WACS and the Polarized Target

Dustin Keller
University of Virginia

April 18, 2016

Outline

- Challenge of WACS from polarized target
- Setup for Polarized WACS (E12-14-006)
- Possibilities of a pure photon beam
- Some Polarized Target Developments
- Summary

History

- PR05-003 deferred with regret by PAC27
- E05-101 approved for 14 days by PAC28
    - Proposed pure photon source at Jan 2006 Hall C
    - E05-101 never run due to scheduling
- E12-14-006 approved at PAC42 (Keller, Zhang, Day)
    - First presentation of pure photon beam for NPS meeting on 10/9/14
        - Other pure photon Hall-A/Hall-C

Polarized WACS

First ever measurement of A_{LL}

$$A_{LL}\frac{d\sigma}{dt} \equiv \frac{1}{2}\left[\frac{d\sigma(\uparrow\uparrow)}{dt} - \frac{d\sigma((\downarrow\uparrow)}{dt}\right]$$

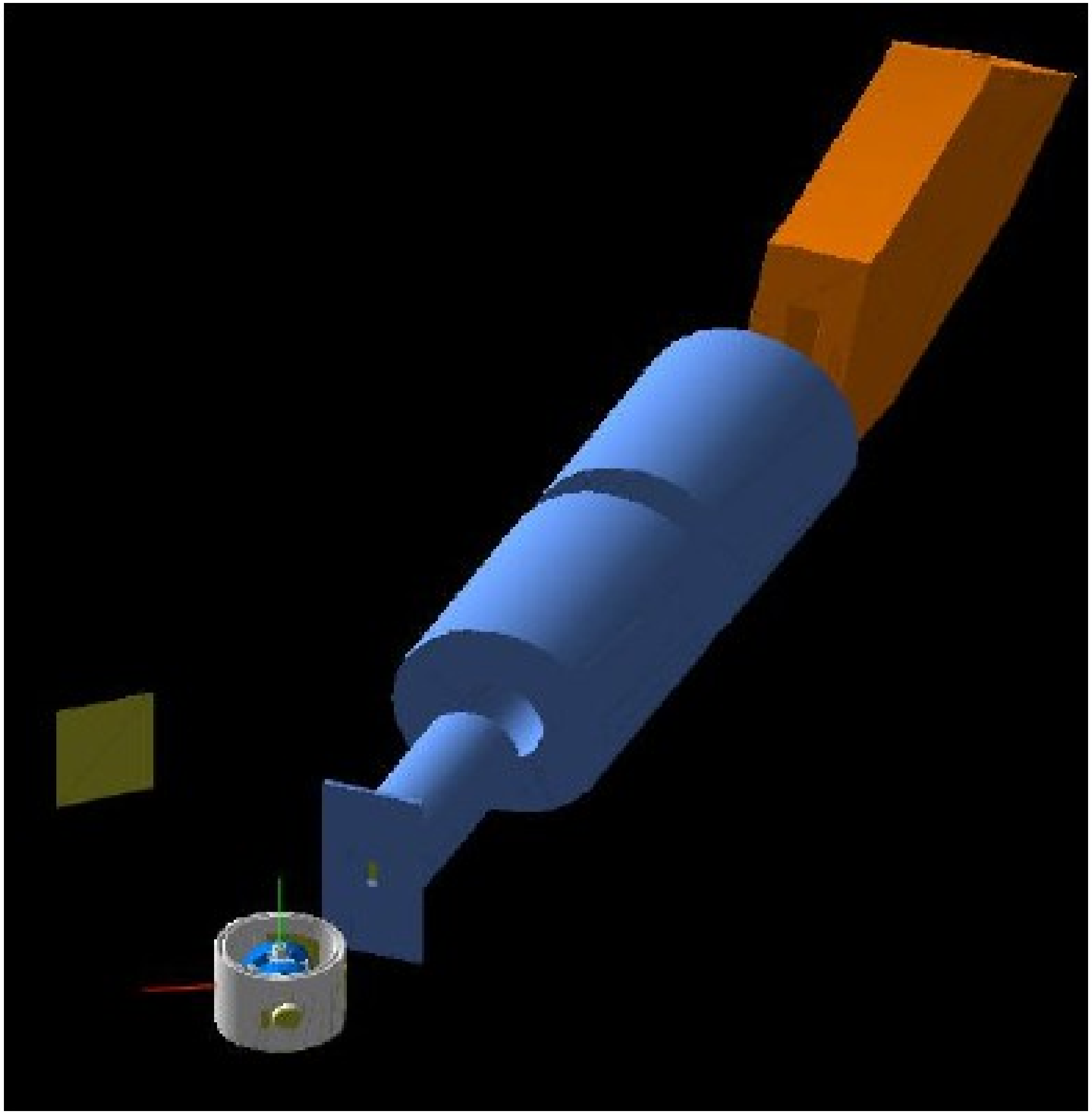
What is the nature of the quark which absorbs and emits photons? Is it a constituent or a current quark?

If the GPD approach is correct, is it indeed true that the RCS reaction proceeds through the interaction of photons with a single quark?

A_{LL} will help discriminate between quark helicity flip and non-flip contributions.

Data on A_{LL} will provide constraints on the GPD integrals

Experiment Setup: HMS + NPS



HMS: **High Momentum Spectrometer**

About 1.66 m to target

The acceptance is determined by the collimater.

Solid Angle = ~7 msr.

Momentum acceptance: +/-9%

dP/P = 0.2%

dTheta_tr =1 mr , dPhi_tr =1 mr

dY_tg = 1 mm

NPS: **Neutral Particle Spectrometer**

Size = 30” (w) x 36” (h)

dE/E = 3%

Positon = 3 mm

Distance to target and vertical offset depends on kinematics

kin. P#	t, $(GeV/c)^2$	θ_γ^{lab}, degree	θ_γ^{cm}, degree	θ_p^{lab}, degree	E_γ^{lab}, GeV	p_p, GeV/c	L, cm	H, cm
P1	-1.7	22	60	45	2.87	1.56	785	41.2
P2	-3.3	37	90	30	2.00	2.52	445	21.5
P3	-5.4	78	136	13	0.88	3.55	245	10.0

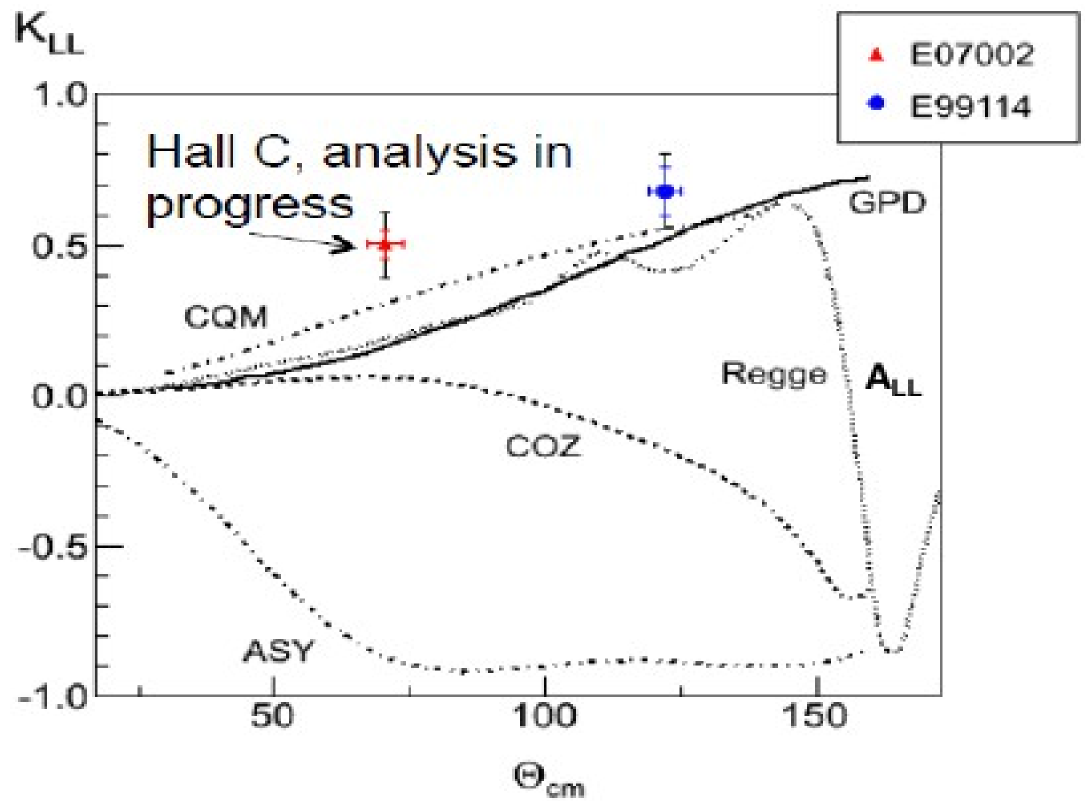
kinematic	P1	P2	P3
N_{RCS}, events	2333	1666	1404
ΔA_{LL}	0.05	0.07	0.09

Source	Systematic
Polarimetry	5%
Packing fraction	3%
Trigger/Tracking efficiency	1.0%
Acceptance	0.5%
Charge Determination	1.0%
Detector resolution and efficiency	1.0%
Background subtraction	4.0%
Total	8%

Existing Data

E07-002:
$s = 8\ GeV^2$
$t = -2.1\ Gev^2$

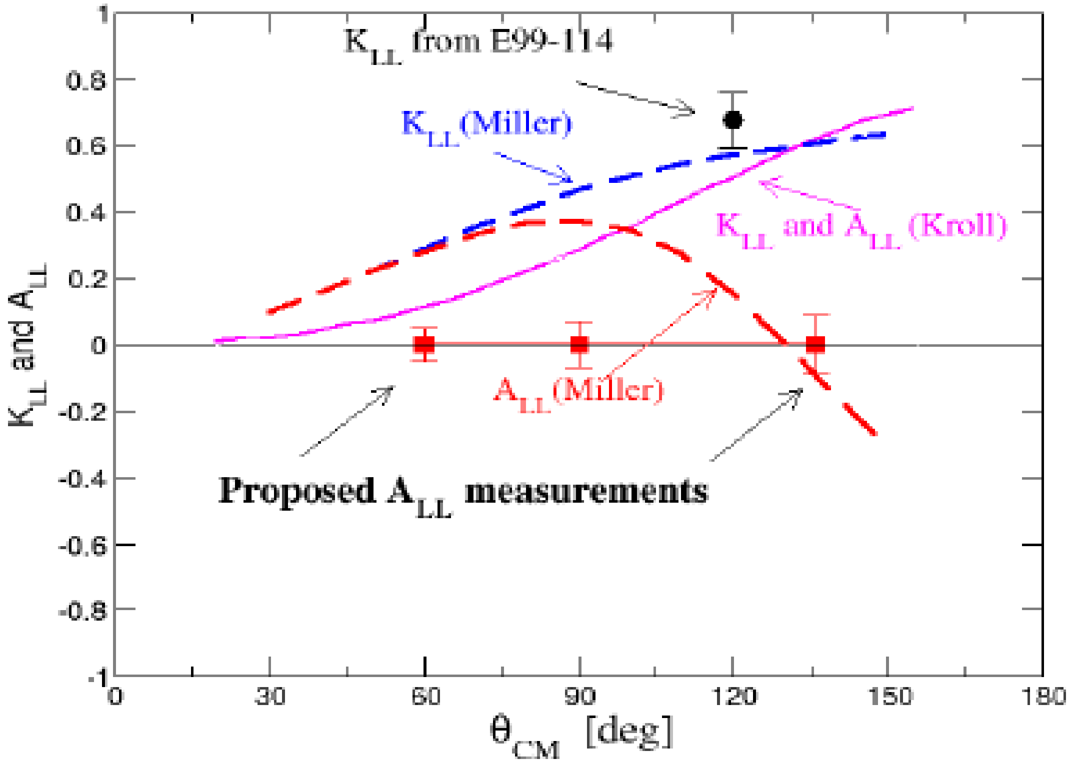
E99-114:
$s = 6.9\ GeV^2$
$t = -4.0\ Gev^2$



K_{LL}: a longitudinal polarization transfer observable, which is related to the helicity of the final proton.

GPD: Huang and Kroll
CQM: Miller's K_{LL}
ASY: Brooks and Dixon
COZ: Chernyak-Ogloblin-Zhitnitsky
Regge: Cano and Laget (A_{LL})

Constraints on Initial State Helicity



A_{LL}: the initial state helicity correlation observables, which involves the helicity of the initial proton

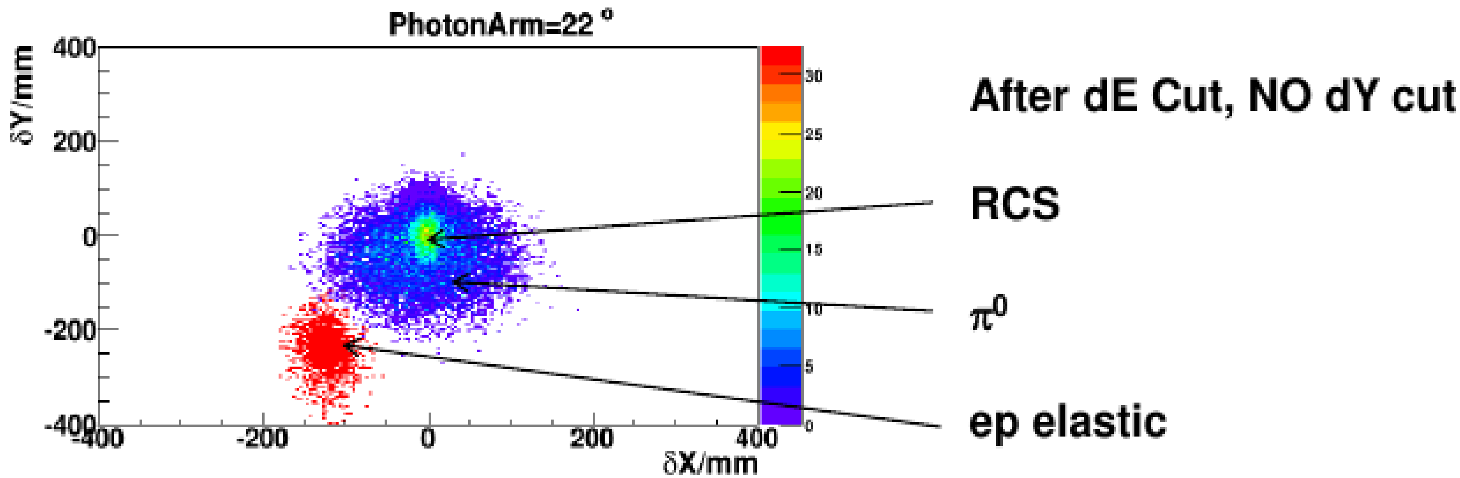
Kroll: $A_{LL} = K_{LL}$

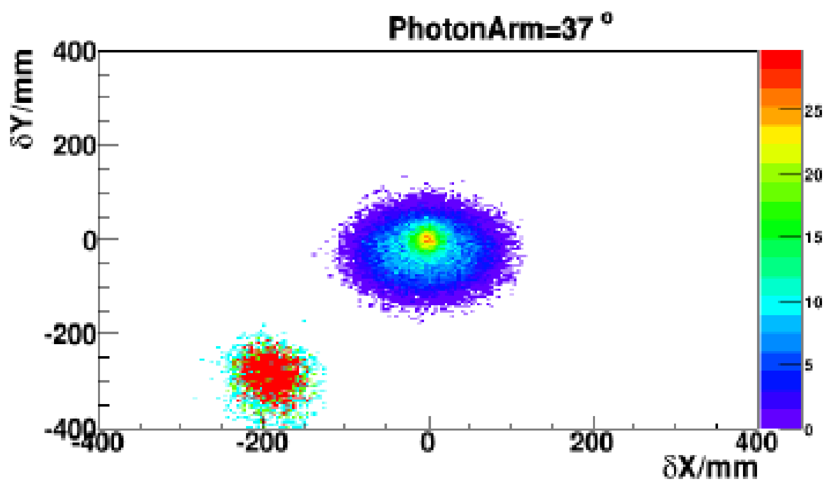
vs

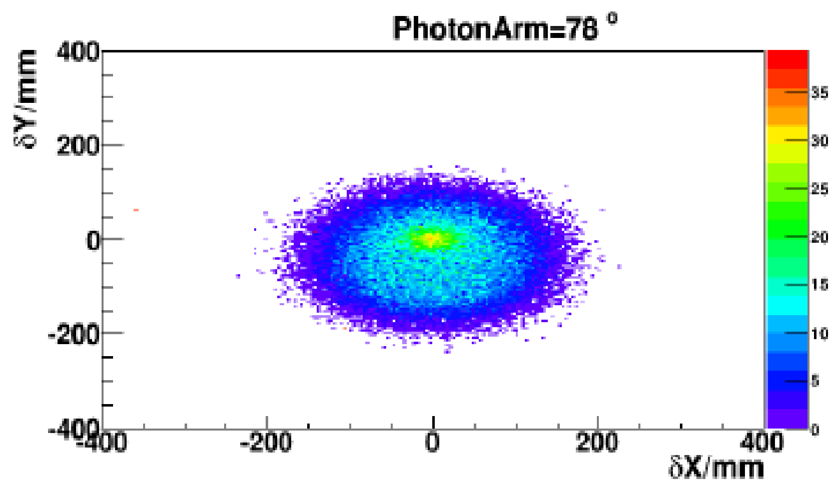
Miller: $A_{LL} \neq K_{LL}$

Miller in Impulse approximation of handbag:
Massive quark
Model wave function same as for E/M form factors
Orbital angular momentum and non-conservation of proton helicity
Good agreement with cross section data But **$A_{LL} \neq K_{LL}$,**
At large backward angles: $A_{LL} \simeq - K_{LL}$

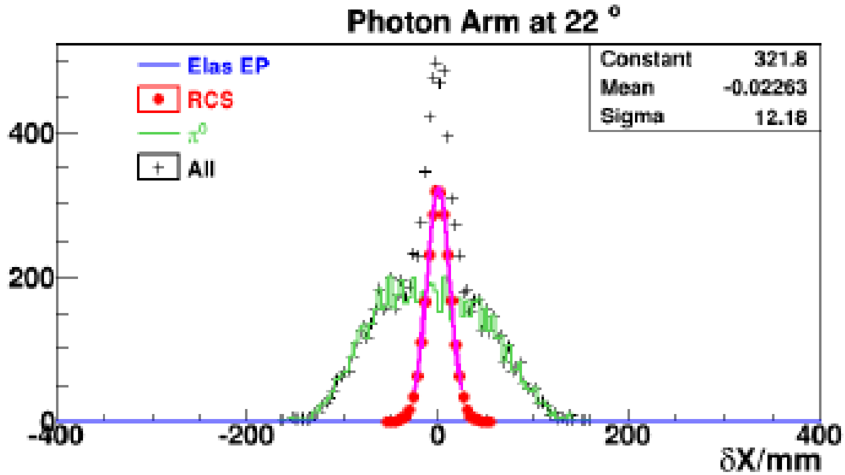
Separation from Background







Separation from Background

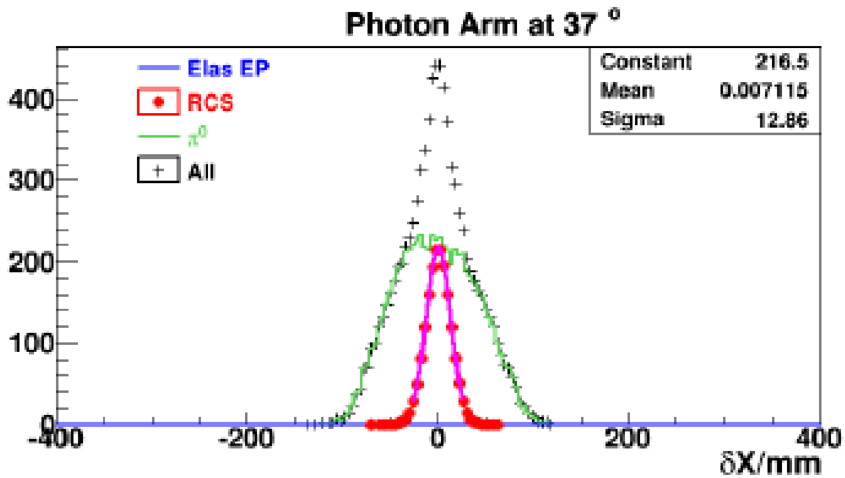


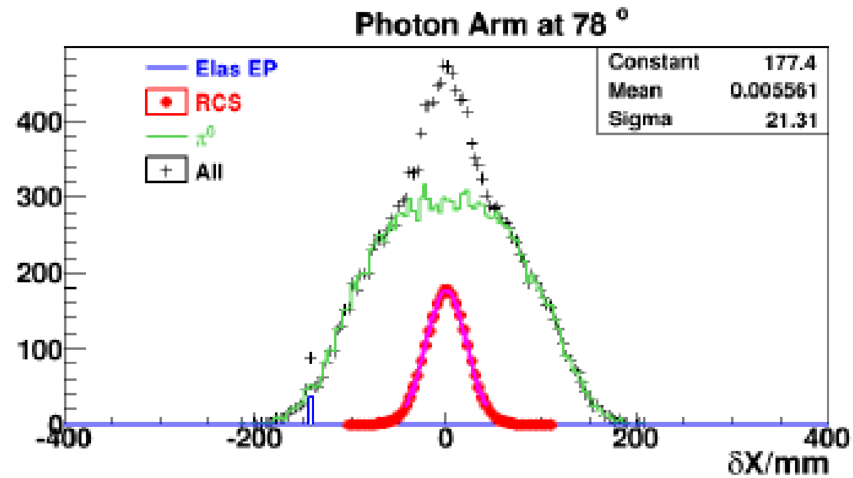
dX: the difference between the measured RCS photon vertical position and the inferred vertical position.

