# PHITS

***P**article and **H**eavy **I**on **T**ransport code **S**ystem*

粒子・重イオン輸送コードPHITSの利用


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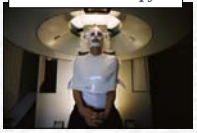
Yukio Sakamoto, Hiroshi Nakashima: JAEA, Japan

Davide Mancusi, Lembit Sihver: Chalmers, Sweden


Title

## Contents







Contents

## *Physical Processes included in PHITS*

- ***Transport*** *between collisions*
  - ***External Field*** *and Optical devices*
    - *Magnetic Field*
    - *Gravity*
    - *Super mirror (reflection)*
    - *Mechanical devices, T0 chopper*
  - ***Ionization process*** *for charge particle*
    - *dE/dx : SPAR, ATIMA code* *(new feature)*
    - *Energy straggling*
    - *Angle Straggling*
- ***Collisions*** *with nucleus*
  - ***Nuclear Data*** *ENDF-B/VI, LA150, …..*
    - *MCNP code,* *+ Event Generator Mode (new feature)*
  - ***Particle Induced Collisions***
    - *JAM code* → *JAMQMD (new feature)*
  - ***Heavy Ion Collisions***
    - *JQMD code*



## *Overview of PHITS (Particle and Heavy Ion Transport code System)*

1951 NMTC (ORNL) ⇒ 1983 NMTC/JAERI High Energy Fission ⇒ 1997 NMTC/JAERI97 CG geometry ⇒ 2001 NMTC/JAM JAM, GG Magnetic Field ⇒ 2003 PHITS JQMD, MCNP Gravity

***PHITS*** *= MCNP + JAM + JQMD*

| | |
|---|---|
| *MCNP* | Neutron, Photon, Electron Transport by Nuclear Data |
| *JAM* | Hadron-Nucleus Collisions up to 200 GeV |
| *JQMD* | Nucleus-Nucleus Collisions by Molecular Dynamics |

***External Field:*** Magnetic Field, Gravity Optical and Mechanical devices

***Language and Parallelism***

- FORTRAN 77
- MPI

***Transport Particle and Energy***

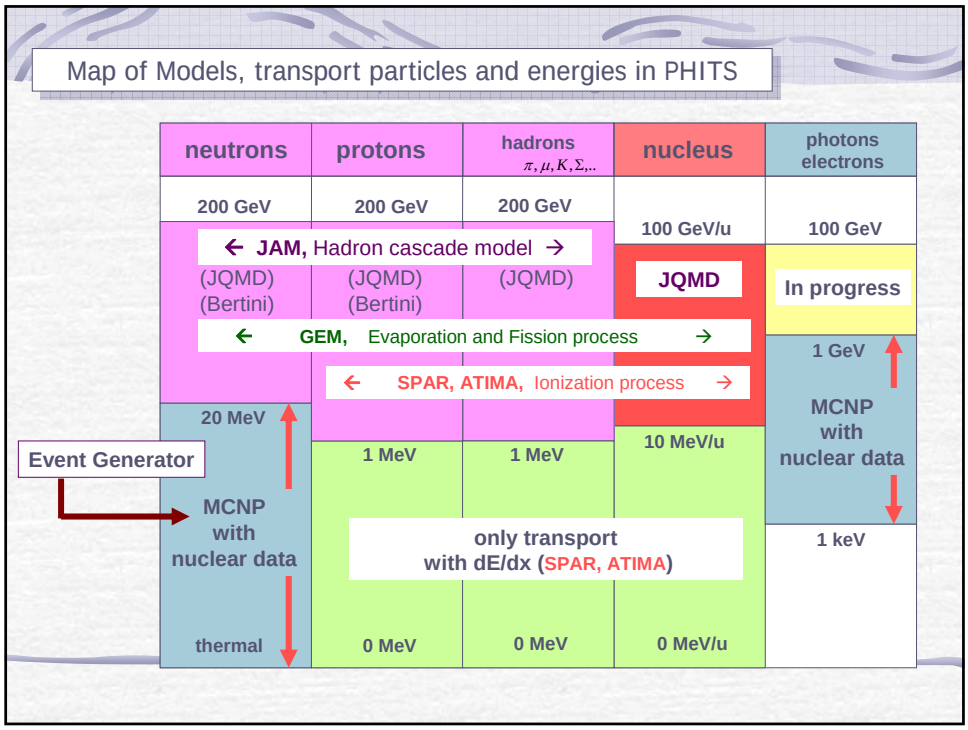
| | |
|---|---|
| Proton | 0 ~ 200 GeV |
| Neutron | $10^{-5}$ eV ~ 200 GeV |
| Meson | 0 ~ 200 GeV |
| Barion | 0 ~ 200 GeV |
| Nucleus | 0 ~ 100 GeV/u |
| Photon | 1 keV ~ 1 GeV |
| Electron | 1 keV ~ 1 GeV |

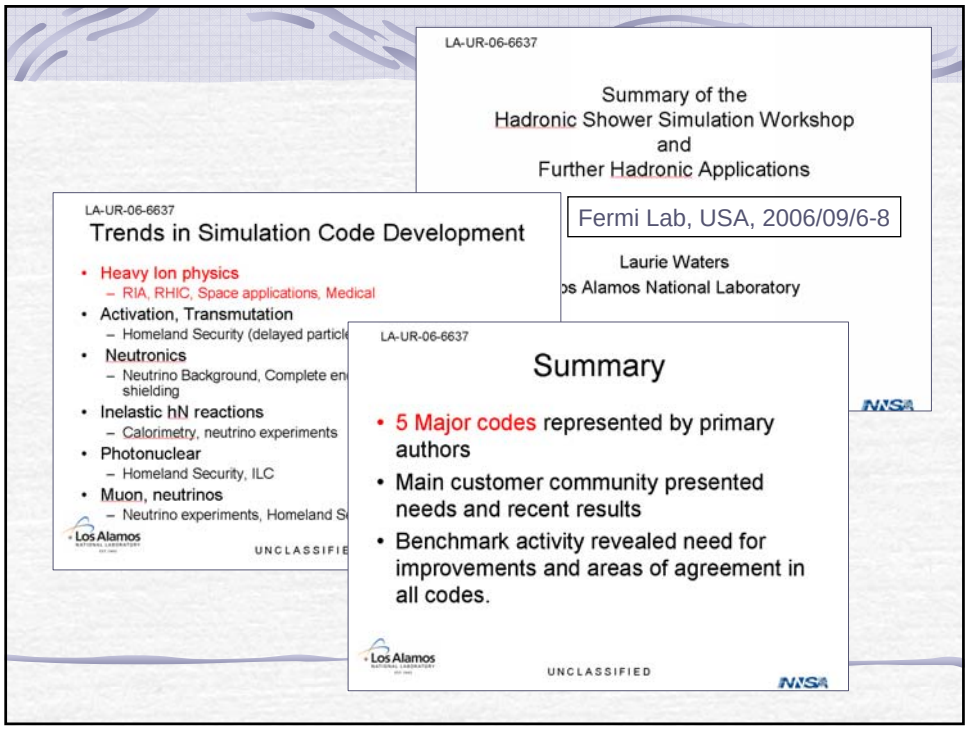
***Geometry:*** CG and GG

***Tally, Mesh and Graphic***

- Tally: Track, Cross, Heat, Star, Time, DPA, Product, LET
- Mesh: cell, r-z, xyz
- Counter:
- Graphic: ANGEL (PS generator)

***PHITS :*** H. Iwase et.al. *J. Nucl. Sci.Technol.* **39** (2002) 1142


Map of Models, transport particles and energies in PHITS
neutrons
protons
hadrons
$\pi, \mu, K, \Sigma, ..$
nucleus
photons
electrons
200 GeV
200 GeV
200 GeV
100 GeV/u
100 GeV
JAM, Hadron cascade model
(JQMD)
(Bertini)
(JQMD)
(Bertini)
(JQMD)
JQMD
In progress
GEM, Evaporation and Fission process
SPAR, ATIMA, Ionization process
1 GeV
MCNP
with
nuclear data
20 MeV
10 MeV/u
Event Generator
1 MeV
1 MeV
MCNP
with
nuclear data
only transport
with dE/dx (SPAR, ATIMA)
1 keV
thermal
0 MeV
0 MeV
0 MeV/u


LA-UR-06-6637
Summary of the
Hadronic Shower Simulation Workshop
and
Further Hadronic Applications
Fermi Lab, USA, 2006/09/6-8
Laurie Waters
Los Alamos National Laboratory
LA-UR-06-6637
Trends in Simulation Code Development
Heavy Ion physics
RIA, RHIC, Space applications, Medical
Activation, Transmutation
Homeland Security (delayed particl
Neutronics
Neutrino Background, Complete en
shielding
Inelastic hN reactions
Calorimetry, neutrino experiments
Photonuclear
Homeland Security, ILC
Muon, neutrinos
Neutrino experiments, Homeland S
Los Alamos
UNCLASSIFIE
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Summary
5 Major codes represented by primary authors
Main customer community presented needs and recent results
Benchmark activity revealed need for improvements and areas of agreement in all codes.
Los Alamos
UNCLASSIFIED
NNSA

## Overview of All-Particle Transport Codes in the World

By G. W. McKinney in FNDA(Fast Neutron Detectors and Applications Conference) April 2006

| General | MCNPX | GEANT4 | FLUKA | MARS | PHITS |
|---|---|---|---|---|---|
| Version | 2.5.0 | 8.0 p1 | 2005 | 15 | 2.09 |
| Lab. Affiliation | LANL | CERN,IN2P3 INFN,KEK,SLAC TRIUMF,ESA | CERN INFN | FNAL | JAEA,RIST GSI Chalmers Univ. |
| Language | Fortran 90/C | C++ | Fortran 77 | Fortran 95/C | Fortran 77 |
| Cost | Free | Free | Free | Free (US Gov.) | Free |
| Release Format | Source & binary | Source & binary | Source & binary | Binary | Source & binary |
| User Manual | 470 pages | 280 pages | 387 pages | 150 pages | 176 pages |
| Users | ~2000 | ~1000 | ~1000 | 220 | 220 |
| Web Site | mcnpx.lanl.gov | cern.ch/geant4 | www.fluka.org | www-ap.fnal.gov/MARS | Under const. |
| Workshops | ~7/year | ~4/year | ~1/year | ~2/year | ~1/year |
| Input Format | Free | C++ main Fixed geometry | Fixed or free | Free | Free |
| Input Cards | ~120 | N/A | ~85 | ~100 | ~100 |
| Parallel Execution | Yes | Yes | No | Yes | Yes |

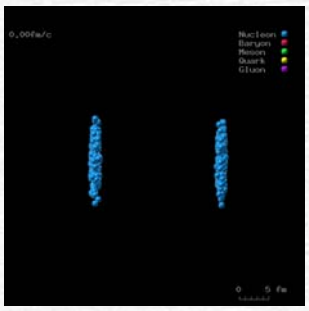
## *JAM code* *for Hadron Nucleus Collisions up to 200 GeV*

***Introducing JAM*** *(Jet AA Microscopic Transport Model)* Y. Nara et.al. *Phys. Rev.* **C61** (2000) 024901

***JAM*** is a ***Hadronic Cascade Model***, which explicitly treats all established hadronic states including resonances with explicit spin and isospin as well as their anti-particles.

