Freezing the Spin of the Proton
The Next Generation Polarized Target for CLAS

Chris Keith
Target Group
Jefferson Lab

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Others involved in this project

Mike Seely Dave Meekins	JLab Target Group
Bernard Mecking Dave Kashy Pete Hemler	JLab Hall B
Amy Comer	JLab Accel. Group
Alex Dzyubak	Univ. South Carolina
Don Crabb[*]	Univ. Virgina
Werner Meyer[*]	Bochum University

Outline of the Talk

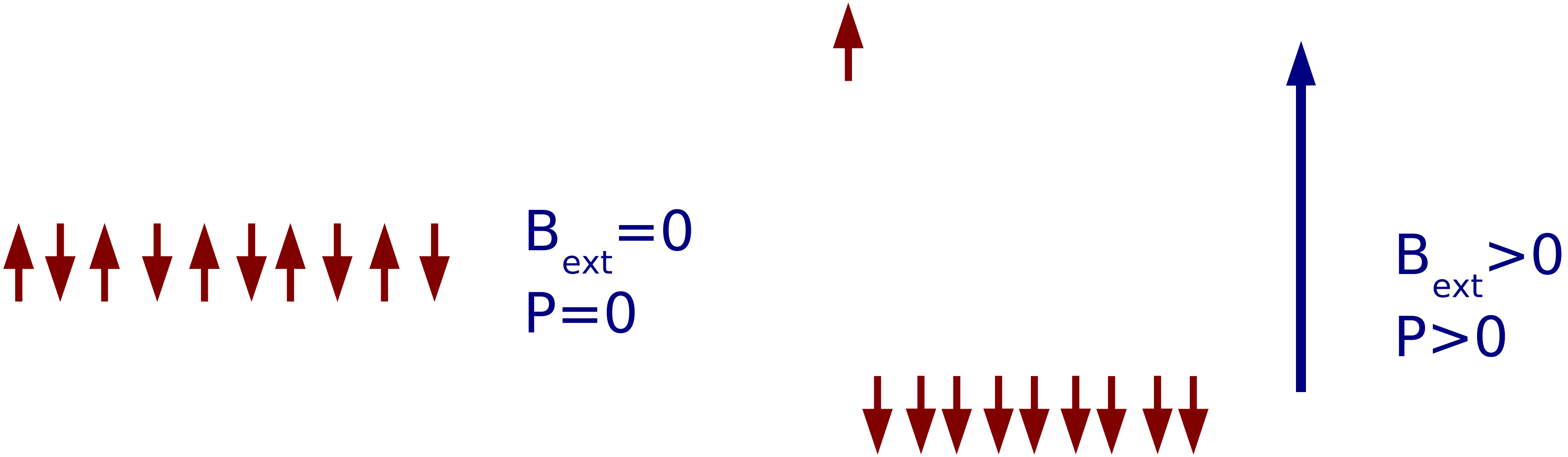
How to polarize spin

1. The Basics of Polarization
2. Polarization and Thermal Equilibrium
3. Brute Force Polarization
4. Dynamic Nuclear Polarization
5. Materials for DNP

How to freeze the spin

The Basics of Polarization

Any ensemble of atoms or nuclei with a magnetic moment can be polarized via the Zeeman interaction: $\vec{\mu}\cdot\vec{B}$



$B_{ext}=0$
$P=0$

$B_{ext}>0$
$P>0$

Zeeman interaction tends to orient (polarize) the magnet moments.

Oscillating EM fields produced by atomic vibrations tends to radomize (de-polarize) the magnetic moments. Characterized by thermal energy *kT.*

Polarization and Thermal Equilibrium

In general the populations of the Zeeman levels (once equilibrium has been reached) will obey a Boltzmann distribution.

$$N(\uparrow)/N(\downarrow)=\exp\left[\frac{(-2\mu B)}{kT}\right]$$

T = temperature

$$P_{te}=\frac{[N(\uparrow)-N(\downarrow)]}{[N(\uparrow)+N(\downarrow)]}=\tanh\left(\frac{\vec{\mu}\cdot\vec{B}}{kT}\right)$$

Thermal equilibrium polarization

The polarization will approach thermal equilibrium with a characteristic *1/e* time constant called t_1, the *“spin-lattice relaxation rate”*

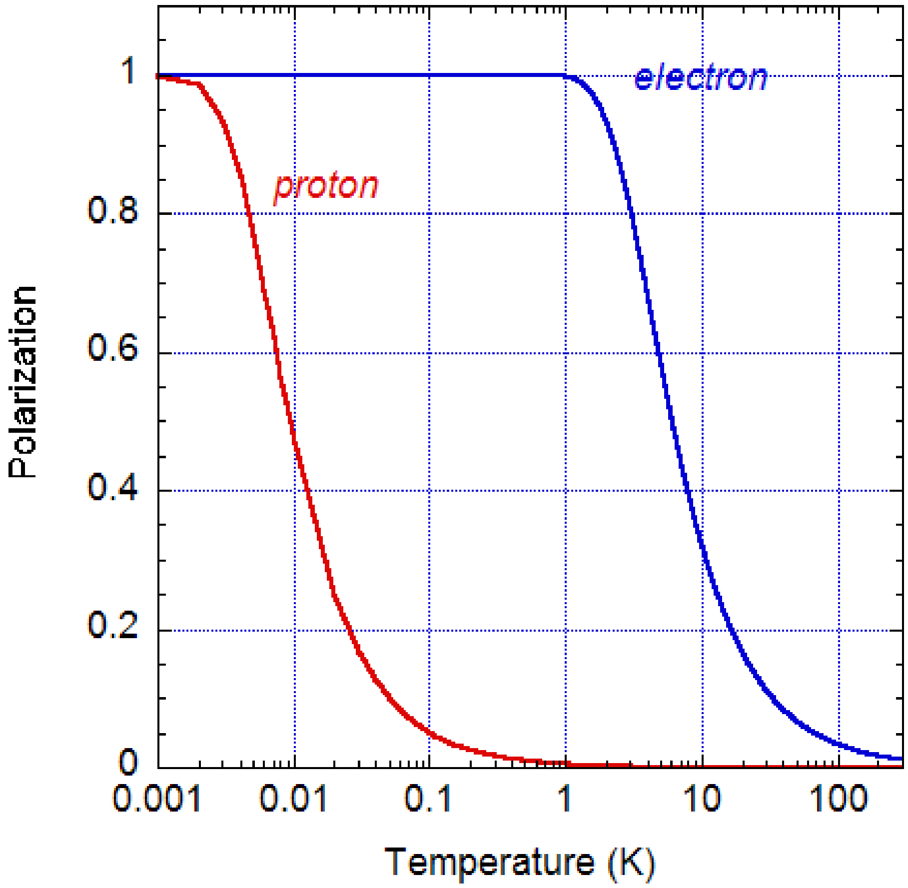
$$P(t)=P_{te}[1-e^{-t/t_1}]$$

Brute Force Polarization

$$P = \tanh\left(\frac{\vec{\mu}\cdot\vec{B}}{kT}\right) \longrightarrow$$

maximize B,
minimize T

5 Tesla



Disadvantages:

1. Requires very large magnet
2. Low temperatures mean low luminosity
3. Polarization can take a very long time

We need a trick!

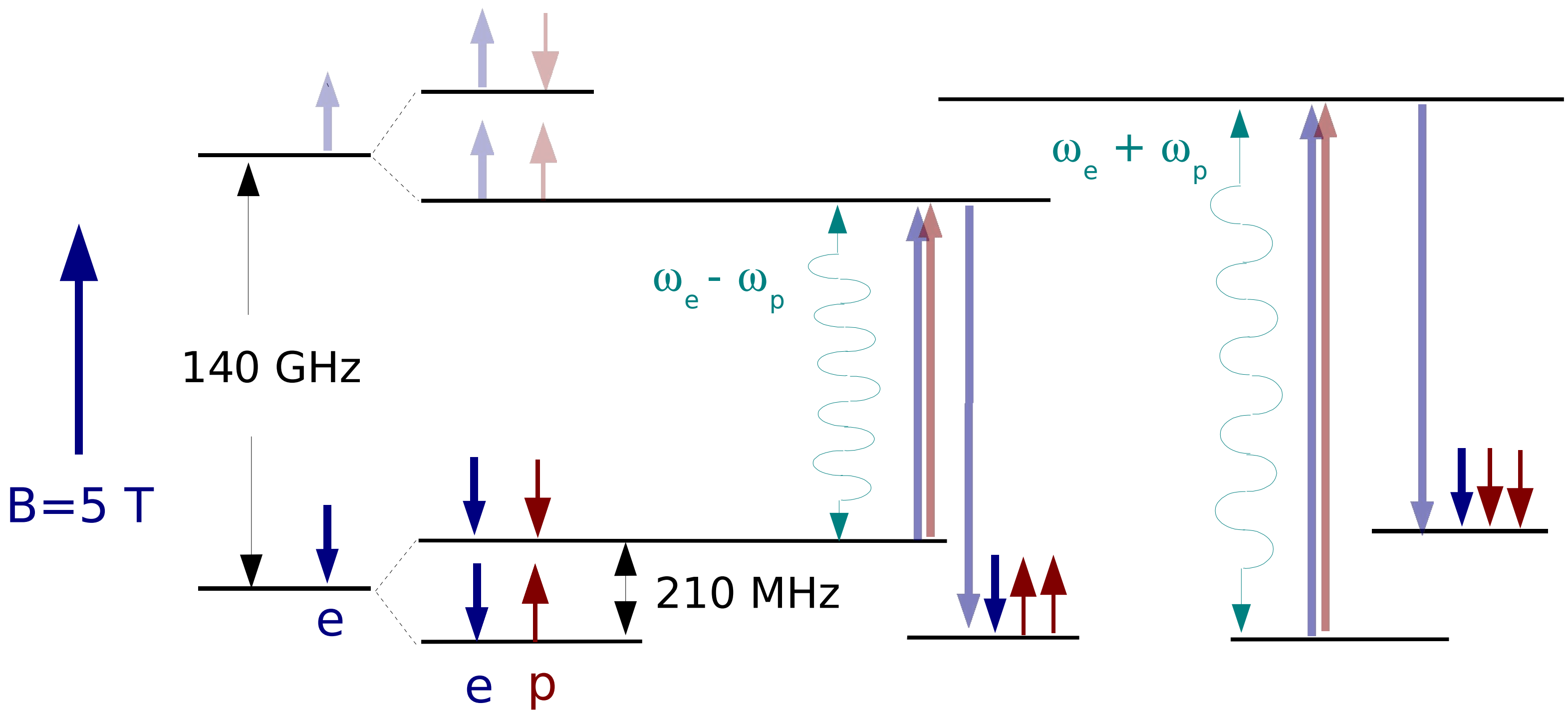
The Trick -- **D**ynamic **N**uclear **P**olarization

Use brute force to polarize free electrons in the target material.
Use microwaves to “transer” this polarization to nuclei. Mutual electron-nucleus spin flips re-arrange the nuclear Zeeman populations to favor one spin state over the other.

For best results, DNP is performed at B/T conditions where electron t_1 is short (ms) and nuclear t_1 is long (minutes)

JLab: $B = 5$ *Tesla*
$T = 1$ *Kelvin*

The Resolved Solid Effect



Zeeman energy levels
of a hydrogen-like atom

Positive
polarization

Negative
polarization

Materials for DNP Targets

- Choice of material dictated by 4 factors:
  1. Maximum polarization
  2. Resistance to ionizing radiation
  3. Presence of unpolarized nuclei $\longrightarrow$ quality factor, $f \equiv \dfrac{\vec{N}}{N_{total}}$
  4. Presence of unwanted, polarized nuclei

- Free electrons must be embedded into target material:
  1. Chemical doping with paramagnetic radicals
  2. Paramagnetic radicals created by ionizing radiation

- Typically 1 free electron can "service" ~ 10^3 free protons

Materials for DNP Targets, examples

Name	Dopant	f	Rad. Resistance
Polyethelyne, C_2H_4	chemical	0.12	low
Polystyrene, C_8H_8	chemical	0.07	low
Propandiol, $C_3H_6(OH)_2$	chemical	0.11	moderate
Butanol, C_4H_9OH	chemical	0.13	moderate
Ammonia, $^{15}NH_3$	radiation	0.17	high
Lithium Hydride, ^{7}LiH	radiation	0.12	very high

