

Bubble Chamber: Experimental Overview

August 18, 2015

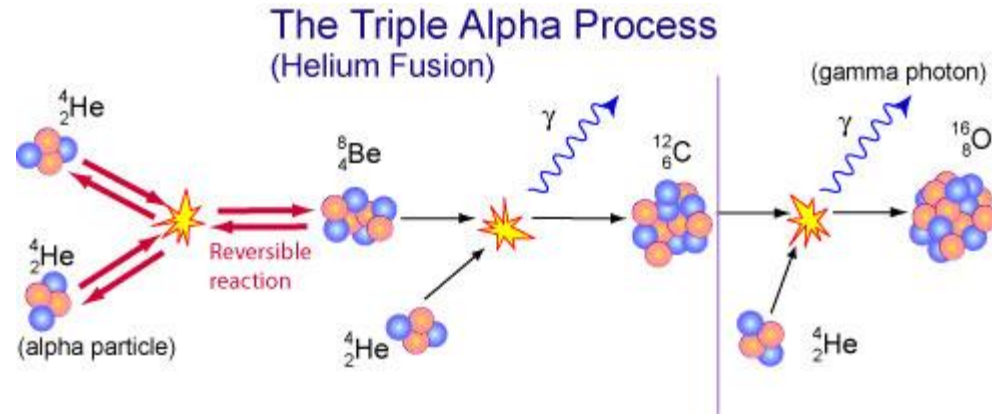
[https://wiki.jlab.org/ciswiki/index.php/Bubble Chamber](https://wiki.jlab.org/ciswiki/index.php/Bubble_Chamber)

OUTLINE

- Nucleosynthesis and $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ Reaction
- Time Reversal Reaction: $^{16}\text{O}(\gamma,\alpha)^{12}\text{C}$
- Electron Beam Requirements
- Bremsstrahlung Beam
- Penfold-Leiss Cross Section Unfolding
- JLab Projected Results
- Test Beamline
- Bubble Chamber Test Plan

NUCLEOSYNTHESIS AND $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$

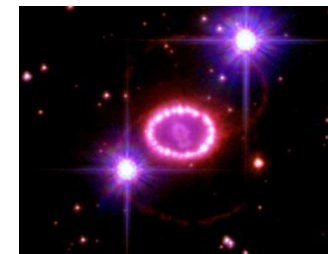
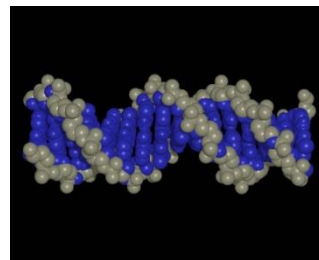
Stellar Helium burning



➤ The *holy grail* of nuclear astrophysics:

Periodic Table of the Elements

1	H	He																	O
2	Li	Be											B	C	N	O	F	Ne	
3	Na	Mg									Al	Si	P	S	Cl	Ar			
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe	
6	Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn	
7	Fr	Ra	Ac	Rf	Ha	Hs	Mt	110	111	112	113								
* Lanthanide Series		Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu				
+ Actinide Series		Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr				



Affects synthesis of most of elements in periodic table

Sets $N(^{12}\text{C})/N(^{16}\text{O})$ (≈ 0.4) ratio in universe

Determines minimum mass star requires to become supernova

HEROIC EFFORTS IN SEARCH OF $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$

➤ Previous cross section measurements:

I. Helium ions on carbon target: $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$

II. Carbon ions on helium gas: $^4\text{He}(^{12}\text{C},\gamma)^{16}\text{O}$ or $^4\text{He}(^{12}\text{C},^{16}\text{O})\gamma$
(Schürmann)

Experiment	Beam Current (mA)	Target (nuclei/cm ²)	Time (h)
Redder	0.7	$^{12}\text{C}, 3 \cdot 10^{18}$	900
Ouellet	0.03	$^{12}\text{C}, 5 \cdot 10^{18}$	1950
Roters	0.02	$^4\text{He}, 1 \cdot 10^{19}$	5000
Kunz	0.5	$^{12}\text{C}, 3 \cdot 10^{18}$	700
EUROGAM	0.34	$^{12}\text{C}, 1 \cdot 10^{19}$	2100
GANDI	0.6	$^{12}\text{C}, 2 \cdot 10^{18}$	
Schürmann	0.01	$^4\text{He}, 4 \cdot 10^{17}$	
Plag	0.005	$^{12}\text{C}, 6 \cdot 10^{18}$	278

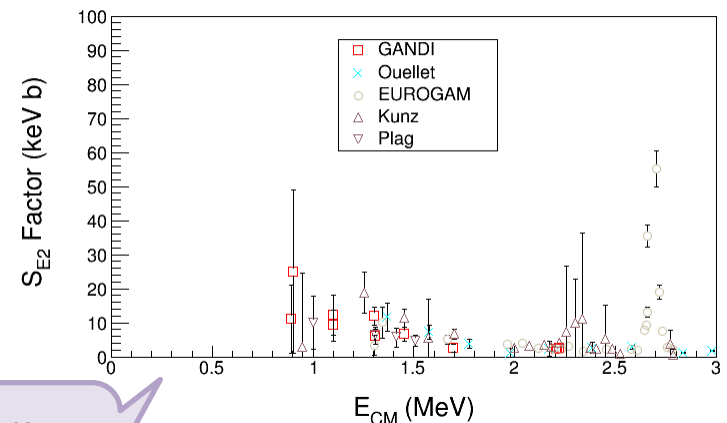
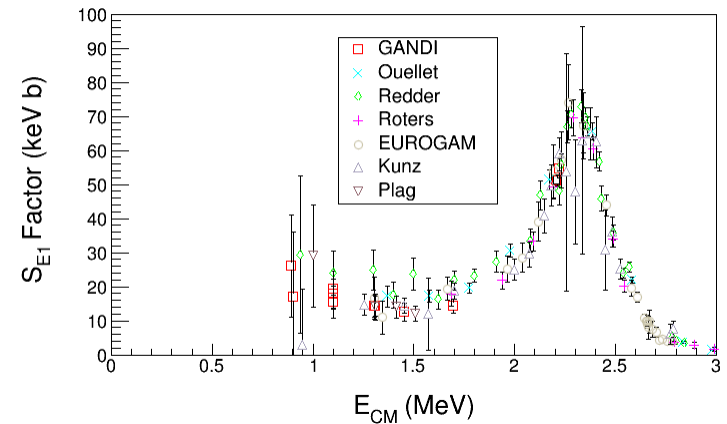
ASTROPHYSICAL S-FACTOR $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$

- Define *S-Factor* to remove both $1/E$ dependence of nuclear cross sections and Coulomb barrier transmission probability:

$$S \equiv E_{CM} \sigma(\alpha, \gamma) e^{2\pi\eta}$$

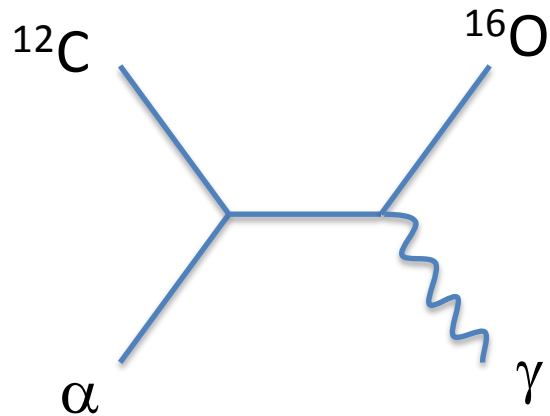
$$\eta = \frac{1}{137} Z_{\alpha} Z_{^{12}\text{C}} \sqrt{\frac{m_{^{12}\text{C}\alpha}}{2E_{CM}}}$$

