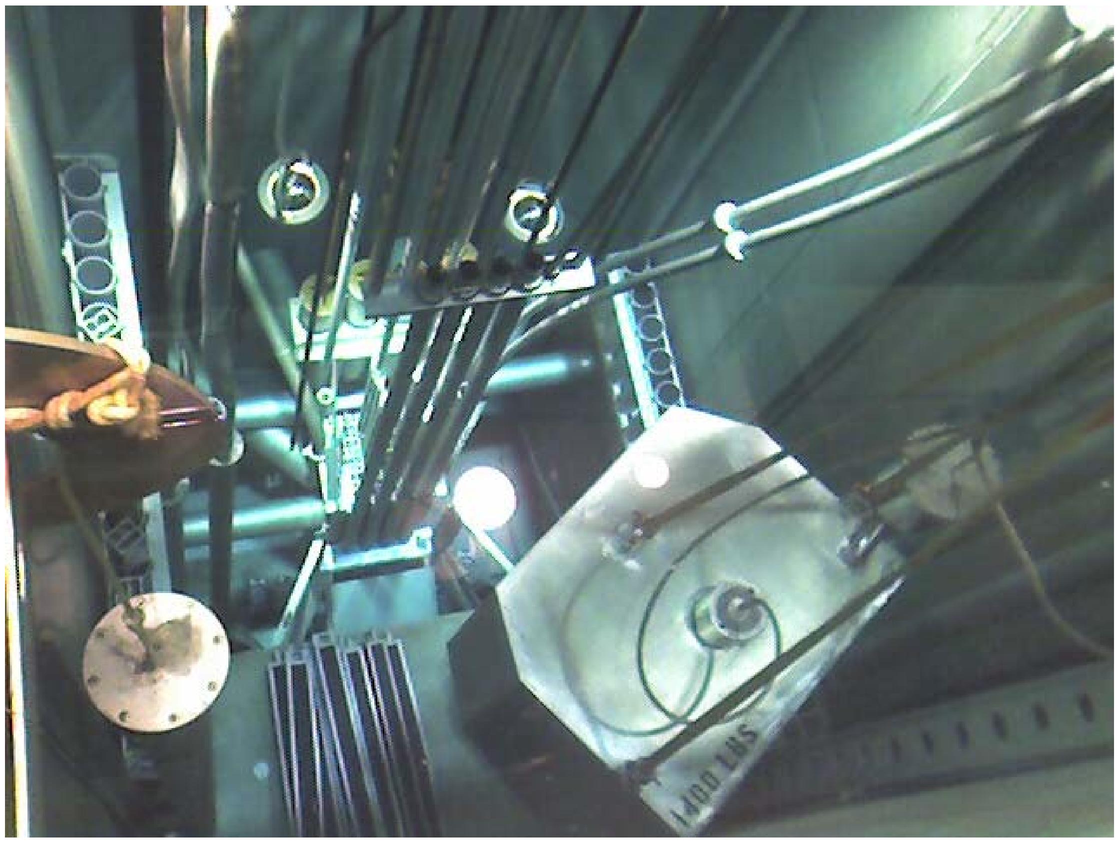
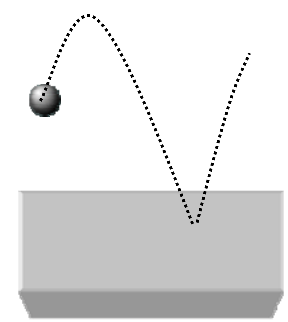
NNbar Experiments using UCN





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n→nbar transition probability (for given α) for free neutrons

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

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

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

In ideal situation of the "vacuum oscillations" $V = 0$ and $\Delta m = 0$

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

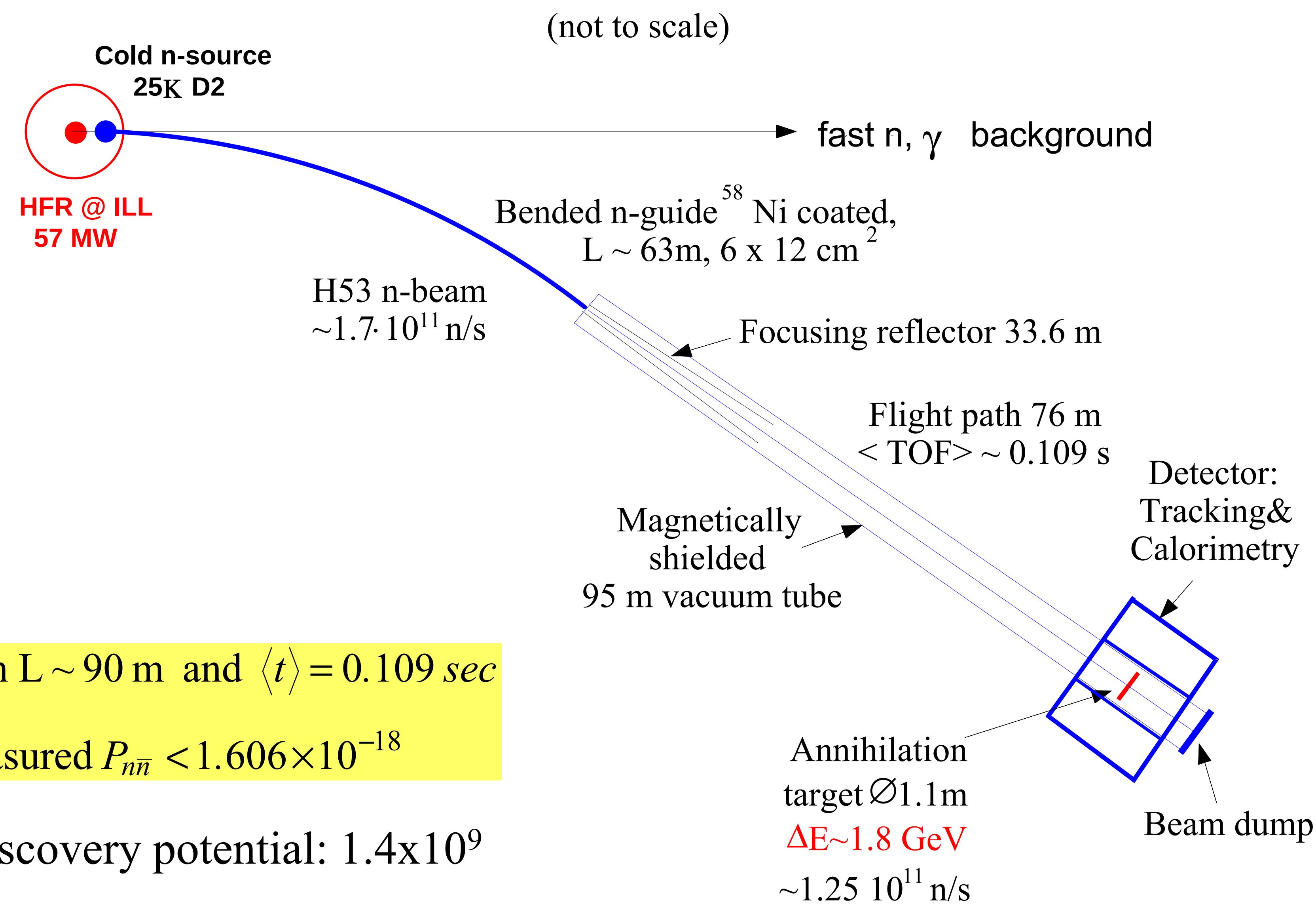
$\tau_{n\bar{n}} = \frac{\hbar}{\alpha}$ is characteristic transition (oscillation) time $[\alpha < 10^{-23} eV]$

$$\text{"Sensitivity"} \propto N_n \cdot \langle t^2 \rangle$$ = "discovery potential"

