FNAL Accelerator Physics and Technology Seminar • June 16, 2011

Increasing yield of cold and ultra-cold neutrons from spallation target for the search of neutron oscillations

Yuri Kamyshkov/ University of Tennessee
email: kamyshkov@utk.edu

HEP "High-intensity frontier" provides great new opportunities for fundamental physics with neutrons

Project X

DAEδALUS

NANO

NNbar

- Project X hopefully will be not only the development of technology of new accelerators but also of new targets.

Classification of neutrons by energy:

Neutrons called	$E_{kinetic}$	T, K	velocity	Wavelength, λ
UCN	~250 neV	~0.003	~ 7 m/s	~ 600 Å
Cold	<3 meV	<35	~ 760 m/s	~ 5 Å
Thermal	~25.9 meV	~ 300	~ 2,224 m/s	~ 1.8 Å
Resonance	~1 eV	$\sim 10^{4}$	$\sim 1.4 \cdot 10^{4}$ m/s	~ 0.3 Å
Slow	~100 eV	$\sim 10^{6}$	$\sim 1.4 \cdot 10^{5}$ m/s	~ 0.03 Å
Intermed. energy	~10 keV	$\sim 10^{8}$	$\sim 1.4 \cdot 10^{6}$ m/s	~ 0.003 Å
Fast	~ 1 MeV	$\sim 10^{10}$	~ 0.046 *c*	~ 0.0003 Å
High energy	~ 100 MeV	$\sim 10^{12}$	~ 0.43 *c*	~ 3 fm
Relativistic	>1 GeV	$>10^{13}$	> 0.875 *c*	< 0.9 fm

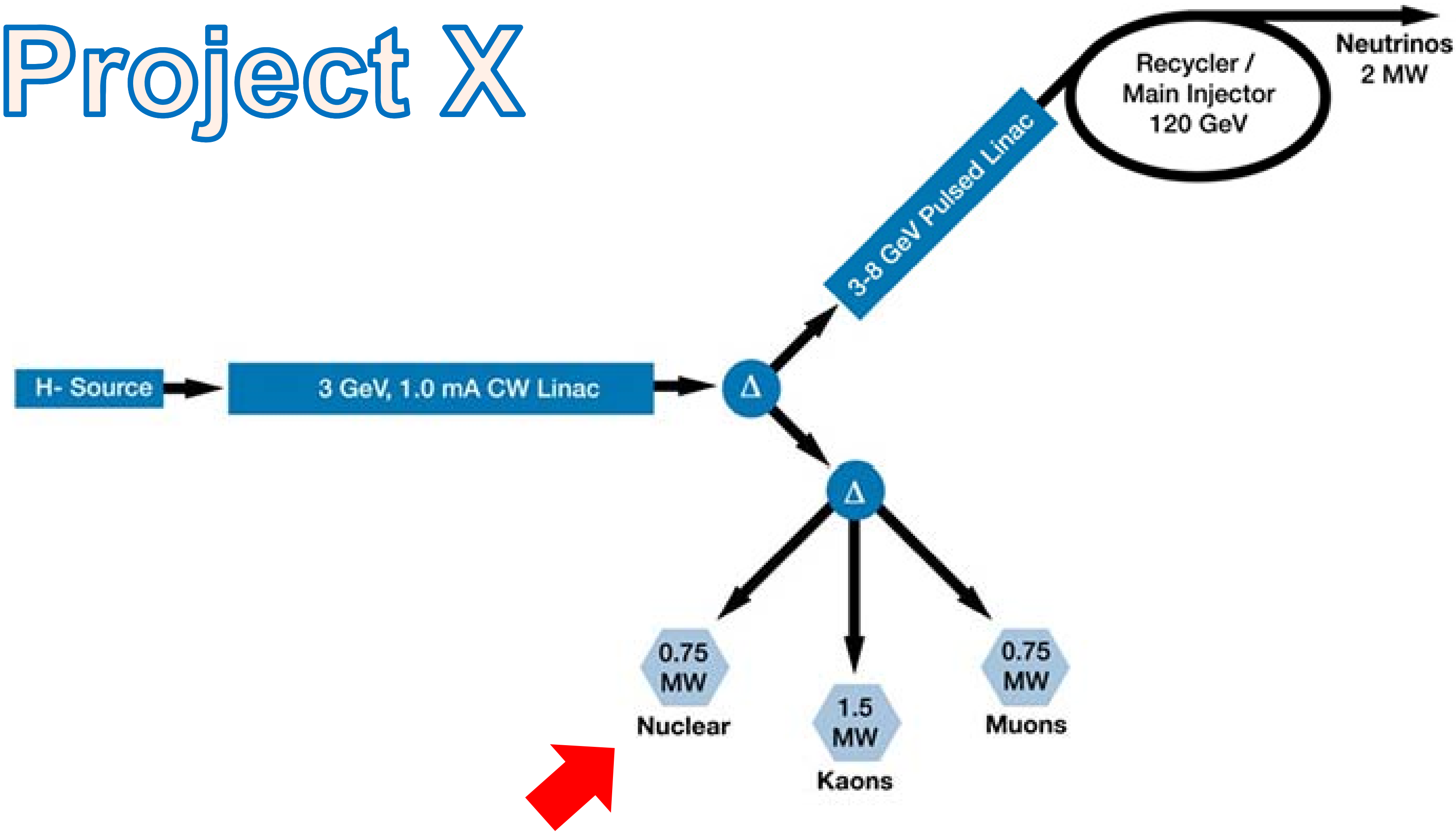
Cold and Ultra-Cold neutrons (UCN) are produced at (or being planned for)

- SNS
- PSI
- ESS
- LANCE
- ILL reactor in Grenoble
- FRM II reactor in Germany
- NIST reactor
- NCSU PULSTAR reactor
- HFIR reactor at ORNL
- New PIC reactor in Russia …

Neutron is a perfect particle for fundamental physics research

- neutral
- lives long ~ 900 sec
- abundant; has large x-seactions
- long observation requires slow velocities
- theory of β-decay → Standard Model; studies of fundamental symmetries; precision lifetime measurements; quantum levels in gravity field, neutron EDM …

Project X



What can be new special with neutrons for Project X and beyond?

- New Physics
  with high discovery potential

- New Technology with more
  observable neutrons than before

Such Physics Exists

- Baryon number violation ΔB=2 $n \longrightarrow \overline{n}$ (appearance)

  Standard Model is renormalizable because of Δ(B–L)=0;
  neutrino masses → Majorana neutrinos with ΔL=2
  that implies ΔB=2 Majorana neutrons, i.e. $n \longrightarrow \overline{n}$

- Neutron disappearance $n \longrightarrow n'$ (mirror neutrons)

  "Mirror neutrons" are part of "mirror world" = right-handed duplicate of the Standard Model, with same but different than in SM interactions, also providing viable explanation of Dark Matter, sterile neutrinos …

- Strong physics motivation:
  see e.g. in "DUSEL Theory white paper"
  http://arxiv.org/abs/0810.4551

Is neutron a Majorana Particle?

In the famous E. Majorana 1937 paper
“Teoria simmetrica dell’elettrone e del positrone”,
Il Nuovo Cimento, v.14, 1937, pp. 171-184:

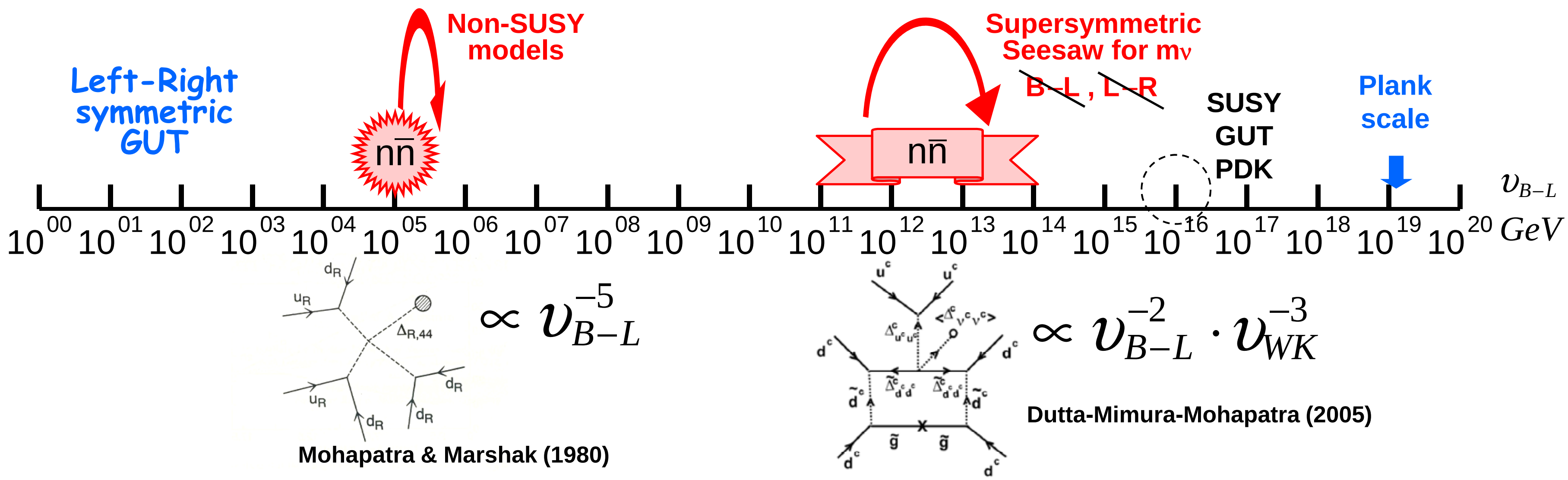
“ ... this method ... allows not only to cast the electron-positron theory into a symmetric form, but also to construct an essentially new theory for particles not endowed with an electric charge (neutrons and the hypothetical neutrinos).”

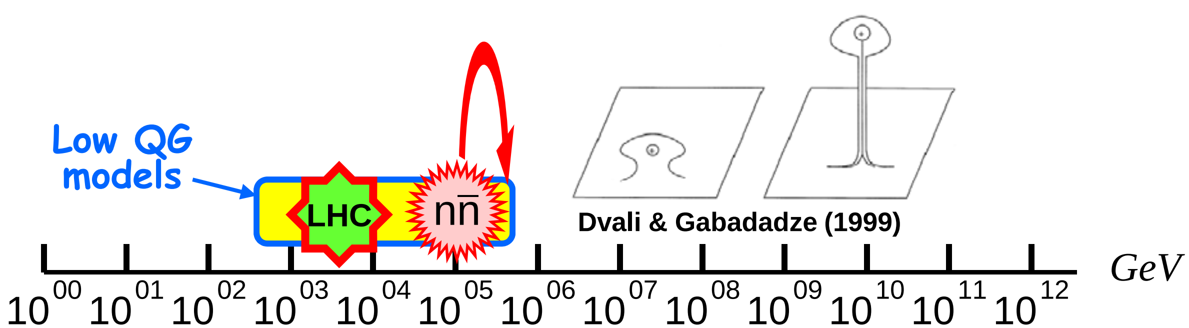
(translated by L. Maiani)

But, antineutron discovered in 1956 by B. Cork et al. @ LBL turned out to be a particle different from neutron. However, the existence of neutron $\rightarrow$ anti-neutron transformation might mean the presence of some fraction of the Majorana component mixed into the neutron wave function.

