2010 Spring

Microstructural Characterization *of* Materials

03.11.2010

Eun Soo Park

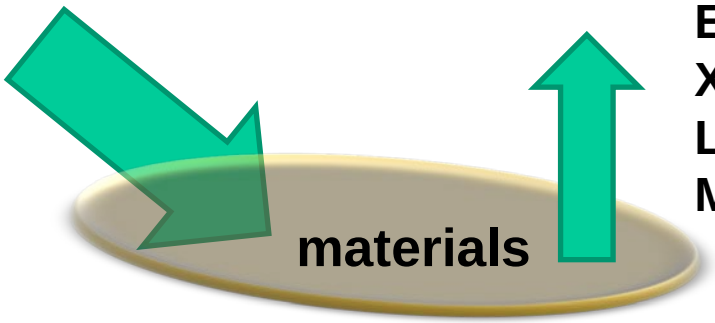
Office: 33-316
Telephone: 880-7221
Email: espark@snu.ac.kr
Office hours: by an appointment

Contents for previous class

Simple idea of analytical tools

Source

Electron
X-ray
Laser
Light
Shockwave
Mechanical



Signal

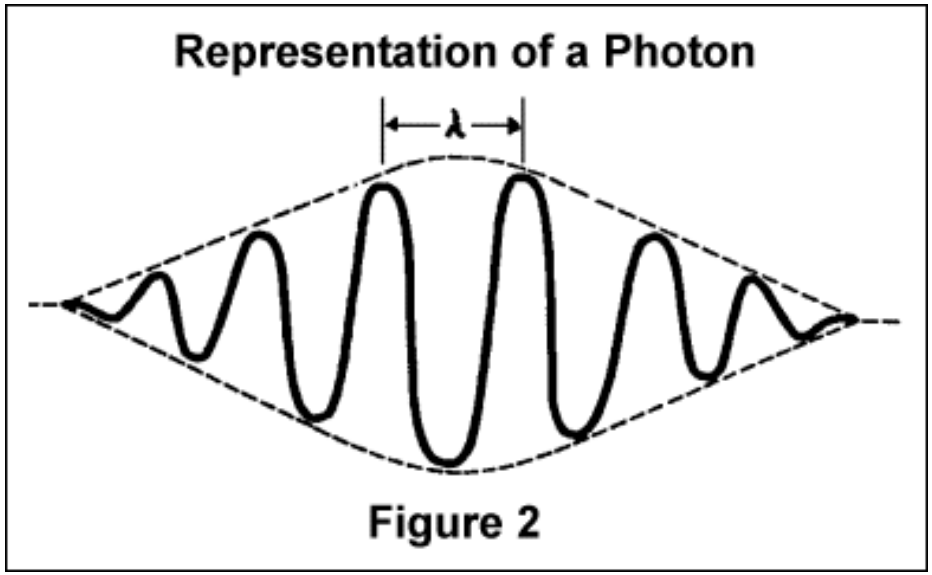
Electron
X-ray
Light
Mechanical

재료에 에너지의 input과 output을 분석하여 microstructure를 규명.

Quantum theory is a theory needed to describe physics on a **microscopic scale**, such as on the scale of atoms, molecules, electrons, protons, etc.

Contents for previous class

***Quantum*:** 어떤 물리량 (E)이 연속값을 취하지 않고 어떤 단위량의 정수배로 나타나는 비연속값을 취할 경우, 그 단위량을 가리키는 용어이다. 예를 들면, photon은 전자기장(EM)의 quantum 임.



➡ 10 photons have an energy equal to ten times a single photon.

Contents for previous class

- Considering Quantum theory,
  Photons can be treated as "***packets of light***" which behave as a particle.

- To describe **interactions of light with matter**, one generally has to appeal to the particle (quantum) description of light.

  Photo-Electric Effect
  Compton Effect

- A single photon has an **energy** given by

$$E = h\nu = hc/\lambda,$$

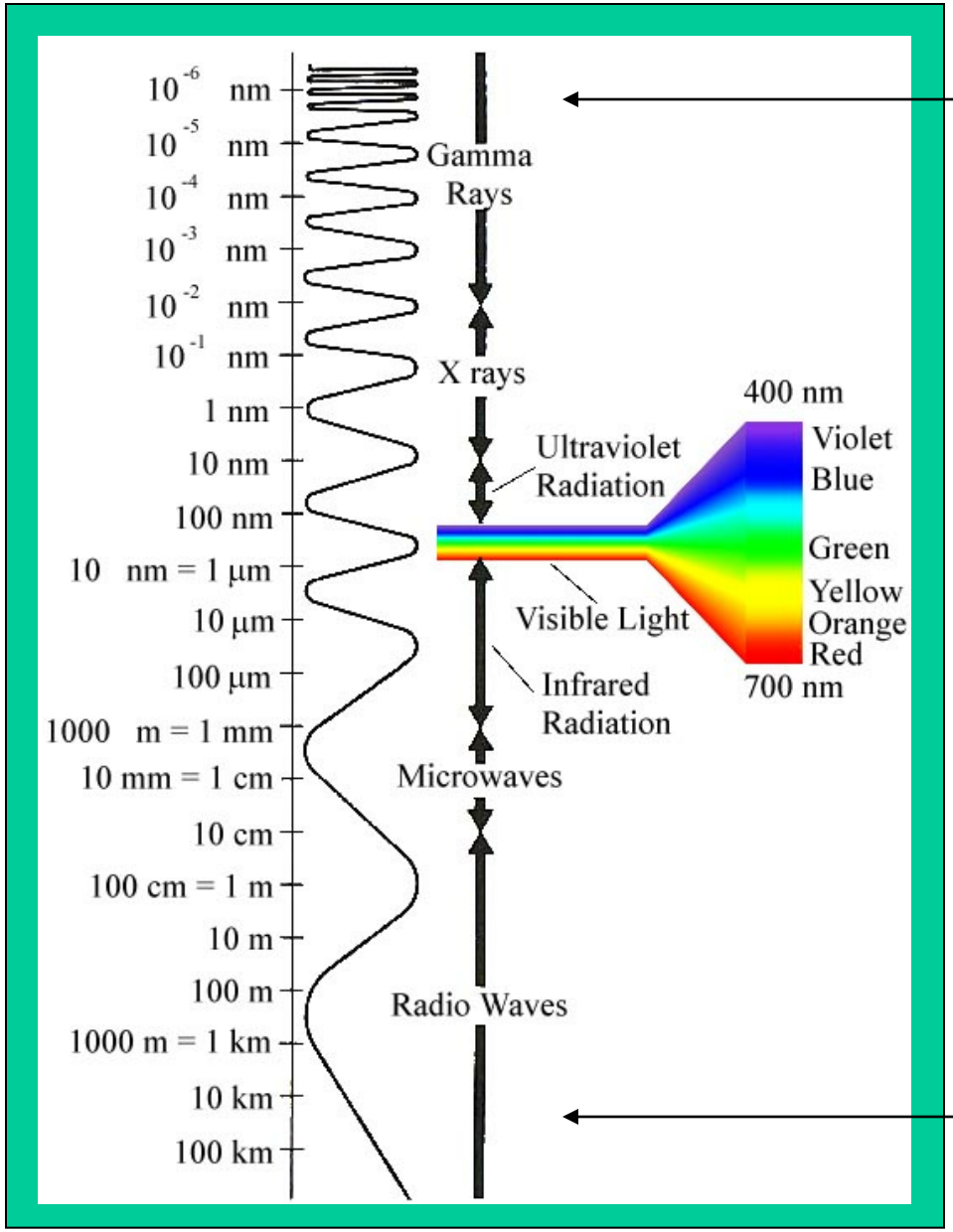
where h = Planck's constant = 6.6×10^{-34} [J s], c = speed of light = 3×10^{8} [m/s]
λ = wavelength of the light (in [m]), ν = frequency

- Photons also carry **momentum**. The momentum is related to the energy by: $p = E / c = h/\lambda$

❖ **Both energy & momentum are inversely proportional to the wavelength!!!**

➡ **The highest energy photons are those which have small wavelength (that's why gamma rays are so dangerous).**

The Electromagnetic Spectrum



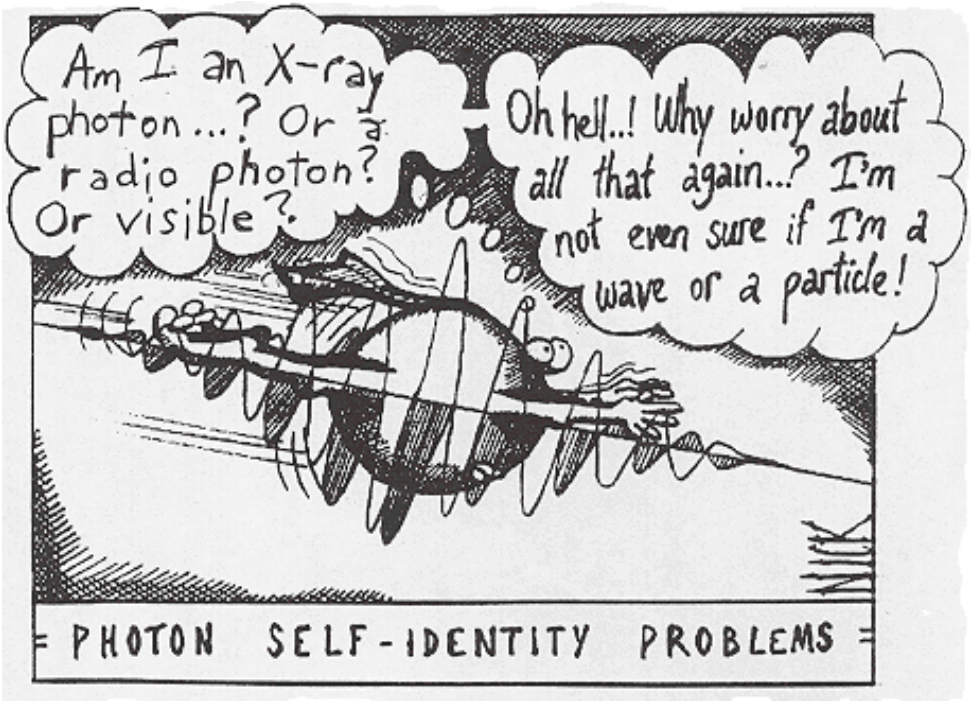
Shortest wavelengths
(Most energetic photons)

$$E = h\nu = hc/\lambda$$

$h = 6.6 \times 10^{-34}$ [J*sec]
(Planck's constant)

Longest wavelengths
(Least energetic photons)

So is light a wave or a particle ?



On **macroscopic scales**, we can treat **a large number of photons as a wave**.

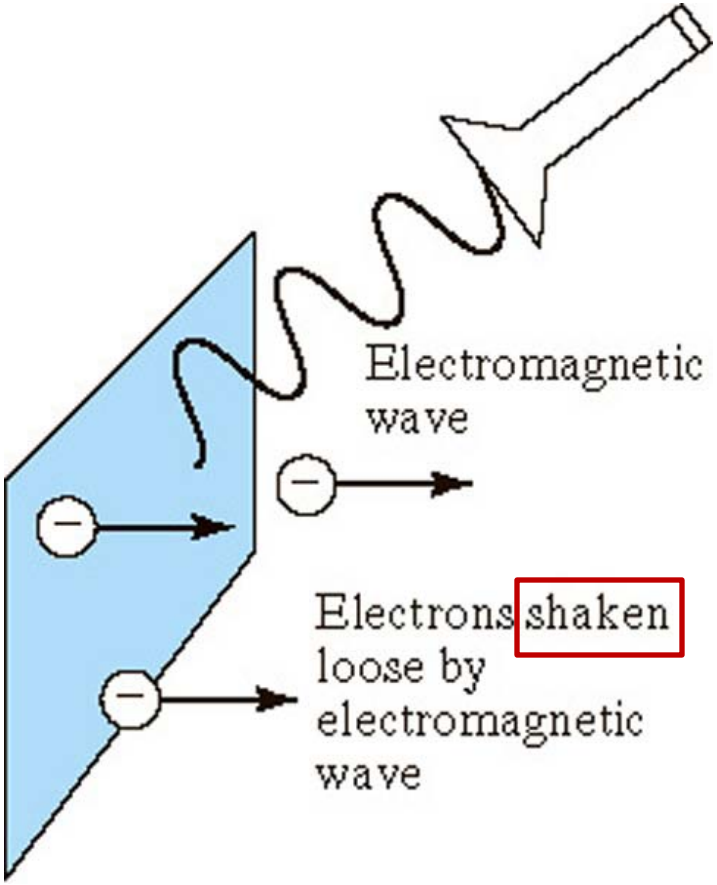
When dealing with **subatomic phenomenon**, we are often dealing with a **single photon**, or a few. In this case, you cannot use the wave description of light. It doesn't work !

