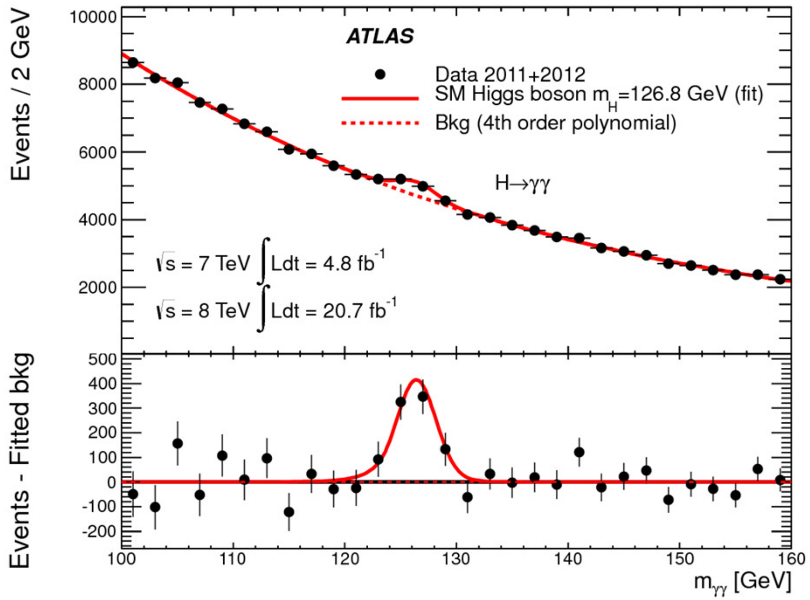
HIBEAM:

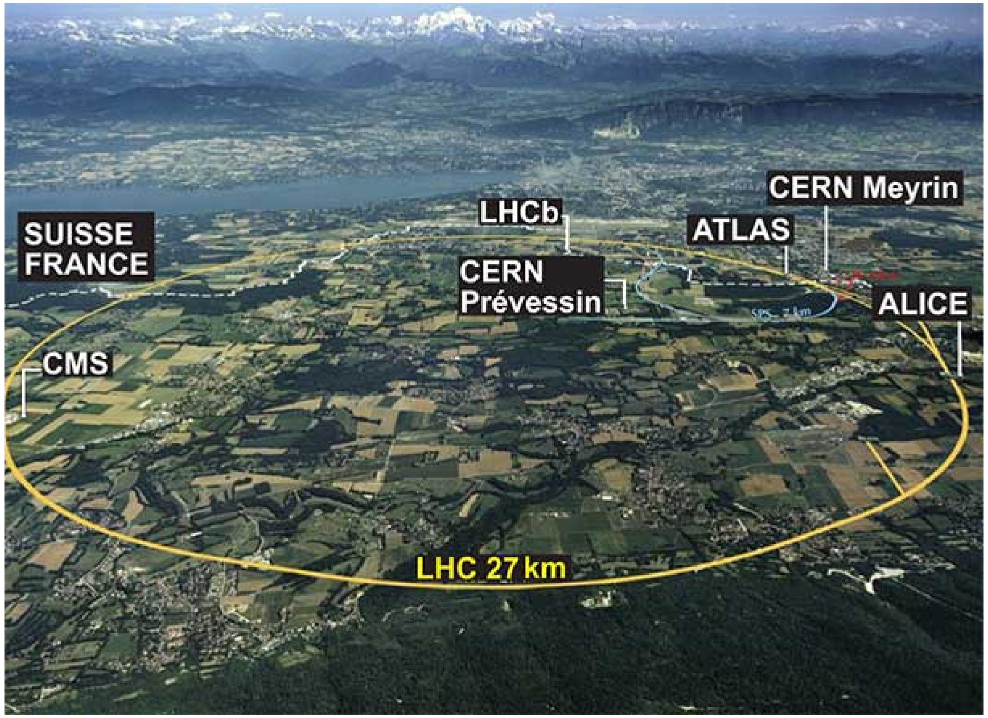
High Intensity Baryon Extraction and Measurement

David Milstead

1. Physics case for HIBEAM
2. HIBEAM
3. Issues and plans

The status of particle physics today





The LHC has observed the Higgs boson and so far confirmed the correctness of the Standard Model.

Many important questions remain unanswered.

HIBEAM could comprise a suite of experiments to address many of these questions.

(1) Baryon number violation

We have never seen a process violate baryon number

(eg $N + N \rightarrow \pi + \pi$, $p \rightarrow e^{+} + \pi^{0}$)

But baryon number is not a "sacred" quantity like electric charge and energy.

Our best theory, the Standard Model, predicts it is rarely violated .

It becomes copiously violated when the Standard Model is extended.

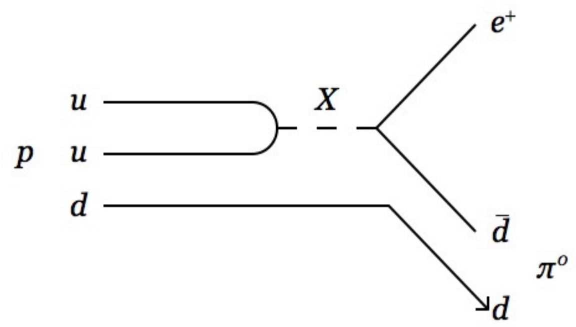
Baryon number violation is needed to explain the matter-antimatter symmetry.

Symbiosis between baryon number and lepton number violation but we must experimentally understand nature's selection rules.

Complementary B, L-violation observables

$\Delta B = \Delta L = 1,$

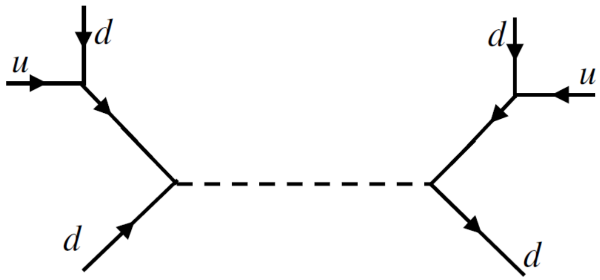
$\Delta(B-L) = 0$



Nucleon decay

$\Delta B = 2, \Delta L = 0,$

$\Delta(B-L) = 2$



$n \to \bar{n}$, NN decay.

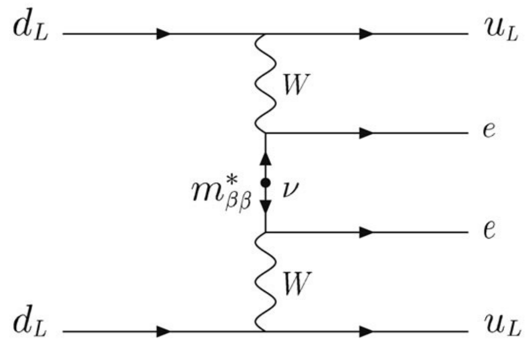
Stable proton.

Few pure BNV searches

Symbiosis

$\Delta B = 0, \Delta L = 2,$

$\Delta(B-L) = 2$



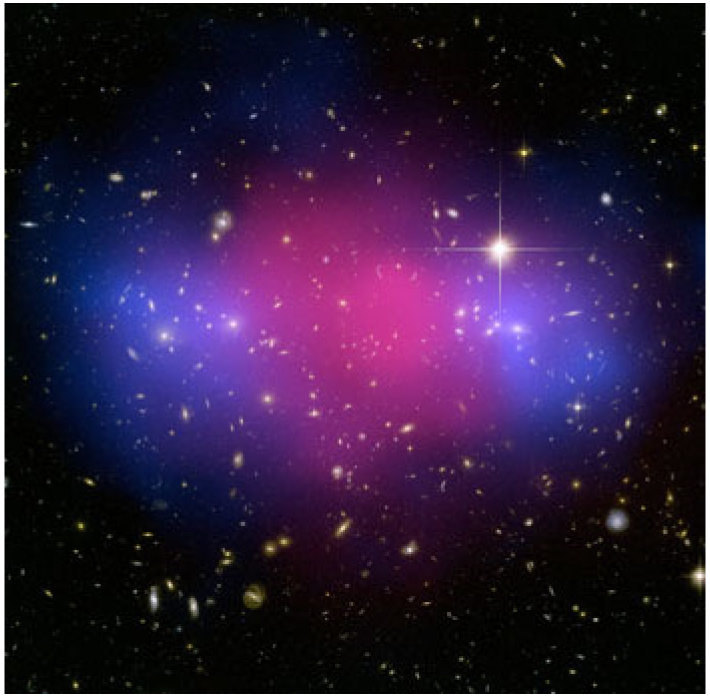
$0\nu\beta\beta$

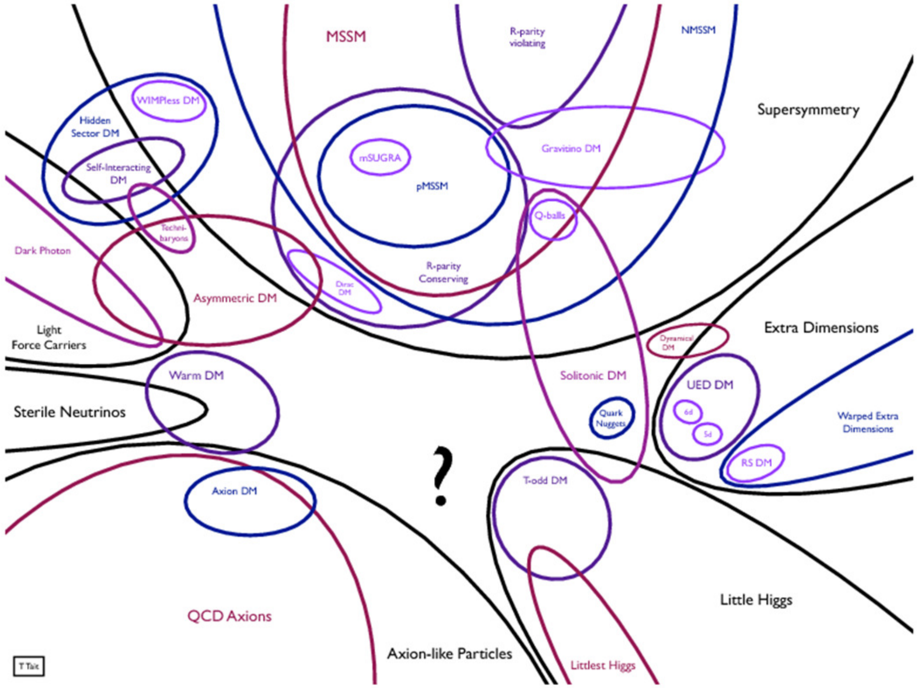
$$n \rightarrow \overline{n}$$

- Theory
  - Baryogenesis via $\not{B}N\not{V}$ (Sakharov condition)
  - Sensitive to new mass scales way beyond the LHC (up to ~10^{15} GeV)
  - Complementarity with open questions in neutrino physics
  - Predicted in theories beyond the SM, eg supersymmetry.

