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

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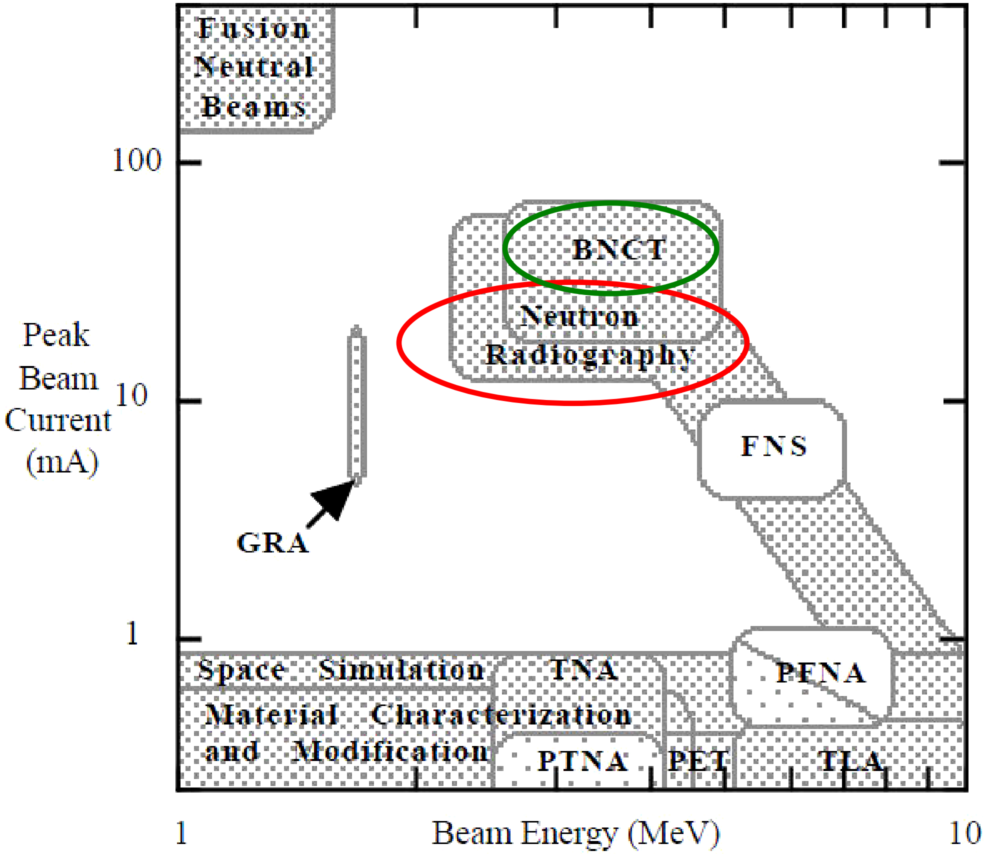
Outline

- 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



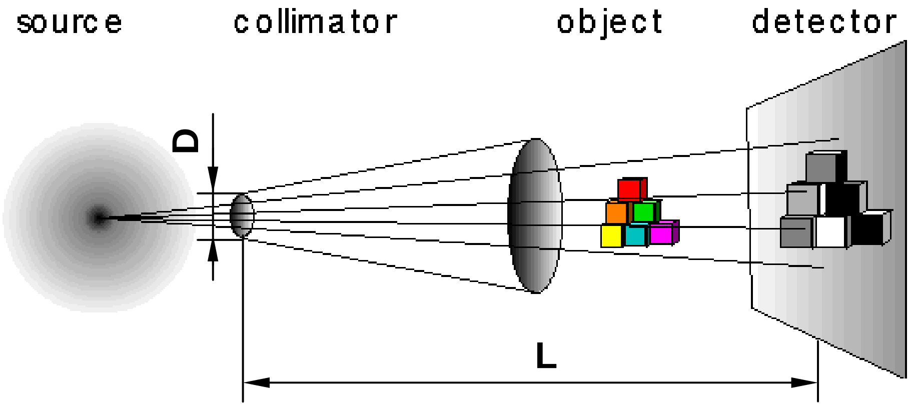
High Duty Factor and Continuous Wave
- Beam Time Structure Not Important for Application
- High Beam Current or High Beam Power Needed

Microsecond Pulses at Low Duty Factor
- Details of Beam Time Structure Not Important
- Low Duty Factor Used to Suppress Backgrounds

Nanosecond Pulses at Low Duty Factor
- Precise Time Structure Important for Application
- Used for Time-of-Flight, Coincidence Techniques

☞ **Gillespie & McMichael, Applications of MeV proton and deuteron linear accelerators. Proc. PAC 95, p107, 1995.**

