Overview of Polarized ^{3}He Gas Targets

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Spin2014, Beijing, China, October 24, 2014

- Introduction to spin and polarized ^{3}He
- Polarized ^{3}He gas targets for high-energy nuclear physics
- Polarized ^{3}He for other applications
- Summary

Acknowledgement: some slides provided by my collaborators

some "borrowed" from colleague's talks on the web

Introduction to Polarized ^{3}He

Spin-Exchange Optical Pumping

Metastability-Exchange Optical Pumping

Asymmetry for Nucleon Spin Measurements

- Double spin symmetries for polarized beam on polarized targets

$$A = \frac{1}{P_b P_t f} \frac{N^{\uparrow\uparrow} - N^{\downarrow\uparrow}}{N^{\uparrow\uparrow} + N^{\downarrow\downarrow}}$$

- Figure of Merit (*FOM*) depends on luminosity, beam and target polarization (squared), dilution factor (squared)

$$FOM = P_b^{\,2} * P_t^{\,2} * f^{\,2} * L$$

$$L = \mathrm{I} * \rho \, [\mathrm{cm}^2\, \mathrm{s}^{-1}]$$

Polarized Luminosity and Polarization

- Luminosity

Internal targets (storage ring)

10^{31}

Polarized external (fixed) targets

Solid (p/d) 10^{35}

Gas (^{3}He) 10^{36} (JLab)

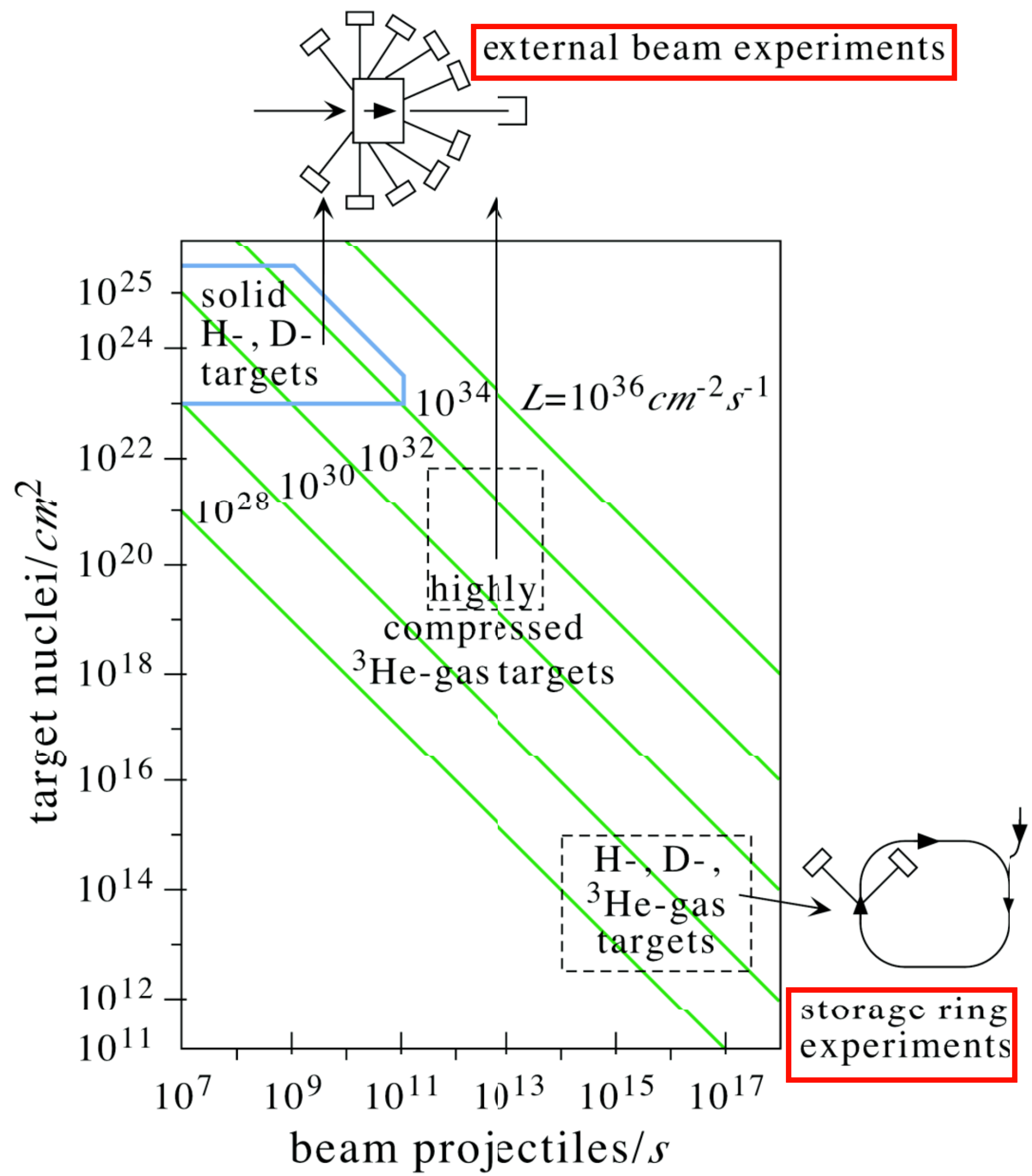
World highest luminosity/FOM

- Polarization (in-high intensity beam)

P_{3He} > 70% (~60%) (JLab)

P_H > 90% (70%)

P_D > 70% (40%)



Polarized ^3He

- Polarized atomic electrons, then spin exchange with ^3He nuclei

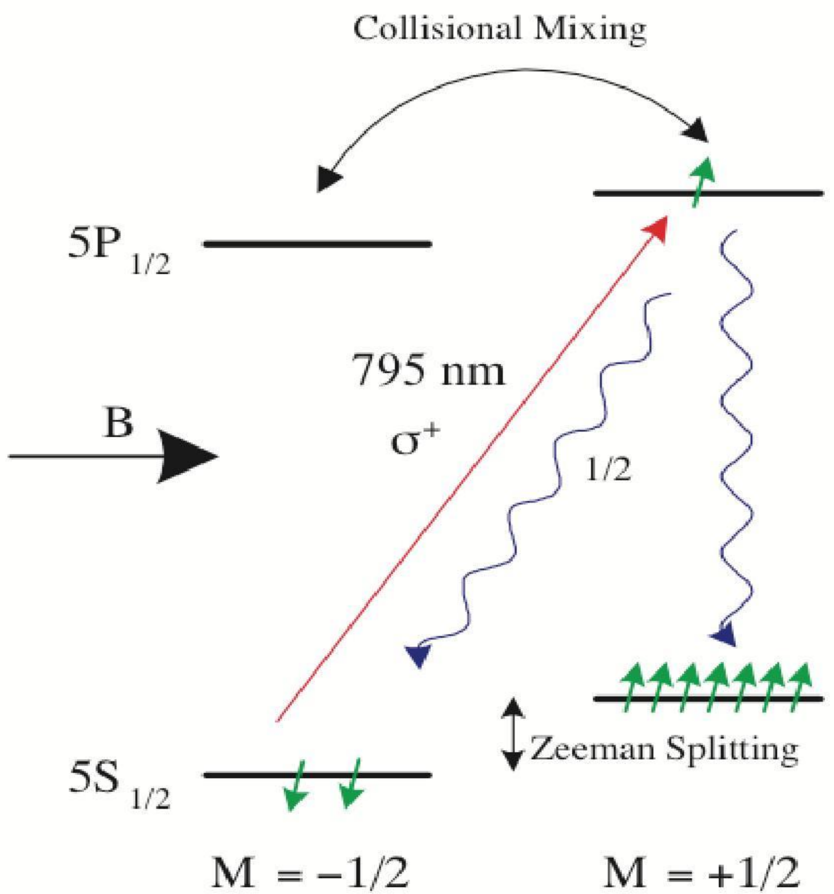
  Issue: ground state, two electrons (full shell),

  opposite spin, can not be polarized (exclusion principle)

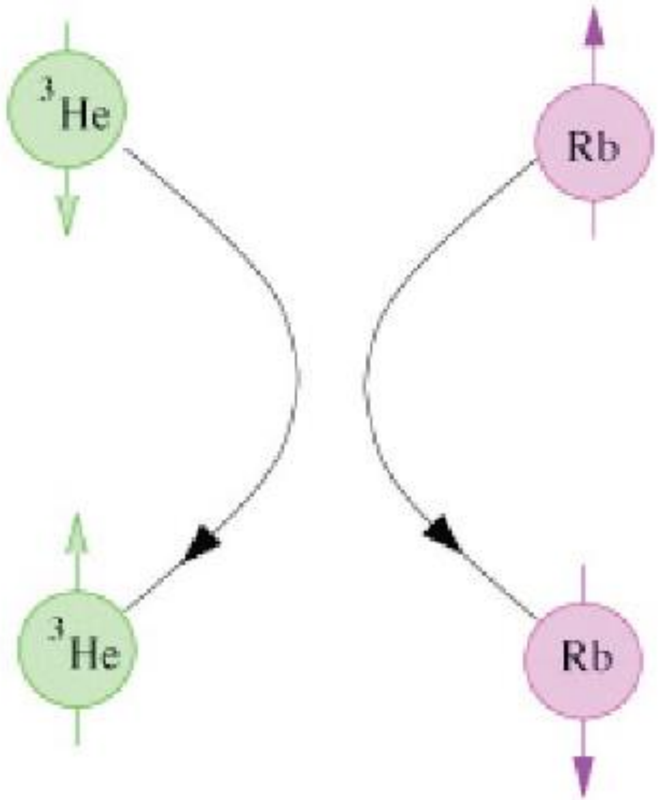
- Solutions:
  1) Alkali (Rb) Optical Pumping Spin Exchange
  2) Meta-stability Exchange Optical Pumping

