Benchmarking PHITS for Heavy-Ion Reactions

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The NSCL is funded in part by the National Science Foundation and Michigan State University.

Acknowledgements

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  – Michigan State University
    - G. Bollen, I. Baek, V. Blideanu (now at CEA-Saclay), M. Hausmann, D. Lawton, P. Mantica, D.J. Morrissey, R.M. Ronningen (PI), B.S. Sherrill, A. Zeller

  – Oak Ridge National Laboratory
    - J.R. Beene, T. Burgess, K. Carter, A. Carrol, D. Conner, T. Gabriel, L. Mansur, I. Remec, D. Stracener, M.Wendel

  – Lawrence Livermore National Laboratory
    - L. Ahle, J. Boles, S. Reyes, W. Stein, M. Stoyer

  – Lawrence Berkeley National Laboratory
    - L. Heilbronn

  – Argonne National Laboratory
    - T. Levand, Y. Momozaki, J. Nolen, C. Reed, and I. Gomes (consultant)

  – GSI
    - H. Geissel and H. Iwase

*Code runners

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Outline of Presentation

Benchmarking PHITS Examples:

- **Comparison between Simulation Results using PHITS and Experimental Data from Heavy Ion Reactions**
  - **Neutron Production**
  - **Neutron Transport Through Thick Shields**
  - **Magnetic Field Capabilities**
  - **Cross Sections for Projectile Fragmentation**
- **Summary**

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Challenging Requirements for Codes and Simulations

- P, n, d, and ion transport (through uranium), their interactions in the targets, beam dumps, magnets, *etc.,* required
  - Transport in magnetic fields required
  - In some cases, charge state distributions should be considered
- Calculation of isotope yields, energy deposition, and radiation damage
- Determination of the radiation fields, dose levels, and shielding requirements during operation
- Calculation of radioactive inventory build-up in the target, post-operation decay heat, and dose rates
    - PHITS/PHITS+DCHAINSP2001 have been meeting our project requirements
- Determination of cooling requirements and stress analysis
- Simulation of rare isotopes “extraction” from the target and transport to the experiments

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Buy This Book!

HANDBOOK ON SECONDARY PARTICLE PRODUCTION AND TRANSPORT BY HIGH-ENERGY HEAVY IONS
(With CD-Rom)

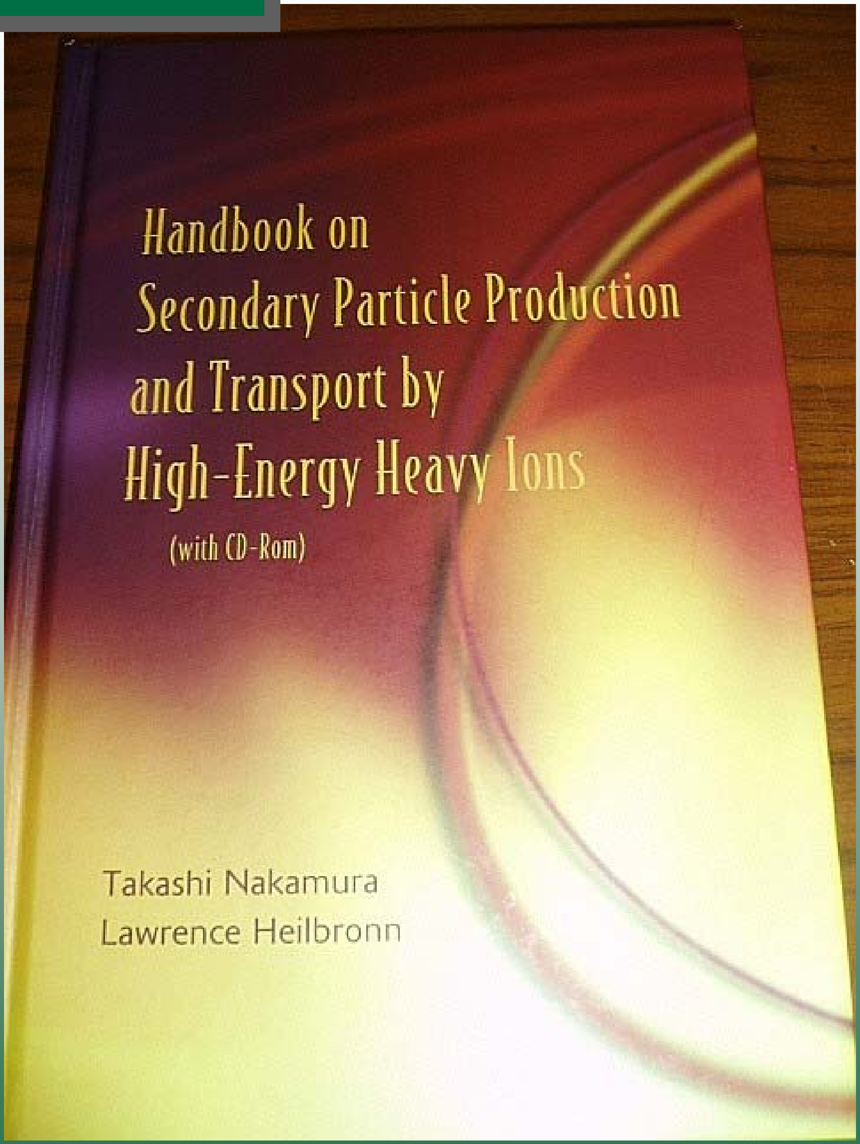
by **Takashi Nakamura** *(Tohoku University, Japan)* **& Lawrence Heilbronn** *(Lawrence Berkeley National Laboratory, USA)*

ISBN 981-256-558-2

World Scientific

www.worldscientific.com

236pp
Pub. date: Dec 2005
US$58 / £33



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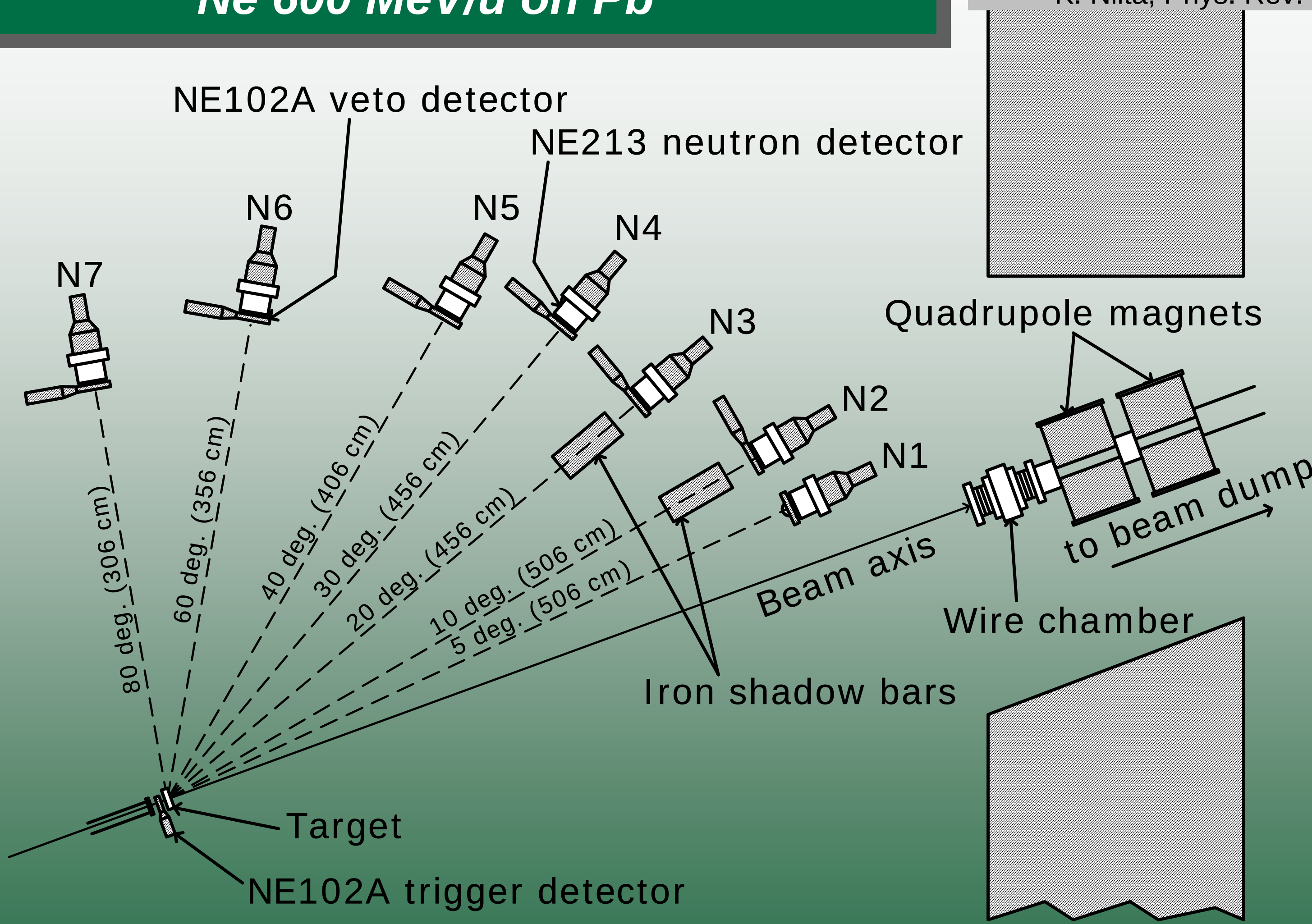
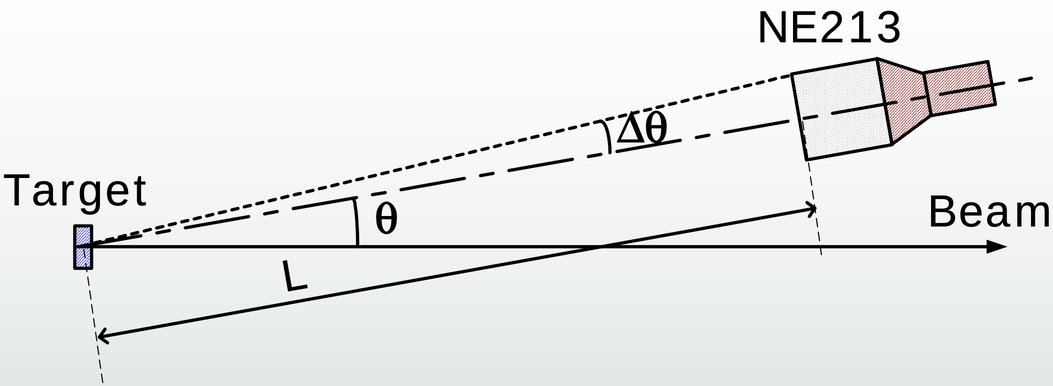
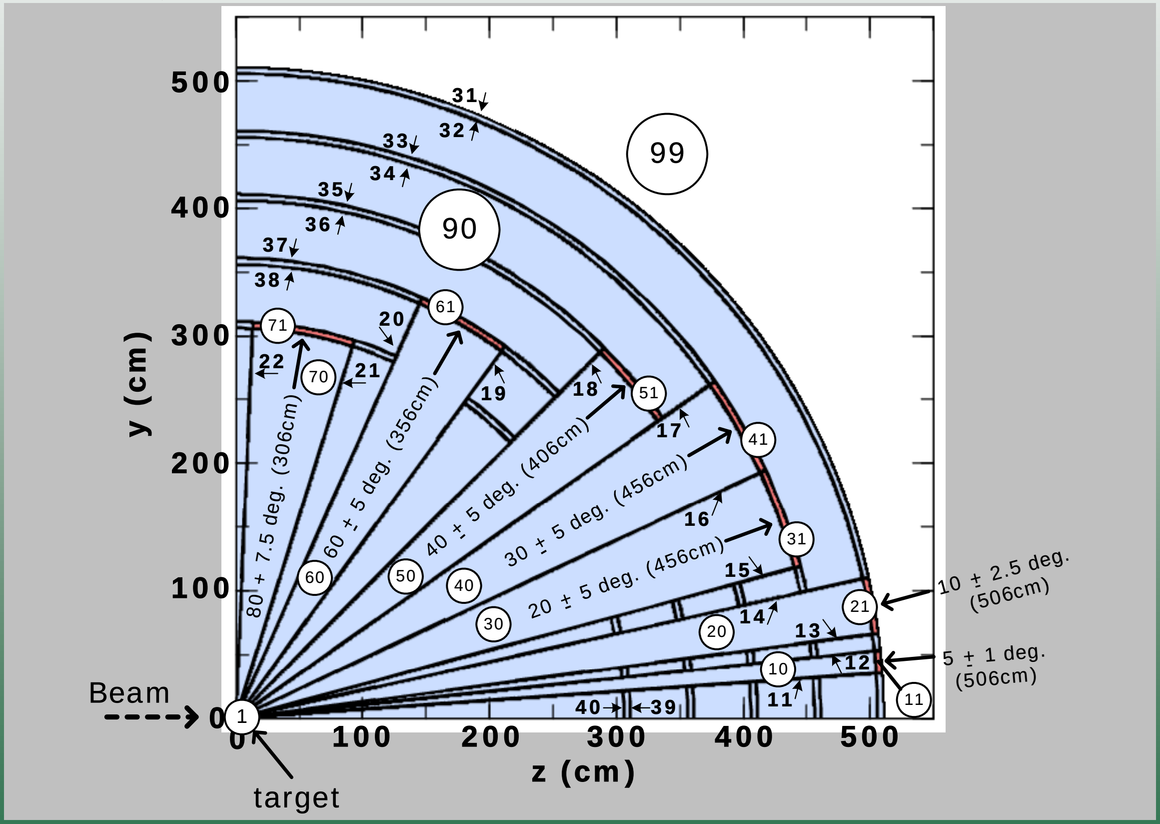
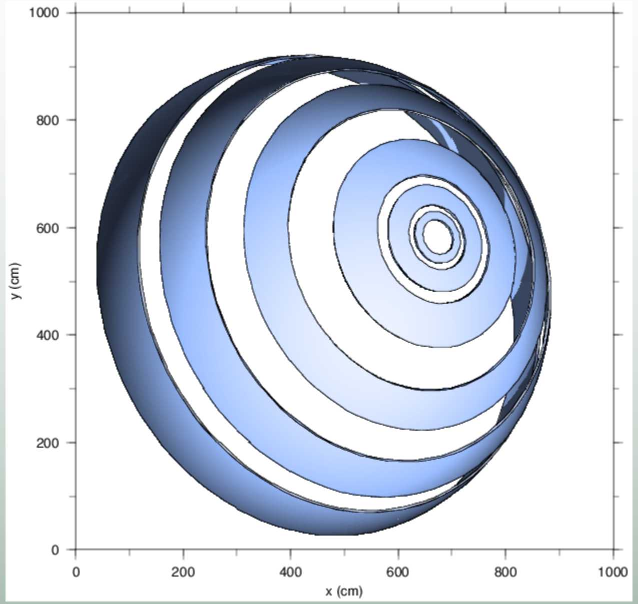
Textbook Example in Handbook: Iwata et al. Experiment: Ne 600 MeV/u on Pb

Y. Iwata, T. Murakami, H. Sato, H. Iwase, T. Nakamura, T. Kurosawa, L. Heilbronn, R.M. Ronningen, K. Ieki, Y. Tozawa, and K. Niita, Phys. Rev. C **64**, 054609(2001).