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

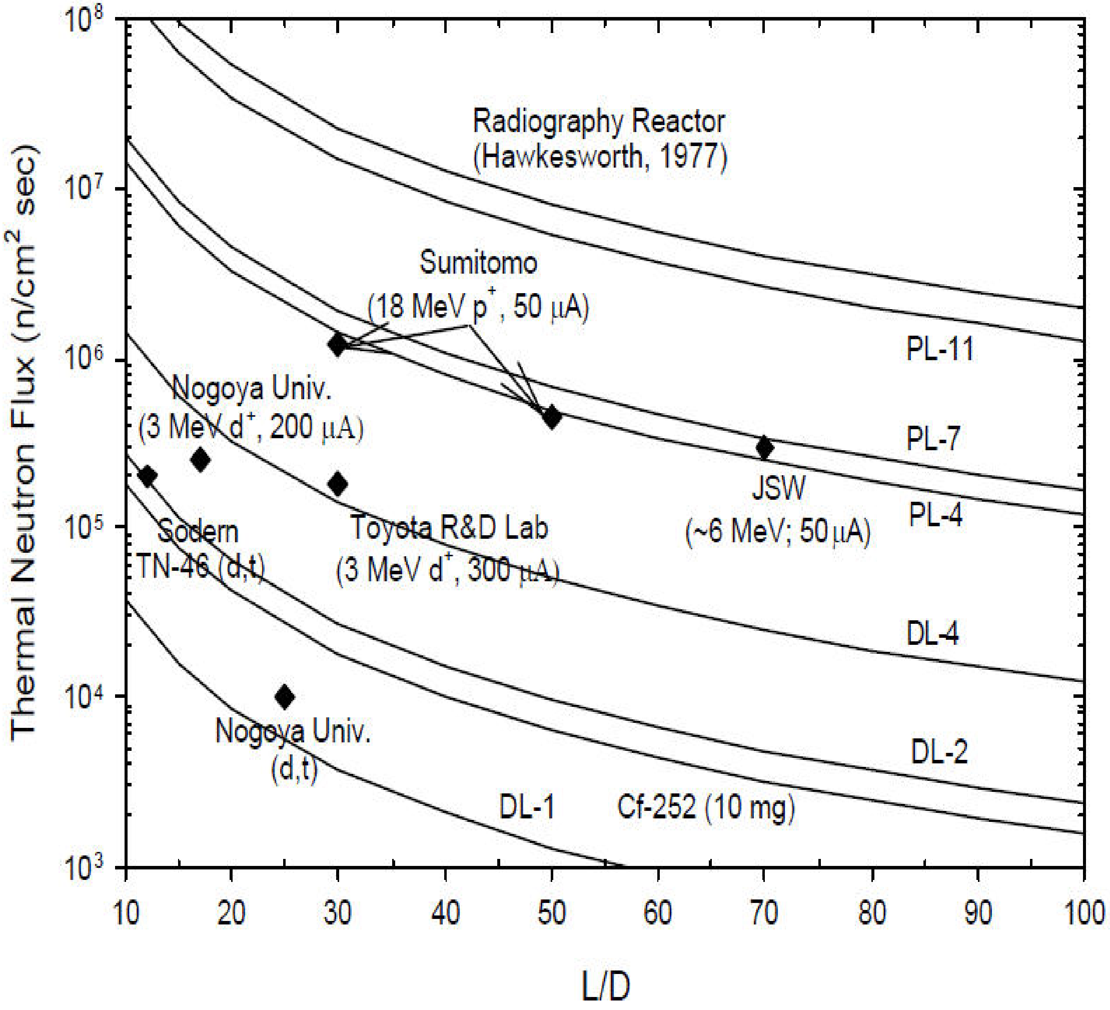
- Reactors
    - High intensity, CW beam
- SNS
    - High intensity, pulsed beam (PSI: CW)
- CANS
    - Middle intensity, reasonable cost
- Isotope source & sealed neutron tube
    - Low intensity, not practical for NR

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

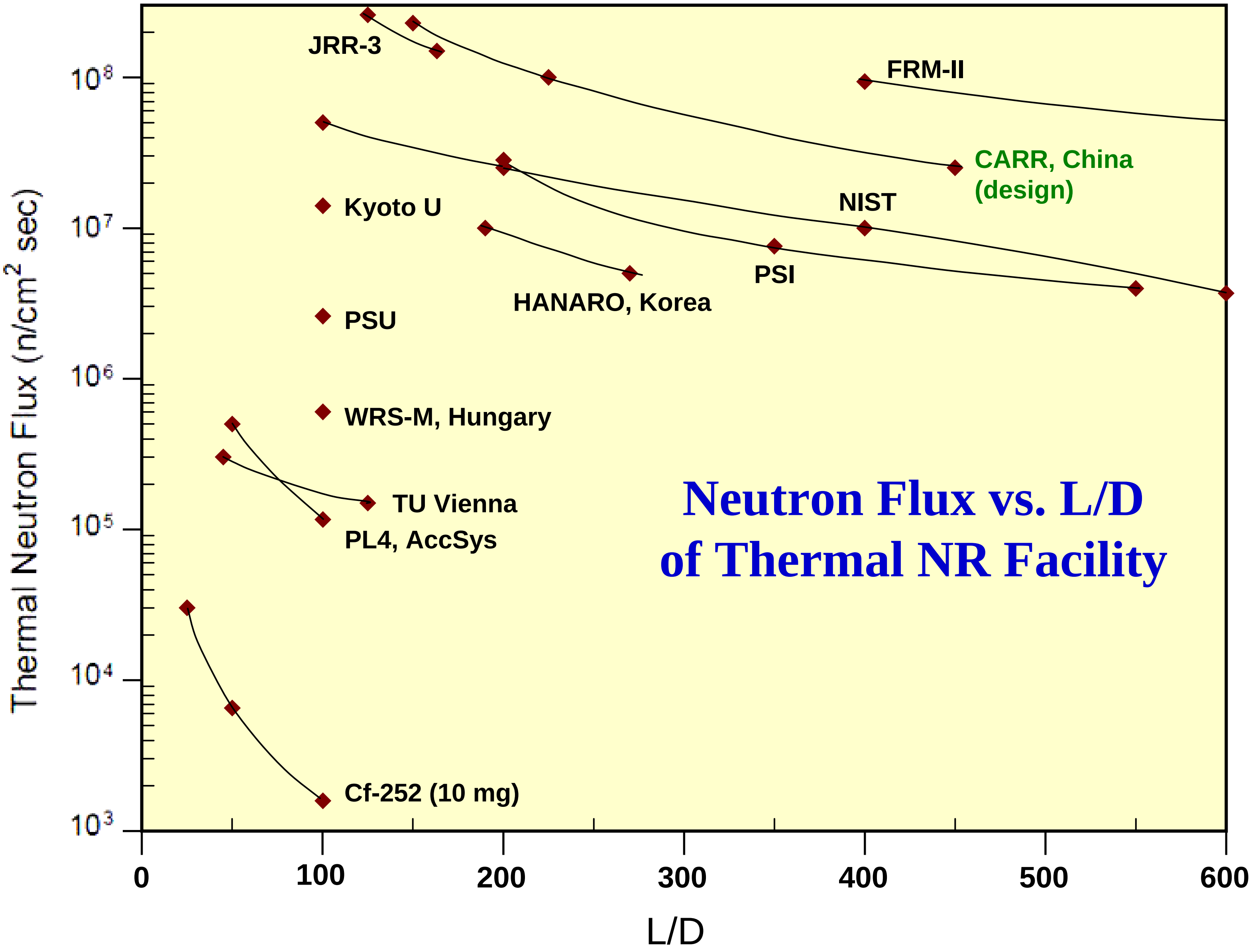


☞ **R.W. Hamm, Multi-purpose Neutron Generators Based on the Radio Frequency Quadrupole Linear Accelerator. Proc. SPIE, 4142: 39, 2000.**

