# Introduction

**Fall, 2020**

**Kyoung-Jae Chung**

***Department of Nuclear Engineering***

**Seoul National University**

# Department of Nuclear Engineering

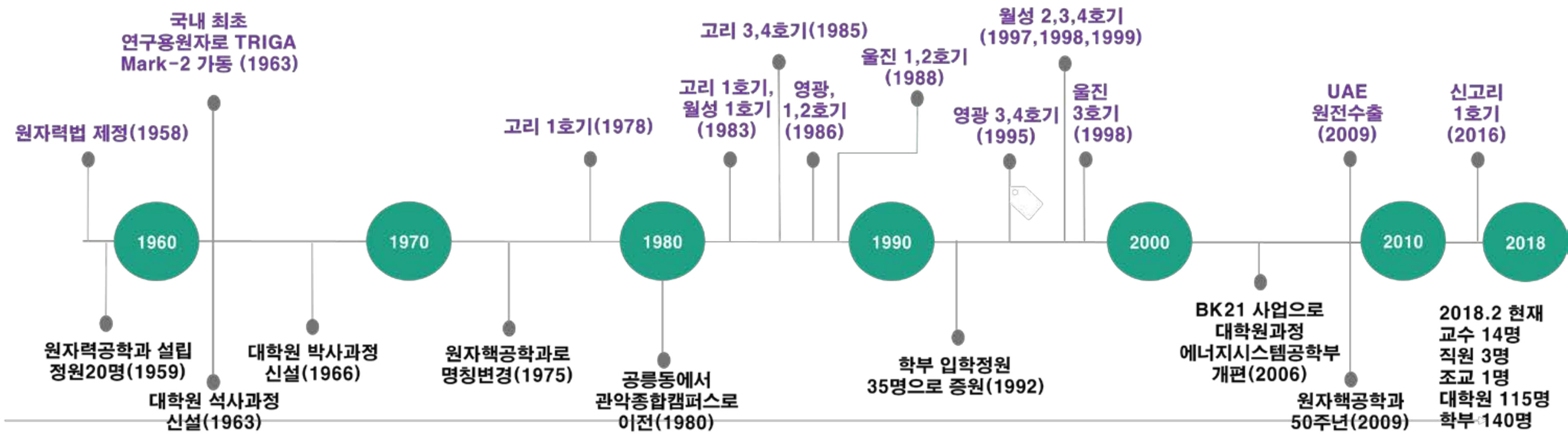
- **원자핵 공학이란?**
  - 원자핵을 기원으로 하는 에너지와 입자를 활용하여 인간에게 편익을 주는 기술의 개발과 이용을 다루는 학문

- **원자력 시스템 분야 → 핵공학개론 1**
  - 핵분열에너지를 이용한 발전과 고온열 생산
  - 안전한 원자력발전소의 설계, 건설, 운영에 필요한 제반 기술

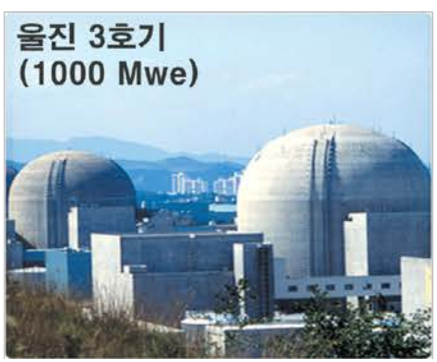
- **핵융합•플라즈마 분야 → 핵공학개론 2**
  - 핵융합에너지를 이용한 발전과 플라즈마 활용
  - 디스플레이, 반도체 생산장비, 폐기물처리, 의료 장비 등

- **방사선•아원자입자 분야 → 핵공학개론 2**
  - 방사선을 이용한 질병의 진단과 치료(X-ray, PET, MRI, BNCT)
  - 비파괴 검사 및 탐색, 개질(신소재 개발), 정밀 계측, 육종 등
  - 입자(전자, 양성자) 가속기, 중성자 발생장치 등

# History of Nuclear Engineering






# Nuclear system engineering

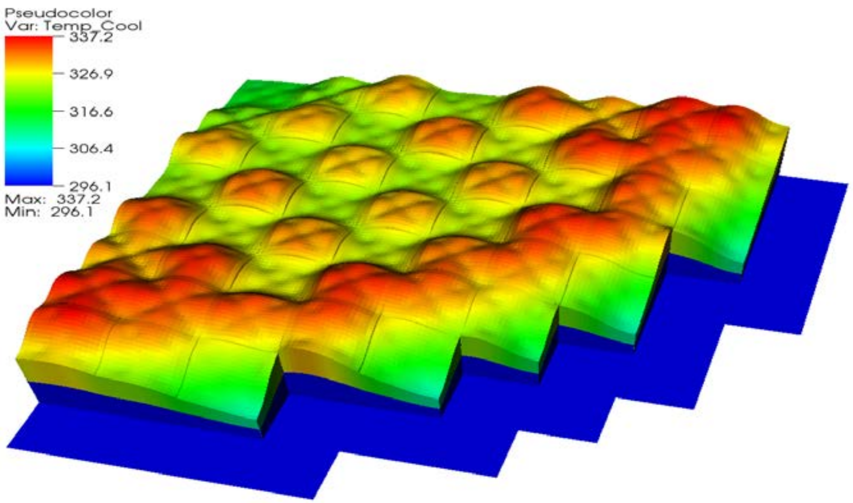
- Reactor physics

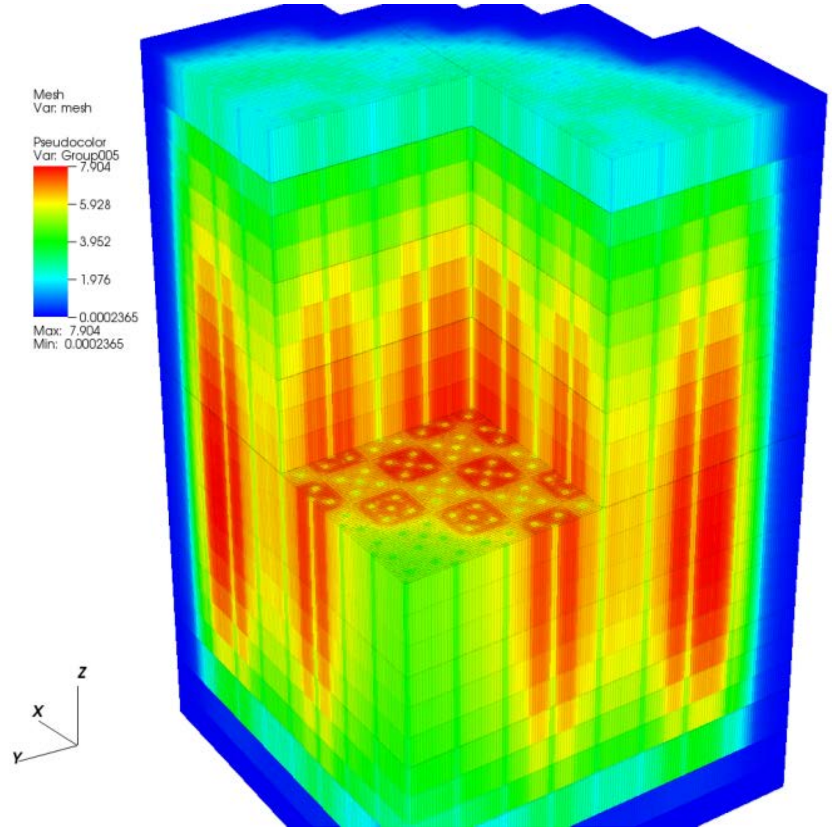
Boltzmann neutron transport equation

$$\hat{\Omega}\cdot\nabla\varphi(\vec{r},E,\hat{\Omega})+\Sigma_t(\vec{r},E)\varphi(\vec{r},E,\hat{\Omega})=\int_{\Omega'}\int_{E'}\Sigma_s(\hat{\Omega}'\to\hat{\Omega},E'\to E)\varphi(\vec{r},E',\hat{\Omega}')dE'd\hat{\Omega}'+\frac{1}{4\pi}\chi(E)\psi(\vec{r})+s'''(\vec{r},E)$$

Navier-Stokes equation

$$\frac{\partial\rho\mathbf{v}}{\partial t}+\nabla\cdot(\rho\mathbf{v}\mathbf{v})=-\nabla p+\nabla\cdot\mathbf{T}+\rho\mathbf{g}$$