Spin exchange Optical Pumping for ^3He

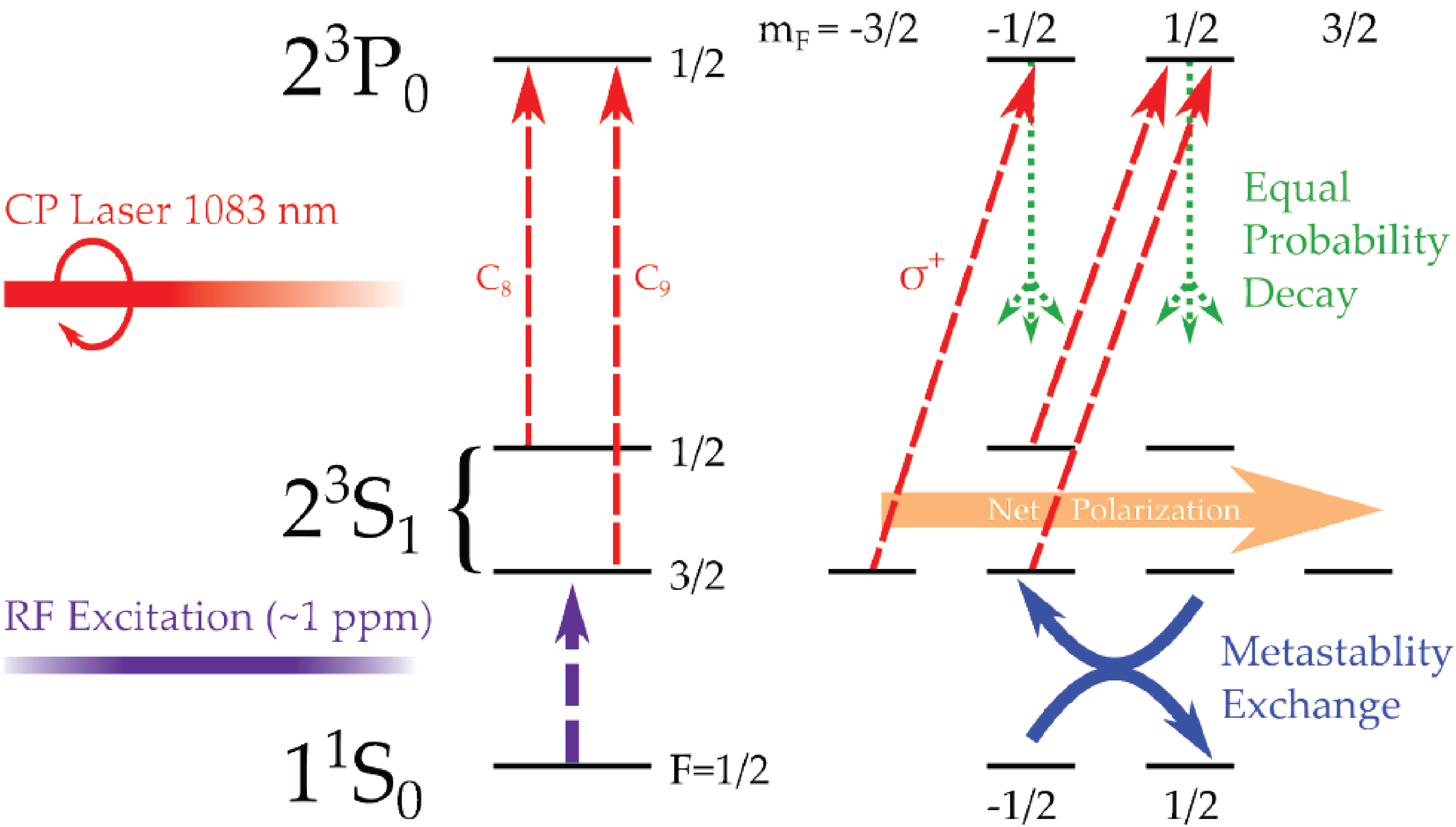
Optical Pumping on Rb atom



Spin exchange



Meta-stability Exchange Optical Pumping



History/Progress in Polarized ^{3}He

- Spin-Exchange Optical Pumping

1960: Bouchiat/Carver/Varnum (Princeton), PRL 5, 373 (1960)

2.8 atm ^{3}He, optically pumped 0.001 mm partial pressure of Rb, **P=0.01%**

we have observed enhancement of the nuclear polarization by a factor of 10^4 above the initial Boltzmann distribution of 10^{-8}.

Now: **10 atm ^{3}He**, Rb-K optical pumping, **P > 70% (JLab/UVa/W&M…)**

- Meta-stability Exchange Optical Pumping

1963: Colegrove/Schearer/Walters (Texas Instruments), PR, 132, 2561 (1963)

~0.001 atm ^{3}He, achieved ~40% polarization

The highest polarization measured by nuclear magnetic resonance was 40±5% in a 5 cm-diam Pyrex sphere with the He^3 gas pressure at 1 mm Hg.

Now: ~**1 atm ^{3}He**, mass production with MEOP, **P > 70% (Mainz)**

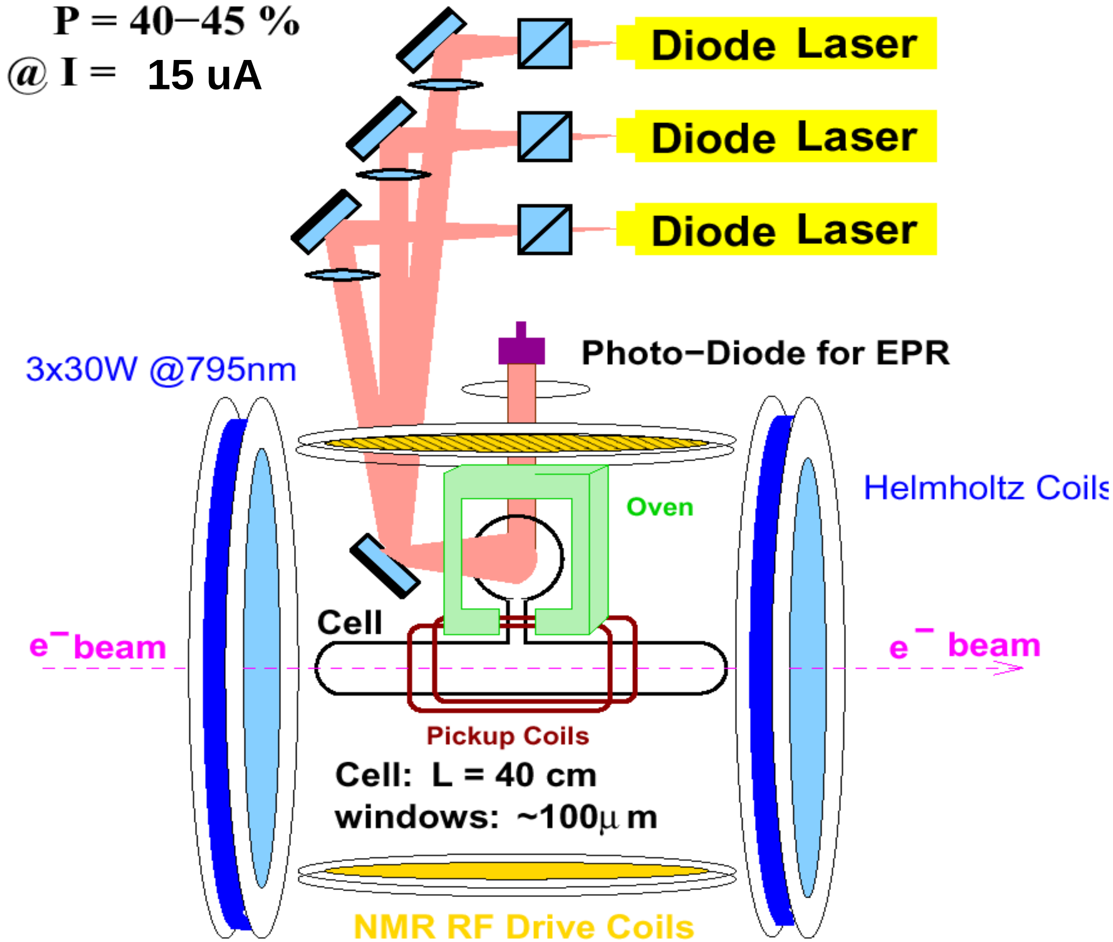
Polarized ^{3}He Target @ JLab: 1998-now

Spin-Exchange Optical Pumping

https://hallaweb.jlab.org/wiki/index.php/Hall_A_He3_Polarized_Target
http://hallaweb.jlab.org/equipment/targets/polhe3/polhe3_tgt.html

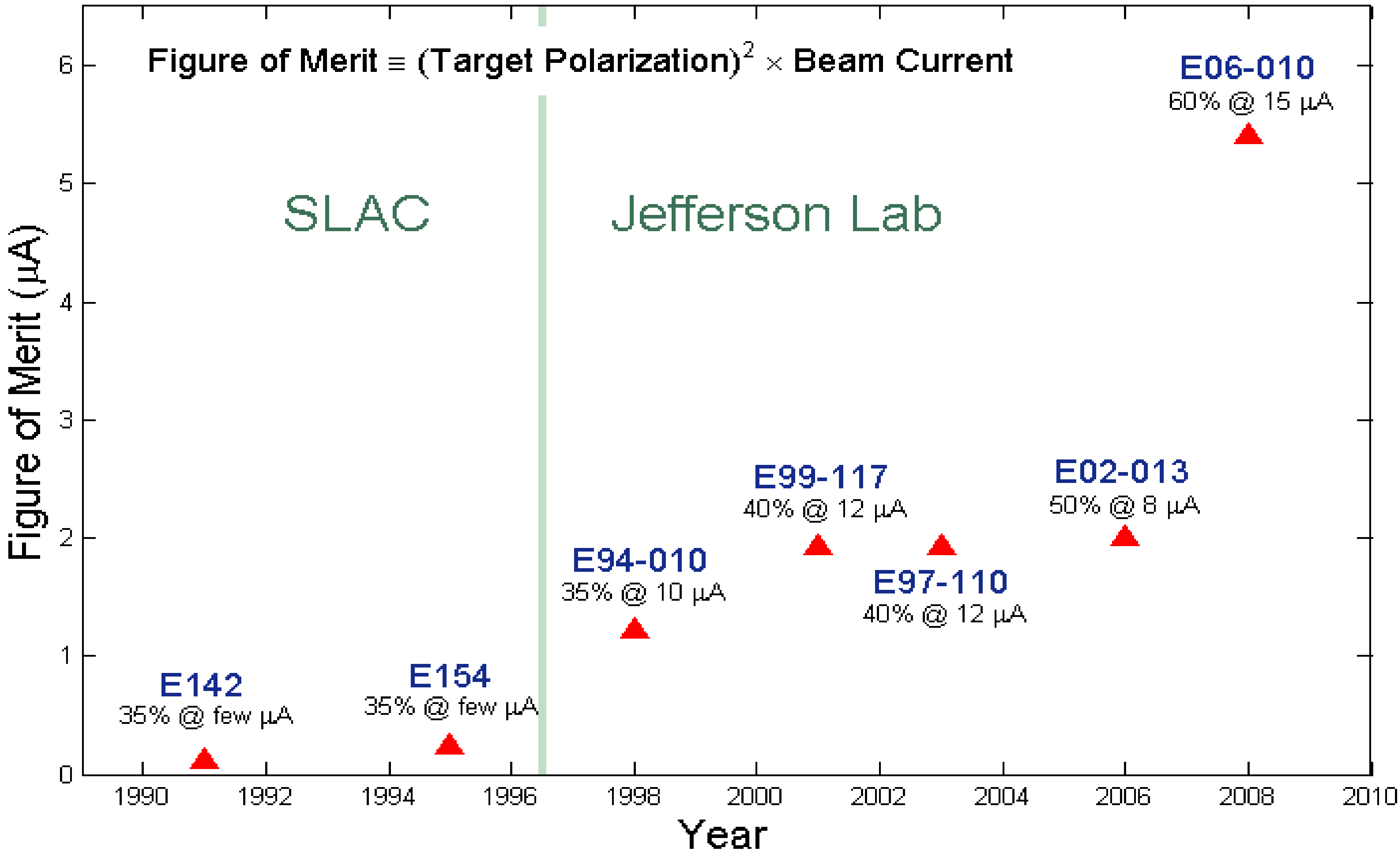
JLab (J. P. Chen), UVa (G. Cates), W&M (T. Averett), Duke (H. Gao), Temple (Z.E. Meziani), Kentucky (W. Korsch), Caltech(E. Hughes)…