Contents for today's class

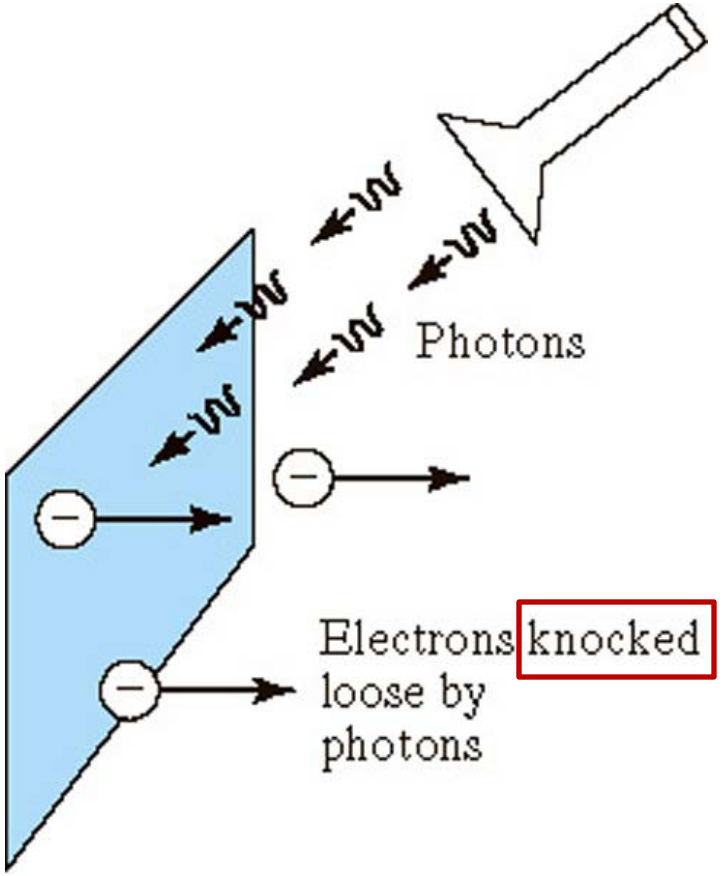
- ❖ ***Quantum Nature of Photons***
- ❖ ***How do we reconcile this with particle picture?***
- ❖ ***Matter Waves ?***
- ❖ ***Real photographs of an electron interference pattern***
- ❖ ***Wave length vs size***
- ❖ ***Remarks on Particle Probes***
- ❖ **방사광 가속기**

Quantum Nature of Photons

Classical Picture



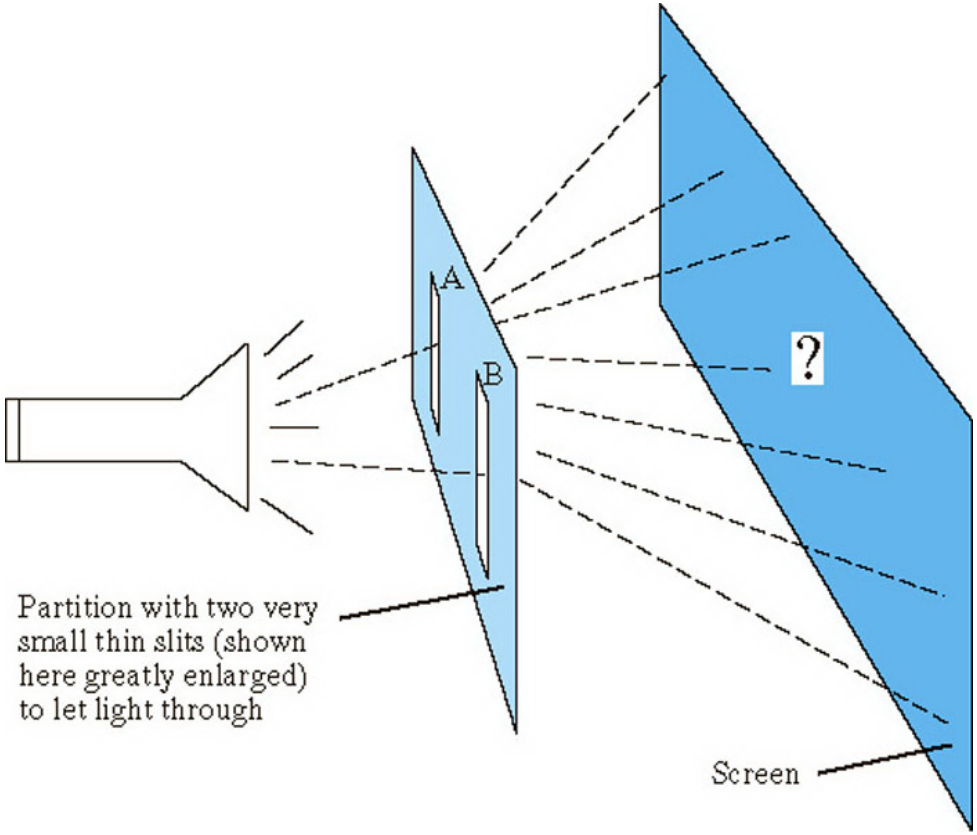
Quantum Picture



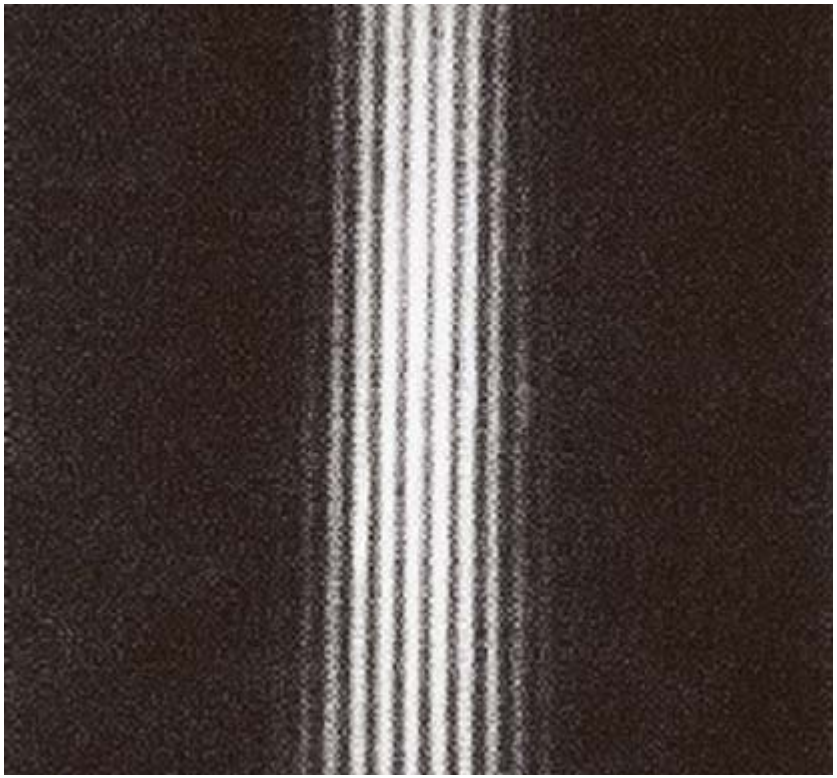
Energy of wave $\propto$ (Amplitude)^2

Energy/photon = hc / λ

Quantum Nature of Photons



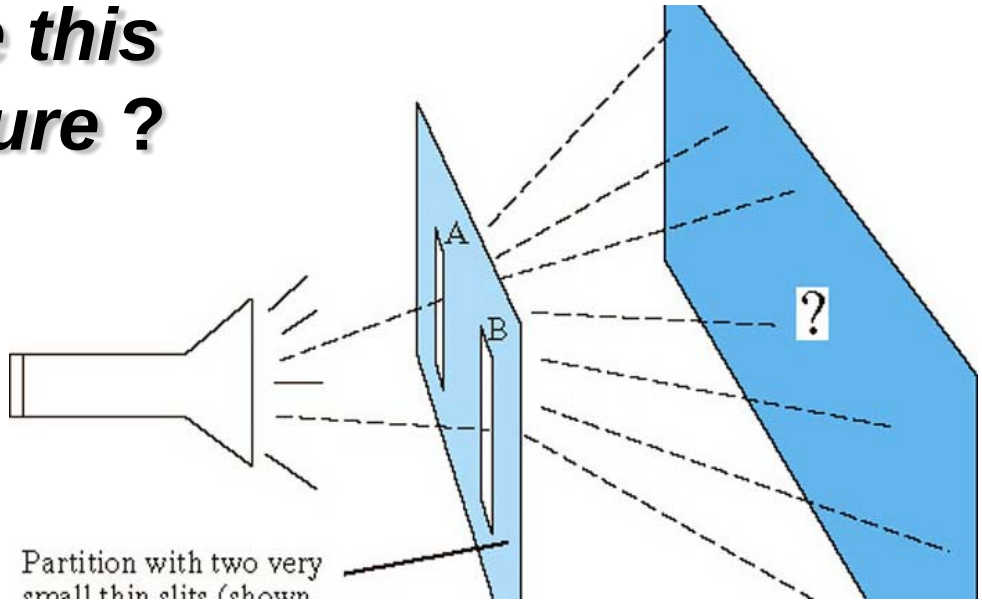
What do you expect to see ?

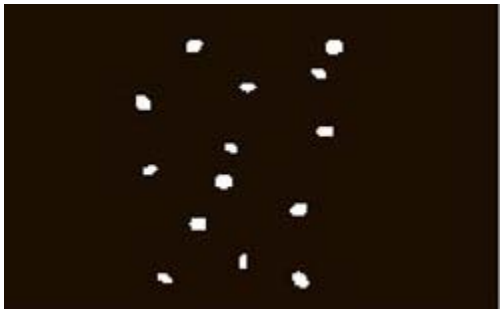


This was one of the defining characteristics of waves

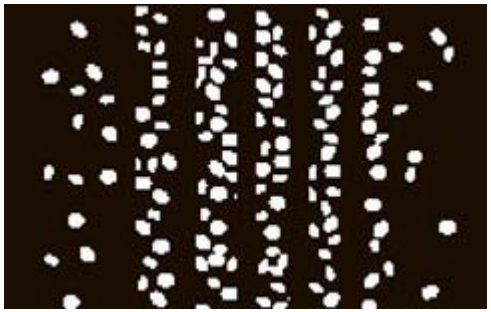
➔ Interference

How do we reconcile this with the particle picture ?