# Nuclear system engineering

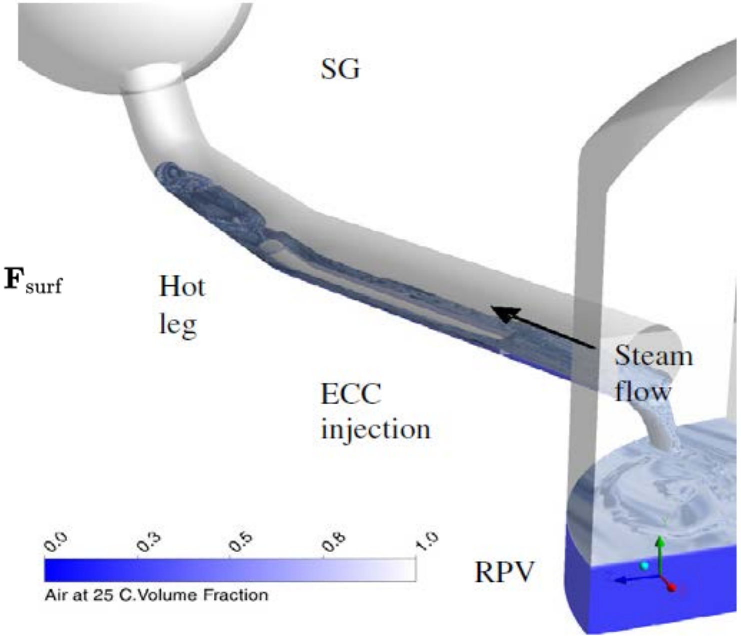
- Thermo-hydrodynamics

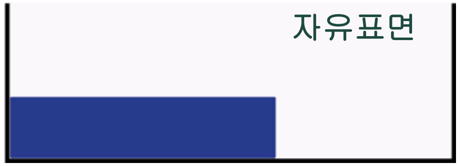
Hydrodynamic equations

$$\frac{\partial}{\partial t}\iiint_V \rho\, dV = -\oiint_S \rho\mathbf{u}\cdot d\mathbf{S}$$

$$\frac{\partial}{\partial t}\iiint_V \rho\mathbf{u}\, dV = -\oiint_S (\rho\mathbf{u}\cdot d\mathbf{S})\mathbf{u} - \oiint_S p\, d\mathbf{S} + \iiint_V \rho\mathbf{f}_{\text{body}}\, dV + \mathbf{F}_{\text{surf}}$$

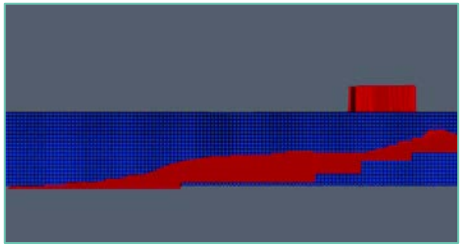
$$\rho\frac{Dh}{Dt} = \frac{Dp}{Dt} + \nabla\cdot(k\nabla T) + \Phi$$





3차원 자유표면


쓰나미 전파

# Fusion & plasma engineering

- Fusion plasma physics: Magneto-hydrodynamics or kinetics

$$\frac{\partial}{\partial t}\iiint_V \rho \, dV = -\oiint_S \rho\mathbf{u}\cdot d\mathbf{S}$$

$$\frac{\partial}{\partial t}\iiint_V \rho\mathbf{u} \, dV = -\oiint_S (\rho\mathbf{u}\cdot d\mathbf{S})\mathbf{u} - \oiint_S p \, d\mathbf{S} + \iiint_V \rho\mathbf{f}_{\text{body}} \, dV + \mathbf{F}_{\text{surf}}$$

$$\rho\frac{Dh}{Dt} = \frac{Dp}{Dt} + \nabla\cdot(k\nabla T) + \Phi$$

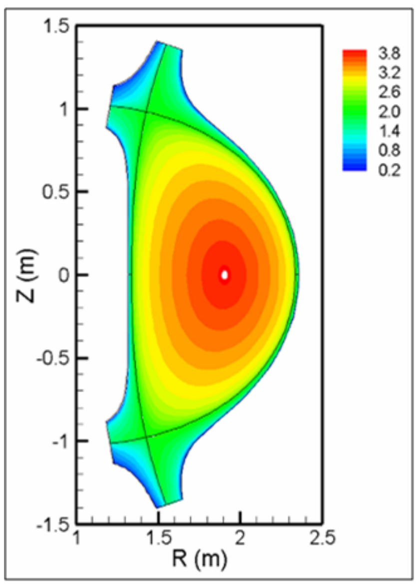
+

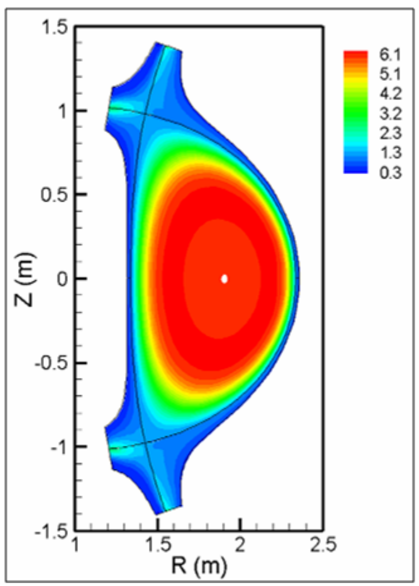
$$\nabla\cdot\mathbf{D} = \rho$$

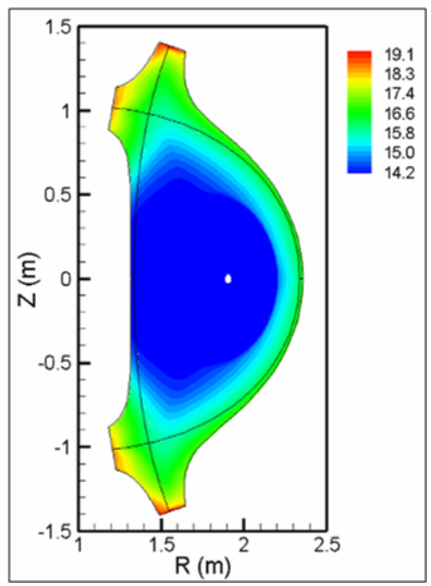
$$\nabla\cdot\mathbf{B} = 0$$

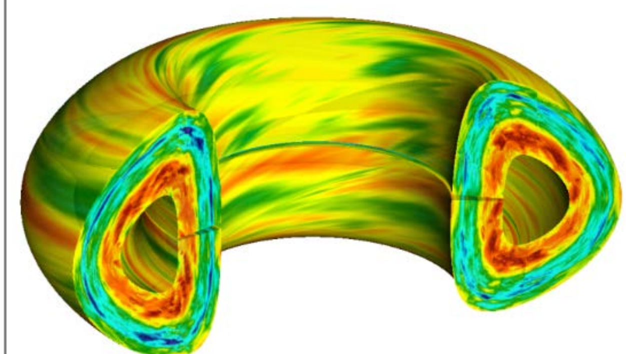
$$\nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t}$$

