Polarized ^3He beams for EIC

Caolionn O'Connell

July 18, 2006

FUTURE PROSPECTS IN QCD AT BNL

Polarized ^{3}He beams for ~~EIC~~ eRHIC

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:: COLLABORATORS ::

J. Alessi, S. Aronson, E. Beebe, D. Lowenstein, A. Pikin, T. Roser, A. Zelenski
BROOKHAVEN NATIONAL LABORATORY

A. Hoffman, R. Milner, F. Simon
MIT/BATES LABORATORY

E. Hughes, C. O'Connell
CALIFORNIA INSTITUTE OF TECHNOLOGY

:: INTRODUCTION ::

- HISTORICAL CONTEXT
- MOTIVATION FOR POLARIZED ^{3}HE BEAMS
- PREVIOUS WORK IN POLARIZED ^{3}HE BEAMS
- ADDITIONAL DEVELOPMENT IN POLARIZED ^{3}HE
- OVERALL DESIGN
  - ^{3}HE SOURCE (MIT BATES)
  - EBIS (BROOKHAVEN)
  - POLARIMETER (CALTECH)
- SCHEDULE
- CONCLUSION

:: HISTORICAL CONTEXT ::

IN REACTION TO THE “PROTON SPIN CRISIS”, THERE WAS A RUSH OF EXPERIMENTS TO MEASURE THE NEUTRON SPIN STRUCTURE

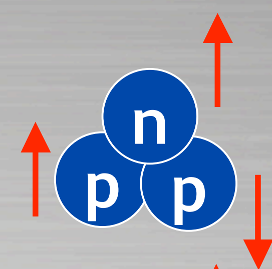
CERN SMC

μ (100 GeV) → **deuterons**

(1993)

SLAC E142

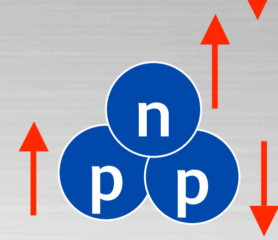
e (22 GeV) → ^{3}He



(1993)

DESY HERMES

e (27 GeV) → ^{3}He



(1996)

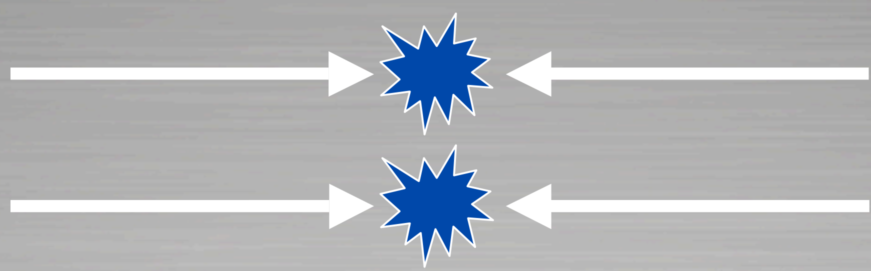
:: HISTORICAL CONTEXT ::

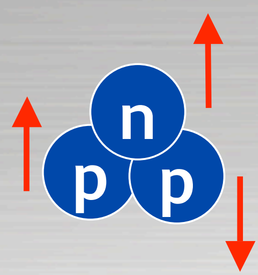
EXPERIMENT	BEAM	ENERGY	TARGET	YEARS
CERN EMC	muons	200 GeV	proton	1987 - 1988
CERN SMC	muons	100 - 200 GeV	proton deuteron	1993 - 1998
DESY HERMES	positrons	27 GeV	proton deuteron ^{3}He	1995 - Present
SLAC E142	electrons	22 GeV	^{3}He	1993 - 1995
SLAC E143	electrons	29 GeV	proton deuteron	1994 - 1996
SLAC E154	electrons	50 GeV	^{3}He	1997
SLAC E155	electrons	50 GeV	proton deuteron	1998 - 2002

MOTIVATION:
Spin structure ⇒ eRHIC

polarized e ⟶ ⟵ **polarized p**

polarized e ⟶ ⟵ **polarized ^{3}He**





neutron spin structure ⇒ polarized ^{3}He ions

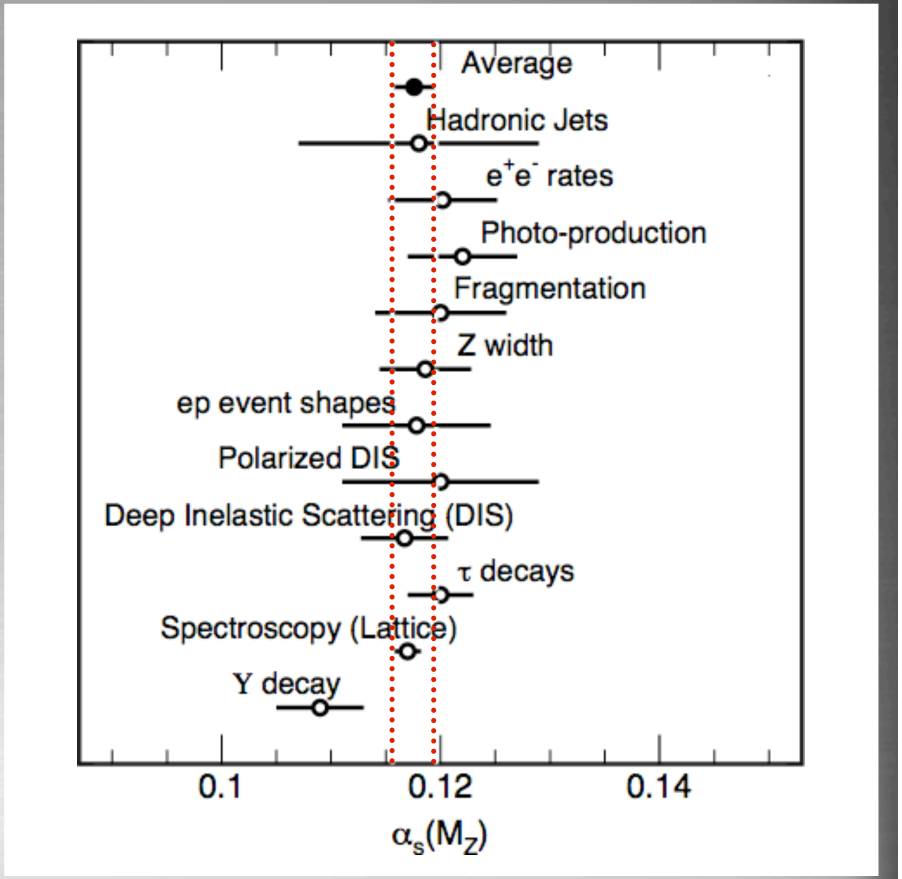
$$\underbrace{\int_0^1 g_1^p(x)dx}_{\text{proton}} - \underbrace{\int_0^1 g_1^n(x)dx}_{\text{neutron}} = \frac{1}{6}\left(\frac{g_A}{g_V}\right)\left(1 - \frac{\alpha_s(Q^2)}{\pi} - \ldots\right)$$

BJORKEN SUM RULE:

