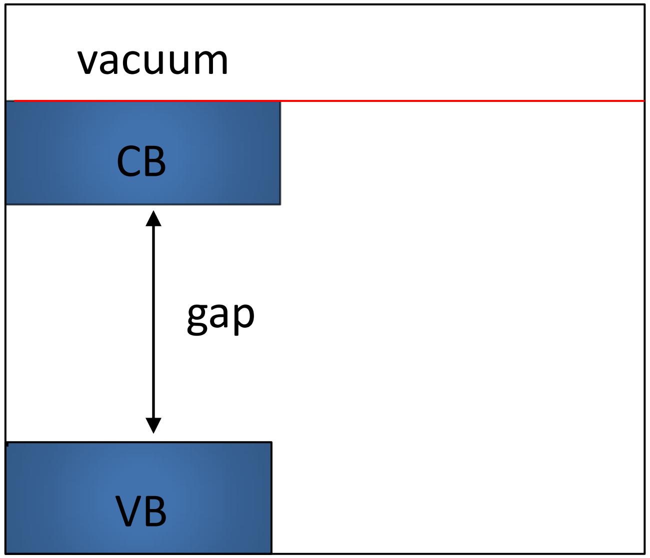


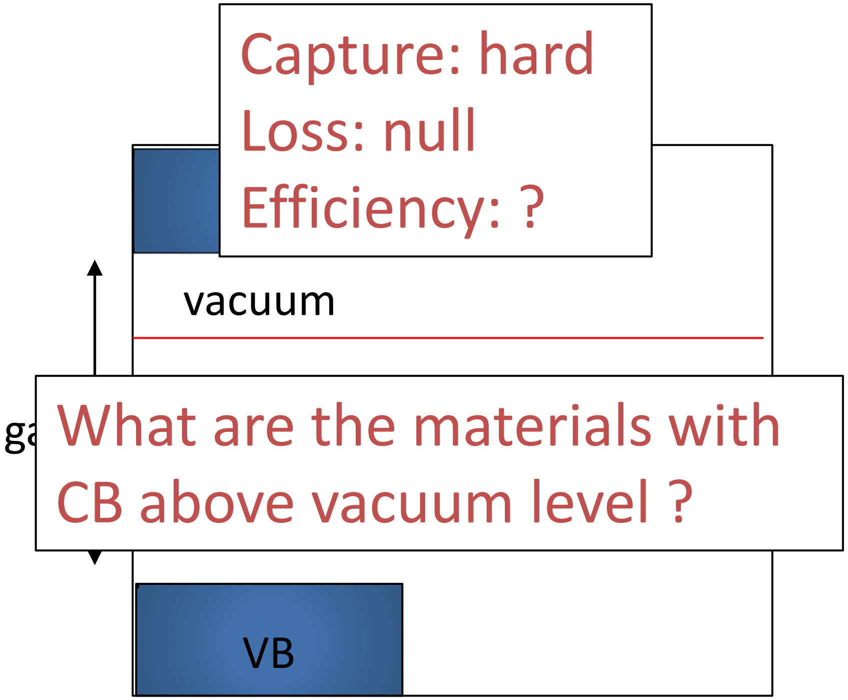
Capture: hard
Loss: null
Efficiency: ?

Materials with conduction band above the vacuum level

Negative-ion enhancer materials



Insulators

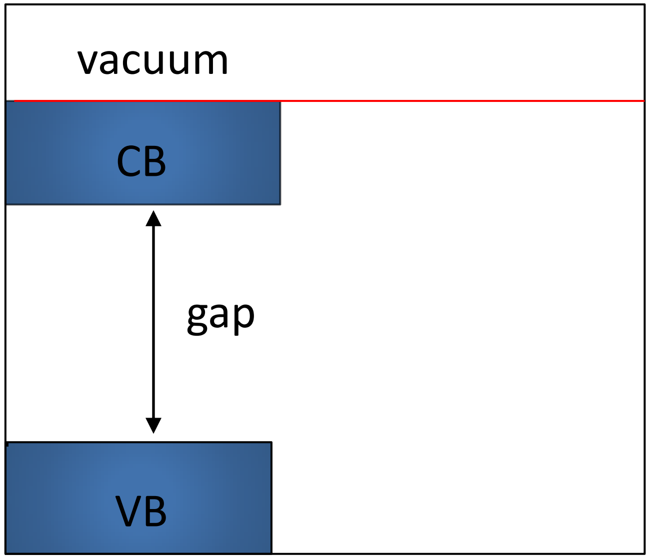


Capture: hard
Loss: null
Efficiency: ?

What are the materials with CB above vacuum level ?

Materials with conduction band above the vacuum level

Negative-ion enhancer materials



Insulators

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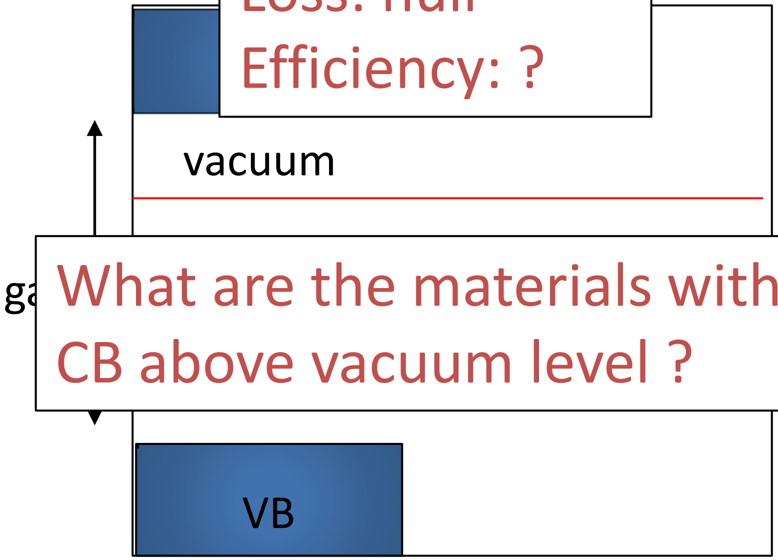
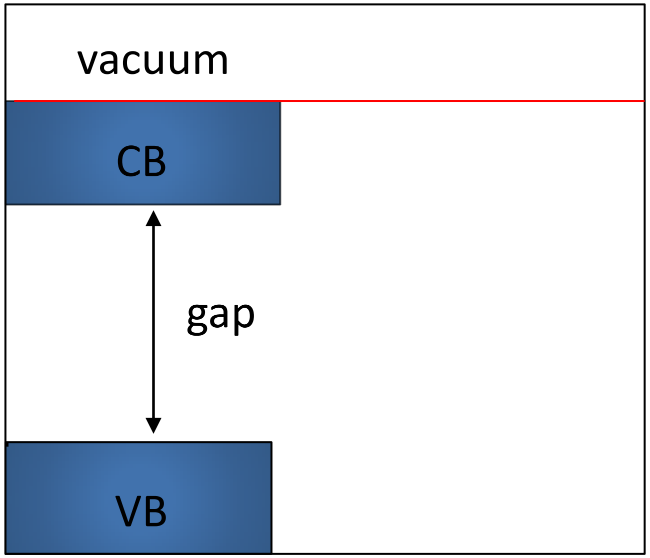
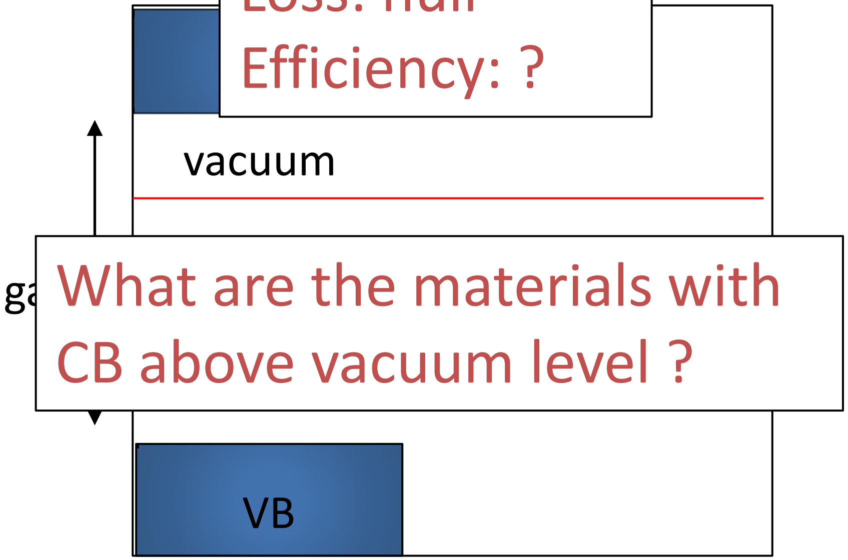


What are the materials with CB above vacuum level ?

Negative-ion enhancer materials



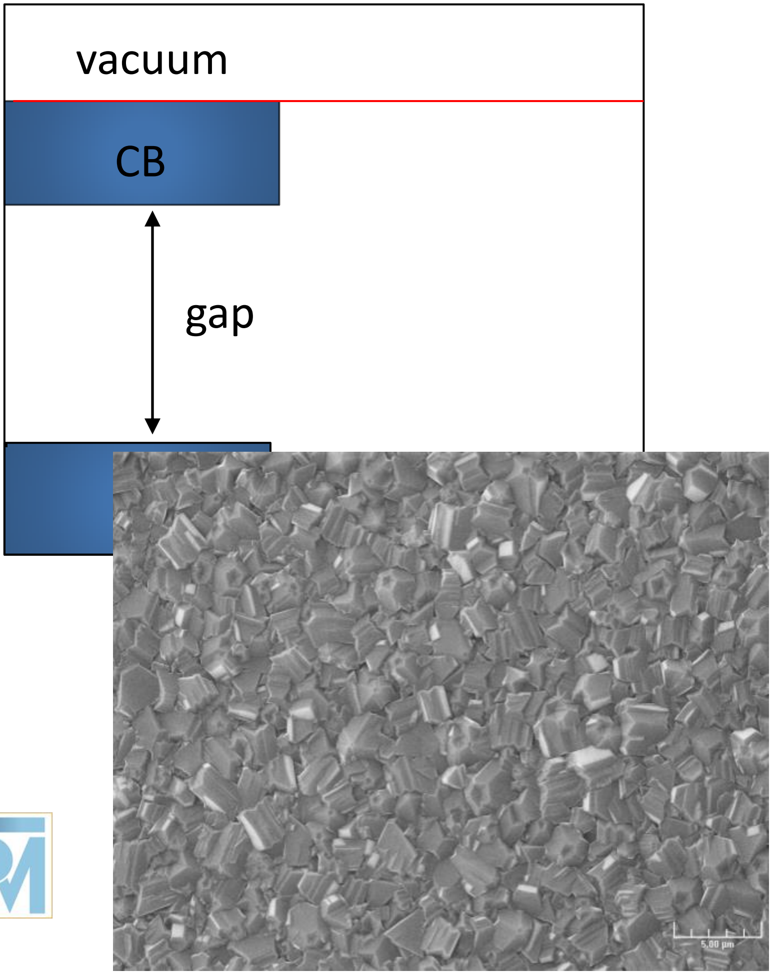
Insulators

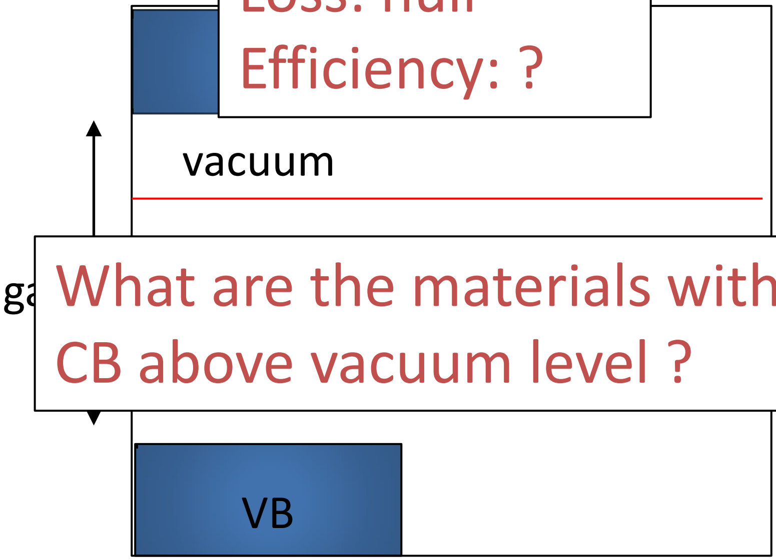


Capture: hard
Loss: null
Efficiency: ?

What are the materials with CB above vacuum level ?

Negative-ion enhancer materials





Capture: hard
Loss: null
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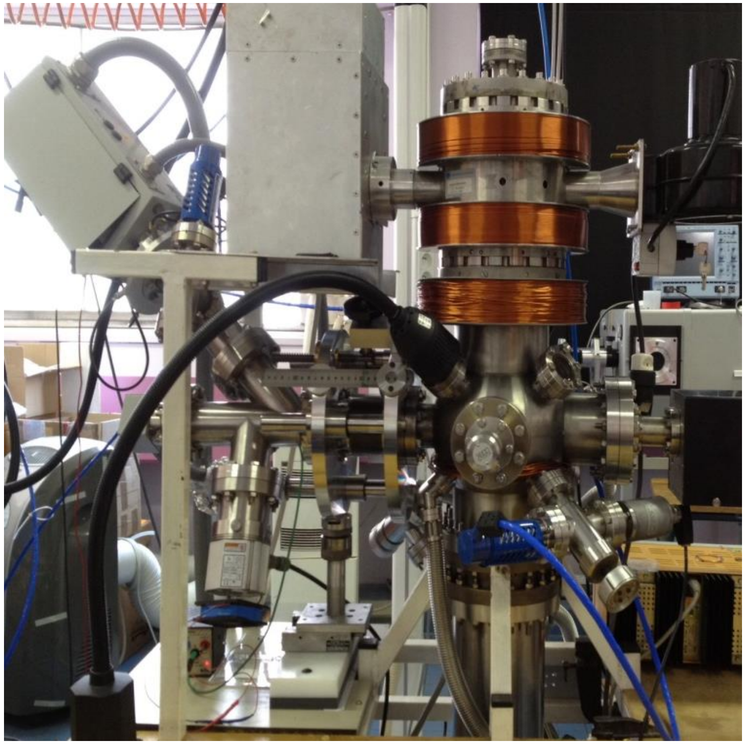
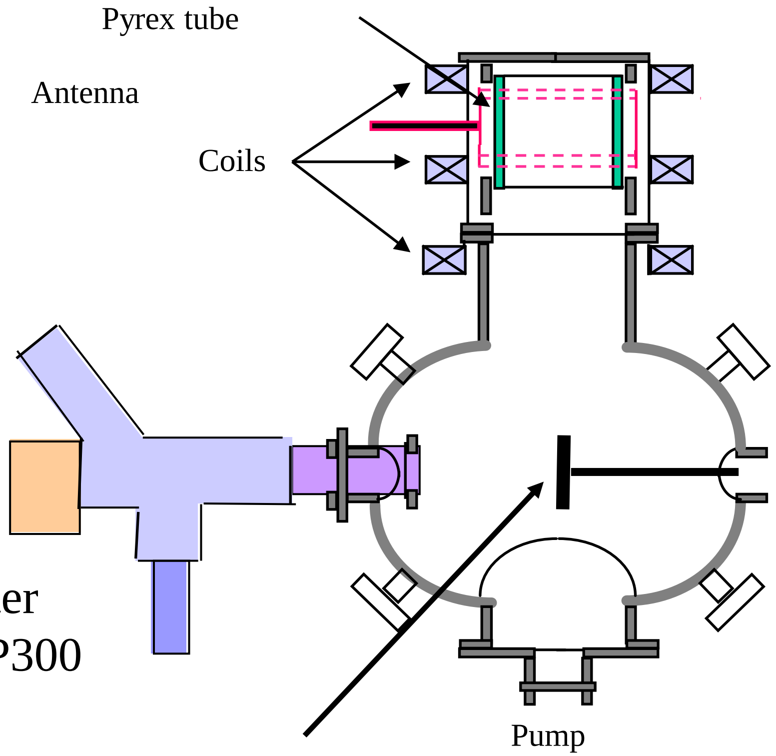
What are the materials with CB above vacuum level ?