- Experiment
  - One of the few means of looking for pure BNV
  - Stringent limit on stability of matter

(2) Dark matter





Dark matter accounts for ~96% of the Universe's mass budget.

The main paradigm (WIMPs) has not produced evidence for DM after 40 years of searches.

We do not know what dark matter is.

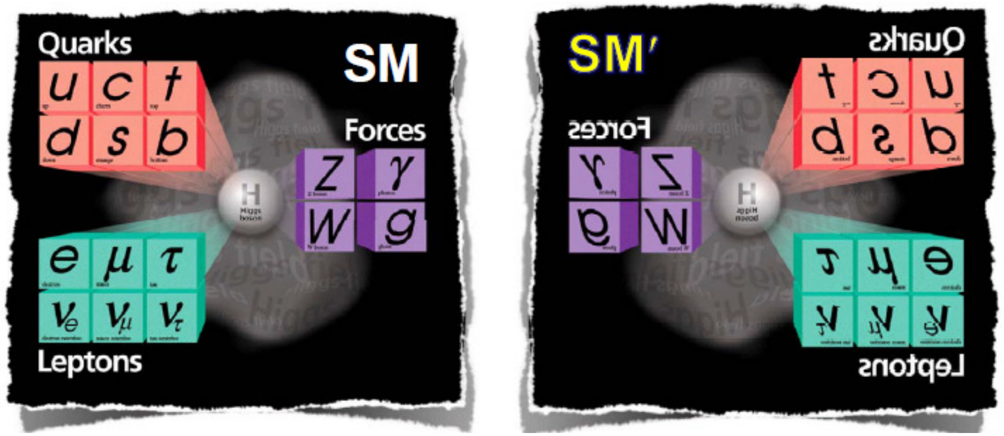
Mirror neutrons

"Hidden/mirror" sector

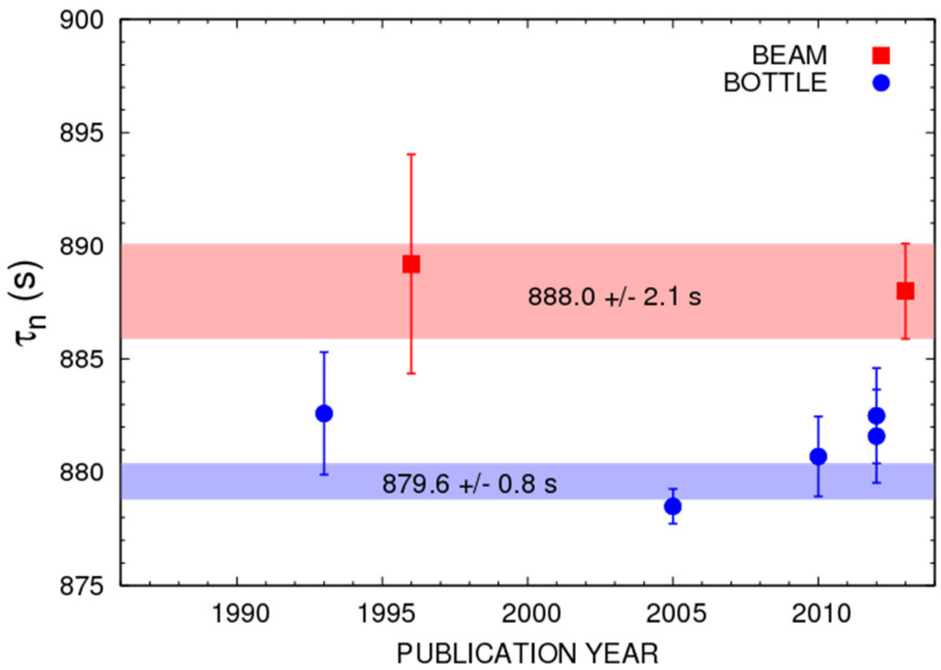
Restores parity symmetry.

Possible mixing for $Q = 0$ particles, eg, $n \to n'$

Mirror matter : dark matter candidates (m< 10 GeV)



Can explain 5σ neutron lifetime discrepancy seen in bottle and beam experiments.



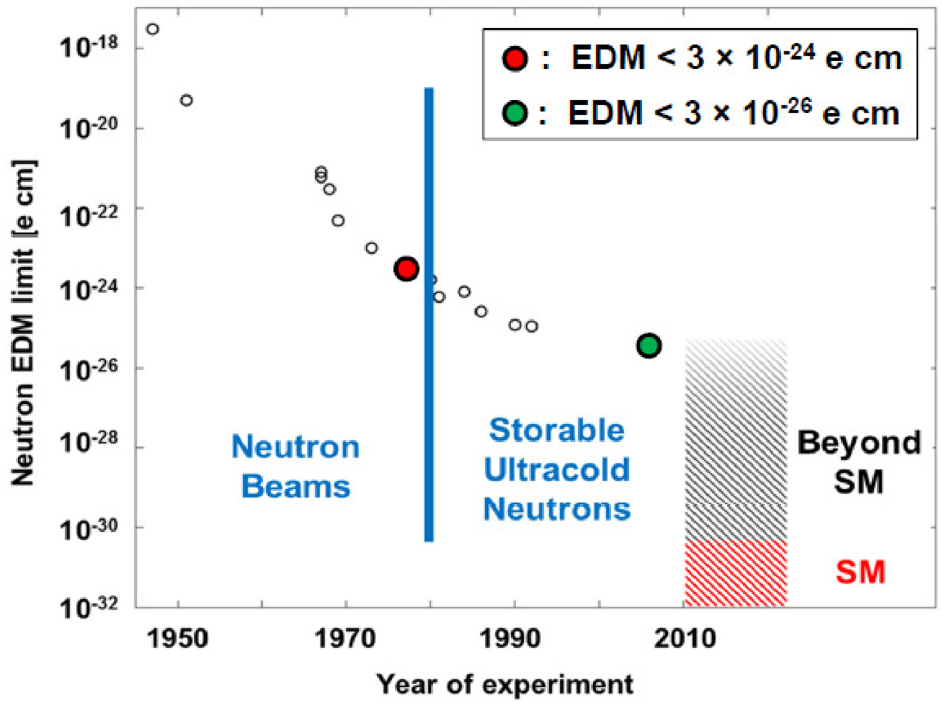
(3) Charge-parity violation

We do not understand where the antimatter has gone.

CP-violation is needed as a condition for producing baryogenesis.

We do not understand why CP is weakly violated (if at all) in the strong force.

A non-zero dipole moment arises from CP violation.



Neutron electric dipole moment

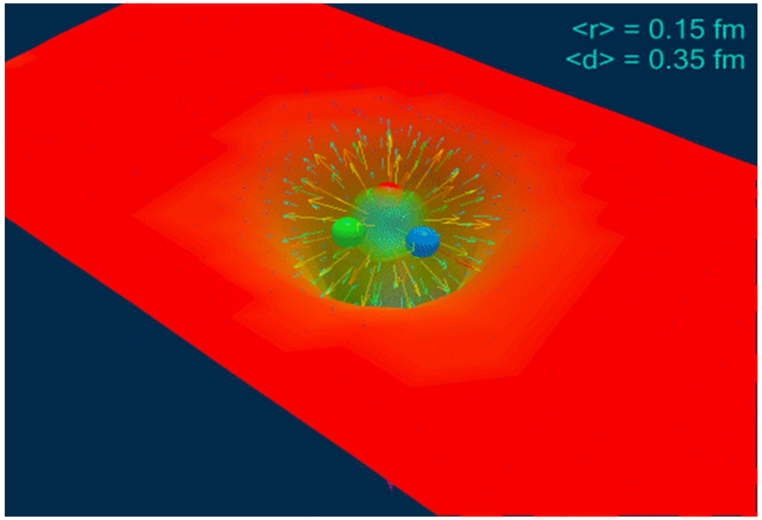
$\Rightarrow$ matter anti-matter asymmetry + strong CP problem

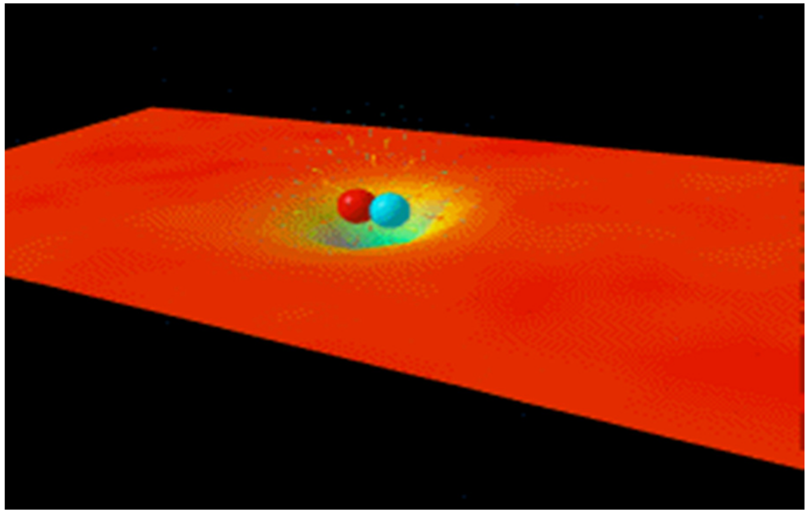
(4) Confinement

We understand well the interactions of quarks involving a large momentum transfer and short distances : $q > \mathcal{O}(\text{GeV}),\ \ r < \mathcal{O}(\text{fm})$

We do not understand well soft momentum transfers and long distances.

