

IAEA Workshop on:
Technology and Applications of
Accelerator Driven Systems (ADS)

13 – 17 October 2003, Trieste, Italy

YACINE KADI
CERN, Switzerland

LECTURES OUTLINE

- **LECTURE 1:** Physics of Spallation and Sub-critical Devices, Fundamentals
(Monday 13/10/03, 10:30 – 12:00)
- **LECTURE 2:** Nuclear Data & Methods for ADS Design
(Monday 13/10/03, 14:00 – 15:30)
- **LECTURE 3:** ADS Design Exercise I & II
(Tuesday 14/10/03, 14:00 – 17:30)
- **LECTURE 4:** ADS Design Examples with the EA-MC Code Package
(Thursday 16/10/03, 10:30 – 12:00)
- **LECTURE 5:** ADS Design Exercise III & IV
(Thursday 16/10/03, 14:00 – 17:30)

ADS DESIGN I

Physics of Spallation & Sub-critical Devices: Fundamentals

Monday, 13 October 2003, 10:30 – 12:00

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Introduction to ADS Design (1)

- The basic process of Accelerator-Driven Systems (ADS) is Nuclear Transmutation:
 - ↓ First demonstrated by Rutherford in 1919 who transmuted ^{14}N to ^{17}O using energetic α -particles
 - ↓ I. Curie and F. Joliot in 1933 produced the first artificial radioactivity using α -particles

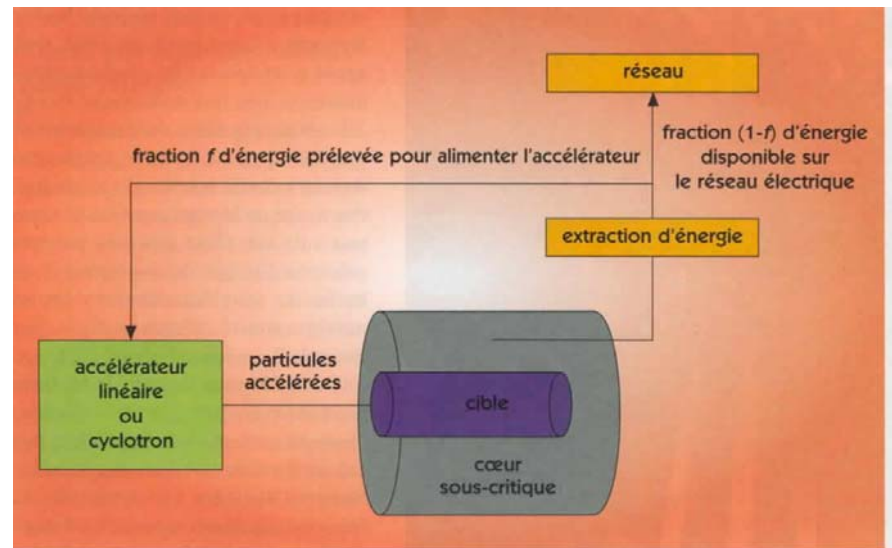
- The invention of the cyclotron by Ernest O. Lawrence in 1939 opened new possibilities:
 - ↓ use of high power accelerators to produce large numbers of neutrons



Introduction to ADS Design (2)

- One way to obtain intense neutron sources is to use a hybrid sub-critical reactor-accelerator system called just Accelerator-Driven System:

- ☆ The accelerator bombards a target with high-energy protons which produces a very intense neutron source through the spallation process.
- 🕒 These neutrons can consequently be multiplied in the sub-critical core which surrounds the spallation target.



Introduction to ADS Design (3)

- ❑ The idea of producing neutrons by spallation with an accelerator has been around for a long time:
 - ☞ In 1950, **Ernest O. Lawrence** at Berkeley proposed to produce plutonium from depleted uranium from Oak Ridge. The Material Testing Accelerator (MTA) project was abandoned in 1954.
 - ☞ In 1952, **W. B. Lewis** in Canada proposed to use an accelerator to produce ^{233}U from thorium, in an attempt to close the fuel cycle for CANDU type reactors.
 - ➔ Concept of accelerator breeder : exploiting the spallation process to breed fissile material directly ➔ soon abandoned.
 - ➔ $I_p \approx 300 \text{ mA}$
 - ☞ Renewed interest in the 1980's and beginning of the 1990's, in particular in Japan (OMEGA project at Japan Atomic Energy Research Institute), and in the USA (**Hiroshi Takahashi et al.** proposal of a fast neutron hybrid system at Brookhaven for minor actinide transmutation and **Charles Bowman** a thermal neutron molten salt system based on the thorium cycle at Los Alamos).

Introduction to ADS Design (4)

- ❑ In November 1993, **Carlo Rubbia** proposed, in an exploratory phase, a first **T**hermal neutron **E**nergy **A**mplifier system based on the thorium cycle, with a view to energy production. As it became clear that in the western world the priority is the destruction of nuclear waste (other sources of energy are abundant and cheap), the system evolved towards that goal, into a **F**ast **E**nergy **A**mplifier. More specifically:

⇒ *Method*: A high energy proton beam interacts in a molten lead (Pb-Bi) swimming pool. Neutrons are produced by the so-called spallation process. Lead is “transparent” to neutrons. Single phase coolant, b.p. ≈ 2000 °C

⇒ *TRU*: They are introduced, after separation, in the form of classic, well tested “fuel rods”. *Fast neutrons*, both from spallation and fission, drift to the TRU rods and fission them efficiently. A substantial amount of net power is produced (up to $\approx 1/3$ of LWR), to pay for the operation.

⇒ *LLFF*: Neutrons leaking from the periphery of the core are used to transmute also LLFF (Tc^{99} , I^{129} )

⇒ *Safety*: The sub-criticality ($k \approx 0.95 \div 0.98$) condition is guaranteed at all times.



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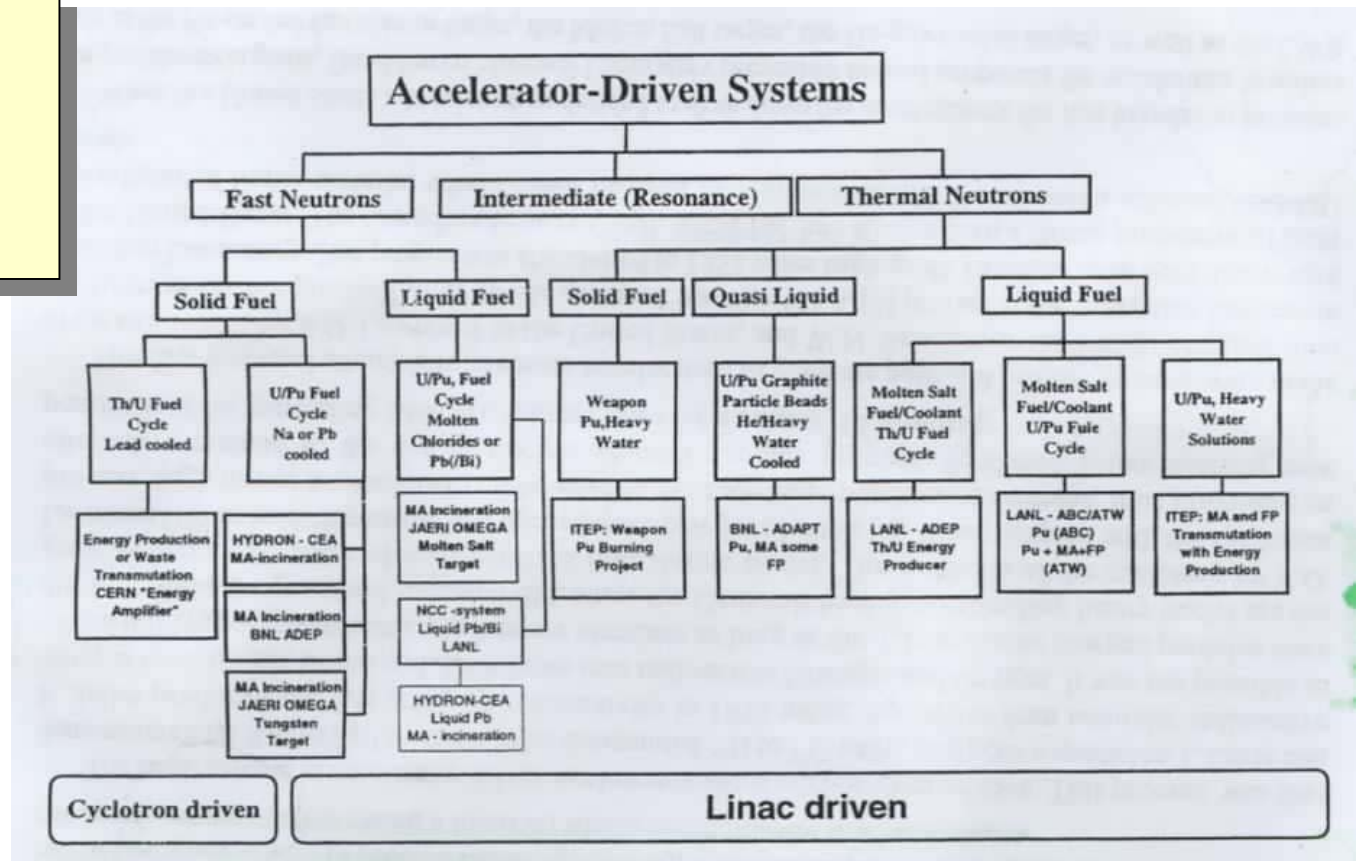
Review of Existing ADS Concepts

- Classification of existing ADS concepts according to their physical features and final objectives:

Ref. IAEA-TECDOC-985

- ⇒ neutron energy spectrum
- ⇒ fuel form (solid/liquid)
- ⇒ fuel cycle
- ⇒ coolant/moderator type

⇒ final objectives



The Spallation Process (1)

- Several nuclear reactions are capable of producing neutrons
 - ↑ However the use of protons minimises the energetic cost of the neutrons produced

Nuclear Reactions	Incident Particle & Typical Energies	Beam Currents (part./s)	Neutron Yields (n/inc.part.)	Target Power (MW)	Deposited Energy Per Neutron (MeV)	Neutrons Emmitted (n/s)
(e,γ) & (γ,n)	e^- (60 MeV)	5×10^{15}	0.04	0.045	1500	2×10^{14}
$H^2(tn)He^4$	H^3 (0.3 MeV)	6×10^{19}	$10^{-4} - 10^{-5}$	0.3	10^4	10^{15}
Fission			- 1	57	200	2×10^{18}
Spallation (non-fissile target)	p (800 MeV)	10^{15}	14	0.09	30	2×10^{16}
Spallation (fissionable target)			30	0.4	55	4×10^{16}

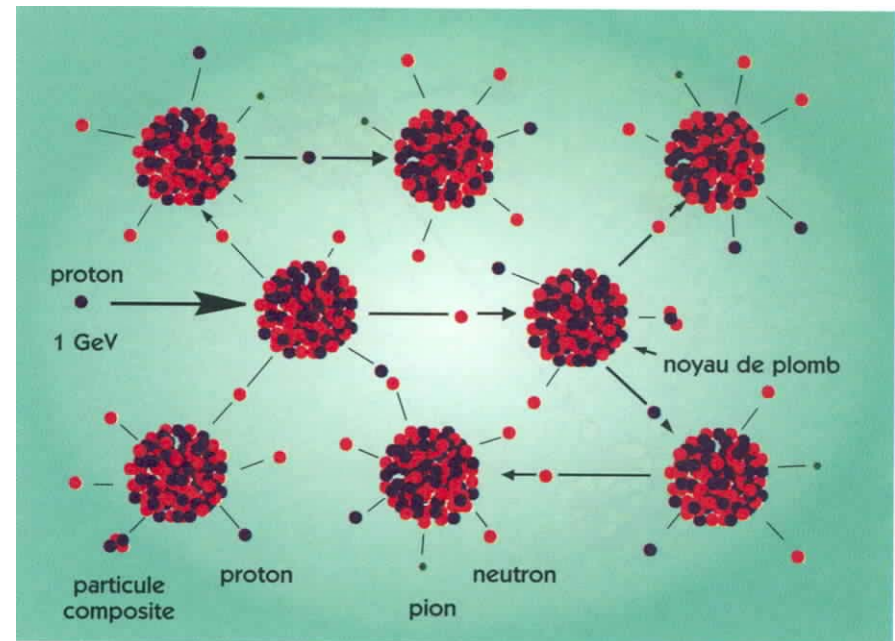
The Spallation Process (2)

- There is no precise definition of spallation ↑ this term covers the interaction of high energy hadrons or light nuclei (from a few tens of MeV to a few GeV) with nuclear targets.