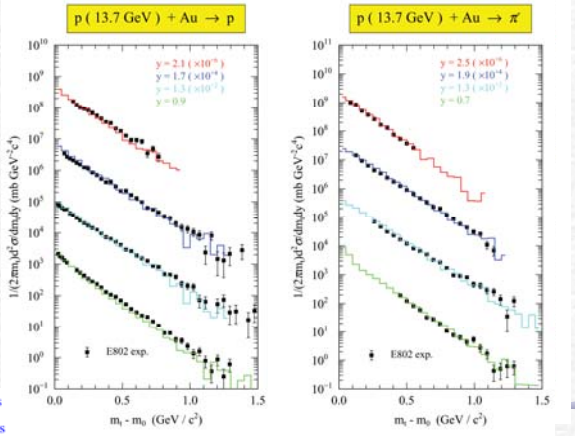
We have parameterized all ***Hadron-Hadron Cross Sections***, based on ***Resonance Model*** and ***String Model*** by fitting the available experimental data.

Au+Au 200GeV/u in cm



119 kinds of Mesons

170 kinds of Baryons




JAM

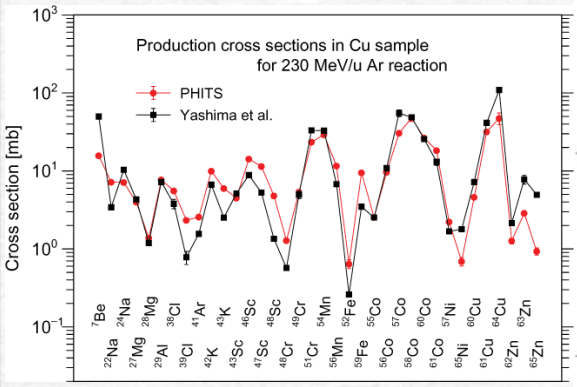
## *JQMD code* *for Nucleus-Nucleus Collisions up to 100 GeV/u*

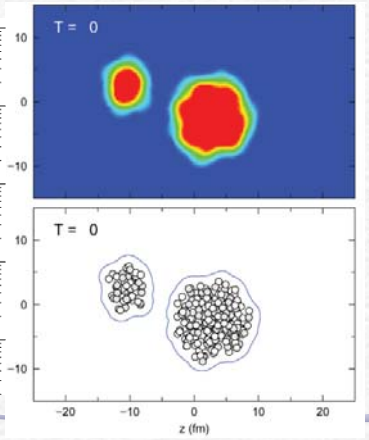
***JQMD*** *(Jaeri Quantum Molecular Dynamics) for Simulation of Nucleus-Nucleus Collisions*

K. Niita et.al. *Phys. Rev.* **C52** (1995) 2620 *http://hadron31.tokai.jaeri.go.jp/jqmd/*

Analysis of Nucleus-Nucleus Collisions by ***JQMD***

$^{56}$Fe 800 MeV/u on $^{208}$Pb

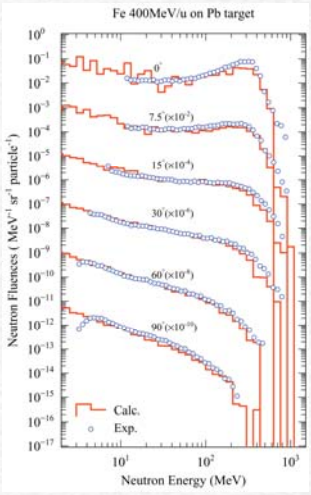


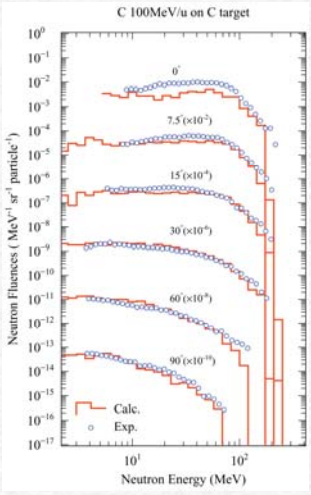




JQMD-1

## Neutron Spectra from Thick Target

***Introducing JQMD in PHITS*** : H. Iwase et.al. *J. Nucl. Sci.Technol.* **39** (2002) 1142




JQMD-2

## *MCNP code* *for Neutron Transport below 20 MeV with Nuclear Data*

***M**onte **C**arlo **N**-**P**article Transport Code System* *developed by Los Alamos National Lab.*

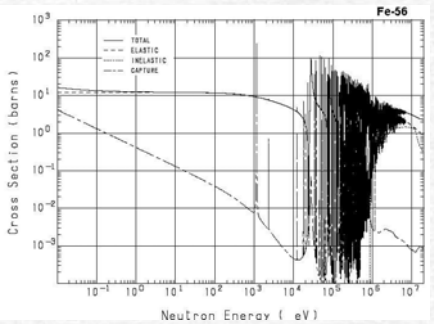
for Neutrons, Photons, Electrons

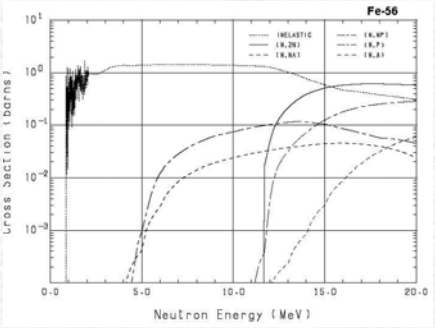
by using Evaluated Nuclear Data, such as **ENDF, JENDL, …**

Applications:

Nuclear Criticality Safety, Radiation Shielding, Fission Reactor Design, …

n-56Fe Reaction Cross Sections




MCNP

## *(2) Application Fields of PHITS*

- **Accelerator**
  - **Spallation Neutron Source (J-PARC)**
    Target design, Beam loss, Heat, DPA, Shielding design, ……
  - **Neutron Optics (J-PARC)**
    Signal-to-background ratio, Shielding design
  - **RIA, GSI, RIKEN,**
    High intense Heavy Ion Accelerator Facilities,
    Heat, DPA, Beam loss, Shielding design, ……
- **Cancer Therapy**
  BNCT (neutron), Proton therapy, Heavy-Ion therapy
- **Space Technology**
  Damage and Shielding by Cosmic Ray,
  Atmospheric Cosmic-Ray
- **Semiconductor Soft Error**
  Secondary Charged Particle and Recoiled Nuclei

Applications

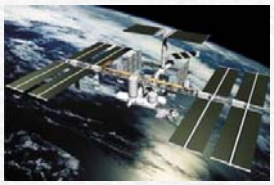
## *Application Fields of* PHITS

**Accelerator**

J-PARC
Spallation Neutron Source
Neutron Optics
Heavy Ion Facilities

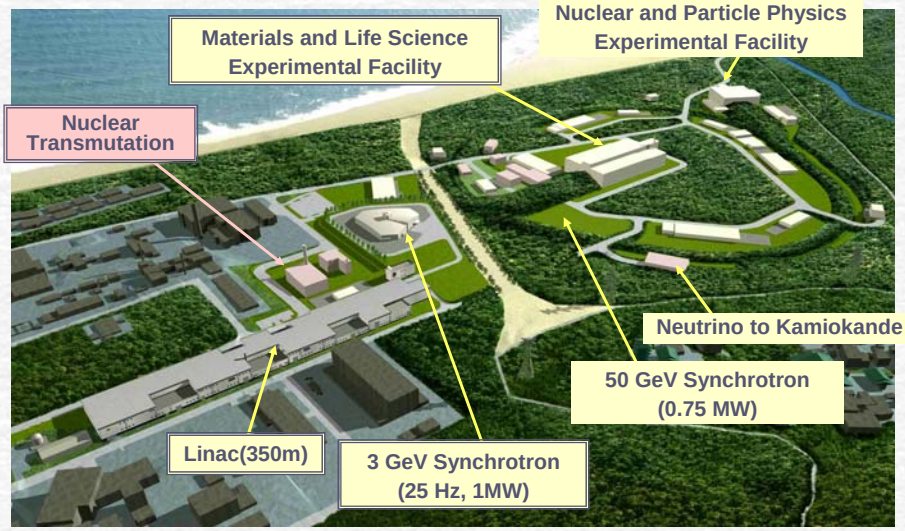
**Cancer Therapy**

**Space Technology**



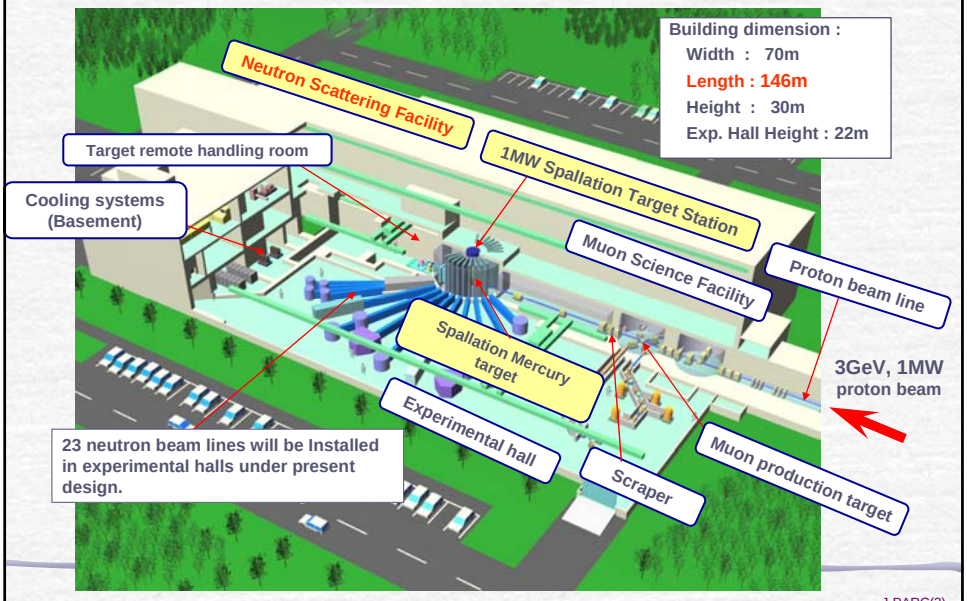
Application (1)

