UCANS~V

The Fifth Meeting of The Union for Compact Accelerator-Based Neutron Sources

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CANS Before UCANS

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Topics

Low-energy charged-particle reactions,

e^- bremsstrahlung photoneutrons, Li curtain

Fission, spallation

Yields, spectra

Accelerators

Problems and opportunities

Cooling and damage

Applications

Prospects

Low-energy charged-particle n-producing reactions

Low-energy charged-particle interactions produce ~ MeV neutrons but few higher energy neutrons. D,T and D,D fusion reactions predominate in the lowest particle-energy implementations, using gas and metal-hydride targets. Li(D,n), Li(p,n), and Be(p,n) reactions prevail in sources driven by few-Mev particle beams, having liquid Li and solid Be targets.

Usually, water is the coolant of choice, because of the extensive body of engineering experience with H_2O.

What Works

Many forms of compact neutron sources are in use.

The smallest of these are generally called “neutron generators.” Sealed-tube neutron generators are very small, gaseous deuterium, based on the (D,D) reaction [~ 2.5 MeV neutrons], or deuterium-tritium low-pressure gas mixtures based on the (D,T) reaction [~ 14 MeV neutrons]. All components—beam target, accelerator head, ion optics, ion source—are in a sealed volume within a metal enclosure. The results are rugged, compact devices that can be operated remotely in steady and pulsed versions.

These are typically used in well-logging and package and shipping inspection. There are many many manufacturers offering varieties of configurations.

What Works

Familiar to many of us are neutron generators having <u>separated – function components</u>: target, and high voltage, ion source, and optics. A long tube separates the cooled target from the high-voltage end. Targets are usually titanium, zirconium, or scandium with copper backing for water cooling, in which D or T is included as metal hydride at concentrations of ~ 0.2 hydrogens/metal atom.

The accelerator may be Cockroft-Walton, VanDeGraaf, or other low-energy type providing several-hundred-kilovolt or several-MeV DC acceleration.

These separated-function neutron generators produce neutrons at a higher rate than sealed-tube generators. But they are larger than sealed-tube sources, and still easily portable. Uses are for package and shipping-container interrogation, in solid-state component testing (single-event upset), radiography, radiation therapy (BNCT), target and moderator neutronics tests, neutron physics education and training, ….

What Is Working and …

Next in the scale of things are what we mostly focus on and call Compact Accelerator-based Neutron Sources, CANS. These are one-off, not commercial scale, specially built to serve local needs and to capitalize on local assets. The Low Energy Neuron Source (LENS) at Indiana University and the Compact Pulsed Hadron Source (CPHS) at Tsinghua University (Beijing) are farthest-along of these facilities. The ESS-Bilbao project proceeds as a joint project of the Basque government, the Spanish Ministry of Science and Innovation, and the ESS consortium. Efforts to make use of low-energy proton beams available at the front-end parts of the ISIS and SNS accelerator systems are under consideration. Since the late 1970s, Lawrence Livermore Laboratory has operated the Rotating Target Neutron Source (RTNS), producing 14-MeV neutrons for radiation damage studies.

We have heard more about these and comparable projects in the UCANS-V meeting.

What Worked: ZING-P as CANS

It would be appropriate to class the 1974-5 ZING-P prototype at Argonne as a Compact Accelerator-based Neutron Source. Its purposes were the following:

- Demonstrate the concept of H^- injection to a synchrotron.
- Test the concepts of a spallation target (a Pb brick at the time).
- Test Cd-decoupled Beryllium-reflected hydrogenous moderators.
- Illustrate slow-neutron scattering applications.

Two instruments, a powder diffractometer and a time-focused crystal-analyzer spectrometer, proved out and produced the data for one student’s PhD thesis. Eventually (1977) the 500-MeV Booster-II replaced Booster-I and drove ZING-P’ (1977-1979) and IPNS for 25 years (1981-2006).