⇒ test fundamental prediction of perturbative QCD

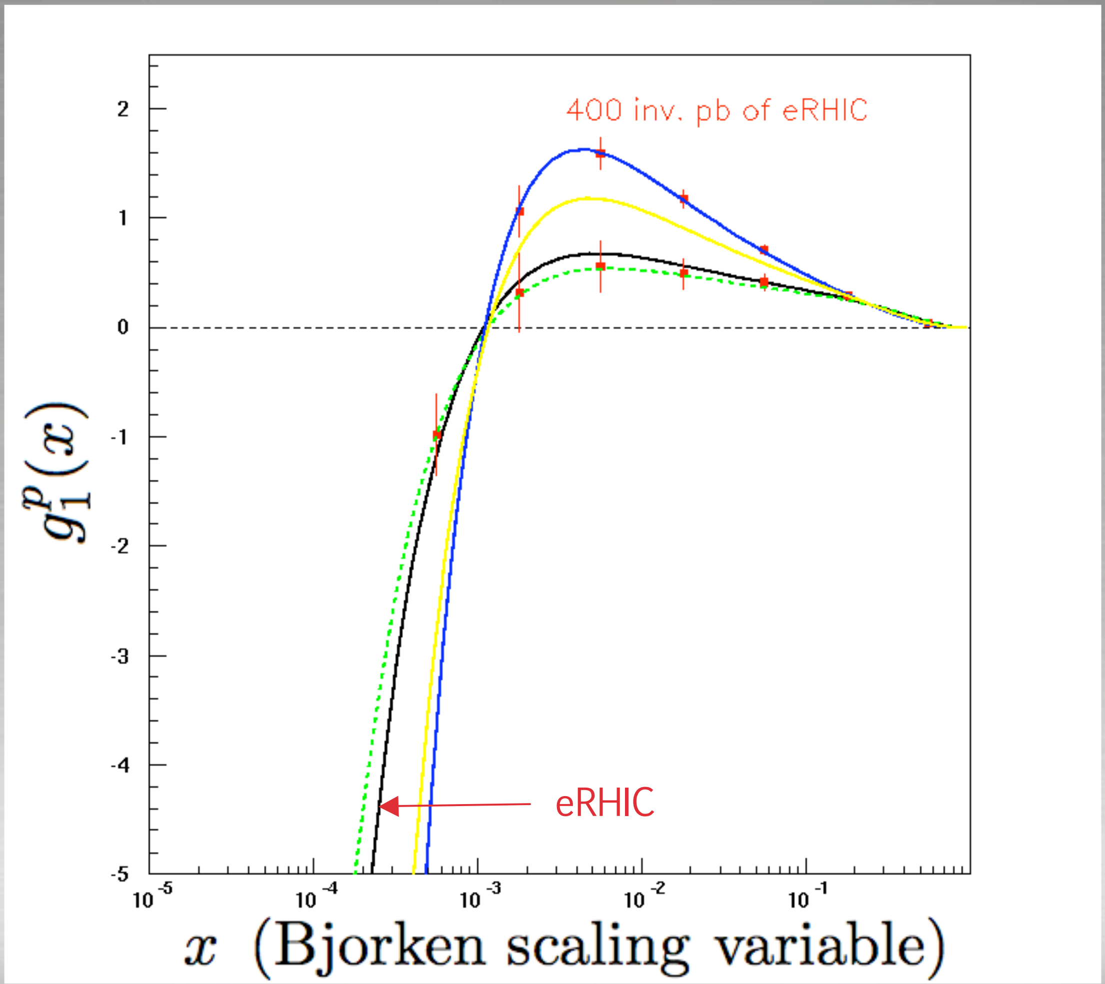
⇒ measurement of α_s is dominated by systematic uncertainties

⇒ ideally, eRHIC can minimize the systematic uncertainties and provide precision data at lower values of x



S. Eidelman *et al.* Phys. Lett. B **592**, 1 (2004)

simulation of proton spin structure function measurement



:: PREVIOUS ^{3}He BEAMS ::

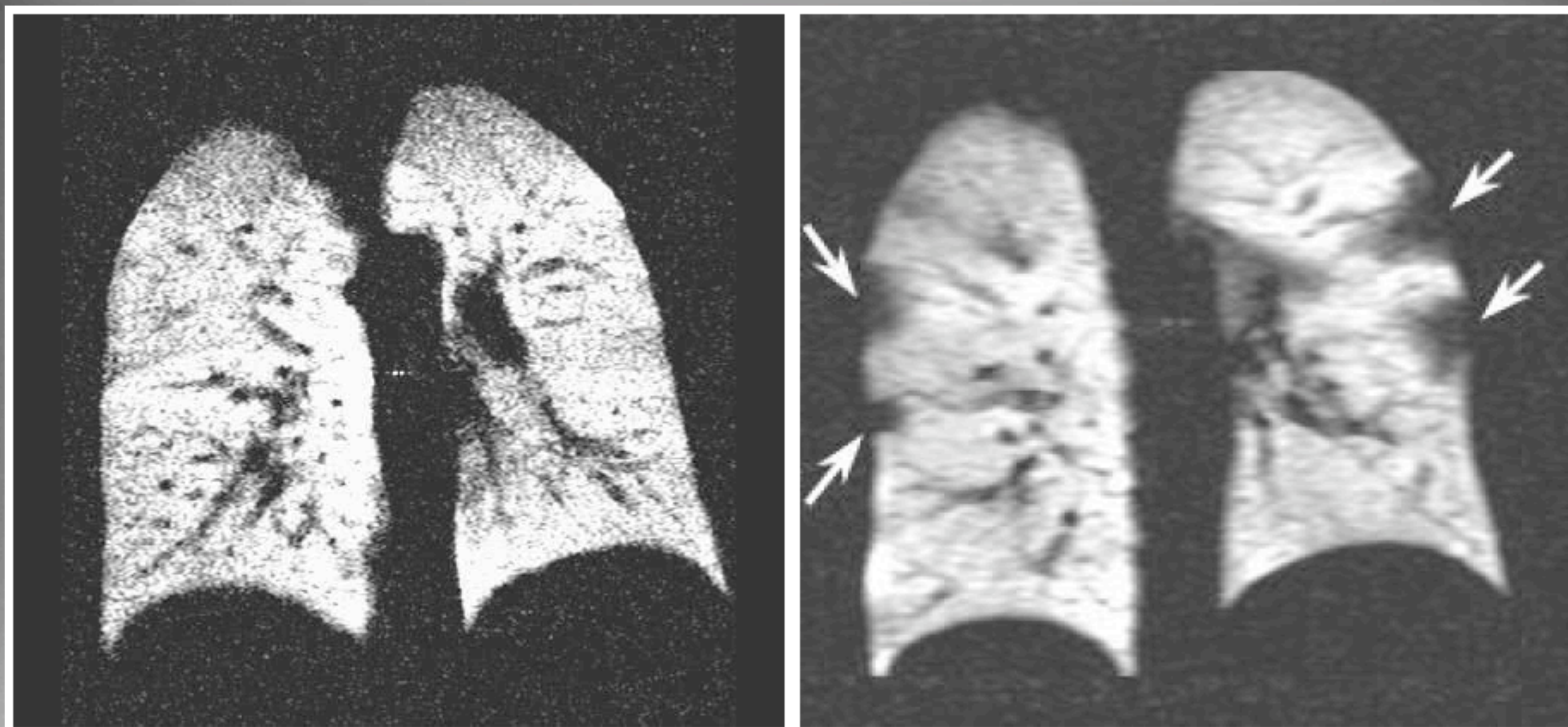
Source	Current	Polarization	Emittance	Beam Energy	Energy Spread	Ion
Birmingham	50 pnA	55-65%	70 mm mrad.	29 keV	100 eV	$^3He^{++}$
Laval	100 nA	95%	25 mm mrad.	12 keV		$^3He^{+}$
Rice/Texas A&M	8 μA	11%	10mm mr MeV$^{1/2}$	16 keV	10-50 eV	$^3He^{+}$

Status from 1984's Workshop on Polarized ^{3}He Beams and Targets in Princeton, NJ

⇒ Mostly from the 1970s-1980s

⇒ Spin-exchange and metastability exchange techniques for ^{3}He polarization have been greatly improved since then due to laser development.

NMR TOMOGRAPHY OF THE LUNGS



non-smoker smoker

University of Mainz
Journal of Magnetic Resonance Imaging Volume 7, Issue 3, 1997. Pages 538-543.

