核破砕中性子利用体系の設計の基礎
（PHITS と基礎データの集積）

RIST
(Research Organization for Information Science & Technology)
(財)高度情報科学技術研究機構
仁井田浩二

1）核破砕中性子源施設の現状
2）施設設計のためのシミュレーションコード PHITS
3）必用な基礎データ

1）核破砕中性子源施設の現状

(1) 中性子散乱施設
JSNS（J-PARC）, SNS（ORNL), SINQ（PSI), ISIS（UK), ……
ESS (Sweden), CSNS, ……

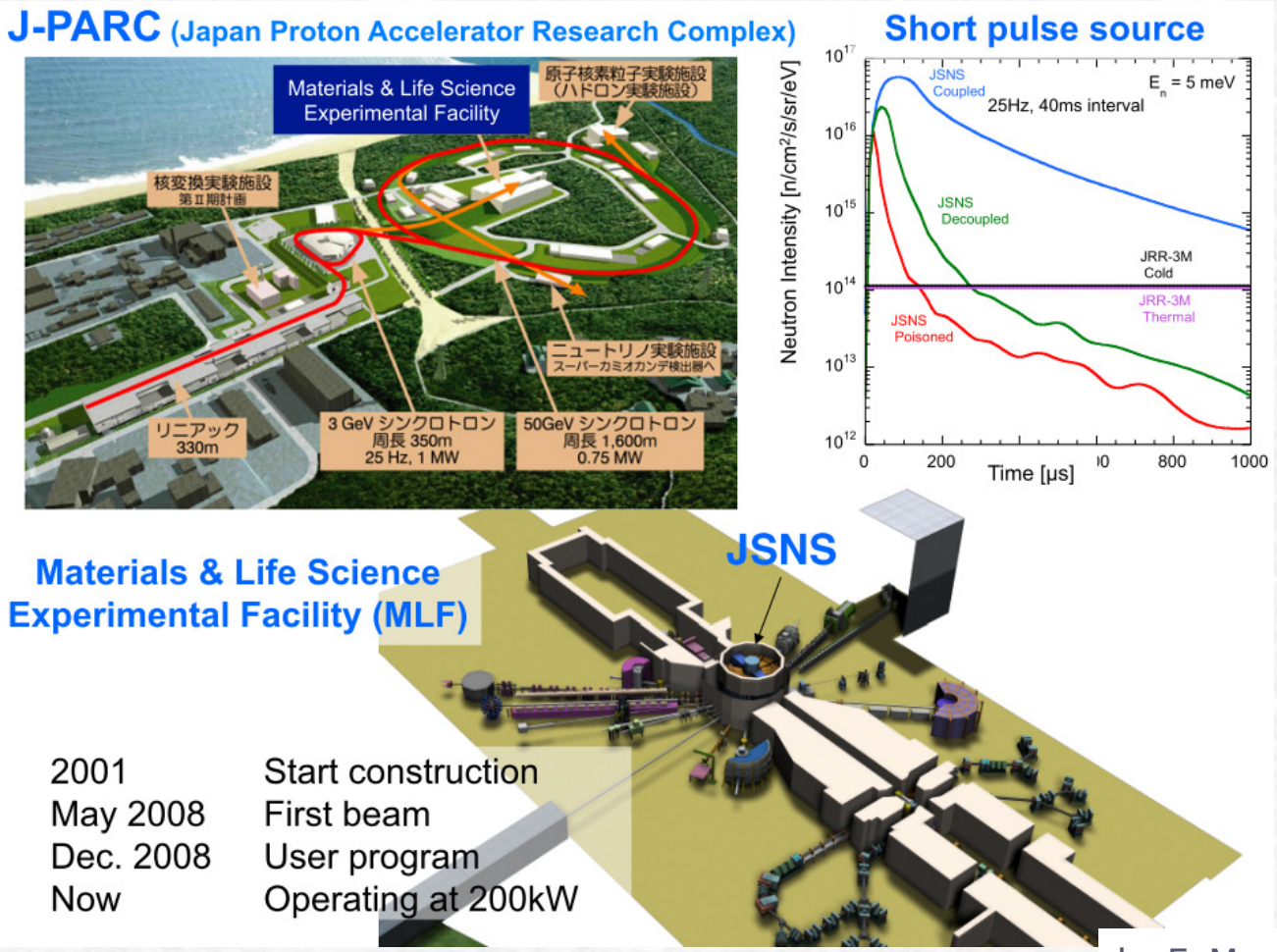
(2) IFMIF (International Fusion Material Irradiation Facility)
（国際核融合材料照射施設）

(3) BNCT (Boron Neutron Capture Therapy)

(4) ADS（Accelerator Driven System)

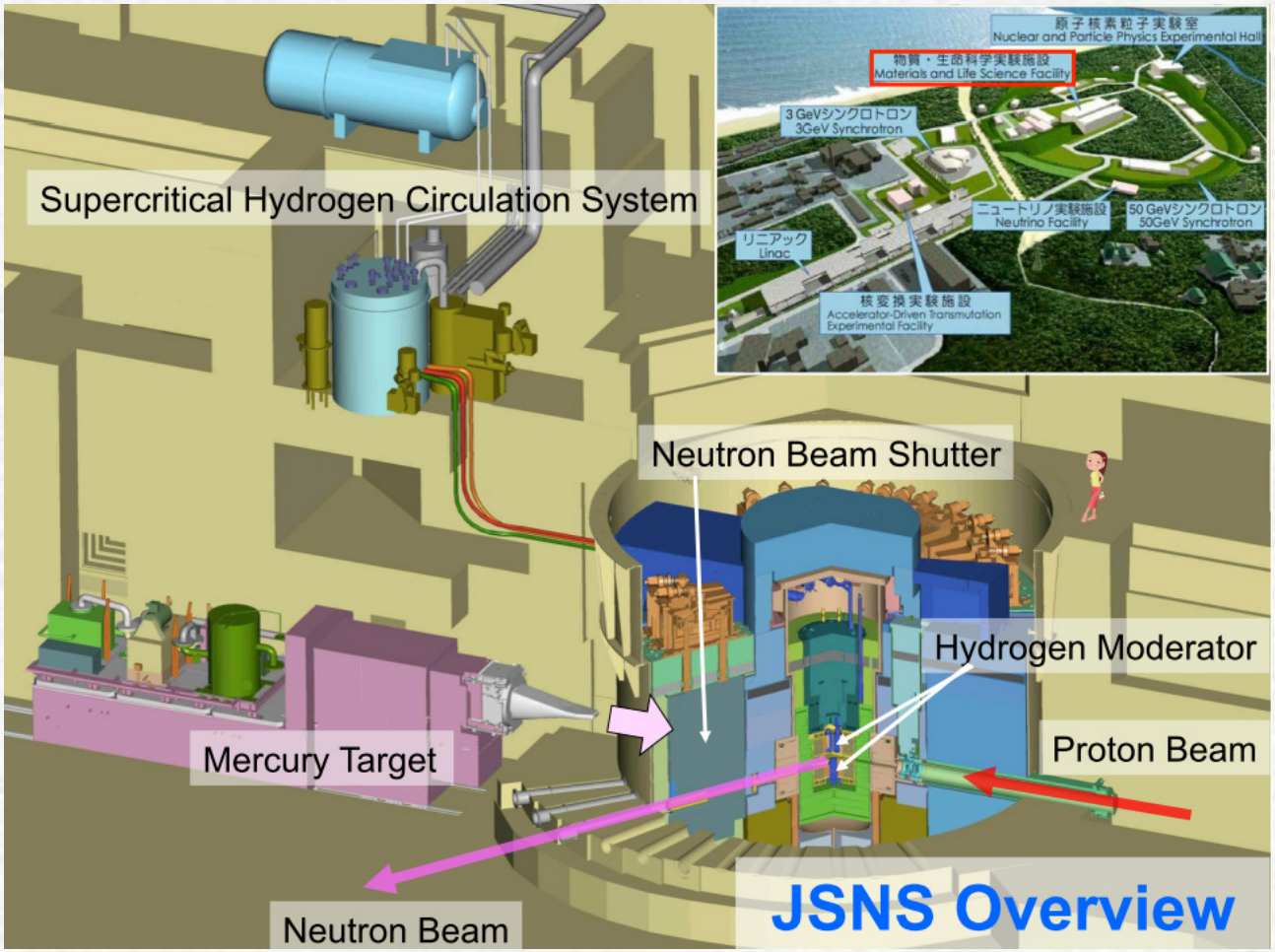
(1) 中性子散乱施設

JSNS（J-PARC） 3GeV proton 1 MW 25Hz → meV neutrons



by F. Maekawa, JAEA

JSNS（J-PARC） Target Moderator System

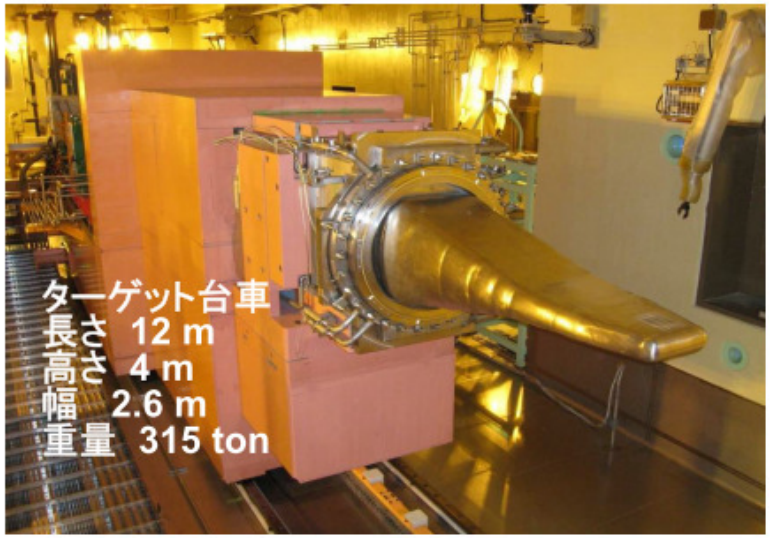


by F. Maekawa, JAEA

JSNS（J-PARC） Target Moderator System

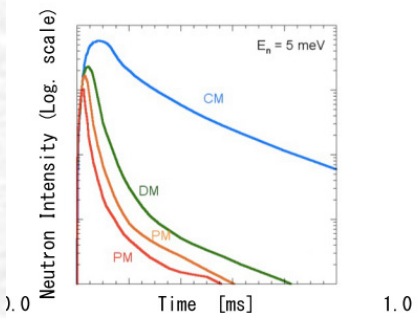
3GeV proton 1 MW 25Hz → meV neutron

磁力で水銀を流す循環システムの開発
重量20トンの水銀を最大約1m/sで流すことで、
効率よく熱を取り除きながら、中性子を発生



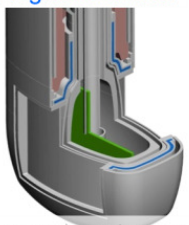
by Y. Ikeda, JAEA

J-PARC Supercritical Hydrogen Moderators



Poisoned Decoupled moderator (PM)

for high resolution



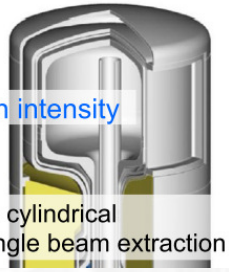
Decoupled moderator(DM)

for balanced performance

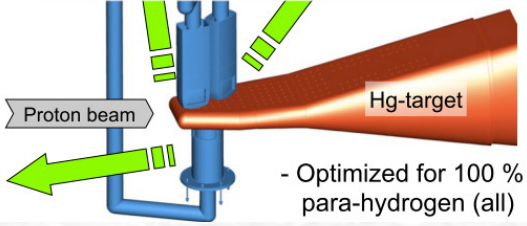
- Adoption of Ag-In-Cd (AIC) alloy for high decoupling energy at 1 eV
- optimized decouple coverage for lower pulse tail
- Adoption of Cd poison

Coupled moderator (CM)

for high intensity



- large & cylindrical
- wide angle beam extraction



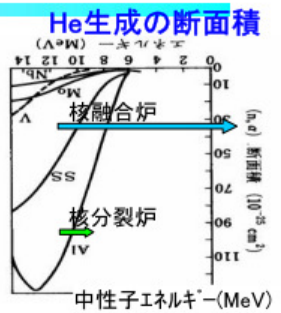
- Optimized for 100 % para-hydrogen (all)

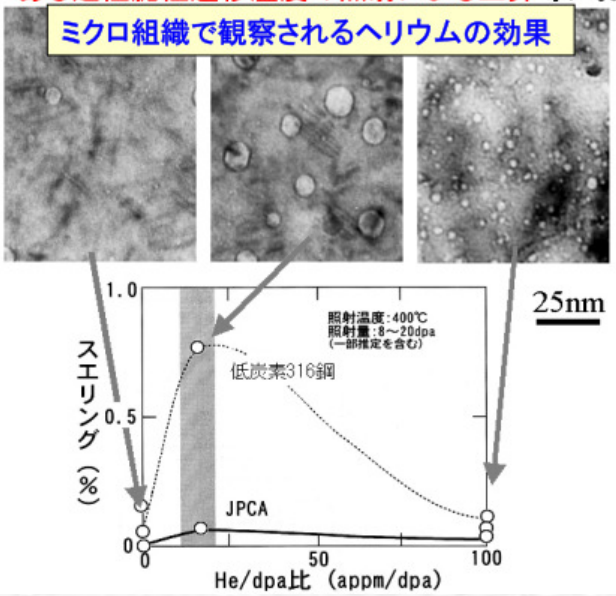
by F. Maekawa, JAEA

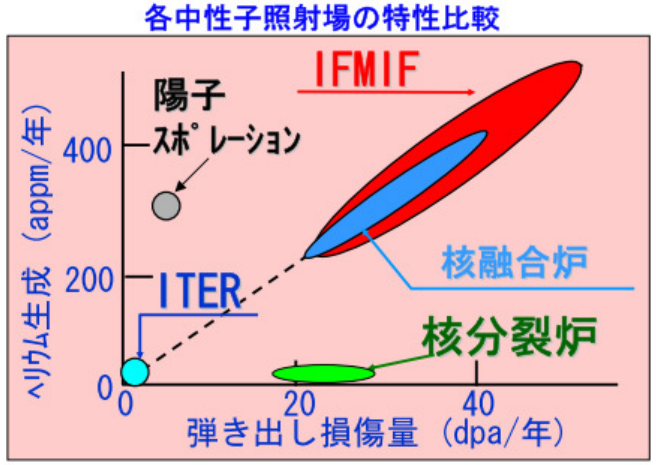
(2) IFMIF (International Fusion Material Irradiation Facility)
（国際核融合材料照射施設）

IFMIFの必要性—照射場の要件

- 照射場は使用環境下の弾き出し損傷量と、中性子によるヘリウム生成等核変換の影響を同時に模擬すること。特にHe／dpa比が核融合条件と一致することが必要。
- He／dpa比によって組織中のボイド生成の様子が大きく異なりスエリング特性が変化。使用温度、損傷速度等の影響も大きく、モデル計算で十分な精度を得ることができない。
- He／dpa比は316鋼等のIASCC、フェライト/マルテンサイト鋼で最重要特性である延性脆性遷移温度の照射による上昇等においても重要。







dpa：原子当たりの弾き出し回数(displacement per atom)
appm：核変換濃度(atom part per million)

3

by H. Matsui, Tohoku uni.