## J-PARC = Japan Proton Accelerator Research Complex




J-PARC(1)

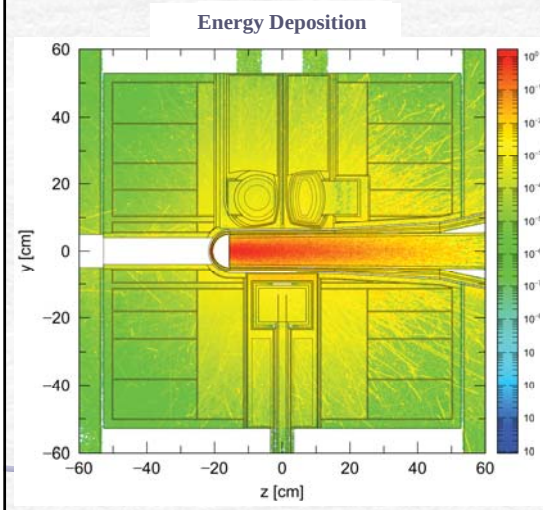
## Materials and Life Science Experimental Facility

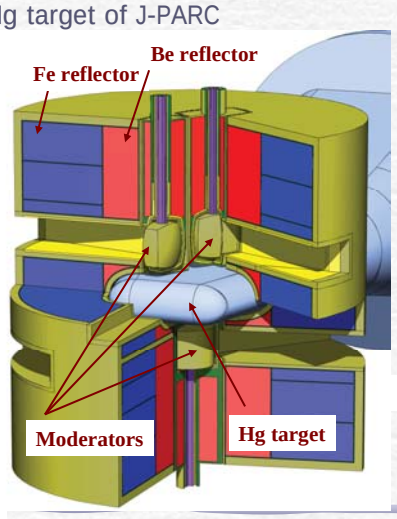



J-PARC(2)

## Spallation Neutron Source in Proton Accelerator Facilities

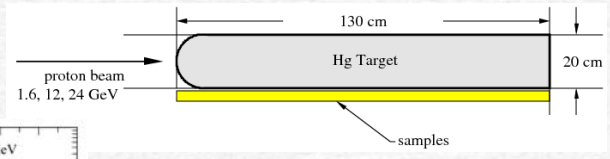
PHITS has been extensively used for
Optimization and Shielding design around Hg target of J-PARC

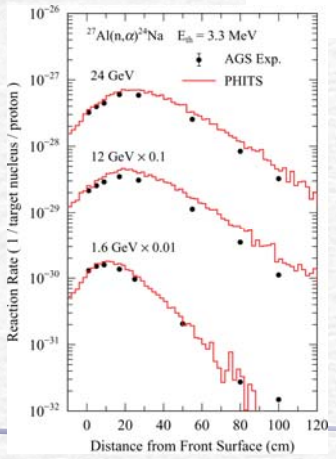


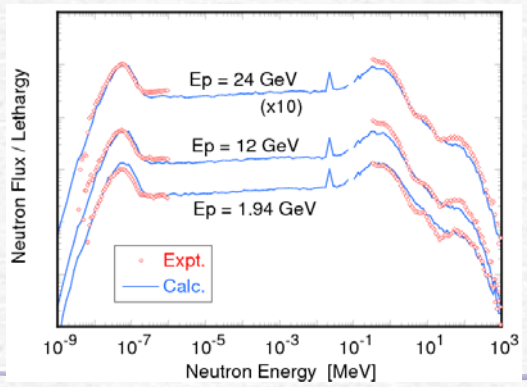




Spallation (2)

## AGS Benchmark Experiments for Spallation Neutron Source



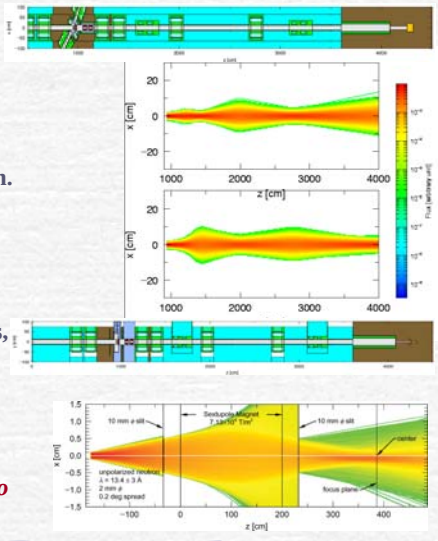




AGS

## *Functions of PHITS for Beam transport*

- **Charged particles and Heavy ions**
  - Dipole and Quadrupole Magnetic field
- **Low energy neutrons**
  - Dipole, Quadrupole and Sextupole Magnetic field coupled with neutron spin.
  - Pulse (Time dependent) Magnetic field
  - Optical devices; Supper mirror
  - Mechanical devices; T0 chopper, ….
  - Gravity

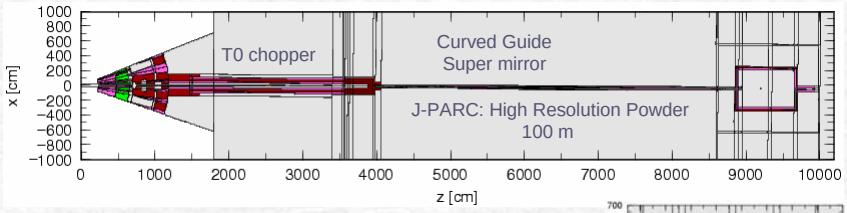


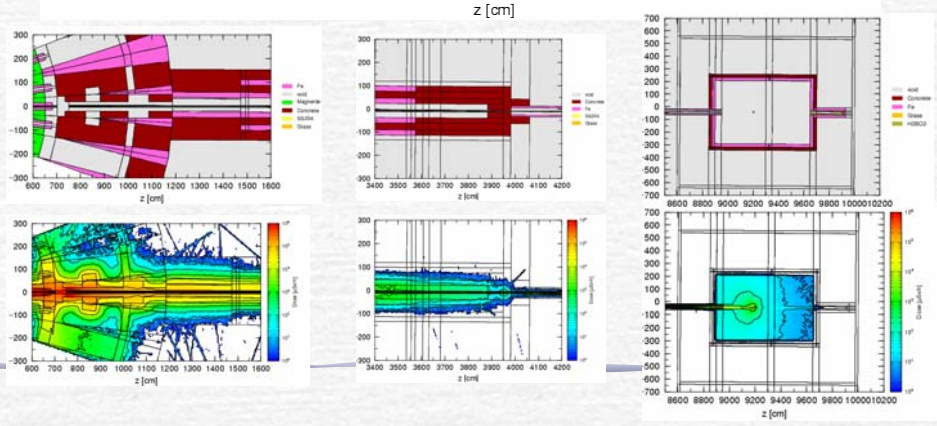
- PHITS can simulate not only the trajectories, but also the collisions and the ionization at the same time.
- ***PHITS can estimate the radiation damage of the magnets and the surroundings, and shielding as well as signal-to-background ratio in neutron beam line.***



Summary of Accelerator

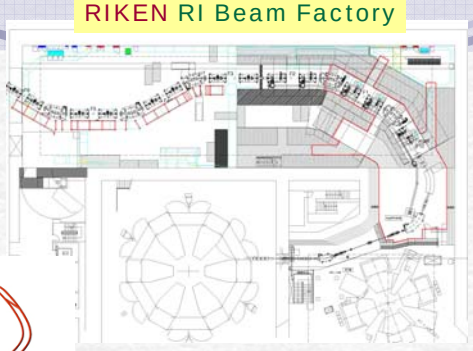
## *Neutron long beam line calculation : Neutron Optics*



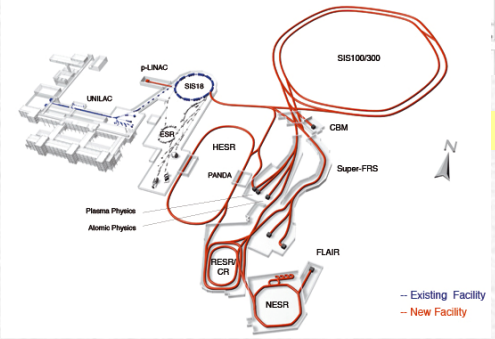



## *PHITS for High Intensity Heavy Ion facilities*

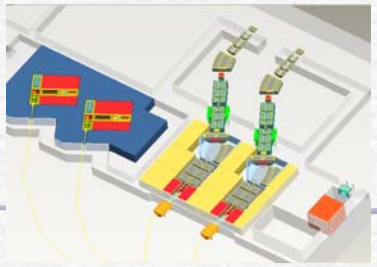
RIKEN RI Beam Factory



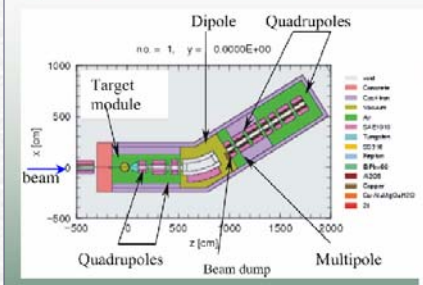
GSI FAIR : Super-FRS facility

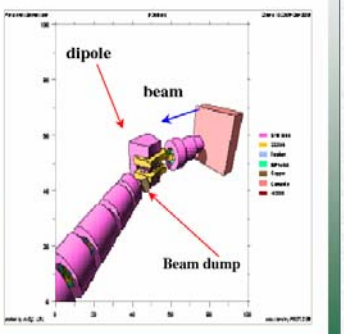



RIA Beam production area



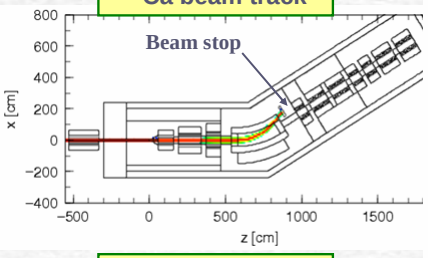
## Fragmentation Pre-Separator in PHITS (Inseok Baek, NSCL/MSU)