After both dY and dE cuts

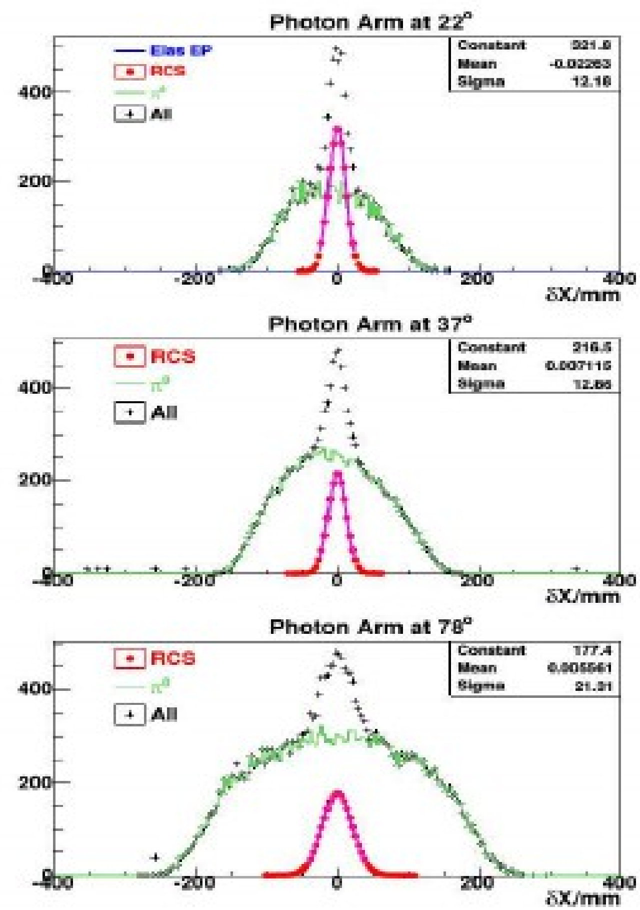
Fit Bg+signal to find out dX resolution, then extract dilution (D) of RCS events.

$$N_{RCS,required} = D/(P_e P_p f_{e\gamma} \Delta A_{LL})^2$$

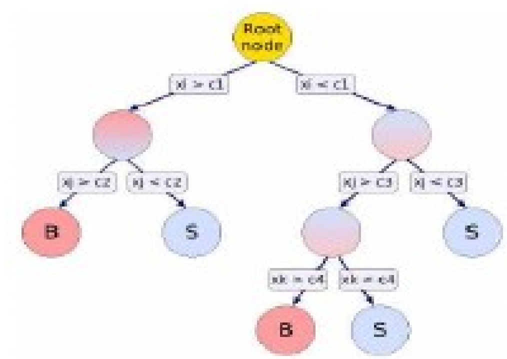


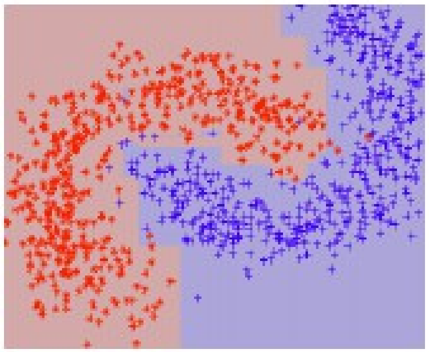


Classification Learning Algorithms

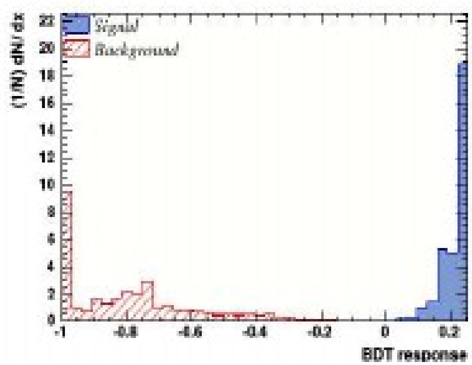


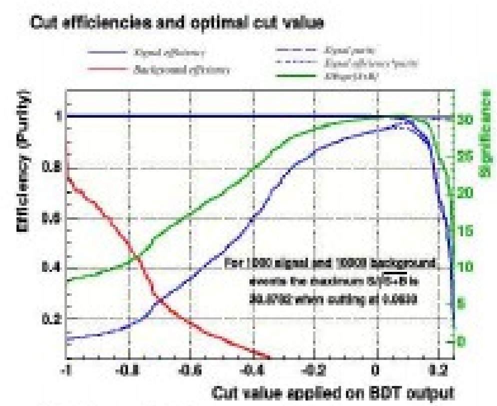
Boosted Decision Tree





BDT efficiency response using tagged MC





Optimize split point: Information Entropy $H = -\sum_c p(c)\log p(c)$

$D = (N_{\gamma,\pi^0} + N_{\gamma,\gamma})/N_{\gamma,\gamma}$ $N_{RCS,required} = D/(P_e P_p f_{e\gamma} \Delta A_{LL})^2$

Expected dilution from simulated data:
Normal method: D=2.0, 2.8, 3.9
BDT: D=1.01, 1.04, 1.07

Also Used for CLAS6 Frost-g9 Dilution

...as well as Hall-D

Challenge of WACS from PT

- Small cross sections
- Low photon flux
- Limited luminosity of DNP targets
    - Mixed photon-electron beam degrades polarization
        - Radiation damage
        - Anneals
        - TEs
        - Swapping material
        - Optics demands knowledge of the photon coordinates at the target (+/- 2 mm)

- Collimation of photon beam inefficient

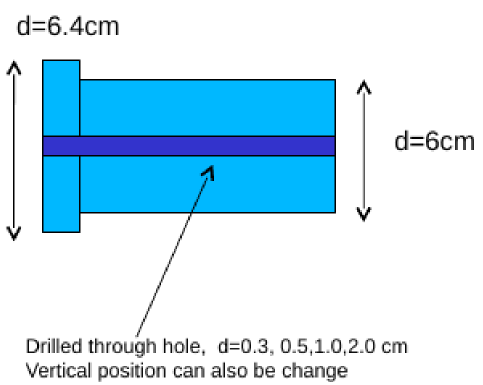
Possibility of a Pure Photon Source

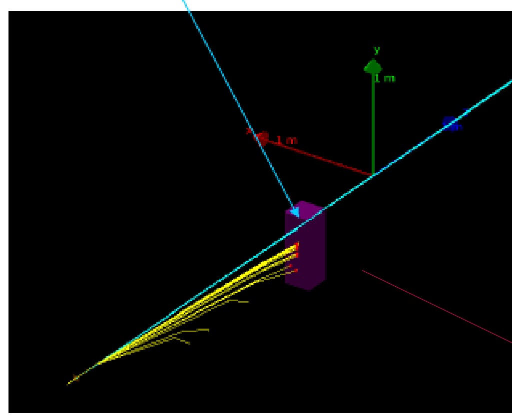
Dump: 60 cm high(y), 20 cm wide(x), 15 cm thick(z)

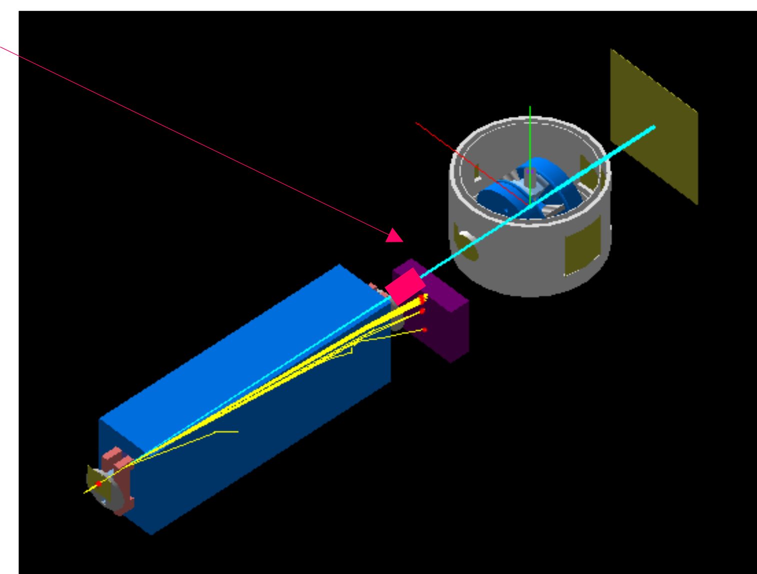
There is a replaceable cylinder block with 6cm diameter. Drilled through this block with a hole of various diameter of 0.3, 0.5, 1, 2 cm. This block is part of the local dump and will be used as the collimator.

The replaceable block used in E12-14-006 will be the one with a 3 mm diameter hole. Photon flux reduce to ~40% due to this collimator if placed radiator 2.7m away

Use Local Beam Dump







Radiator right at front of bender

Separated Function Pure Photon Beam

Place dipole magnet right after the radiator to bend 1 uA e$^-$ beam to a 10k-watt local dump

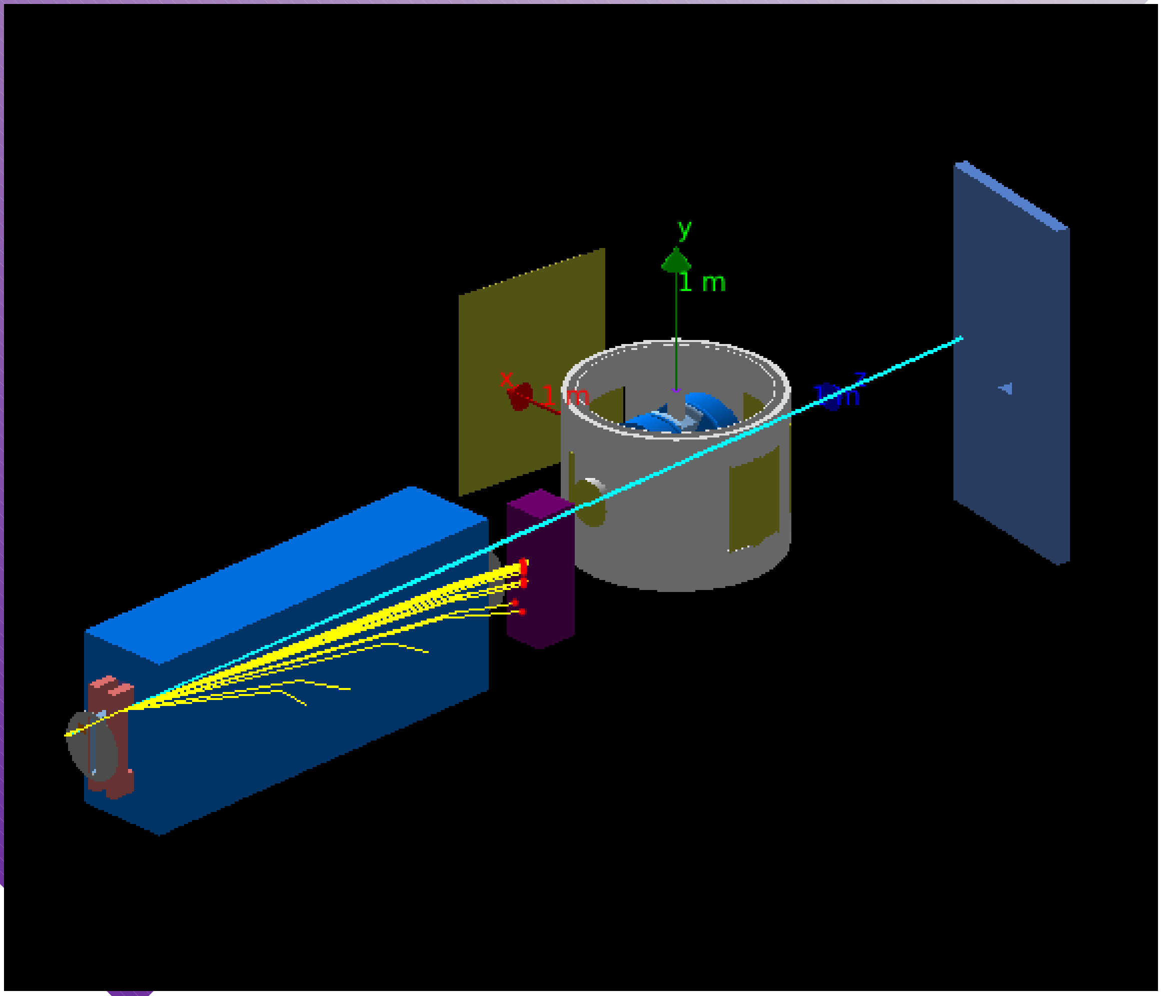
We can reuse the 2m-long FZ dipole (and a power supply), from G2P experiment. Not ideal but it exists.

For **BdL=2.2 Tesla-meter, 4.4|6.6| 11 GeV** beam electron deflection are ~22|~14|~8 cm at the local dump.

Collimator sits on top of the local dump, 3mm diameter in this case, can be changed.

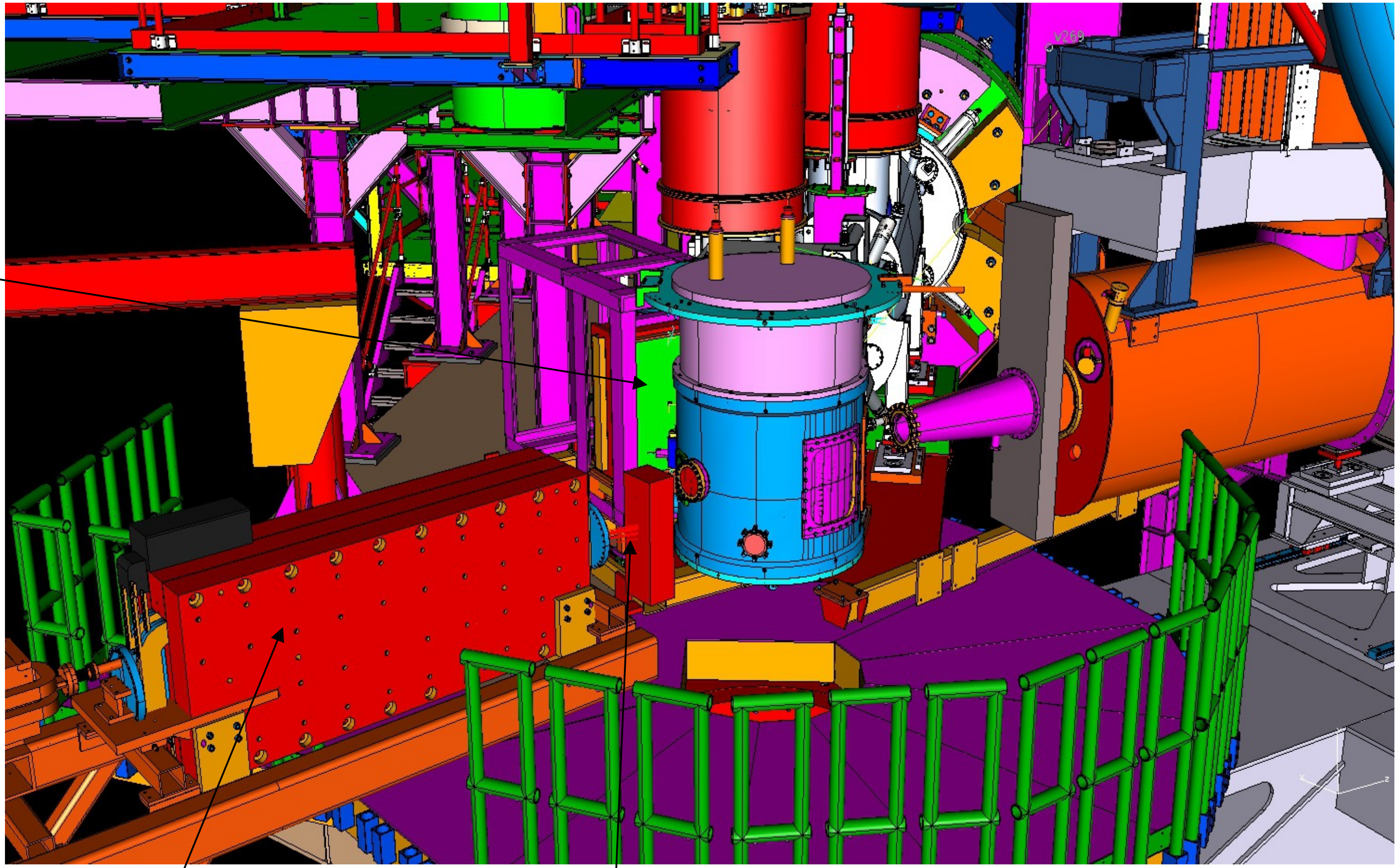
1.0 uA beam current results in ~5x10^{11} γ /s

Shielding not shown, depends on experiment.

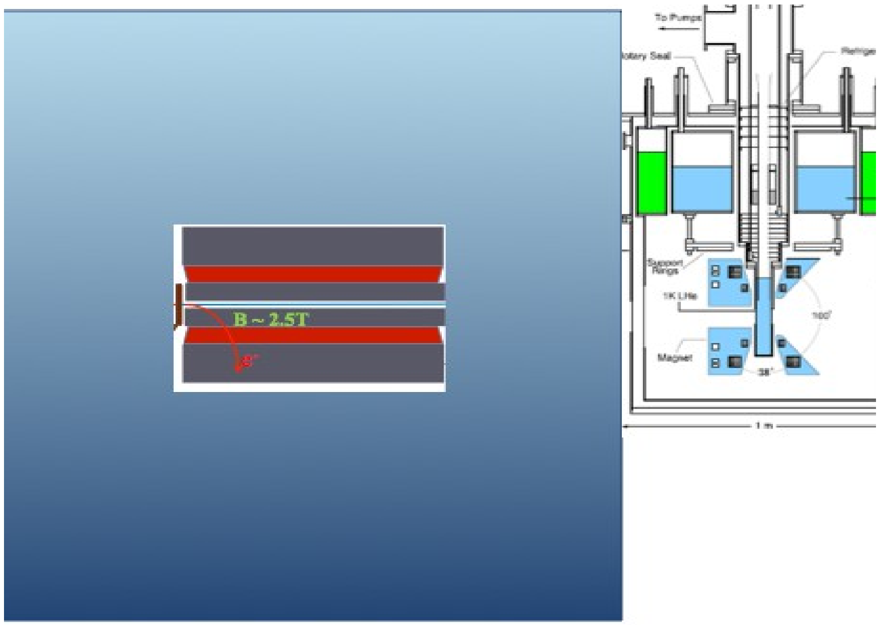


10% copper radiator located at -3.5m (upstream)
FZ magnet located at (x=0, y=-0.1m, z=-2.3m)
Local dump at z=-0.8m (15 cm tungsten, 42.7 radiation length)

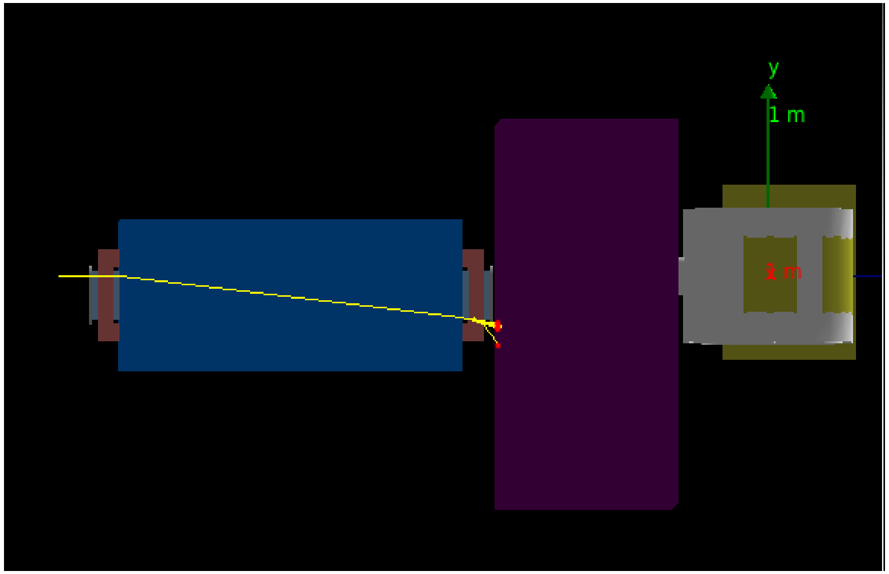
Pure Photon Source at Hall-C



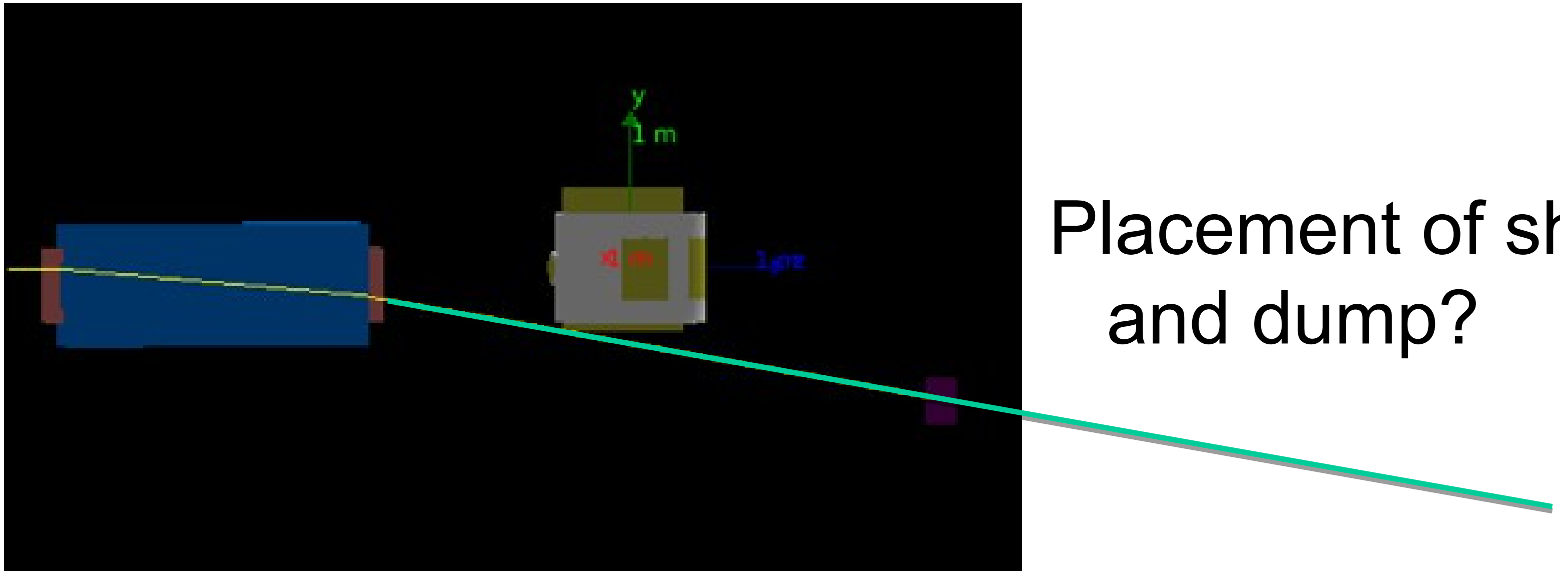
Some Bender Options



Magnet in Shielding



Separate Dump and Magnet



Placement of shielding and dump?