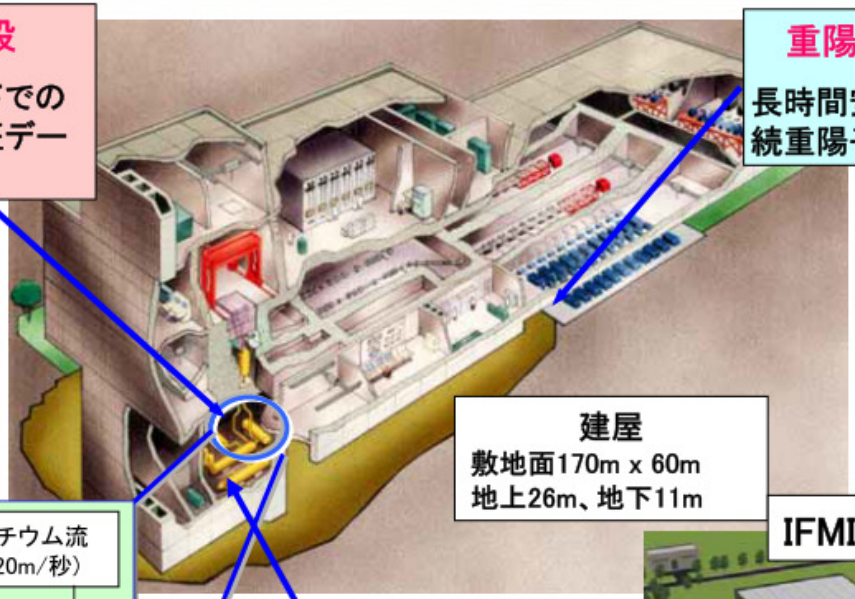
IFMIF施設の概要

テストセル施設

核融合炉照射条件下での材料性能の工学実証データを取得

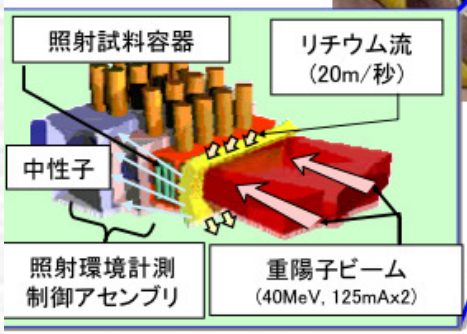
重陽子線形加速器

長時間安定に10MWの連続重陽子ビームを生成



建屋

敷地面170m x 60m
地上26m、地下11m

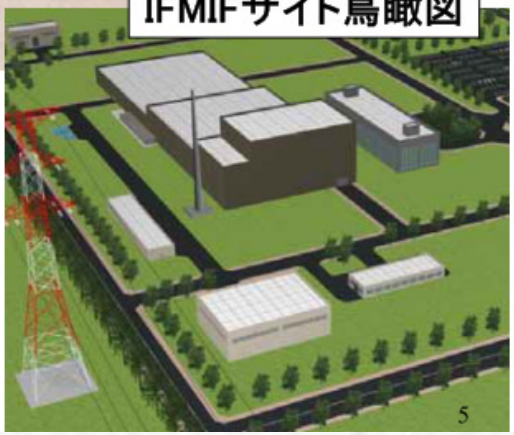


中性子重照射試験の原理

液体Liターゲットループ

1GW/m^{2}のビーム入熱に耐えて大量の核融合中性子を発生

IFMIFサイト鳥瞰図



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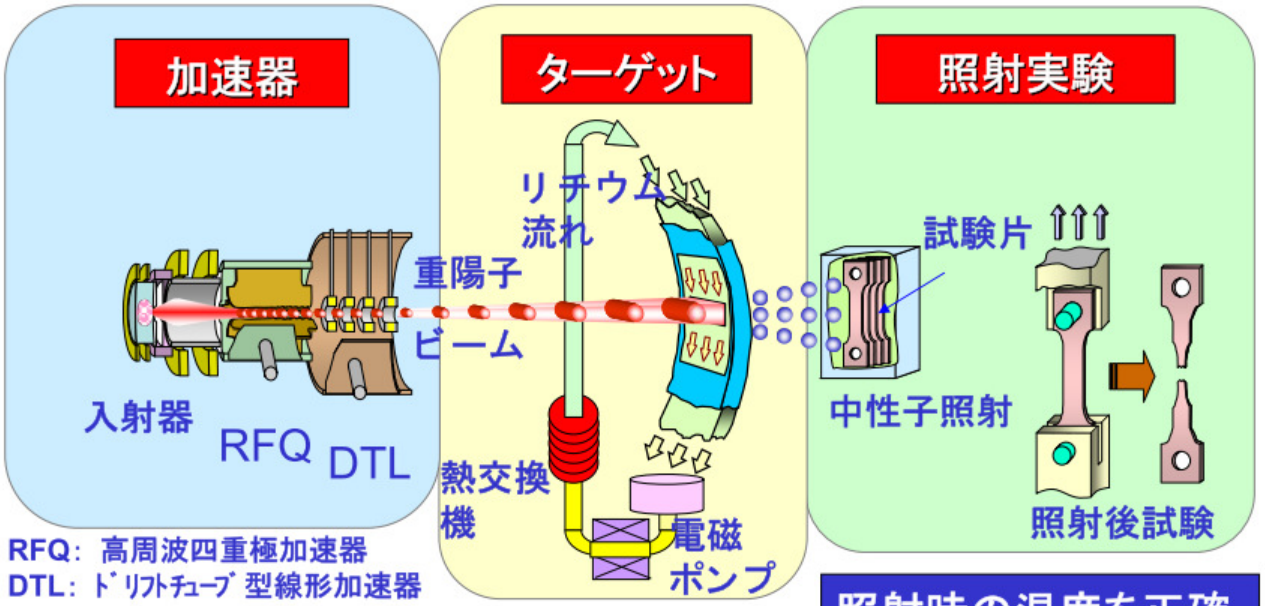
d(40MeV) + Li → neutron　14MeV 中性子照射場の模擬

IFMIFの開発項目



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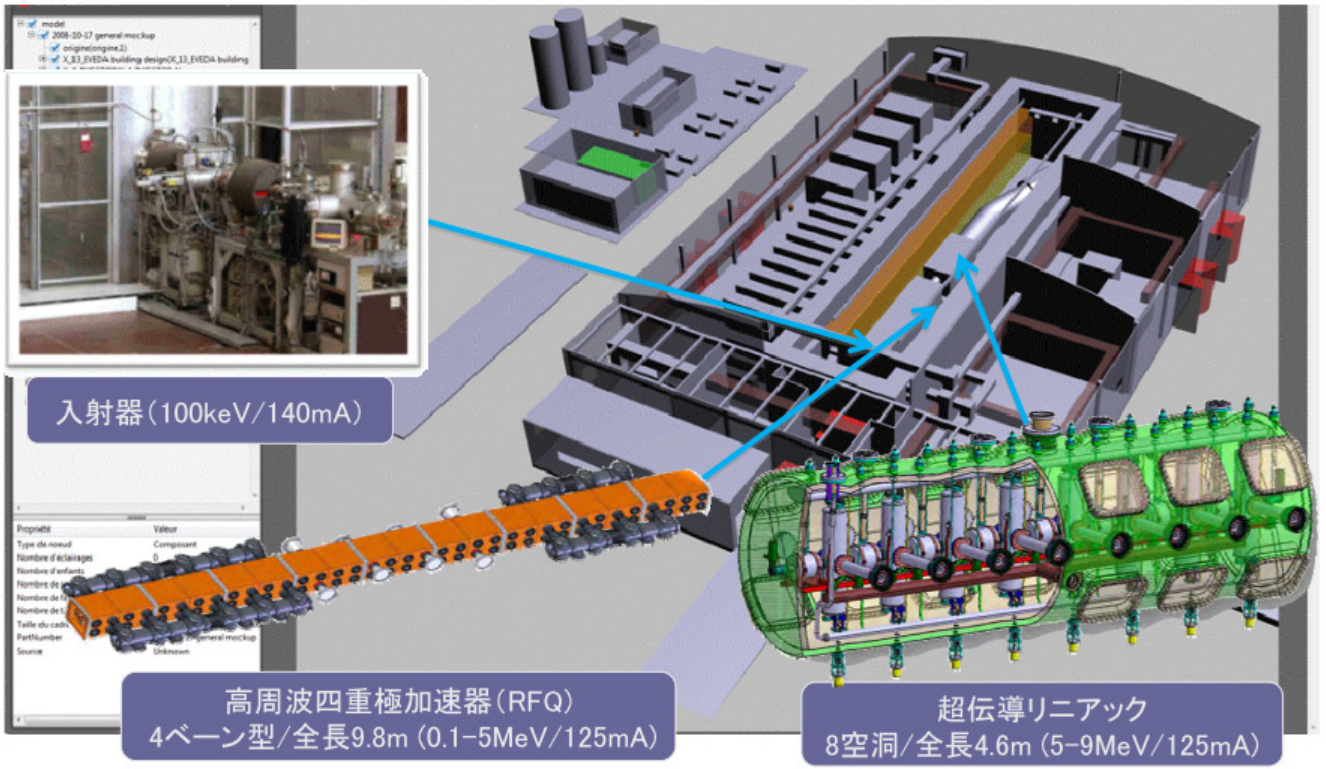
青森県六ヶ所村

IFMIF/EVEDA事業：加速器系開発（建屋と原型加速器）

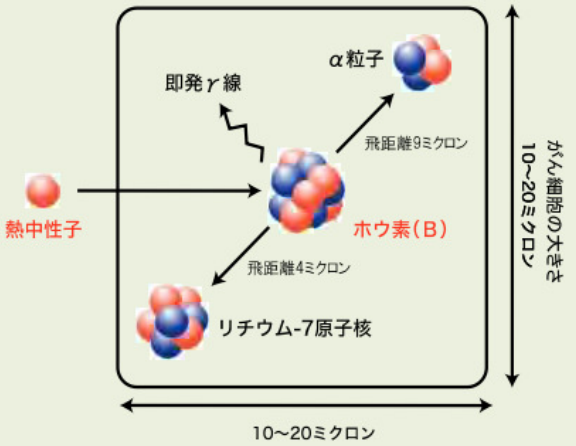


by T. Tsunematsu, JAEA

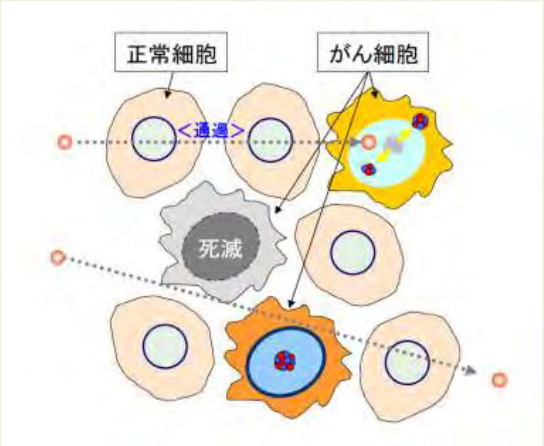
(3) BNCT (Boron Neutron Capture Therapy)

BNCTの原理

● がん細胞内での熱中性子とホウ素の反応



α 粒子とリチウム-7原子核
↓
がん細胞を選択的に破壊



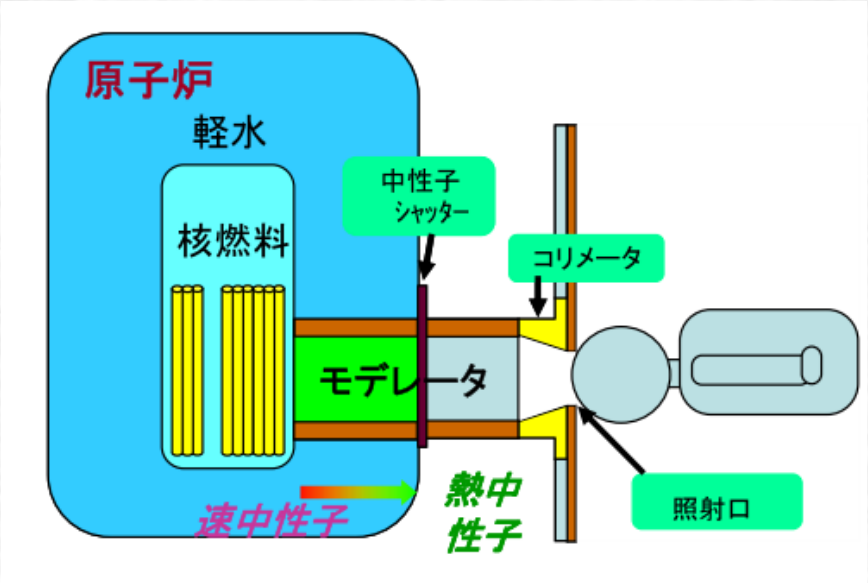
ホウ素の取り込まれていない細胞へのダメージは小さく、

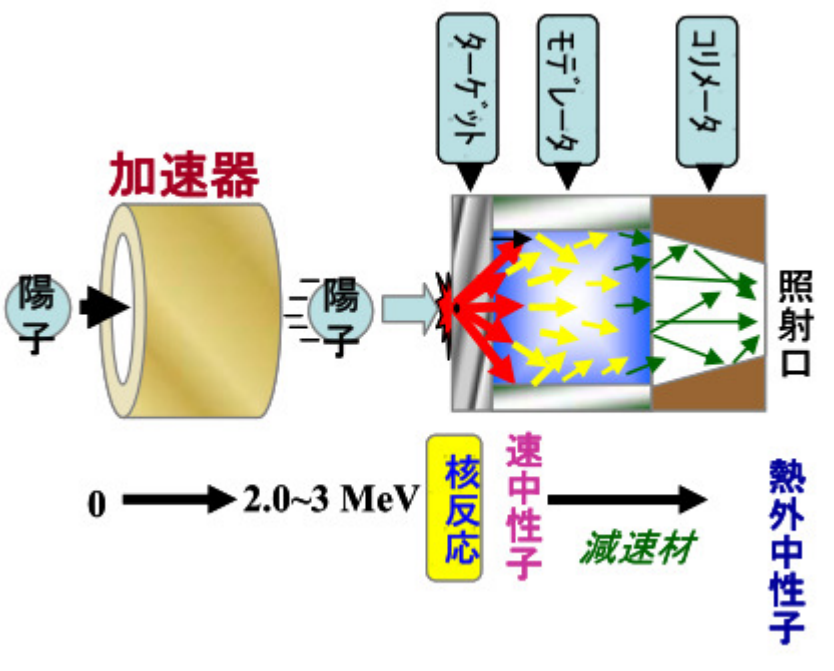
ホウ素を取り込んでいるがん細胞は死滅する。

ホウ素化フェニルアラニン(BPA)を投与すると、がん細胞に選択的に吸収され、
がん細胞のみがBNCTにより集中的にα線照射され死滅する。
BPAの体内分布はPETで定量的に確認可能である。

by 国立がんセンター

原子炉利用から加速器駆動BNCTへ



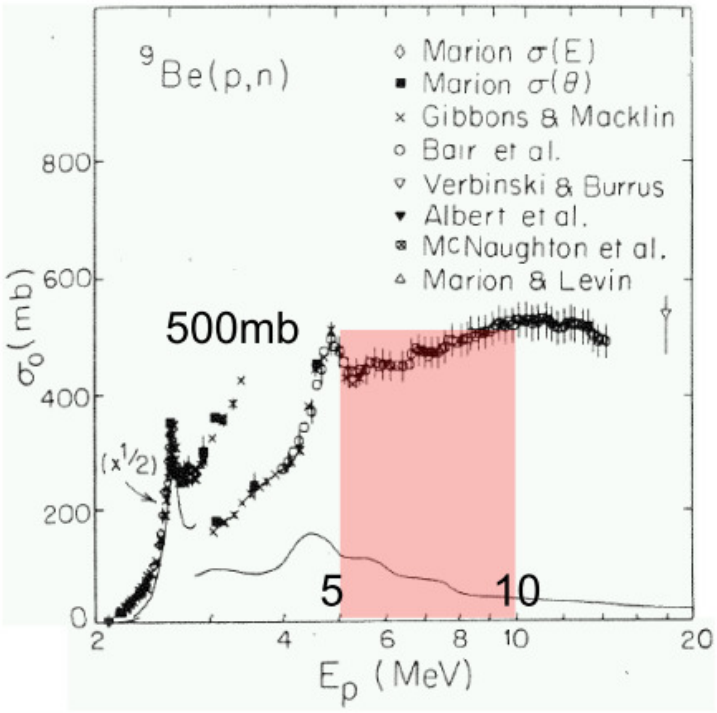


by 国立がんセンター

加速器を利用した医療用中性子源

BNCTの要求：$10cm^2$の腫瘍に対して$2x10^{13}$ 個の中性子が必要

$^7Li(p,n)$ や $^9Be(p,n)$反応で中性子を発生
陽子ビームエネルギー → 5-10MeV
問題　中性子束が小さい
→平均ビーム電流 ＞数10mA
厚いターゲットでは熱負荷 ～100kW
従来の加速器では達成困難
cf. J-PARC I～0.3mA



by T. Shibata, JAEA

(4) ADS（Accelerator Driven System）

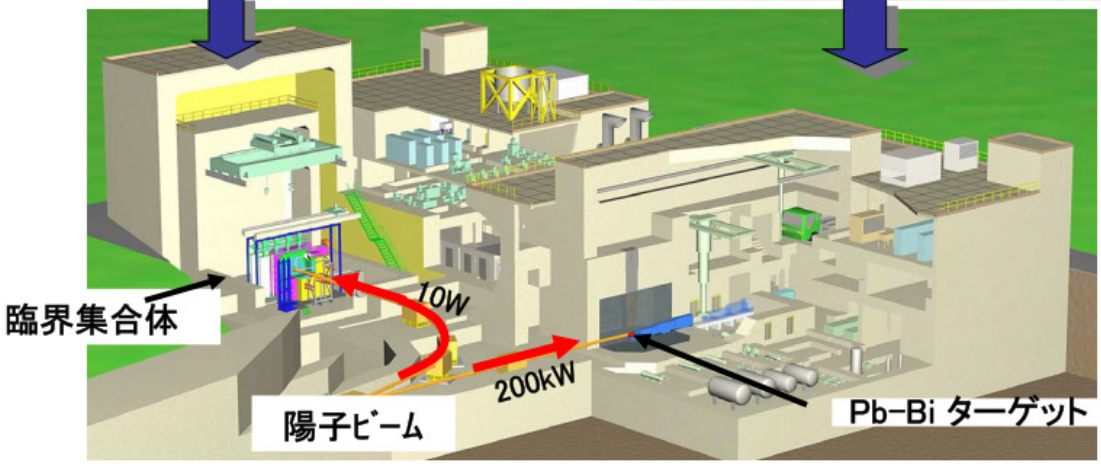
J-PARC 次期計画 核変換実験施設

核変換物理実験施設
TEF-P

目的：低出力で未臨界炉心の物理的性質を探るとともに、ADSの運転制御経験を蓄積する
施設区分：原子炉（臨界実験施設）
陽子ビーム：600MeV、10W
熱出力：500W以下

ADSターゲット試験施設
TEF-T

目的：200kWの陽子ビームで核破砕ターゲットの技術開発と材料の研究開発を行う
施設区分：放射線発生装置
陽子ビーム：600MeV、200kW
ターゲット材料：鉛・ビスマス



by JAEA

PHITS : *Particle and Heavy Ion Transport code System*

- General-purpose 3D Monte Carlo transport code system,
  for all particles and Heavy Ions
  with all energies from meV upto 200 GeV
- All in one package including graphic utility,
  its physical models are fully integrated.