(N_n number of neutrons sampled, t^2 square of flight time)

Experiment with free neutrons

Best reactor measurement at ILL/Grenoble reactor in 89-91 by Heidelberg-ILL-Padova-Pavia Collaboration



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

measured $P_{n\bar{n}} < 1.606 \times 10^{-18}$

discovery potential: $1.4\mathrm{x}10^{9}$

PDG 2004:
Limits for both
free reactor neutrons and
neutrons bound inside nucleus

Bound n: J. Chung et al., (Soudan II)
Phys. Rev. D 66 (2002) 032004 $> 7.2 \cdot 10^{31}$ years

Free n: M. Baldo-Ceolin et al.,
(ILL/Grenoble) *Z. Phys* **C63** (1994) 409
with $P = (t/\tau_{free})^2$

$$\tau_{bound} = R \cdot \tau_{free}^2$$

$$\text{where } R \sim 10^{23}\, s^{-1}$$

R is "nuclear suppression factor"
Uncertainty of *R* from nuclear
models is ~ factor of 2

LIMIT ON $n\bar{n}$ OSCILLATIONS

Mean Time for $n\bar{n}$ Transition in Vacuum

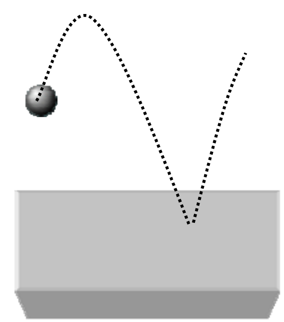
A test of $\Delta B=2$ baryon number nonconservation. MOHAPATRA 80 and MOHAPATRA 89 discuss the theoretical motivations for looking for $n\bar{n}$ oscillations. DOVER 83 and DOVER 85 give phenomenological analyses. The best limits come from looking for the decay of neutrons bound in nuclei. However, these analyses require model-dependent corrections for nuclear effects. See KABIR 83, DOVER 89, ALBERICO 91, and GAL 00 for discussions. Direct searches for $n \to \bar{n}$ transitions using reactor neutrons are cleaner but give somewhat poorer limits. We include limits for both free and bound neutrons in the Summary Table.

VALUE (s)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>1.3 × 10^8	90	CHUNG	02B	SOU2	*n* bound in iron
>8.6 × 10^7	90	BALDO-...	94	CNTR	Reactor (free) neutrons
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>1 × 10^7	90	BALDO-...	90	CNTR	See BALDO-CEOLIN 94
>1.2 × 10^8	90	BERGER	90	FREJ	*n* bound in iron
>4.9 × 10^5	90	BRESSI	90	CNTR	Reactor neutrons
>4.7 × 10^5	90	BRESSI	89	CNTR	See BRESSI 90
>1.2 × 10^8	90	TAKITA	86	CNTR	*n* bound in oxygen
>1 × 10^6	90	FIDECARO	85	CNTR	Reactor neutrons
>8.8 × 10^7	90	PARK	85B	CNTR	
>3 × 10^7		BATTISTONI	84	NUSX	
> 2.7 × 10^7–1.1 × 10^8		JONES	84	CNTR	
>2 × 10^7		CHERRY	83	CNTR	

Search with free neutrons is far
more efficient than with bound neutrons

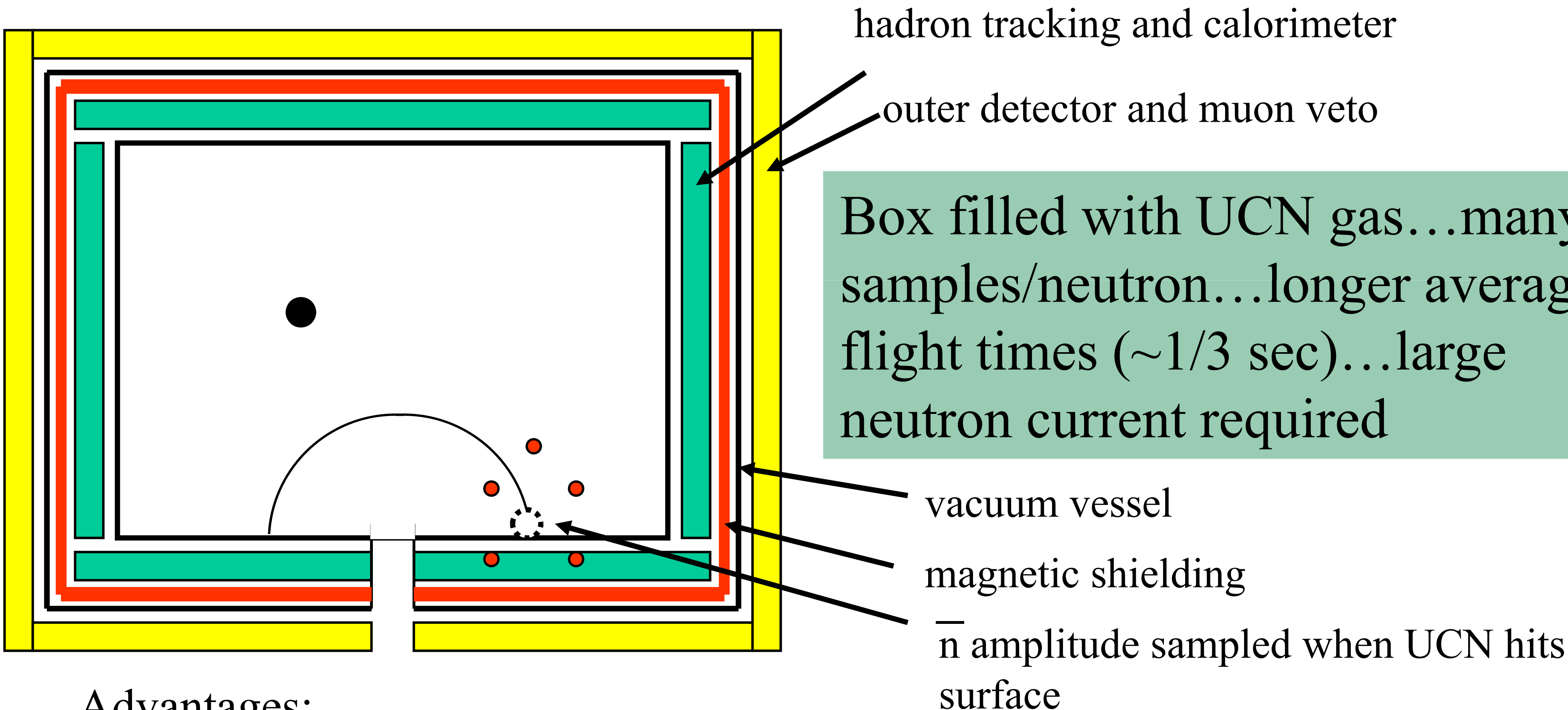
What are Ultracold Neutrons?