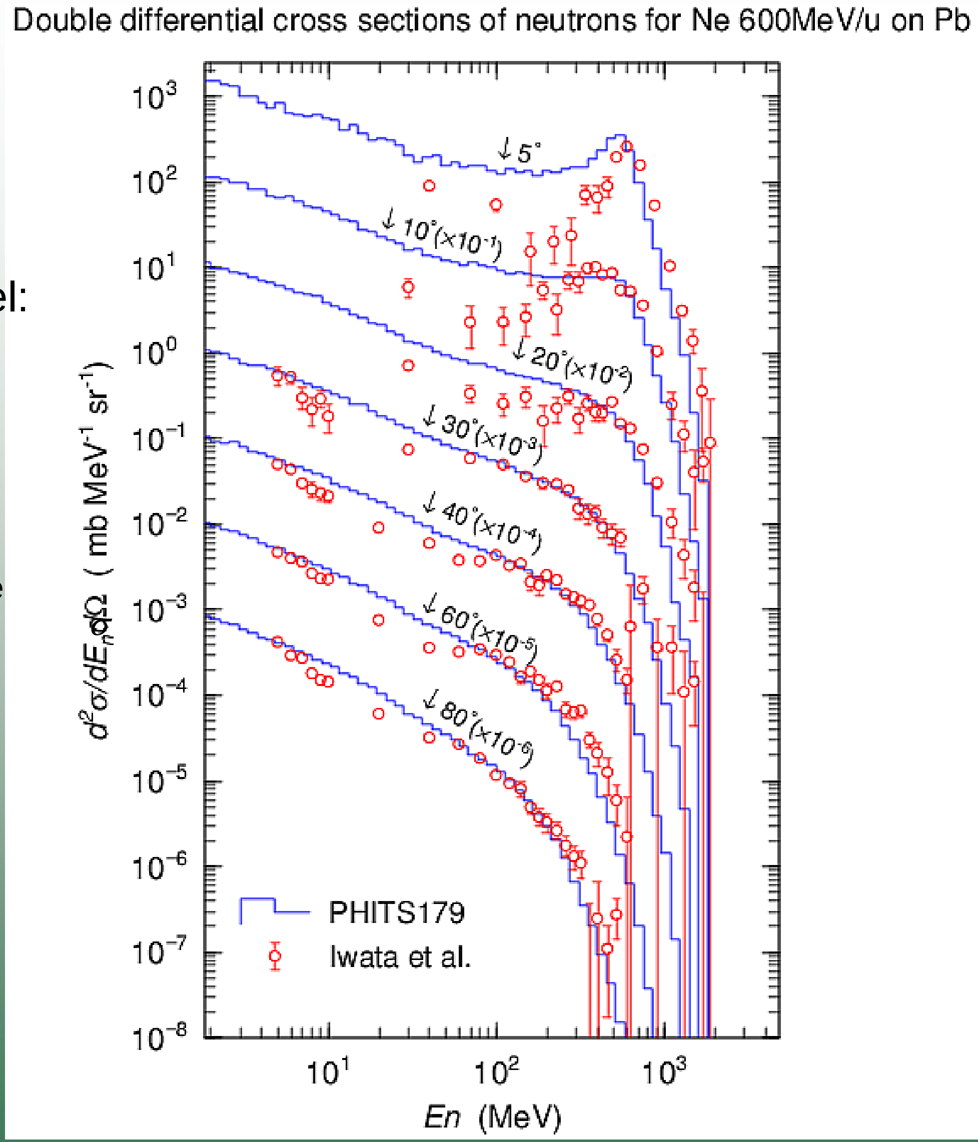



NE213
Target
Δθ
θ
Beam
L


y (cm)
z (cm)
Beam
target
99
90
80 ± 7.5 deg. (306cm)
60 ± 5 deg. (356cm)
40 ± 5 deg. (406cm)
30 ± 5 deg. (456cm)
20 ± 5 deg. (456cm)
10 ± 2.5 deg. (506cm)
5 ± 1 deg. (506cm)


y (cm)
x (cm)

Y. Iwata, T. Murakami, H. Sato, H. Iwase, T. Nakamura, T. Kurosawa, L. Heilbronn, R.M. Ronningen, K. Ieki, Y. Tozawa, and K. Niita, Phys. Rev. C **64**, 054609(2001).



Simple Picture – “Moving Source” Model:

1. Projectile breakup (< 20°, ~ beam velocities)

$$\frac{d^2\sigma}{p_c^2 dp_c d\Omega_c} = N \exp\left(-\frac{p_c^2}{2\sigma^2}\right)$$

p_c is neutron momentum in rest frame of source

σ related to internal momentum of nucleons within source

+

2. Breakup of decaying overlap region

+

3. Decay of target remnant (< ~ 20 MeV)

2. & 3. - $$\frac{d^2\sigma}{p_c^2 dp_c d\Omega_c} = \frac{N}{(2\pi T)^{3/2}} \exp\left(-\frac{p_c^2}{2mT}\right)$$

HIMAC Experiment (NIRS, Chiba, Japan) 10P012 Collaboration

- **LBNL:** L. Heilbronn, C. Zeitlin
- **NIRS:** Y.Iwata, T. Murakami
- **Tohoku University:** T. Nakamura, H. Iwase, H. Sato, E. Mihara
- **Rikkyo University:** K. Ieki, Y. Tozawa
- **Electrotechnical Lab:** T. Kurosawa

Beams:

^{4}He @ 230 MeV/u

N, Kr, Xe @ 400 MeV/u

Fe @ 500 MeV/u

Ne @ 600 MeV/u

Targets:

CH_2, Li, C, Al, Cu, Pb

Secondary Neutron-Production Cross Sections from Heavy-Ion Interactions between 230 and 600 MeV/nucleon

L. Heilbronn, C. J. Zeitlin, Y. Iwata, T. Murakami, H. Iwase, T. Nakamura, T. Nunomiya, H. Sato, H. Yashima, R.M. Ronningen, and K. Ieki

Submitted to Nuclear Science and Engineering (August, 2006)

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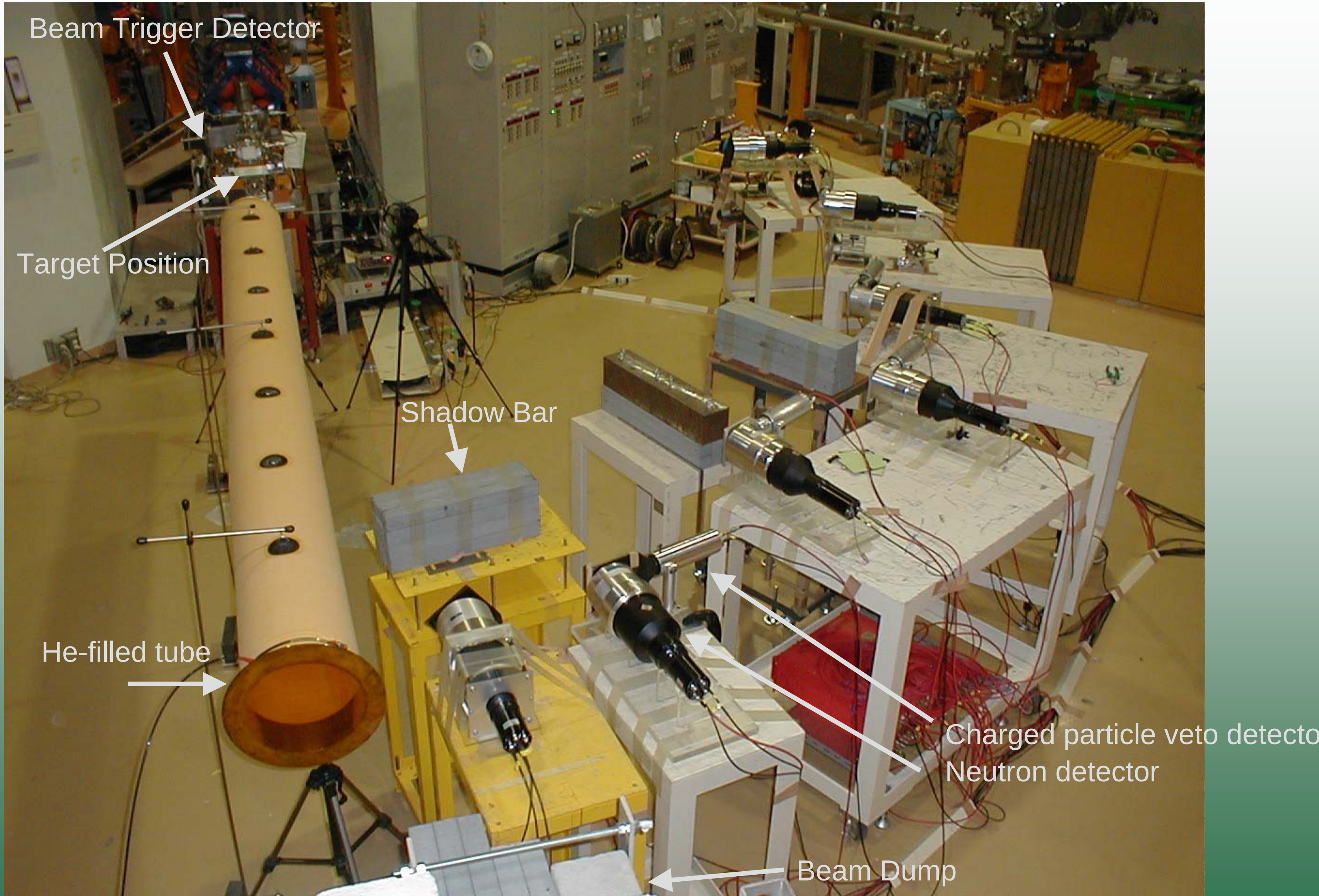

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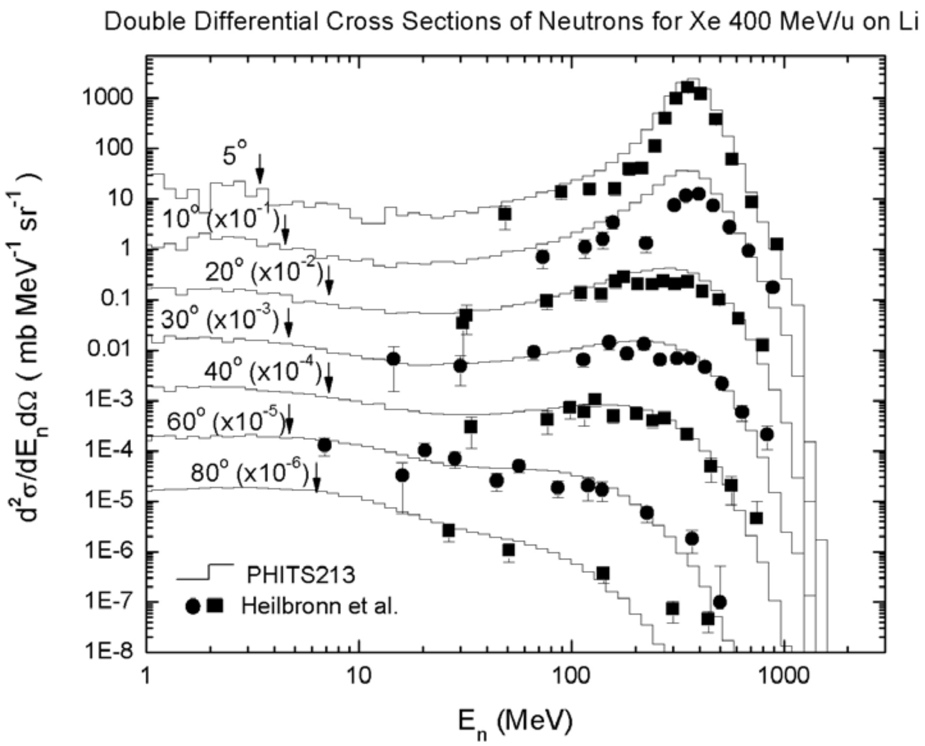
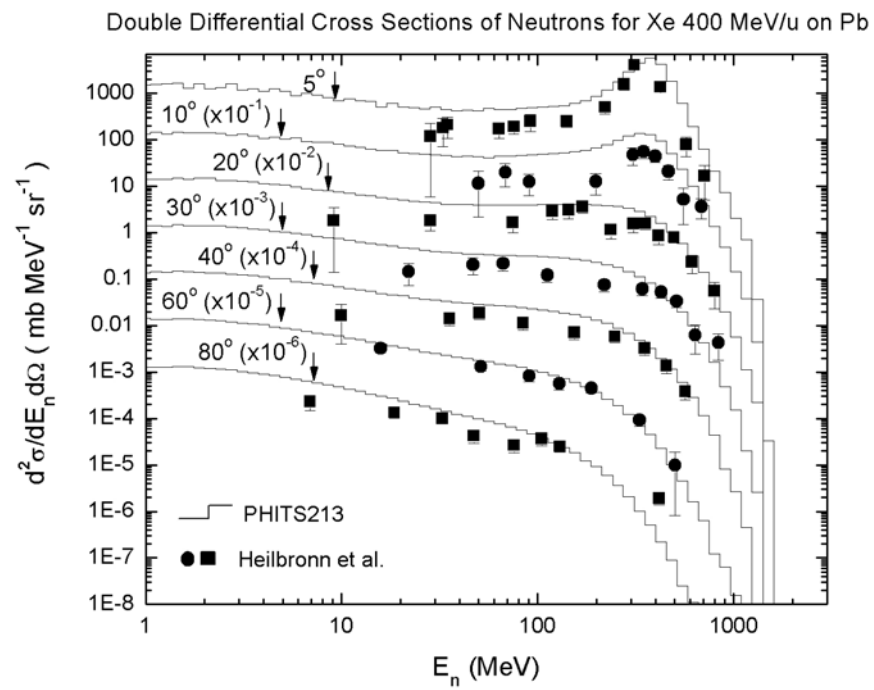


Preliminary:

- Target, detector array in vacuum
- No helium tube
- Data uncorrected for neutron attenuation (in target, in air)