$\Rightarrow$ Quark confinement i.e. why we never see individual quarks.





1. Physics case for HIBEAM ✓
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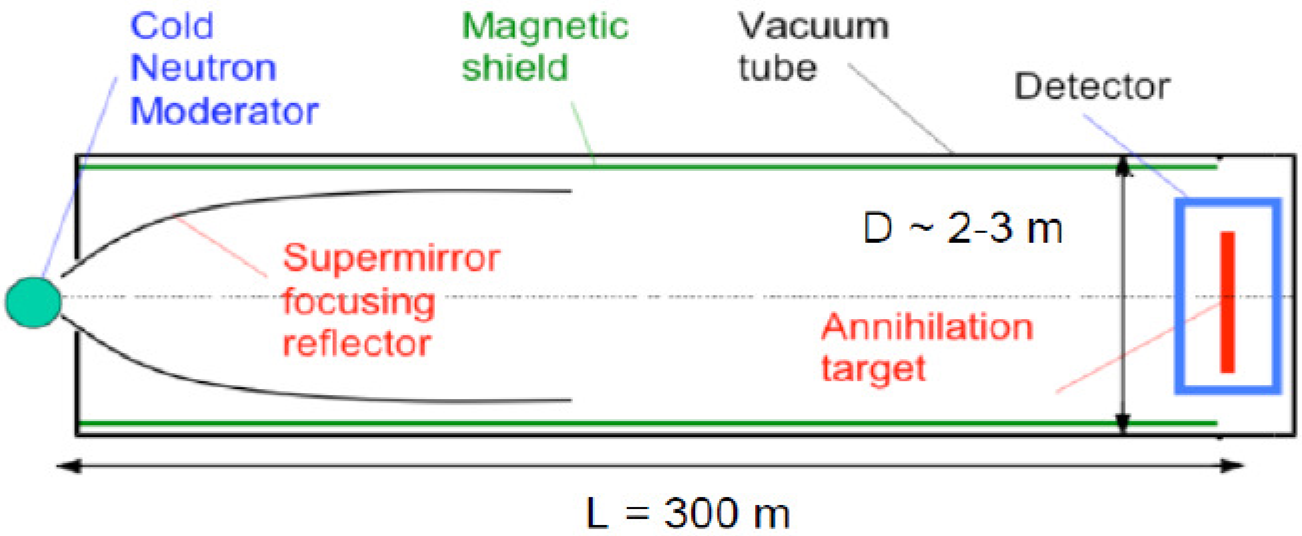
nnbar@ESS



Sensitivity $= (\text{free neutron flux at target}) \times P(n \rightarrow \overline{n}) \propto N_n t^2$

- Cold neutrons (E<5 meV, v<1000ms^{-1})
- Low neutron emission temperature (50-60 K)
- Supermirror transmission and transit time
- Large beam port option, large solid angle to cold moderator.

Ultimate increase in sensitivity for $P_{n\bar{n}} \sim 10^3$ compared to previous experiment (ILL)

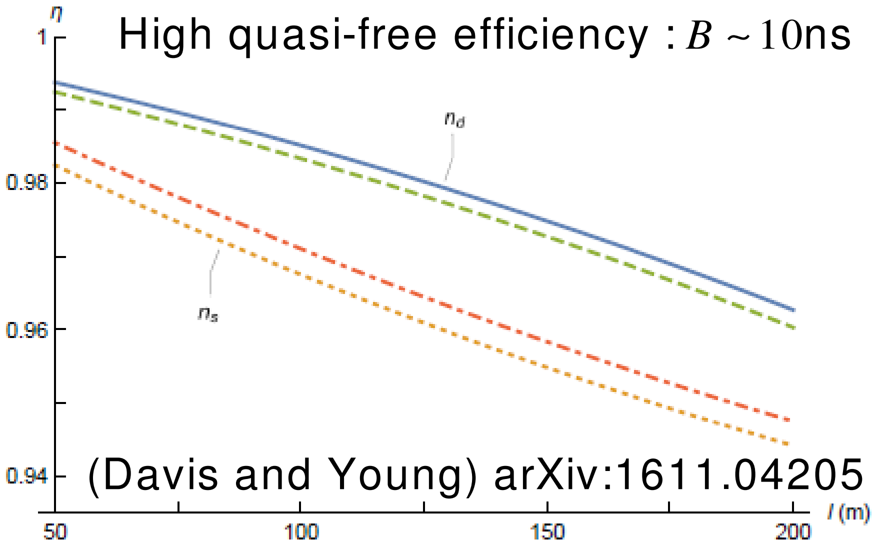
- Neutron guiding, larger opening angle, higher flux, particle ID technologies, running time.

The need for magnetic shielding

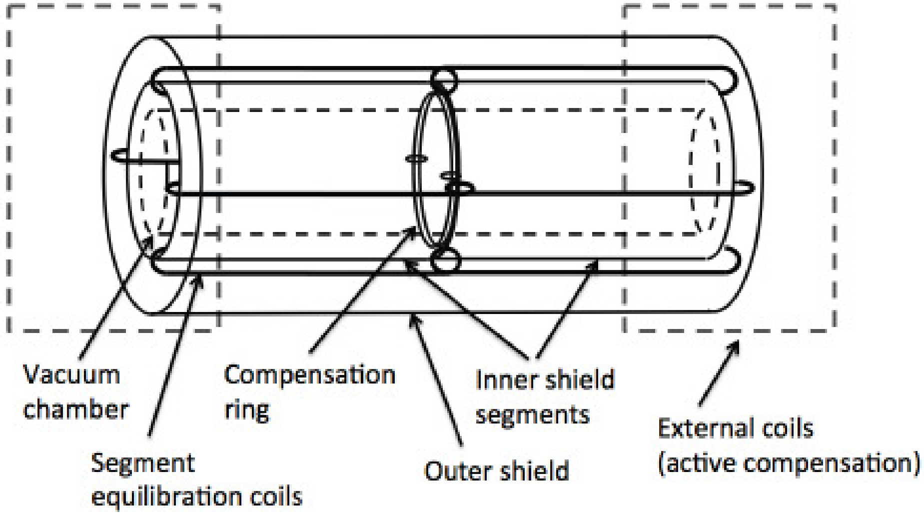
$$n(\mu\downarrow) \quad \bar{n}(\mu\uparrow)$$
$$B \sim 0$$

$$n(\mu\downarrow)$$
$$2\vec{\mu}\bullet\vec{B} \qquad E$$
$$\bar{n}(\mu\uparrow)$$

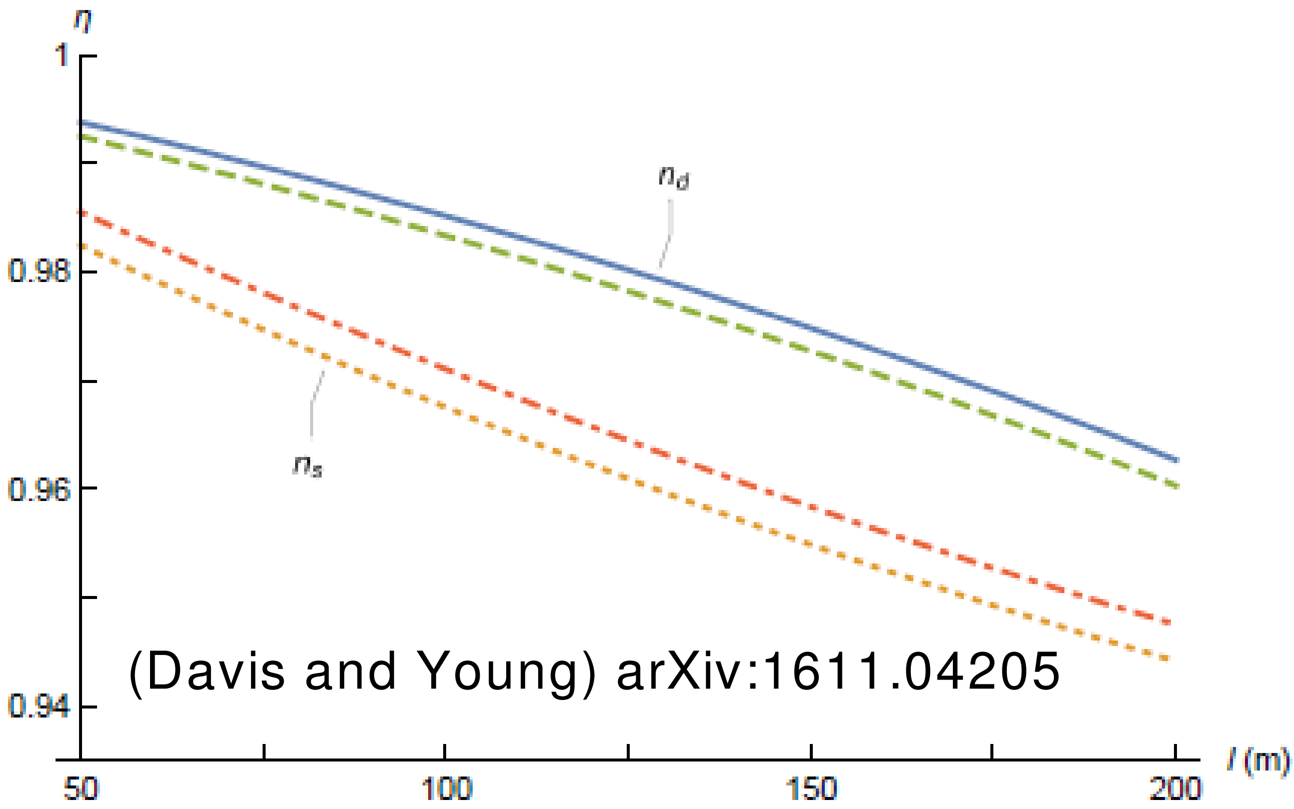
Degeneracy of $n, \bar{n}$ broken: $\Delta E = 2\vec{\mu}\bullet\vec{B}$