- UCN : K.E. < $V_{Fermi} \leq 340$ neV
  reflect, for any angle of incidence, from some material surfaces→can be stored for times comparable to the β-decay lifetime in material bottles!



- Materials with high V_{Fermi} :
  Diamond like carbon → $V_F \leq 300$ neV
  ^{58}Ni →$V_F \leq 340$ neV

NNbar with UCN: pros and cons



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

Advantages:

- No beamline required: more compact
- Sources soon available: less expensive
- Same ability to turn "on" and "off" effect w/magnetic field

Disadvantages:

- Limits less stringent than those obtained with CN beam geometry

Possible sources (large UCN currents)

- ILL (world's strongest source at present) $3x10^6$ UCN/s at present with 8cm x 16cm guide – single purpose mode
- **Potentially competitive SD_2 sources**:
  - PULSTAR w/ 3.5 MW upgrade: $4x10^7$ UCN/s (in SD_2); begin test operation at 1 MW in 2008
  - PSI (pulsed): $5x10^9$ in close-coupled storage volume, every 4 to 8 minutes; begin test operation in Oct., 2008
  - FRM II: (?) huge CN flux; begin operation roughly 2012 (project funded 2007)
- **LHe superthermal sources** (see talk of Masuda)

Extraction efficiency from SD_2 and limiting UCN population in experiment?

The Collaboration

- NCState Physics Department:

  R. Golub, P. Huffman, A. R. Young and graduate students, C. Cottrell, G. R. Palmquist, Y.-P. Xu

- NCState Nuclear Engineering Department:

  B. W. Wehring, A. Hawari, E. Korobkina

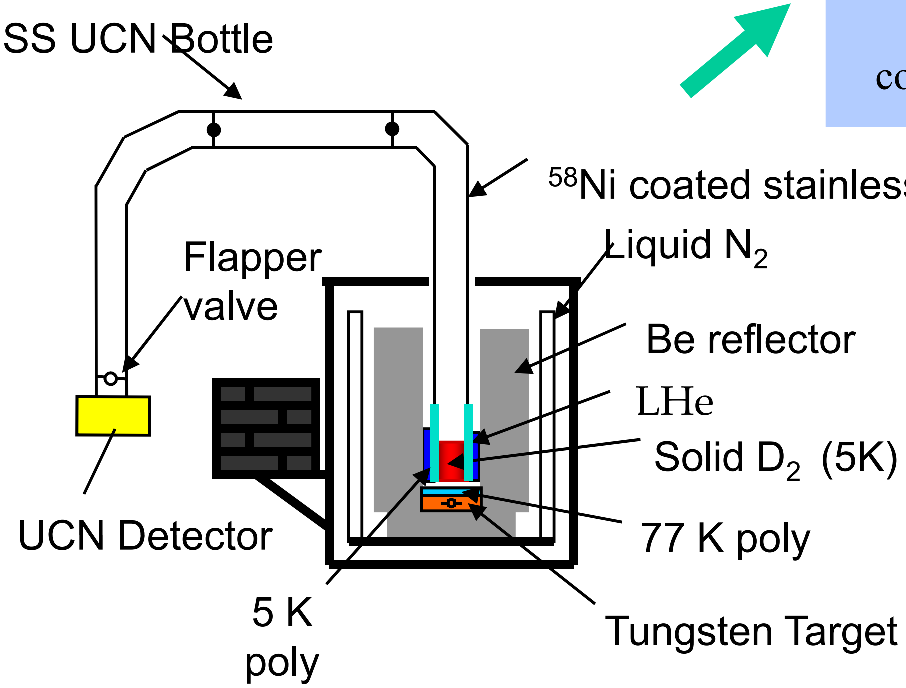
- PULSTAR technical staff

  A. Cook, K. Kincaid, G. Wicks

Local research groups with overlapping interests:

- H. Gao
- T. Clegg (weak interactions res.)

Key UCNA Prototype Results



τ_{para} = 1.2 ± .14 (stat) ± .20 (syst) ms

C. L. Morris *et al.*, Phys. Rev. Lett. **89**, 272501 (2002)

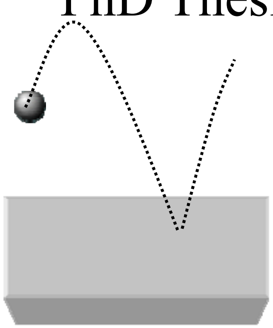
confirmed: F. Atchison et al., Phys. Rev. Lett. **95**, 182502 (2005)

$\rho_{UCN} \rightarrow 145 \pm 7$ UCN/cm^3

A. Saunders *et al*., Phys. Lett. B **593**, 55 (2004)

confirmed: F. Atchison et al., Phys. Rev. C. **71**, 054601 (2005)

