Neutron Sources Globally

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Spallation Neutron Source

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Neutron sources…

general term referring to a variety of devices that emit neutrons, irrespective of the mechanism used to produce the neutrons

- **Small**
  - Spontaneous fission, \((\alpha, n), (\gamma, n), n\) generators

- **Medium**
  - Plasma focus/pinch devices, light ion accelerators, photoneutron/photofission systems

- **Large**
  - Reactors, fusion devices (NIF, JET, etc.), spallation sources

*We’ll focus on large facilities*
What are the needs?

- From a target point of view
  - High beam power capability
  - High reliability
  - High availability
  - Good conversion efficiency (n/p)
  - Low absorption cross section
  - Minimize R&D

- Spallation targets are designed for a variety of applications
  - High brightness (peak flux)
    - SNS, JPARC, ISIS
  - Average brightness (flux over a large area)
    - APT, MTS, UCN sources

Source design should be customized for the application.
Focus on some accelerator neutron sources

• High-power
  – LAMPF/LANSCE
    • APT project
  – SINQ/MegaPIE
  – ESS/SNS/JPARC
  – Eurisol

• ADS specific
  – RACE

What has occurred over the last 15 years that we can use?

• Basic source neutronics
Los Alamos Neutron Science Center
(or Los Alamos Meson Physics Facility)

• 800-Mev, nominally 1 mA proton beam
• 800-MeV reached in 1972
• Three beams: H+, H-, p-
• Highest power proton linac for many years
• Contributions:
  – High power capability
  – Solid target technology
  – Radiation damage to materials
  – Code verification & validation
Solid (W) targets at LANL

- **Plate targets (~14 µA/cm²)**
  - Same peak current density as SNS

- **Rod targets (~70 µA/cm²)**
  - Bare
  - Clad

LANL contributions from S. Maloy
Decrease in Diameter of Bare Tungsten Rods Confirmed Tungsten Corrosion Rate

- Capsule irradiated for 2 months in 800 MeV, 1 mA proton beam (~2x10^{21} \text{ p/cm}^2)
- Measured the diameter of all 19 tungsten rods in the leading rod bundle
- The loss of tungsten on rods scaled with Gaussian beam shape
- Implied corrosion rate of ~1 mm/year
- Measured Helium concentration of ~740 appm
Removal of Tungsten Neutron Source After Irradiation

- Clad Tungsten Source cut from Insert and transported to CMR Hot Cells
- Peak proton density $\sim 70 \mu A/cm^2$
- Helium leak test performed in hot cells showed clad rods still leak tight after irradiation
- Discoloration on outside surface due to high nitric acid irradiation environment
Compression Stress/Strain Results for Irradiated Tungsten Show Increase in Yield Stress with Dose above 4 dpa

Stress/Strain Curves for Tungsten Irradiated to 4-23 dpa

Stress, σ/MPa

Strain, ε/%
Code V&V: Decay heat experiment

Phosphor

W target

p
Calculated and measured decay heat

2 decay heat measurements
Multiple n/p measurements
Energy deposition
Radionuclide production
Materials damage
Materials corrosion experiments

Elapsed time since beam-off (h)
SINQ (Paul Scherrer Institut)

- ~570-MeV protons incident on a solid target, ~1.2 MW
- Continuous source
- Vertical beam insertion upward
- Contributions:
  - Continuous operation with high reliability
  - High-power liquid metal target demonstration
  - Radiochemistry of liquid metal targets
  - Beam on target imaging
  - Materials irradiation data

SINQ contributions from M. Wohlmuther, J. Neuhausen
High reliability operations

• During MegaPIE startup

• One significant trip in 12 hours (more than ~1 minute)

• Probably good enough for a transmutation demonstration
MegaPIE target at SINQ

- LBE target installed in existing solid target location
- Full process, from design to safety evaluation, from licensing to high-power operations
- Operated from August 14, 2006 to the end of 2006
Target disassembly

- The aluminum safety hull was removed July 2009
- Picture: The “remains” of the Leak Detector (LD)
- Black smut was deposited on one side of the LD
- The beam entrance window region looked whitish/lucent
Samples for analysis

TC3

H06

H07

H08

H09

MegaPIE has produced over 1,000 samples for analysis

PIE starts in 2011
Po extraction from LBE: Results

- Influence of gas plenum
- Temperature curves
- Influence of water content of (Na,K)OH
- Relative amounts of LBE/MOH