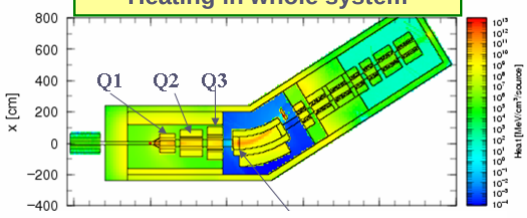




## RIA Beam production area

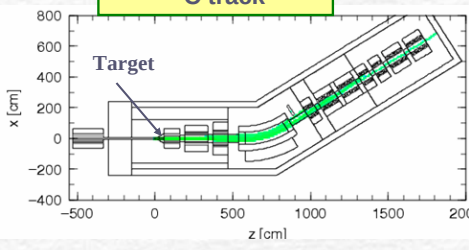
### $^{48}$Ca beam track



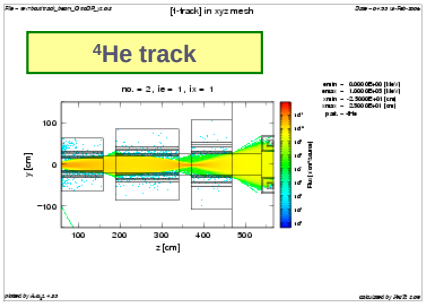

### Heating in whole system



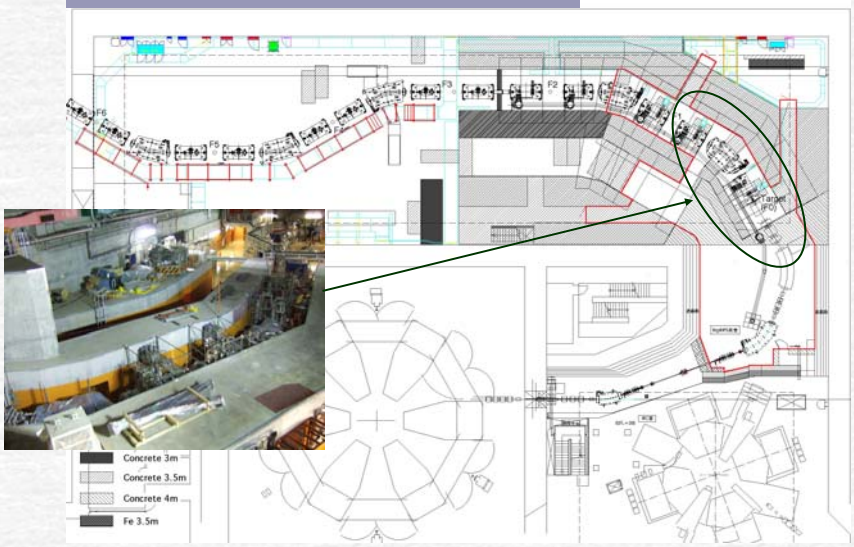

### $^{22}$C track




### $^{4}$He track



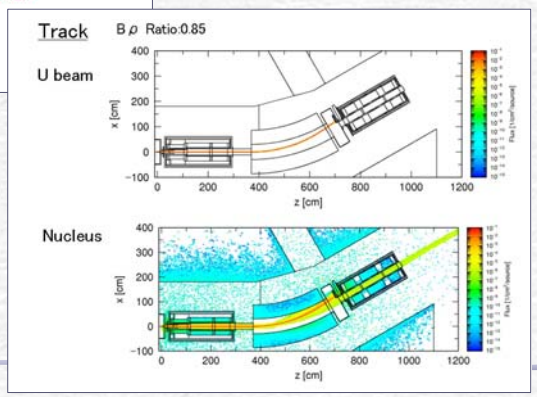
## RIKEN RIBF: RI Beam Factory




## PHITS Simulation for BigRIPS

2006/5 Expert-Meeting at RIKEN
BigRIPS Team

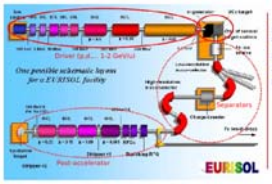
1. Heat load
2. Radiation damage
3. DPA



dapnia
cea
saclay

EURISOL Design Study

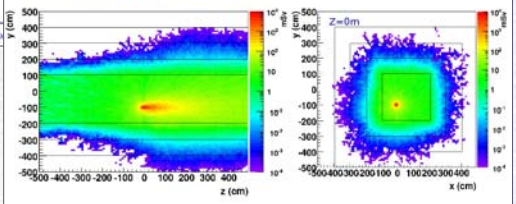
## First calculation of post-accelerator shielding with PHITS code




RAPP Benjamin CEA/DSM/DAPNIA/SPhN Join SAFERIB/Task 5 meeting, October 200

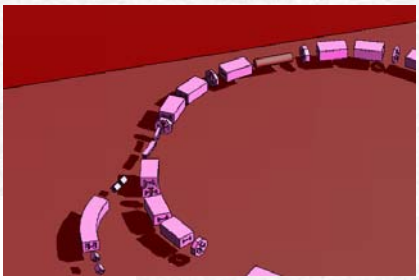
### Dose map

Dose given by a total beam loss of 1 second
(Sn132 beam, 100 MeV/a, Intensity = 1 µA)

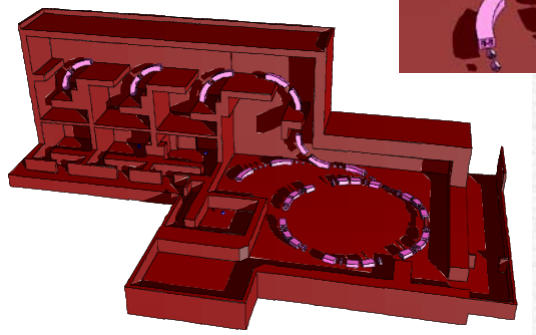



RAPP Benjamin CEA/DSM/DAPNIA/SPhN Join SAFERIB/Task 5 meeting, October 2006 5

## *PHITS for Shielding of Carbon Therapy Facilities*

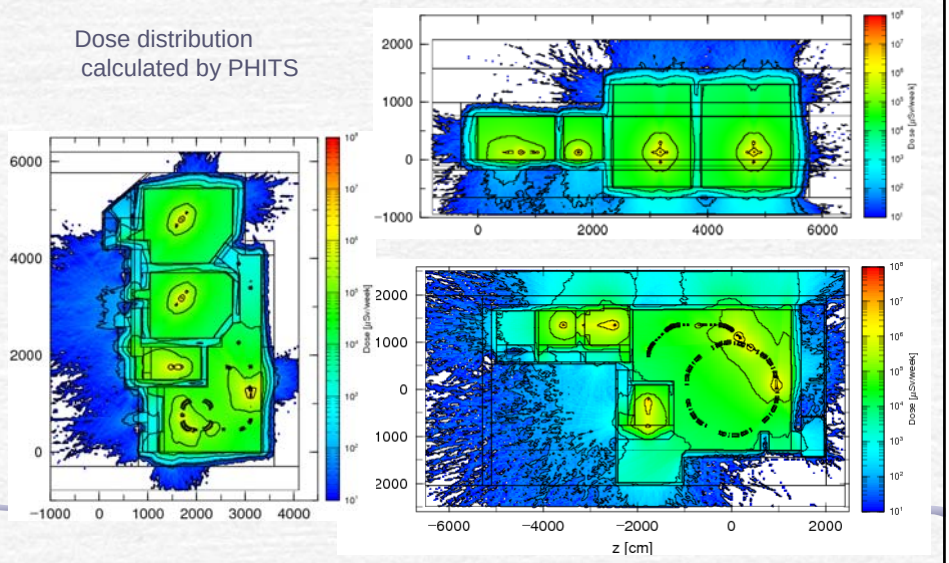


3D view by PHITS



## Shielding of Proton and Carbon therapy facilities

Dose distribution
calculated by PHITS



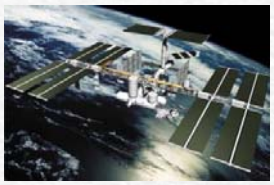

## *Application Fields of* PHITS

**Accelerator**

**Cancer Therapy**

BNCT
Proton and
Heavy Ion Therapy

**Space Technology**

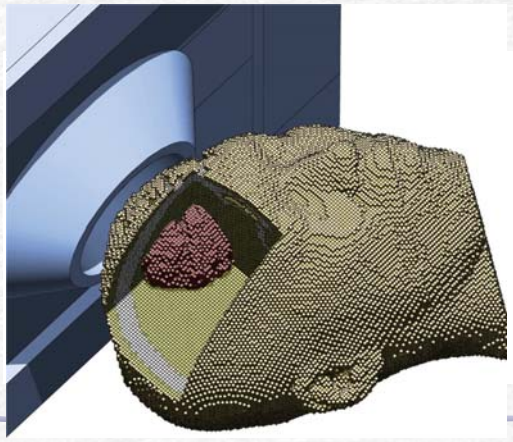


## *JCDS (Jaeri Computational Dosimetry System) for BNCT*

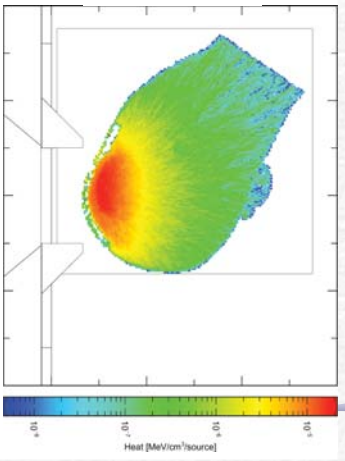
**Boron Neutron Capture Therapy at Dept. Research Reactor, JAERI**

***JCDS* creates the Voxel data from CT and MRI data for MCNP ( PHITS ) calculation.**

3D view by PHITS



Dose distribution




BNCT

## *Event Generator Mode of PHITS*

How to estimate the deposit energy of charged particles and nuclei for neutron transport below 20 MeV

| MCNP type | ⟺ | PHITS |
|---|---|---|
| Transport based on Boltzmann equation with nuclear data | | Event Generator Mode with nucleus transport |
| Local Approximation (Kerma factor) | | Energy Deposition in event by event |
| Average Values | | Deposit energy distribution |

This assumption is not valid for :

- Size of system is smaller than Range of charged particles
- Distribution is necessary instead of average value

Energy is conserved in average
No correlation

↓

**Only one-body observables**

Treat all ejectiles of collisions.
Energy and Momentum are conserved in each collision.