↑ It corresponds to the reaction mechanism by which this high energy projectile pulls out of the target some nucleons and/or light particles, leaving a residual nucleus (spallation product)

↑ Depending upon the conditions, the number of emitted light particles, and especially neutrons, may be quite large

↑ This is of course the feature of outermost importance for the so-called ADS



The Spallation Process (3)

- At these energies it is no longer correct to think of the nuclear reaction as proceeding through the formation of a compound nucleus.

☆ Fast Direct Process:

- ↑ Intra-Nuclear Cascade (nucleon-nucleon collisions)

⌚ Pre-Compound Stage:

- ↑ Pre-Equilibrium
- ↑ Multi-Fragmentation
- ↑ Fermi Breakup

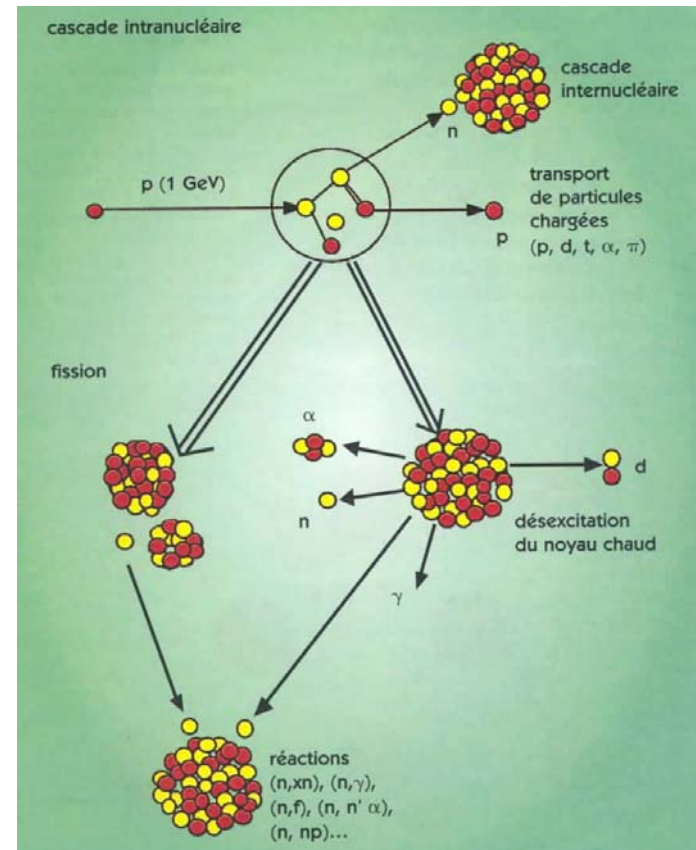
⌚ Compound Nuclei:

- ↑ Evaporation (mostly neutrons)
- ↑ High-Energy Fissions

⊕ Inter-Nuclear Cascade

⌚ Low-Energy Inelastic Reactions

- ↑ (n, xn)
- ↑ (n, nf)
- ↑ etc...



The Spallation Process (4)

□ The relevant aspects of the spallation process are characterised by:

☞ **Spallation Neutron Yield** (i.e. multiplicity of emitted neutrons)

→ determines the requirement in terms of the accelerator power (current and energy of incident proton beam).

☞ **Spallation Neutron Spectrum** (i.e. energy distribution of emitted neutrons)

→ determines the damage and activation of the structural materials (design of the beam window and spallation target)

☞ **Spallation Product Distributions**

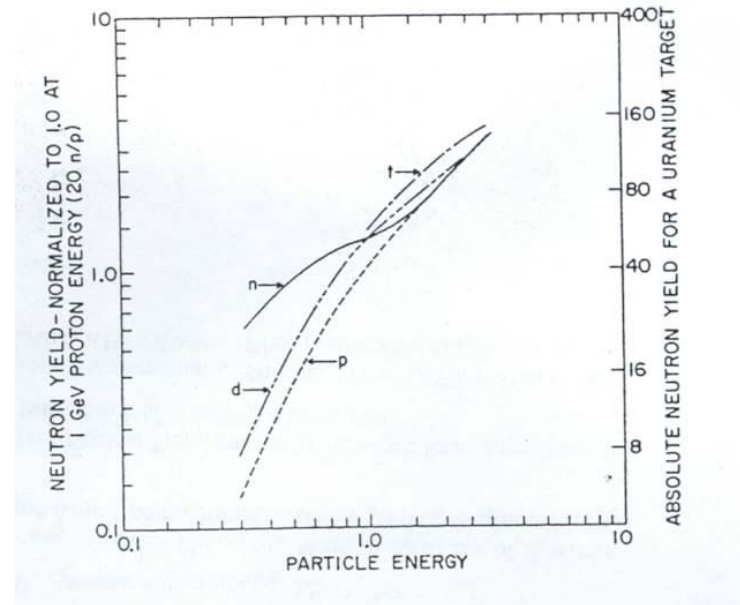
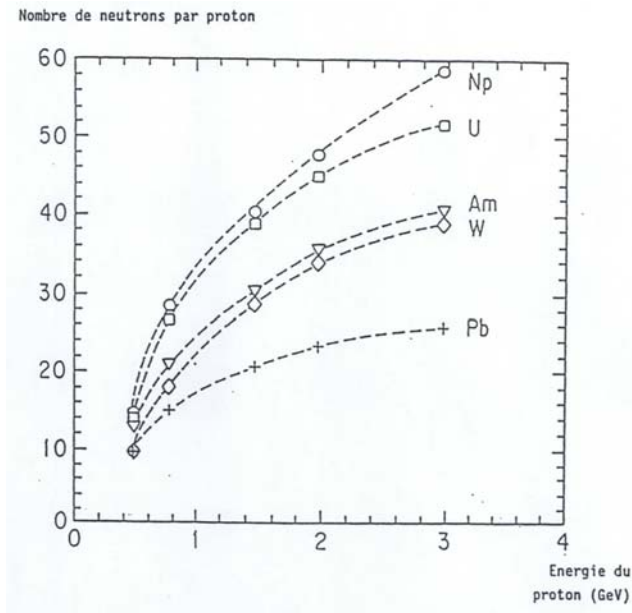
→ determines the radiotoxicity of the residues (radioprotection requirements).

☞ **Energy Deposition**

→ determines the thermal-hydraulic requirements (cooling capabilities and nature of the spallation target).

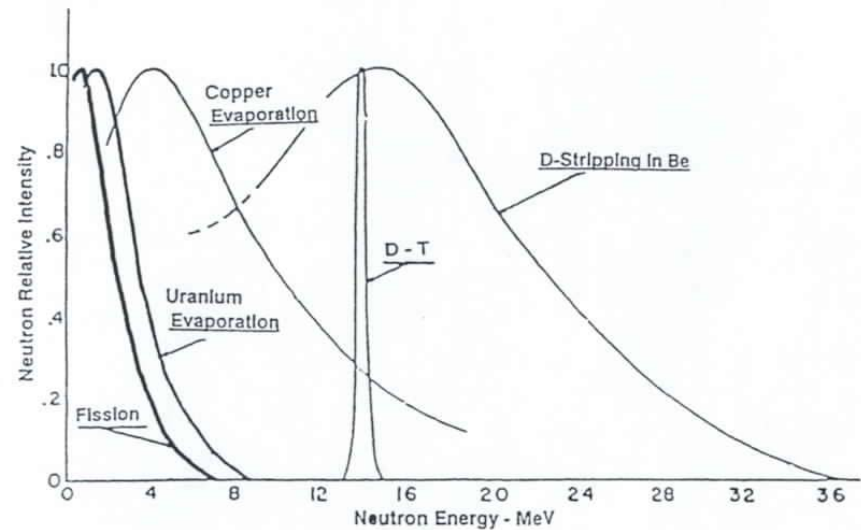
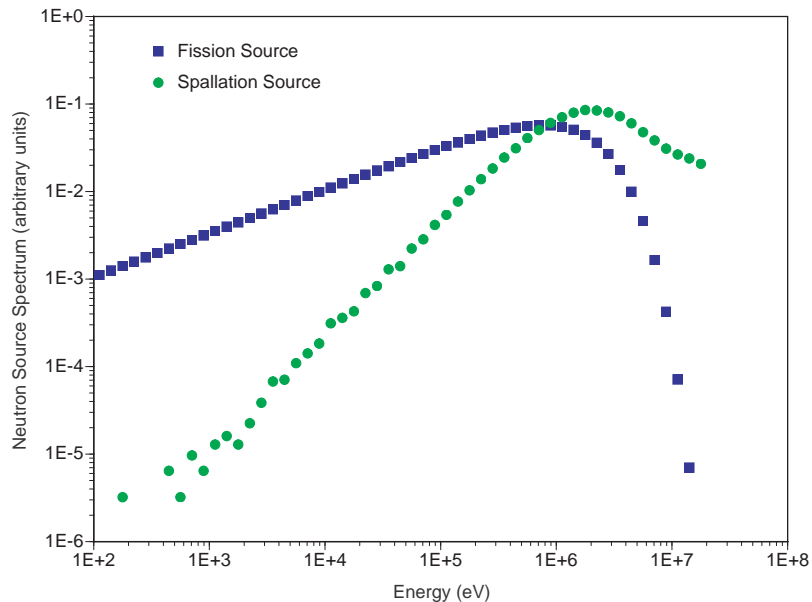
Spallation Neutron Yield

- ❑ The number of emitted neutrons varies as a function of the target nuclei and the energy of the incident particle \leftarrow saturates around 2 GeV.
- ❑ Deuteron and triton projectiles produce more neutrons than protons in the energy range below 1-2 GeV \leftarrow higher contamination of the accelerator.



Spallation Neutron Spectrum

- The spectrum of spallation neutrons evaporated from an excited heavy nucleus bombarded by high energy particles is similar to the fission neutron spectrum but shifts a little to higher energy $\leftarrow \langle E_n \rangle \approx 3 - 4 \text{ MeV}$.



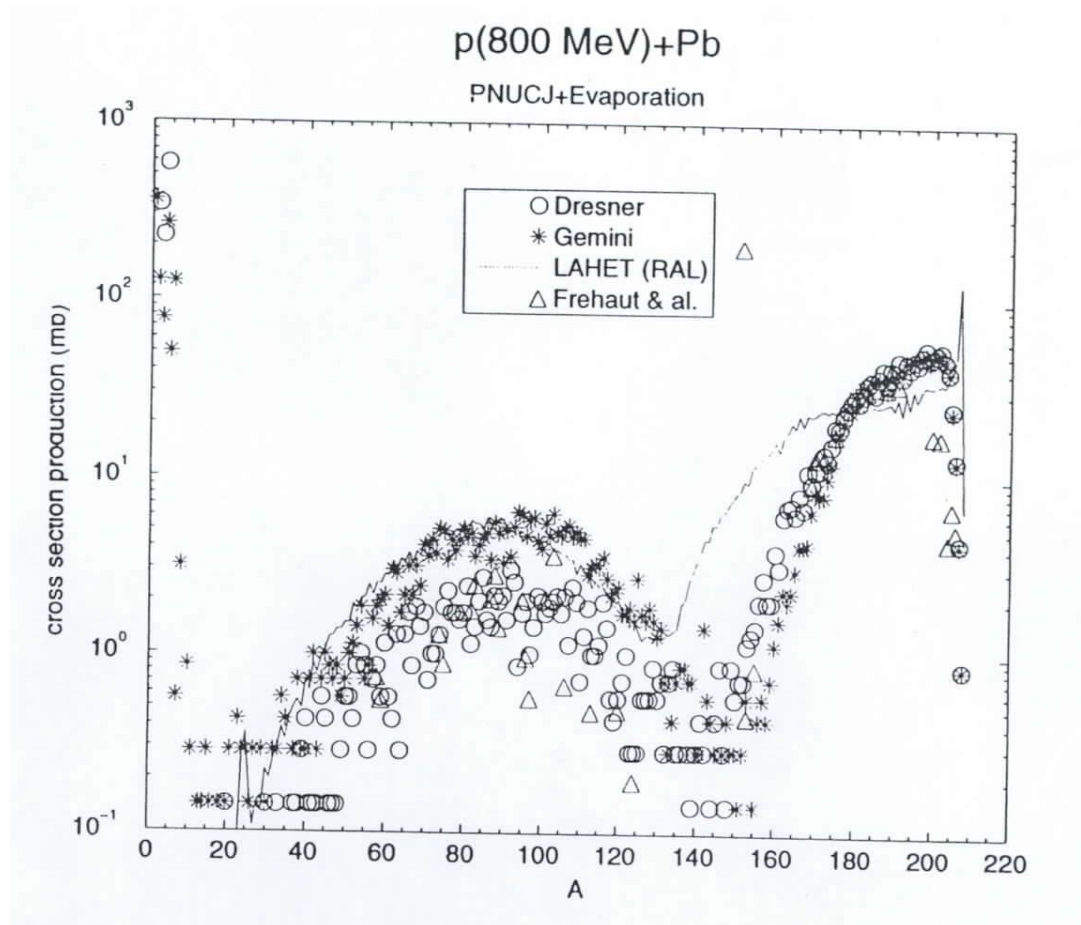
Spallation Product Distribution (1)