Author	$S_{\text{tot}}(300)$ (keV b)
Hammer (2005)	162 ± 39
Kunz (2001)	165 ± 50



R-matrix Extrapolation to stellar helium burning at $E = 300$ keV

TIME REVERSAL REACTION

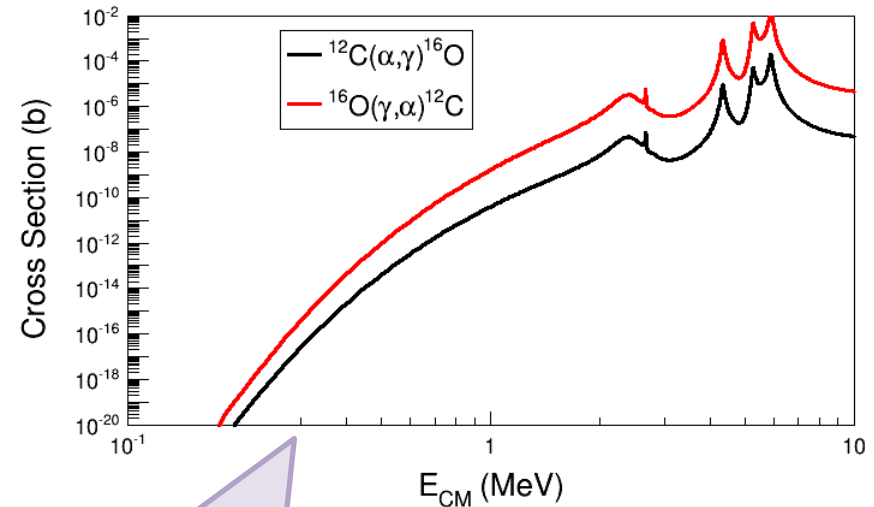


$$m_{12C\alpha} c^2 = \frac{M(^{12}\text{C}) \cdot M(\alpha)}{M(^{12}\text{C}) + M(\alpha)} = 2796 \text{ MeV}$$

$$Q = +7.162 \text{ MeV}$$

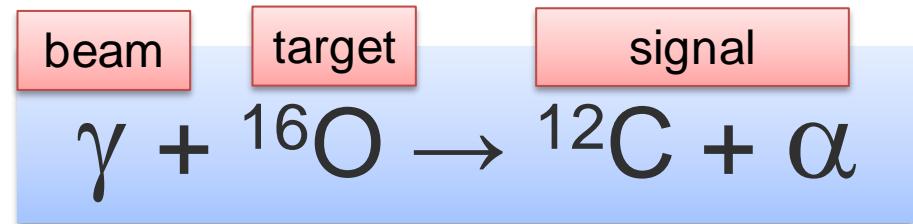
$$E_\gamma \cong E_{CM} + Q$$

$$\sigma_{(\gamma,\alpha)}(E_\gamma) = \frac{m_{12C\alpha} c^2 E_{CM}}{E_\gamma^2} \sigma_{(\alpha,\gamma)}(E_{CM})$$



Stellar helium burning at
 $E = 300 \text{ keV}$, $T = 200 \cdot 10^6 \text{ K}$

NEW APPROACH: REVERSAL REACTION + BUBBLE CHAMBER



- Extra gain (factor of 100) by measuring time reversal reaction
- Bremsstrahlung at JLab $\sim 10^9 \gamma/\text{s}$ (top 250 keV)
- Target density up to 10^4 higher than conventional targets. Number of ${}^{16}\text{O}$ nuclei = $3.5 \times 10^{22}/\text{cm}^2$ (3.0 cm cell)
- Measures total cross section σ_{tot} (or $S_{\text{tot}} = S_{\text{E1}} + S_{\text{E2}}$)
- Solid Angle and Detector Efficiency = 100%
- Electromagnetic debris (electrons and gammas, or positrons) do NOT trigger nucleation (detector is insensitive to γ -rays by at least 1 part in 10^{11})

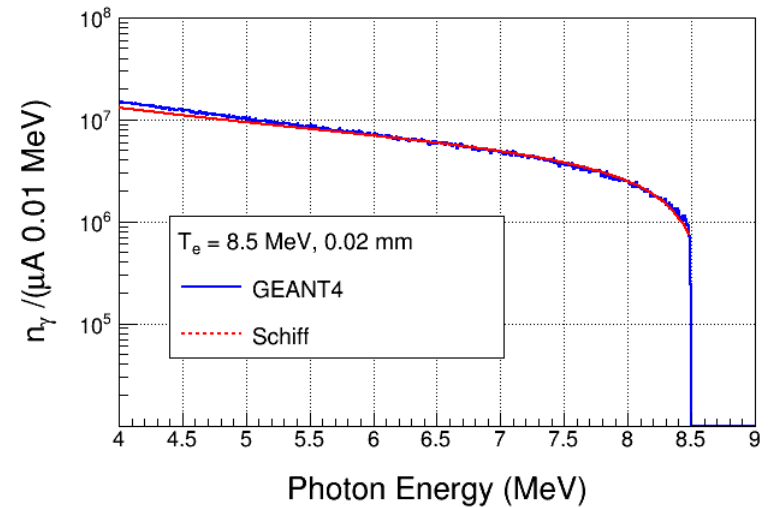
ELECTRON BEAM REQUIREMENTS

I. Beam Properties at Radiator:

Beam Kinetic Energy, (MeV)	7.9 – 8.5
Beam Current (μA)	0.01 – 100
Absolute Beam Energy Uncertainty	<0.1%
Relative Beam Energy Uncertainty	<0.02%
Energy Resolution (Spread), σ_T/T	<0.06%
Beam Size, $\sigma_{x,y}$ (mm)	1
Polarization	None

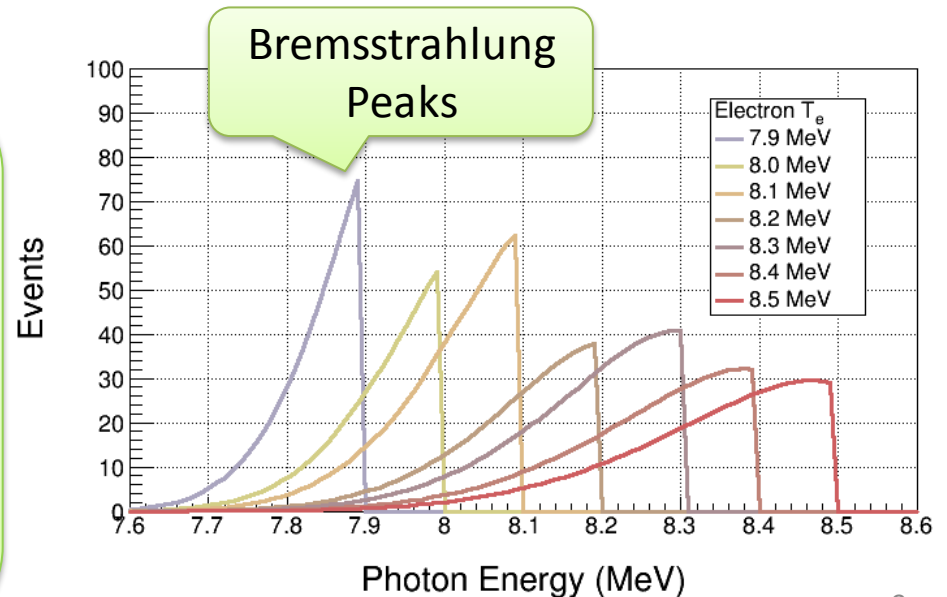
BREMSSTRAHLUNG BEAM

- Use both GEANT4 and FLUKA to calculate Bremsstrahlung spectra (we will not measure Bremsstrahlung spectra)
- Monte Carlo simulation of Bremsstrahlung at radiotherapy energies is well studied, accuracy: $\pm 5\%$



$^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$ is ideal case for Bremsstrahlung beam and Penfold–Leiss Unfolding:

- Very steep cross section; only photons near endpoint contribute to yield
- No-structure (resonances)



PENFOLD-LEISS CROSS SECTION UNFOLDING

- Measure yields at: $E = E_1, E_2, \dots, E_n$ where, $E_i - E_{i-1} = \Delta$, $i = 2, n$

$$Y(E_i) = \int_{th}^{E_i} n_\gamma(E_i, k) \sigma(k) dk \approx \sum_{j=1}^i N_\gamma(E_i, \Delta, E_j) \sigma(E_j)$$