5 major codes for all particle transport in a world

	MCNPX	GEANT4	FLUKA	MARS	PHITS
Lab. Affiliation	LANL	CERN,IN2P3 INFN,KEK,ESA, SLAC,TRIUMF	CERN INFN	FNAL	JAEA,RIST, KEK, Chalmers Univ.
Language	Fortran 90/C	C++	Fortran 77	Fortran 95/C	Fortran 77
Release Format	Source & binary	Source & binary	Source & binary	Binary	Source & binary
Users	~2000	~1000	~1000	220	220
Parallel Exec.	Yes	Yes	No	Yes	Yes

By G. W. McKinney in FNDA (Fast Neutron Detectors and Applications Conference) April 2006
Revised by L. Waters in HSS06 (Hadronic Shower Simulation Workshop) Sep. 2006

Physical Processes included in PHITS

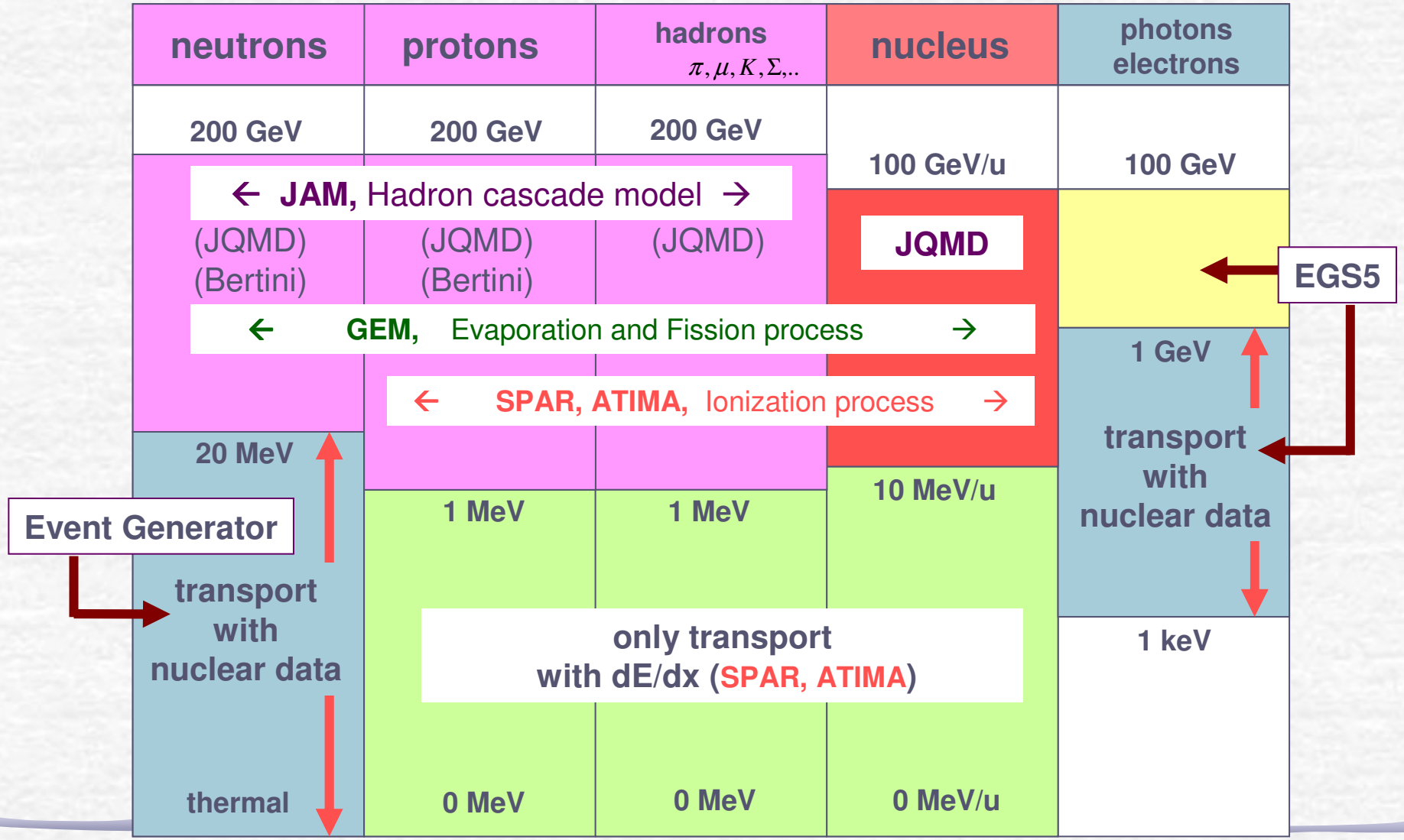
Transport
between collisions

- **External Field** *and Optical devices*
  - *Electric, Magnetic Field*
  - *Gravity*
  - *Super mirror (reflection)*
  - *Mechanical devices, T0 chopper*
- **Ionization process** *for charge particle*
  - *dE/dx : SPAR, ATIMA code*
  - *Energy straggling*
  - *Angle Straggling*

Collisions
with nucleus

- **Nuclear Data** *ENDF-B/VI, LA150, …..*
  - *Event Generator Mode (new feature)*
- **Particle Induced Collisions**
  - *JAM code*
    - *JAMQMD (new feature)*
- **Heavy Ion Collisions**
  - *JQMD code*

Map of Models, transport particles and energies in PHITS



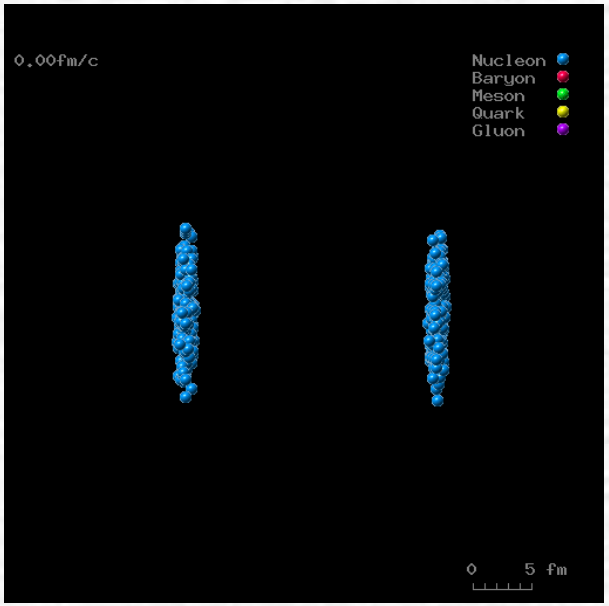
JAM code for Hadron Nucleus Collisions up to 200 GeV

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.

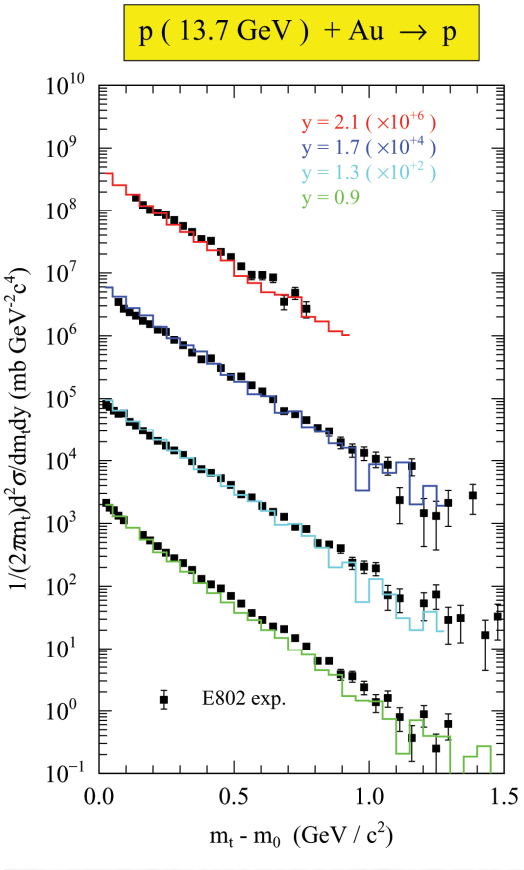
We have parameterized all ***Hadron-Hadron Cross Sections***, based on ***Resonance Model*** and ***String Model*** by fitting the available experimental data.

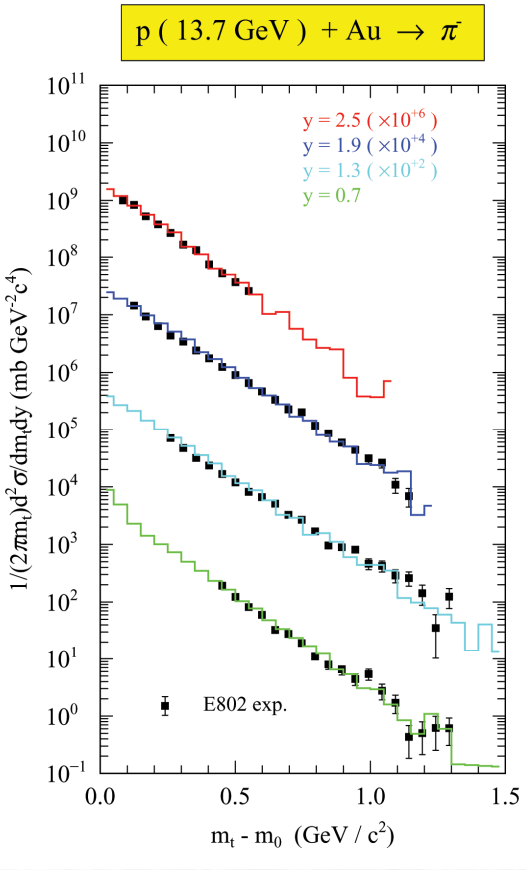
Au+Au 200GeV/u in cm



119 kinds of Mesons

170 kinds of Baryons





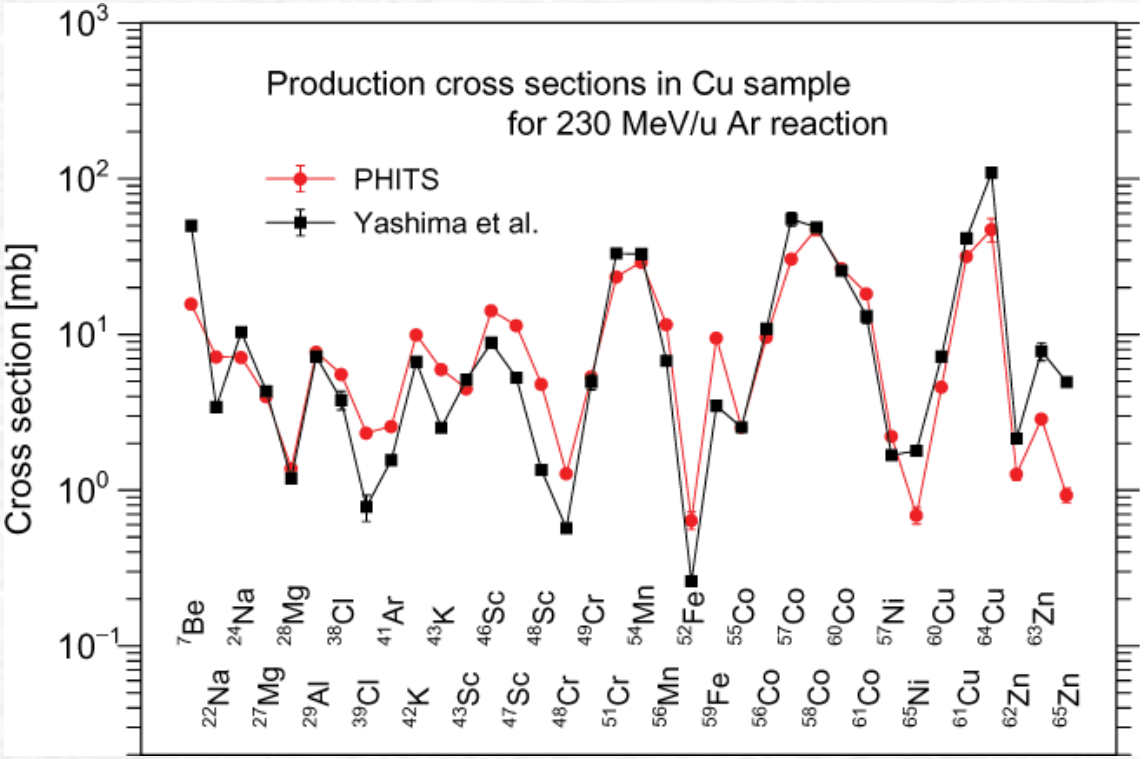
JQMD code *for Nucleus-Nucleus Collisions up to 100 GeV/u*

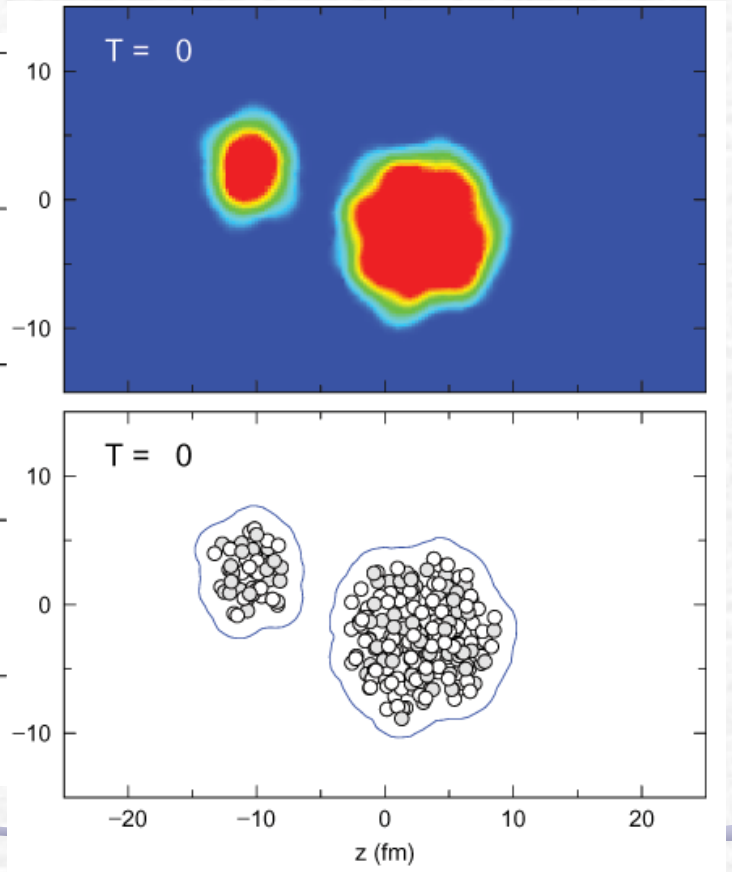
JQMD *(Jaeri Quantum Molecular Dynamics) for Simulation of Nucleus-Nucleus Collisions*

K. Niiita 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

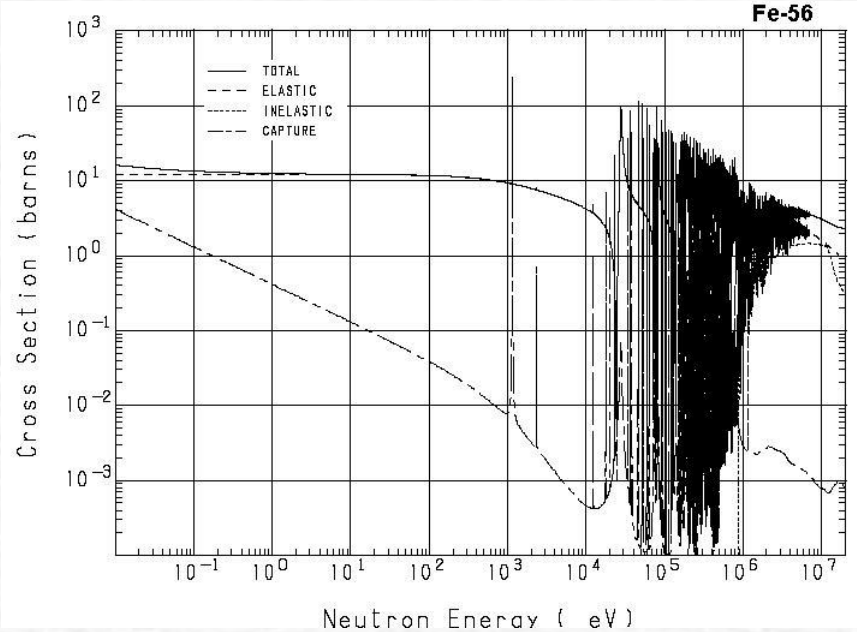


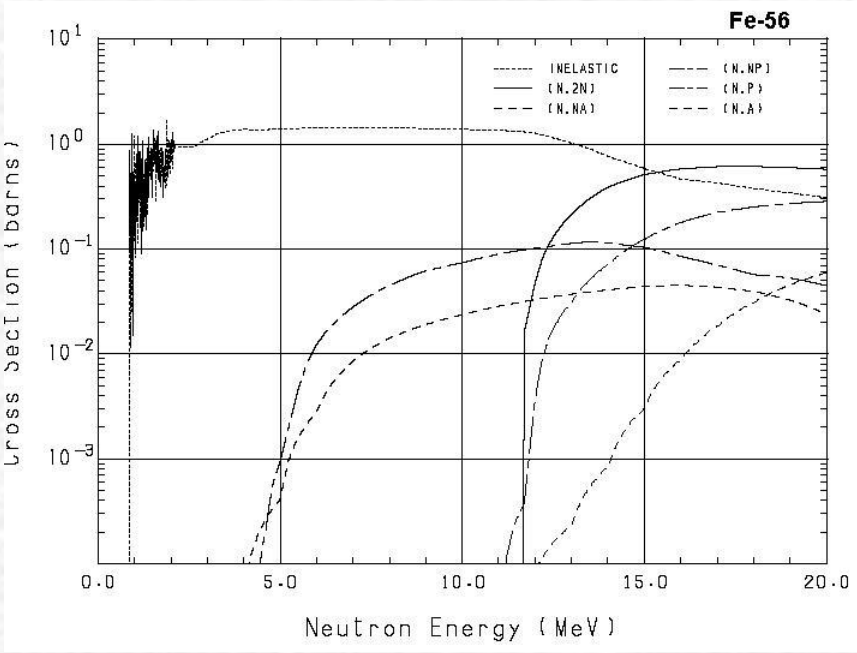


Neutron Transport *below 20 MeV with Nuclear Data*

Transport for Neutrons, Photons, Electrons
by using ***Evaluated Nuclear Data***, such as **ENDF, JENDL, …**

