Bubble Chamber: Experimental Overview

August 18, 2015

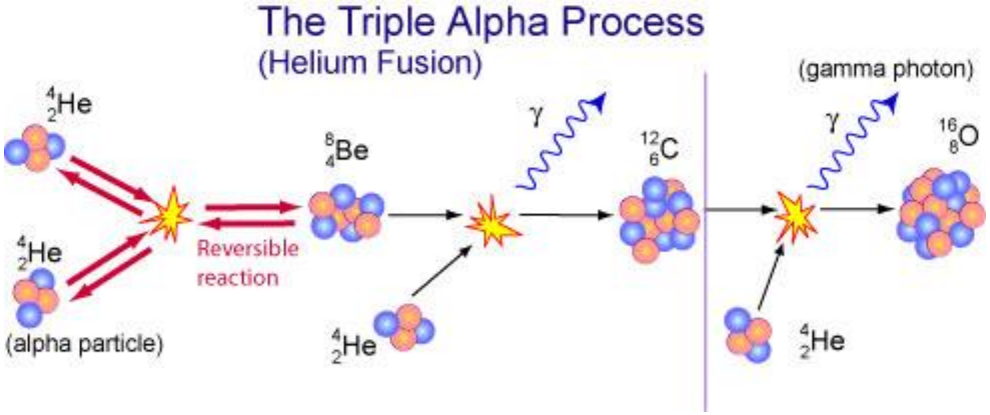
https://wiki.jlab.org/ciswiki/index.php/Bubble_Chamber

OUTLINE

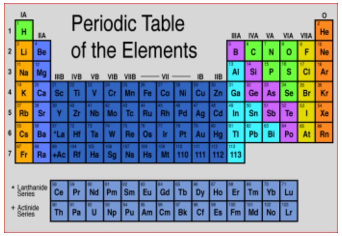
- Nucleosynthesis and $^{12}C(\alpha,\gamma)^{16}O$ Reaction
- Time Reversal Reaction: $^{16}O(\gamma,\alpha)^{12}C$
- Electron Beam Requirements
- Bremsstrahlung Beam
- Penfold-Leiss Cross Section Unfolding
- JLab Projected Results
- Test Beamline
- Bubble Chamber Test Plan

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

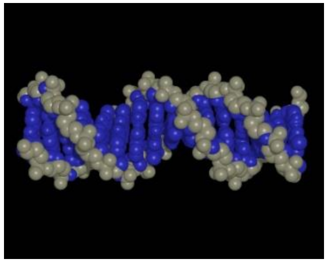
Stellar Helium burning



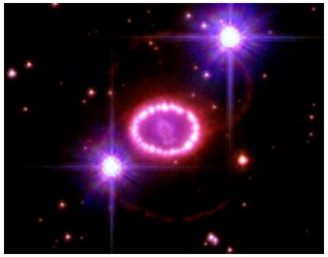
- The *holy grail* of nuclear astrophysics:



Affects synthesis of most of elements in periodic table



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



Determines minimum mass star requires to become supernova

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

- Previous cross section measurements:

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

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

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

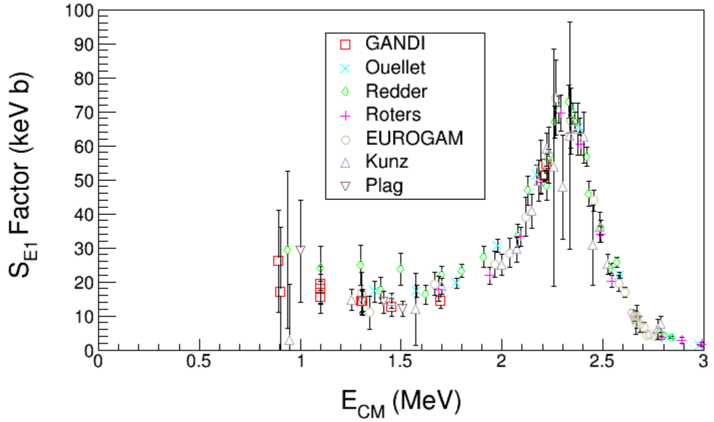
ASTROPHYSICAL S-FACTOR $^{12}C(\alpha,\gamma)^{16}O$

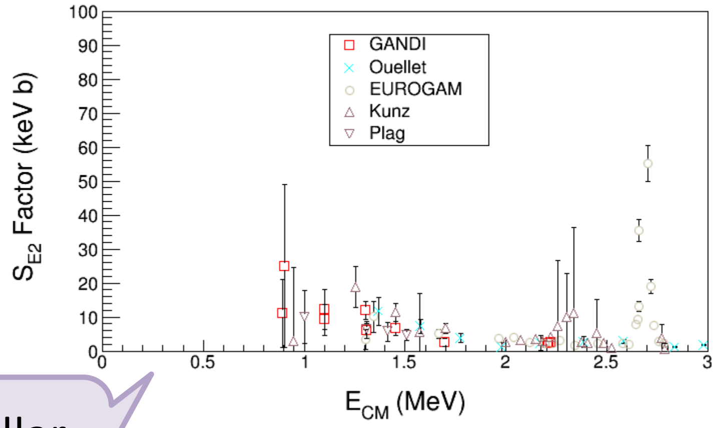
- Define *S-Factor* to remove both 1/E dependence of nuclear cross sections and Coulomb barrier transmission probability:

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

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

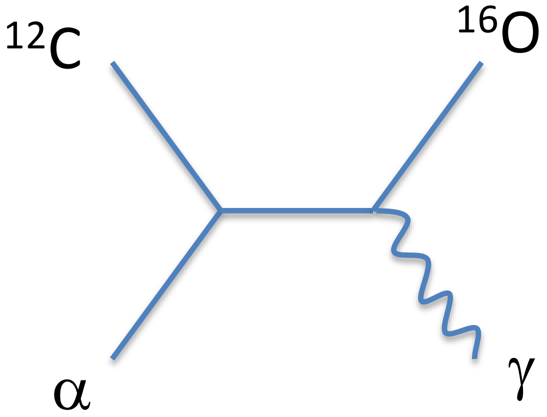
Author	$S_{tot}(300)$ (keV b)
Hammer (2005)	162±39
Kunz (2001)	165±50





<u>R-matrix Extrapolation</u> to stellar helium burning at E = 300 keV

TIME REVERSAL REACTION

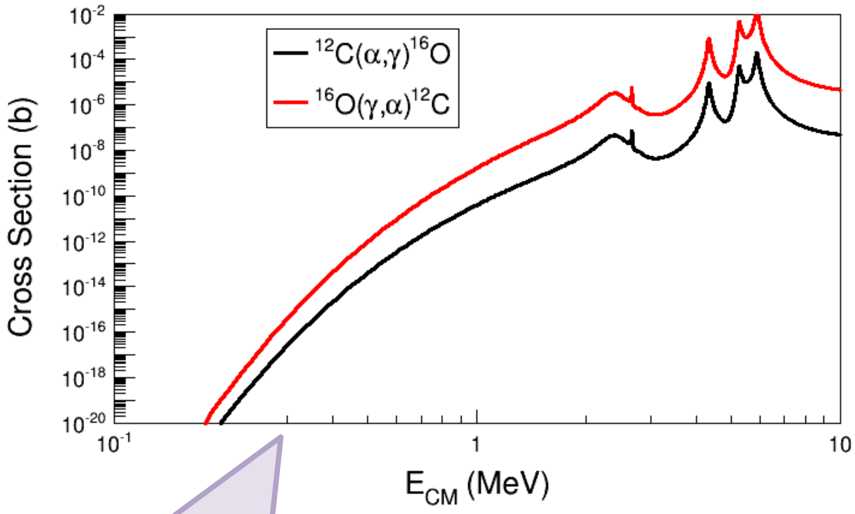


$$m_{^{12}C\alpha}c^2 = \frac{M(^{12}C)\cdot M(\alpha)}{M(^{12}C)+M(\alpha)} = 2796\ \text{MeV}$$