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 n/(cm2 s)**. This corresponds to an exposure time of about 1000s = 16 min (with efficient digital imaging detectors). For dynamic imaging the lower level of neutron intensity has been found to be **1e6 n/(cm2 s)**.
  - The lower limit … was found at the level of **250 kW** (example, TU Vienna)

☞ **IAEA consultancy meeting report, Non destructive and analysis techniques using neutrons. 08CT14309, 2009.**



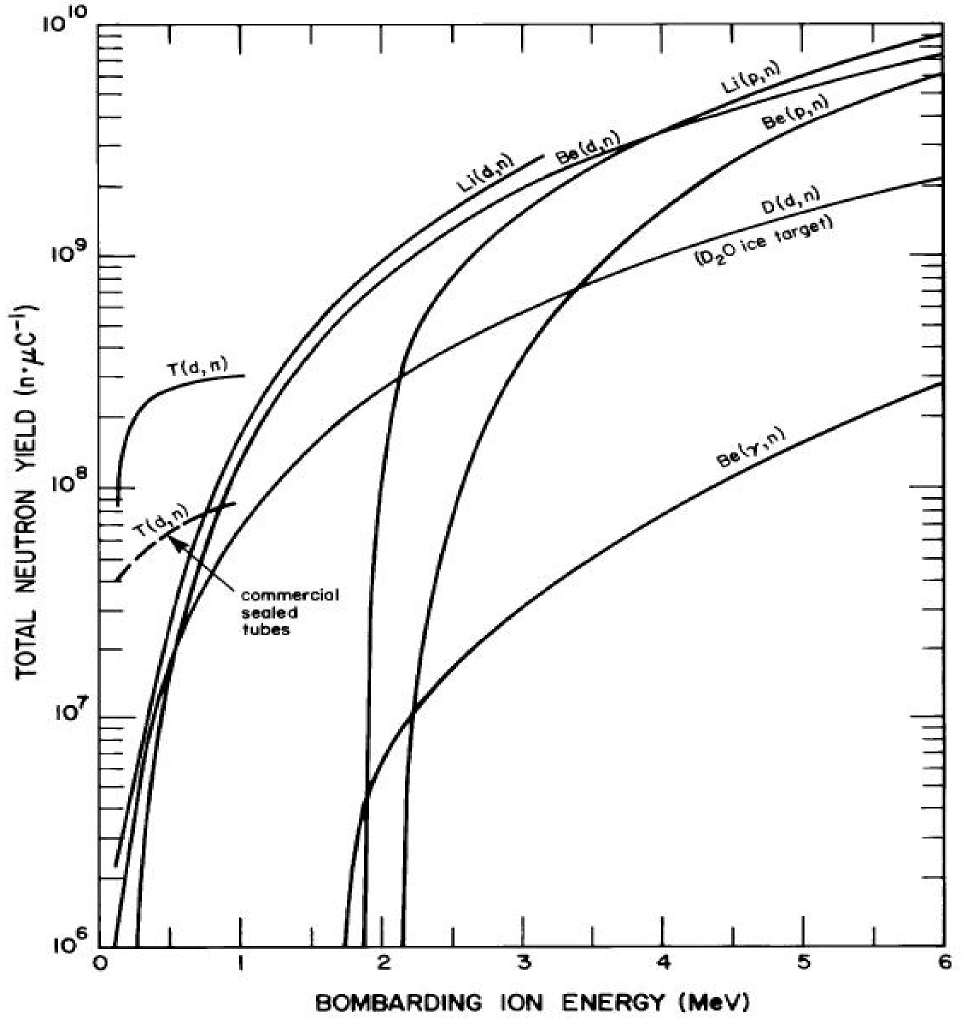
Neutron Flux vs. L/D of Thermal NR Facility

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)

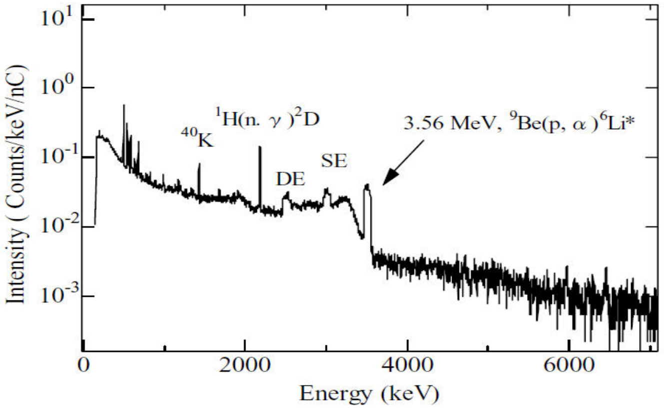
☞ **M.R. Hawkesworth, Neutron Radiography: Equipment and Methods. Atomic Energy Review, 15: 169-220, 1977.**

Problems of NR with CANS

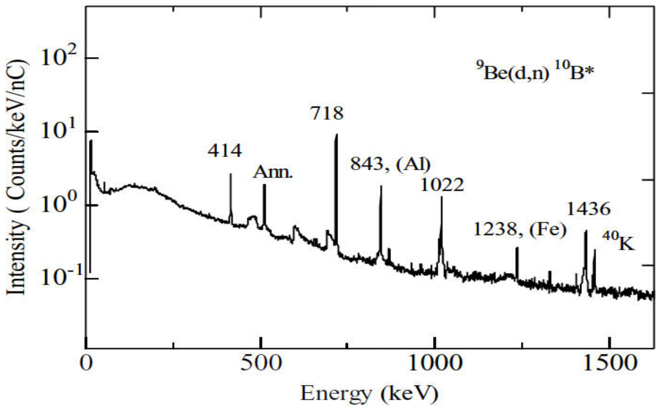
- **γ background**
  - **From beam-target reaction, especially Be (d, n) reaction**
  - **From neutron non-elastic scattering, neutron capture and (n, γ) reaction**