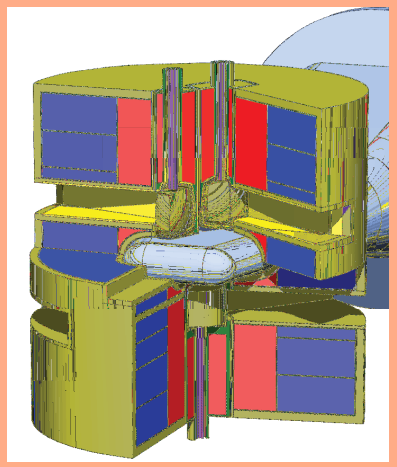
n-56Fe Reaction Cross Sections





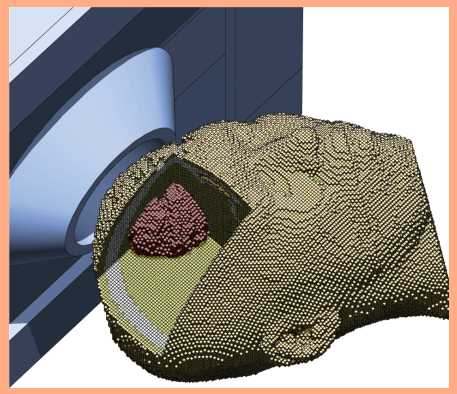
Application Fields of PHITS

Accelerator



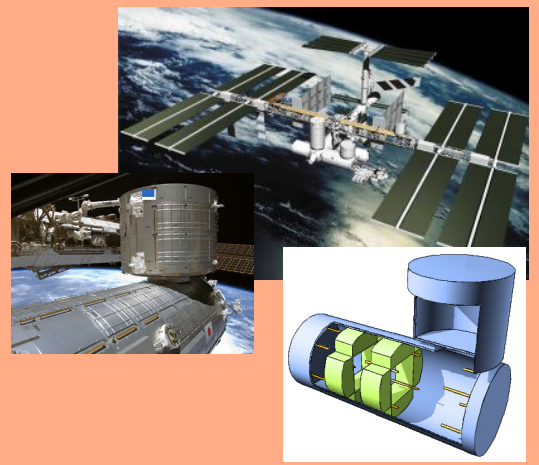
J-PARC
Spallation Neutron Source
Neutron Optics
Heavy Ion Facilities

Cancer Therapy



BNCT
Proton and
Heavy Ion Therapy

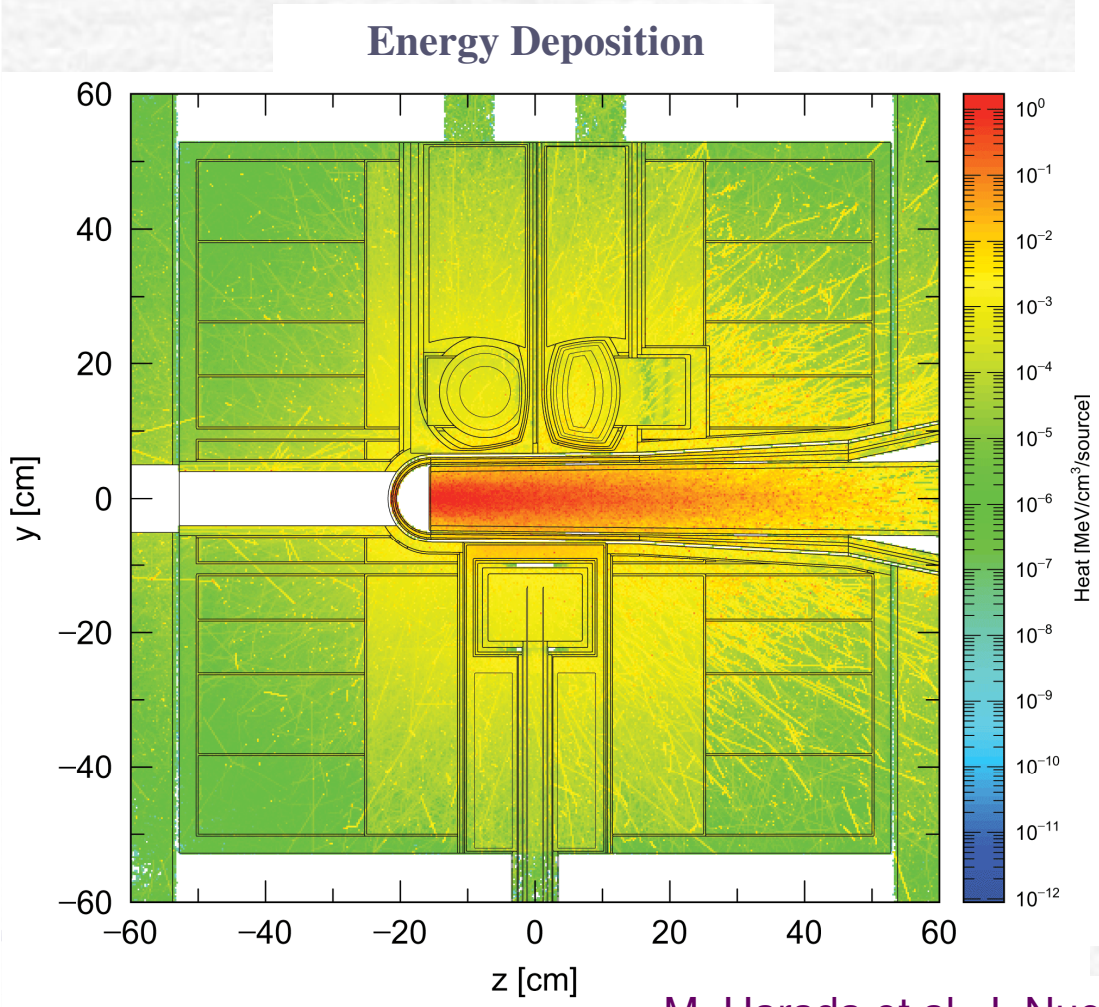
Space Technology

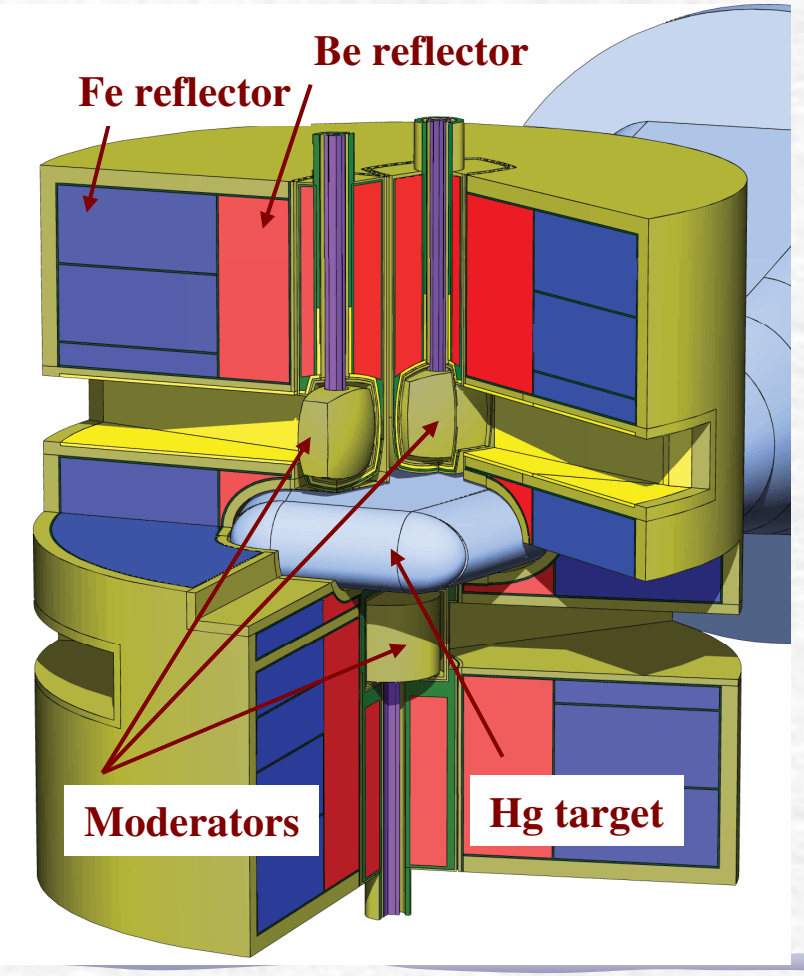


Dose in Space Shuttle
Atmospheric Cosmic-Ray

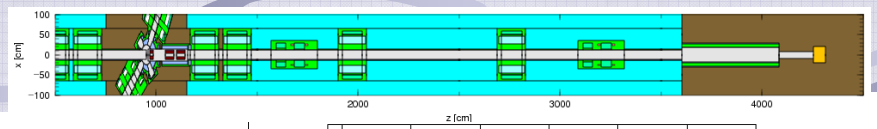
Spallation Neutron Source in Proton Accelerator Facilities

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



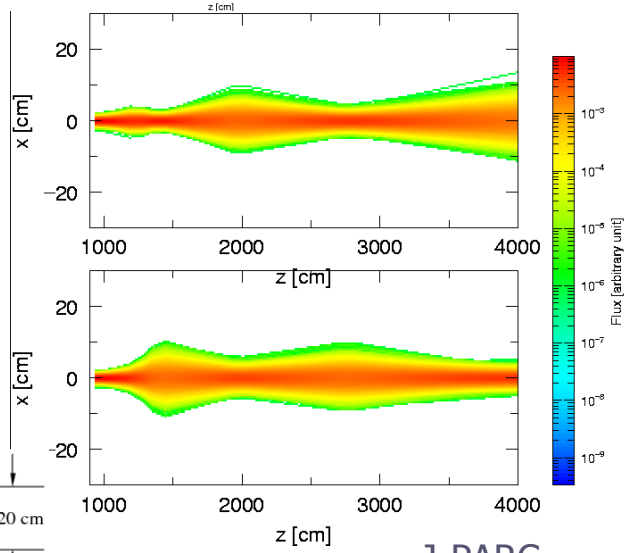


M. Harada et.al, J. Nucl. Matrial. **343** (2005) 197

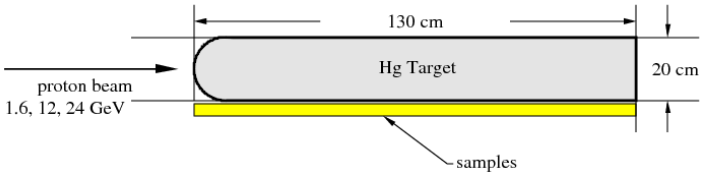


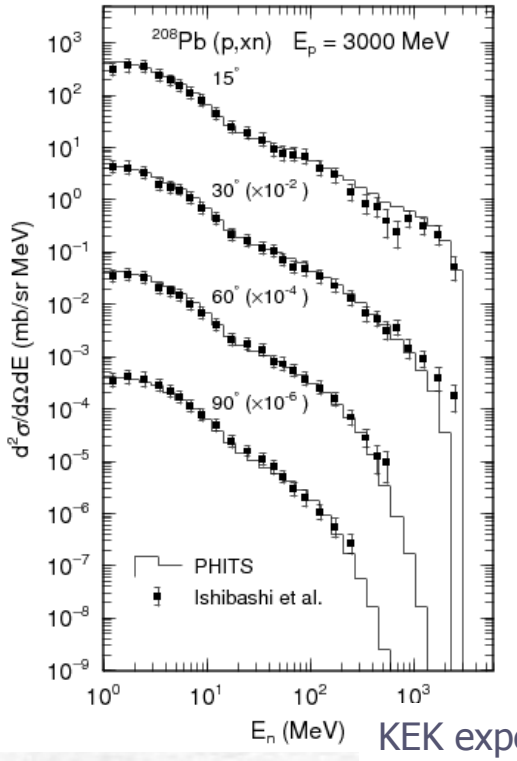
Wide energy range

1) proton beam transport
   (magnetic, electric fields, …)
2) high energy nuclear reactions
   (nuclear reaction models, JAM, QMD,…)
3) thermal and cold neutron transport
   (Nuclear Data, JENDL, ENDF,…)

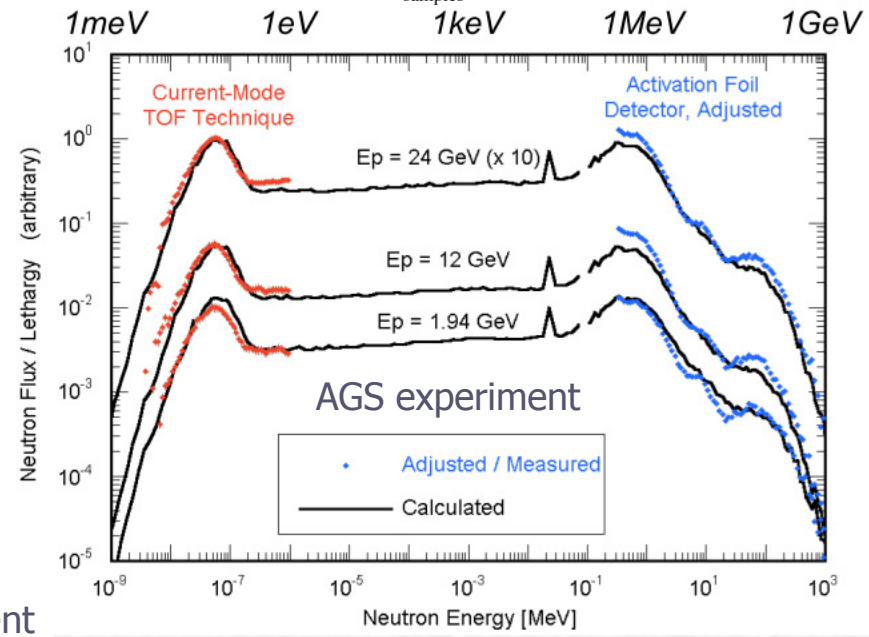


J-PARC



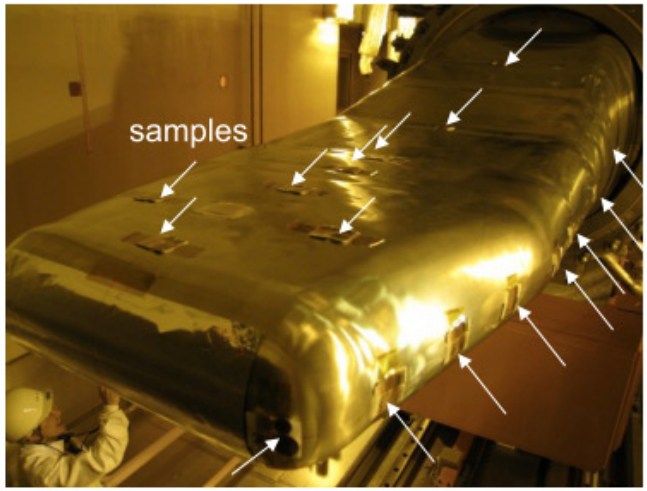


KEK experiment

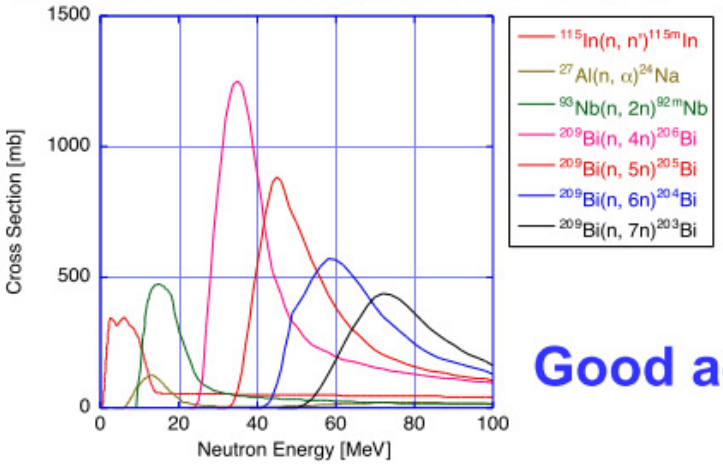


High-energy Neutrons around the Target

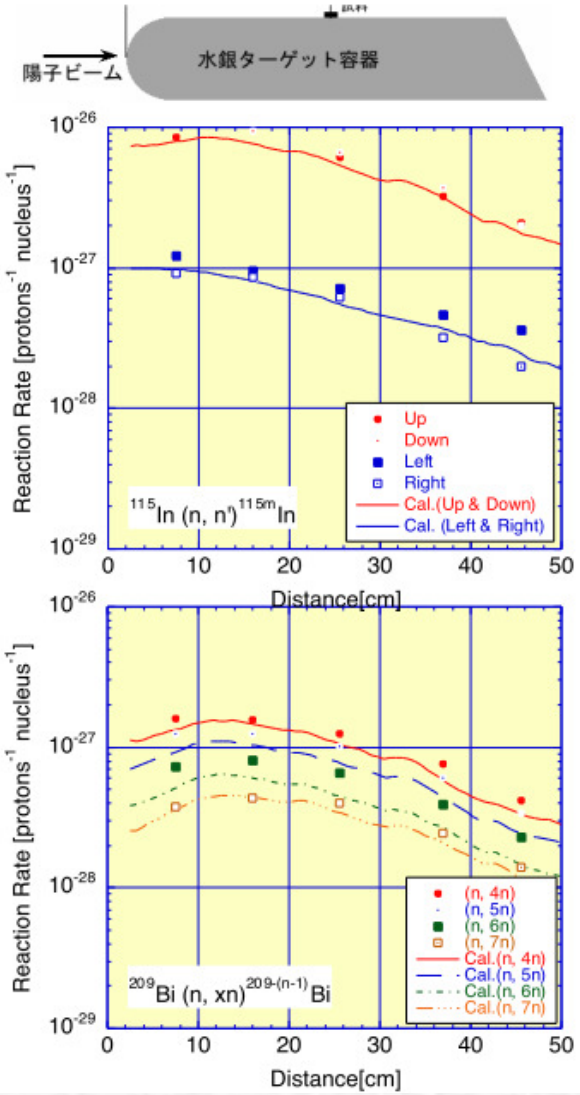
Neutron flux distributions around the Hg-target was measured by the foil activation method.