ZING-P also demonstrated the use of outmoded components:

- Notably the adaptation of the 2-GeV Cornell synchrotron to the 200-MeV, ~ 100-nA (~20 W proton beam power) Booster-I proton machine
- The incorporation of existing ANL infrastructure into a useful testing facility.

What Worked: JESSICA as CANS

In the late 1990s workers constructed a full-scale mockup of the then-current design of the ESS, JESSICA, based on the 2.5-GeV COSY cooler synchrotron at Jülich and having a liquid-mercury target. These were the purposes of the installation were:

- Validate codes and data on spallation neutron production.
- Investigate moderator scattering kernels and geometries.

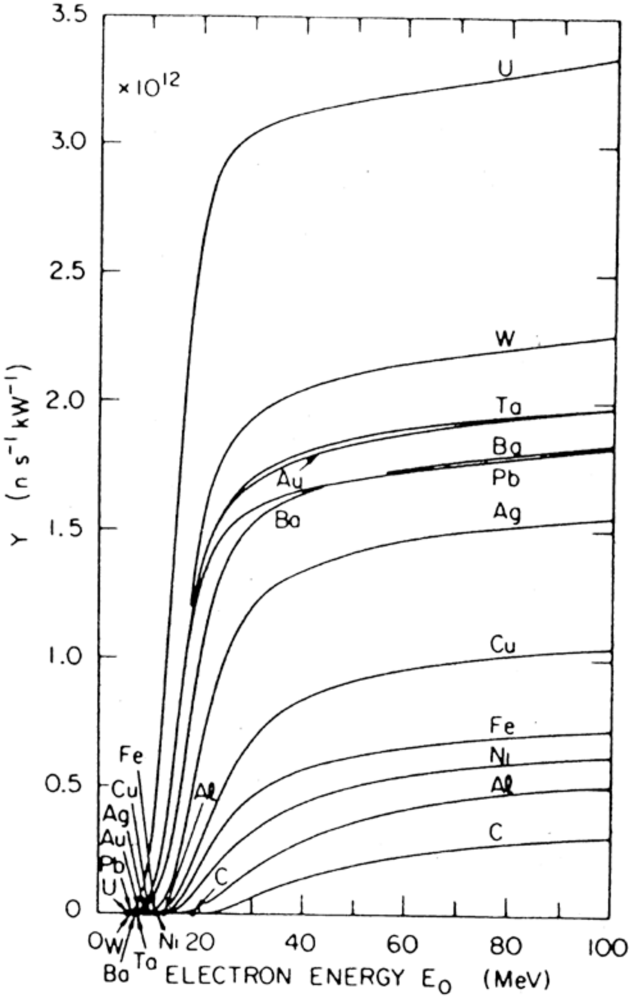
COSY provided $4x10^8$ to $4x10^9$ protons per pulse at 0.03 Hz at energies up to 2.5 GeV. The JESSICA experiments were significant:

- Gave support to ESS design.
- Provided information on moderator materials with potential uses in ESS and elsewhere.
- Illustrated the use of existing accelerator and infrastructure for low-power experiments.