Active and passive shielding.



Quasi-free limit



Magnetic field suppresses neutron-antineutron conversion.

High efficiency for quasi-free neutrons up to ~ 10 nT

Maximum tolerable field to be determined.

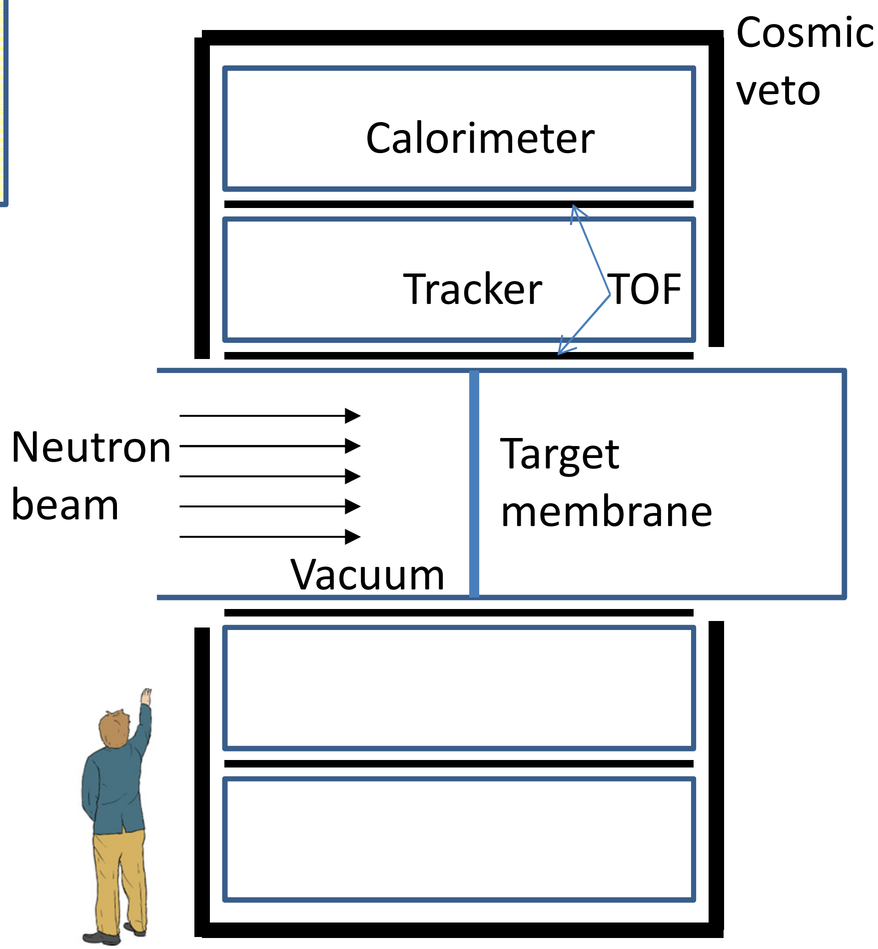
Detector

Expect $\bar{n} + N \rightarrow \sim 5\pi$ at $\sqrt{s} \sim 2$ GeV.

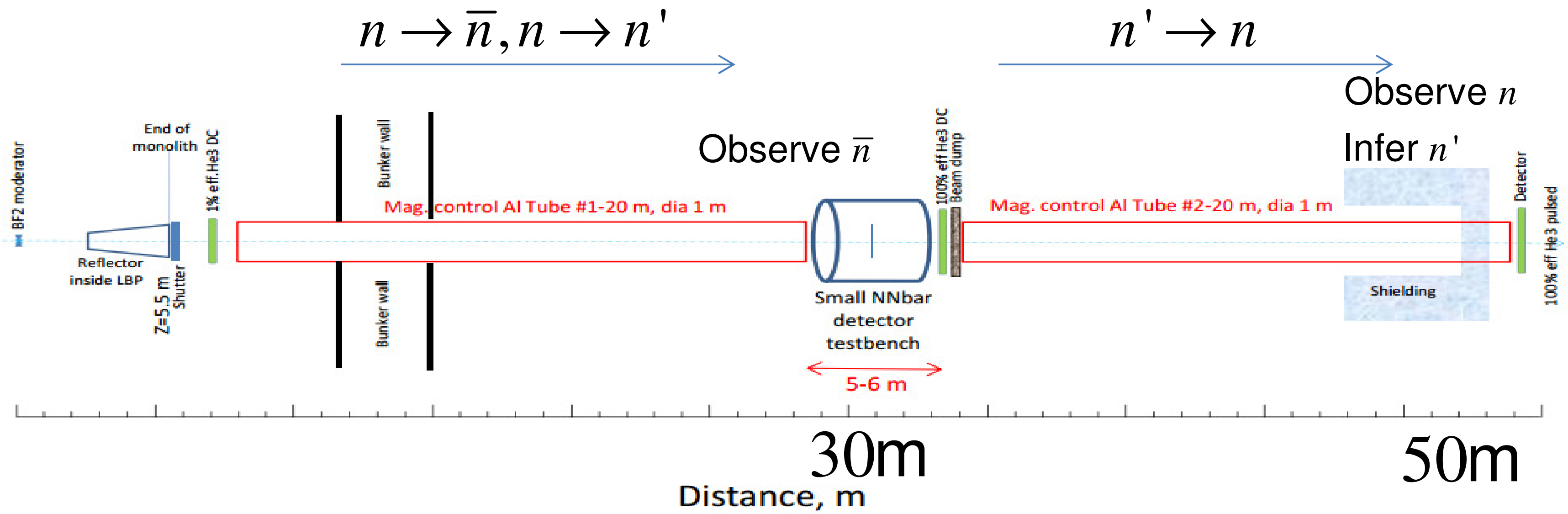
Detector design for high efficiency $(\varepsilon > 0.5)$

and low bg (~ 0).

- Annihilation target - carbon sheet
- Tracker - vertex reconstruction
- Time-of-flight system
  - scintillators around tracker.
- Calorimeter
  - lead + scintillating and clear fibre.
- Cosmic veto - plastic scintillator pads
- Trigger - Track and cluster algorithms



HIBEAM



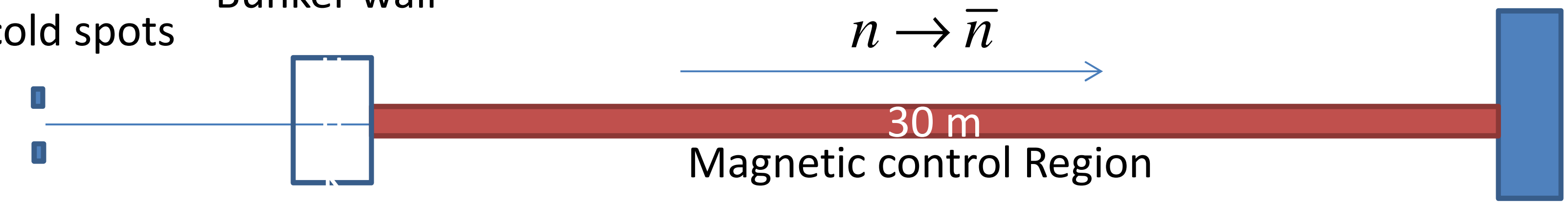
Lower scale experiment including prototypes for full later experiment

- High-m mirrors/focusing
- Magnetic shielding
- Neutron monitoring
- Detector
- BG

Physics

- Improve sensitivity wrt ILL
- Search for mirror neutron regeneration
- Other possible experiments (beam EDM, weak nucleon interactions, sensitivity to new long distance forces)

HIBEAM: $n \rightarrow \bar{n}$



Intensity at 50x50cm detector at 50m
5.12×10^{11}n/s (<1 eV)