J-PARC



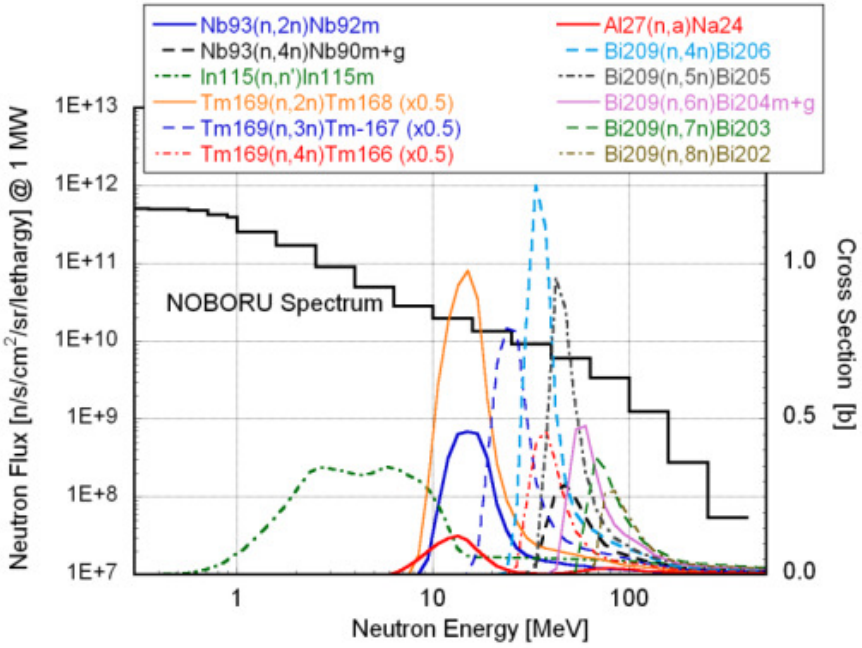
Good agreement !



by F. Maekawa, JAEA

High-energy Neutrons in the Beam

- Source term for shielding calculation of neutron instruments, large impact on construction cost
- Calc. / Expt. ~ 1.4 in average.
- Adequacy of simulation calculation for HE neutrons was also confirmed.



J-PARC

BL10 (DM), L=14m

Reaction	Approx. Energy Range [MeV]	Calc./Expt.
$^{115}In(n,n')^{115m}In$	1 - 15	1.34
$^{27}Al(n,\alpha)^{24}Na$	7 - 20	1.68
$^{93}Nb(n,2n)^{92m}Nb$	10 - 25	1.67
$^{93}Nb(n,4n)^{90m+g}Nb$	40 - 70	1.38
$^{169}Tm(n,2n)^{168}Tm$	10 - 25	1.64
$^{169}Tm(n,3n)^{167}Tm$	20 - 40	1.35
$^{169}Tm(n,4n)^{166}Tm$	30 - 60	1.35
$^{209}Bi(n,4n)^{206}Bi$	25 - 50	1.47
$^{209}Bi(n,5n)^{205}Bi$	35 - 70	1.33
$^{209}Bi(n,6n)^{204}Bi$	45 - 90	1.15
$^{209}Bi(n,7n)^{203}Bi$	60 - 120	1.53
$^{209}Bi(n,8n)^{202}Bi$	75 - 150	1.15

by F. Maekawa, JAEA

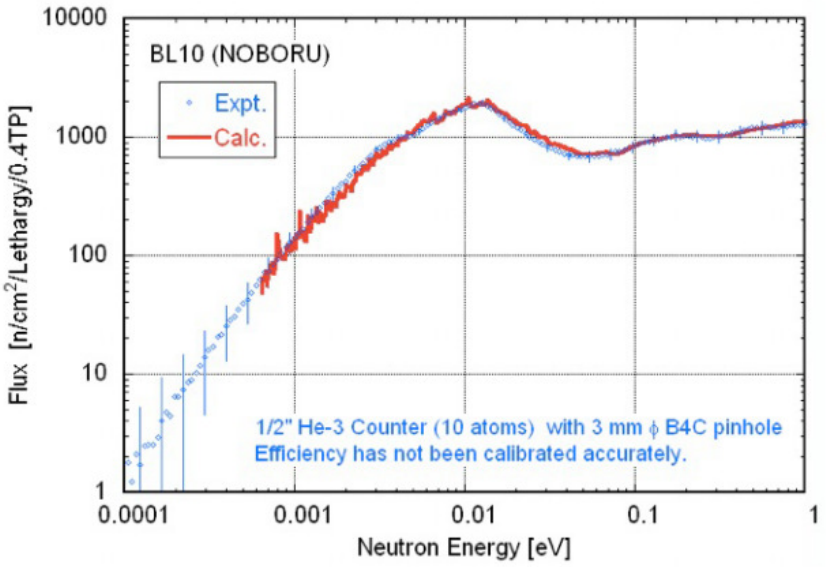
Comparison of Measurements of J-PARC with PHITS predictions

Agreements mostly within ±20% in energy integrated flux below 0.4 eV per unit proton beam power between the measurements and calculations

without any normalization

for CM, DM and PM

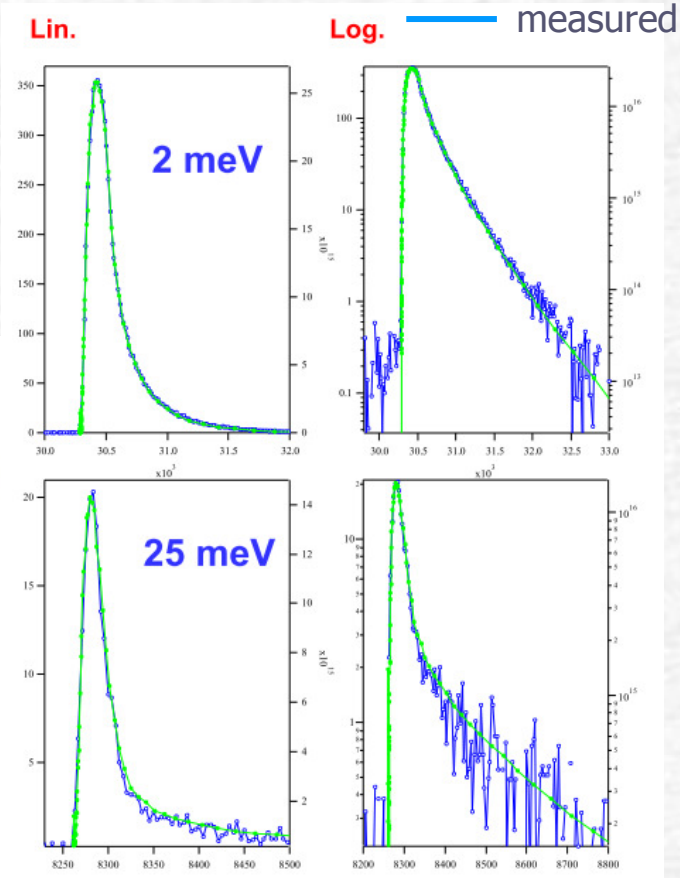
for BLs without guide tubes.



BL01 Pulse shape

PHITS

measured

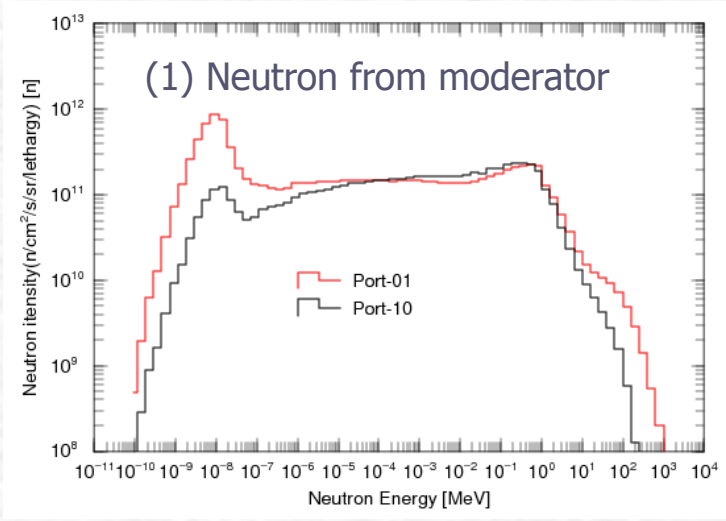


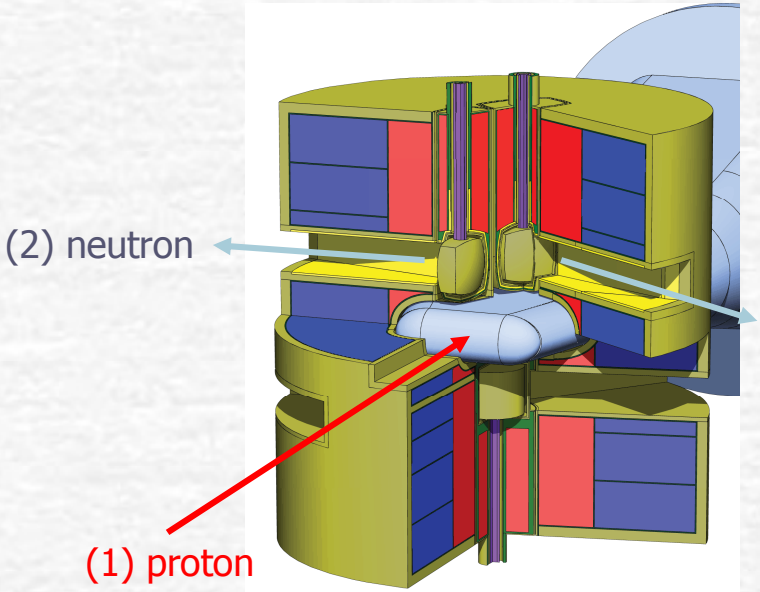
by F. Maekawa, JAEA

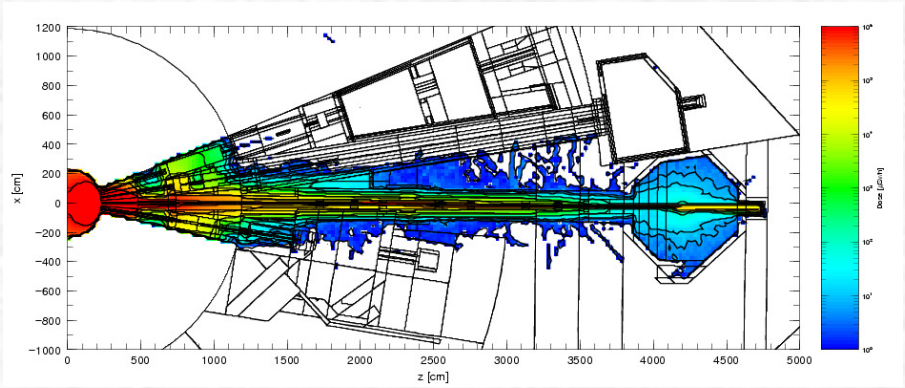
Discrepancies (1/3 ~ 1/2) were found between measured and calculated fluxes for some BLs with guide tubes. This may suggest a possibility of misalignment of guide tubes.

Variance reduction for Long beam line calculations by Monte Carlo method

1) Tow steps calculation
   1. proton ---> moderator
   2. moderator ---> beam line
2) Duct source
   equal number of particles
   on the wall by changing the weight