PhD Thesis: Chen-Yu Liu

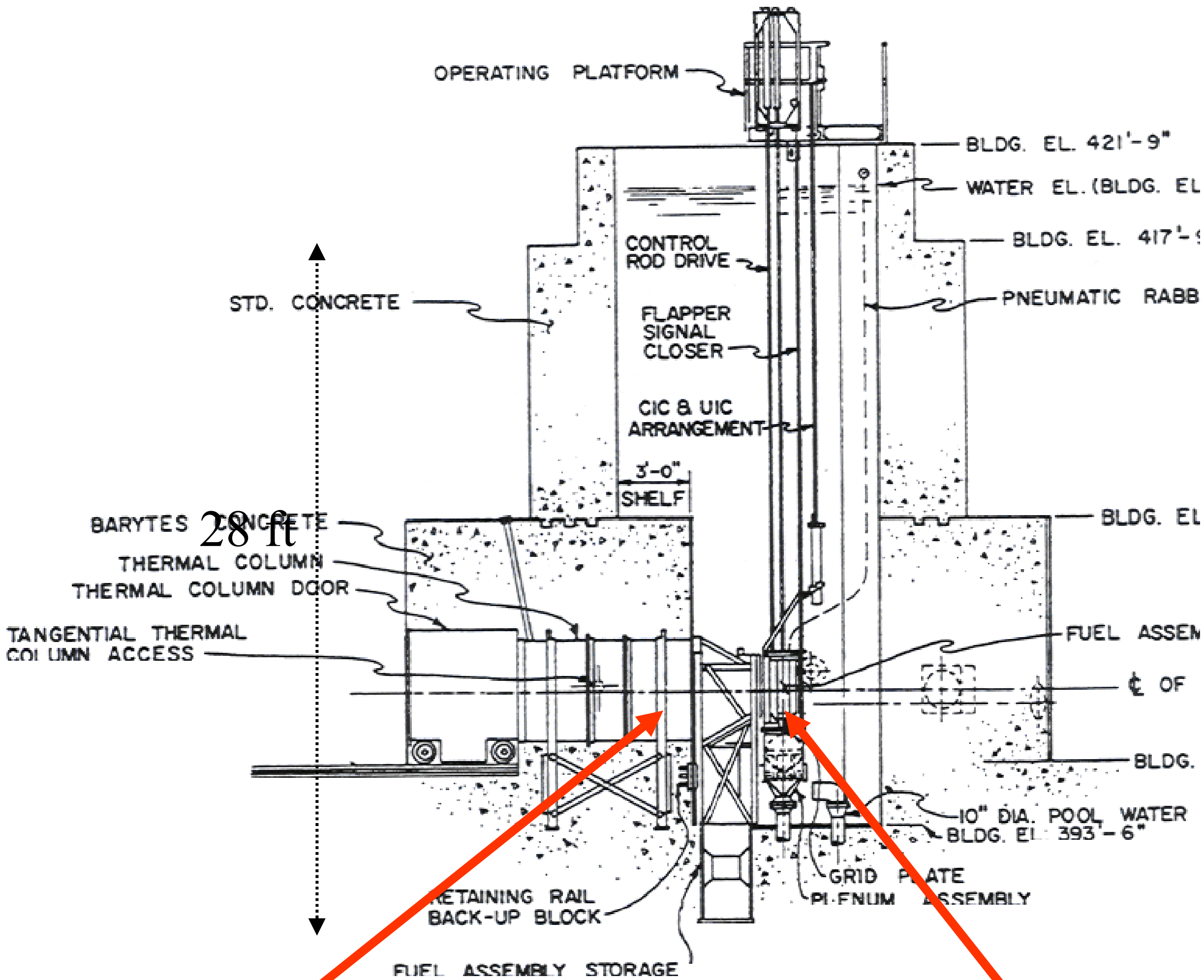


Diamondlike Carbon Films

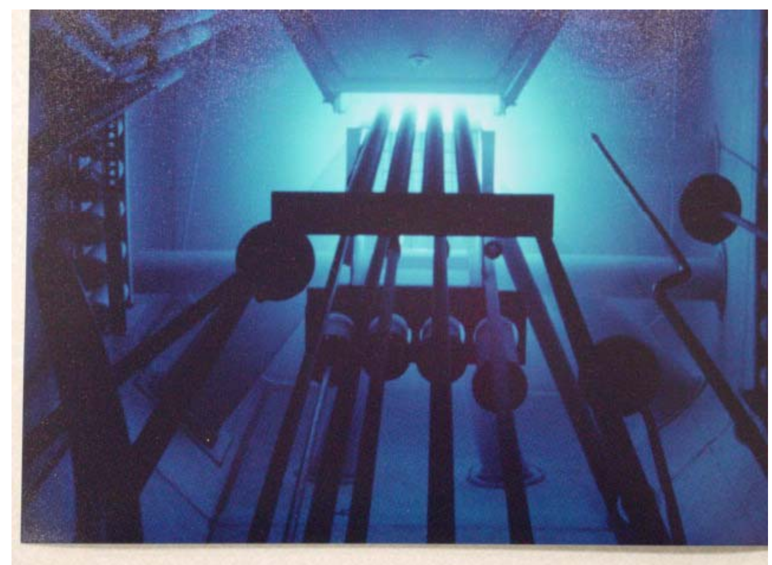
300 neV > V_{fermi} > 270 neV, specularity > 99%, lpb < 10^{-4}

PhD Thesis: Mark Makela

NCSU PULSTAR Reactor



- Sintered UO_2 pellets
- 4% enriched
- 1-MW power
- Light water moderated and cooled
- Just 1997 issued a new license for about 2017 years of operation



Source located in thermal column (outside reactor proper)

Core

Licensing and operation

Not a "power reactor"!

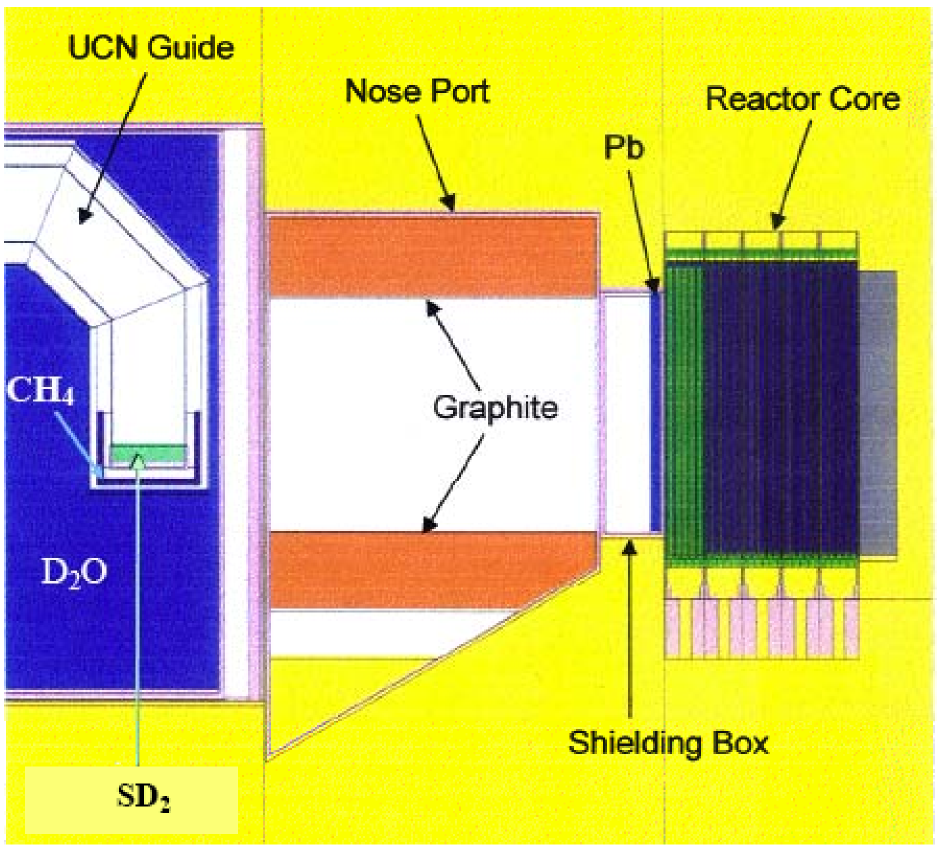
- University-owned reactors licensed by NRC
- NRC Policy – The 1954 Atomic Energy Act paragraph 104 for non power reactors states "the utilization facilities for research and development should be regulated to the minimum extent consistent with protecting the health and safety of the public and promoting the common defense and security." – this policy working for us!
- Licensing ammendments made by PULSTAR staff: 2-3 person team, reviewed by 2 internal NCSU committees and the NRC – we run safely, but with minimum paperwork…
- Students and staff trained to operate reactor

Straightforward and reasonable in scope!