↓

**Any observables**
**Beyond one-body observables**

Event Generator Mode

## *Event Generator Mode for low energy neutrons in PHITS*

Neutron data + Special Evaporation Model

We use the channel cross sections and neutron energy spectrum of the first neutron and assume the binary decay of recoiled nucleus.

| | | | |
|---|---|---|---|
| **Neutron channels** | **capture** | $\Gamma_n = 0$ | charged particle and photon decay |
| | **elastic** | | final state is uniquely determined |
| | **(n,n')** | $\Gamma_n = 0$ | charged particle and photon decay after the first neutron emission |
| | **(n,Nn')** | $\Gamma_n \neq 0$ | all particle and photon decay after the first neutron emission |

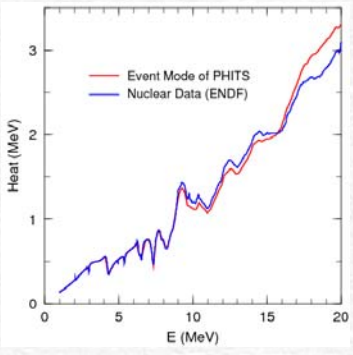
By this model, we can determine all ejectiles (neutrons, charged particles, nucleus and photons) with keeping energy and momentum conservation.

PHITS can transport all charged particle and nucleus down to zero energy and estimate deposit energy without local approximation (kerma factor).

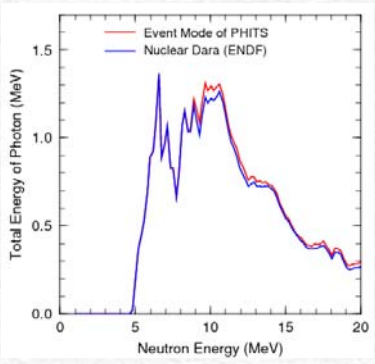


## *Validation of Event Generator Mode*

C target, Inclusive



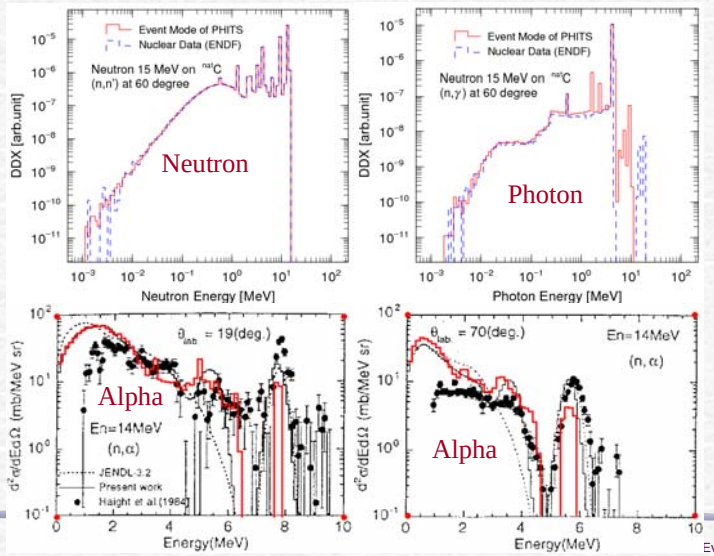

Total energy of charged particles
( kerma factor )




Total energy of Photon

## *Validation of **Event Generator Mode***

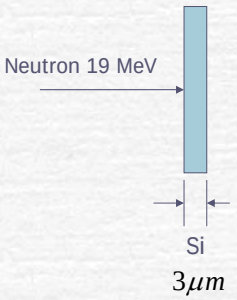
C target, DDX



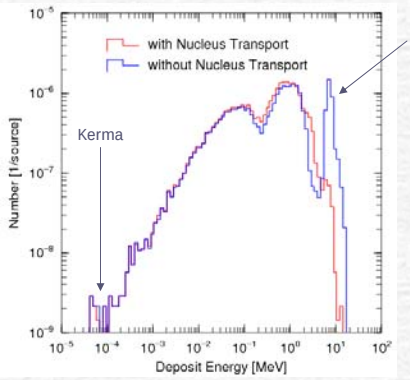



## *An example of **Event Generator Mode***

Neutron-induced semiconductor soft error
SEU: single event upset



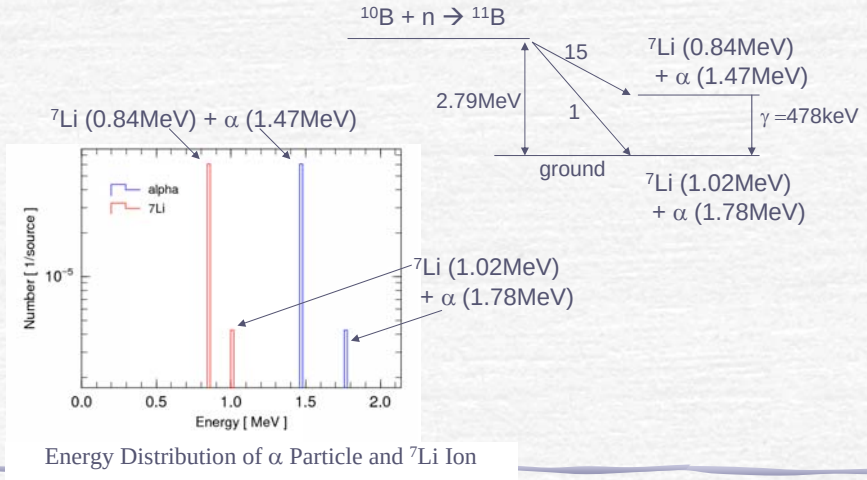

Deposit Energy Distribution by PHITS




Leakage of recoil nucleus from Si

## *Microdosimetric Treatments of BNCT*

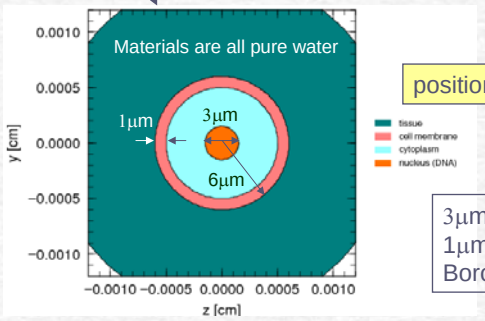
***Event Generator Mode*** = treat all ejectiles with energy and mom. conservation




Energy Distribution of α Particle and $^{7}$Li Ion after $^{10}$B (n,α) $^{7}$Li capture reaction

## Microscopic Toy Model for BNCT

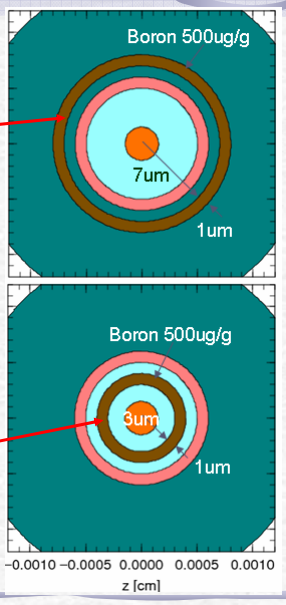
6μm radius spherical cell, 3μm nucleus (target region), all material is pure water