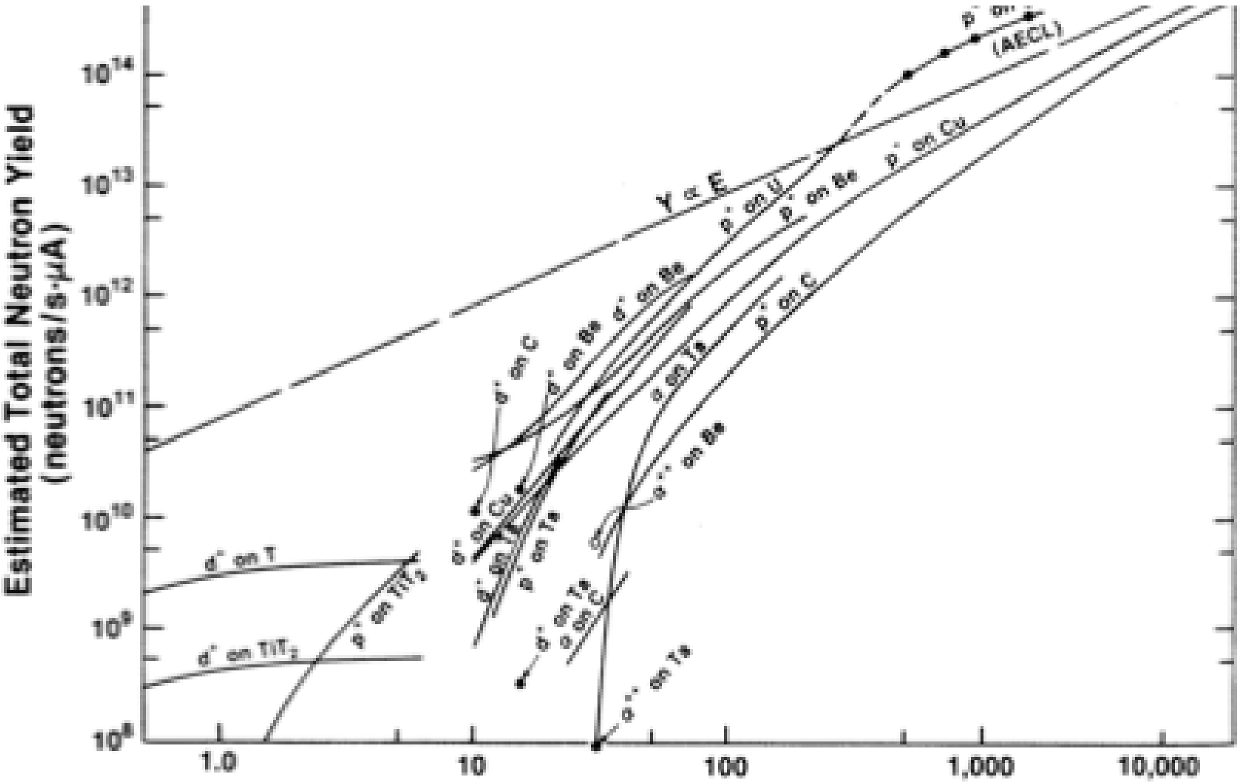
e^- Bremsstrahlung Photoneutron Sources

Electron linacs serve as neutron sources in many places. The figure shows neutron yields as functions of target material and electron energy. Yields level off for energies above about 50 MeV. The maximum target power, limited by target material properties, is about 50 kW.

Heat to be dissipated amounts to about 2800 MeV per neutron.



Neutron Yields for Various Charged-Particle Reactions



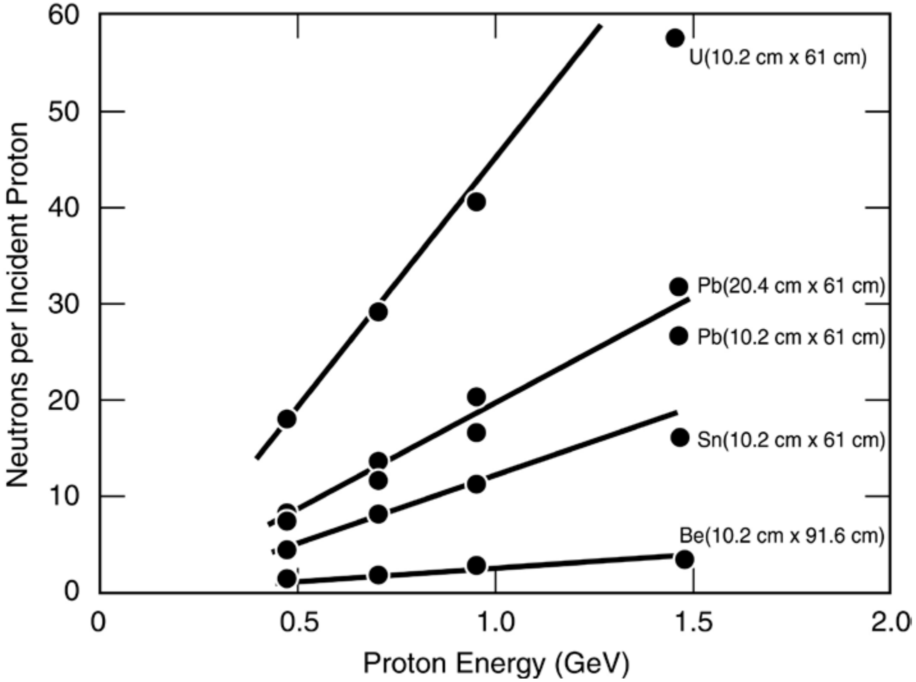
The low-energy reactions all require dissipating most of the incident charged-particle energy as heat, amounting to ~ 1000 MeV per useful neutron: Fission, ~ 200 MeV/n; spallation, ~ 30 MeV/n).