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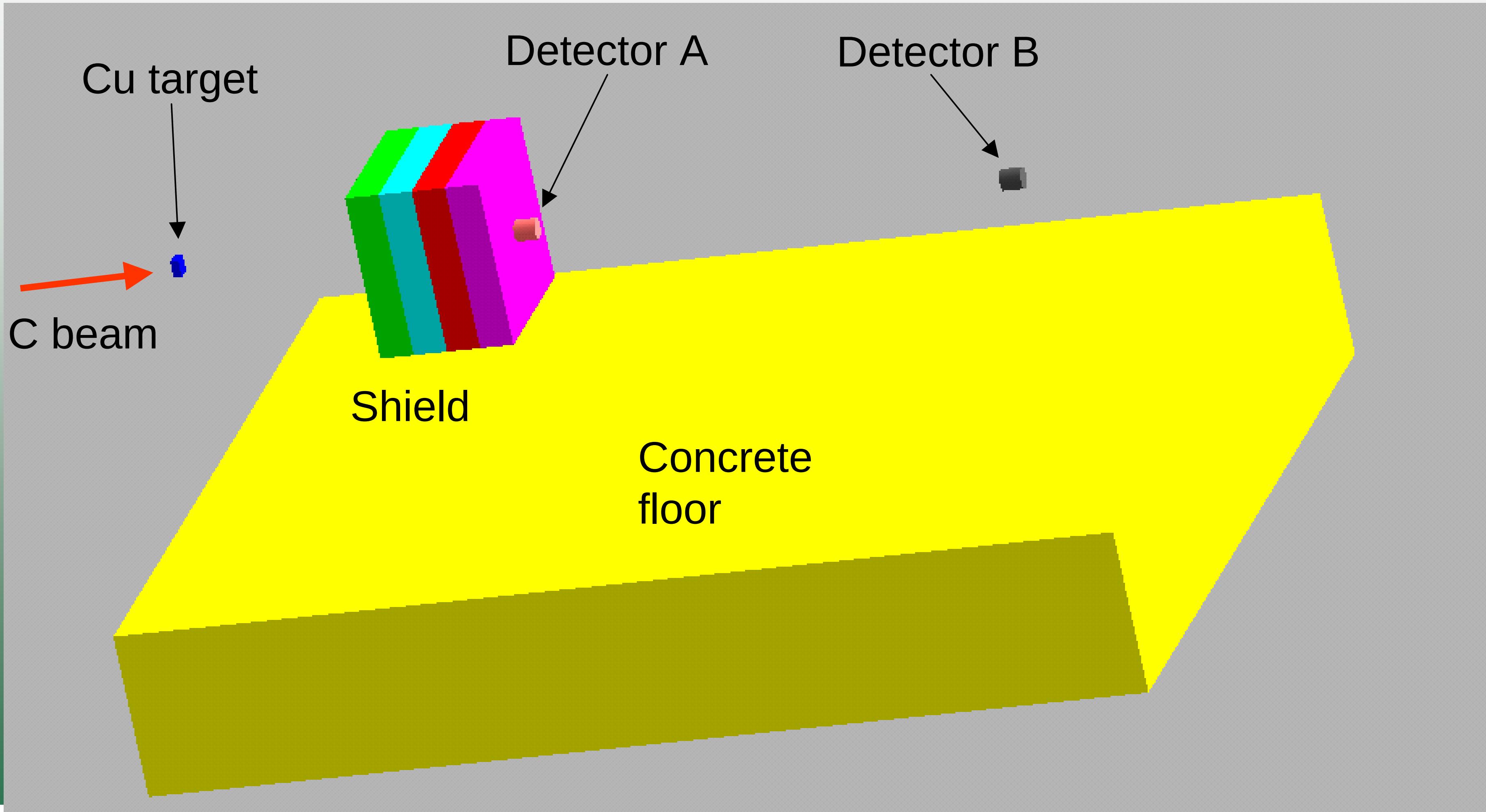
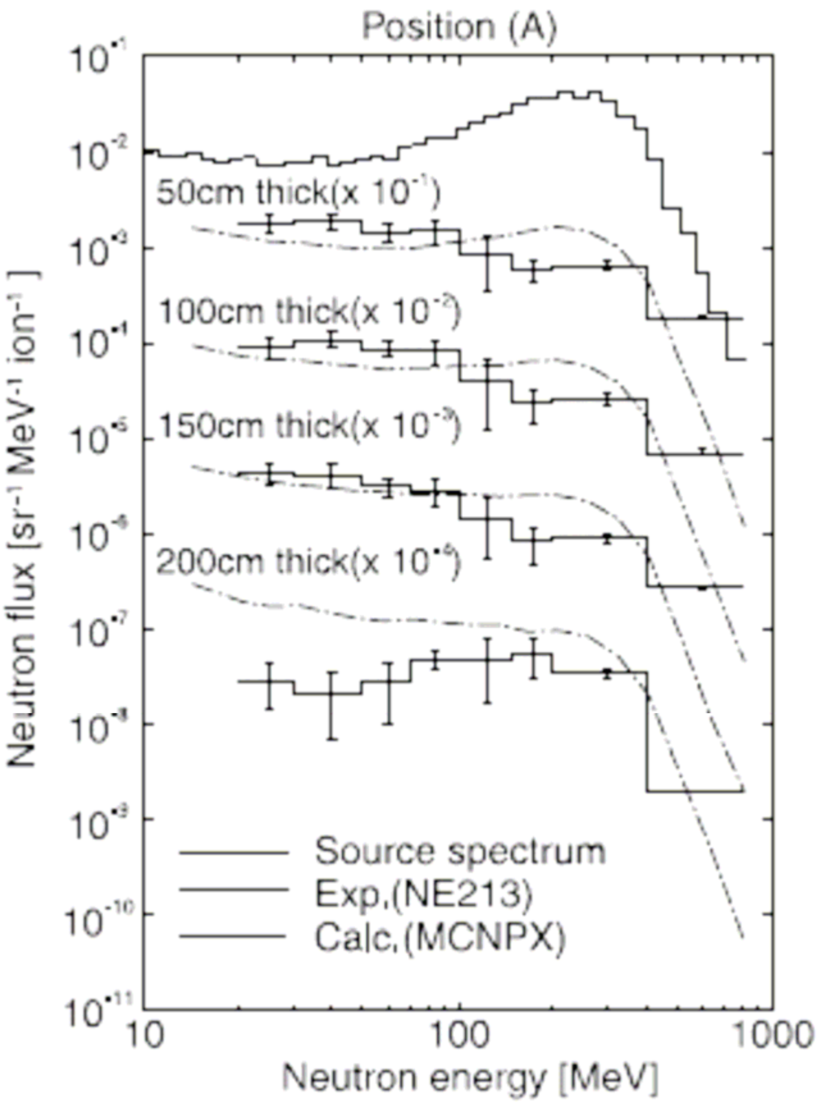
Benchmarking PHITS against Experimental Data on Neutrons Behind Thick Shields – Susana Reyes (LLNL)

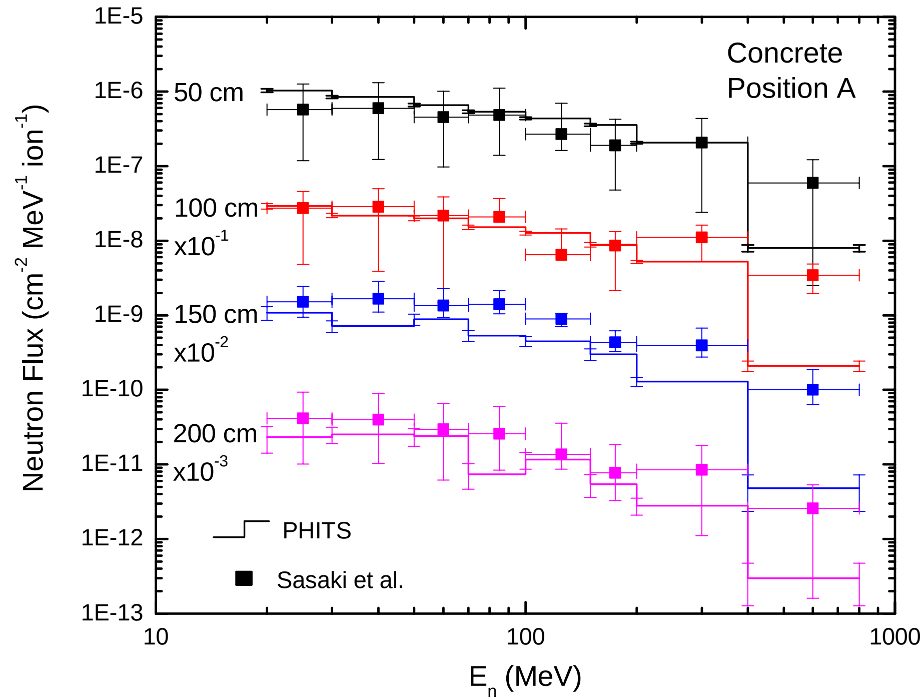
- Data on neutron spectra behind thick shields of iron and concrete:
  - M. Sasaki, E. Kim, T. Nunomiya, T. Nakamura, N. Nakao, T. Shibata, Y. Uwamino, S. Ito, and A. Fukumura, Nucl. Sci. Eng. 141, 140 (2003)
  - M. Sasaki, N. Nakao, T. Nunomiya, T. Nakamura, A. Fukumura, and M. Takada, Nucl. Instrum. Meth. B 196, 113 (2003)
- Ion beam is 400 MeV/nucleon C, on Cu stopping target (5 cm thick, 10x10 cm square)
- Concrete blocks are 50 cm thick, 100x100 cm^2, spectra measured for 50, 100, 150 and 200 cm shielding
- Iron blocks are 20 cm thick, 100x100 cm^2, spectra measured for 20, 40, 60, 80 and 100 cm shielding
- Neutron spectra measured by Ne213 detector
  - position A: directly behind downstream side of last shielding block
  - position B: 498 cm downstream from target

Geometry for the PHITS Simulation



Concrete shielding, detector in position A





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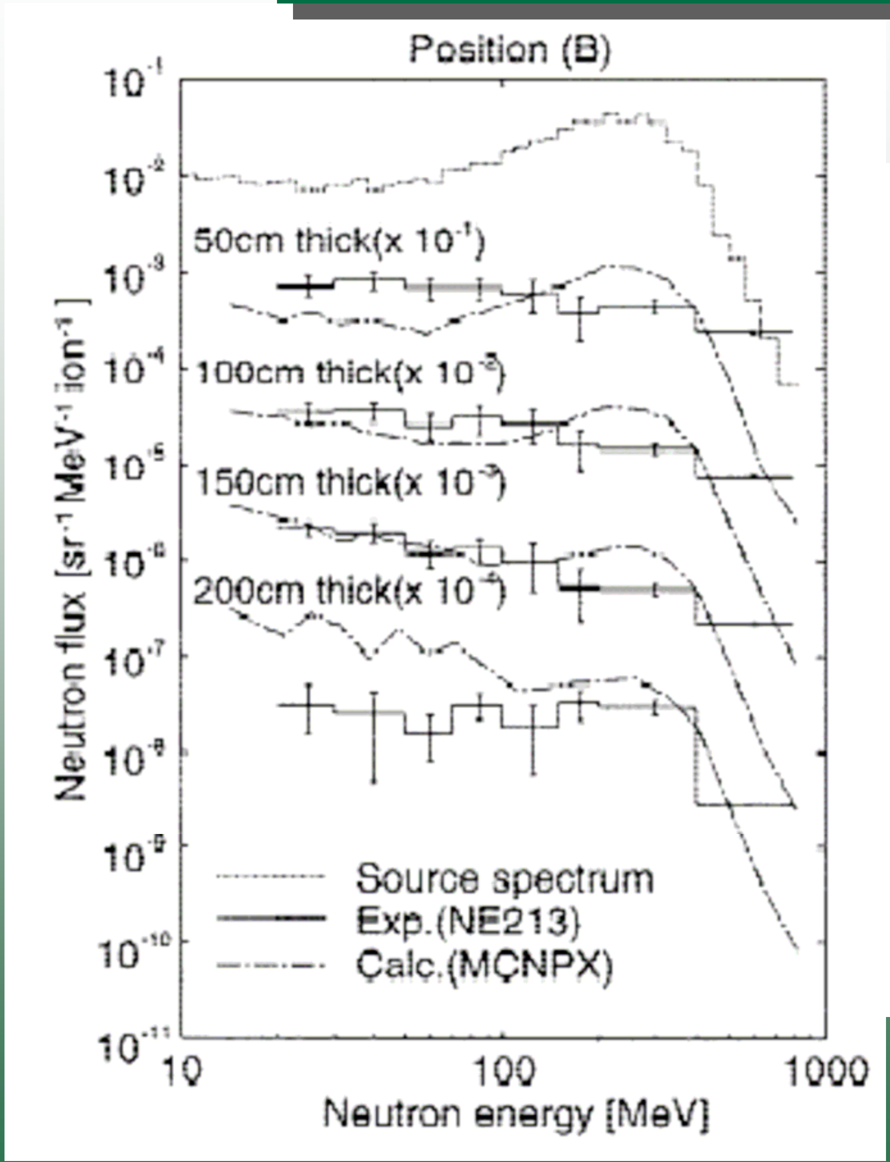
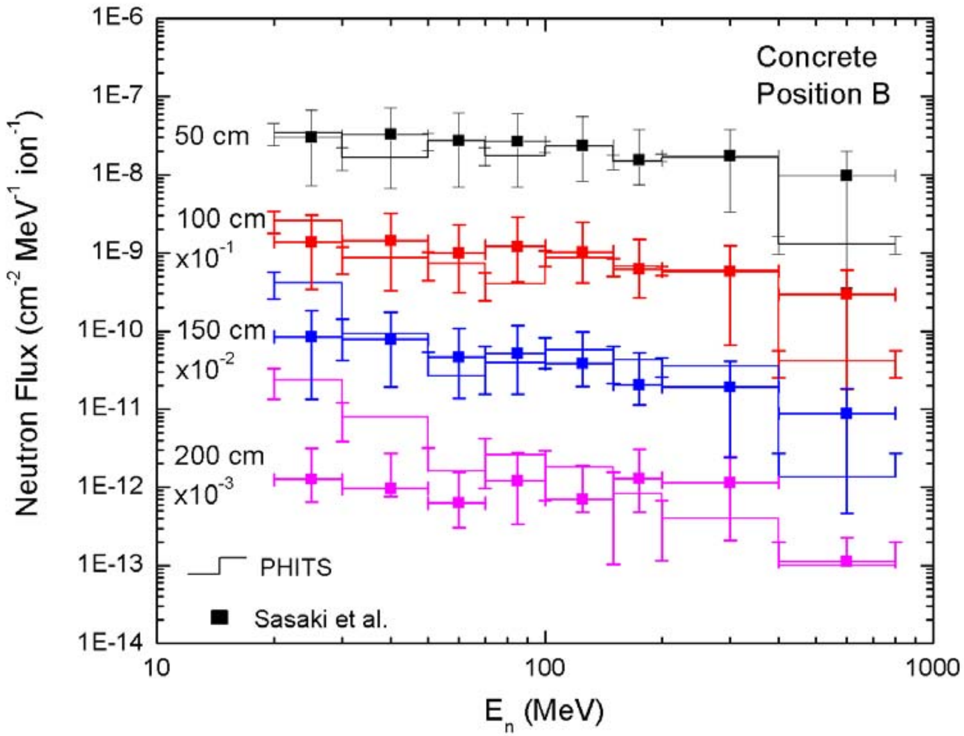
Concrete shielding, detector in position B