Experimental set-up





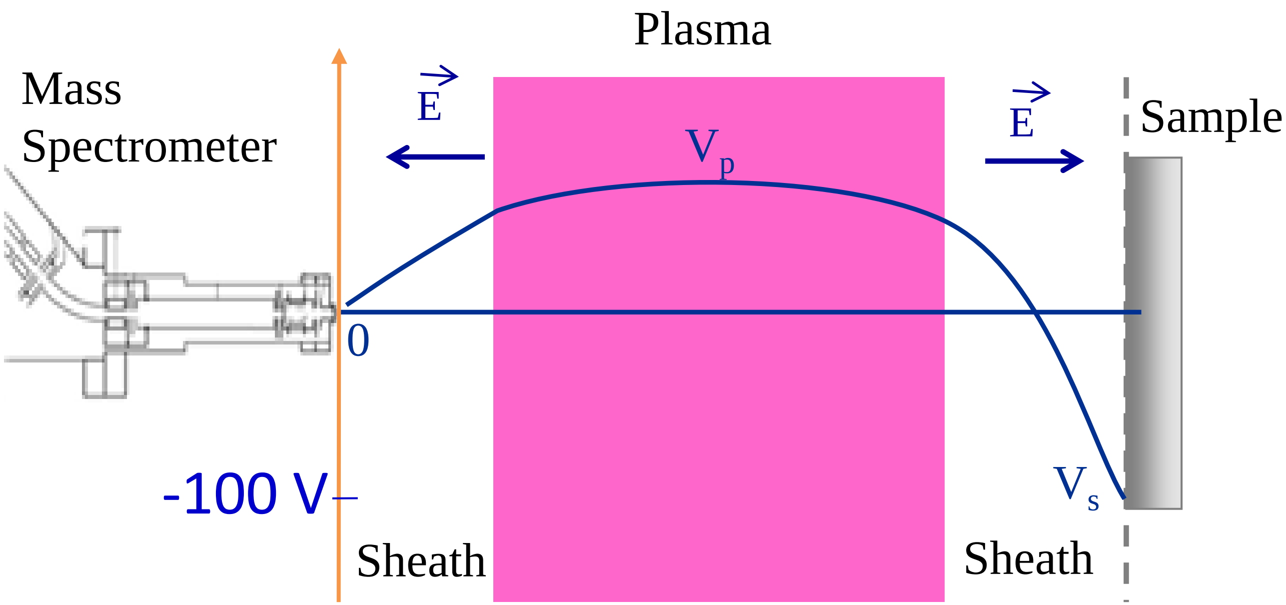
Mass
spectrometer
Hiden EQP300

Sample material:
Formation of negative-ions

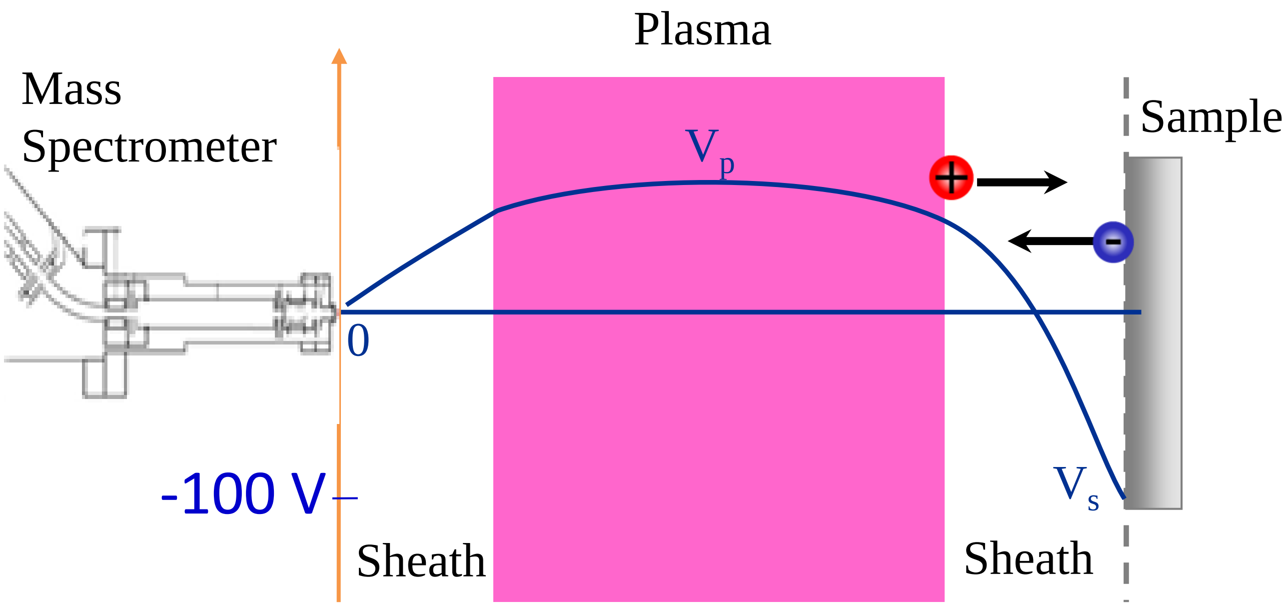
- H_2 and D_2 plasma
- P = 30-900 W

- No magnetic field
- Pr = 0.2 – 2 Pa

Experimental set-up



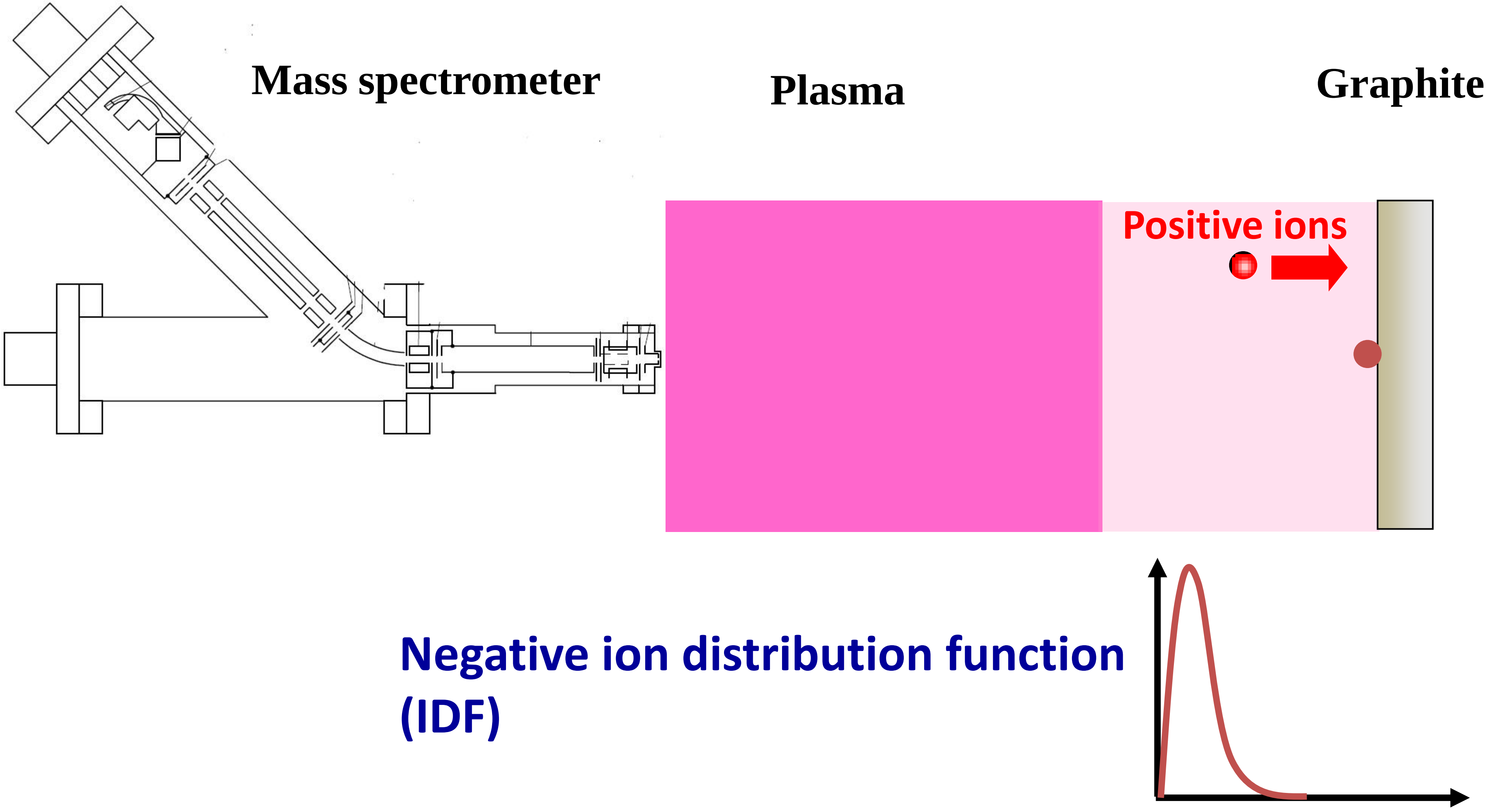
Experimental set-up



Negative-ions (i^-) are self-extracted:

Advantages: simple extraction, sample materials can be changed easily

Drawback: Bad control of surface state. It is strongly dependant on plasma conditions and ion bombardment (Ex situ surface analysis)



Mass spectrometer

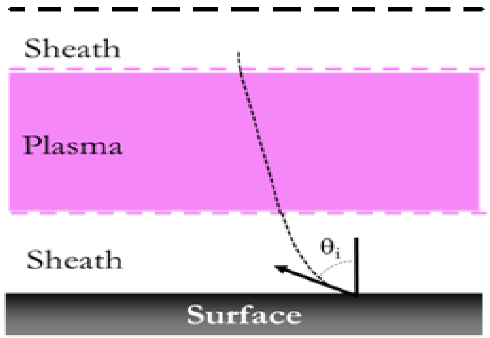
Plasma

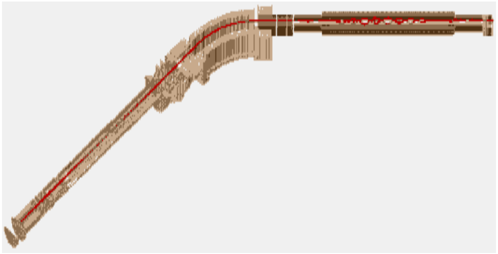
Graphite

Positive ions

Negative ion distribution function (IDF)

Surface





F(E,θ) : NIDF of i^- emitted by the surface

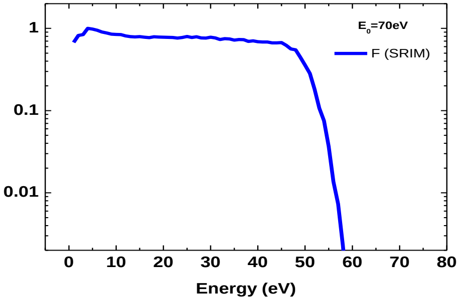
⊗

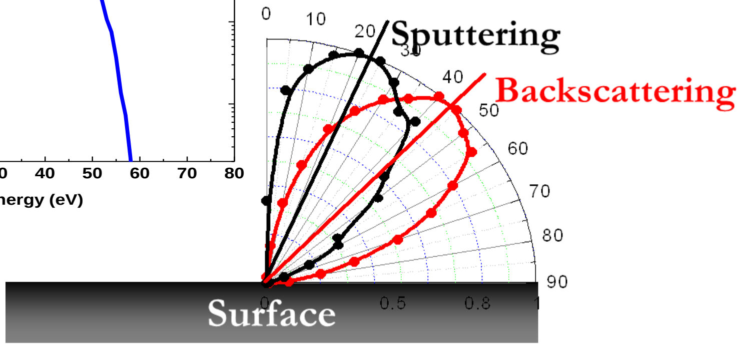
Plasma transmission

⊗

Mass spectrometer transmission

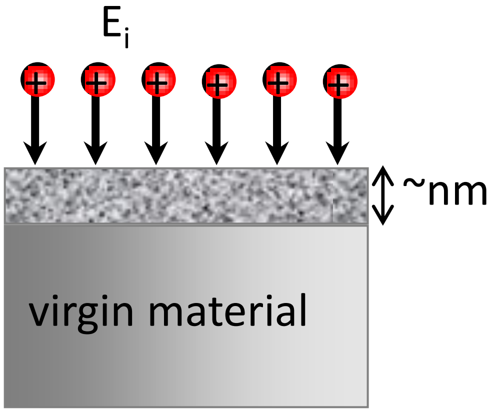
SRIM results





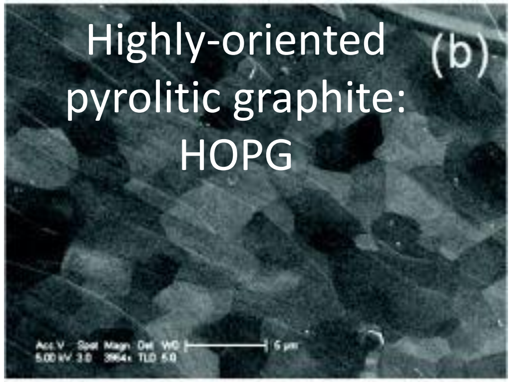
SRIM software is used to obtain an initial guess of the surface distribution function

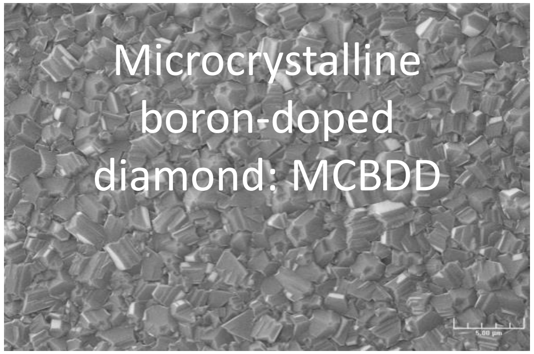
NI yield on carbon materials

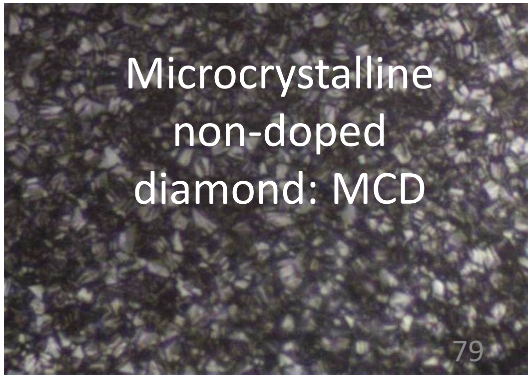


Optimum for NI production

?



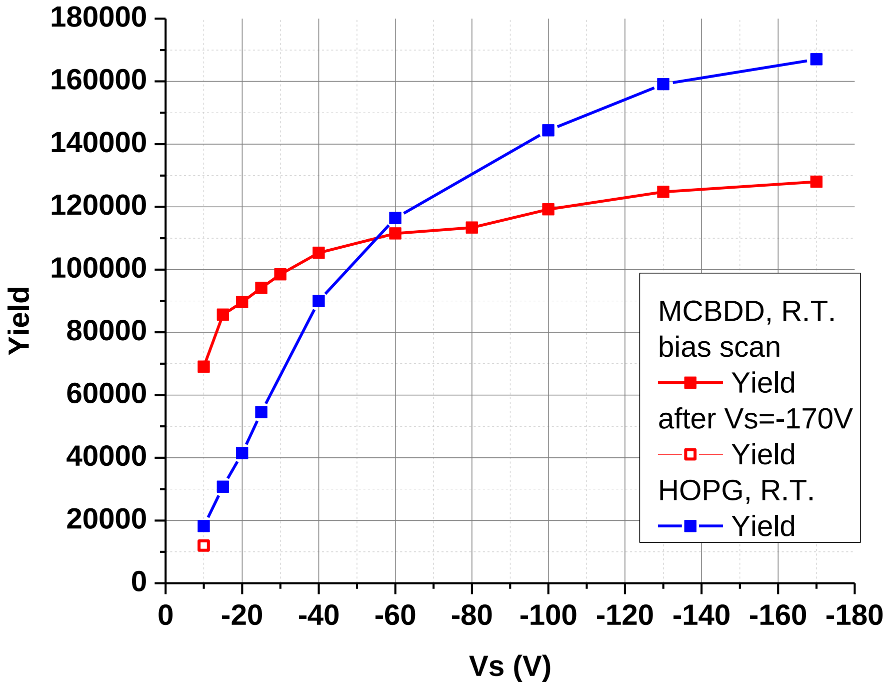




Surface state can depend on:

- **Surface temperature**
- **Bias time**
- **Bias voltage**
- **Plasma exposure time**

Negative ion yield at RT vs. V_s

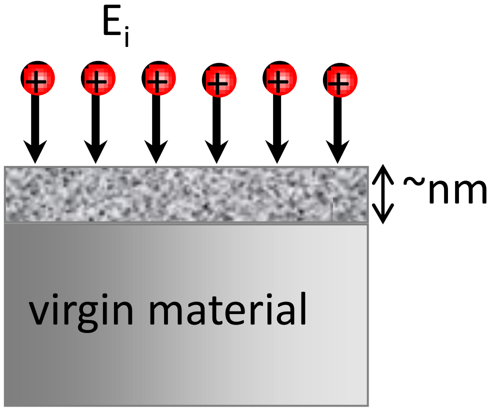


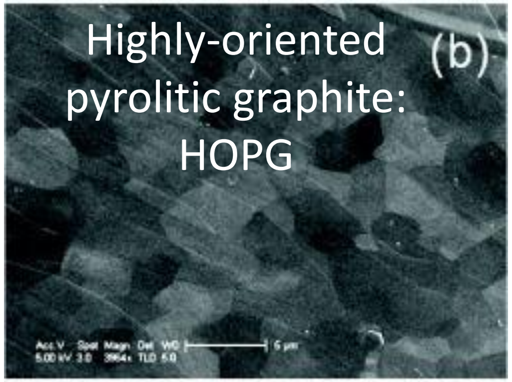
- MCBDD is the best NI producer at RT and low bias.
- MCBDD is also easily polarized to the desired bias.
- After high bias exposure, the MCBDD surface produces 7 times less NI at V_s = -10V