:: DEVELOPMENT ELSEWHERE ::

Nuclotron at JINR in Dubna, Russia [1]

⇒ Goal to make intensive polarized $^3He^{++}$ beam
⇒ Spin exchange with an optically pumped Rb-vapor
⇒ ~50% polarization
⇒ Ion beam intensity 2-5x10^{11} ions/pulse

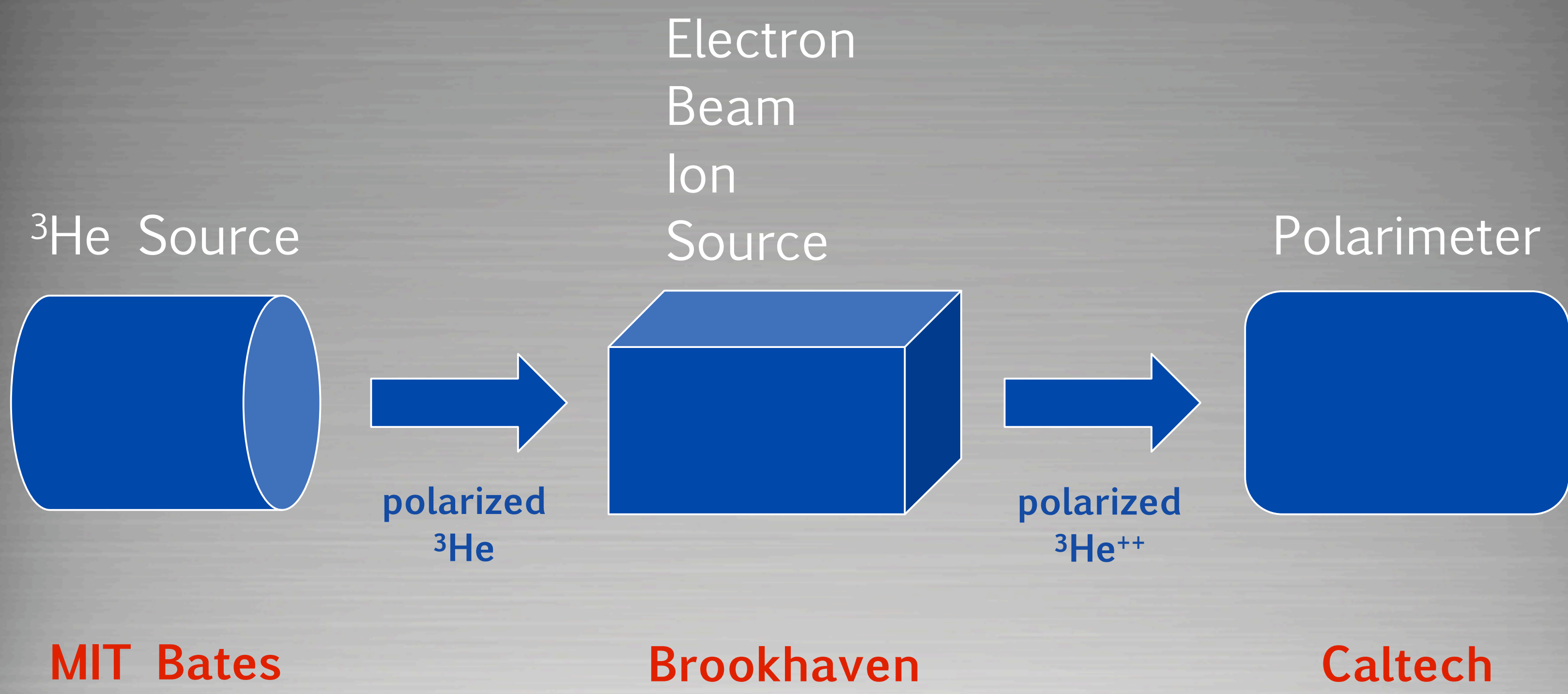
RCNP at Osaka University in Japan [2]

⇒ Extensive work on producing a highly-polarized $^3He^+$ beam.

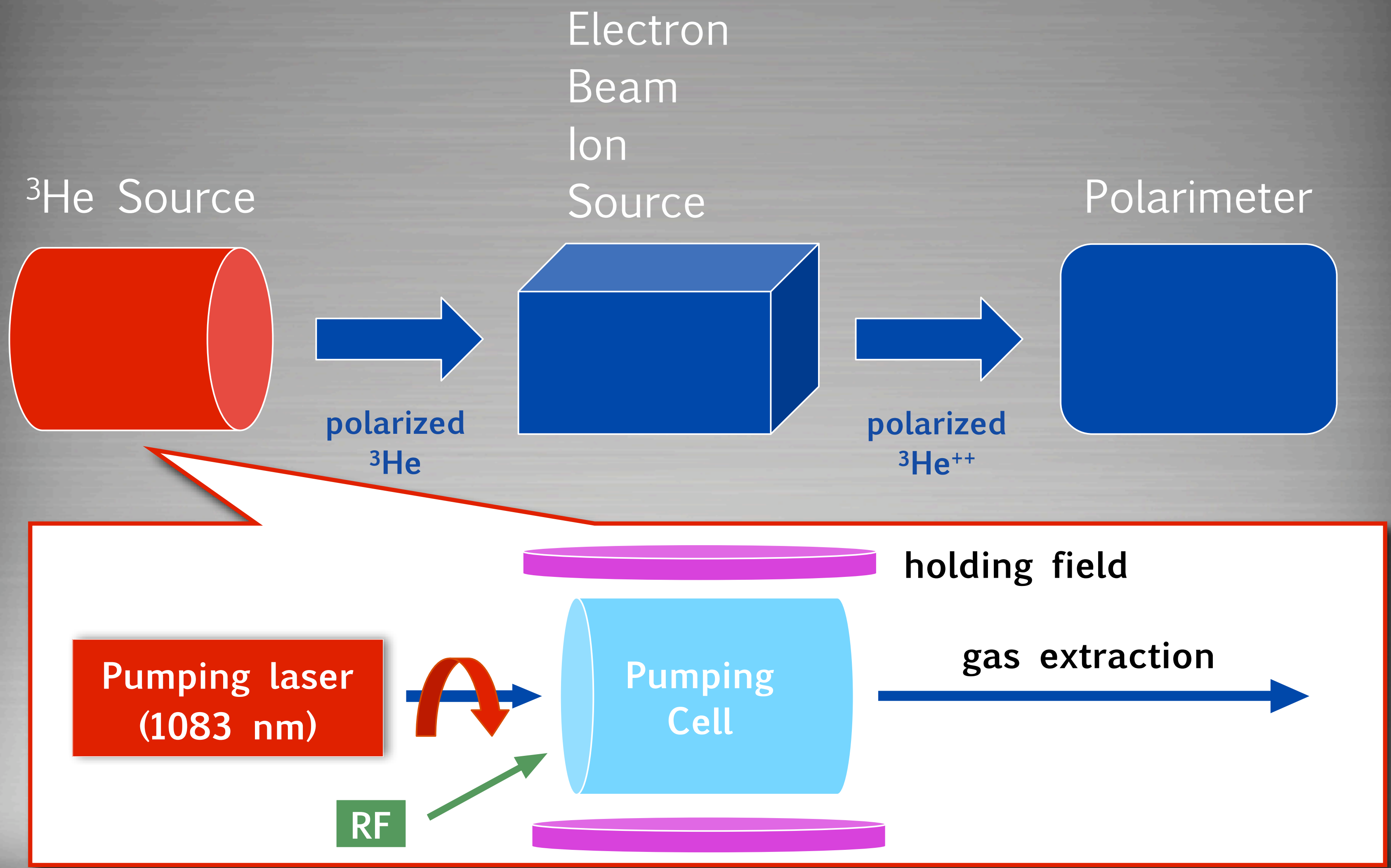
[1] N. N. Agapov "A Proposal of a polarized $^3He^{++}$ Ion Source with Penning Ionizer for JINR" at *Polarized Sources and Targets* in Tokyo, Japan, 2005