![Graph showing Po extraction from LBE under different gas atmospheres and temperatures.](image-url)
Beam on target monitoring: VIMOS

- Tungsten mesh through which the beam passes
- Beam profile monitored via a camera and optics
- Reliable operation since 2004
- Important part of the safety case and determining target lifetime
STIP Irradiation Series

- Five campaigns, thousands of samples
- SINQ target rods replaced by materials samples
Typical STIP samples

130 mm length
10.8 mm diameter
Spallation Neutron Source (ESS, J-PARC)

• Three spallation sources designed in the same timeframe
  – ESS was first, but not funded
  – SNS was based largely on the ESS concept, then advanced
  – J-PARC was ~18 months after SNS

• SNS is nominally 1-GeV, 1.4 MW
  – PUP to 1.3 GeV, 1.8 MW in 2016

• Contributions:
  – Liquid metal target development
  – Solid rotating target development
  – Beam on target imaging
  – PIE data
The SNS target is mercury circulating inside a stainless steel vessel at 24 liters/second

- System is capable of 1.4 MW beam power on target
- Target module must be replaced periodically due to embrittlement of the steel
- Beam induced cavitation damage might limit target module life more severely than radiation damage at high beam power
Mercury Targets - SNS and JSNS

SNS Parameters

316L mercury vessel and water shroud
1 MW design
200 mm x 70 mm beam spot
0.125 A/m² peak current density @ 1 MW
24 l/s mercury flow
SNS Target Development - typical component development

Mercury Thermal Hydraulic Loop (MTHL)

Water Thermal Hydraulic Loop (WTHL)

Target Test Facility (TTF)
SNS Mercury System Layout

All major components required unique designs:
- Drain paths for leaks to collection tank
- Remote handling
- Mercury seals

*Hg Detector is strapped on pipe here*

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Managed by UT-Battelle for the U.S. Department of Energy
In-beam testing at WNR

• Since 2001, 4 in-beam damage test campaigns have been conducted at the WNR test investigating:
  - Vessel materials & hardening treatments
  - Beam intensity
  - Pulse numbers (1000 maximum)
  - Target geometry & cooling channels
  - Mercury flow
  - Small gas bubble mitigation
  - Gas wall mitigation
  - Lead bismuth
Next WNR Hg target experiment is planned for 2011

• This will investigate small gas bubble mitigation with improved bubblers
• Flowing mercury system required
• Will be done in close collaboration with JPARC team

Pump system

Bubblers & damage test plates
Solid rotating target development

- Designed for a 1.3 GeV, 3 MW proton beam
- Tungsten target with steel support
  - 1.2 m diameter
- Mockup built and tested for over 1,000 hours of operation
  - Lifetime >5 years
SNS target imaging system

- Based on flame sprayed coatings
- Essentially beam phosphors sprayed onto the target vessel
- Tests at WNR gave reasonable feedback for Chromia doped Alumina
SNS target imaging system (2)

• Imaging system was successful
• Light intensity decreases as a function of time
• Lasts as long as the target, but better understanding is desired
Original target module was replaced in July 2009 because of radiation damage

- Exceeded dpa goal of 5 dpa (reached ~ 8 dpa), but we still do not know how long the target will last at high power

- Exterior appearance is as new

- Boroscope examination completed
  - Camera light died in ~40 seconds; surface dark and textured (coated with Hg?)

- Samples cut from target nose November 5th
• Target after sampling
• Right of center shows slightly higher peaking than left on imaging system
PIE of the first target vessel

• Contract with B&W to clean and test the first target vessel
• Samples are ~10 rem/hr at 1 foot
• Inner target vessel sample is badly pitted due to cavitation damage erosion
• Where is the vessel material going?
EURISOL 4 MW Mercury target*

Off-line test in Hg loop at Institute of Physics University of Latvia (IPUL)
Mats Lindroos

*Cyril. Kharoua@esss.se / Workshop on Applications of High Intensity Proton Accelerators
October 19-21, 2009 Fermi
National Accelerator Laboratory, Batavia, IL, USA
Target Window Design

• The design of the target window for high power densities on the order of 1 MW/liter will be very challenging
  – SNS @ 2 MW with .25 A/m² and 1 GeV had peak heating of ~ .8 MW/liter
  – 316 LN window needed to be ~ 1.5 mm to limit thermal stress