Volterra Integral Equation of First Kind

- Solution can be written in two forms:

$$\sigma_i = \frac{1}{N_{ii}} \left[y_i - \sum_{j=1}^{i-1} (N_{ij} \sigma_j) \right]$$

- Or, Matrix form:

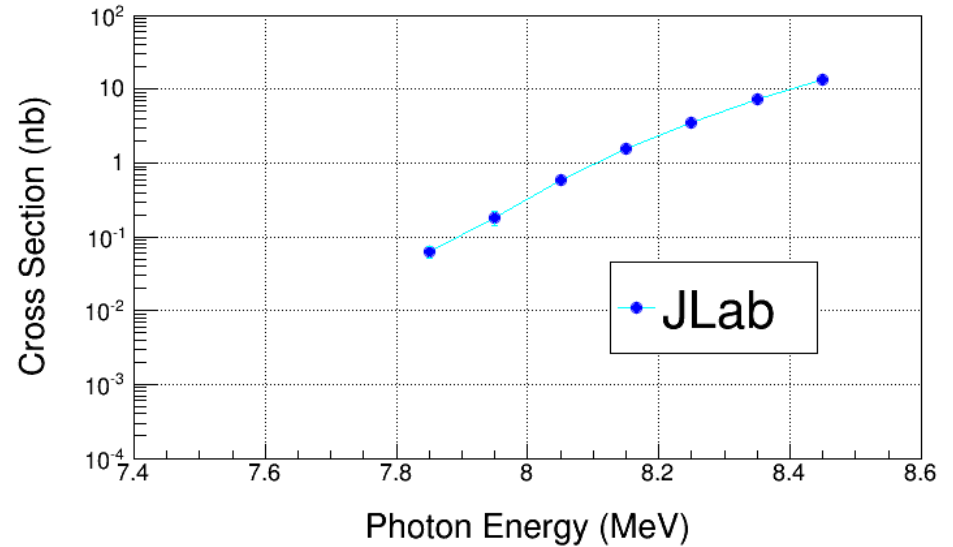
$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} = \begin{bmatrix} N_{\gamma,11} & 0 & \cdots & 0 \\ N_{\gamma,21} & N_{\gamma,22} & \cdots & 0 \\ \vdots & \ddots & \ddots & 0 \\ N_{\gamma,n1} & N_{\gamma,n2} & \cdots & N_{\gamma,nn} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \vdots \\ \sigma_n \end{bmatrix}$$

$$[Y] = [N] \bullet [\sigma]$$

$$[\sigma] = [N]^{-1} \bullet [Y]$$

Method of Quadratures:
numerical solution of integral
equation based on replacement
of integral by finite sum

Electron Beam K. E.	Cross Section (nb)	Stat Error (no bg, %)	Stat Error (with bg, %)
7.9	0.046	4.4	24.5
8.0	0.185	6.0	20.7
8.1	0.58	6.3	14.7
8.2	1.53	8.2	13.8
8.3	3.49	9.1	13.3
8.4	7.2	10.6	13.8
8.5	13.6	12.2	14.8



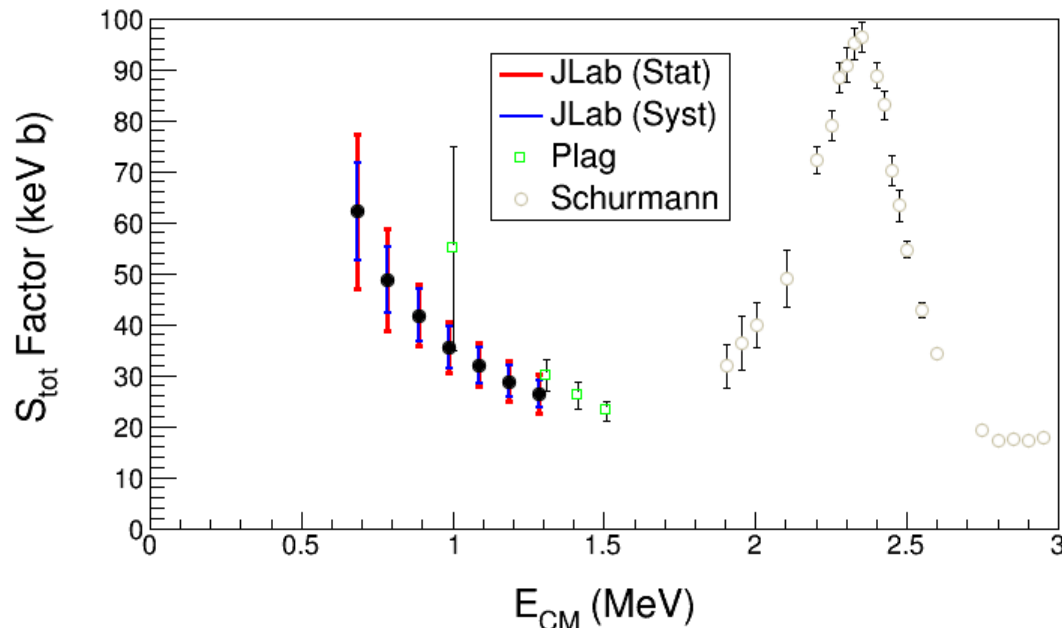
Absolute Beam Energy, δE	0.1%
Beam Current, $\delta I/I$	3%
Photon Flux, $\delta \varphi/\varphi$	5%
Radiator Thickness, $\delta R/R$	3%
Bubble Chamber Thickness, $\delta T/T$	3%
Bubble Chamber Efficiency, ε	5%

Electron Beam K. E.	Cross Section (nb)	Sys Error (Energy, %)	Sys Error (Total, %)
7.9	0.046	12.5	15.3
8.0	0.185	10.2	13.5
8.1	0.58	8.3	12.2
8.2	1.53	7.0	11.4
8.3	3.49	6.0	10.7
8.4	7.2	5.3	10.5
8.5	13.6	4.7	10.1

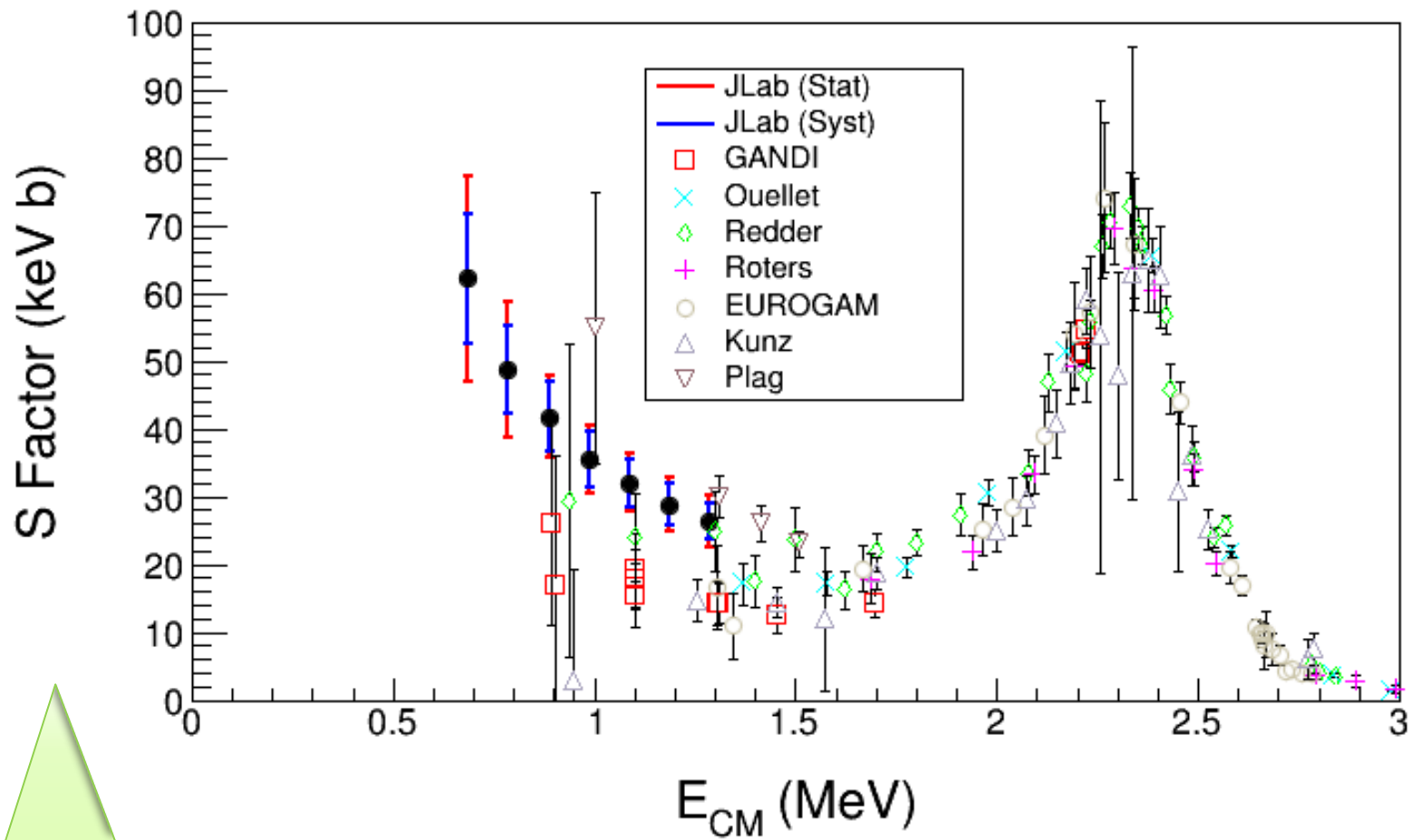
JLAB PROJECTED $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ S-Factor