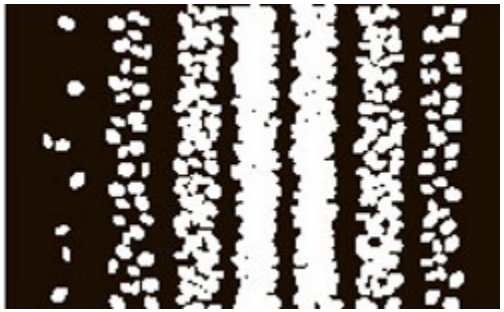




Very short exposure
14 photon impacts



Longer exposure
~150 photon impacts



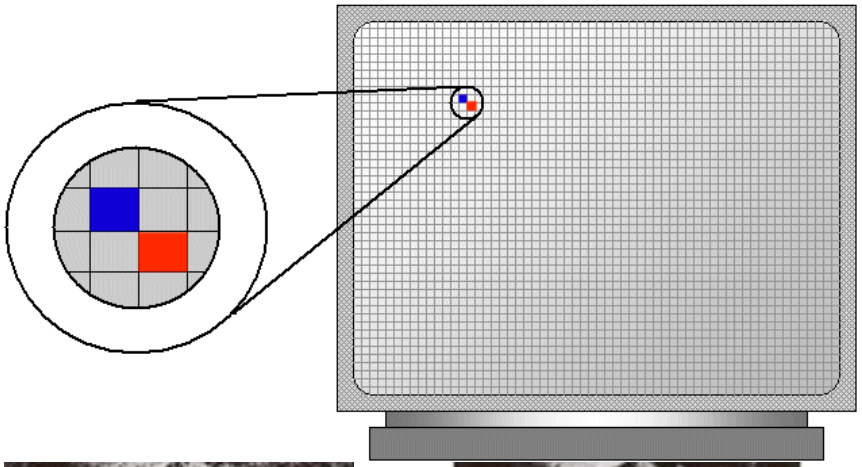
Much longer exposure
a few thousand
photon impacts

Photons, Digital Camera & Images

Using a digital camera with many pixels !

Picture + Element: 디지털 이미지의 최소단위

A given pixel is very, very small
➔ gives fine image resolution



The individual spots on this image and on the previous one are the actual results of <u>individual photons striking the pixel array</u>.

Wave picture cannot account for individual pixels in camera being hit.

~100,000 photons

~1 M photons

~4 M photons

~30 M photons

Matter Waves ?

One might ask:

"If light can behave like a particle, might particles act like waves"?

The short answer is **YES**. The explanation lies in the realm of quantum mechanics, and is beyond the scope of this course.
However, you already have been introduced to the answer.

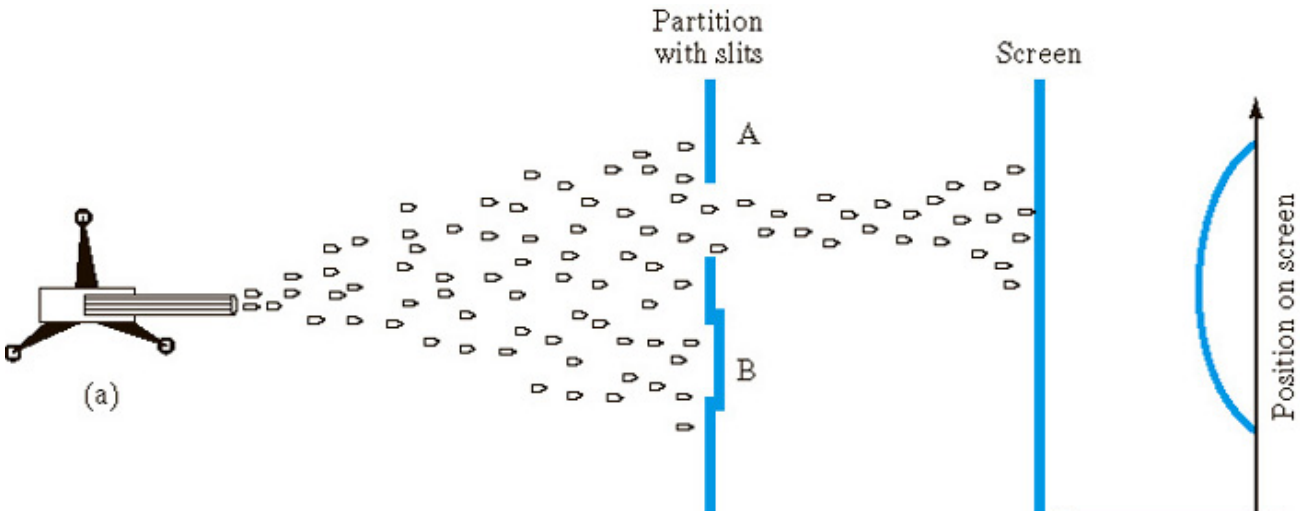
Particles, like photons, also have a wavelength given by:

$$\lambda = h/p = h / mv$$

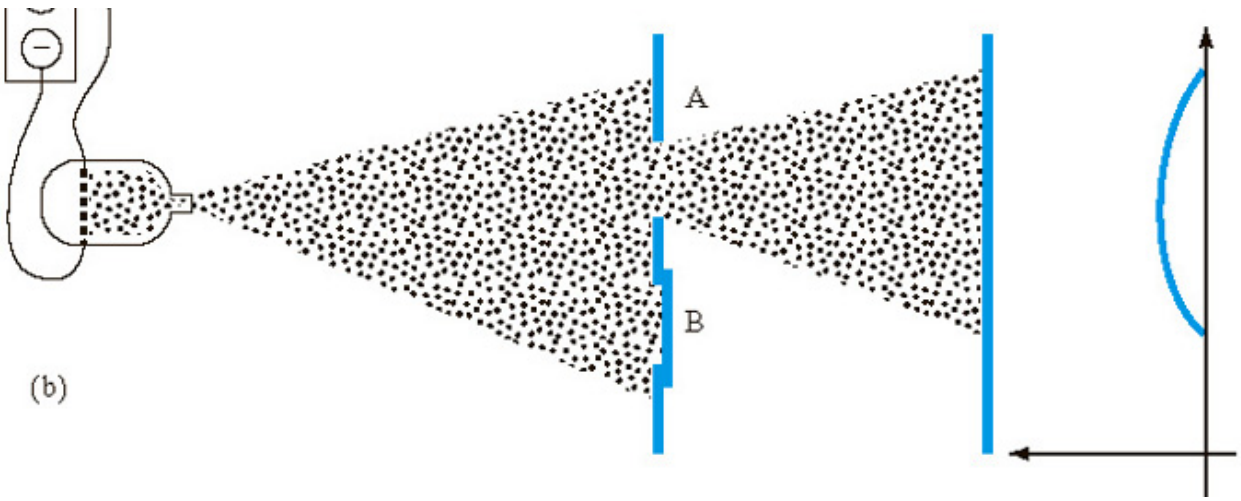
That is, the wavelength of a particle depends on its momentum, just like a photon!

The main difference is that **matter particles have mass**, and photons don't !

Do particles exhibit interference ?

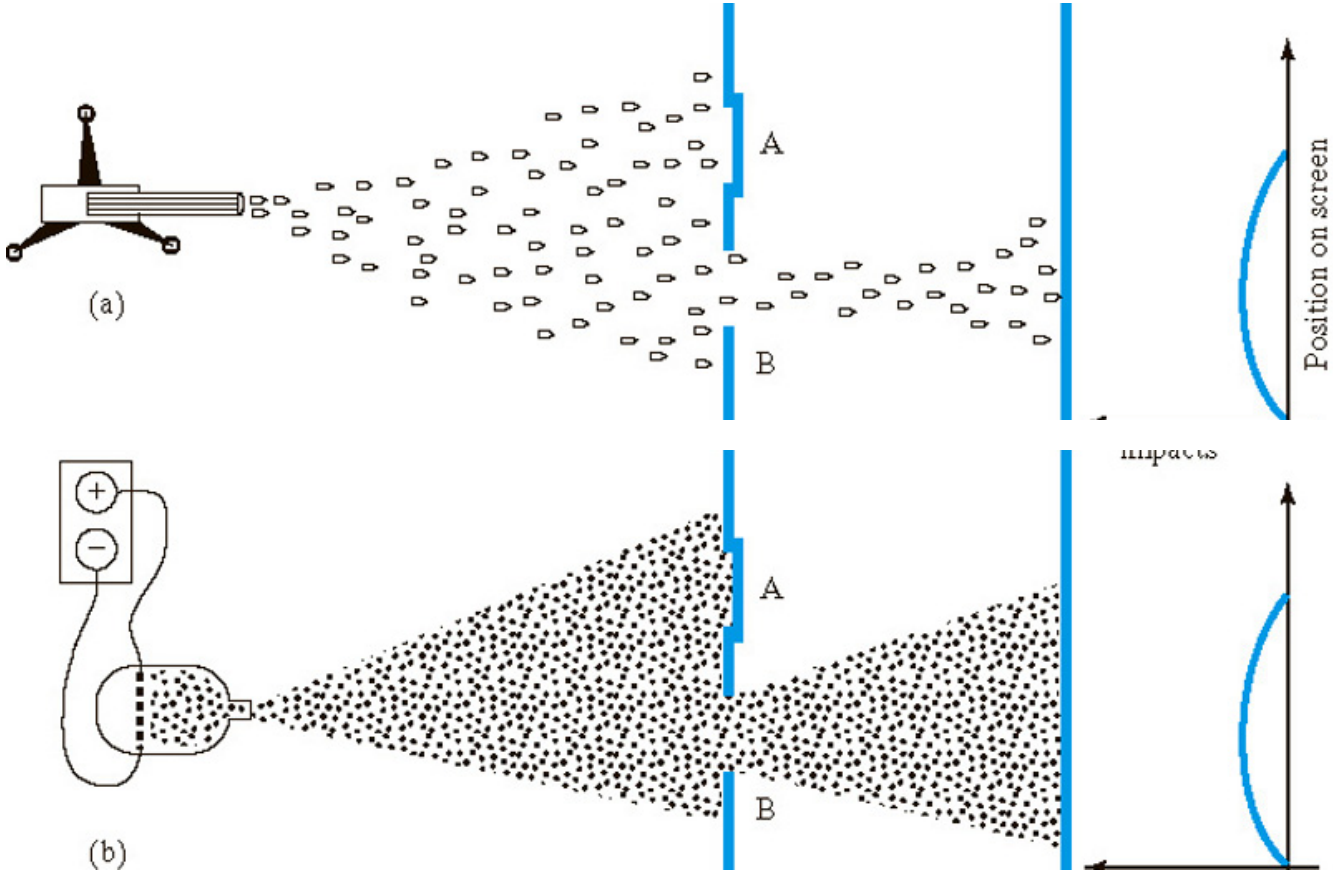


Firing bullets at a "double -slit" with one slit closed



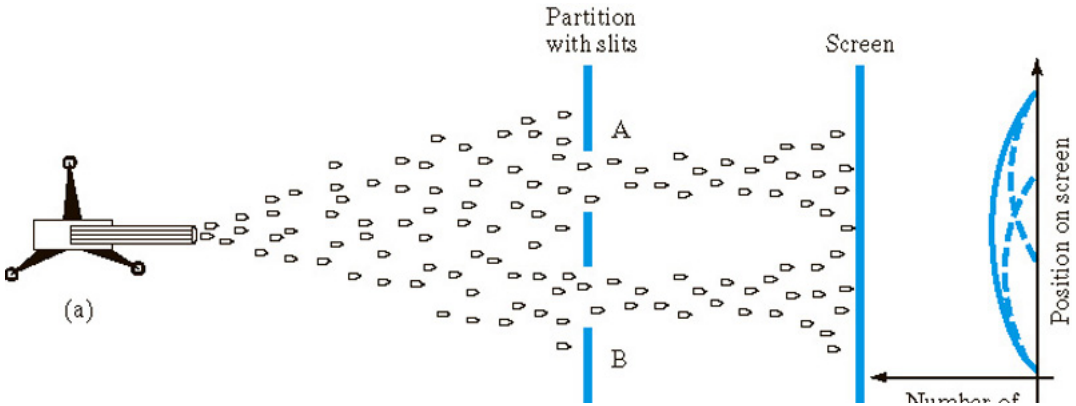
Firing electrons at a "double -slit" with one slit closed

What about the other slit ?