→ the surface state change at high V_s is unfavorable for the NI production

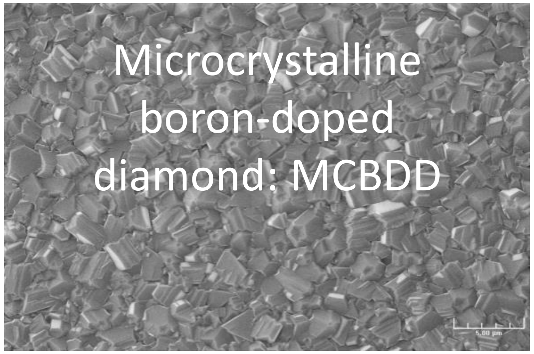
NI yield on carbon materials

$V_s = -130$ V

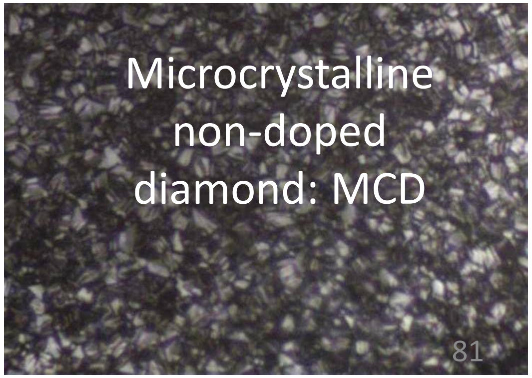




Highly-oriented pyrolitic graphite: HOPG

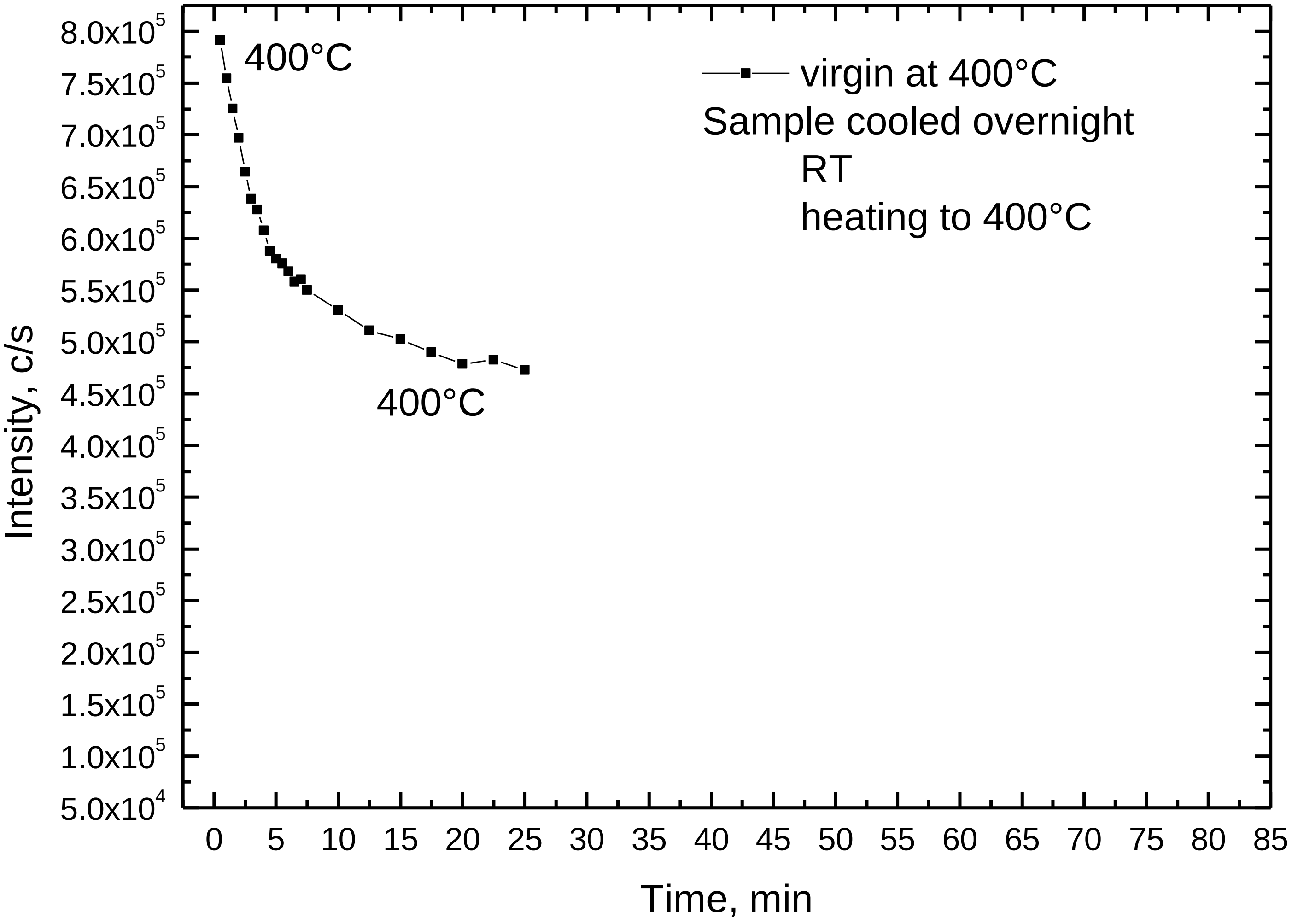


Microcrystalline boron-doped diamond: MCBDD

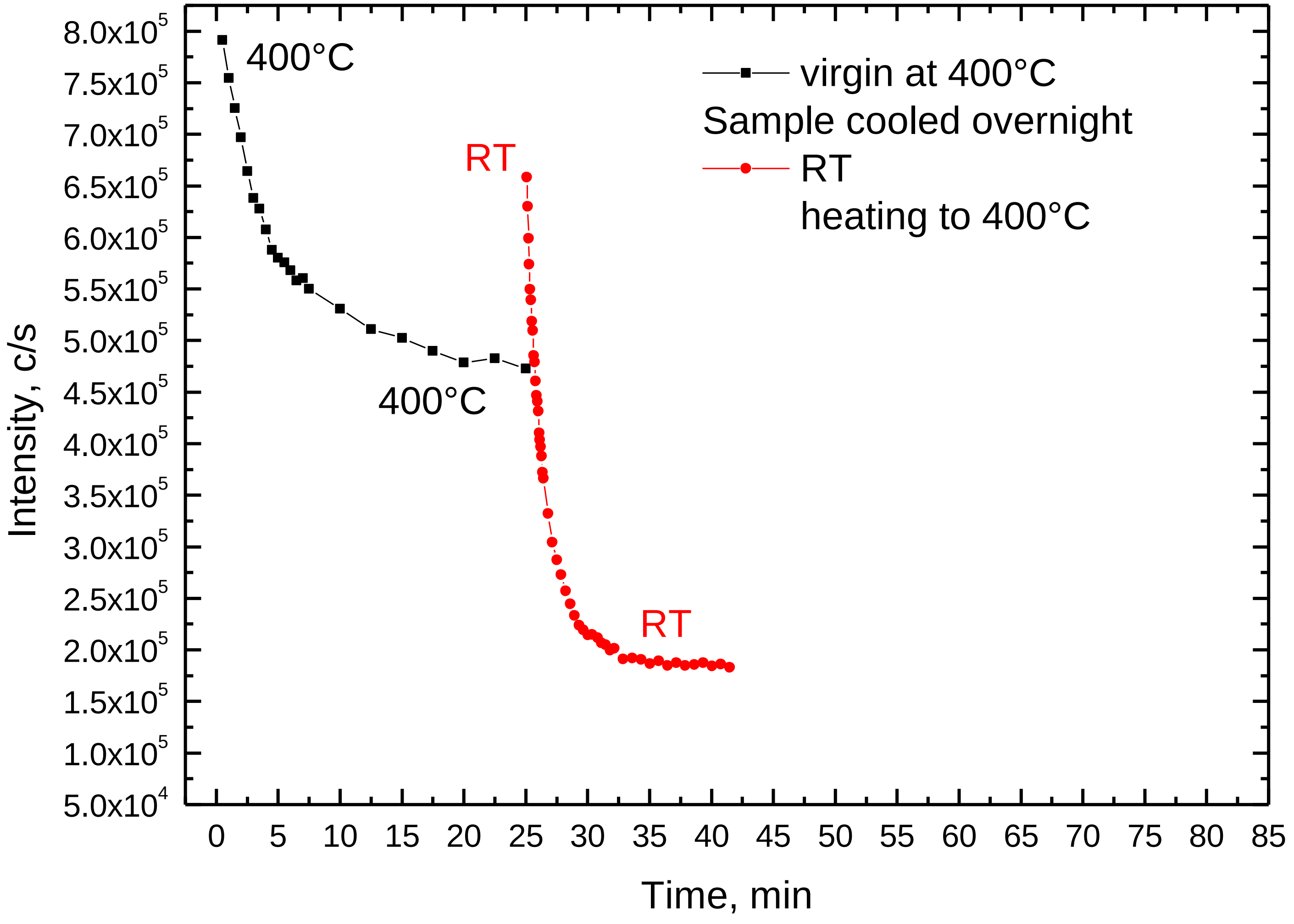


Microcrystalline non-doped diamond: MCD

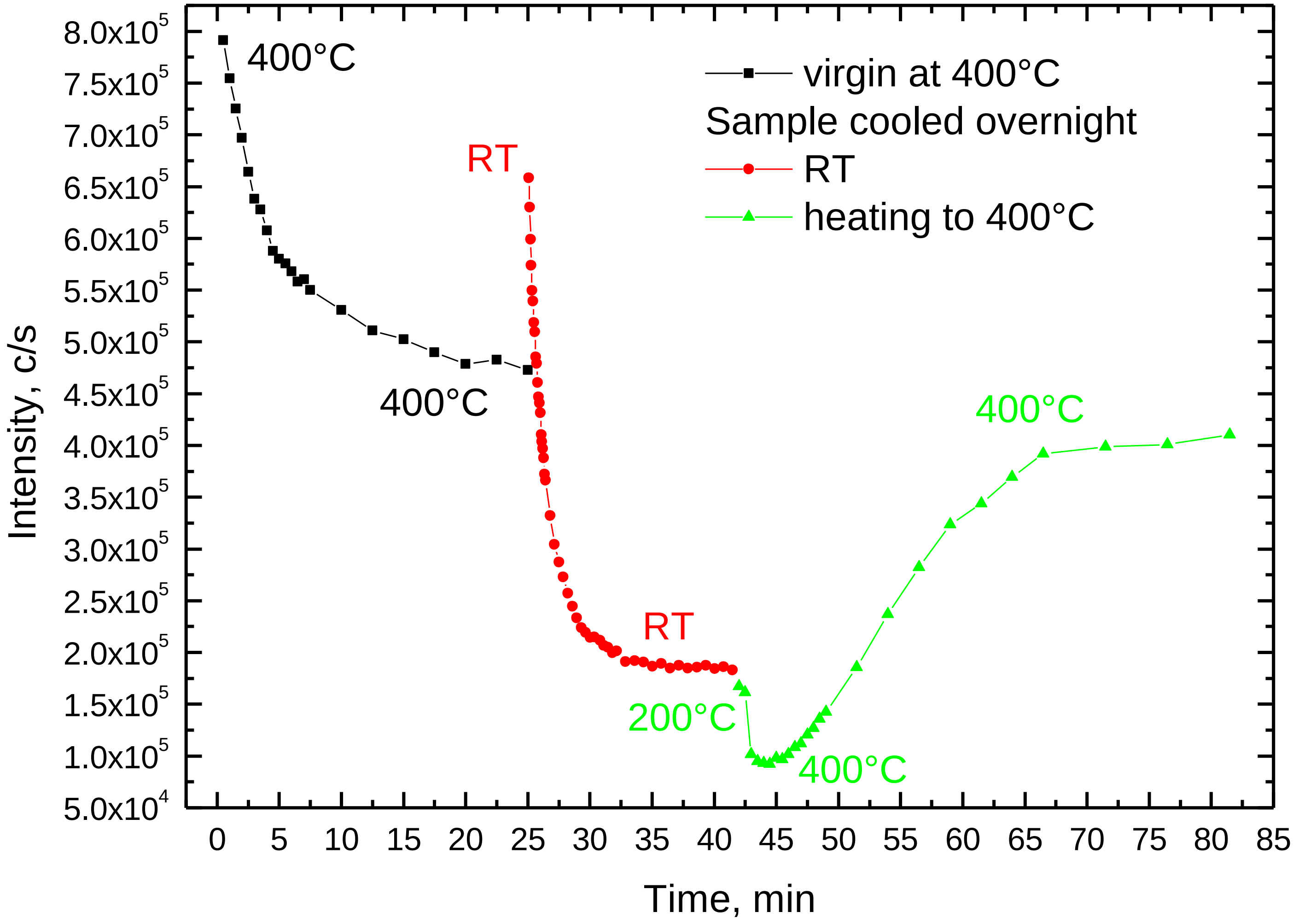
MCBDD: time evolution V_s = -130 V



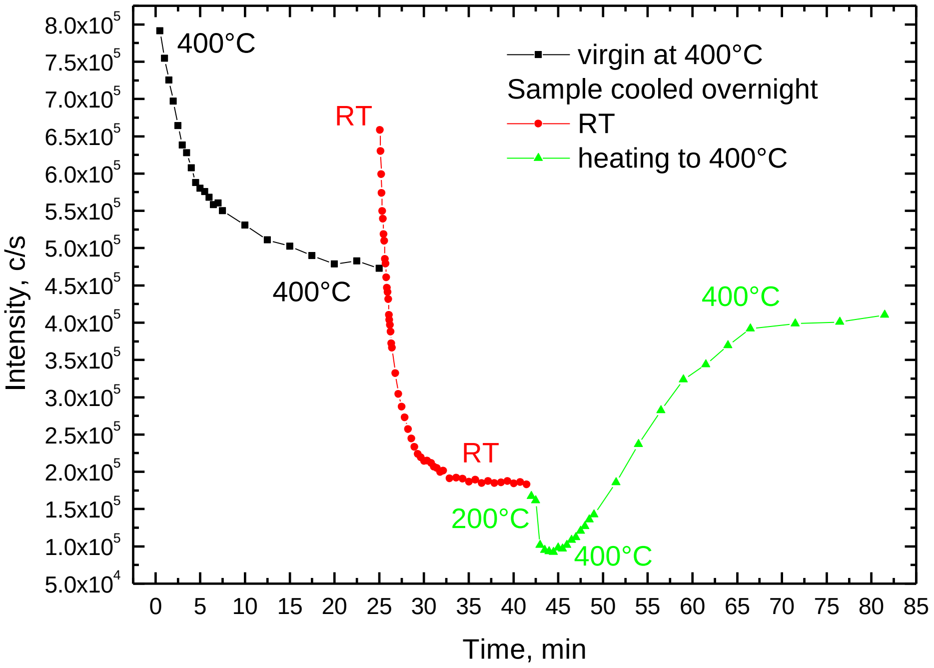
MCBDD: time evolution V_s = -130 V



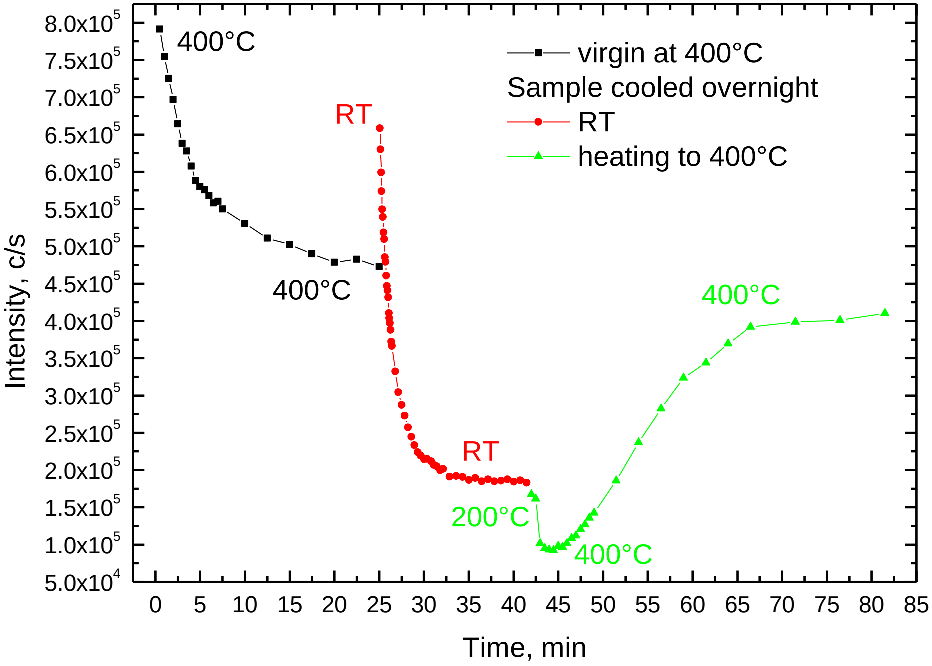
MCBDD: time evolution V_s = -130 V



MCBDD: time evolution V_s = -130 V



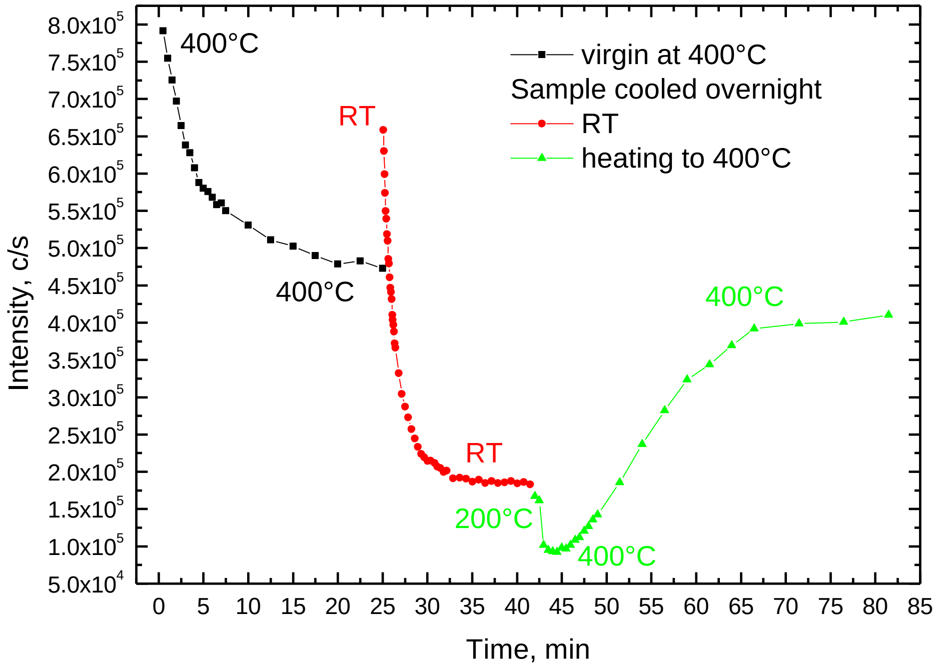
MCBDD: time evolution V_s = -130 V



For diamond materials:

- **Surface degradation is unfavorable for NI production**
- **At 400°C surface is partially recovered → enhanced NI yield**

MCBDD: time evolution V_s = -130 V



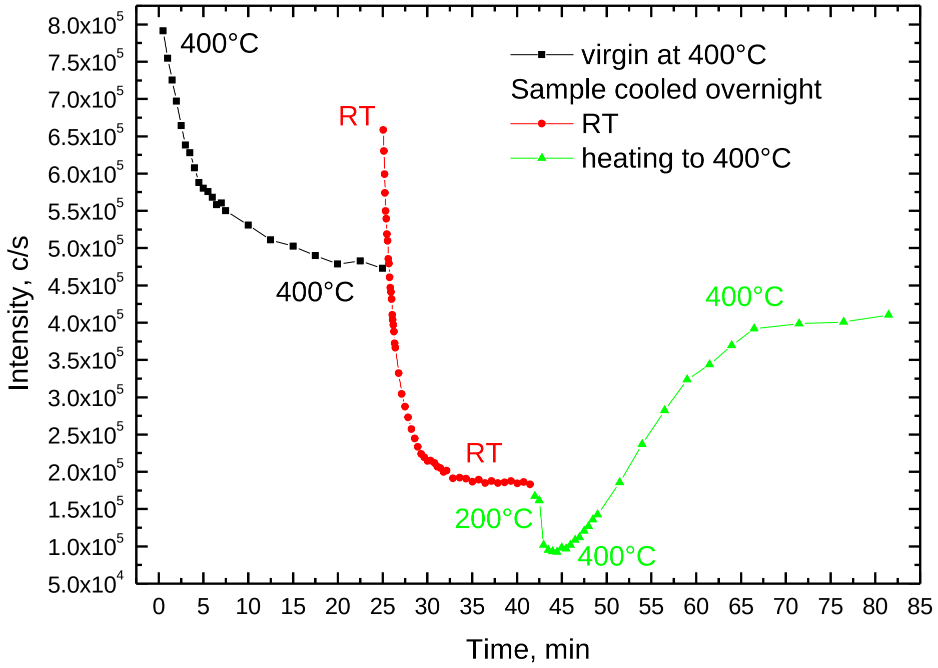
For diamond materials:

- **Surface degradation is unfavorable for NI production**
- **At 400°C surface is partially recovered → enhanced NI yield**

Conclusion:

- **Diamond - successful NI enhancer (MCBDD most stable)**

MCBDD: time evolution V_s = -130 V



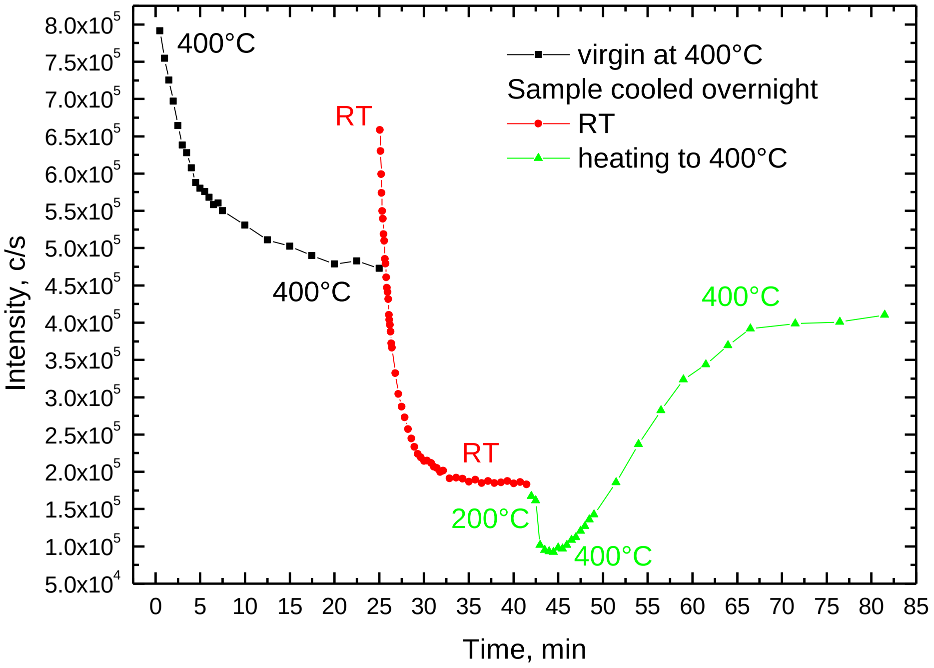
For diamond materials:

- **Surface degradation is unfavorable for NI production**
- **At 400°C surface is partially recovered → enhanced NI yield**

Conclusion:

- **Diamond - successful NI enhancer (MCBDD most stable)**
- **sp^3 phase dominant, defects worsen the performance**

MCBDD: time evolution V_s = -130 V

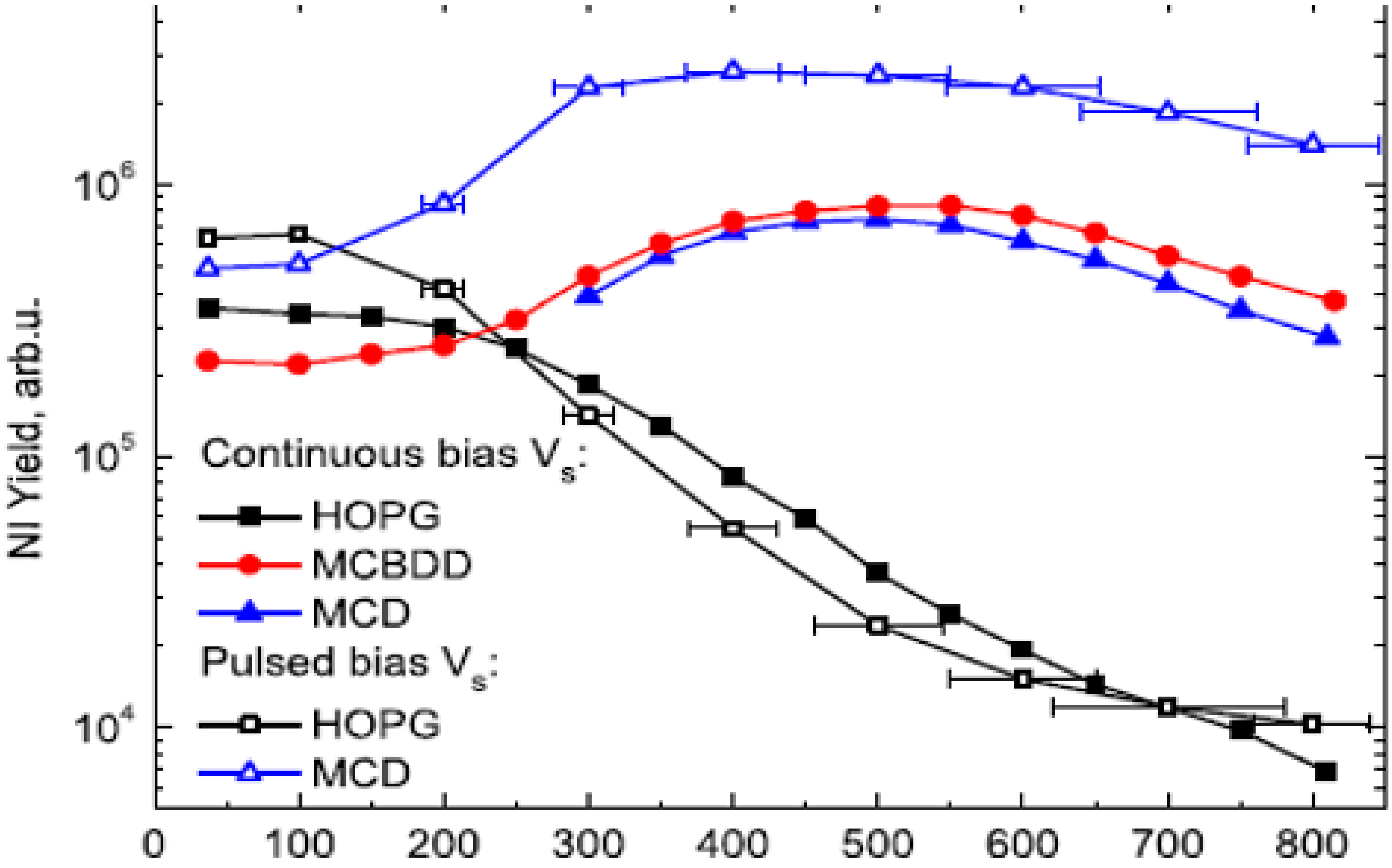


For diamond materials:

- **Surface degradation is unfavorable for NI production**
- **At 400°C surface is partially recovered → enhanced NI yield**

Conclusion:

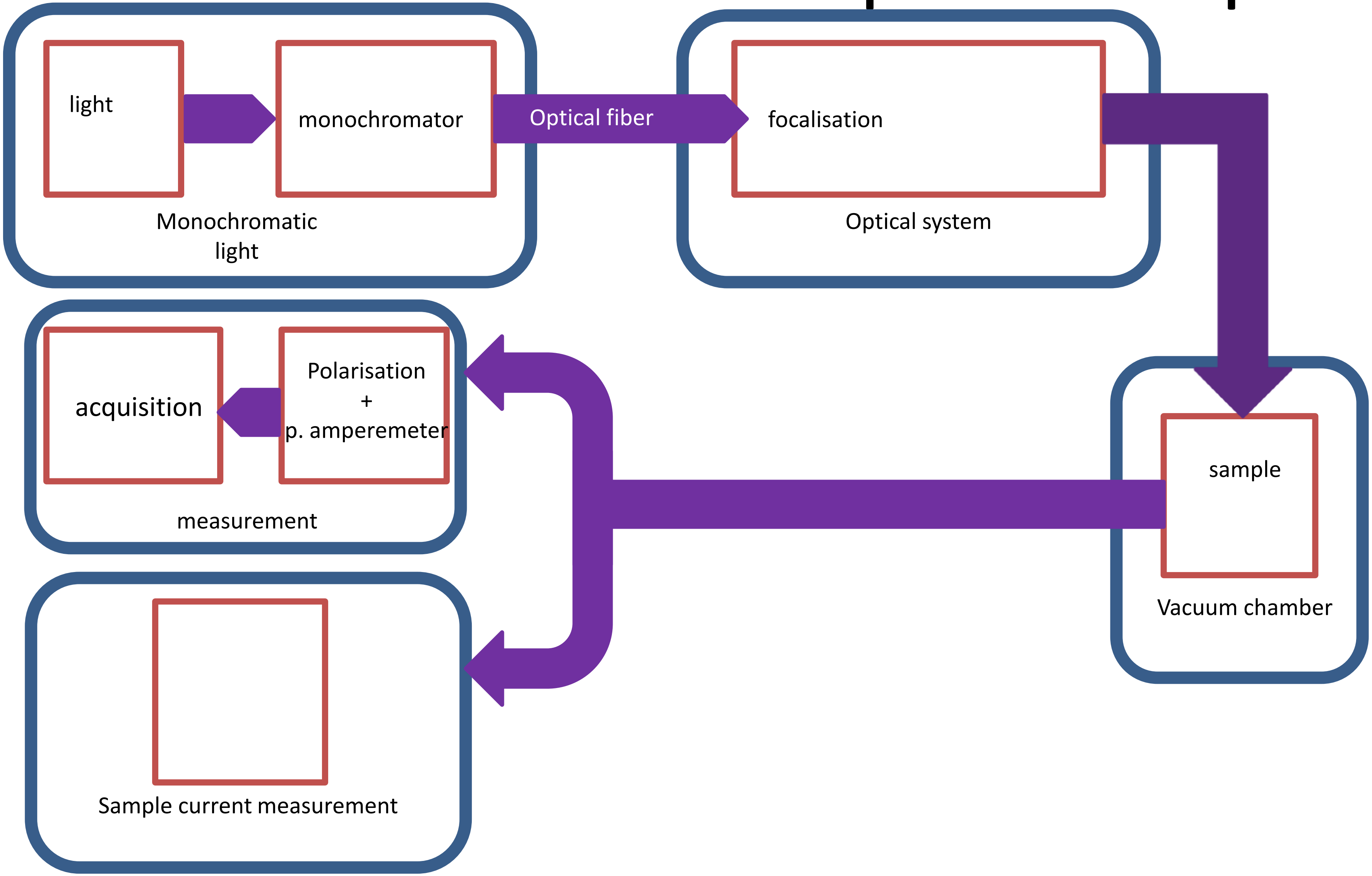
- **Diamond - successful NI enhancer (MCBDD most stable)**
- **Surface heating results in partial reconstruction (more details obtained by surface diagnostics)**


NI Yield, arb.u.
10^4
10^5
10^6
0
100
200
300
400
500
600
700
800
Continuous bias V_s:
HOPG
MCBDD
MCD
Pulsed bias V_s:
HOPG
MCD

Conclusion(?)