Extend Kinematic

1uA 6.6 GeV beam, 10% radiator

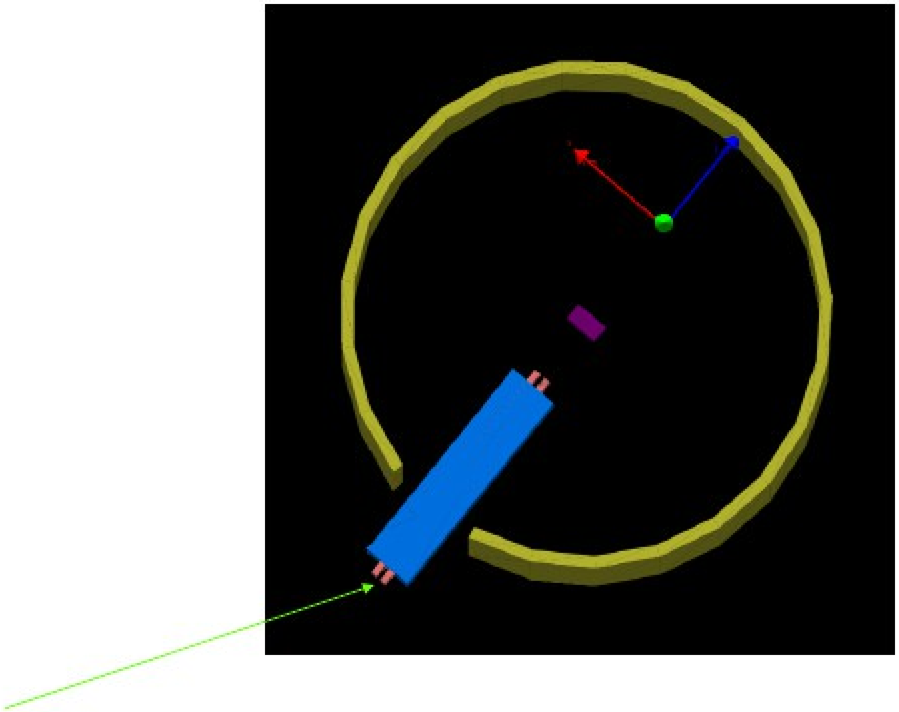
Point#	HMS (deg)	HMS P0 (GeV/c)	NPS (deg)	Distance (cm)	Vertical Offset(cm)	γ_{cm}
5	27.5	3.02	35	300	13	90
6	30	2.81	31.5	350	15	85

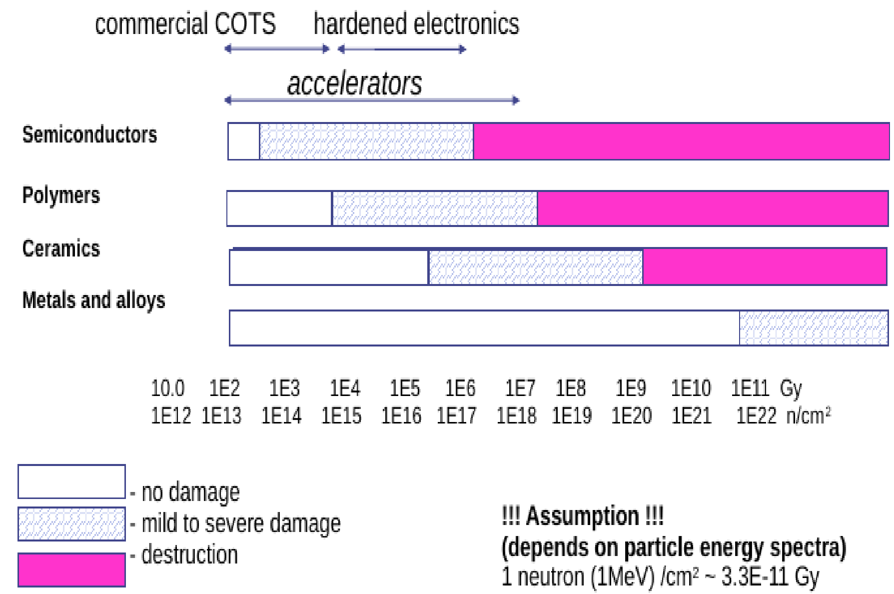
$$N_{RCS,required} = D/(P_e P_p f_{e\gamma} \Delta A_{LL})^2$$

Point#	t	u	D(all/sig)	Time(h)	Stat	Uncertainty
6.6 <						
5	-4.4	-3.7	11.5	500	2376	9.8%
6	-3.6	4.5	5.6	250	3769	5.4%

Radiation Studies

For high u, t, s with highest photon intensity considering distance from dump to target, position of radiator, and required shielding





Radiator: z=-370 cm,
C-type Magnet: 2-m long, centered at (0,-10,-270) cm, B=2.0T
Dump (Not Shown): 30x30x15 cm, centered at (0,-20,-103) cm
Virtual Boundary: vacuum, inner R is 200 cm, thickness 20cm. Co-centered with dump.

Advantages and Concerns

- Eliminate electron backgrounds: e-p elastic and epγ events.
- Target averaged polarization increases from 70% to ~90%
- Collimator reduces photon flux down to 40% (if using 2-m long FZ magnet).
- Heat load from photon beam is essentially zero – dominant heat load is form microwaves.
- Beam current can be increased from 100 nA to 1000 nA (limited by the colling power of the local dump and radiation budget).
- Overhead time will be greatly reduced (by half): fewer anneals, target changes and TE measurements (associated with target changes).

Conservatively speaking, the F.O.M could be improved by a factor of 10.

Concerns:
•Radiation in the hall
•Shielding need to be applied to protect detector and electronics

Minimum Plan for Kinematics

We want to measure the angular dependence of A_{LL}

$\theta_{CM} = 60^o$:

1. To compare with existing K_{LL} data.
2. At a location that K_{LL} is close to A_{LL}.
3. For NPS calibration.

$\theta_{CM} = 90^o$:

1. Largest $|t||u|$, which is optimal for testing the polarized target WACS handbag amplitudes.
2. Helpful to clarify the role of the power suppressed helicity flip.
3. Understand the hard reaction mechanism.

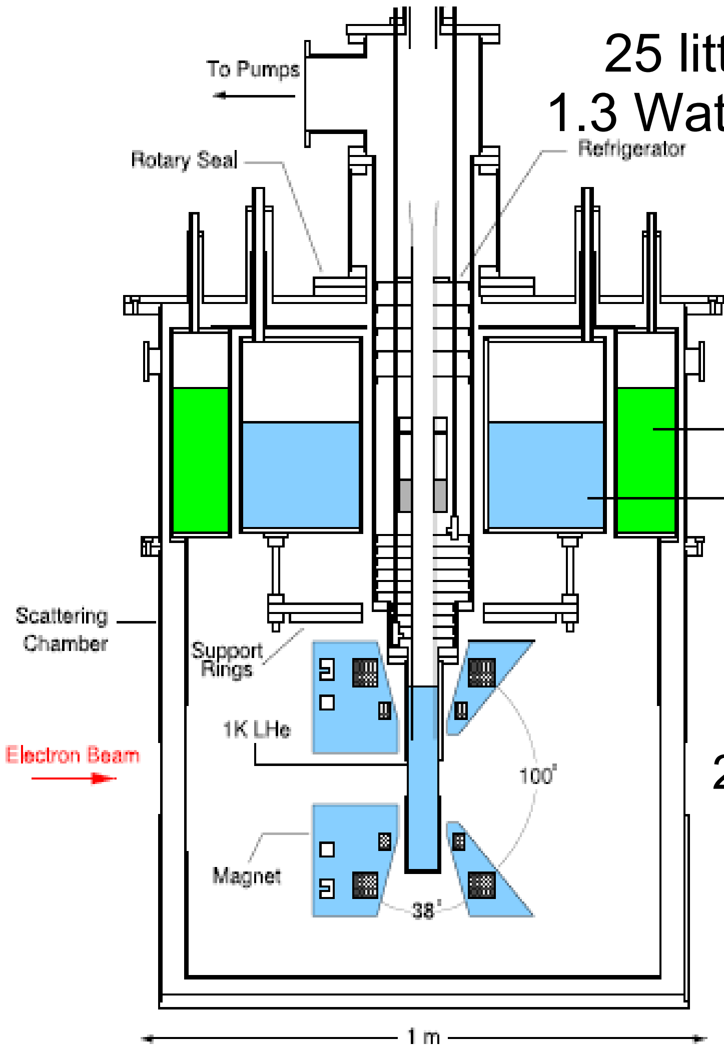
$\theta_{CM} = 136^o$:

1. The best kinematics point to probe the divergence between A_{LL} and $K_{LL.}$
2. Help to build our understanding of quark orbital angular momentum in the proton.

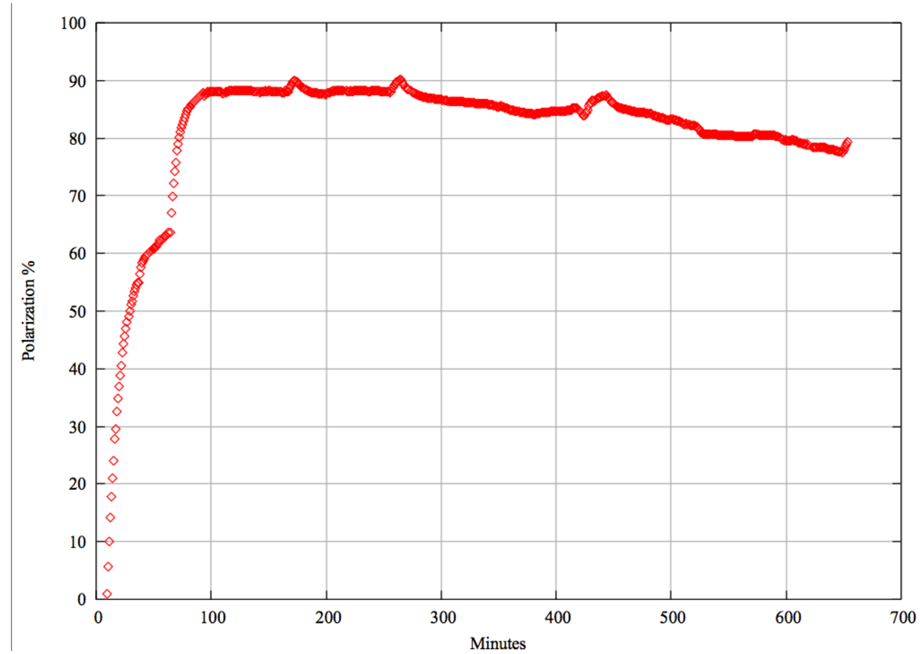
UVA/Jlab Polarized Target

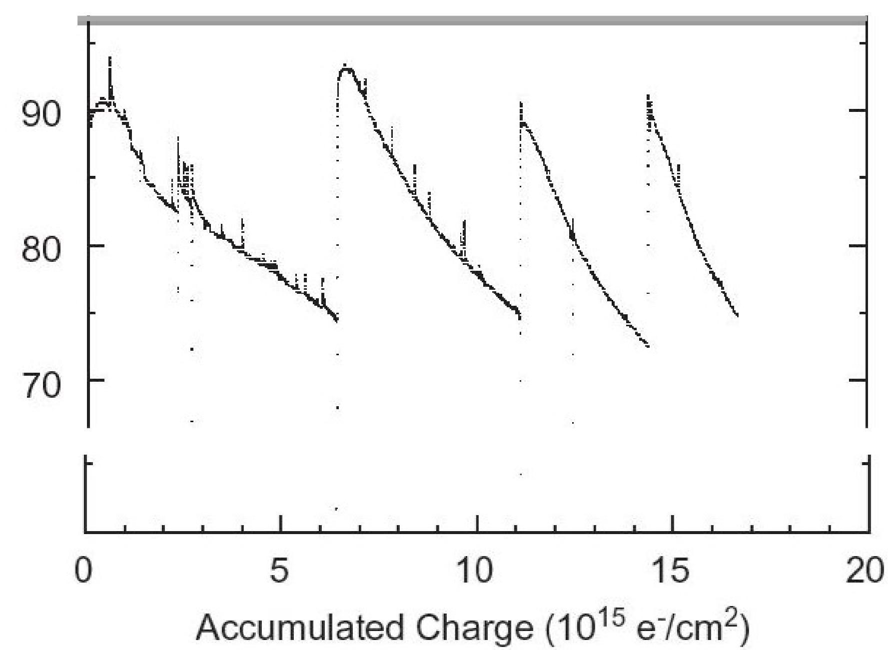
Evaporation System with NH_3

25 litters/min
1.3 Watts Cooling

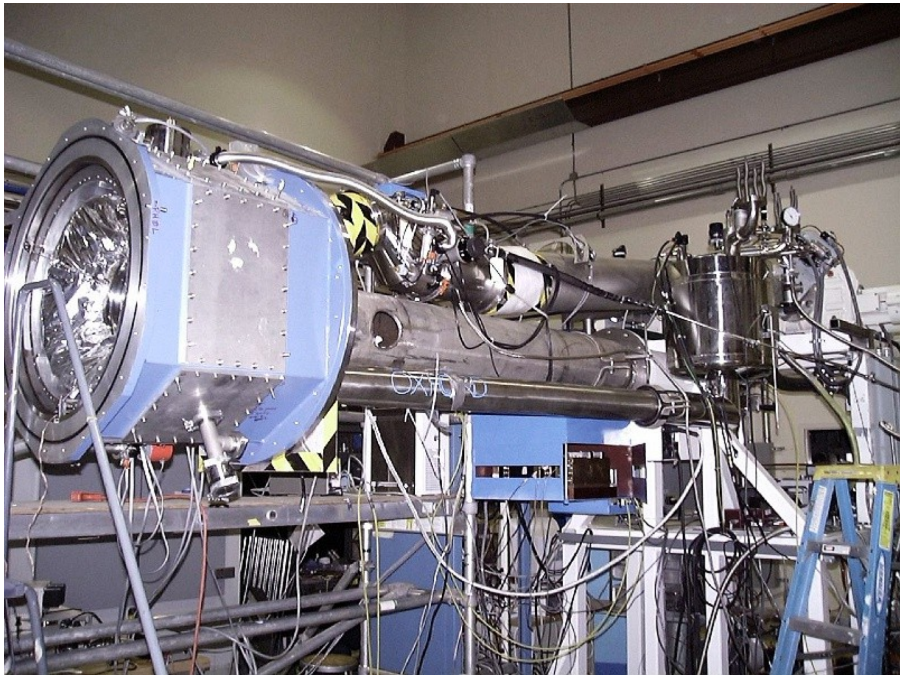


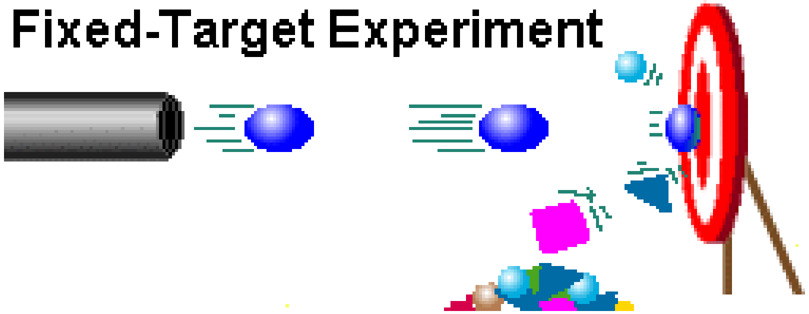
20 cm bore





What is a (*Solid*) Polarized Target

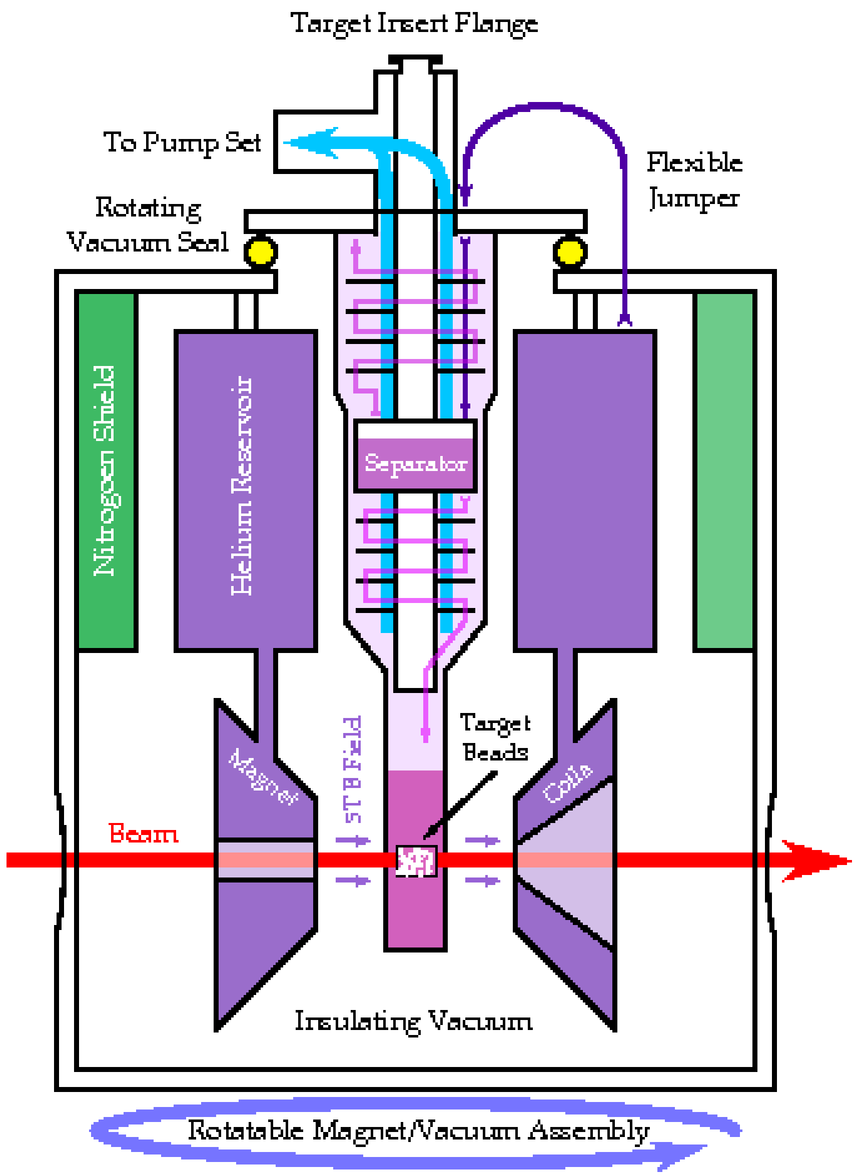




$FOM = n_t f^2 P^2$

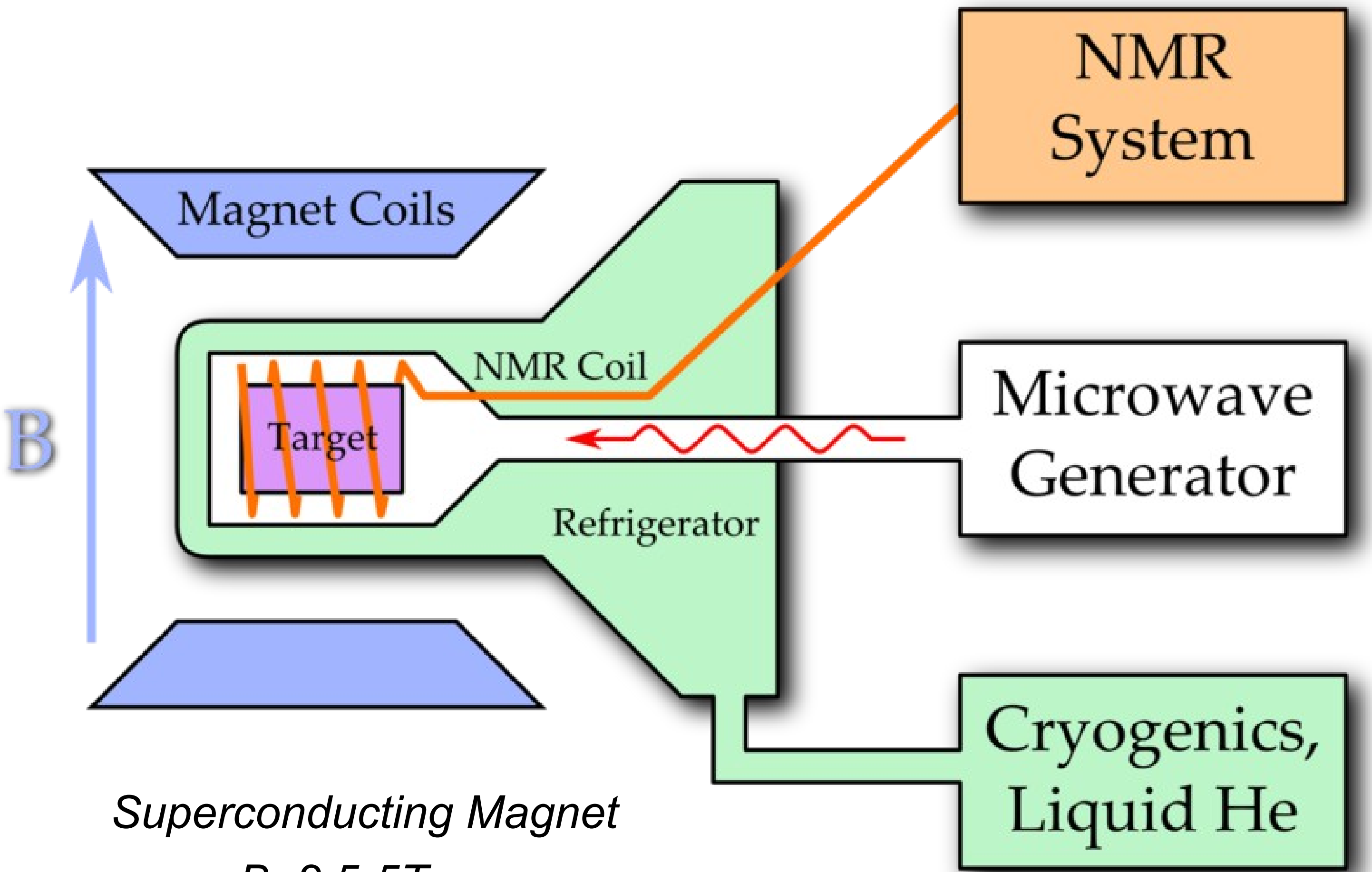
- Fixed Scattering Experiment Target
- Specific Spin Species Orientation
- Highest Possible Luminosity (FOM)