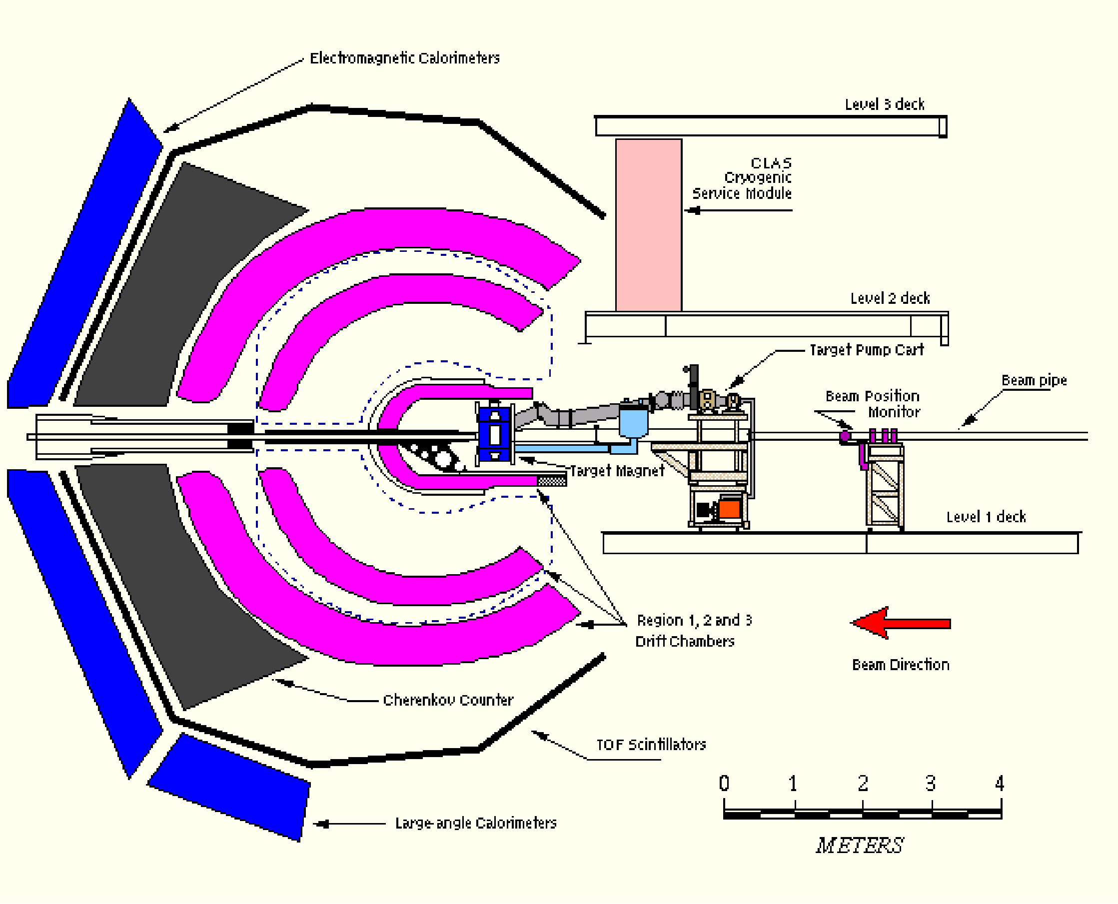
The Current Hall B Polarized Target

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

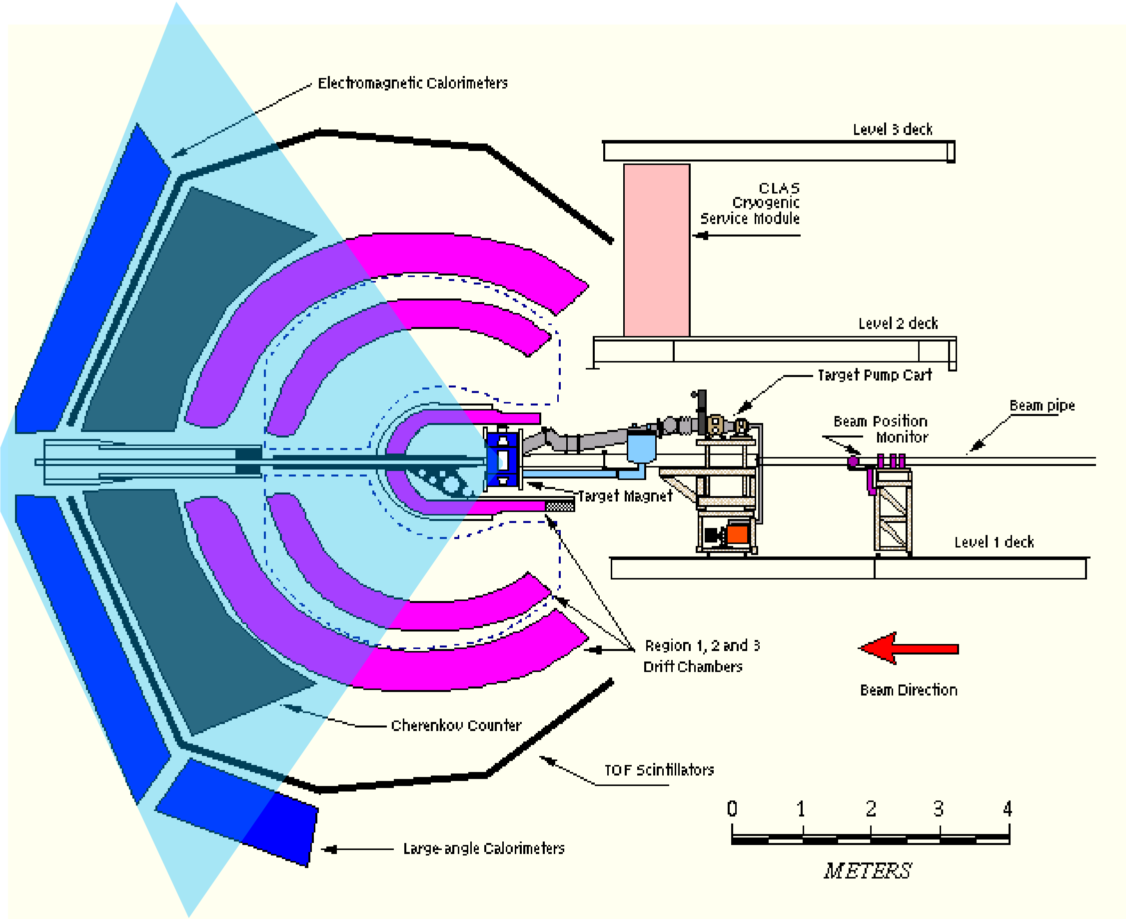
Used for several experiments (beam current ~ 3 nA)
over a 10 month period during 1999, and 2000-2001

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!

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

The Frozen Spin Target

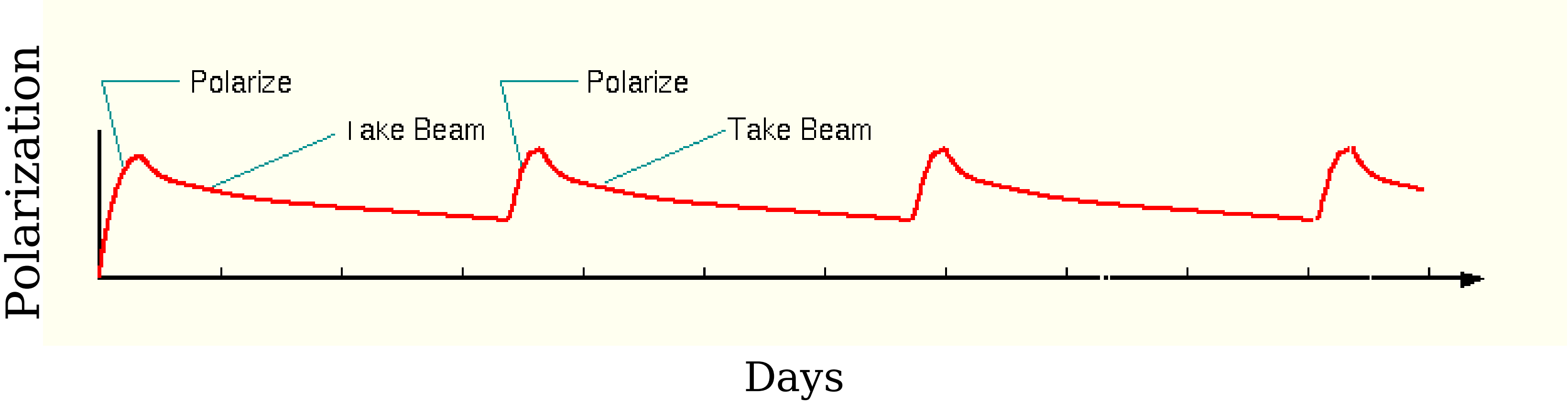
1. Polarize target material via DNP at 5T and 0.5K

2. After optimum polarization is obtained, turn off microwaves, and magnet

3. Use a 2nd magnet (~0.5 T) and very low temperatures to “freeze” the polarization

4. Polarization will decay very slowly with a time constant (hopefully) of several days

5. After polarization decays to about 50% of its initial value, go back to Step 1



Outline of the Talk

~~How to polarize spin~~

How to freeze the polarization

1. The Basics of Frozen Spin
2. Specs. for the Hall B Target
3. Magnets
4. Refrigeration

Specifications for the Hall B Frozen Spin Target

Beam: Tagged photons

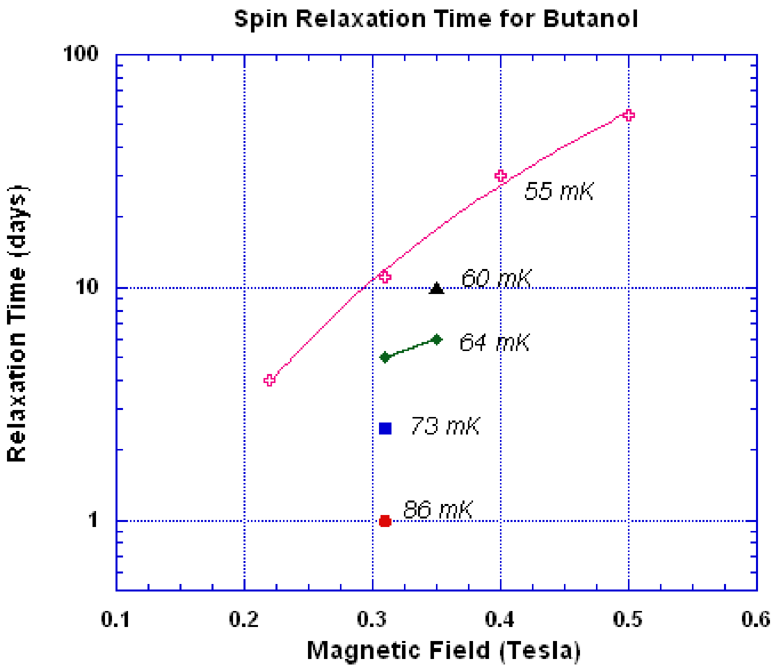
Target: Ø15 mm × 50 mm butanol (C_4H_9OH) $\mathcal{L} \sim 10^{30} - 10^{31}$/s cm^2

Polarizing Magnet: 5 Tesla warm bore solenoid

Holding Magnet: 0.3 – 0.5 Tesla internal solenoid

Refrigerator Cooling Power: Q ~ 20 mW @ 0.3 K

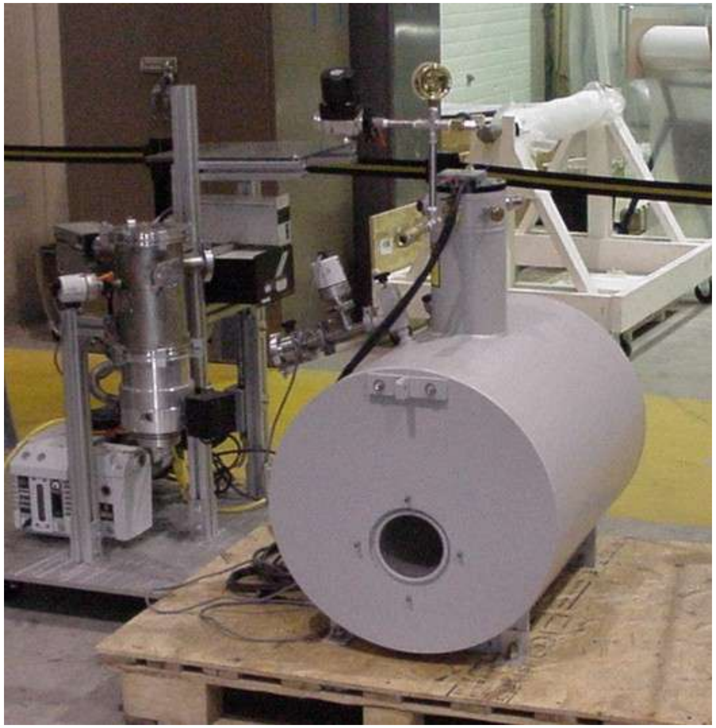
Q ~ 10 μW @ 0.05 K



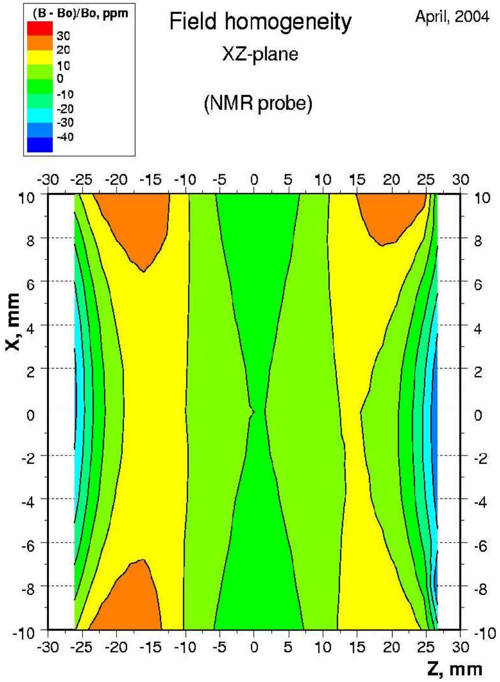
Ch. Bradtke
PhD Thesis, Univ. Bonn, 1999

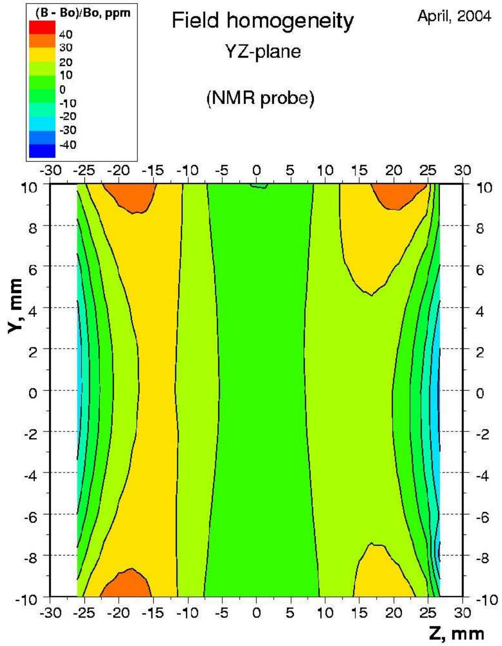
Polarizing Magnet

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



Cryomagnetics, Inc.
Oak Ridge, TN, USA

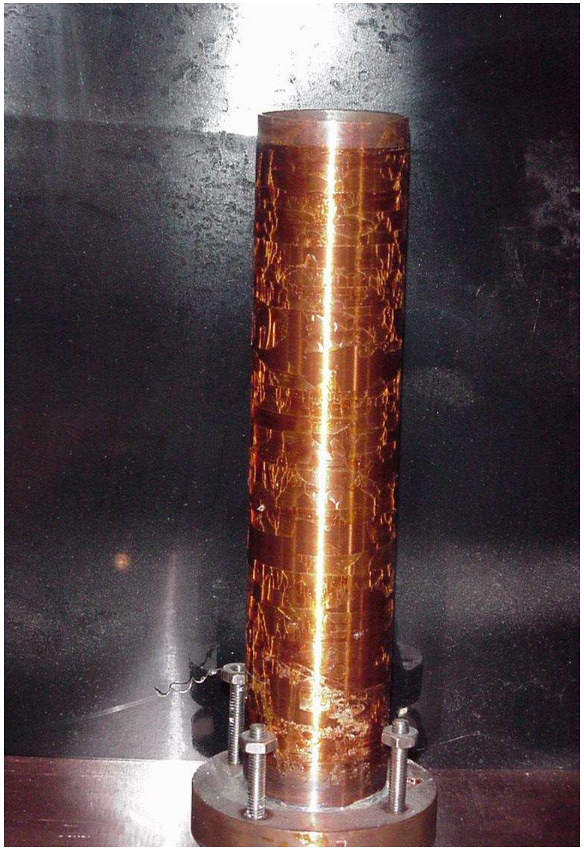


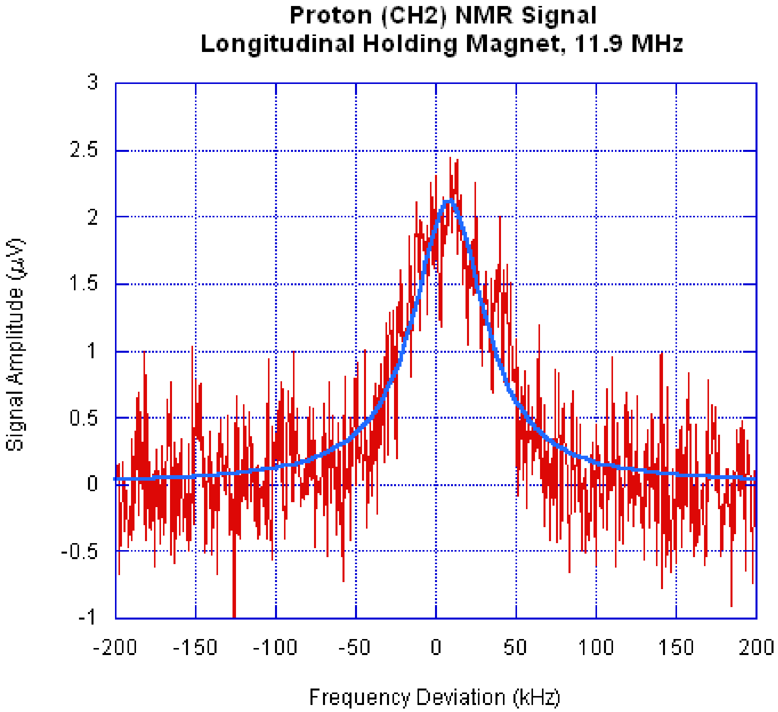


A. Dzyubak, priv. comm..

Holding Magnet

Dimensions: Ø 40 × 250 × 0.3 mm
Max. Field: 0.32 Tesla
Homogeneity: $\Delta B/B \sim 3\ 10^{-3}$