□ The spallation product distribution varies as a function of the target material and incident proton energy. It has a very characteristic shape:

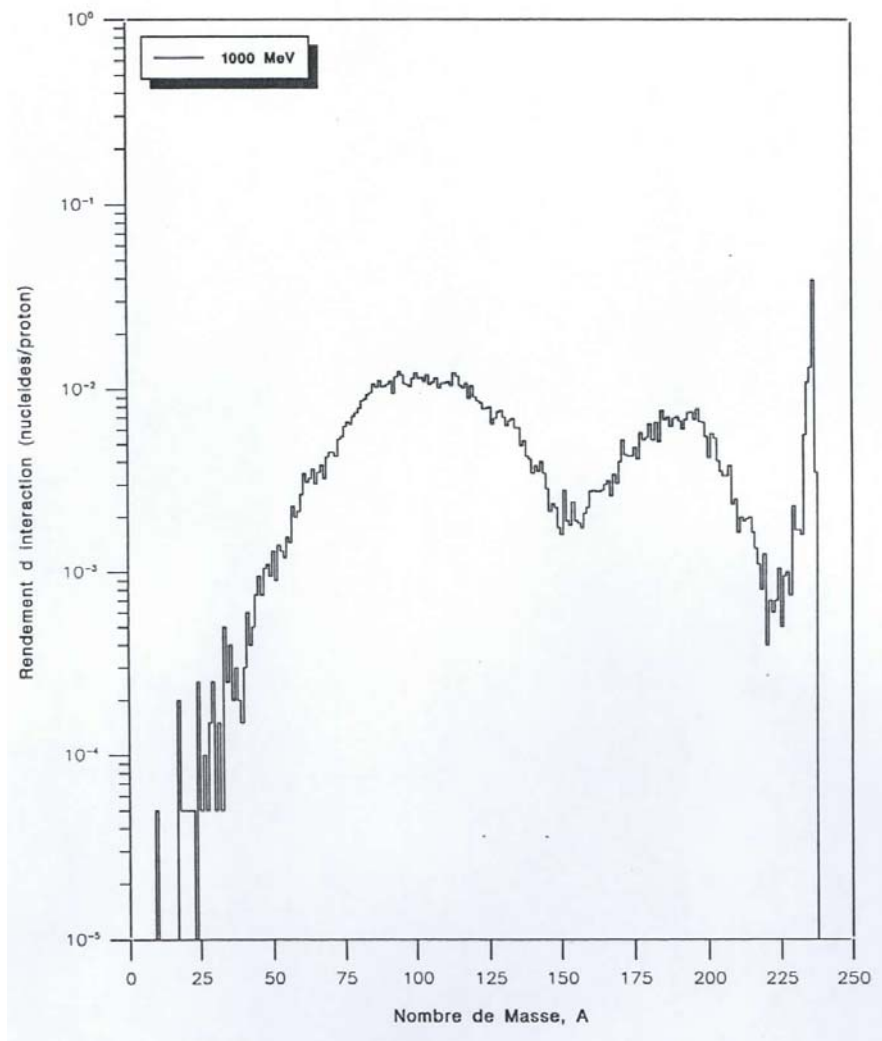
↔ At high masses it is characterized by the presence of two peaks corresponding to (i) the initial target nuclei and (ii) those obtained after evaporation

↔ Three very narrow peaks corresponding to the evaporation of light nuclei such as (deuterons, tritons, ^3He and α)

↔ An intermediate zone corresponding to nuclei produced by high-energy fissions



Spallation Product Distribution (2)



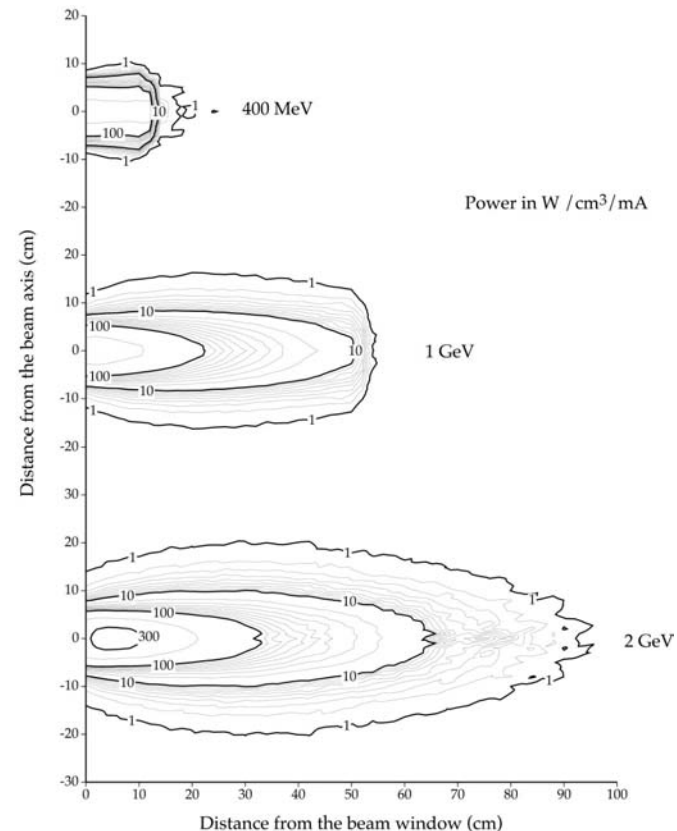
Energy Deposition

- Example of the heat deposition of a proton beam in a beam window and a Lead target
 - ↔ which takes into account not only the electromagnetic interactions, but all kind of nuclear reactions induced by both protons and the secondary generated particles (included neutrons down to an energy of 20 MeV) and gammas.

↑ Increasing the energy of the incident particle affects considerably the power distribution in the Lead target. Indeed one can observe that, while the heat distribution in the axial direction extends considerably as the energy of the incident particle increases, it does not in the radial direction, which means that the proton tracks tend to be quite straight. ↑ **Lorentz boost**

↑ Heat deposition is largely contained within the range of the protons. But while at 400 MeV the energy deposit is exactly contained in the calculated range (16 cm), this is not entirely true at 1 GeV where the observed range is about 9% smaller than the calculated ($r_{\text{calc}} = 58 \text{ cm}$, $r_{\text{obs}} \sim 53 \text{ cm}$). At 2 GeV the difference is even more relevant ($r_{\text{calc}} = 137 \text{ cm}$, $r_{\text{obs}} \sim 95 \text{ cm}$). This can be explained by the rising fraction of nuclei interactions with increasing energy, which contribute to the heat deposition and shortens the effective proton

range.



Models and Codes for High-Energy Nuclear Reactions (1)

- The processes are calculated by intra- and inter-nuclear cascade codes developed by several laboratories in the world ⇐ Reviews by Hiroshi Takahashi, BNL (1991) & Mashnik et al., LANL (2000)

Intranuclear Cascade Models (INC)

R. Serber, *Phys. Rev.*, **72** (1947) 1114.

M. L. Goldberger, *Phys. Rev.*, **74** (1948) 1268.

N. Metropolis, R. Bivins, M. Storm, A. Turkevich, J. M. Miller, and G. Friedlander, *Phys. Rev.*, **110** (1958) 185; *Phys. Rev.*, **110** (1958) 204.

$N, \pi + A$:

H. W. Bertini, *Phys. Rev.*, **188** (1969) 1711; *Phys. Rev. C*, **1** (1970) 423; **6** (1972) 631.

V. S. Barashenkov, A. S. Il'inov, N. M. Sobolevskii, and V. D. Toneev, *Sov. Phys. Usp.*, **16**, 31 (1973).

S. G. Mashnik and A. J. Sierk, "Improved Cascade-Exciton Model of Nuclear Reactions," *Proc. SARE4, September 1998, TN*, p. 29; Eprint: nucl-th/98120669.

Y. Yariv and Z. Frankel, *Phys. Rev. C*, **20** (1979) 2227.

K. Chen, Z. Fraenkel, G. Friedlander, J. R. Grover, J. M. Miller, and Y. Shimamoto, *Phys. Rev.*, **166**, 948 (1968);

J. N. Ginocchio, *Phys. Rev. C*, **17** (1978) 195.

J. Cugnon, C. Volant, and S. Vuillier, *Nucl. Phys. A*, **620** (1997) 475.

Bruyères-le-Châtel INC: O. Bersillon et al., *Proc. ADTTA'96, Kalmar, 1996*, p. 520; H. Duarte, *Proc. ADTTA'99, Praha, 1999*, paper MO-O-C17; O. Bersillon, *Proc. SARE-5/SATIF-5, Paris, 2000*.

Medium Effect in INC: E. Suetomi, N. Kishida, and H. Kadotami, "An Analysis of the Intranuclear Cascade Evaporation Model with In-Medium Nucleon-nucleon Cross Sections," *Phys. Lett. B*, **333**, 22 (1994); H. Takada, "Nuclear Medium Effect in the Intranuclear Cascade Calculation," *J. Nuc. Sci. & Techn.*, **33**, 275 (1996).

Reviews:

A. S. Iljinov, M. V. Kazarnovsky, and E. Ya. Paryev, *Intermediate-Energy Nuclear Physics*, CRC Press, Boca Raton (1994).

L. Ray, G. W. Hoffmann, and W. R. Coker, *Phys. Rep.*, **212** (1992) 223.

Z. Fraenkel, *Nucl. Phys. A* (1984) 428.

V. S. Barashenkov and V. D. Toneev, *Interaction of High Energy Particle and Nuclei with Atomic Nuclei*, (in Russian) Atomizdat, Moscow (1972).

Models and Codes for High-Energy Nuclear Reactions (2)

Pre-Equilibrium Models (> 100 modifications)

Semi-Classical, Exciton and Hybrid models:

J. J. Griffin, *Phys. Rev. Lett.*, **17** (1966) 478.

C. K. Cline, *Nucl. Phys. A*, **193** (1972) 417.

G. D. Harp, J. M. Miller, and B. J. Berne, *Phys. Rev.*, **165** (1968) 1166.

M. Blann, *Phys. Rev. Lett.*, **28** (1972) 757.

Reviews:

E. Gadioli and P. E. Hodgson, *Pre-Equilibrium Nuclear Reactions*, Clarendon Press, Oxford (1992).

H. P. Gruppelaar, P. Nagel, and P. E. Hodgson, *Riv. Nuovo Cim.*, **9** (1986) 1.

K. Seidel, D. Seeliger, R. Reif, and V. D. Toneev, *Fiz. Elem. Chast. i Atom. Yad. (Sov. J. Part. Phys.)*, **7** (1976) 499.

M. Blann, *Annu. Rev. Nucl. Sci.*, **25** (1975) 123.

Quantum-Mechanical, MSC and MSD:

H. Feshbach, *Proc. Int. Conf on Nucl. Phys., Munich, 1973*, p. 631;
Proc. Int. Conf on Nucl. Reaction Mechanisms, Varenna, 1977, p. 1.

