Neutron Radiography with Compact Accelerator at Peking University: Challenges and Solutions

Guo Zhiyu

State Key Lab of Nuclear Physics & Technology
School of Physics, Peking University, China

2010. 8. 17
Outline

• Motivation
• Background
• Problems of NR with CANS
• PKUNIFTY: the solutions
• Conclusions
• Poster A1: Design of PKUNIFTY accelerator facility
• Poster T2: Design of PKUNIFTY moderator assembly
Motivation

• To set up a compact accelerator-driven thermal neutron radiography facility
• To fit the basic requirements of NR
• The size is as small as possible
• The cost is as low as possible
• The goals as an experimental platform:
  ▪ Education and training
  ▪ Technology development
  ▪ Application investigation
Applications of CANS

Performance of NR

- Spatial Resolution
- Contrast
- S/N Ratio
- Field of View

Neutron Beam Quality
- Neutron Flux at imaging plane
- L/D Ratio
- Cd Ratio (neutron spectrum purity)
- n/γ Ratio
NS of NR

- Reactors
  - High intensity, CW beam
- SNS
  - High intensity, pulsed beam (PSI: CW)
- CANS
  - Middle intensity, reasonable cost
- Isotope source & sealed neutron tube
  - Low intensity, not practical for NR
Problems of NR with CANS

• Limited neutron flux and L/D
  ▪ The performance of NR largely depends on the neutron flux at imaging plane and L/D
  ▪ The neutron flux at imaging plane is proportional to $D^2/L^2$
  ⇒ It is important to obtain enough thermal neutron intensity (higher fast neutron yield and thermalization efficiency)
Neutron Flux vs. L/D

Neutron Flux vs. L/D

• Neutron flux requirement
  ▪ Despite of the reactor power, a flux level was identified for practical neutron imaging with thermal or cold neutrons: $1e5 \text{n/(cm}^2\text{s)}$. This corresponds to an exposure time of about $1000s = 16 \text{ min}$ (with efficient digital imaging detectors). For dynamic imaging the lower level of neutron intensity has been found to be $1e6 \text{n/(cm}^2\text{s)}$.
  ▪ The lower limit … was found at the level of $250 \text{ kW}$ (example, TU Vienna)

IAEA consultancy meeting report, Non destructive and analysis techniques using neutrons. 08CT14309, 2009.
Neutron Flux vs. L/D of Thermal NR Facility
Problems of NR with CANS

• Neutron yield vs. size and cost
  ▪ Neutron yield depends on selected nuclear reaction and beam energy/current
  ▪ Higher beam energy ask longer accelerator and more RF power
  ▪ Higher beam current ask better accelerator technology and more RF power
  ▪ Both higher energy and current means more cost
  ⇒ It is difficult to realize small size, low cost and high neutron yield simultaneously
Neutron Yields of CANS

Main reactions:
- Li (p, n)
- Be (p, n)
- Li (d, n)
- Be (d, n)
- D (d, n)
- T (d, n)

Problems of NR with CANS

- $\gamma$ background
  - From beam-target reaction, especially Be (d, n) reaction
  - From neutron non-elastic scattering, neutron capture and (n, $\gamma$) reaction
  - Bad S/N ratio & CCD lifetime

Problems of NR with CANS

• Limited Cd ratio
  ▪ Thermalization gives a continuum
  ▪ Epithermal neutrons will reduce the resolution
  ▪ To insert filter will reduce the neutron flux largely (may down to 1/6 or even bad)
  ▪ No filter means bad Cd ratio
  ⇒ Difficult choice between n flux and Cd ratio
Problems of NR with CANS

• Beam loss
  ▪ High current beam always has halo, which is easy lost during transmission
  ▪ Lost beam ions with certain energy can active the accelerator component materials
  ▪ Deuterons lost in the structure materials may become target atoms and generate neutrons under the beam bombarding

⇒ Beam loss should be restricted
Problems of NR with CANS

• Summary
  ▪ Limited neutron flux and L/D
  ▪ Neutron yield vs. size and cost
  ▪ $\gamma$ background
  ▪ Limited Cd ratio
  ▪ Beam loss
PKUNIFTY: the Solutions

• Main design principles
  ▪ Can be used for basic industrial applications and technology development of thermal NR
  ▪ Smaller size and lower cost with acceptable neutron flux and L/D ratio
  ▪ RFQ accelerator with RF transmitter using tetrode amplifier but klystron
  ▪ Try to find the way to get higher n/γ ratio and Cd ratio without large flux attenuation
PKUNIFTY: the Solutions

• Be (d, n) reaction was selected
  ▪ Lower beam energy is possible than proton
  ▪ Be target is easier to handle than Li

• Tetrode TH781 was selected
  ▪ 400 kW peak power with 10% duty factor can be delivered at around 200 MHz