- Research on negative ion sources without Cs.
- Laboratory experimental apparatus
- Plasma-surface interactions
- Other materials
- Developement of an in-situ diagnostic for Work Function measurement.

Photoemission Yield spectroscopie



light

monochromator

Optical fiber

Monochromatic light

focalisation

Optical system

sample

Vacuum chamber

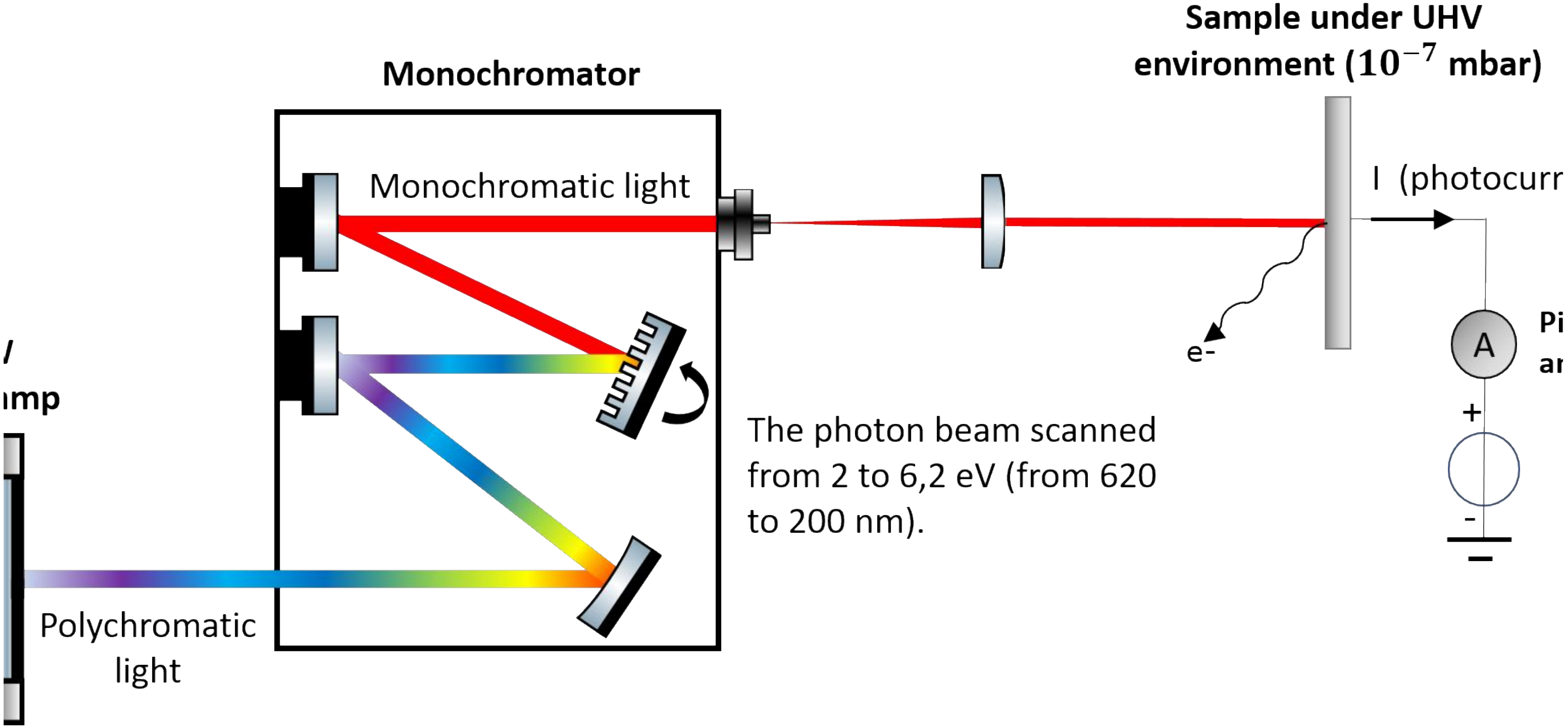
acquisition

Polarisation + p. amperemeter

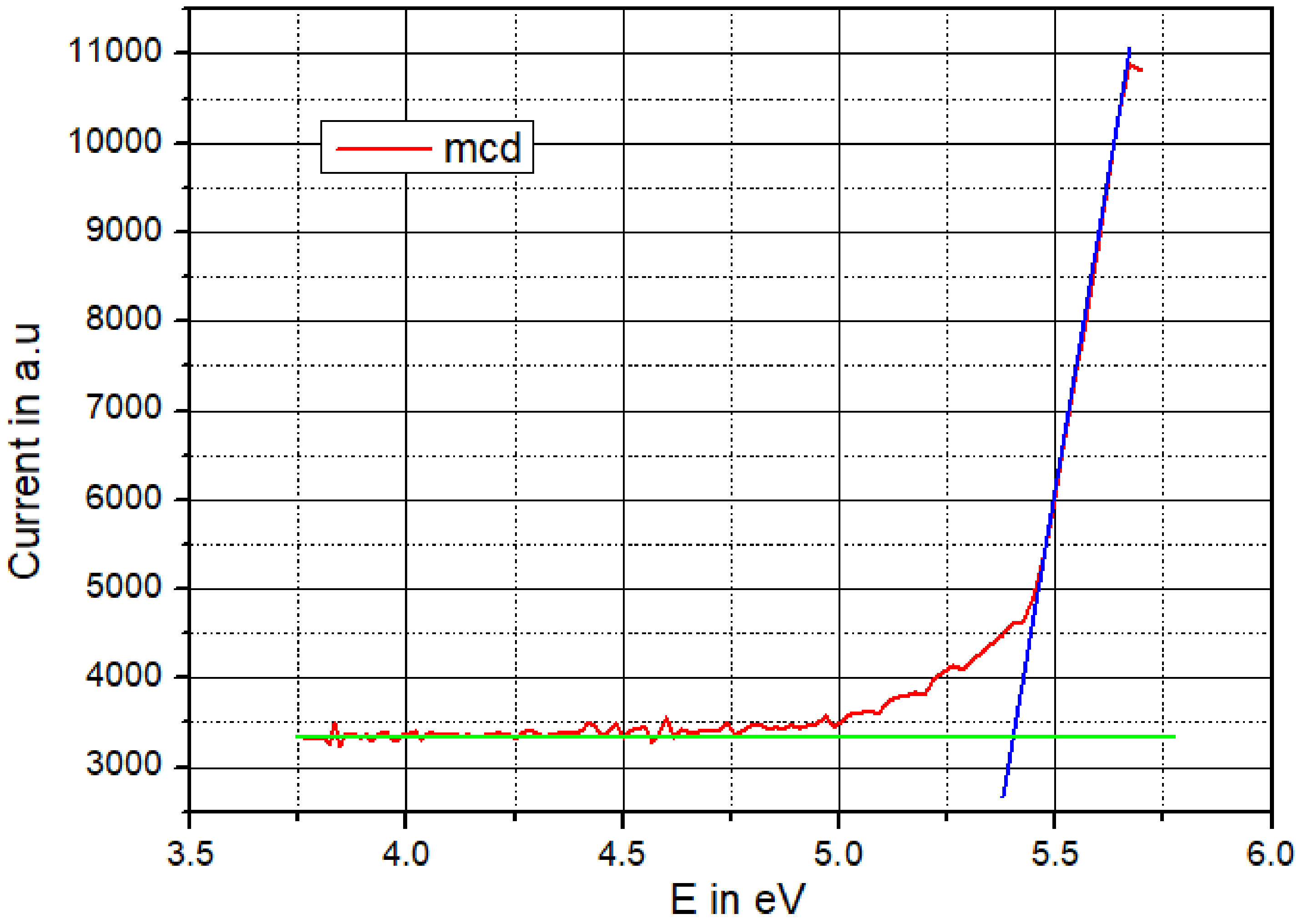
measurement

Sample current measurement

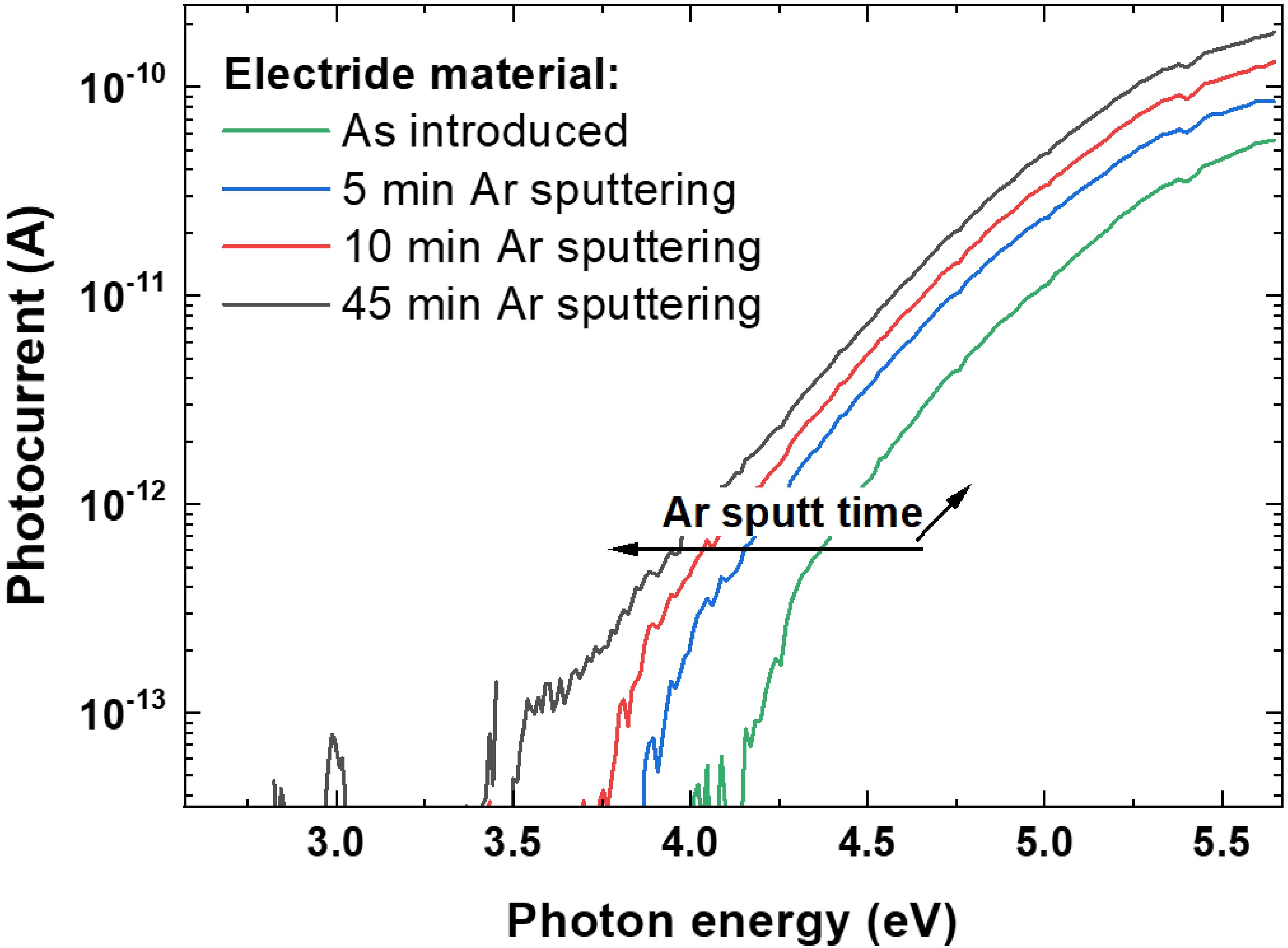
ıp



The photon beam scanned from 2 to 6,2 eV (from 620 to 200 nm).



Evolution of the photocurrent with the photon energy


Electride material:
As introduced
5 min Ar sputtering
10 min Ar sputtering
45 min Ar sputtering
Ar sputt time
Photocurrent (A)
10^{-10}
10^{-11}
10^{-12}
10^{-13}
3.0
3.5
4.0
4.5
5.0
5.5
Photon energy (eV)

Institut
Sciences de la Fusion et
de l'Instrumentation en
Environnements Nucléaires
Aix*Marseille Université

Institute of Fusion Sciences and Instrumentation in Nuclear Environments
ISFIN

Y. Marandet (CNRS, PIIM), Director
G. Cartry (AMU, PIIM) Deputy for education,
C. Reynard-Carette (AMU, IM2NP) Deputy for Research
S. Ploquin-Donzenac (AMU, project manager)

Outline

- Introduction : AMU institutes
- Perimeter of the ISFIN institute : labs & faculty
- Research topics
- Setting up a graduate school

AMU institutes in a nutshell

- Structuration process of AMU launched in 2016 and nearing completion now

- Creation of 13 (+5) Institutes, with the aim of
  - building a **research identity** for the University
  - strengthening the link between teaching and research : **graduate schools**
  - having a **knock on effect** on the whole AMU teaching offer

- Backbone of AMU proposal for a call for project currently open to strengthen the links between teaching and research over the next ~10 years

General overview of AMU institutes

Archeology

Institut Archéologie méditerranéenne Aix-Marseille Université

Mathematics/Computer Sciences
(AI)

Institut Archimède Mathématiques-Informatique Aix-Marseille Université

Cancer/Immunology

Institut Cancer et Immunologie Aix-Marseille Université

Creativity/Innovations

Institut Créativité et Innovations Aix-Marseille Université

Medical Imaging
(Medical Radioisotopes)

Institute Marseille Imaging Aix-Marseille Université

Rare diseases

Institut Marseille Maladies rares Aix-Marseille Université

Mechanics & Engineering

Institut Mécanique et Ingénierie Aix-Marseille Université

Institut Méditerranéen pour la Transition Environnementale Aix-Marseille Université

Environmental transition
Safety, Energy Mix

Institut Microbiologie, Bioénergies et Biotechnologie Aix-Marseille Université

Microbiology/Bioenergy

Institut NeuroMarseille Aix-Marseille Université

Neurosciences

Institut Physique de l'Univers Aix-Marseille Université

Physics of the Universe

Institut Sciences de la Fusion et de l'Instrumentation en Environnements Nucléaires Aix-Marseille Université

Fusion/NI

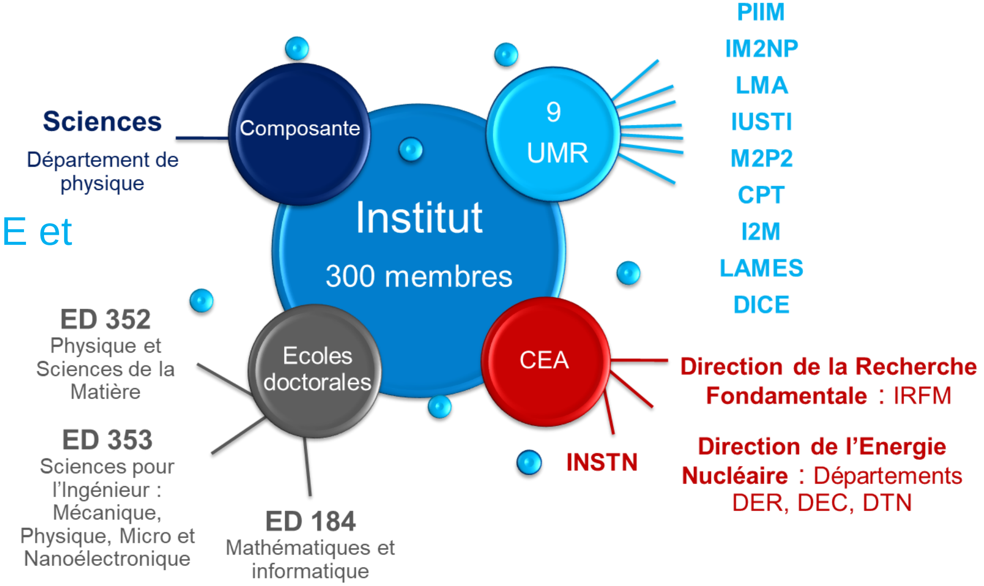
Institut Sociétés en Mutation en Méditerranée Aix-Marseille Université

Societies in mutation

Outline

- Introduction : AMU institutes
- **Perimeter of the ISFIN institute : labs & faculty**
- Research topics
- Setting up a graduate school

- **~150 reshearchers at AMU + ~150 at CEA**
- **Grouping several structures**
  - 9 Labs
  - 2 institutes at CEA Cadarache (IRESNE et IRFM)
  - 2 common AMU/CEA labs LIMMEX et MISTRAL
  - 3 Doctoral Schools
- **Focused on nuclear energy applications**
- **Both on Research and Teaching**
- **Several partners**
  - EDF
  - IRSN



Institut

300 membres

Composante

Sciences

Département de physique

9 UMR

PIIM

IM2NP

LMA

IUSTI

M2P2

CPT

I2M

LAMES

DICE

CEA

Direction de la Recherche Fondamentale : IRFM

Direction de l'Energie Nucléaire : Départements DER, DEC, DTN

INSTN

Ecoles doctorales

ED 352

Physique et Sciences de la Matière

ED 353

Sciences pour l'Ingénieur : Mécanique, Physique, Micro et Nanoélectronique

ED 184

Mathématiques et informatique

Outline

- Introduction : AMU institutes
- Perimeter of the ISFIN institute : labs & faculty
- **Research topics**
- Setting up a graduate school

Main Research Topics

- Plasma wall interactions and edge plasma physics
- Plasma confinement

[E. Serre, M2P2]
[Y. Camenen,PIIM]

- Instrumentation, sensors, microsensors, electronics
- Characterization & modelling of materials and structures

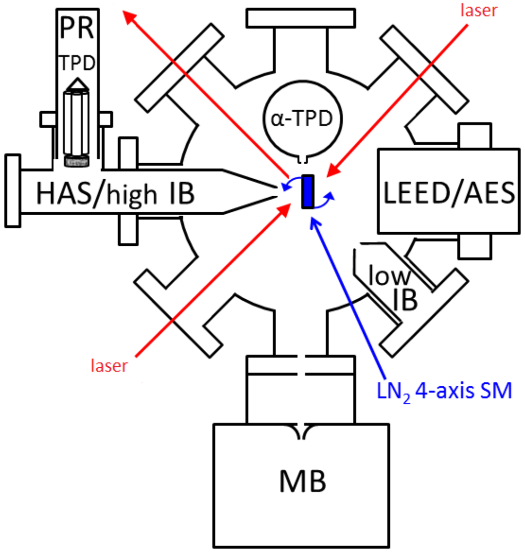
[C. Reynard-Carette, IM2NP]
[N. Favretto-Cristini,LMA]

- Thermal diagnostics and measure of thermophysical properties
- Social sciences (Sociology, law, …)

[J.-L. Gardarein, IUSTI]
[C. Mattina, LAMES]

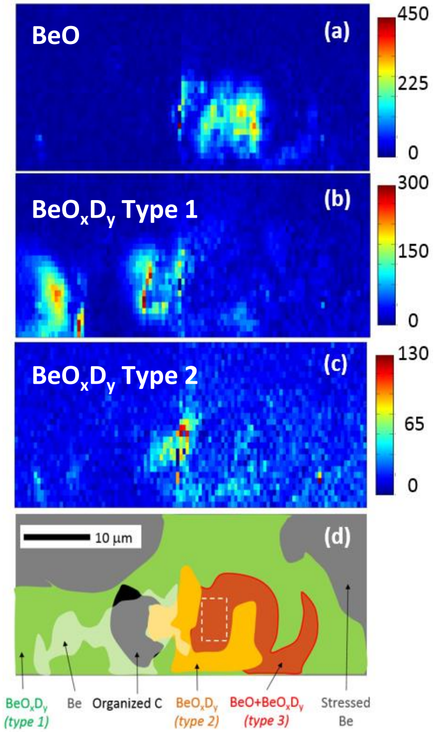
Most of this research is conducted in close partnership with CEA

Plasma wall interactions and edge plasma physics

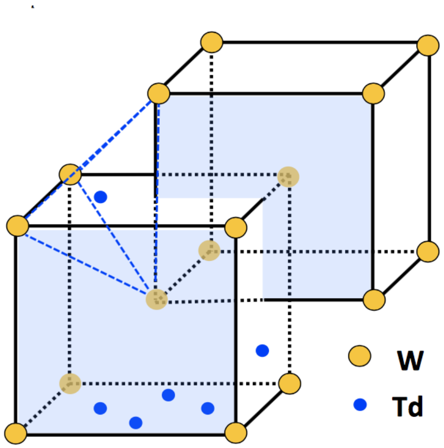


Advanced **MU**lti-beams experiment for **P**lasma **S**urface **I**nteraction studies

R. Bisson et al.



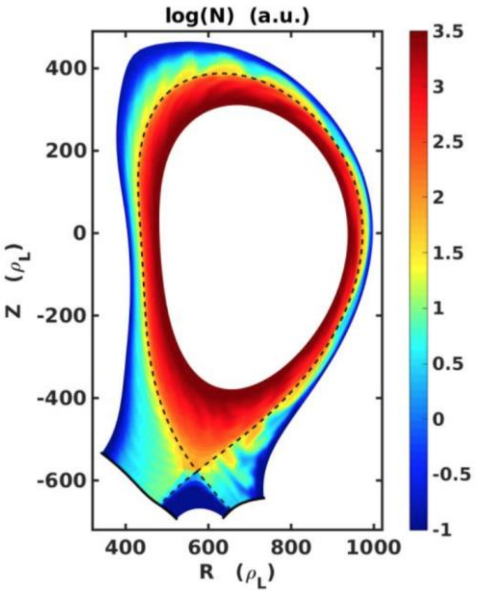
C. Pardanaud et al.