Refrigeration below 4.2 K – Evaporative Cooling

In order to evaporate 1 mole of ^{4}He, heater must supply:
L ~ 80 J/mol *(L is latent heat of vaporization)*

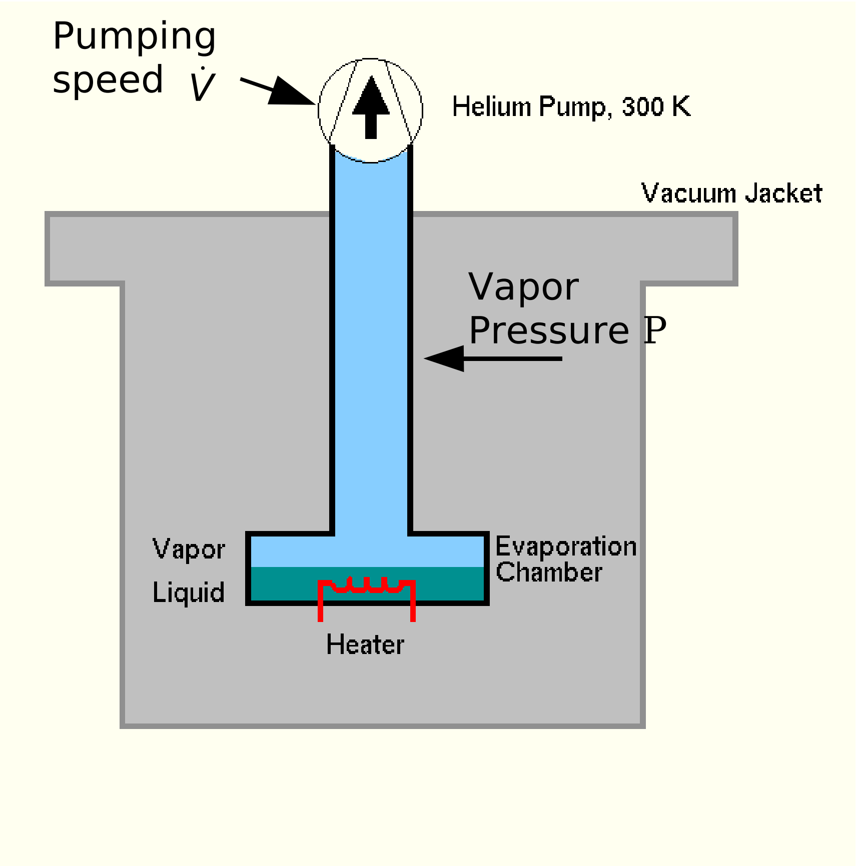
In absence of a heater, liquid will absorb heat from surroundings and temperature will drop.

Cooling power of a evaporation 'fridge is simply:

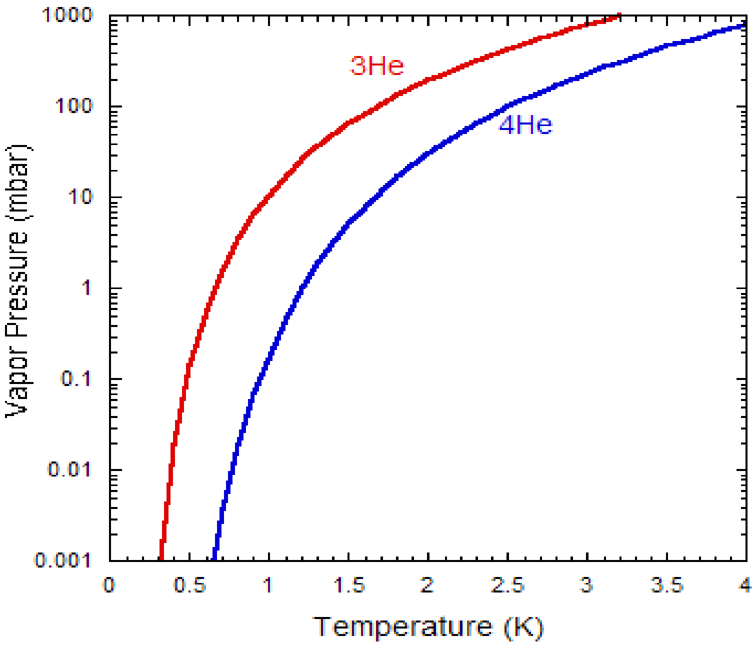
$$\begin{aligned}\dot{Q} &= \dot{n} L \\ &= \dot{V} P L\end{aligned}$$

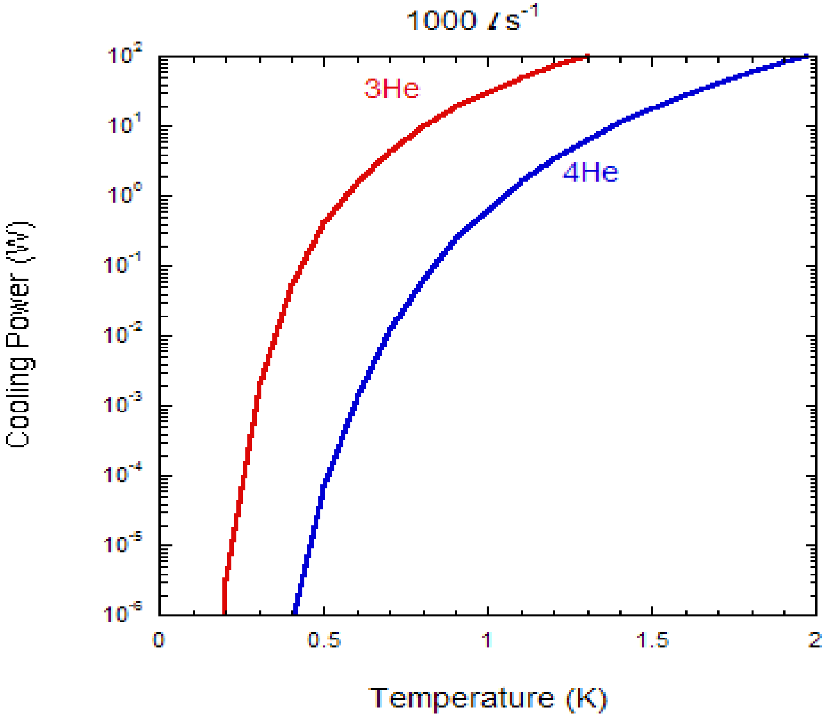
But since $P \propto \exp(-1/T)$

$$\longrightarrow \boxed{\dot{Q} \propto \exp(-1/T)}$$



Evaporative Cooling

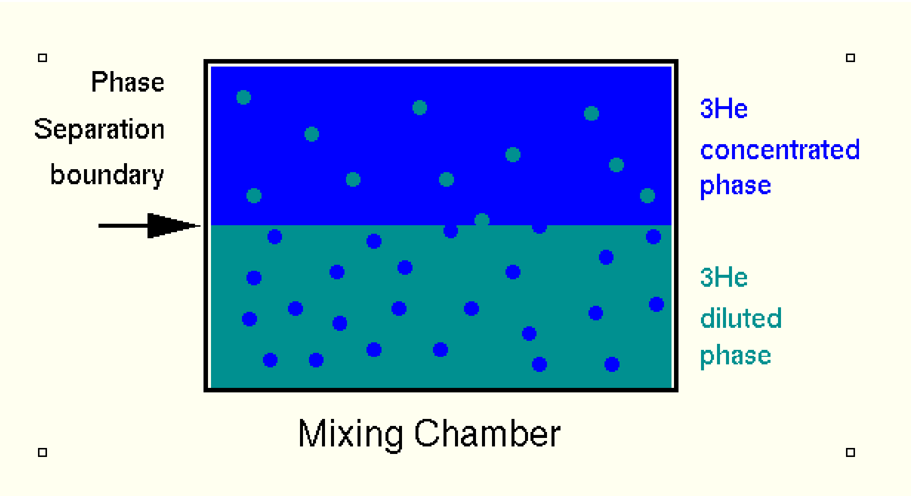


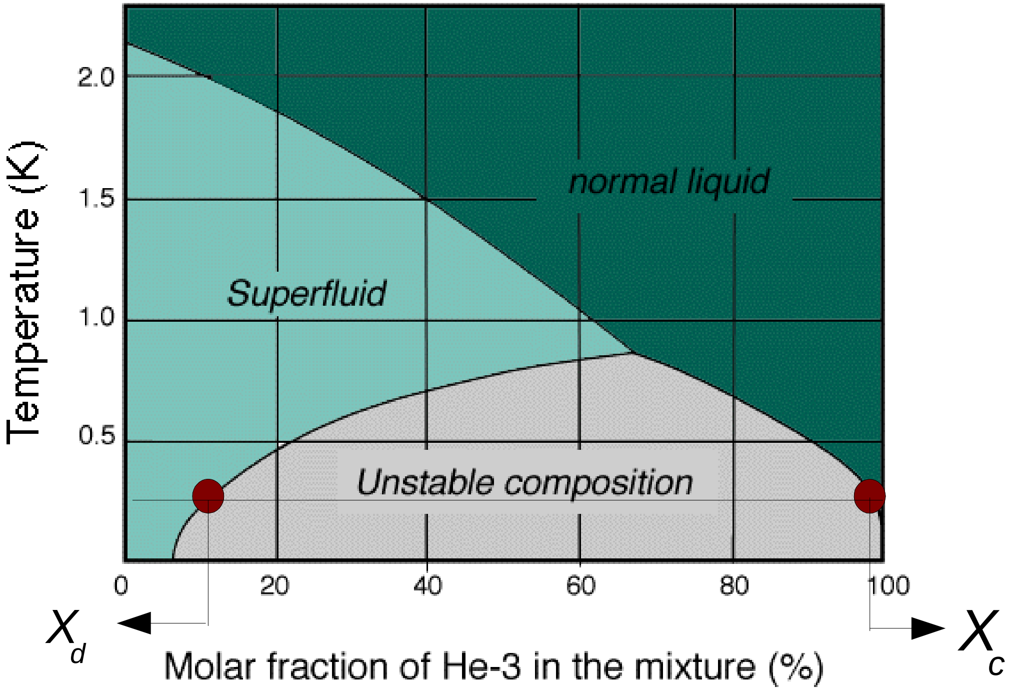


Insufficient for freezing the spin!

^{3}He/^{4}He Dilution Refrigeration

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





- The specific heat of a ^{3}He atom is higher in the lower, dilute phase than in the upper, concentrated phase.

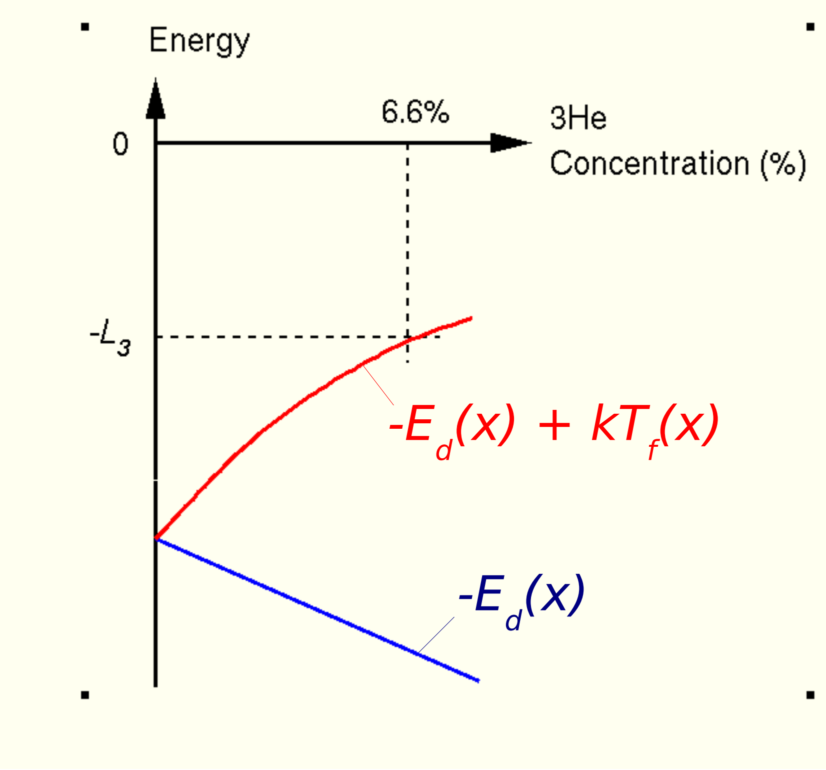
$$C_d = 107\,T \quad J/mol\,K$$

$$C_c = 25\,T \quad J/mol\,K$$

- Therefore, ^{3}He will absorb energy when it dissolves into the dilute phase.

^{3}He in the Dilute Phase

Even at absolute zero, ^{3}He will dissolve into ^{4}He until a concentration of 6.6% is reached.



Binding energy of a ^{3}He atom in **conc** phase is $-L_3$, latent heat of ^{3}He

Binding energy of a ^{3}He atom in **dilute** phase is $-E_d(x)$

Total energy of a ^{3}He atom in **dilute** phase is sum of binding energy and kinetic energies, $kT_f(x)$

At a concentration of $x=6.6\%$, the total energy of ^{3}He in the dilute phase is same as the binding energy in the concentrated (pure) phase.

