Cyclotron option for Accelerator Driven System

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  - 0.3 MW cyclotron system: Therapy cyclotron as the first step toward ADS
  - 3 MW cyclotron system: Main cyclotron for ADS

Nuclear power

❖ **The long-term threats facing humanity**

- **Climate change**
- **Exhaustion of energy**

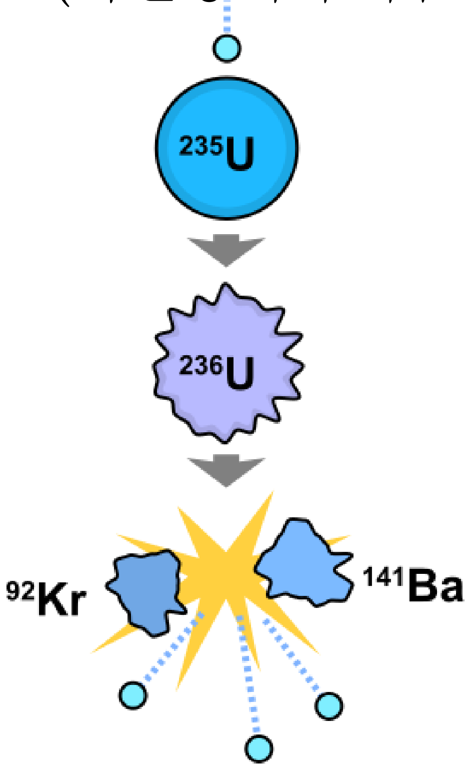
❖ **Nuclear power**

- **The practicable alternative**
- **Strong advantage and strong drawback**

❖ **Nuclear power drawback**

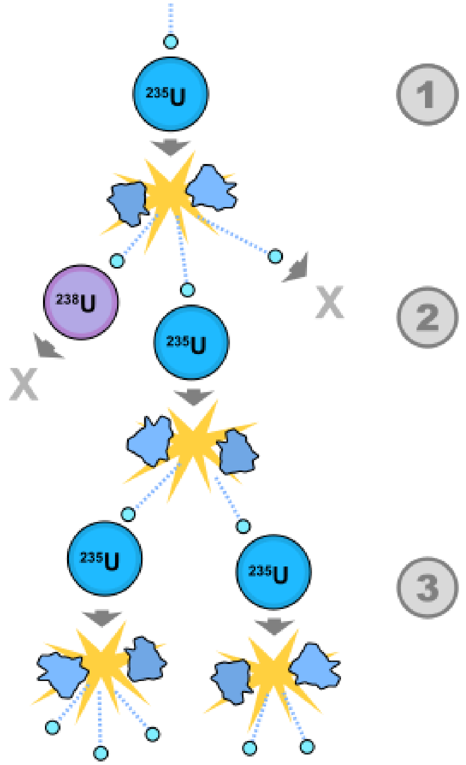
- **Chernobyl disaster (Supercritical)**
- **Radiation active waste**

- 원료=우라늄 238(96%)+우라늄235(4%)
  (자연상태 우라늄: U238(99.3%))

