Development of a Frozen Spin Target for CLAS

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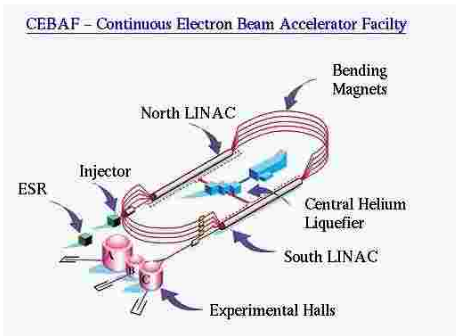
Target Group
Jefferson Lab

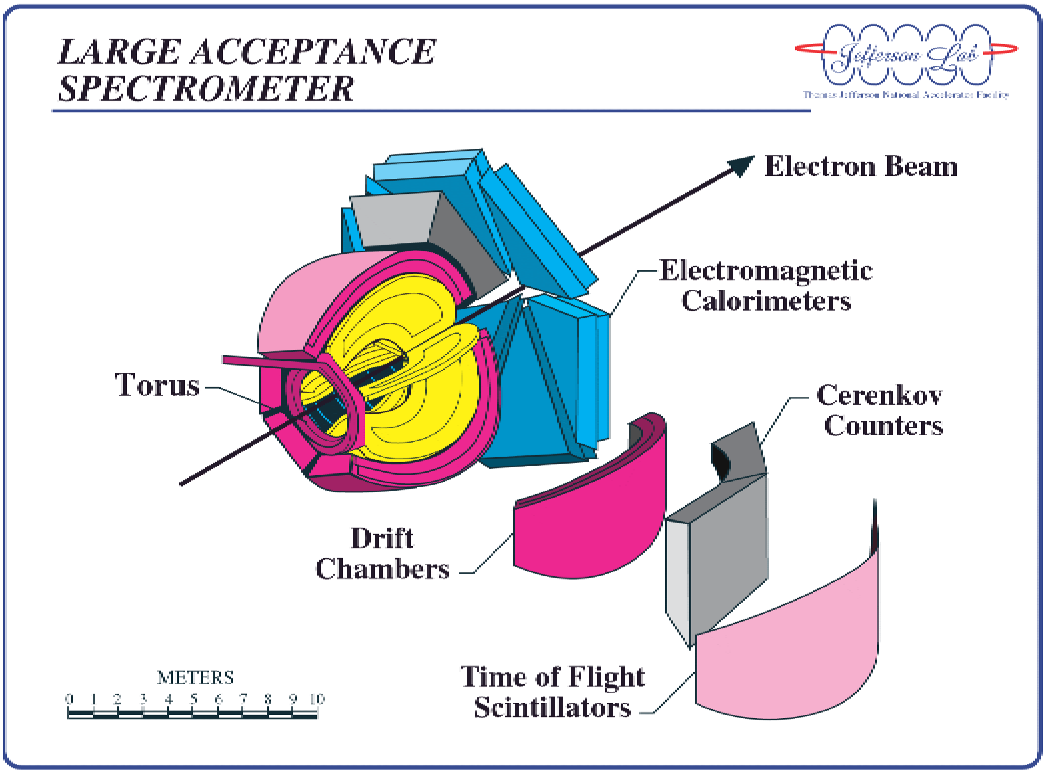
June 4, 2005

Miltenberg



Jefferson Lab Milestones

1976 CEBAF proposed
1983 DOE awards contract to SURA
1987 Groundbreaking for accelerator
1993 1st Experiments commence
1996 Name changed to Th. Jefferson Nat'l Accelerator Facility
1997 5-pass beam (4 GeV) simultaeously delivered to all 3 Halls
2000 6 GeV enhanced design goal met

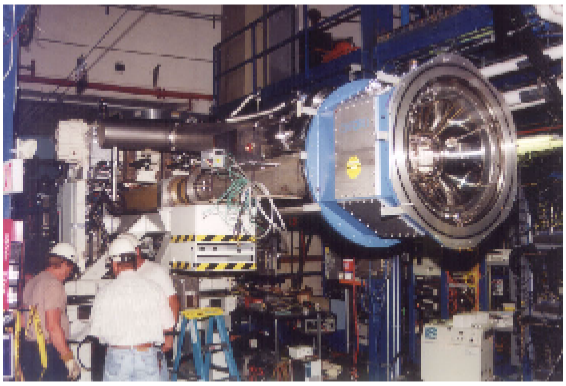


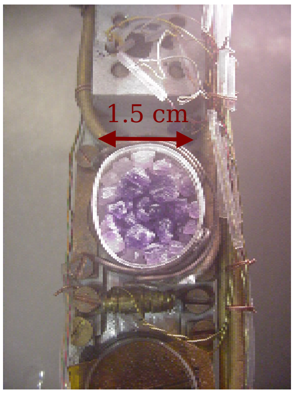
The Conventional Hall B Polarized Target