Cryogenic Polarized Targets



- Beam : *Neutron, Photon, Electron, Proton, Muon*
- Target : *Proton, Neutron, Deuteron*
- System Types: *Evaporation and Dilution*

General System



Polarization Detection

Tuned To Larmor of spin species

Proton (42.6 MHz/T)

Larmor-ESR

50-185 GHz

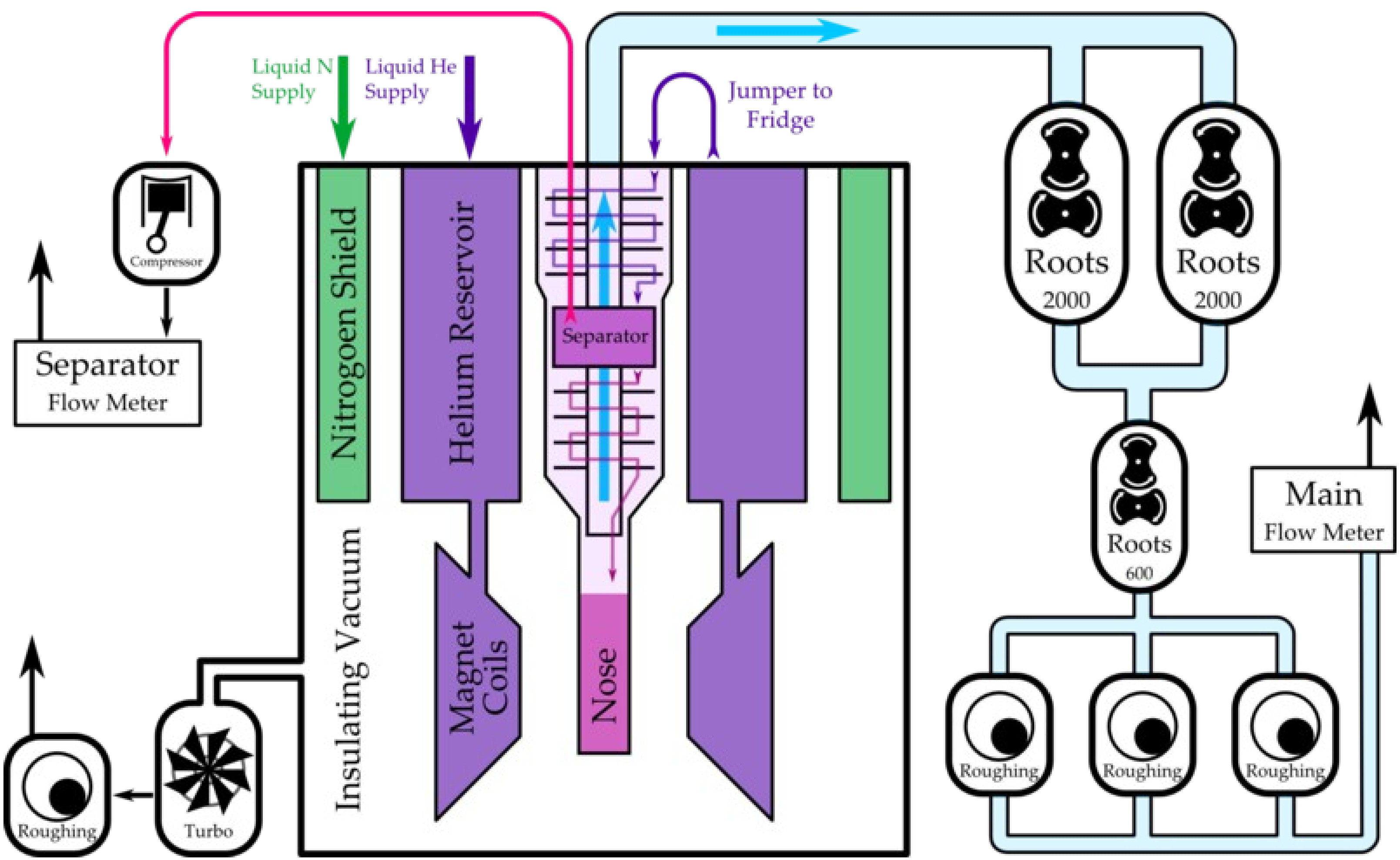
~140 GHz at 5T

T=0.03-1K

Superconducting Magnet

B=2.5-5T

Vacuum Pumping Subsystem



Cryogenic Instrumentation

The Concept of Polarization

- *P* -Polarization is the degree the spin align
- *ρ* The normalized density matrix
- For a set of *N* spins *I*
- In thermal equilibrium a Boltzmann distribution is established

$$P = -\frac{1}{NI}\mathrm{Tr}\left\{\rho\sum_{i=1}^{N} I_z^i\right\}$$

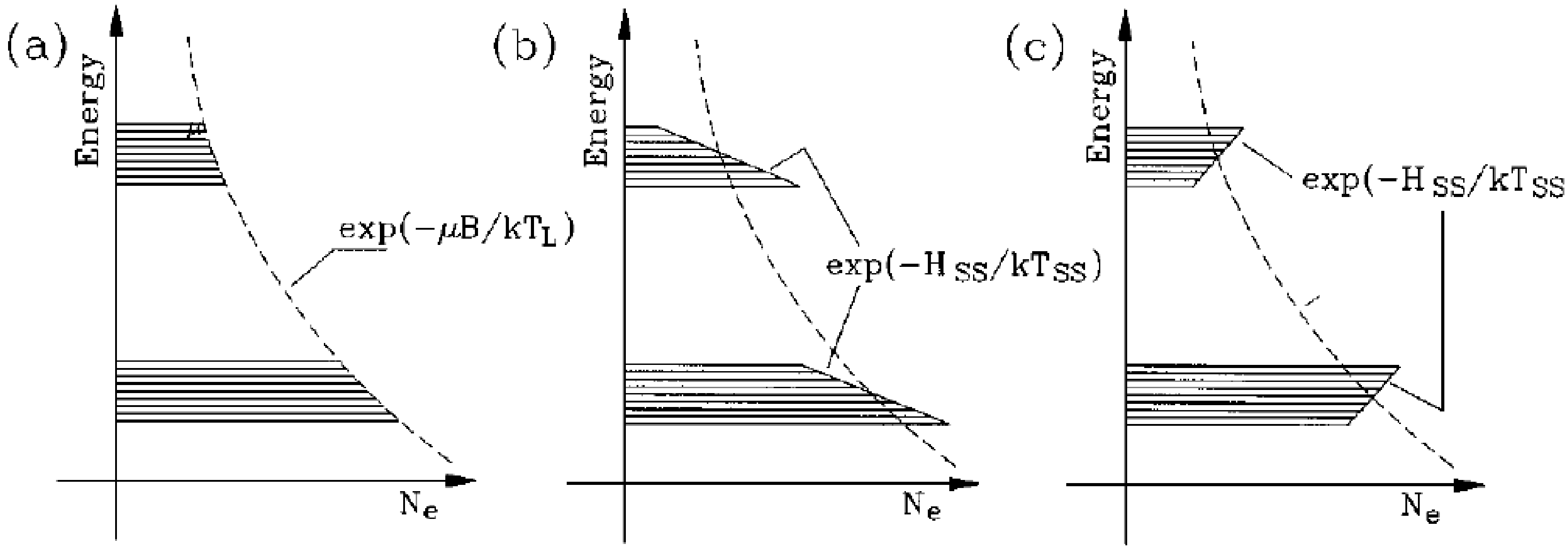
$$P = \frac{2m}{N} = \frac{N_- - N_+}{N}$$

$$P_0 = \tanh\left(\frac{\hbar\omega_{0I}}{2k_B T}\right)$$

Spin Temperature → *P(T)*

Dynamic Nuclear Polarization

- Transfer of spin polarization from electrons to nuclei using RF irradiation in a magnetic field
- Nuclear spins align using the polarization reservoir of the electrons made possible by the electrons quick relaxation rate
- Alignment of electron spins at a given magnetic field and temperature is described by the Boltzmann distribution under the thermal equilibrium
- Polarization of the nuclei depends on target material characteristics, relaxation rate, and concentration of paramagnetic centers

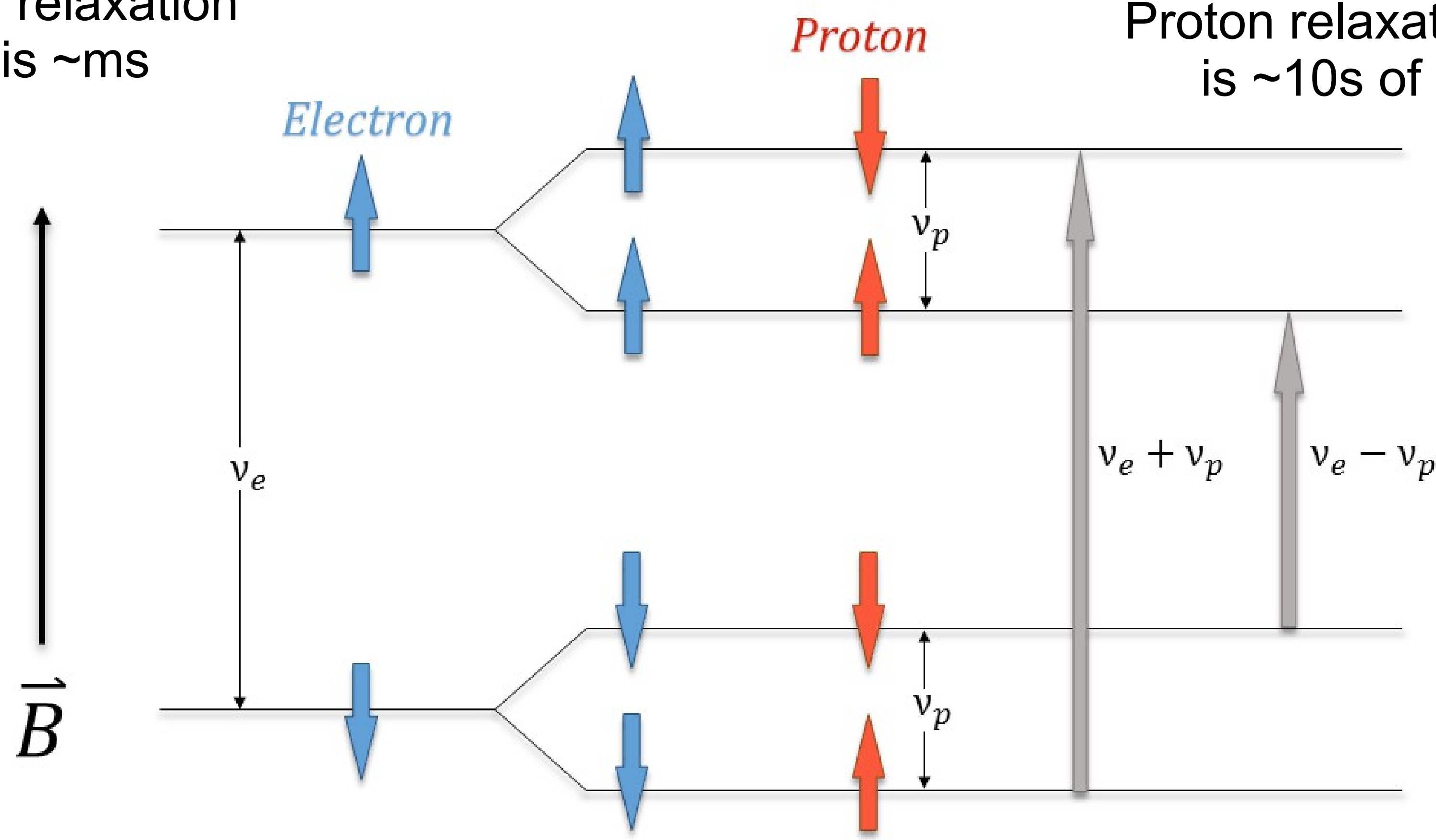


- (a) Thermal Equilibrium with single ST
- (b) For positive spin-spin temp
- (c) For negative spin-spin temp

Zeeman Splitting

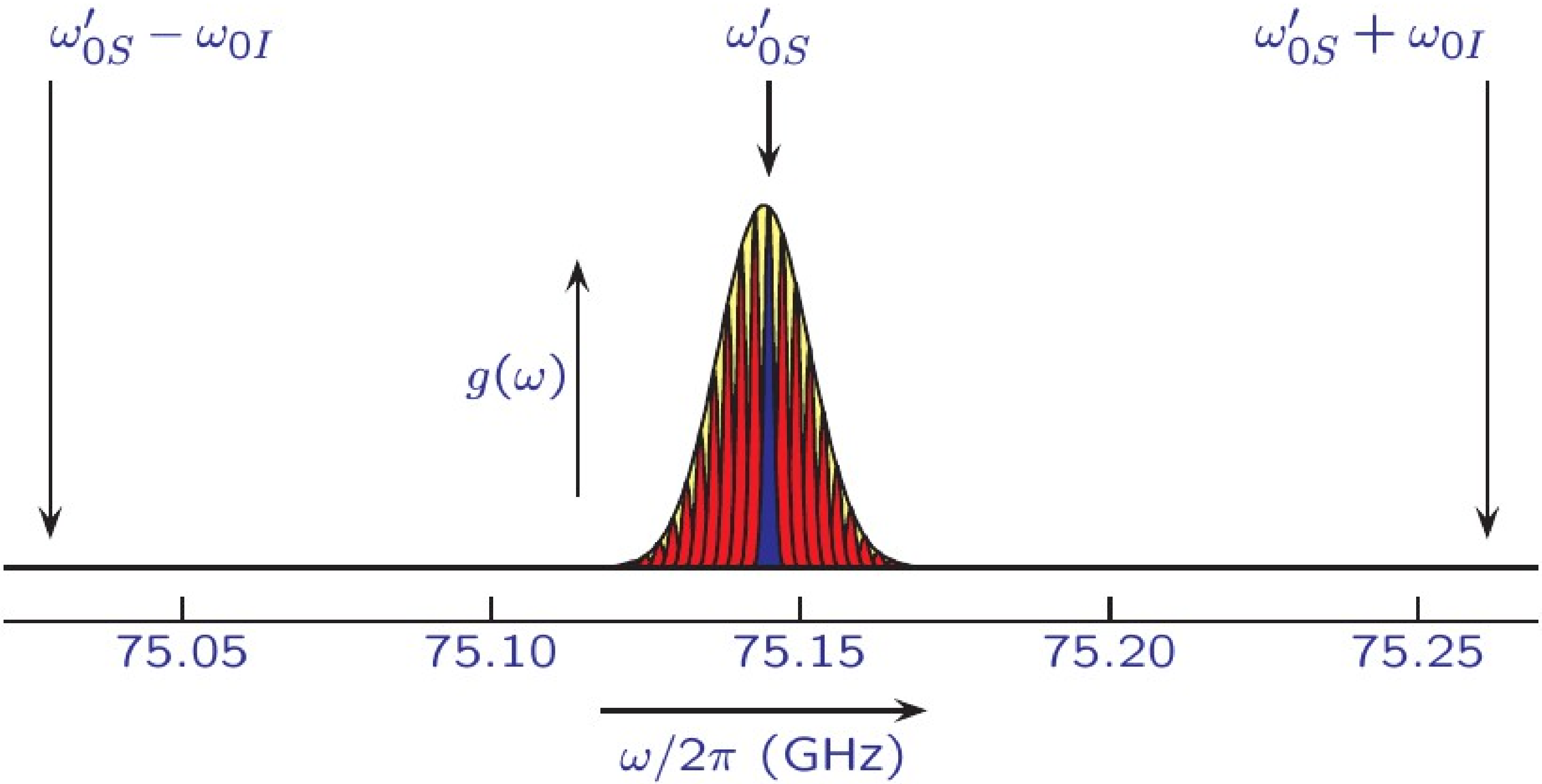
Electron relaxation time is ~ms

Proton relaxation time is ~10s of min.



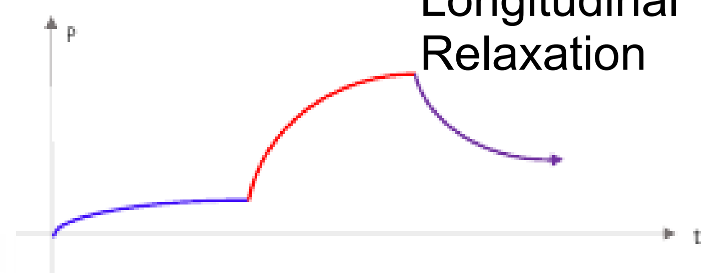
Solid Effect: Spin sees static holding field ***B*** causing a Zeeman Splitting with Microwave inducing ESR transitions

Narrow ESR line → Solid Effect



Solid Effect

Longitudinal
Relaxation



Longitudinal Buildup

"Ramp-ups" follow an exponential growth

Frequency response can be approximated as a second order system

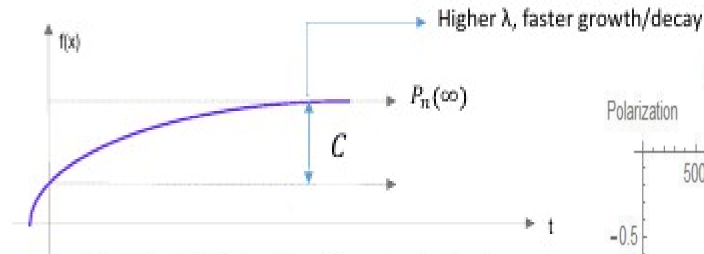
$$P_n(t) = -[(\lambda_1 + a_{11})/a_{12}]C_1 e^{-\lambda_1 t} - [(\lambda_2 + a_{11})/a_{12}]C_2 e^{-\lambda_2 t} + P_n(\infty),$$

$$P_n(t) \approx P_n(\infty) + C_1 e^{-\lambda_1 t} + C_2 e^{-\lambda_2 t}$$

$$\lambda_1 = \frac{C\theta + 1}{2} \qquad \lambda_2 = \frac{C\theta + 1}{2} + \beta(C+1) \qquad \theta \ll \beta \qquad C = \frac{n_e}{n_n}$$