$$\nabla\times\mathbf{H} = \mathbf{J} + \frac{\partial\mathbf{D}}{\partial t}$$



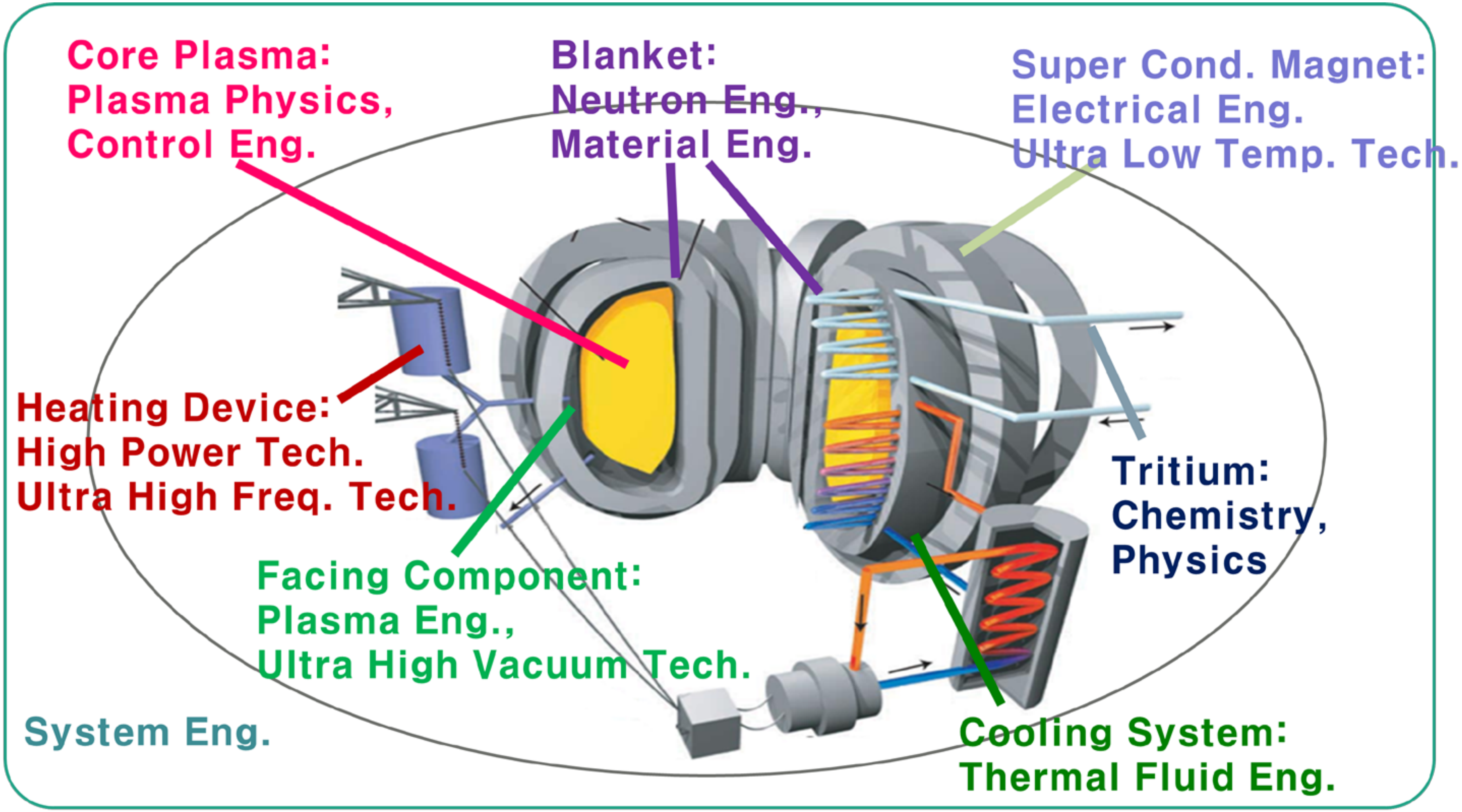



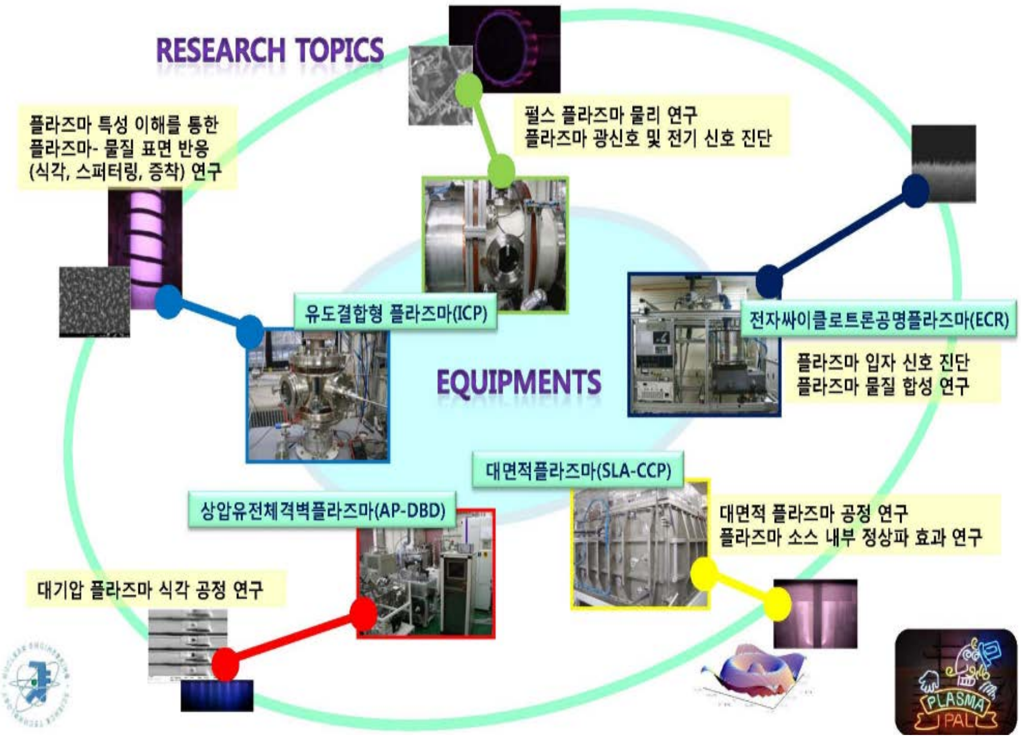
# Fusion & plasma engineering

- Fusion reactor engineering



# Fusion & plasma engineering

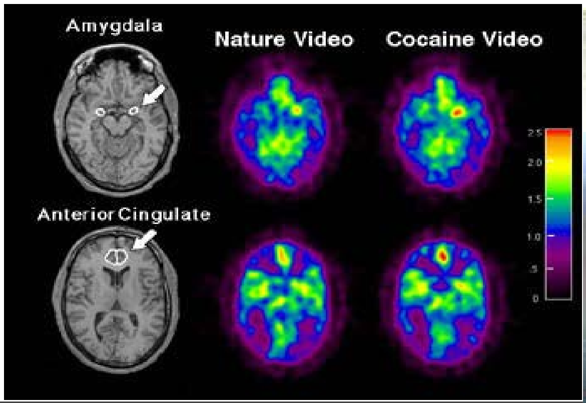
- Plasma applications

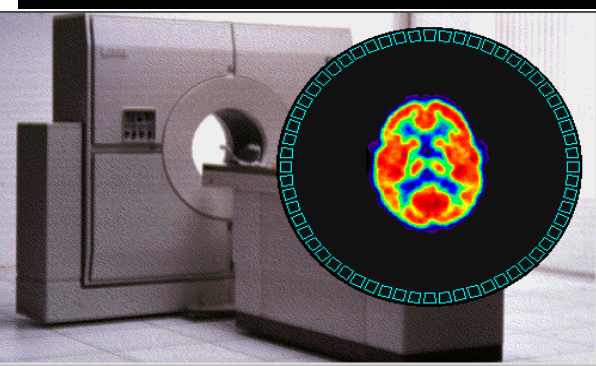


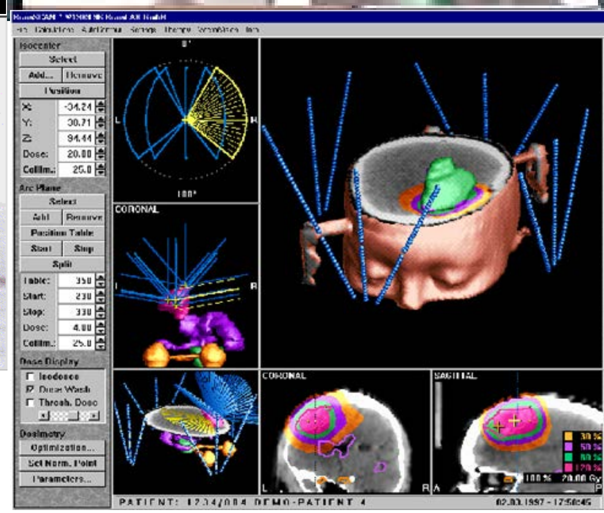

01 - 플라즈마 텔레비전
02 - 플라즈마 코팅된 항공기 엔진
03 - 플라즈마를 사용한 LED
04 - 플라즈마 CVD를 사용하여 제작한 안경
05 - 플라즈마 이온 주입된 인공관절
06 - 플라즈마 레이저를 사용한 의류 제단
07 - 플라즈마 헤드램프
08 - 플라즈마를 사용한 수소 연료전지
09 - 플라즈마 연소장치
10 - 플라즈마 머플러
11 - 플라즈마 오존 처리장치
12 - LCD
13- 플라즈마를 사용한 태양전지
14 - 플라즈마를 사용한 반도체 제조
15 - 플라즈마 의료 처리
16 - 플라즈마 처리된 고분자
17 - 플라즈마 처리된 섬유
18 - 플라즈마 처리된 의료장치
19 - 플라즈마 표면처리된 컨테이너
20 - 플라즈마 표면처리된 유리
21 - 플라즈마 램프