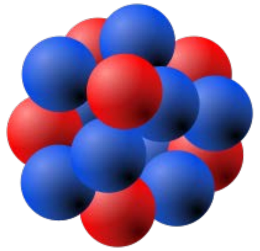


평균 2.6개

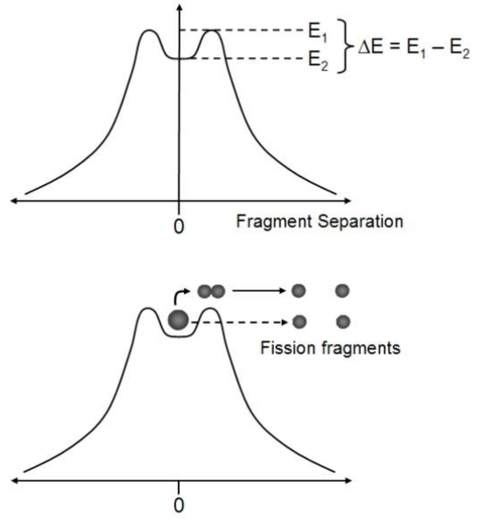
핵분열



Chain Reaction



핵=양성자(red)+중성자(blue)
중성자는 핵반응의 필수요소



The Nuclear Potential and Nuclear Fission

T.-Y. Lee, ADS meeting, PAL

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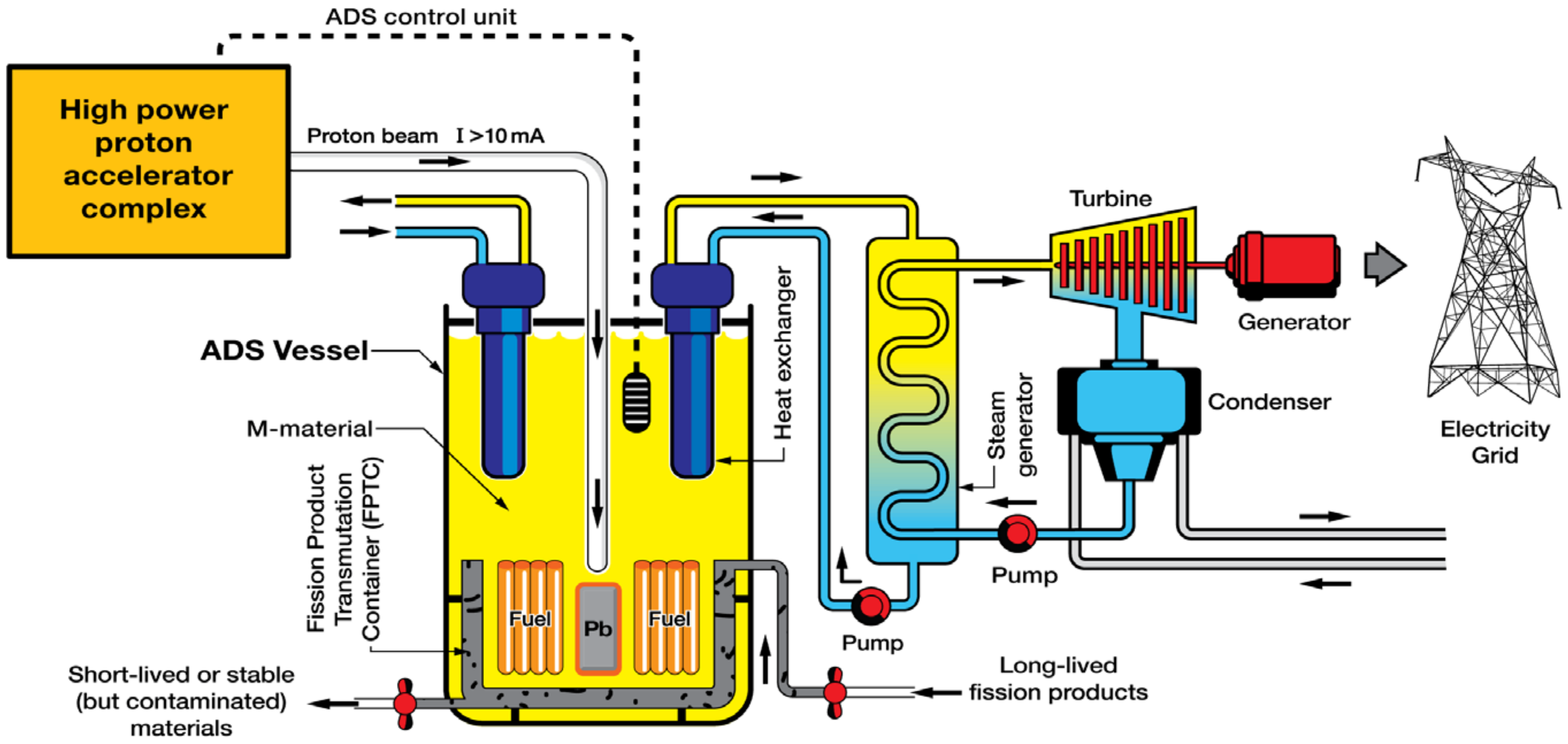
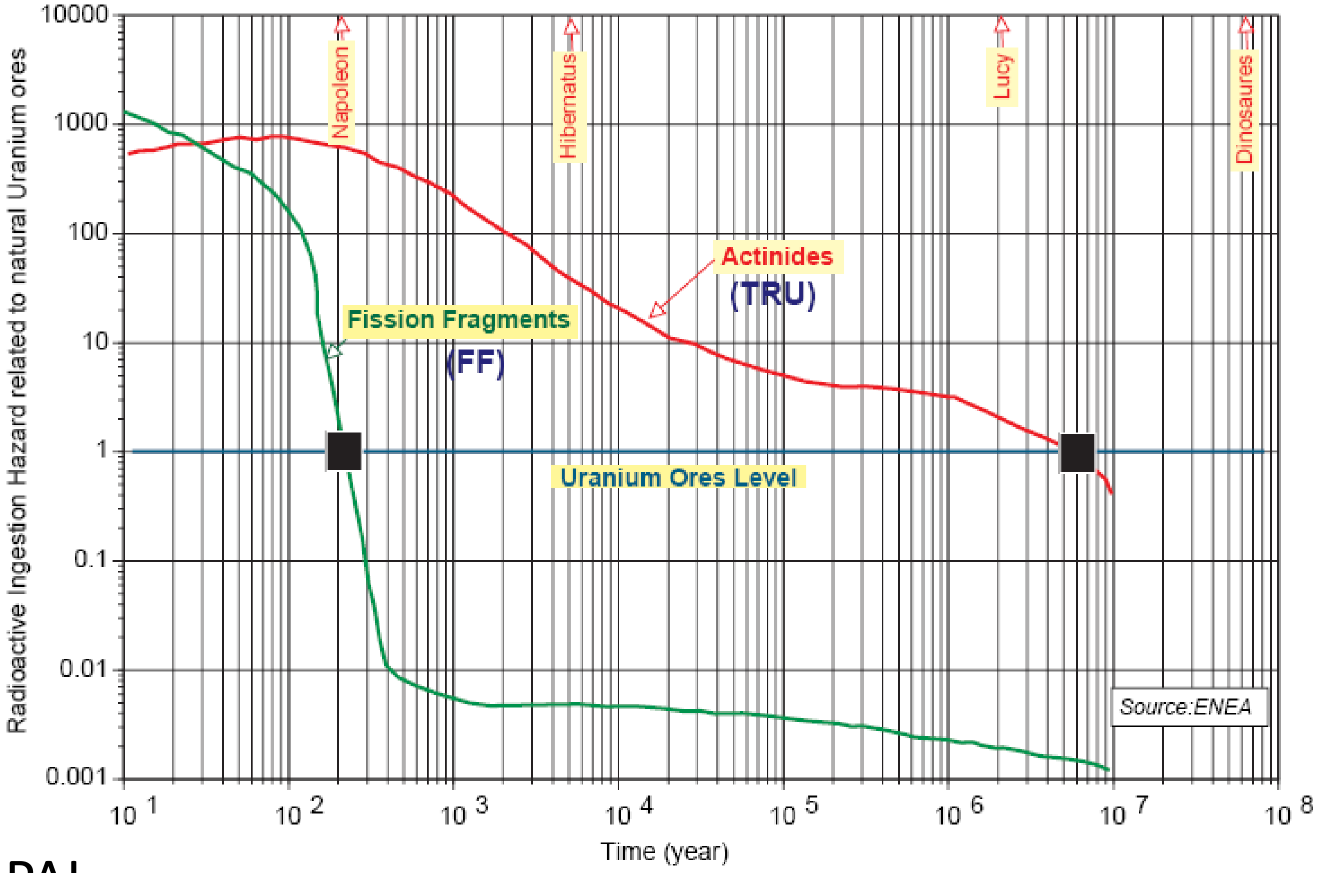
Accelerator Driven System (ADS)