[2] M. Tanaka "Production of a nuclearly polarized $^3He^+$ beam by multiple electron capture and stripping collisions" Phys. Rev. A 60, R3354-R3357 (1999)

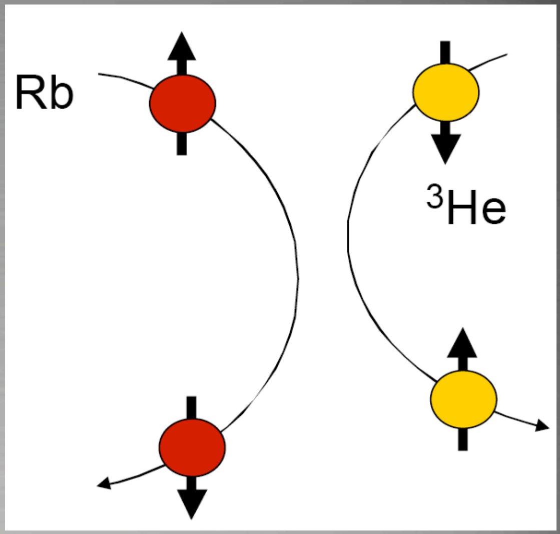
:: OVERALL ::


^{3}He Source
Electron
Beam
Ion
Source
Polarimeter
polarized
^{3}He
polarized
$^3He^{++}$
MIT Bates
Brookhaven
Caltech

:: ^{3}He SOURCE ::


Electron
Beam
Ion
Source
3He Source
Polarimeter
polarized
3He
polarized
3He++
holding field
Pumping laser
(1083 nm)
Pumping
Cell
gas extraction
RF

:: ^{3}He SOURCE ::



Spin Exchange:

- ⇒ Rb vapor mixed with ^{3}He
- ⇒ Rb polarized by optical pumping
- ⇒ ^{3}He polarized through collisions with Rb
- ⇒ Long time scales
- ⇒ Rb has to be removed from ^{3}He
- ⇒ Typical pressures a few bar

Optical Pumping and Metastability Exchange:

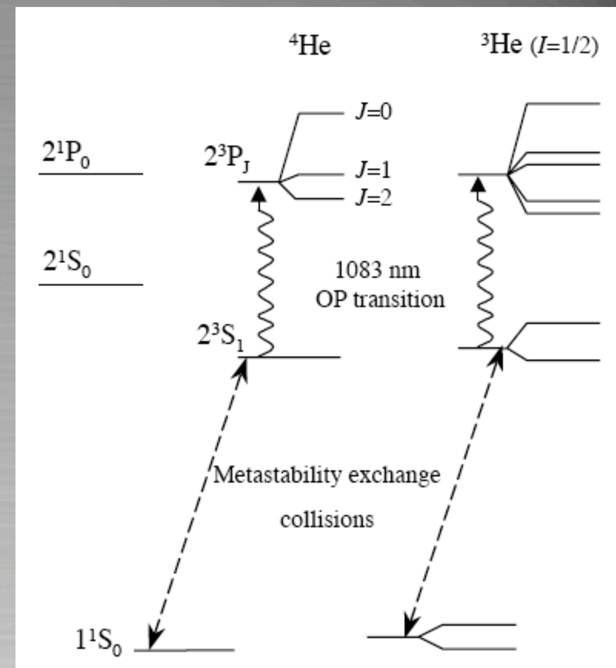
- ⇒ Directly pump an excited state of ^{3}He
- ⇒ Roughly ten times faster than spin-exchange, at the price of greater mechanical complexity
- ⇒ Weak external magnetic field (~10 Gauss)
- ⇒ Works only at low pressure (~1mbar)

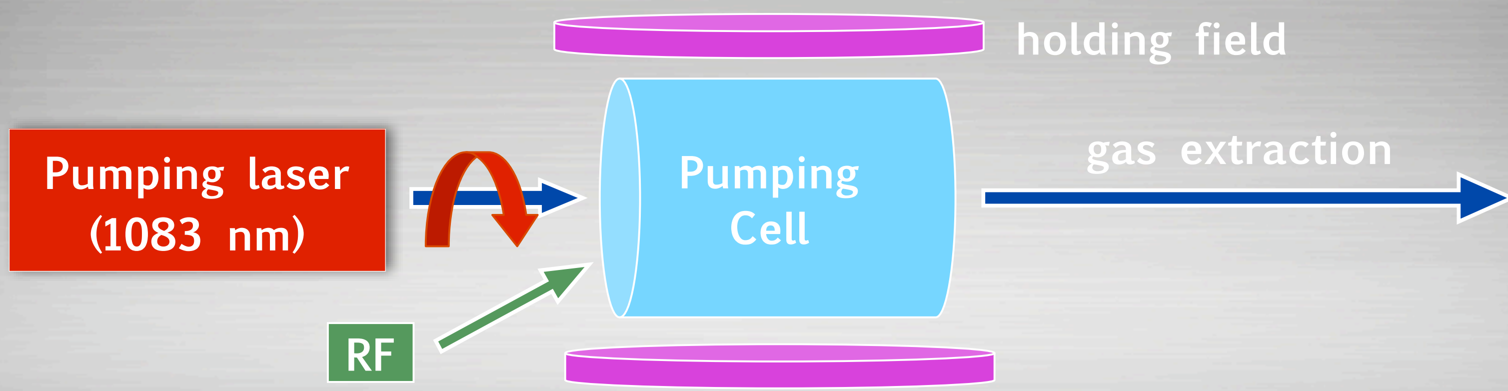
:: ^{3}He SOURCE ::

METASTABILITY EXCHANGE

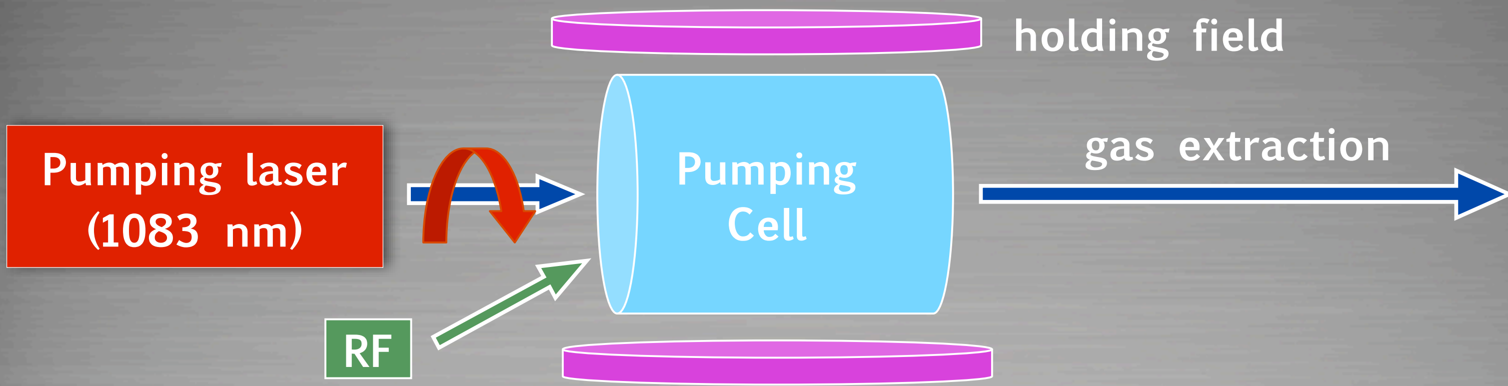
An RF discharge populates the atoms in the exited metastable 2^3S state which are then polarized by optical pumping using the 2^3S – 2^3P transition at 1083 nm.

The polarization is transferred to the 1^1S ground state through metastability exchange collisions.