- Statistical Error: dominated by background subtraction from $^{18}\text{O}(\gamma,\alpha)^{14}\text{C}$ (depletion = 5,000)

Electron Beam K. E.	Gamma Energy (MeV)	E_{CM} (MeV)	Cross Section (nb)	S_{tot} Factor (keV b)	Stat Error (%)	Sys Error (Total, %)
7.9	7.85	0.69	0.046	62.2	24.5	15.3
8.0	7.95	0.79	0.185	48.7	20.7	13.5
8.1	8.05	0.89	0.58	41.8	14.7	12.2
8.2	8.15	0.99	1.53	35.5	13.8	11.4
8.3	8.25	1.09	3.49	32.0	13.3	10.7
8.4	8.35	1.19	7.2	28.8	13.8	10.5
8.5	8.45	1.29	13.6	26.3	14.8	10.1



Bubble Chamber experiment measures total S-Factor, $S_{E1} + S_{E2}$



Total S-Factor $\sim S_{E1}$
 (S_{E2} is small)

SUPERHEATED TARGETS

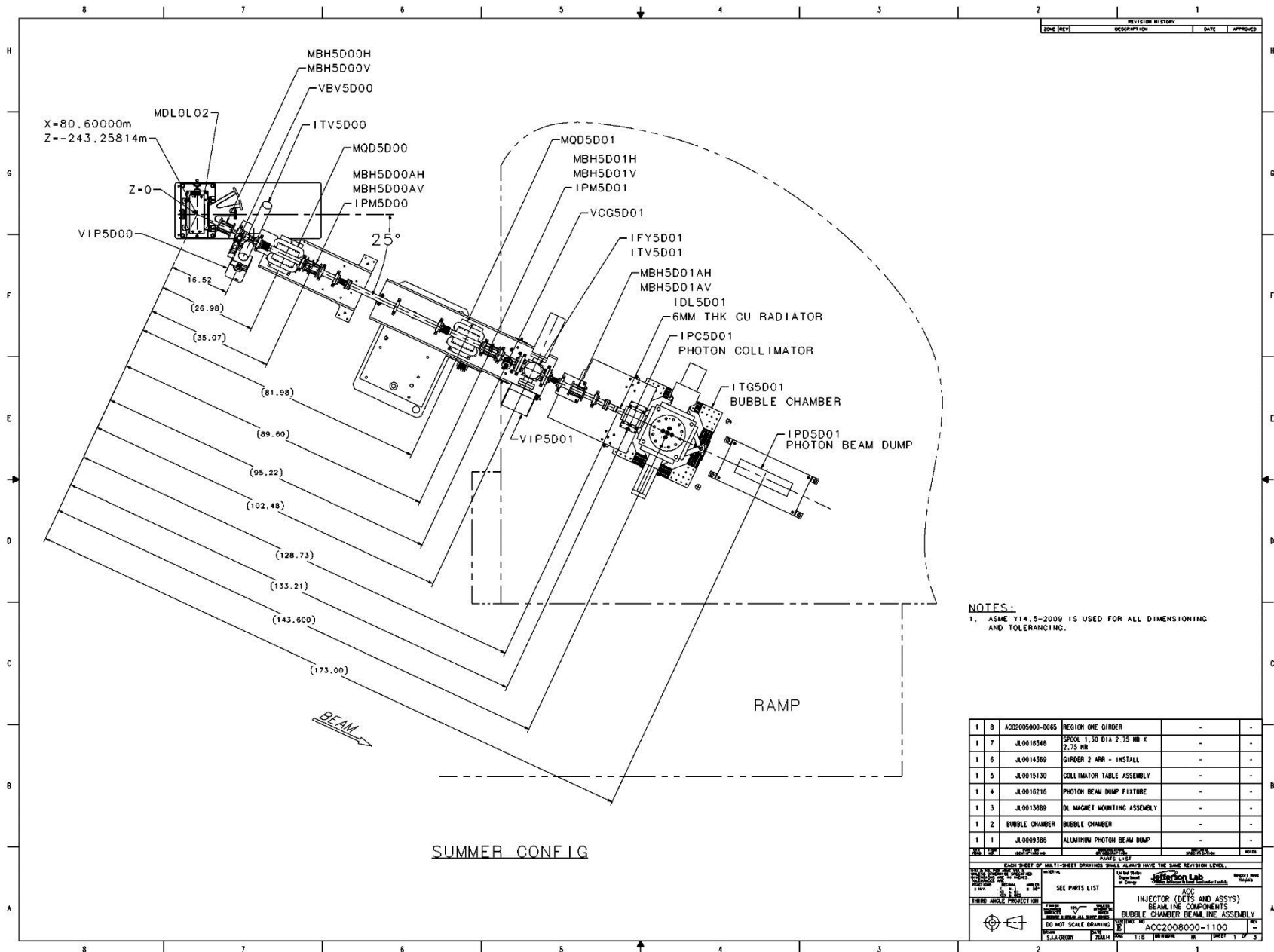
- I. List of superheated liquids to be used in experiment:

	N₂O Targets	¹⁶O	¹⁷O	¹⁸O
	Natural Target	99.757%	0.038%	0.205%
Physics	¹⁶ O Target		Depleted > 5,000	Depleted > 5,000
	¹⁷ O Target		Enriched > 80%	<1.0%
Measure Backgrounds	¹⁸ O Target		<1.0%	Enriched > 80%

- II. Readout:

- I. Fast Digital Camera
- II. Acoustic Signal to discriminate between neutron and alpha events

TEST BEAMLINE



NOTES:
 1. ASME Y14.5-2009 IS USED FOR ALL DIMENSIONING AND TOLERANCING.