JLab Polarized ^{3}He Target

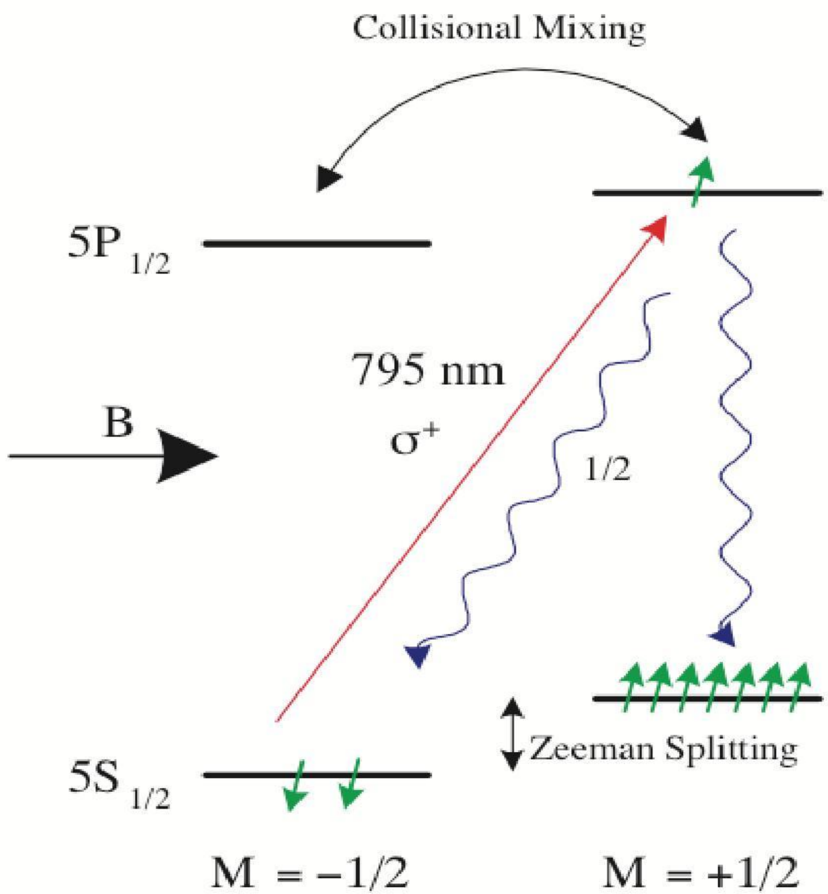


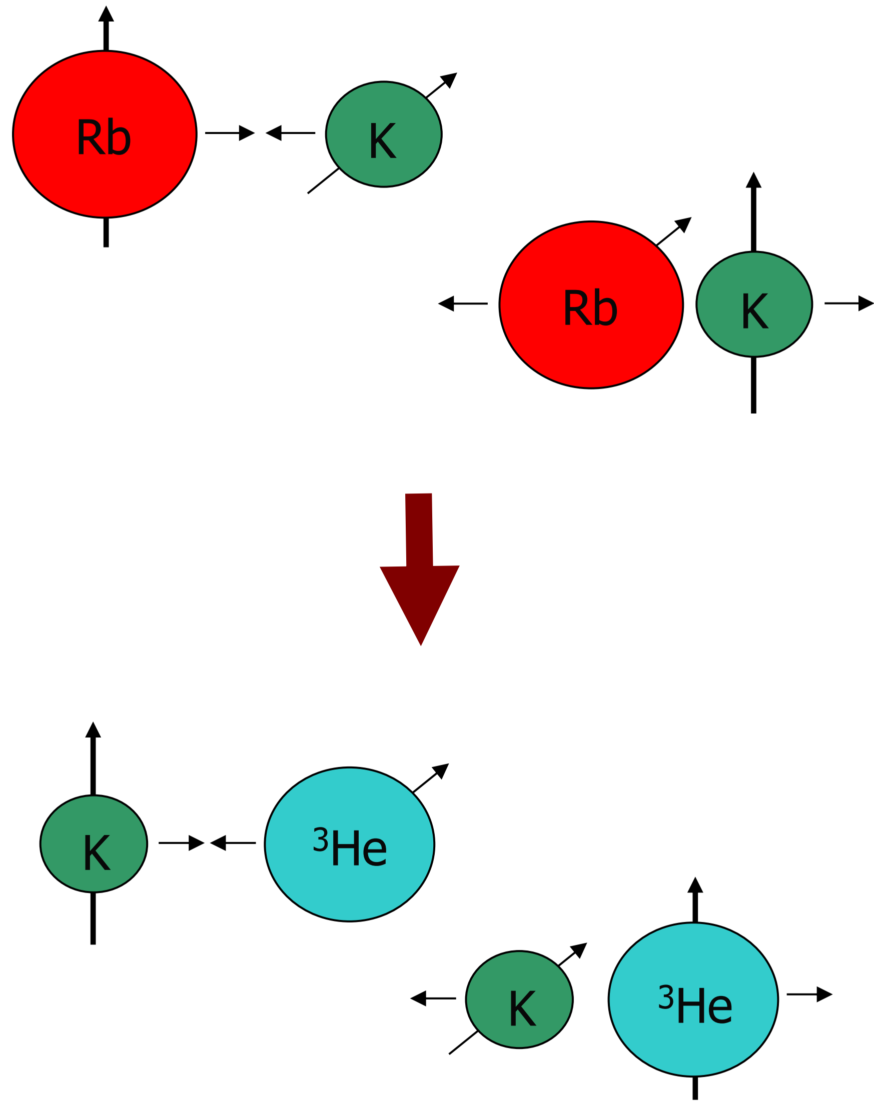
- ✓longitudinal, transverse and vertical
- ✓Luminosity=10^{36} (1/s) (highest in the world) upgrade on the way to 10^{37}
- ✓High in-beam polarization ~ 60% (>70% no beam)
- ✓Effective polarized neutron target
- ✓13 completed experiments 8 approved with 12 GeV (A/C)