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

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

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



Stellar helium burning at
E = 300 keV, T=200 10^6 K

NEW APPROACH: REVERSAL REACTION + BUBBLE CHAMBER

$$\overset{\text{beam}}{\gamma} + \overset{\text{target}}{{}^{16}\mathrm{O}} \longrightarrow \overset{\text{signal}}{{}^{12}\mathrm{C} + \alpha}$$

- Extra gain (factor of 100) by measuring time reversal reaction
- Bremsstrahlung at JLab $\sim 10^9\ \gamma$/s (top 250 keV)
- Target density up to 10^4 higher than conventional targets. Number of ^{16}O nuclei = $3.5 \times 10^{22}/\mathrm{cm}^2$ (3.0 cm cell)
- Measures total cross section σ_{tot} (or $S_{tot}=S_{E1} + S_{E2}$)
- 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})

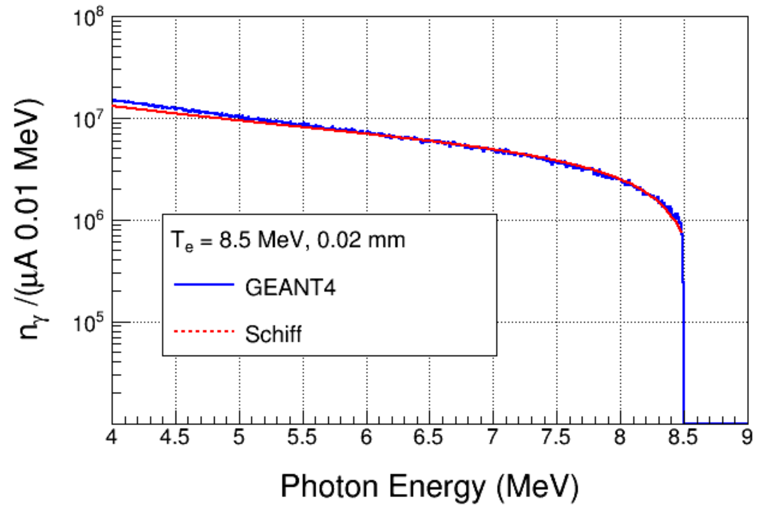
ELECTRON BEAM REQUIREMENTS

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

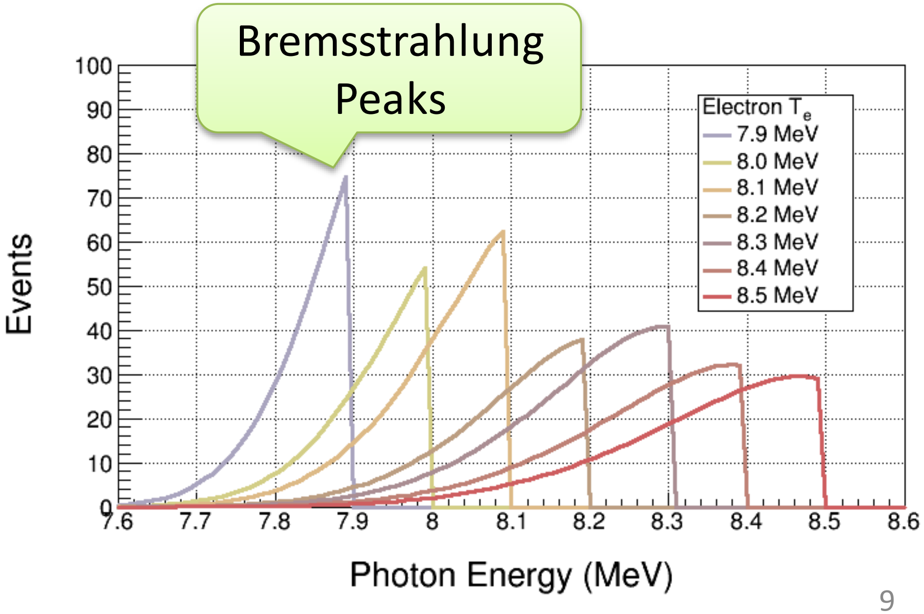
BREMSSTRAHLUNG BEAM

- 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: ±5%



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

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


Bremsstrahlung Peaks

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

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

- Solution can be written in two forms:

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

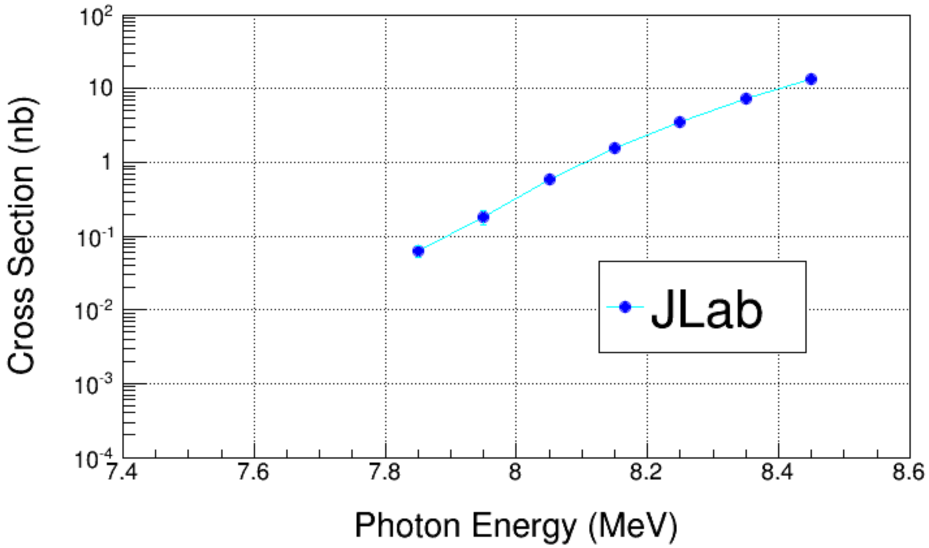
- Or, Matrix form:

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

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

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

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



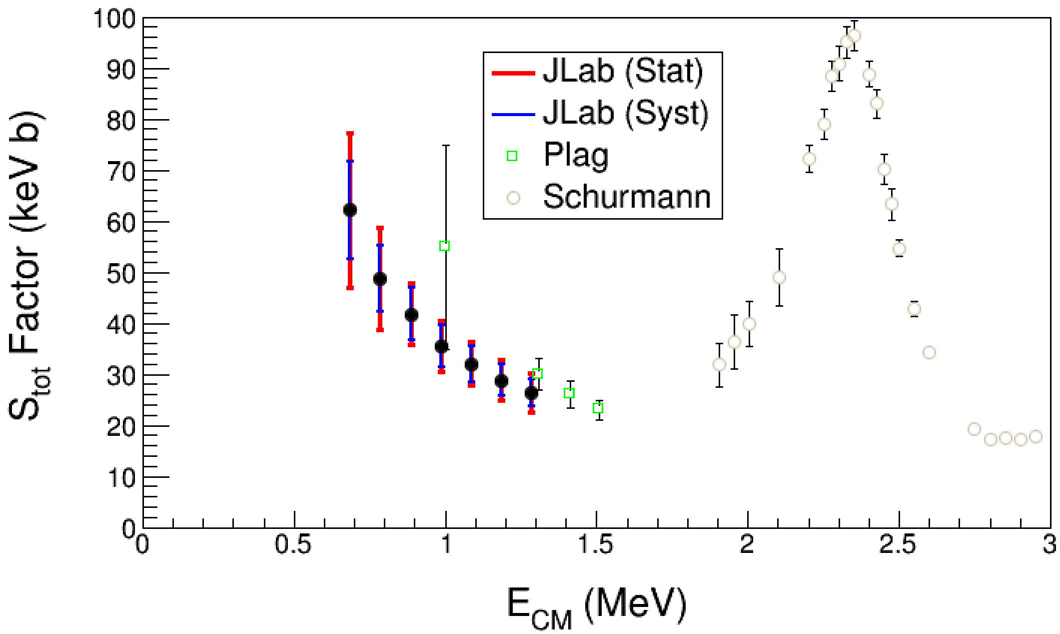
Absolute Beam Energy, δE	0.1%
Beam Current, $\delta I/I$	3%
Photon Flux, $\delta\varphi/\varphi$	5%
Radiator Thickness, $\delta R/R$	3%
Bubble Chamber Thickness, $\delta T/T$	3%
Bubble Chamber Efficiency, ε	5%