Figure of Merit [FOM] (nnbar): $nt^2 = nl^2/v^2 = 2.25 \times 10^8 \frac{ns^2}{s}$

$$l = 30\ m$$

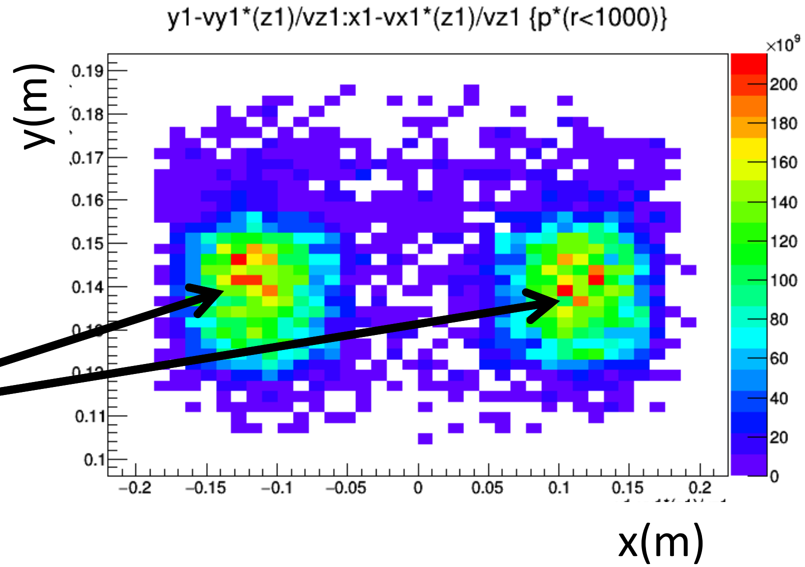
Improved (x5) with neutron mirror focusing
2 x ILL FOM in one year nominal operation.

Simulation of neutron production and propagation towards target

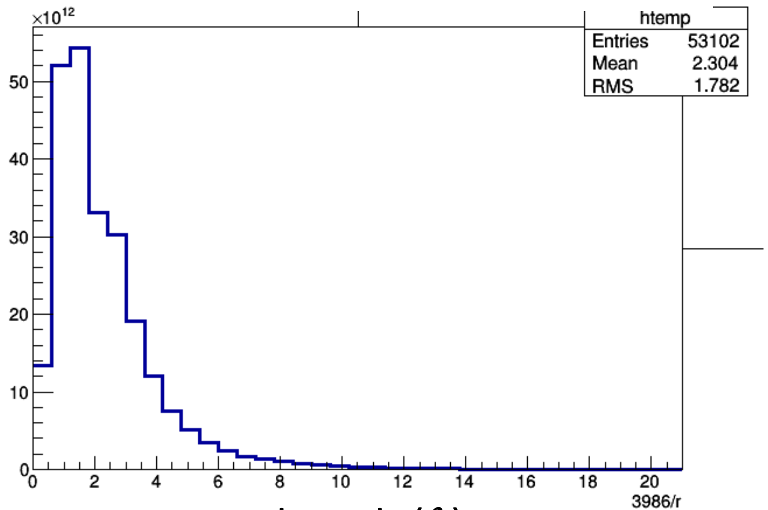
MNCPX used to calculated neutrons in BF2 upper moderator. Neutron flux at tally surface covering 4 π made by Esben. (3.6M events produced)

Neutron traces which pass through $N\bar{N}$ beam por selected. (53K events)

Two cold spots separated by ~25 cm.

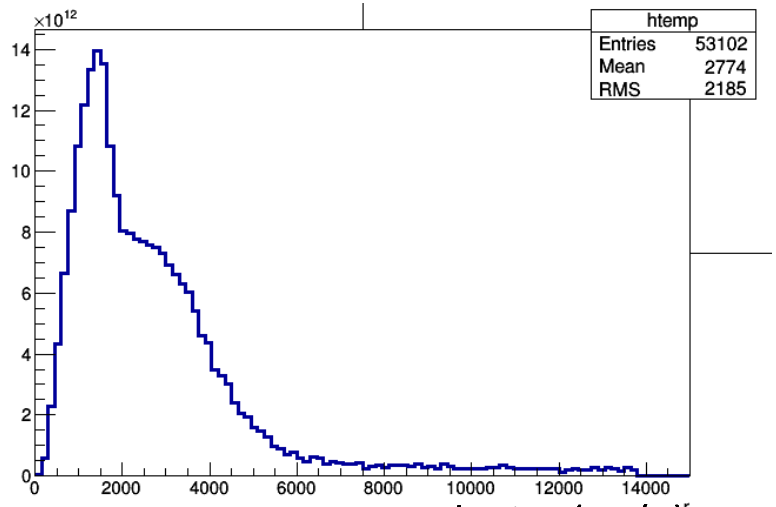


Source Spectrum for $N\bar{N}$ port



Wavelength (λ)

Source Spectrum for $N\bar{N}$ port



Velocity (m/s)

Reflector Geometry

Eq. of ellipsoid centered at z=Δz
and symmetric about rotation in z

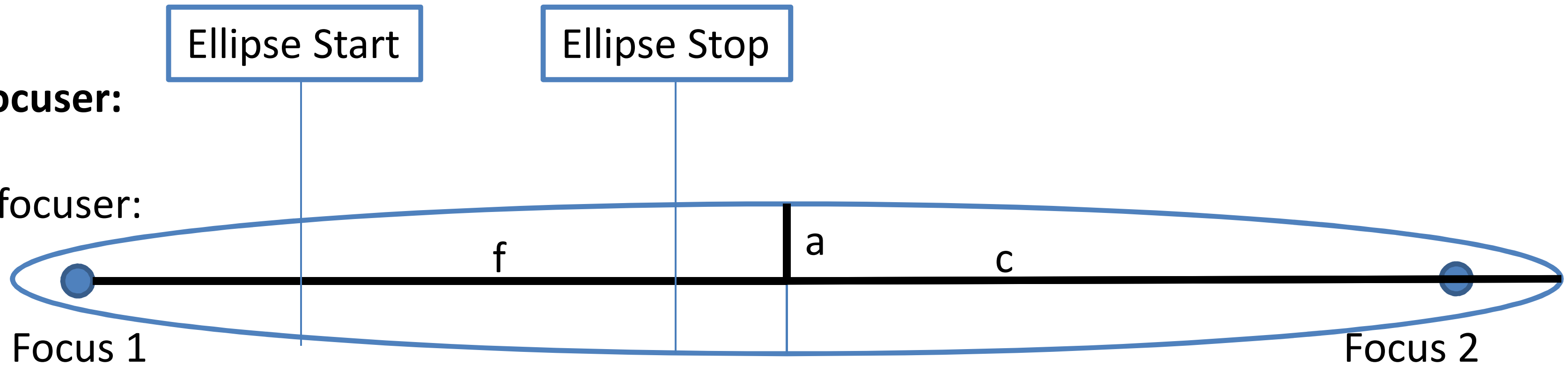
$$\left(\frac{r}{a}\right)^2 + \left(\frac{z-\Delta z}{c}\right)^2 = 1 \; where \; r = \sqrt{x^2+y^2}$$

$$f = \sqrt{c^2 - a^2}$$

The ellipse can be described by f, a, and Δz

One focuser:

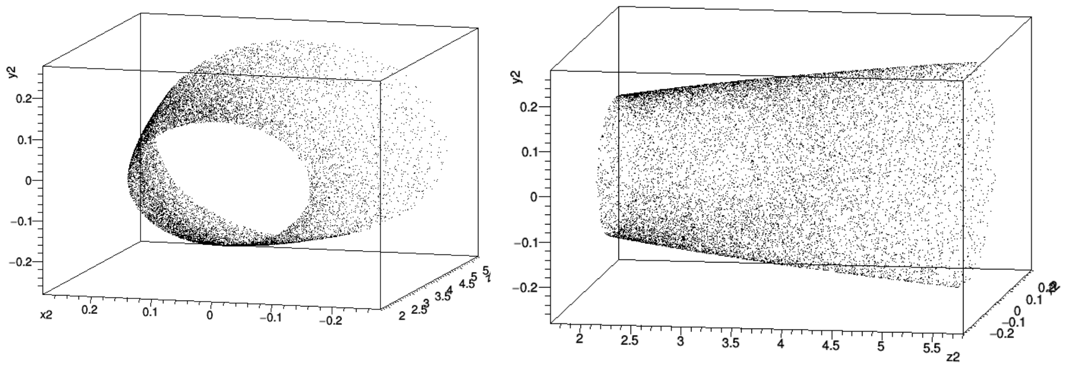
One focuser:



Focus 1
Source
z=0m

Focus 2
Detector
z=54m

3-D visualization



HIBEAM ellipsoid:
a = 40 cm
f = 27 m
Start-Stop = 2m-5.5m
Focus 1(y,x) = (13.5 cm, 12cm)
Super mirror m=7

Effect of m=7

When a neutron is reflected off the elliptical surface its transverse velocity is calculated and its weight is decreased by the reflection coefficient according to the data file (swiss neutronics 2012).

m=7 assumed.