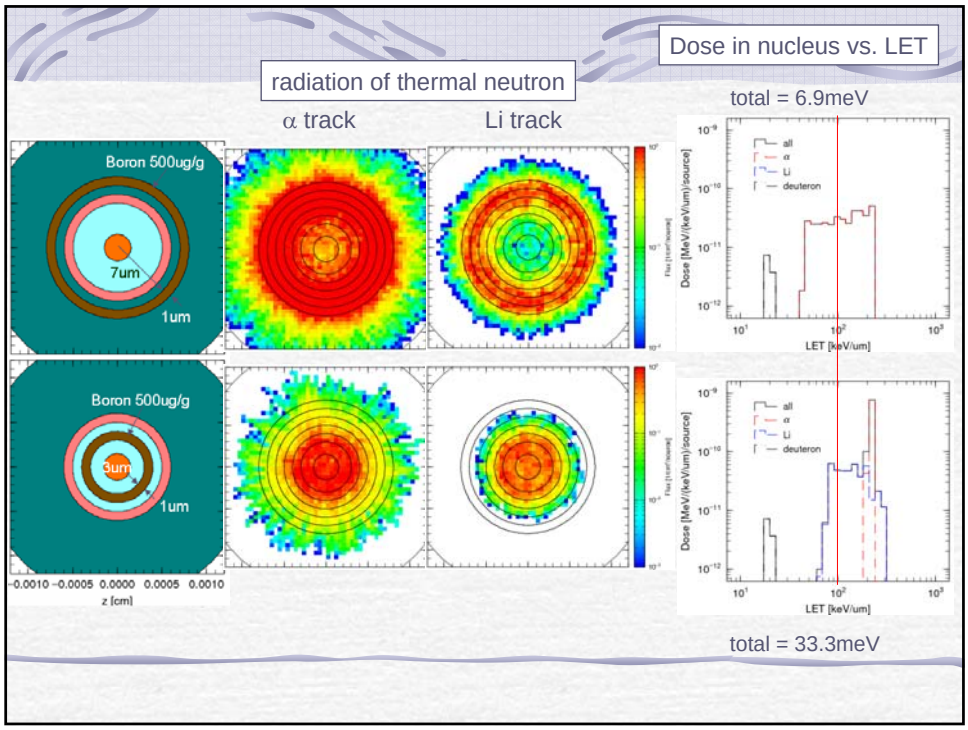


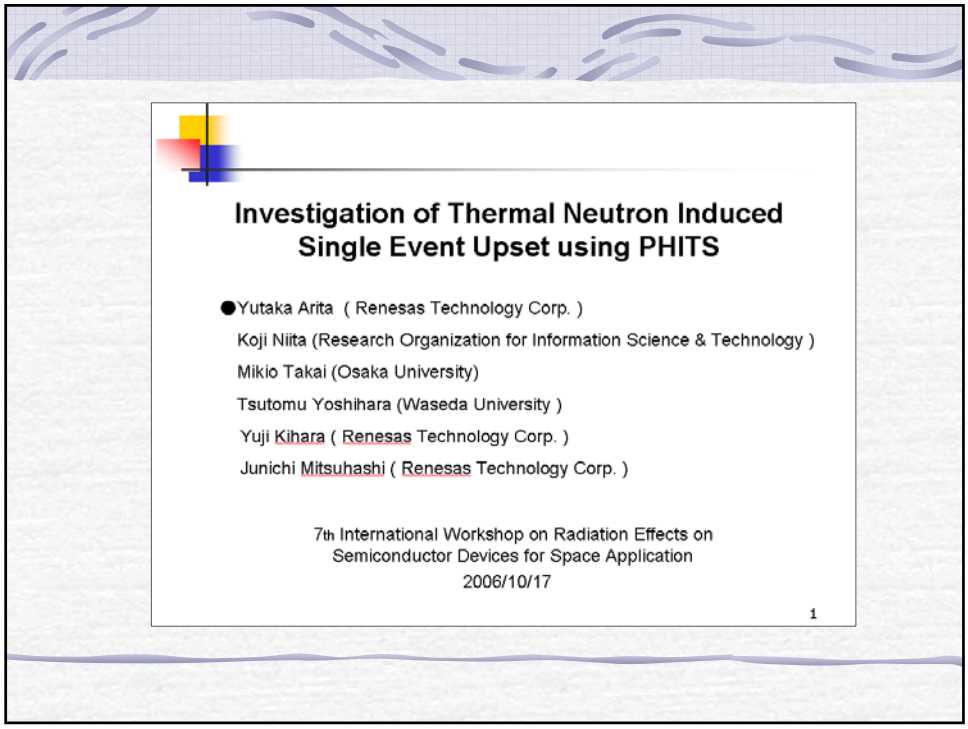

position of $^{10}$B

7μm radius, 1μm thickness Boron 500μg/g

3μm radius, 1μm thickness Boron 500μg/g





## Investigation of Thermal Neutron Induced Single Event Upset using PHITS


●Yutaka Arita ( Renesas Technology Corp. )

Koji Niita (Research Organization for Information Science & Technology )

Mikio Takai (Osaka University)

Tsutomu Yoshihara (Waseda University )

Yuji Kihara ( Renesas Technology Corp. )

Junichi Mitsuhashi ( Renesas Technology Corp. )



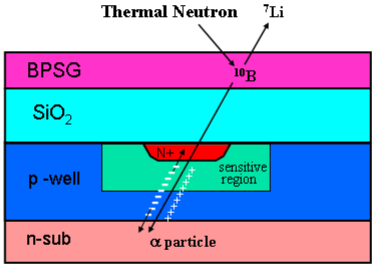
7th International Workshop on Radiation Effects on Semiconductor Devices for Space Application

2006/10/17


1

## Background

- Thermal neutron induced Single Event Upset (SEU)

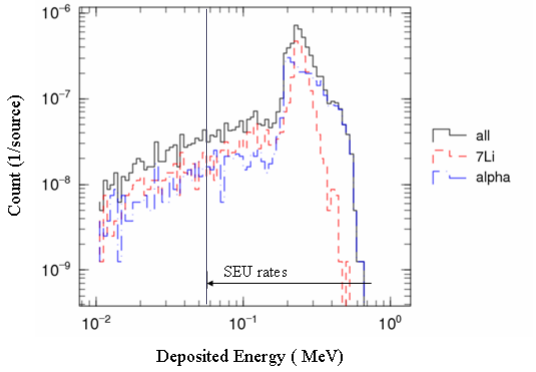



- Process technology < 0.25 μm
- Thermal Neutron + $^{10}$B⟶ α (1.48 MeV) + $^{7}$Li (840 KeV)
- Electrons are collected to N+ region by drift current and/or by diffuion current

3

## Result of simulation

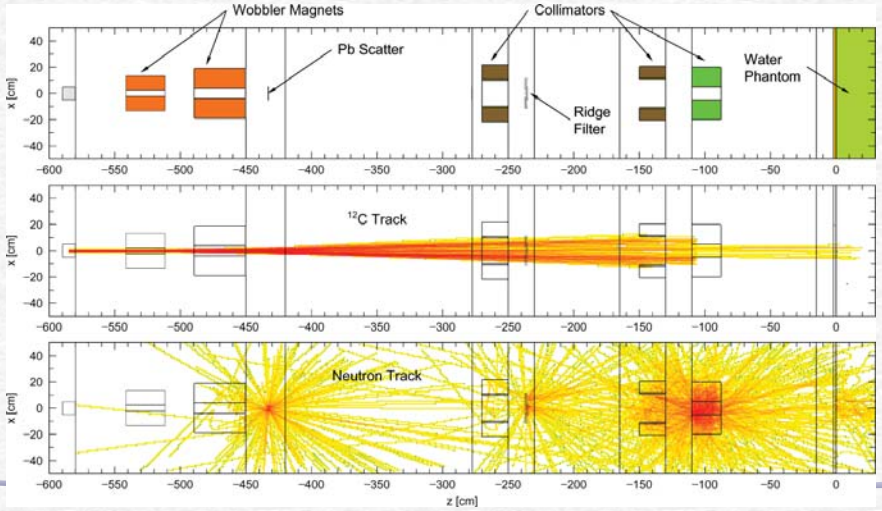
- Deposit energy of α particle and $^{7}$Li in sensitive region




13

## *Heavy Ion Therapy by HIMAC in NIRS (1)*

Design study of small size carbon therapy system
Compact size ⇒ transverse distribution ⇒ 3D Monte Carlo simulation ⇒ **PHITS**

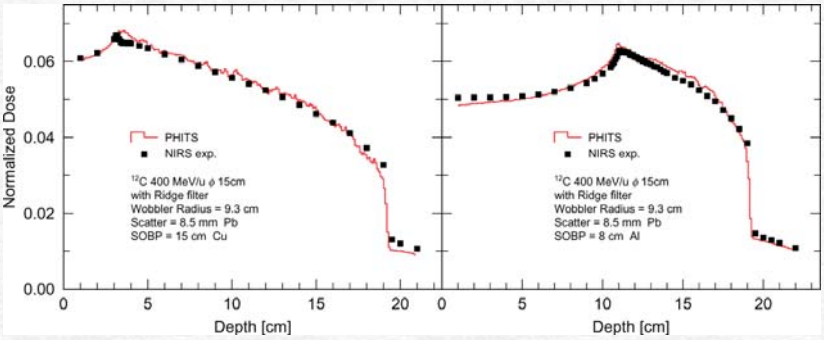





## *Heavy Ion Therapy by HIMAC in NIRS (2)*

Dose distributions in the water phantom with Wobbler magnet, Scatter, and Ridge filter.

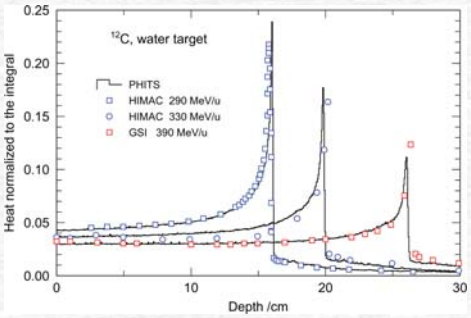
Transverse and Longitudinal distribution of dose in the water phantom can be well reproduced by 3D Monte Carlo calculation of PHITS.

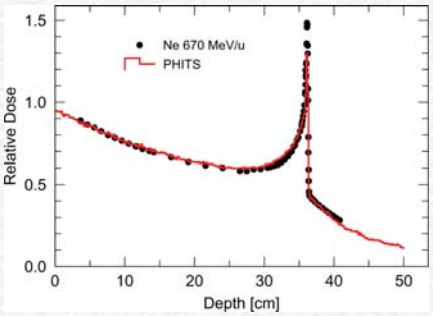



H. Nose et.al., *J. Nucl. Sci. Technol.*, **42** (2005) 250

## Benchmark Test of Bragg Peak

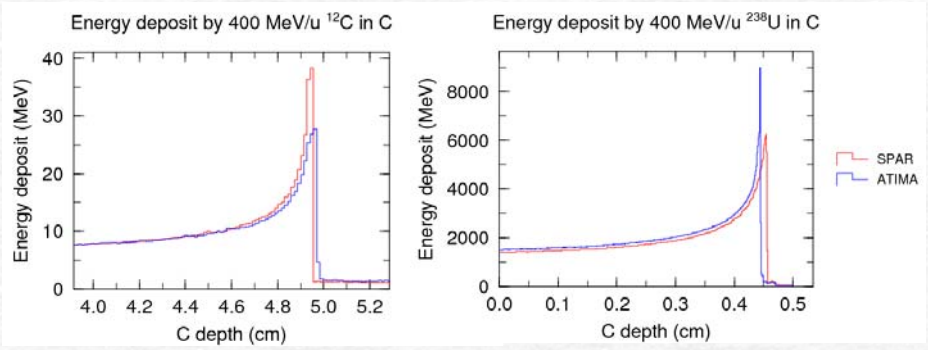
Depth Dose Distribution in Water Phantom