:: ^{3}He SOURCE ::

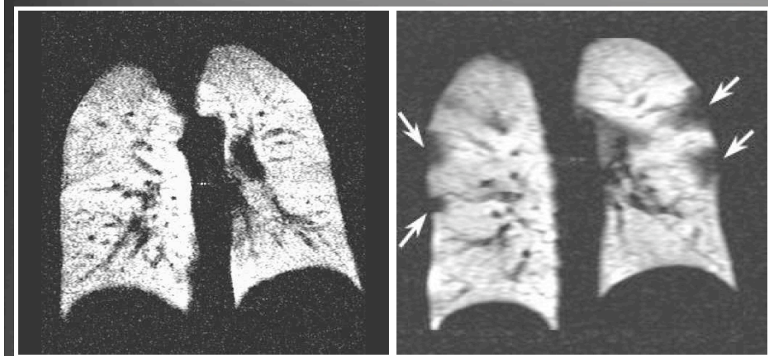


Critical Components

- ⇒ Flow Rate: Time an atom typically spends in the pumping cell
- ⇒ Laser Power: Determines maximum polarization and possible flow rates
- ⇒ Gas purity: Impurities lead to depolarization
- ⇒ Gas extraction line: Field gradients and wall interactions lead to depolarization

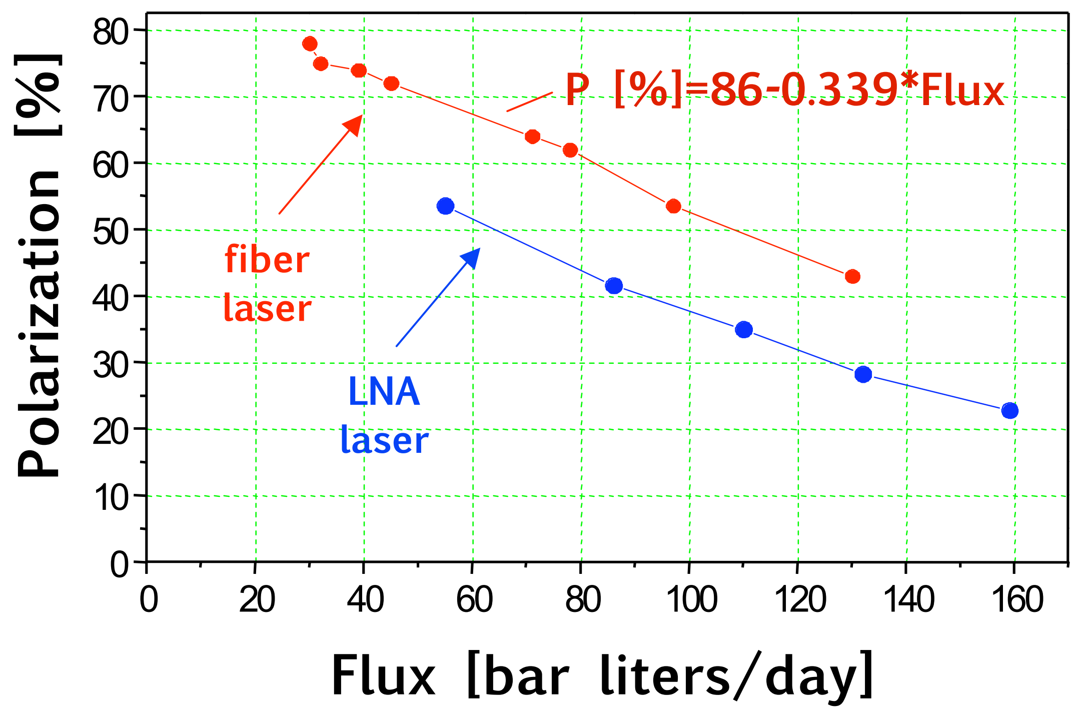
:: ^{3}He SOURCE :: lasers

:: MIT ::
:: CALTECH ::
:: BROOKHAVEN ::



50 bar liters/day = 1.5 x 10^{19} atoms/sec

Performance of the Mainz (Prof. Heil *et al.*) ^{3}He Polarizer and Compressor with old (LNA-laser 8W) and new (IRP-fiber laser 25 W) laser system



:: ^{3}He SOURCE ::

⇒ **EXPECTATION:** Polarization ~70-80% with fiber laser

⇒ **EXPECTATION:** Production rate of ~10^{15} polarized atoms/s.

Design considerations:

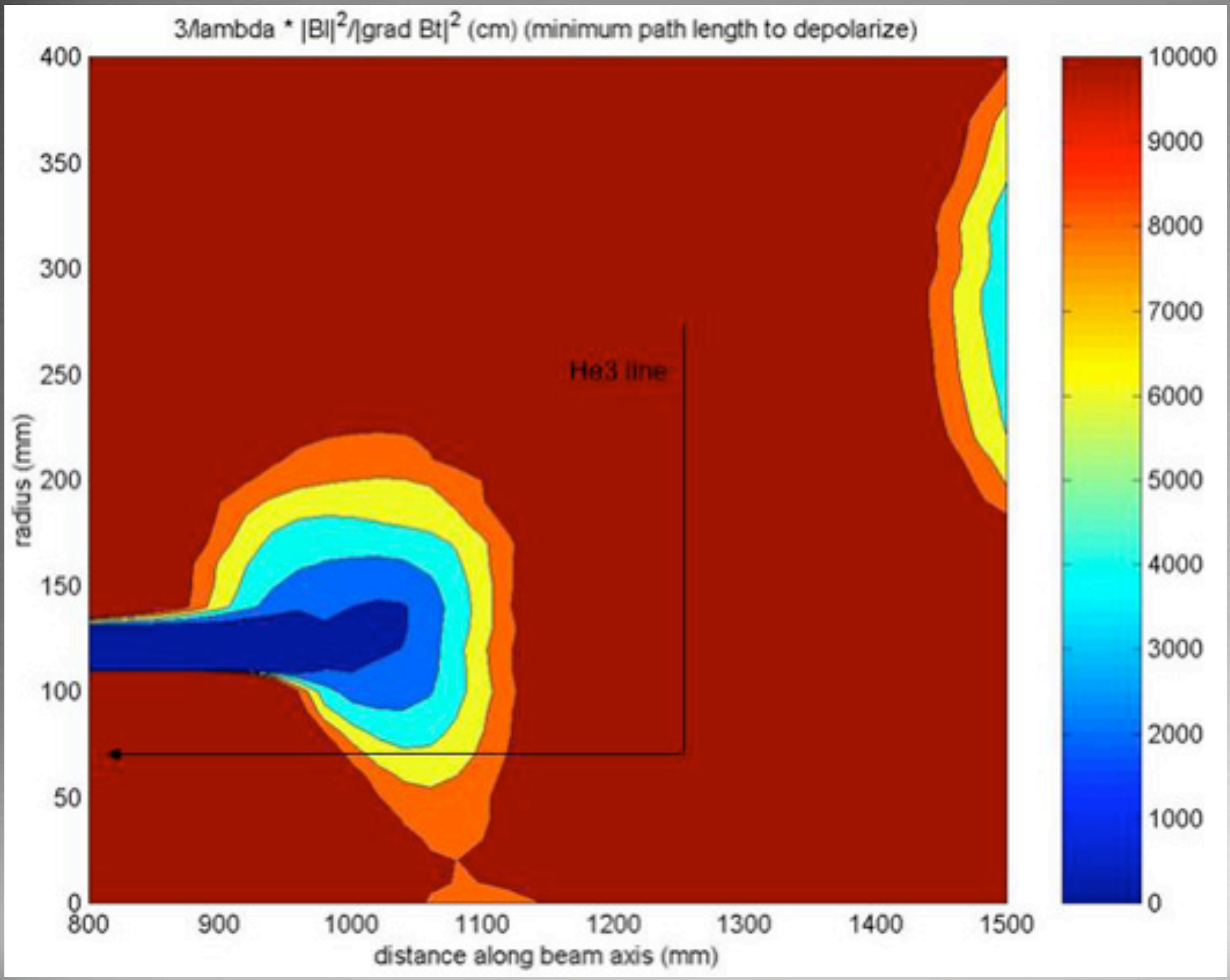
PUMPING CELL VOLUME

- ⇒ For a flow rate of 10^{15} atoms/s minimal volume 10 ml
- ⇒ Time needed to reach maximum polarization ~100 s