Y. Ferro et al.

Plasma wall interactions and edge plasma physics

- ➢ Edge numerical modeling
  Soledge/Tokam3X

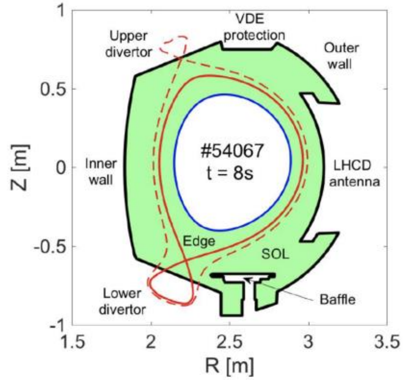


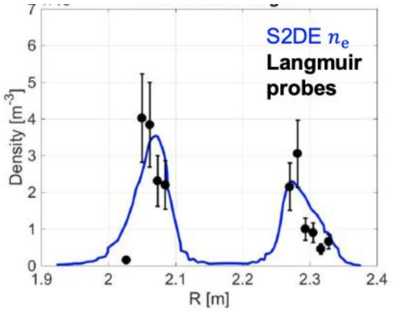
M2P2/IRFM (E. Serre, P. Tamain)

- ➢ Thermal Diagnostics for WEST

IUSTI (J.-L Gardarein, J. Gaspard)

- ➢ Interpretative modelling for WEST

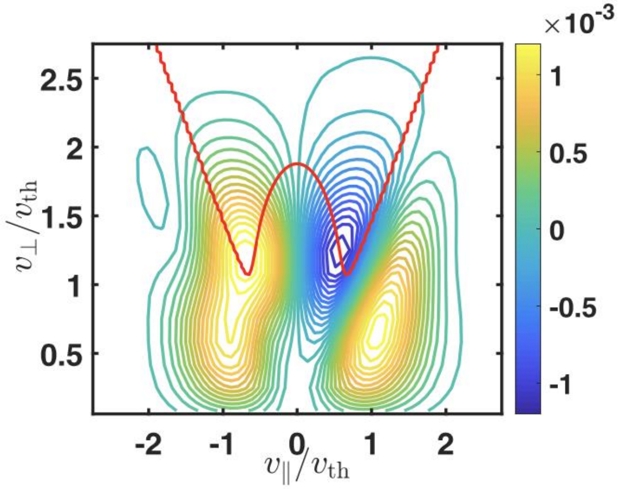




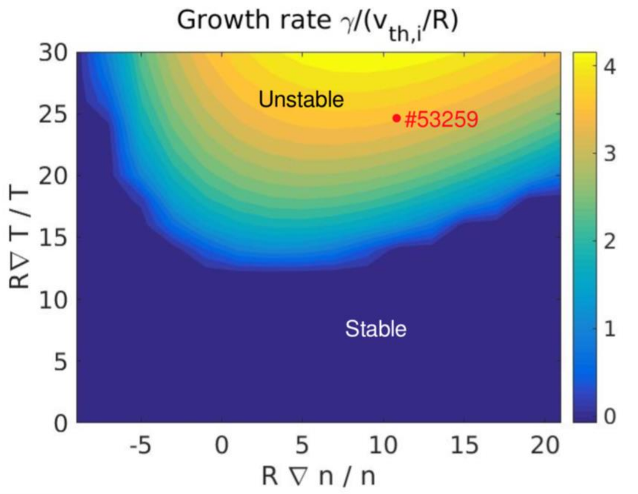
PIIM/IRFM (A. Gallo, G. Ciraolo)

Plasma confinement

- Fundamentals of gyrokinetics theory (Vitttot, Chandre – CPT, I2M)
- Integrated modelling & model reduction through neural networks (Camenen, Bourdelle, PIIM/IRFM)
- Fast particles physics (Zarzoso PIIM/IRFM)
- Interactions MHD/Turbulence (Agullo PIIM/IRFM)



D. Zarzoso et al.



O. Agullo et al.

Graduate School perimeter

- Master of Physics & Master of Instrumentation, measurements and metrology
- PhD Program
- Short courses, seminars
- Summer Schools (ITER School, EFMMIN, …)

Internationalization is key indicator, **starting from the master**

- Building on the European master of Science in Nuclear Fusion and Engineering Physics coordinated by AMU since 2018 et **ERASMUS MUNDUS since 2019** (P. Beyer)

- Creating a **new international lecture track** on **the instrumentation of large nuclear installations** (M. Carette)

- Integrating **social sciences** (interculturality, problem-based learning), with contributions from MIT

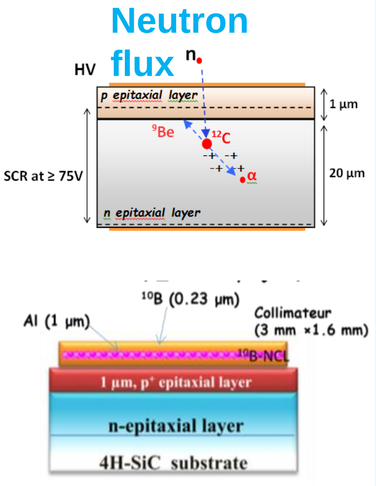
Thank You for Your attention

Спасибо большое.

Research axis in Instrumentation, Sensor, Microsensor and Electronics

Within the framework of the LIMMEX joint laboratory (Lab. of Instrumentation, Measurement under EXtrem conditions)

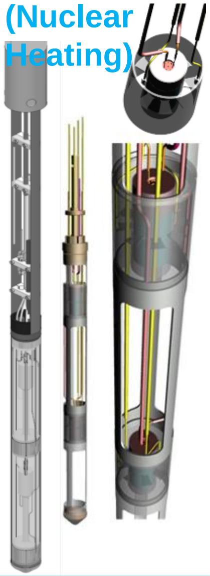
- **R&D for Instrumentation and Measurements under harsh conditions**
- **Application field: Fission and more recently fusion**
- **Three research topics:**
  - **Nuclear instrumentation/detection**
    - Photon and neutron measurements (SiC and Diamond detectors, Fission and ionization chambers, SPNDs, SPGDs, dosimeters, TLD, OSLD)
  - **Thermal measurements**
    - Nuclear absorbed dose rate (nuclear heating rate) measurements (differential calorimeters, single-cell calorimeter, gamma thermometer)
    - Thermal properties (DSC, LFA, Conductimeter)
  - **New materials for detection**
- **From materials to electronics**



SiC detectors

AMU-CEA Patent
B2944-HD15654

Absorbed dose rate (Nuclear Heating)



Calorimeters

AMU-CEA Patent
FR1553136A

Research axis in Instrumentation, Sensor, Microsensor and Electronics

➢ Challenges

- **Online measurements** under irradiation conditions (Jules Horowitz Reactor)

  - for the quantification of experimental conditions inside channel before the integration of irradiation device

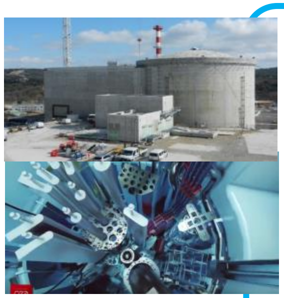
  - for the measurement of key parameters during in-pile study on the accelerated ageing of materials and on nuclear fuels (understanding the behavior)

  - for the monitoring of the structure

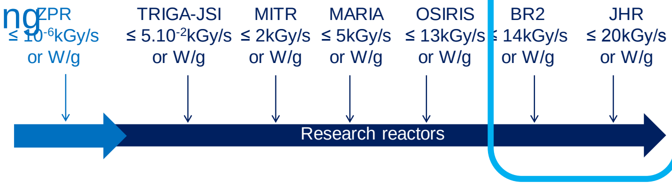
- **Miniaturization** of sensors and detectors, innovative sensors
- Improvement of **metrological characteristics** of sensors

  (sensitivity, linearity, range, calibration)

- Inter-comparison/ coupling of sensors and associated methods
- Nuclear instrumentation for new conditions and/or new reactors **(Fusion)**



100MWth
5.5 10^{14}
n/(cm²s) f
E>1MeV
16
DPA/yea
20W/g



ZPR
≤ 10^{-6}kGy/s
or W/g

TRIGA-JSI
≤ 5.10^{-2}kGy/s
or W/g

MITR
≤ 2kGy/s
or W/g

MARIA
≤ 5kGy/s
or W/g

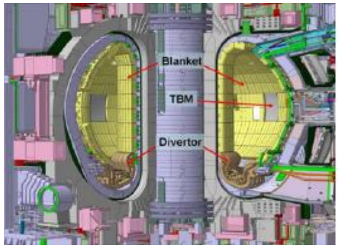
OSIRIS
≤ 13kGy/s
or W/g

BR2
≤ 14kGy/s
or W/g

JHR
≤ 20kGy/s
or W/g

Research reactors

2025

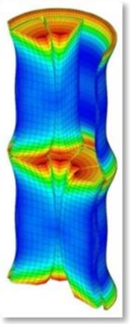


Research axis in Materials and Structures
(Mechanics, Acoustics, Modeling, Experiments)

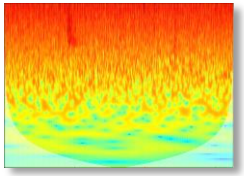
- **Within the framework of a joint laboratory MISTRAL (Modeling, Inspection and characterization of materials and STRuctures for Advanced Low carbon energies)**

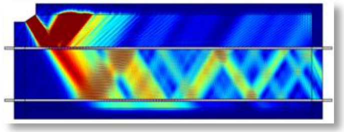
- **Two main topics**
  - **Prediction and analysis of material and structure behavior**
    - Development of theoretical models and numerical tools to study and describe
      - effect of microstructural parameters at macroscopic scale (homogenization theories)
      - local behavior (e.g. interactions between fuel pellets and cladding) and/or the global behavior (e.g. interactions between fluid flow and fuel assembly) based on micro/meso/macro and multi-physics coupling
    - Computational fluid dynamics modeling (with diphasic aspects for instance)

      (Fusion: ongoing PhD on mechanical modeling of supraconductors wires)



  - **Structure Health Monitoring** (at different scales, from the reactor to the containment barriers) using non destructive acoustical methods
    - Detection and characterization of defaults (e.g. cracks, cladding rupture, welding…) in structures
    - Modeling and quantification of the pathologies developed in damaged areas
    - Development of experimental procedures for real-time monitoring of integrity of structures





Outline

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- Integrating **social sciences** (interculturality, problem-based learning), with contributions from MIT

PhD Program

- 20 phD positions **co-funded** over 5 years
  - Focused on the intersection of priorities of the institute and the partners
  - Select topics first, students next, possibly on year N+1
  - Possibility for PhD students to apply for mobility (proposal writing, …)

- Other PhD students working in Fusion/Fission associated to the events (20 PhD students per year), as well as master students

Conclusions

- Fusion & Nuclear instrumentation formally identified as a **key topic** for AMU over the next 5-10 years
- The institute is the **entry point** for fusion/fission related business at AMU
- Most of the research is in close collaboration with CEA
- Action focused on the PhD & Master program in view to strengthen the link between training & research
- Promotes the transfers from techniques developed for fission to fusion
- Additional points : ANIMMA Conference, …

Back-up slides

ANIMMA CONFERENCE

(Advancements in Nuclear Instrumentation Measurement Methods and their Applications)

- ❑ **Created in 2009**
- ❑ **Involving AMU, CEA, SCK-CEN, JSI, IEEE NPSS**
- ❑ **6 editions (2009-France, 2011-Belgium, 2013-France, 2015-Portugal, 2017-Belgium, 2019-Slovenia) + 1 edition (2021-Czech Republic)**
- ❑ **Composed of**
  - ➢ **Several sessions/topics**
    - ○ Fundamental physics
    - ○ **Fusion diagnostics and technology**
    - ○ Nuclear power reactors monitoring and control
    - ○ Research reactors
    - ○ Nuclear fuel cycle
    - ○ Decommissioning, dismantling and remote handling
    - ○ Safeguards, homeland security
    - ○ Severe accident monitoring
    - ○ Environmental and medical sciences
    - ○ Education, training and outreach
  - ➢ **Keynotes, Plenaries, Invited, Orals, Posters**
  - ➢ **Workshops (since 2013) (Fission and Fusion topics)**
  - ➢ **Short-courses with practices**
  - ➢ **Industrial exhibition**
  - ➢ **Visit**
- ❑ **350-450 participants per edition**
- ❑ **Proceedings published and articles in IEEE journals (IEEE TNS, IEEE TPS)**

2019

ANIMMA 2019

Portorož Slovenia 17 – 21 June

The sixth international conference on Advancements in Nuclear Instrumentation Measurement Methods and their Applications (ANIMMA) will take place from 17 to 21 June 2019 in Grand Hotel Bernardin, Portorož, Slovenia.

Committee Chairs

Prof. Dr. Abdallah Lyoussi

Prof. Dr. Michel Giot

Dr. Igor Jencic

Dr. Luka Snoj

Dr. Christelle Reynard-Carette

Dr. Ludo Vermeeren

APPLICATION FIELDS

- Fundamental physics
- Fusion diagnostics and technology
- Nuclear Power Reactors Monitoring and Control
- Research reactors
- Nuclear fuel cycle
- Decommissioning, dismantling and remote handling
- Safeguards, homeland security
- Severe accident monitoring
- Environmental and medical sciences
- Education, training and outreach

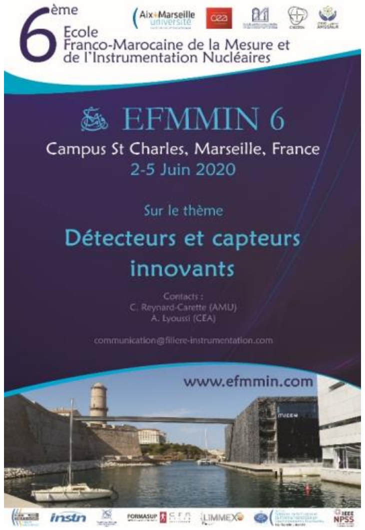
www.animma.com

Contact

EFMMIN SCHOOL

(Ecole Franco-Marocaine de la Mesure et de l’Instrumentation Nucléaires)

- ❑ **Created in 2010**
- ❑ **Involving AMU, CEA, CNESTEN, Mohammed V University, AMSSNUR**
- ❑ **5 editions + 1 edition (2020)**
  - ➢ **A specific topic per edition**
    - ○ Research reactors (2010-Morroco)
    - ○ Nuclear fuel cycle (2011-France)
    - ○ Medicine and environment (2014-Morroco)
    - ○ Dismantling and radioactive waste characterization (2016-France)
    - ○ Nuclear and radiological safety and security (2018-Morroco)
    - ○ **Innovative detectors and sensors (2020-France)**



6ème
Ecole
Franco-Marocaine de la Mesure et
de l’Instrumentation Nucléaires

EFMMIN 6
Campus St Charles, Marseille, France
2-5 Juin 2020

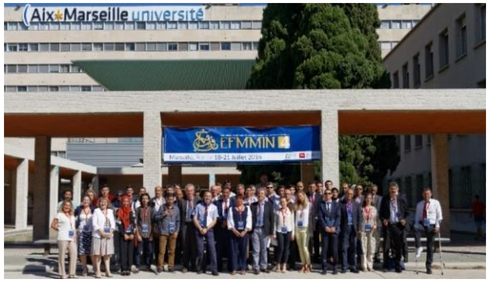
Sur le thème
Détecteurs et capteurs innovants

Contacts :
C. Reynard-Carette (AMU)
A. Lyoussi (CEA)

communication@filiere-instrumentation.com

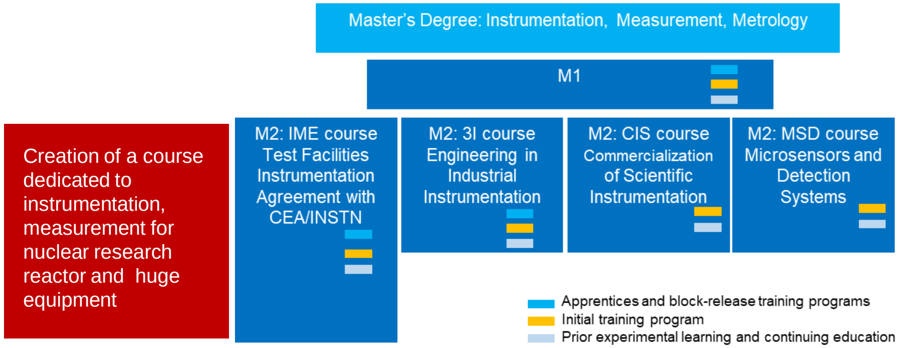
www.efmmin.com

- ❑ **Conferences, Courses, workshops, posters, visits**
- ❑ **50 participants (PhD, Post-Doc, M2, Young researchers …) + 10 speakers**



Master's degree in INSTRUMENTATION, MEASUREMENT, METROLOGY

- ❑ **Created in 2004 inside the Filière Instrumentation (Department of Physics, Faculty of Sciences, AMU)**
- ❑ **Up to 150 students per year**
- ❑ **Quality certification (ISO 9001)**
- ❑ **Committee involving socio-economic partners**
- ❑ **EDF agreement (internship grants, seminars, visits)**
- ❑ **International mobility program (MOBIL-APP, Academy of Excellence, A*MIDEX)**
  - ➢ **involving CEA, EDF, CFA, MIT, SCK-CEN, CNESTEN, NCBJ, JSI**
- ❑ **Alumni network**
- ❑ **Various programs (apprenticeship, initial training program, continuing education, prior experimental learning)**
- ❑ **A high professional integration rate**
- ❑ **At present 4 courses**
  - ➢ **in particular "Test Facilities Instrumentation course" owning an agreement with CEA/INSTN (specialization in nuclear instrumentation and detection)**
- ❑ **Action: creation of a new international course dedicated to instrumentation for nuclear research reactors and huge equipment**



Master's Degree: Instrumentation, Measurement, Metrology

M1 🟦 🟨 ⬜

Creation of a course dedicated to instrumentation, measurement for nuclear research reactor and huge equipment

M2: IME course Test Facilities Instrumentation Agreement with CEA/INSTN 🟦 🟨 ⬜

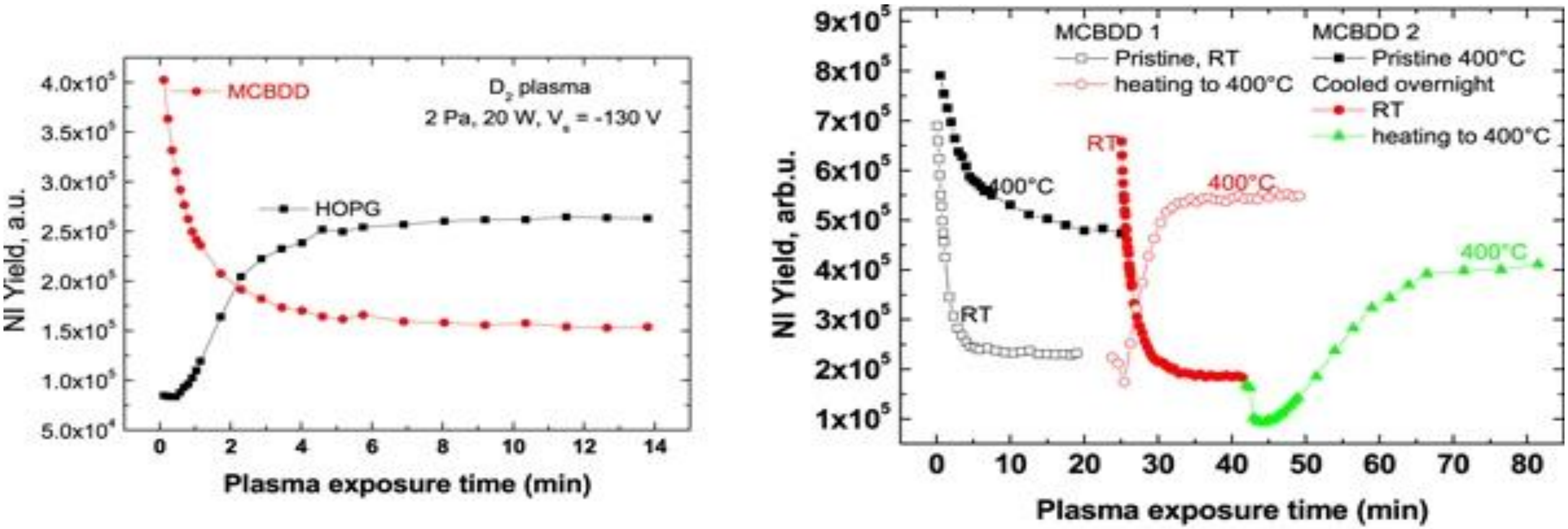
M2: 3I course Engineering in Industrial Instrumentation 🟦 🟨 ⬜

M2: CIS course Commercialization of Scientific Instrumentation 🟨 ⬜

M2: MSD course Microsensors and Detection Systems 🟨 ⬜

🟦 Apprentices and block-release training programs
🟨 Initial training program
⬜ Prior experimental learning and continuing education

Figure 7 from Alternative solutions to caesium in negative-ion sources: a study of negative-ion surface production on diamond in H2/D2 plasmas
Gilles Cartry et al 2017 New J. Phys. 19 025010 doi:10.1088/1367-2630/aa5f1f



a

b

Outline

Accelerators

Satellite

- Negative-ions outside fusion ?