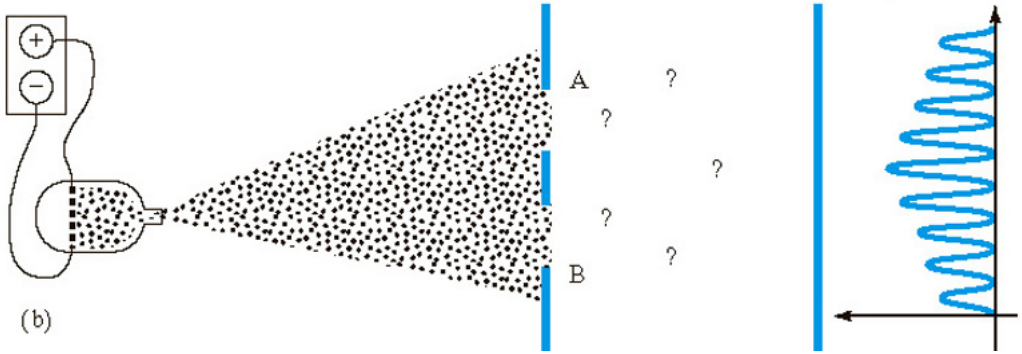


Again, you just get a rather expected result…

What if both slits are open ?



With bullets, you get what appears to be a simple “sum” of the two intensity distributions.



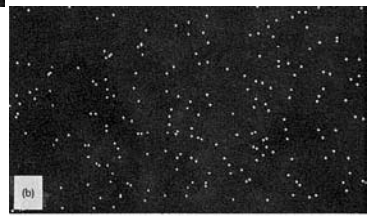
With electrons, you find an “interference” pattern, just like with light waves ?

Huh ? Come again ?

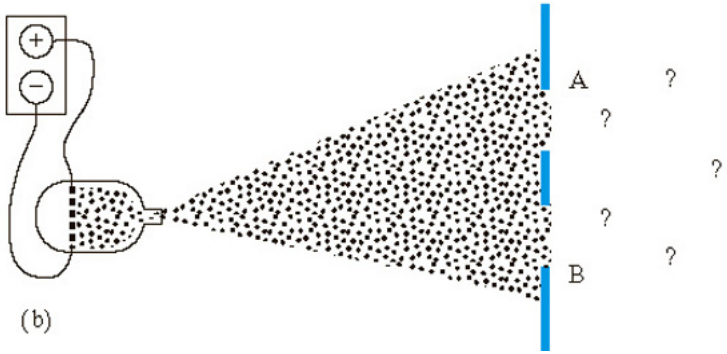
So, forms of matter do exhibit wave behavior (electrons) and others (bullets) don’t ? What’s going on here ?

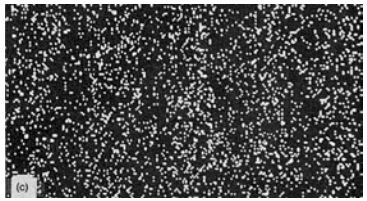
Real photographs of an electron interference pattern…

.01 [s]
10 electrons



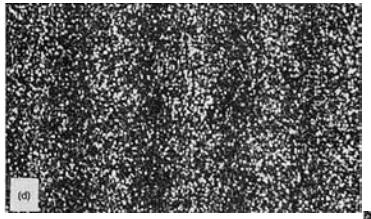
.1 [s]
100 electrons

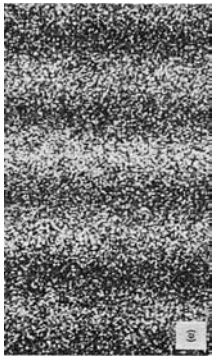




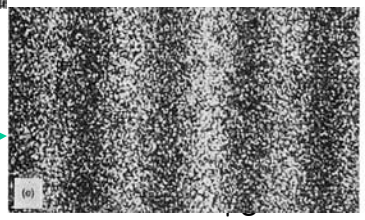
3 [s]
3000 electrons

20 [s]
20,000
electrons





70 [s]
70,000
electrons



Notice the clear interference fringes. Clear indication of wave phenomenon.

Matter Waves (cont)

Compute the wavelength of a 1 [kg] block moving at 1000 [m/s].

$\lambda = h/mv = 6.6\text{x}10^{-34}$ [J s] / (1 [kg])(1000 [m/s])

$= \mathbf{6.6\text{x}10^{-37}}$ **[m].**

This is **immeasureably small.**

➔ For ordinary "everyday objects", we don't experience that ***matter can behave as a wave***.

But, what about small particles ?

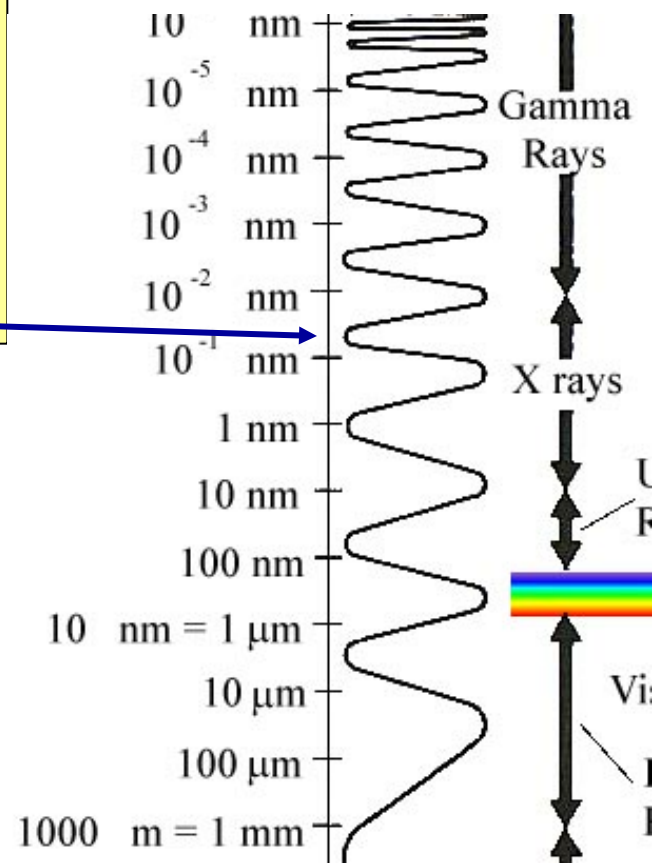
Compute the wavelength of an electron ($m = 9.1 \times 10^{-31}$ [kg]) moving at 1×10^{7} [m/s].

$\lambda = h/mv$

$= 6.6 \times 10^{-34}$ [J s]/(9.1×10^{-31} [kg])(1×10^{7} [m/s])

$= \mathbf{7.3 \times 10^{-11}}$ **[m].**

= 0.073 [nm]

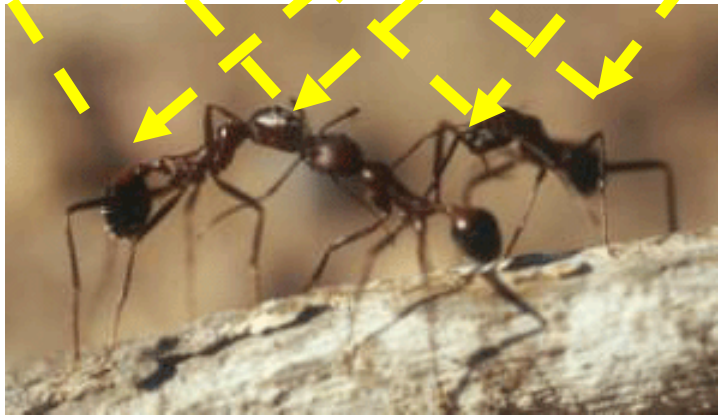


These electrons have a wavelength in the region of X-rays

How do we see ?

Light reflects (scatters) from
a surface and reaches our eye.

Our eye forms an image
of the object.

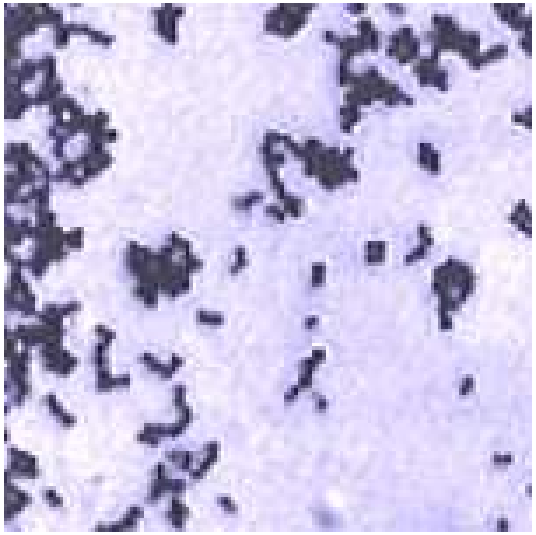


Wavelength versus Size

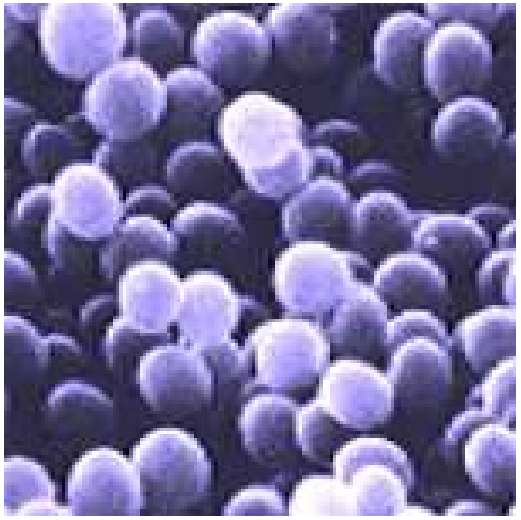
Even with a visible light microscope, we are limited to being able to resolve objects which are at least about

$$10^{-6}\ [\mathrm{m}] = 1\ [\mu\mathrm{m}] = 1000\ [\mathrm{nm}]\ \text{in size.}$$

This is because visible light, with a wavelength of ~500 nm (=0.5 μm) cannot resolve objects whose size is smaller than it's wavelength.



Bacteria, as viewed using visible light



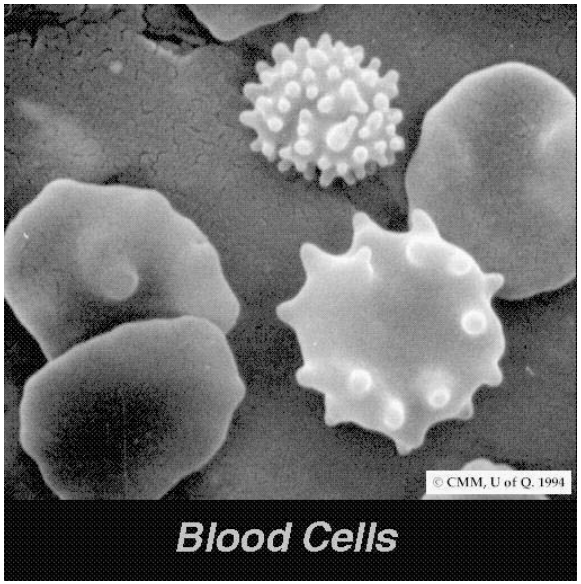
Bacteria, as viewed using electrons !

Electron Microscope

➔ The **electron microscope** is a device which uses the **wave behavior of electrons** to make images which are otherwise too small for visible light!

This image was taken with a Scanning Electron Microscope (SEM).