Figure-of-Merit History for High Lumiosity Polarized ^{3}He



Rb-K Hybrid Optical Pumping for ^3He



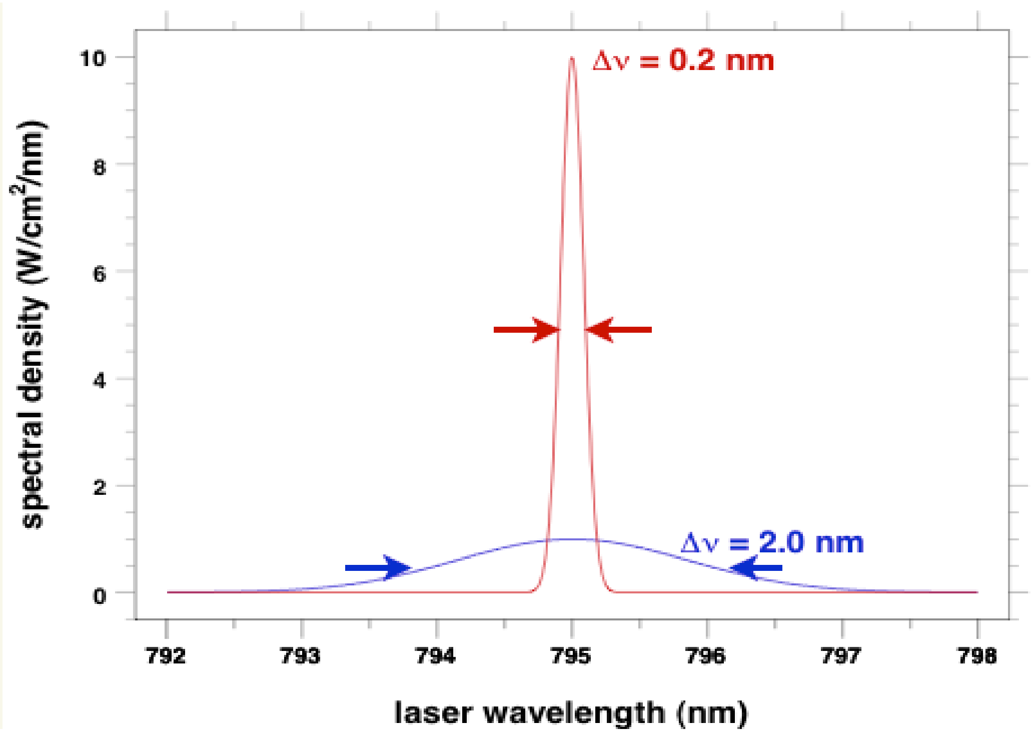


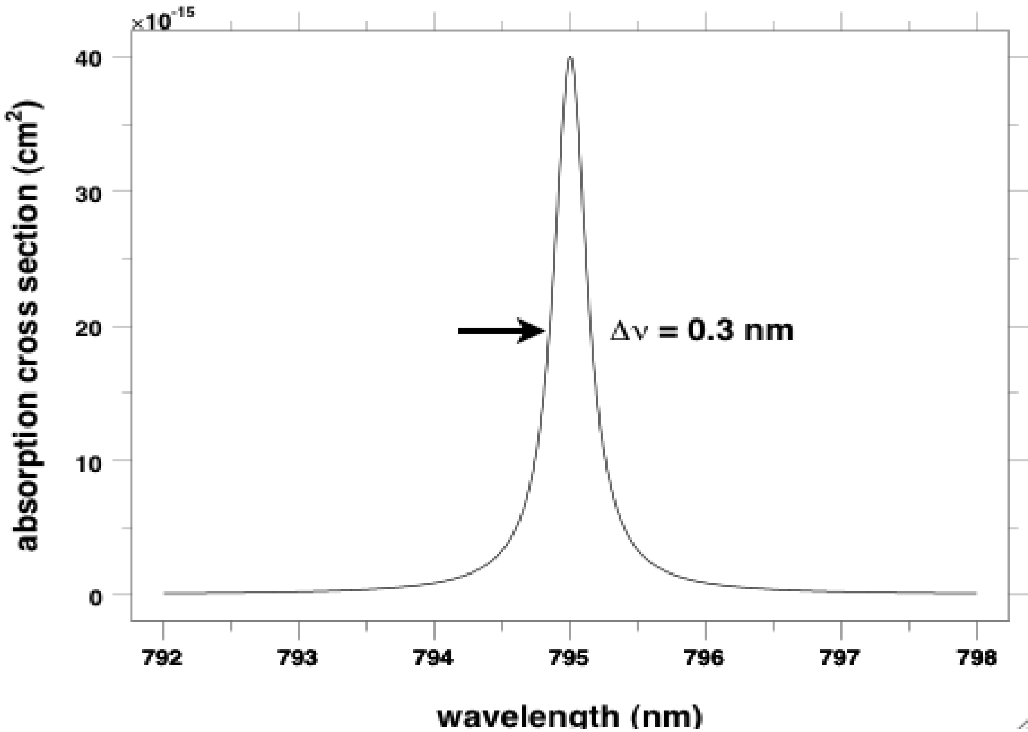
Narrow-width Lasers

With new narrow-width lasers, polarizations > 70%

Left: Blue is current lasers, Red is Comet laser

Right: Absorption spectrum of Rb

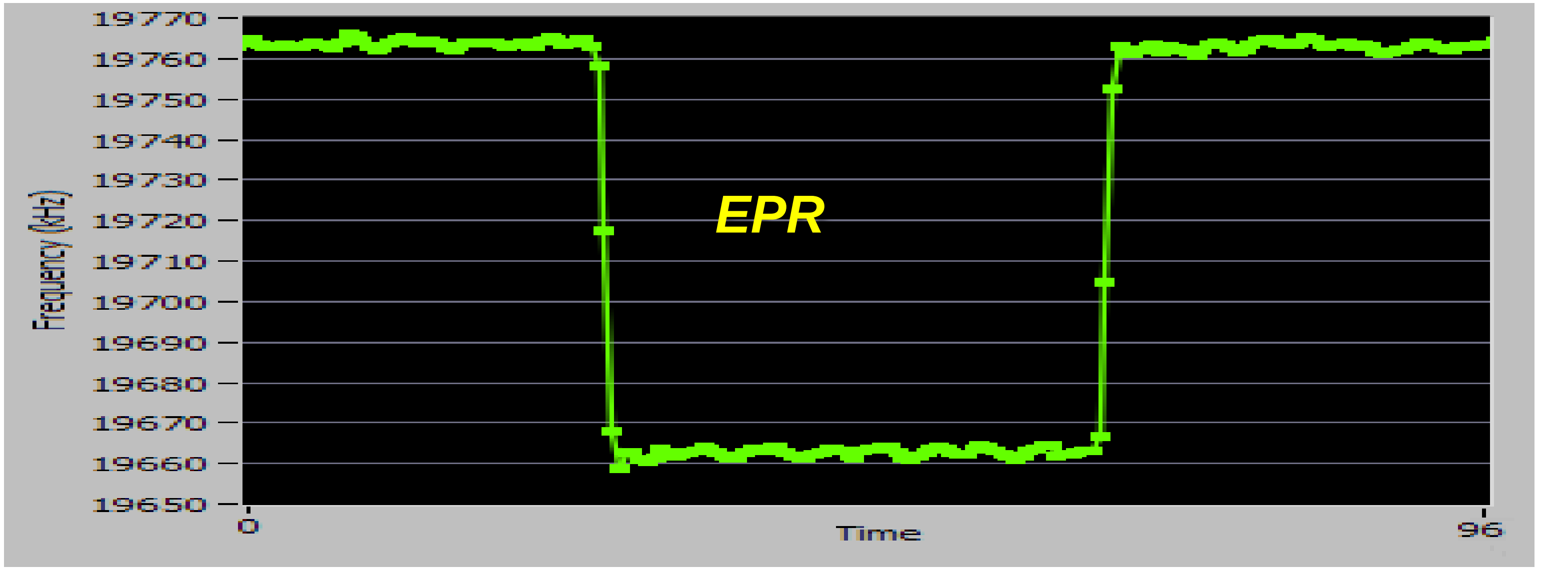


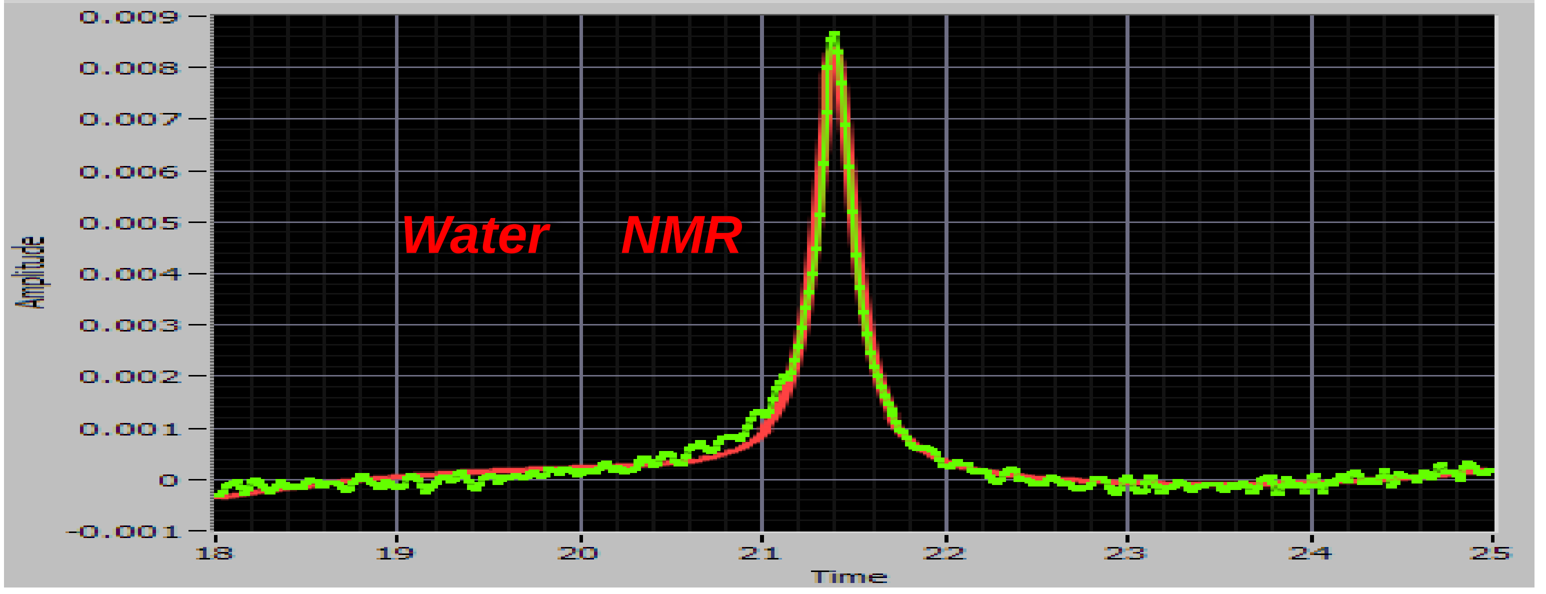


Polarimetry

- Two methods: **NMR and EPR**, precision 2-3%
- NMR (nuclear magnetic resonance)
  - RF field
  - AFP (adiabatic fast passage) sweep through resonance when target spin flips, induced signal through pickup coils
  - Needs calibration from a known (water calibration)
- EPR (electron-paramagnetic resonance)
  - Rb energy level splitting (D2 light) corresponding to main field +/- a small field due to ^{3}He polarization
  - Using AFP to flip ^{3}He spin. Frequency difference of lights emitted proportional to ^{3}He polarization
  - No calibration needed
- Cross checking with elastic asymmetry measurements