Spallation Neutron Yield vs. Proton Energy

Absolute Global Neutron Yield

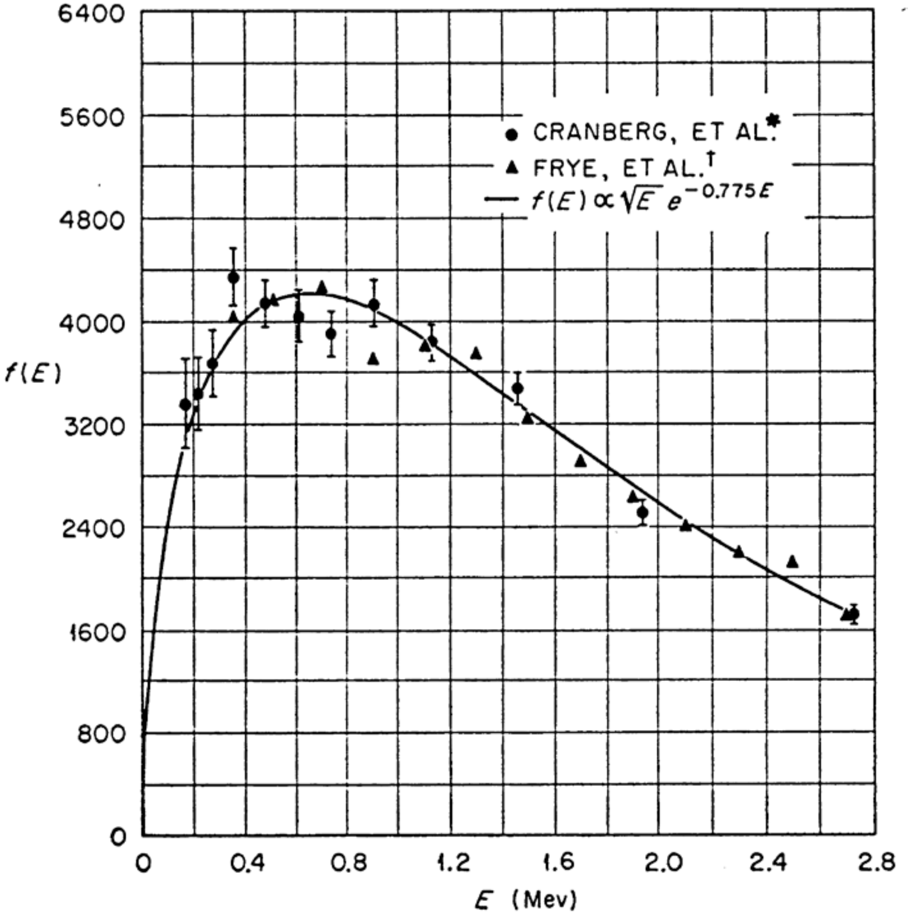
(neutrons/proton)

- = 0.1(E_{GeV} - 0.12)(A+20), except fissionable materials;
- = 50.(E_{GeV} - 0.12), 238U.