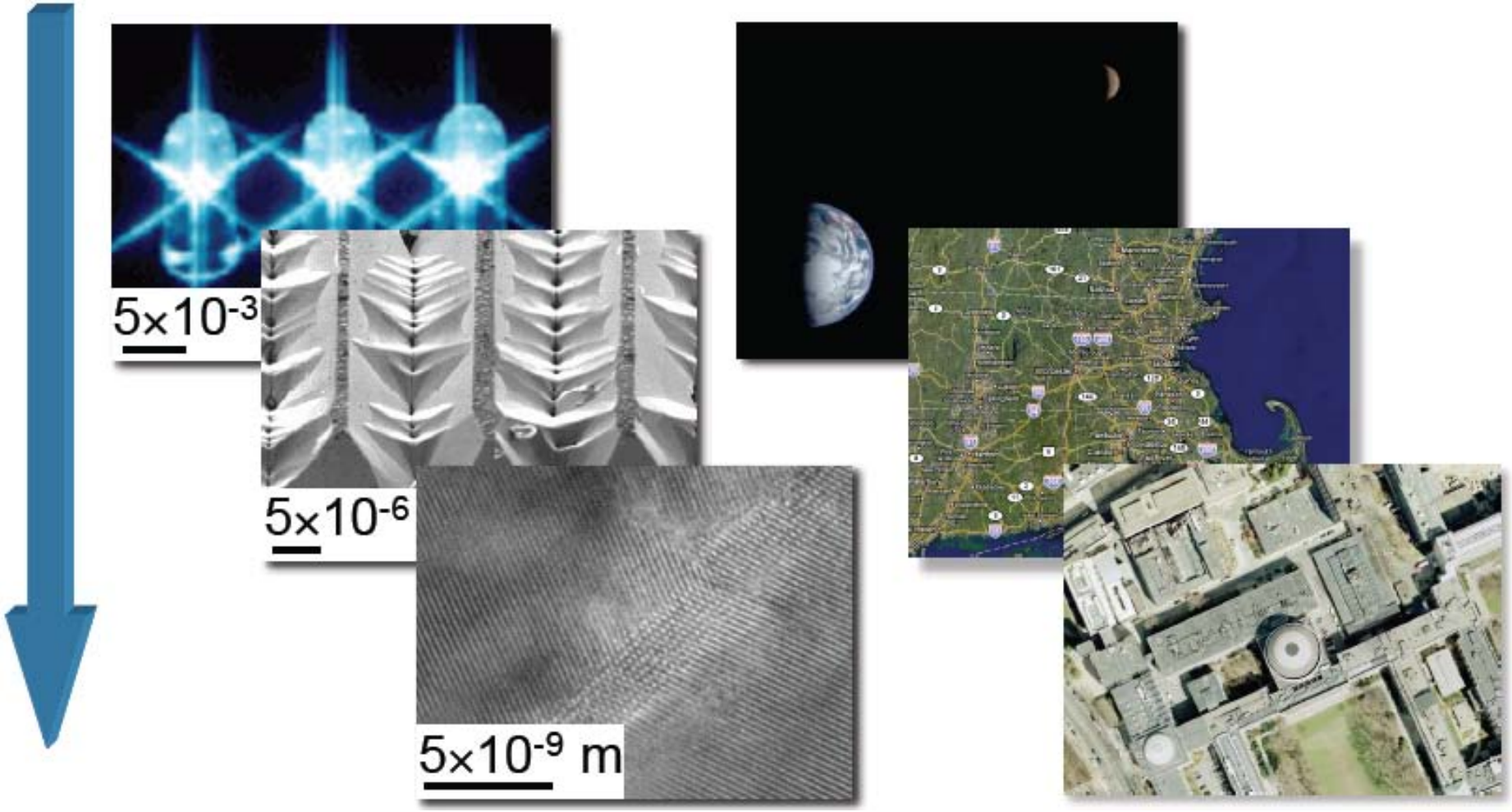
These devices can resolve features down to about 1-5 nm. This is about 250 times better than can be done with visible light microscopes!

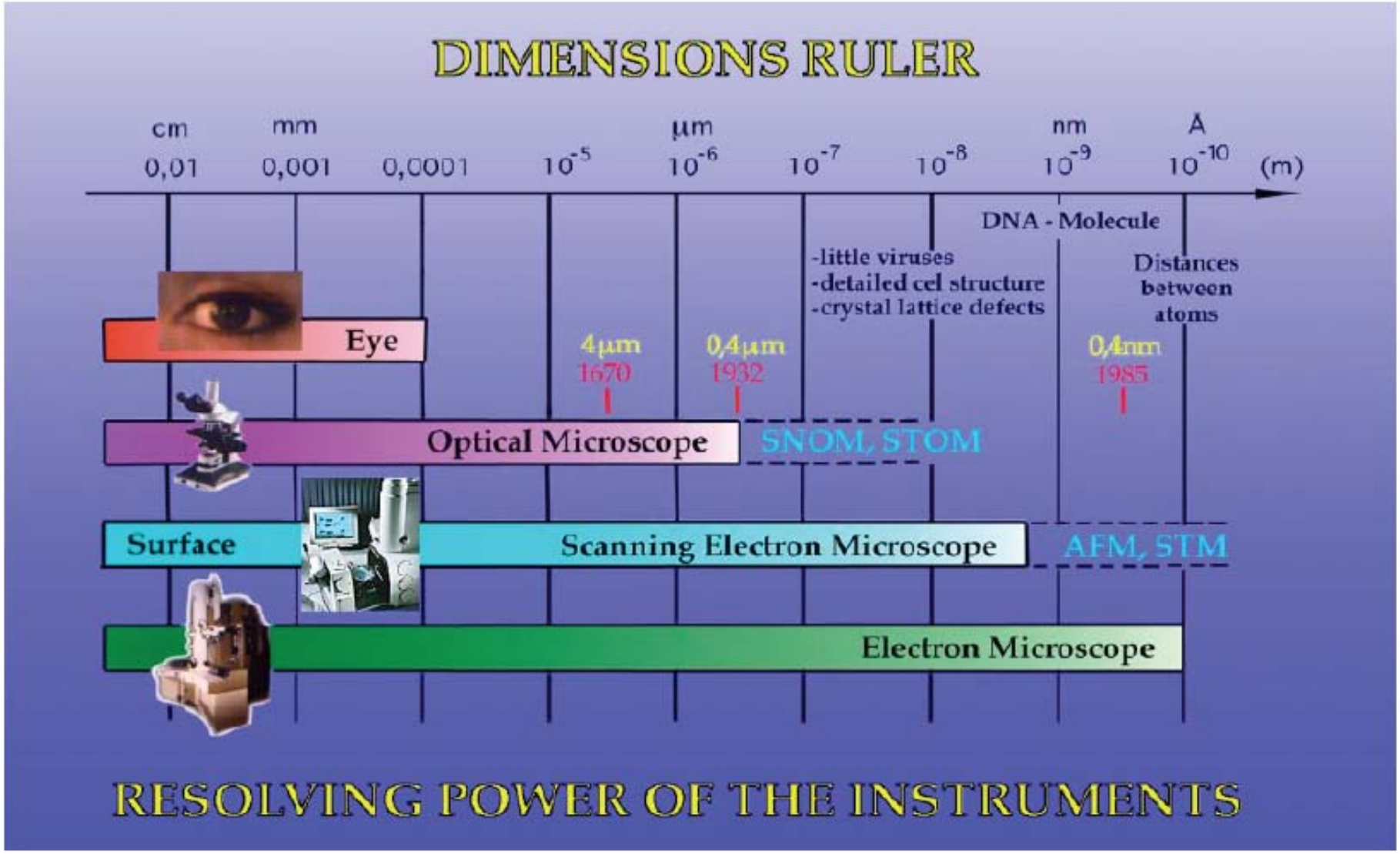


IMPORTANT POINT HERE:

High energy particles can be used to reveal the structure of matter !

scale




DIMENSIONS RULER
cm
mm
µm
nm
A
0,01
0,001
0,0001
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
(m)
DNA - Molecule
-little viruses
-detailed cel structure
-crystal lattice defects
Distances between atoms
Eye
4µm
1670
0,4µm
1932
0,4nm
1985
Optical Microscope
SNOM, STOM
Surface
Scanning Electron Microscope
AFM, STM
Electron Microscope
RESOLVING POWER OF THE INSTRUMENTS

Remarks on Particle Probes

- We have now asserted that **high energy particles** (electrons in the case of a SEM) can provide a way to **reveal the structure of matter** beyond what can be seen using an optical microscope.

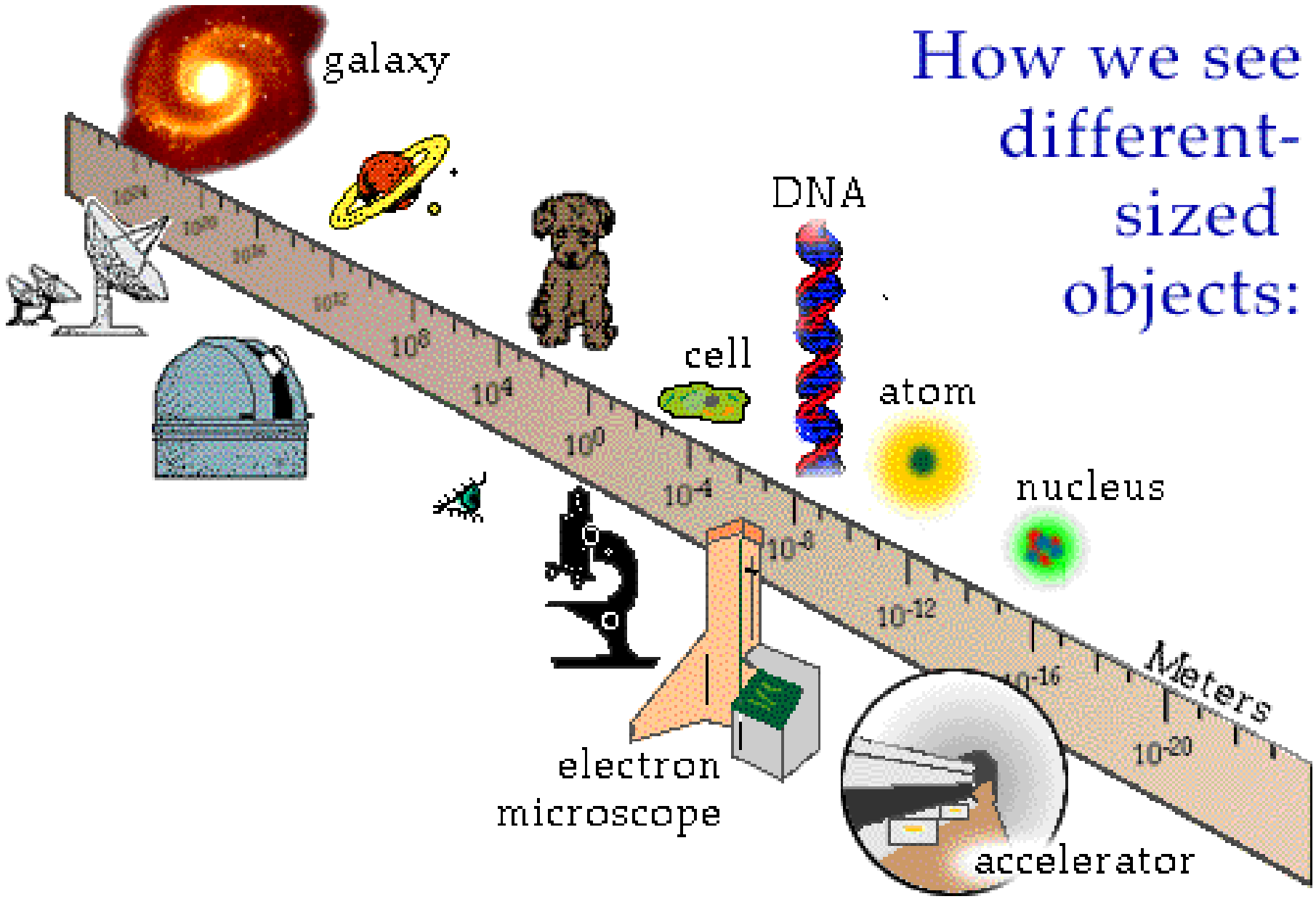
- The **higher the momentum of the particle**, the smaller the deBroglie wavelength ($\lambda = \mathbf{h/mv}$).