H. Feshbach, A. Kerman, and S. Koonin, *Ann. Phys. (N.Y.)*, **125** (1980) 429.

Review:

R. Bonetti, A. J. Koning, J. M. Akkermans, and P. E. Hodgson, *Phys. Rep.*, **247** (1994) 1.

$A + A$:

J. Cugnon, D. Kinet, and J. Vandermeulen, *Nucl. Phys. A*, **379** (1982) 553.

V. D. Toneev and K. K. Gudima, *Nucl. Phys. A*, **400** (1983) 173c.

Y. Yariv and Z. Frankel, *Phys. Rev. C*, **24** (1981) 448.

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C. Y. Fu, T. A. Gabriel, and R. A. Lillie, "PICA95: An Intranuclear-Cascade Code for 25 MeV to 3.5 GeV Photon-Induced Nuclear Reactions," *Proc. SATIF3, Sendai, Japan, May 1997*, p. 49;

T. A. Gabriel and R. G. Alsmiller, Jr., *Phys. Rev.*, **182** (1969) 1035;

T. A. Gabriel, *Phys. Rev. C*, **13** (1976) 240.

A. S. Iljinov, I. A. Pshenichnov, N. Bianchi, E. De Sanctis, V. Muccifora, M. Mirazita, and P. Rossi, *Nucl. Phys. A*, **616** (1997) 575;

K. K. Gudima, A. S. Iljinov, and V. D. Toneev, "A Cascade Model for Photonuclear Reactions," *JINR Communication P2-4661*, Dubna (1969);

V. S. Barashenkov, F. G. Geregi, A. S. Iljinov, G. G. Jonsson, and V. D. Toneev, *Nucl. Phys. A*, **231** (1974) 462;

T. Gabriel, G. Maino, and S. G. Mashnik, "Analysis of Intermediate Energy Photonuclear Reactions," JINR Preprint E2-94-424, Dubna (1994).

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$\bar{N} + A$:

A. S. Iljinov, V. I. Nazaruk, and S. E. Chigrinov, *Nucl. Phys. A*, **382** (1982) 378;
S. G. Mashnik, *Rev. Roum. Phys.*, **37** (1992) 179.

J. Cugnon, P. Deneye, and J. Vandermeulen, *Nucl. Phys. A*, **517** (1990) 533.

M. R. Clover, R. M. De Vries, N. J. Di Giacomo, and Y. Yariv, *Phys. Rev. C*, **26** (1982) 2138.

...

Models and Codes for High-Energy Nuclear Reactions (3)

Multifragmentation

- Probabilistic models
- Macroscopic statistical models
- Microscopic dynamical models
- Molecular Dynamics; Quantum Molecular Dynamics
- Kinetic models
- Sequential evaporation or very asymmetric fission
- Hybrid models
- ...

Reviews:

L. G. Moretto, R. Ghetti, L. Phair, K. Tso, and G. J. Woaniak, *Phys. Rep.*, **287** (1997) 249.

J. P. Bondorf, A. S. Botvina, A. S. Iljinov, I. N. Mishustin, and K. Sneppen, *Phys. Rep.*, **257** (1995) 133.

G. Peilert, H. Stöcker, and W. Greiner, *Rep. Prog. Phys.*, **57** (1994) 533.

A. Bonasera, F. Gulminelli, and J. Molitoris, *Phys. Rep.*, **243** (1994) 1.

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E. Fermi, *Prog. Theor. Phys.*, **5** (1950) 570.

A. P. Zhdanov, P. I. Fedotov, *Sov. Phys. JETP*, **18** (1964) 313;

M. Épharre, É. Gradsztajn, *J. Phys. (Paris)*, **28** (1967) 747.

T. S. Subramanian, J. L. Romero, F. P. Brady, D. H. Fitzgerald, R. Garrett, G. A. Needham, J. Ullmann, J. W. Watson, C. I. Zanelli, D. J. Brenner, and R. E. Prael, *Phys. Rev.*, **C34** (1986) 1580;

D. J. Brenner and R. E. Prael, *At. Nucl. Data Tables*, **41** (1989) 71.

Semiempirical Systematics

Reviews:

T. A. Gabriel and S. G. Mashnik, "Semiempirical Systematics for Different Hadron-Nucleus Interaction Cross Sections," JINR Preprint E4-96-43, Dubna (1996).

A. J. Koning, "Review of High Energy Data and Model Codes for Accelerator-Based Transmutation," ECN-C-93-005, Petten (January 1993).

J. Hüfner, "Heavy Fragments Produced in Proton-Nucleus and Nucleus-Nucleus Collisions at Relativistic Energies," *Phys. Rep.*, **125**, 129 (1985).

V. S. Barashenkov and V. D. Toneev, *Interaction of High Energy Particles and Nuclei with Atomic Nuclei* (Moscow, Atomizdat, 1972).

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Recent Useful Systematics:

R. Silberberg, C. H. Tsao, and A. F. Barghouty, "Updated Partial Cross Sections of Proton-Nucleus Reactions," *Astrophys. J.*, **501** (1998) 911-919.

C. H. Tsao, A. F. Barghouty, and R. Silberberg, "Nuclear Cross Sections and the Composition, Transport, and Origin of Galactic Cosmic Rays," in *Topics in Cosmic-Ray Astrophysics*, Horizons in World Physics series, vol. 230, Nova Science Publishers, Inc., Commack, New York, 1999, pp. 141-168.

K. Summerer and B. Blank, "Modified Empirical Parametrization of Fragmentation Cross Sections," *Phys. Rev. C* **61**, 034607 (2000).

R. K. Tripathi, F. A. Cucinotta, and J. W. Wilson, "Accurate Universal Parametrization of Absorption Cross Sections," *Nucl. Instr. Meth. B* **117**, 347 (1996).

R. K. Tripathi, J. W. Wilson, and F. A. Cucinotta, "Nuclear Absorption Cross Sections Using Medium Modified Nucleon-Nucleon Amplitudes," *Nucl. Instr. Meth. B* **145**, 277 (1998).

R. K. Tripathi, F. A. Cucinotta, and J. W. Wilson, "Medium Modified Nucleon-Nucleon Cross Sections in a Nucleus," *Nucl. Instr. Meth. B* **152**, 425 (1999).

Models and Codes for High-Energy Nuclear Reactions (4)

Evaporation models

Classical:

- V. F. Weisskopf and D. H. Ewing, *Phys. Rev.*, **57** (1940) 472;
V. Weisskopf, *Phys. Rev.*, **52** (1937) 295.
- I. Dostrovsky, Z. Frankel, and G. Friedlander, *Phys. Rev.*, **116** (1959) 683.
I. Dostrovsky and Z. Frankel, *Phys. Rev.*, **118** (1960) 781.
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- V. D. Toneev, "Interaction of Fast Nucleons with Nuclei. II. Evaporation Cascade," *JINR Report B1-2740*, Dubna (1966) (in Russian).
- A. S. Iljinov, M. V. Mebel, N. Bianchi, E. De Sanctis, C. Guaraldo, V. Lucherini, V. Muccifora, E. Polli, A. R. Reolon, and P. Rossi, *Nucl. Phys. A*, **543** (1992) 517.
- J. Benlliure, A. Grewe, M. de Jong, K.-H. Schmidt, and S. Zhdanov, *Nucl. Phys. A*, **628** (1998) 458.
- S. Furihata, "Statistical Analysis of Light Fragment Production from Medium Energy Proton-Induced Reactions," Eprint: nucl-th/0003036, 15 Mar 2000.

Quantum-Mechanical:

- W. Hauser and H. Feshbach, *Phys. Rev.*, **87** (1952) 366; H. Feshbach, A. Kerman, and S. E. Koonin, *Ann. Phys. (N.Y.)*, **125** (1980) 429.
- R. Bonetti, L. Colli Milazo, and M. Melanotte, *Phys. Rev. C*, **27** (1983) 1003.
- M. B. Chadwick, R. Bonetti, and P. E. Hodgson, *J. Phys. G: Nucl. Part. Phys.*, **15** (1989) 237.
- M. Herman, G. Reffo, and H. A. Weidenmüller, *Nucl. Phys. A*, **536** (1992) 124.

Reviews:

- E. Vogt, *Adv. Nucl. Phys.*, **1** (1968) 268.
- V. S. Barashenkov and V. D. Toneev, *Interaction of High Energy Particle and Nuclei with Atomic Nuclei*, (in Russian) Atomizdat, Moscow (1972).
- R. Bonetti, M. B. Chadwick, P. E. Hodgson, B. V. Carlson, and M. S. Hussein, *Phys. Rep.*, **202** (1991) 171.

Models and Codes for High-Energy Nuclear Reactions (5)

High Energy Fission

N. Bohr and J. A. Wheeler, *Phys. Rev.*, **56** (1939) 426.

Statistical Models of Fission:

P. Fong, *Statistical Theory of Nuclear Fission*, Gorgon and Breach Science Publishers, New York (1969).

V. D. Toneev, *JINR Report B1-2812*, Dubna (1966) (in Russian);
V. S. Barashenkov and S. Yu. Shmakov, *JINR Communication E2-12902*, Dubna (1979).

F. S. Alsmiller, R. G. Alsmiller, Jr., T. A. Gabriel, R. A. Lillie, and J. Barish, *Nucl. Sci. Eng.*, **79** (1981) 147; **79** (1981) 166.

H. Takahashi, *Nucl. Sci. Eng.*, **87** (1984) 432.

N. V. Stepanov, ITEP Preprints ITEP-81 and ITEP-55, Moscow (1987 and 1988).

Dynamical Models of Fission:

G. D. Adeev, I. I. Gonchar, V. V. Pashkevich, N. I. Pischasov, and O. I. Serdyuk, *Sov. J. Part. Nucl.*, **19** (1988) 529; I. I. Gonchar, *Phys. Part. Nucl.*, **26** (1995) 394.

G. D. Adeev, A. S. Botvina, A. S. Iljinov, M. V. Mebel, N. I. Pischasov, and O. I. Serdyuk, *Preprint INR 816/93*, Moscow (1993).

Semi-Phenomenological Models:

F. Atchinson, in *Targets for Neutron Beam Spallation Sources*, Jül-Conf-34, Kernforschungsanlage Jülich GmbH (1980).

Y. Nakahara, *J. Nucl. Sci. Technol.*, **20** (1983) 511.

P. P. Jauho, A. Jokinen, M. Leino, J. M. Parmonrn, H. Penttilä, J. Äystö, K. Eskola, and V. A. Rubchenya, *Phys. Rev. C*, **49** (1994) 2036.

Sequential binary decays using the code GEMINI:

R. J. Charity, M. A. McMahan, G. J. Wozniak, R. J. McDonald, L. G. Moretto, D. G. Sarantites, L. G. Sobotka, G. Guarino, A. Pantaleo, L. Fiore, A. Gobbi, and K. D. Hildenbrand, *Nucl. Phys. A*, **483** (1988) 371.

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A. S. Iljinov, M. V. Kazarnovsky, and E. Ya. Paryev, *Intermediate-Energy Nuclear Physics*, CRC Press, Boca Raton (1994).

D. Hilscher and H. Rossner, "Dynamics in Nuclear Fission," *Ann. Phys. Fr.*, **17** (1992) 471.

M. G. Jtkis and A. Ya. Rusanov, *Phys. Part. Nucl.*, **29** (1998) 160.

Models and Codes for High-Energy Nuclear Reactions (6)

Ultrarelativistic energies

Gribov-Regge theory (Perturbative QCD doesn't apply yet)

- Quark Gluon String Model (QGSM)
- String Gas Model (SGM)
- Dual Parton Model (DPM)
- QCD Parton Model (PCM)
- Relativistic Quantum Molecular Dynamics (RQMD)
- HERWIG, ISAJET, PYTHIA, VECBOS, PAPAGENO, ..., event generators
- CALOR89 code
- Lund FRITIOF code
- VENUS (Very Energetic Nuclear Scattering) code
- GEANT4 code
- MARS code
- FLUKA (FLUctuating KAscade code)
- ...

Reviews:

T. C. Awes and S. P. Sorensen, *Nucl. Phys. A*, **498**, 123c (1989).

K. D. Lane, F. E. Paige, T. Skwarnicki, and W. J. Womersley, *Phys. Rep.*, **278** (1997) 291.

...