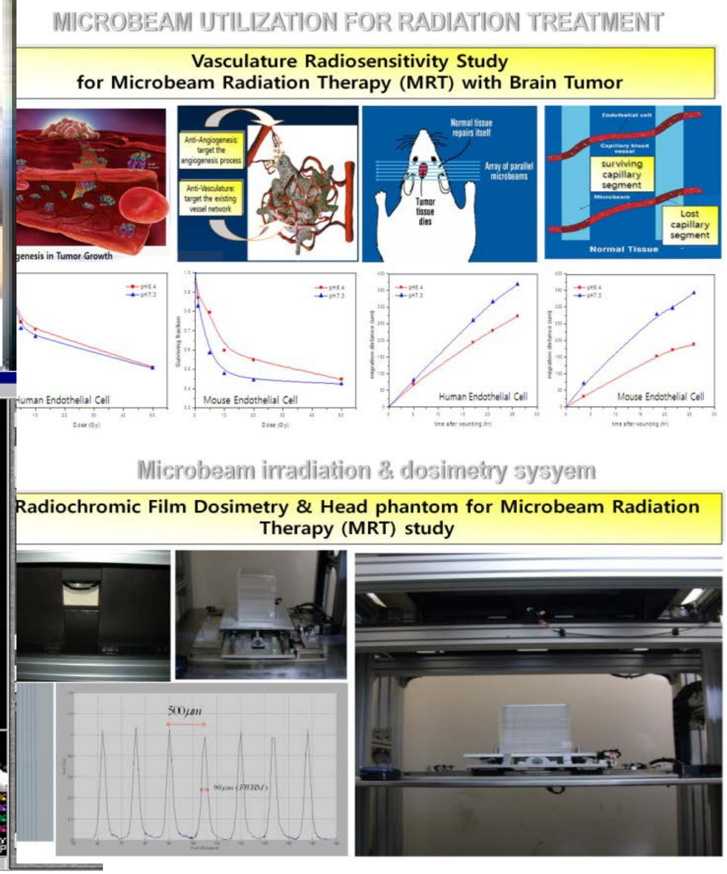
# Radiation engineering

- Radiation biology and medical application



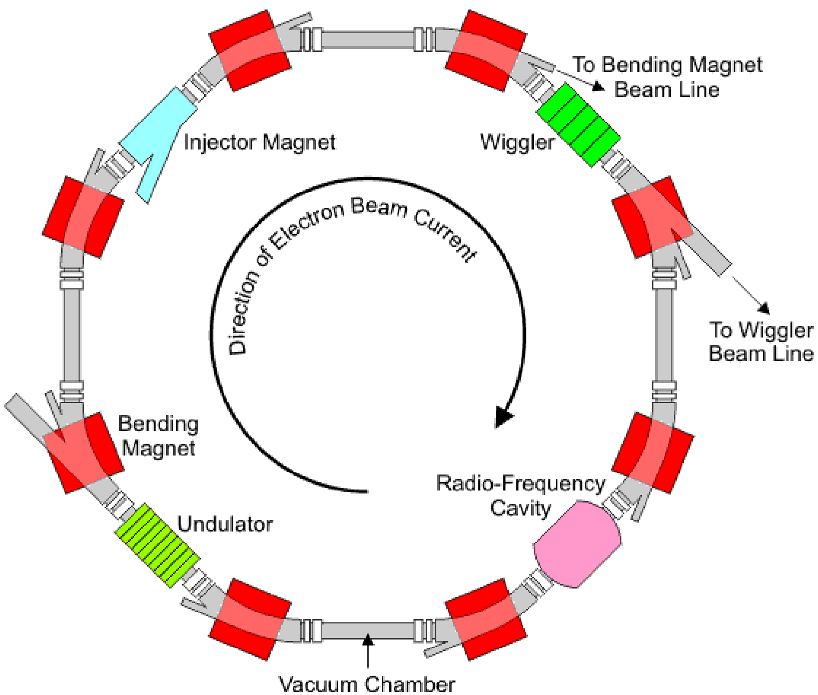



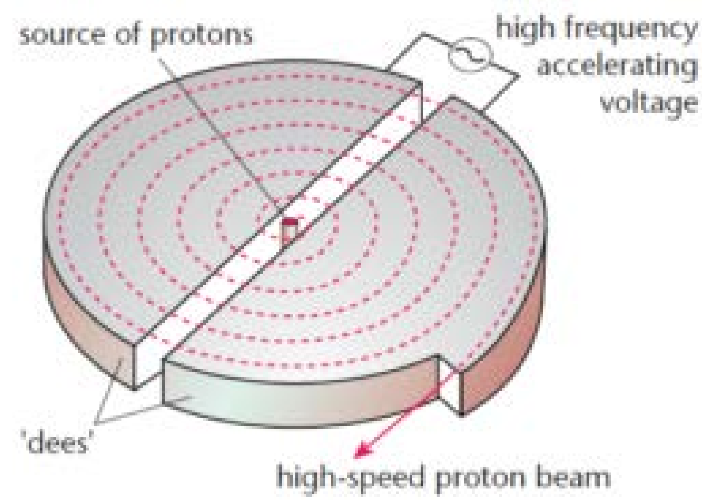


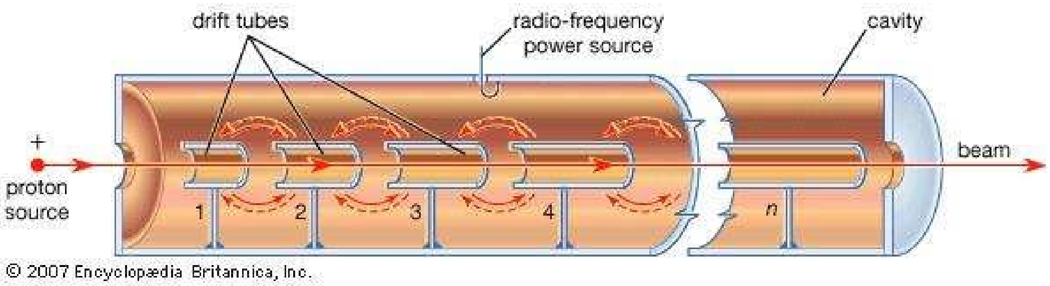



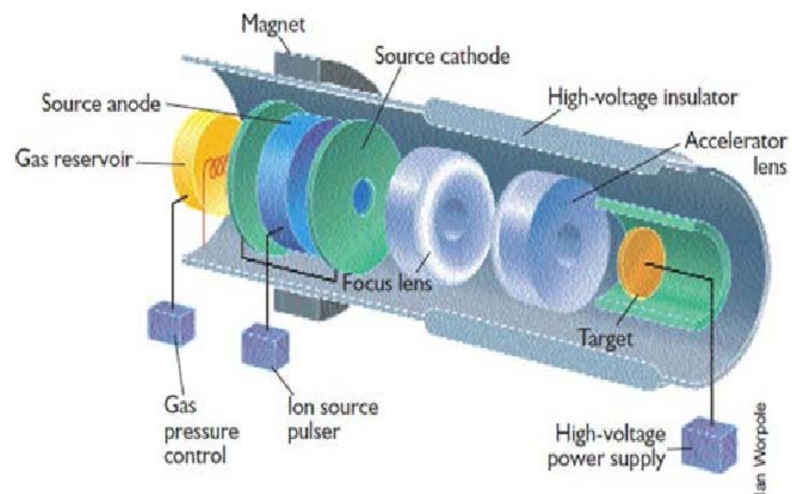
# Radiation engineering

- Radiation source and particle accelerator



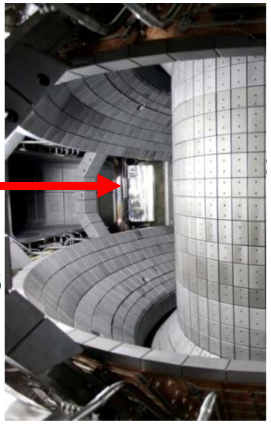



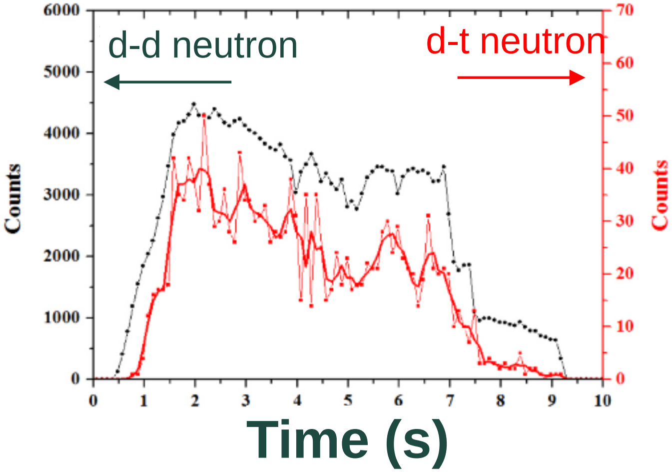
# Radiation engineering

- Radiation detection and measurement

**NE213 scintillation detector**

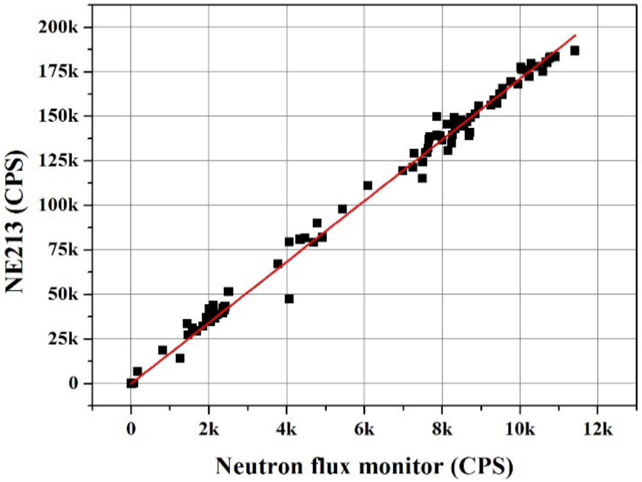
**8.2 m from magnetic axis**



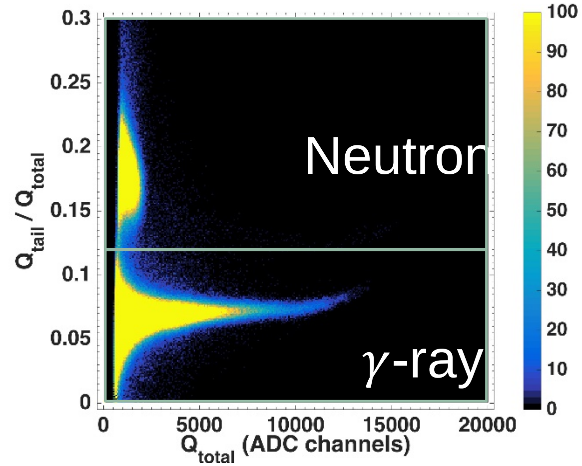



- **Radiation shield**


- **Linearity with conventional NFM**




- **Neutron and gamma ray discrimination**



# Syllabus of Nuclear Engineering 2

- **Radiation engineering**
  - Radiation and radioactivity
  - Radiation interaction with matter
  - Radiation source technology
  - Detection and measurement of radiation
  - Radiation dose and hazard assessment
- **Plasma engineering**
  - Basic concepts of plasmas
  - Plasma and sheath
  - Plasma source technology
  - Plasma applications and related issues
- **Fusion engineering**
  - Fusion energy
  - Various fusion concepts
  - Tokamaks
  - Issues in fusion nuclear technology

# Textbooks and references

- **Radiation engineering**
  - J. Turner, Atoms, Radiation, and Radiation Detection, Wiley (2007)
  - Arthur Beiser, Concepts of Modern Physics (6th ed.), Mc-Graw Hill (2003)