Desirable Attributes

- Properties
  - Heavy loading of U-235 -- 12.5 kg
  - Low ratio of H to U-235 atoms
  - High ratio of fast to thermal flux in the core
- Benefits
  - Long core lifetime
  - High fast-flux leakage
  - High sensitivity to reflector material

Source Schematic



- Floodable Helium Nose Port
- Heavy Water Thermal Moderator
- ^{58}Ni-coated guides

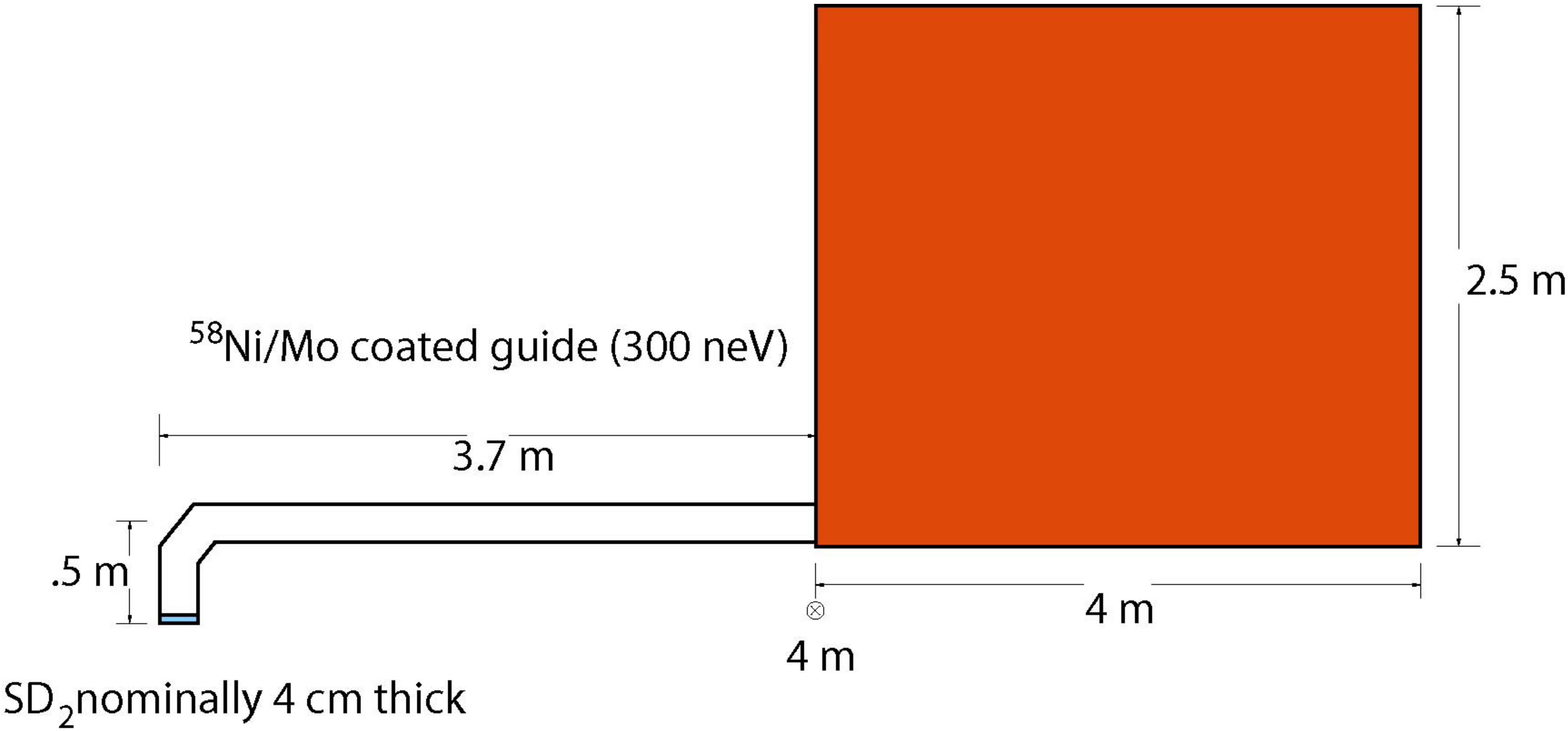
Expected Results at 1 MW

- 5×10^{11} n/cm^2/s CN Flux in D_2 volume
- 0.8×10^4 – 1.5×10^4 n/cm^3/s UCN Production (LANL recent results
- ~250-400 UCN/cm^3 Limiting Density (τ_{SD2}>25 ms)
- >30 UCN/cm^3 Useful Density (~20 at UCN/cm^3 ILL)

For the future:

- **Power upgrade consistent with facility and cryogenics to 3-4 MW**
- Explore other converters (LHe, SO2, ?) and other CN moderators

The geometry:



How do we model transport?

The Monte Carlo

- Runge-Kutta numerical integration
- Gravity, magnetic fields (if needed), and wall reflections
- Non-specular reflections via various models (Gaussian, isotropic and Lambertian—(from Golub, Richardson, Lamoreaux)
- Assume n̄ annihilated on each collision

(Kerbikov, n-n̄ workshop, 2002)

- ~300 neV Fermi potential in box (measured for DLC at SPEAR)
- No vacuum isolation foil between SD_2 and experiment

Preliminary results for base case (annhilation det eff = 1, 1 year running):

NCState geometry, 4 cm thick SD2, 18 cm guides,.050s SD2 lifetime, model storable UCN