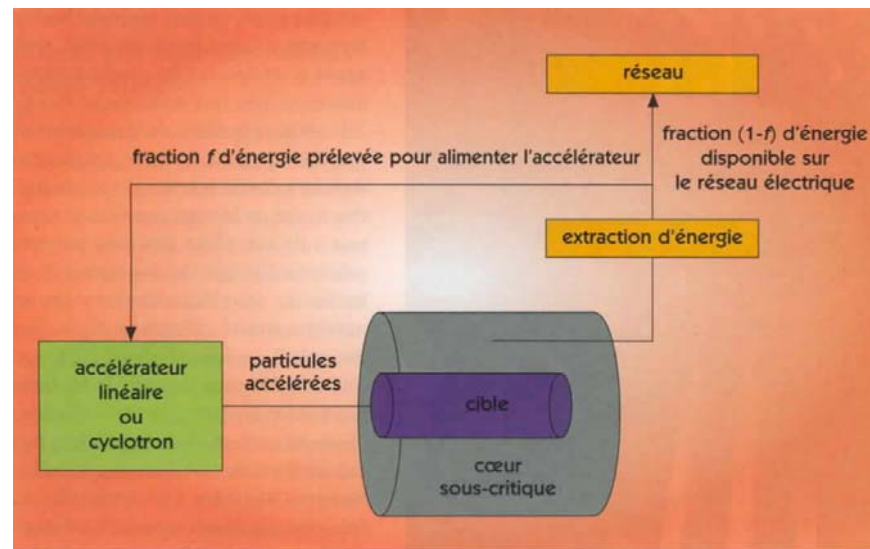
GEANT4, User's Documents, Physics Reference Manual, last update 08/04/99:
<http://wwwinfo.cern.ch/asd/geant4/G4UsersDocuments/UsersGuides/PhysicsReferenceManual/html/PhysicsReferenceManual.html>

H. Kitsuki, N. Shigyo, and K. Ishibashi, "Parametrization of Neutron Production Double-Differential Cross Sections above Several Tens-Mev by the use of Moving Source Model," Proc. 1999 Symp. on Nuclear Data, November 18-19, 1999, JAERI, Tokai, Japan, JAERI-Conf 2000-05, pp. 278-283 (2000).

B. S. Sychev, *Cross Sections of High Energy Hadron Interactions on Nuclei* (Russian Academy of Science, Moscow Radiotechnical Institute, Moscow, 1999).

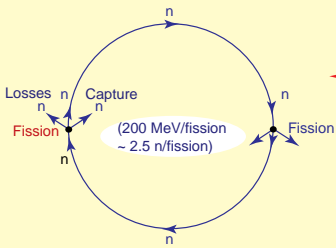
Physics of Sub-Critical Systems (1)

- In Accelerator-Driven Systems a *Sub-Critical blanket* surrounding the spallation target is *used to multiply the spallation neutrons*.



Physics of Sub-Critical Systems (2)

Chain Reaction



Effective neutron multiplication factor

$$k = \frac{\text{Production}}{\text{Absorption} + \text{Losses}}$$

Self-sustained process:

$$k = 1$$

(if $k < 1$ the Reactor stops

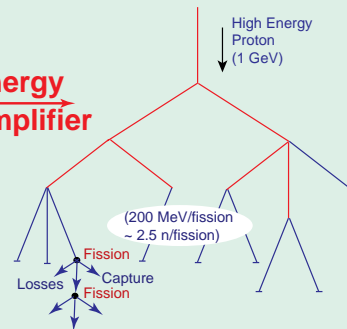
if $k > 1$ the Reactor is supercritical)

⇒ The time derivative of the power kept equal to zero by control

Critical Reactor

Nuclear Cascade

Energy Amplifier



Externally driven process:

$$k < 1 \quad (k = 0.98)$$

$$E_{\text{tot}} = G \times E_p$$

Energy Produced

Beam Energy

⇒ Constant Energy Gain

☆ ADS operates in a non self-sustained chain reaction mode

↑ minimises criticality and power excursions

⌚ ADS is operated in a sub-critical mode

↑ stays sub-critical whether accelerator is on or off

↑ extra level of safety against criticality accidents

⌚ The accelerator provides a control mechanism for sub-critical systems

↑ more convenient than control rods in critical reactor

↑ safety concerns, neutron economy

⌚ ADS provides a decoupling of the neutron source (spallation source) from the fissile fuel (fission neutrons)

⌚ ADS accepts fuels that would not be acceptable in critical reactors

↑ Minor Actinides

↑ High Pu content

↑ LLFF...

Physics of Sub-Critical Systems : *Multiplication Factor (1)*

Care must be taken in the interpretation of the effective neutron multiplication factor k_{eff} (ratio between the neutron population in two subsequent generations) when dealing with an externally driven subcritical system. In the classic theory of one group diffusion for the uniform reactor, we can write the neutron transport equation as:

$$\frac{1}{v} \frac{d\psi}{dt} = D (\nabla^2 + B^2) \psi(x, t) \quad (1)$$

If we suppose to factorise the solution as $\psi(x, t) = \phi(x)\varphi(t)$, we are left with a classical eigenvalue problem. The eigenvalues that give the correct boundary conditions are:

$$B^2 - n \frac{\pi^2}{a^2} = \frac{v\Sigma_f - \Sigma_a}{D} - n \frac{\pi^2}{a^2}$$

where a is the size of the reactor. To every value of n corresponds an eigenfunction. The time dependent part is then:

$$\frac{1}{vD} \frac{d\varphi(t)}{dt} = (B^2 - n \frac{\pi^2}{a^2}) \varphi(t)$$

and to every value of n corresponds a time component:

$$\varphi_n(t) = e^{Dv(B^2 - n\pi^2/a^2)t}$$

If $B^2 < \pi^2 a^{-2}$, the reactor is subcritical and the fluence dies away. If $B^2 > \pi^2 a^{-2}$, the reactor is supercritical and it diverges. In case the reactor is not critical, an associated critical reactor is defined where B_0^2 is defined as

$$B_0^2 = \frac{(v/k_{eff})\Sigma_f - \Sigma_a}{D} = \frac{\pi^2}{a^2}$$

Physics of Sub-Critical Systems : *Multiplication Factor (2)*

This is the correction that we have to apply to the average number of neutrons produced per fission to make the reactor critical. Solving for k_{eff} we have:

$$k_{eff} = \frac{\nu \Sigma_f}{\Sigma_a + D \pi^2 / a^2}$$

where k_{eff} can be interpreted as the number of fission neutrons produced for each neutron absorbed. If the system is in the eigenstate relative to B^2 and not B_0^2 then the net multiplication factor due to fission is:

$$M_{eff} = \frac{1}{1 - k_{eff}}$$

This simple theory can be generalised in different ways to a more realistic situation, but two aspects are neglected since the start, i.e. the nonfission multiplicative processes and the possible presence of an external source. The nonfission multiplication could be taken into account as a modification of Σ_a , and still the previous development would hold.

In this development k_{eff} is an intrinsic property of the system. If the fluence distribution is not an eigenstate of the operator, the net multiplication factor will be different, but this will not change the value of k_{eff} . We can still define formally a value of k as $k_{src} = 1 - 1/M_{src}$ but it will depend on the fluence as well as on the system. In particular, in the presence of an external source, this value will depend on the position and spectrum of the source neutrons. We will indicate hereon with k_{src} the value of k calculated from the net multiplication factor M_{src} in the presence of an external source.

Physics of Sub-Critical Systems : *Source Importance (1)*

By definition a constant power operation requires ν/k_{eff} neutrons per fission, which means that an external source has to provide a number of neutrons per fission which is

$$\mu_{eff} = \nu \left(\frac{1}{k_{eff}} - 1 \right) = \frac{\nu}{M_{eff} - 1}$$

if they are distributed exactly as the eigenfunction of the stationary problem. In the case of an arbitrary external source, this number becomes:

$$\mu_{src} = \nu \left(\frac{1}{k_{src}} - 1 \right) = \frac{\nu}{M_{src} - 1}$$

The ratio: is known as the importance of source neutrons.

$$\frac{\mu_{eff}}{\mu_{src}} = \frac{(1 - k_{eff}) / (k_{eff} / \nu)}{(1 - k_{src}) / (k_{src} / \nu)} = \varphi^* \quad (2)$$

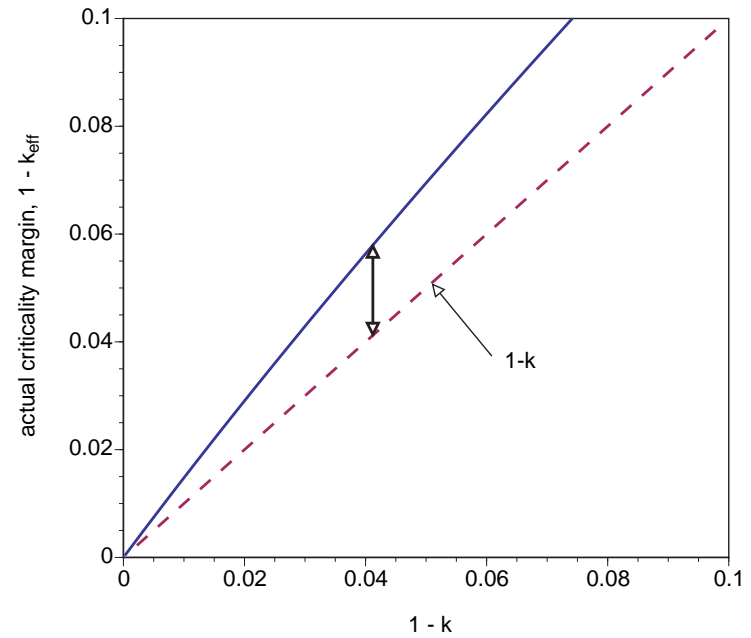
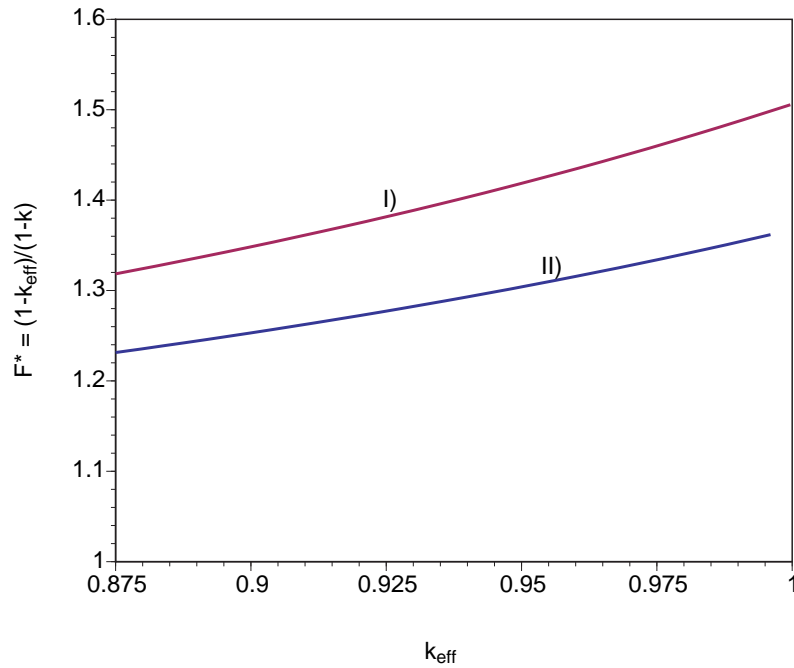
The operational safety margin on k_{∞} for an ADS with multiplication M, can be written as

$$\Delta k_{\infty}^{crit}(M) = k_{\infty}(M) \frac{\varphi^*}{M - 1}$$

In general, it is found that the neutron source importance grows with k and that at given k, it increases with

- the "containment" of the neutron source;
- the ratio of the neutron diffusion length to the size of fissile core;
- the presence of an absorbing medium, "enclosing" the fissionable core, which, in a sense, limits the "widening" of the neutron flux distribution as k is increased

Physics of Sub-Critical Systems : *Source Importance* (2)



Physics of Sub-Critical Systems : *Spatial Distribution (1)*

To compute the neutron flux and the neutron current we use **diffusion theory**, according to which the current is given by

$$\mathbf{J} = -D\nabla\phi,$$

where $D = l_{tr}/3$ is the diffusion coefficient, l_{tr} is the neutron transport mean free path, given by $l_{tr} = (\Sigma_t - \bar{\mu}\Sigma_s)^{-1}$, where Σ_t , Σ_s , and Σ_a , are respectively the macroscopic total cross section, the scattering cross section and the absorption cross section, and $\bar{\mu}$ is the average value of the cosine of the scattering angle in the laboratory system. Since in an EA the fuel is cooled (and the neutrons diffused and moderated) by a high-Z material, then one can take $l_{tr} \cong (\Sigma_a + \Sigma_s)^{-1}$.