Protons (and deuterons) in $^{15}NH_3$ ($^{15}ND_3$) are **continuously** polarized by 140 GHz microwaves at 5 Tesla, 1 Kelvin

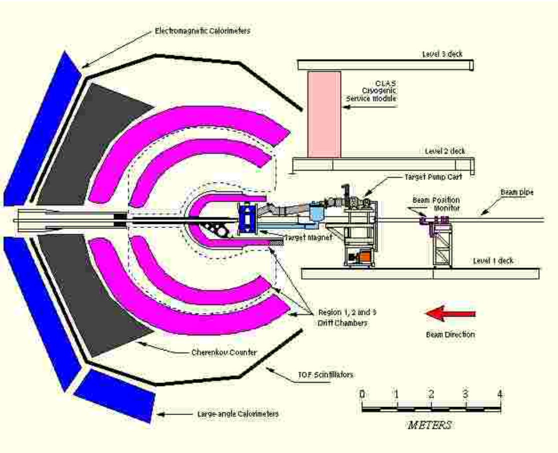
Used for several experiments (beam current ~ 3 nA) over a 10 month period during 1999, and 2000-2001

Proton polarization: ~75 - 85%
Deuteron polarization: ~25 - 35%

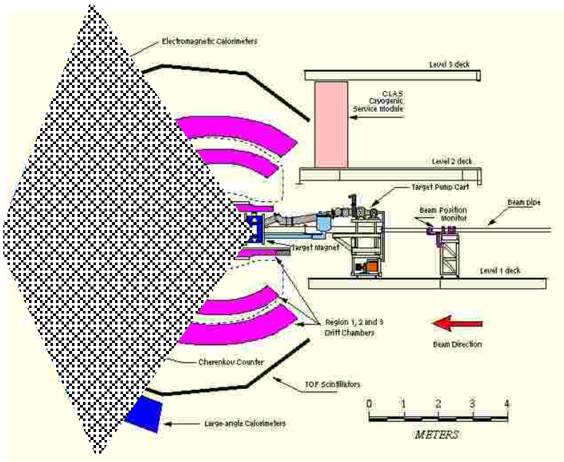




The Current Hall B Polarized Target



The Current Hall B Polarized Target



Problem:

We have a “4π” detector. We need a “4π” target!

Frozen Spin Polarized Targets

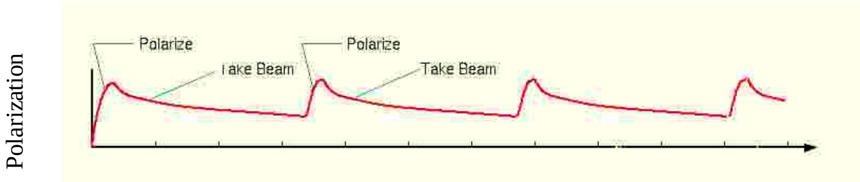
Two steps

1. Polarize target material (NH_3, C_4H_9OH, ^6LiD, ...)
at high field (2.5 – 5.0 T) and moderate temperature (.2 - .4 K)

2. Reduce target temperature to ~ 50 mK, and hold polarization
with reduced field (0.3 – 0.5 T)

The target polarization then decays exponentially during the data acquisition phase of the experiment.

The target must be re-polarized (step 1) every few days.