REV	NO	DESCRIPTION	DATE	BY	CHKD
1	8	ACC2005000-0065 REGION ONE GIRDER	-	-	-
1	7	JL0018546 SPOOL 1.50 DIA 2.75 MR X 2.75 MR	-	-	-
1	6	JL0014369 GIRDER 2 APR - INSTALL	-	-	-
1	5	JL0015130 COLLIMATOR TABLE ASSEMBLY	-	-	-
1	4	JL0016216 PHOTON BEAM DUMP FIXTURE	-	-	-
1	3	JL0015889 DL MAGNET MOUNTING ASSEMBLY	-	-	-
1	2	BUBBLE CHAMBER	-	-	-
1	1	JL0009366 ALUMINUM PHOTON BEAM DUMP	-	-	-

PROJECTION: THIRD ANGLE PROJECTION

SCALE: 1:1

DATE: 1/18/2009

BY: [Signature]

CHKD: [Signature]

APP'D: [Signature]

DESCRIPTION: INJECTOR (DETS AND ASSYS) BEAMLINE COMPONENTS BUBBLE CHAMBER BEAMLINE ASSEMBLY

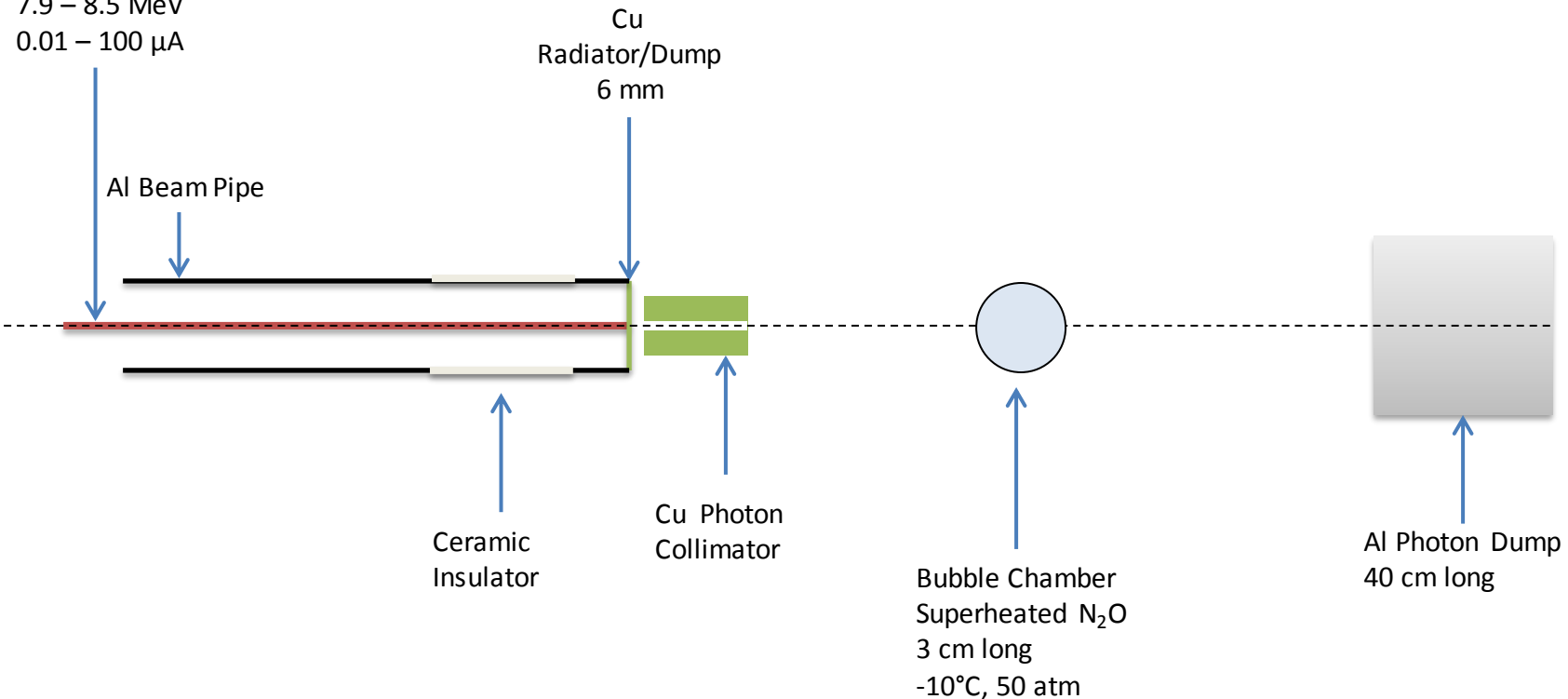
PROJECT NO: ACC2008000-1100

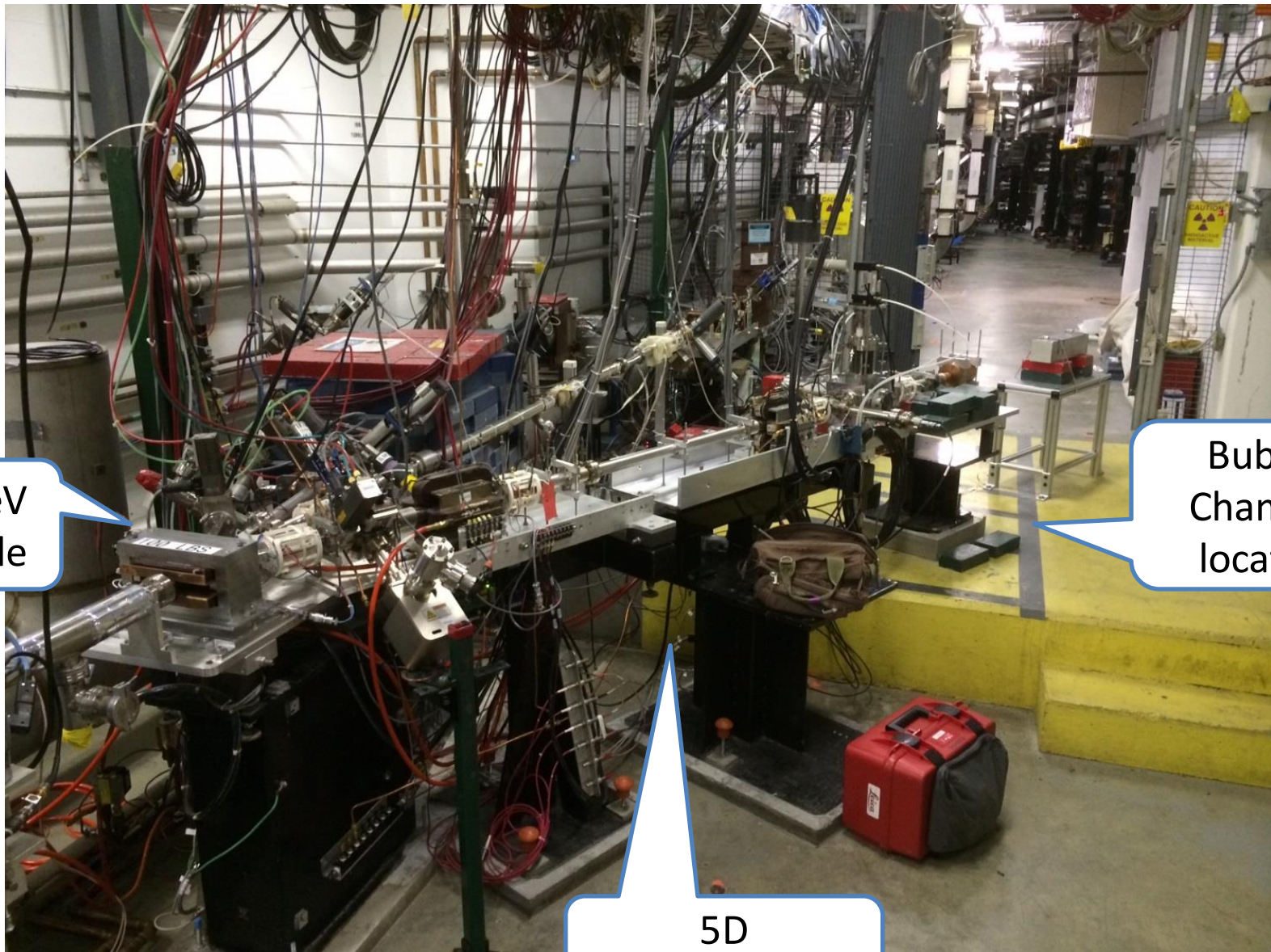
REV: 1 OF 3

SCHEMATICS OF TEST BEAMLINE

- Power deposited in radiator (100 μ A and 8.5 MeV) :
 - I. 6 mm: Energy loss = 8.5 MeV, P = 850 W
- Pure Copper and Aluminum (high neutron threshold):
 - I. $^{63}\text{C}(\gamma, n)$ threshold = 10.86 MeV
 - II. $^{27}\text{Al}(\gamma, n)$ threshold = 13.06 MeV