  ⇨Bad S/N ratio & CCD life time

☞ **Miyamaru et al., Measurement of Gamma-ray emission from p-Li, p-Be and d-Be reactions for accelerator-based BNCT. Proc. ICNCT-12, p374, 2006.**



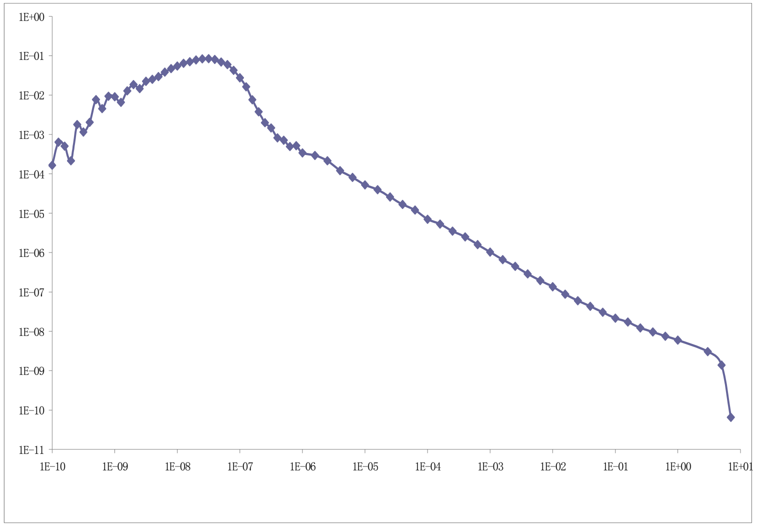
γ Spectrum of Be (p, n) @ Ep = 3 MeV



γ Spectrum of Be (d, n) @ Ed = 3 MeV

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**
  - **γ 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

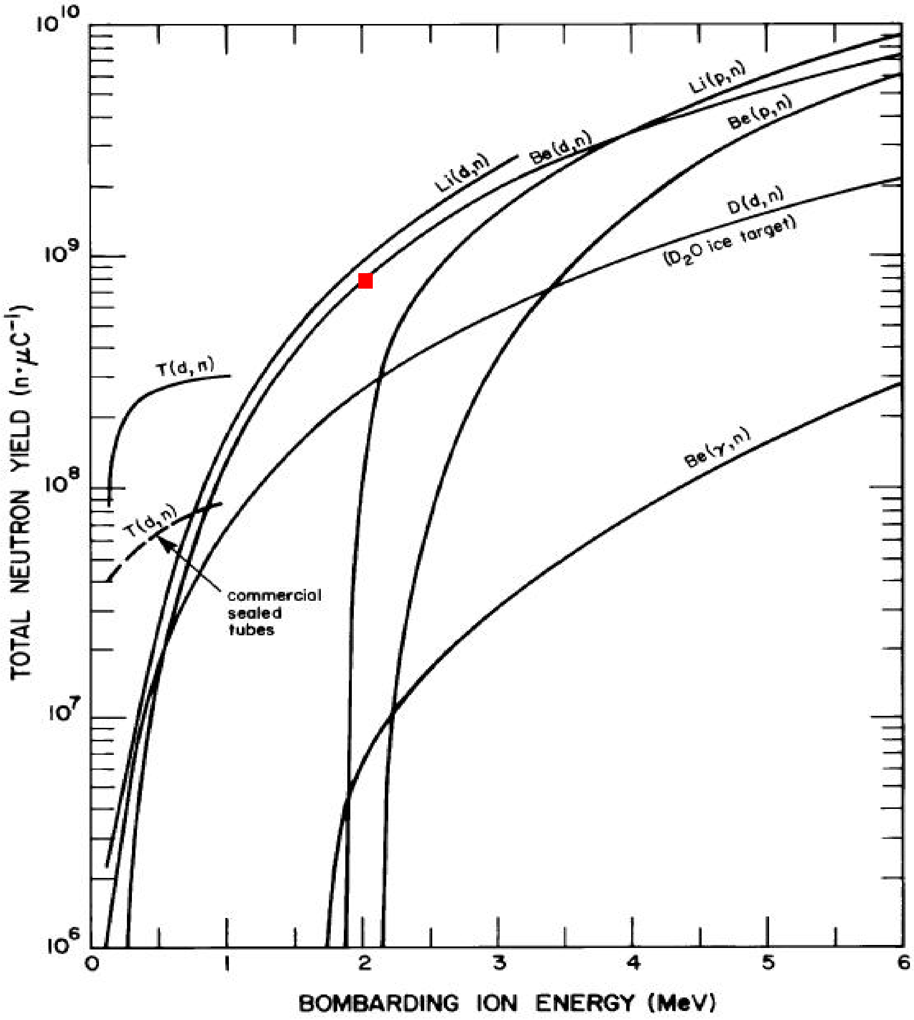
- Be (d, n) reaction was selected
  - Lower beam energy is possible than proton
  - Be target is easier to handle than Li
- Tetrode TH781 was selected
  - 400 kW peak power with 10% duty factor can be delivered at around 200 MHz
- Deuteron beam parameters
  - 40 mA peak current with 1 ms pulse width 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 Ed = 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**