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

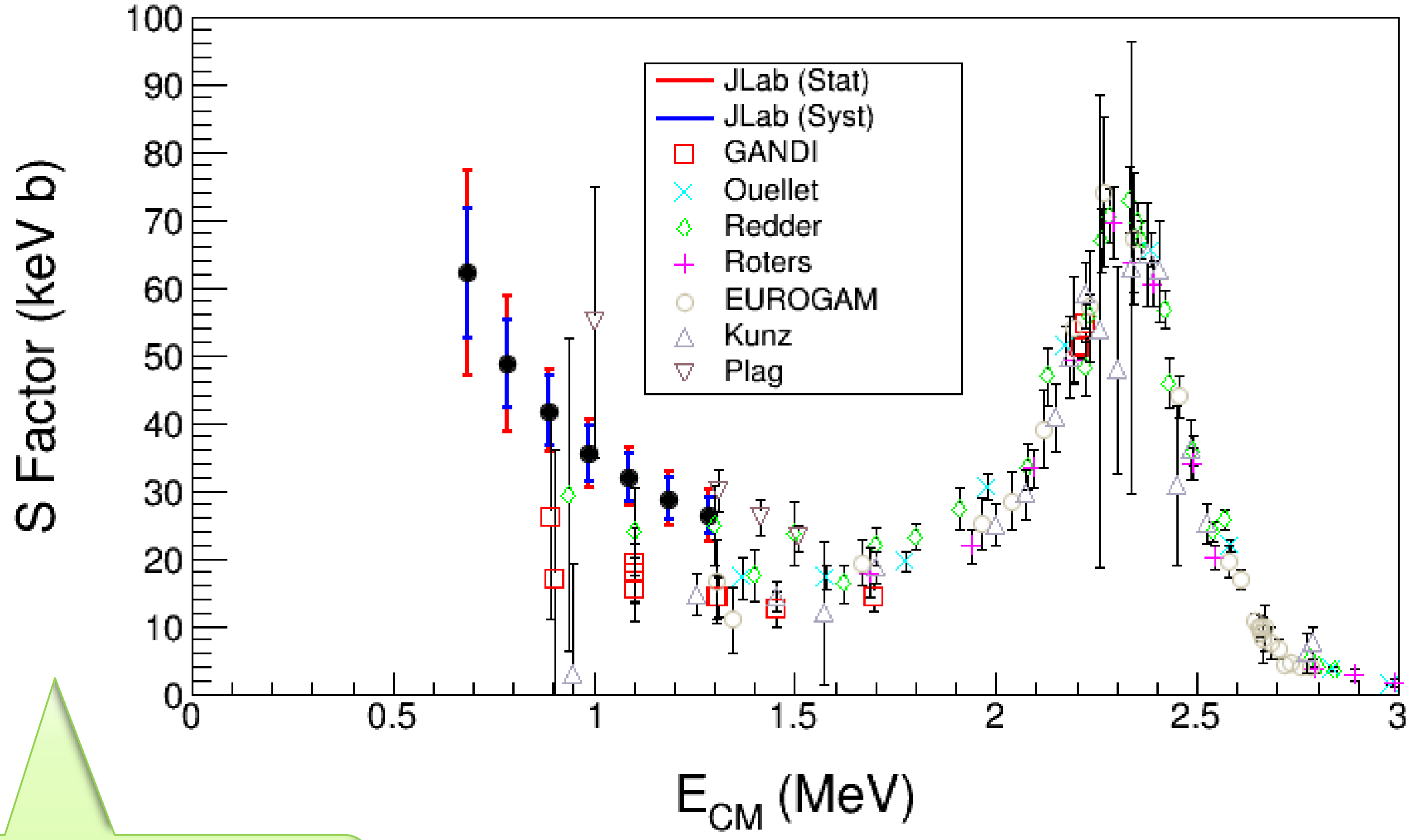
JLAB PROJECTED $^{12}C(\alpha,\gamma)^{16}O$ S-Factor

- Statistical Error: dominated by background subtraction from $^{18}O(\gamma,\alpha)^{14}C$ (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 ~ S_{E1}
(S_{E2} is small)

SUPERHEATED TARGETS

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

N_2O Targets	^{16}O	^{17}O	^{18}O
Natural Target	99.757%	0.038%	0.205%
^{16}O Target		Depleted > 5,000	Depleted > 5,000
^{17}O Target		Enriched > 80%	<1.0%
^{18}O Target		<1.0%	Enriched > 80%