  - A. Waltar, Radiation and Modern Life: Fulfilling Marie Curie's Dream, Prometheus Books (2004)
  - C. Grupen and M. Rodgers, Radioactivity and Radiation, Springer (2016)
  - Arthur Beiser, Concepts of Modern Physics (6th ed.), Mc-Graw Hill (2003)
  - N. Tsoulfanidid and S. Landsberger, Measurement and Detection of radiation, CRC Press (2015)

- **Plasma engineering**
  - F. Chen, Introduction to Plasma Physics and Controlled Fusion, Springer (2016)

- **Fusion engineering**
  - G. McCracken and P. Stott, Fusion: The Energy of the Universe, Elsevier (2005)
  - F. Chen, An Indispensable Truth, Springer (2011)

# Curriculum

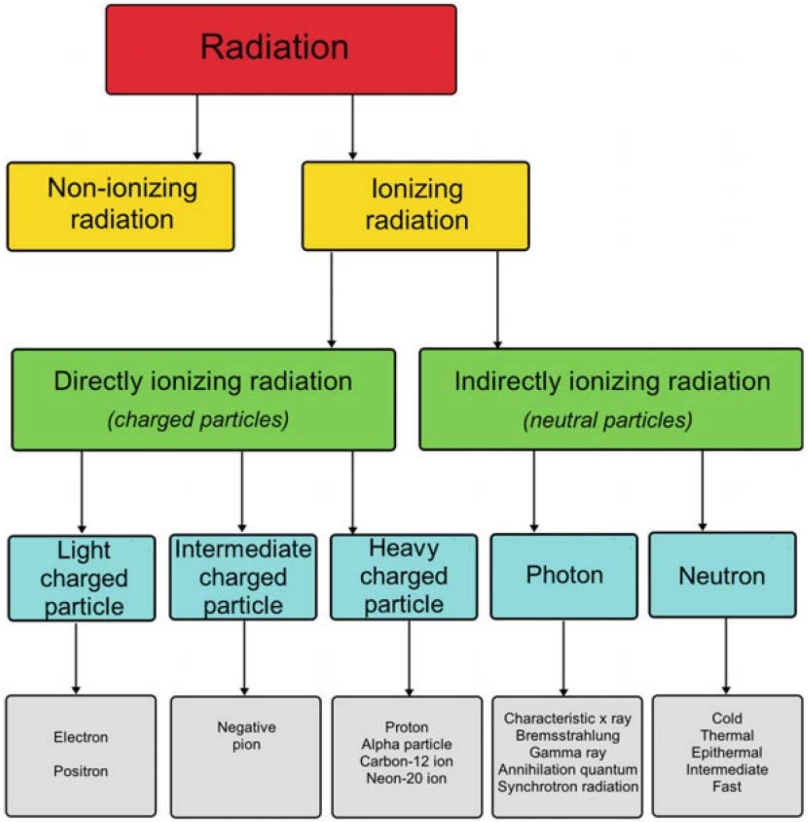
| | | | | | | |
|---|---|---|---|---|---|---|
| 3 | 전공필수 | 원자로이론 | 3 | 전공선택 | 원자력 계통 | 3 |
| | | 플라즈마기초 | 3 | | 원자로 동역학 및 제어 | 3 |
| | | 방사선공학 | 3 | | 핵융합기초 | |
| | 전공선택 | 시스템공학열역학 | 3 | | 시스템에너지 전달공학 | |
| | | 에너지물리화학 | | | 방사선의 산업 및 의학응용 | 3 |
| | | 플라즈마전자역학 II | 3 | | 핵융합플라즈마 실험 | |
| | 학문의 기초 | 고급영어 | 2 | | 수치해석기초/원자력재료기초 | 3 |
| | | | | 전공필수 | 원자핵공학세미나 | 1 |
| | | | | 공대필수교양 | 창의성 교과목/문화와 예술 | 3 |
| | 학점 소계 | | 17 | 학점 소계 | | 16 |
| 4 | 전공선택 | 원자로 안전공학 | 3 | 전공선택 | 확률론적 안전해석 | 3 |
| | | 응용핵물리 | | | 핵부품소재설계 | |
| | | 원자로시스템실습 | 3 | | 원자로수치해석과 설계 | 3 |
| | | 산업플라즈마공학 | | | 핵계측 | |
| | | 원자력법과 사회 | 3 | | 공학지식의 실무응용 | 3 |
| | | 원자로열유체실험/ | 3 | | 에너지 정책 및 경제 | |
| | | 방사선의과학기초 | | | | |
| | 공대필수교양 | 사회성 교과목+ 인간과 사회 | 3 | | | |
| | 학점 소계 | | 18 | 학점 소계 | | 18 |