This fraction should be small (otherwise it would be already observed) unless there are some suppression conditions or mechanisms are present.

$Scales\ of\ \ n \to \bar{n}\ \ (B-L)V$





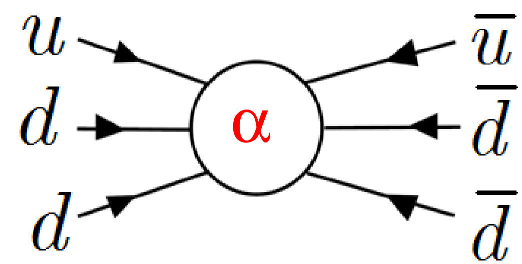
n→nbar transition probability

$$\Psi = \begin{pmatrix} n \\ \bar{n} \end{pmatrix}$$ mixed n-nbar QM state

All beyond SM physics is here

$$\mathrm{H} = \begin{pmatrix} E_n & \alpha \\ \alpha & E_{\bar{n}} \end{pmatrix}$$ Hamiltonian on the system

α-mixing amplitude



where E_n and $E_{\bar{n}}$ are non-relativistic energy operators:

$$E_n = m_n + \frac{p^2}{2m_n} + U_n \quad ; \quad E_{\bar{n}} = m_{\bar{n}} + \frac{p^2}{2m_{\bar{n}}} + U_{\bar{n}}$$

Important assumptions :

- $\alpha(n \to \bar{n}) \cong \alpha(\bar{n} \to n) = \alpha$ (i.e. T-invariance is hold)
- there is a reference frame where $p = 0$
- $m_n = m_{\bar{n}}$ (as CPT required); $(m_n - m_{\bar{n}}) / m_n = (9 \pm 5) \times 10^{-5}$
- gravipotential for n and $\bar{n}$ is the same: $\Delta U = U_n - U_{\bar{n}} = 0$ (S. Lamoreaux et al., 1991)
- magnetic moment $\mu(\bar{n}) = -\mu(n)$ as follows from CPT [BTW, $\mu(\bar{n})$ not measured!]
- Earth mag. field can be screened down to nT level

n→nbar transition probability (for given α)

For $H = \begin{pmatrix} m_n + V & \alpha \\ \alpha & m_{\bar{n}} - V \end{pmatrix}$;

$$P_{n\to\bar{n}}(t) = \frac{\alpha^2}{\alpha^2 + (V + \Delta m/2)^2} \times \sin^2\left[\frac{\sqrt{\alpha^2 + (V + \Delta m/2)^2}}{\hbar} t\right]$$

↑ famous Rabi's formula for 2-state system

where V is a potential different for neutron and anti-neutron
(e.g. due to non-compensated Earth mag. field; or as part of gravipotential)
t is observation time in the experiment, and $\Delta m = m_n - m_{\bar{n}}$ (if CPT is violated)

In an ideal situation of no suppression i.e.
"vacuum oscillations" : $V = 0$ and $\Delta m = 0$,
and experimentally t ~ 0.1 s to 10 s

$$P_{n\to\bar{n}} = \left(\frac{\alpha}{\hbar} \times t\right)^2 = \left(\frac{t}{\tau_{n\bar{n}}}\right)^2$$

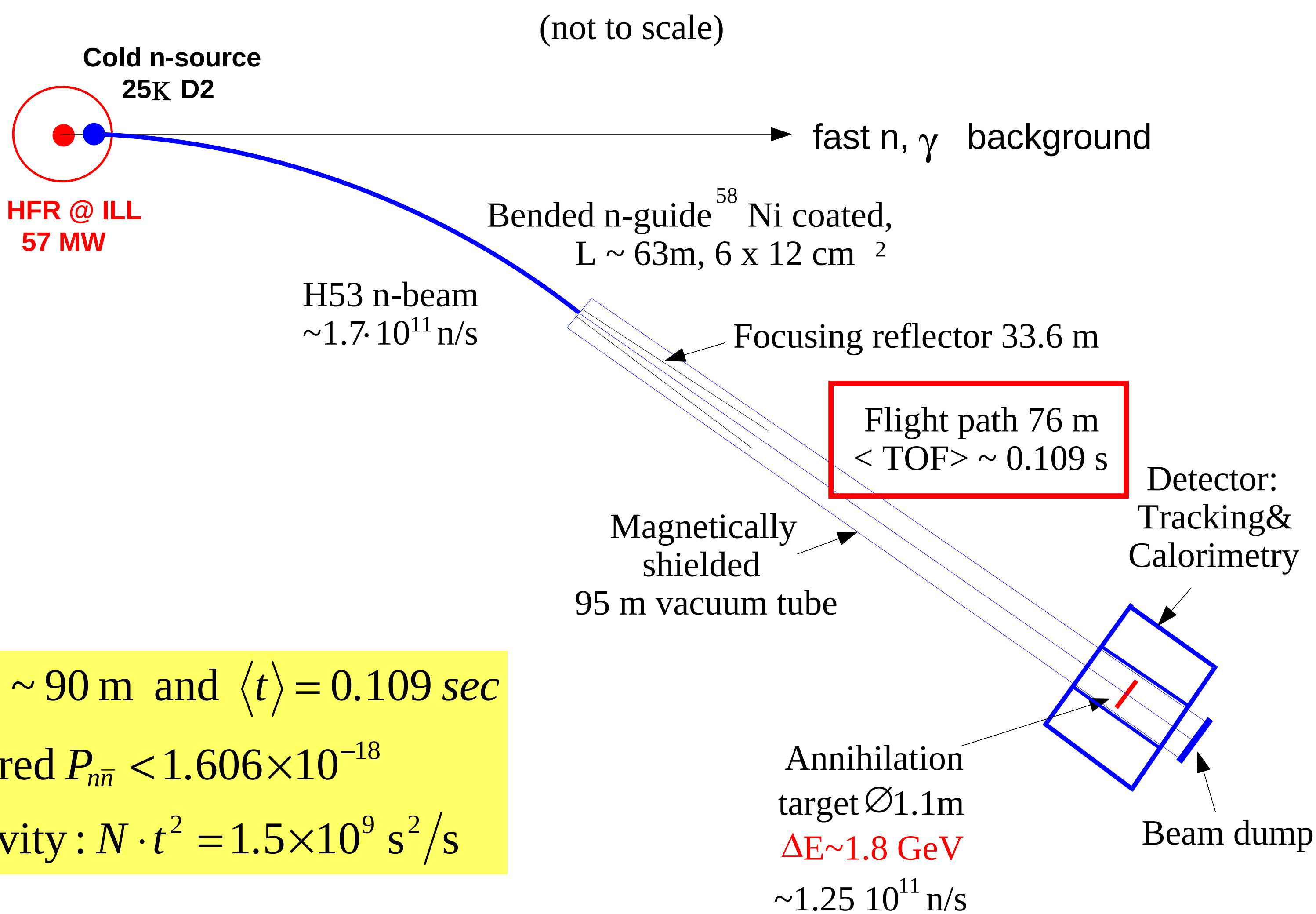
$\tau_{n\bar{n}} = \frac{\hbar}{\alpha}$ is characteristic "oscillation" time [$\alpha < 2 \cdot 10^{-24} eV$ from present limits]

Predictions of theoretical models: observable effect around $\alpha \sim 10^{-25} - 10^{-26} eV$

Previous n-nbar search experiment with free neutrons

At ILL/Grenoble reactor in 89-91 by Heidelberg-ILL-Padova-Pavia Collaboration

M.Baldo-Ceolin M. et al., Z. Phys., C63 (1994) 409



$$\text{with L} \sim 90\text{ m and } \langle t \rangle = 0.109\ sec$$

$$\text{measured } P_{n\bar{n}} < 1.606\times10^{-18}$$

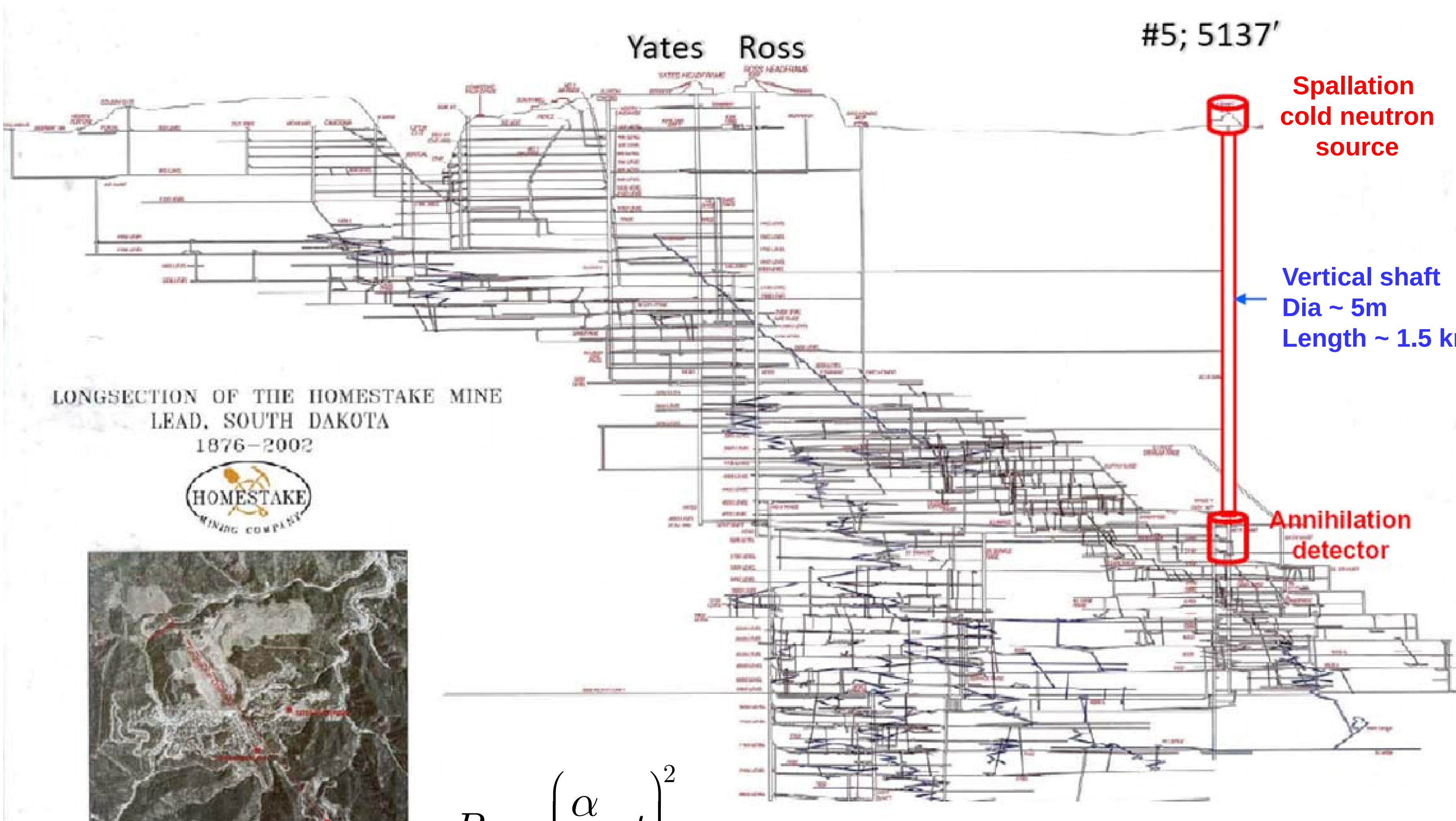
$$\text{sensitivity}: N \cdot t^2 = 1.5\times10^{9}\ \text{s}^2/\text{s}$$