Primary flux: 4.0 x 10^7 (below 305 neV) -- 3.5 MW

Box loading efficiency: 30%

325s avg. residency in experiment

Best case: diffuse walls, specular floor

discovery potential = 2.3×10^9 Ns

$\tau_{nn} > 1.1 \times 10^8$ s

Ultimate Reach with PULSTAR

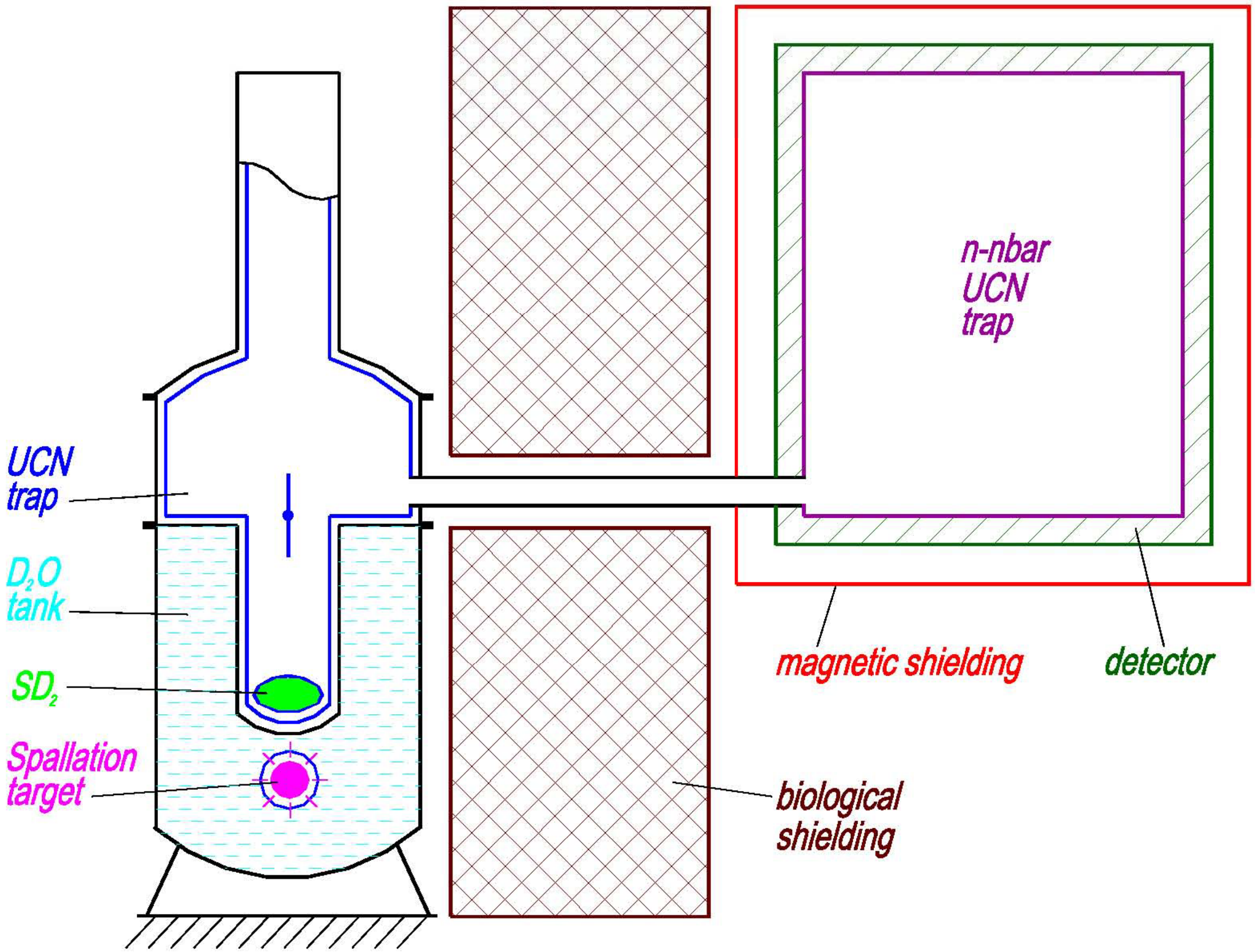
- "straightforward gains"
  - 4 years of running
  - increase source thickness: x1.5

  $\tau_{nn} > 2.7\text{x}10^8$ s

- "speculative gains"
  - 5 liter solid O_2 source, in principle x5 or more

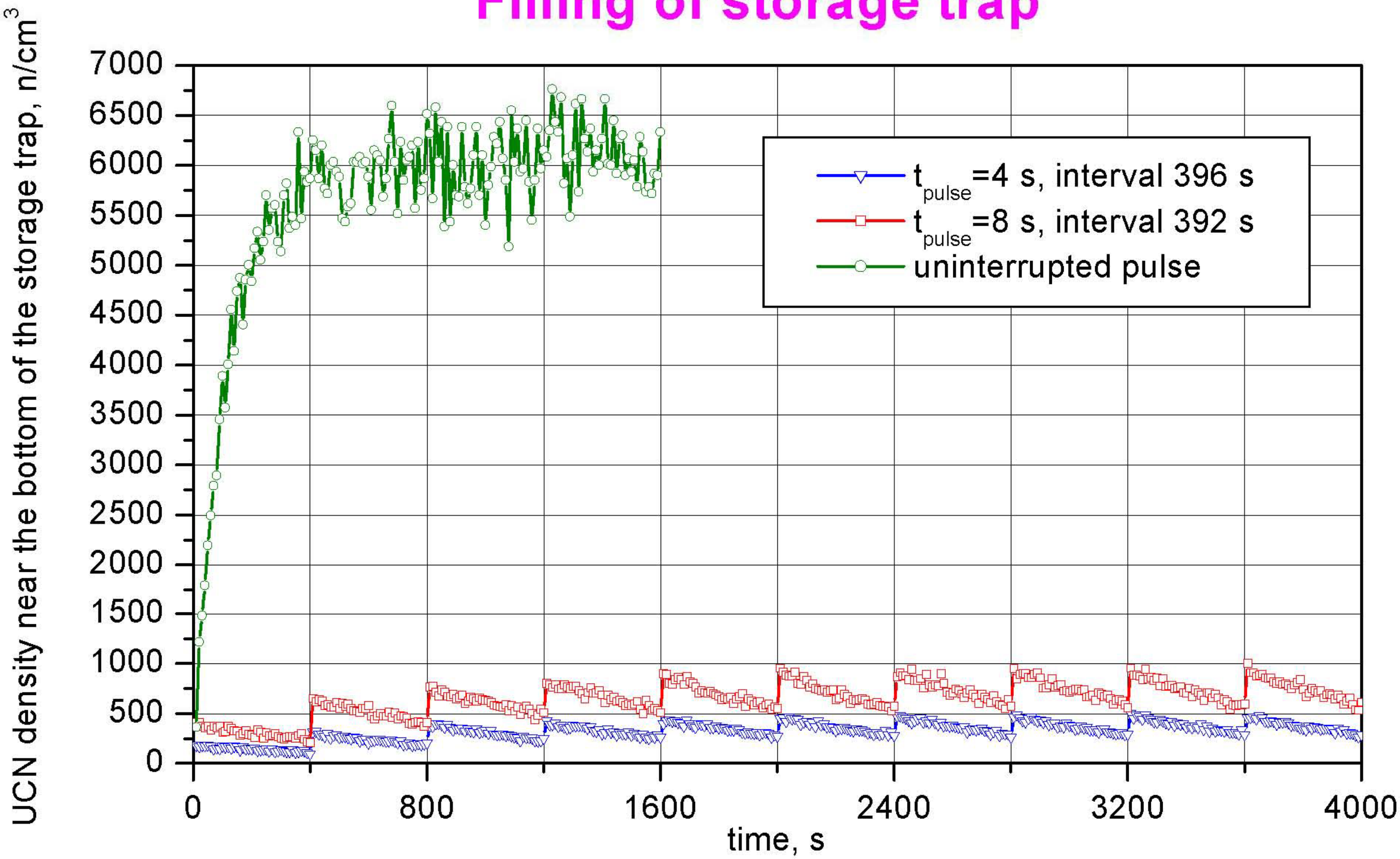
    even larger gains possible, but **current challenge is to grow large transparent crystals** useful for UCN sources, research program of C.-Y. Liu
  - Multiple reflections (x1-4) Serebrov and Fomin & coherent $\bar{n}$ amplitude enhancement x2(?) Golub and Yoshiki

Systematic studies of the PSI UCN source optimized for NNbar by A. Serebrov and V. Fomin