Specifications for the Hall B Frozen Spin Target

Beam: Tagged photons

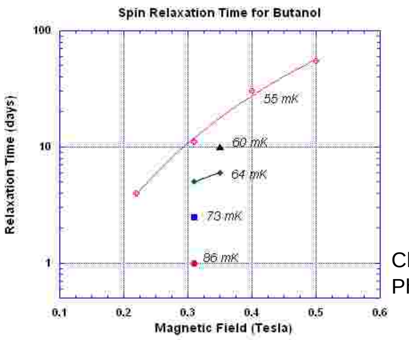
Target: Ø15 mm × 50 mm butanol (C_4H_9OH) $\mathcal{L} \sim 10^{30} – 10^{31}$/s cm^2

Polarizing Magnet: 5 Tesla warm bore solenoid

Holding Magnet: 0.3 – 0.5 Tesla internal solenoid

Refrigerator: $^3He/^4He$ dilution 'fridge Q ~ 20 mW @ 0.3 K

Q ~ 10 μW @ 0.05 K



Ch. Bradtke
PhD Thesis, Univ. Bonn, 1999

Physics Program with Polarized Target and Tagged Photons

Approved Experiments

- E02-112: Missing Resonance Search in Hyperon Photoproduction
- E01-104: Helicity Structure of Pion Photoproduction
- E03-105: Pion Photoproduction from a Polarized Target

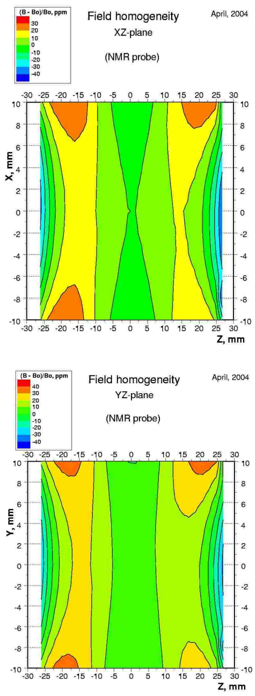
Letter of Intent

- LOI-020104: Photoproduction Using Polarized Beam and Target

Polarizing Magnet

Max. Field: 5.1 T
ΔB/B: $< 3\times10^{-5}$
Bore: Ø127 mm

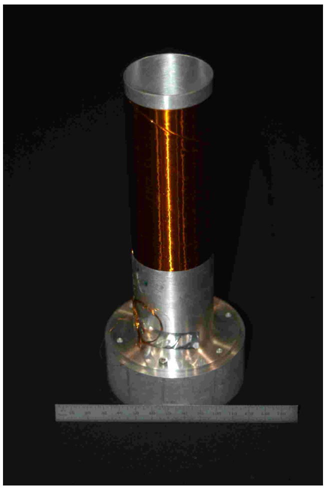
Cryomagnetics, Inc.
Oak Ridge, TN, USA

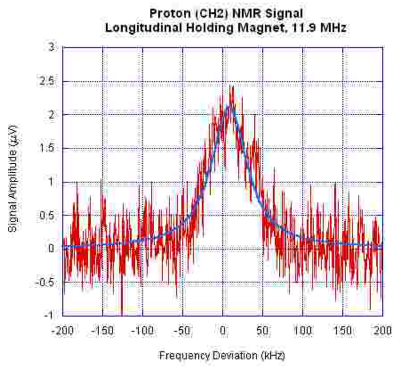


A. Dzyubak, priv. comm..

Holding Magnet, Longitudinal

Wire: Ø.1 mm multifilament NbTi, three layers
Dimensions: Ø 50 × 110
Max. Field: 0.42 Tesla
Homogeneity: $\Delta B/B \sim 3\ 10^{-3}$



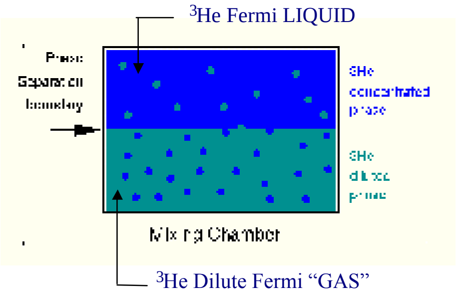


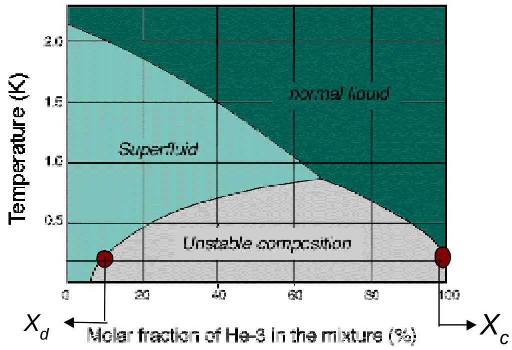
Holding Magnet, Transverse (Prototype)

Wire: Ø.1 mm multifilament NbTi, three layers
Dimensions: Ø 40 × 355 mm
Max. Field: 0.27 Tesla
Homogeneity: $\Delta B/B \sim 5\ 10^{-3}$

$^3He/^4He$ Dilution Refrigeration

- below 0.8 K, a $^3He/^4He$ mixture will separate into two phases





- if ^3He atoms are removed (distilled) from lower phase ^3He atoms from upper phase will cross the phase boundary to reestablish equilibrium

- ^3He will absorb energy when it dissolves into the dilute phase.