NNbar Experiment

- There is a possibility with new experiments to extend the experimental sensitivity by 3-4 orders of magnitude in discovery of new phenomenon. Present limit $\tau_{(NNbar)} > 3.5 \times 10^8$ s (bound n); $> 8.6 \times 10^7$ s (free n)
- Unique annihilation signature, no background $\rightarrow$ one event = discovery
- If observed, will be possible to switch effect ON/OFF by external mag. field
- If observed: possible to study new physics e.g. CPT violation at scale > m_P
- If not observed: will set new limits on the matter stability beyond PDK reach
- Tests BSM theoretical HEP models, R-L symmetry, B–L violation, …

➢ Ideally one needs to watch transformation of neutron at rest. Since neutrons live ~ 900 sec many neutrons needed. "Thermal neutrons ~ 25 meV" $\Rightarrow$ 2,200 m/s (Maxw.); "cold neutrons" : ~ 700 m/s; "UCN" : <7 m/s. Need powerful source on n initially produced with MeV energies moderated down to cold and to UCN velocities.

Our NNbar proposal for DUSEL with vertical layout



$$P_1 = \left(\frac{\alpha}{\hbar}\cdot t\right)^2$$

$n \rightarrow n'$ mirror transition (neutron disappearance)

$$\text{For } H = \begin{pmatrix} m_n + V & \alpha \\ \alpha & m_n' + V' \end{pmatrix}; \qquad P_{n\rightarrow\bar{n}}(t) = \frac{\alpha^2}{\alpha^2 + \Delta V^2} \times \sin^2\left[\frac{\sqrt{\alpha^2 + \Delta V^2}}{\hbar} t\right]$$

Complete QM treatment by Z. Berezhiani in Eur. Phys. J. C. (2009) 64: 421-431

- $V' = \vec{\mu}' \cdot \vec{B}'$ is not known. Educated guesstimate B'~ 0.1 Gauss on Earth
- By varying V one can try compensation $\rightarrow$ disappearance probability can be function of B (lab magnetic field) and its direction
- Life time of UCN in the storage trap might be affected by external mag. field
- Recent experiment of A. Serebrov et al performed at ILL/Grenoble [NIM A611, 137 (2009)] and reanalyzed by Z. Berezhiani et al (2011, to be published soon) indicates ~ 5σ magnetic field +direction effect on the UCN storage time

Nuclear Instruments and Methods in Physics Research A 611 (2009) 137–140

A.P. Serebrov et al, Search for neutron–mirror neutron oscillations in a laboratory experiment with ultra-cold neutrons

Time between wall collisions ~0.3 s

Filling = 150 s
Storage = 300 s
Counting = 150 s

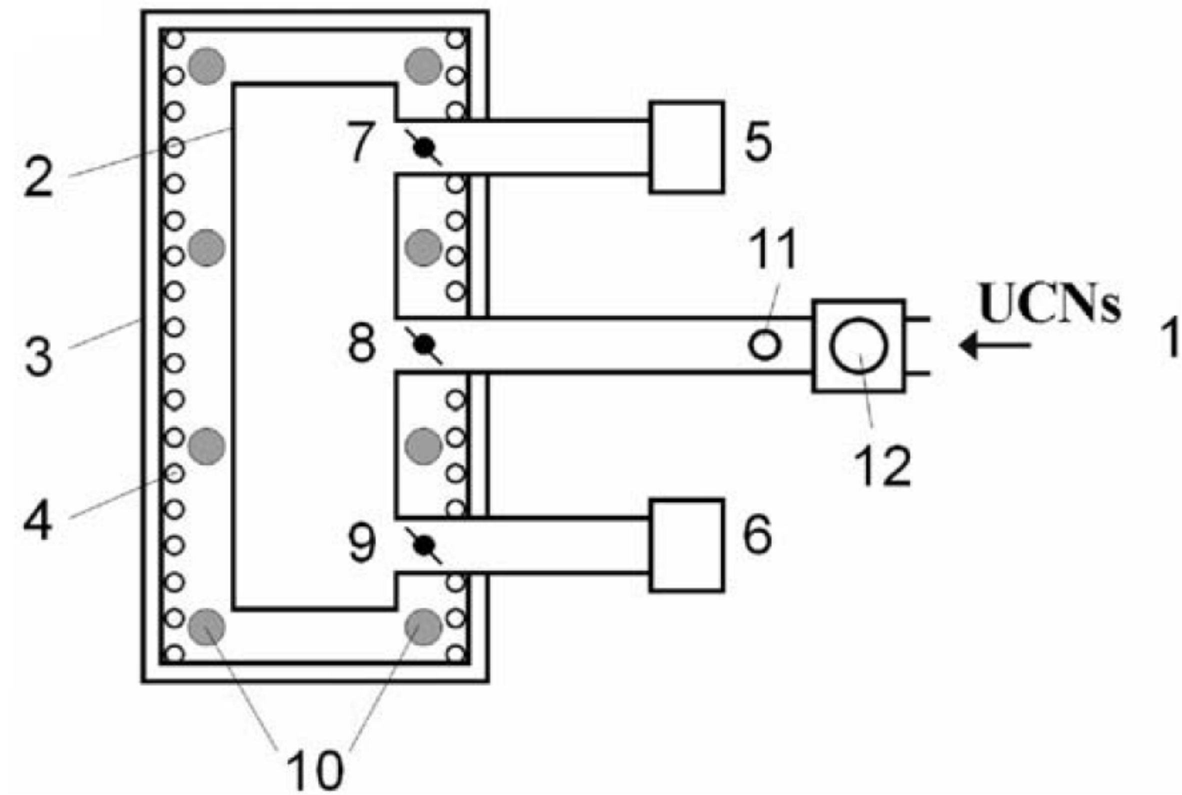


Fig. 1. Experimental setup (top view). 1: UCN input guide; 2: UCN storage chamber; 3: magnetic shielding; 4: solenoid; 5–6: UCN detectors; 7–9: valves; 10: Cs-magnetometers, 11: monitor detector, 12: entrance valve.

Neutron Disappearance

$$P_B(t) = p_B(t) + d_B(t)\cdot\cos\beta$$

,where β is an angle between $\vec{B}$ and $\vec{B}'$

$$p(t), d(t) = \frac{\sin^2\left[(\omega-\omega')t\right]}{2\tau^2(\omega-\omega')^2} \pm \\ \pm \frac{\sin^2\left[(\omega+\omega')t\right]}{2\tau^2(\omega+\omega')^2}$$