Thermodynamics of the Dilution Refrigeration

H. London, 1951:

If ^{3}He is somehow preferentially removed from the lower part of the mixing chamber, ^{3}He from the upper part will absorb heat from its surroundings in order to dissolve into the dilute phase and reestablish equilibrium.

Mixing occurs at a constant chemical potential: $H_d - T\,S_d = H_c - T\,S_c$

Assuming a dilution rate of $\dot{n}$ mol/s, cooling power is $\dot{n}\Delta H$

$$\begin{aligned} H_c &= \int C_c\,dT \\ &= \underline{12.5\,T^2} \end{aligned}$$

$$\begin{aligned} H_d &= H_c + T(S_d - S_c) \\ &= 12.5\,T^2 + T\int\left(\frac{C_d}{T} - \frac{C_c}{T}\right)dT \\ &= 12.5\,T^2 + T(107\,T - 25\,T) = \underline{94.5\,T^2} \end{aligned}$$

“Ideal” cooling power of the dilution process:

$$\dot{Q} = \dot{n}[H_d - H_c] = 82\,\dot{n}\,T^2 \quad Watt/mol\,K^2$$

Practical Dilution Refrigeration

- ^{3}He is “distilled” from the lower, dilute phase of the mixing chamber

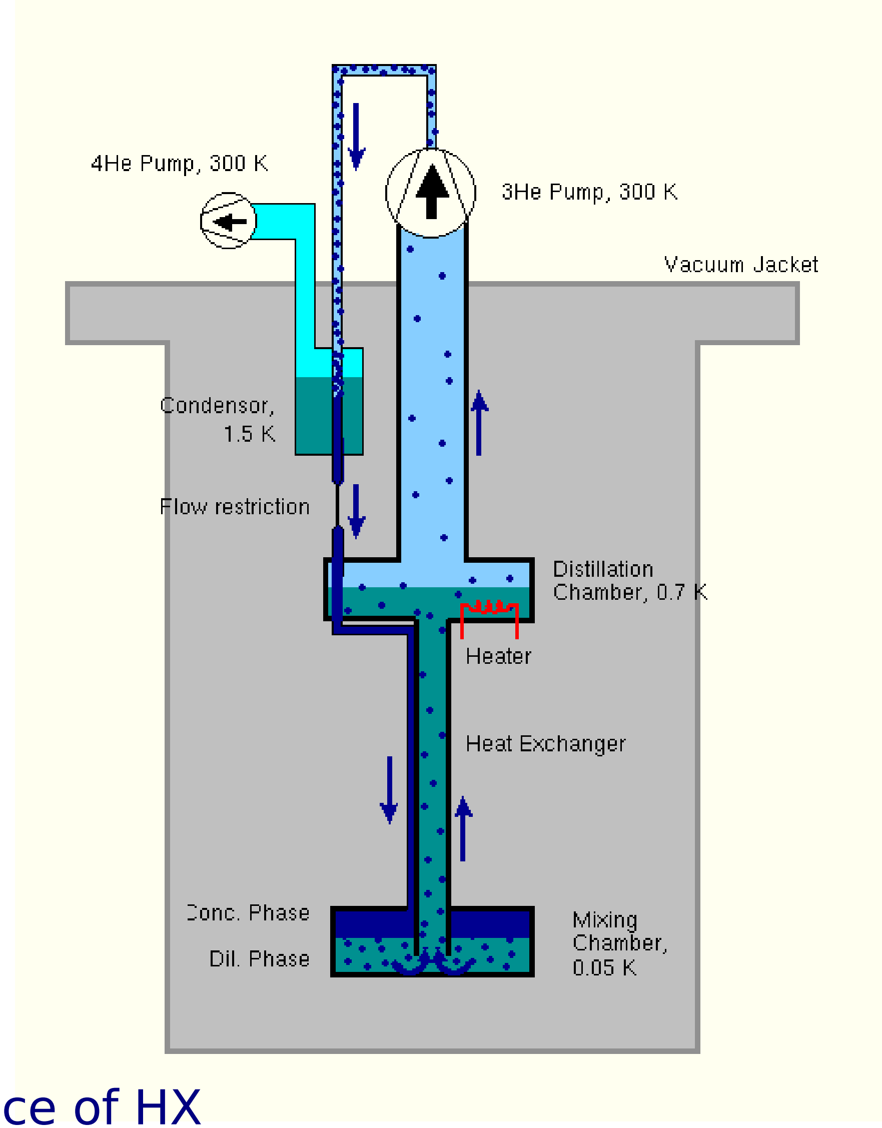
- after distillation, the ^{3}He is recondensed in a LHe bath at ~1.5K

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

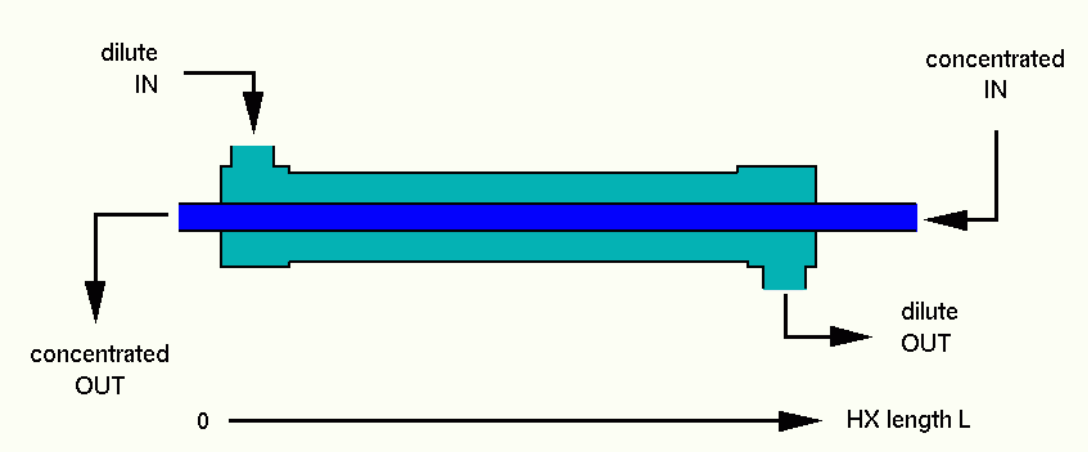
$$\dot{Q}(T_m) = \dot{n}[H_d(T_m^2) - H_c(T_c^2)]$$

$$= \dot{n}[94.5T_m^2 - 12.5T_c^2]$$

Performance of HX determines T^2_c



Heat Exchange between ^3He_d and ^3He_c



Heat Flow: $^3He_c \longrightarrow$ HX walls $\longrightarrow$ ^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

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

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

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

Axial conduction

s = sectional area
κ = thermal cond.
x=dir. of fluid flow

Frictional heat

η = viscosity
Z = flow impedance
ρ = fluid density

Kapitza conduction

A = HX area (1 side)
R_{kT} = total Kap. resistivity

Enthalpy change

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

Performance of an "Ideal" Heat Exchanger

dilute side $$\cancelto{0}{s_d \frac{d}{dx}\left[\kappa_d(T)\frac{dT_d}{dx}\right]} + \cancelto{0}{\eta_d \dot{V}_d^2 \frac{dZ_d}{dx}} + \frac{dA}{dx}\frac{(T_c^4 - T_d^4)}{4R_{kT}} = \dot{n} C_d \frac{dT_d}{dx}$$

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

conc. side $$\cancelto{0}{s_c \frac{d}{dx}\left[\kappa_c(T)\frac{dT_c}{dx}\right]} + \cancelto{0}{\eta_c \dot{V}_c^2 \frac{dZ_c}{dx}} + \frac{dA}{dx}\frac{(T_c^4 - T_w^4)}{4R_{kT}} = -\dot{n} C_c \frac{dT_d}{dx}$$

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

$$\boxed{\begin{aligned} \frac{(T_c^4 - T_d^4)}{4R_k} &= \dot{n} C_d \frac{dT_d}{dx} = 107\,T\,\dot{n}\frac{dT_d}{dx} \\ \frac{(T_c^4 - T_d^4)}{4R_k} &= \dot{n} C_c \frac{dT_c}{dx} = -25\,T\,\dot{n}\frac{dT_c}{dx} \end{aligned}} \longrightarrow T_d^2(x) = \left(\frac{25}{107}\right)^2 T_c^2(x)$$

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

Temperature of $^3\mathrm{He}_c$
entering mixing chamber

Cooling Power with Ideal Heat Exchanger

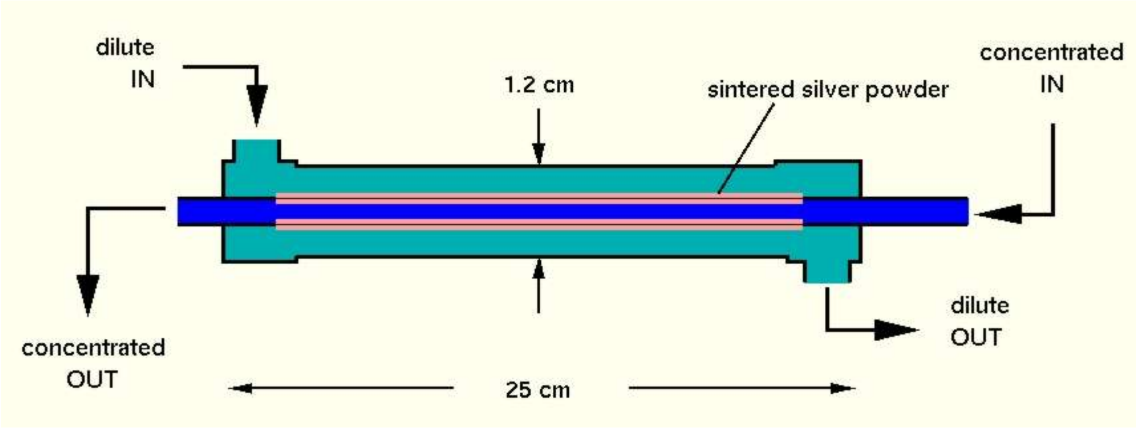
(Giorgio Frossati, 1986)

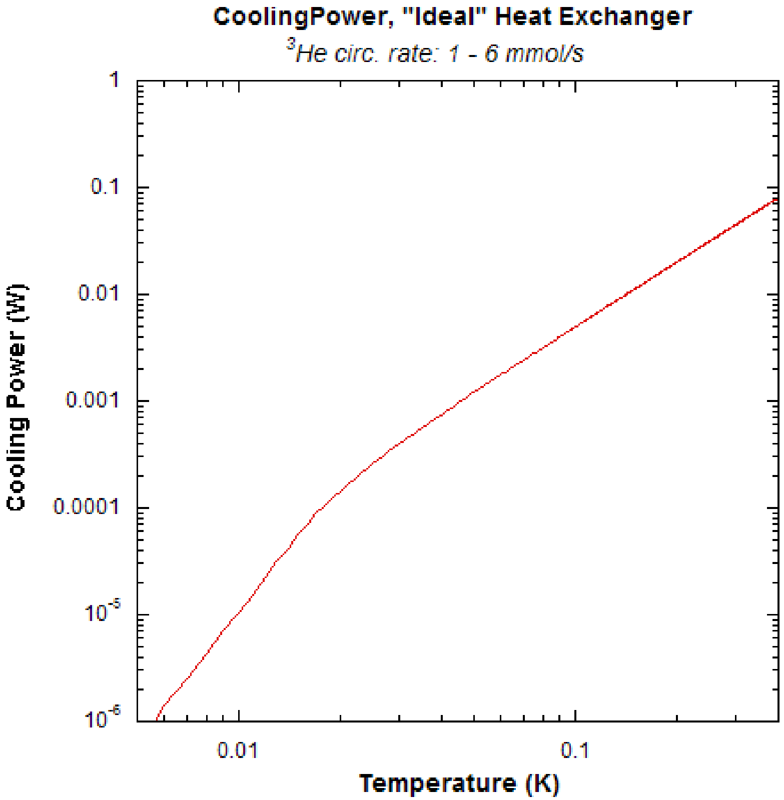
Cooling power, assuming “ideal” heat exchange is determined by molar flow rate and R_k/A of heat exchanger

$$\begin{aligned}\dot{Q}(T_m) &= \dot{n}\ \left[94.5\,T_m^2 - 12.5\,T_c^2\right] \\ &= \dot{n}\ \left[94\,T_m^2 - 625\,\frac{R_{kT}}{A}\,\dot{n}\right]\end{aligned}$$