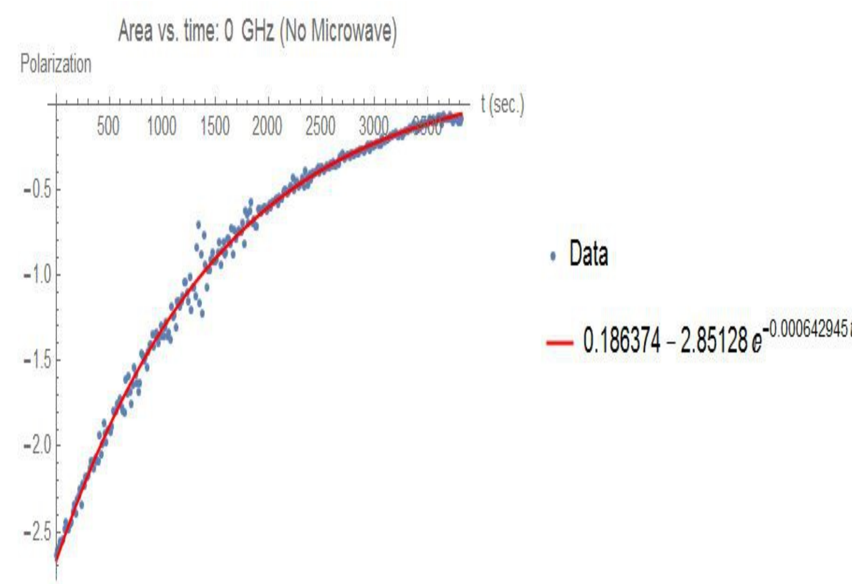
First exponential term extremely small (can essentially be neglected)

$$P_n(t) \approx P_n(\infty) + C_1 e^{-\lambda t}$$

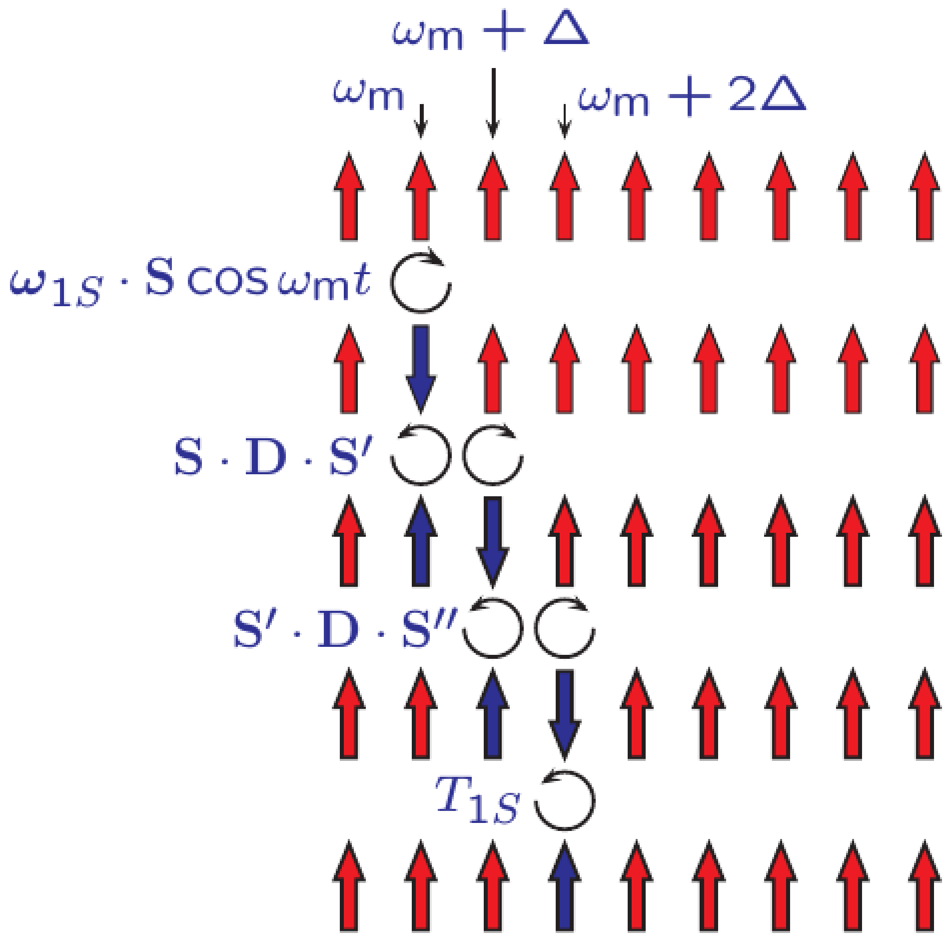


$^*P_n(\infty) = C$, *if starting from* $t = 0, P = 0$

Spin-lattice
Relaxation rate
$t_1 = T/\ln(P/P_0)$



DNP to Enhance Faster than DPM



Spin-Lattice Relaxation

flip-flop rate

$$\boxed{\frac{1}{T_{2S}}}$$

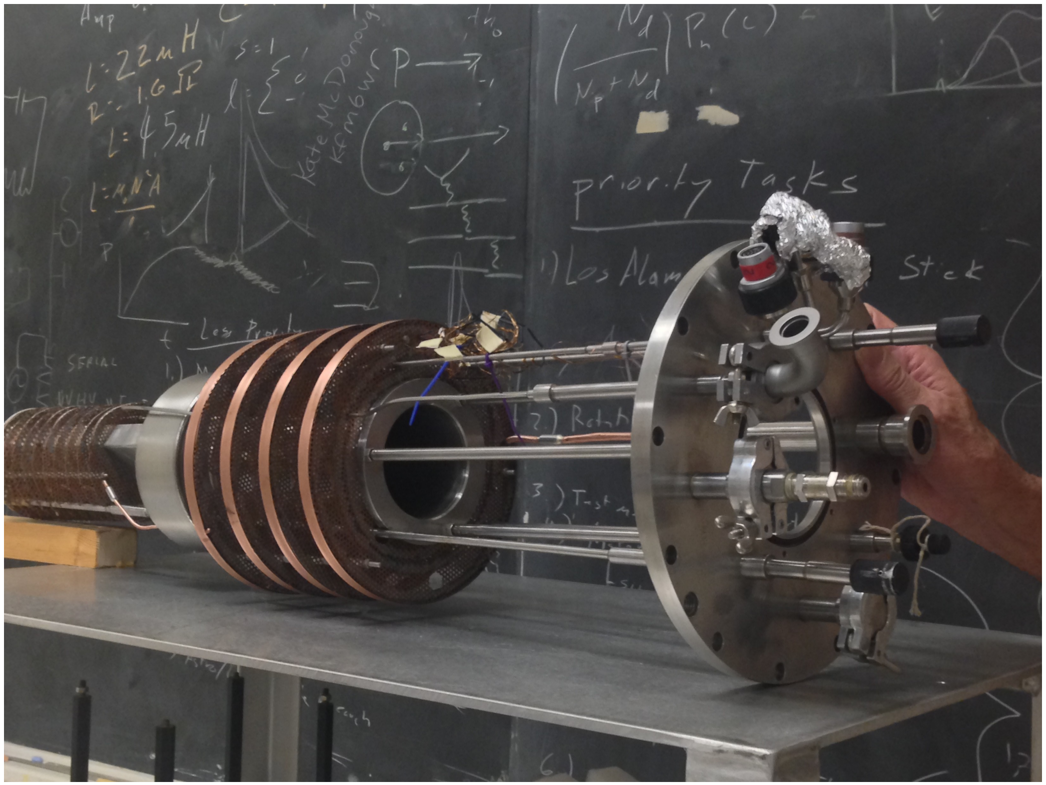
diffusion rate

$$\boxed{\frac{1}{\omega_{0I} T_{2S}^2}}$$

Mechanisms In DNP

- narrow ESR line $< \omega_{0I}$ — **well-resolved solid effect**
- broad ESR line $> \omega_{0I}$
  - weak μ-wave field $\omega_{1S}T_{2S} < 1$
    - fast spectral diffusion $\dfrac{1}{\omega_{0I}T_{2S}^2} > \dfrac{1}{T_{1S}}$ — **thermal mixing**
    - slow spectral diffusion $\dfrac{1}{\omega_{0I}T_{2S}^2} < \dfrac{1}{T_{1S}}$ — **cross effect**
  - strong μ-field $\omega_{1S}T_{2S} > 1$ — **differential solid effect**

Evaporation Fridge



- Max CC: ~100 nA
- Dilution factor f<50%
- Luminosity: 10^{35} cm^{-2}s^{-1}
- 1 K (high cooling power)
- Polarization: p~98%, n~42, d~46%

UVA Polarized Target System

Microwave

Target Insert

Pumps

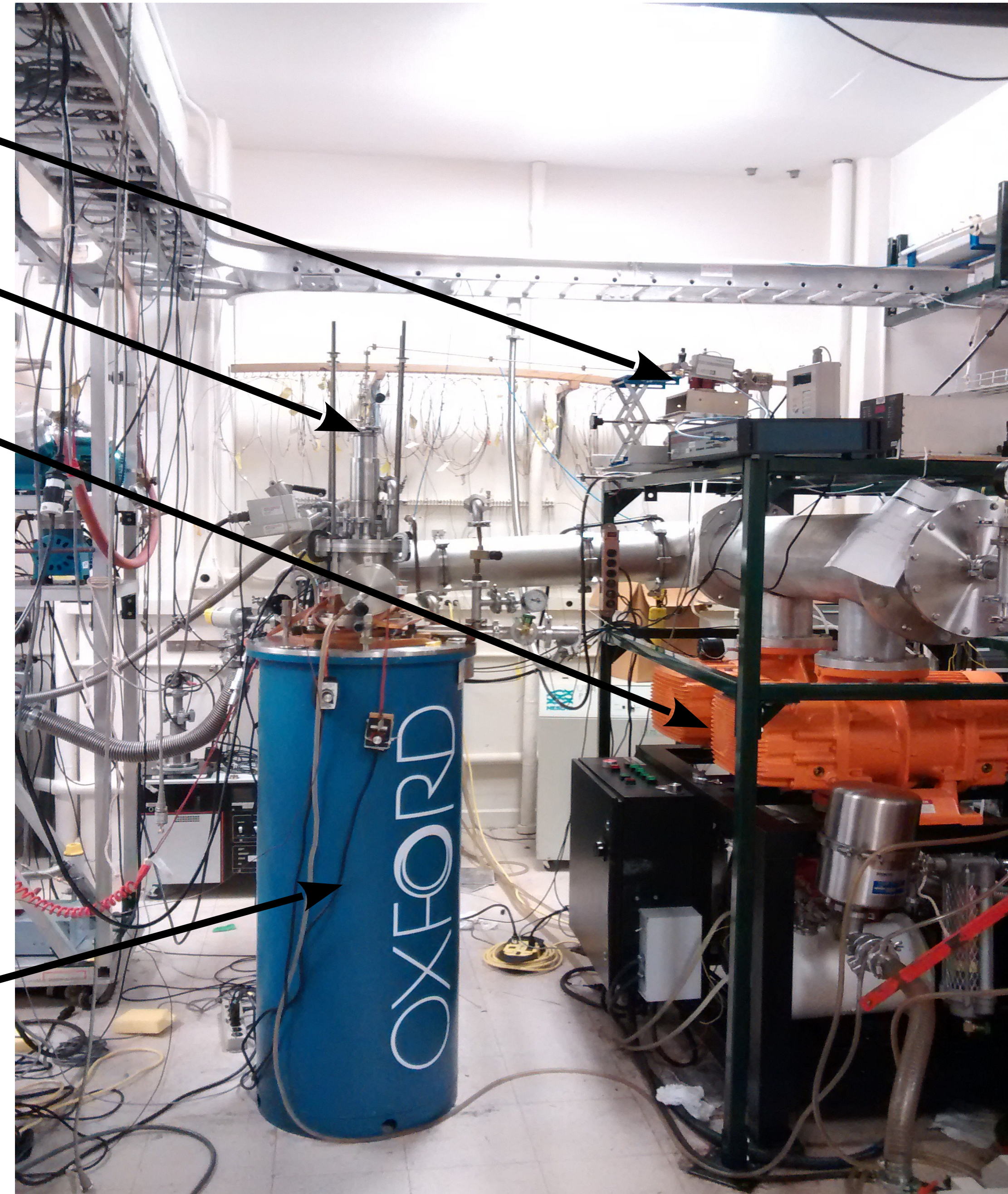
Two Parallel
2063 m^3/Hour

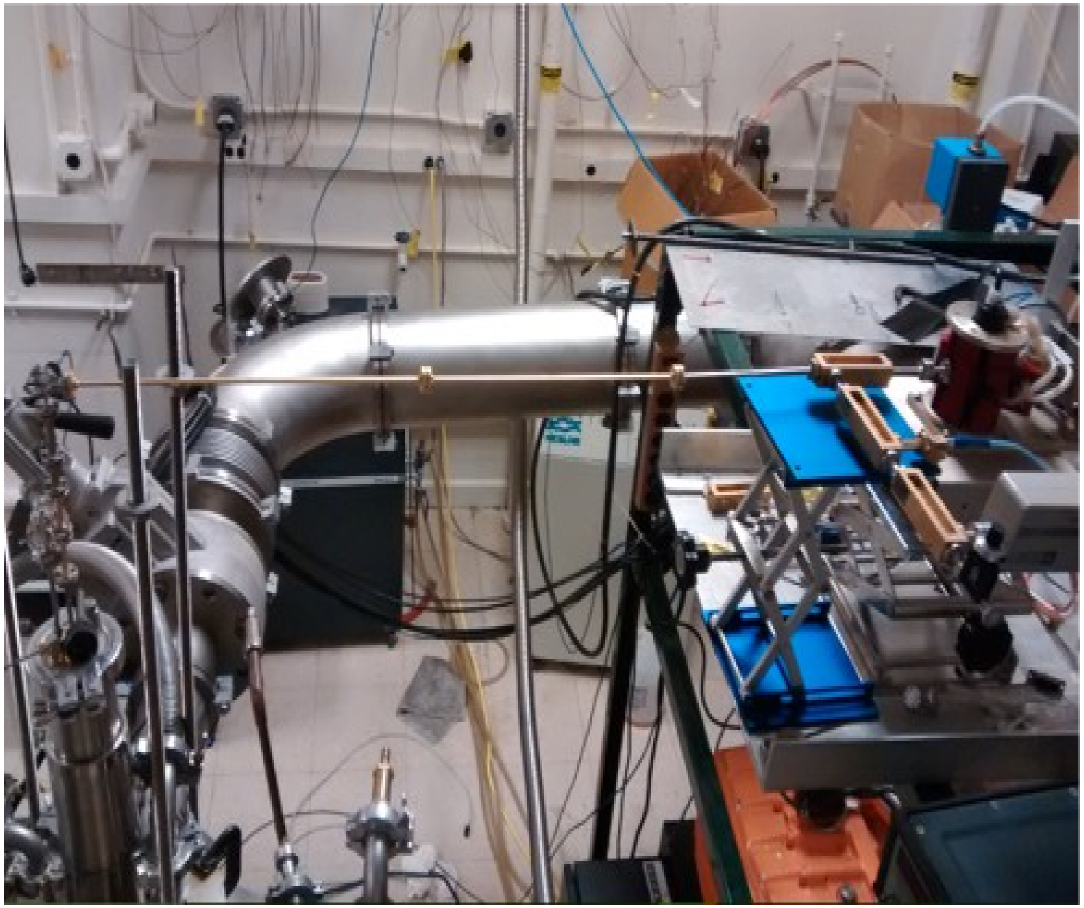
600 m^3/Hour

Two Parallel
2000 m^3/Hour

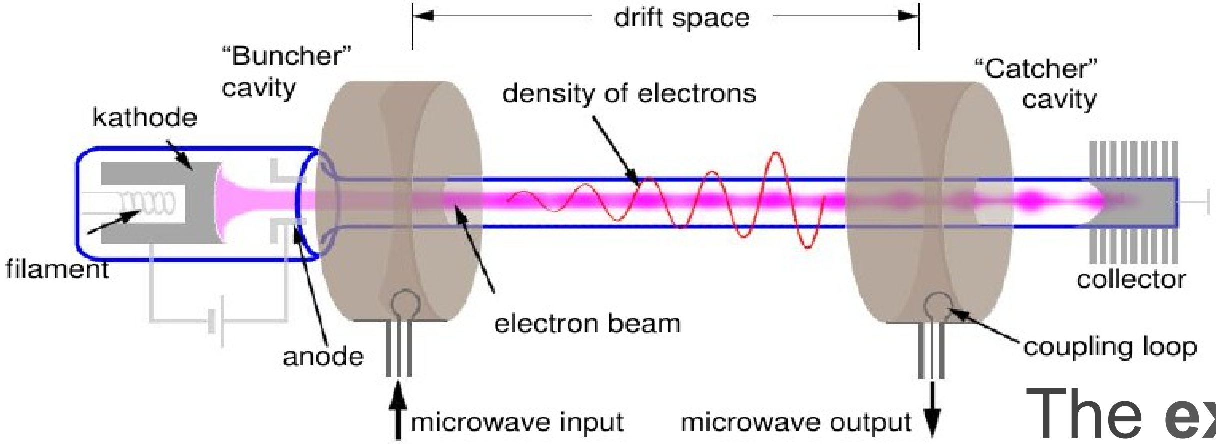
1W (~0.121 Torr)

Magnet



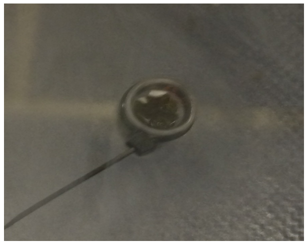


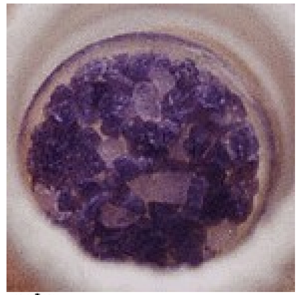
Target Insert



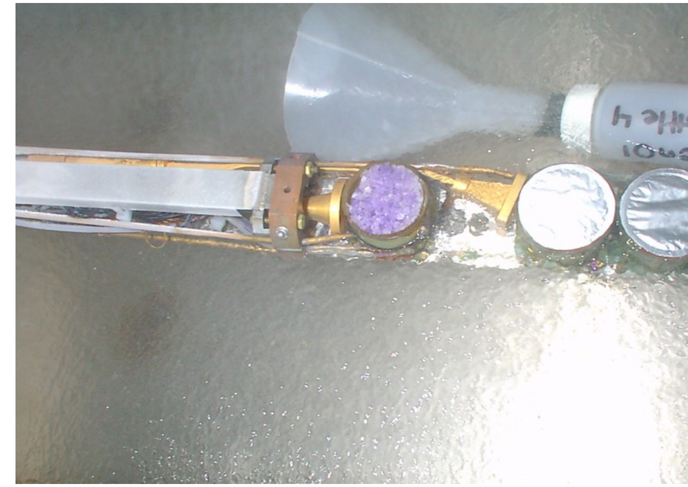
The extended interaction oscillator (EIO)

Free Radicals - Dopants





NH_3



NIST irradiation 14 MeV at 87 K under liquid argon Dose ~ 10^{17} e^-/cm^2

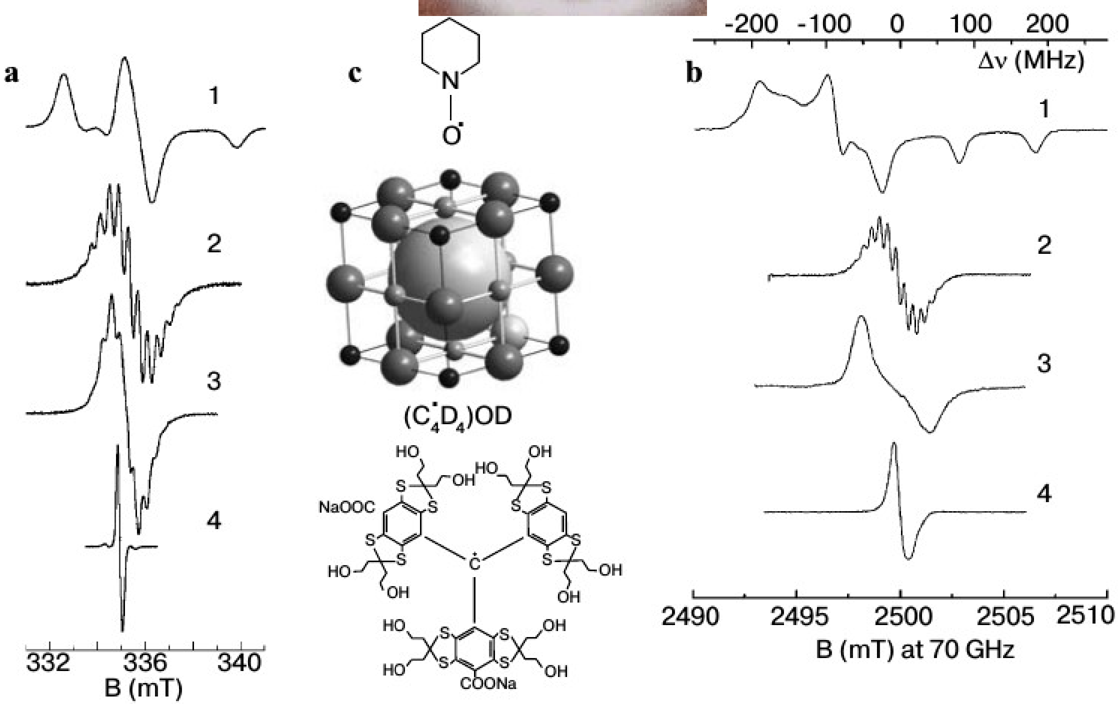
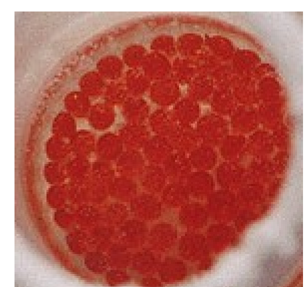
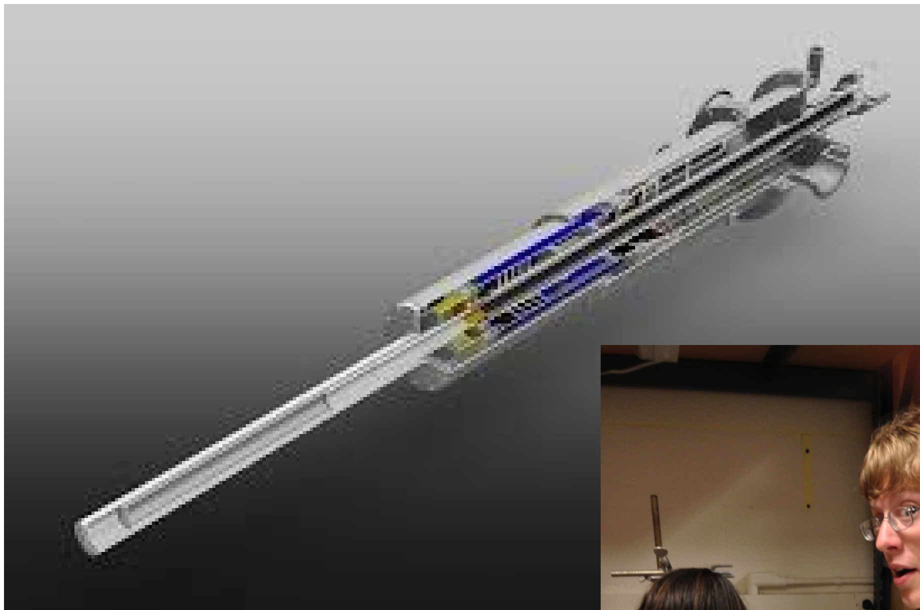


Fig. 6. X-band (**a**) and V-band (**b**) ESR spectra of TEMPO-doped d-butanol (1), irradiated ^{6}LiD (2), irradiated d-butanol (3), and trityl-doped d-propanediol (4). **c** Corresponding radicals.