T.-Y. Lee, ADS meeting, PAL

Requirement for ADS

Resulting beam requirements

- Particle type: protons
- Particle energy: >500 MeV
- Beam power: multiple MW
  - depending on chosen sub-criticality, reactor design,...
- Very high reliability
  - Beam trips must be resolved within a few seconds
  - Imposing severe thermal stress on the reactor materials/components
  - Any longer beam trip requires a time-consuming restart of the reactor.
  - Consequence: MTBF > multiple weeks

Adrian Fabich, SCK CEN, IPAC20

Requirement for ADS

Derived accelerator requirements

- DC-operation
  - less space charge, reduced stress on spallation target, solid state amplifiers possible, ...
- Fault tolerance schemes needed: Within a few seconds:
  - Detect failure
  - Deploy a new configuration
  - Fast recommissioning: return to full-power beam-operation
- 2 accelerator options:
  - Cyclotron
  - Linac
  - N.B.: also a 400 MeV FFAG options studied

Adrian Fabich, SCK CEN, IPAC20

Two options for ADS

❖ Our working group has been performing two options: Cyclotron (this presentation) and Linac (Prof. Chung).

❖ Each option has their own advantage and disadvantage.

[Cyclotron]

Simple

Cost-effective

Limit to get energy

NC or SC

Good reliability

PSI / Texas A&M

…

[Linac]

Large scale

Expensive

Easy to get energy

SC

Depend on SRF

C-ADS / MYRRHA

…

Working group in Korea

❖ No budget but working group on study stage.

❖ PAL: Design, Beam dynamics, RF, Vacuum, etc.

- S. Shin, G. Hahn, J. Hu, B. Oh, T. Ha

❖ SNU: HTC SC magnet

- S. Hahn, J. Park

❖ KERI: SC magnet

- J. Cho,

❖ KBSI: Ion source

- B. Lee, J. Park

❖JINR, NFRI, UNIST: Review and magnet design

- H. Kim, M. Chung

❖ Research exchange association for cyclotron: SKKU, IBS, KBSI, KAERI, SNU, KU, KERI, PAL, UNIST

Beam dynamics program I

- ❖ **Equilibrium orbit program with second order transfer matrix.**
- ❖ **This program might be necessary on high vertical focusing field for ADS.**
- ❖ **Collaboration result between PAL and UNIST**

$$\frac{dx}{d\theta}=\frac{p_r}{p_\theta}x+\frac{rP^2}{p_\theta^3}p_x+f_{11}x_0^2+f_{12}x_0p_{x0}+f_{13}p_{x0}^2+f_{14}z_0^2+f_{15}z_0p_{z0}+f_{16}p_{z0}^2$$

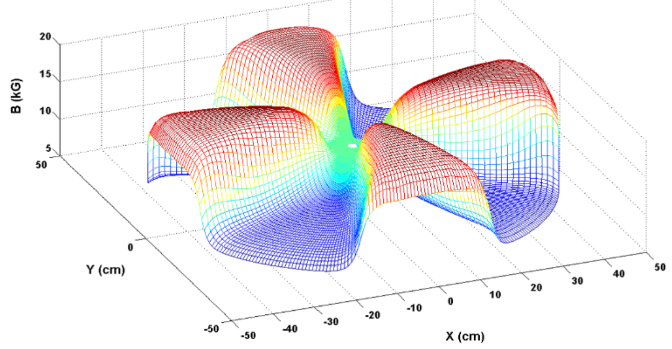
$$\frac{dp_x}{d\theta}=-\frac{p_r}{p_\theta}p_x-\left(B+r\frac{\partial B}{\partial r}\right)x+f_{21}x_0^2+f_{22}x_0p_{x0}+f_{23}p_{x0}^2+f_{24}z_0^2+f_{25}z_0p_{z0}+f_{26}p_{z0}^2$$

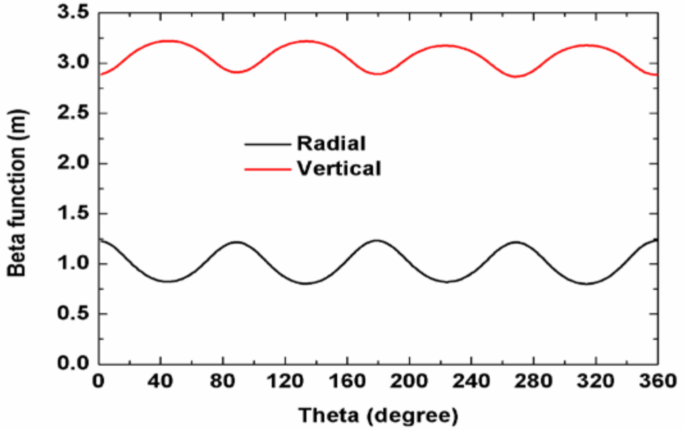
$$\frac{dz}{d\theta}=\frac{r}{p_\theta}p_z+g_{11}x_0z_0+g_{12}x_0p_{z0}+g_{13}p_{x0}z_0+g_{14}p_{x0}p_{z0},$$