- As the **wavelength decreases**, **finer and finer details about the structure of matter are revealed** !

- We will return to this very important point.
  - ➔ To explore matter at its smallest size, we need **very high momentum particles** !
  - ➔ Today, this is accomplished at facilities often referred to as "**atom-smashers**". We prefer to call them "**accelerators**"

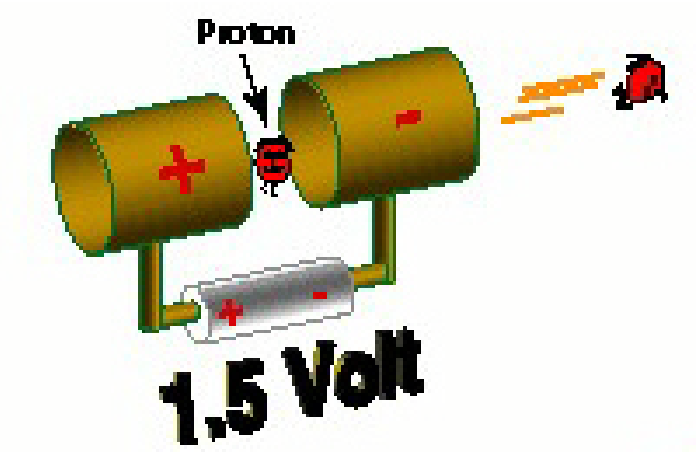
Pohang accelerators

How we see different-sized objects:



가속에 필요한 전기장

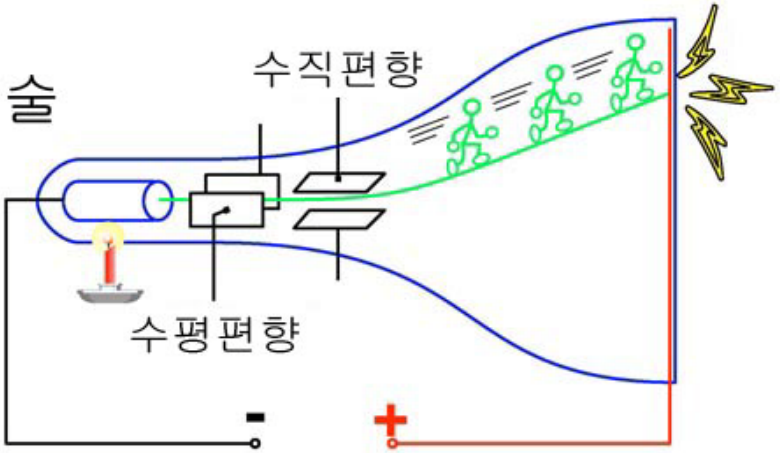
- 가속기는 전하를 띤 입자(하전입자: 전자, 양성자 등)만 가속시킨다.
- 전기장 : 하전입자를 가속시킨다.
- 자기장은 방향을 바꾼다.
- 에너지 단위 : 전자볼트 (eV)



우리 집에 있는 가속기 → TV

왜 전자를 사용하는가?

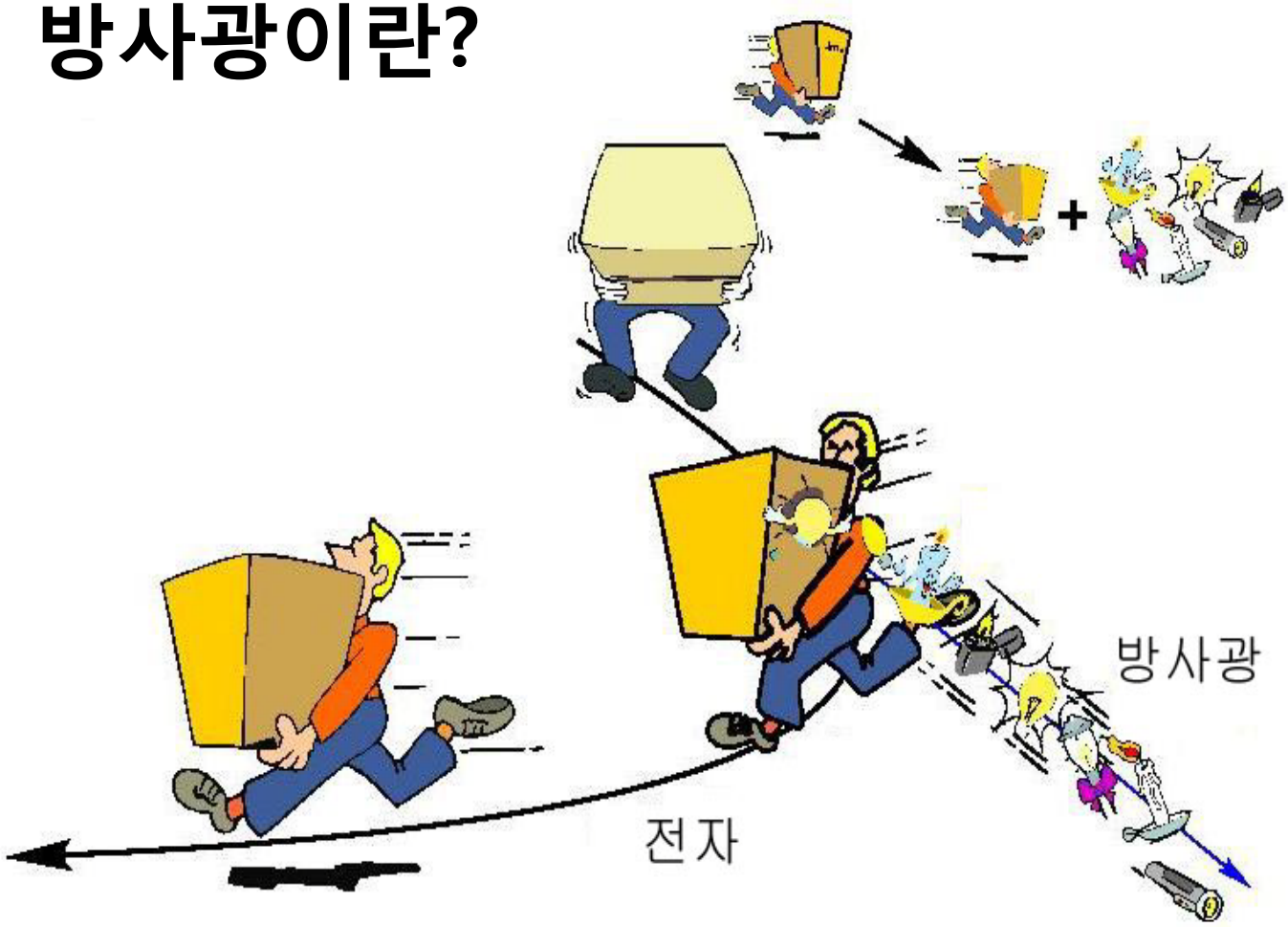
- TV에 쓰이는 기술



- 가속하기 쉽다.
- 방사광

	1.5 V	~ 700 km/s
	12 V	~2000 km/s
20 000 V		~90 000 km/s
800 000 000 V	BESSY I	299 792,40 km/s
1 700 000 000 V	BESSY II	299 792,44 km/s

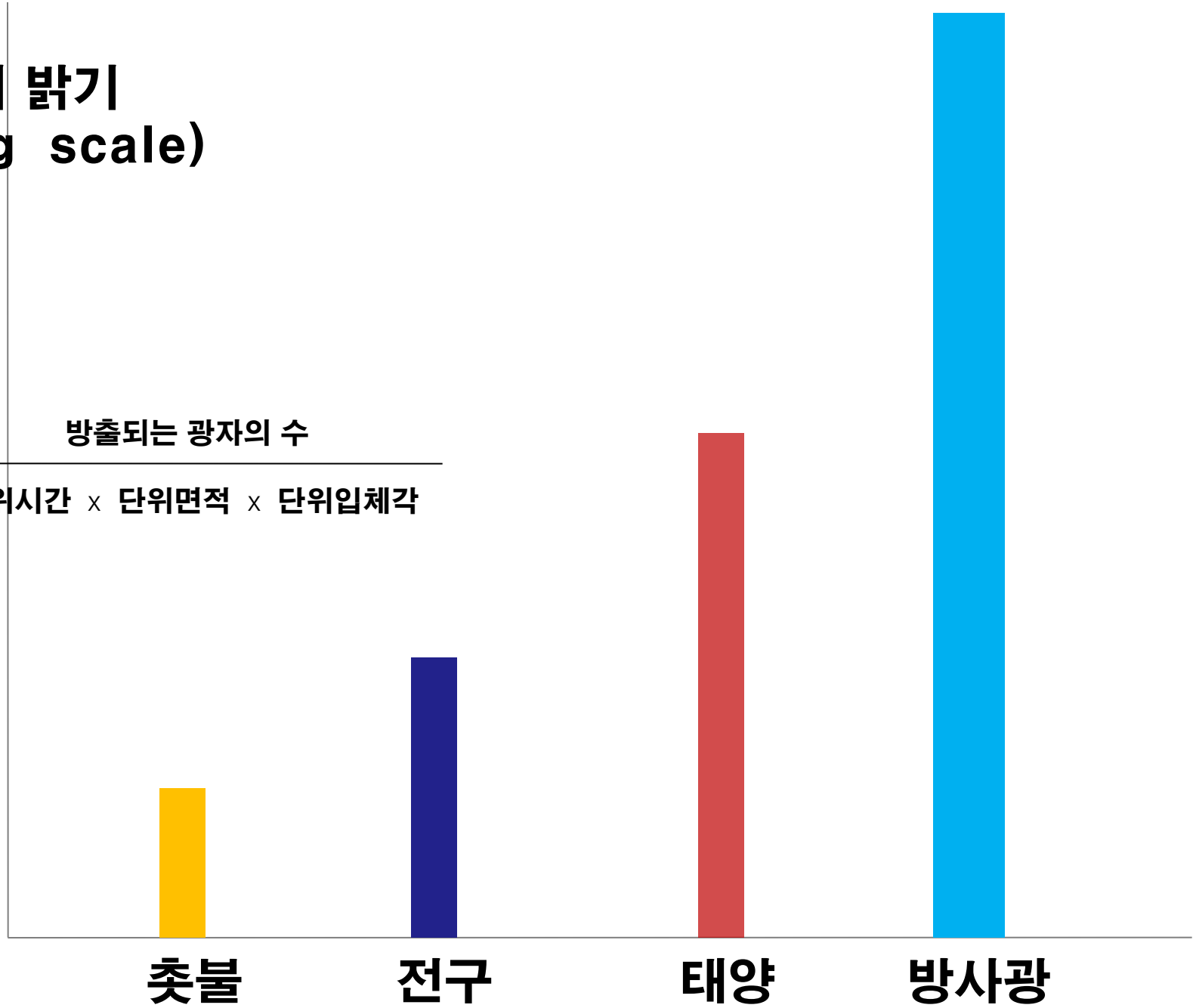
방사광이란?