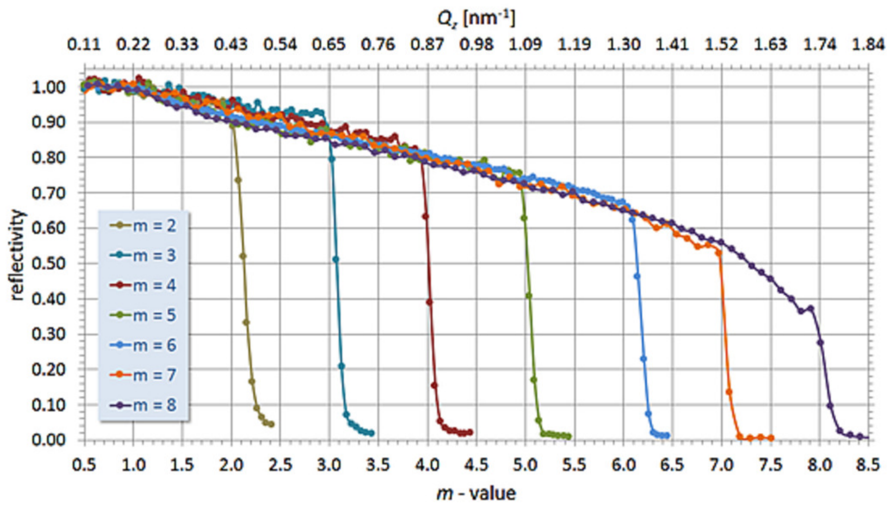
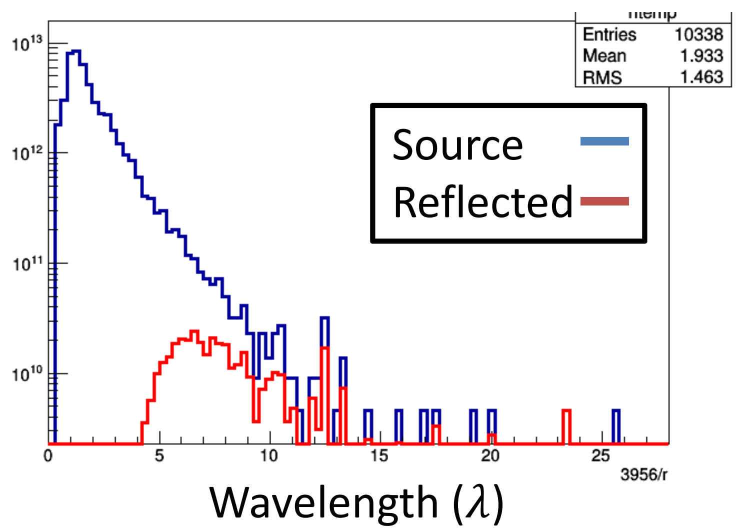
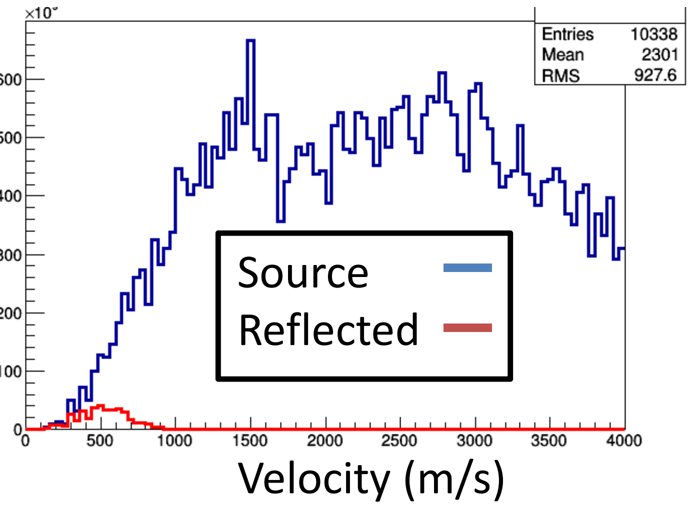


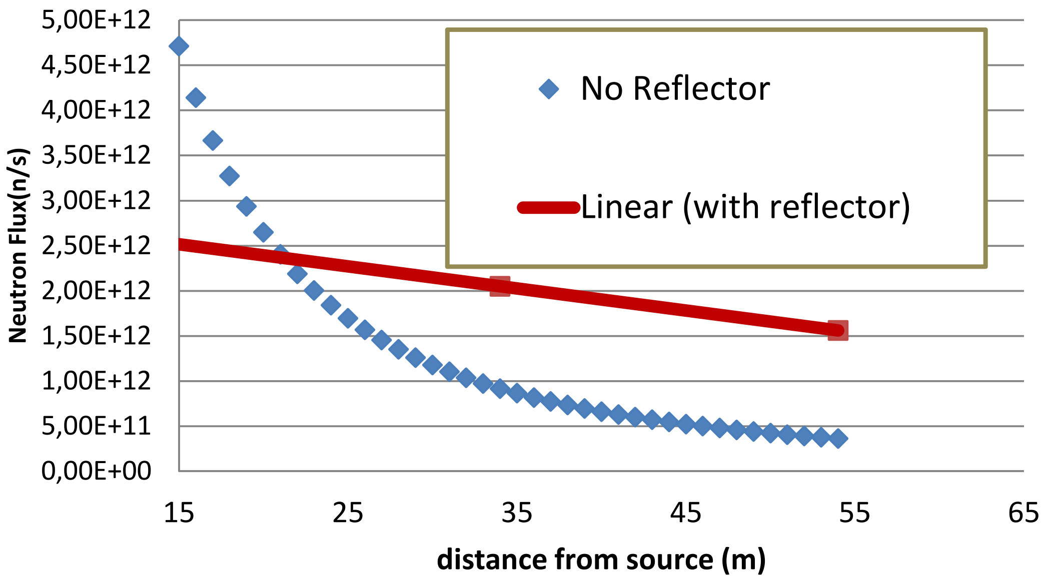
Figure 1: Reflectivity profiles of Ni/Ti & non-depolarising supermirror coatings 2 ≤ m ≤ 8.

Result of m=7 mirror with Ellipse 1(z=3-5.5m) focus= 3m minor-radius=24 cm Ellipse 2 (7-20m) focus=22m minor-radius=1m





Performance of the Reflector



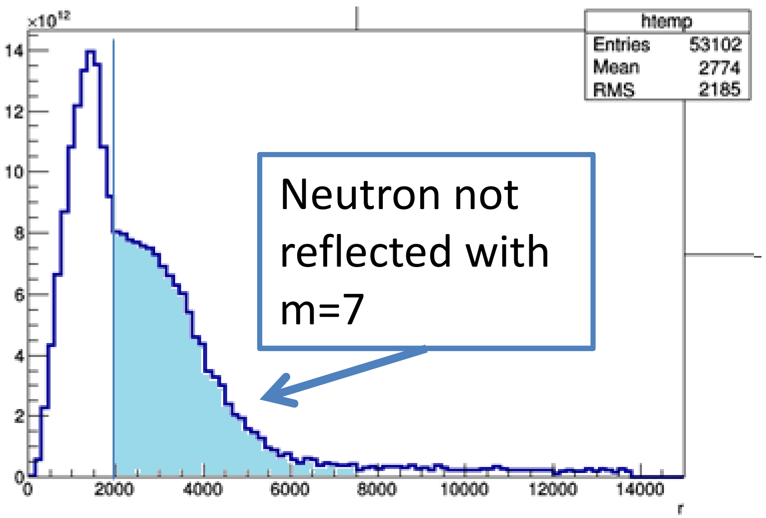
Without a reflector the neutron flux $\propto \frac{1}{R^2}$.

At 55 m the reflector provides an additional flux of $\sim 10^{12} \frac{n}{s}$ within a cylinder of 0.5 m diameter.

This effectively makes the source 5 times brighter

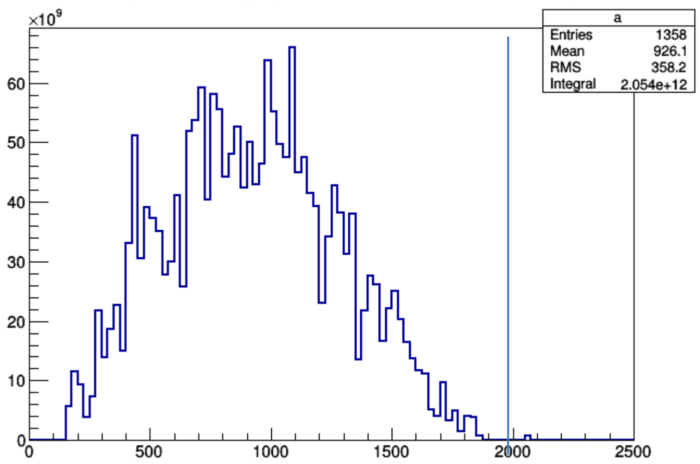
Spectrum of Reflected Neutrons

Source Spectrum for LBP



Velocity (m/s)