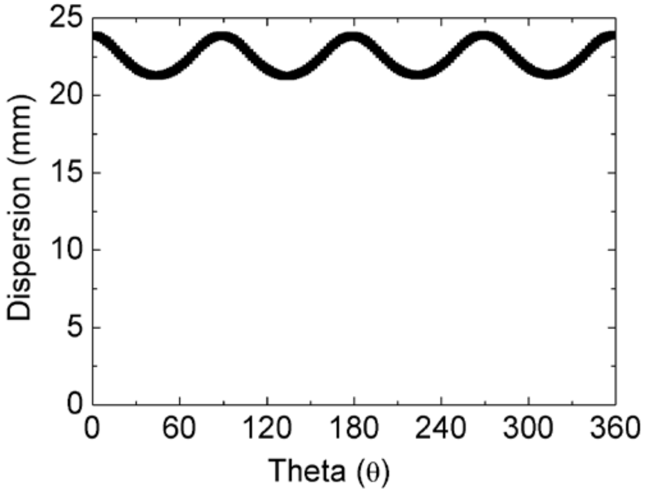
$$\frac{dp_z}{d\theta}=\left(r\frac{\partial B}{\partial r}-\frac{p_r}{p_\theta}\frac{\partial B}{\partial\theta}\right)z+g_{21}x_0z_0+g_{22}x_0p_{z0}+g_{23}p_{x0}z_0+g_{24}p_{x0}p_{z0}$$

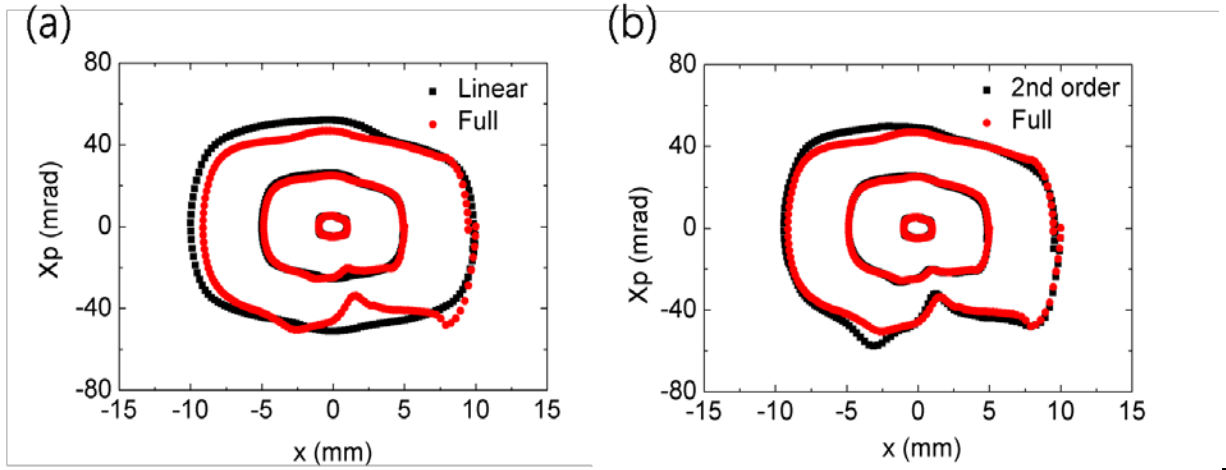
$$\frac{d\tau}{d\theta}=\frac{\gamma r}{p_\theta}x+\frac{\gamma rp_r}{p_\theta^3}p_x+h_1x_0^2+h_2x_0p_{x0}+h_3p_{x0}^2+h_4z_0^2+h_5z_0p_{z0}+h_6p_{z0}^2$$