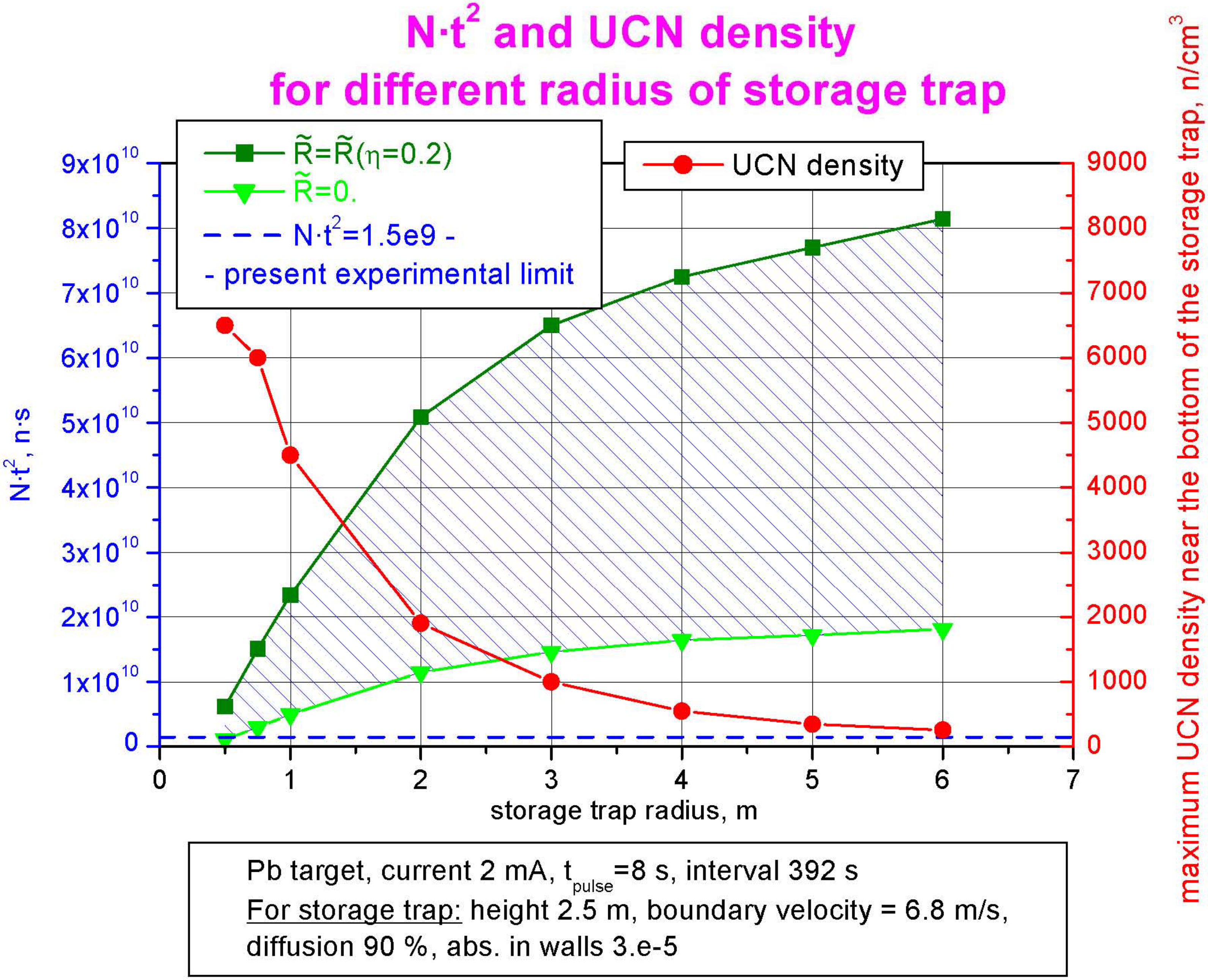


Mode of operation: beam pulsed w/ valve open, then valve closed and UCN stored in system (can, in principle, accumulate)

Filling of storage trap



Pb target, current 2 mA
For storage trap: height 2.5 m, radius 3 m,
boundary velocity = 6.8 m/s, diffusion 90 %, abs. in walls 3.e-5



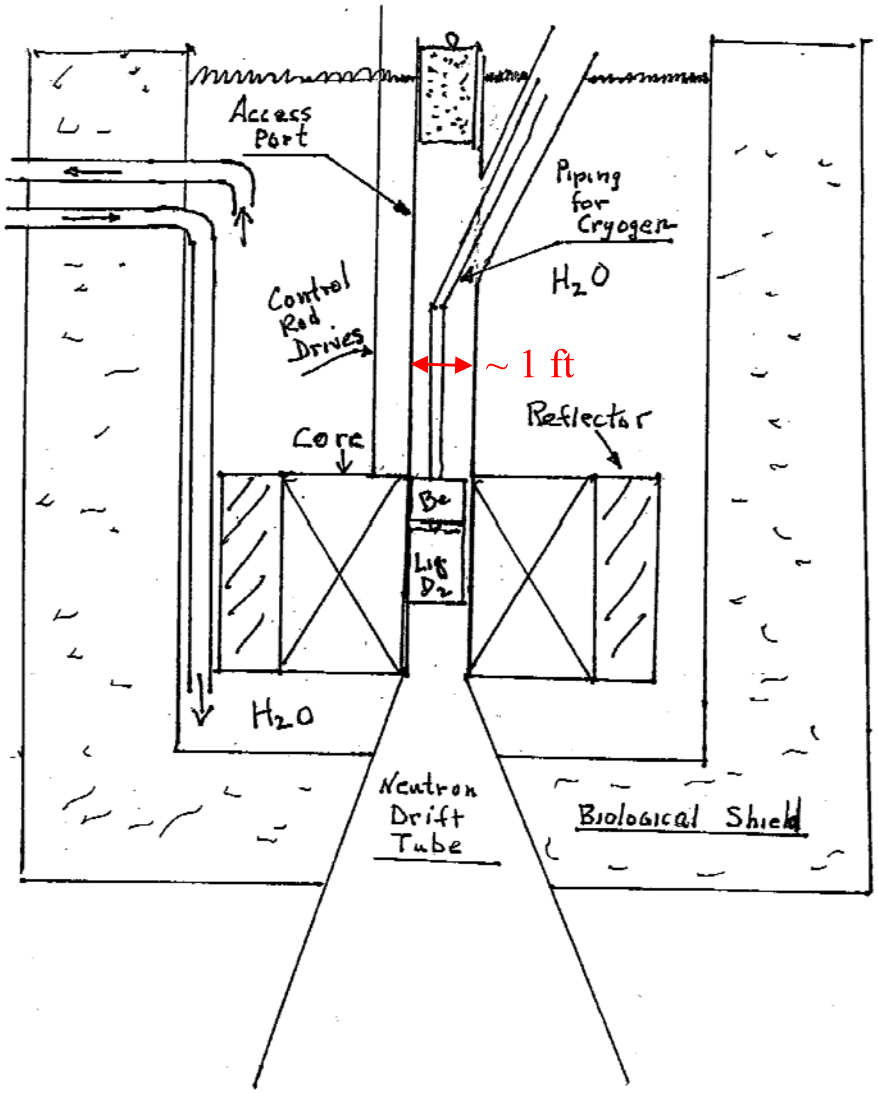
N·t² and UCN density
for different radius of storage trap
R̃=R̃(η=0.2)
R̃=0.
N·t²=1.5e9 -
- present experimental limit
UCN density
N·t², n·s
maximum UCN density near the bottom of the storage trap, n/cm³
storage trap radius, m
9x10¹⁰
8x10¹⁰
7x10¹⁰
6x10¹⁰
5x10¹⁰
4x10¹⁰
3x10¹⁰
2x10¹⁰
1x10¹⁰
0
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
1
2
3
4
5
6
7
Pb target, current 2 mA, t pulse=8 s, interval 392 s
For storage trap: height 2.5 m, boundary velocity = 6.8 m/s,
diffusion 90 %, abs. in walls 3.e-5