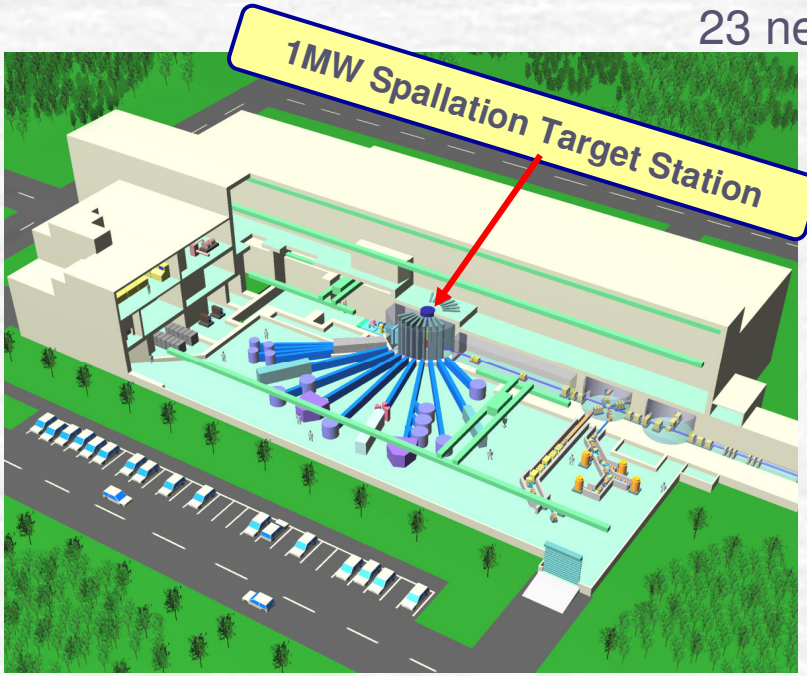


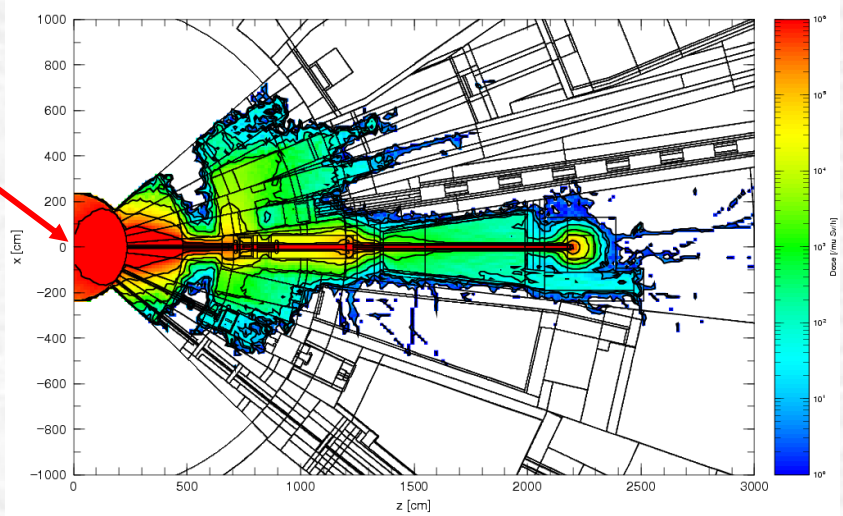


(2) Long beam line calculations by the duct source

Shielding design for neutron scattering instruments in J-PARC

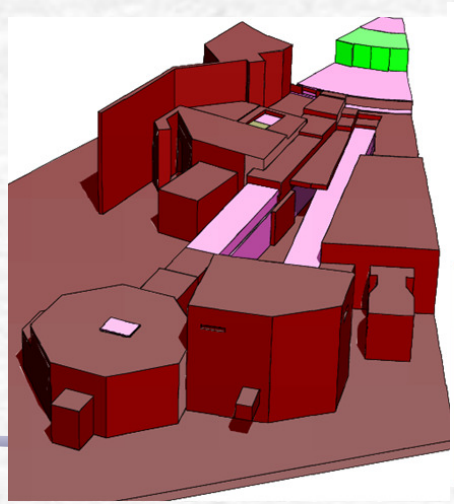
23 neutron beam lines

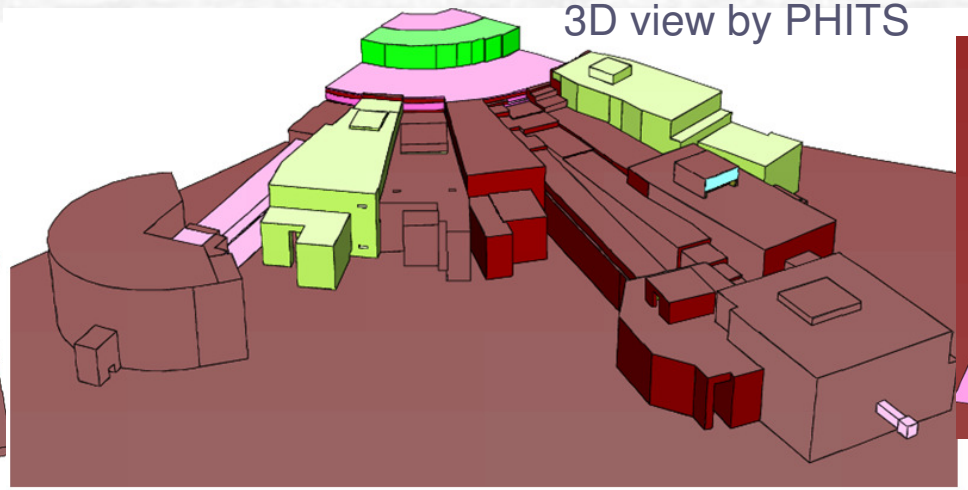


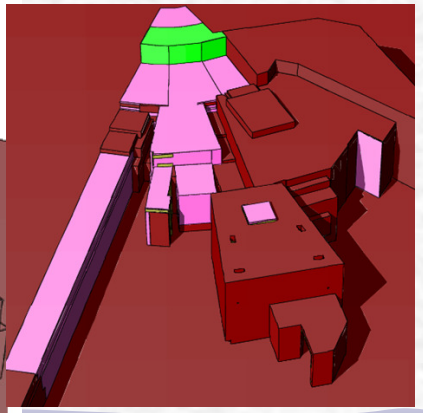


Dose distribution

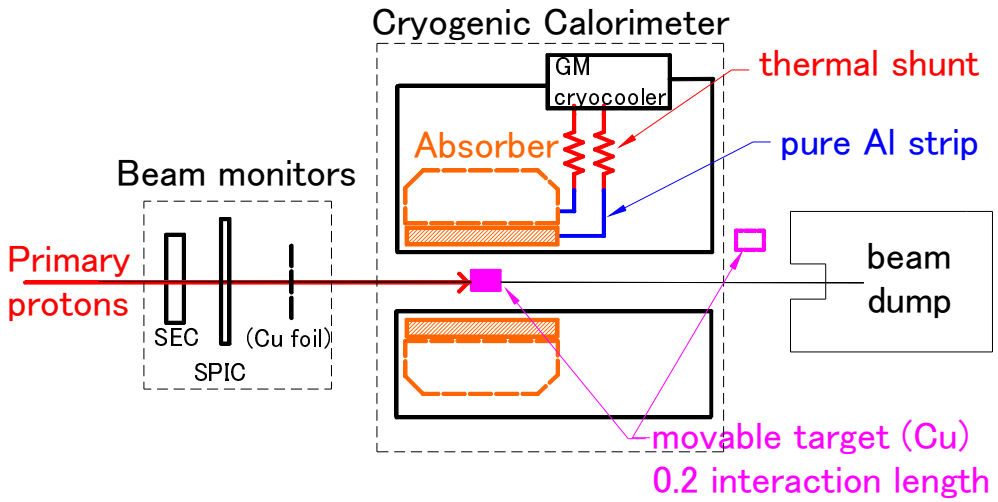
3D view by PHITS



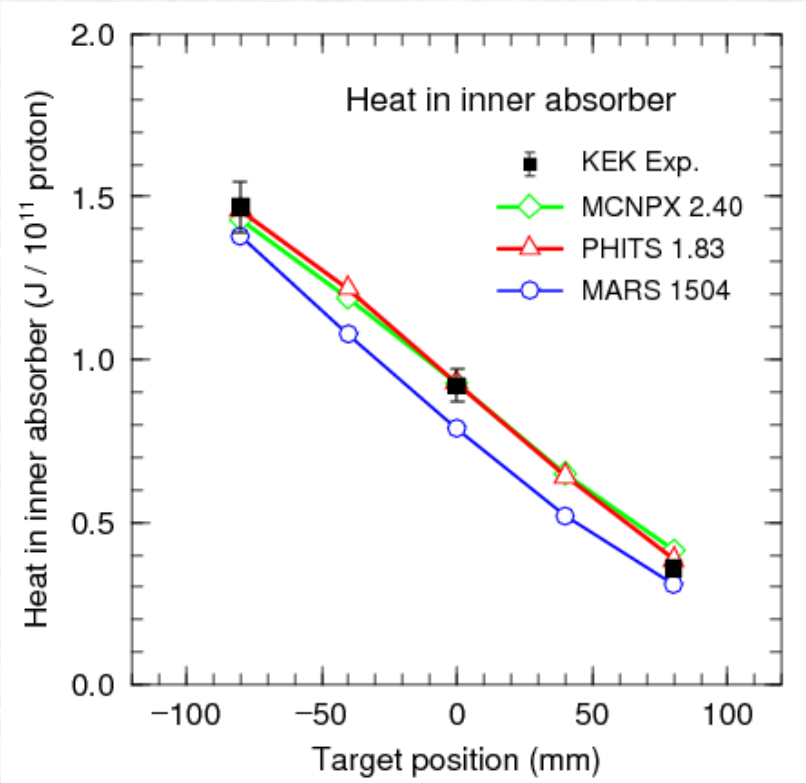


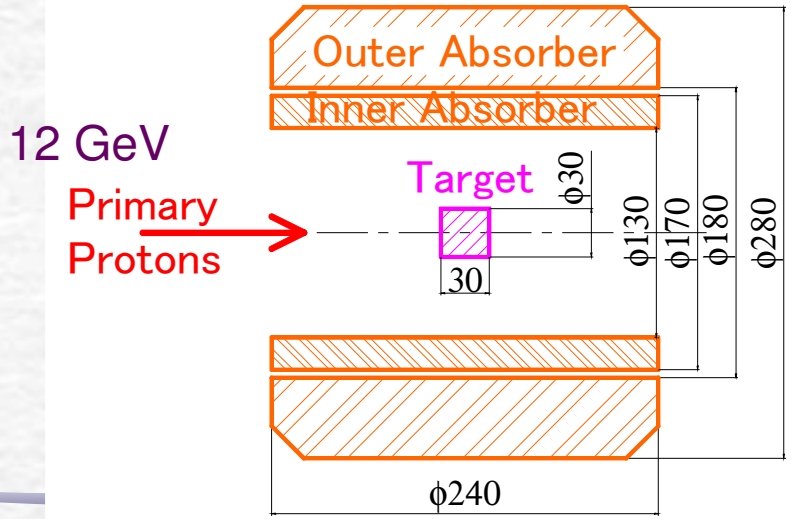


Benchmark test of HEAT : compared with KEK experiment



Exp. and Cal. by H. Ohnishi et.al.
Nucl. Instr. and Meth. A545 (2005) 88



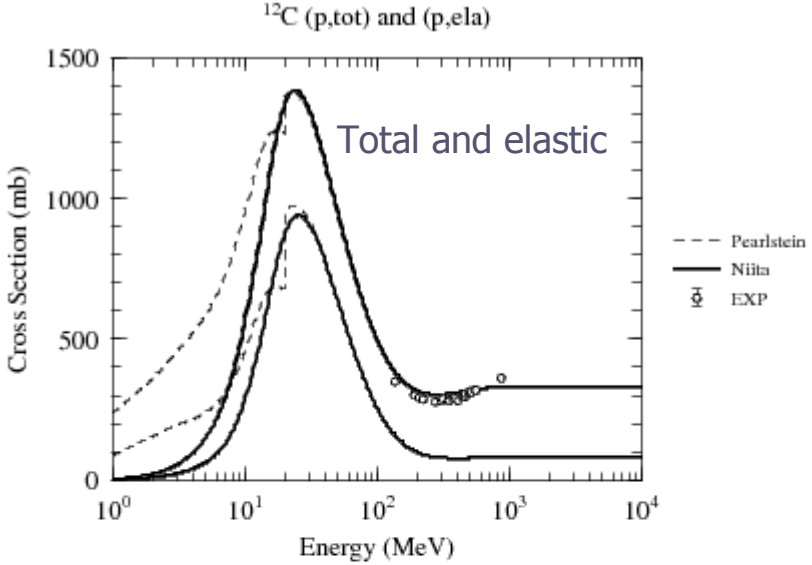


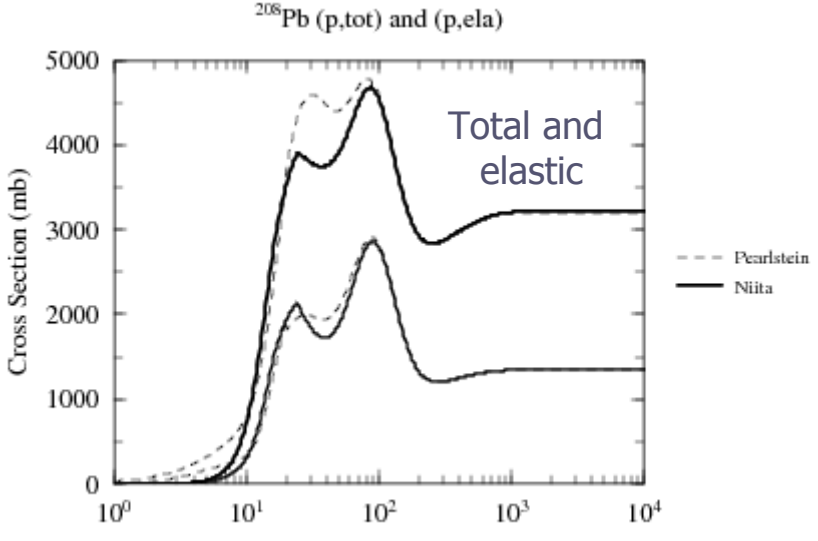
MCNPX: calculated by N. Matsuda

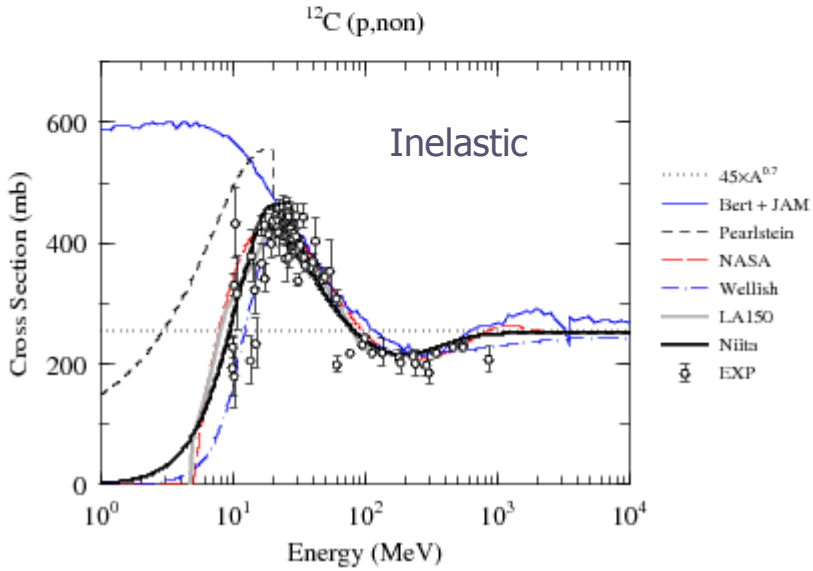
1）核破砕中性子源施設の現状
2）施設設計のためのシミュレーションコード PHITS
3）必用な基礎データ

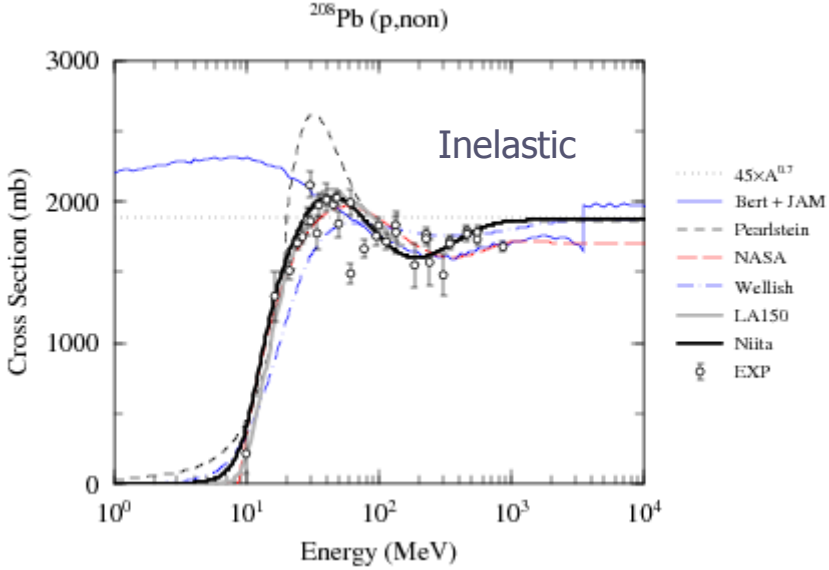
http://nds121.iaea.org/alberto/mediawiki-1.6.10/index.php/Main_Page