Coefficient	Value
f_{11}	$\frac{P^2}{p_\theta^3}X_{11}X_{21}+\frac{3}{2}\frac{rp_rP^2}{p_\theta^5}X_{21}$
f_{12}	$\frac{P^2}{p_\theta^3}(X_{11}X_{22}+X_{12}X_{21})+2\times\frac{3}{2}\frac{rp_rP^2}{p_\theta^5}X_{21}X_{22}$
f_{13}	$\frac{P^2}{p_\theta^3}X_{12}X_{22}+\frac{3}{2}\frac{rp_rP^2}{p_\theta^5}$
f_{14}	$\frac{1}{2}\frac{rp_r}{p_\theta^3}Z_{21}^2$
f_{15}	$\frac{rp_r}{p_\theta^3}Z_{21}Z_{22}$
f_{16}	$\frac{1}{2}\frac{rp_r}{p_\theta^3}Z_{22}^2$
f_{21}	$\left(-\frac{\partial B}{\partial r}-\frac{r}{2}\frac{\partial^2B}{\partial r^2}\right)X_{11}^2-\frac{1}{2}\frac{P^2}{p_\theta^3}X_{21}^2$
f_{22}	$(-2\frac{\partial B}{\partial r}-r\frac{\partial^2B}{\partial r^2})X_{11}X_{12}-\frac{P^2}{p_\theta^3}X_{21}X_{22}$
f_{23}	$\left(-\frac{\partial B}{\partial r}-\frac{r}{2}\frac{\partial^2B}{\partial r^2}\right)X_{12}^2-\frac{1}{2}\frac{P^2}{p_\theta^3}X_{22}^2$
f_{24}	$\frac{1}{2}r\left(\frac{\partial^2B}{\partial r^2}+\frac{1}{r}\frac{\partial B}{\partial r}+\frac{1}{r^2}\frac{\partial^2B}{\partial\theta^2}\right)Z_{11}^2+\frac{\partial B}{\partial\theta}\frac{1}{p_\theta}Z_{11}Z_{21}-\frac{1}{2}\frac{1}{p_\theta}Z_{21}^2$
f_{25}	$r\left(\frac{\partial^2B}{\partial r^2}+\frac{1}{r}\frac{\partial B}{\partial r}+\frac{1}{r^2}\frac{\partial^2B}{\partial\theta^2}\right)Z_{11}Z_{12}+\frac{\partial B}{\partial\theta}\frac{1}{p_\theta}(Z_{11}Z_{22}+Z_{12}Z_{21})-\frac{1}{p_\theta}Z_{21}Z_{22}$
f_{26}	$\frac{1}{2}r\left(\frac{\partial^2B}{\partial r^2}+\frac{1}{r}\frac{\partial B}{\partial r}+\frac{1}{r^2}\frac{\partial^2B}{\partial\theta^2}\right)Z_{12}^2+\frac{\partial B}{\partial\theta}\frac{1}{p_\theta}Z_{12}Z_{22}-\frac{1}{2}\frac{1}{p_\theta}Z_{22}^2$
g_{11}	$\frac{1}{p_\theta}X_{11}Z_{21}+\frac{rp_r}{p_\theta^3}X_{21}Z_{21}$
g_{12}	$\frac{1}{p_\theta}X_{11}Z_{22}+\frac{rp_r}{p_\theta^3}X_{21}Z_{22}$
g_{13}	$\frac{1}{p_\theta}X_{12}Z_{21}+\frac{rp_r}{p_\theta^3}X_{22}Z_{21}$
g_{14}	$\frac{1}{p_\theta}X_{12}Z_{22}+\frac{rp_r}{p_\theta^3}X_{22}Z_{22}$
g_{21}	$\left(\frac{\partial B}{\partial r}+r\frac{\partial^2B}{\partial r^2}-\frac{p_r}{p_\theta}\frac{\partial^2B}{\partial r\partial\theta}\right)X_{11}Z_{11}-\frac{p_r^2}{p_\theta^3}\frac{\partial B}{\partial\theta}X_{21}Z_{11}$
g_{12}	$\left(\frac{\partial B}{\partial r}+r\frac{\partial^2B}{\partial r^2}-\frac{p_r}{p_\theta}\frac{\partial^2B}{\partial r\partial\theta}\right)X_{11}Z_{12}-\frac{p_r^2}{p_\theta^3}\frac{\partial B}{\partial\theta}X_{21}Z_{11}$
g_{13}	$\left(\frac{\partial B}{\partial r}+r\frac{\partial^2B}{\partial r^2}-\frac{p_r}{p_\theta}\frac{\partial^2B}{\partial r\partial\theta}\right)X_{12}Z_{11}-\frac{p_r^2}{p_\theta^3}\frac{\partial B}{\partial\theta}X_{22}Z_{11}$
g_{14}	$\left(\frac{\partial B}{\partial r}+r\frac{\partial^2B}{\partial r^2}-\frac{p_r}{p_\theta}\frac{\partial^2B}{\partial r\partial\theta}\right)X_{12}Z_{22}-\frac{p_r^2}{p_\theta^3}\frac{\partial B}{\partial\theta}X_{22}Z_{12}$
h_1	$\frac{\gamma p_r}{p_\theta^3}X_{11}X_{21}+\frac{1}{2}\left(\frac{\gamma r}{p_\theta^3}+\frac{3\gamma rp_r^2}{p_\theta^5}\right)X_{21}^2$
h_2	$\frac{\gamma p_r}{p_\theta^3}(X_{11}X_{22}+X_{12}X_{21})+2\times\frac{1}{2}\left(\frac{\gamma r}{p_\theta^3}+\frac{3\gamma rp_r^2}{p_\theta^5}\right)X_{21}X_{22}$
h_3	$\frac{\gamma p_r}{p_\theta^3}X_{12}X_{22}+\frac{1}{2}\left(\frac{\gamma r}{p_\theta^3}+\frac{3\gamma rp_r^2}{p_\theta^5}\right)X_{22}^2$
h_4	$\frac{1}{2}\frac{\gamma r}{p_\theta^3}$
h_5	$\frac{\gamma r}{p_\theta^3}$
h_6	$\frac{\gamma r}{p_\theta^3}$









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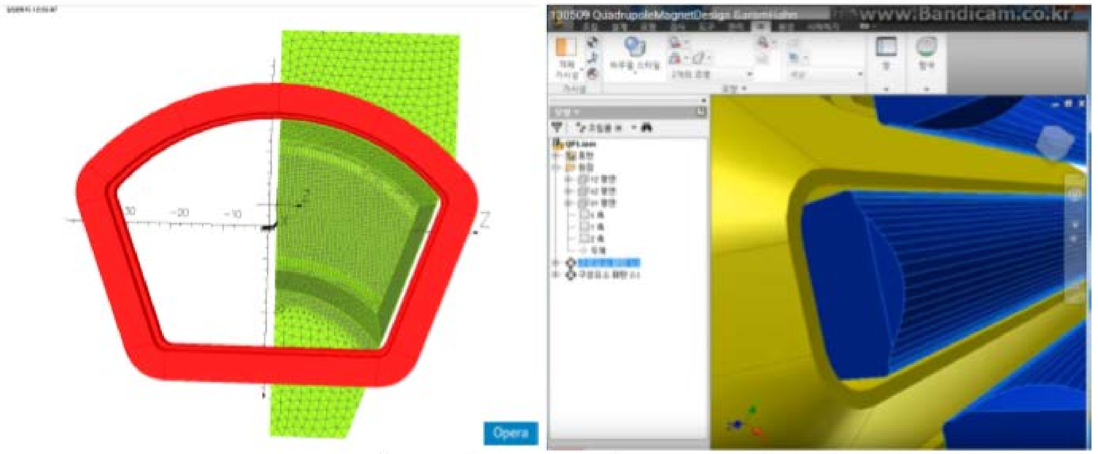
Beam dynamics program II

- ❖ PAL: Particle Accelerator Library by Garam Hahn.
- ❖ 2D/3D Vector analysis, 4D interpolation, RK4 tracker, etc.
- ❖ Apps: Beam line tracker, EQ orbit finder, FANA, G4KHIMA, etc.