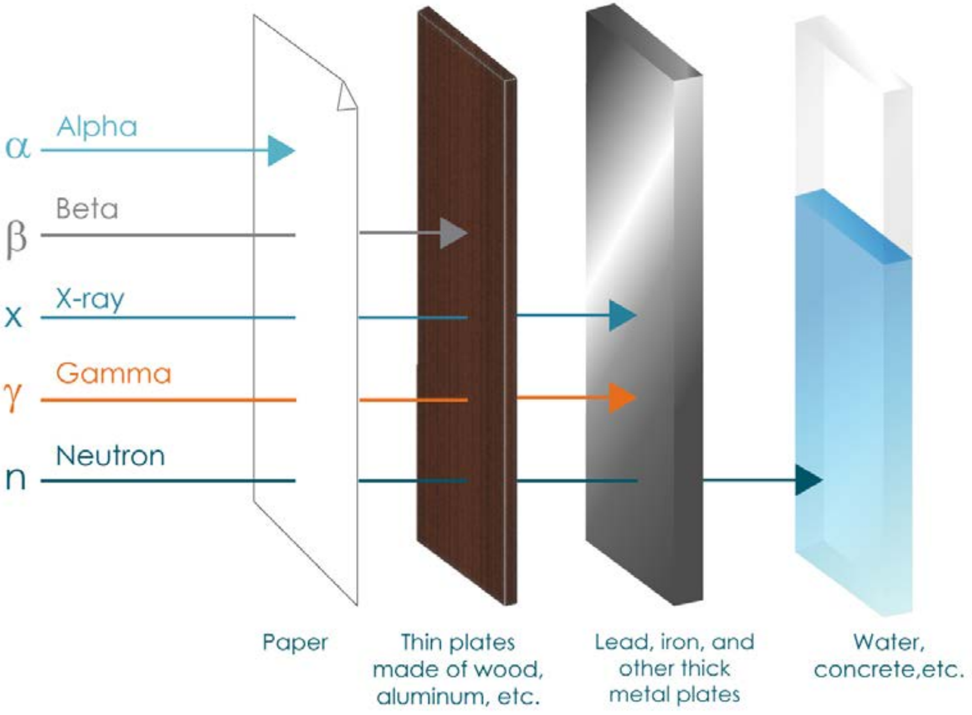
- 원자력시스템 공학
- 핵융합·플라즈마 공학
- 방사선 공학

| | | 원자핵공학과 학문 세부 분야 | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 교과목 | 원자로 시스템 | 원자로 물리 | 원자력 열수력 | 시스템 안전 | 핵연료 및 핵재료 | 시스템 계측·제어 | 핵주기 | 방사선 방호 | 방사선 계측·기기 | 입자 가속기 | 방사선 이용 | 핵융합 플라즈마 물리 | 핵융합로 시스템 | 산업 플라즈마 | 핵통제 | 원자력 정책 |
| 1-1 | 컴퓨터의개념및실습 | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● |
| | 신입생세미나 | | | | | | | | | | | | | | | | |
| 1-2 | 원자핵공학의미래 | | | | | | | | | | | | | | | | |
| 2-1 | 공학수학1 | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● |
| | 공학물리기초 | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● |
| | 핵공학개론1 | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● |
| | 핵공학기초실험* | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |
| 2-2 | 공학수학2 | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● |
| | 핵공학현대물리 | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● |
| | 핵공학개론2 | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● |
| | 플라즈마전자역학1 | | | | | | | | | | | | | | | | |
| | 시스템공학수력학 | | | | | | | | | | | | | | | | |
| 3-1 | 원자로이론 | | | | | | | | | | | | | | | | |
| | 플라즈마기초 | | | | | | | | | | | | | | | | |
| | 방사선공학 | | | | | | | | | | | | | | | | |
| | 플라즈마전자역학2 | | | | | | | | | | | | | | | | |
| | 에너지물리화학 | | | | | | | | | | | | | | | | |
| | 원자로열유체실험* | | | | | | | | | | | | | | | | |
| 3-2 | 원자핵공학세미나1 | | | | | | | | | | | | | | | | |
| | 수치해석기초 | | | | | | | | | | | | | | | | |
| | 원자력재료기초 | | | | | | | | | | | | | | | | |
| | 원자로동역학및제어 | | | | | | | | | | | | | | | | |
| | 핵융합플라즈마실험* | | | | | | | | | | | | | | | | |
| | 핵융합기초 | | | | | | | | | | | | | | | | |
| | 열역학및원자력시스템 | | | | | | | | | | | | | | | | |
| | 방사선산업및의학응용 | | | | | | | | | | | | | | | | |
| 4-1 | 학사논문연구1 | | | | | | | | | | | | | | | | |
| | 원자로물리실험* | | | | | | | | | | | | | | | | |
| | 핵부품소재설계 | | | | | | | | | | | | | | | | |
| | 원자로안전공학 | | | | | | | | | | | | | | | | |
| | 원자력시스템실습* | | | | | | | | | | | | | | | | |
| | 확률론적안전해석 | | | | | | | | | | | | | | | | |
| | 원자력시스템실습 | | | | | | | | | | | | | | | | |
| | 응용핵물리 | | | | | | | | | | | | | | | | |
| | 방사선의과학기초 | | | | | | | | | | | | | | | | |
| | 산업플라즈마공학 | | | | | | | | | | | | | | | | |
| | 원자력법과사회 | | | | | | | | | | | | | | | | |
| 4-2 | 학사논문연구2 | | | | | | | | | | | | | | | | |
| | 원자로수치해석과설계 | | | | | | | | | | | | | | | | |
| | 확률론적안전해석 | | | | | | | | | | | | | | | | |
| | 핵계측 | | | | | | | | | | | | | | | | |
| | 에너지정책및경제 | | | | | | | | | | | | | | | | |
| | 공학지식의실무응용 | | | | | | | | | | | | | | | | |

# Classification of radiation

- Radiation: transportation of mass and energy through space



# Directly and Indirectly Ionizing Radiation

- Directly Ionizing Radiation: Comprises charged particles (electrons, protons, α-particles, heavy ions) that deposit energy in the absorber through a direct one-step process involving Coulomb interactions between the directly ionizing charged particle and orbital electrons of the atoms in the absorber.

- Indirectly Ionizing Radiation: Comprises neutral particles (photons such as x-rays and γ-rays, neutrons) that deposit energy in the absorber through a two-step process as follows:
  - In the first step a charged particle is released in the absorber (photons release either electrons or electron/positron pairs, neutrons release protons or heavier ions).
  - In the second step, the released charged particles deposit energy to the absorber through direct Coulomb interactions with orbital electrons of the atoms in the absorber.