and $\omega' = \frac{1}{2}\left|\mu B'\right|$

$$A_B^{\text{det}}(t) = \frac{N_{-B}(t) - N_B(t)}{N_{-B}(t) + N_B(t)}$$

Reasonable interpretation:
$\tau > 1s; \quad B' \sim 0.1G$

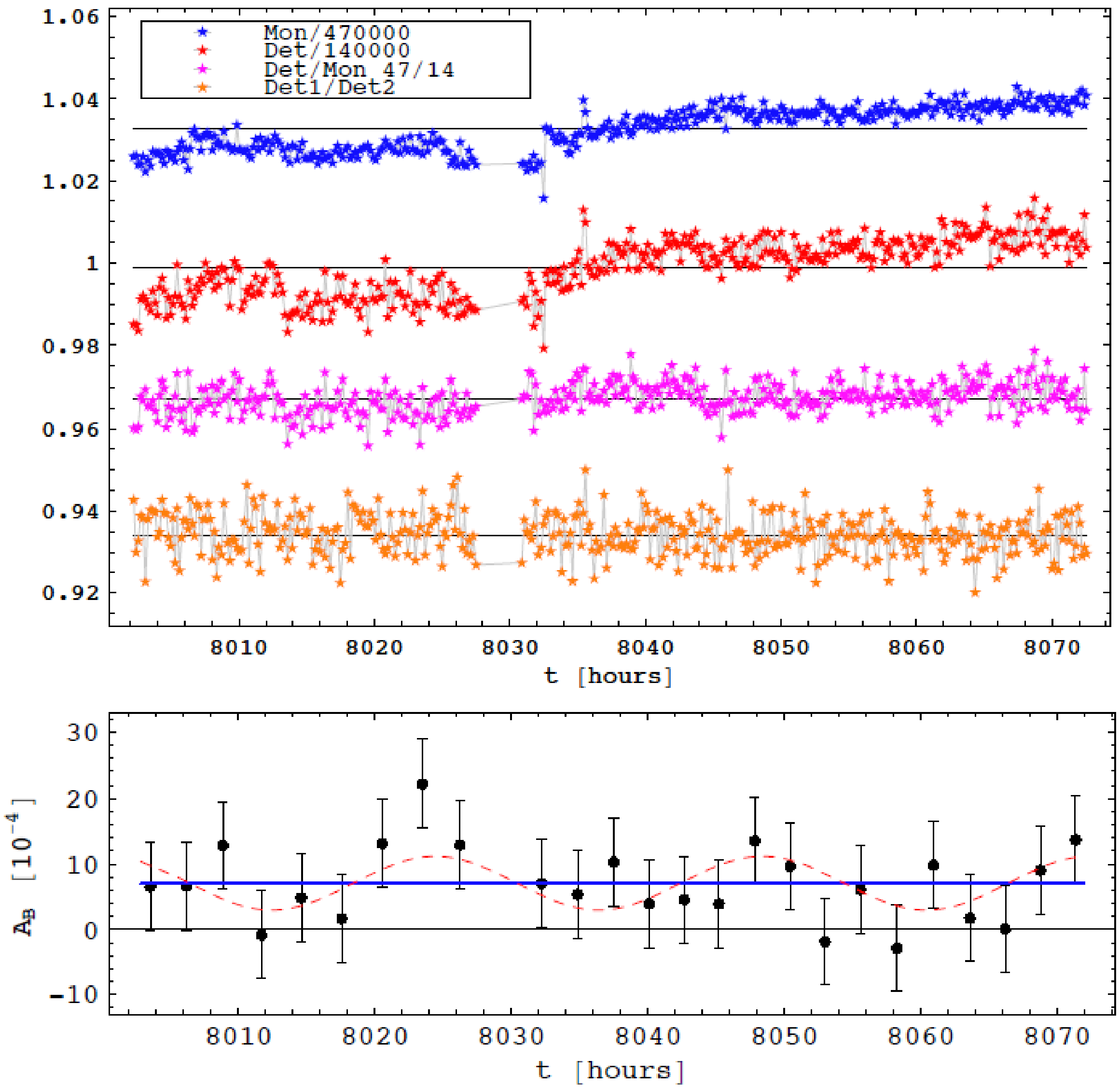
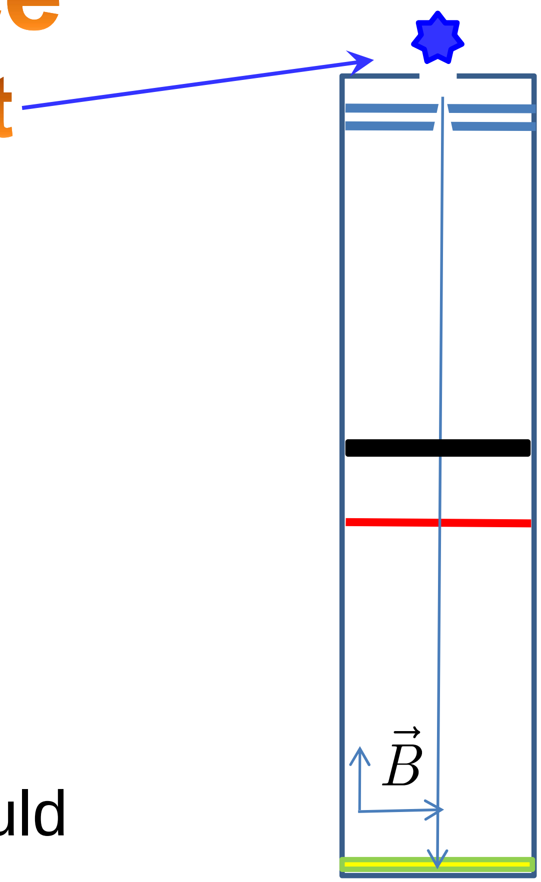


Fig. 1. Upper Panel: *from up to down, the monitor and detector counts in* $\{\boldsymbol{B}\}$ *series,* M *and* $N = N_1 + N_2$ *normalized respectively to 470000 and 140000; and the ratios* $N/M\,(\times 47/14)$ *and* N_1/N_2. Lower Panel: *results for* $A_{\rm B}^{\rm det}$ *binned by two* $\{\boldsymbol{B}\}$ *cycles (16 measurements), with the constant and periodic fits.*

Simple n disappearance
with project X nuclear target



- Let’s assume that ~ 100 m long MINOS shaft can be used
- 10 m/s neutron falls 100 m for ~ 3.5 s.
- Pulsed target operation would explores different velocities
- Variation of lab field B and its direction should detect resonance in the disappearance
- If one absorbs all neutrons in the max of disappearance it will be possible to observe the regeneration effect (appearance on neutrons)

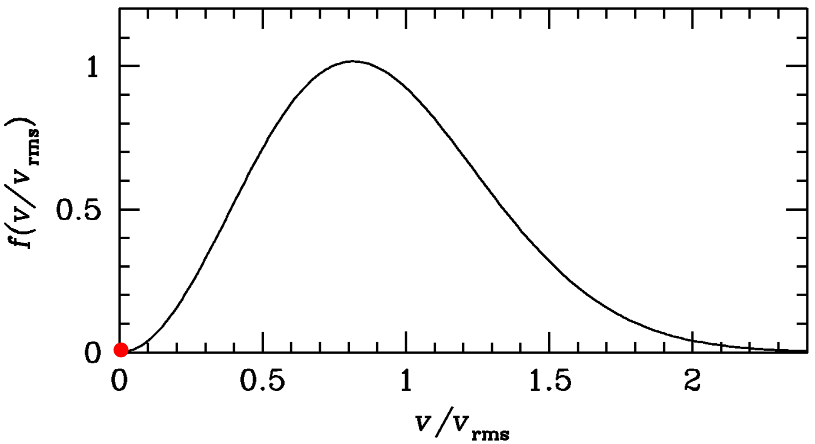
Slow n- technologies

- Electrically neutral neutrons are difficult to manipulate with by E-M field: neutrons are produced from nuclei and moderated by collisions $\rightarrow$ statistical ensemble with continuous spectrum and Temperature

- Neutrons produced in fission or spallation with MeV energy can be efficiently moderated to "thermal" energy in meV range by elastic collisions with light elements: H, D, He …

- For thermal (or lower energy) neutrons their wavelength became comparable with inter-atomic distances ~ 2 Å and elastic scattering becomes coherent and not dissipative. E.g. neutrons thermalized in the LD_2 bath at ~20K (at ILL) have temperature ~35K.

- UCN with v < 7 m/s is a tiny part of the thermal spectrum at 35K <v> ~ 760 m/s. E.g. at ILL flux of ~10^{15} n/cm^2/s cooled down to 35K produces UCN density of ~ 50 UCN/cm^3 [or ~ 3×10^6 n/s]



UCN Conversion

- Thermal spectrum : tiny part
- Cryogen moderator: better (limit T_n~35K with Liq. D_2)
- Solid CH_4 or CD_4 as cold moderators are not quite explored
- Solid D_2 ! (limited thermoconductivity)
- Superfluid He !!!
- Solid Oxygen ? (Indiana U)

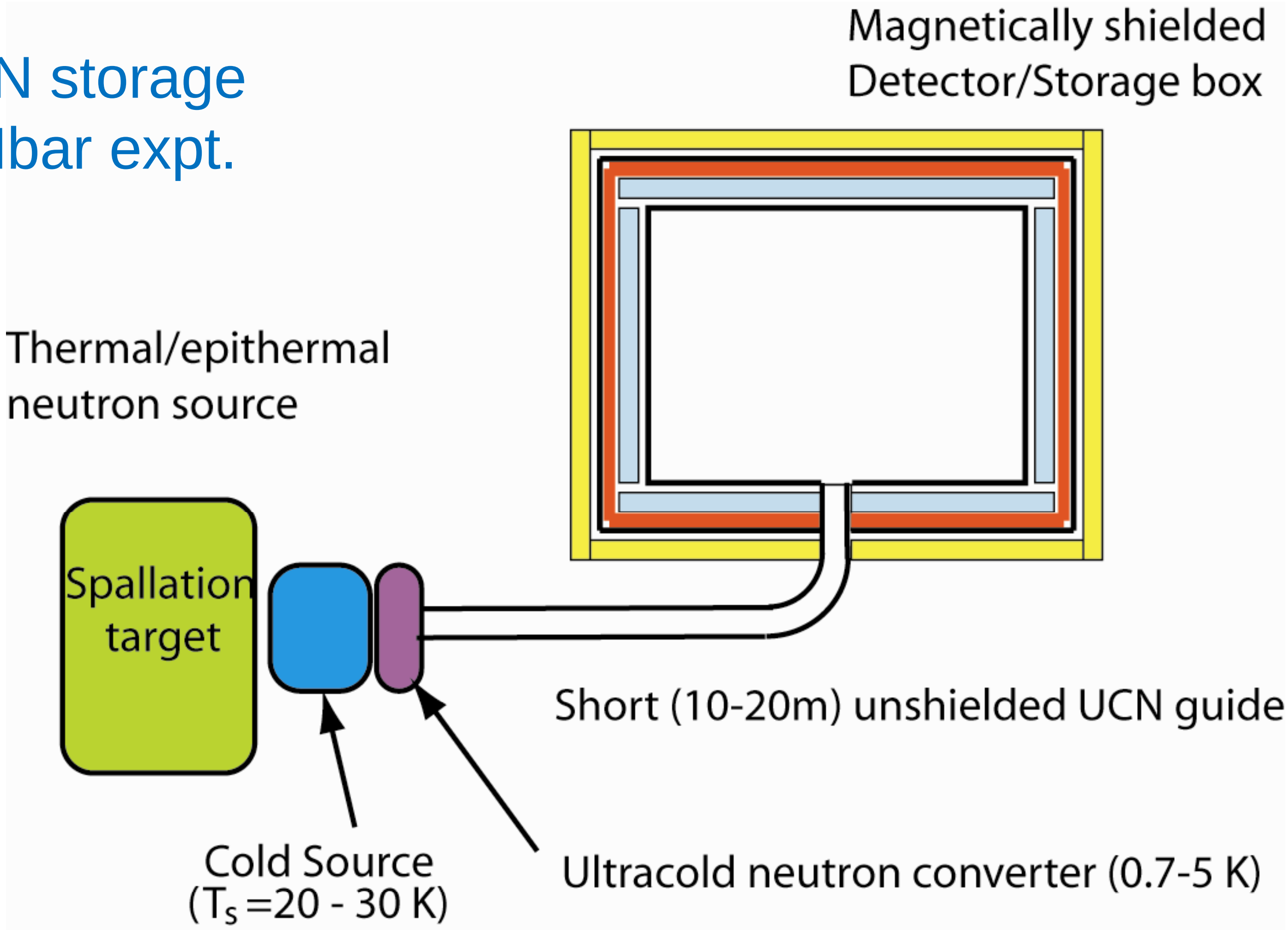
Possible UCN sources

- ILL: $3x10^6$ UCN/s available now

- **Potentially competitive SD_2 sources**:
  - PULSTAR reactor w/ 3.5 MW upgrade: $1.2x10^7$ UCN/s
  - PSI (10-20 kW spallation target– 1 MW peak): $5x10^9$ in close-coupled storage volume, every 4 to 8 minutes; operation in 2011
  - FRM II reactor (24 MW): perhaps 4×10^7 UCN/s; begin operation roughly 2012 (project funded 2007)