• EURISOL found their window design margins less than desired

• Windowless solutions in principal would allow higher power densities
  – MYRRHA has investigated for ~ 10 years and considers it to be promising
  – EURISOL experimented with transverse flow and obtained stable flows without beam
  – Argonne National Laboratory experiments with lithium films under electron beam heating were promising for high power densities
RACE Project was initiated at Idaho State University in July 2003

- Examine coupling of accelerators and targets to subcritical reactor systems for developing transmutation technology
- Use inexpensive, compact, transportable electron linear accelerators (linacs)
  - 20-25 MeV
  - heavy targets (e.g. lead, tungsten, or uranium)
  - bremsstrahlung photons generate neutrons
  - \( \sim 10^{12} \text{ n/s/kWe of 25 MeV electrons} \)

RACE slides from project director Denis Beller
Initial RACE Project Plans

• **Phase I (ISU)**  ’03-'04
  – Purpose: develop instrumentation and experience for Phase II

• **Phase II (UT-Austin)**  ’05
  – TRIGA coupled ADS

• **Phase III (Texas A&M)**  ’06
  – Possibly with used core in a purpose-built configuration
  – Cancelled
RACE Progress

• ISU RACE
  – 2003-2005 design, NRC licensing, and low multiplication testing
  – First full-core loading Dec ’05
  – ADS tests Dec ’05 through Oct. ’06

• Texas RACE
  – Initial experiments at UT-Austin in ’05
  – Longer campaign Jan-Mar ’06
  – TRIGA Returned to normal critical operations Mar 31, ’06
  – Several papers in AccApp’07
ISU RACE
subcritical assembly and accelerator
ISU-IAC Subcritical Assembly

- 150 U-Al fuel plates, 0.08” x 3” x 26”, Al-clad U-Al, 20% enriched,
- 3 horizontal rows, 6 mm spacing
- Accelerator target in center
- RG graphite reflector (8-12”)
- $k_{\text{eff}} \sim 0.93$ to 0.94 (per ideal MCNPX)
  $\Rightarrow$ Multiplication about 10
- Peak instantaneous flux:
  $\sim 10^{13} - 10^{14}$ n/cm$^2$/s in the fuel
RACE fuel trays (without fuel) and target inside the graphite reflector
ISU-IAC RACE target

- **W-Cu; 2 3/4” dia. X 3.5” long**
- **MCNPX: \(\sim 10^{12}\) neutrons/s/kWe**
- **Also a prompt, strong high-energy gamma ray signal**
The University of Texas at Austin TRIGA Mark II Research Reactor

- BP #3
- BP #2
- BP #4
- BP #5
- Core
- Reflector (Graphite)
- Pool (H₂O)
- Biological Shield (Concrete)
RACE Accomplishments

• Licensed, constructed, and conducted ADS experiments

• Five ADS Experiments Workshops (3 were international)

• RACE-ECATS collaboration
  – Target design
  – T-H feedback evaluation

• Education of students at ISU, UT-Austin, U Mich., Texas A&M, and UNLV
Neutronic Performance of Lead and Tungsten Targets

(Stopping-length targets bombarded on axis by 1-GeV protons)

55-cm-long Natural Lead

30-cm-long Natural Tungsten
Tungsten Target Performance Relative to Lead

(Stopping-length targets bombarded on axis by 1-GeV protons)
Basic Target Concepts

- SOLID TARGET
- SPLIT TARGET
- SPLIT, RADIAL COMPOSITE TARGET
- SPLIT-COMPOSITE TARGET
Neutronic Performance of a Split Target and a Split, Radially-Composite Target

(50-cm-dia, stopping-length targets bombarded on axis by 1-GeV protons)
Summary

• Discussed a few of the accelerator neutron sources and what we could learn from them
  – 3 or 4-MW targets appear to be straightforward
    • Both liquid (long pulse or CW) and solid rotating
  – Radiation damage data exists from LANL and PSI
    • AFCI handbook and papers
    • Watch for additional results
  – Code verification and validation experiments have been completed
    • Expensive – only do what needs to be done
  – Target imaging systems have been designed and tested
  – Po handling experience exists
    • Learn from or collaboration?
Summary (cont.)

• Small coupling experiments were successful in the past
  – Good for the university/students, and good for gaining experience
  – What could be done in this mode now?

• Detailed source design could lead to a target design that is easier to engineer for a demonstration experiment
  – Has it been considered?