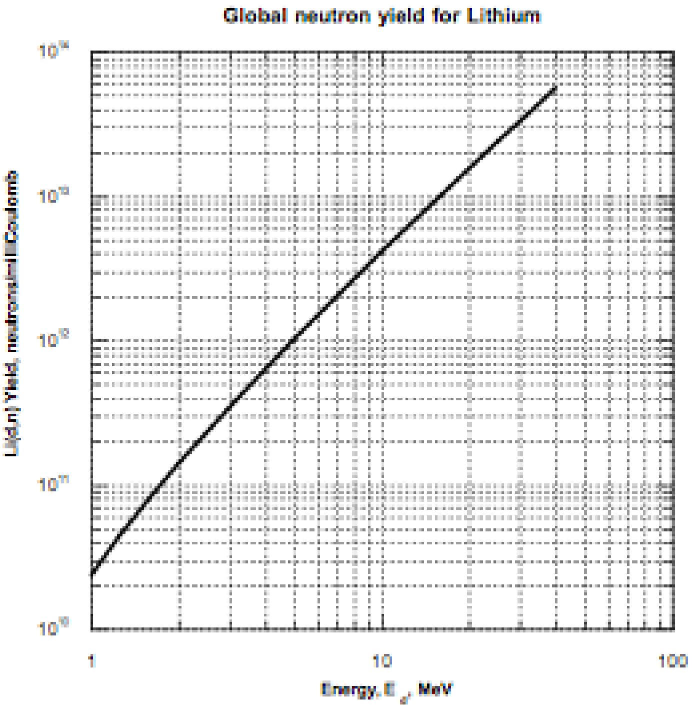
Evaporation Neutron Spectrum

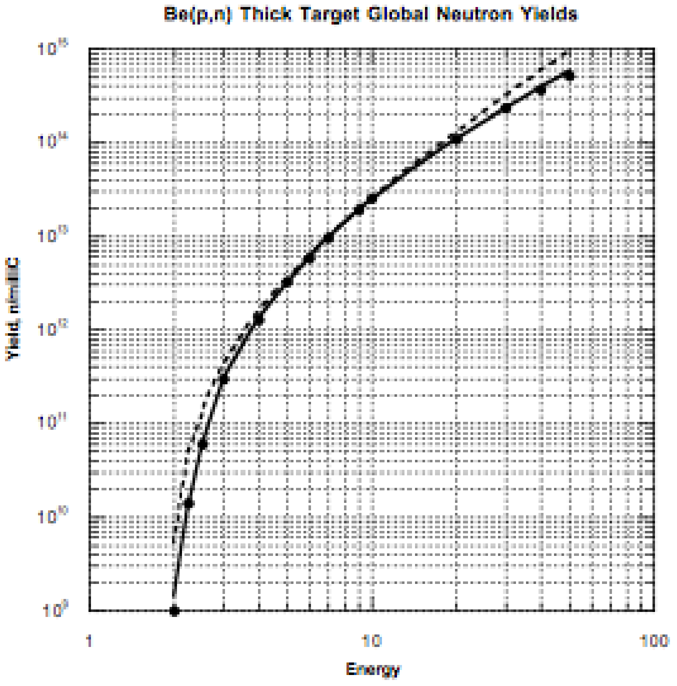
Fission, e^-photoneutron, and spallation processes produce neutrons in similar evaporation spectra with mean energies around 2 MeV.



Lithium and Beryllium

Li(d,n) is probably most efficient target materials for neutron production by ~2 MeV charged particles. Be(p,n) is best for energies above about 2 meV.