Magnet Builder

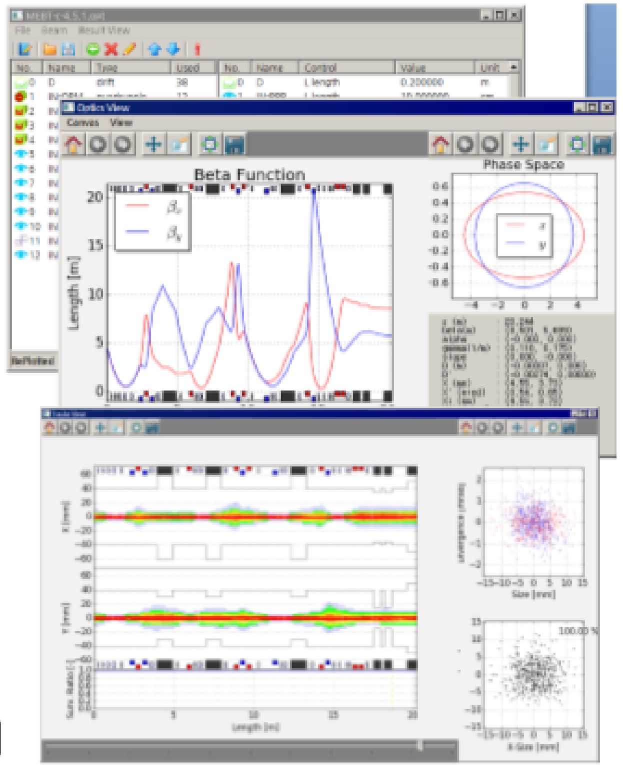
- Automatic File Generation
  - FEM Simulation : Opera3D COMI, Superfish POISSON
  - CAD Drawing : Autodesk Inventor, Free CAD v14



https://www.youtube.com/watch?v=PPFh4vHQSgc

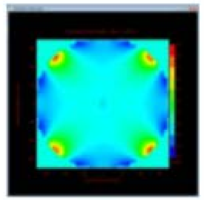
Optics Expert

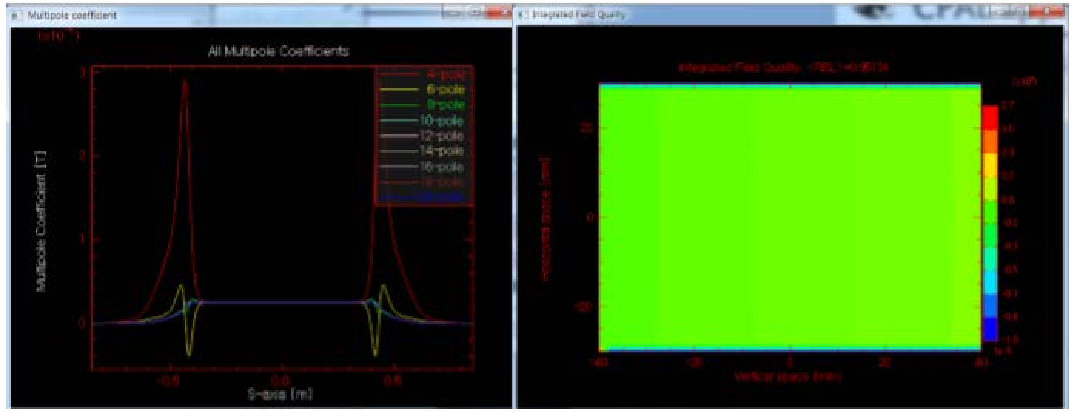
- Linear Beam Optics Calc.
- Features
  - Graphic User Interface
  - Mouse drag tuning
  - Easy beam definition
  - Minimization algorithm
  - Real-time Calc. & visualization
  - Inverse tracing
  - Optical tracking (Tr. ratio Calc.)
  - Save As (MadX, TRACE3D, WinAgile)
  - Making a report (Latex, Excel) as automated manner
  - 제어와 연동 가능한 라이브러리



FANA : Field Analyzer

- Evaluation of Magnetic Field Quality
  - Multipole Analysis
  - Integrated Field Quality Analysis