Spin Temperature Theory: Narrow paramagnetic resonance (EPR) line enables Creation of high inverse spin temperatures – High Polarizations

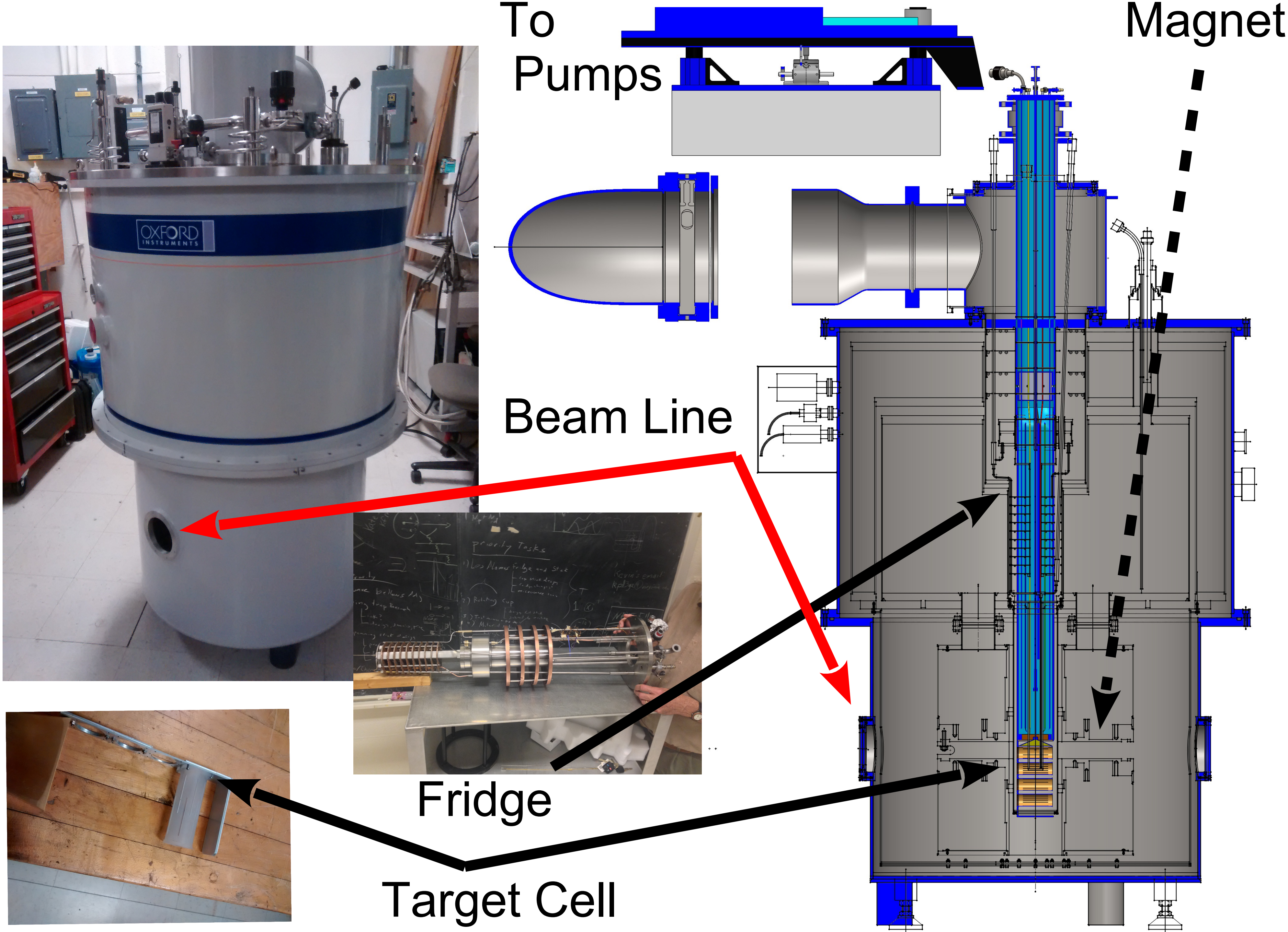
Some Polarized Target Developments



Some Polarized Target Developments

- Fermi-Lab E1039 Polarized Drell-Yan
- NMR Development
- HALL-B Horizontal Fridge (Polarized EMC)
- Adiabatic Fast Passage
- Microwave Automation Control
- Tensor Polarization Enhancement
- Rotating Target

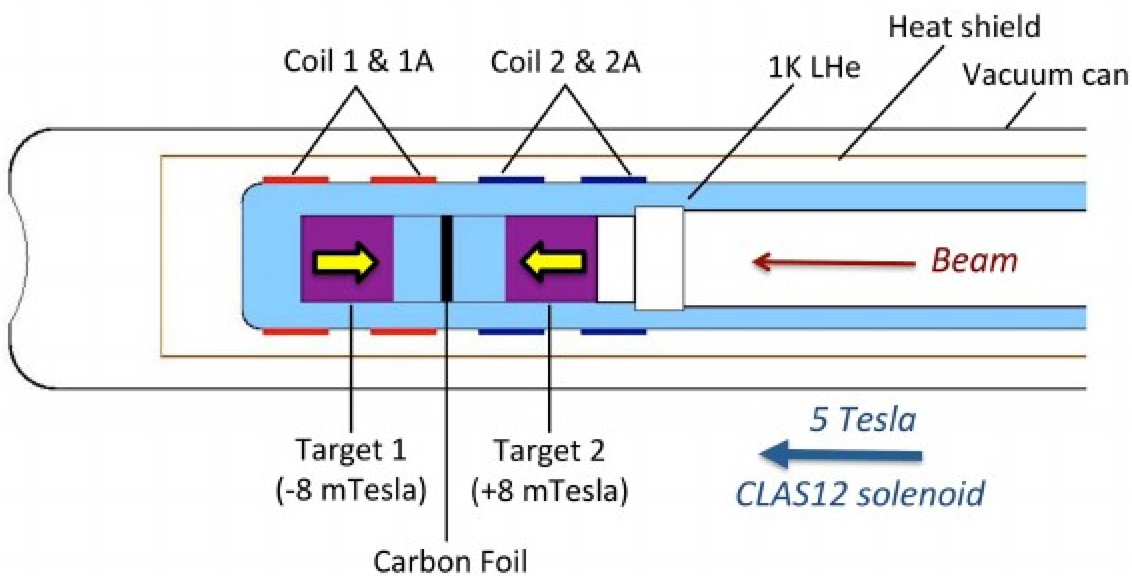
Polarized Drell-Yan (E1039)



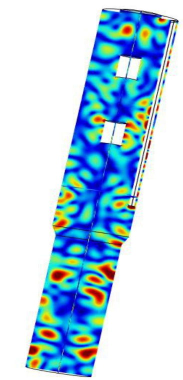
Hall-B Polarized Target

Simultaneous Data on two Target States

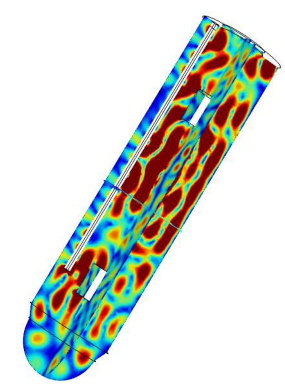
We also hope to use internal superconducting shim coils to adjust the polarizing field for multiple target samples, allowing independent polarizations with one microwave source



Nose of Target

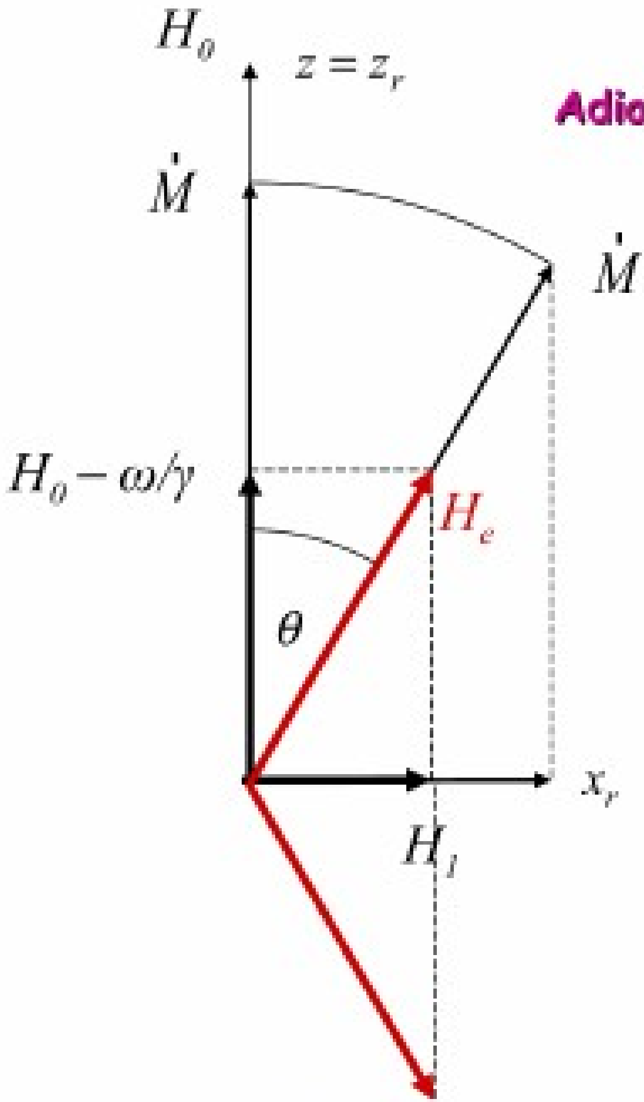


Not Optimized



Optimized as microwave Cavity

Adiabatic Fast Passage at 1 K



Adiabatic: $\frac{dH}{dt} = \gamma H_1^2$ **Fast** (faster than relaxation): $\frac{1}{\tau} = |\gamma H_1|$

External field $\vec{H}$ contains **rf field**

static field: $H_z = H_0$ rf field: $H_x = 2H_1 \cos(\omega t)$

$$\vec{H} = H_0 \hat{z} + H_1 \cos(\omega t)\hat{x} + H_1 \sin(\omega t)\hat{y}$$

rotating frame

$$\vec{H}_e = (H_0 - \frac{\omega}{\gamma})\hat{z}_r + H_1 \hat{x}_r \qquad \tan\theta = \frac{H_1}{H_0 - (\omega/\gamma)} = \frac{\omega_1}{\omega_0 - \omega}$$

Larmor frequency: $\omega_0 = \gamma H_0$

For any vector $\vec{\mu}$ satisfying a similar equation of motion the angle between $\vec{\mu}$ and $\vec{H}$ remains constant provided the change of direction of $\vec{H}$ in time is sufficiently slow

AFP Efficiency

AFP was performed on different target materials

Spin-flip efficiencies for different materials are shown below
(δp = pol. ratio before and after spin-flip)

UVA recently achieved over 50% AFP efficiency for NH_3

UVA-study

Nuc.lei	Dopant	Spins/g	δp
ND_3	Irr.	$2x10^{17}$	-0.88
NH_3	Irr.	$2X10^{17}$	-0.57
D-but.	Irr.	$1X10^{17}$	-0.77

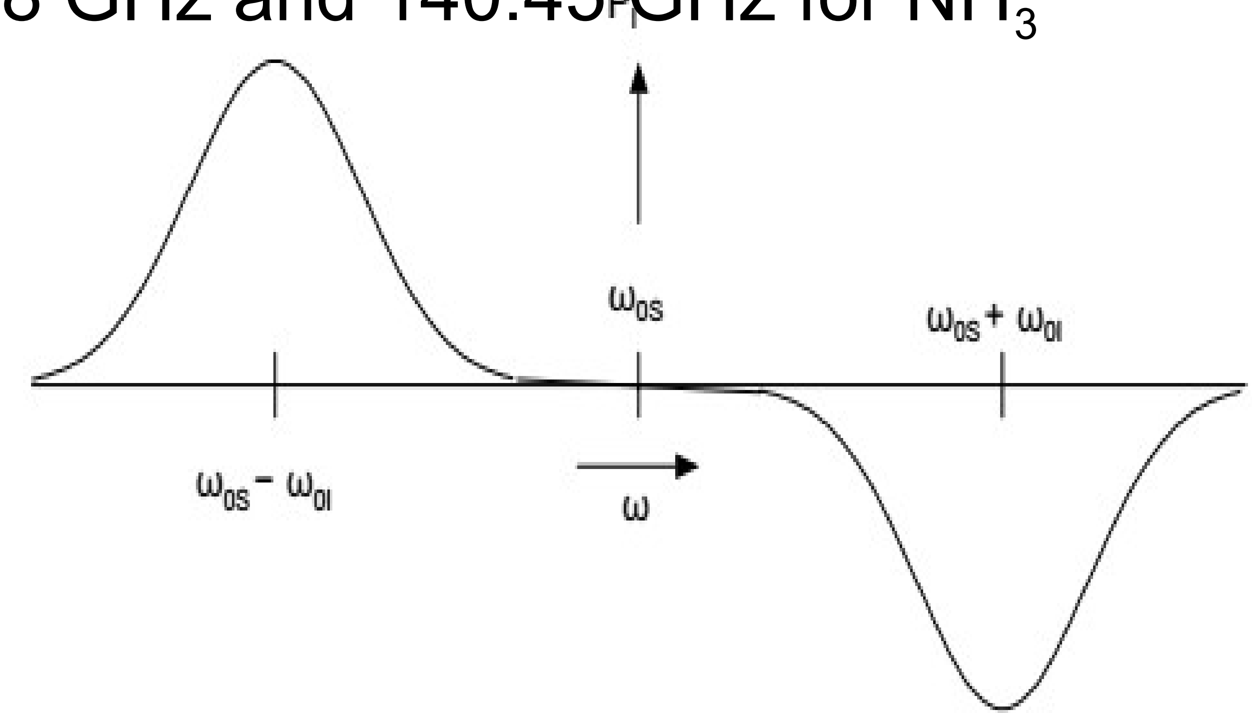
Table 1
Results from AFP experiments with various nuclei in different target materials

Nuclei	Substance dopant	e^- conc. (spins/g)	δP^{max}
^1H	1-butanol EHBA-Cr(V)	2.0×10^{19}	−0.76
^7Li	^7LiH	low	−0.90
^1H	(irradiated)		−0.90
^{19}F	8-fluoro-1-pentanol	1×10^{20}	−0.37
^1H	TEMPO		−0.40
^2H	1-butanol-d_{10}	2.36×10^{19}	−0.92
	EHBA-Cr(V)-d_{22}	6.35×10^{19}	−0.90

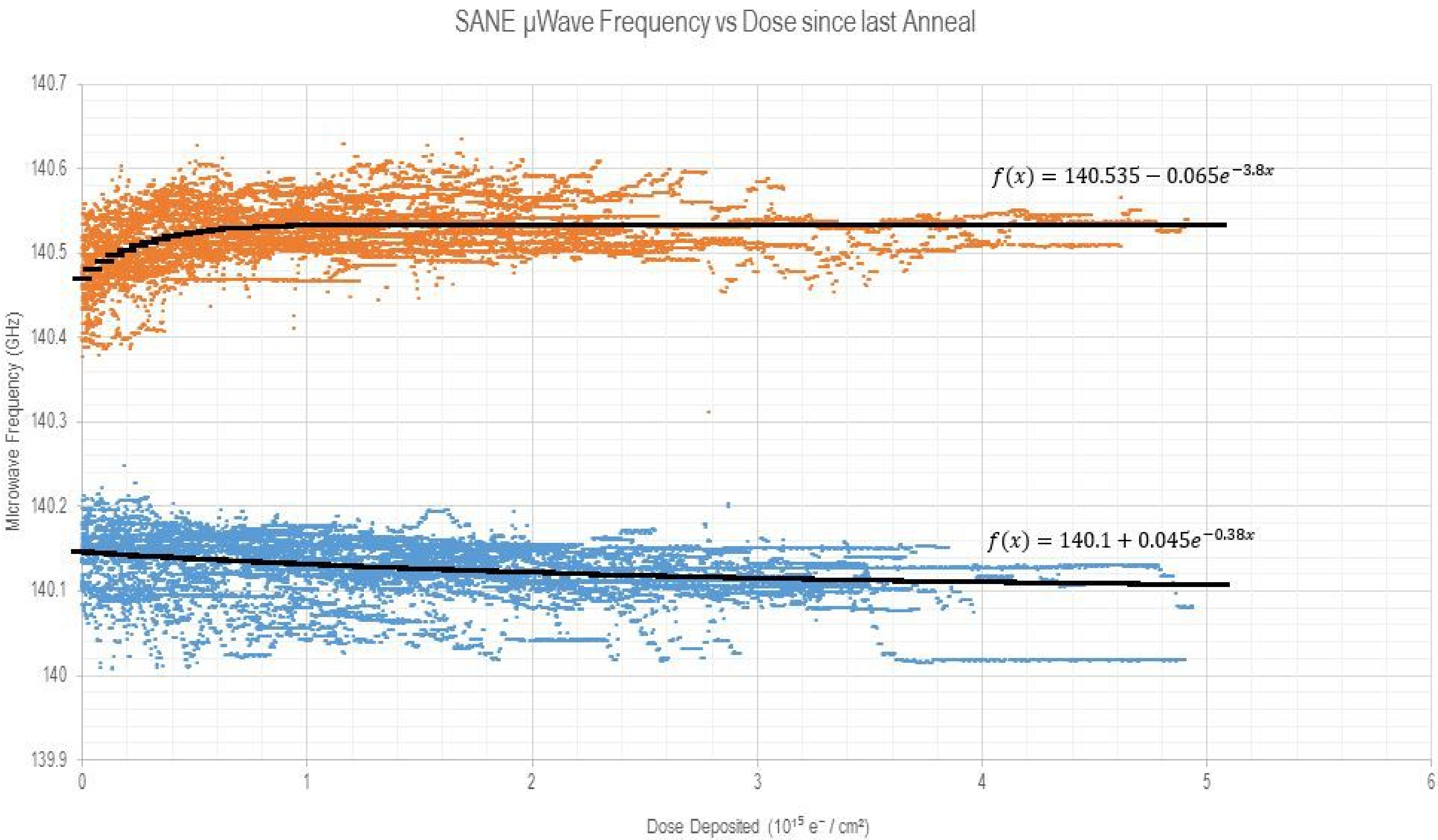
NIM A 356 (1995) 108

Microwave Frequency

- Dictated by difference in nuclear Larmor and electron paramagnetic resonance frequencies (EPR)
- 140.18 GHz and 140.45 GHz for NH_3

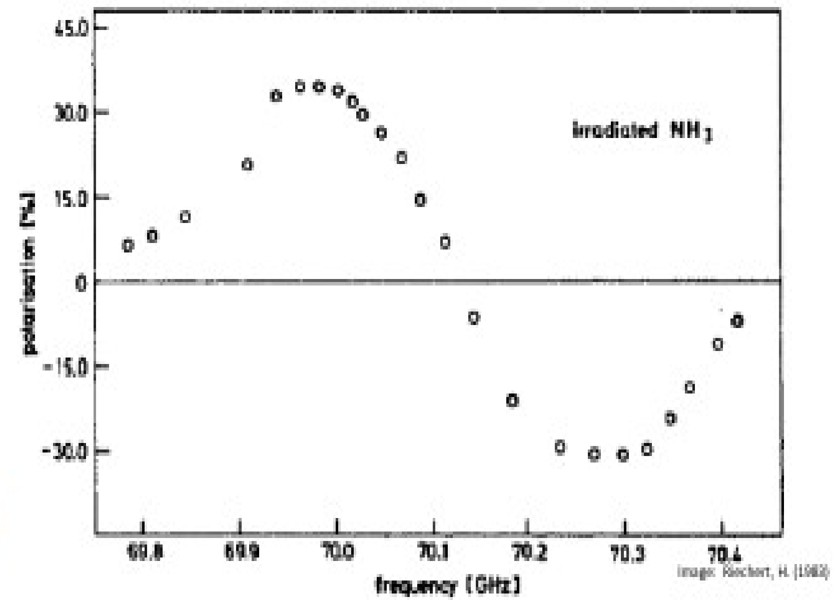


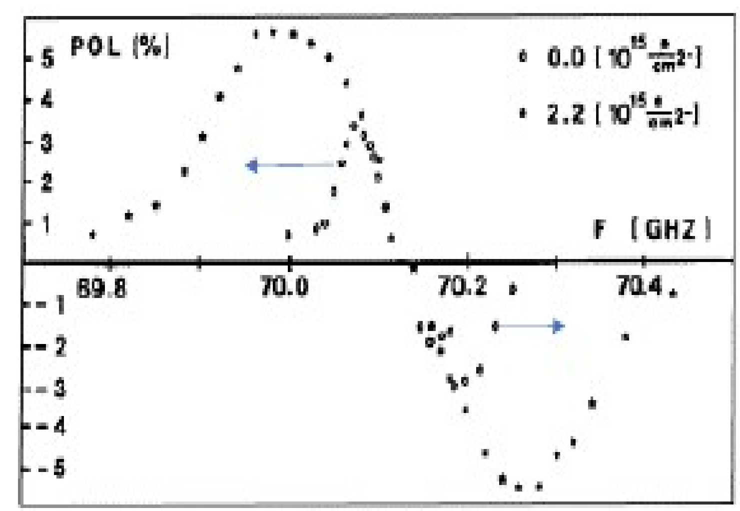
Manual Frequency Control



“Frequency Drift”

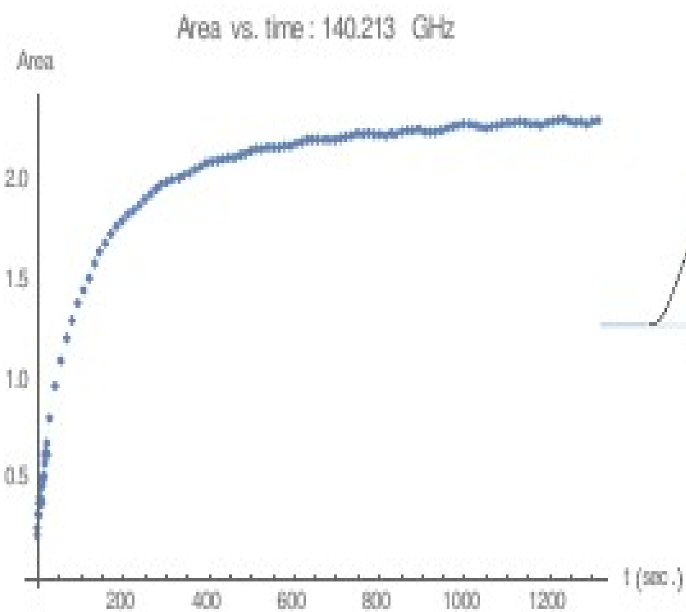
- Optimal frequency for positive and negative polarization is *not* constant
- Changes take place as more centers are created in the material as a result of irradiation.
- Steady state of polarization at a particular frequency also vulnerable to other variables such as temperature, radiation damage, number of anneals, etc.