- **LHe superthermal sources**
  - TRIUMF (5-10 kW spallation target; 50 kW peak): $5x10^7$ UCN/s
  - Dedicated 1.9K source (200 kW): $3.3x10^8$ UCN/s

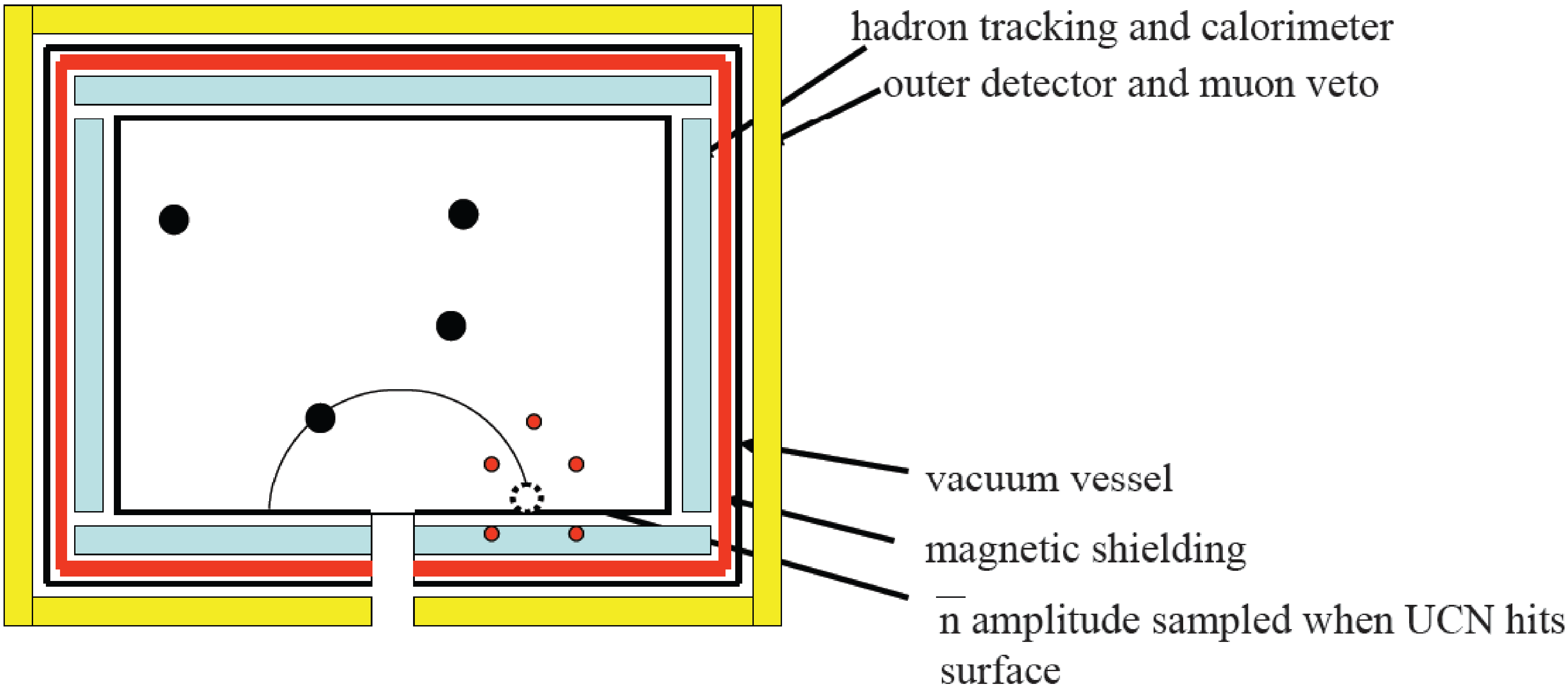
UCN storage NNbar expt.



Spallation neutrons are produced in 4π but used for ucn conversion only in a small fraction of a solid angle.
In best A. Young's (NCSU) scenario with a dedicated 1.9K, 200 kW source: 3.3×10^8 ucn/s can be made available in the transport tube.

Albert Young/NCSU

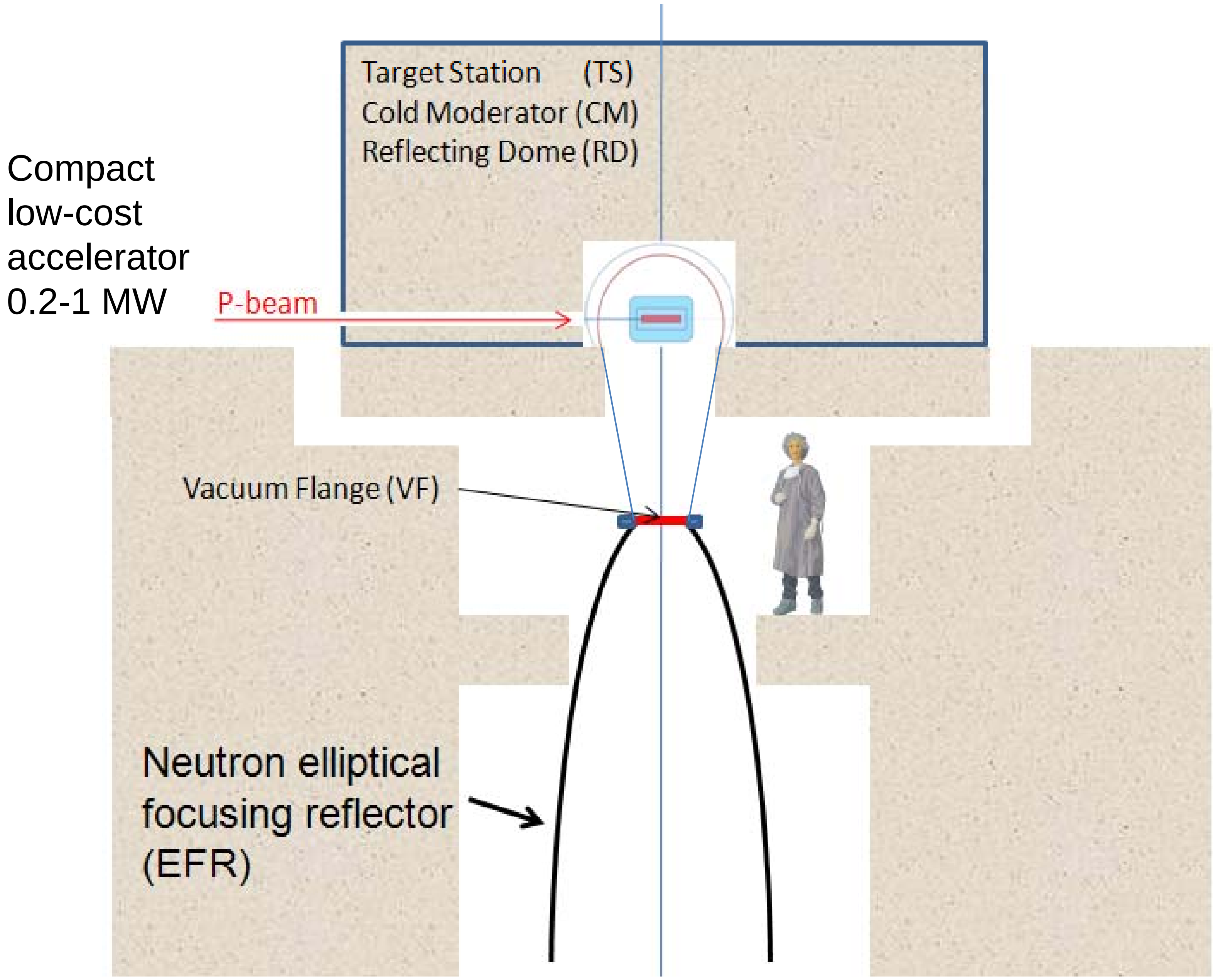
NNbar with UCN



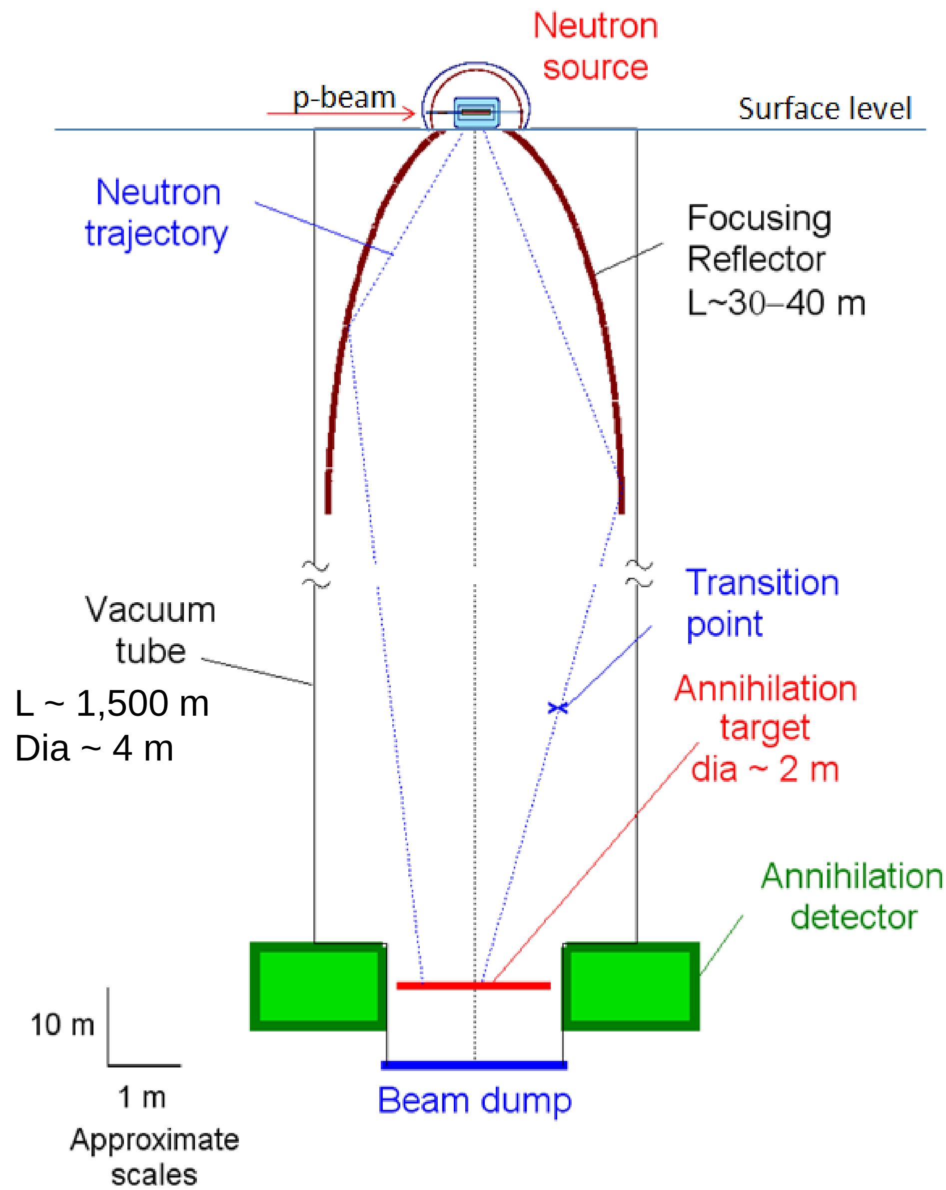
Box filled with UCN gas…many samples/neutron
longer average flight times (~1/3 sec)
large neutron current required