^{3}He PATH FROM PUMPING CELL TO EBIS

- ⇒ Magnetic field gradients lead to depolarization

:: ^{3}He SOURCE :: transport

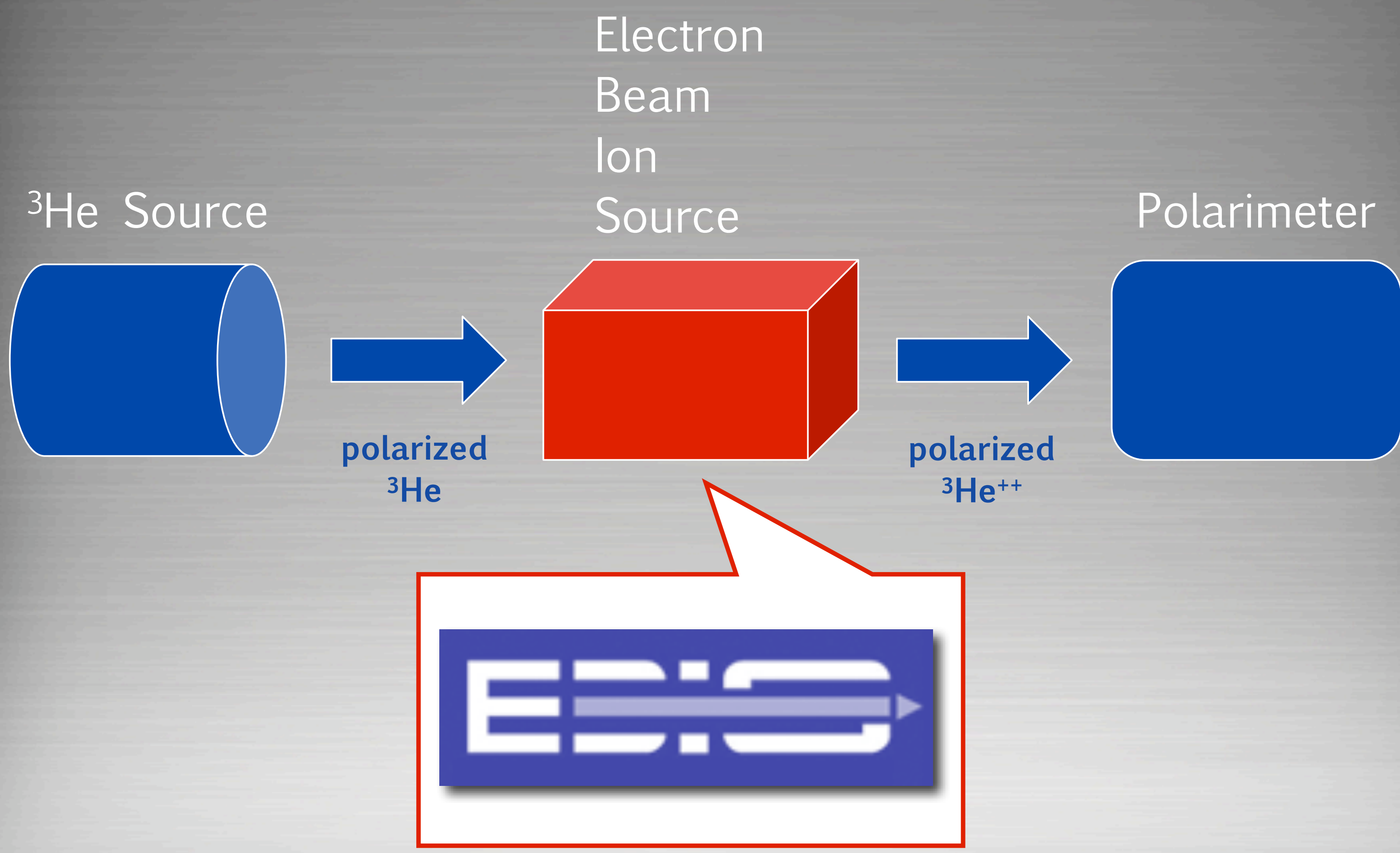


Need to avoid large field gradients to limit depolarization

Calculation based on field map of EBIS magnet

:: EBIS ::

:: MIT ::
:: CALTECH ::
:: BROOKHAVEN ::



:: EBIS ::

⇒ Brookhaven is developing a new pre-injector system based on an Electron Beam Ion Source (EBIS) design.

⇒ EBIS will improve both the performance and the operational simplicity of the machine, as well as allowing flexibility in the type of atomic species used and the ability to deliver beam to multiple users.

⇒ Brookhaven has successfully built a full power, half-length prototype for EBIS called the Electron Beam Test Stand (EBTS) to demonstrate an EBIS capable of meeting the RHIC requirements.

⇒ The EBTS is now being used to study the basic physics of a high-intensity source.

:: EBTS ::

:: MIT ::
:: CALTECH ::
:: BROOKHAVEN ::

	Achieved	RHIC
Ion	Au^{32+}	Au^{32+}
I_e	10 A	10 A
J_e	~575 A/cm^2	575 A/cm^2
$t_{confinement}$	35 ms	35 ms
L_{trap}	0.7 m	1.5 m
Capacity	0.51 x 10^{12}	1.1 x 10^{12}
Au neutralization	70% *	50%
% in desired Q	20%	20%
Extracted charge	55 nC	85 nC
Ions/pulse	1.5 x 10^9 (Au^{32+}) *	3.3 x 10^9 (Au^{32+})
Pulse width	10-20 μs	10-40 μs

* Estimated result for data with 8A e-beam

:: EBTS ::

⇒ Polarized ^3He gas is injected in the EBIS ionizer.

⇒ The ionization in EBIS occurs in a 50 kG field.

⇒ The field greatly suppresses the depolarization in the intermediate He^+ single charge state where the critical field for $^3He^+(1S)$ is 3.1 kG.

⇒ The charge ratio $He^{++}/He^+ >> 1$.

⇒ The number of He^{++} ions is limited to maximum charge which can be confined in EBIS (about 2.5×10^{11} of $^3He^{++}$/store).