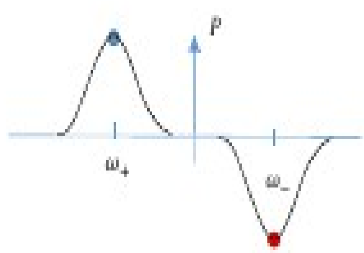


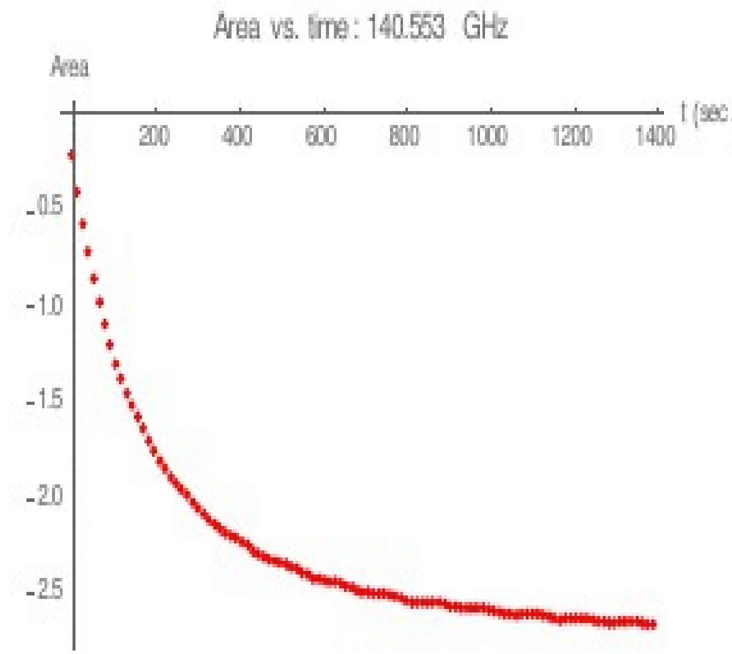


Maintaining Highest Polarization

- Manually maintaining optimal polarization is tedious, error prone
- If characteristics of polarization growth/decay are understood, process can be automated
  - Input = EIO voltage divider value ∝ μ-wave frequency
  - Output = Polarization value from PDP software

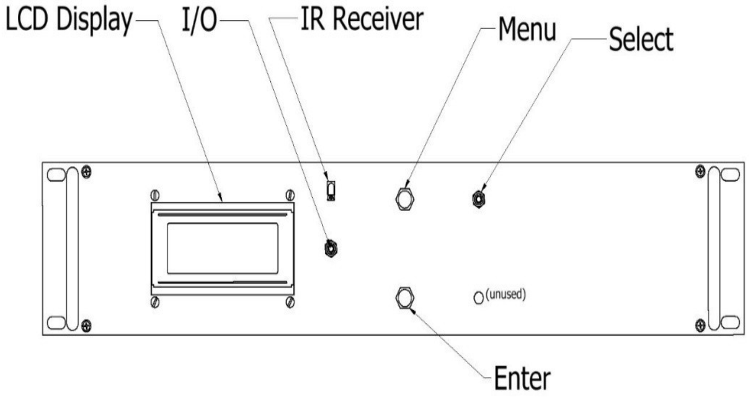


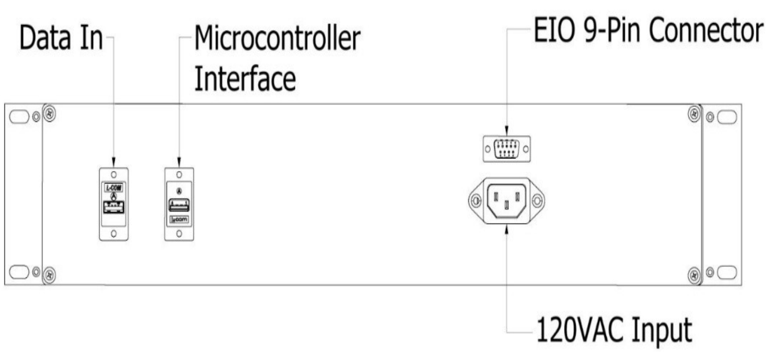




Creating a Controller

- Standard 2U Rack-mount hard wear
- Front-panel readout and user interface
- Remote control
- Uses Parallax Micro-controller P8X32A, 8 core overclocked 100 MHz, ADC: AD7680 (16-bit, 100kSPS), motor control L298N H-Bridge

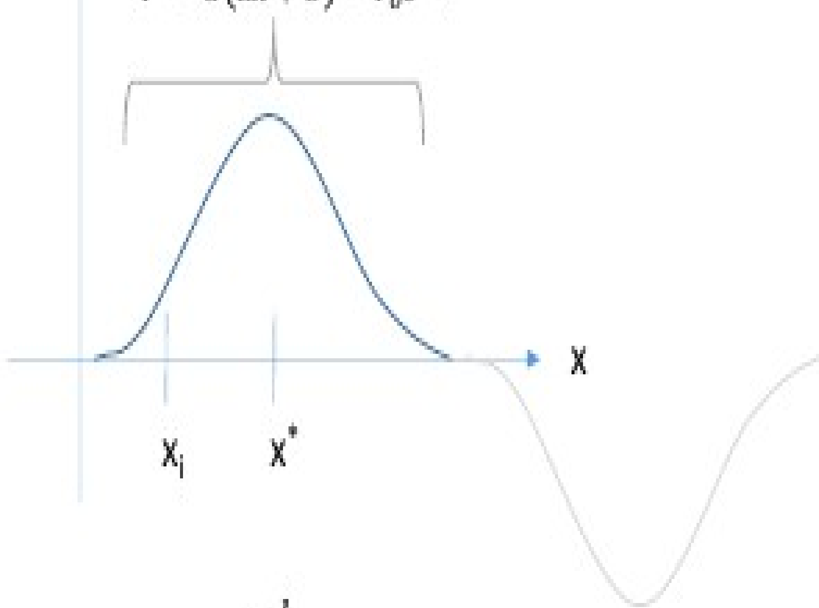




Frequency Seeking Algorithm

- Original algorithm used recursive estimators of a, b in $P_o e^{-\frac{1}{2}(ax+b)^2}$ to determine which position to move to next.

$$P = G(ax+b) = P_o e^{-\frac{1}{2}(ax+b)^2}$$



$$x^* = \frac{-b}{a}$$

$$x_{i+1} = -\frac{b_{i+1}}{a_{i+1}} + \varepsilon_{i+1}$$

$$\overbrace{|\varepsilon_{i+1}| < \frac{a}{0.2}}^{\text{Probing signal}}$$

$$a_{i+1} = a_i + C_i[P_i - G(a_i x_i + b_i)]$$

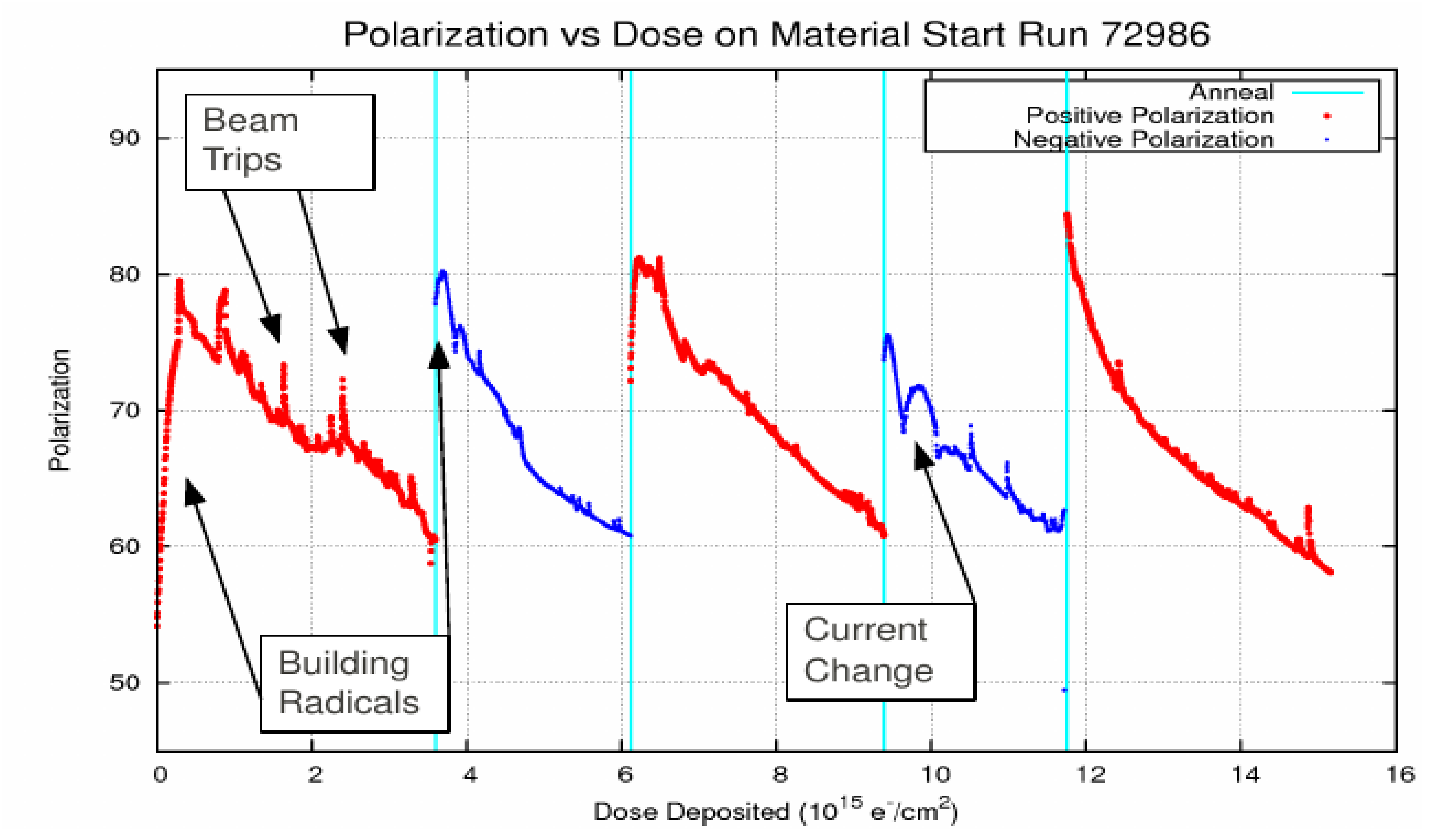
$$b_{i+1} = b_i + D_i[P_i - G(a_i x_i + b_i)]$$

$$C_i = \frac{\partial G_1}{\beta + (\partial G_1)^2 + (\partial G_2)^2} \qquad \partial G_1 = \left.\frac{\partial G(ax_i + b)}{\partial a}\right|_{ai,bi}$$

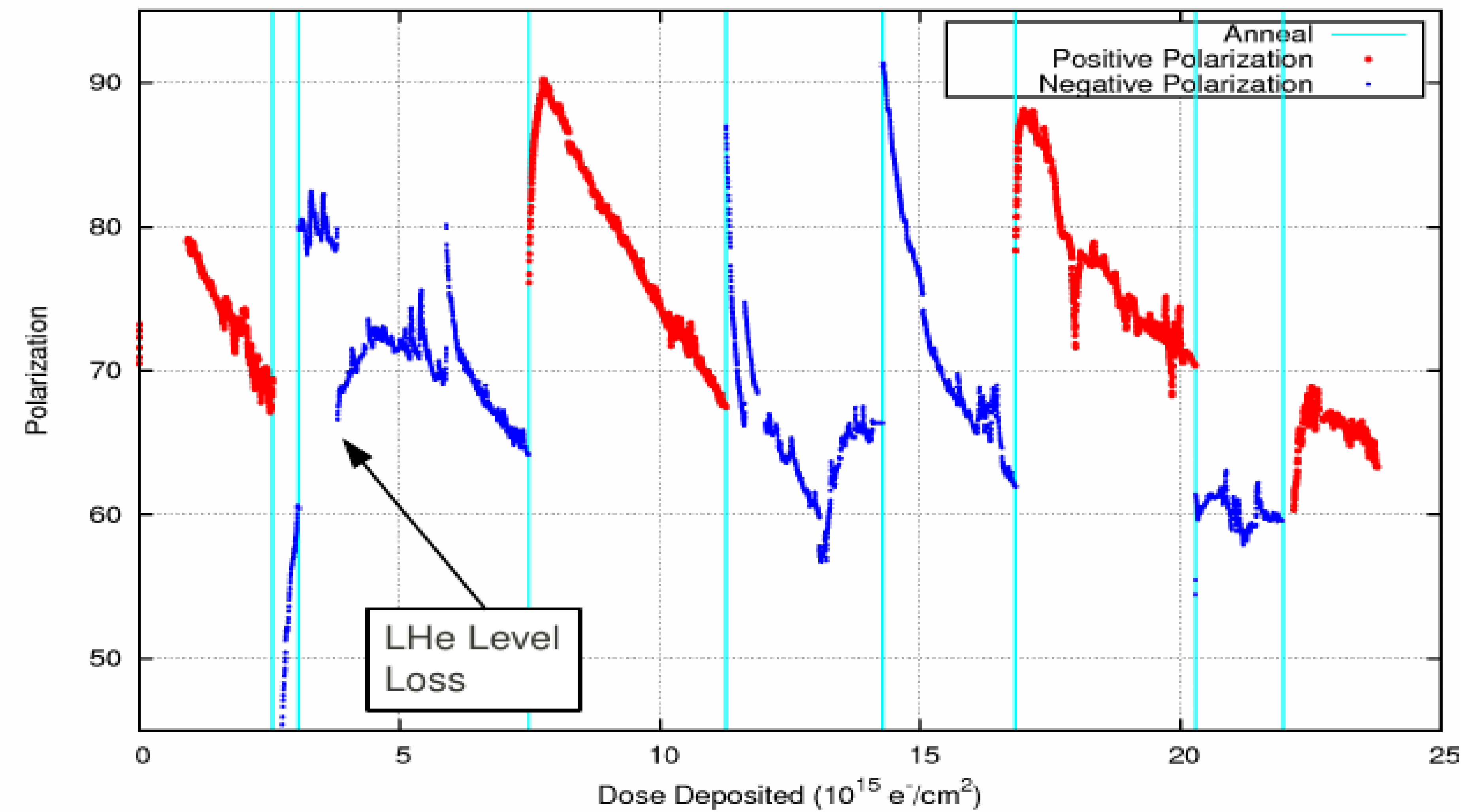
$$D_i = \frac{\partial G_2}{\beta + (\partial G_1)^2 + (\partial G_2)^2} \qquad \partial G_2 = \left.\frac{\partial G(ax_i + b)}{\partial b}\right|_{ai,bi}$$

$$\beta \rightarrow 0.1(P_o)$$

Characteristics of Polarization



Characteristics of Polarization



System Characterization, Simulation

"Ramp-ups" follow an exponential growth

Frequency response can be approximated as a second order system

$$P_n(t) = -[(\lambda_1 + a_{11})/a_{12}]C_1 e^{-\lambda_1 t} - [(\lambda_2 + a_{11})/a_{12}]C_2 e^{-\lambda_2 t} + P_n(\infty), \qquad (10)$$

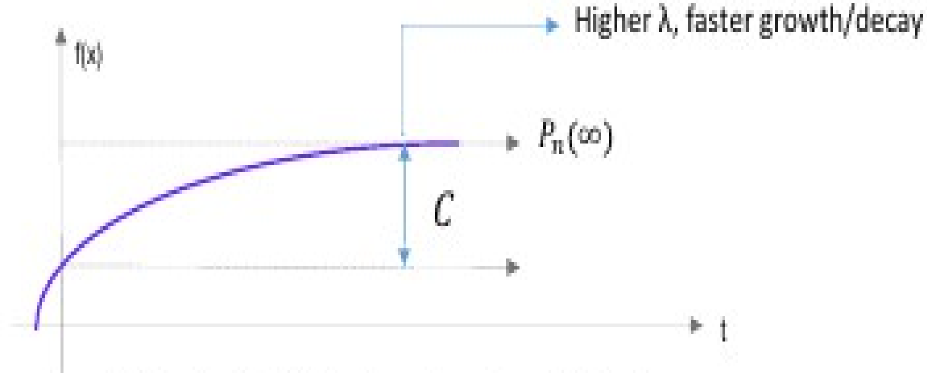
Credit: [illegible]

$$P_n(t) \approx P_n(\infty) + C_1 e^{-\lambda_1 t} + C_2 e^{-\lambda_2 t}$$

$$\lambda_1 = \frac{C\theta + 1}{2} \qquad \lambda_2 = \frac{C\theta + 1}{2} + \beta(C+1) \qquad \theta \ll \beta \qquad C = \frac{n_e}{n_n}$$

First exponential term extremely small (can essentially be neglected)

$$P_n(t) \approx P_n(\infty) + C_1 e^{-\lambda t}$$



$^*P_n(\infty) = C$, *if starting from* $t = 0, P = 0$

Some Overhead Optimization

Pure Photon Source can minimize target maintenance and overhead

For e^--beam target polarization will eventually decay so quickly in beam that annealing frequently enough is not practical ($^{14}NH_3$ this occurs at about 25 Pe^-/cm^2)

For polarized WACS a pure photon beam has the following advantages:

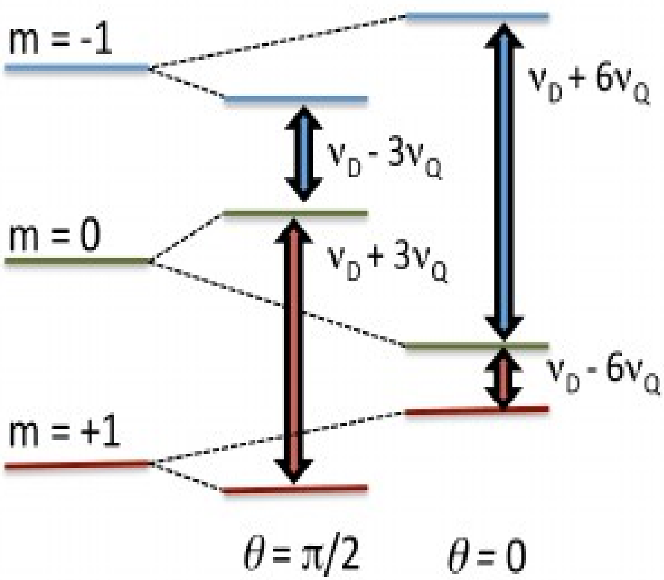
- Polarization will eventually decay so quickly in beam that annealing frequently enough is not practical
  - $^{14}NH_3$ this occurs at about 25 Pe^-/cm^2
  - Reduced target maintenance/overhead time
- Possible to significantly increase incoming beam current from nominal 100 na to 1 μA (~30 nA equivalent)
- Annealing: Heat material to allow excess radicals to recombine
- 70-100K for 10-60 minutes
  - $^{14}NH_3$ at 100 nA must anneal at 8 hours (~3 Pe^-/cm^2)
  - $^{14}NH_3$ at 10 nA must anneal at 90 hours

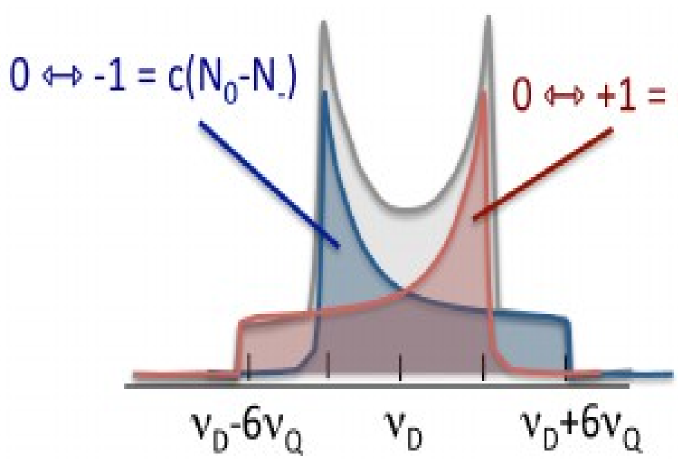
The Need For Tensor Polarized Target

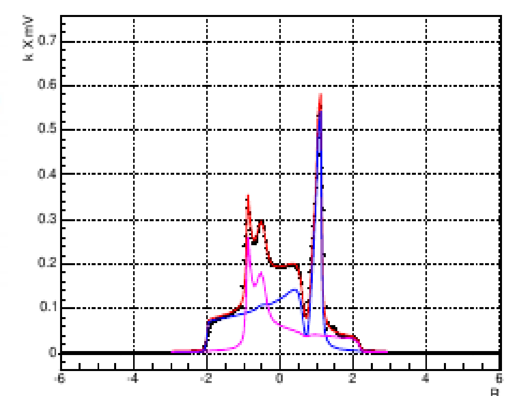
- Deuteron also has an electric quadrupole moment, $eq_D = 2.86\ e{\cdot}fm^2$
- eq_D interacts with electric field gradients within the lattice producing two, overlapping NMR lines (Pake doublet)

$$E_m = -h\nu_D m + h\nu_Q\left[3\cos^2\theta - 1\right]\left[3m^2 - I(I+1)\right]$$

ν_D = deut. Larmor freq.
ν_Q = ND_3 quadrupole freq.
eq = deuteron quadrupole moment
θ = angle between elec. & mag. fields