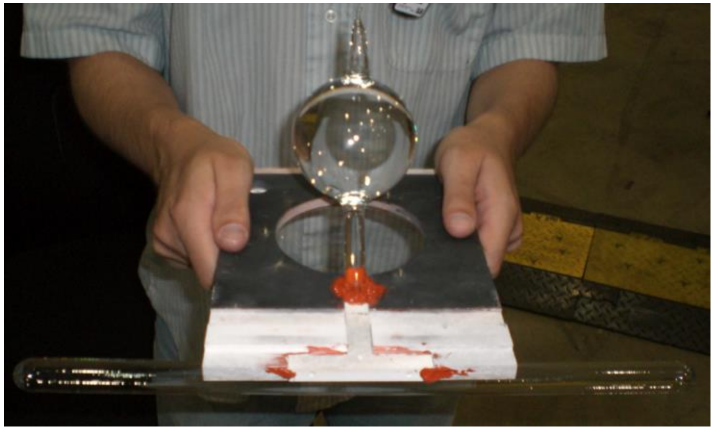
EPR and Water NMR

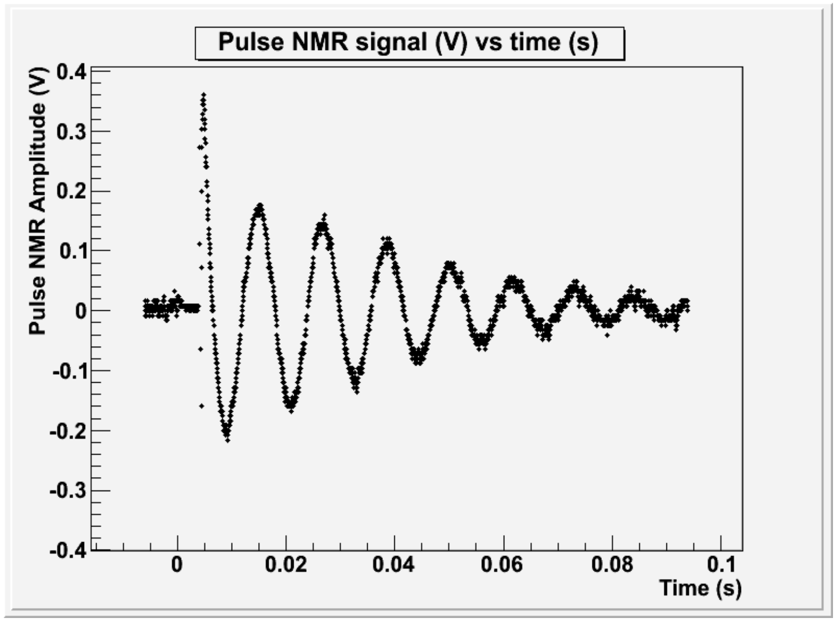


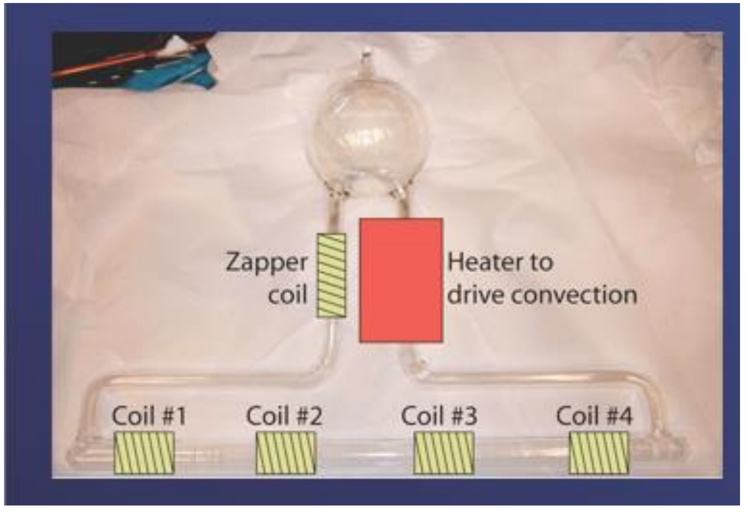


Ongoing Upgrade for Future Experiments

- 8 approved new experiments at JLab
- Aiming for luminosity **L ~ 10^{37} cm^{-2}s^{-1}**
  - Single transfer tube → two transfer tubes
    allowing convection-driven gas flow
  - Metal target chamber to withstand high beam current
- Pulsed NMR Polarimetry







Other US Polarized ^{3}He Facilities

UVa, W&M, Duke, New Hampshire, NIST, Wisconsin, Michigan, …

Polarized ^{3}He at UVa (Gordon Cates)/ W&M (Todd Averett)

- Collaborating on JLab polarized ^{3}He program
- Produce target cells for JLab experiments
- R&D on upgrade for polarized ^{3}He for JLab experiments

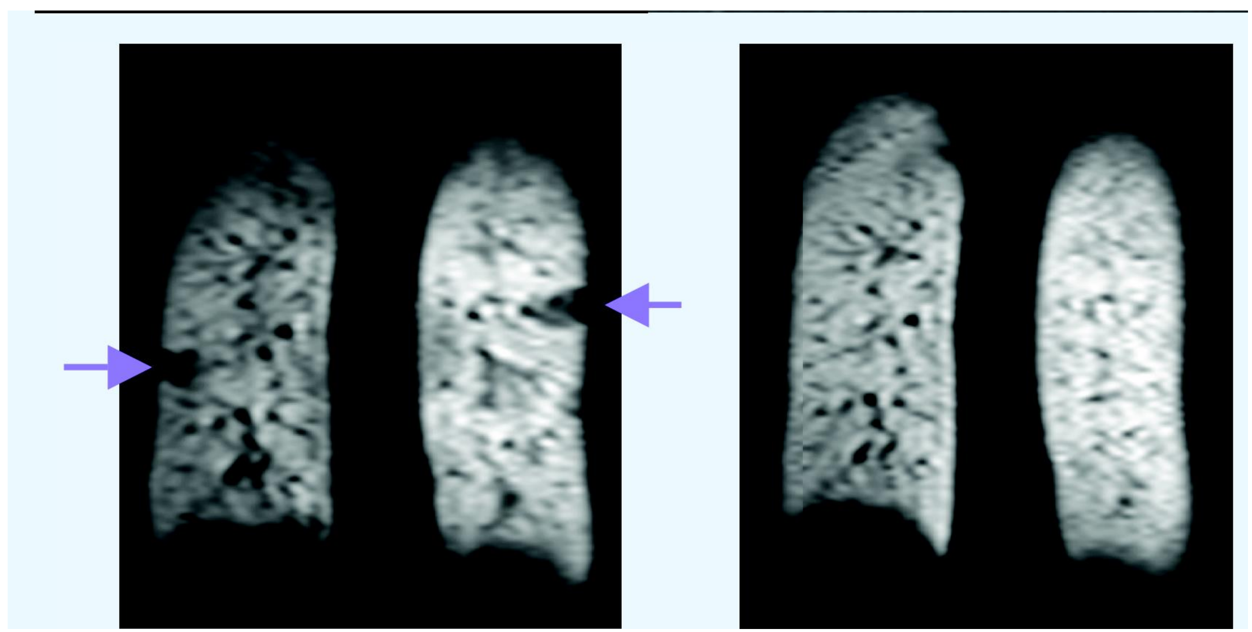
G. Cates' talk

- UVa *Center for In-vivo Hyperpolarized Gas MR Imaging (2000)*
- Both ^{3}He and ^{129}Xe

- ^{3}He Spin density MRI

Courtesy of T. Altes et al., University of Virginia

Inhaled Bronchodilator
Asymptomatic Asthmatic

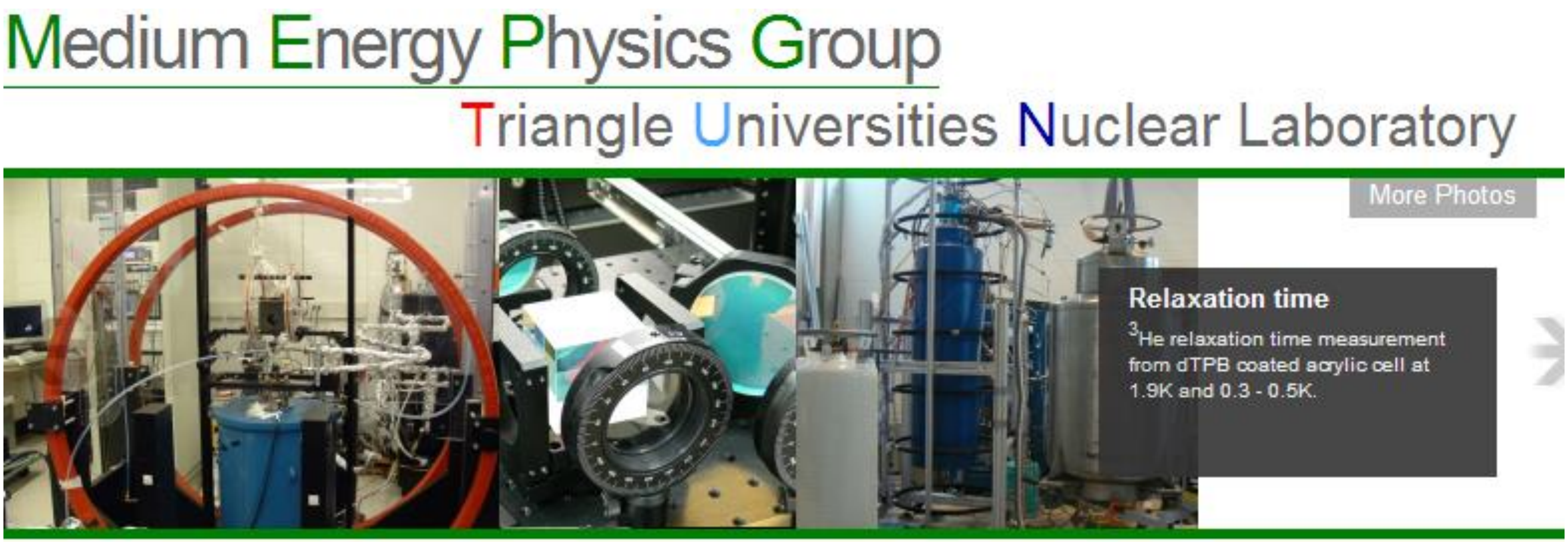


Polarized ^{3}He at Duke (Haiyan Gao)

- Collaborating on JLab polarized ^{3}He program
- ^{3}He spin structure with High Intensity γ Source (HIγS)
- Neutron Electric Dipole Moment (EDM)
- Search for Spin-Dependent Short-Range Force (collaboration with Fudan U.)