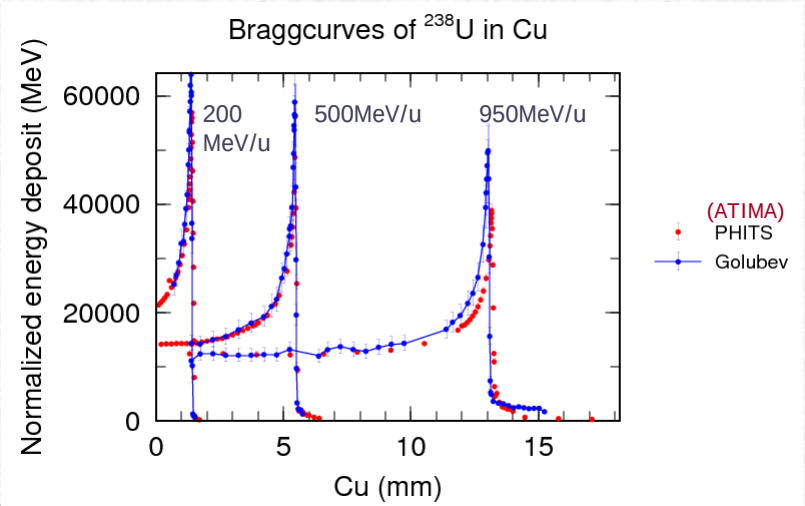




Bragg Peak

## Benchmark Test of Bragg Peak with SPAR and ATIMA

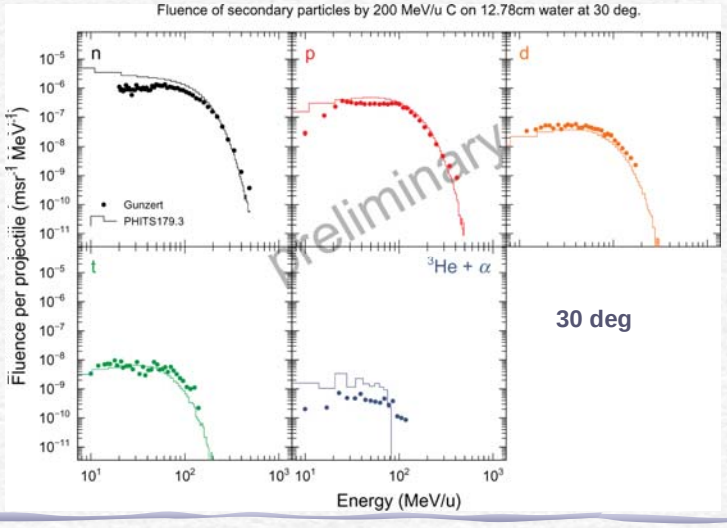



SPAR and ATIMA



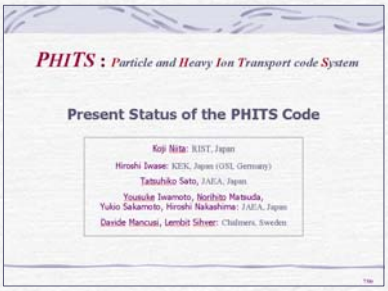

## Secondary Particles Production Cross Section

From 200 MeV/u Carbon beam on 12.78 cm depth Water




Fluence

"The Japan Taiwan Symposium on Simulation in Medicine"
Tsukuba, Japan, 2006/12/13-14


PHITS : Particle and Heavy Ion Transport code System

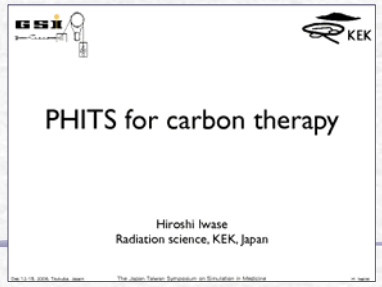
Present Status of the PHITS Code

Koji Niita: RIST, Japan
Hiroshi Iwase: KEK, Japan (GSI, Germany)
Tatsuhiko Sato, JAEA, Japan
Yousuke Iwamoto, Norihito Matsuda,
Yukio Sakamoto, Hiroshi Nakashima: JAEA, Japan
Davide Mancusi, Lembit Sihver: Chalmers, Sweden

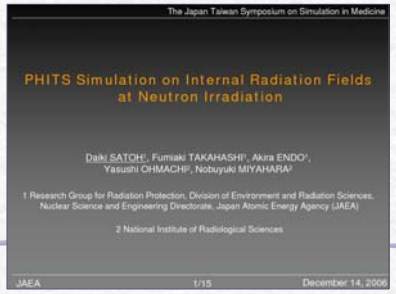

Dose Analysis of Small Size Cancer Therapy System with PHITS code

Hiroyuki Nose[1),5)],
Koji Niita[2)], Masataka Komori[3)], Nobuyuki Haruna[4)],
and Tatsuaki Kanai[1),5)]

1) Ishikawajima-Harima Heavy Industries Co., Ltd.
2) Research Organization for Information Science and Technology
3) National Institute of Radiological Sciences
4) Osaka University
5) Tokyo Institute of Technology


PHITS for carbon therapy

Hiroshi Iwase
Radiation science, KEK, Japan


The Japan Taiwan Symposium on Simulation in Medicine

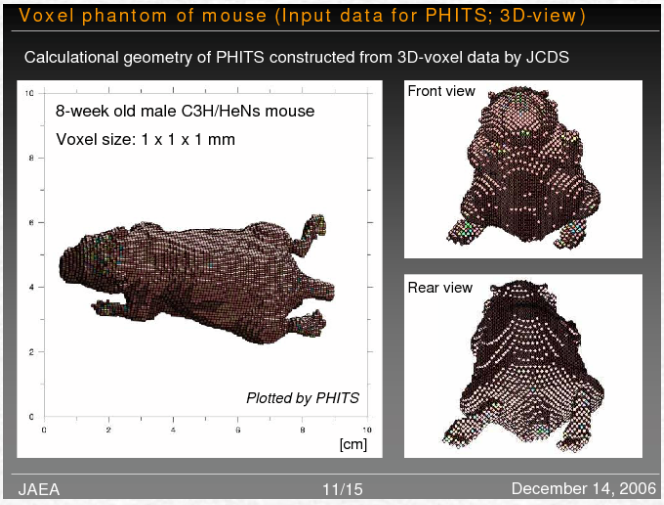
PHITS Simulation on Internal Radiation Fields at Neutron Irradiation

Daiki SATOH[1], Fumiaki TAKAHASHI[1], Akira ENDO[1],
Yasushi OHMACHI[2], Nobuyuki MIYAHARA[2]

1 Research Group for Radiation Protection, Division of Environment and Radiation Sciences, Nuclear Science and Engineering Directorate, Japan Atomic Energy Agency (JAEA)

2 National Institute of Radiological Sciences

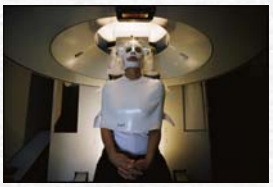
JAEA 1/15 December 14, 2006



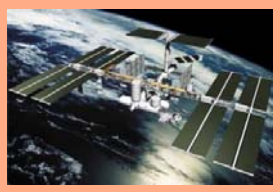
## *Application Fields of PHITS*

**Accelerator**

**Cancer Therapy**



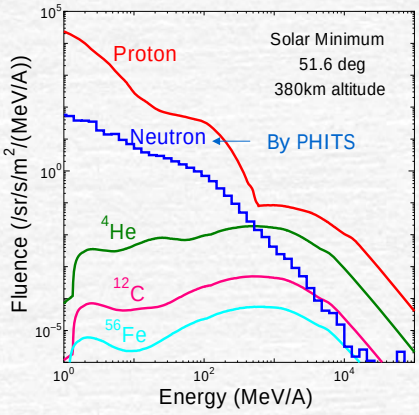
**Space Technology**



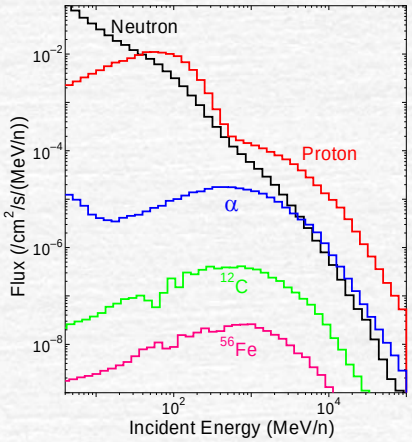
Dose in Space Shuttle
Atmospheric Cosmic-Ray



## Space Radiation



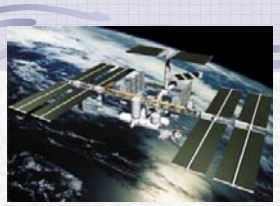

Spectra outside spacecraft
by CREME96




Spectra inside spacecraft
by PHITS

by T. Sato

## Space Radiation

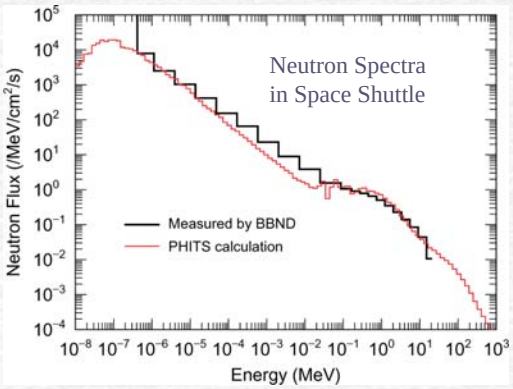


Dose estimation in Space Shuttle ⟸ Galactic Cosmic Ray

- High energy proton, Heavy Ion (Z<28)
  Trapped Proton
- Proton, Heavy Ion Transport,
  Neutron produced by Shuttle
  and Atmosphere of Earth
  (Albedo neutron)