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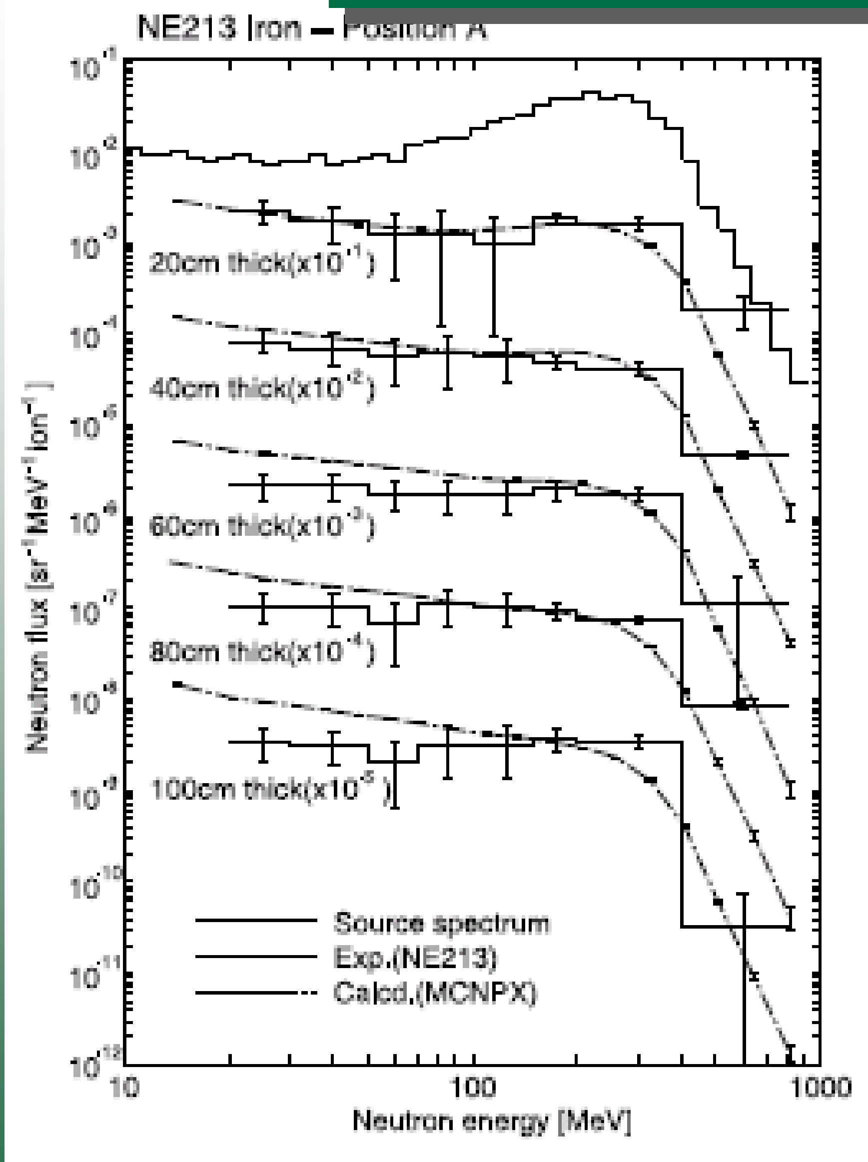
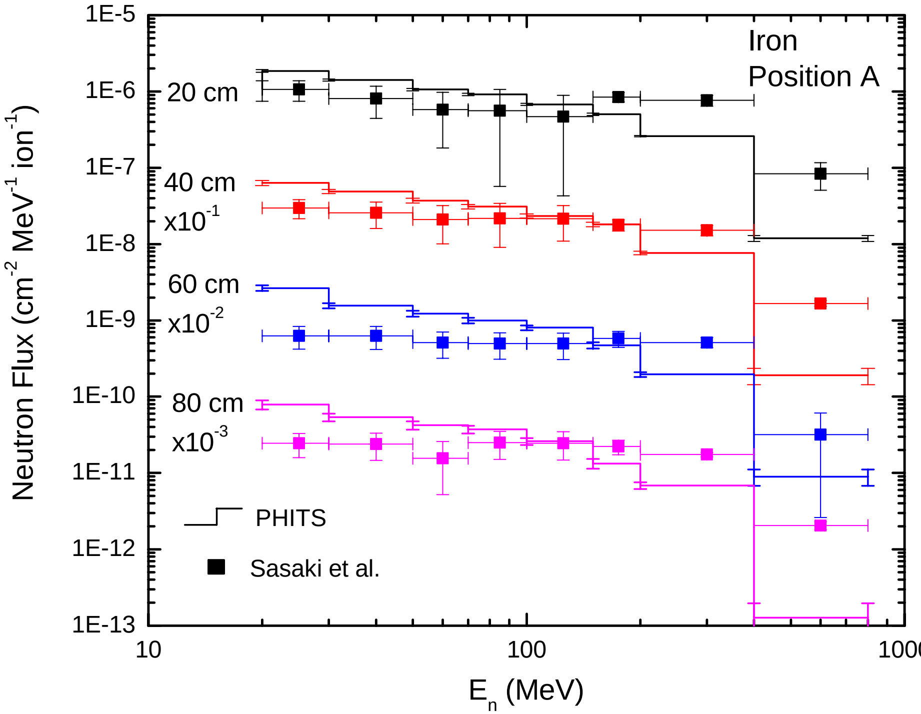
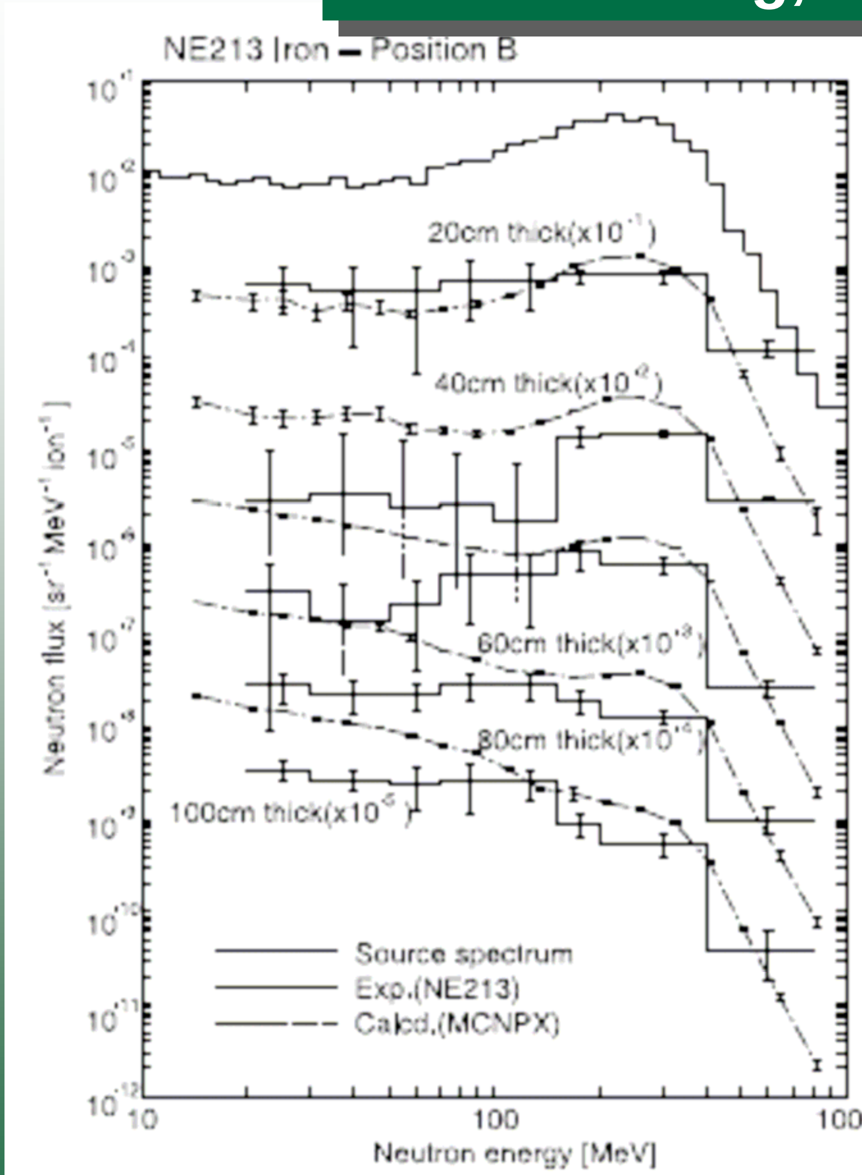
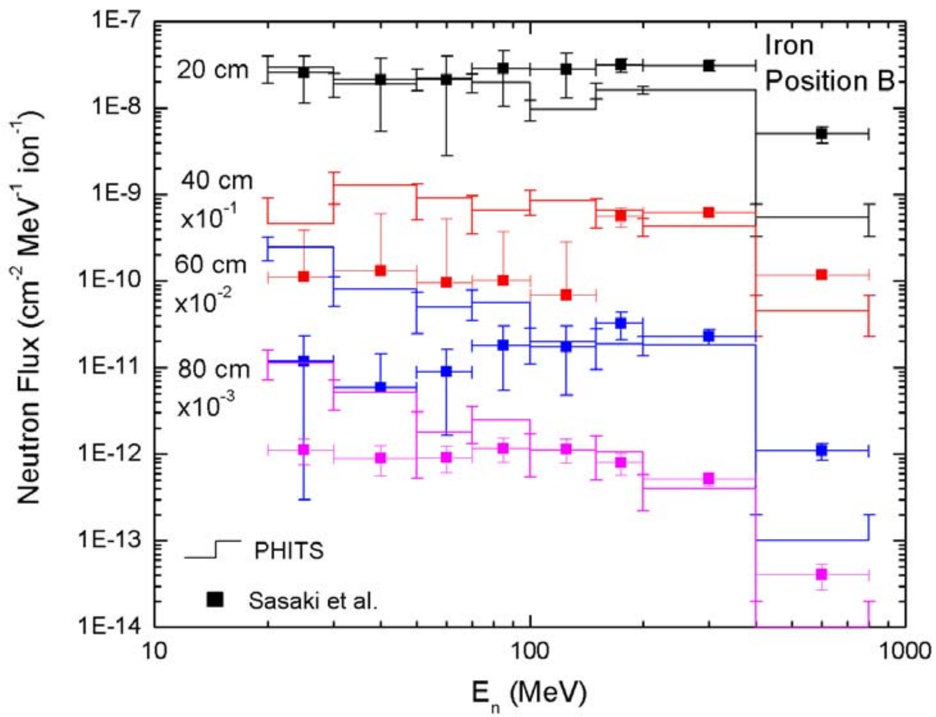
Iron shielding, detector in position A





Iron shielding, detector in position B





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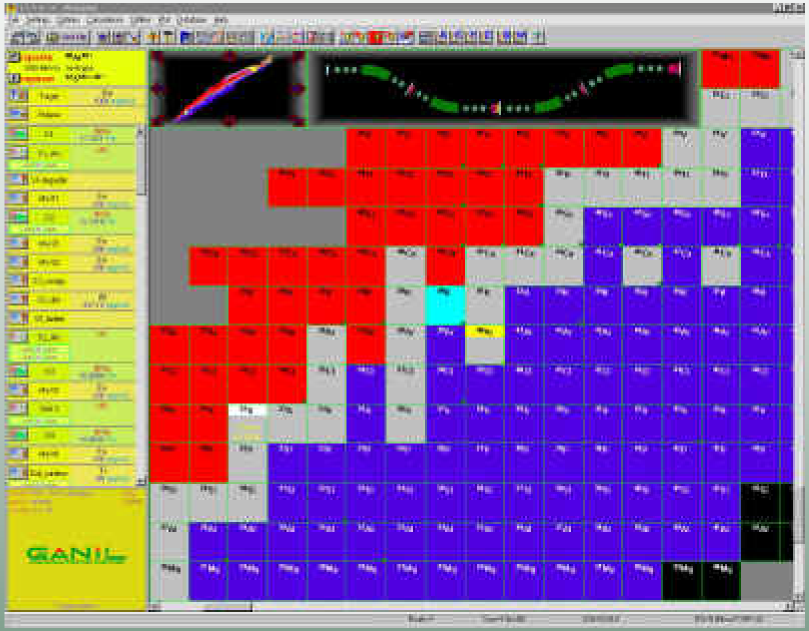
Evaluating the Dipole Magnetic Field Option of PHITS for a Heavy Ion Beam

- LISE++ for "optimized Li target" for production of ^{26}Ne fragments
  - ^{86}Kr beam at 500 MeV/u
  - Target thickness is 9.6 cm
    - "optimized" for fragment
    - (Thick! 38% energy loss)
  - Dipole set to 2.5806 T with Bρ = 8 Tm
    - "This is just a test"-not operationally useful!
- PHITS
  - 86Kr beam at 500 MeV/u
  - 1 mm diameter
  - Simple cylindrical target in vacuum "pipe"
  - Box "dipole" with 2.5806 T field
  - 10,000 source particles
- Track-Crossing
  - XYZ mesh
    - To obtain fragment trajectories in magnetic field
- Surface Crossing
  - Region mesh
    - To obtain numbers of fragments leaving target

LISE++



Oleg Tarasov and Daniel Bazin

Nucl. Phys. **A** 746 (2004)411

http://groups.nscl.msu.edu/lise

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From Michal Mocko *et al.*, Michal's Ph.D. Thesis (MSU), Sept. 2006

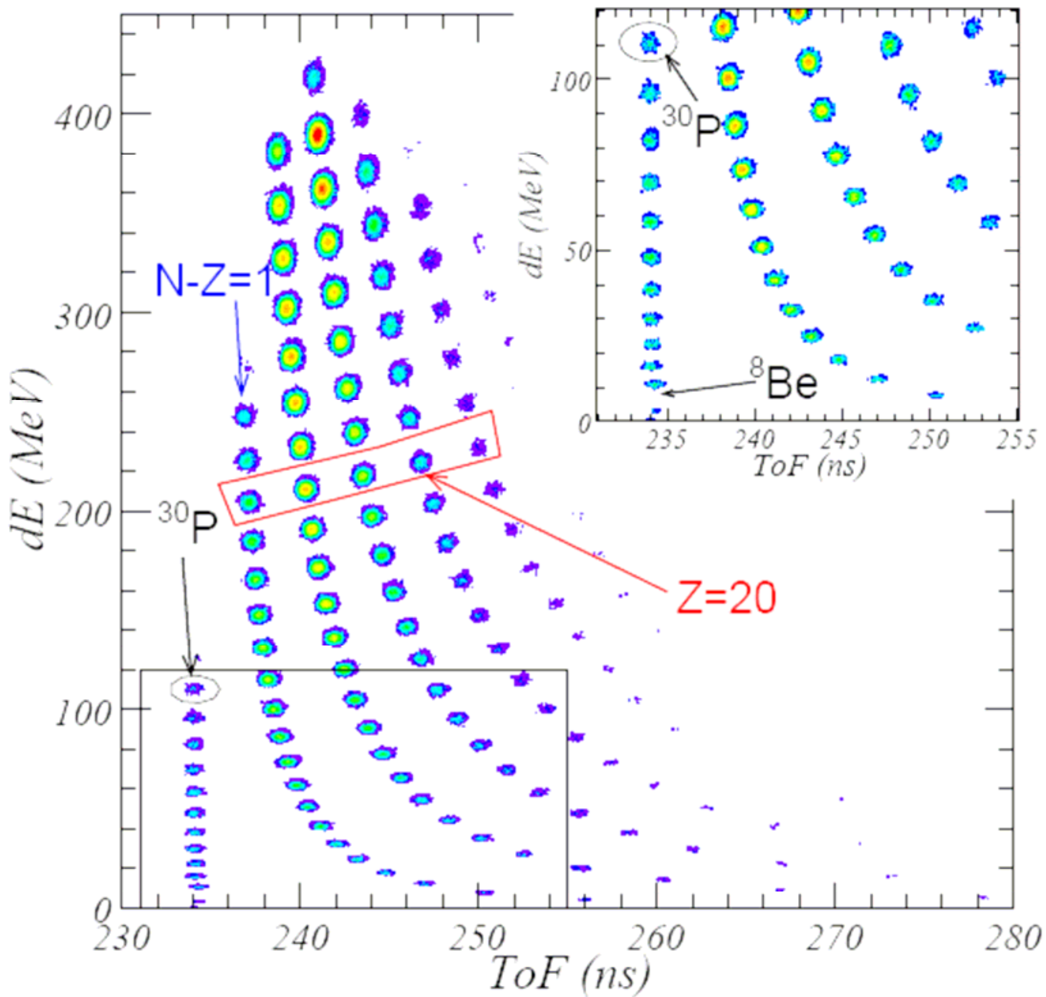
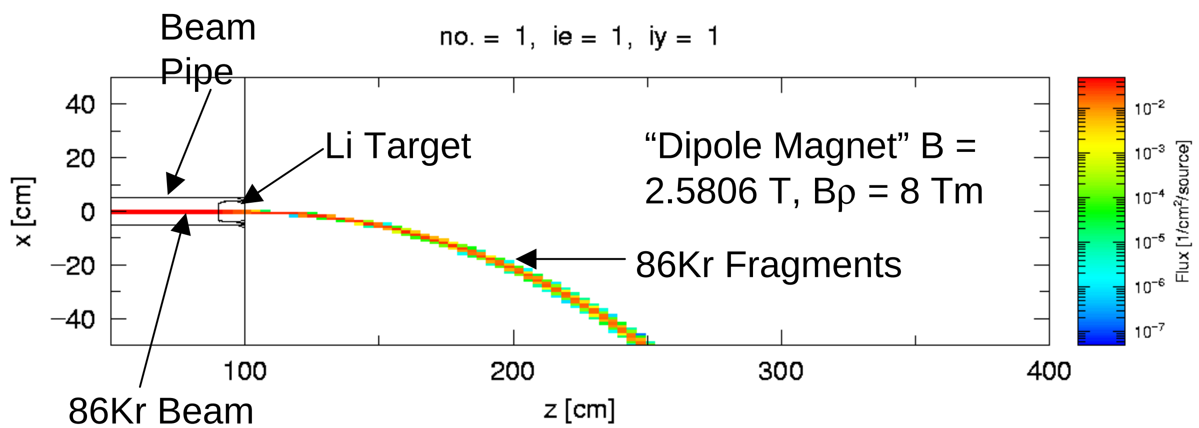
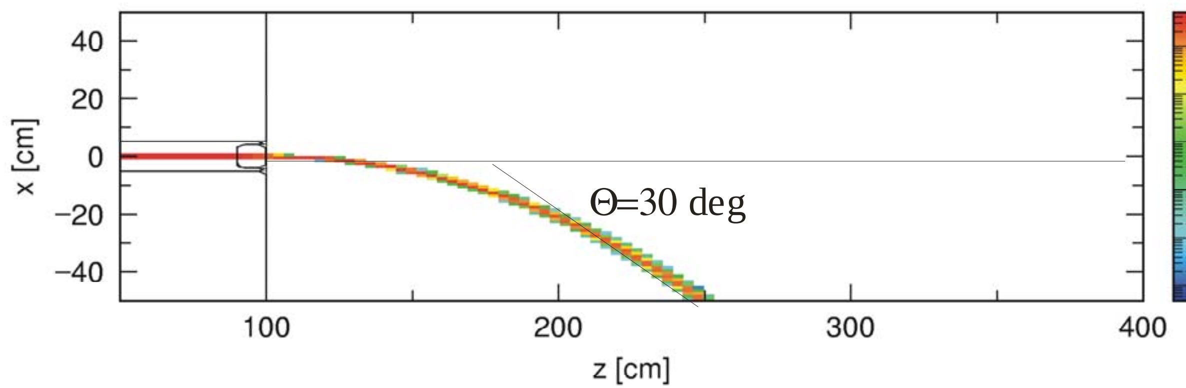


Figure 2.6: The PID spectrum of a simulated of $N = Z$ setting for $^{58}Ni+^{9}Be$ reaction at 140 MeV/u using LISE++ [56] for the A1900 fragment separator. Parameters of the simulation: $B\rho$=3.6 Tm, 0.2% momentum acceptance.