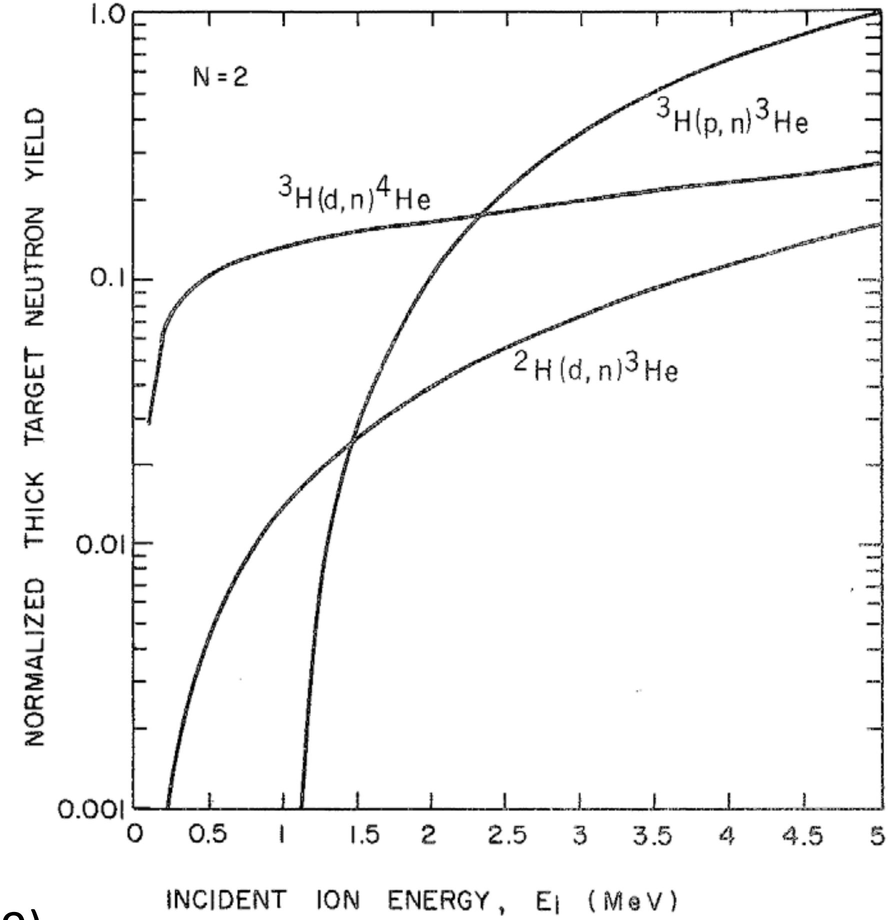




Hydrogen Isotope Reactions

For the lowest charged-particle energies, deuterons and protons on deuteron-and tritium-loaded titanium-metal targets are good choices. For lowest energies, (d,t), that is, ^{3}He(d,n)^{4}He, has highest yield and produces 14.-MeV neutrons. The (d,d) reaction, That is, ^{2}H(d,n)^{3}He produces 2.2 MeV neutrons. The figure shows global thick-target yields and loading ratios around 10 a% H/Ti.

From Halbleib and Scott, “Theoretical Neutron Production from Hydrogen Isotope Reactions”, Sandia Laboratory report SC-R-69-1272 (April 1969).