Sintered Silver Heat Exchangers

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



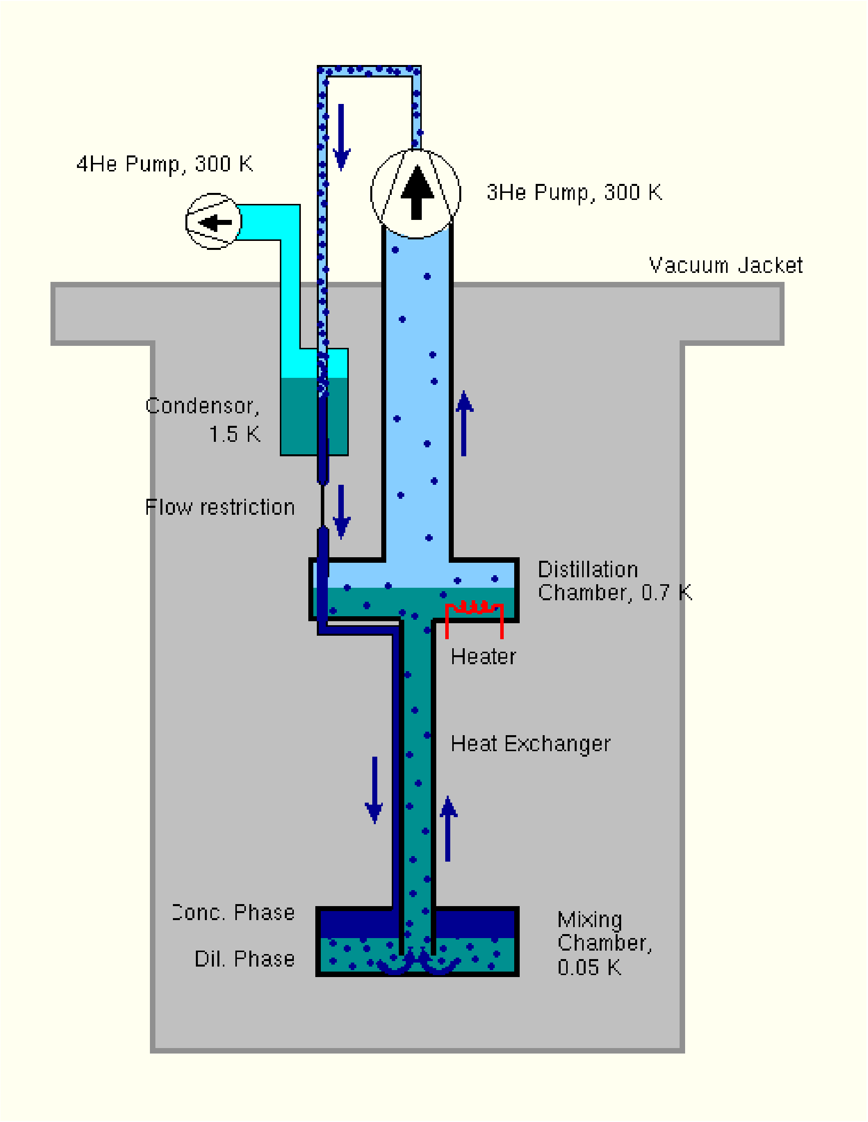


JLab: 1 micron Ag powder
Sinter at 250 °C ➡ 0.5 m^2/g

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

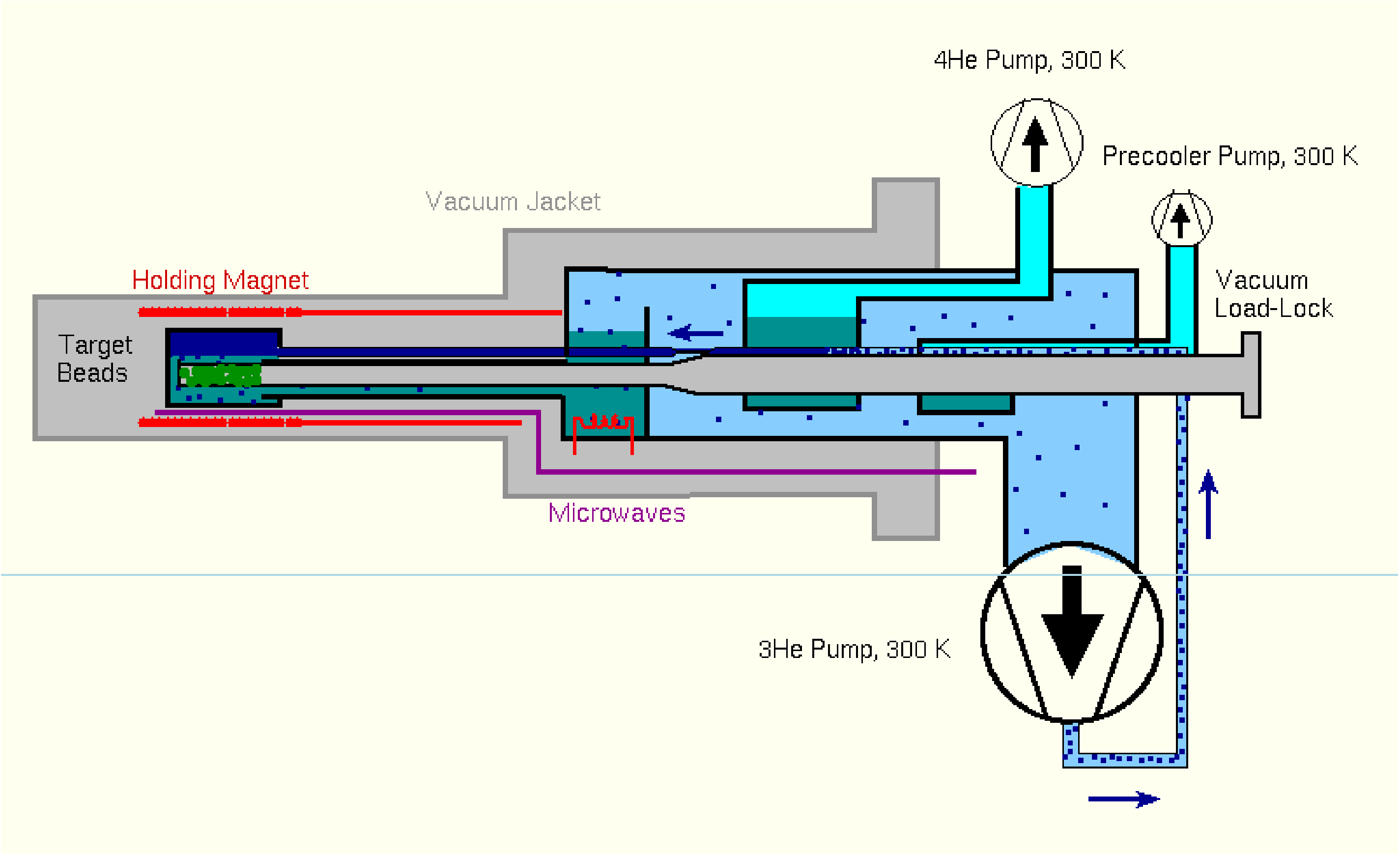
An example of a commercial, vertical dilution refrigerator



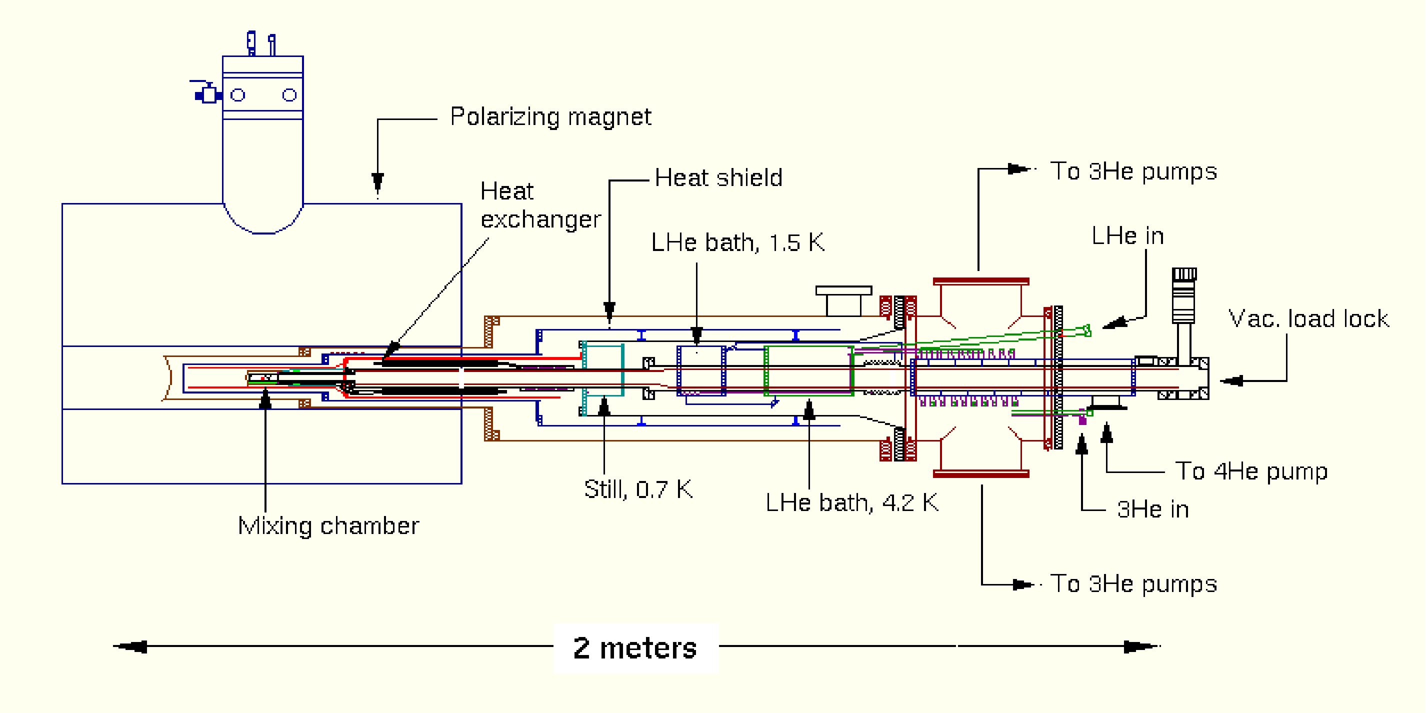
Very nice, but it won't fit inside CLAS...

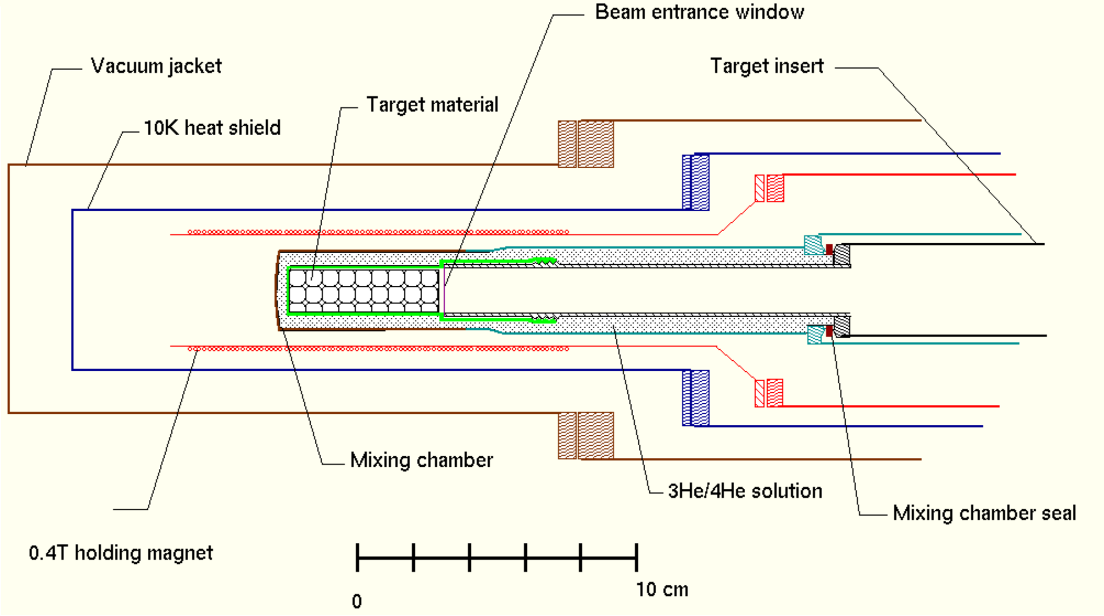
Horizontal Dilution Refrigerator for Frozen Spin Target