- heat absorbed by n moles is: $Q = n\,[H_d(T_m) - H_c(T_m)]$

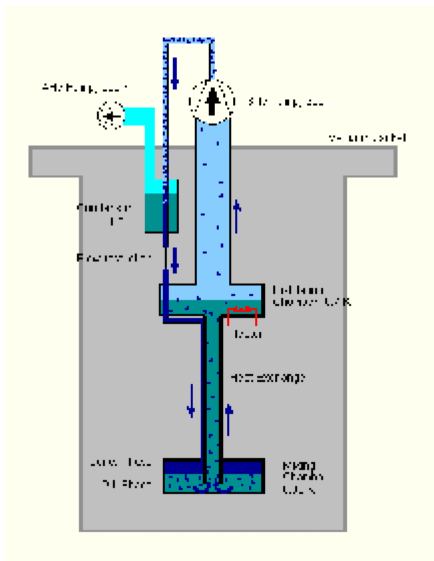
$$= n\,[94.5\,T^2 - 12.5\,T^2] = 82\,n\,T^2 \quad \text{J/mol K}^2$$

Continuous Dilution Refrigeration

- ^3He is "distilled" from the lower, dilute phase of the mixing chamber

- after distillation, the ^3He is recondensed in a LHe bath at ~1.5K and returned to mixer at elevated temperature T_c

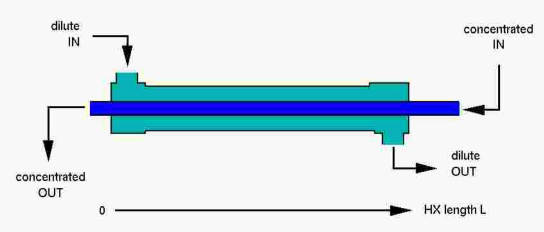
- the cooling power and min. temperature depend strongly on heat exchange between the conc. (warm) and dil. (cold) fluid streams



$$\dot{Q}(T_m) = \dot{n}[H_d(T_m^2) - H_c(T_c^2)]$$
$$= \dot{n}[94.5T_m^2 - 12.5T_c^2]$$

Performance of HX determines T_c

Heat Exchange between Concentrated and Dilute Phases



Heat Flow: ^3He_c → HX walls → ^3He_d

At low temperatures, the main impediment to heat transfer is the thermal boundary (Kapitza) resistance R_k between the helium and the HX walls

Only a small fraction of phonons from liquid will enter the HX walls

$$\frac{\rho_1 v_1^3}{\rho_2 v_2^3} \propto 10^{-5} \longrightarrow \dot{Q}_K = \frac{A}{2R_K}\left[T_2^4 - T_1^4\right]$$

Or a more familiar form:

$$\dot{Q}_K = \frac{\Delta T}{R} = \frac{AT^3}{R_k}\Delta T$$

Heat transfer drops fast at low T !

Performance of an "Ideal" Heat Exchanger

(Giorgio Frossati, 1986)

dilute side
$$s_d \frac{d}{dx}\left[\kappa_d(T)\frac{dT_d}{dx}\right] + \eta_d \dot{V}_d^2 \frac{dZ_d}{dx} + \frac{dA}{dx}\frac{(T_c^4 - T_d^4)}{4R_{kT}} = \dot{n} C_d \frac{dT_d}{dx}$$

$C_d \sim 107 \cdot T$ J/K

conc. side
$$s_c \frac{d}{dx}\left[\kappa_c(T)\frac{dT_c}{dx}\right] + \eta_c \dot{V}_c^2 \frac{dZ_c}{dx} + \frac{dA}{dx}\frac{(T_c^4 - T_d^4)}{4R_{kT}} = -\dot{n} C_c \frac{dT_d}{dx}$$

$C_c \sim 25 \cdot T$ J/K

Axial conduction
s = sectional area
κ = thermal cond.