Electron K.E.
7.9 – 8.5 MeV
0.01 – 100 μ A



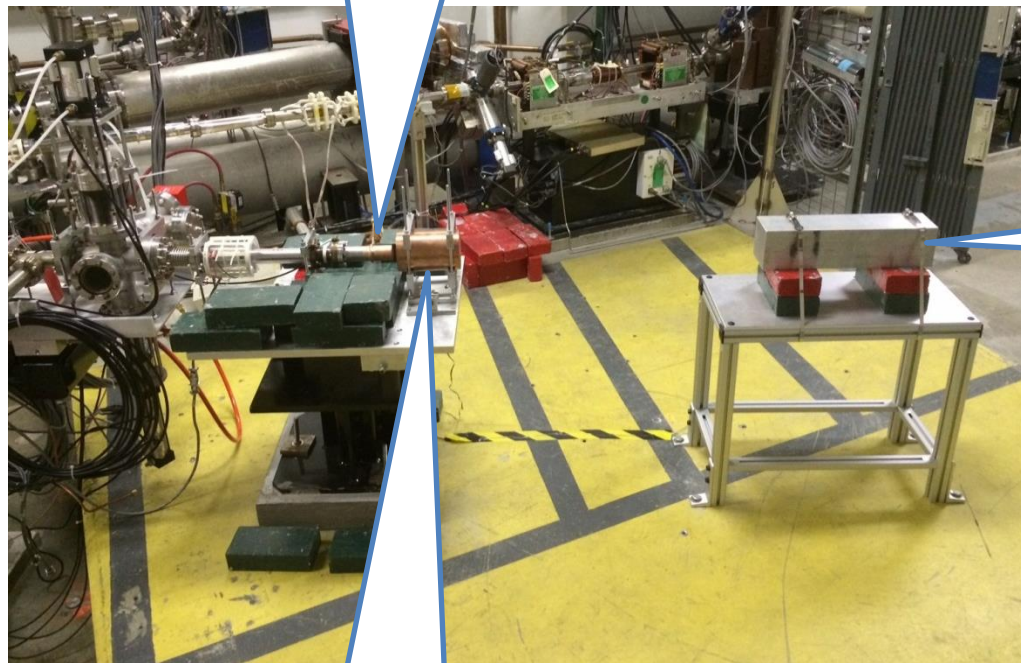


5 MeV
Dipole

Bubble
Chamber
location

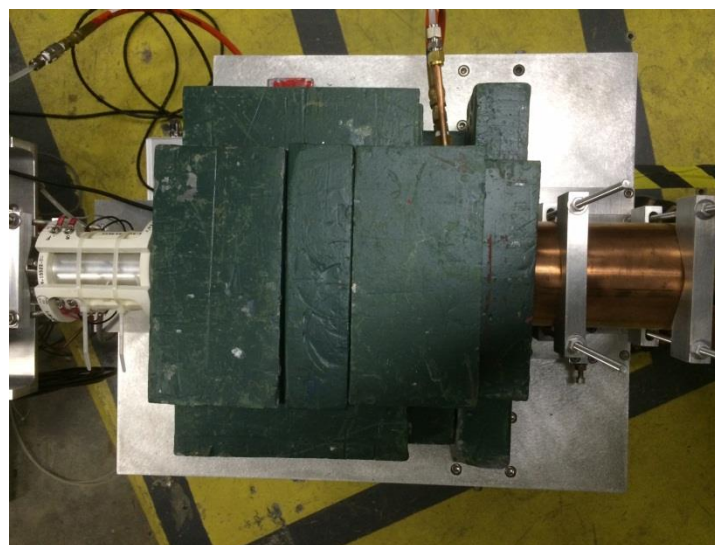
5D
Spectrometer

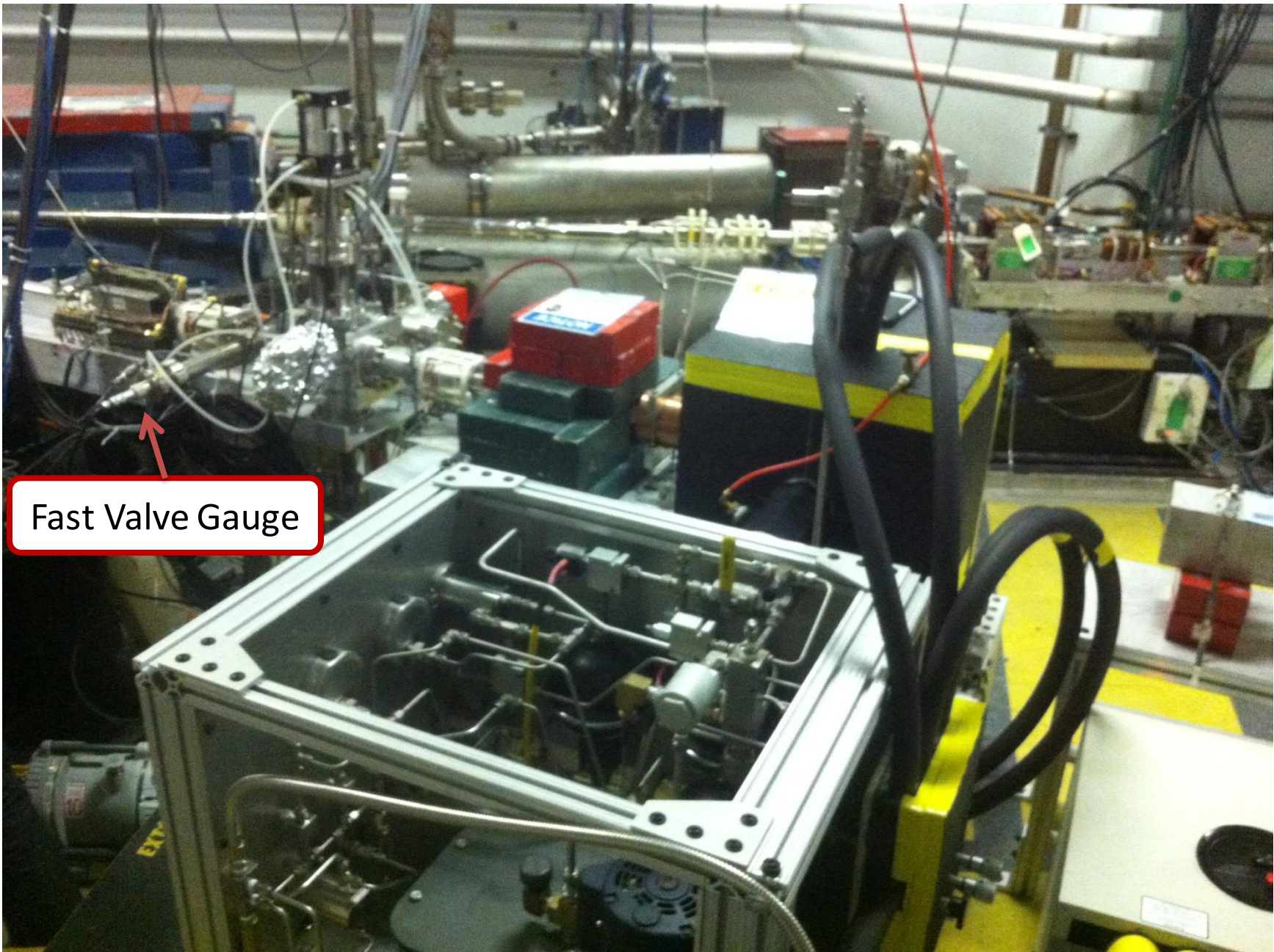
Cu Electron
Radiator/Dump



Al Photon
Dump

Cu Photon
Collimator





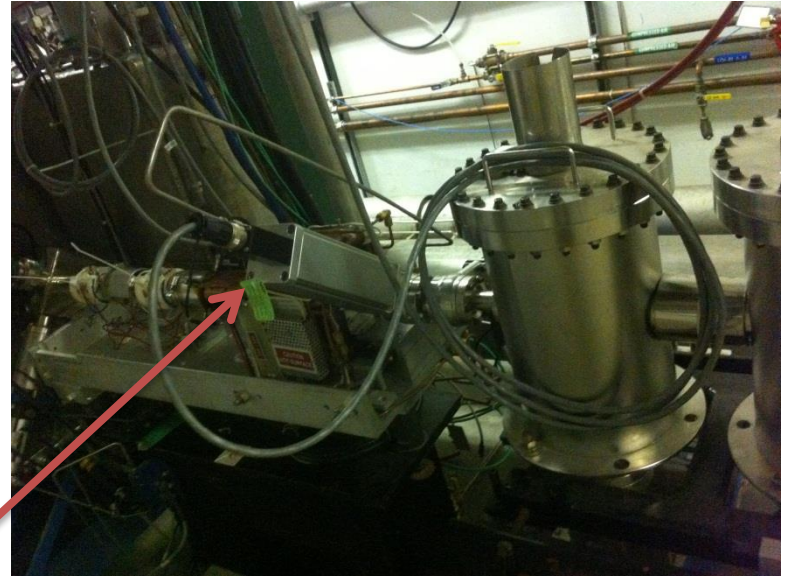
Fast Valve Gauge

NEW BEAMLINE ELEMENTS

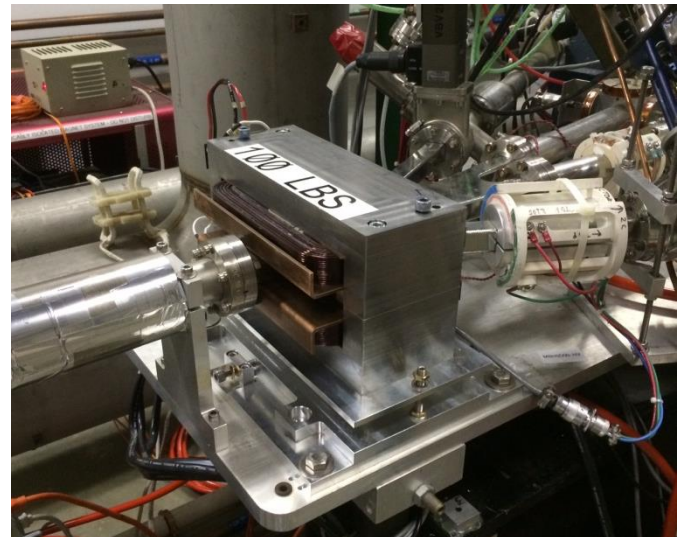
➤ New Beamline elements installed in support of Bubble Chamber experiment:

I. Fast Valve after $\frac{1}{4}$ Cryounit

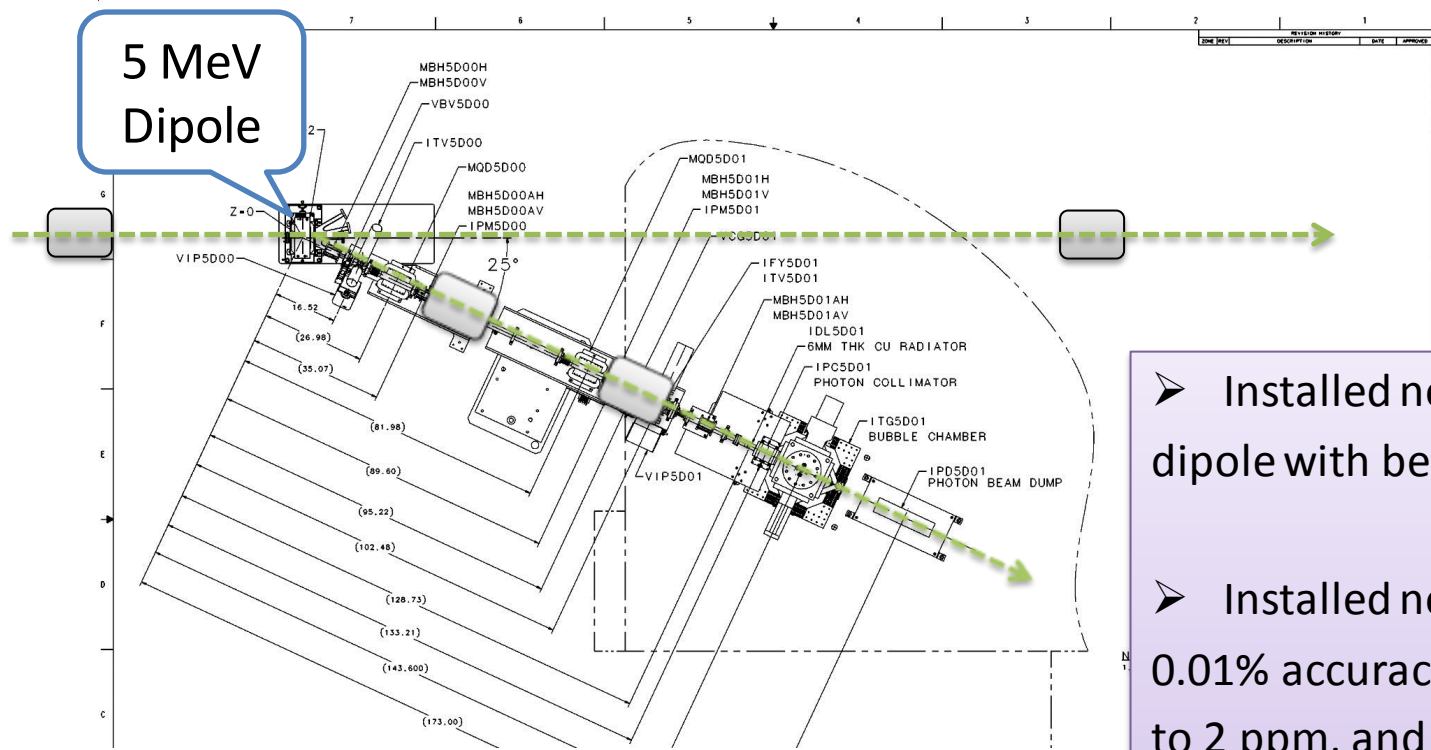
Protect $\frac{1}{4}$ Cryo-unit from vacuum failure



II. New MDL0L02 Dipole Magnet



MEASURING ABSOLUTE BEAM ENERGY



5 MeV Dipole

Beam Position Monitor (BPM)

Electron Beam Momentum

$$p = \frac{\int Bdl}{\theta}$$

- Installed new higher field dipole with better uniformity
- Installed new Hall probe: 0.01% accuracy, resolution to 2 ppm, and a temperature stability of 10 ppm/°C
- Still need to shield Earth's and other stray magnetic fields

TEST BEAMLINER COMMISSIONING

- Beamline was ready since Fall 2014
- Approved to run 10 μA CW and 10 MeV/c
- Completed hot checkout and beam checkout
- Beam Studies completed so far:
 - I. Delivered 10.0 μA 10.0 MeV/c for 5 hours in August 2015
 - II. Measured beam momentum at different $\frac{1}{4}$ cryo-unit settings
 - III. Measured beam charge at different beam currents
- Re-doing realistic thermal analysis to be able to run up to 100 μA

BUBBLE CHAMBER TEST PLAN

1. Fill with natural N_2O – test bubble chamber systems operation
2. With beam on bubble chamber radiator (Sept 9 – Sept 18, 2015):
 - I. How does CCD camera perform under beam-on conditions?
 - II. Count rates on bubble chamber. Do we get single or multiple bubbles from Bremsstrahlung beam exposure?
 - III. Measure gamma ray beam spatial profile as reflected by bubble distribution. Is collimator effective in defining the gamma-ray beam?
3. Background measurements:
 - I. Measure beam off environmental background in chamber-injector area
 - II. Measure beam on background by looking outside fiducial volume
 - III. Measure background with beam to Faraday Cup in CEBAF beamline (about two meters from chamber)
 - IV. Measure neutron events in chamber. Neutron radiation detectors in injector region will indicate if any neutrons are generated (especially at beam energies higher than 8.5 MeV).