The neutron flux is the solution of the equation

$$\nabla^2\phi + B_M^2\phi + \frac{C}{D} = 0,$$

where C is the contribution of the external source (neutrons per unit volume and unit time), B_M is the so-called material buckling

$$B_M^2 = \frac{k_\infty - 1}{L^2},$$

k_∞ and L are, respectively, the infinite multiplication coefficient and the diffusion length:

$$k_\infty = \frac{\nu\Sigma_f}{\Sigma_a}, \quad L = \sqrt{\frac{D}{\Sigma_a}},$$

ν is the average fission multiplicity, and Σ_a is the macroscopic cross section.

Physics of Sub-Critical Systems : *Spatial Distribution (2)*

As it is well known , if we consider a finite, system, with vanishing flux at the (extrapolated) boundaries, and a source also vanishing at and outside the boundaries, we can write the solution in terms of the eigenvectors ψ_n of the characteristic "wave equation"

$$\nabla^2 \psi + B^2 \psi = 0 \quad ,$$

which form a complete orthonormal basis, each eigenvector ψ_n corresponding to an eigenvalue B_n . We normalize the eigenfunctions in such a way that $\int \psi_n^2 dV = 1$; and introduce the volume integrals of the eigenfunctions :

$$\Psi_n = \int_V \psi_n(\mathbf{x}) dV \quad .$$

We then write the (known) outer source as

$$C(\mathbf{x}) = \sum_{n=1}^{\infty} c_n \psi_n(\mathbf{x}) \quad ,$$

with the expansion coefficients given by

$$c_n = \int_V C(\mathbf{x}) \psi_n dV \quad ,$$

so that the space integrated source neutron rate can be written as

$$Q = \int_V C(\mathbf{x}) dV = \sum_{n=1}^{\infty} c_n \Psi_n \quad .$$

The (unknown) neutron flux can be expanded in the same basis, too,

$$\phi(\mathbf{x}) = \sum_1^{\infty} \phi_n \psi_n(\mathbf{x})$$

Physics of Sub-Critical Systems : *Spatial Distribution (3)*

A straightforward solution is found for a **homogeneous medium**. Indeed, in this case, by substituting the expansions for the source and the flux we obtain an independent equation for each n , giving the coefficient of the flux as a function of that of the source :

$$\phi_n = \frac{1}{\Sigma_a} \frac{c_n}{1 - (k_\infty - B_n^2 L^2)} = \frac{c_n}{\Sigma_a (1 + B_n^2 L^2)} \frac{1}{1 - k_n} ,$$

where

$$k_n = \frac{k_\infty}{1 + B_n^2 L^2} .$$

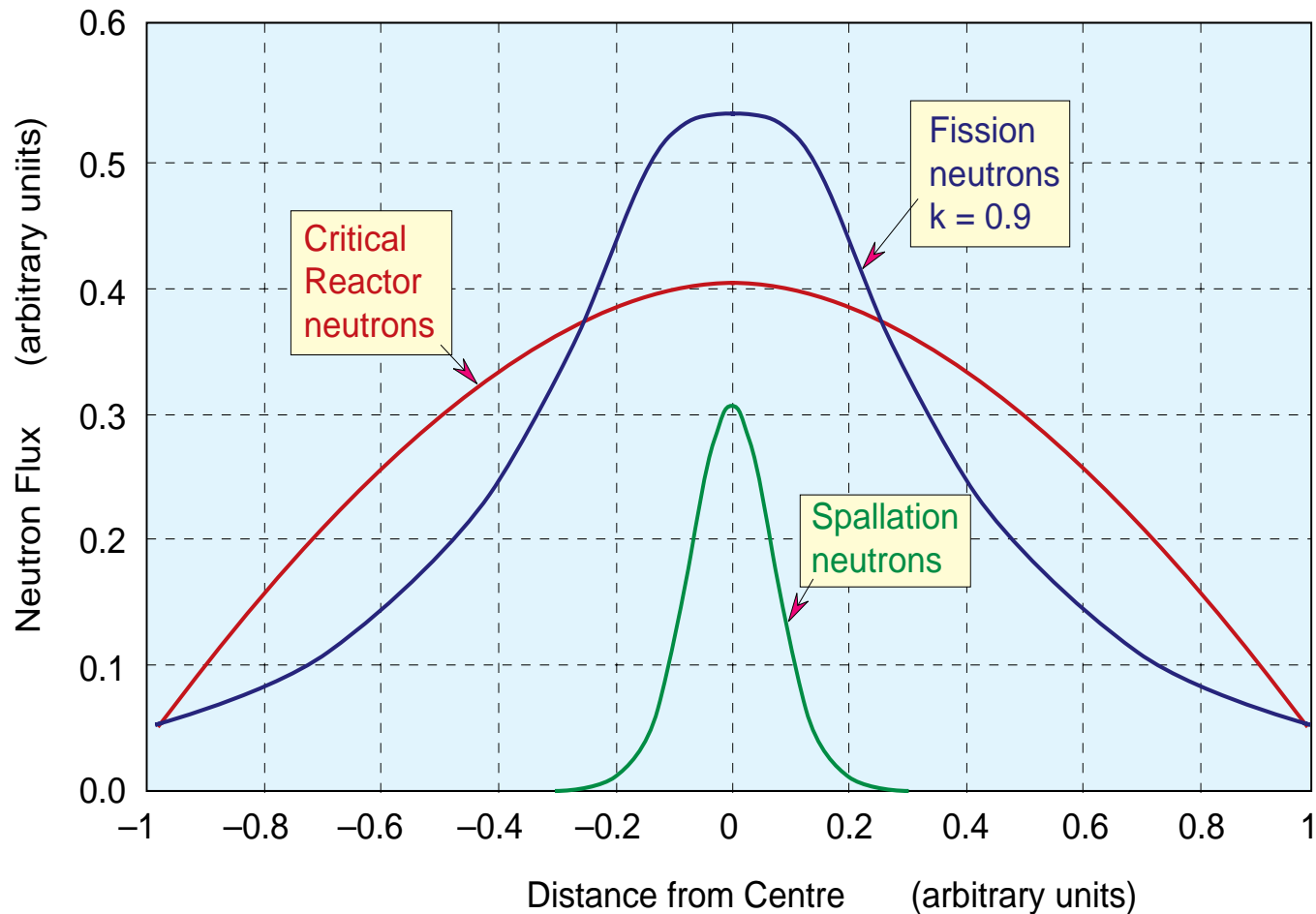
As anticipated, we see that if all k_n 's are smaller than unity, then the flux is given by a linear superposition of eigenmodes; as soon as $k_1 = 1$ the system becomes critical; the source is no more needed to sustain the system, and the only surviving mode is the fundamental one.

If $\frac{k_\infty - 1}{L^2} > 0$, the solutions are of sinus form: $\Psi_{lmn} = \sqrt{\frac{8}{abc}} \sin \pi \frac{lx}{a} \cdot \sin \pi \frac{my}{b} \cdot \sin \pi \frac{nz}{c}$;

If $\frac{k_\infty - 1}{L^2} = -\gamma^2$, the solutions are of exponential form: $\left\{ \begin{array}{l} \Psi(x) = A_1 e^{-\gamma x} + B_1 e^{\gamma x} \\ \Psi(y) = A_2 e^{-\gamma y} + B_2 e^{\gamma y} \\ \Psi(z) = A_3 e^{-\gamma z} + B_3 e^{\gamma z} \end{array} \right\}$;

Physics of Sub-Critical Systems : *Spatial Distribution (4)*

SPATIAL DISTRIBUTION OF THE NEUTRON FLUX



Physics of Sub-Critical Systems : *Source Amplification (1)*

- ❑ In an accelerator driven, sub-critical fission device \Leftrightarrow the "primary" (or "source") neutrons produced via spallation initiate a cascade process.
- ❑ The source is then "amplified" by a factor $M \Leftrightarrow$ the beam power is "amplified" by a factor $G = G_0 M$
- ❑ If we assume that all generations in the cascade are equivalent, we can define an average criticality factor k (ratio between the neutron population in two subsequent generations), so that:

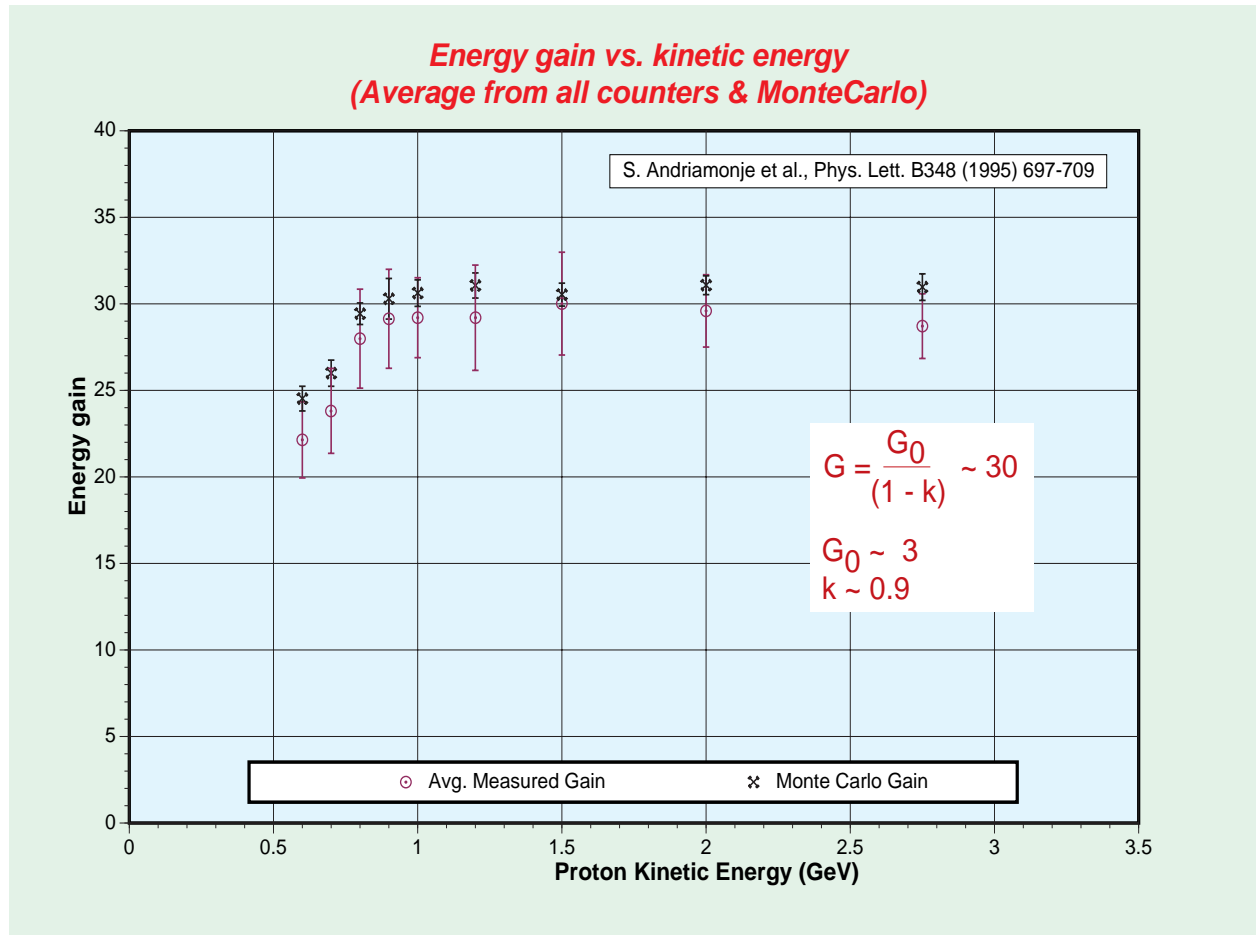
$$M = 1 + k + k^2 + k^3 + \dots = \frac{1}{1 - k}$$

- ❑ Hence:

$$\text{Energy Gain: } G \equiv \frac{\text{Energy Produced by ADS}}{\text{Energy Provided by Beam}} = \frac{G_0}{(1 - k)}$$

- ❑ The G_0 constant contains the spallation information: $G_0 \sim 3$ for uranium, $G_0 \sim 2.7$ for lead.