Frictional heat
η = viscosity
Z = flow impedance
V = molar volume

Kapitza conduction
A = HX area (mean)
R_{kT} = total Kap. resistivity

Enthalpy change
C = specific heat

Frossati: design HX so that 1st and 2nd terms are small compared to the 3rd

$$T_c^2 = \frac{2.25}{(1-(25/107)^2)}\frac{R_{kT}}{A}\dot{n} \approx 50\frac{R_{kT}}{A}\dot{n}$$

Temperature of ^3He_c entering mixing chamber

Cooling Power with Ideal Heat Exchanger

(Giorgio Frossati, 1986)

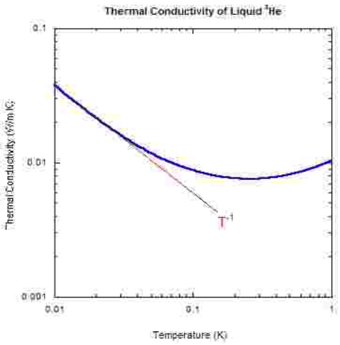
Cooling power, assuming "ideal" heat exchange is determined by molar flow rate and R_k/A of heat exchanger

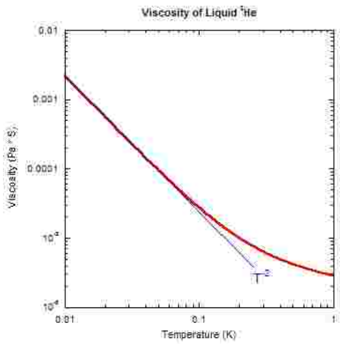
$$\dot{Q}(T_m) = \dot{n}\,[94.5T_m^2 - 12.5T_c^2]$$
$$= \dot{n}\,[94.5T_m^2 - 625\frac{R_{kT}}{A}\dot{n}]$$

Build HX with low R_{kT}
OR, large Area

Optimization of Heat Exchanger Geometry

To optimize heat exchangers, must consider heat leaks due to both axial conduction and frictional heating





$$Q_{cond} = \frac{\pi D^2}{4L}\int \kappa(T)\,dT = aD^2$$

$$Q_{fric} = \eta\left(\frac{128L}{\pi D^4}\right)(\dot{n}V)^2 = bD^{-4}$$

Minimize $Q_{con} + Q_{fric}$: $\frac{d}{dD}(aD^2 + bD^{-4}) = 0$ ➞ $D_{opt} = (2b/a)^{1/6}$

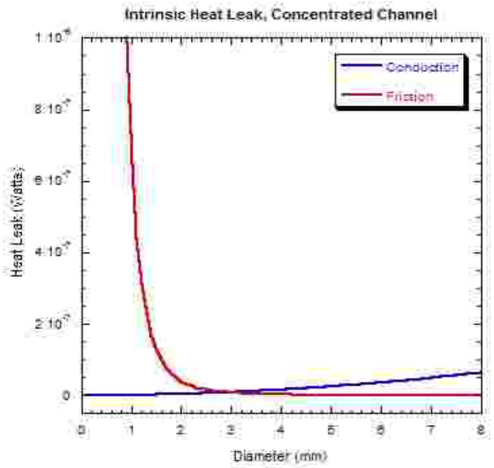
Intrinsic heat leak as a function of tube diameter

HX Length: 1.5 m

Flow rate: 1 mmol/s

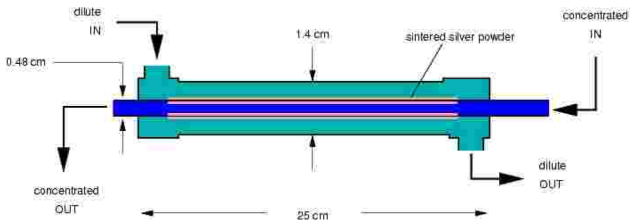
Inlet temperature: 200 mK

Outlet temperature: 20 mK

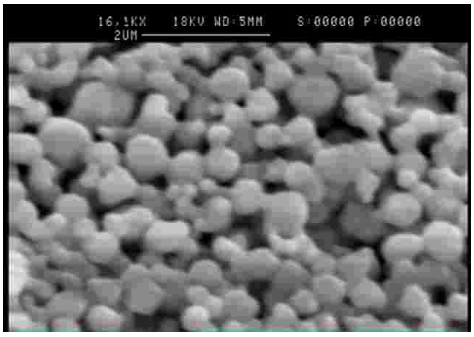


Sintered Silver Heat Exchangers

- large surface areas are necessary to overcome Kapitza resistance
- use sinters of ultra-fine silver powder to provide several m^2 of area