Total, inelastic and elastic cross sections. Nucleon-Nucleus

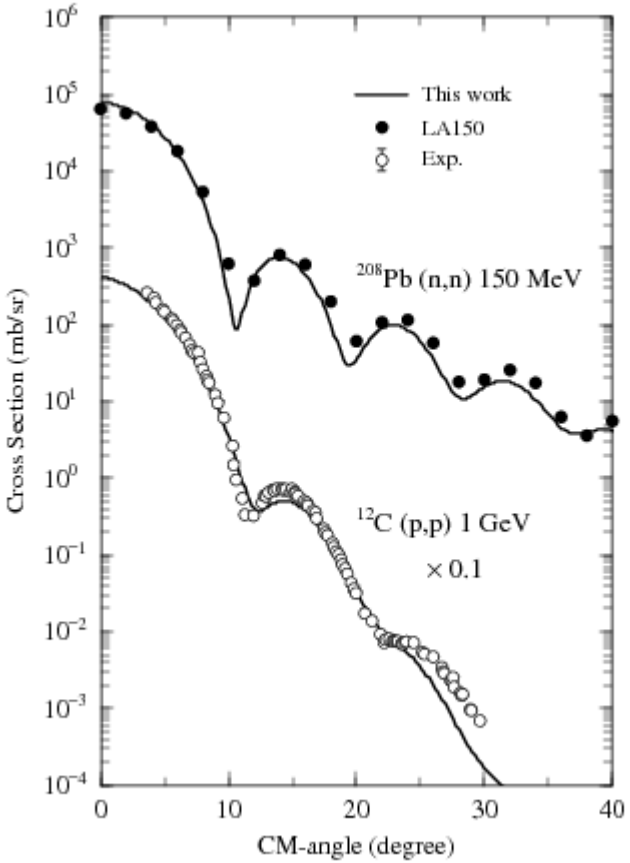


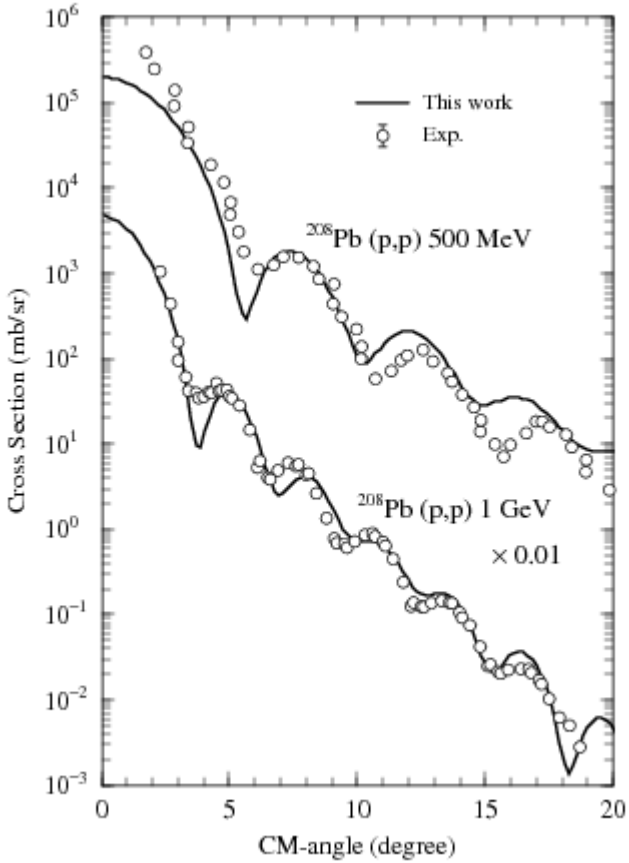






elastic cross sections





Nucleon-Nucleon elastic cross sections

核子-核子断面積の媒質効果

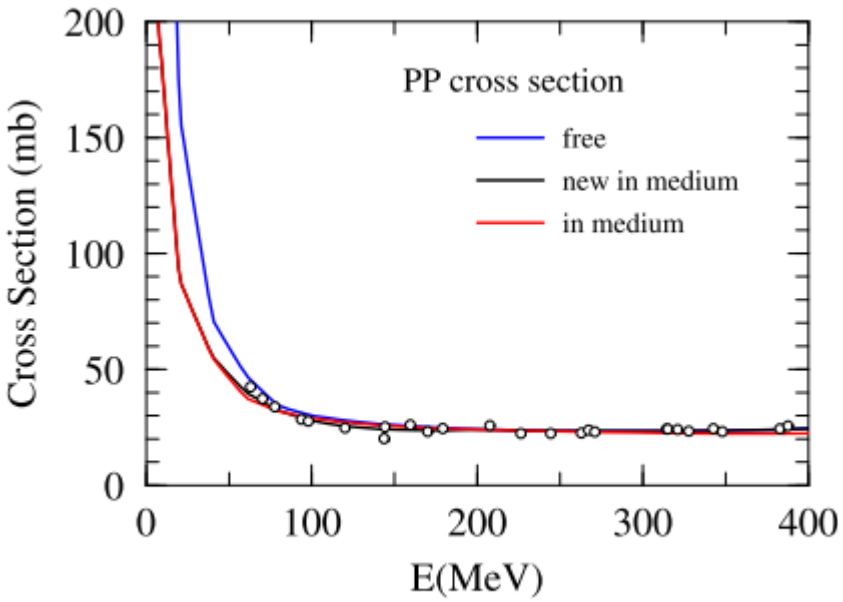


図 2.36: PP 断面積

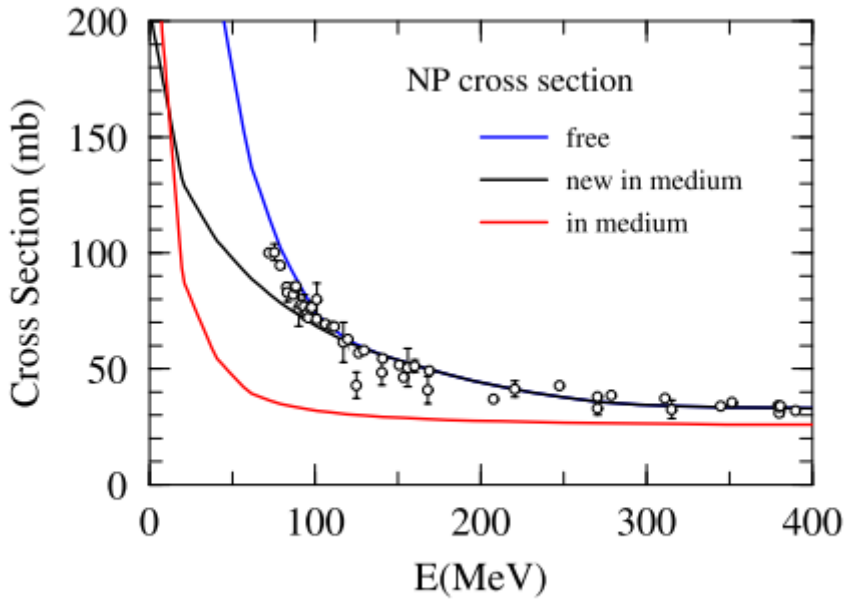


図 2.37: NP 断面積

(p,n) reactions from thin target

核子-核子断面積の媒質効果

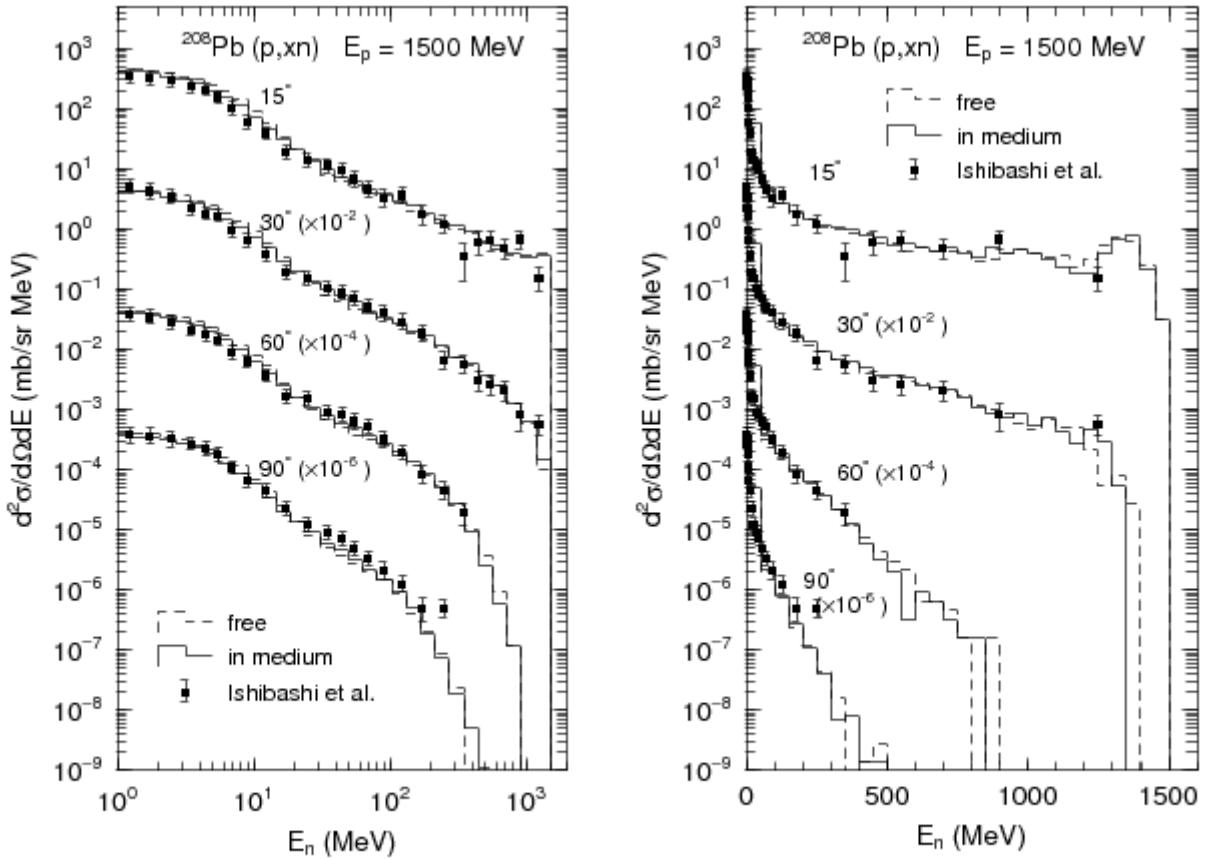


図 2.9: ^{208}Pb (p,xn) E_p = 1500 MeV 媒質効果

(p,n) reactions from thin target

核子-核子断面積の媒質効果

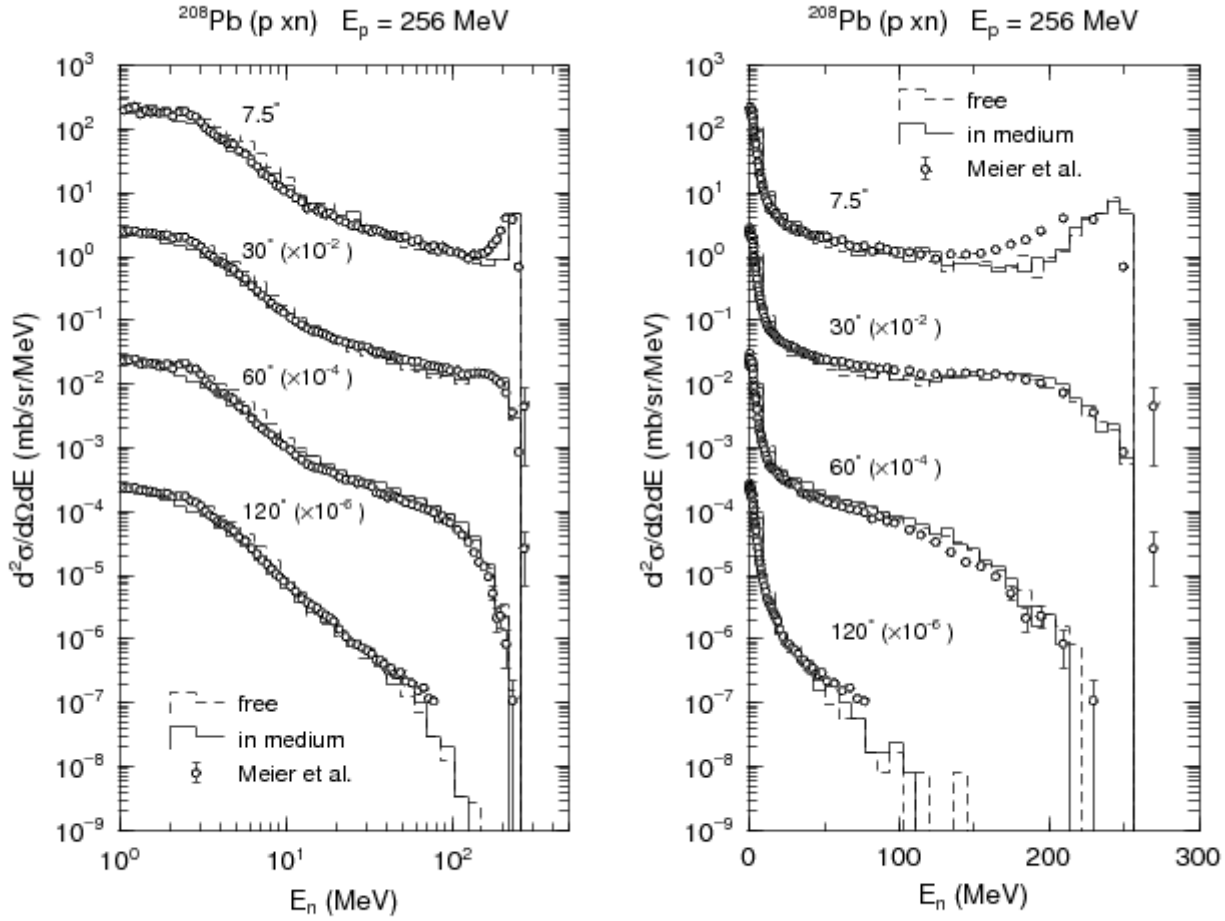
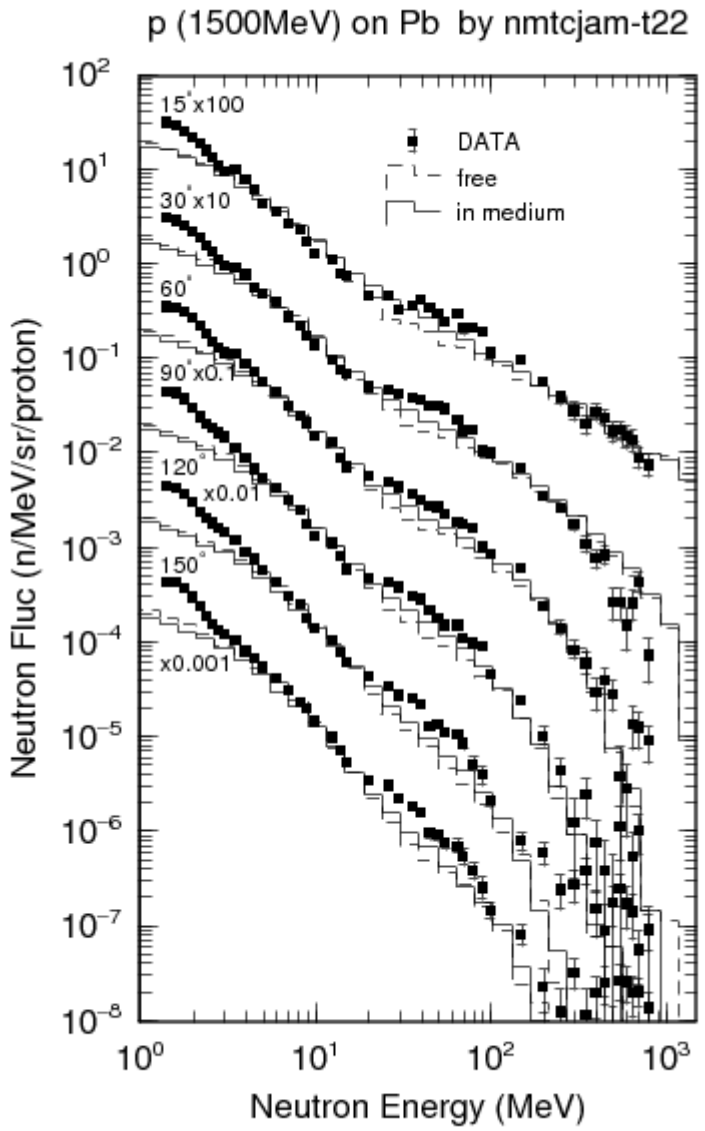


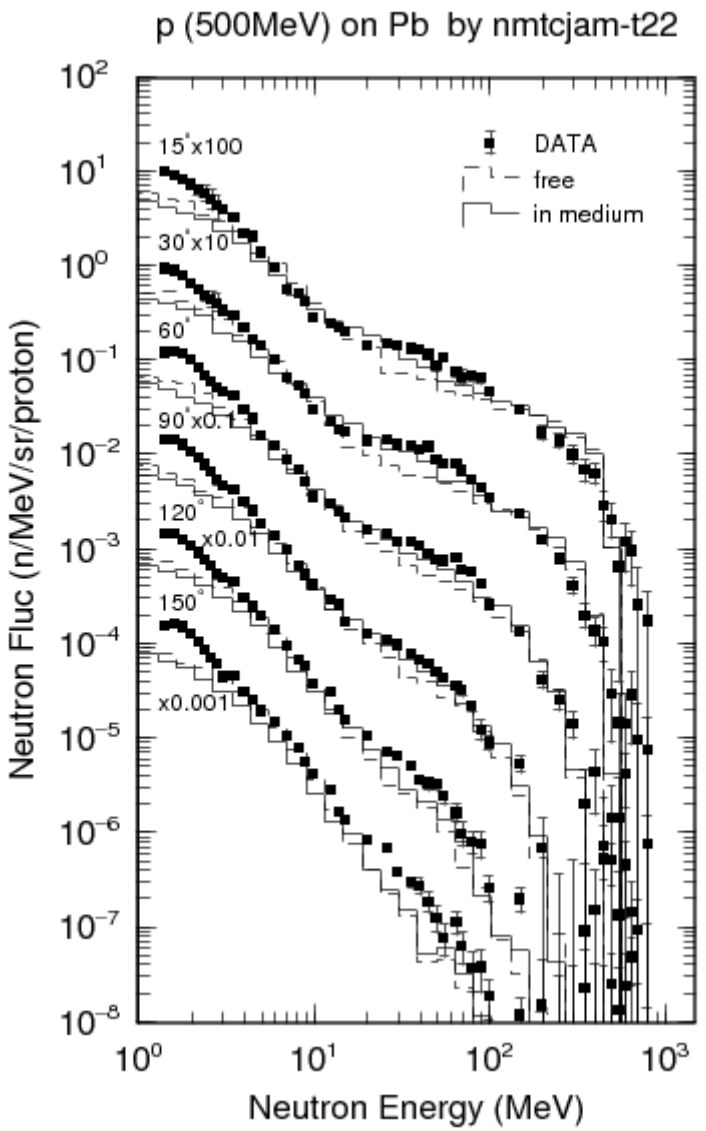
図 2.10: ^{208}Pb (p,xn) E_p = 256 MeV 媒質効果