Is the Fragment Bent to the Correct Location?

86Kr beam at 500 MeV/u on 9.6 cm Li target





$$\theta = \frac{BL}{0.3 \times B\rho \times 0.0582}$$

For 30 degrees, 8 Tm, 2.5806 T:
L calc = 1.62 m
L measured = 1.62 m

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Yield Comparisons

Fragment	PHITS Fragment per source particle	LISE++ Fragment per pnA	 Fragment per incident 86Kr	PHITS/LISE
86Kr	3.43E-01	2.60E+09	4.17E-01	**0.8**
82Br	4.90E-03	3.34E+07	5.35E-03	**0.9**
77Se	2.40E-03	1.99E+07	3.19E-03	**0.8**
64Cu	2.30E-03	1.27E+07	2.04E-03	**1.1**
61Ni	3.90E-03	1.11E+07	1.78E-03	**2.2**
43Ca	5.30E-03	6.55E+06	1.05E-03	**5.0**

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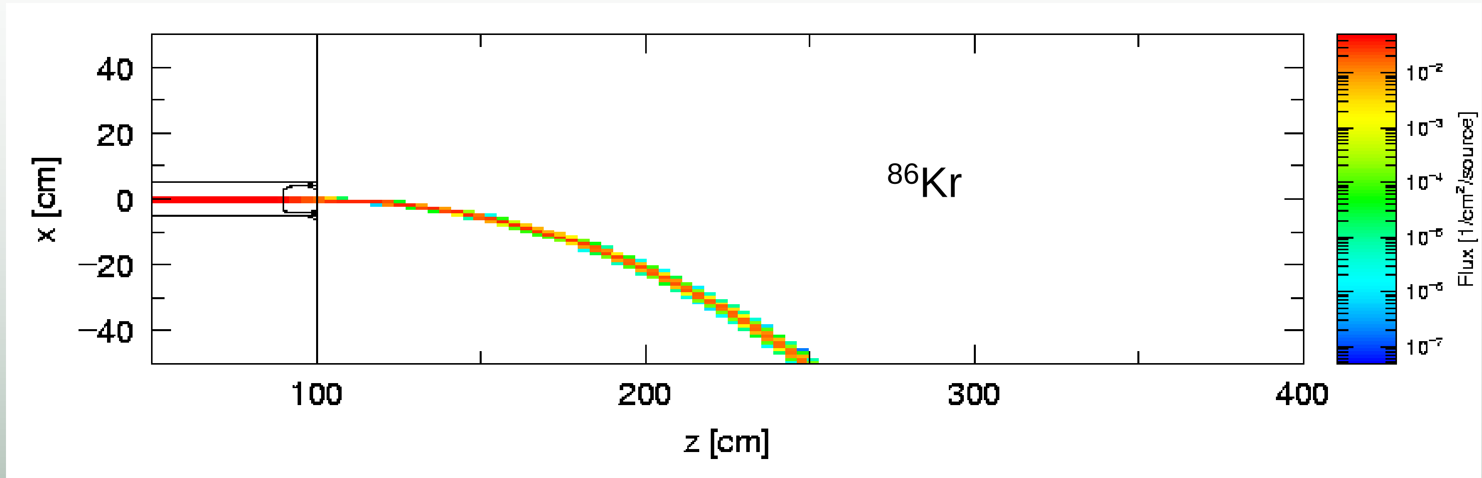
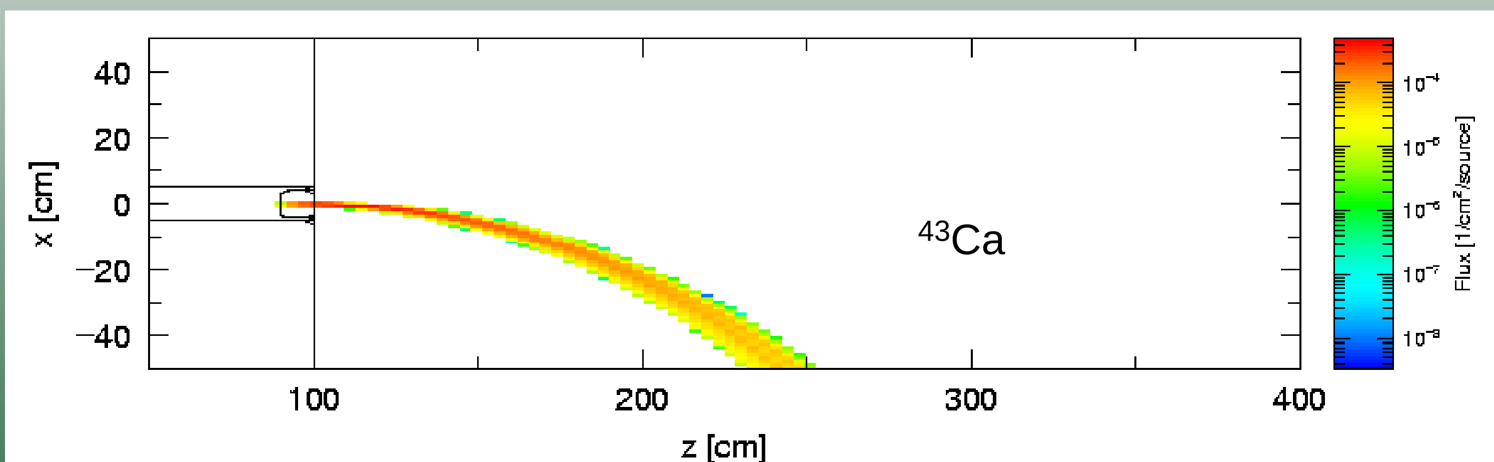
Compare ^{86}Kr to ^{43}Ca: Note Momentum Spread





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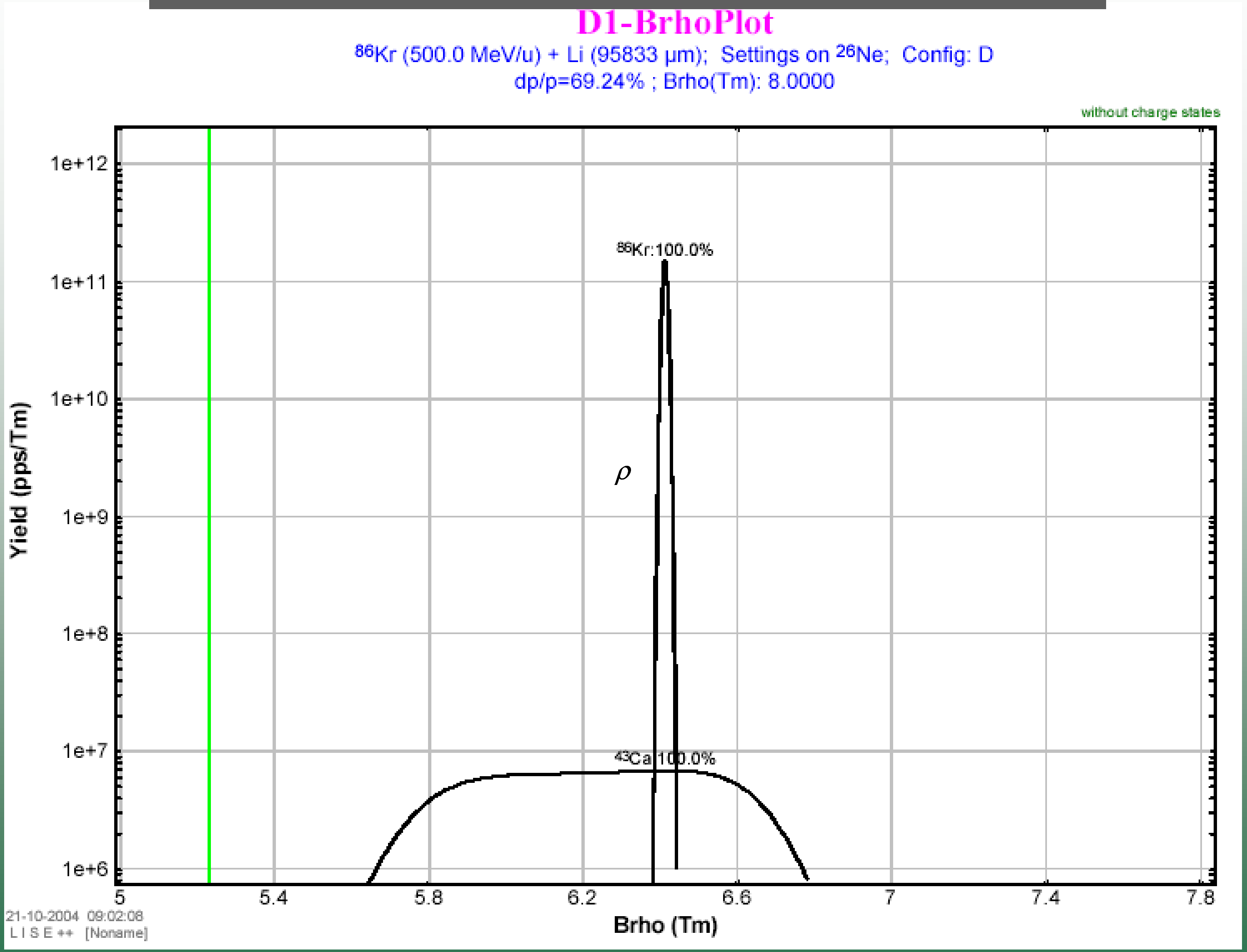
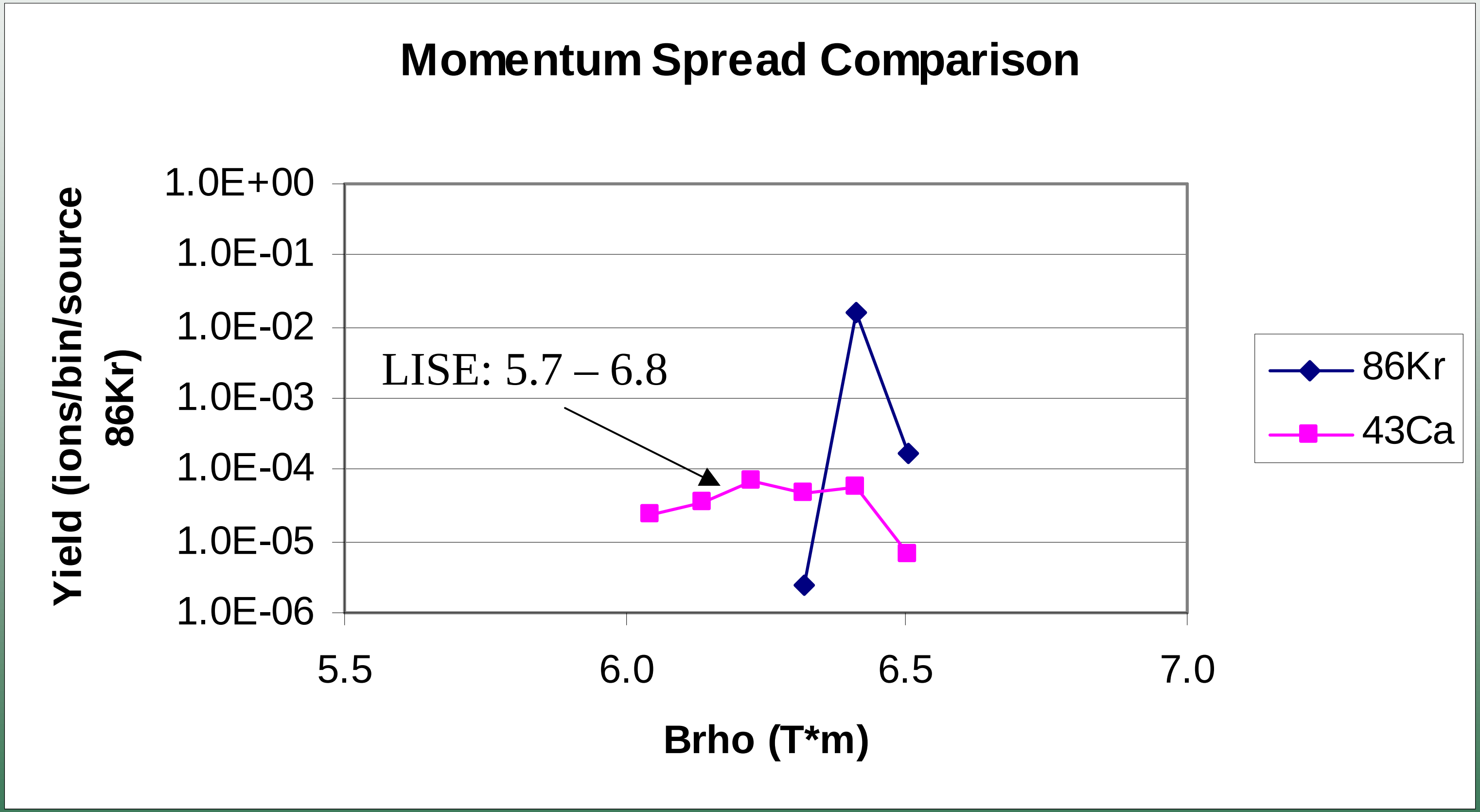
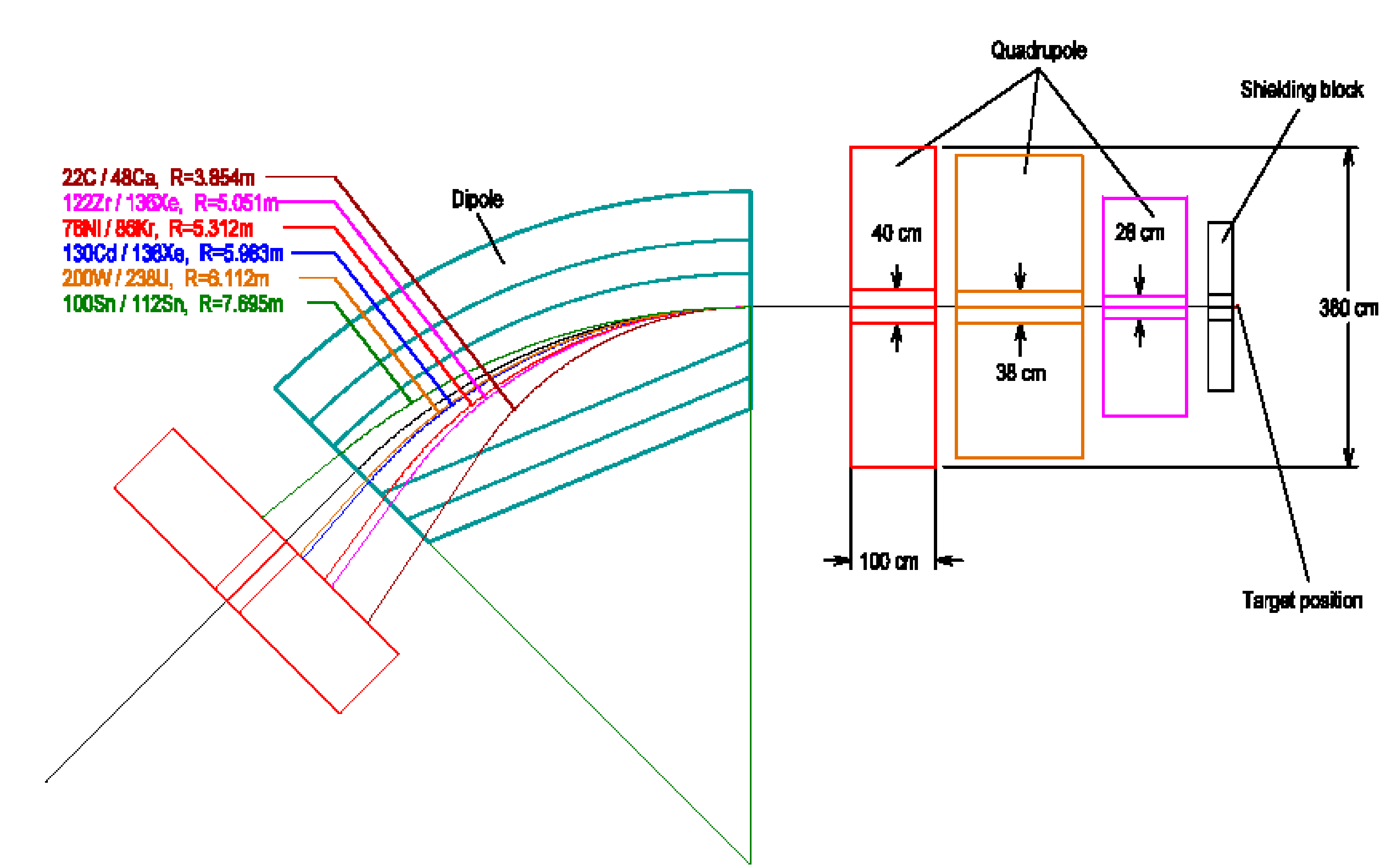
LISE++: B-Rho Plot for ^{86}Kr and ^{43}Ca