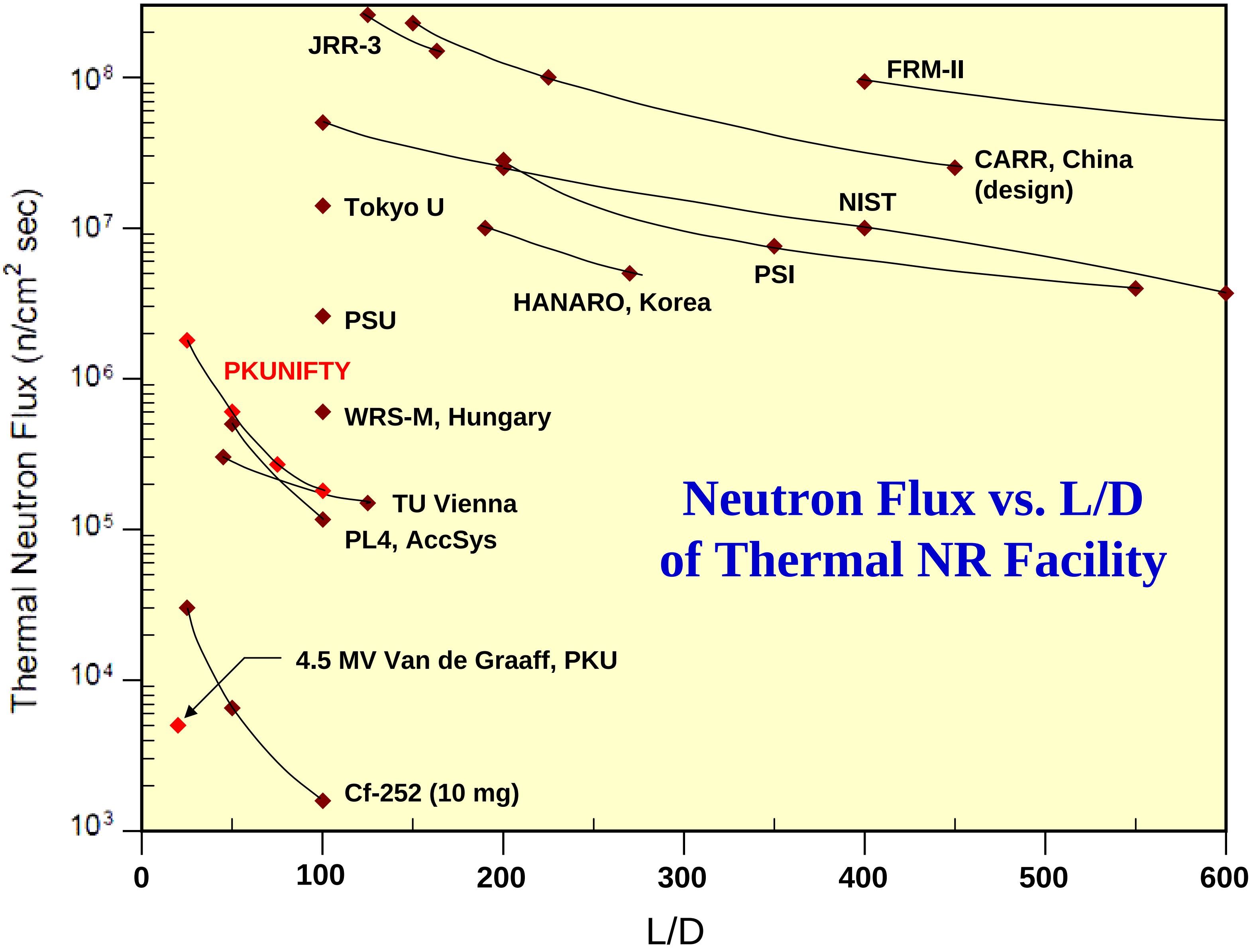
PKUNIFTY: the Solutions

- **Collimator design**
  - **90° from the beam axis**
  - **Inner collimator + Outer collimator**
  - **Changeable aperture**

⇨ Fast neutrons and γ ray can be attenuated effectively, n/γ = 1 × 10^{10} n/cm^2/Sv

⇨ L/D can be adjusted flexibly (15 - 200)

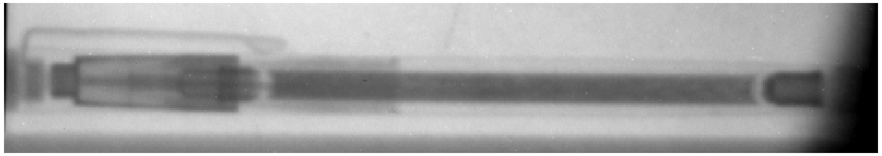
⇨ Neutron flux 5 × 10^5 n/cm^2/s @ L/D = 50



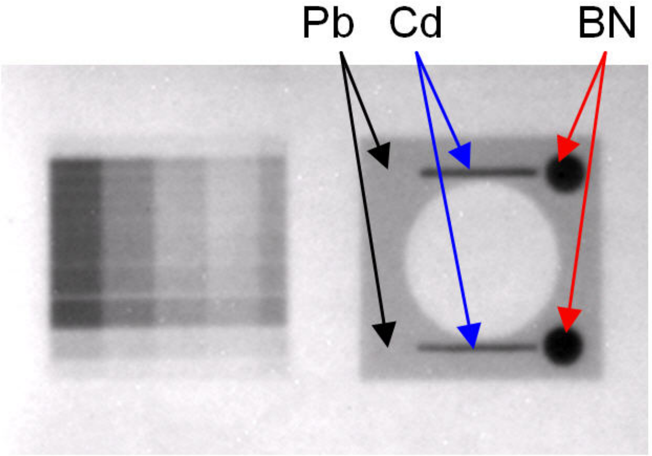
Neutron Flux vs. L/D of Thermal NR Facility

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 5×10^3 n/cm^2/s @ L/D = 20**