(p,n) reactions from thick target

20 cm thickness

核子-核子断面積の媒質効果





Neutron flux in thick Fe target

500 cm radius, 600 cm thickness

核子-核子断面積の媒質効果

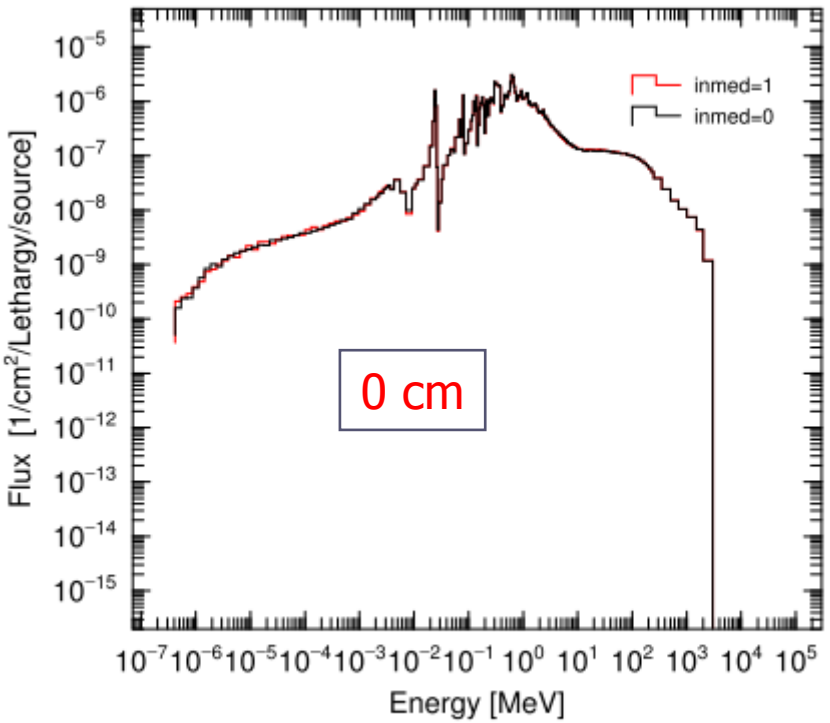


図 2.38: PHITS, 中性子、z = 0 cm

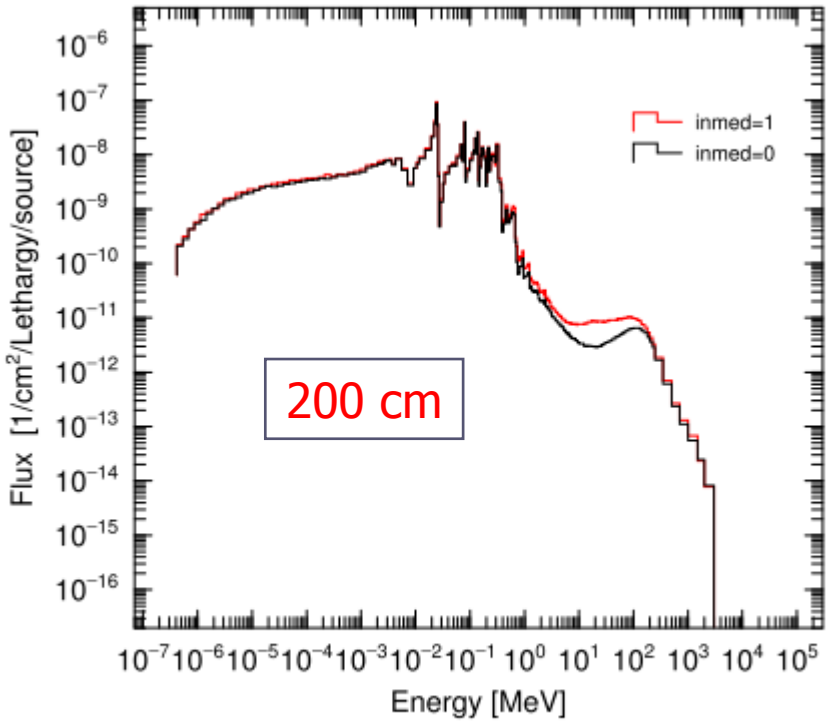


図 2.39: PHITS, 中性子、z = 200 cm

500 cm radius, 600 cm thickness

核子-核子断面積の媒質効果

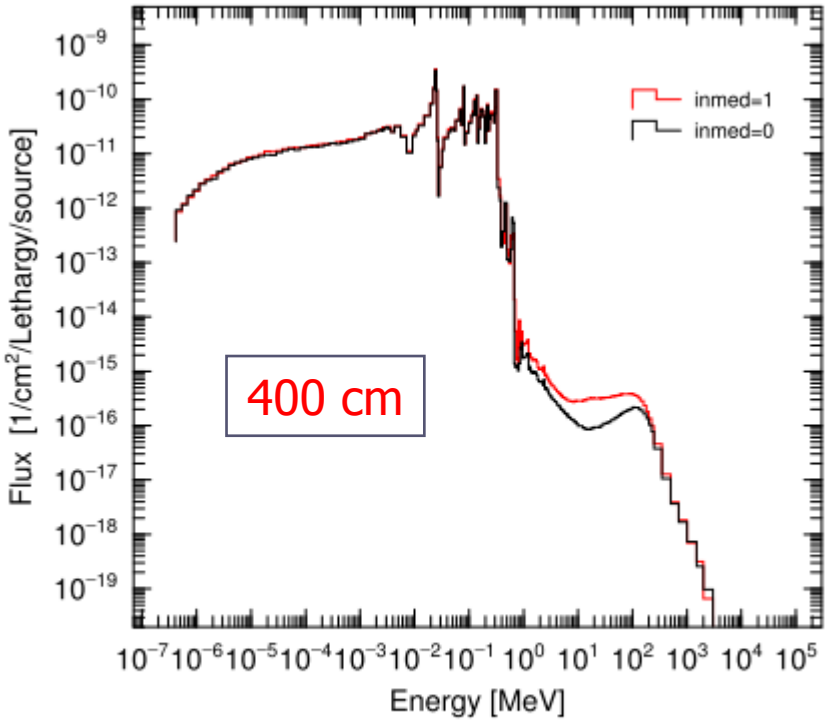


図 2.40: PHITS, 中性子、z = 400 cm

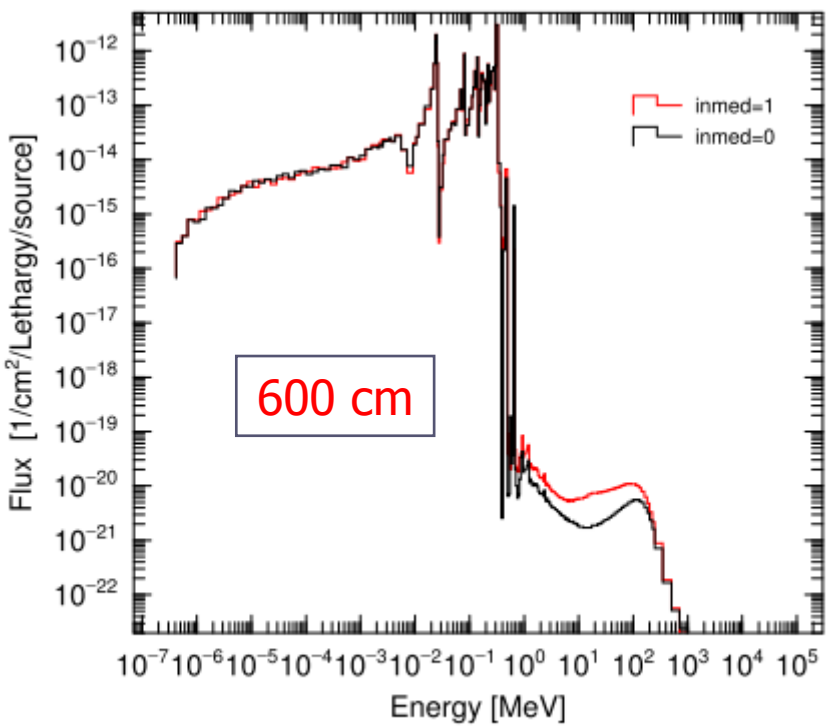
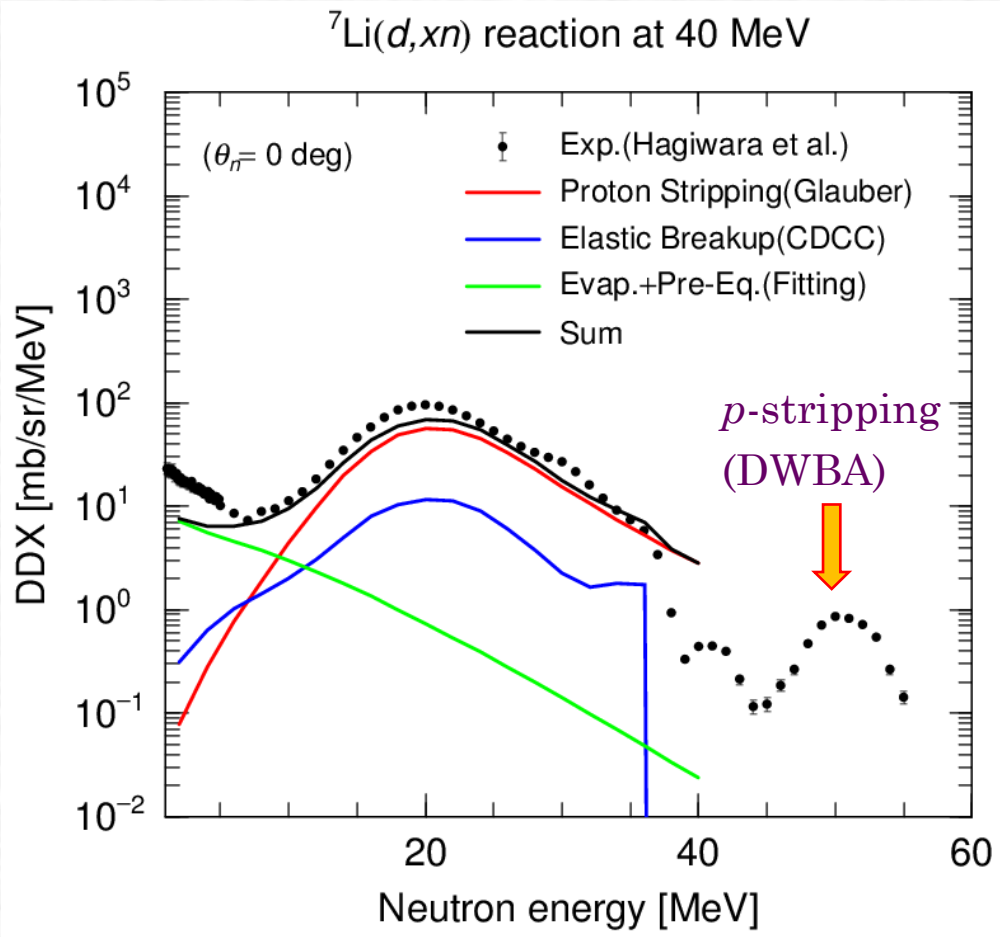


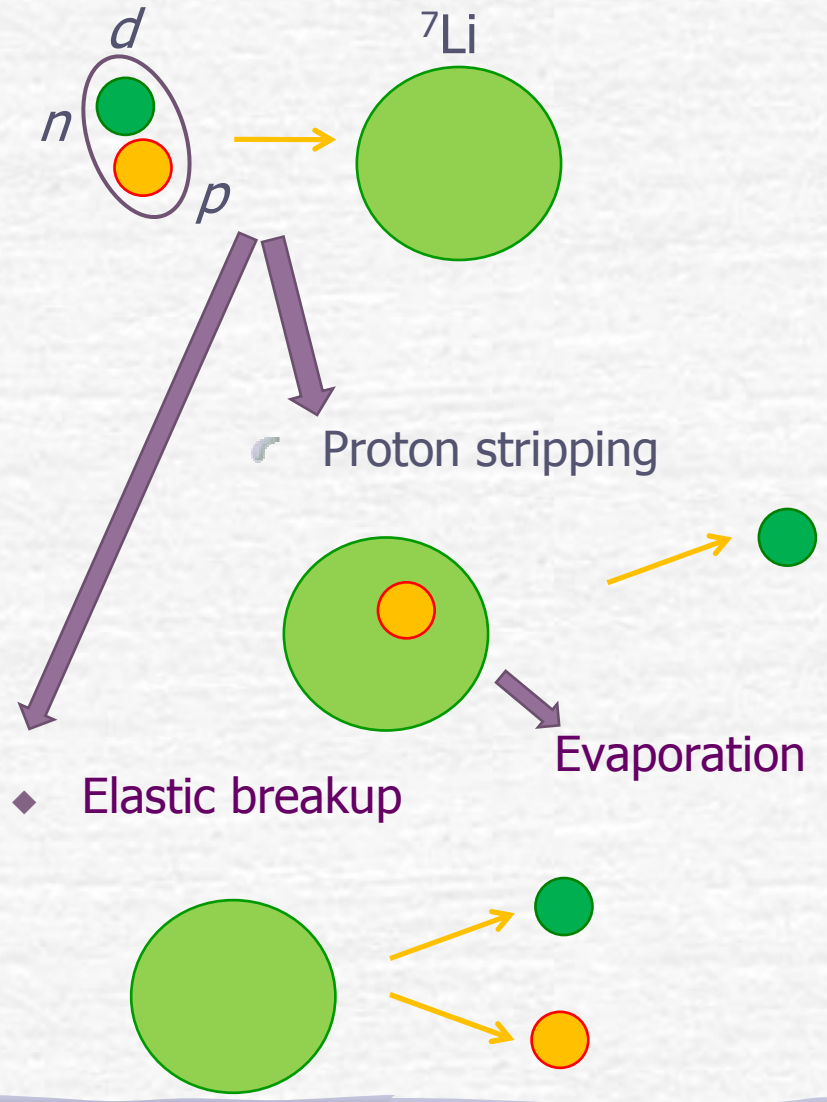
図 2.41: PHITS, 中性子、z = 600 cm

New event generator mode

by S. Hashimoto, JAEA

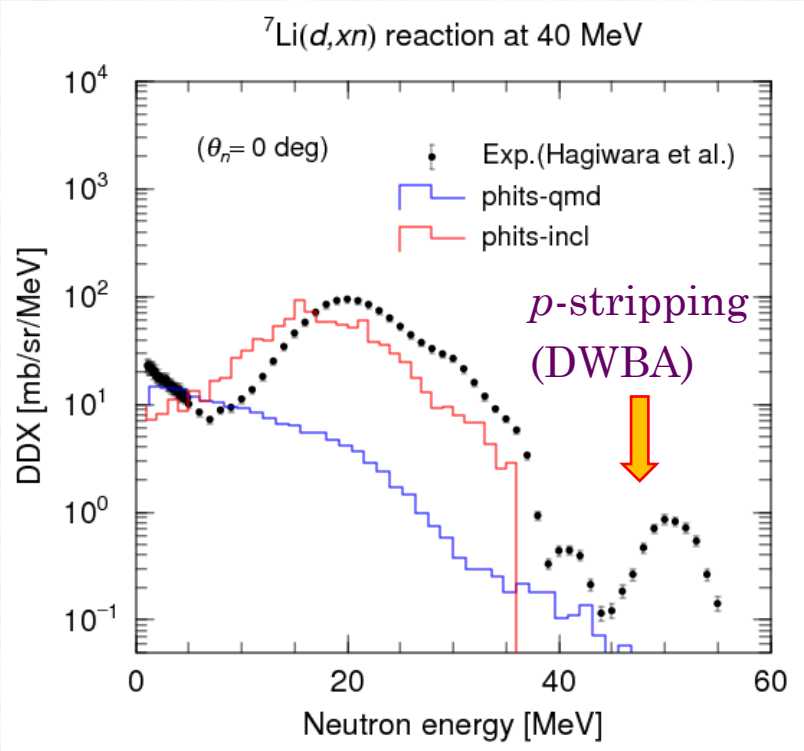


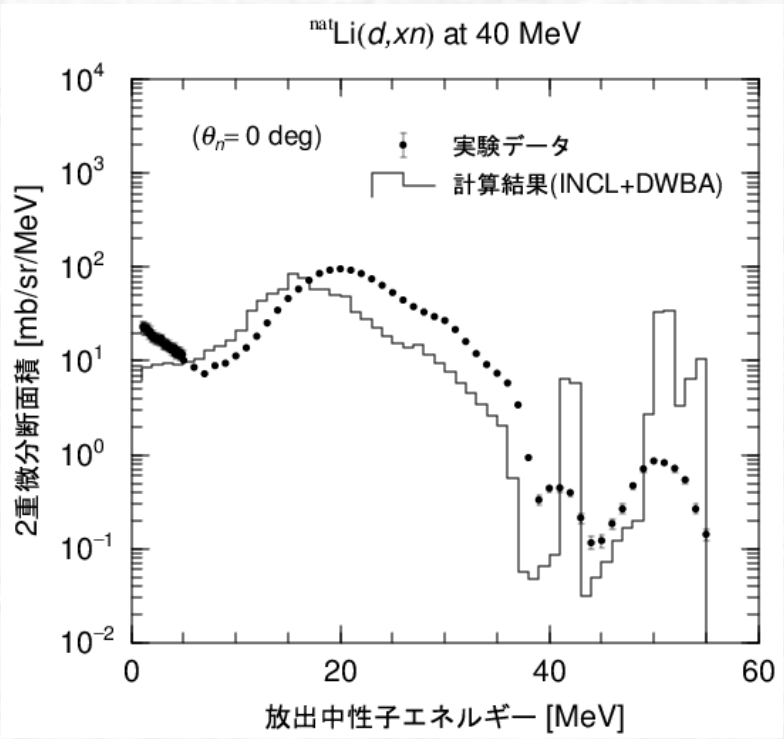
T. Ye, Y. Watanabe, K. Ogata, PRC80,014604(2009)



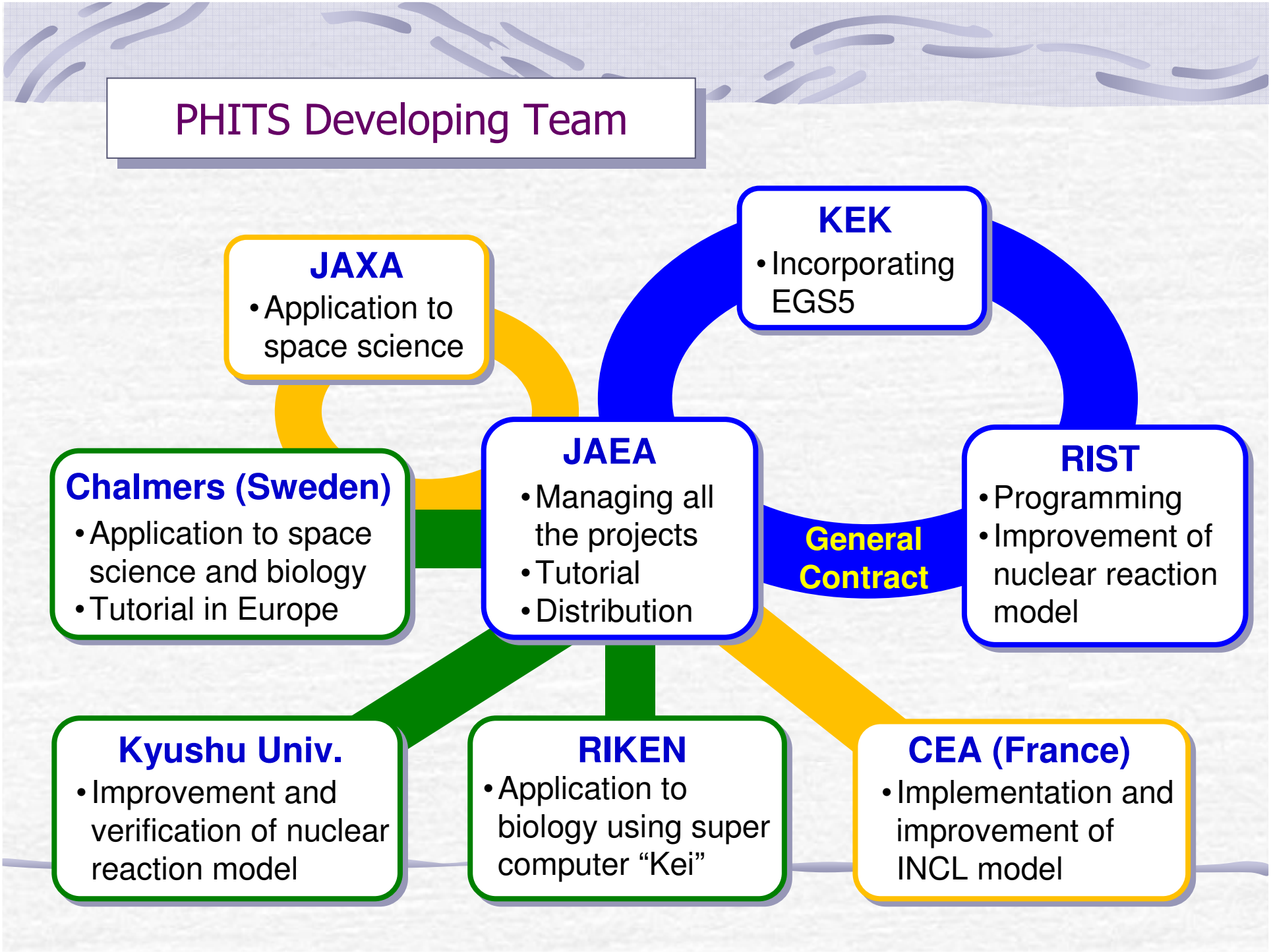
New event generator mode

Preliminary result
by S. Hashimoto, JAEA





PHITS Developing Team



PHITS Developing Team

- 仁井田浩二（RIST）：主プログラマー，核反応モデル改良
- 松田規弘（JAEA）：講習会・HP担当，DCHAIN-SP組込
- 橋本慎太郎（JAEA）：マニュアル担当，核反応モデル改良
- 岩元洋介（JAEA）：ML担当，DPA計算機能改良，核反応モデル検証実験
- 岩瀬広（KEK）：EGS5組込
- 佐藤達彦（JAEA）：開発とりまとめ，マイクロドジメトリ機能改良
- 中島宏（JAEA）：J-PARC遮へい評価，核反応モデル検証実験
- 坂本幸夫（JAEA）：ユーザー管理
- 深堀智生（JAEA）：核データライブラリ整備
- 千葉敏（JAEA）：核反応モデル改良
- Lembit Sihver（Chalmers, Sweden）：欧州普及担当，医療・宇宙への応用

将来の開発者（ポスドク）

- 野田秀作（JAEA）：光核反応モデル改良
- 太田周也（JAEA）：核反応モデル改良
- ？？？？（JAEA）：核反応モデル検証実験（現在募集中！）

How to get PHITS

- PHITS home page : → http://phits.jaea.go.jp/index.html

- How to get PHITS :
  from OECD/NEA Data Bank and RSICC of ORNL

  → http://www.oecd-nea.org/tools/abstract/detail/nea-1857/
  → http://www-rsicc.ornl.gov/codes/ccc/ccc7/ccc-778.html