Reflected Neutron Spectrum

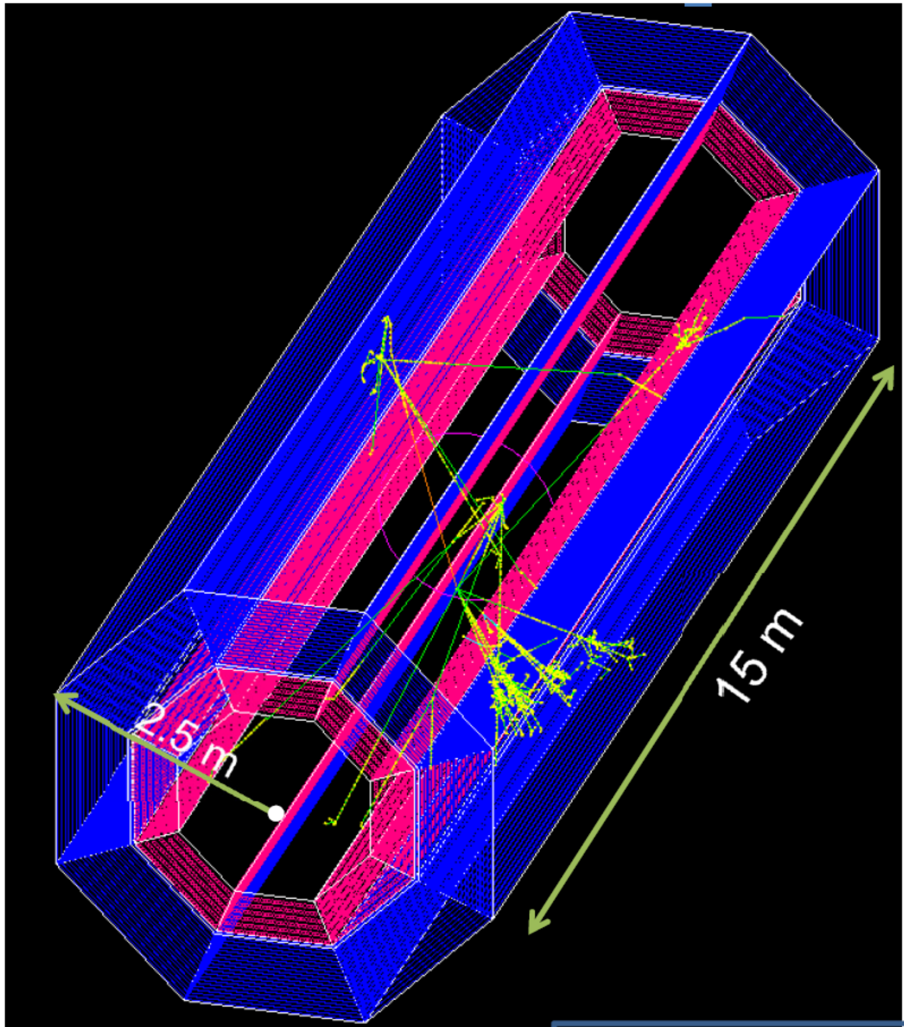


Velocity (m/s)

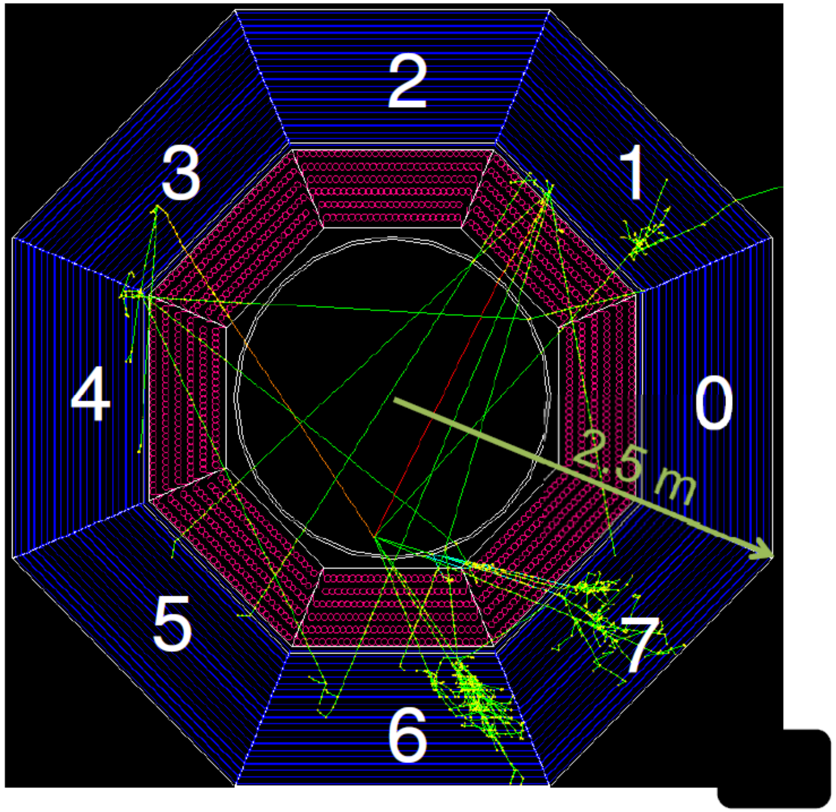
The super mirror reflector is only able to reflect neutrons with low transverse momentum.

This essential cuts the reflected spectrum at 2000 m/s providing a colder beam.

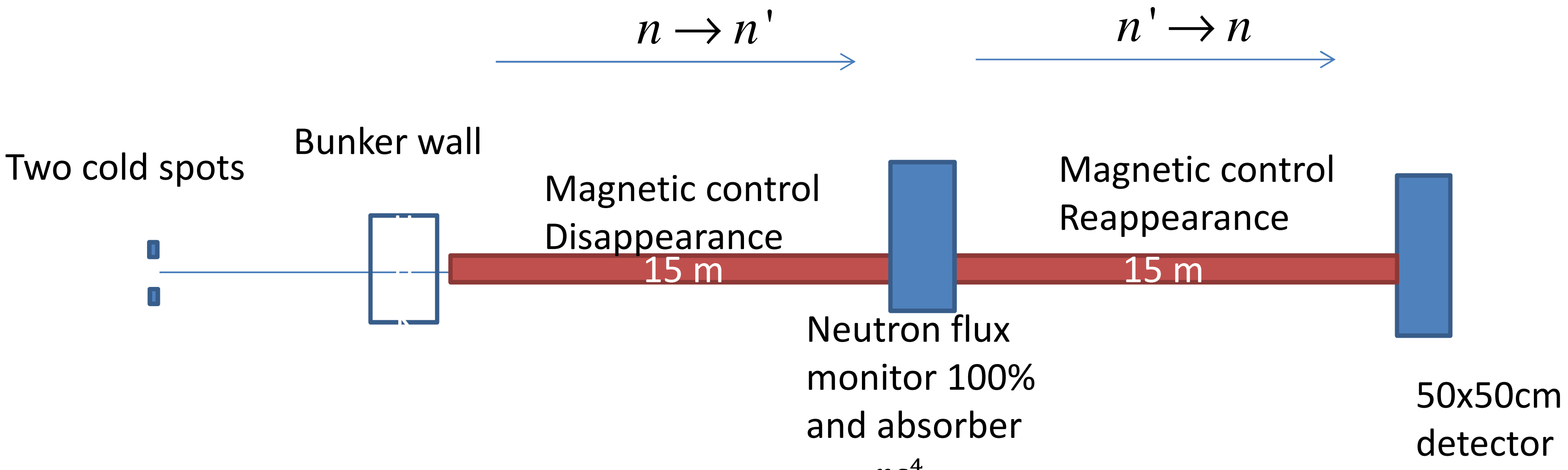
Detector simulation



$$\overline{n} + {}^{12}C \rightarrow {}^{11}C + \pi's$$



$HIBEAM$: n->n'->n
Neutron Mirror Neutron Regeneration Experiment



FOM (for n->n'->n): $nt^4 = nl^4/v^4 = 2.5 \times 10^4 \frac{ns^4}{s}$
($l = 15m$)

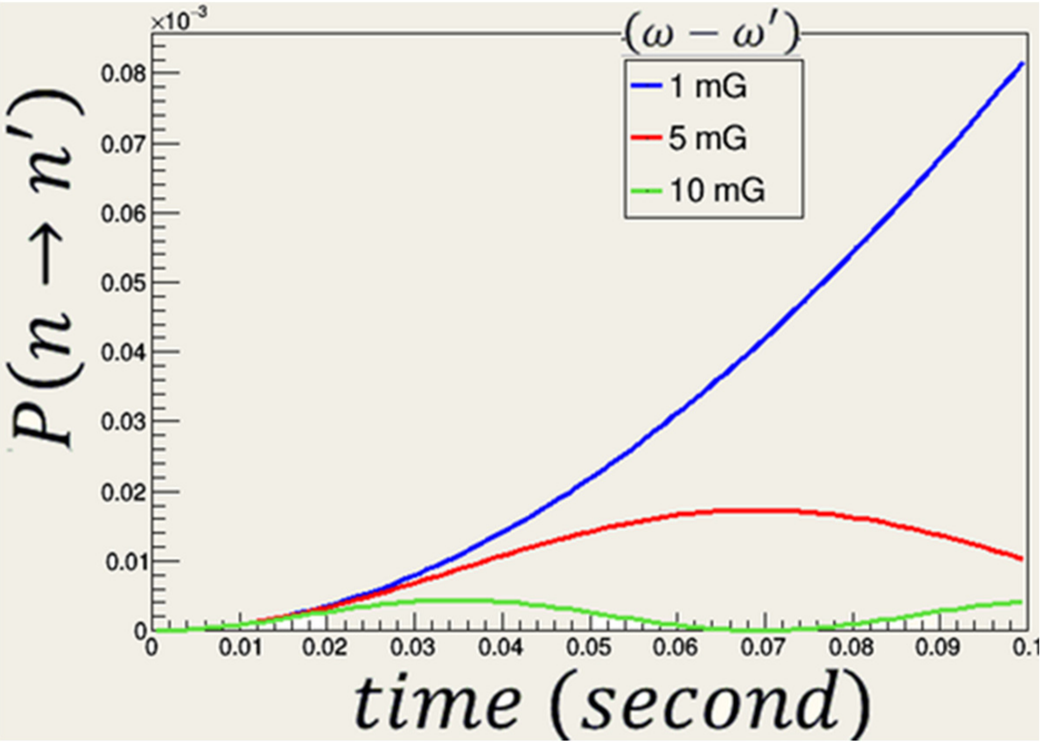
Probability to go $n \to n' \propto t^2$ (Neutron disappearance)
Probability to go $n' \to n \propto t^2$ (Neutron appearance)
Probability of $n \to n' \to n \propto t^4$ (Neutron Regeneration)