Ball pen with metal cover



ASTM BPI & SI indicators

☞ **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**

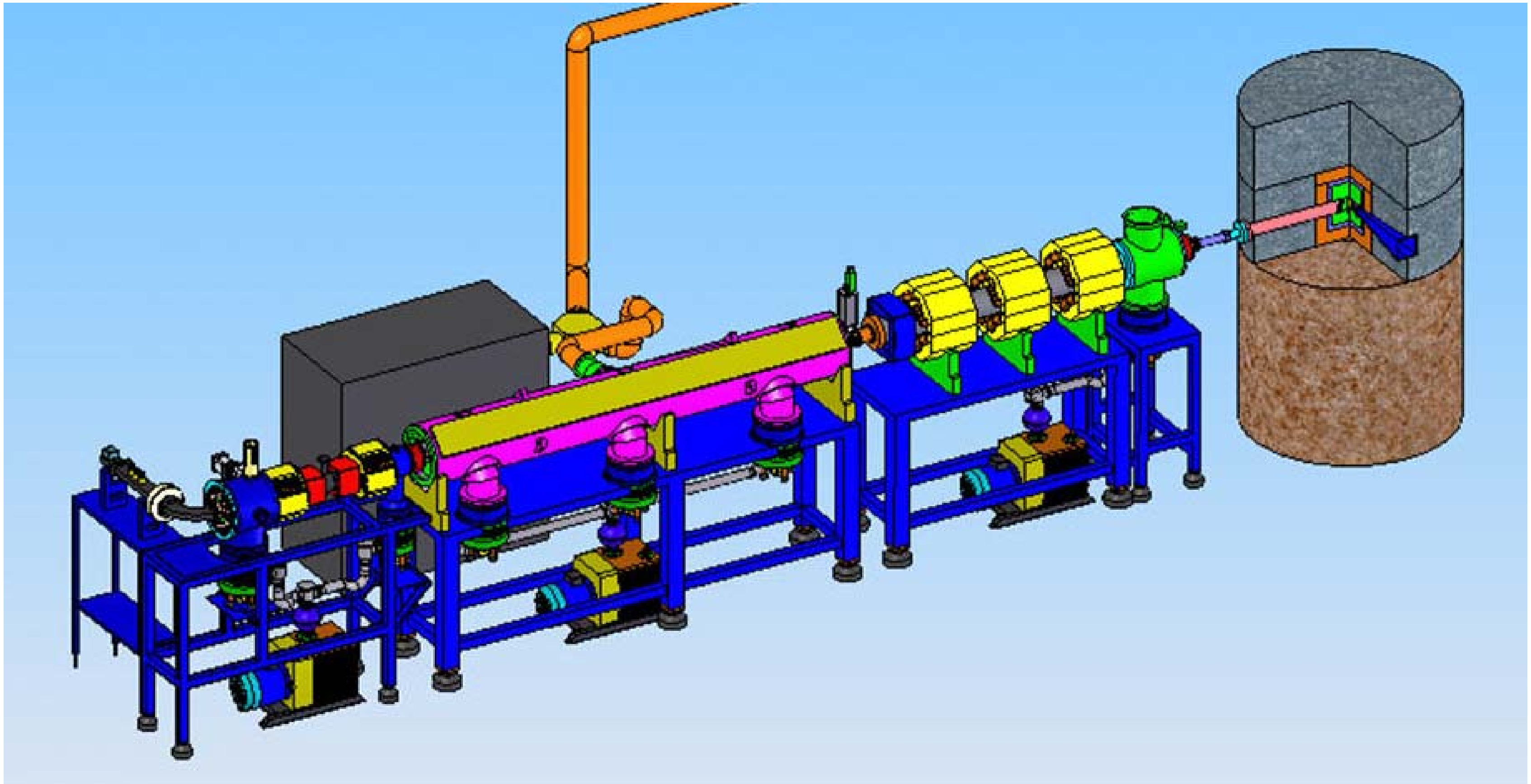
PKUNIFTY: the Solutions

- **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**

Poster-6 (A1)

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

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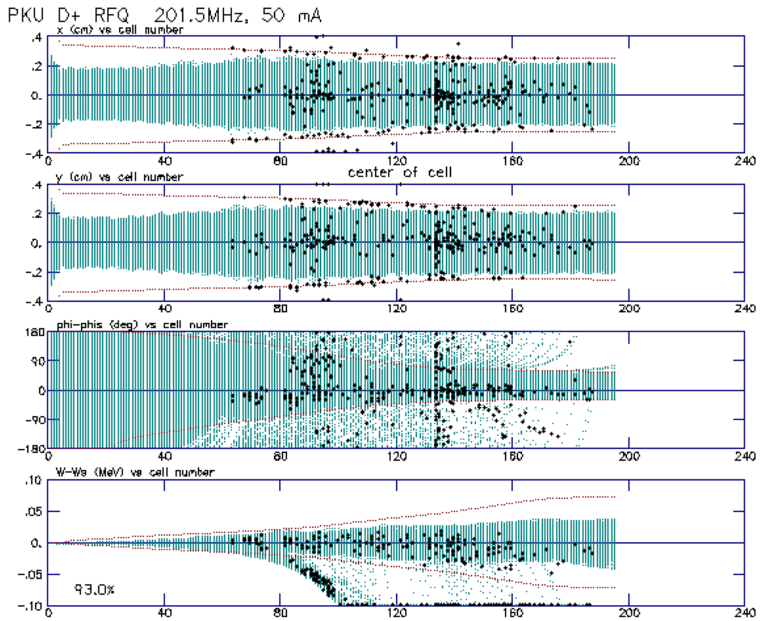
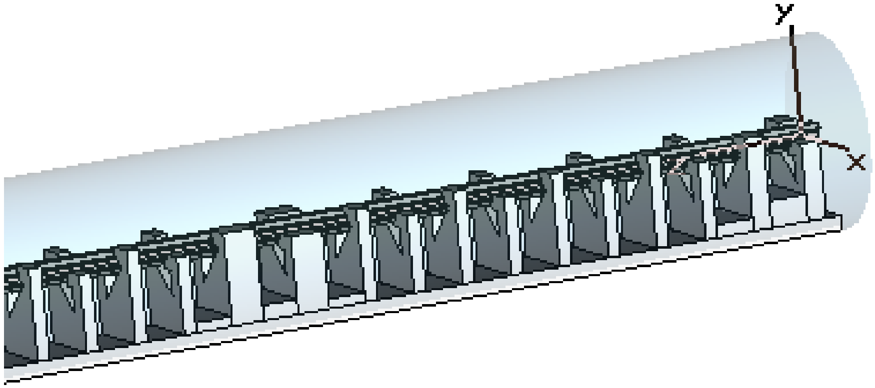
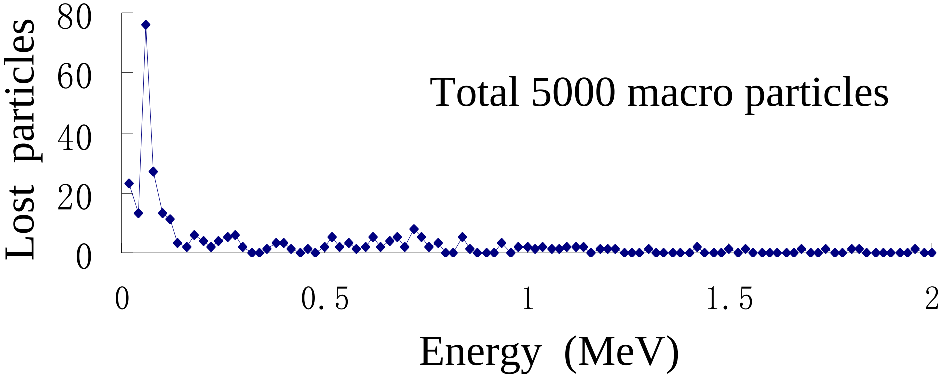
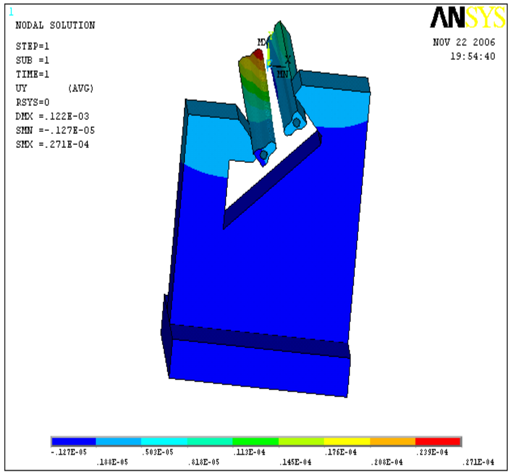
D^+ RFQ design