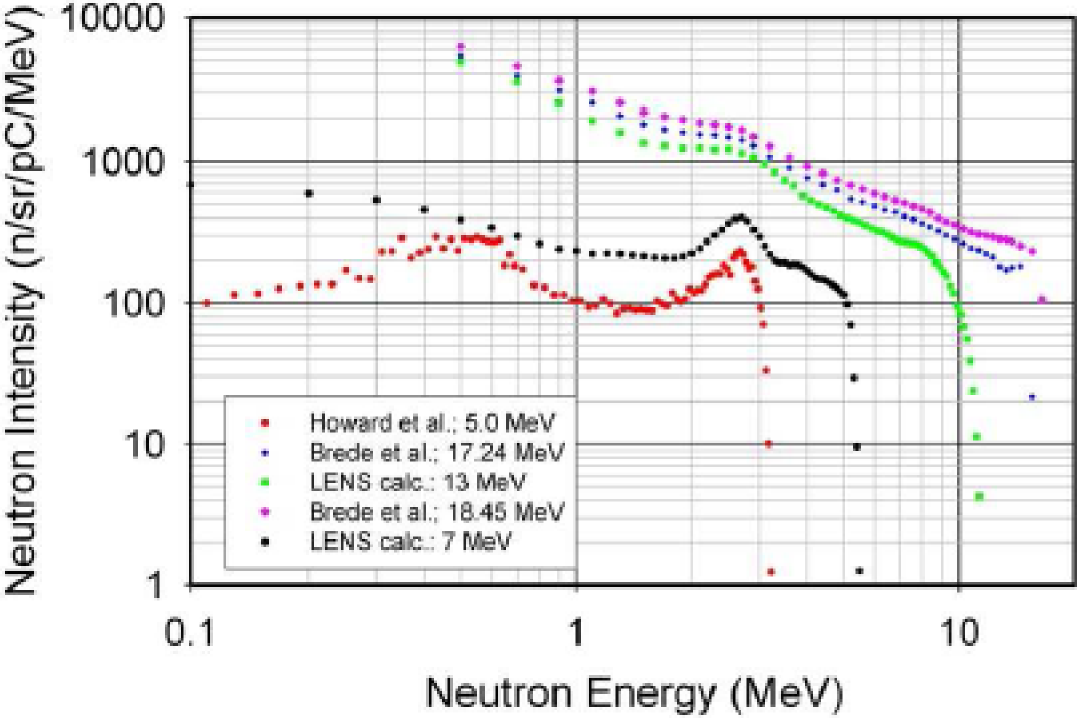
Lithium-Curtain Target

The technology of lithium-curtain targets is under development for the International Fusion Materials Irradiation Testing Facility (IFMIF), to generate high fluxes of monoenergetic fast neutrons (5, 10, 15 MeV) for first-wall fusion reactor materials damage studies. The concept implements a deuteron stripping reaction in a thin, flowing, liquid lithium curtain, with ~ 5 MW beams of ~ 30-MeV deuterons.

That idea is far out of scale for CANS, but the engineering experience at IFMIF may be relevant for small sources based on the low-energy Li(d,n) reaction in a thin liquid lithium target, which is why I mention it here.

Low-Energy Neutron Sources

Be(p,n) neutron spectra for different proton energies



Global neutron yield for Be(p,n) neutrons

$Y(E_p) = 3.42 \times 10^8 (E_p - 1.87)^{2.05}$ n/μιλλιCoul

Problems

Problems that arise in the design of neutron-producing target systems:

- Heat transfer from target to coolant.
- Corrosion of target material in contact with coolant.
- End-of-range accumulation of spent projectile ions.
- Thermal stresses.
- Vapor pressure of coolant and target material.
- Massive shielding—especially of 14-MeV sources.
- Stability of funding.

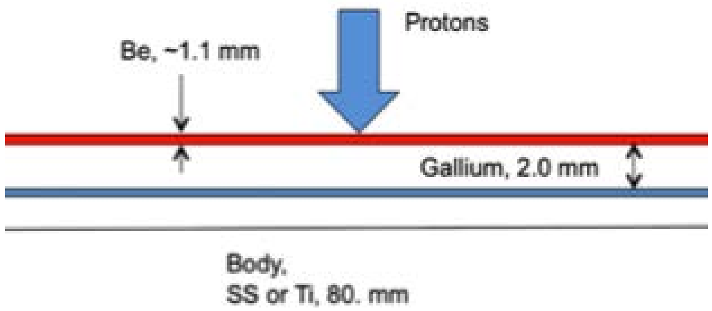
Gallium Coolant

Gallium has many advantages for cooling CANS targets:

- Low melting (~ 30° C)m, high boiling (~ 2200° C) (No DNB problem).
- Desirable thermophysical properties like water.