C. Fu's talk

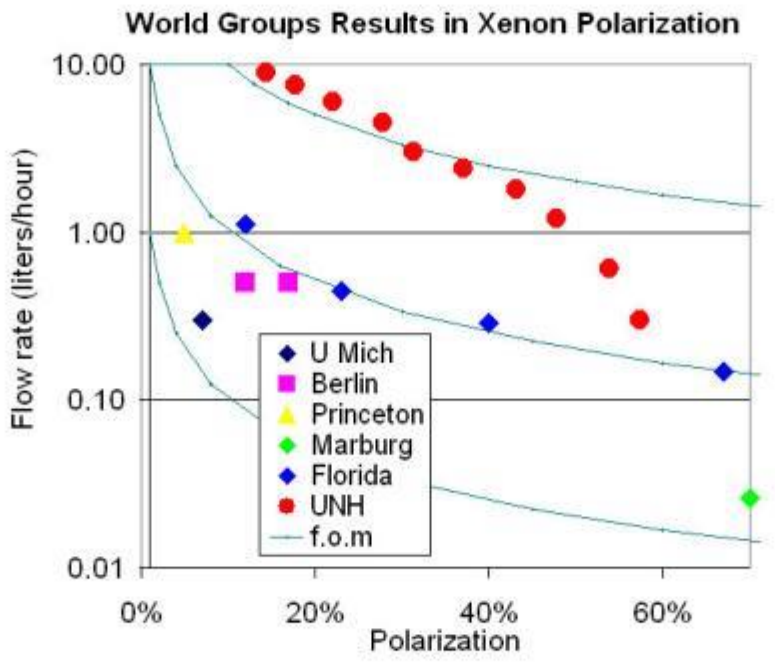
- Establishing collaboration on polarized ^{3}He R&D for at Tsinghua

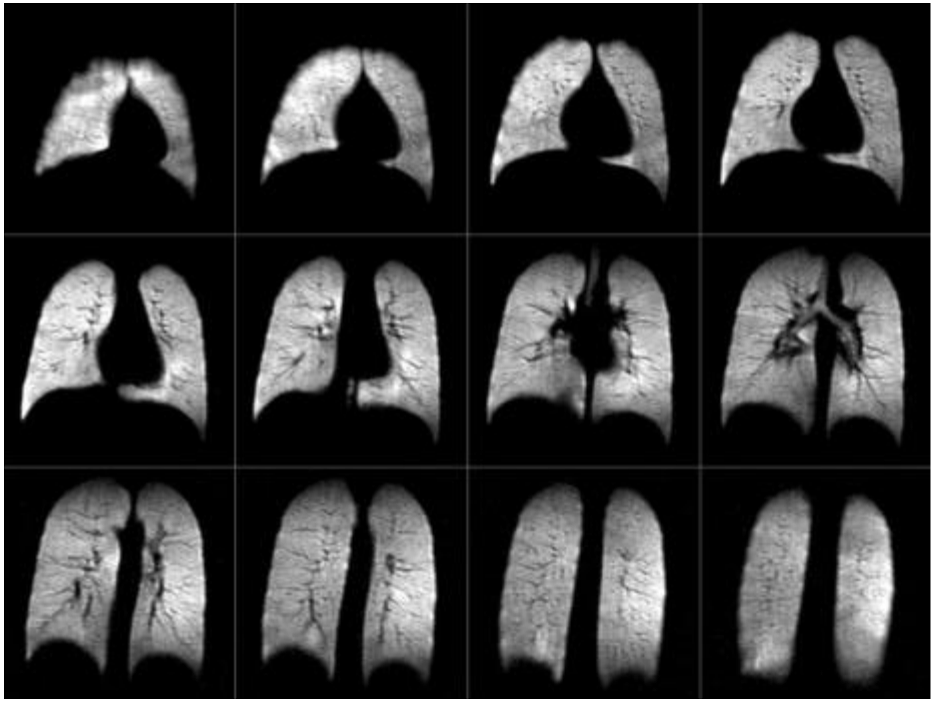


New Hampshire Center for Xenon Imaging

(W. Hersman)

- Functional Lung Imaging
- Low-field and ultra-low-field imaging
- Functional dissolved-state imaging
- Biomedical imaging simulations
- Also R&D on polarize 3He

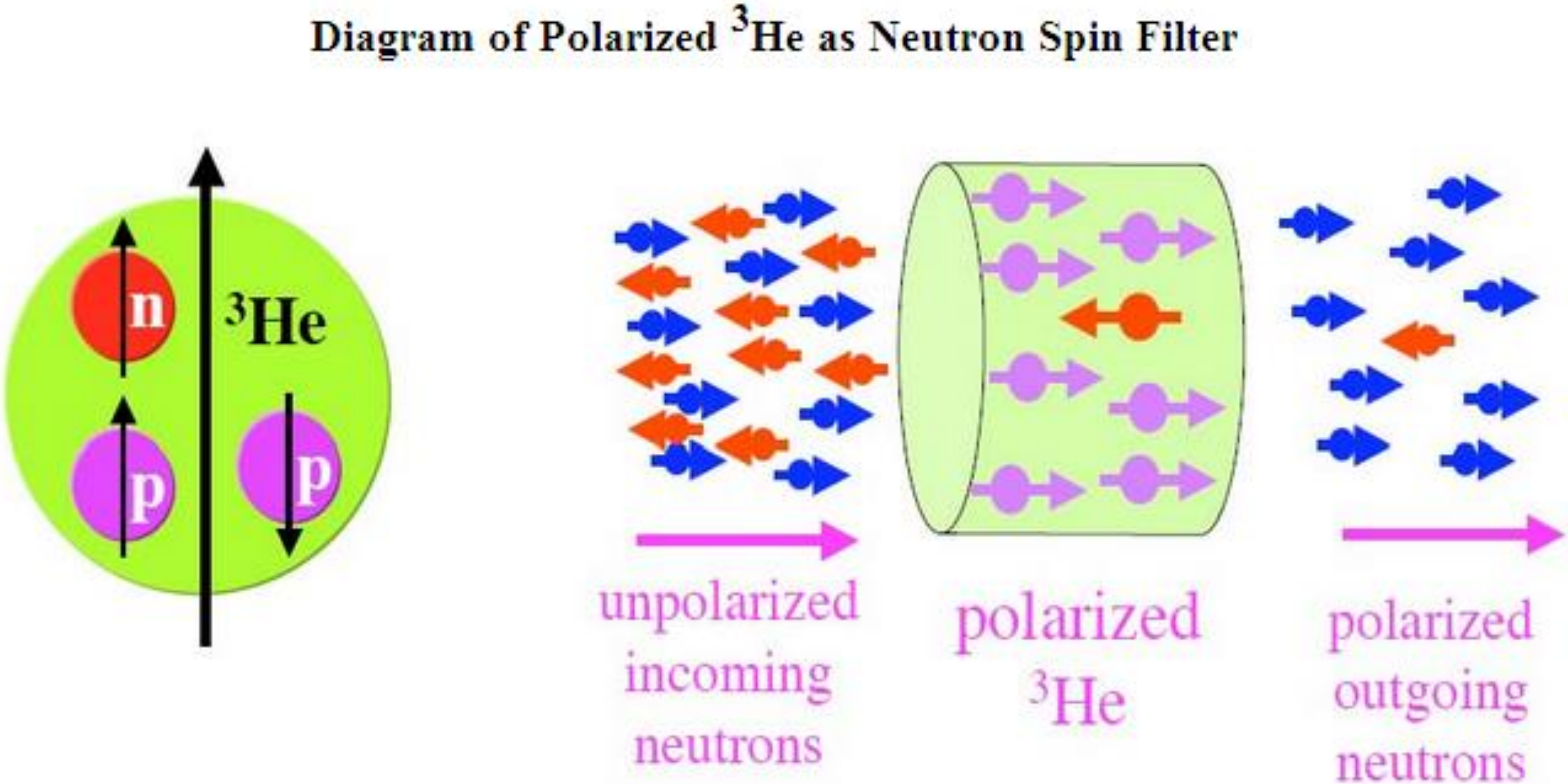




(Xemed LLC)

Polarized ^3He @ NIST and Wisconsin

- NIST, SEOP polarized ^3He as Neutron Spin Filter for material science experiments with neutron scattering — **T. Gentile**



- Wisconsin: R&D on SEOP polarized ^3He to improve performance — **T. Walker**
- Search for Axion-like Particles using dual-species NMR ^{129}Xe and ^{131}Xe
- Optically pumped alkali magnetometers for biomedical applications

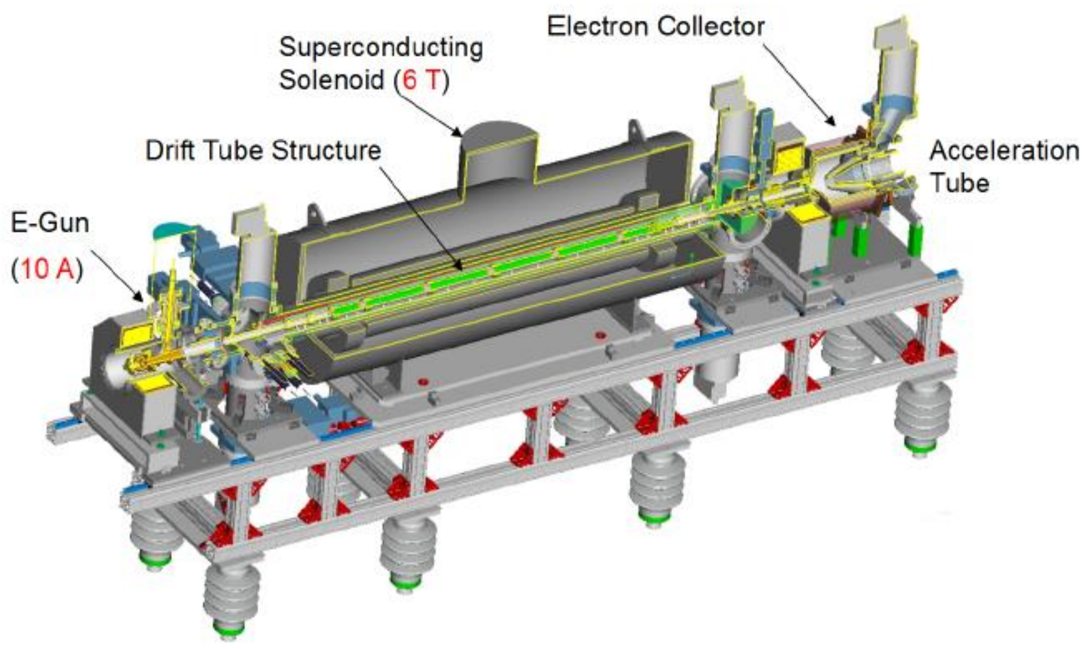
Polarized ^{3}He at Michigan (T. Chupp)