Physics of Sub-Critical Systems : *Source Amplification (2)*



Review of Sub-Critical Core Experiments

- Highly specified experiments have been carried out to verify the fundamental physics principle of Accelerator-Driven Sub-Critical Systems:

★ **The First Energy Amplifier Test (FEAT):** S. Andriamonje et al. Physics Letters B 348 (1995) 697–709 and J. Calero et al. Nuclear Instruments and Methods A 376 (1996) 89–103;

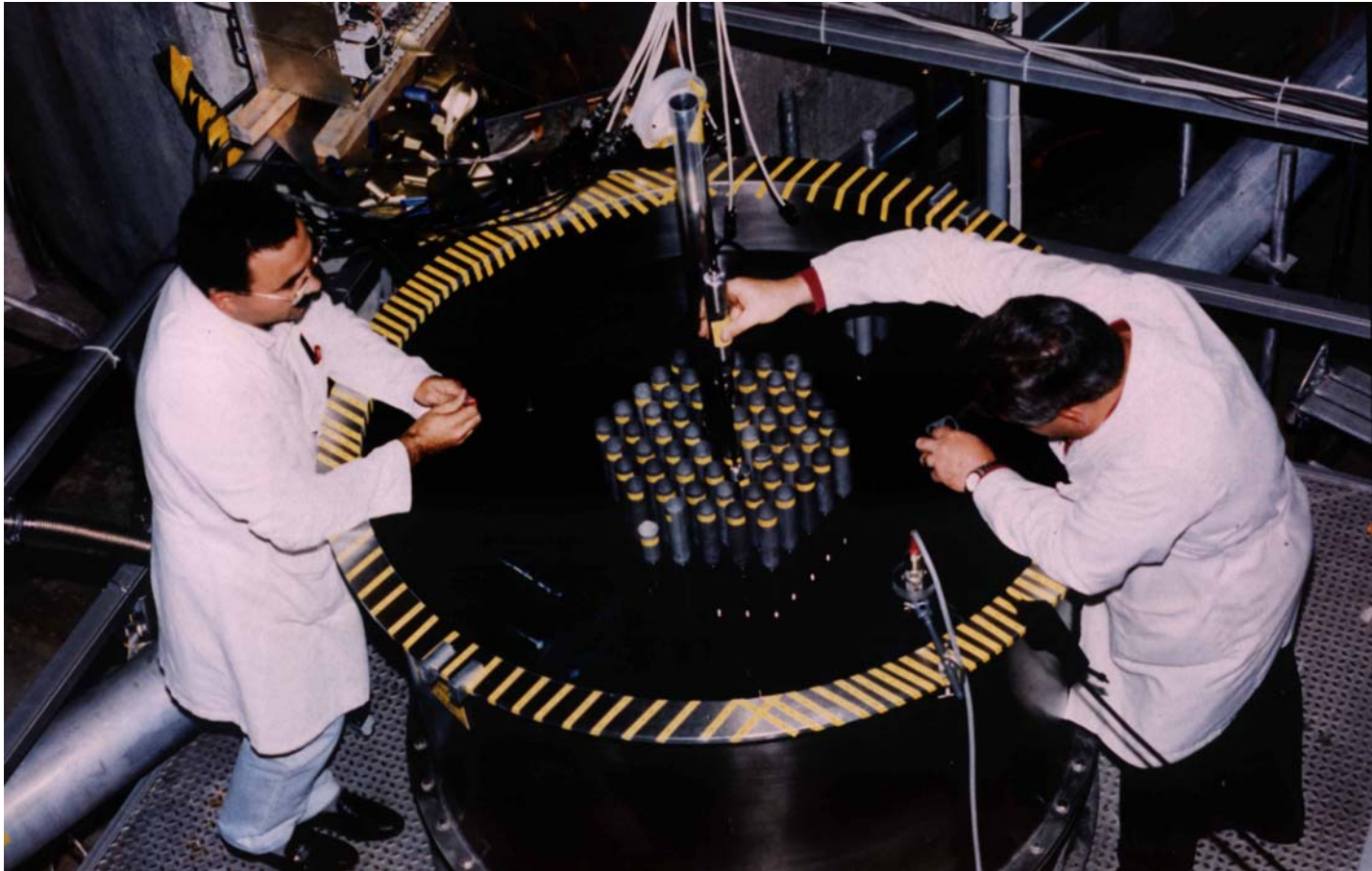
🕒 **The MUSE Experiment (MUltiplication de Source Externe):** M. Salvatores et al., 2nd ADTT Conf., Kalmar, Sweden, June 1996;

🕒 **The YELINA Experiment (ISTC-B-70):** S. Chigrinov et al., Institute of Radiation Physics & Chemistry Problems, National Academy of Sciences, Minsk, Belarus.

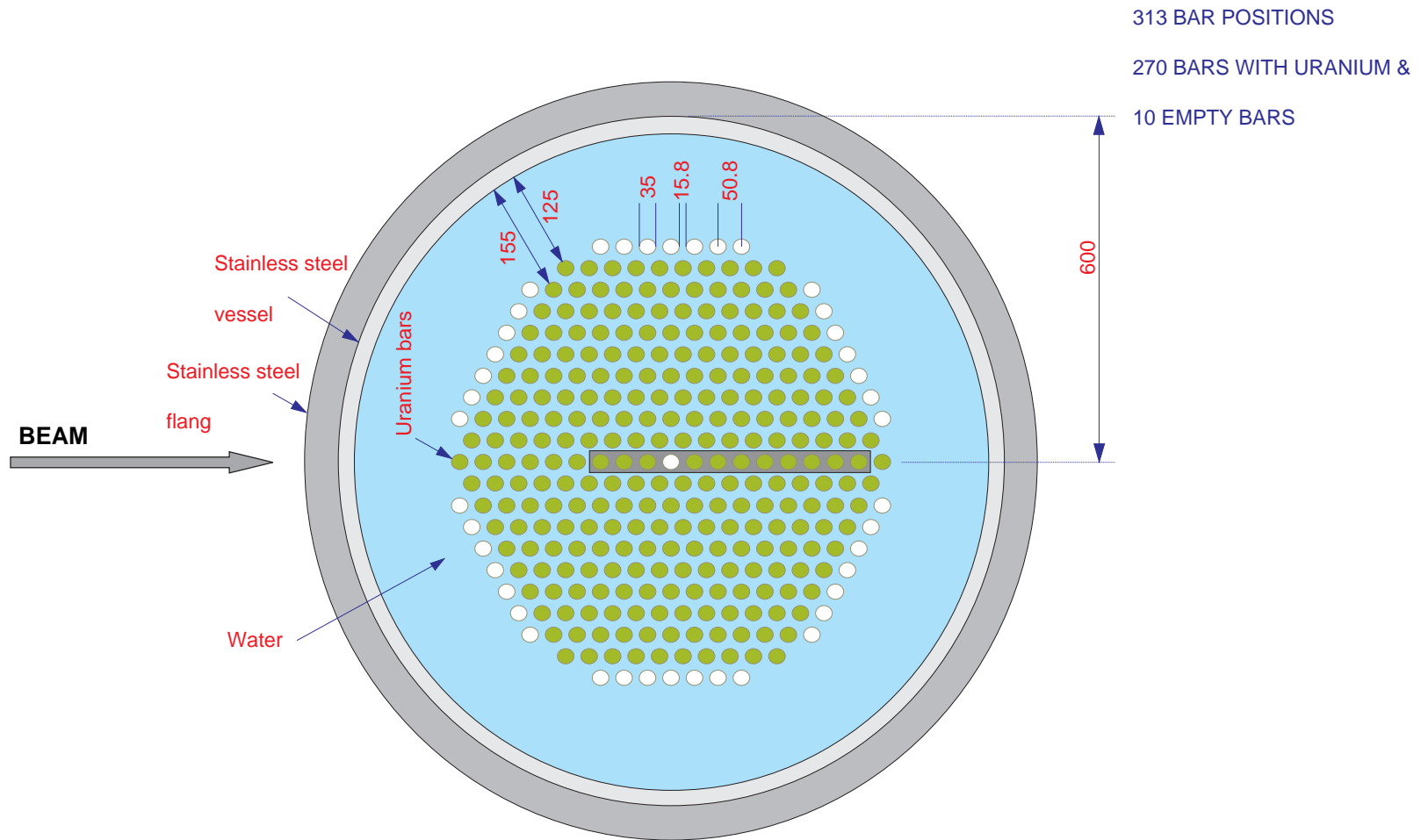
The FEAT Experiment (1)

- ❑ The core of the concept (giving in fact its name to the “Energy Amplifier”) is the production of substantial amounts of energy, over and above the kinetic energy brought in by the accelerator beam.
- ❑ From that stems the concept of an "energy gain" G . In conditions of practical interest, the gain is predicted to be $G = 30$ to 60 , which, taking into account the relevant efficiencies, was easily shown to be much more than is needed to power the accelerator.
- ❑ The main purpose assigned to the test is therefore to ascertain that there is such a gain and that its magnitude is in agreement with the value predicted by the simulation.
 - ↪ The beam intensity that we used (of the order of 10^8 protons/second) was much smaller (by five orders of magnitude) than the one normally delivered by the CERN Proton Synchrotron (PS);
 - ↪ The power produced during the test was **1 Watt**, i.e. nine orders of magnitude less than that of a fully fledged 1000 MW EA unit necessitating a dedicated high intensity accelerator (typically, a few mA of proton beam at 1 GeV);
 - ↪ The total energy release in the volume of the assembly is calculated by taking the heat release measured at the different points by the thermometers and the variation with distance of the energy release to perform the integration over the volume. The thermometers register the complete energy release not only from fission fragments but also from gammas following neutron capture and from radioactive decays.

The FEAT Experiment (2)



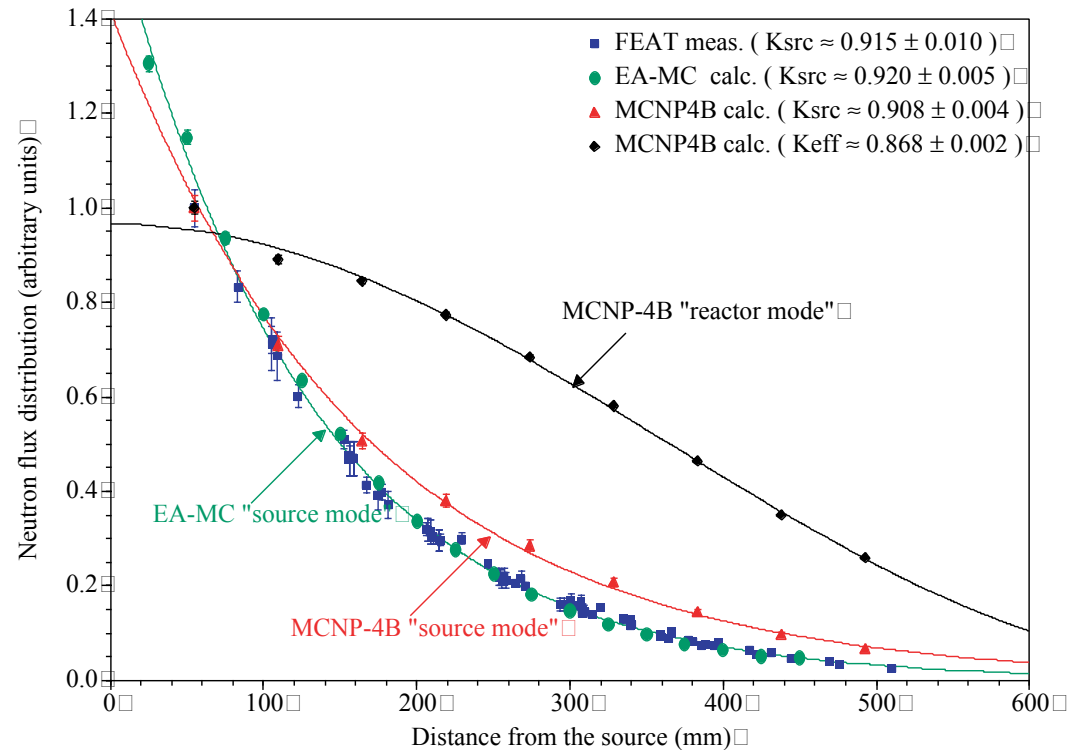
The FEAT Experiment (3)