Disadvantage: incompatible with some materials, OK with others.

A gallium-cooled beryllium metal target for 13-MeV protons



Demonstrated at MIT in 1997: tandem accelerator,

4.1 MeV, ~ 2 mA protons on Ga-cooled Be metal target.

Blackburn, B. W. and J. C. Yanch, Liquid gallium cooling of a high-power beryllium target for boron neutron capture therapy. www.trshare.triumf.ca/ buckley/ wttc/pdf/1999/p7.pdf.

Also J. M. Carpenter, Gallium-cooled target for CANS, NIM A (2011)doi:10.1016/j.nima.2010.12.032 (UCANS-1 proceedings)

Gallium

Forward-looking CANS designers might profitably incorporate gallium-compatible cooling system components to facilitate upgrading from lower-power water coolant to higher-power gallium coolant.

Adapting e^- Synchrotrons as Proton Synchrotrons

Abandoned GeV electron-synchrotron injectors at synchrotron light facilities might be converted in the course of facility upgrades into drivers for neutron facilities, for example, a case with accelerated electron energy 1.5 GeV.

The fundamental observation is that the maximum field and bending magnets and possibly the vacuum chamber radius are given, for the existing electron energy. The radius is $R=p/(qB)$, where p is the particle momentum and q is the particle charge. For the case at hand, R = 4.584 m. For the (fully relativistic) electrons, p=1.5 GeV/c.

The K.E. of a proton (circulating oppositely) with the same momentum is $E_p=[(m_pc^2)^2+c^2p^2]^{1/2}-m_pc^2$, which for the same momentum as 1.5 GeV electrons is $E_p=0.834$ GeV —good for spallation neutron production.

Adapting e^- Synchrotrons (Cont'd)

In the case at hand, the electron energy at injection is 50 meV and p=0.05 GeV/c when the bending field is minimum. The corresponding proton energy is E_p = 1.34 MeV, which is lower than needed; therefore the proton energy and the field at injection can be higher, say 7 MeV, suited to modern RFQs. Of course one would inject and strip H^- ions and accelerate the protons. The higher the injection energy, the higher the space charge limit in proportion to $(beta)^2(gamma)^3$, where beta = v/c and $gamma=(1-beta^2)^{-1/2}$.

Many questions beyond this cursory suggestion remain for accelerator experts and facility designers. As always in the case of reworking existing equipment, the cost of the rework may exceed the cost of new and therefore requires caution from the outset.

A precedent is the 1970s adaptation of the Cornell 2-GeV synchrotron for the 200-MeV ZING-P.

Applications of CANS

- Testing and refining scattering instrument concepts
  - Larmor-precession concepts, e. g., SESANS
  - Time-focusing concepts
- Testing detectors
  - Advanced scintillators
  - ^{10}B-based detectors
- Solving the problem of H_2 release and burping in irradiated cold CH_4
  - Use the ~ 10 MeV proton beam to load the moderator *in situ* at low temperature (after the first collision, resulting secondary, etc. protons are the same as in moderator service).
  - Slowly warm the moderator through the 65 K release temperature, monitor H_2 release and temperature.
  - Make theory, devise control method.

Applications of CANS (Cont'd)

- Test new moderator concepts and materials, e.g., guided moderators, … .
- Educate and train students (hire them to help design and build the new CAS and instruments).
- Carry out easy scientific experiments.

  All in-house, preparing for time on big facilities.

  SANS, powder diffraction, molecular spectroscopy
- Devise and test filter/converter combinations to simulate atmospheric neutron fields in small and large facilities
- Carry out Single-Event-Upset events in solid-state devices.

  …

We need more ideas, a major goal for UCANS-V.

THANK YOU!