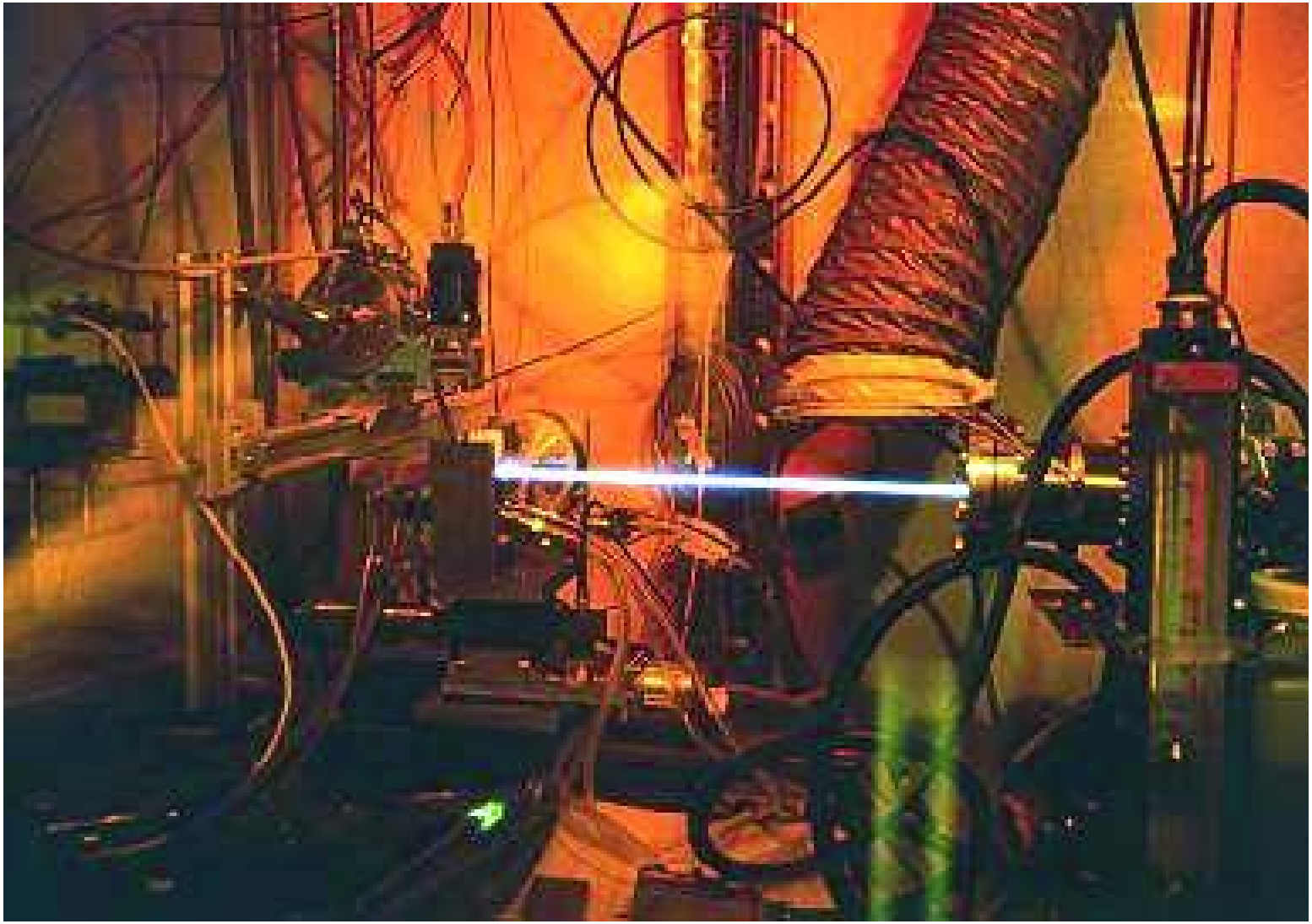
- 광속으로 달리는 전자가 자기장 속을 지나면서 방향을 틀 때 접선방향으로 방출되는 아주 강력한 빛(high energy photons)을 말한다.
- 포항방사광 가속기는 태양보다 10억 배 이상 밝다.
- 방출되는 빛은 가시광선은 물론 자외선에서 X선에 이르는 모든 파장을 망라한다.

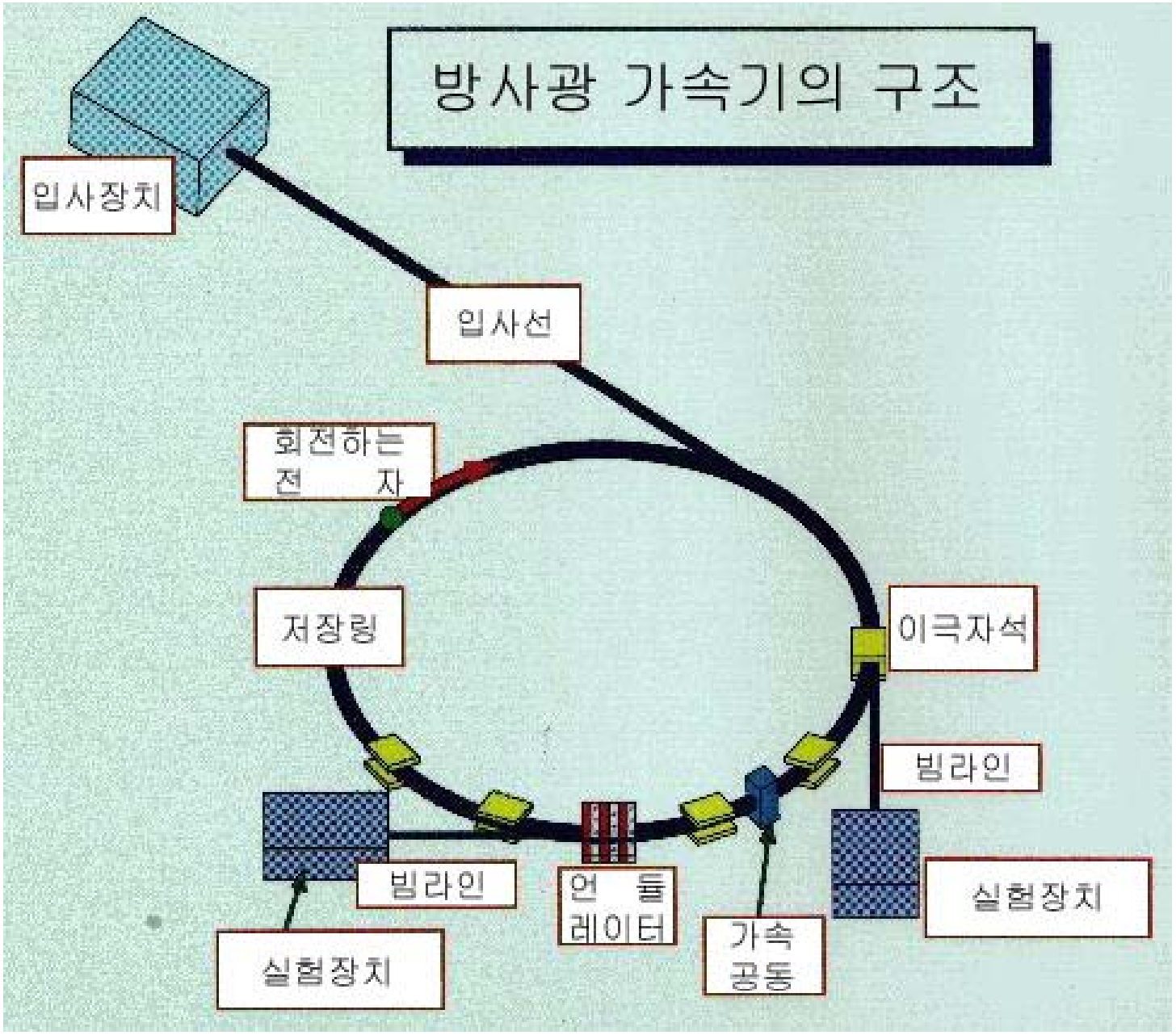
빛의 밝기
(log scale)

$$\text{밝기} = \frac{\text{방출되는 광자의 수}}{\text{단위시간} \times \text{단위면적} \times \text{단위입체각}}$$

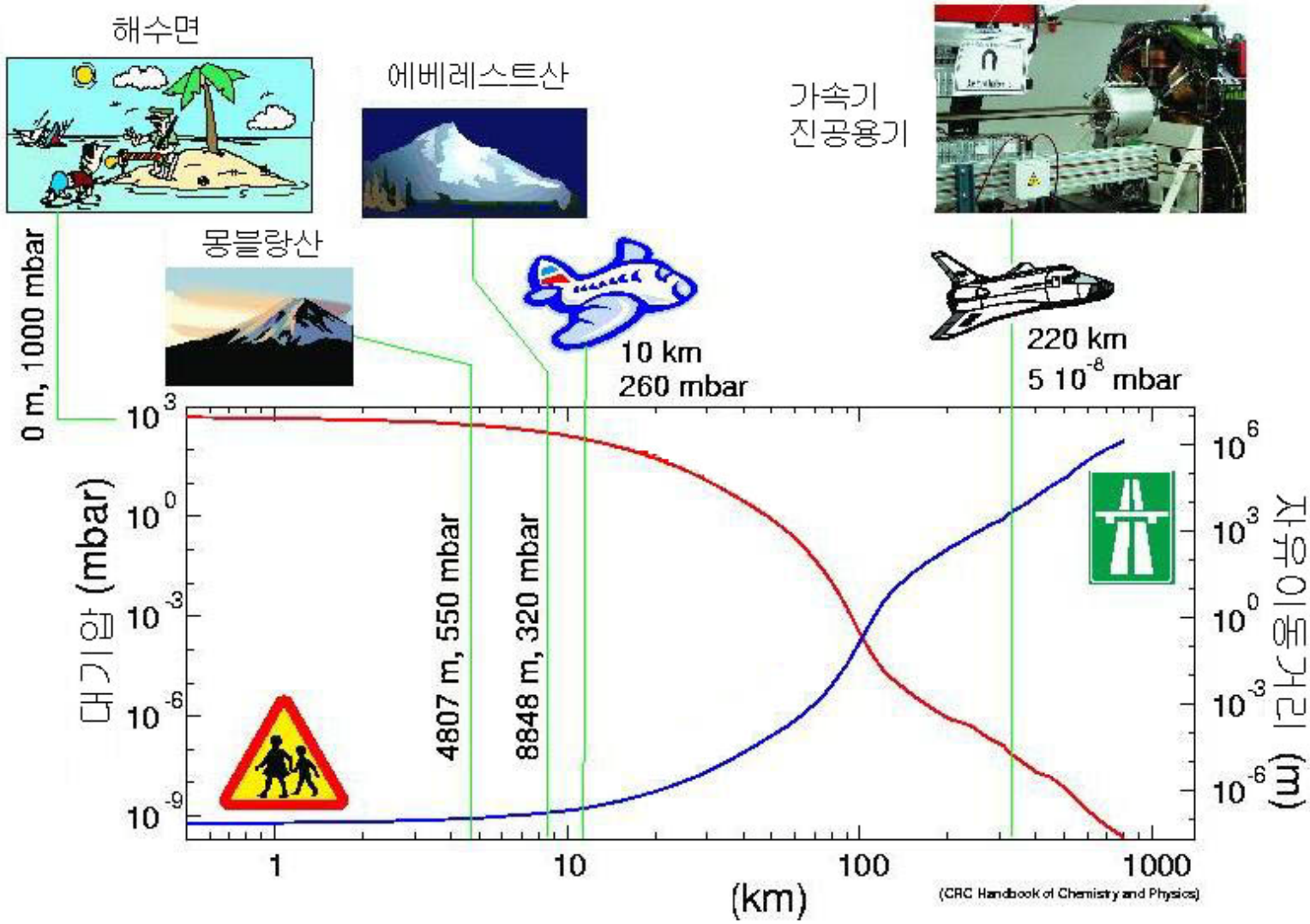


방사광의 실제 모습




방사광 가속기의 구조
입사장치
입사선
회전하는
전 자
저장링
이극자석
빔라인
빔라인
언 듈
레이터
가속
공동
실험장치
실험장치

진공도


해수면
에베레스트산
가속기
진공용기
몽블랑산
0 m, 1000 mbar
10 km
260 mbar
220 km
5 10^-8 mbar
4807 m, 550 mbar
8848 m, 320 mbar
대기압 (mbar)
자유이동거리 (m)
(km)
(CRC Handbook of Chemistry and Physics)