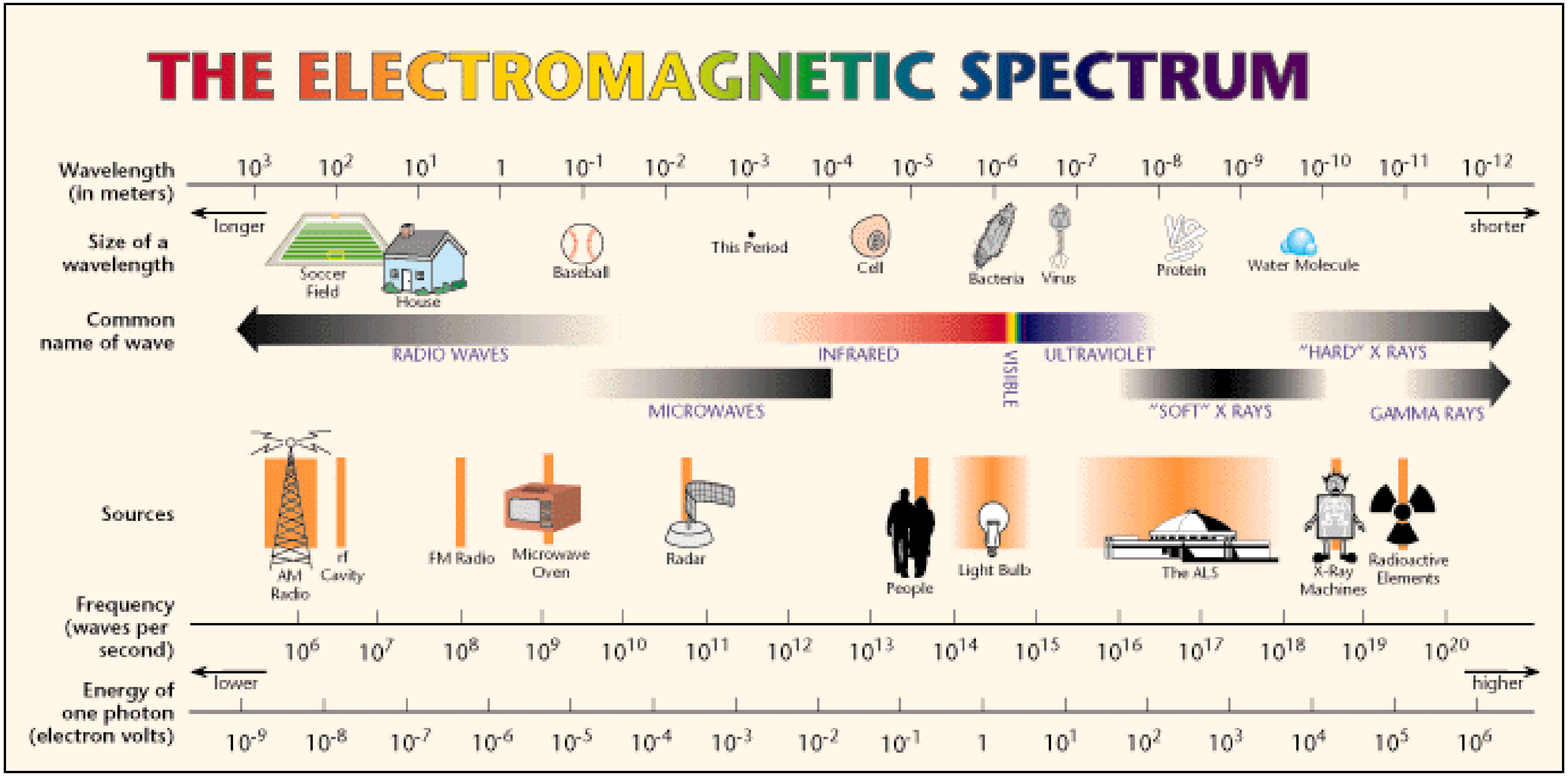
# Photons

- A photon is regarded as a quantum of excitation in the underlying electromagnetic field.

$$E = h\nu = \frac{hc}{\lambda}$$

$$p = \frac{h\nu}{c} = \frac{h}{\lambda}$$

1 eV ~ 1,240 nm



# Low LET and High LET Radiation

- The ionization density produced by ionizing radiation in tissue depends on the linear energy transfer (LET) of the ionizing radiation beam.
- The LET is defined as the mean amount of energy that a given ionizing radiation imparts to absorbing medium (such as tissue) per unit path length and is used in radiobiology and radiation protection to specify the quality of an ionizing radiation beam.
- The LET is measured in keV/μm with 10 keV/μm separating the low LET (sparsely ionizing) radiation from the high LET (densely ionizing) radiation.

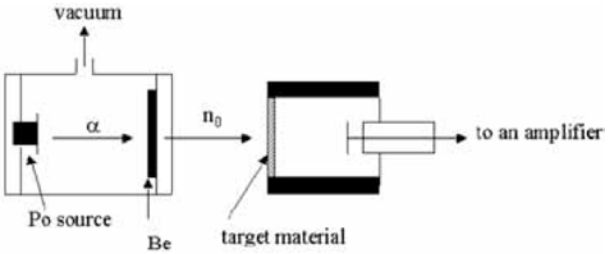
| Low LET radiation | LET (keV/μm) | High LET | LET (keV/μm) |
|---|---|---|---|
| x-rays: 250 kVp | 2 | Electrons: 1 keV | 12.3 |
| $\gamma$-rays: Co-60 | 0.3 | Neutrons: 14 MeV | 12 |
| x-rays: 3 MeV | 0.3 | Protons: 2 MeV | 17 |
| Electrons: 10 keV | 2.3 | Carbon ions: 100 MeV | 160 |
| Electrons: 1 MeV | 0.25 | Heavy ions | 100–2000 |

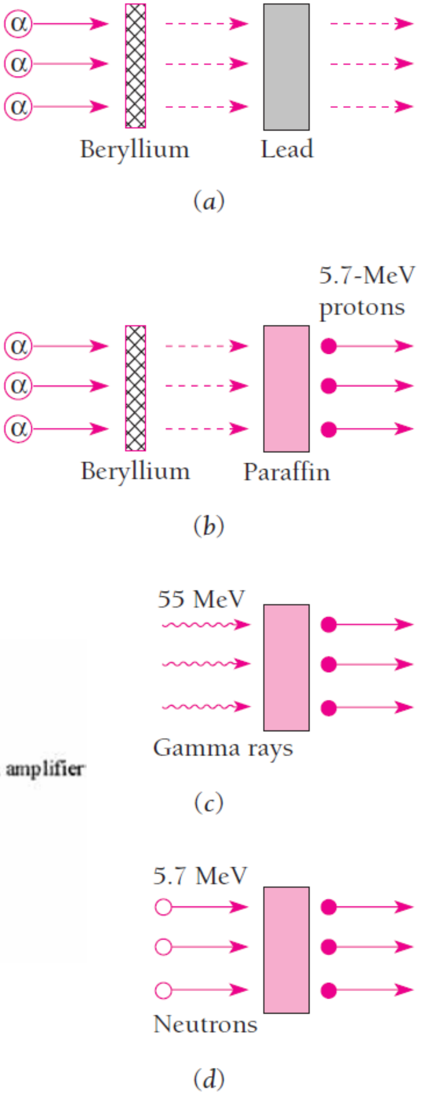
# Chadwick's paper (Nature, 1932)

**Possible Existence of a Neutron**

It has been shown by Bothe and others that beryllium when bombarded by α-particles of polonium emits a radiation of great penetrating power, which has an absorption coefficient in lead of about 0·3 $(cm.)^{-1}$. Recently Mme. Curie-Joliot and M. Joliot found, when measuring the ionisation produced by this beryllium radiation in a vessel with a thin window, that the ionisation increased when matter containing hydrogen was placed in front of the window. The effect appeared to be due to the ejection of protons with velocities up to a maximum of nearly $3 \times 10^9$ cm. per sec. They suggested that the transference of energy to the proton was by a process similar to the Compton effect, and estimated that the beryllium radiation had a quantum energy of $50 \times 10^6$ electron volts.

I have made some experiments using the valve counter to examine the properties of this radiation excited in beryllium. The valve counter consists of a small ionisation chamber connected to an amplifier, and the sudden production of ions by the entry of a particle, such as a proton or α-particle, is recorded by the deflexion of an oscillograph. These experiments have shown that the radiation ejects particles from hydrogen, helium, lithium, beryllium, carbon, air, and argon. The particles ejected from hydrogen behave, as regards range and ionising power, like protons with speeds up to about $3{\cdot}2 \times 10^9$ cm. per sec. The particles from the other elements have a large ionising power, and appear to be in each case recoil atoms of the elements.

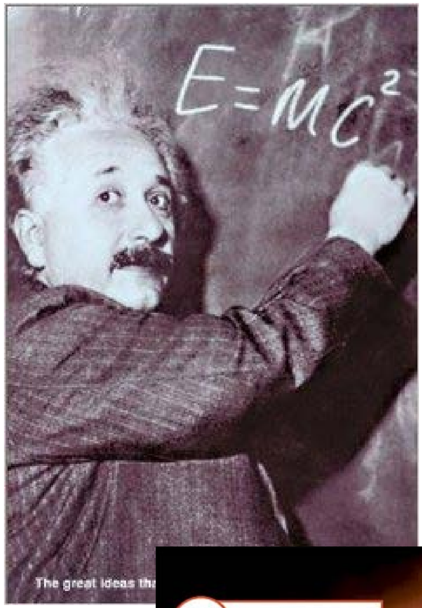
# Chadwick's paper (Nature, 1932)

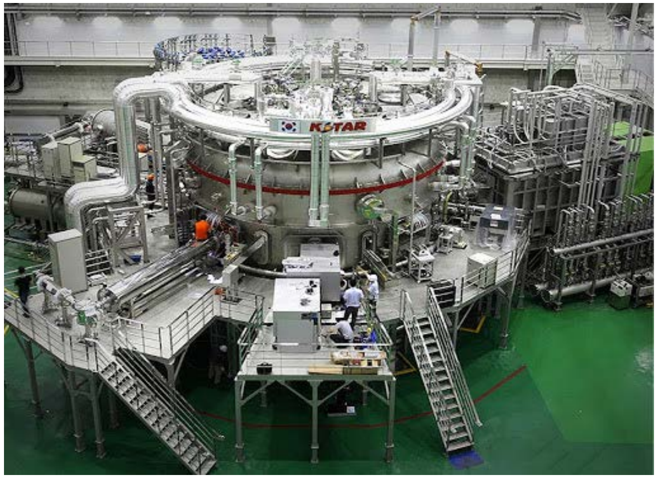
If we ascribe the ejection of the proton to a Compton recoil from a quantum of $52 \times 10^6$ electron volts, then the nitrogen recoil atom arising by a similar process should have an energy not greater than about 400,000 volts, should produce not more than about 10,000 ions, and have a range in air at N.T.P. of about 1·3 mm. Actually, some of the recoil atoms in nitrogen produce at least 30,000 ions. In collaboration with Dr. Feather, I have observed the recoil atoms in an expansion chamber, and their range, estimated visually, was sometimes as much as 3 mm. at N.T.P.