- R&D on SEOP polarized ^{3}He
- Nuclear physics (neutron spin structure)
- Fundamental Physics with Neutron
- Atomic EDM

Polarized ^{3}He Beam Source R&D for EIC @ MIT (R. Milner)

- Based on MEOP
- Doubly ionization $^3He^{++}$ for injection
- Goal: ~70% @ 30G 1 torr
- Transfer ~ 10^{-14} ^{3}He/s to EBIS @ 5T & 10^{-7} torr
- Deliver $1.5X10^{11}$ $^3He^{++}$ per 20 μs pulse

J. Maxwell's talk



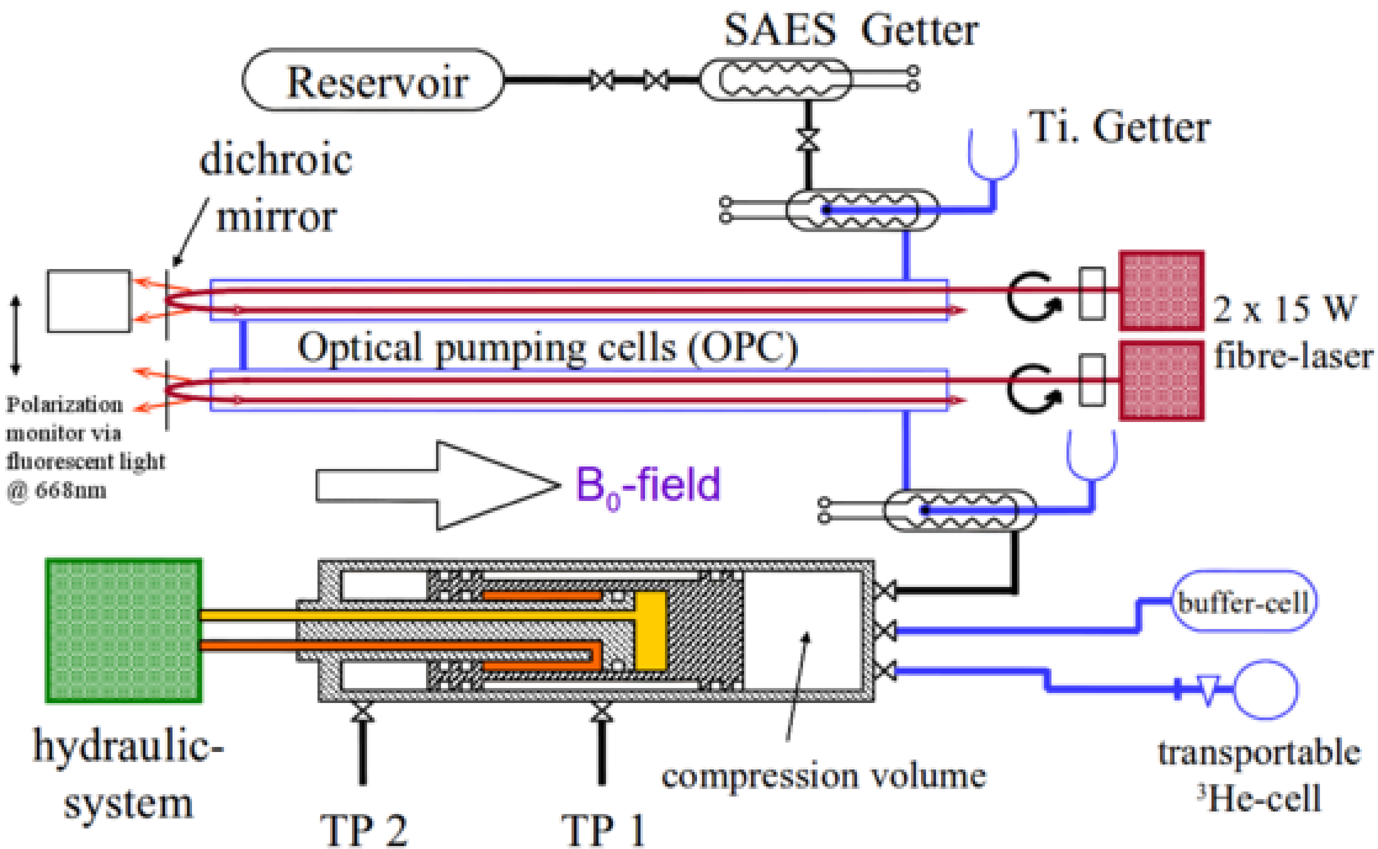
RHIC's Electron Beam Ion Source

Polarized ^{3}He Facility in Europe
Mainz (**W. Heil et al.**), …

Meta-Stability Exchange Optical Pumping

Current ^{3}He Polarizing Facility in Mainz

- P=75-78% @ 1 bar-liter/Hour for fundamental science
- P~ 65% @ 2-3 bar-liter/Hour for medical application
- "Polarized Helium Lung Imaging Network“
- “Magnetic Resonance Imaging for Diagnosis and Monitoring of COPD and Asthma”



Applications of Polarized ^{3}He @ Mainz

F. Allmendinger's talk

K. Tullney's talk

- Fundamental applications
  - Symmetry test He3/Xe-129
  - Search for new short-rang force (axion-like)
  - Search for Electric Dipole Moment of Xe-129
  - Accurate measurements of high magnetic field
  - Medium energy physics: neutron form factor, GDH sum rule
- Fundamental physics with cold and ultracold neutrons
  - angular correlation of beta-particle and neutrino in beta-decay
  - Neutron lifetime
- Medical Applications
  - MRI of the lung with ^{3}He and ^{129}Xe

Polarized ^{3}He Facilities in Asai

Japan, Korea, China (Lanzhou, Tsinghua, …)

Polarized ^{3}He in Japan: Neutron Spin Filter

H. Kira et al.

- Japan: SEOP polarized 3He as Neutron Spin Filter
- Developed for the pulsed neutron beam at J-PARC BL10 beamline

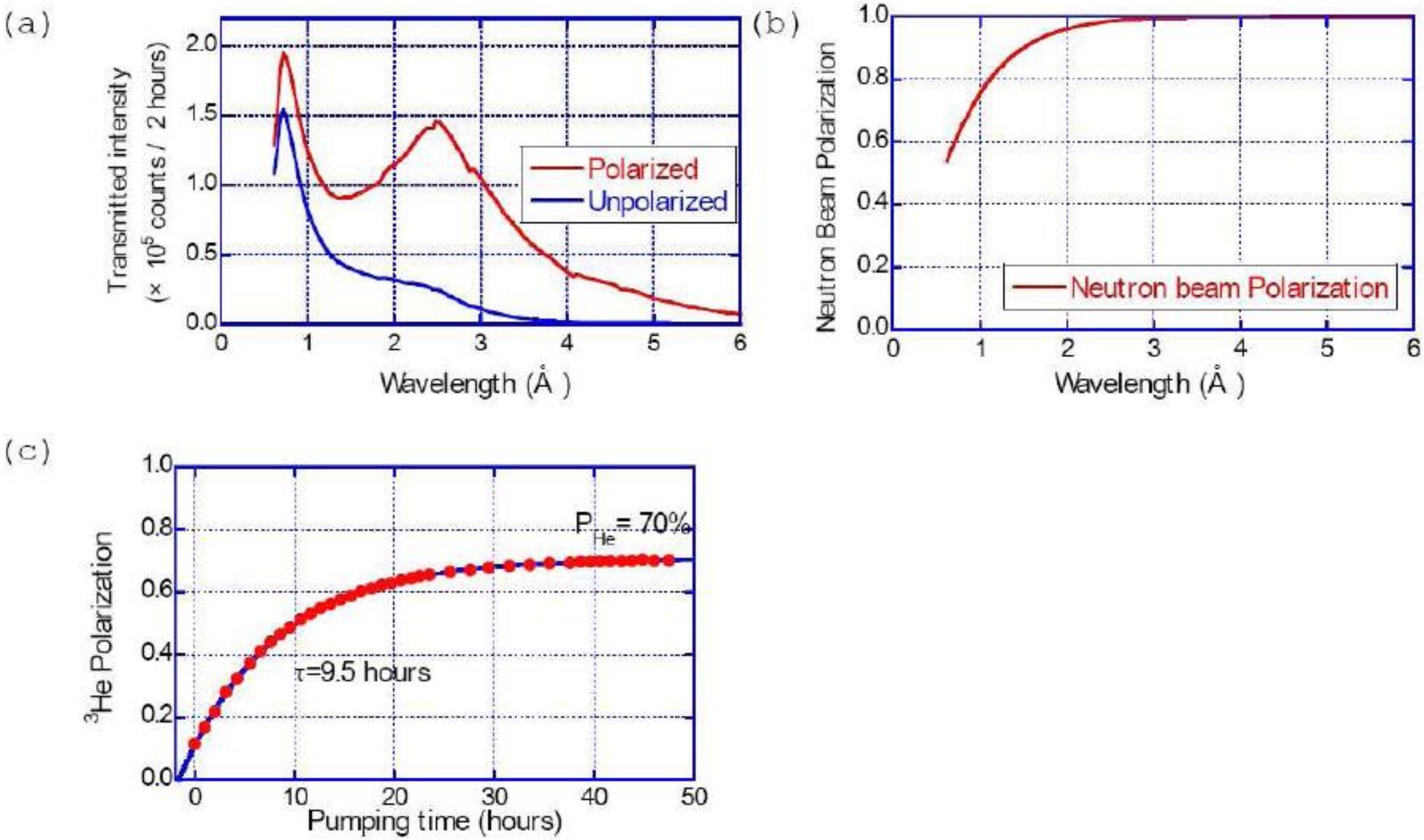
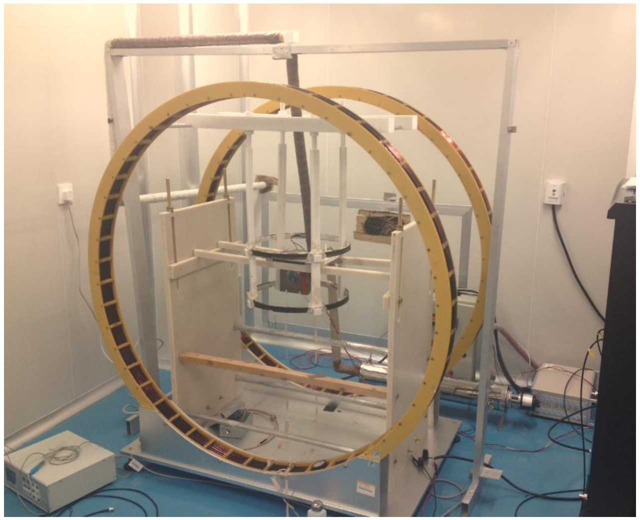
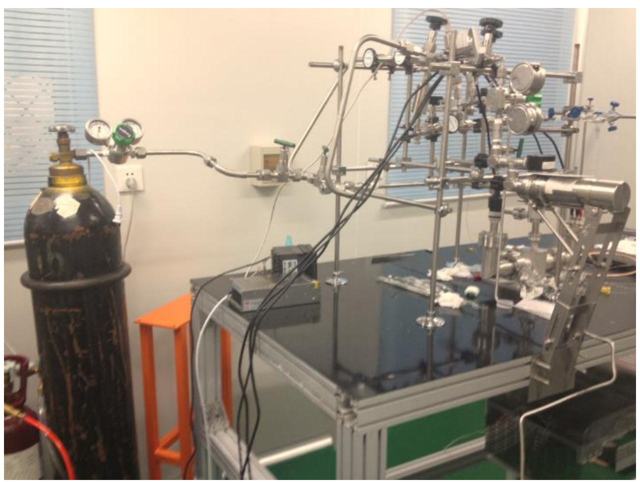