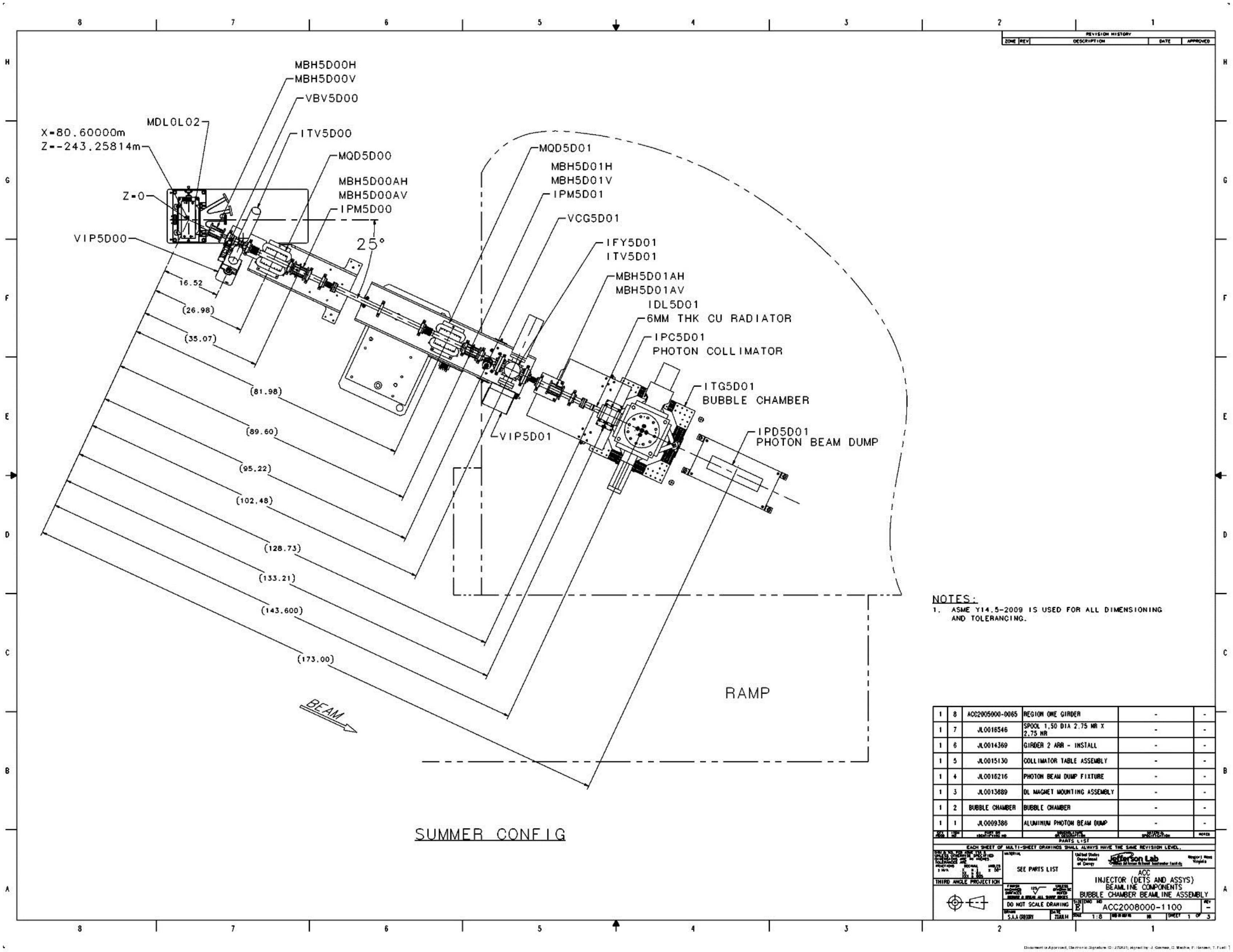
Physics

Measure Backgrounds

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.

QTY REQD	ITEM NO	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL SPECIFICATION	NOTES
1	8	ACC2005000-0065	REGION ONE GIRDER	-	-
1	7	JL0016546	SPOOL 1.50 DIA 2.75 NR X 2.75 NR	-	-
1	6	JL0014369	GIRDER 2 ARR - INSTALL	-	-
1	5	JL0015130	COLLIMATOR TABLE ASSEMBLY	-	-
1	4	JL0016216	PHOTON BEAM DUMP FIXTURE	-	-
1	3	JL0013689	DL MAGNET MOUNTING ASSEMBLY	-	-
1	2	BUBBLE CHAMBER	BUBBLE CHAMBER	-	-
1	1	JL0009386	ALUMINUM PHOTON BEAM DUMP	-	-

PARTS LIST

EACH SHEET OF MULTI-SHEET DRAWINGS SHALL ALWAYS HAVE THE SAME REVISION LEVEL.

THIRD ANGLE PROJECTION

MATERIAL: SEE PARTS LIST

DO NOT SCALE DRAWING

DRAWN: S.A.A GREGORY DATE: 22JUL14

United States Department of Energy
Jefferson Lab
Newport News Virginia

ACC
INJECTOR (DETS AND ASSYS)
BEAMLINE COMPONENTS
BUBBLE CHAMBER BEAMLINE ASSEMBLY

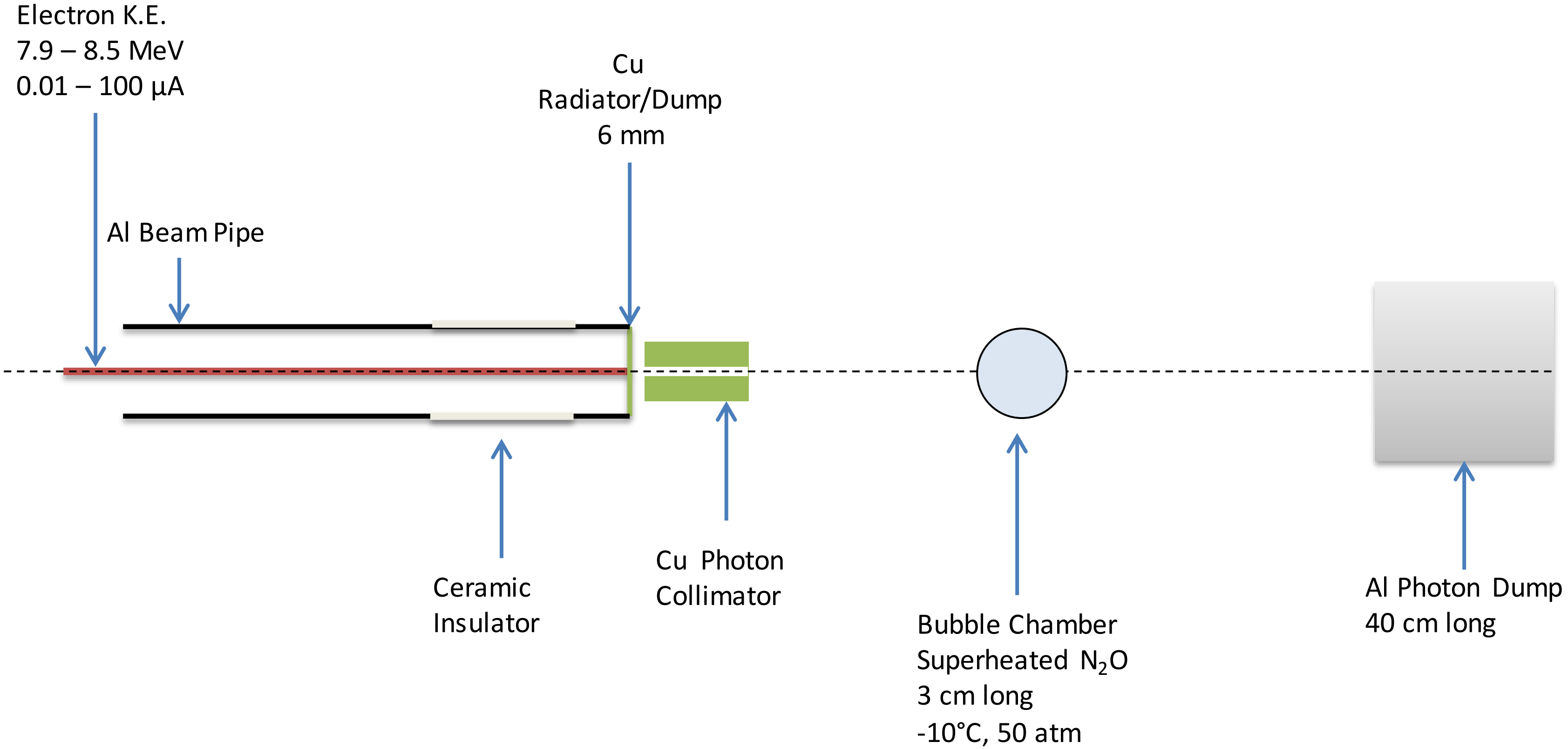
SIZE: E DWG NO: ACC2008000-1100 REV: -

SCALE 1:8 SHEET 1 OF 3

Document is Approved, Electronic Signature ID: 272631; signed by: J. Gomez, D. Machie, P. Hansen, T. Fuell

SCHEMATICS OF TEST BEAMLINE

- Power deposited in radiator (100 μA and 8.5 MeV) :
  1. 6 mm: Energy loss = 8.5 MeV, P = 850 W
- Pure Copper and Aluminum (high neutron threshold):
  1. $^{63}C(\gamma,n)$ threshold = 10.86 MeV
  2. $^{27}Al(\gamma,n)$ threshold = 13.06 MeV