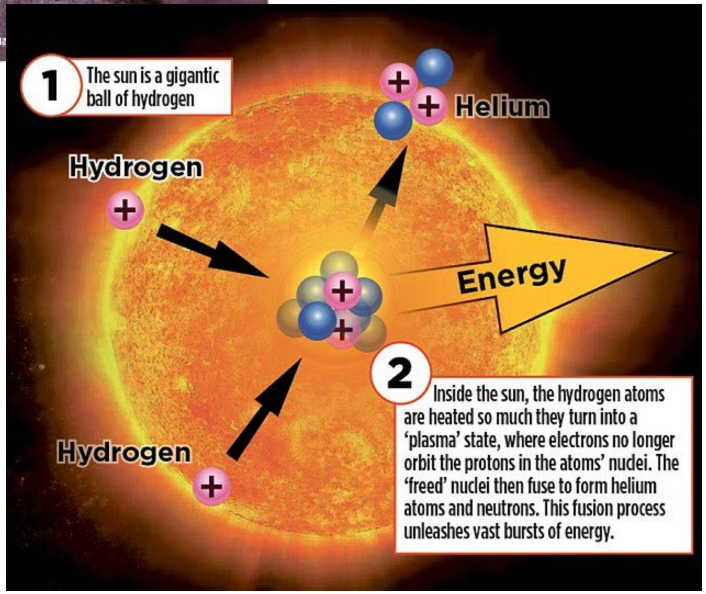
These results, and others I have obtained in the course of the work, are very difficult to explain on the assumption that the radiation from beryllium is a quantum radiation, if energy and momentum are to be conserved in the collisions. The difficulties disappear, however, if it be assumed that the radiation consists of particles of mass 1 and charge 0, or neutrons. The capture of the $\alpha$-particle by the $Be^9$ nucleus may be supposed to result in the formation of a $C^{12}$ nucleus and the emission of the neutron. From the energy relations of this process the velocity of the neutron emitted in the forward direction may well be about $3 \times 10^9$ cm. per sec. The collisions of this neutron with the atoms through which it passes give rise to the recoil atoms, and the observed energies of the recoil atoms are in fair agreement with this view. Moreover, I have observed that the protons ejected from hydrogen by the radiation emitted in the opposite direction to that of the exciting $\alpha$-particle appear to have a much smaller range than those ejected by the forward radiation.

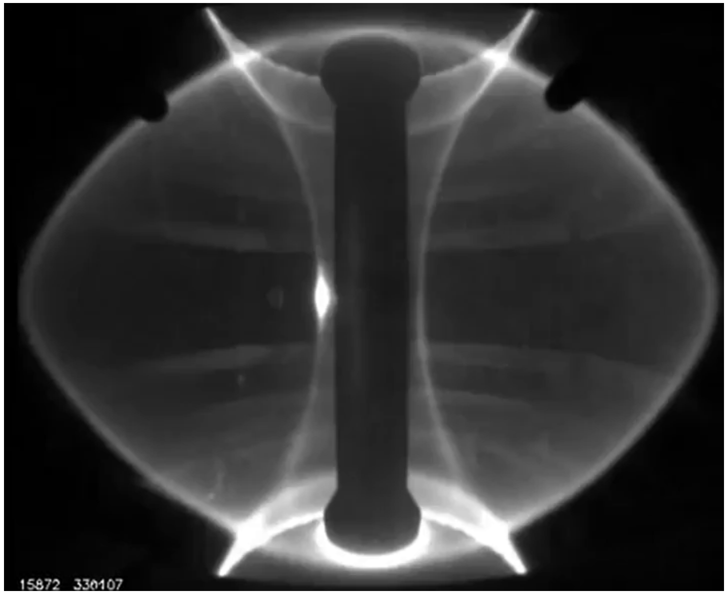
$${}^{9}_{4}Be + \alpha \rightarrow {}^{12}_{6}C + n$$

# The Sun's energy

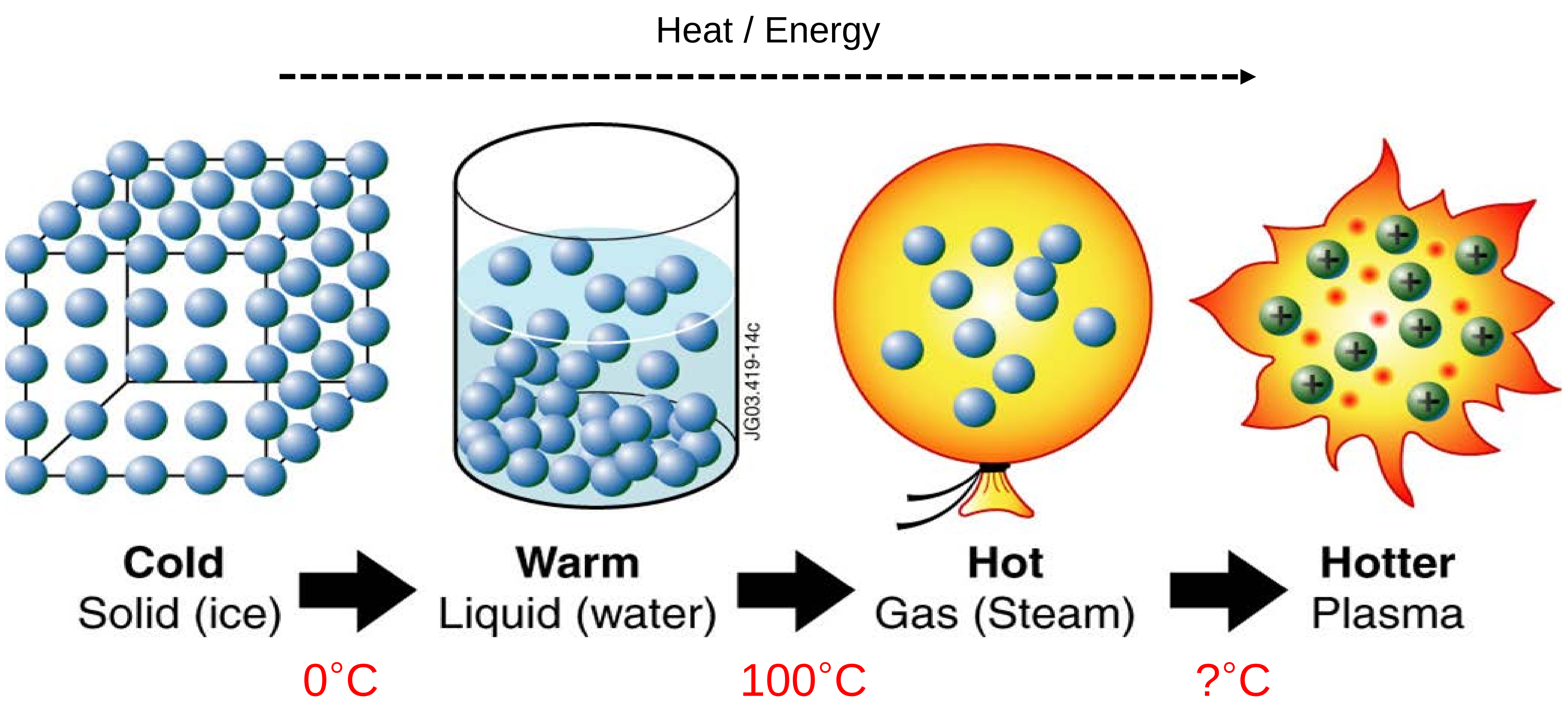




# What is a plasma?




- A Plasma is quasi-neutral gas of charged and neutral particles which exhibits collective behavior. (Francis F. Chen)
- Plasma is a gas in which a certain portion of the particles are ionized. (Wikipedia)

# Semiconductor manufacturing

Samsung Announces the Exynos 9825 SoC: First 7nm EUV Silicon Chip

by Andrei Frumusanu on August 6, 2019 9:30 PM EST