T.O. Niinikoski, CERN 1971

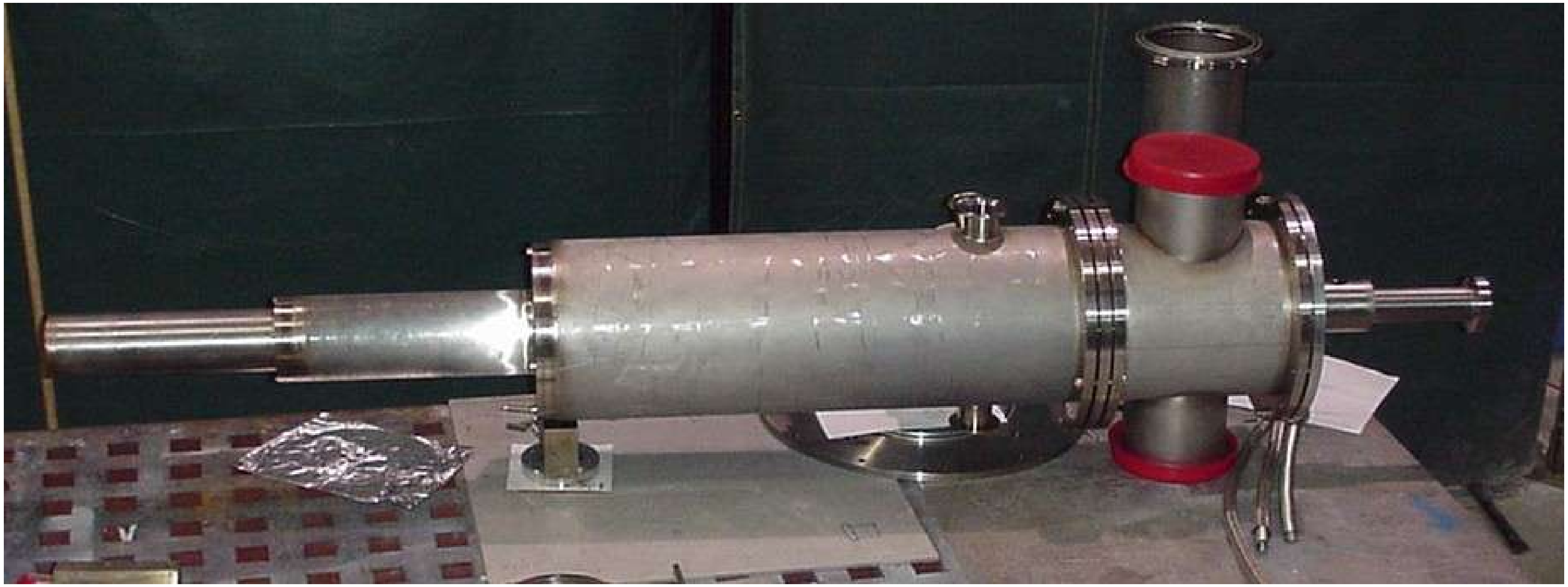


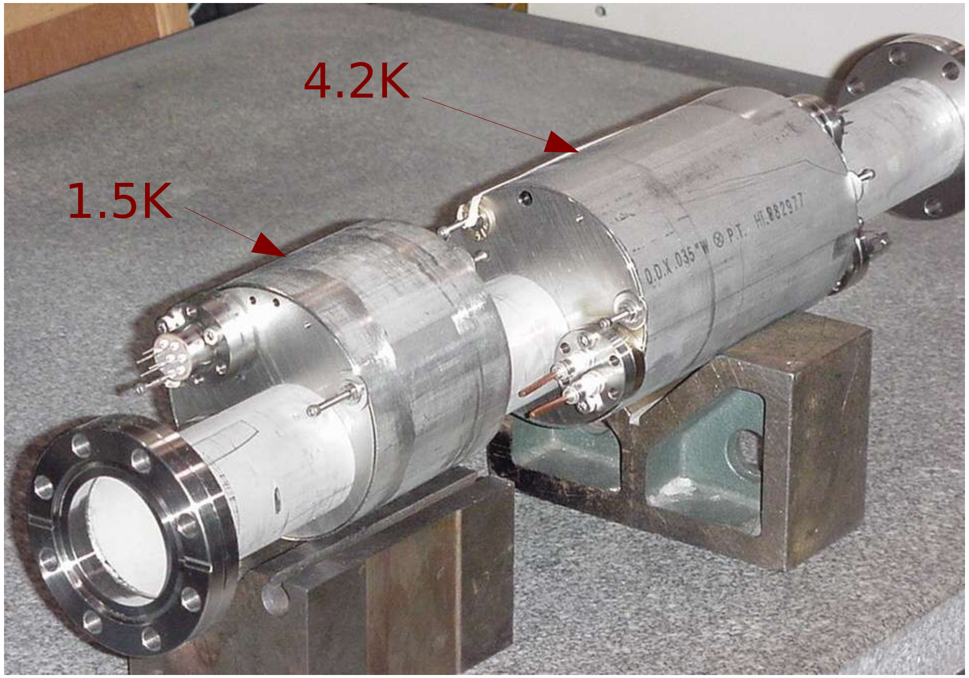
Hall B Frozen Spin Target





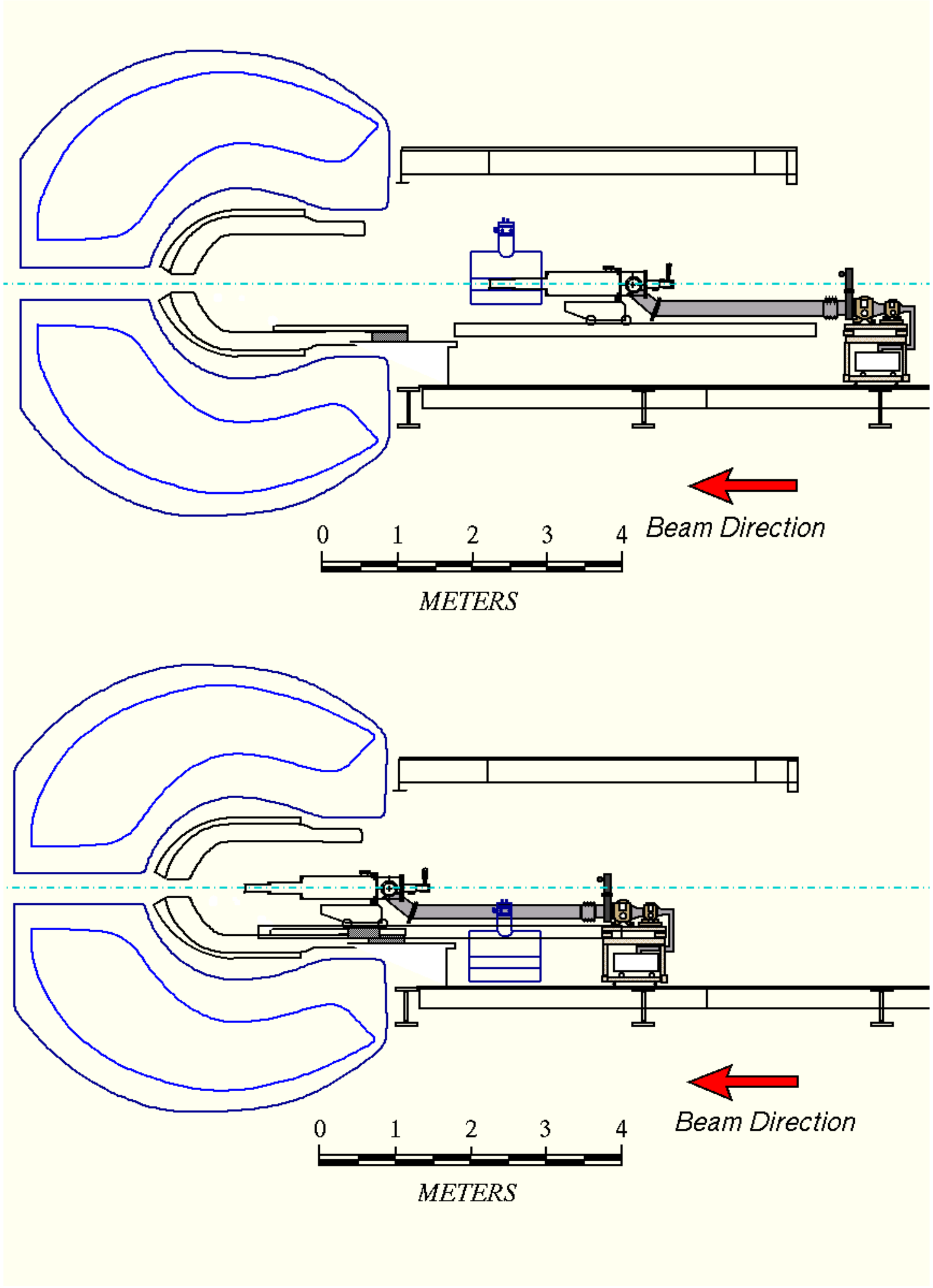
Outer Vacuum Jacket





^{4}He Precooling Stages

The Frozen Spin Waltz



Step 1: Polarizing

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

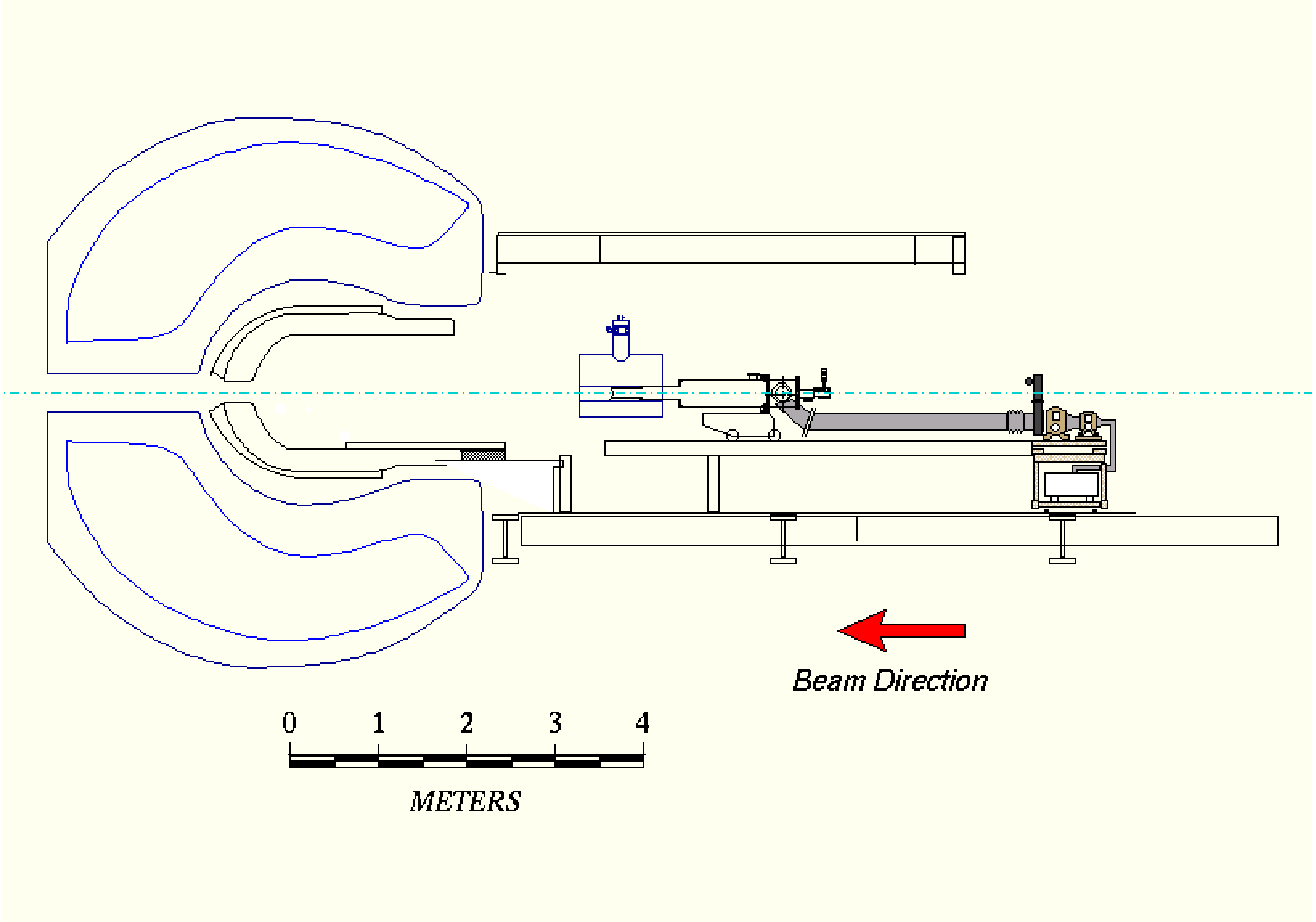
- Target is inserted into magnet, magnet energized, microwaves on