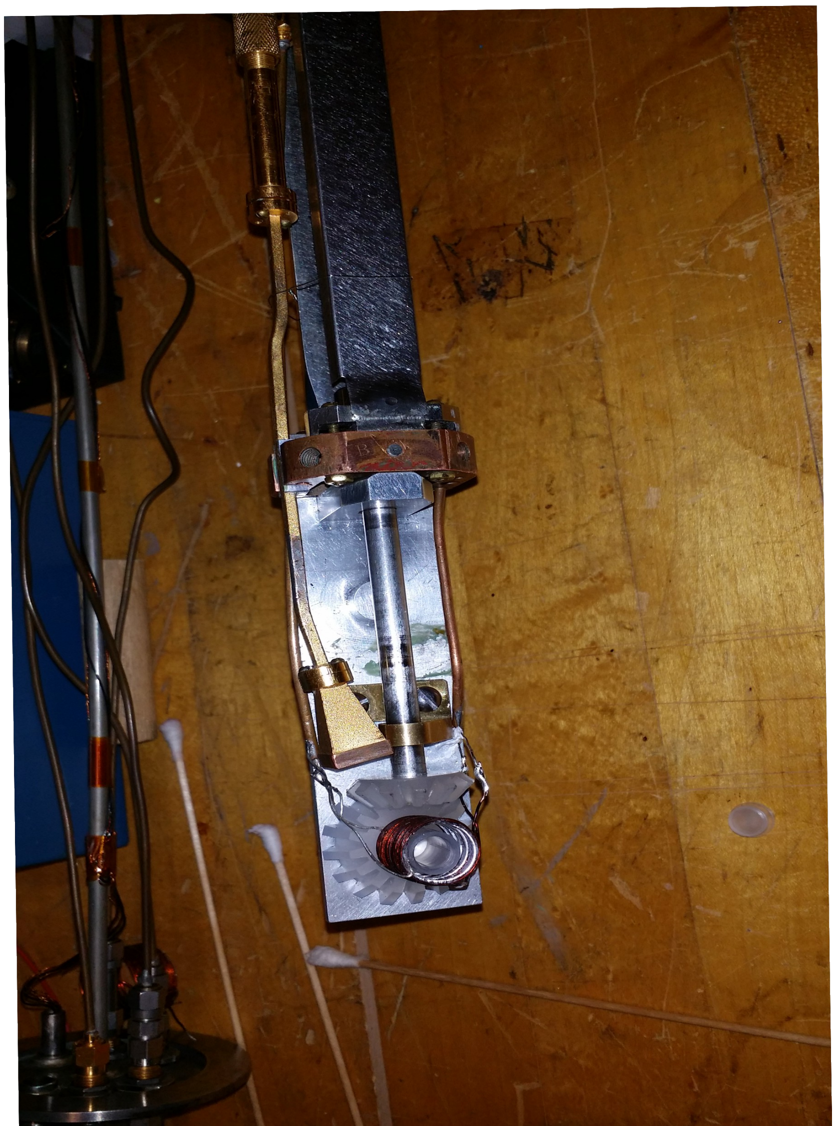


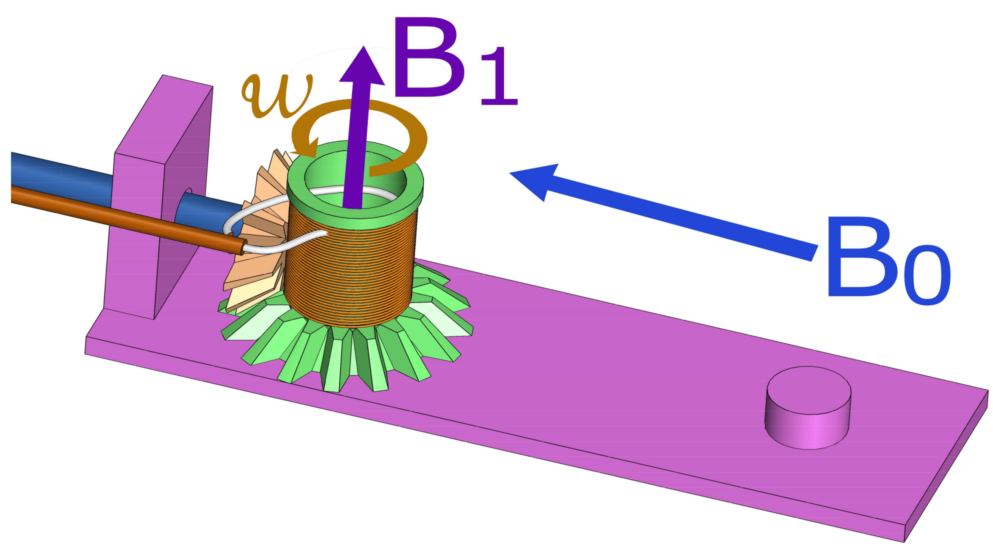




RF used to manipulate spin polarization state
(also used for $\underline{N}H_3$)

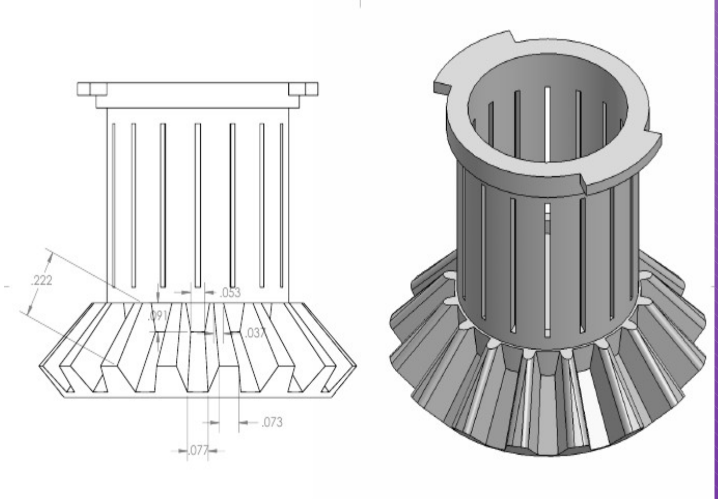
Rotating Target

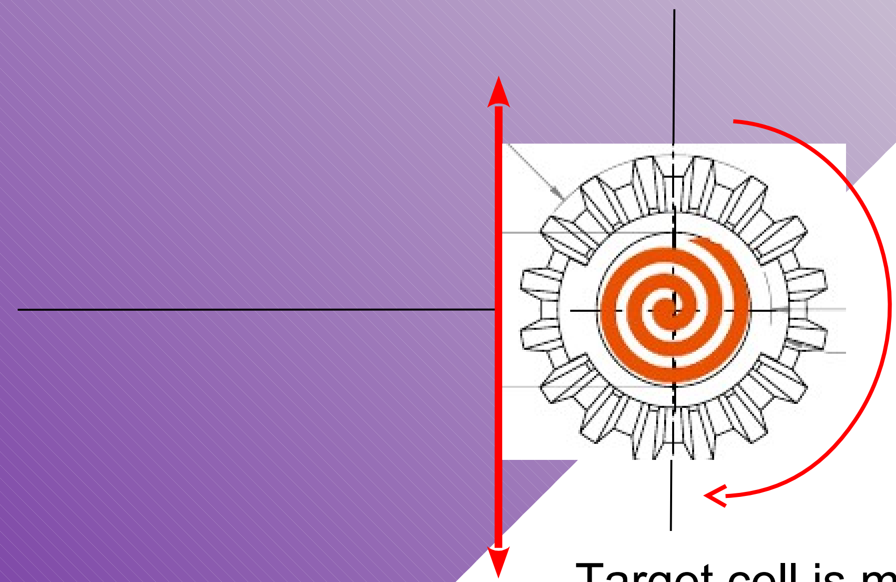




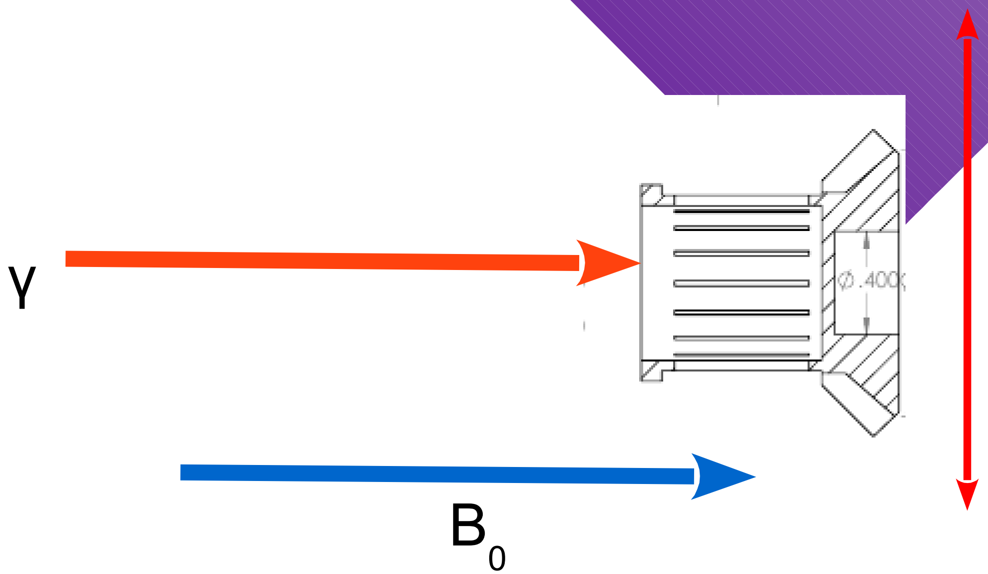
Rotating Target for WACS

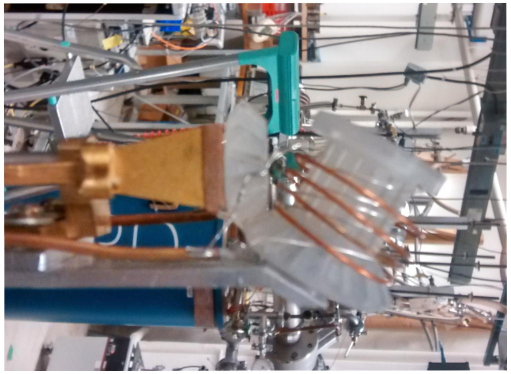
No need to raster electron beam
Full and uniform irradiation of target
2 mm fixed photon beam





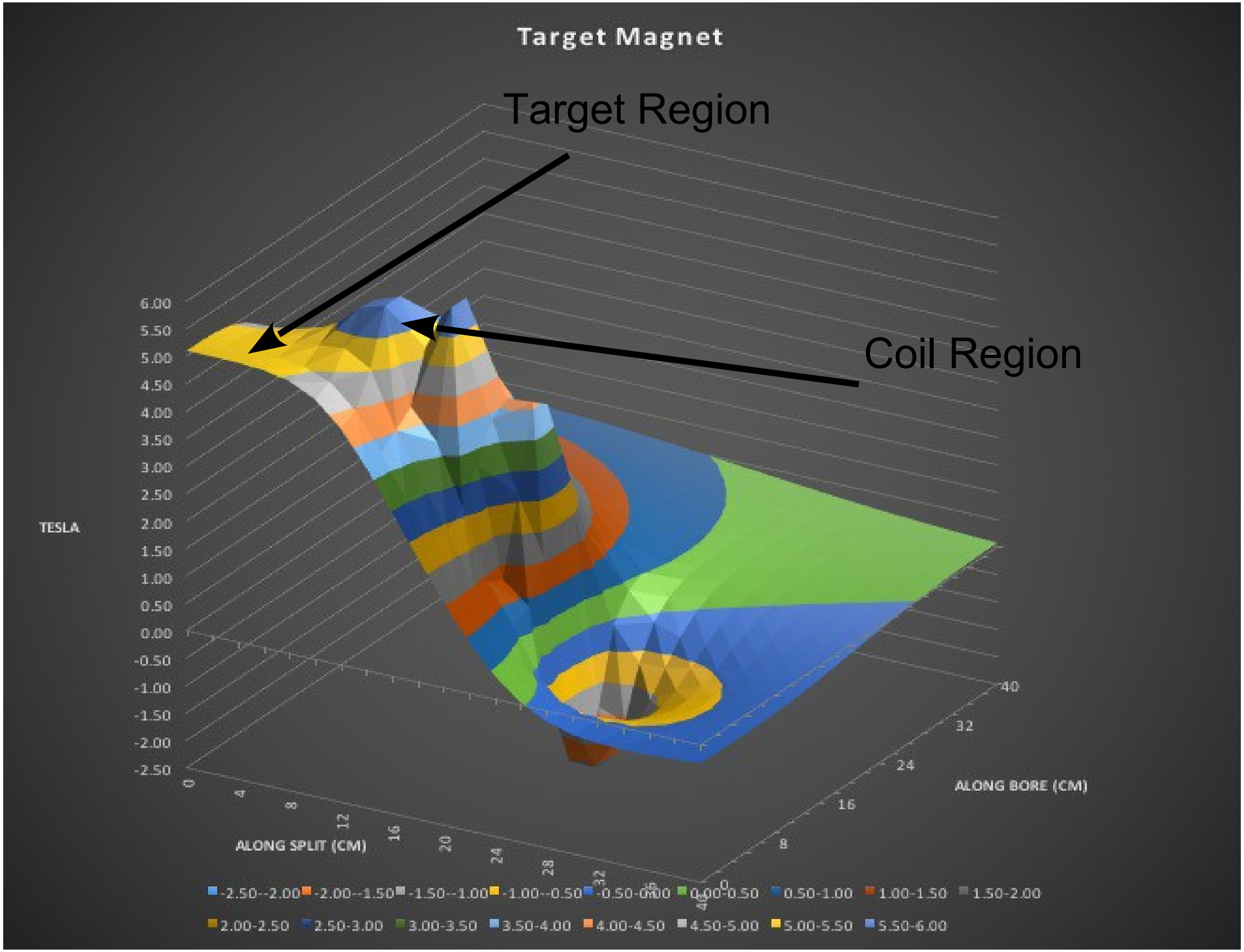
Target cell is moving up and down with rotation



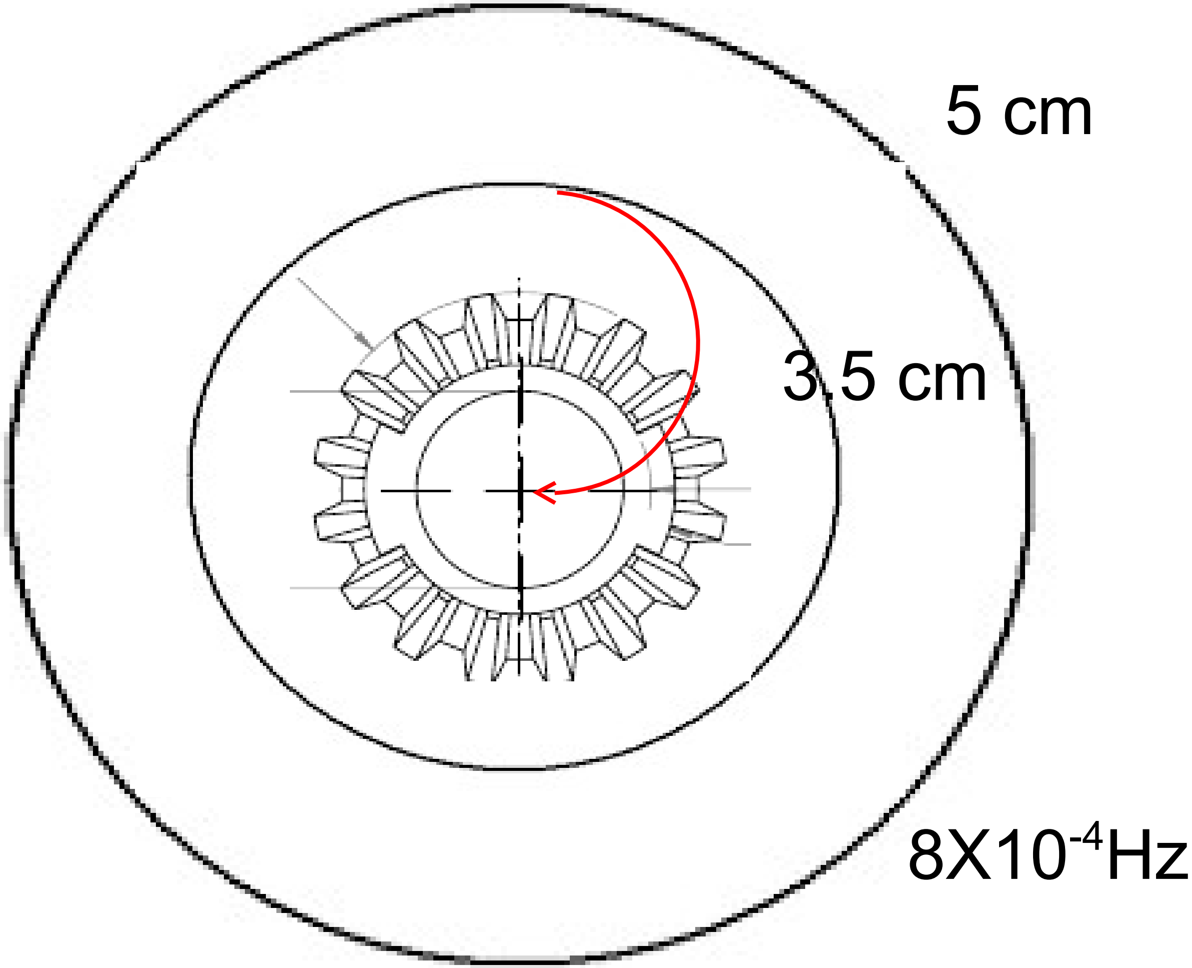


UVa already rotating target for alignment enhancement studies

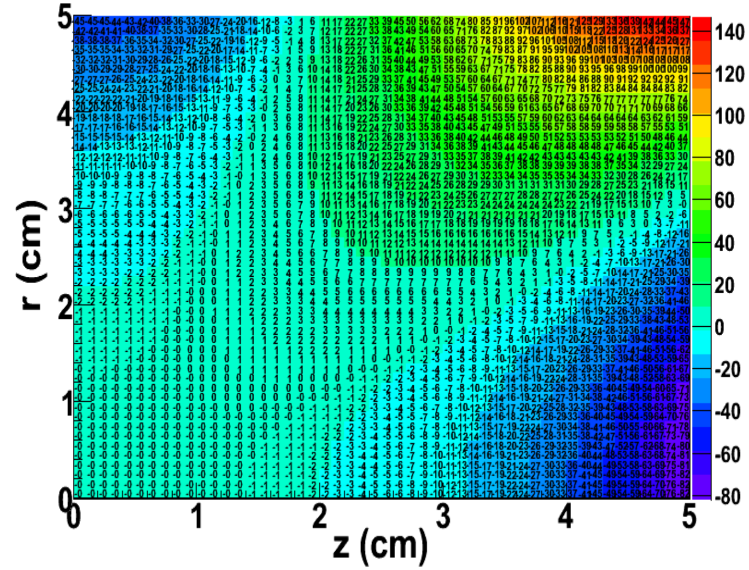
Field Map


Target Magnet
Target Region
Coil Region
TESLA
6.00
5.50
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
ALONG SPLIT (CM)
0
4
8
12
16
20
24
28
32
36
40
ALONG BORE (CM)
0
8
16
24
32
40
-2.50--2.00
-2.00--1.50
-1.50--1.00
-1.00--0.50
-0.50-0.00
0.00-0.50
0.50-1.00
1.00-1.50
1.50-2.00
2.00-2.50
2.50-3.00
3.00-3.50
3.50-4.00
4.00-4.50
4.50-5.00
5.00-5.50
5.50-6.00

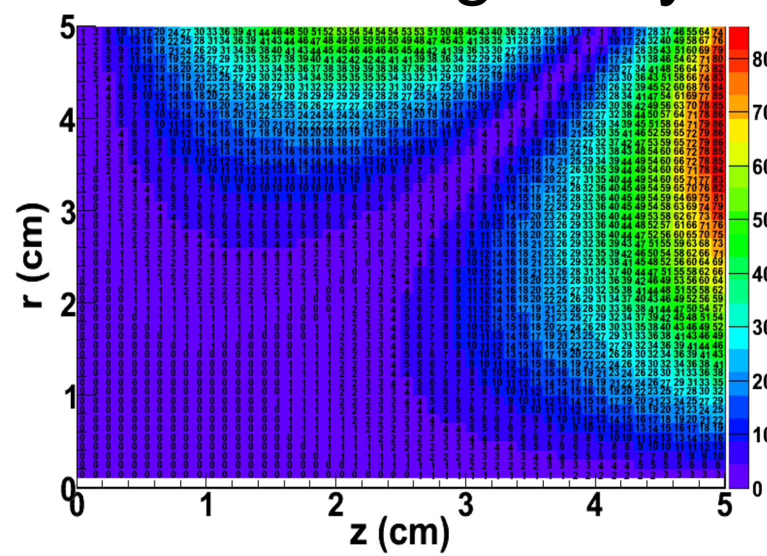
Larger Target



Bz-Homogeneity



Br-Homogeneity



$$P_n(t) = -[(\lambda_1 + a_{11})/a_{12}]C_1 e^{-\lambda_1 t} - [(\lambda_2 + a_{11})/a_{12}]C_2 e^{-\lambda_2 t} + P_n(\infty)$$

$$P_n(t) \approx P_n(\infty) + C_1 e^{-\lambda_1 t} + C_2 e^{-\lambda_2 t}$$

$t_1 = 1/T\Theta_1$

$$\lambda_1 = \frac{C\theta + 1}{2} \qquad \lambda_2 = \frac{C\theta + 1}{2} + \beta(C + 1) \qquad \theta \ll \beta$$

Summary

E12-16-004 was approved by PAC42 for 15 days
at 4.4 GeV beam

A pure photon beam can be achieved with a CPS or some
configuration of bender to beam dump
could make it possible to improve kinematics

Improves F.O.M by factor ~10 assuming use 1 uA beam
current with 2m long FZ dipole

Presently studying optimization with respects to distance to
radiator, distance from dump to target, shielding, current, and
target behavior

Use of RF, Microwave Optimization, Rotation

More Polarized WACS