Extend previous sensitivity

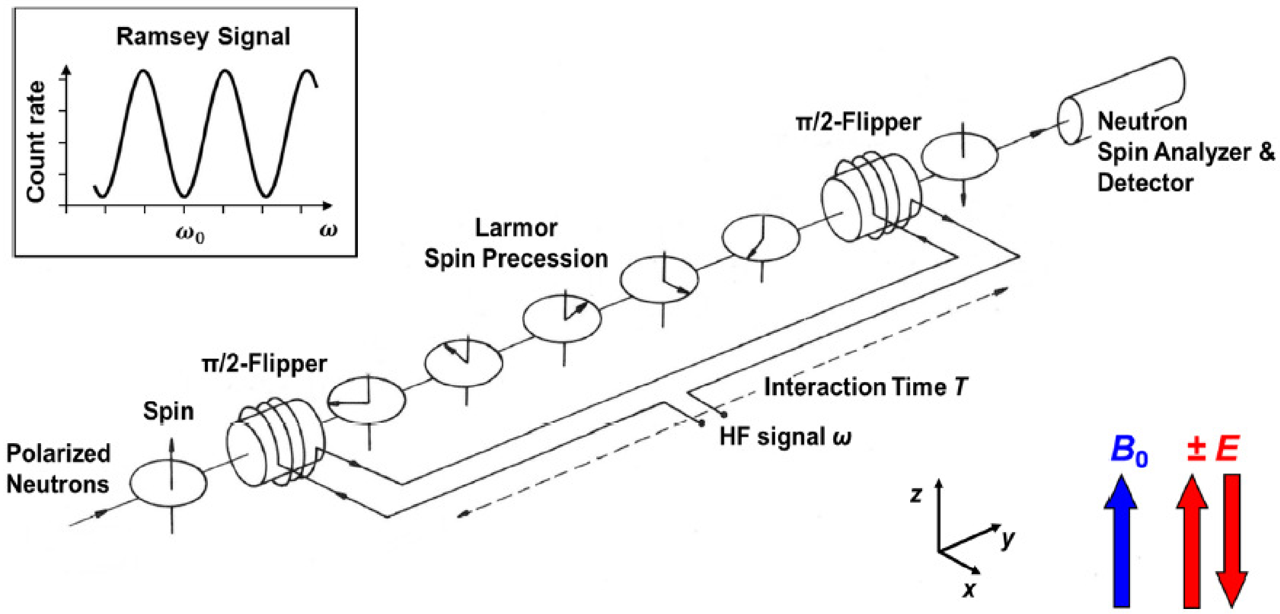
Mirror neutrons

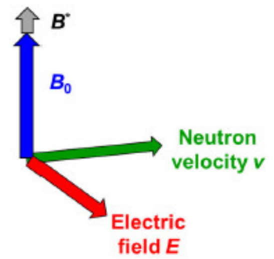
Match magnetic fields in normal and mirror sectors for conversion.

Controlled magnetic fields.



Neutron EDM





Neutron beam EDM searches limited due to $(v \times E)$ systematic

$\Rightarrow$ effective magnetic field and a false EDM signal.

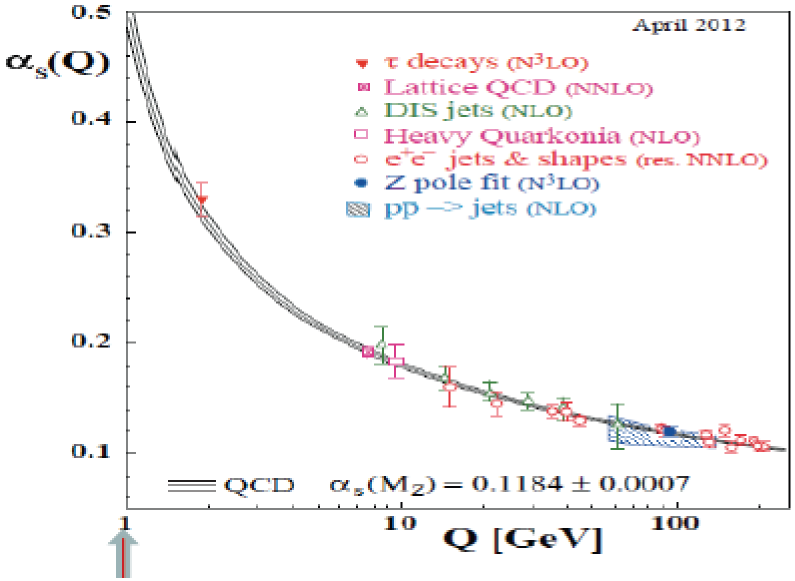
Can be directly measured with high intensity pulsed source (ESS).

$\Rightarrow$ Competitive nEDM sensitivity (F. Piegsa).

Probing the strong force

Weak nucleon-nucleon interactions.

Slow neutrons - zero electric charge, small magnetic moment, small electric polarisability.



High neutron polarisation
->spin-dependent interactions.

$\Rightarrow$ n-p parity violation

n-^{3}He parity violation

Exotic spin-dependent neutron interaction experiments.

Inexpensive.

1. Physics case for HIBEAM ✓
2. HIBEAM ✓
3. Issues and plans

Issues

- Large Beam Port is an essential asset
  - 10^o x 10^o aperture open in the inner shielding layer of the monolith. Must be reserved now – it cannot be replaced/improved later.
- Full nnbar requires ~400 ILL units per year
  - large area moderator (LD2)
  - BF2 lower moderator use (more expensive) lobed reflector but ~200-250 ILL per year
- We sit outside the standard ESS program. Need a path towards a prospective approval.

Tentative timescales

- HIBEAM
  - Early physics
  - Several experiment in parallel (nnbar and mirror neutrons)
  - R&D for full experiment
  - Up to ~2025
- Aim for full experiment in 2025 with proposal ~2020

nnbar@ESS –> Hibeam

Expression of Interest for
A New Search for Neutron-Anti-Neutron Oscillations at ESS

	Name	Affiliation
Main proposer	Gustaaf Brooijmans	Columbia University
Co-proposers	Torsten Åkesson	Lund University
	David Baxter	Indiana University
	Hans Calen	Uppsala University
	Lorenzo Calibbi	Université Libre de Bruxelles
	Luis Castellanos	University of Tennessee
	Joakim Cederkäll	Lund University
	Peter Christiansen	Lund University
	Christophe Clément	Stockholm University
	Brian Cole	Columbia University
	Caterina Doglioni	Lund University
	Claes Fahlander	Lund University
	Gabriele Ferretti	Chalmers University of Technology
	Peter Fierlinger	TU Munich
	Matthew Frost	University of Tennessee
	Franz Gallmeier	University of Tennessee, Oak Ridge National Laboratory
	Kenneth Ganezer	California State University Dominguez Hills
	Richard Hall-Wilton	ESS
	Vincent Hedberg	Lund University
	Lawrence Heilbronn	University of Tennessee
	Andreas Heinz	Chalmers University of Technology
	Go Ishikawa	Nagoya University
	Håkan Johansson	Chalmers University of Technology
	Tord Johansson	Uppsala University
	Leif Jönsson	Lund University
	Yuri Kamyshkov	University of Tennessee
	Masaaki Kitaguchi	Nagoya University
	Esben Klinkby	ESS, Technical University of Denmark
	Balasz Konya	Lund University
	Andrzej Kupsc	Uppsala University
	Mats Lindroos	ESS
	Else Lytken	Lund University
	Bernhard Meirose	University of Texas, Dallas
	David Milstead	Stockholm University
	Rabindra Mohapatra	University of Maryland
	Thomas Nilsson	Chalmers University of Technology
	Anders Oskarsson	Lund University
	Robert Pattie	Los Alamos National Laboratory
	Christoffer Petersson	Chalmers University of Technology
	David Phillips	North Carolina State University
	Amlan Ray	VECC, Kolkata, India
	Filippo Resnati	CERN
	Arthur Ruggles	University of Tennessee
	Utpal Sarkar	Physical Research Laboratory, Ahmedabad, India
	Alexander Saunders	Los Alamos National Laboratory
	Hirohiko M. Shimizu	Nagoya University
	Robert Shrock	Stony Brook University
	David Silvermyr	Lund University
	Samuel Silverstein	Stockholm University
	Oxana Smirnova	Lund University
	Per Erik Tegner	Stockholm University

Expression of interest (2015)

A series of workshops and Expression of Intent

International with a large Swedish contingenet :SU,LU,UU,Chalmers

Collaboration: Co-spokespersons G. Broojimans and D. Milstead.

: Lead scientist Y. Kamyshkov

Particle Physics Strategy

European:

h) Experiments studying quark flavour physics, investigating dipole moments, searching for charged-lepton flavour violation and performing other precision measurements at lower energies, such as those with neutrons, muons and antiprotons, may give access to higher energy scales than direct particle production or put fundamental symmetries to the test. They can be based in national laboratories, with a moderate cost and smaller collaborations. *Experiments in Europe with unique reach should be supported, as well as participation in experiments in other regions of the world.*

US P5 report:

- With a mix of large, medium, and small projects, important physics results will be produced continuously throughout the twenty-year P5 timeframe. In our budget exercises, we maintained a small projects portfolio to preserve budgetary space for a set of projects whose costs individually are not large enough to come under direct P5 review but which are of great importance to the field. This is in addition to the aforementioned small neutrino experiments portfolio, which is intended to be integrated into a coherent overall neutrino program.

Consensus in the field is to pursue experiments with unique capabilities and physics reach.

Summary

- Hibeam can tackle a number of important open questions in modern physics
- Hibeam is the first step in a two stage set of experiments.
    - Exceed nnbar sensitivity from ILL, new mirror neutron searches + other experiments and R&D for complete experimental program
- International collaboration
- Great opportunity for a very competitive suite of fundamental physics experiments at the ESS which fits well within the international pp program.