Albert Young/NCSU

Scheme of Vertical Experiment with Spallation Source

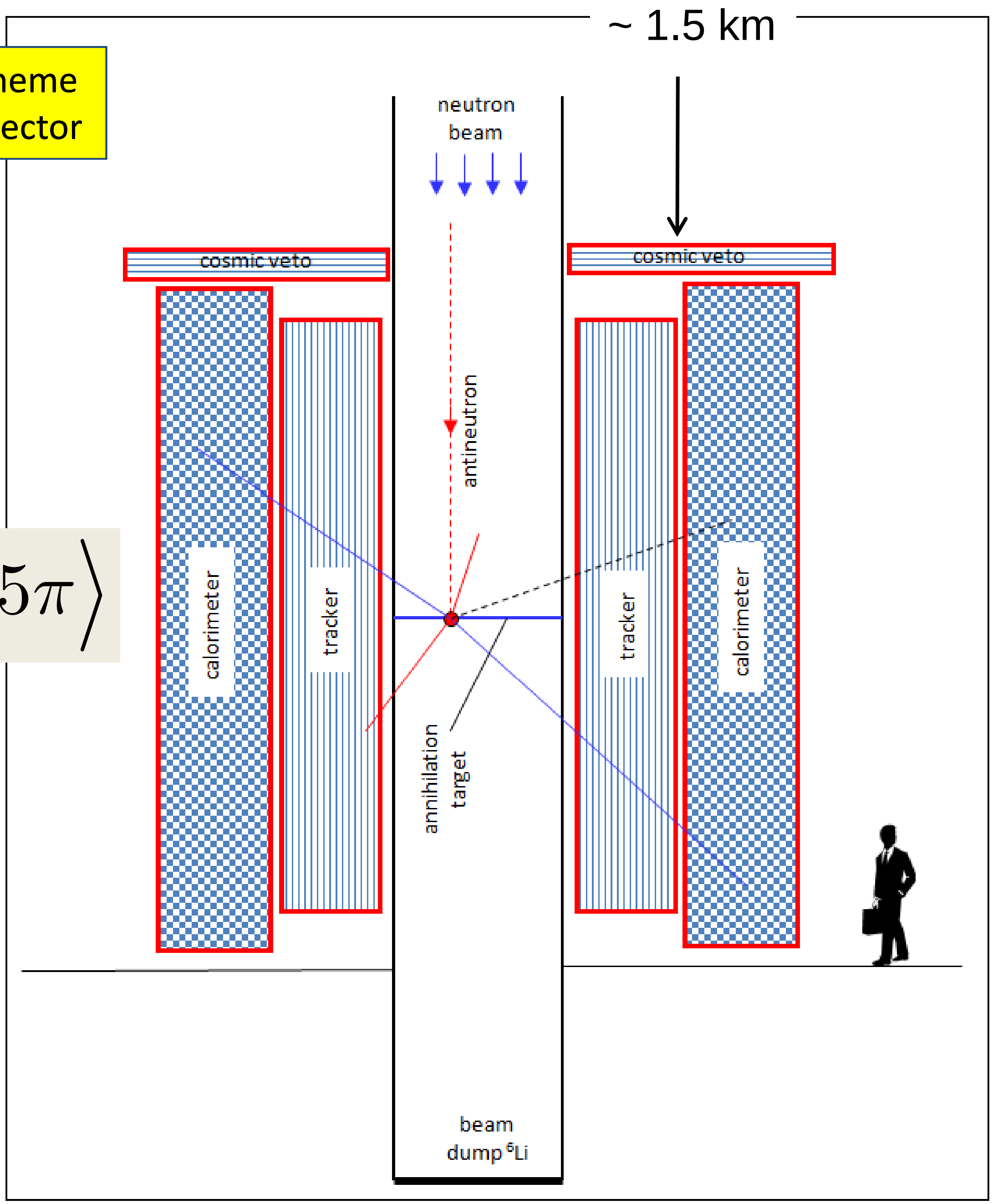


Schematic view of the vertical NNbar experiment at DUSEL with spallation neutron source provided by dedicated high-current accelerator, e.g. by a CW cyclotron 0.2 – 1 MW advocated by DAEδALUS Collaboration



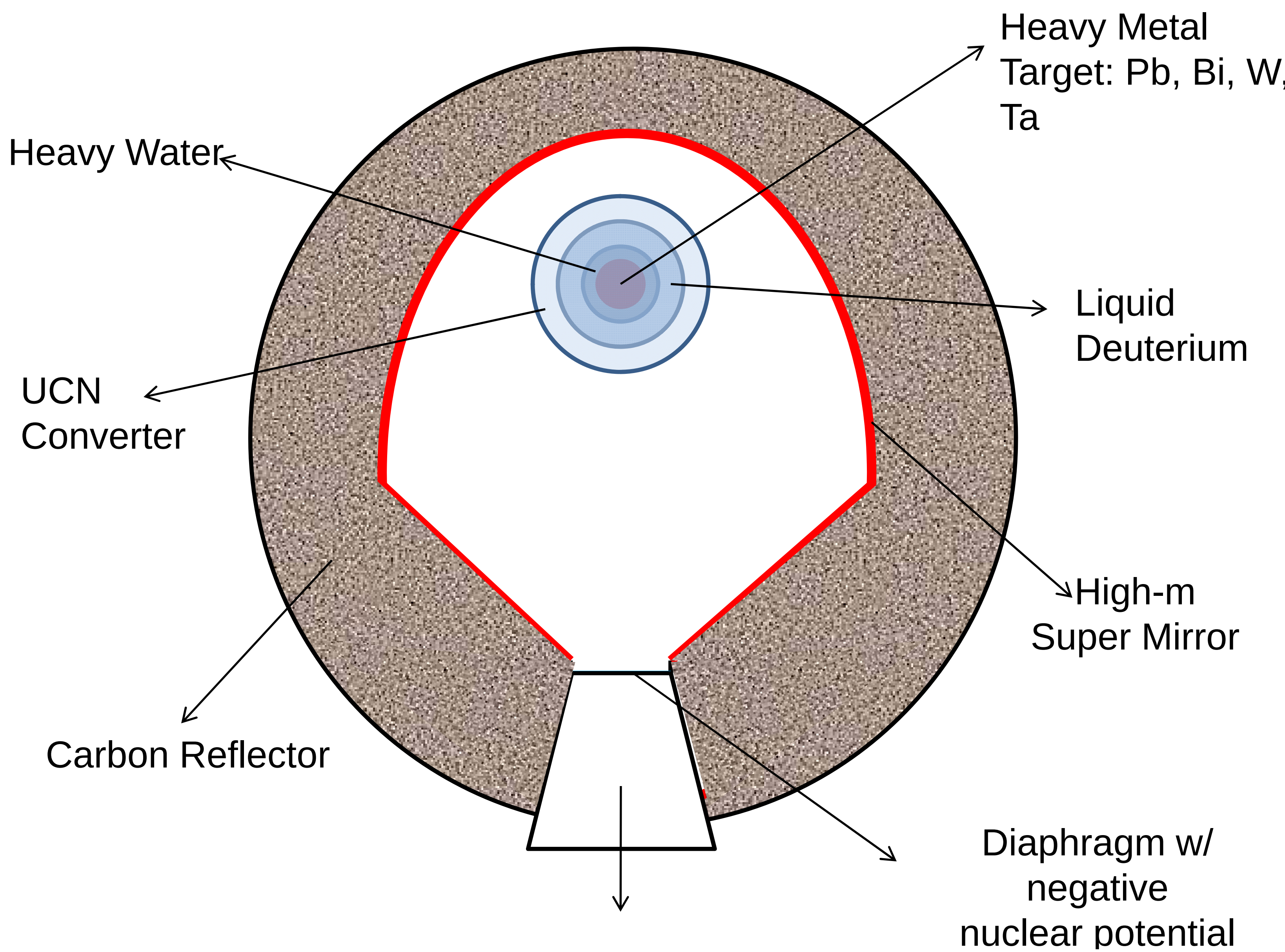
The conceptual scheme of antineutron detector

$$\overline{n} + C \rightarrow \langle 5\pi \rangle$$



Schematic of New spallation target with UCN converter

(view along the beam)



Advantage of UCN target for NNbar

Use definition of UCN as $v < 7m / s$

In vertical motion $\Delta h = v_0 t + \frac{gt^2}{2}$

Cold neutrons with $v_0 \simeq 700$ m/s

will fly vertical 1 km for time 1.4 s (DUSEL);

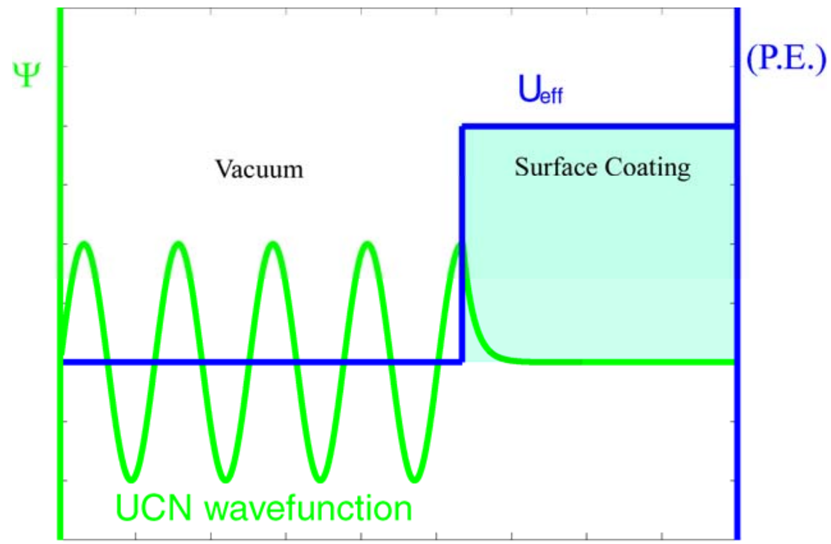
UCN with v_0=0 -10 m/s for ~ 14 s

50 m/s ~ 10 s

$$P_{n\bar{n}} \propto \Phi_n(v) \cdot d\Omega \cdot \varepsilon(v) \cdot \left(\frac{L}{v}\right)^2 = N_n \cdot (t)^2$$

Gain of $(10)^2$ in sensitivity per neutron is possible!