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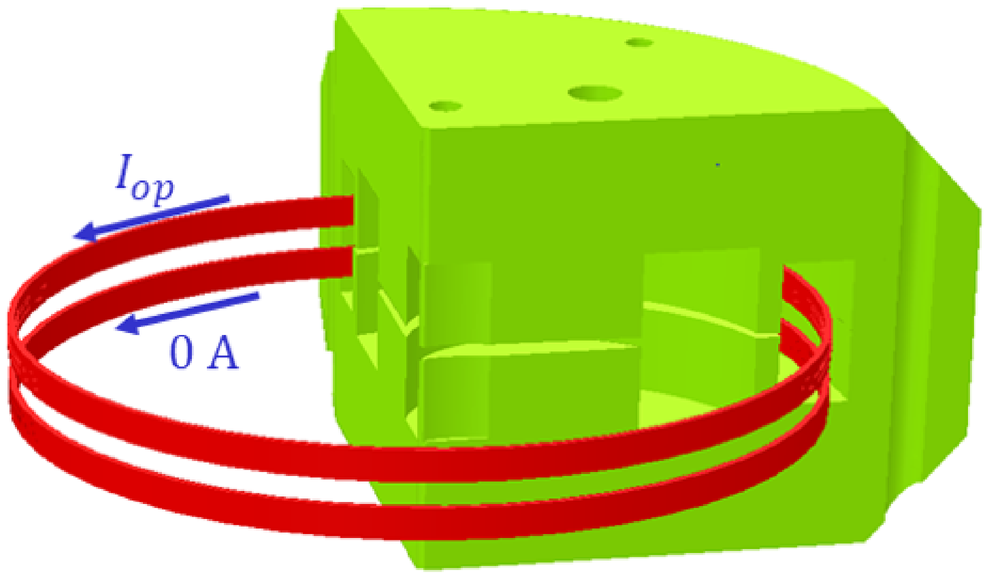
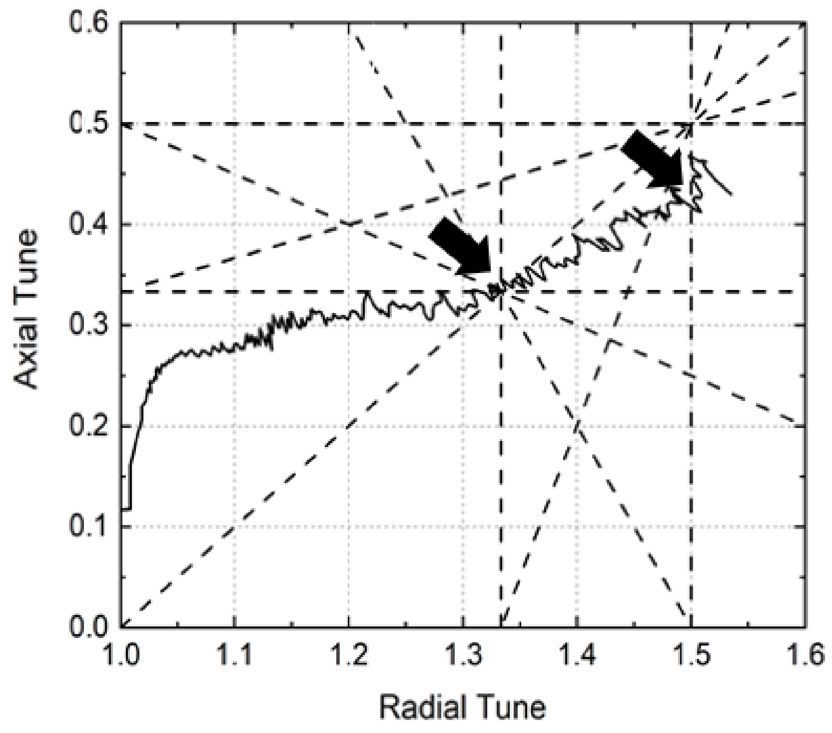
Preliminary design study

- ❖ **Key Concepts: No Insulation (NI) / Multi-Width (MW) / Cryocooling**
- ❖ **Electromagnetic Design: Parameter Sweep for Main Yoke**
- ❖ **Electromagnetic Design: Hill Yoke Design toward isochronous field**
- ❖ **Mech. Analysis with Force Balance Equation: Peak Strain < 0.33 %**
- ❖ **Preliminary Quench Analysis: 168 K Rise, 4.3 MN Unbalanced Fource**

Fig. Quarter model for magnetic simulation



10 MeV to 4620 MeV with 10 MeV interval



IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 30, NO. 4, JUNE 2020 4400705

A Design Study on No-Insulation HTS Isochronous Cyclotron Magnet for Carbon Ion Therapy

Jeonghwan Park, Garam Hahn, Jeseok Bang, Uijong Bong, Kibum Choi, Jung Tae Lee, and Seungyong Hahn

***Abstract*—Provided that a cyclotron system requires DC magnetic field, the no-insulation (NI) high temperature superconductor (HTS) magnet may be a good candidate as it may enable the cyclotron magnet to be more compact and reliable, yet operate under the liquid-helium-free environment. Here we report on a design study on an NI HTS isochronous cyclotron magnet for an acceleration of carbon ion up to an energy level of 385 MeV/u.**

beam; and (3) simplicity to operate magnet by requiring of fixed DC magnetic field.

Encouraged by the recent progress of the no-insulation (NI) high temperature superconductor (HTS) magnet technology [9]–[16], multiple groups have proposed NI HTS magnets, as an alternative of its low temperature superconductor (LTS) coun-

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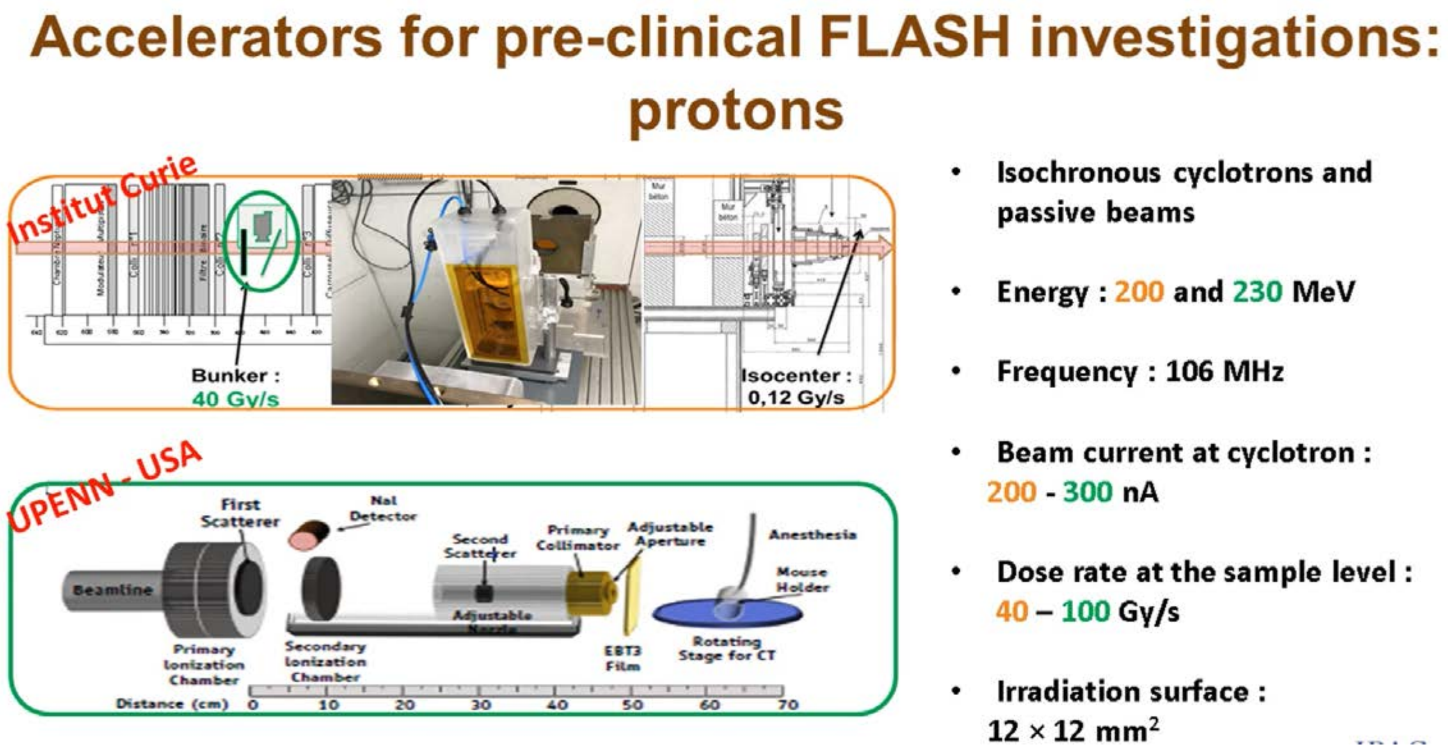
0.3 MW Cyclotron