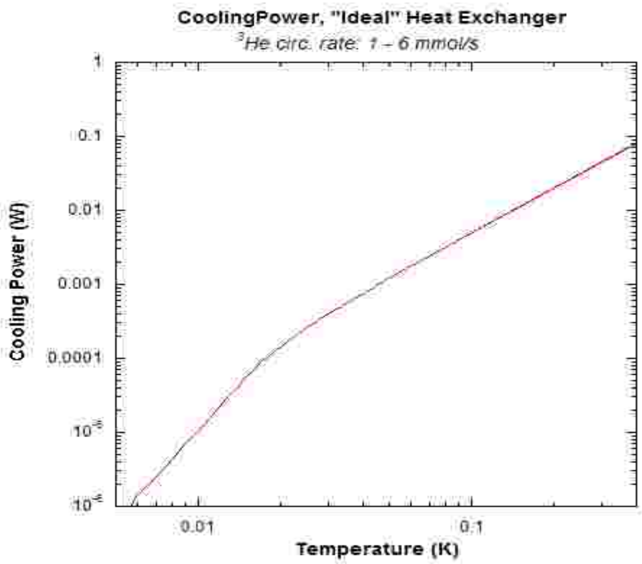
JLab: Use 5 identical segments (in series) between Still and Mixer



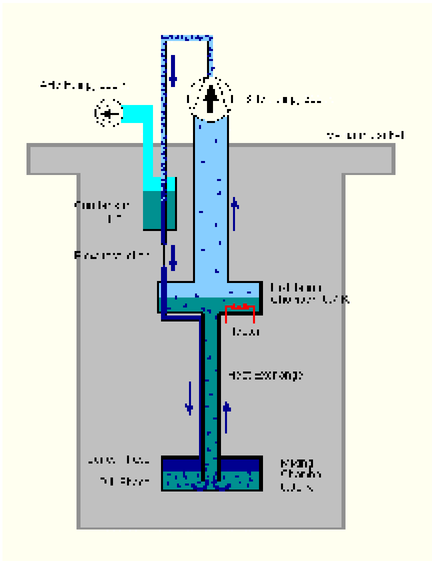
1 micron Ag powder

Sinter at 250 °C → 0.5 m^2/g

each segment:	Dil. = 15 g = 7.5 m^2 Conc.= 8.5 g = 4.2 m^2
5 segments:	Dil. = 37.5 m^2 Conc. = 21 m^2