Compare Momentum Spread PHITS Simulation vs LISE++ Simulation



Where Do Primary Beam and Fragments Go?



Sample Beam-Fragment Combinations (from Brad Sherrill, MSU)

Fragment	Beam	Charge State	Fraction	Beam Energy MeV/u	Target Thickness mg/cm2	Fragment Brho	Beam Brho	Ratio	Beam Power in Target (kW)	Dump Power (kW)
122Zr	136Xe	54	1	500	3500	9.015	6.8786	0.763017194	153	247
130Cd	136Xe	54	1	500	3320	7.846	7.0896	0.903594188	139	261
78Ni	86Kr	36	1	520	5300	8.33	6.6832	0.802304922	150	250
22C	48Ca	20	1	350	3300	9.959	5.7971	0.582096596	89.2	310.8
200W	238U			400	1100	7.4968		0.923100523	102	
		92	0.04				6.9203			11.92
		91	0.29				6.9963			86.42
		90	0.6				7.0741			178.8
		89	0.06				7.1536			17.88
		88	0.003				7.2349			0.894
100Sn	112Sn	50		500	4000	4.843	5.6286	1.162213504	186	

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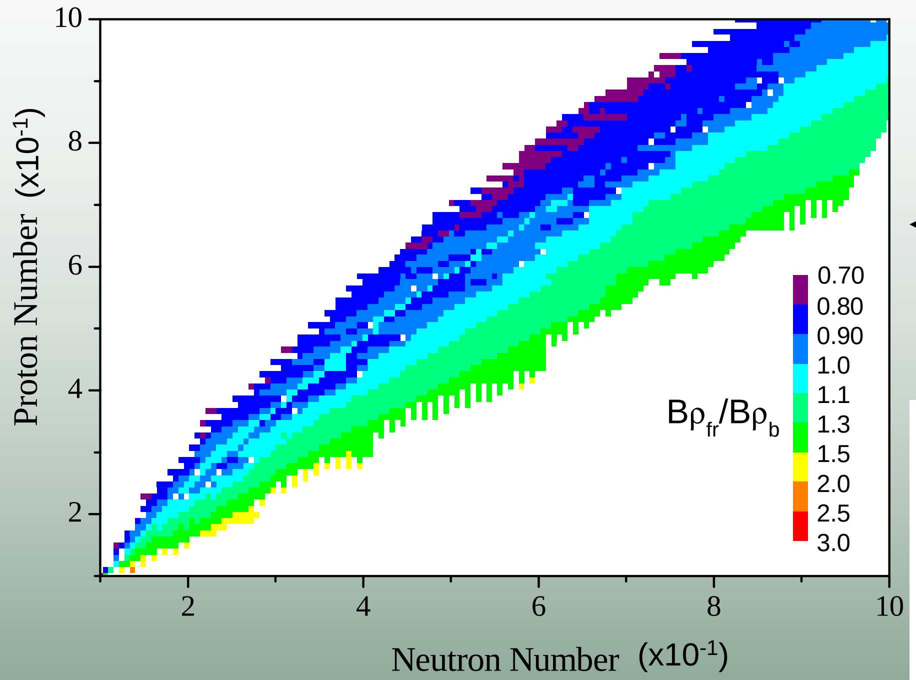
Where Does the Primary Beam Stop? (Brad Sherrill, MSU)

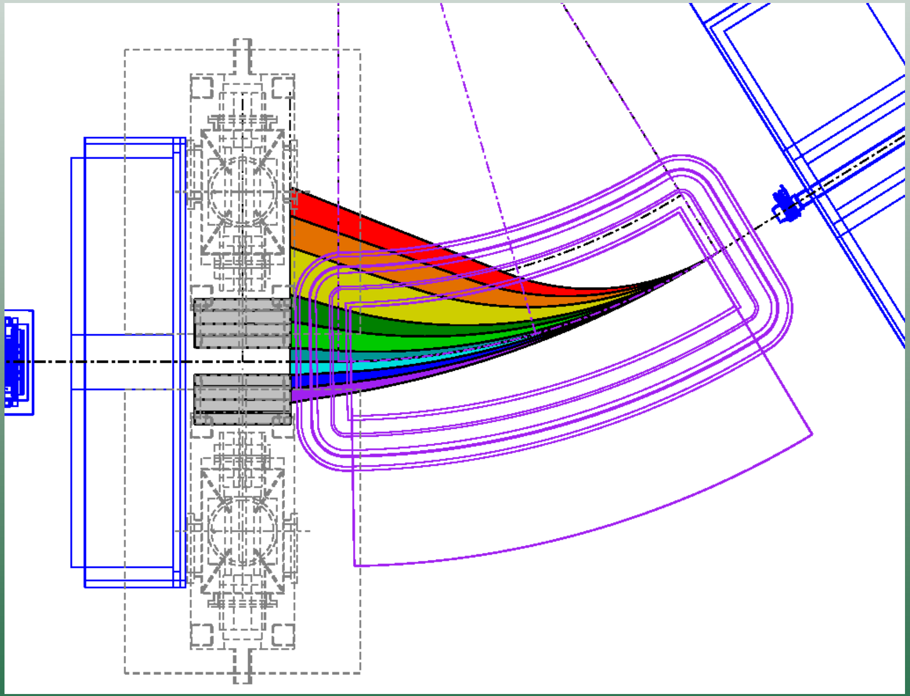


Possible rare isotope beams are represented by squares.

The color of the square tells the relative primary beam rigidity.

Locations of primary beams are shown, for the fragment-primary beam families shown above.

In some of our simulations, the ratio of fragment-to-primary beam rigidity was about 0.9.



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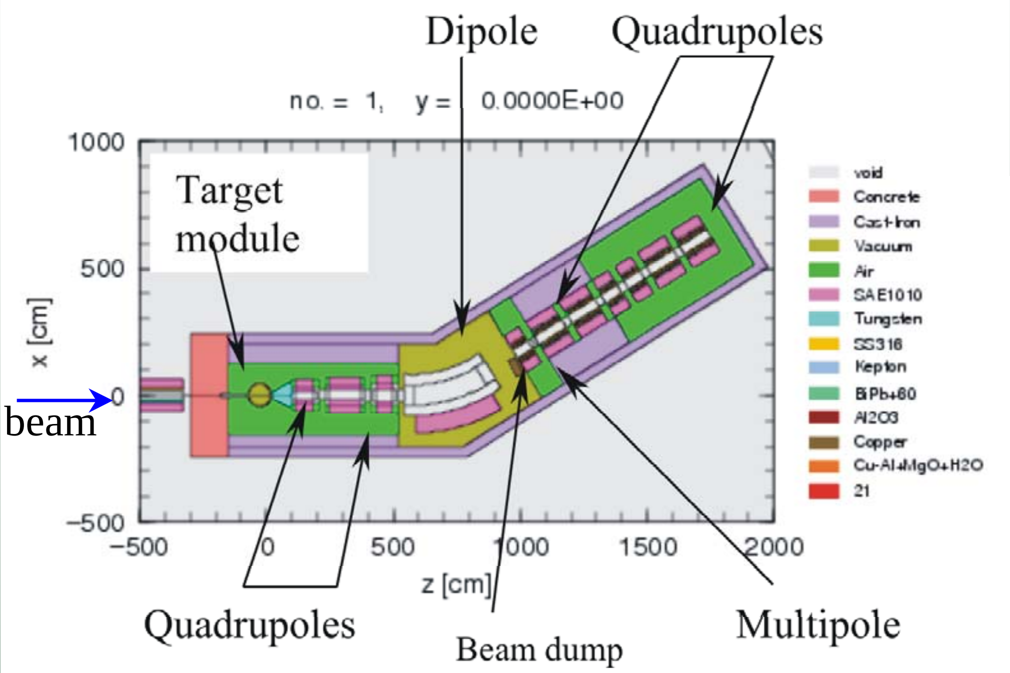
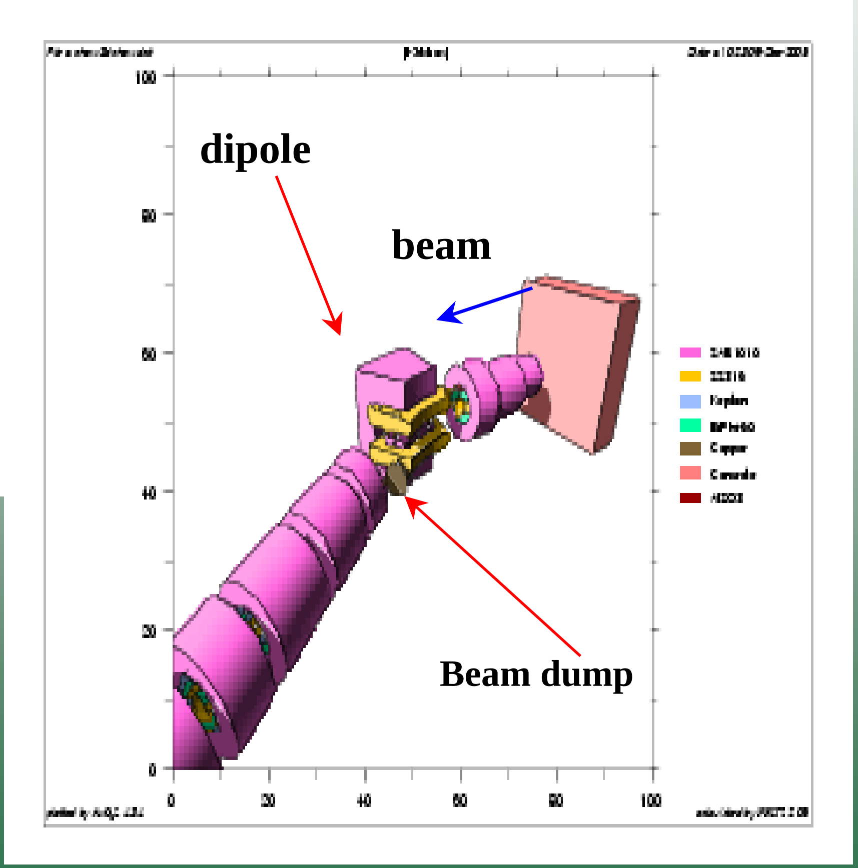
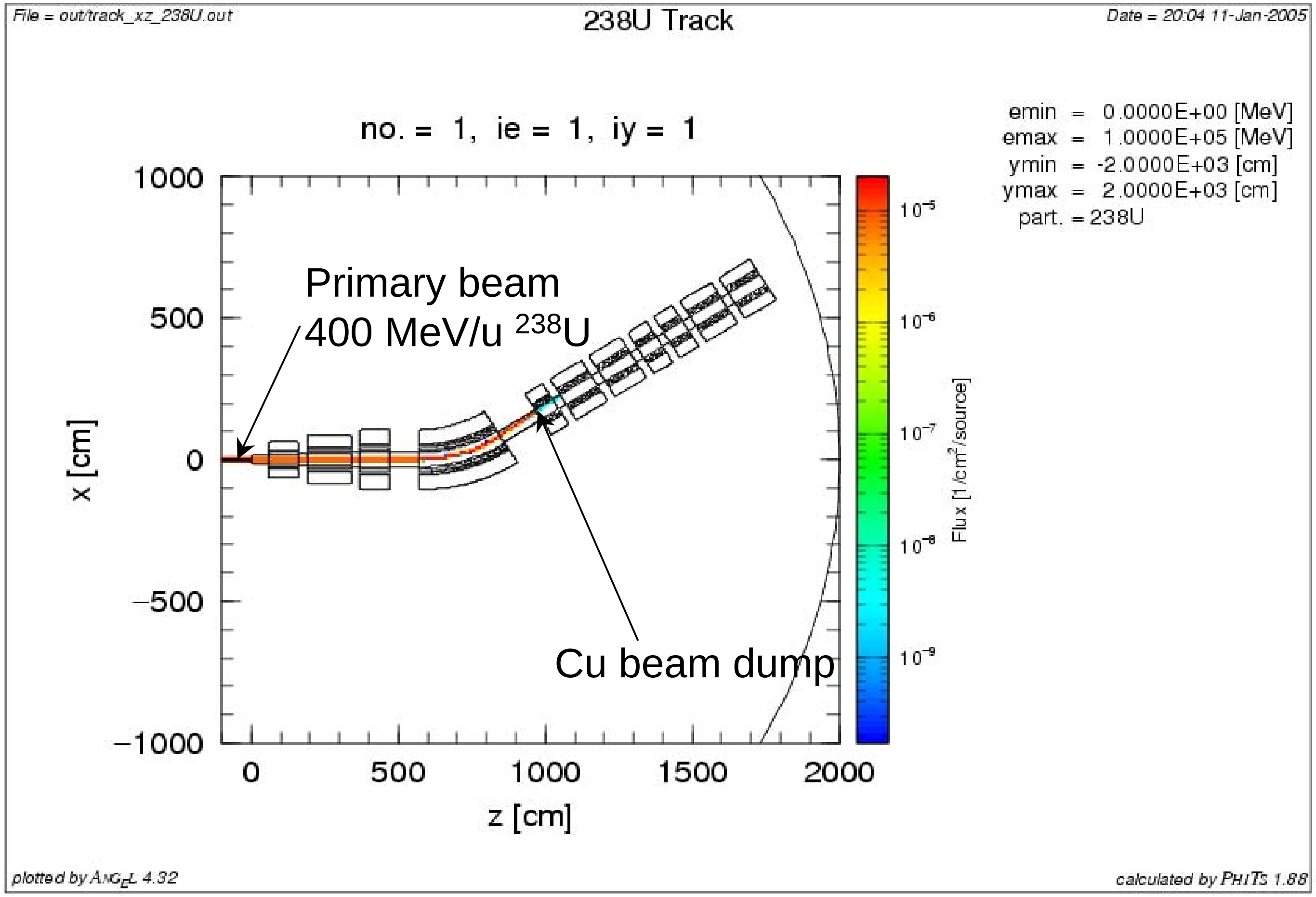
Fragmentation Pre-Separator in PHITS (Inseok Baek, NSCL/MSU)