Electron K.E.
7.9 – 8.5 MeV
0.01 – 100 μA

Cu
Radiator/Dump
6 mm

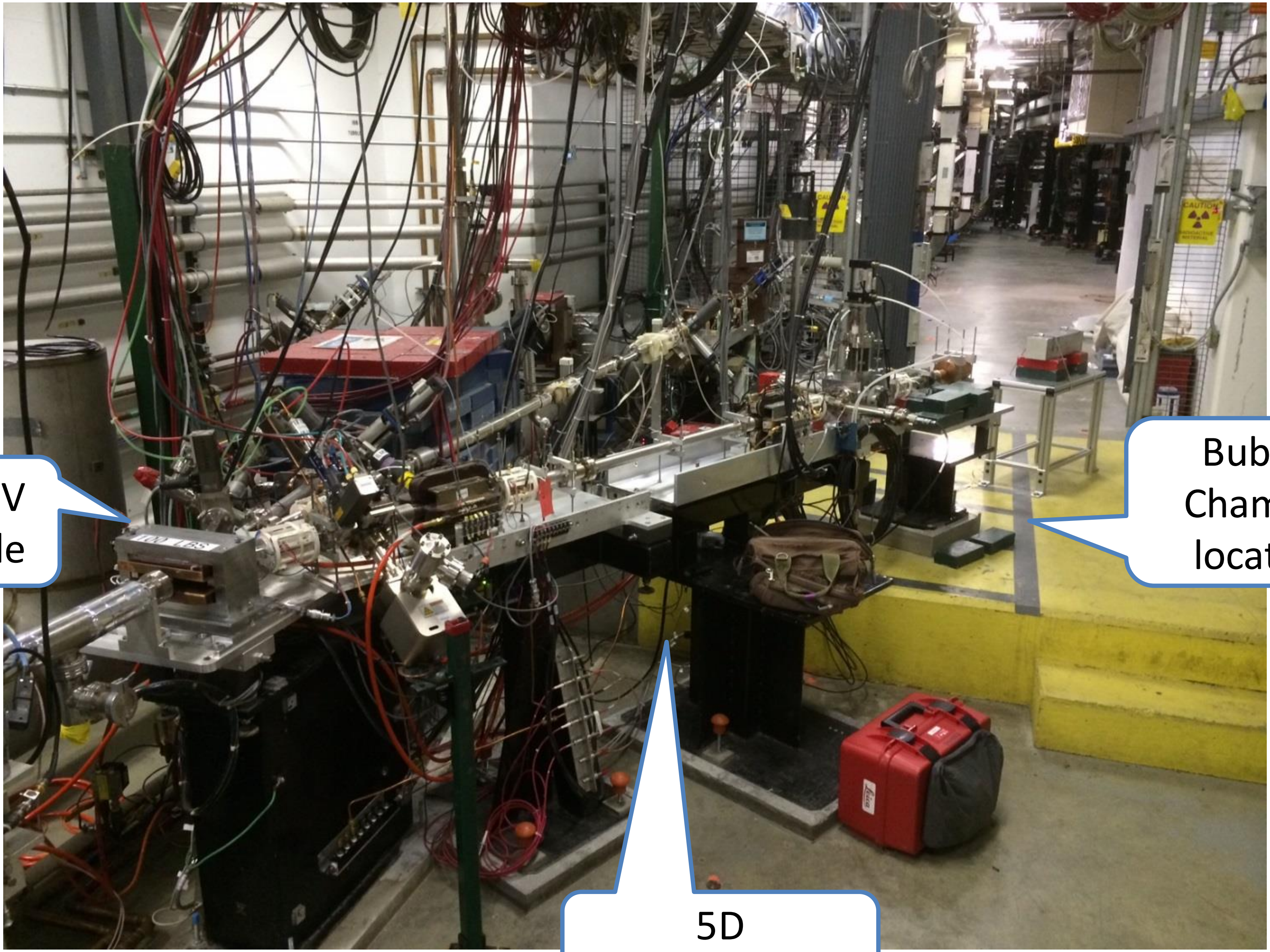
Al Beam Pipe

Ceramic
Insulator

Cu Photon
Collimator

Bubble Chamber
Superheated N_2O
3 cm long
-10°C, 50 atm

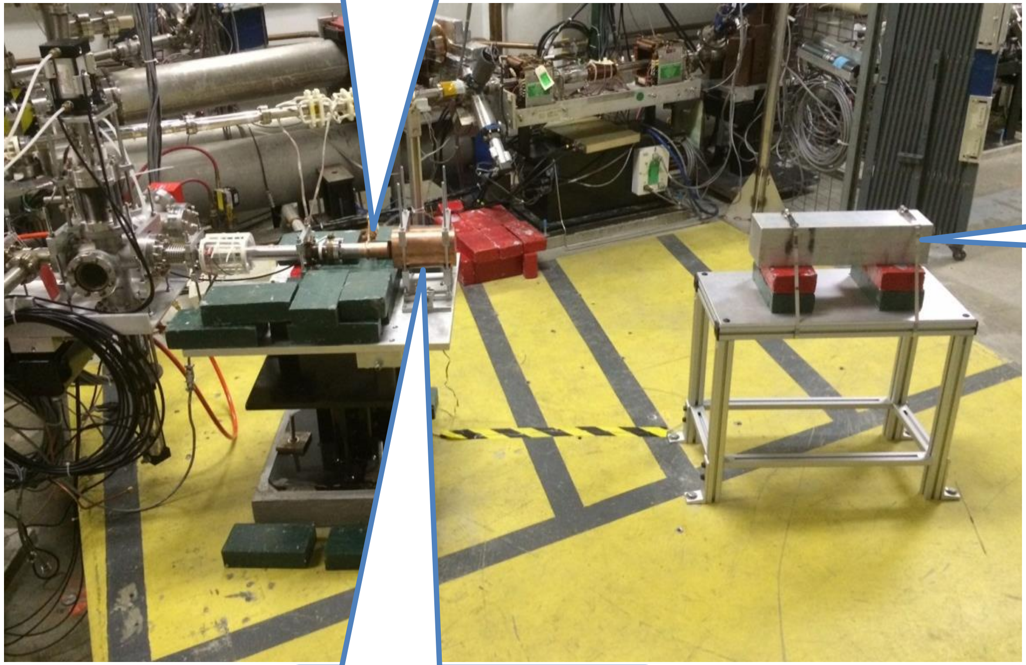
Al Photon Dump
40 cm long



5 MeV Dipole

5D Spectrometer

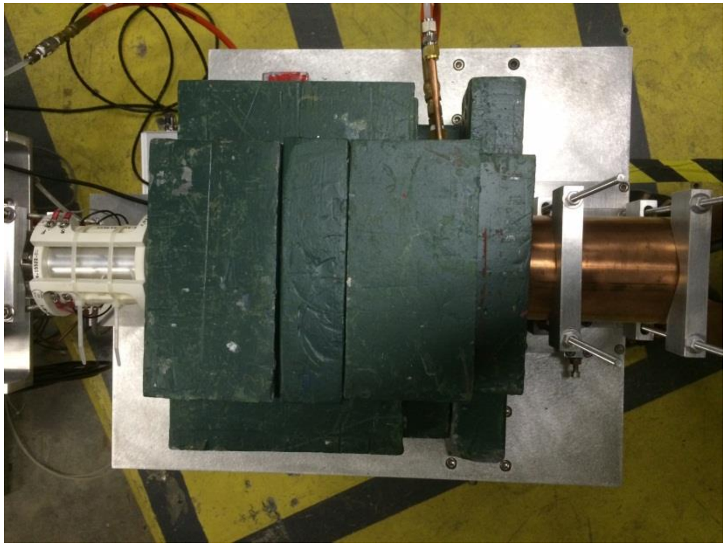
Bubble Chamber location

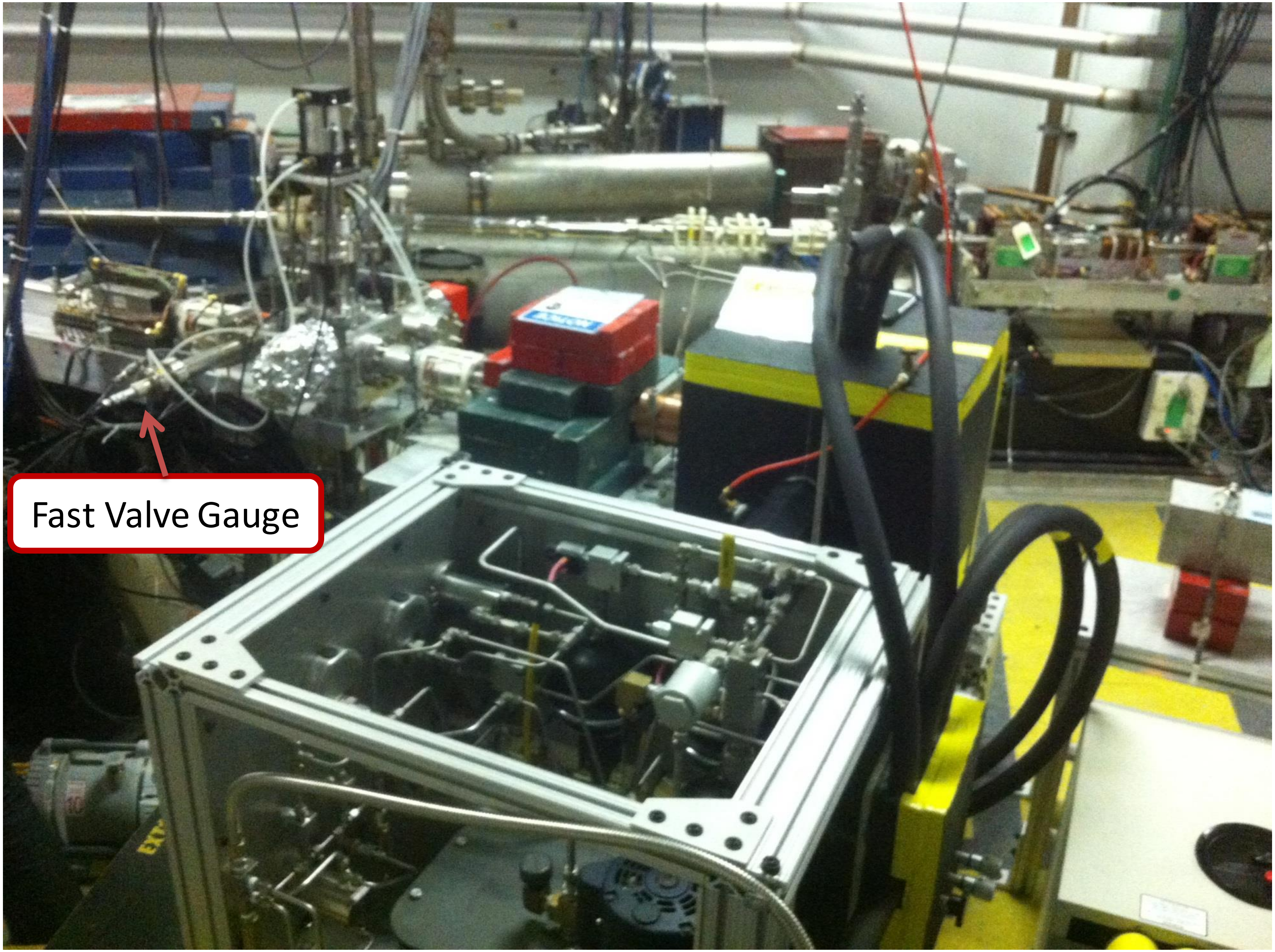


Cu Electron Radiator/Dump