An example of a commercial, vertical dilution refrigerator

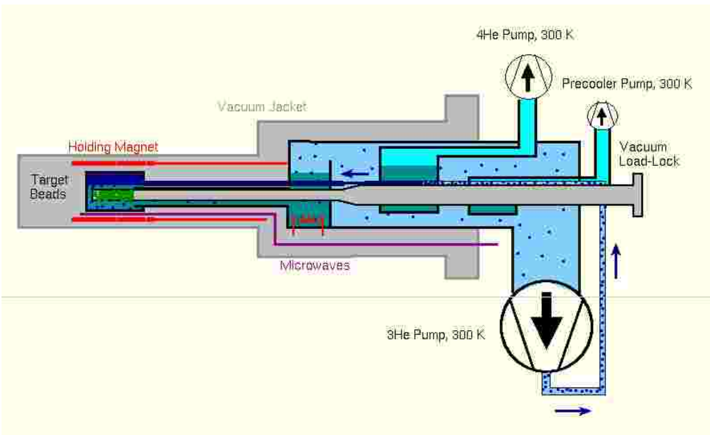


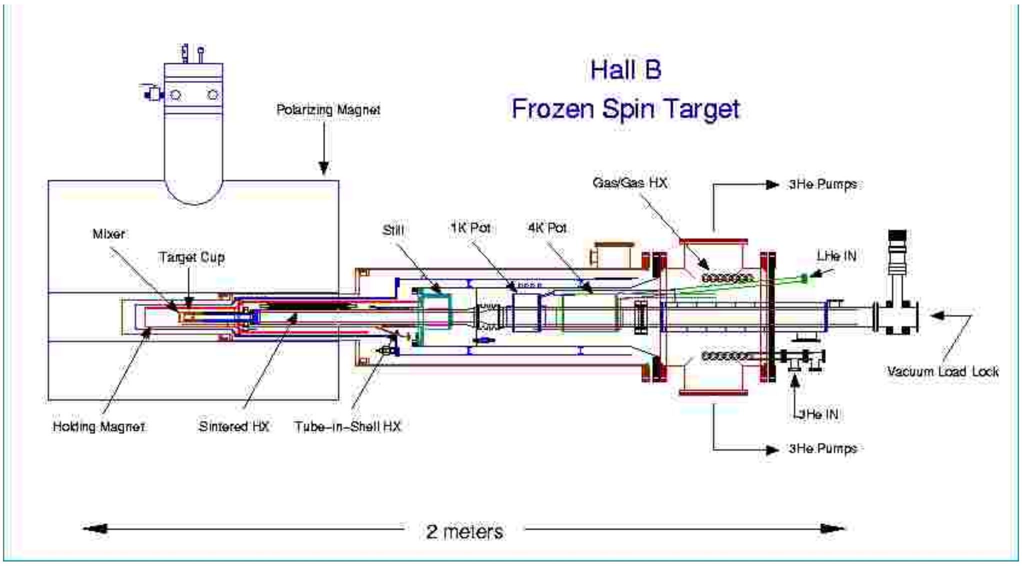
© Leiden Cryogenics, BV

Very nice, but it won't fit inside CLAS...

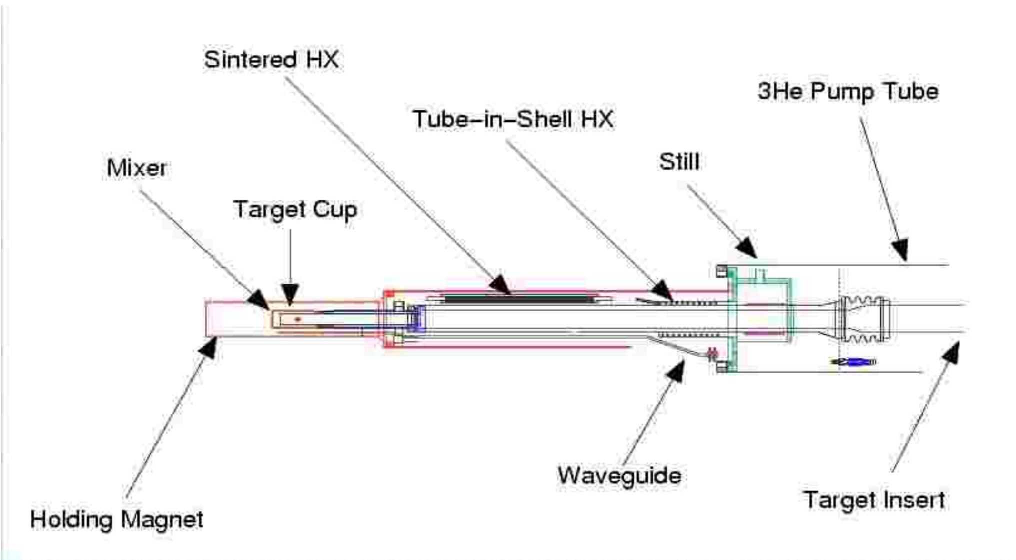
Horizontal Dilution Refrigerator for Frozen Spin Target