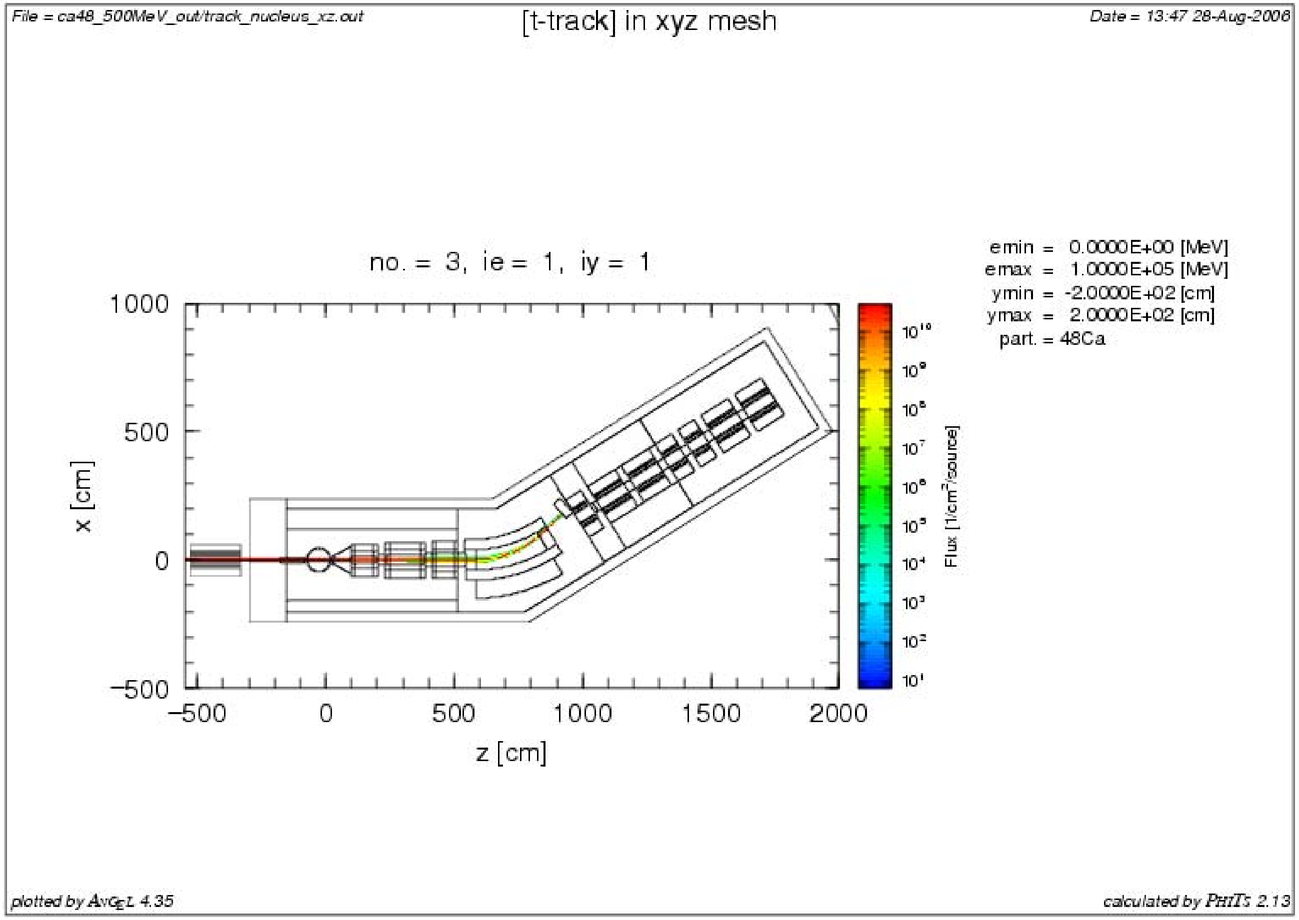




Transport of Primary Beam using PHITS (Inseok Baek, NSCL/MSU)



Tracking the Primary Beam
^{48}Ca 500 MeV/u on Be Target



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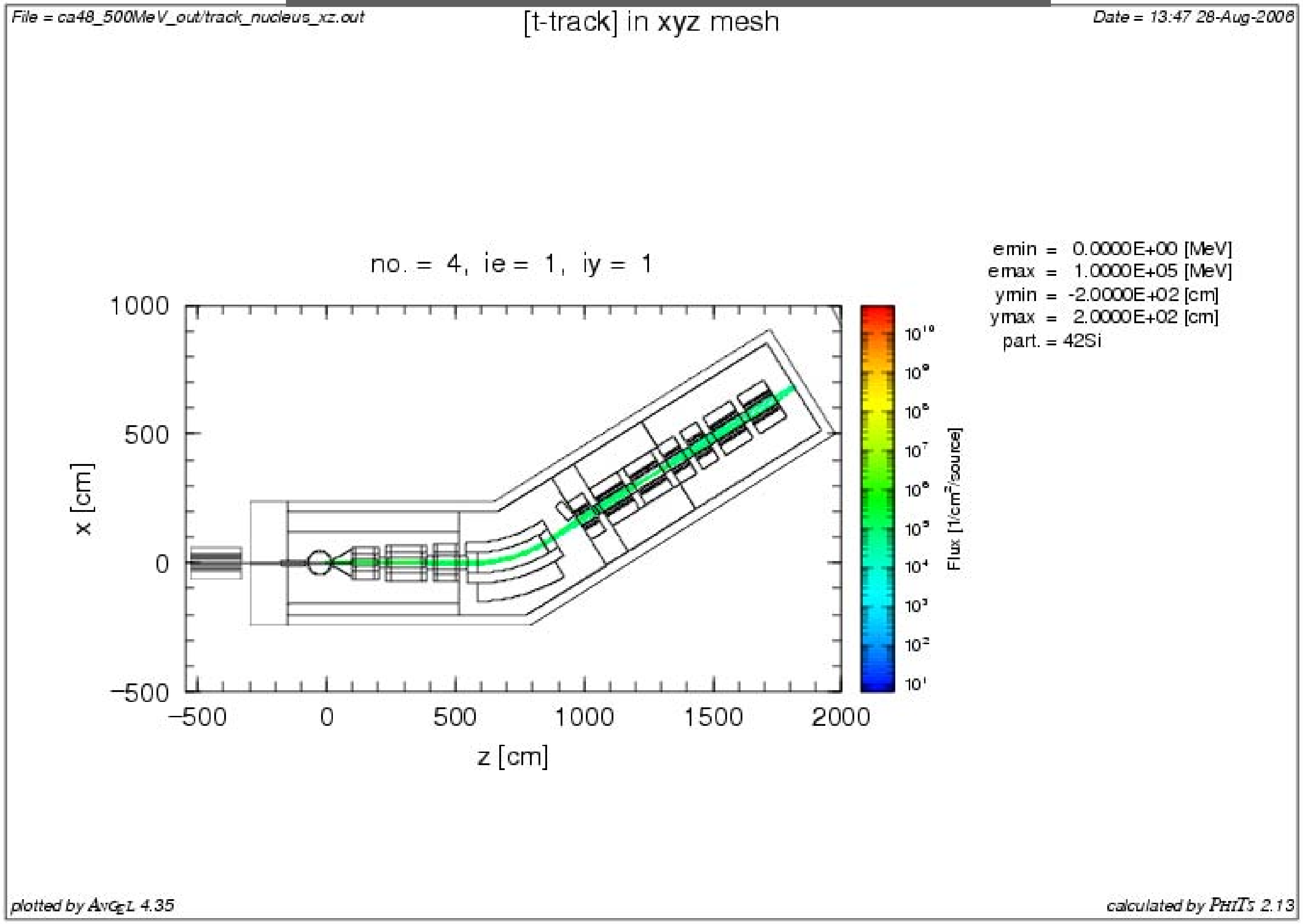
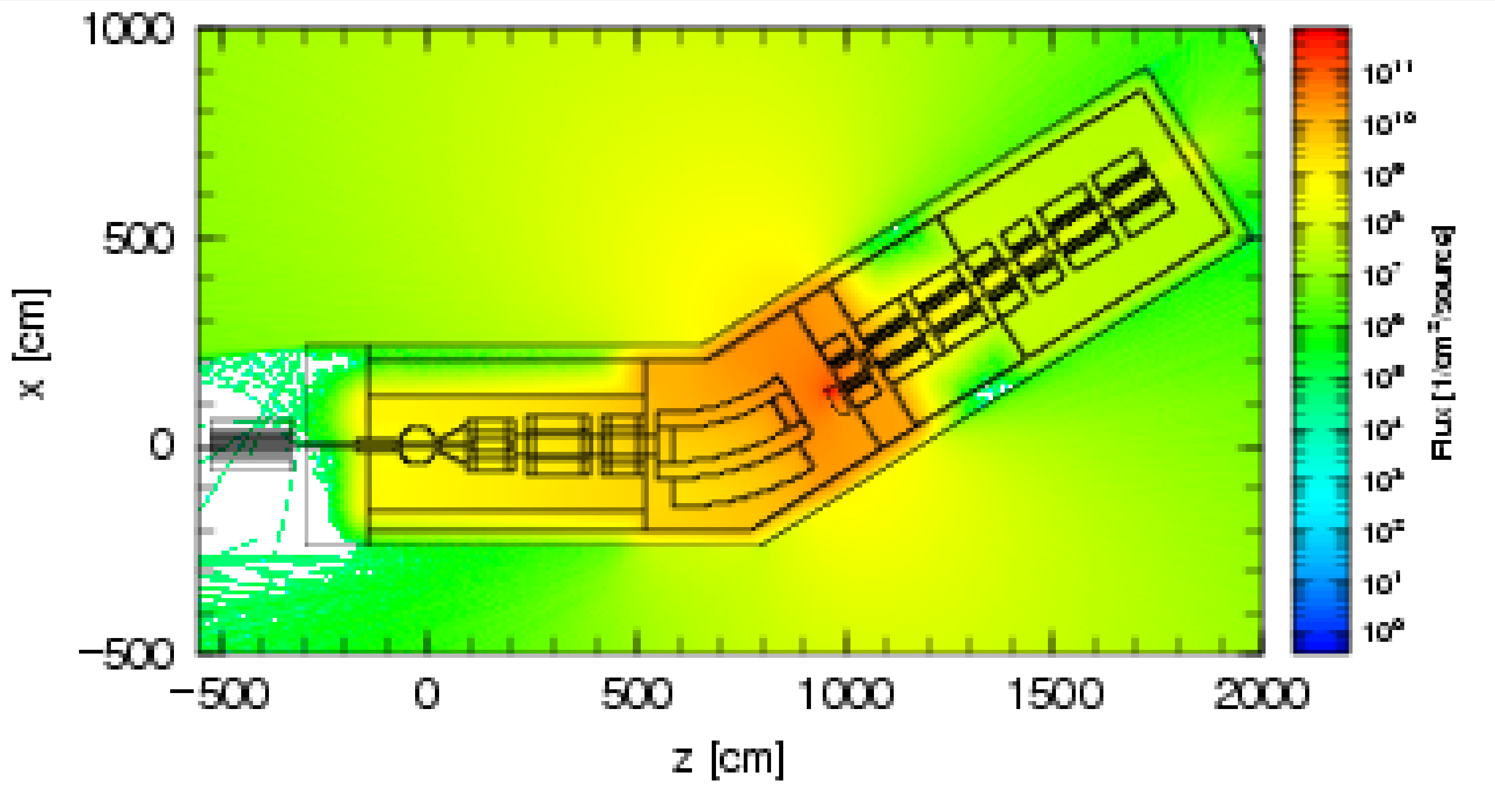
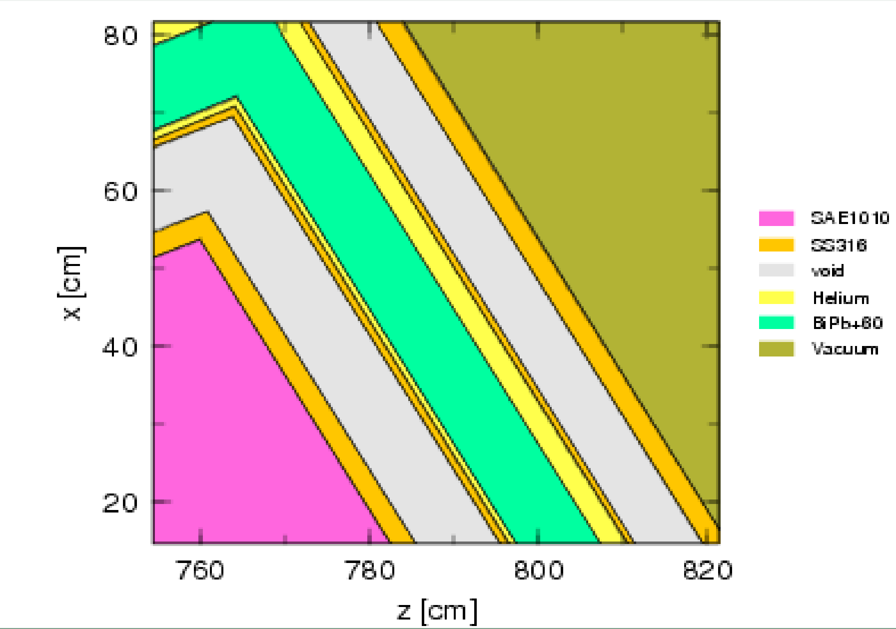
Tracking the Fragment ^{42}Si from ^{48}Ca 500 MeV/u on Be Target

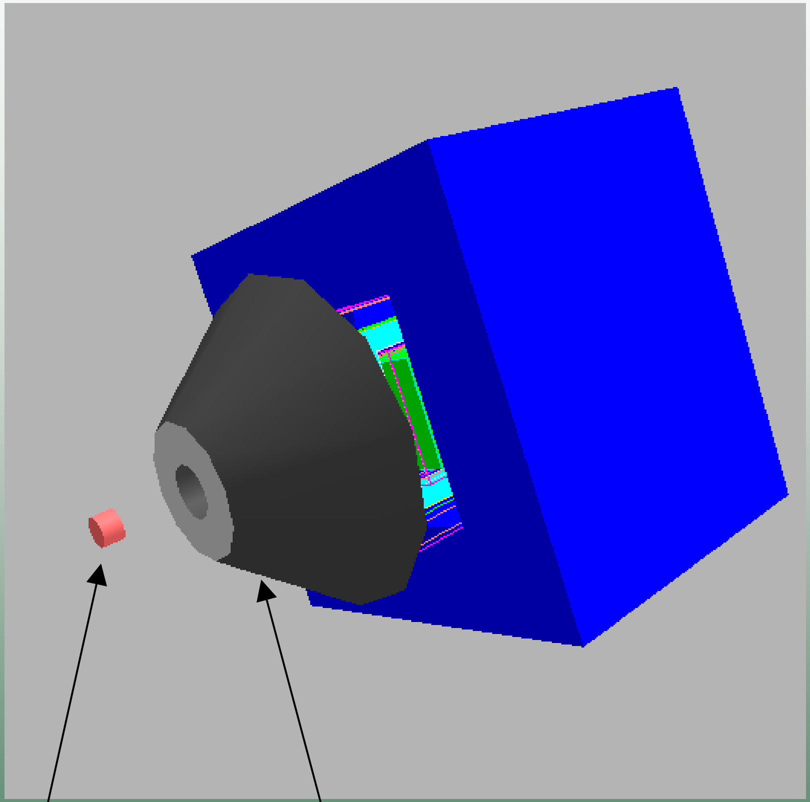


Neutron Flux in Pre-Separator using PHITS: 48Ca beam at 500 MeV/u Normalized to 400 kW