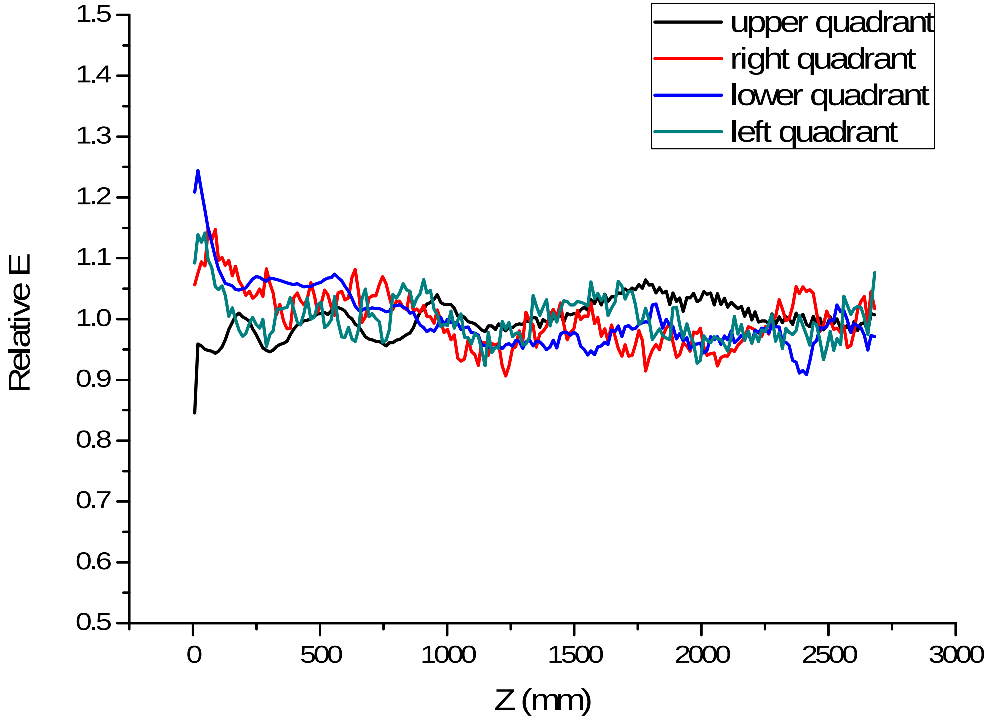


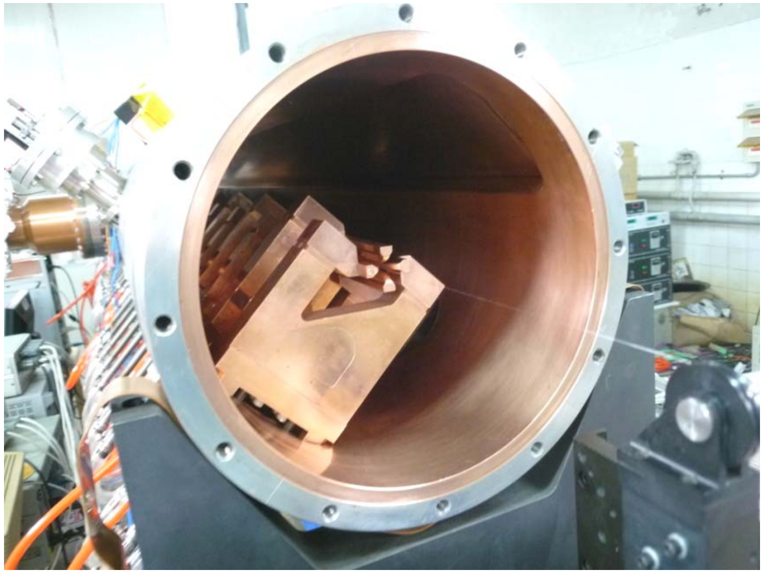
Total 5000 macro particles



D^+ RFQ bead pull measurement

- **201.5MHz, Q=3350**
- **Field distribution**





Test bench

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D^+ RFQ vacuum test

- **Vacuum is better than 2 × 10^{-5} Pa**

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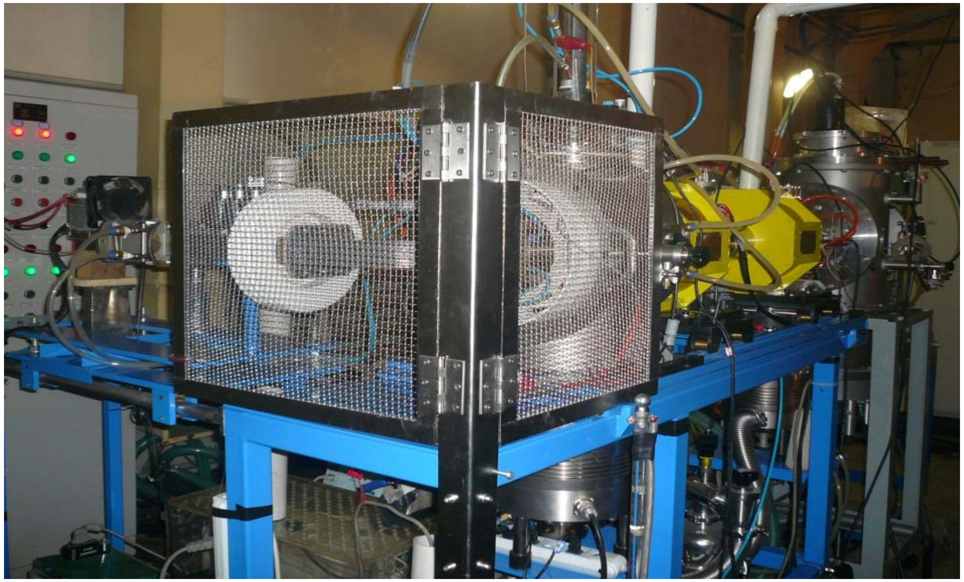
Other components

- **ECR ion source & LEBT**

  100 mA p or 80 mA D^+ @ 50kV

  0.1-1ms pulse @ 100 Hz



- **RF transmitter**

Poster-7 (T2)

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

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What is an idea moderator for us?

- **High efficiency:**