Neutron reflection

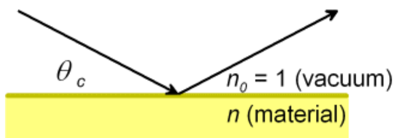


Case where $E < U_{eff}$

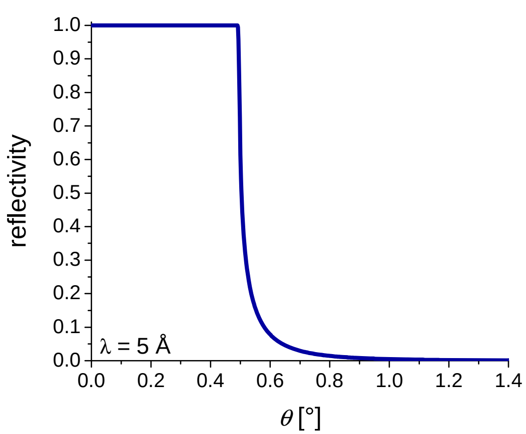
concept of neutron super-mirrors

neutron reflection at grazing incidence (< ≈2°)

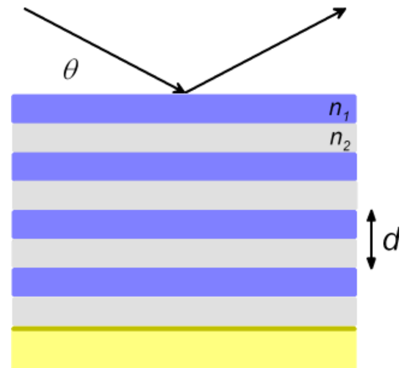
@ smooth surfaces



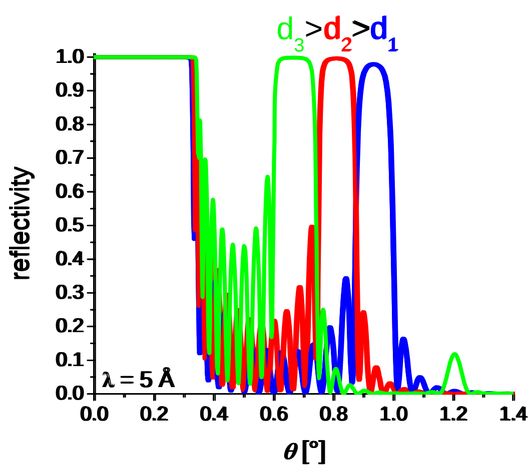
- refractive index $n < 1$
- total external reflection
  e.g. Ni $\theta_c = 0.1$ °/Å