Comparison (4y expt)

- PULSTAR (1.0 MW): $\tau_{nn} > 1.3 \times 10^8$ s
- PULSTAR (3.5 MW), optimized: $\tau_{nn} > 2.7 \times 10^8$ s (no "speculative" gains)
- SuperK: $\tau_{nn} > 2.7 \times 10^8$ s
- PSI (accumulation mode): $\tau_{nn} > 6.1 \times 10^8$ s
- FRM II: ?
- Vertical CN beam: $\tau_{nn} > 5 \times 10^9$ s

} p/o ratio ? (PSI, FRM II)

Annular core TRIGA reactor (GA) for N-Nbar search experiment



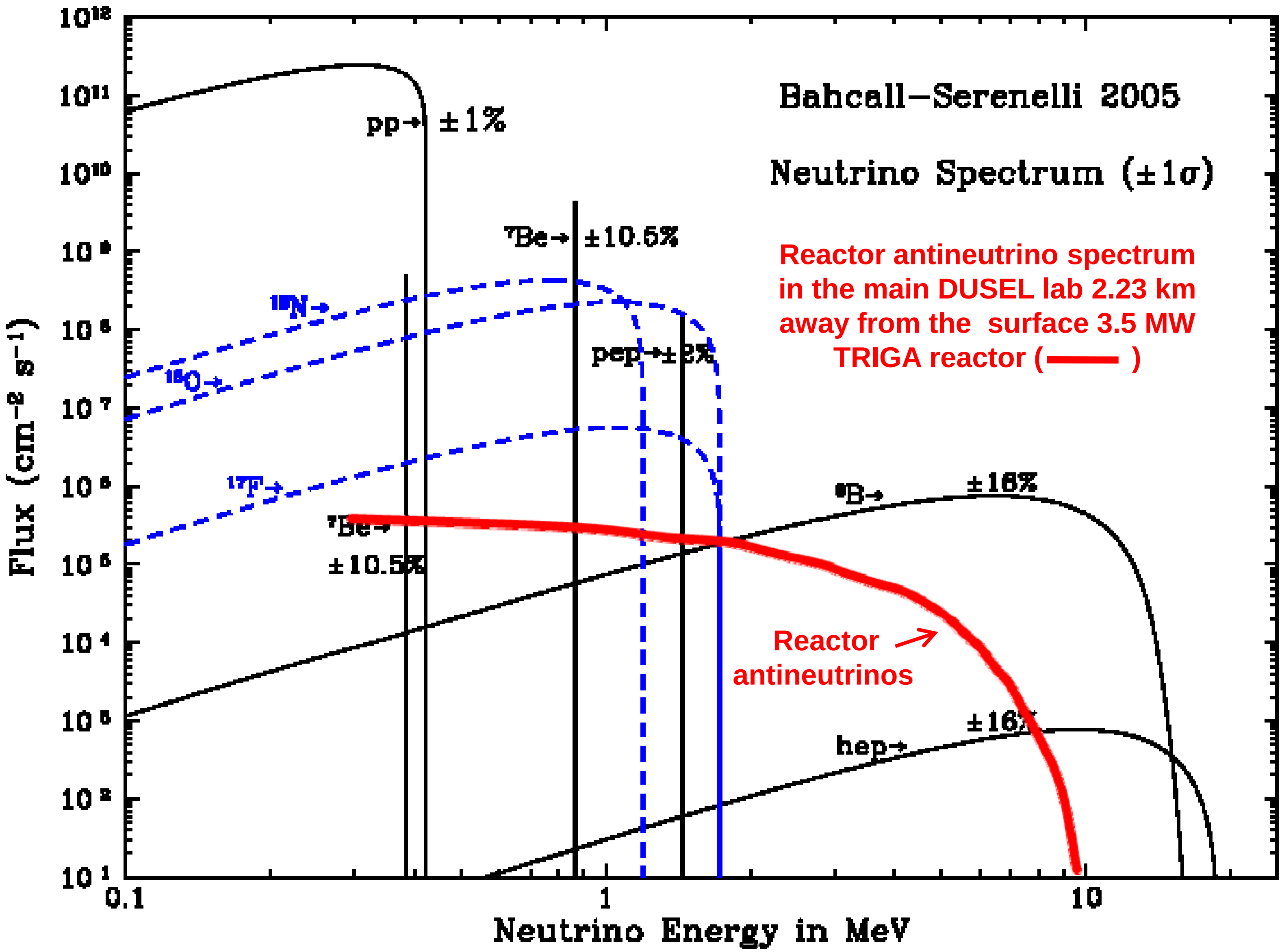
Courtesy of W. Whittemore
(General Atomics)

- GA built ~ 70 TRIGA reactors 0.01÷14 MW (th)
- 19 TRIGA reactors are presently operating in US (last commissioned in 1992)
- 25 TRIGA reactors operating abroad (last commissioned in 2005)
- some have annular core and vertical channel
- most steady, some can be pulsed up to 22 GW
- safe ~ 20% LEU uranium-zirconium hydride fuel
  safe with respect to proliferation issues
  U-ZrH fuel safe from nuclear excursions

<u>Economic solution for n-nbar:</u>
annular core TRIGA reactor 3.4 MW
with convective cooling, vertical channel,
and large cold LD_2 moderator (T_n ~ 35K).
Unperturbed thermal flux in the vertical
channel ~ 2×10^{13} n/cm^2/s

Licensing and Operation of University-Owned TRIGA Reactors

- University campus already planned for SUSEL site
- Many TRIGA reactors already operated by universities
- Reactor owned by university can be licensed and operated in same fashion as PULSTAR reactor! A modest staff and reasonable effort is required to prepare licensing documents and operate such a reactor



Slide prepared by K. Ganezer

Conclusions

- Modest improvements (at least) in the free n-n̄ oscillation time possible with an optimized university reactor-based SD_2 source
- Stronger planned sources could be utilized for significant improvements in sensitivity to n-n̄ oscillations
- The vertical CN source geometry appears to be the most sensitive approach – but still permits experiments to exploit advantages of university-owned reactors!