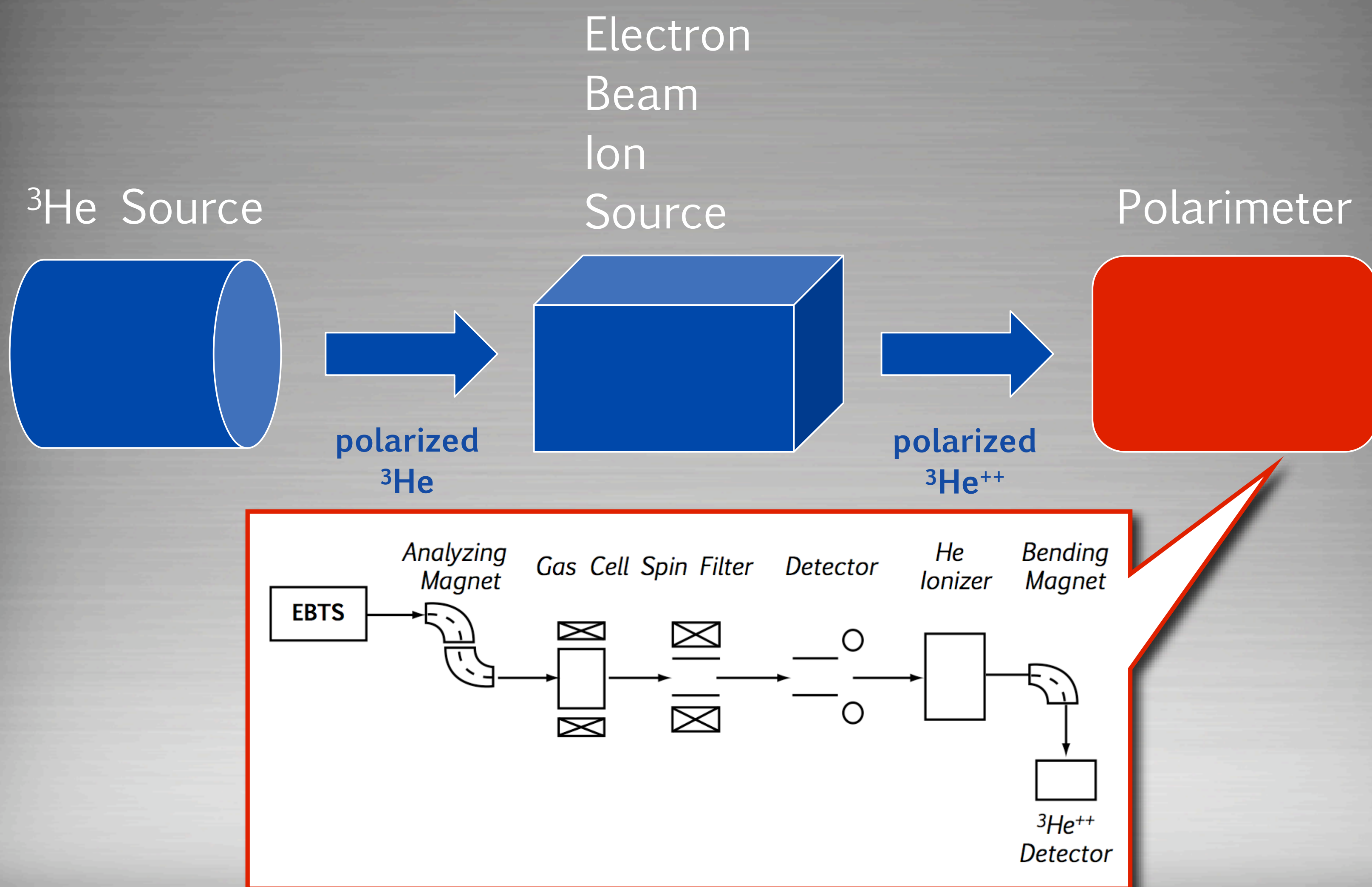
⇒ Expectation of $\sim 10^{11}$ He^{++}/pulse exiting EBIS.

:: EBTS :: energy

Presently:	EBIS output for $^3He^{++}$ = 40 keV
~ August, 2006:	Platform output for $^3He^{++}$ = 200 keV
~ September, 2007:	RFQ output for $^3He^{++}$ = 900 keV

:: POLARIMETER ::

:: MIT ::
:: CALTECH ::
:: BROOKHAVEN ::



:: POLARIMETER ::

HIGH-ENERGY

⇒ After acceleration (~MeV), reactions can be used for polarization measurements. For example:

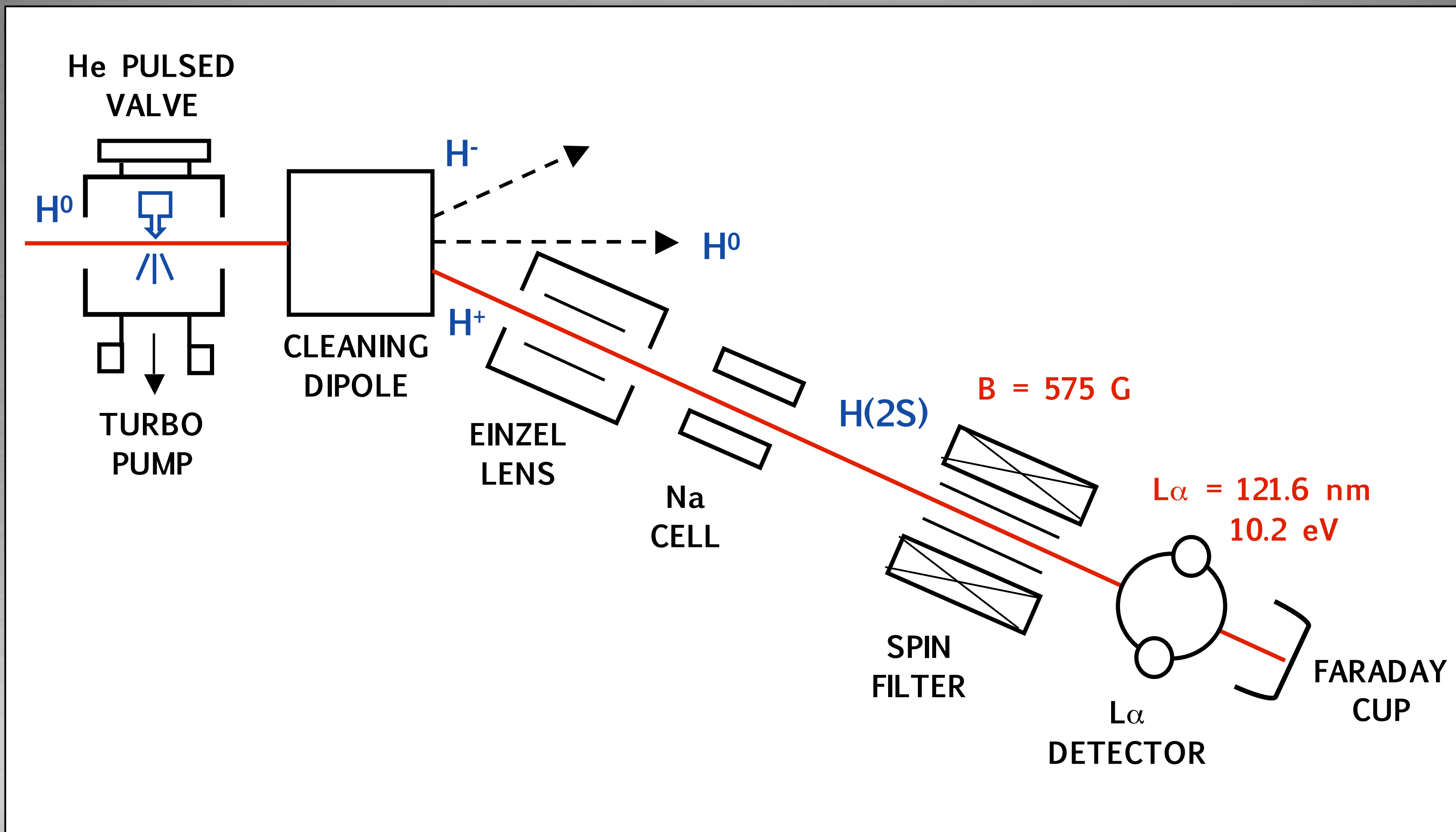
$$^3He + D \rightarrow p + {}^4He + 18.35 \text{ MeV.}$$

LOW-ENERGY

⇒ Since the energy of the ^{3}He beam exiting EBTS is 40 keV, the polarization measurement must be based on atomic interactions rather than nuclear scattering. A Lamb-shift polarimeter exploits the difference in lifetime between the $2S_{1/2}$ and $2P_{1/2}$ excited states of ^{3}He to measure its longitudinal polarization.