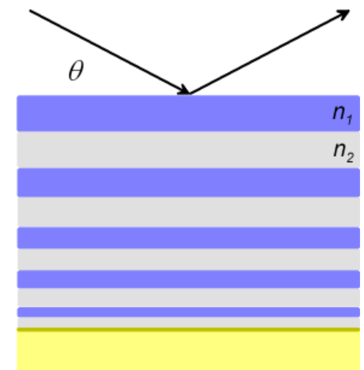
@ multilayer

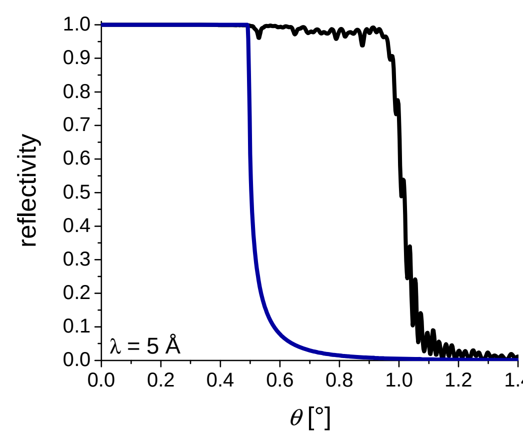


$$\lambda = 2d\sin\theta$$

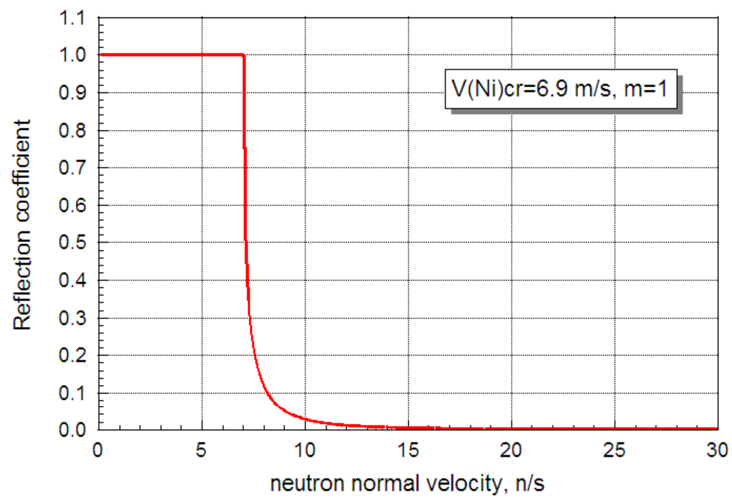


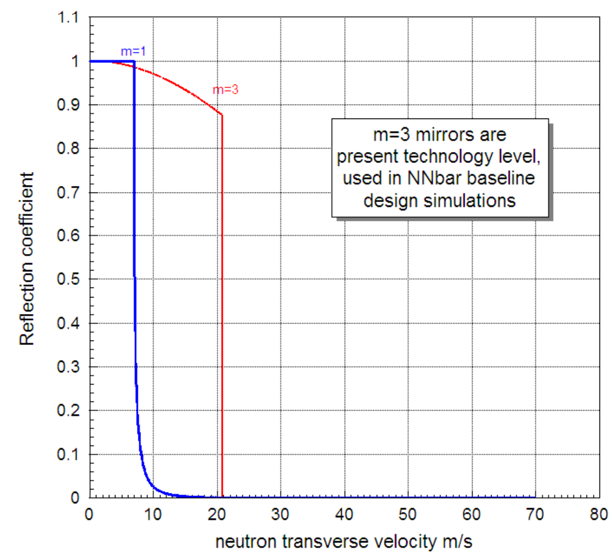
@ supermirror



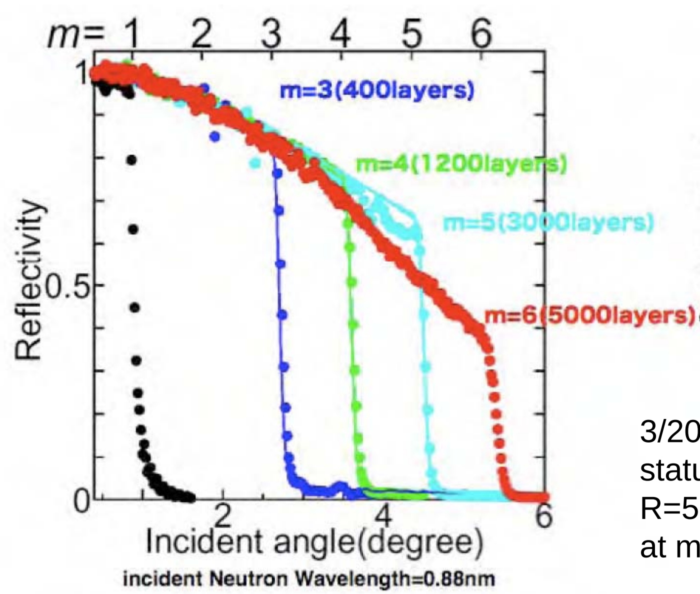


Development of high-m neutron reflectors



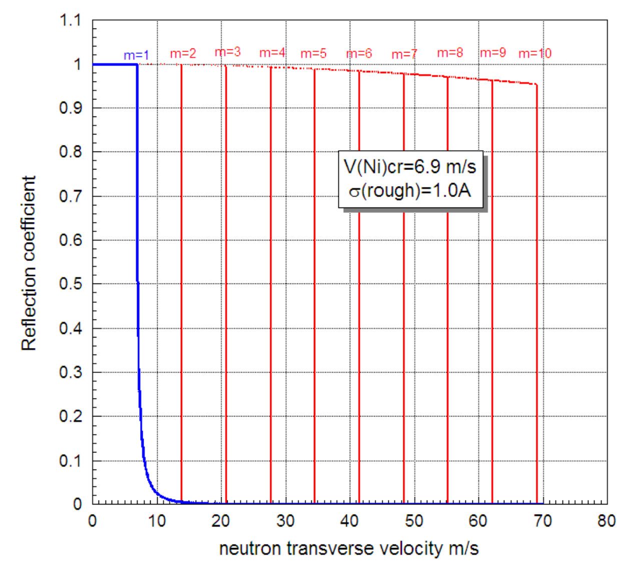


H. Shimizu, KEK/Japan

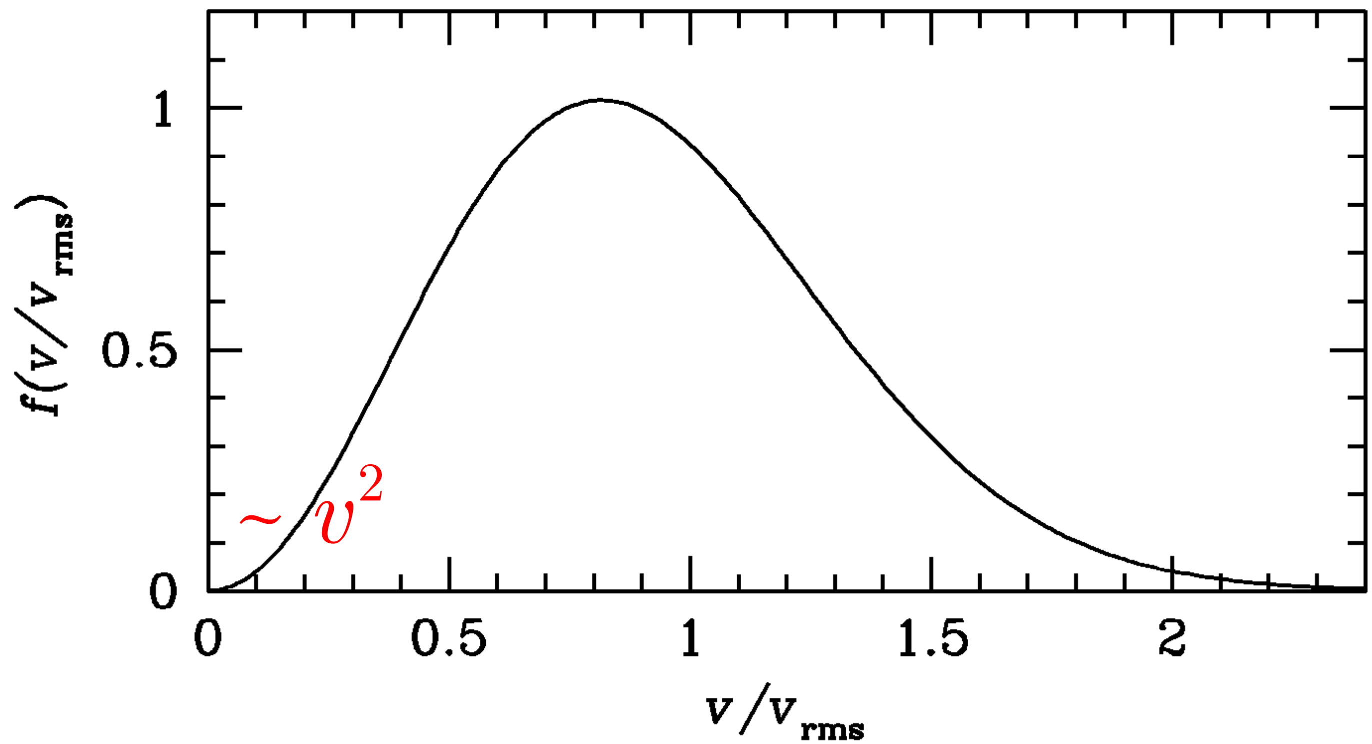


M.Hino et al., Nucl. Instrum. Methods A529 (2004) 54

3/2011 status R=50% at m=10



Economically possible in future



$$N_n \propto \int_0^{v_{max}} v^2 dv \quad \rightarrow \quad \text{perfect } m = 10 \text{ reflection}$$

might yield $\times 1000$ more neutrons.

For non-perfect mirrors and captures in the system the yield can be smaller, hopefully leaving gain factor of 10 -100.

UCN gain factors (in number of neutrons):
$\times$ 10 from production solid angle;
$\times$ 10-100 from super-mirror reflections;
$\times$ 0.1 from focusing reflector acceptance
+ cold neutrons

Total possible factor ~ 100 of ucn production enhancement
3×10^8 ucn/s $\rightarrow 3\times10^{10}$ ucn/s

N-Nbar sensitivity

	HFIR	DUSEL	X/UCN	NANO/UCN
P, MW	85	3.5	0.2	0.2
Layout	horizontal	vertical	vertical	vertical
Distance, m	300	1,000	100	1,000
N [n/s]	8.5×10^{12}	3×10^{11}	3×10^{10}	3×10^{10}
t^2 [s^2]	0.073	2	~10	~182
Nt^2	6.2×10^{11}	6×10^{11}	3×10^{11}	5.5×10^{12}
In ILL units	$\times$400	$\times$400	$\times$200	$\times$4000

How reliable are these estimates one can find only with R&D

"Cold neutron spallation target collaboration":

UT Physics: Geoff Greene, Tom Handler, Yuri Kamyshkov;
UT NE: Larry Townsend, Larry Heilbronn, Art Ruggles;
ORNL/SNS: Tony Gabriel, Phil Ferguson;
Students: Chris Tate, Davis Cooper

+ A. Young (NCSU), M. Snow (Indiana), H. Shimizu (KEK),
VECC and PRL (India)
VECC = Variable Energy Cyclotron Centre in Kolkata
PRL = Physics Research Laboratory in Ahmedabad

Plan: to collaborate with FNAL in the cold target development for project X; as a first step write R&D Proposal to DOE and/or NSF for funding of the conceptual design of cold spallation target

UCN Spallation Target R&D goals

(FNAL + Cold Target Collaboration)

- Determine maximum power to withstand (hopefully > 0.2 MW)
- Optimize configuration and layout
- Determine cold flux and vector velocity spectrum
- Provide model for sensitivity simulations
- Find approximate cost
- Study staging options

❑ Besides Project X this study can be useful for SNS Target-II design

❑ Some parts of technology development and training can be used in ADS

Growing up Collaboration with India

- Intellectual theoretical contribution: R. Mohapatra, J. Pati, K. Babu, R. Cowsik …
- Existing Site: cliff of Mt. Abu (PRL site)
- NANO Collaboration is being formed between India-US-Japan.
- Construction of the cyclotron can be hopefully funded by DAE-VECC

  ~ 1 MW, ~0.8 GeV, CW within Indian road-map for ADSR
- MW Cyclotron R&D with DAEδDALUS Collaboration provides the scheme
- First meeting of NANO Collaboration at VECC in Kolkata July 20-22

  (FNAL is invited)

Indian Accelerator Program Driven by ADSR

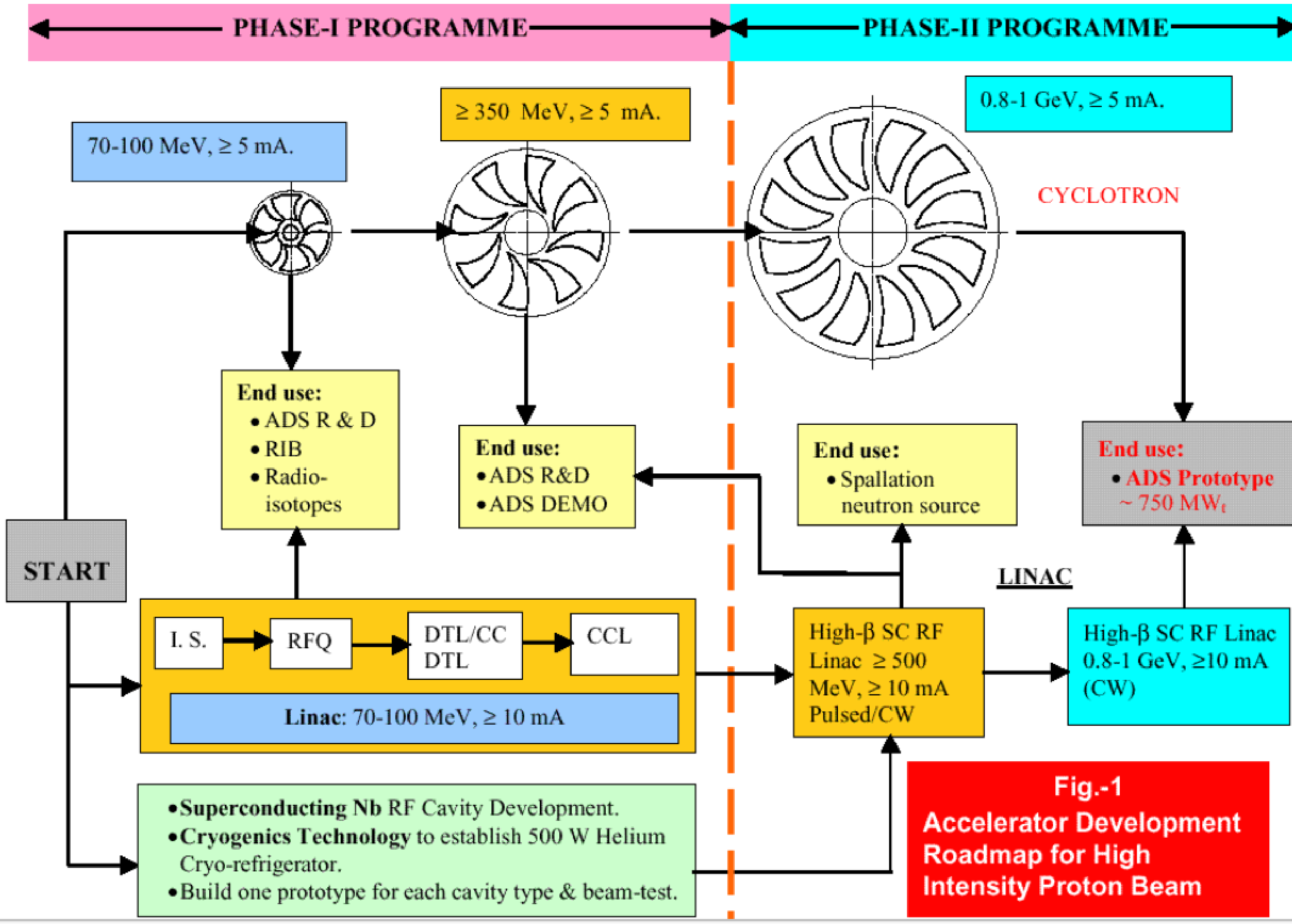


Fig.-1
Accelerator Development Roadmap for High Intensity Proton Beam

NANO N-Nbar search experiment

In India can be viewed

- ✓ Possibility of a major scientific discovery
- ✓ Observation of matter to antimatter transformation
- ✓ Discovery of a new Force on Nature
- ✓ Large scientific impact on particle physics and cosmology
- ✓ Science and technology benefits even for “no discovery”
- ✓ Presently no competition with other groups/countries
- ✓ Unique facility in India (Mt. Abu)
- ✓ Synergy with Th ADSR research and accelerator apps

Vision of Future Physics Experiments

(assuming Cold Spallation target is available)

1. $n \longrightarrow n'$ vertical experiment using e.g. existing MINOS 350-ft shaft; pulsed operation; will probably require less average power and will be less expensive. $\rightarrow$ Discovery of or search for mirror transformations; finding possible nature of dark matter; precision measurement of mirror magnetic field.

2. $n \longrightarrow \overline{n}$ search vertical experiment in the same vertical shaft CW or pulsed operation with max available flux, probably will require different optimization of Cold Target/Experiment layout. For 3 years of target operation search sensitivity can be improved by $\times$30 from present best limit (for bound neutrons).

3. Ultimate sensitivity $n \longrightarrow \overline{n}$ search in a large vertical shaft in 1.5-km shaft at DUSEL (??) or in 1.2-km in NANO. Use same cold target design with accelerator provided either by Linac technology or by compact Cyclotron developments advocated by DAEδALUS, both hopefully being developed for ADS