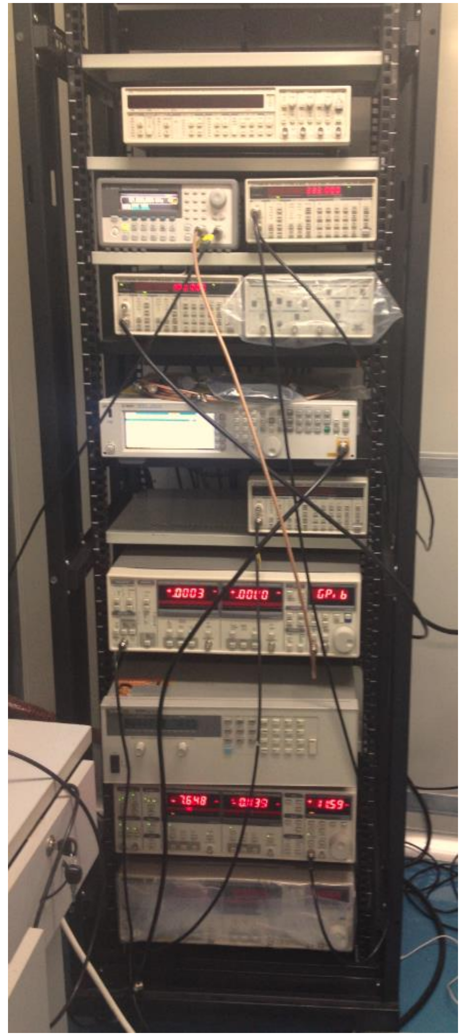
Figure 3. (a) Wavelength dependence of the transmitted neutron beam intensity for the NSF with polarized and depolarised ^{3}He gas. (b) Calculated neutron polarization. (c) Pumping time dependence of the ^{3}He gas polarization measured during in-situ SEOP.

Polarized ^{3}He @ Lanzhou Univ.

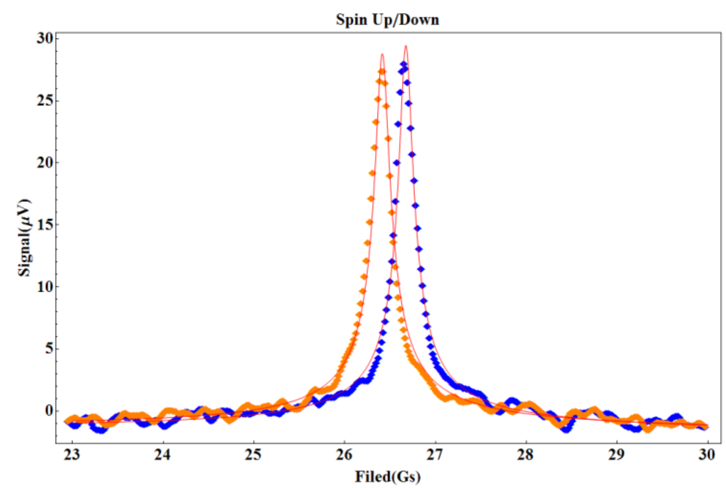
B. Hu, Y. Zhang, *et al.*





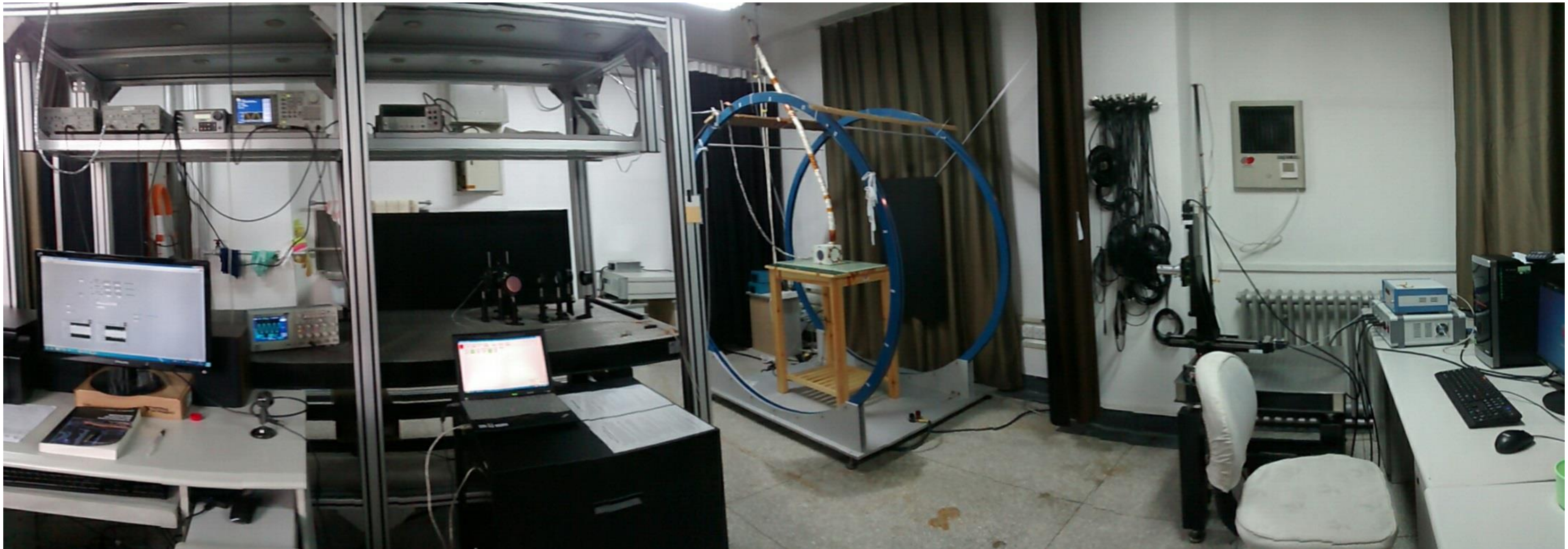


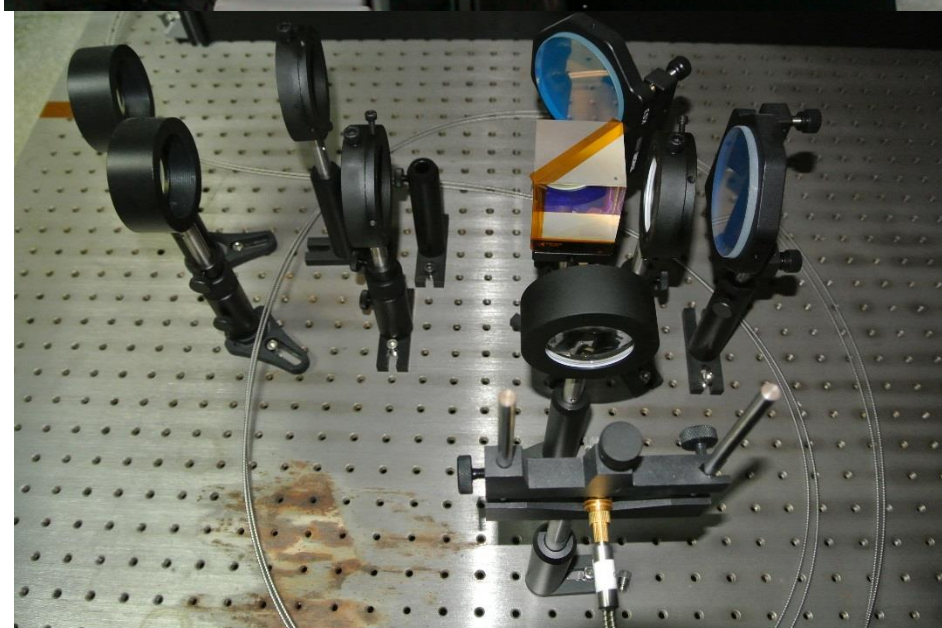
- clean room
- **gas filling system**
- SEOP
- Obtained 1st polarization
- NMR (3He and water)
- EPR (commissioning)



Polarized ^{3}He Lab at Tsinghua for fundamental symmetry studies

H. Gao et al.





Summary

- Spin and polarization: amazing phenomenon with broad applications
- Introduction to polarized ^{3}He: SEOP and MEOP, tremendous progress
- Polarized ^{3}He: critical for neutron spin structure study,
  wide range of fundamental physics,
  medical imaging and other applications
- JLab: SEOP, neutron and ^{3}He spin physics
  Highest polarized luminosity and highest FOM
  Future: improve luminosity by one order of magnitude
- Polarized 3He groups in USA, Europe and Asia
- Pioneering work just started in China (Lanzhou/Hefei, Tsinghua, …)
- Useful tool for spin physics and great potential for applications