• Deuteron beam parameters
  ▪ 40 mA peak current with 1 ms pulse width and 10% duty factor @ 2 MeV energy
  ▪ Average beam power of 8 kW
PKUNIFTY: the Solutions

- Neutron yield of PKUNIFTY
  - Neutron yield of Be (d, n) reaction at $E_d = 2$ MeV
    $Y = 8 \times 10^8$ n/µC
  - With average current 4 mA
    $Y = 3 \times 10^{12}$ n/s
PKUNIFTY: the Solutions

- Target/moderator/reflector/shielding assembly design
  - Target: 45° from the beam axis
  - Moderator: Polyethylene
  - Reflector: Water
  - Shielding: Pd + Boron doped Polyethylene
PKUNIFTY: the Solutions

• Collimator design
  ▪ 90° from the beam axis
  ▪ Inner collimator + Outer collimator
  ▪ Changeable aperture
  ⇒ Fast neutrons and γ ray can be attenuated effectively, \( n/\gamma = 1 \times 10^{10} \text{ n/cm}^2/\text{Sv} \)
  ⇒ L/D can be adjusted flexibly (15 - 200)
  ⇒ Neutron flux \( 5 \times 10^5 \text{ n/cm}^2/\text{s} @ \text{L/D} = 50 \)
Neutron Flux vs. L/D of Thermal NR Facility
PKUNIFTY: the Solutions

- **Pre-study on NR technology**
  - Using 4.5 MV Van de Graaff and Be (d, n) reaction
  - With thermal neutron flux of $5 \times 10^3$ n/cm²/s @ L/D = 20

Yubin Zou et al., Experimental study on neutron radiography with accelerator based neutron source using D-Be reaction. Proc. WCNR-8, p87, 2008.
PKUNIFTY: the Solutions

- Cd ratio improvement
  - Cd ratio = 2 @ L/D = 50 without filter
  - We are trying to improve it with less thermal neutron flux loss, the methods are being investigated
PKUNIFTY: the Solutions

• Deuteron beam loss control
  ▪ Reasons of beam loss in RFQ cavity: beam mismatch and the emittance growth due to space charge forces couple the longitudinal and transverse particle motions
  ▪ A matched quasi-equipartitioning design method was adopted
  ⇒ The energy of most deuteron particles lost in RFQ cavity is less than 100 keV
PKUNIFTY: the Solutions

• Bird view of CANS for PKUNIFTY
Conclusions

• There are some special demands to CANS when it is used for neutron radiography

• Choice has to be made for neutron flux vs. L/D ratio, neutron yield vs. size and cost, how to improve n/γ ratio and Cd ratio, as well as the beam loss control

• PKUNIFTY gives a possible solution, and it is expected to start its commissioning and operation next year
Design of PKUNIFTY Accelerator Facility

Yuanrong Lu, Xueqing Yan, Kun Zhu, Shixiang Peng, Shuli Gao, Guo Zhiyu

State Key Lab of Nuclear Physics & Technology
School of Physics, Peking University, China

2010. 8.
D\(^{+}\) RFQ design

Total 5000 macro particles

Lost particles

Energy (MeV)

0 0.5 1 1.5 2

Lost particles

0 20 40 60 80
D\(^+\) RFQ bead pull measurement

- 201.5MHz, Q=3350
- Field distribution

![Graph showing field distribution with quadrants labeled as upper, right, lower, and left.]

Test bench

2010. 7
D\(^+\) RFQ vacuum test

- Vacuum is better than \(2 \times 10^{-5}\) Pa
Other components

• **ECR ion source & LEBT**
  100 mA p or 80 mA D⁺ @ 50kV
  0.1-1ms pulse @ 100 Hz

• **RF transmitter**
Design of PKUNIFTY Moderator Assembly

Yubin Zou, Weiwei Wen, Han Li, Guoyou Tang, Dawei Mo, Guo Zhiyu

State Key Lab of Nuclear Physics & Technology
School of Physics, Peking University, China

2010. 8.
What is an idea moderator for us?

• High efficiency:
  More thermal neutron output

• Pure beam:
  Less fast neutron and gamma output

• Low background:
  Assembled with shield

• Compact size
Optimization

• **Moderator size**
  Thermal neutron flux increases with the moderator size until its saturation

• **Neutron beam direction**
Moderator structure & parameters

- **Material:** PE + Water
- **90° between collimator and beam line**
- **L/D range:** 15-200 or more
- **Thermal neutron flux:** $5 \times 10^5 \text{n/cm}^2/\text{s}$ @ L/D=50
- **Cd ratio:** ~2
- **n/γ:** better than $1 \times 10^{10} \text{ n/cm}^2\cdot\text{Sv}$
Thank you for your attention!