Al Photon Dump

Cu Photon Collimator



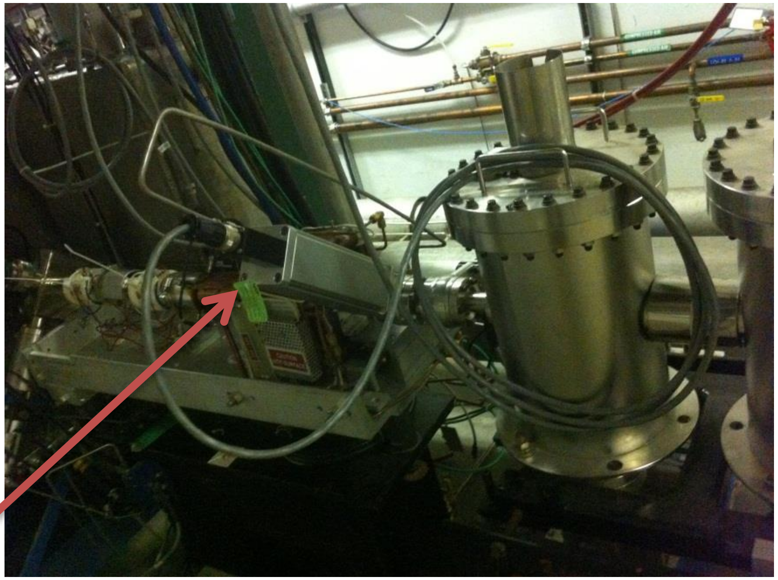


Fast Valve Gauge

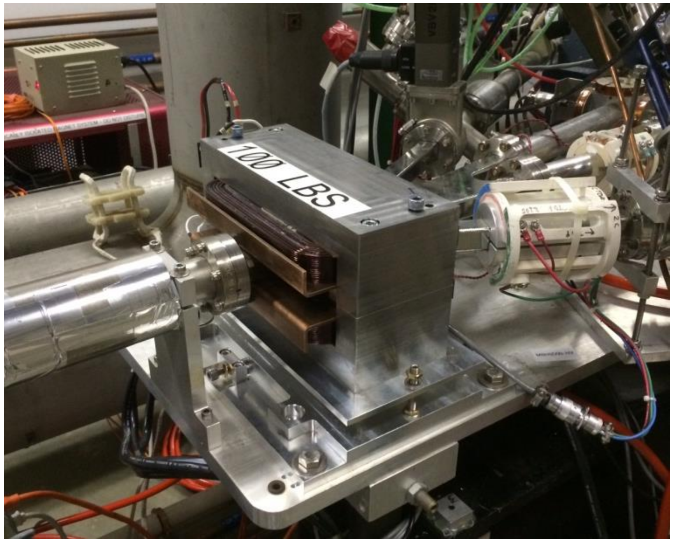
NEW BEAMLINE ELEMENTS

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

I. Fast Valve after ¼ Cryounit

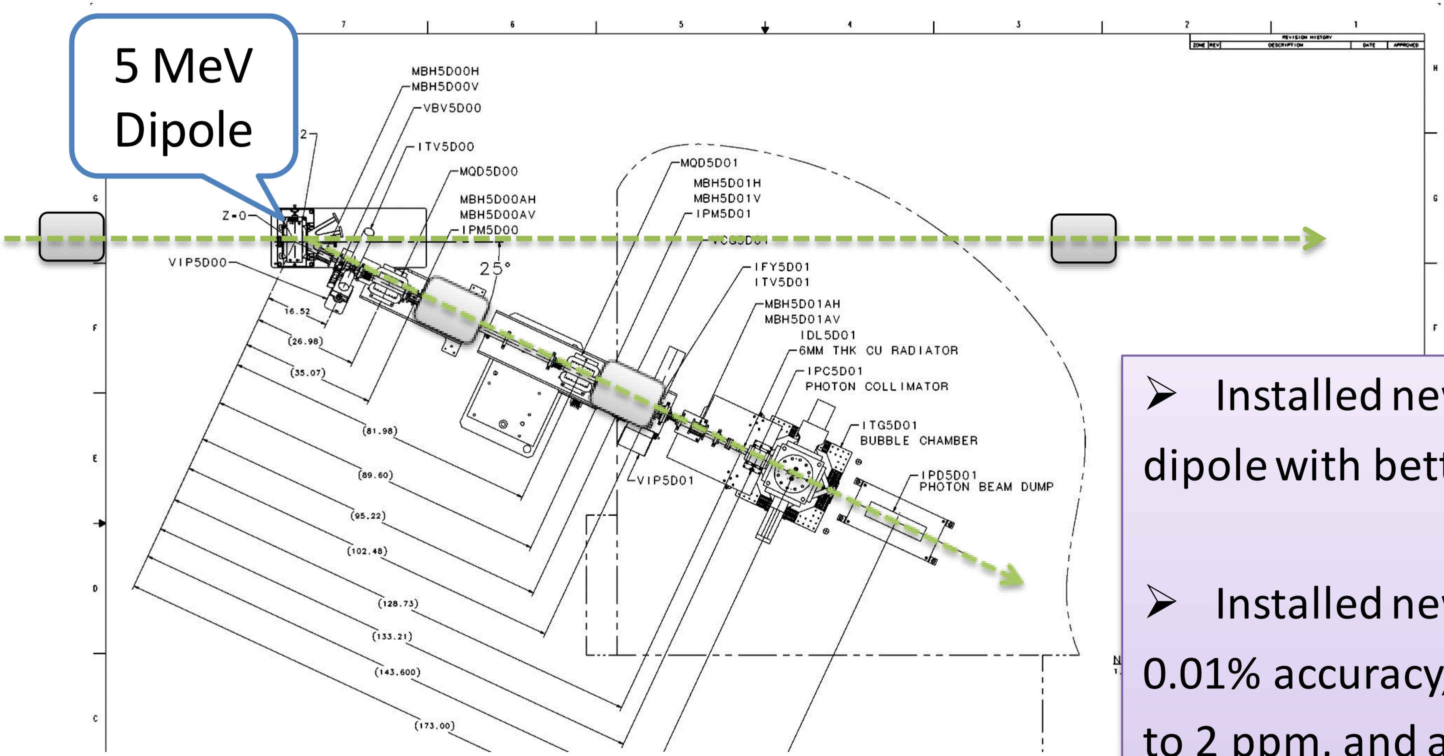


Protect ¼ Cryo-unit from vacuum failure



II. New MDL0L02 Dipole Magnet

MEASURING ABSOLUTE BEAM ENERGY



5 MeV Dipole

- ➢ 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