Space propulsion

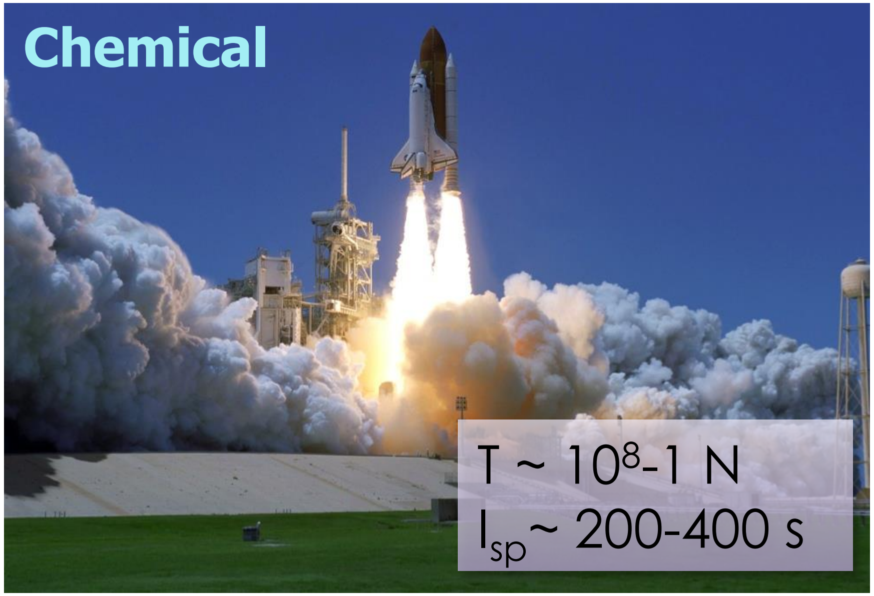
Microelectronics

AMS

SIMS

Space propulsion

$$m\frac{dv}{dt} = -\frac{dm}{dt}v_g \left\{ \begin{array}{ll} \textbf{Trust} & T = \frac{dm}{dt}v_g \text{ (force)} \\ \textbf{Specific Impulse} & I_{sp} = \frac{v_g}{g_0} \text{ (time)} \end{array} \right.$$



Chemical

$T \sim 10^8$-1 N

$I_{sp} \sim$ 200-400 s

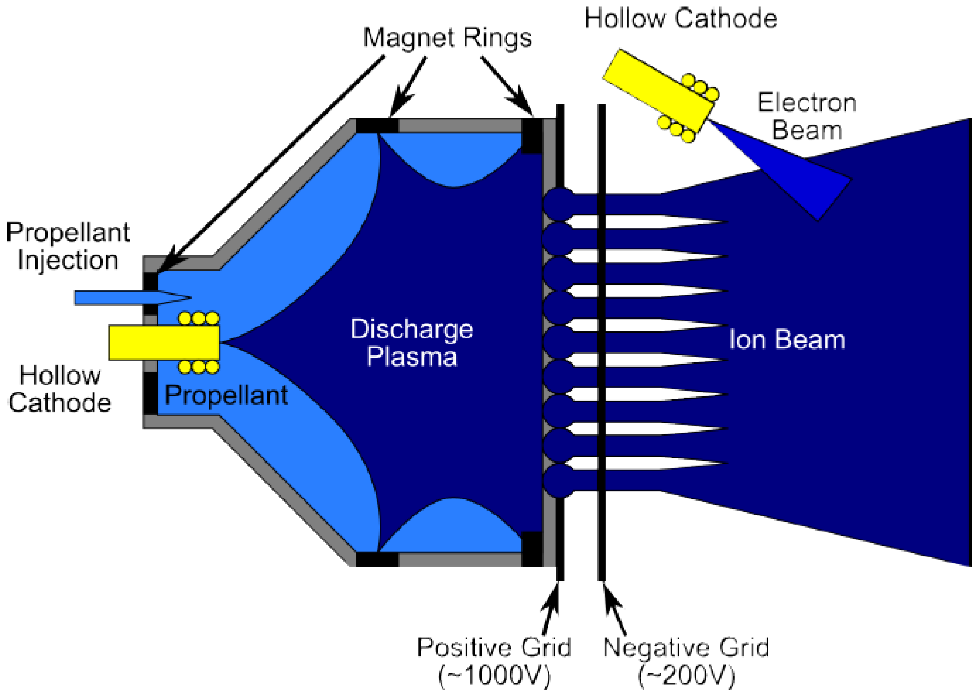
Electrical

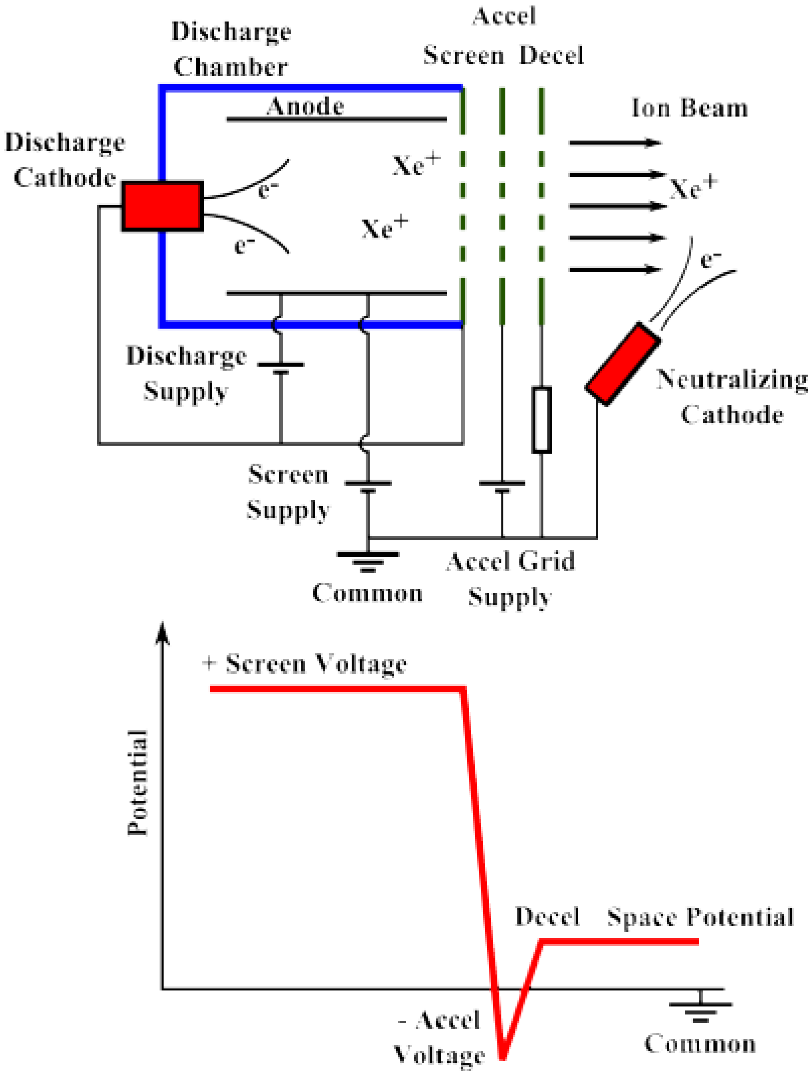
T < 1 N

$I_{sp} >$ 2000 s

From Ane Aanesland, LPP, Polytechnic School, Paris

Space propulsion

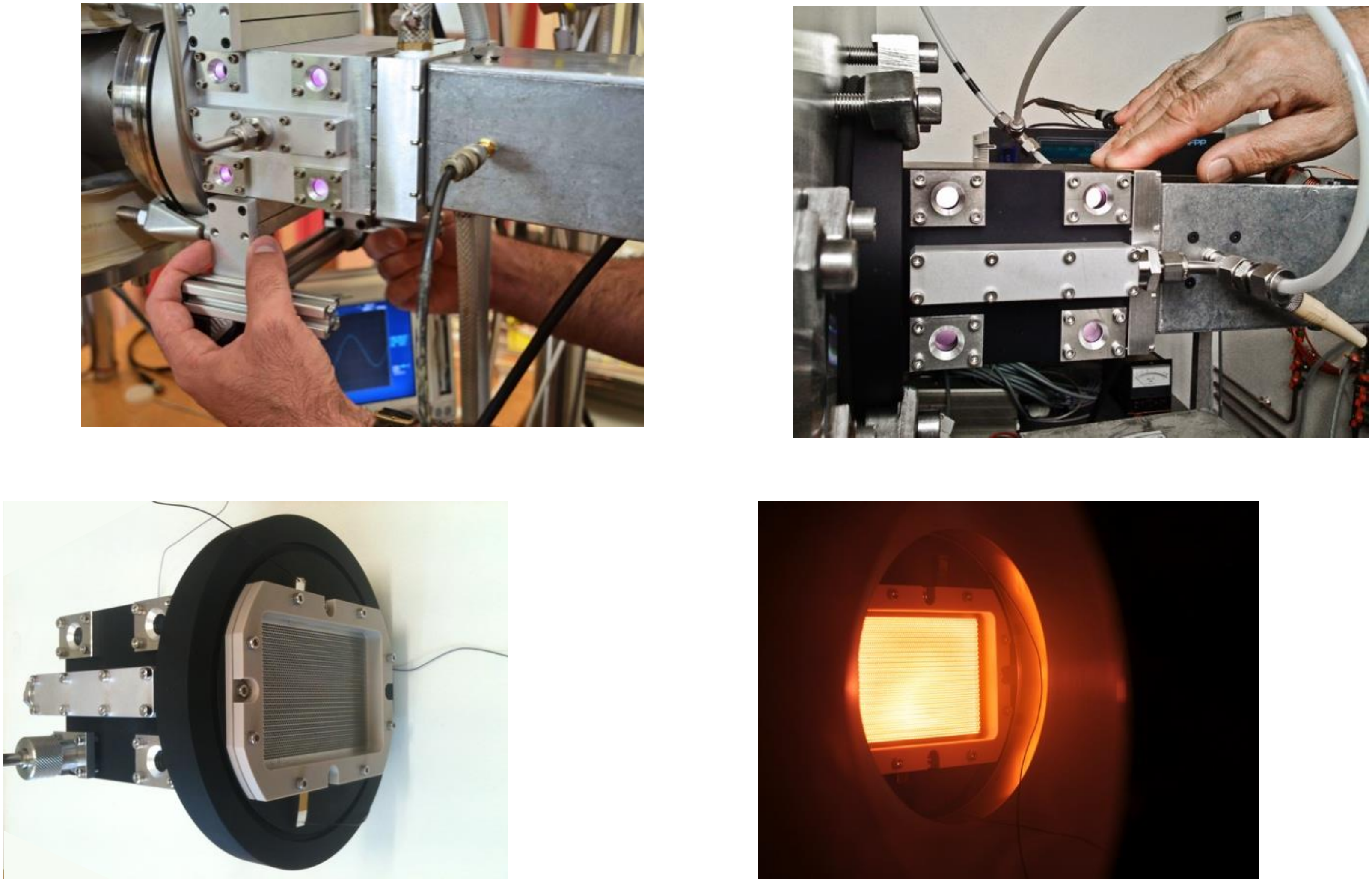




From Dennis Gerst PhD thesis, ICARE Laboratory, Orléans

Space propulsion

Space propulsion



From Ane Aanesland, LPP, CNRS

Outline

Accelerators

Satellite

- Negative-ions outside fusion ?

Space propulsion

Microelectronics

AMS

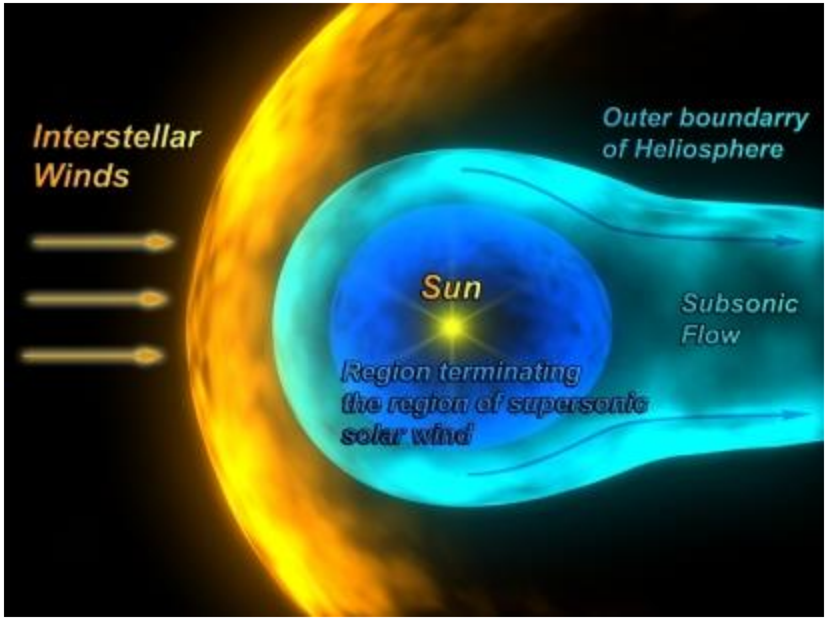
SIMS

Space satellites

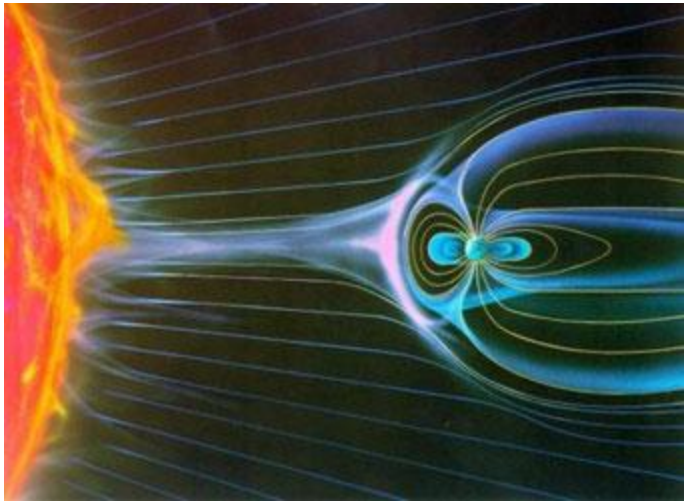
From Ane Aanesland, LPP, CNRS

Space satellites

- Neutral energy ranges from 10eV to several keV
- They cannot be detected directly because of the photon background and their low energy
- They have to be ionized and accelerated to be detected



Heliosphere

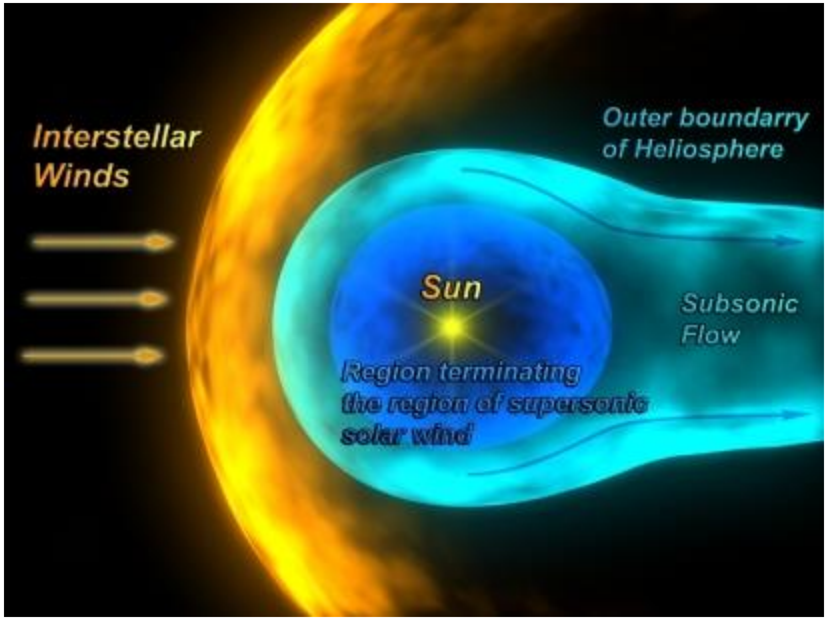


Magnetosphere

From Ane Aanesland, LPP, CNRS

Space satellites

How can we ionize low energy neutrals ?



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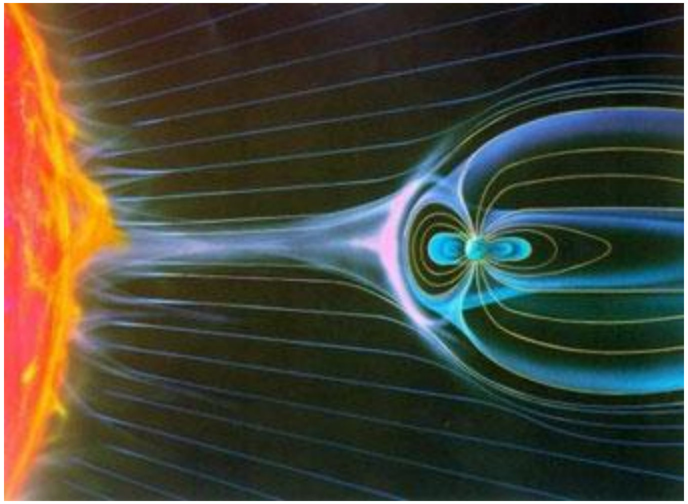


Magnetosphere

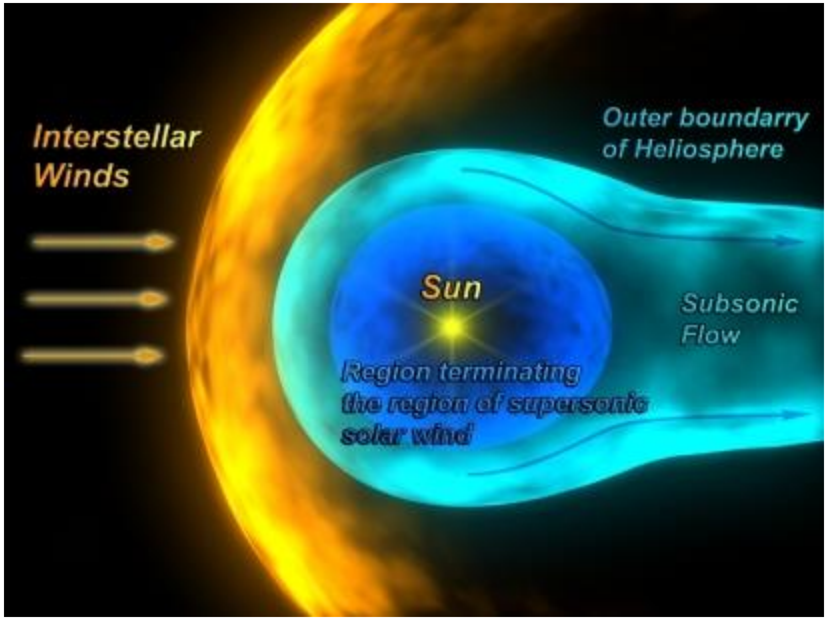
From Ane Aanesland, LPP, CNRS

Space satellites

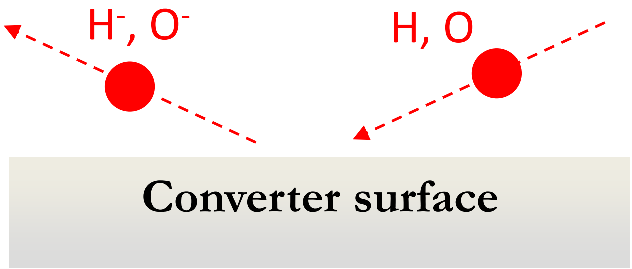
How can we ionize low energy neutrals ?