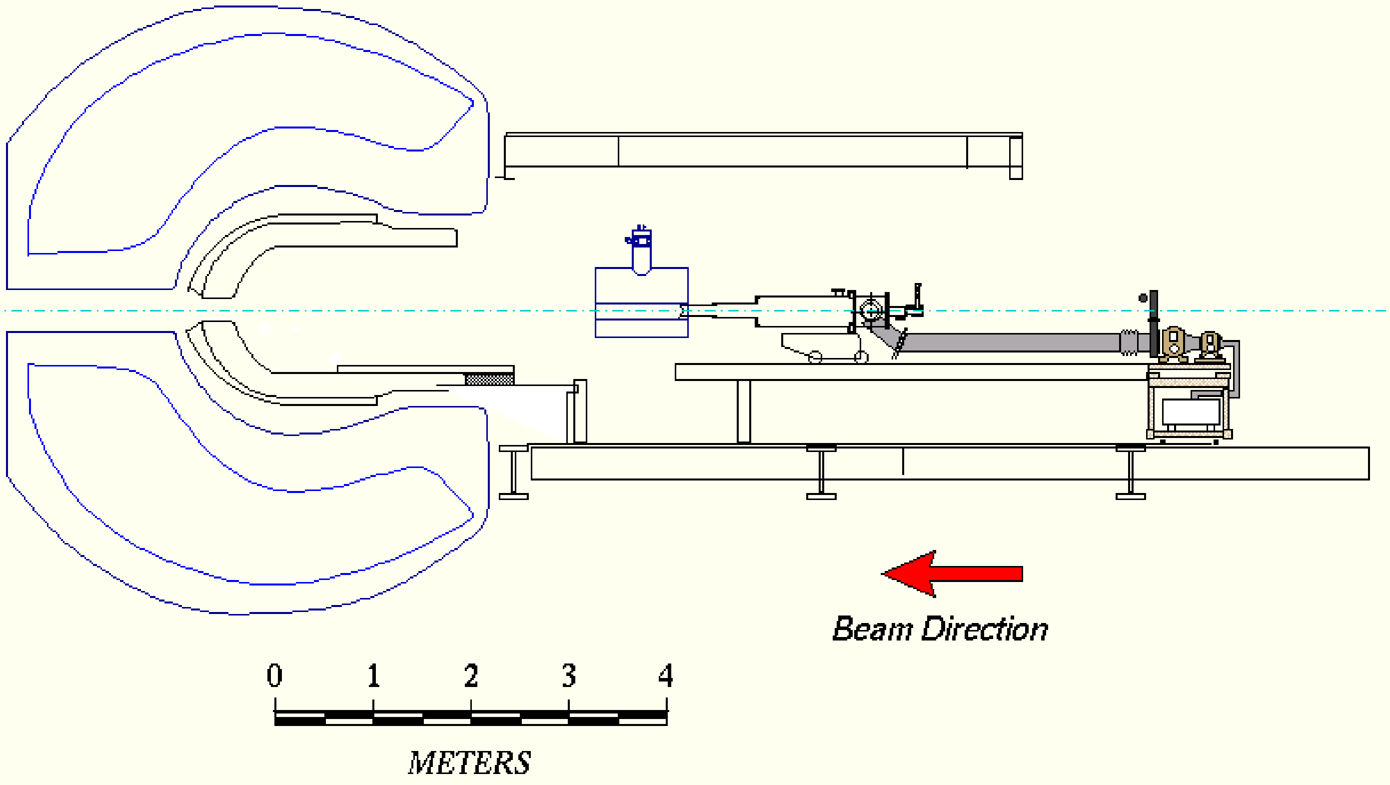
Step 2: Beam On

- Microwaves off, magnet off, holding coil on

- Target is fully retracted, magnet is lowered

-Target is fully insert into CLAS


Beam Direction
0
1
2
3
4
METERS


Beam Direction
0
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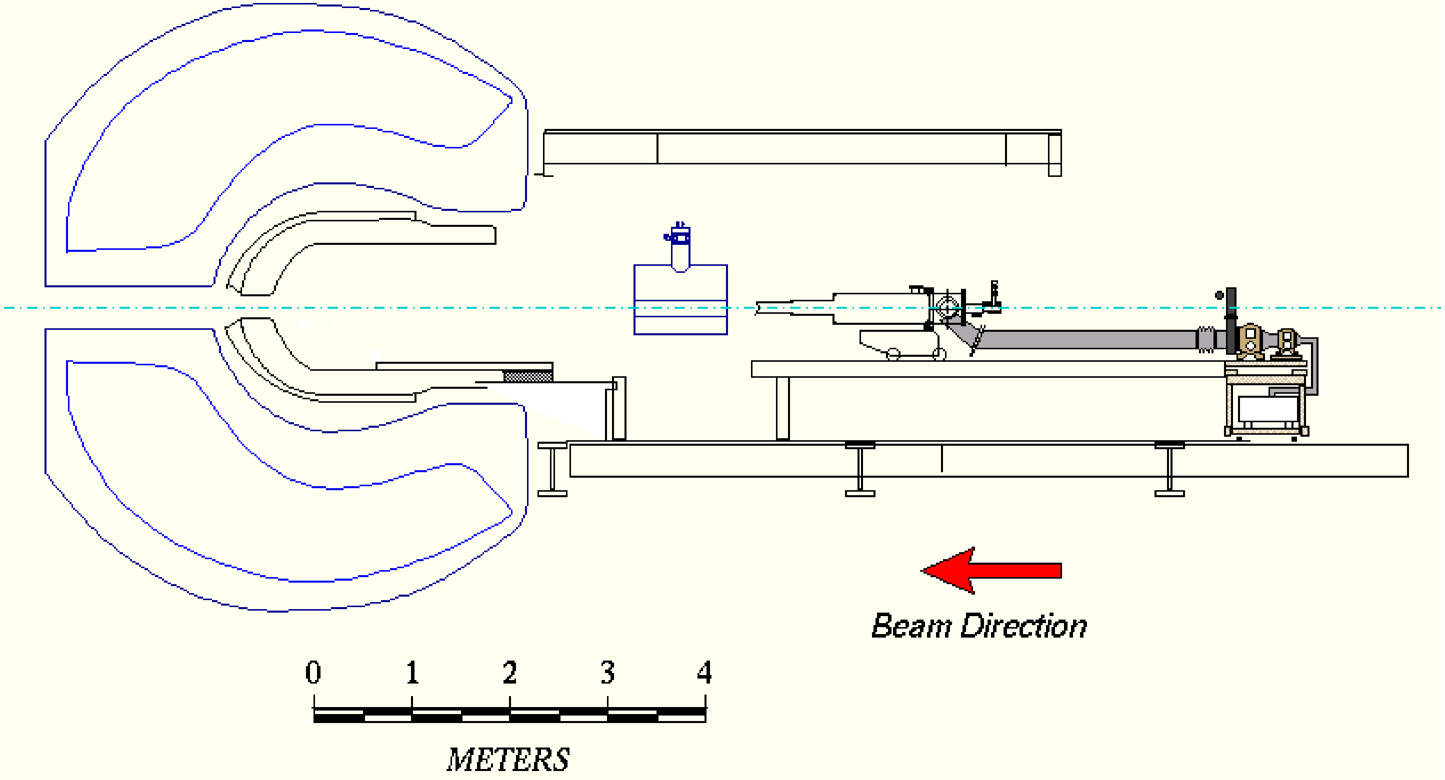
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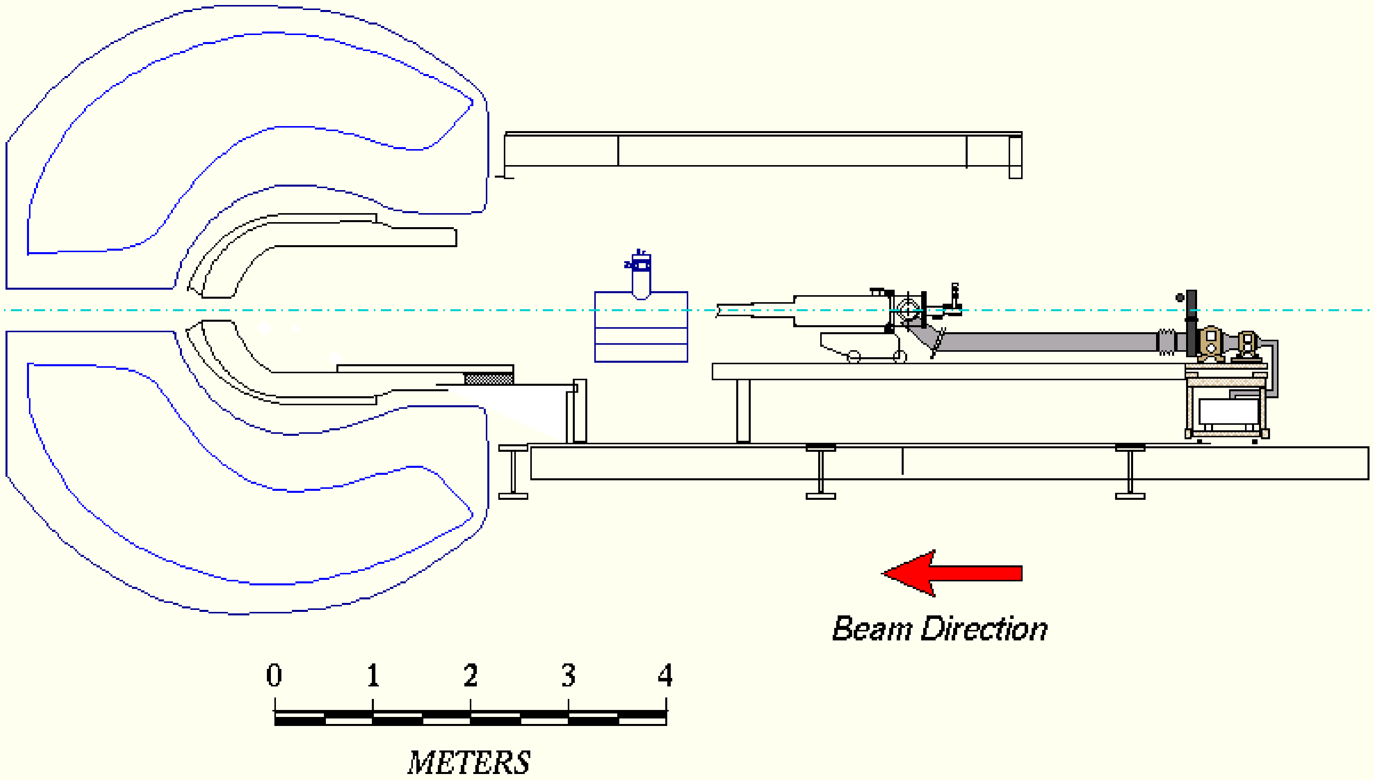
Beam Direction
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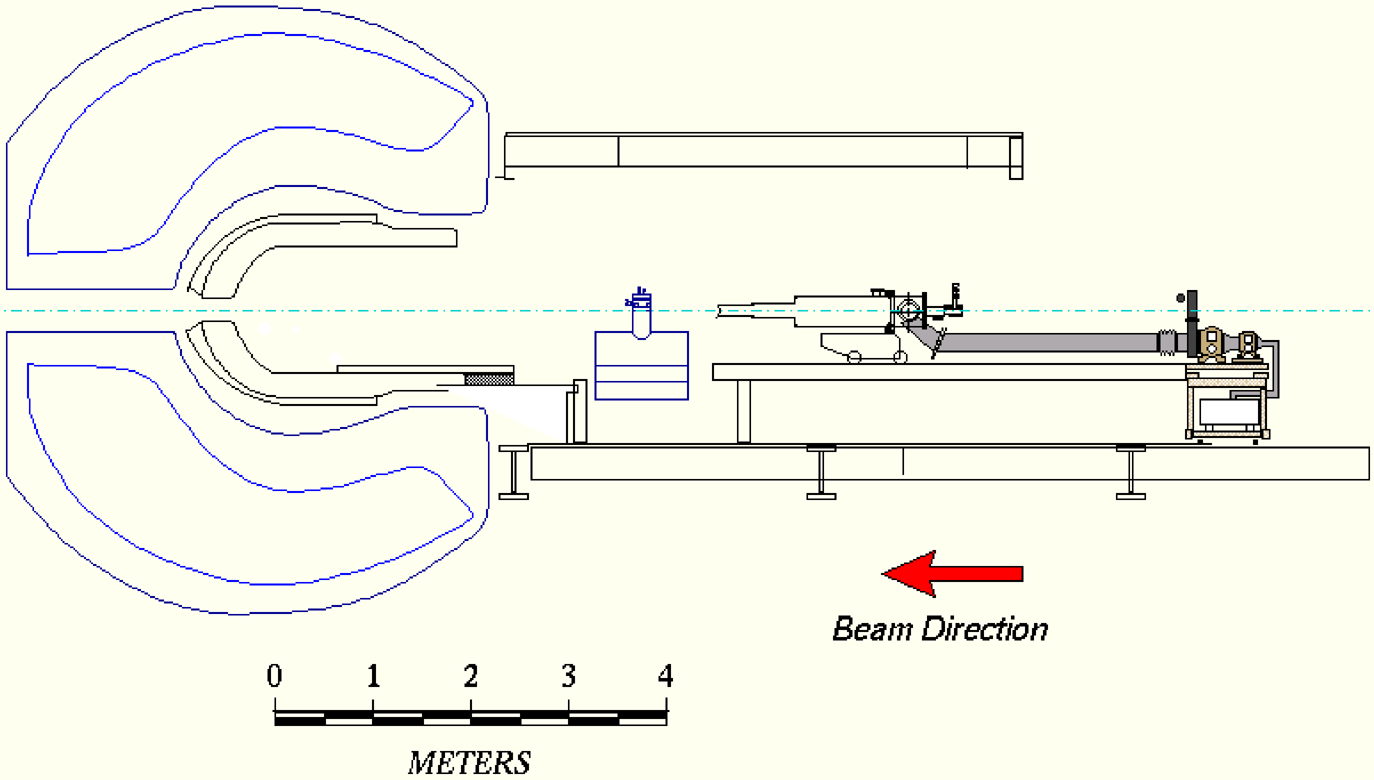
METERS


Beam Direction
0
1
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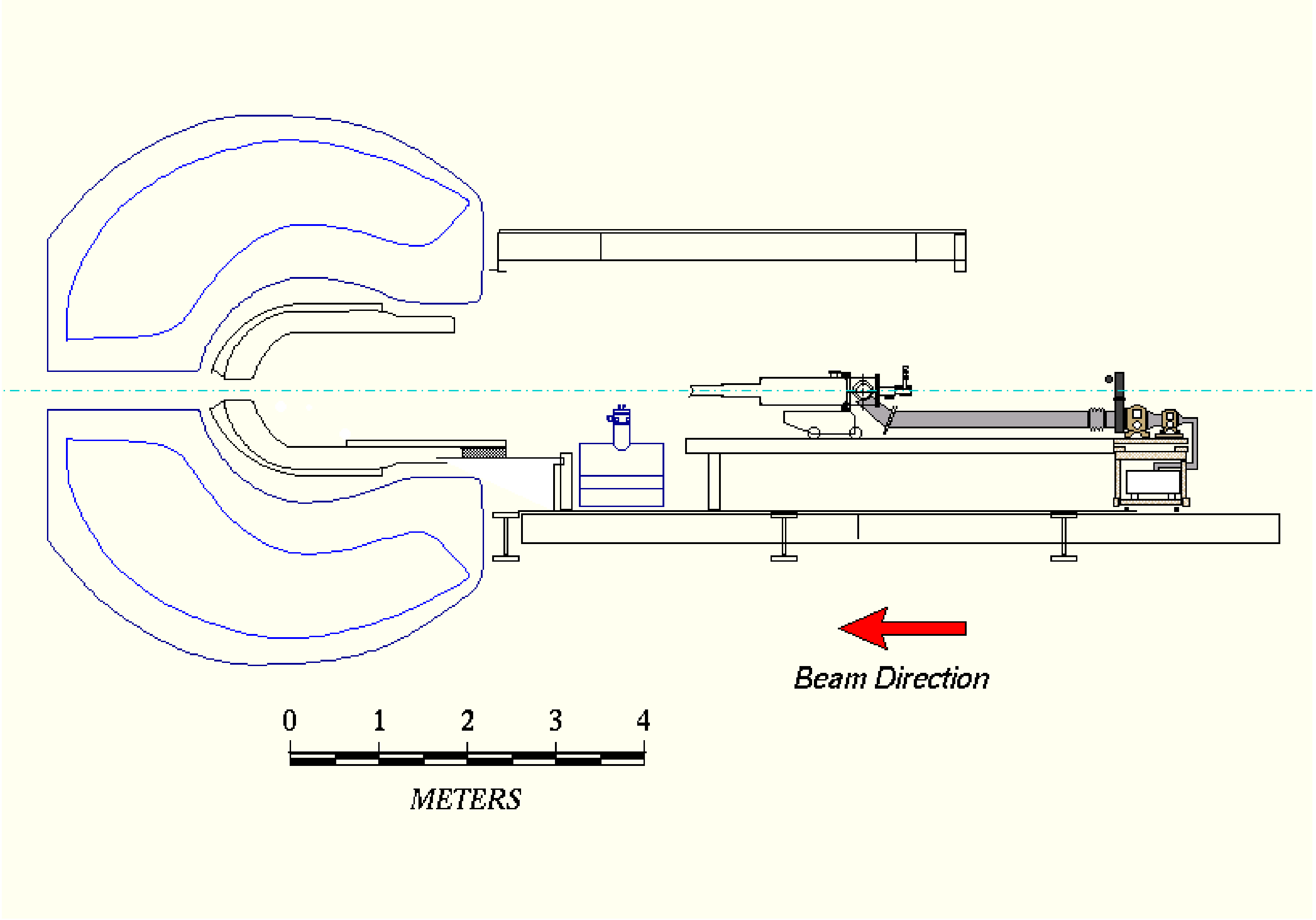
METERS