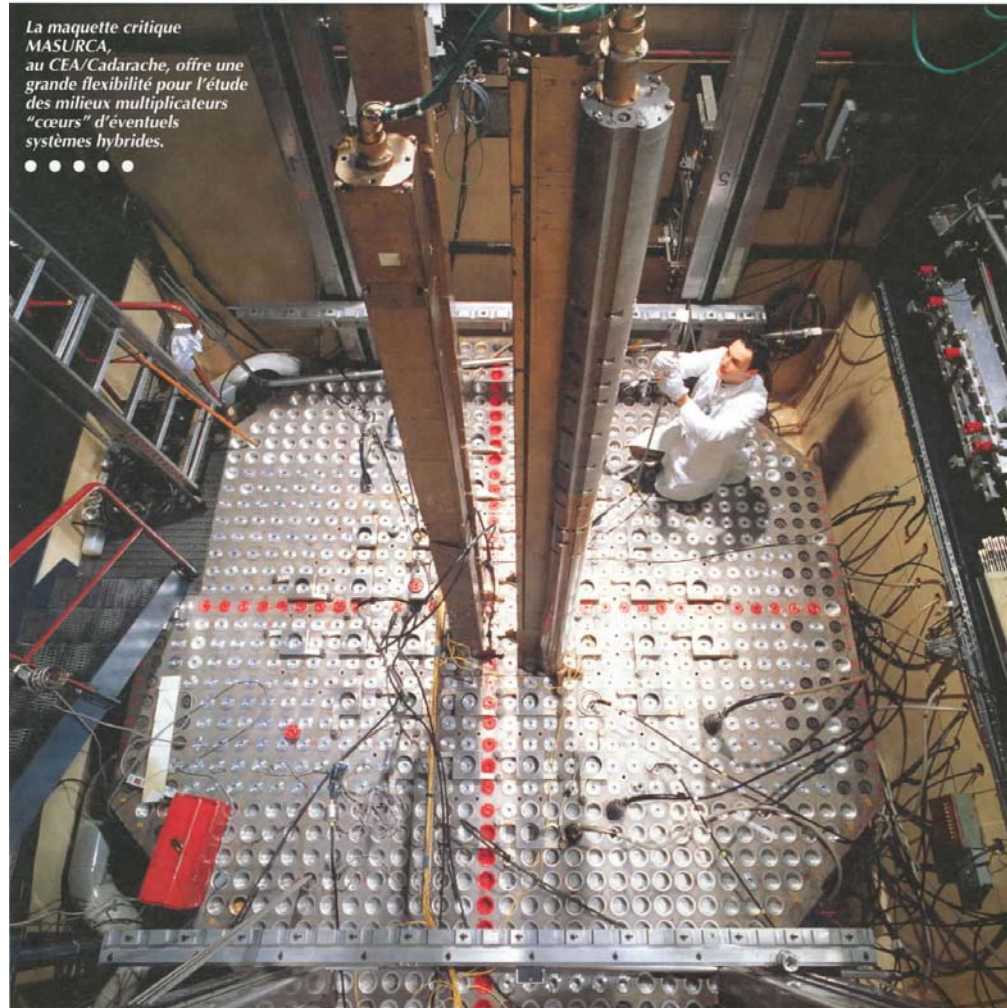
The FEAT Experiment (4)

↑ The neutronic behavior of the assembly has been calibrated with the help of a 58 GBq neutron source (Am-Be) inserted in the centre of the device. The neutron flux measured with a boron loaded counter is shown below, and confirms the expected exponential behavior as a function of the distance from the source.

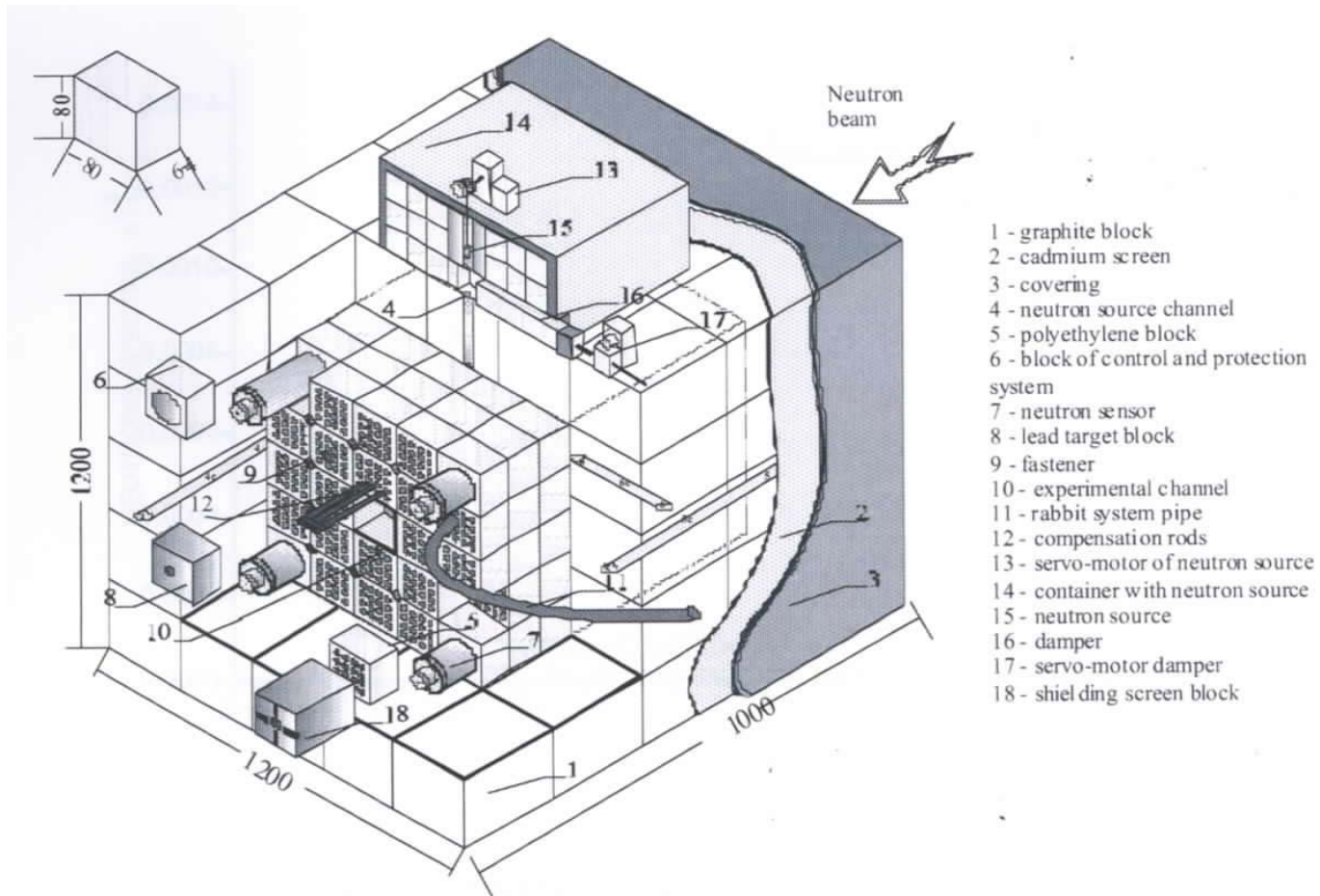
↑ We find a multiplication factor for a point-like centered source of $k = 0.915 \pm 0.010$. This is in good agreement with EA-MC calculations which give $k = 0.920 \pm 0.005$.



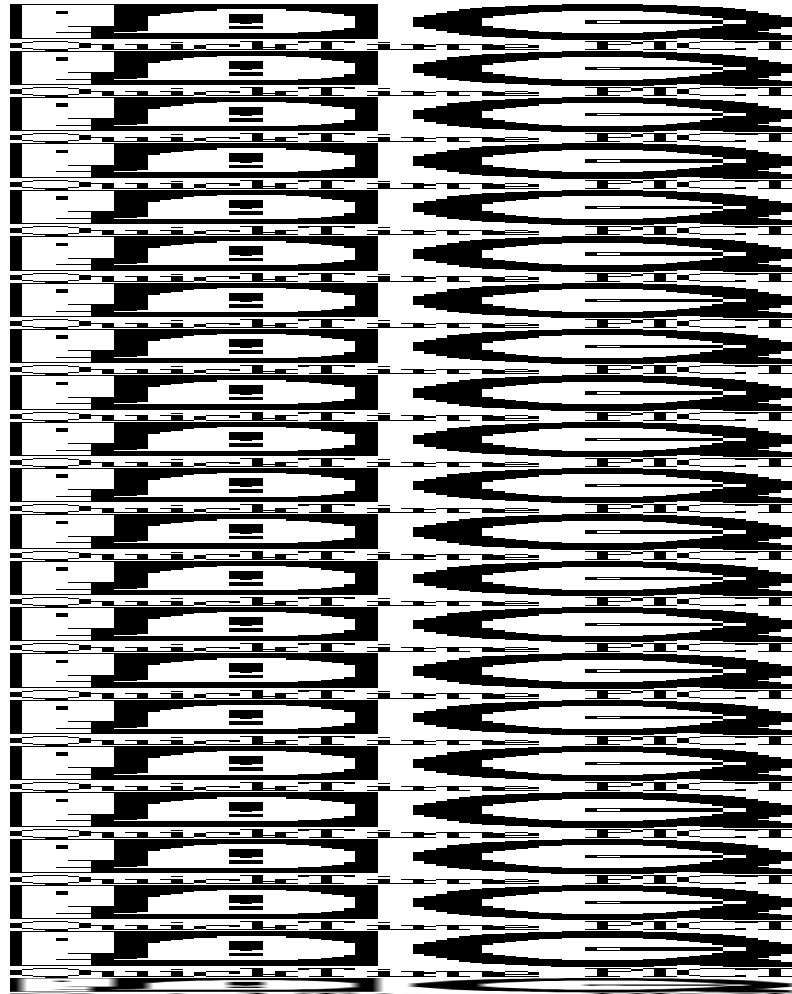
The MUSE Experiment



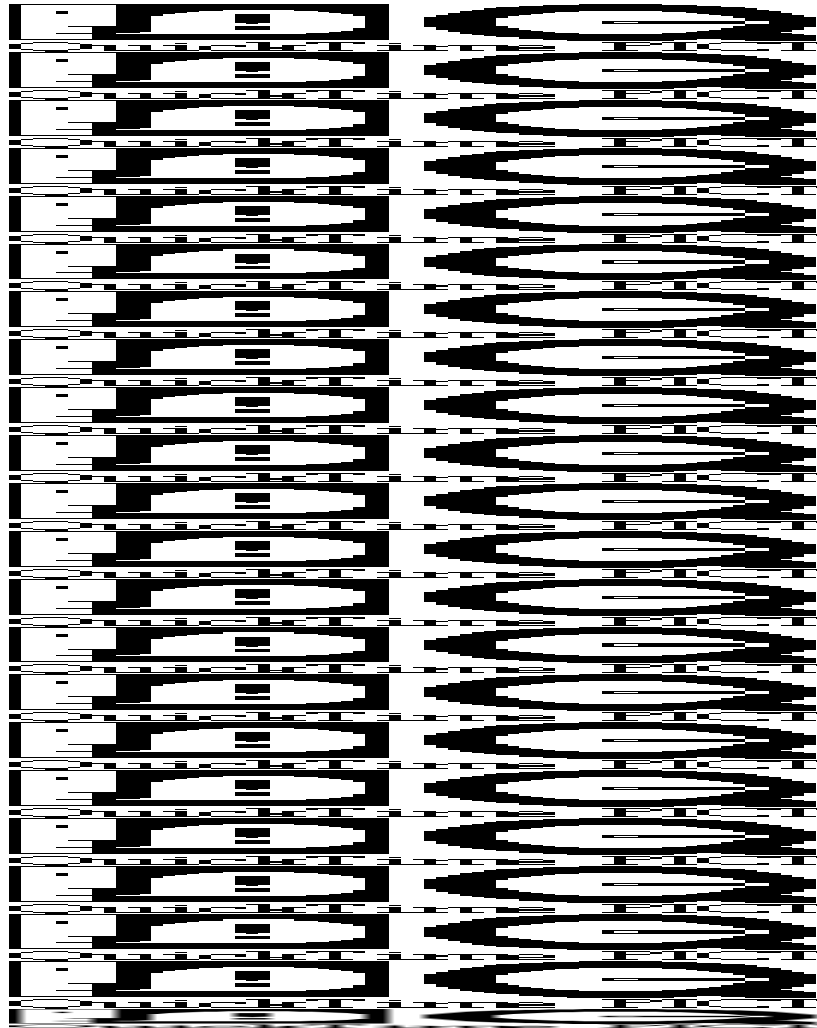
The YELINA Experiment (1)



The YELINA Experiment (2)



The YELINA Experiment (3)



The YELINA Experiment (4)

Experiment & calculations:
 k_{eff} vs. fuel load