4. Fill with C_2F_6 – test bubble chamber systems operation. This is planned later in September after first beam test.
 5. With beam (planned in October, 2015)
 - I. Measure few data points of from $^{19}F(\gamma, \alpha)^{15}N$ ($Q = +4.013$ MeV) to perform a Penfold-Leiss unfolding
 - II. Compare measured cross section to our HIGS data
- Fluorine is nice for a first Penfold-Leiss unfolding:
- Only one stable natural isotope (^{19}F)
 - Low electron beam energy (4.6 – 5.2 MeV) – below threshold of any background reaction

Can we measure a cross section below 1 nb?
Our limit at HIGS – see next two slides

MEASURING $^{19}\text{F}(\gamma, \alpha)^{15}\text{N}$ AT HIGS



Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb



First determination of an astrophysical cross section with a bubble chamber:
The $^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$ reaction

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R. Raut^{e,f,1}, G. Rusev^{e,f,2}, A.P. Tonchev^{e,f,3}

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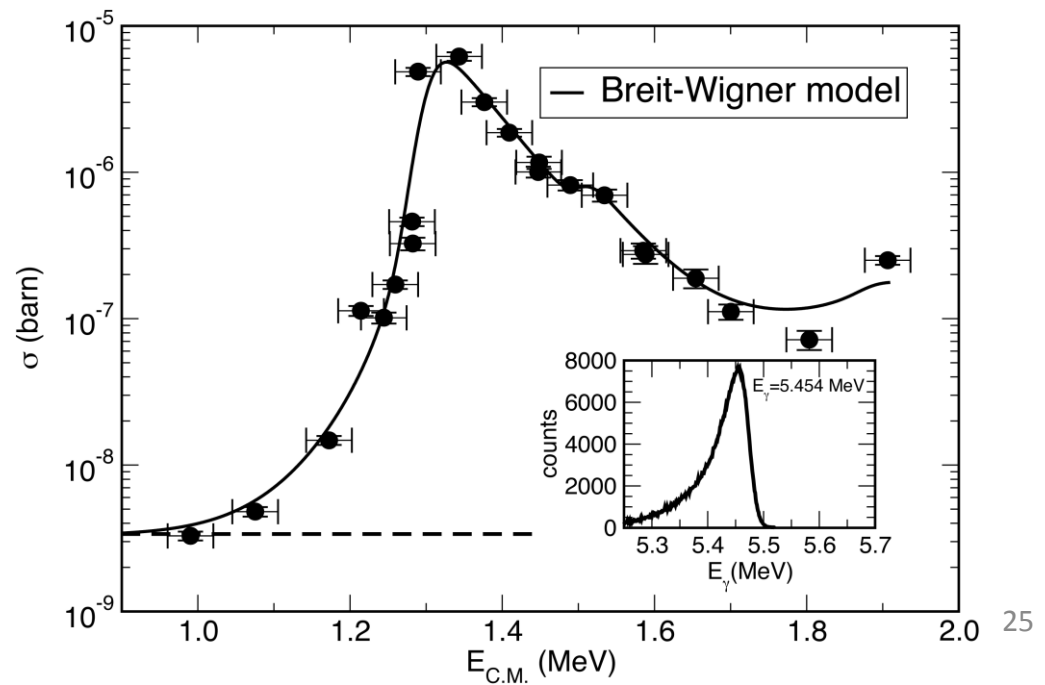
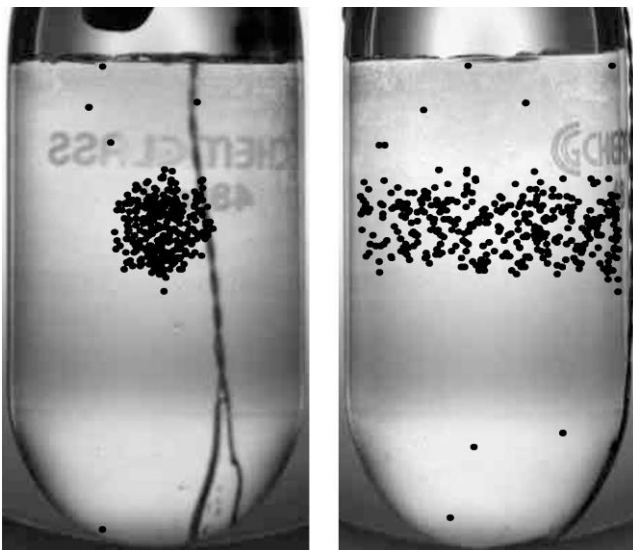
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BREMSSTRAHLUNG BACKGROUND AT HIGS

Electron Beam Energy: 400 MeV

Electron Beam Current: 41 mA

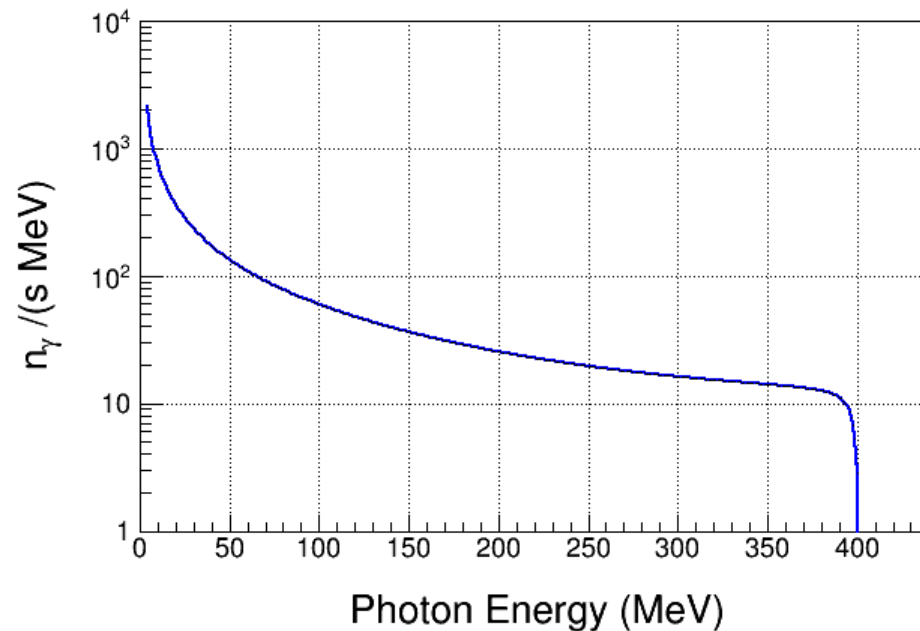
Interaction Length: 35 m

Vacuum: 2×10^{-10} Torr

Residual Gas: $Z = 10$



Strong Bremsstrahlung
Background
(when coupled with large
cross sections at high energies)



BACKUP SLIDES

Polarized Source

Injector Vacuum

Vacuum Main Menu

Injector SRF

West Recombiner

Com	Value
VIP2I01 Gun 2 Cathode	1.87e-09
VIP3I01 Gun 3 Cathode	1.99e-11
VIP1I01 Y Chamber	5.69e-10
VIP1I02 Laser Chamber	1.59e-10
VIP1I03 Wein Entrance	9.99e-12
VIP1I04 Wein Exit	2.99e-09
VIP1I05 DP Can	1.84e-09
VIP1I07 Pol Src FC	5.20e-09
VIP0I01 A1 Aperature	4.62e-09
VIP0I02 A2 Aperature	4.87e-09

DIG	Value
DIG 02	7.38e-01
DIG 07	4.88e-01
DIG 03	4.98e-01
DIG 04	5.18e-01

DIG	Value
DIG 04	5.13e-01
OL02	9.67e+00
DIG12	1.59e+01
OL03	8.88e+00
2D00A	5.15e+00
DIG 05	0.88e+00
DIG 06	1.22
DIG 08	1.38e+00

Glassman Gun Current report: IGL1100POTread: 3.23702

SRF Controls

Injector Zone Status

RESET RE-MOTE

Open All SRF Valves

Zone Fault

Personal Zone: E-Beam

Air Pressures for Valve Control

VIP0I04: 29.11

Turn on all ion pumps