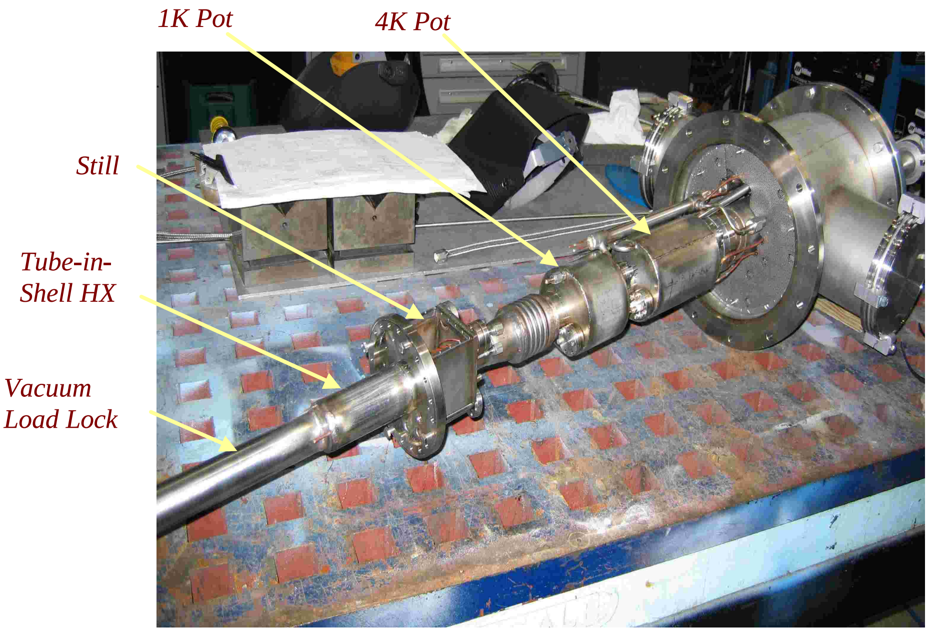
T.O. Niinikoski, CERN 1971





Dilution Unit





Outer Vacuum Jacket

Gas/Gas HX

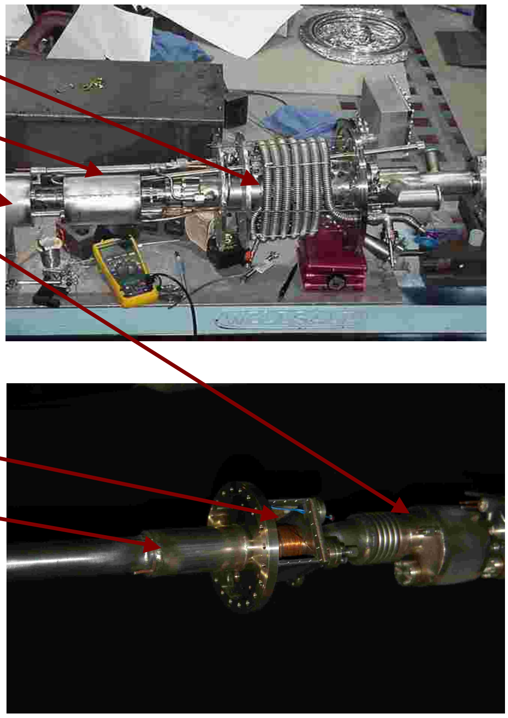
4K Pot

^{4}He Precooling Stages

1K Pot

Distillation Chamber

Tube-in-Shell HX

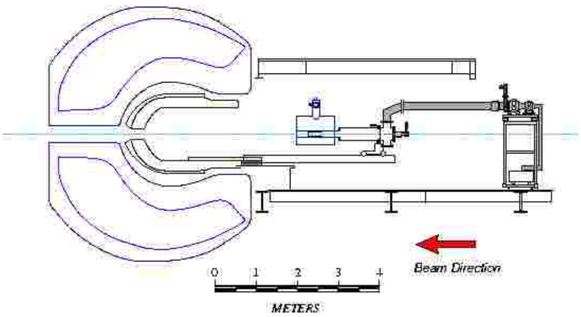


The Frozen Spin Waltz

Step 1: Polarizing

- Target is fully retracted, magnet is lifted to beam height

- Target is inserted into magnet, magnet energized, microwaves on

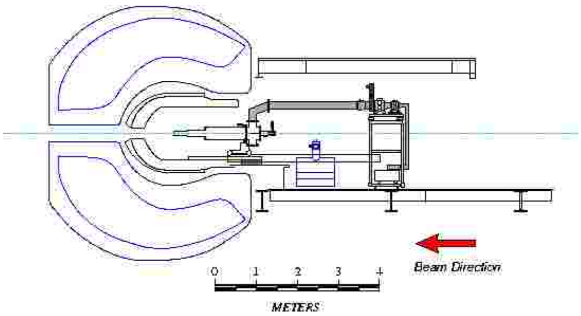


Step 2: Beam On

- Microwaves off, magnet off, holding coil on

- Target is fully retracted, magnet is lowered

-Target is fully inserted into CLAS



Summary

- A frozen spin polarized target for tagged photon experiments is under development at Jefferson Lab.

- 5 Tesla polarizing magnet is in house.

  - Superconducting holding coils (~1mm thick) are under development.
    - longitudinal solenoid (0.4 Tesla) constructed and tested
    - prototype of transverse dipole has been tested (0.3 Tesla)

- Horizontal dilution refrigerator is under construction.

- Positioning system for Hall B is still in conceptual design stage.