▭ Beam Position Monitor (BPM)

Electron Beam Momentum

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

TEST BEAMLINE 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 ¼ 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.

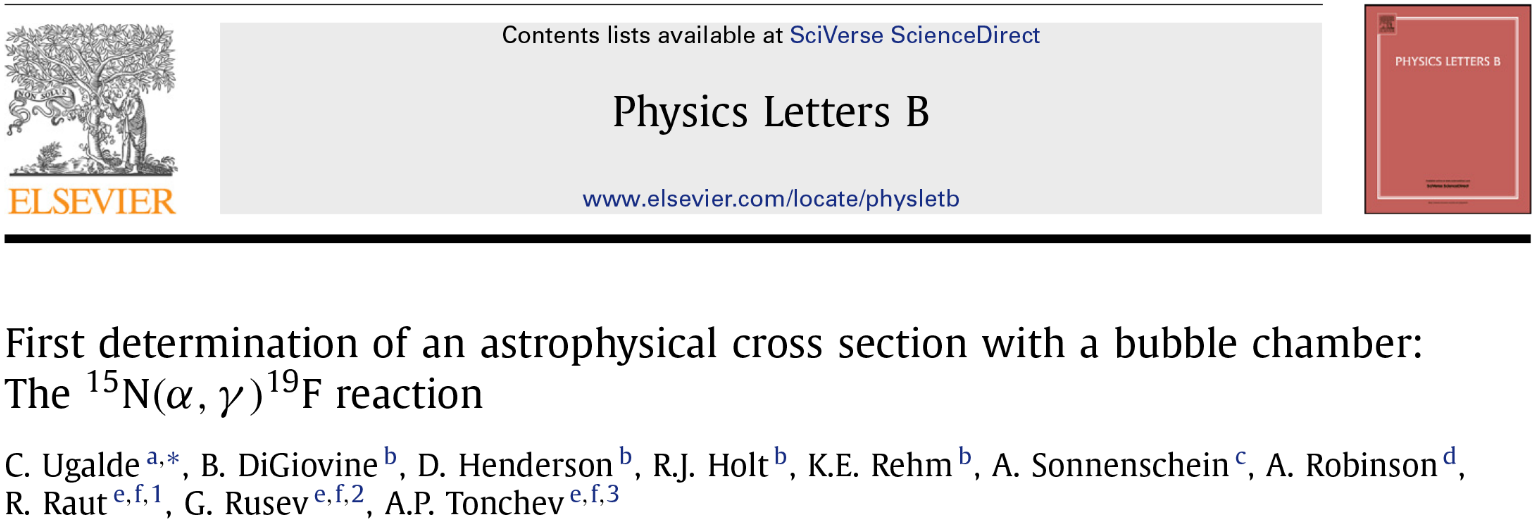
5. With beam (planned in October, 2015)

   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 3 nb?
our limit at HIGS – see next two slides