- The most efficient way has been recognized to be neutral to negative-ion surface conversion !

  Electron ionization efficiency: 10^{-3}-10^{-6} %, Carbon foil method not operating in this range of energy

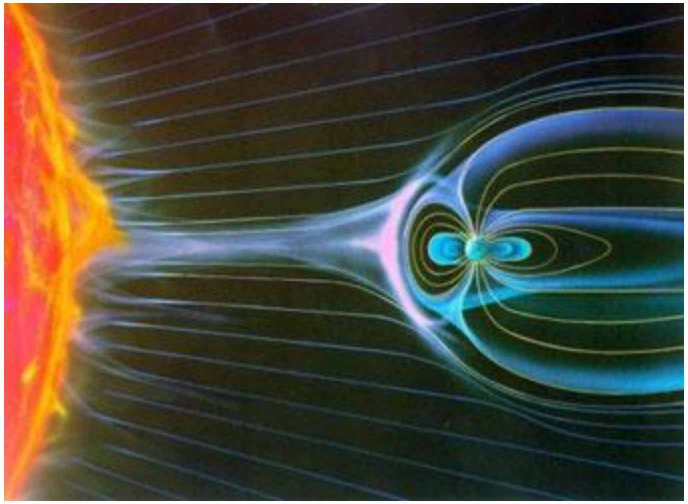


Heliosphere


H^-, O^-

H, O

Converter surface

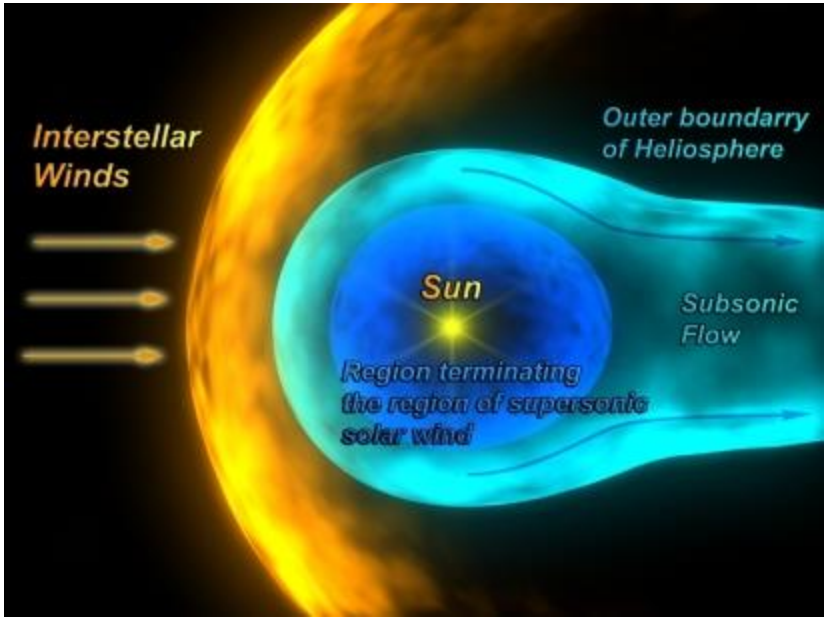


Magnetosphere

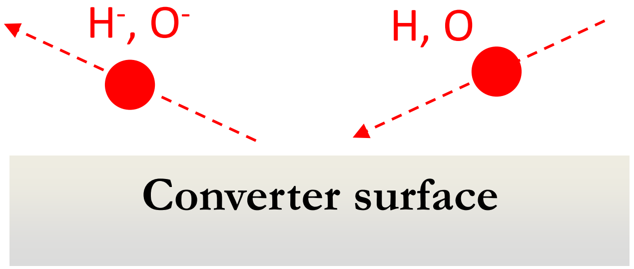
From Ane Aanesland, LPP, CNRS

Space satellites

What kind of converter material should we use ?

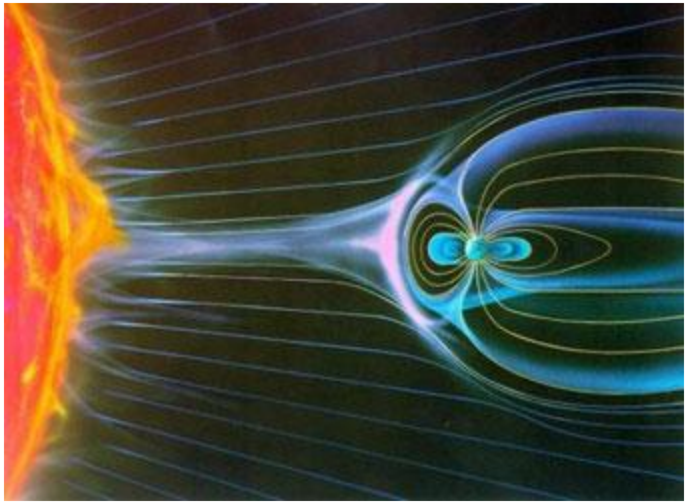


Heliosphere


H^-, O^-

H, O

Converter surface

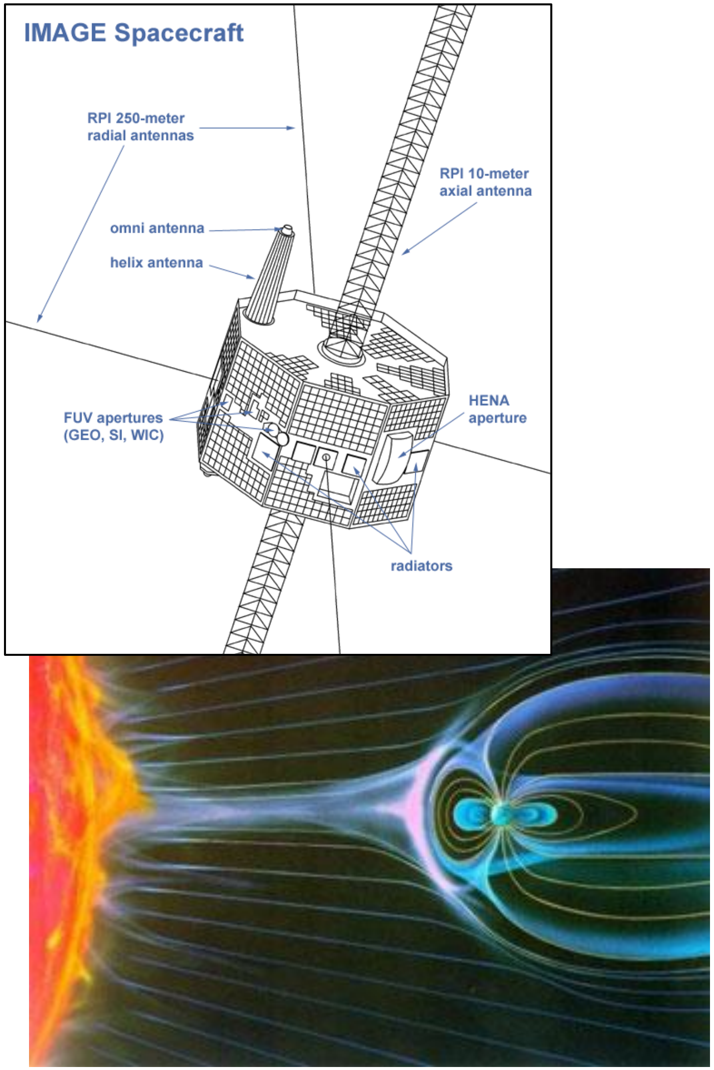


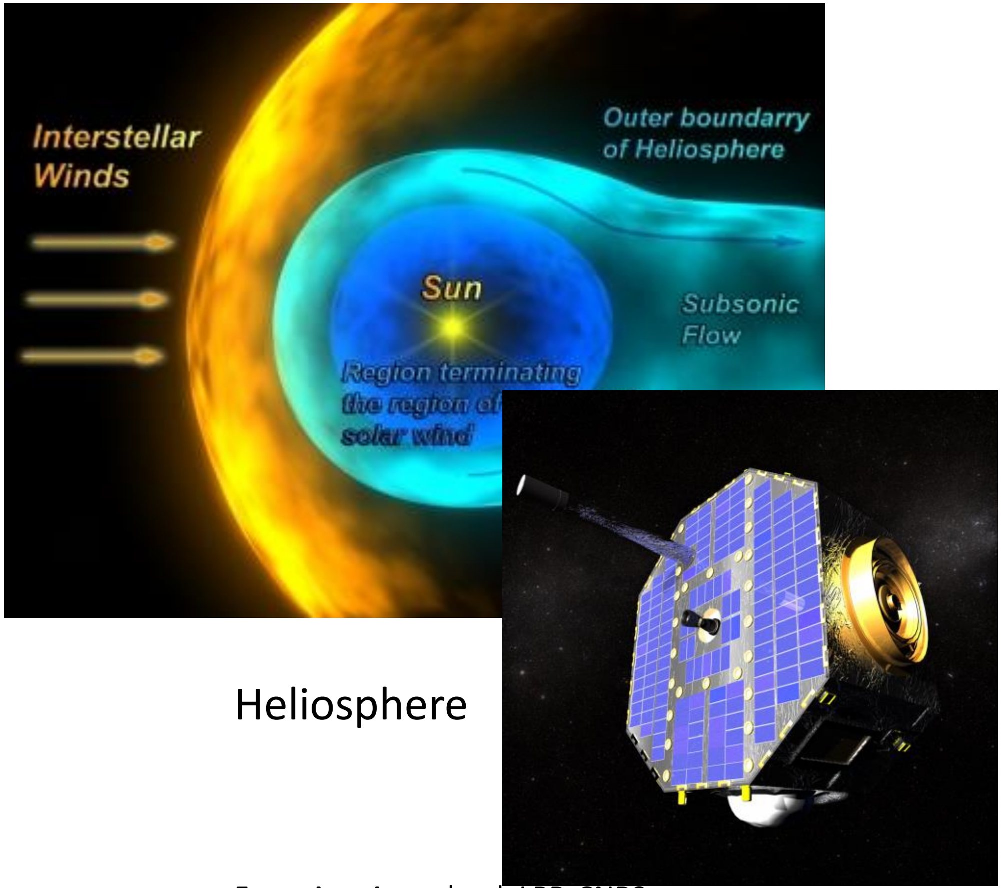
Magnetosphere

From Ane Aanesland, LPP, CNRS

Space satellites

What kind of converter material should we use ?





Heliosphere

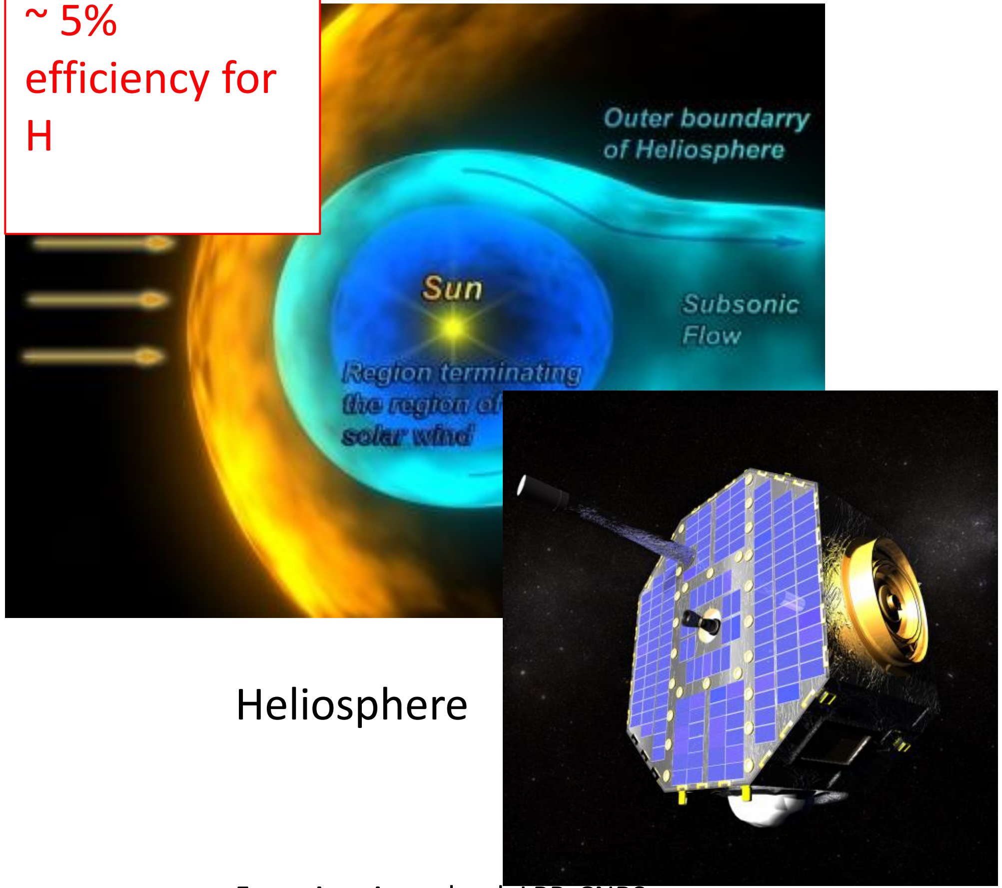
Magnetosphere

From Ane Aanesland, LPP, CNRS

Space satellites

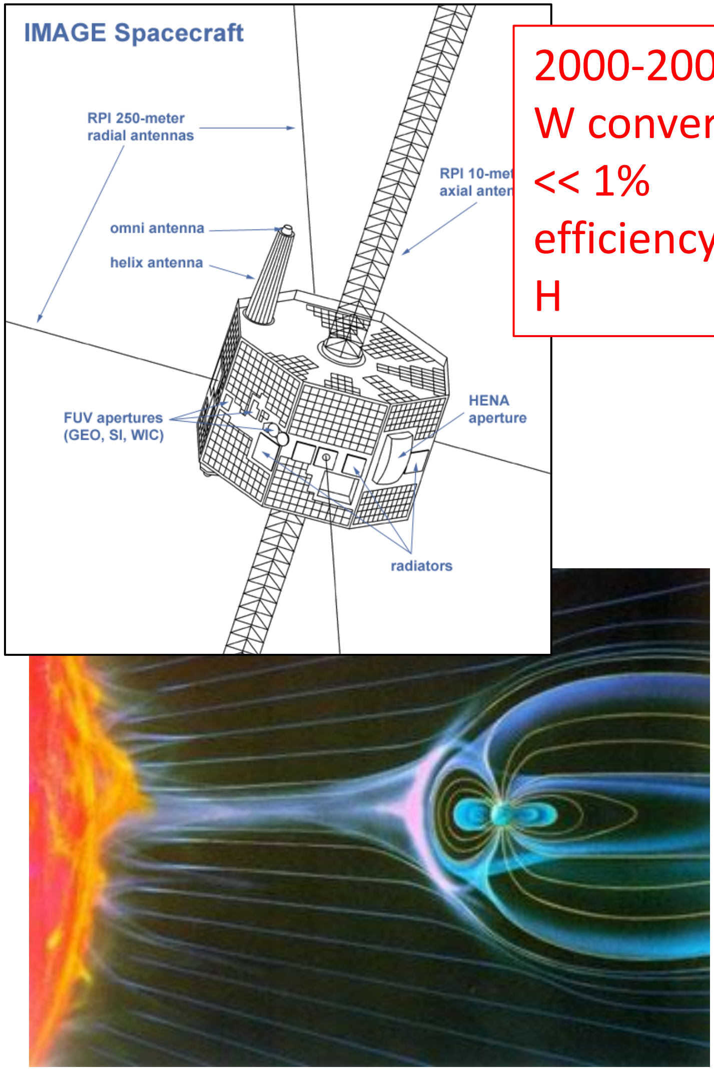
What kind of converter material should we use ?

2008-
DLC converter
~ 5%
efficiency for
H



Heliosphere

2000-2006
W converter
<< 1%
efficiency for
H



Magnetosphere

From Ane Aanesland, LPP, CNRS

Outline

Accelerators

Satellite

- Negative-ions outside fusion ?