“Realistic” Quadrupole Geometry using BNL Design with Realistic Material Compositions





Target

Hevimet shield

Frames are cryostat walls

HTS Coil: Ag+BSCCO

Insulator: AlO+He

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Projectile Fragmentation Experiments at the NSCL

- Michal Mocko *et al.*
- Michal's Ph.D. Thesis:
  - *Advisor: M. Betty Tsang*
  - *Title: "Rare Isotope Production"*
  - *Defended September 6, 2006*
  - *Paper submitted to Physical Review C*

Beams:

^{40,48}Ca, ^{58,64}Ni @ 140 MeV/u

^{86}Kr @ 64 MeV/u – done at RIKEN

Targets:

^{9}Be, ^{181}Ta

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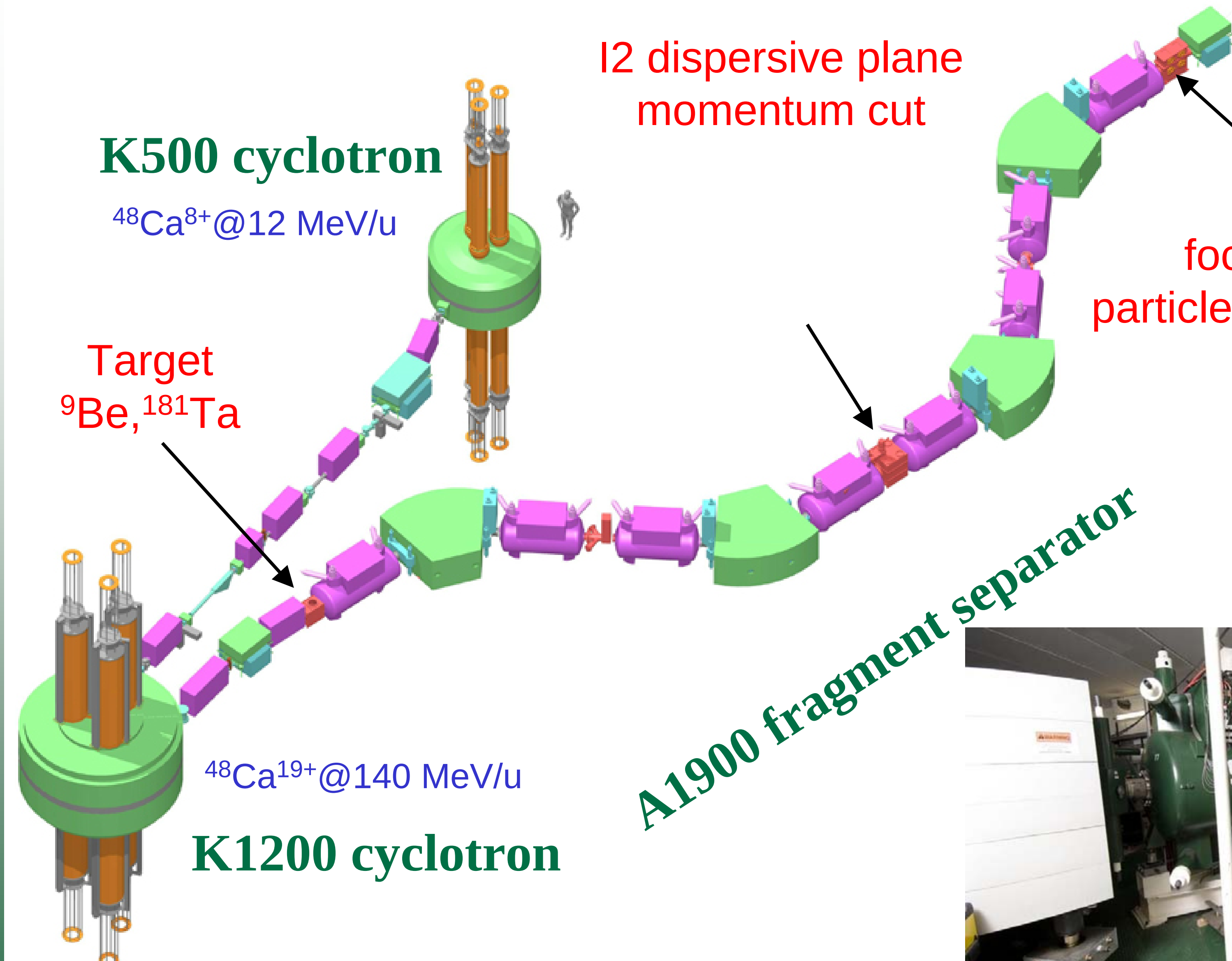
NSF



Coupled Cyclotron Facility

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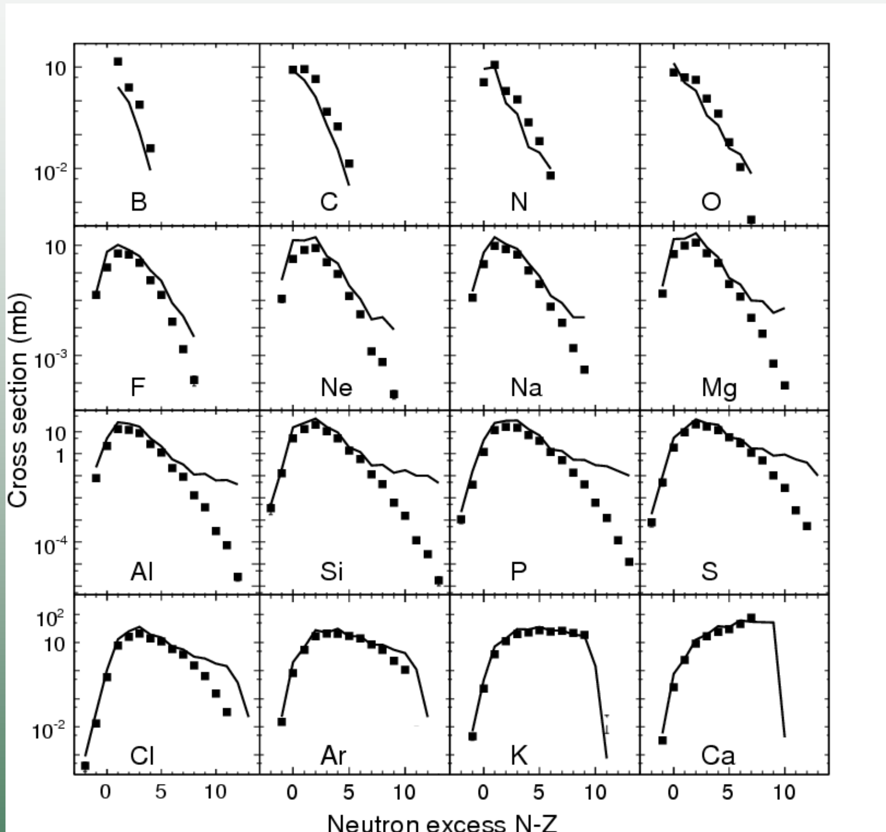
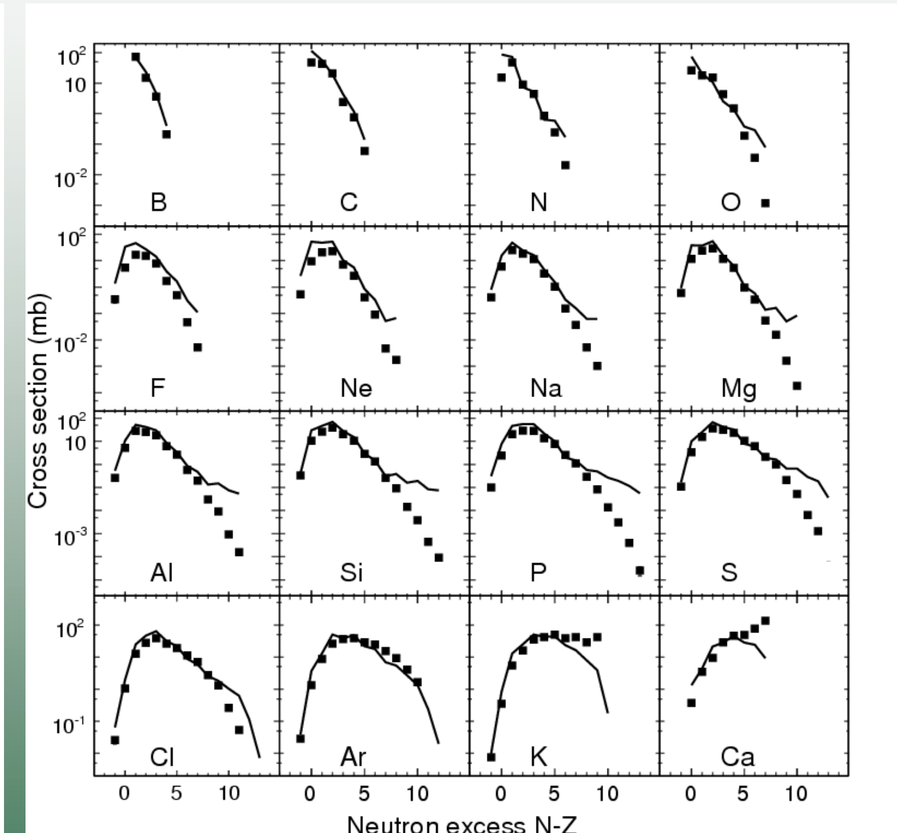
$^{48}Ca^{19+}$ at 140 MeV/u

Be Target



Ta Target



PHITS213 (nqtmax = 100 fm/c)

Exp

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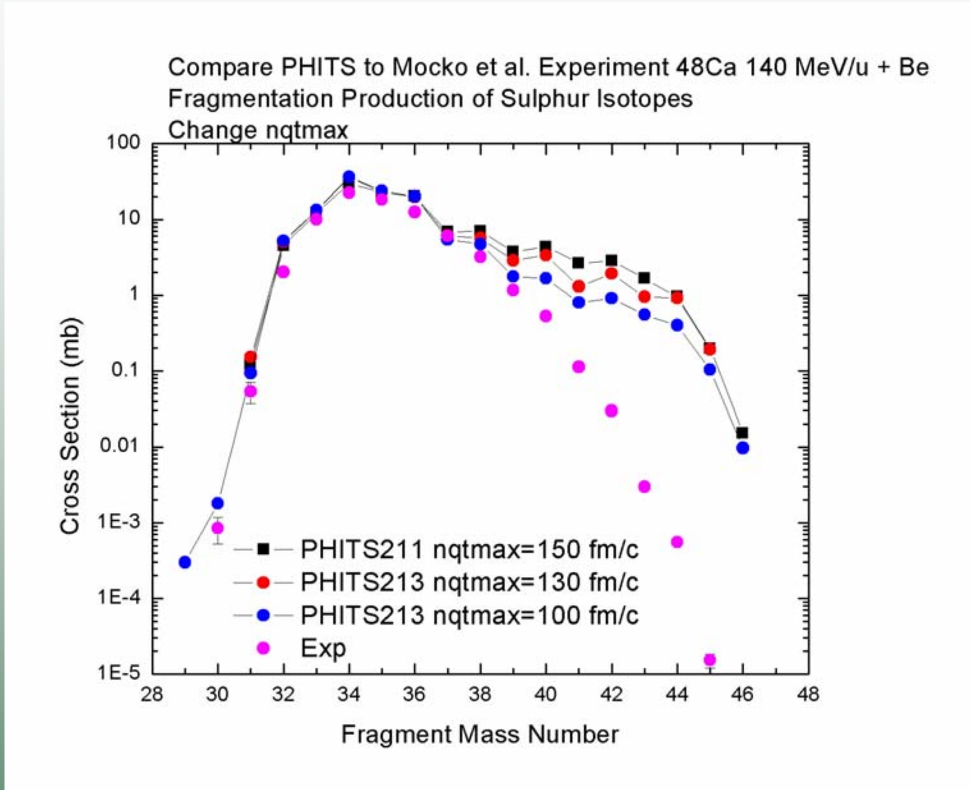

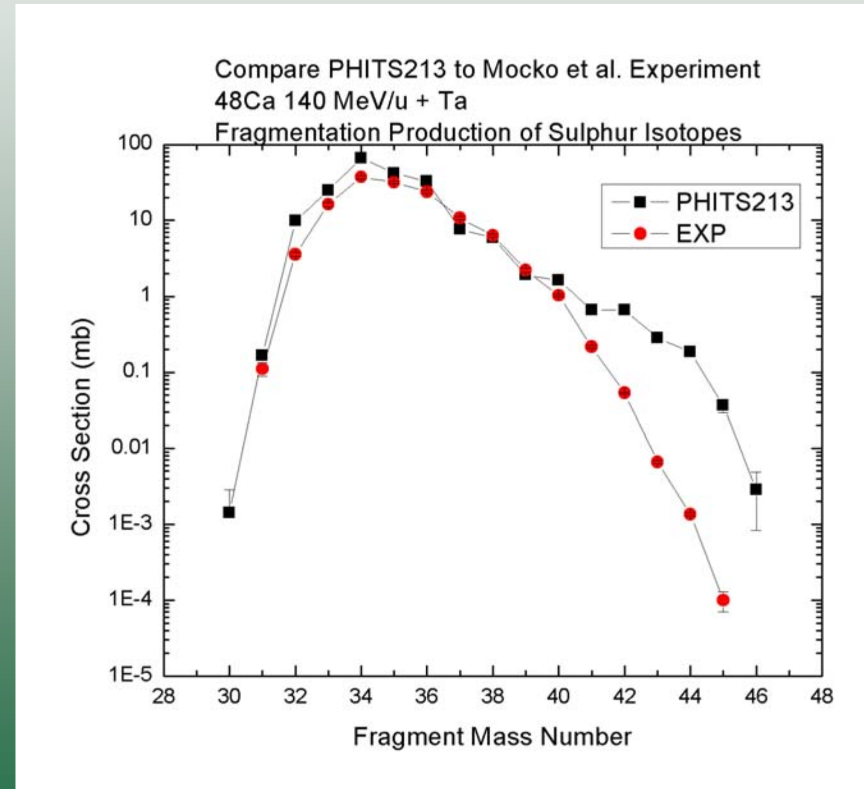

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Summary

- We wish to thank Koji Niita and the PHITS development team for PHITS
- PHITS has many features useful to help design the next generation of exotic beam facilities
- PHITS performs very well when comparing to existing data
  - True for light-ion reactions as well as heavy ion reactions
- Suggestions for improvements
  - Continue to improve models
  - Benchmark against new data sets
  - New data sets needed from the heavy ion community
    - Radiation damage (DPA)
    - Heating
  - Include charge state distributions
- Thank you to:
  - Nikolai Mokhov and the organizers of HSS06
  - My RIA R&D colleagues
  - You who are code developers
  - You, my audience

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