  More thermal neutron output
- **Pure beam:**

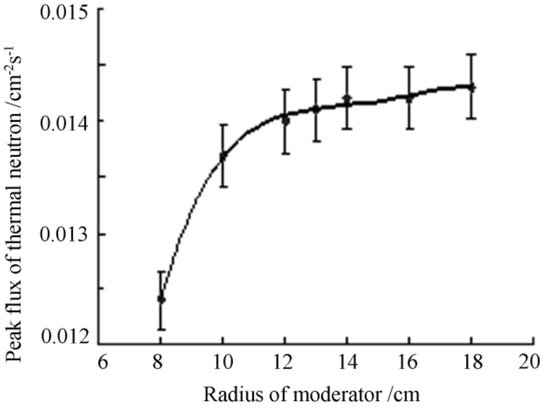
  Less fast neutron and gamma output
- **Low background:**

  Assembled with shield
- **Compact size**

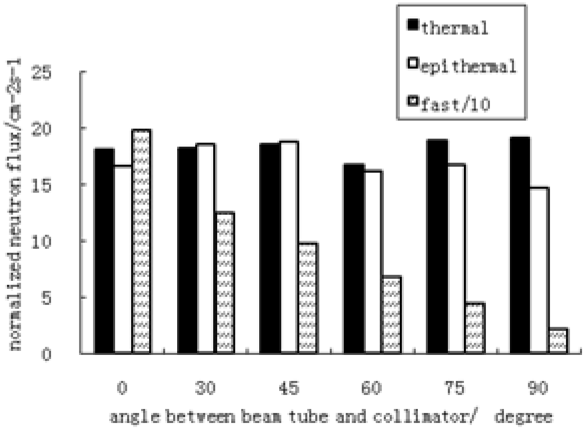
Optimization

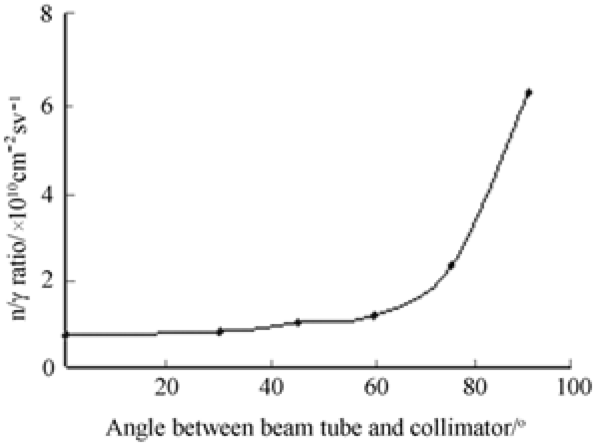
- **Moderator size**

  Thermal neutron flux increases with the moderator size until its saturation



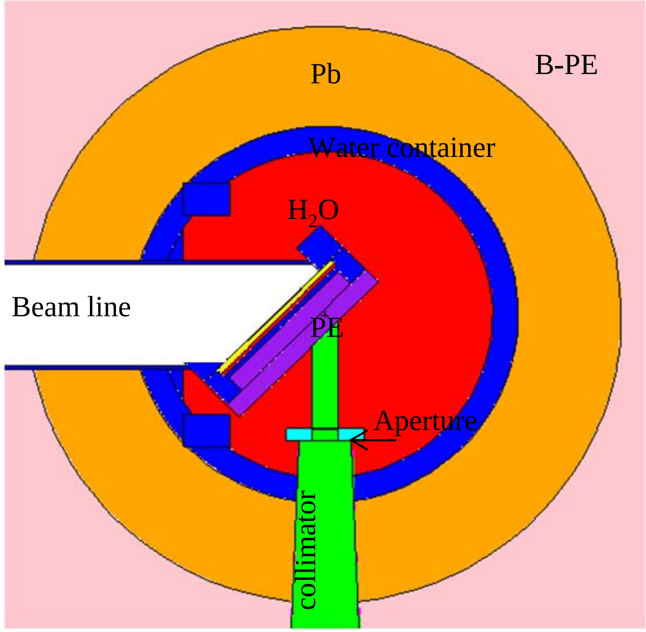
- **Neutron beam direction**





Moderator structure & parameters

- **Material: PE + Water**
- **90^o between collimator and beam line**
- **L/D range: 15-200 or more**
- **Thermal neutron flux:**
  5×10^5n/cm^2/s @ L/D=50
- **Cd ratio: ~2**
- **n/ γ : better than**
  1×10^{10} n/cm^2·Sv




Thank you for your attention !