Space propulsion

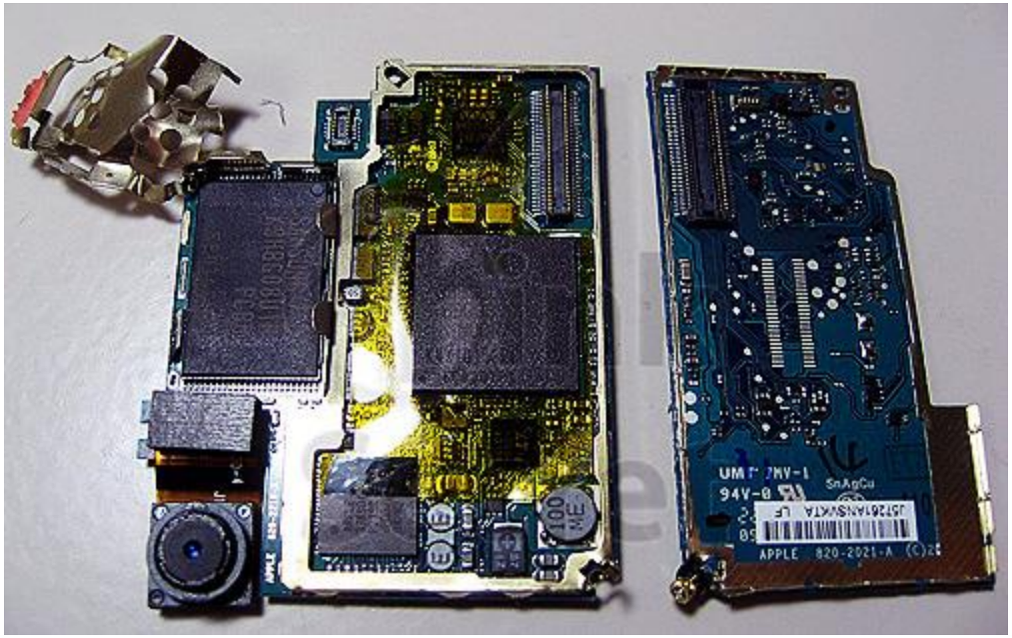
Microelectronics

AMS

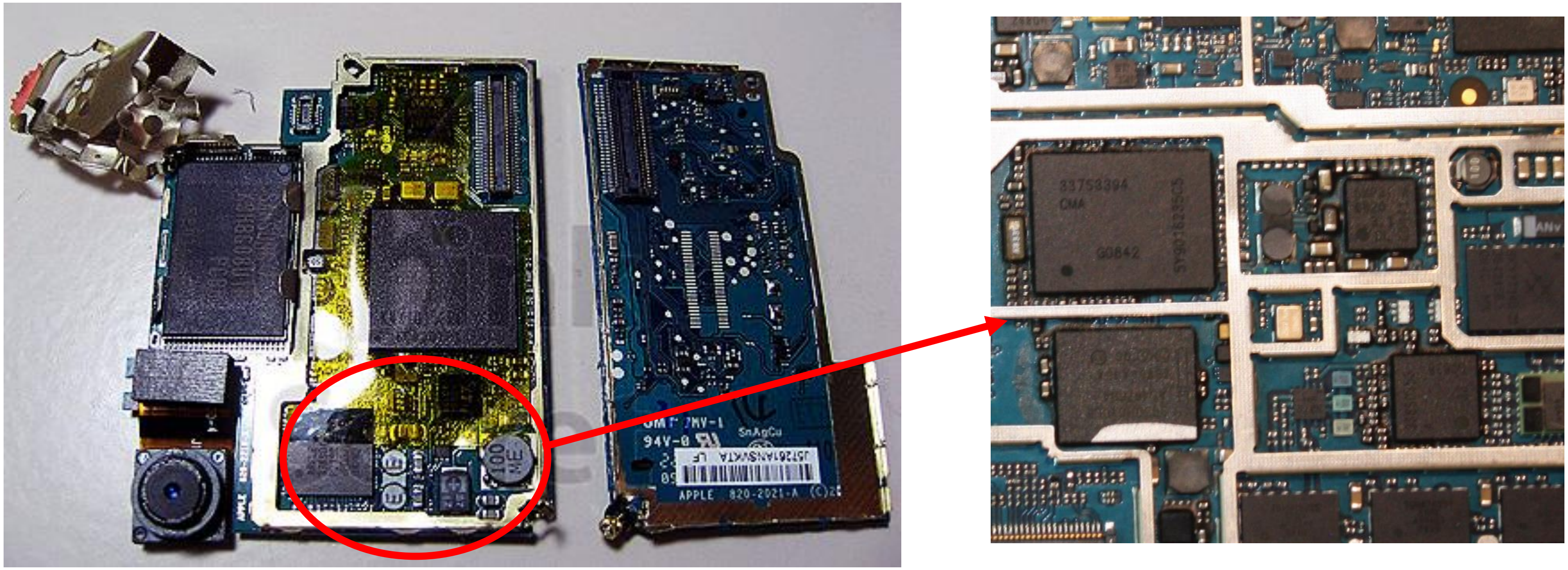
SIMS

Microelectronics

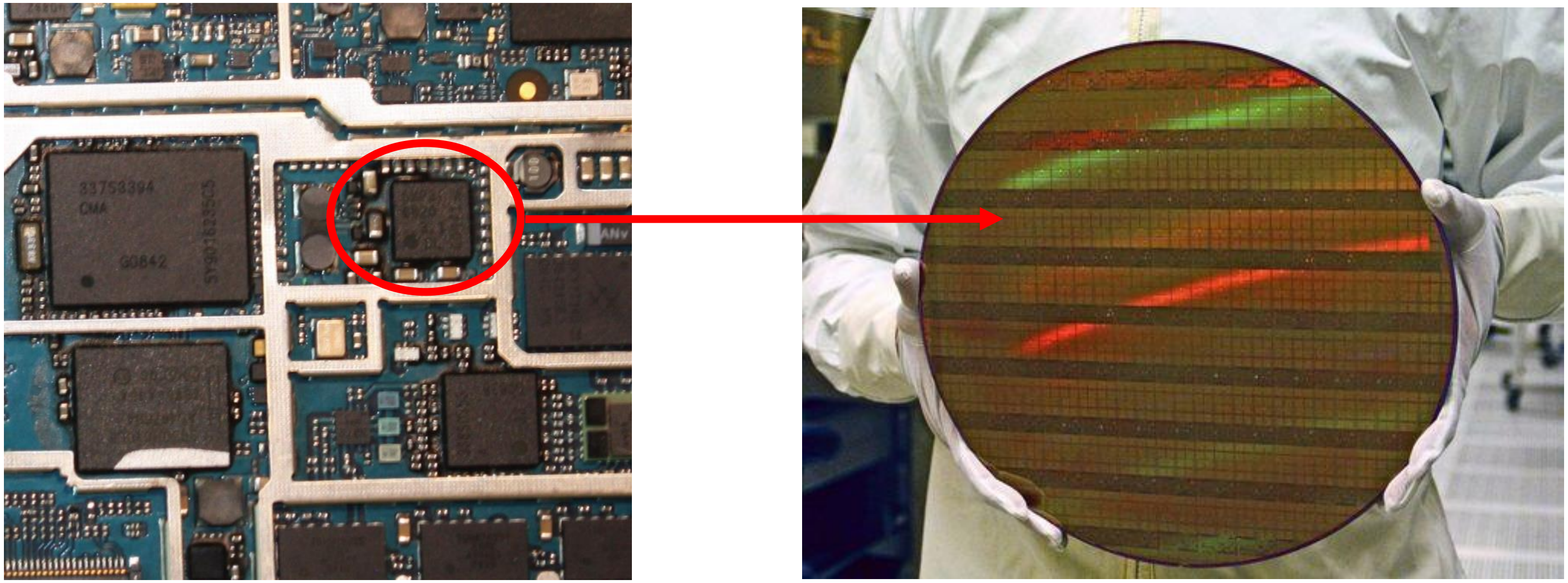
Microelectronics



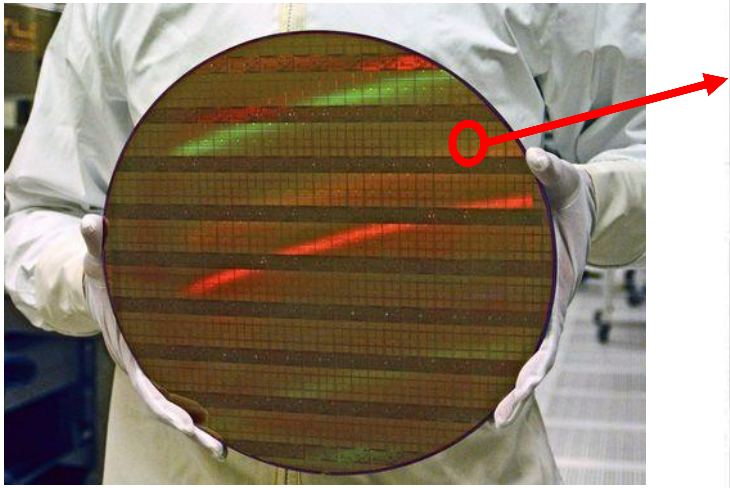
Microelectronics

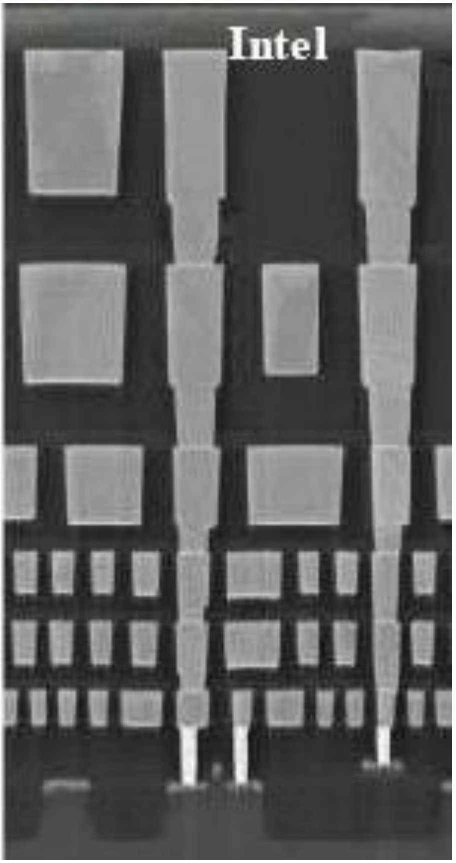


Microelectronics

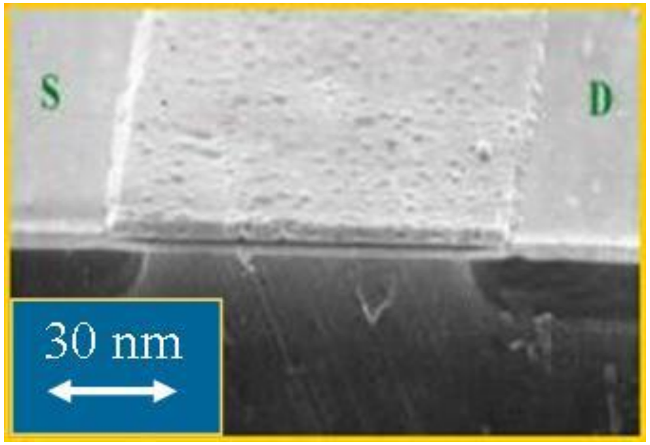


Microelectronics



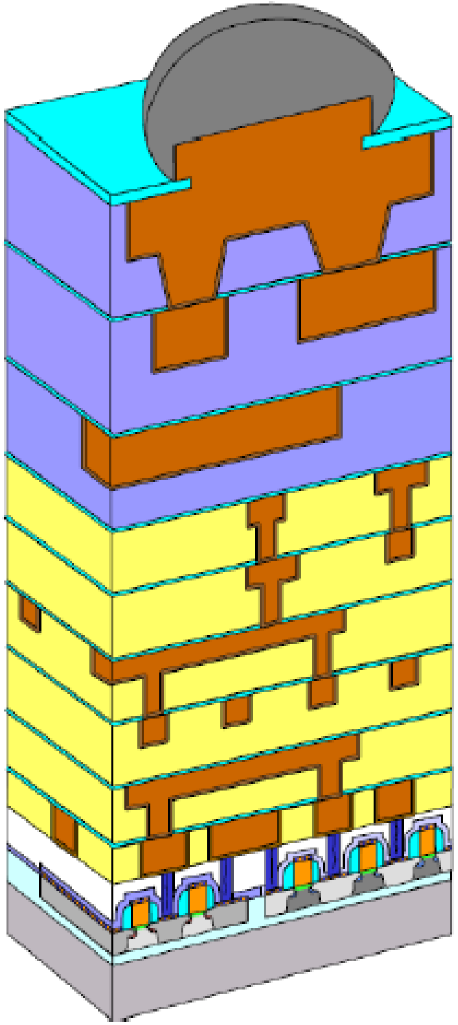


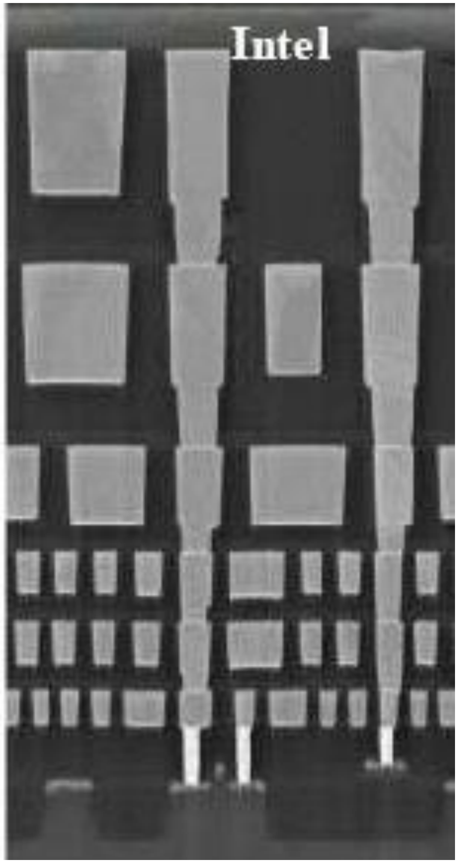
200 nm



Microelectronics

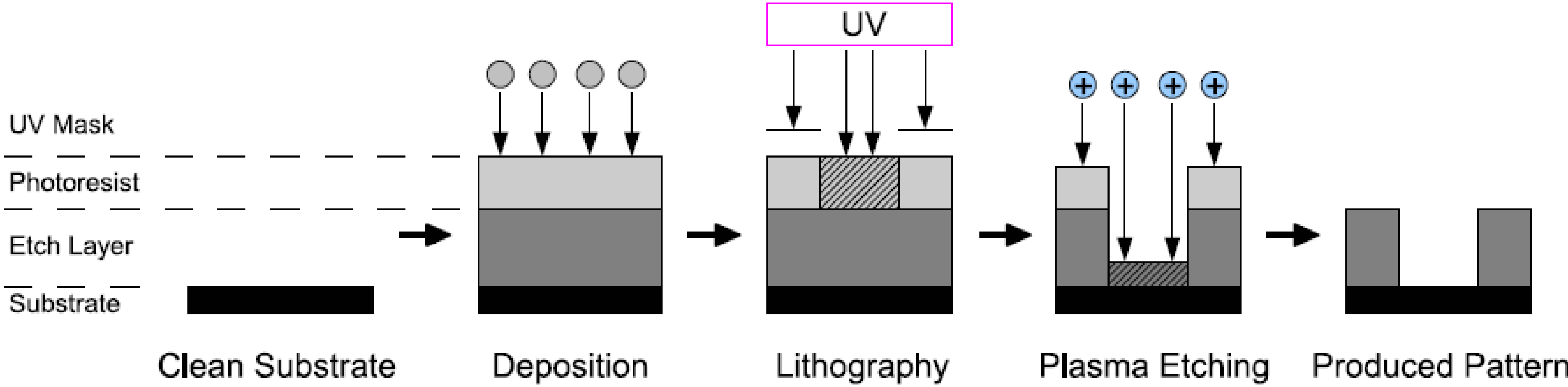
- 🟧 Poly-Si Electrode
- 🟩 Thermal SiO_2
- ⬜ SiO_2
- ⬜ P+ Doped Silicon
- ⬜ N Doped Silicon
- ⬜ P Doped Silicon
- 🟦 Nitride
- ▥ Cobalt Silicide
- ⬜ BPSG
- 🟦 Tungsten
- 🟨 OSG or other Dielectric
- 🟫 Barrier Liner
- 🟫 Copper
- 🟪 FSG
- ⬛ Lead-free Solder

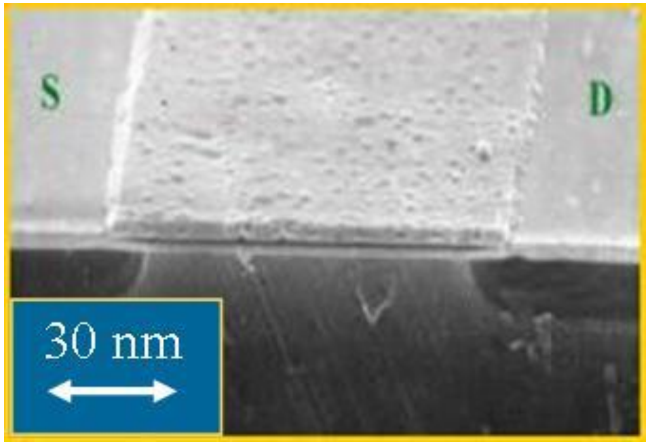


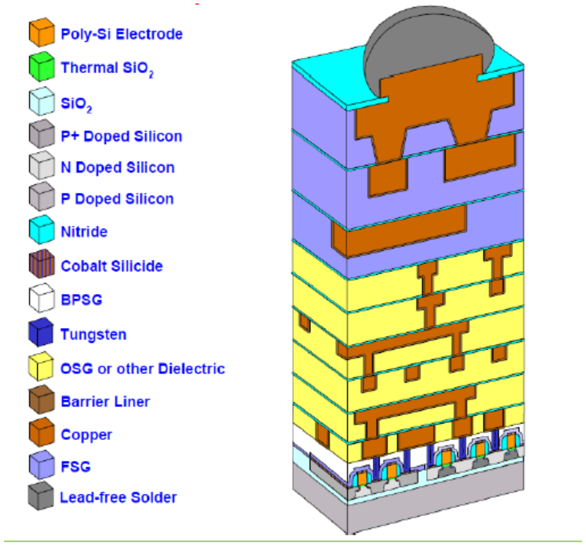


200 nm ⟷

Microelectronics

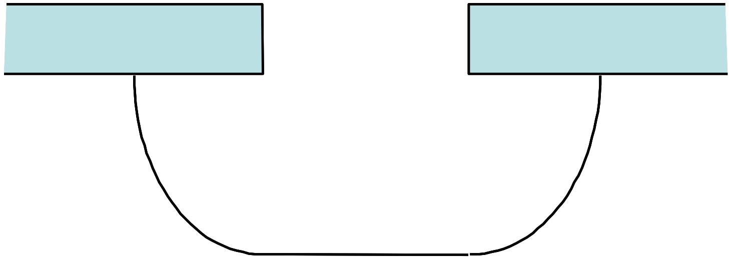






Microelectronics

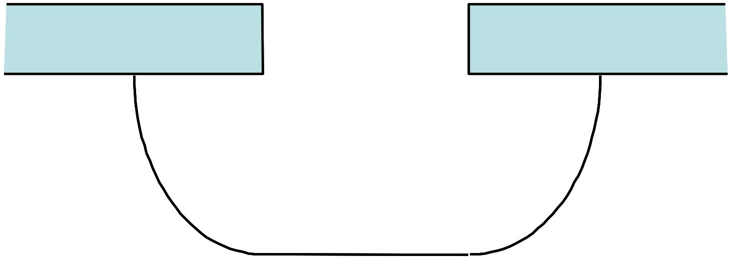
Why plasma etching ?



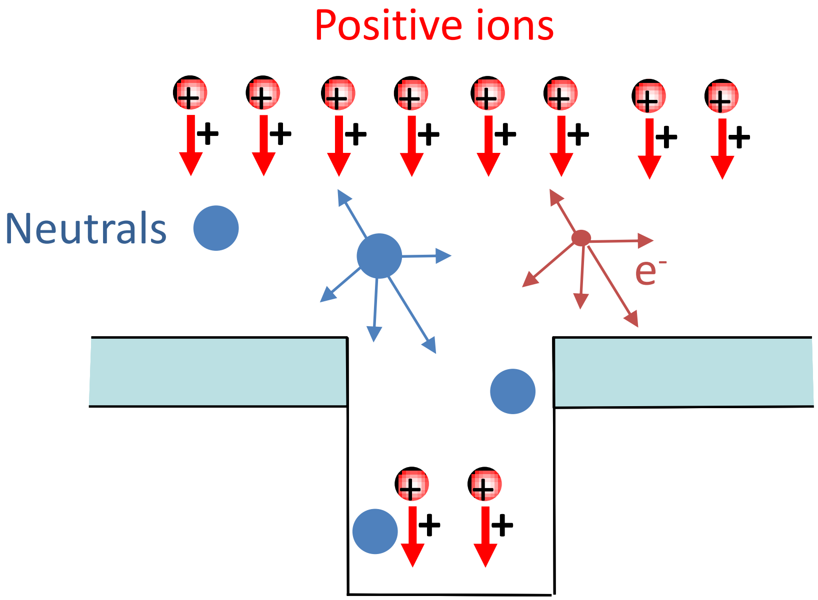
Chemical etching
=> Isotropic etching

Microelectronics

Why plasma etching ?



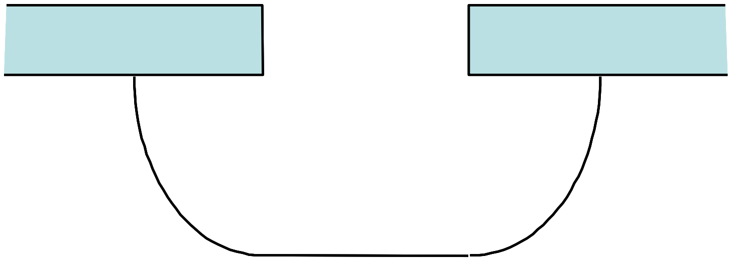
Chemical etching
=> Isotropic etching



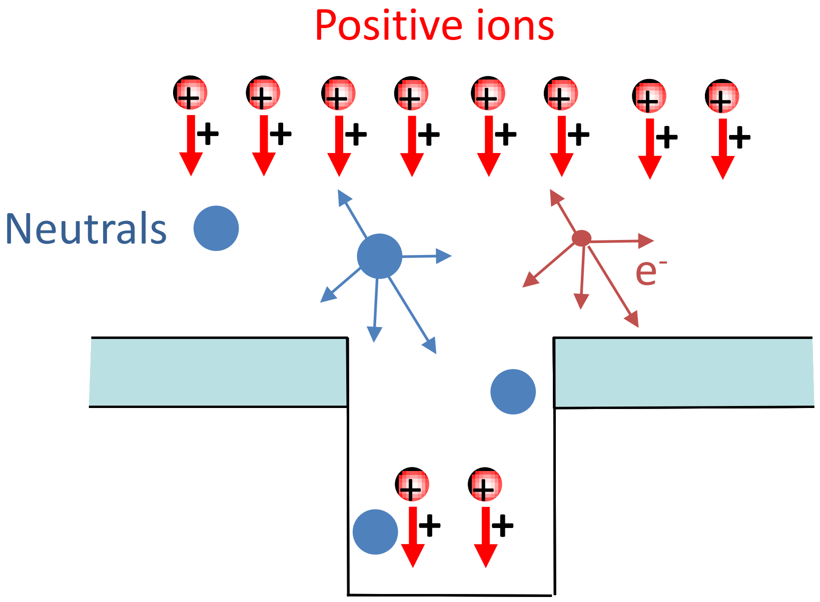
Plasma etching
=> Anisotropic etching

Microelectronics

Why plasma etching ?



Chemical etching
=> Isotropic etching

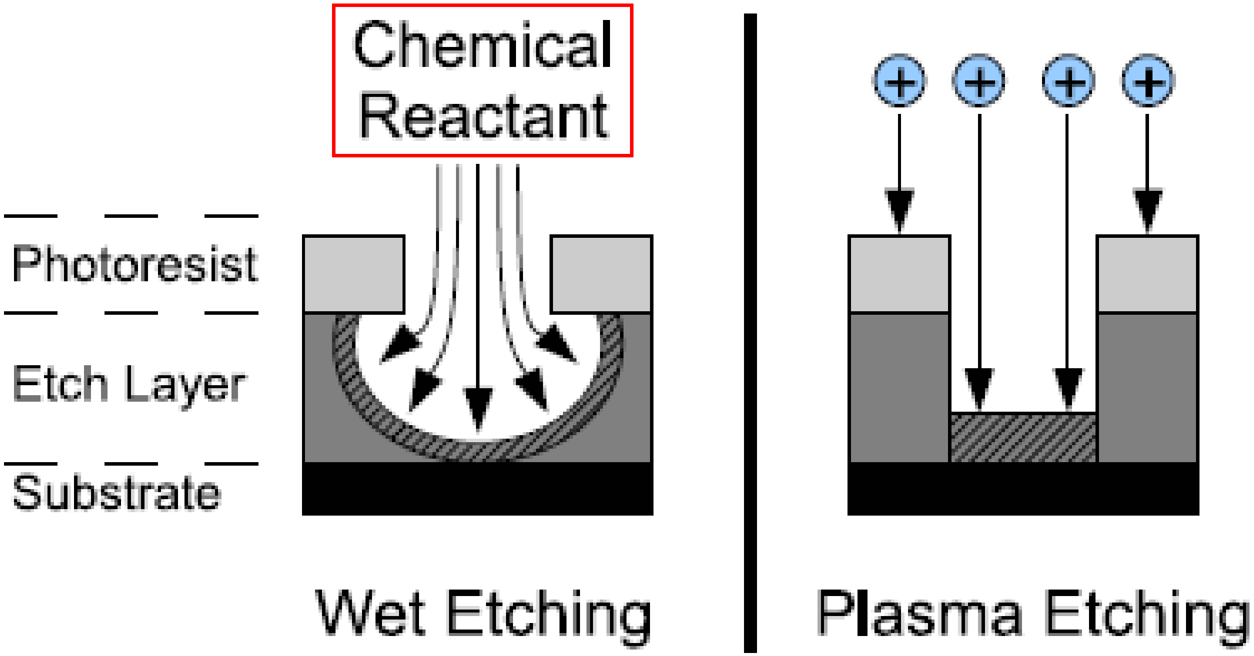


Plasma etching
=> Anisotropic etching

- Ions weaken bonds only at the bottom of the trench
- No etching of sidewalls

Microelectronics

Why plasma etching ?



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