Beam Direction
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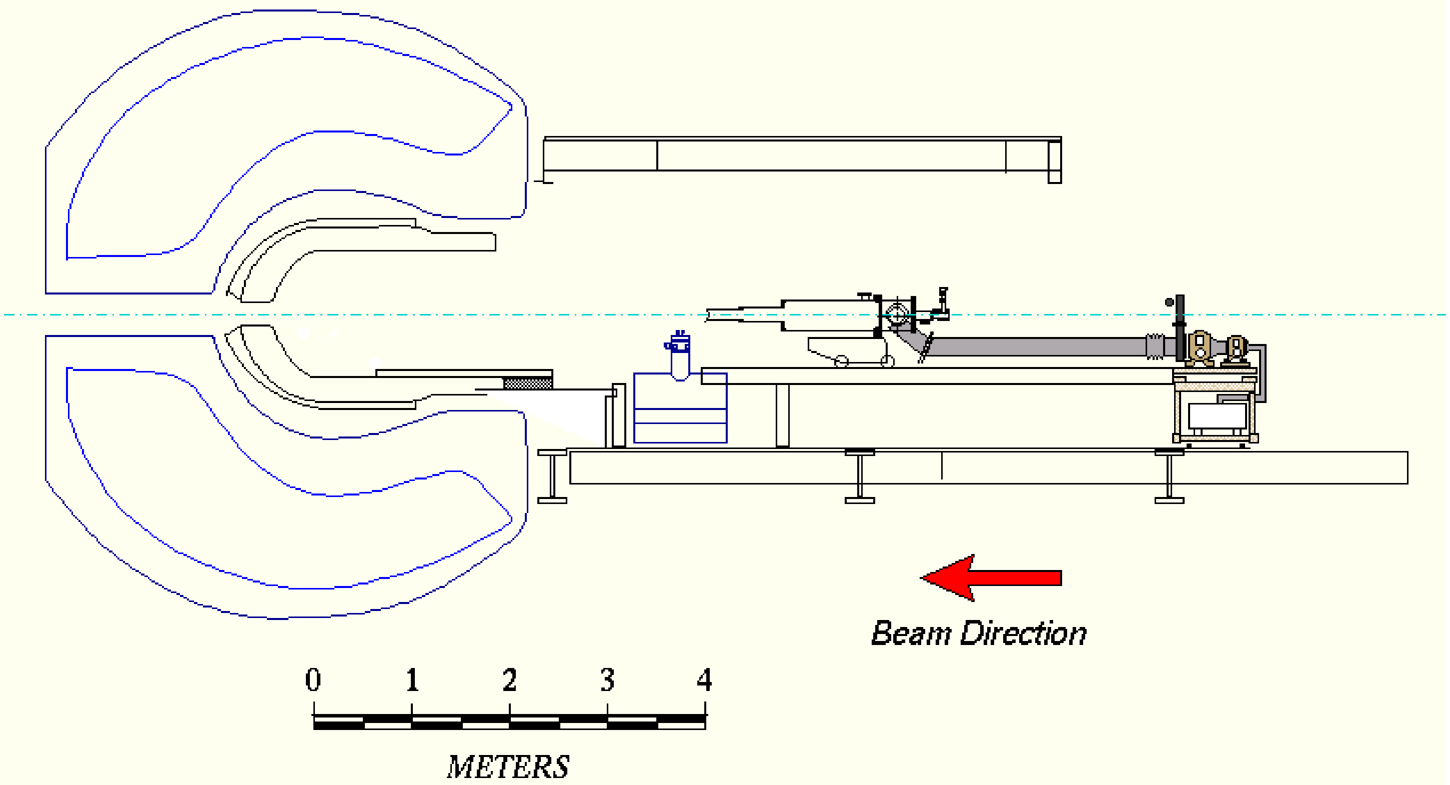
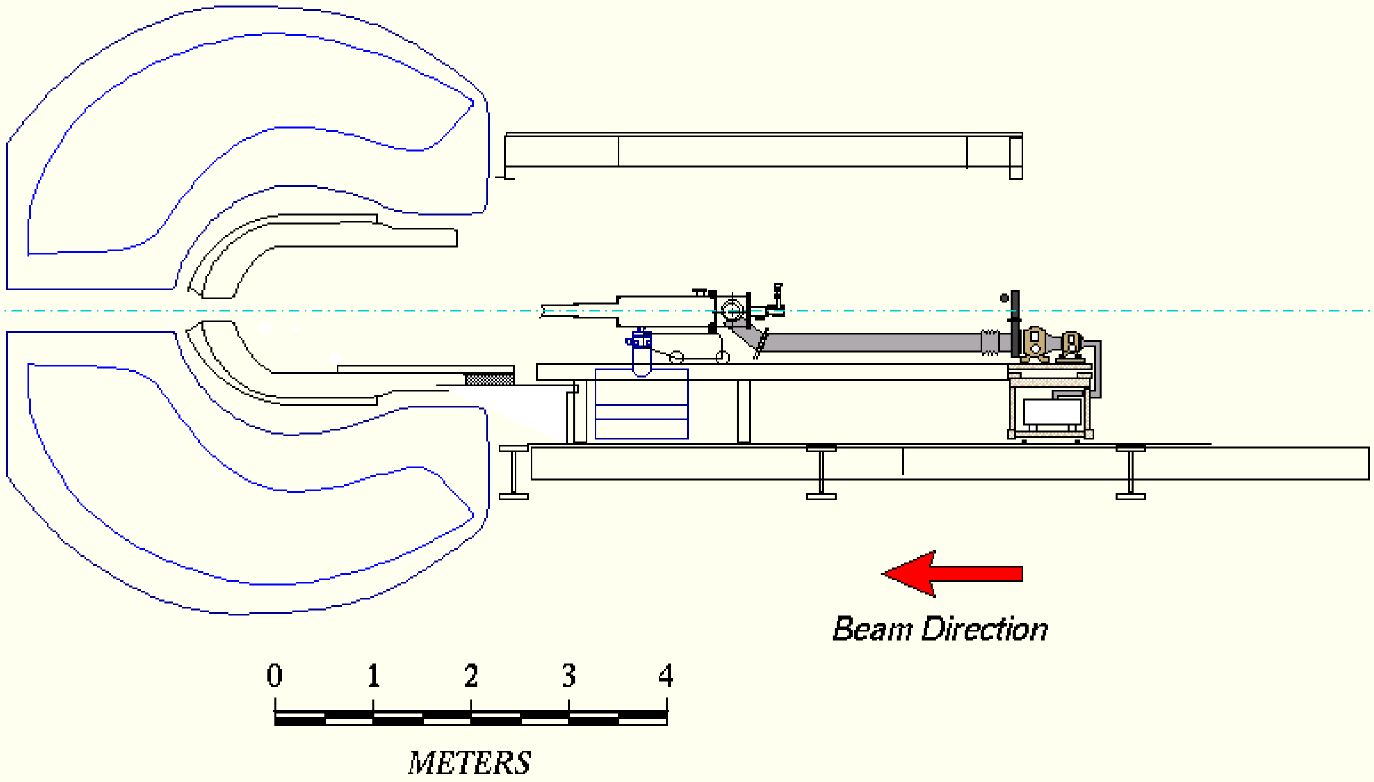

Beam Direction
0
1
2
3
4
METERS


Beam Direction
0
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2
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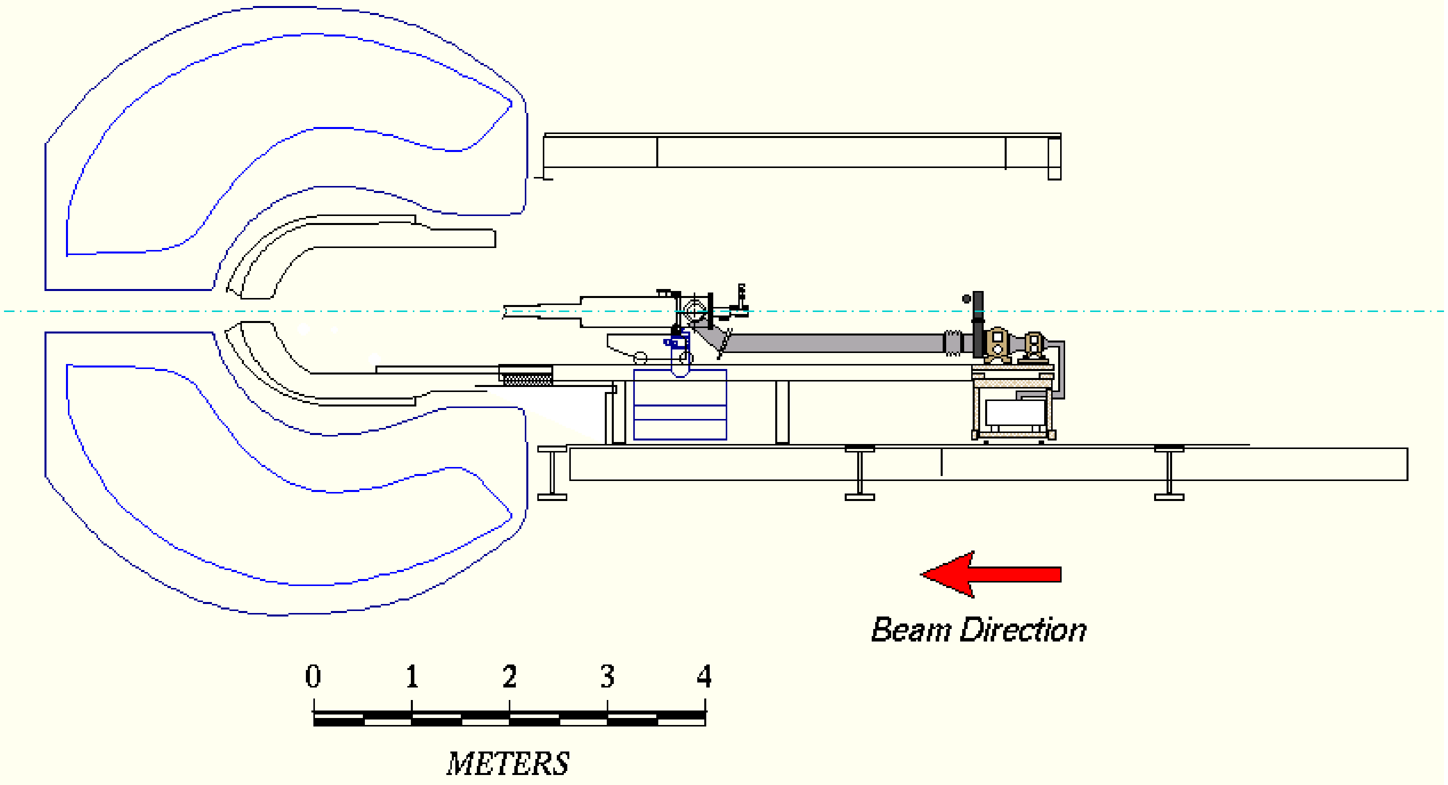
METERS


Beam Direction
0
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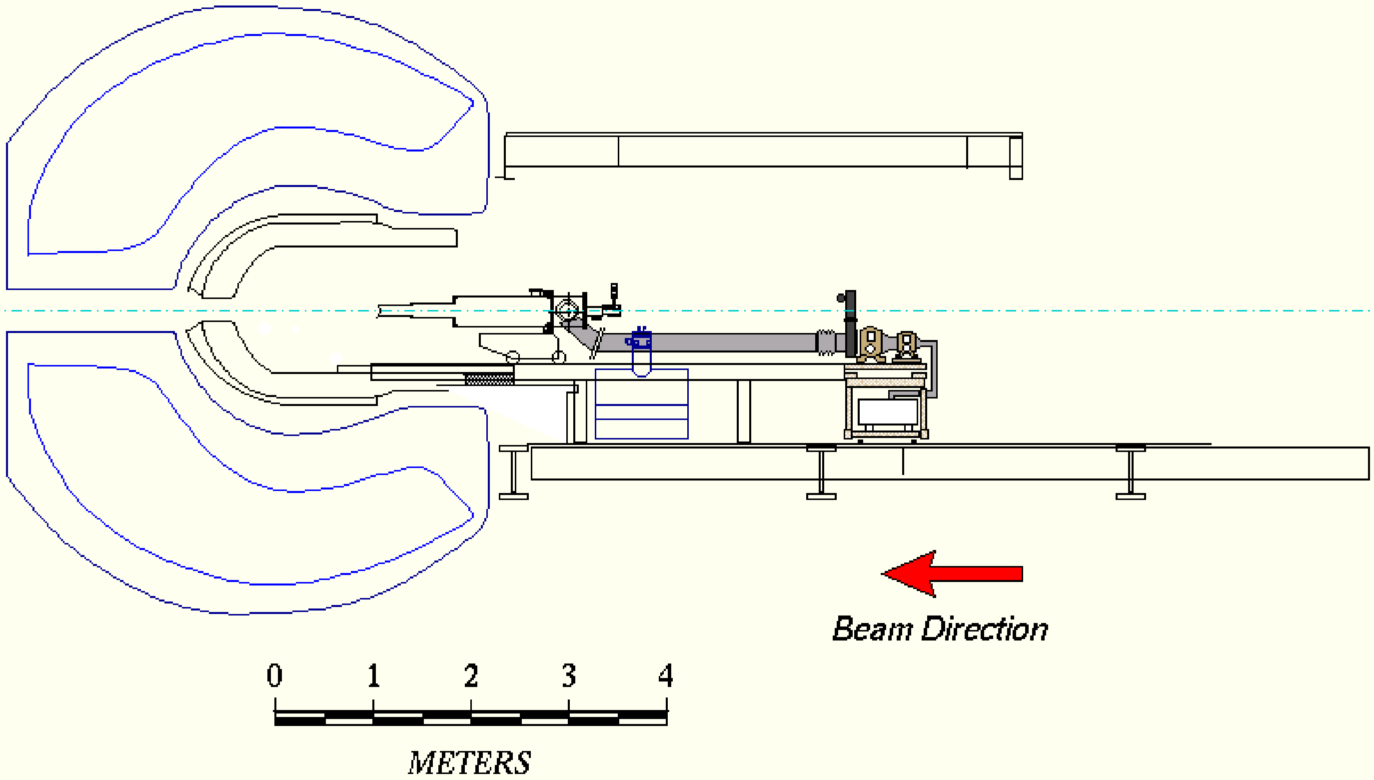
METERS


Beam Direction
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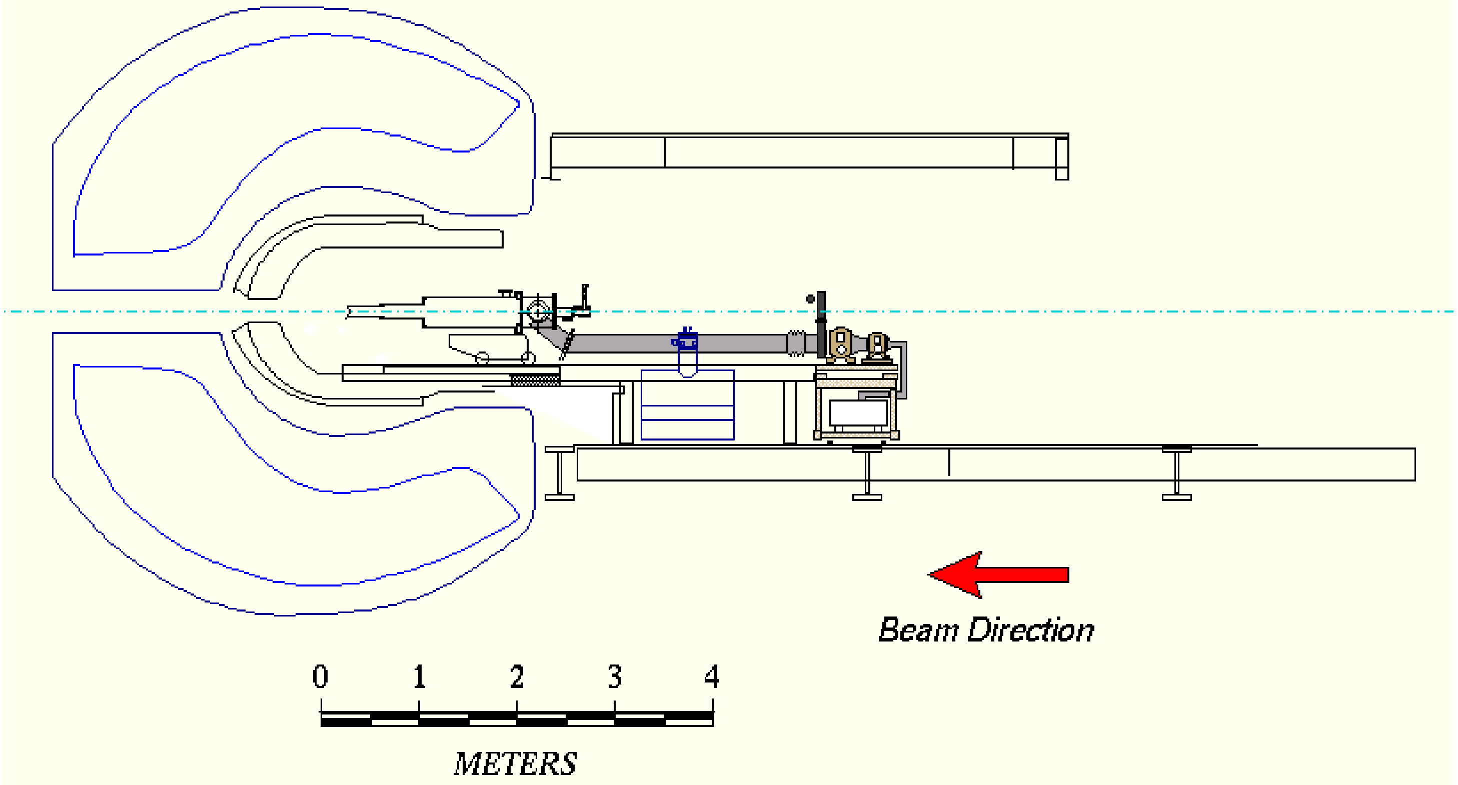
METERS


Beam Direction
0
1
2
3
4
METERS

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), both longitundinal and transverse, are under development.

- Horizontal dilution refrigerator is under construction.

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

Racetrack coils for transverse holding magnet (untested)