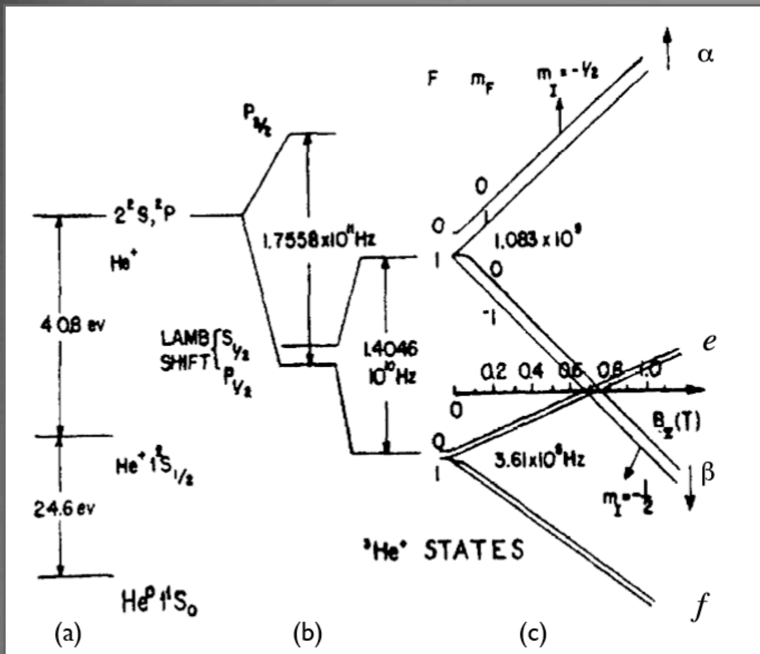
:: POLARIMETER ::

Brookhaven presently has a Lamb-shift polarimeter in place for measuring the polarization of protons.



:: POLARIMETER ::

:: MIT ::
:: CALTECH ::
:: BROOKHAVEN ::

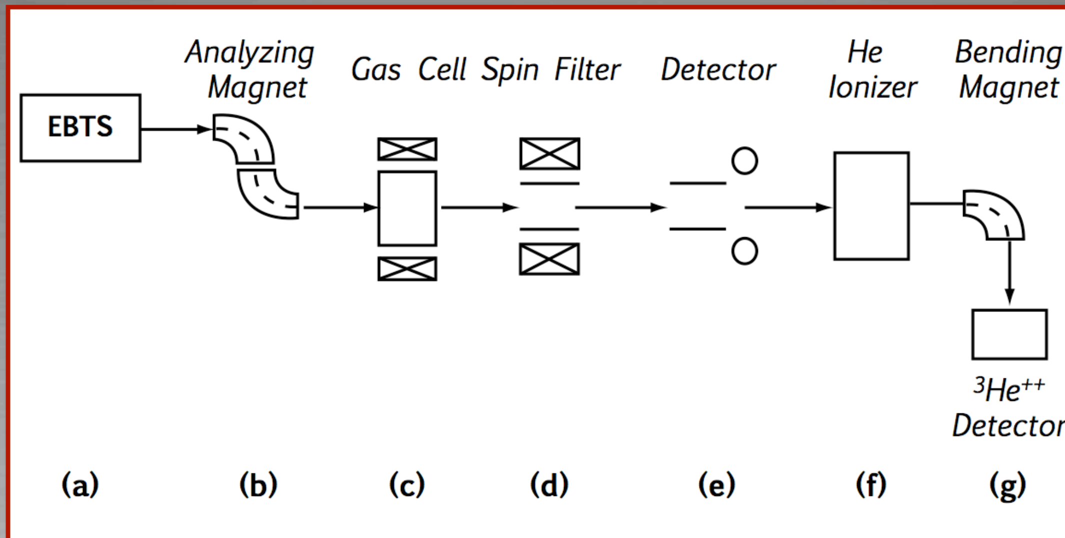


⇒ Lamb-shift is the energy shift between the $2S_{1/2}$ and $2P_{1/2}$ states (1405 MHz or 5.8×10^{-6} eV).

⇒ In the absence of any external fields, the $2P_{1/2}$ state decays rapidly (τ_P » 10^{-10} s), while the $2S_{1/2}$ state is metastable ($\tau_S = 2 \times 10^{-3}$ s).

⇒ However, in the presence of an external electric field, the metastable state rapidly decays due to Stark mixing with the $2P_{1/2}$ state. This effect is referred to as "quenching" of the metastable state.

:: POLARIMETER :: overview



(a) EBTS produces the $^3He^{++}$ ions.

(b) A bending magnet to ensure a beam of pure $^3He^{++}$ ions.

(c) A gas cell with an external magnetic field to produce $^3He^{+}(2S)$. Ions in the $2P_{1/2}$ immediately decay.

(d) A spin filter ($E \perp B$) to quench the β-states of the metastable $2S_{1/2}$ ions.

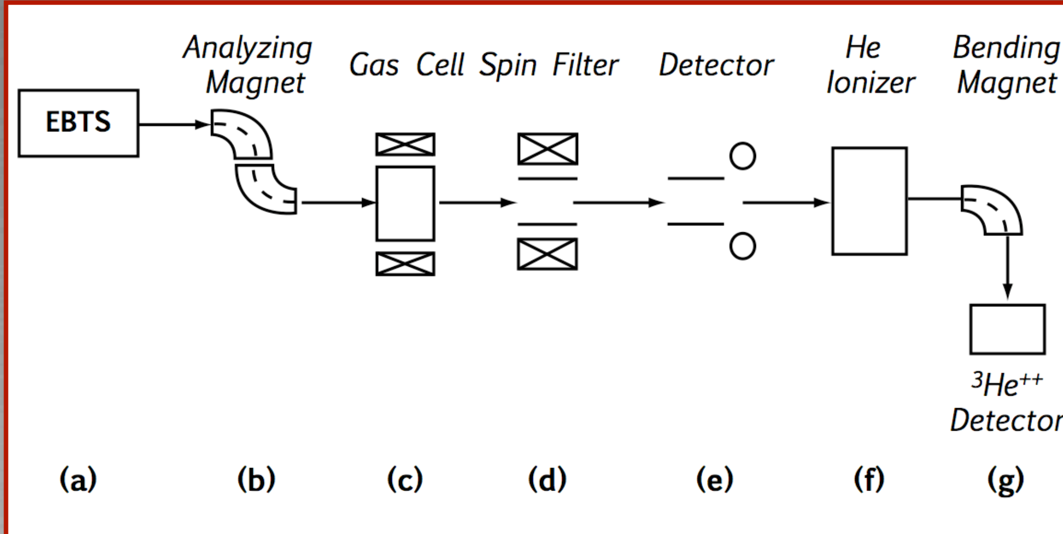
(e) The remaining metastable ions are quenched and produce 40.8 eV photons captured on silicon detectors.

(f) A ^3He ionizer to produce $^3He^{++}$.

(g) Bending magnet and second detector.

:: POLARIMETER ::

:: MIT ::
:: CALTECH ::
:: BROOKHAVEN ::



$$P_z = \frac{2}{1-\frac{x}{\sqrt{1+x^2}}}\left(\frac{I_+}{I_0}-1\right)$$

$$P_z = \frac{2}{1-\frac{x}{\sqrt{1+x^2}}}\left(\frac{I_+-I_-}{I_++I_-}\right)$$

$x = \frac{B}{B_c}$

I_0 : Count for zero polarization

I_+ : Count for polarization

I_- : Count for polarization with magnetic field reversed

:: TIMELINE ::

⇒ Fall '06: Get funding

⇒ Fall '06 - Winter '07: Design

⇒ Winter '07 - Winter '08: Build

⇒ Winter '08: Commission with EBTS

:: CONCLUSIONS ::

⇒ Goal: 70-80% polarization using metastability exchange technique

⇒ Goal: Extend EBTS work to include ^3He

⇒ Goal: Build a Lamb-shift polarimeter to test polarization of ^3He beam after EBTS

⇒ Proof of principle in 2-3 years

⇒ Specific to eRHIC