포항가속기연구소

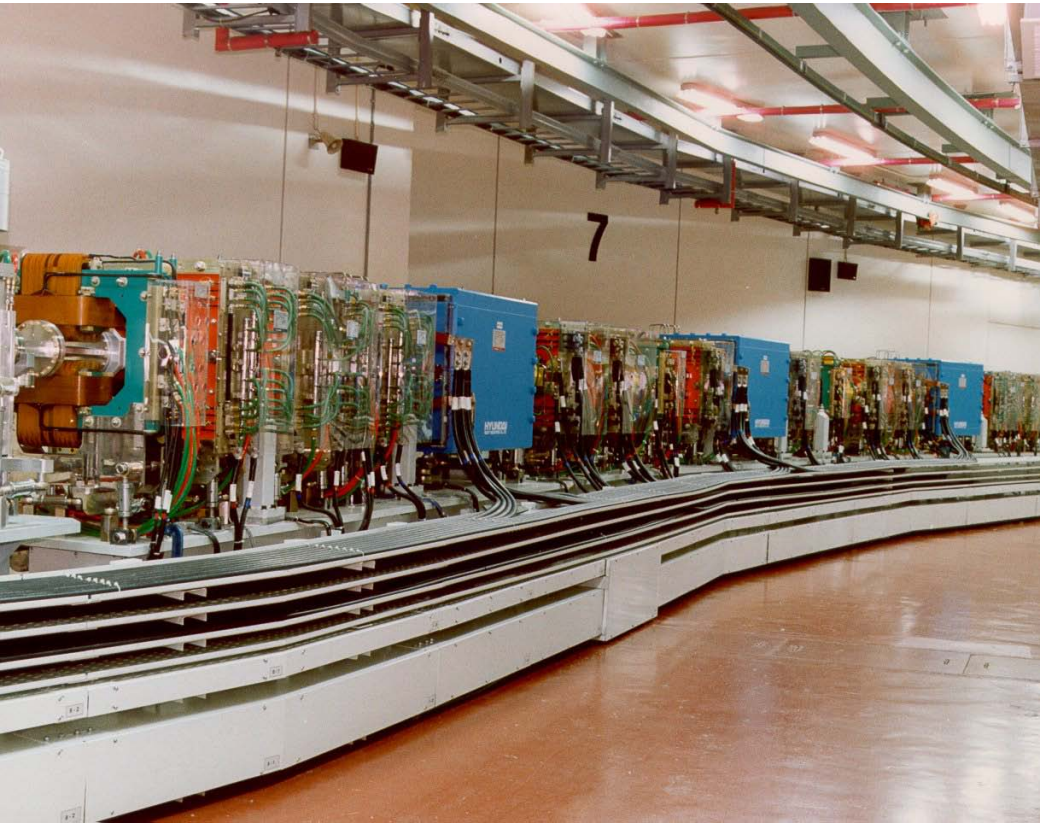
포항 방사광 가속기

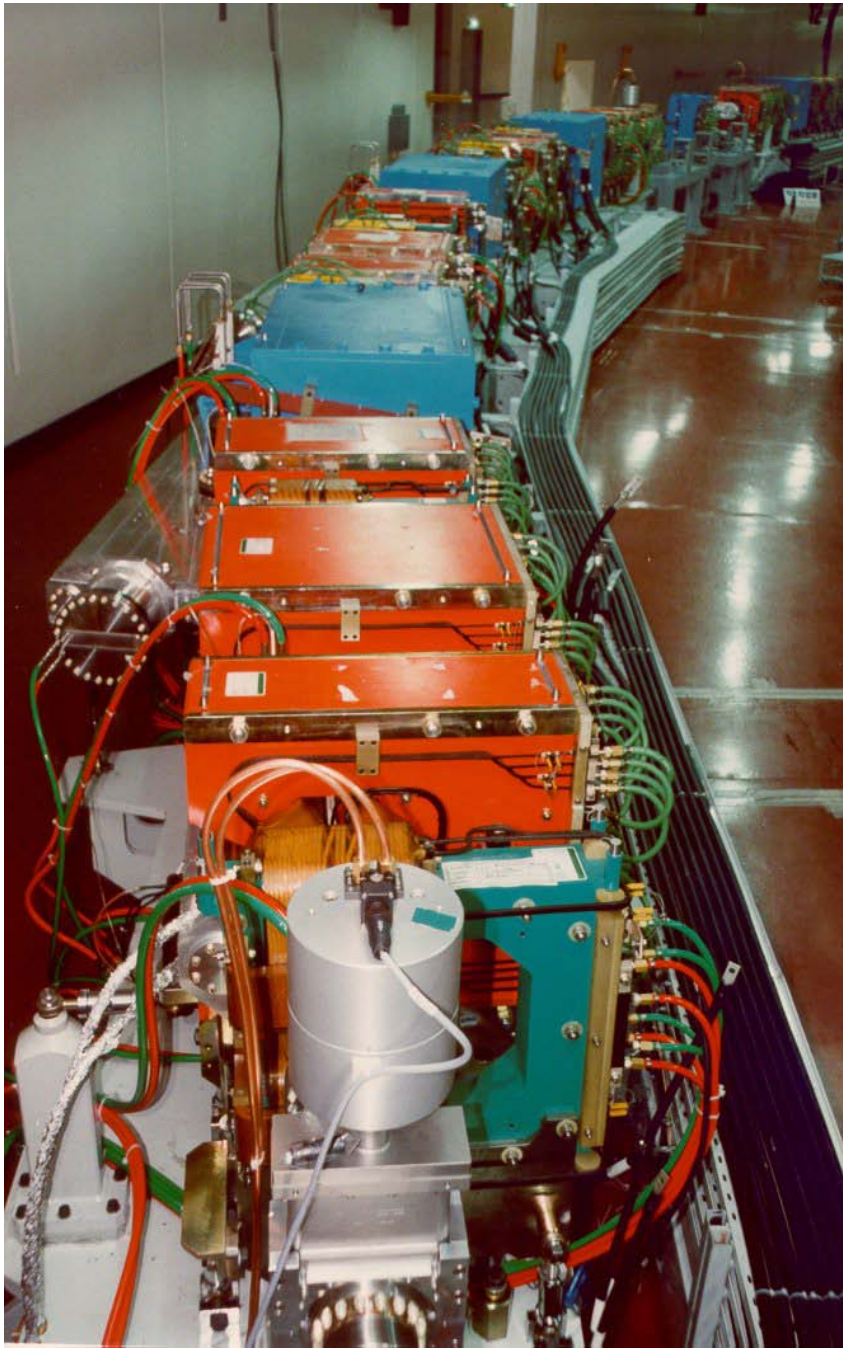
- 우리나라 최대의 본격적인 가속기
- **제 3세대형** : 삽입장치를 최대한 사용
- 방사광 발생용 저장링 : 2.5 GeV
  - **둘레 280 m, 세계 4위급**
- 입사용 선형가속기 : 2.5 GeV
  - **길이 160 m, 세계 3위급**
- 1988년부터 설계 시작, 1994년 완성
- 총 건설비 : 1500억원
  - 포철 900억, 정부 600억 지원
- 매년 약 180억원의 운영비는 정부 지원

선형가속기 본체

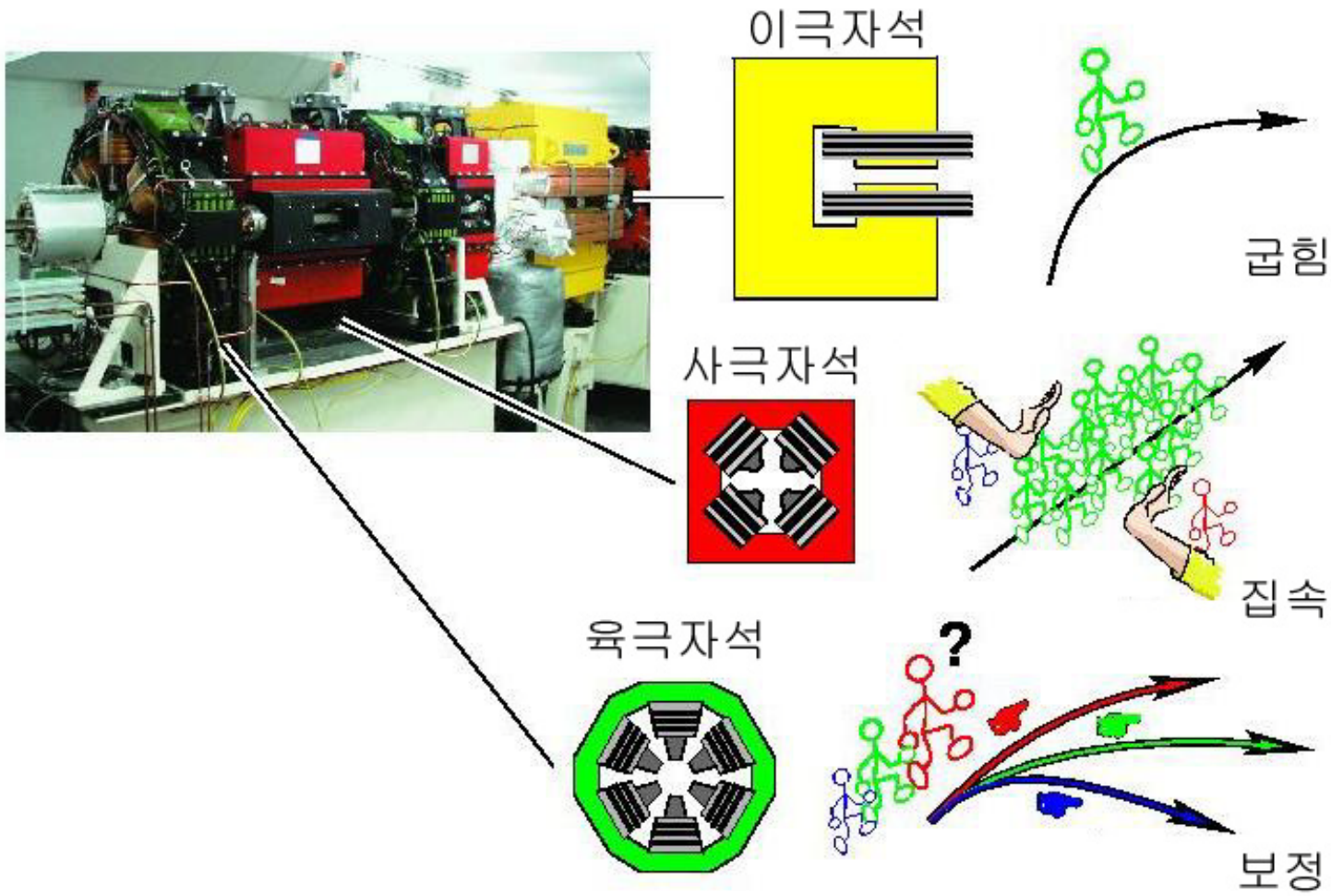
선형가속기 지상층

저장링





저장링 속의 자석들



빔라인

- 빔라인은 방사광을 실험장치까지 유도하는 장치이다.
- 빔라인의 주요부품은 분광기와 거울이다.

포항가속기 연구소 빔라인 실험장치들

OCTOBER 2006

PLS Beamline Status

Construction	------	4 beamlines
Commissioning	═══	1 beamlines
Operation	═══	26 beamlines

*Technical Building II :펨토초-원적외선(fs-FIR)

Summary

- ***Light*** is made up of ***photons***, but in macroscopic situations, it is often fine to **treat it as a wave**.

- When looking at the microscopic world, there is only 1 thing that works… Light is made up of photons (particles of light).

- Photons carry both energy & momentum.

$$\boxed{E = hc / \lambda} \qquad \boxed{p = E/c = h / \lambda}$$

- Matter also exhibits wave properties. For an object of mass m, and velocity, v, the object has a wavelength, $\lambda = h / mv$

- One can probe 'see' the fine ***details of matter*** by using **high energy particles** (they have a small wavelength !) ➔ Can reveal the tiniest things !