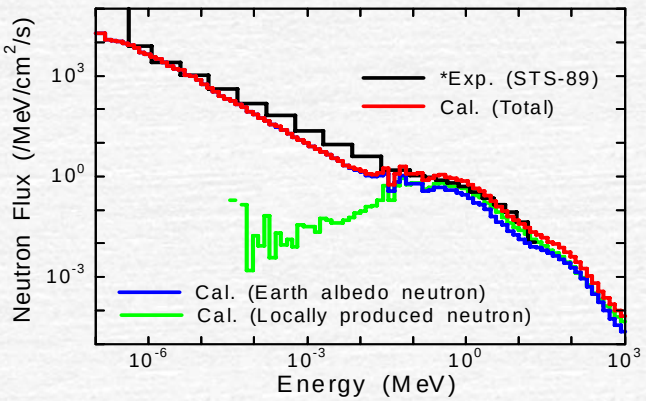
**PHITS calculation**

**PHITS can simulate**
**Heavy Ion transport and**
**low energy Neutron in 3D Geometry**



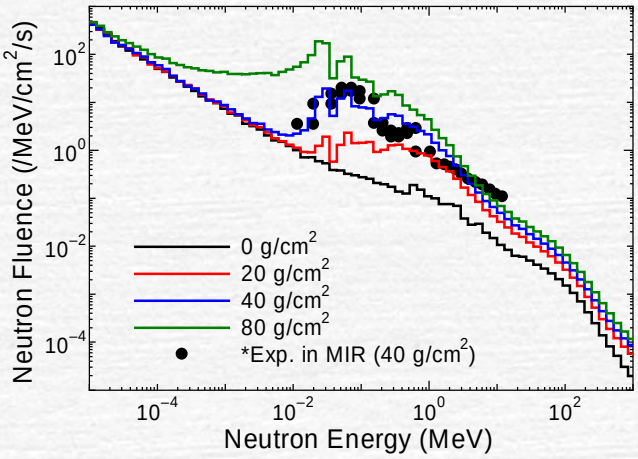

T. Sato et.al. *Radiat. Meas.* **41** (2006) 1142






Neutron Spectra inside Space Shuttle

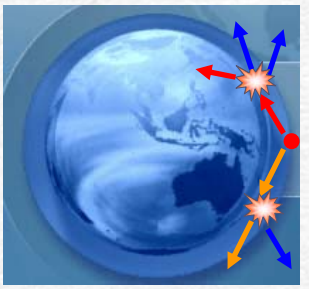
by T. Sato



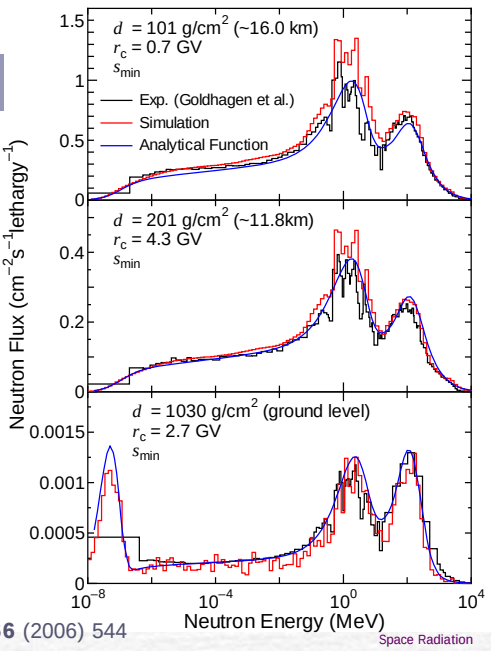

Neutron Spectra inside Cylindrical Shell

by T. Sato

## Neutron spectrum in atmosphere



CREME96
+
PHITS with JENDL-HEfile

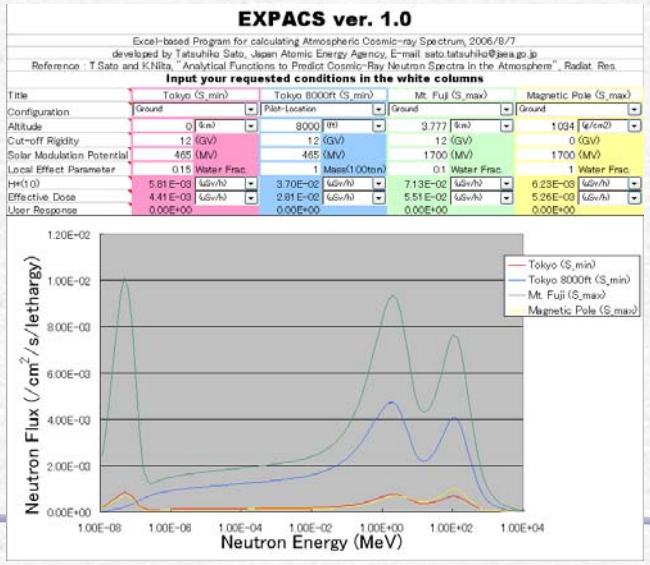



T. Sato and K. Niita, *Radiat. Res.*, **166** (2006) 544

Space Radiation

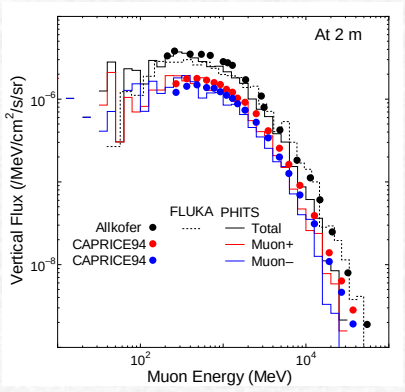
## EXPACS : *Excel-based Program for calculating Atmospheric Spectrum*

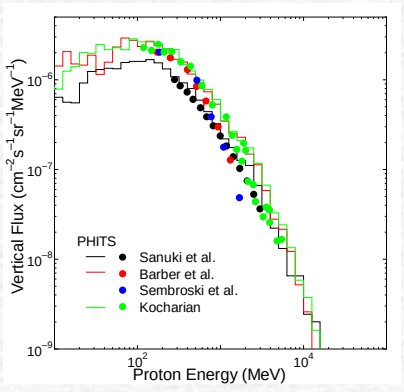
http//www3.tokai-sc.jaea.go.jp/rphpwww/radiation-protection/expacs/expacs.html



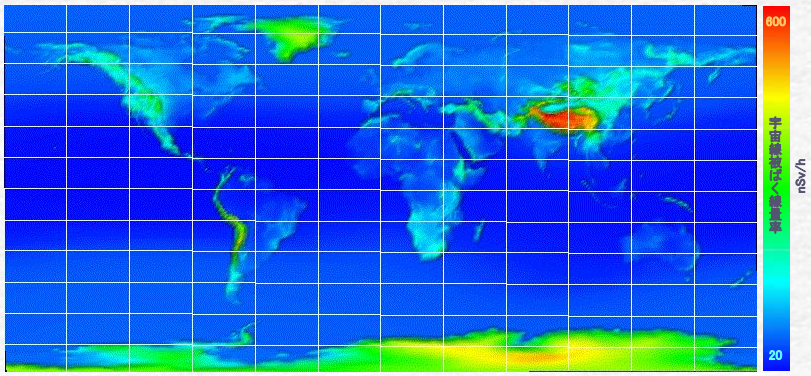

by T. Sato

## Muon and Proton Spectra on the earth




by T. Sato

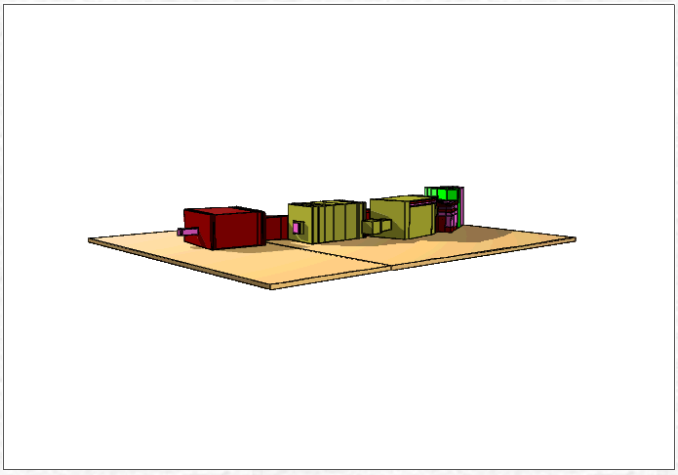



2006年6月の地表面における宇宙線被ばく線量率マップ
標高の高いチベット高原や，磁極に近いグリーンランドや南極で線量率が高くなる

by T. Sato

## *User Interfaces of* PHITS

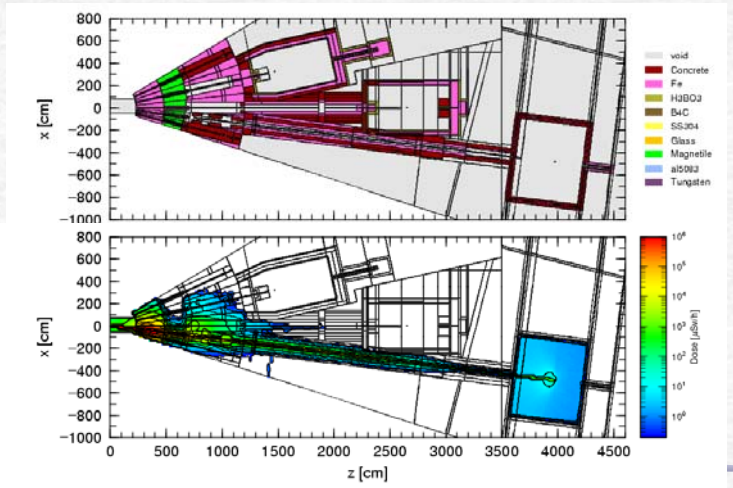
**3D view of the calculation model**



Utilities (1)

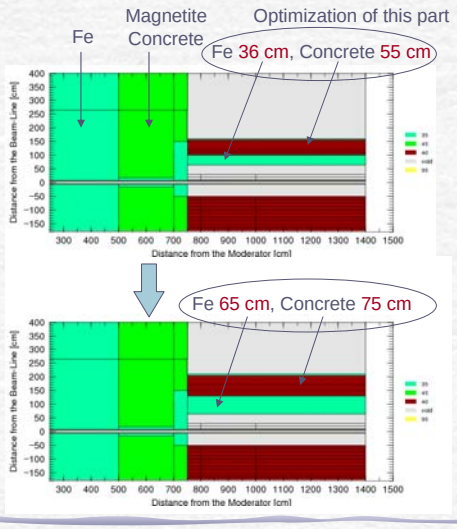
## *User Interfaces of* PHITS

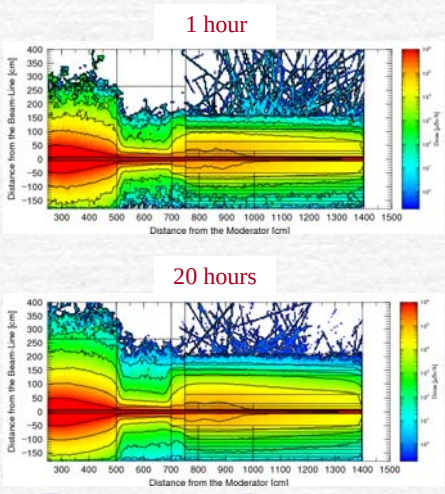
**2D view and 2D output of the final results by color clusters and contour plots with geometry**






**2D output of the intermediate results of a certain interval of histories. This function is very powerful for optimization study !!!**



## *Present and Future of PHITS*

### *Typical Features of the present PHITS code.*

- Heavy Ion transport ( JQMD and Ionizaiton Processes ).
- Low Energy Neutron Transport ( By Evaluated Nuclear Data ).
- Functions of Beam Transport ( Magnetic Field and the other Devices ).
- Event Generator Mode:
  - Deposit Energy (Heat) without Local Approximation.
  - Deposit Energy Distribution ( Beyond One-Body Observables ).

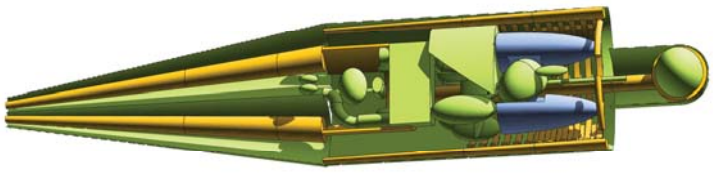
### *In future:*

- Microscopic treatment of ionization processes.
- DCHAIN-SP, Radioactivity Calculation
- Photo-Nuclear Reaction
- EGS4, High Energy Photon and Electron Transport

Future

## *Distribution of PHITS*

**PHITS** *ver.2.13* and **ANGEL** *ver.4.35*
*have been released from JAEA.*



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