❖ Good candidate on Flash therapy

❖ Also good candidate on high power injector

❖ First step: Proto-type low energy high current Cyclotron (10 MeV, 1 mA , proton)

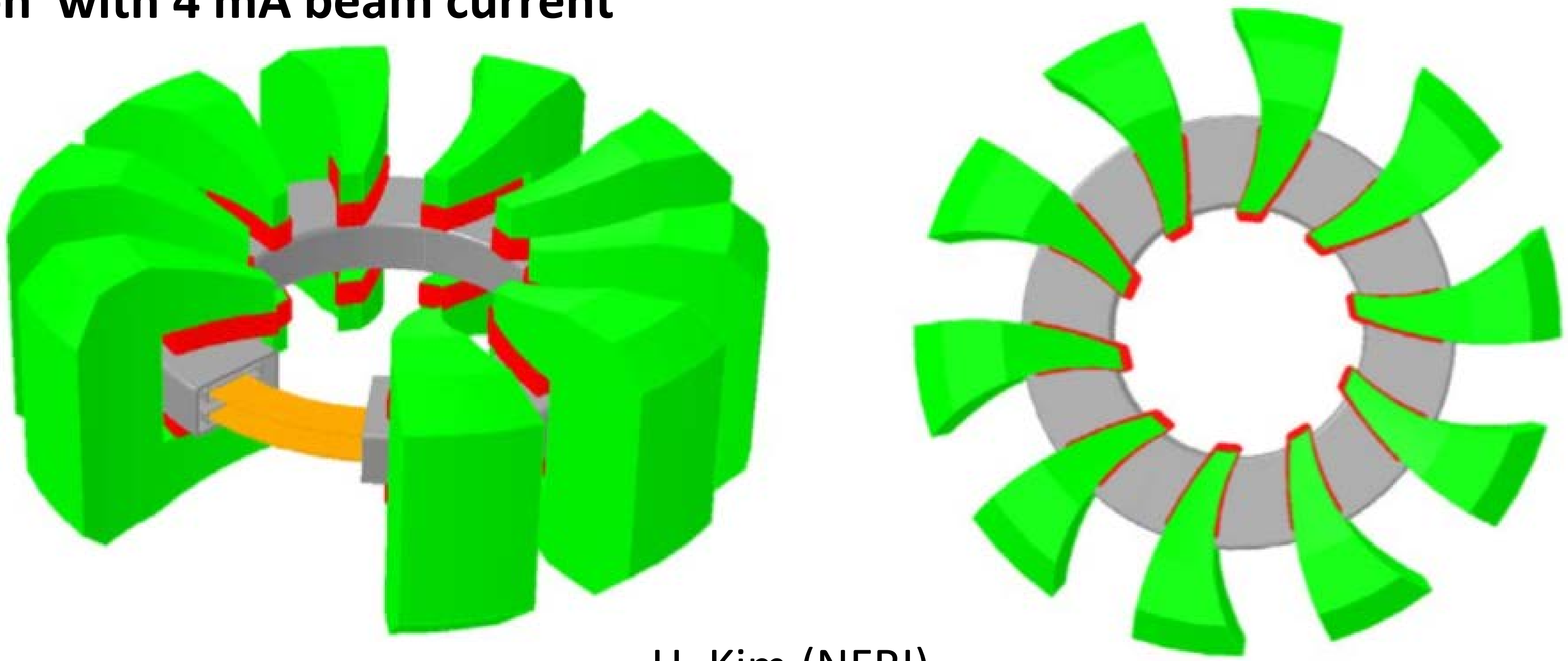
❖ Second step: 0.3 MW cyclotron for Flash therapy as well as injector for ADS



A. Patriarca, Institut Curie, IPAC20

3 MW Cyclotron

- ❖ Third step: 3 MW main cyclotron for ADS
- ❖ Multi layer separated-sector cyclotron by Dr. H. Kim and Prof. J. Chai (SKKU)
  - increasing the maximum beam current by two layers and double frequency RF system (four injector)
  - low cost but high power efficiency
  - 750 MeV Proton with 4 mA beam current



H. Kim (NFRI)

Thank you!