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



Contents lists available at SciVerse ScienceDirect

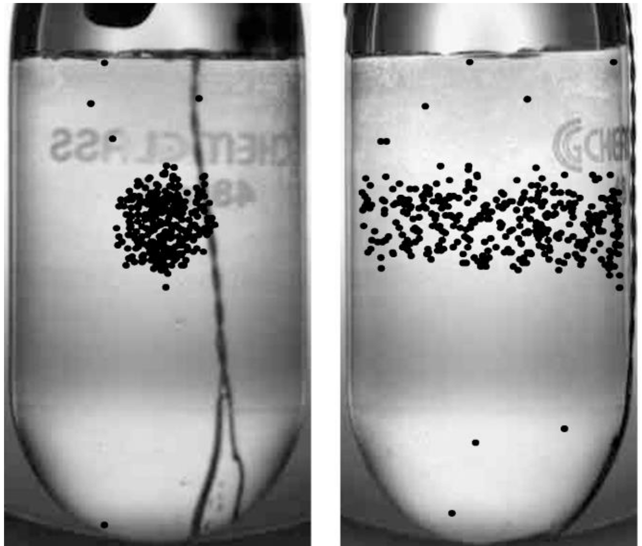
Physics Letters B

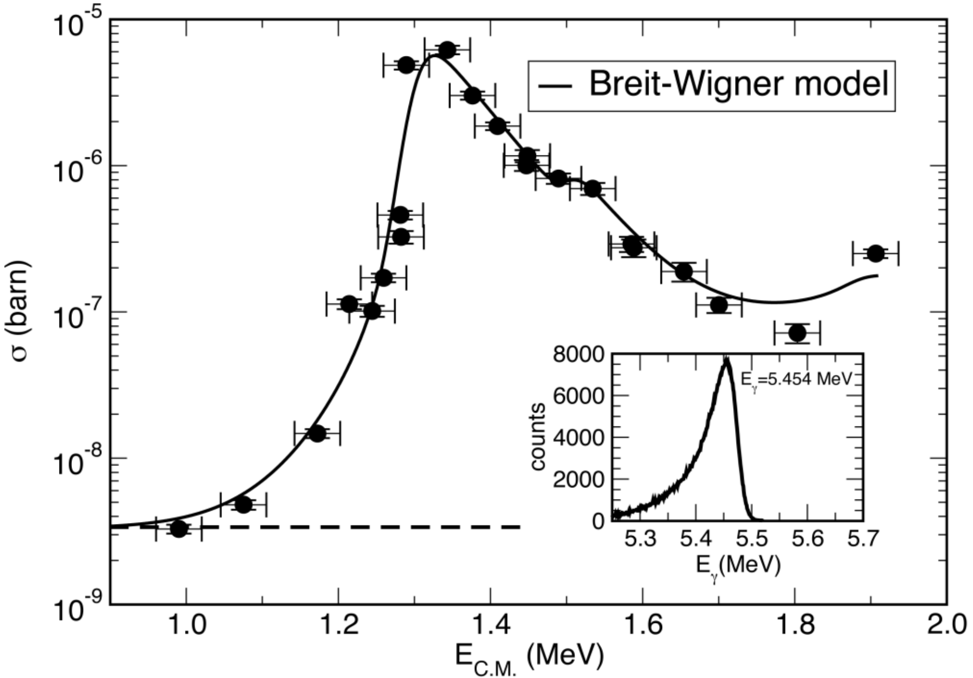
www.elsevier.com/locate/physletb

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

C. Ugalde [a,*], B. DiGiovine [b], D. Henderson [b], R.J. Holt [b], K.E. Rehm [b], A. Sonnenschein [c], A. Robinson [d], R. Raut [e,f,1], G. Rusev [e,f,2], A.P. Tonchev [e,f,3]

[a] *Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637, USA*
[b] *Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA*
[c] *Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*
[d] *Department of Physics, University of Chicago, Chicago, IL 60637, USA*
[e] *Department of Physics, Duke University, Durham, NC 27708, USA*
[f] *Triangle Universities Nuclear Laboratory, Durham, NC 27708, USA*

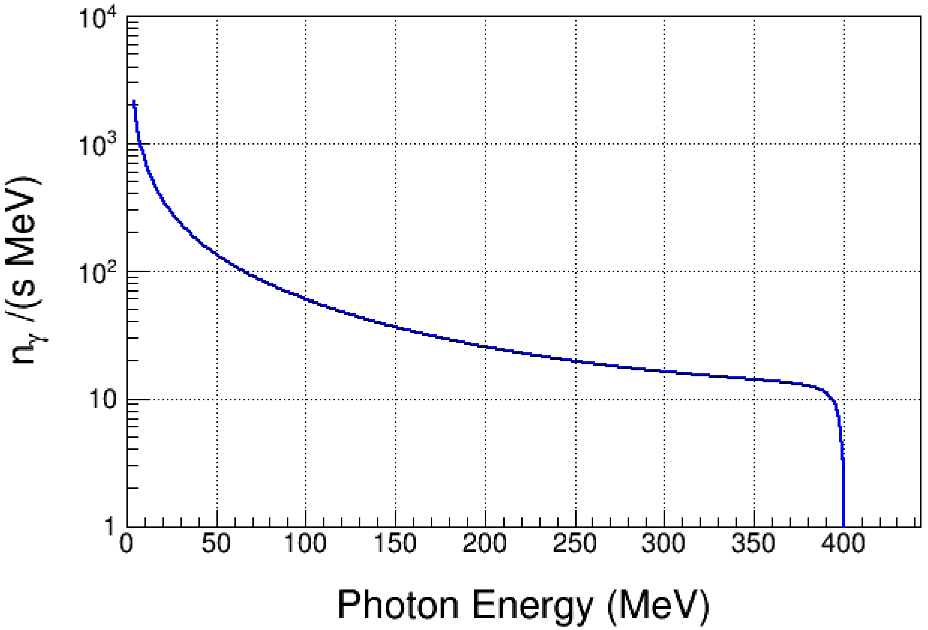




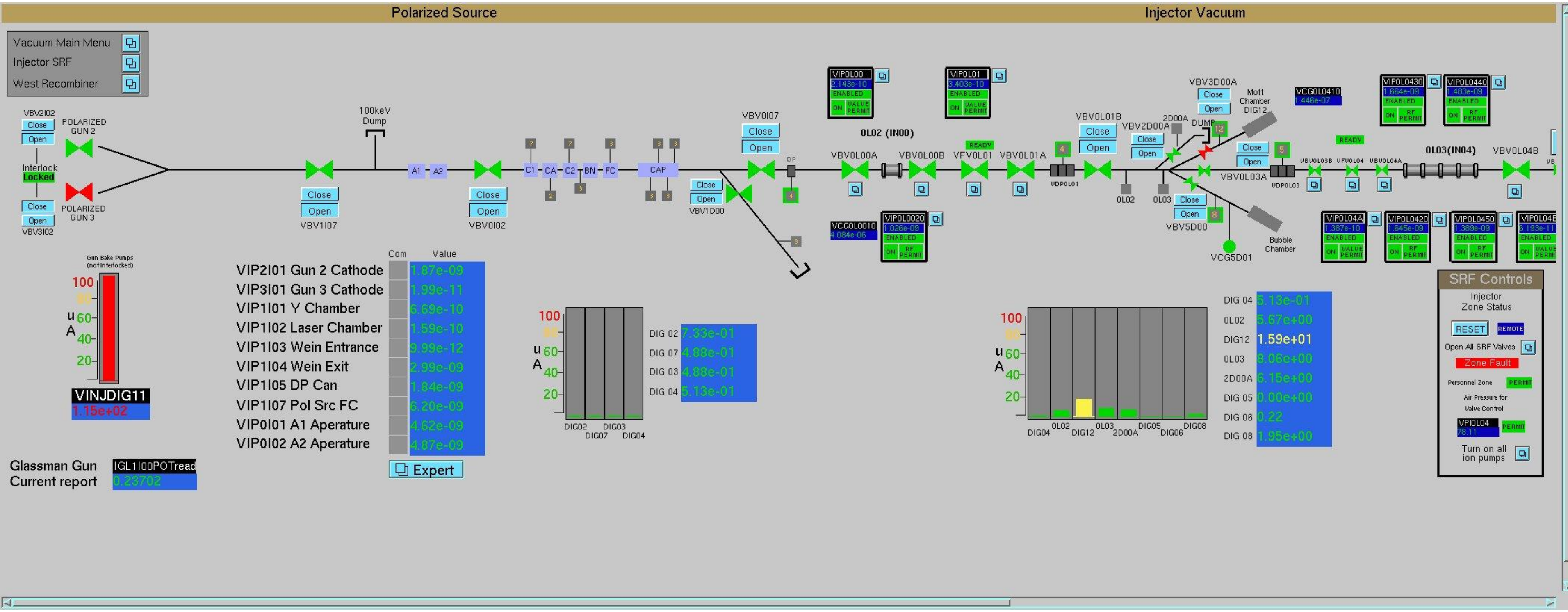
BREMSSTRAHLUNG BACKGROUND AT HIGS

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



VIP0L00 2.143e-10 ENABLED ON VALVE PERMIT
VIP0L01 3.403e-10 ENABLED ON VALVE PERMIT
VCG0L0010 4.084e-06
VIP0L0020 1.026e-09 ENABLED ON RF PERMIT
VCG0L0410 1.446e-07
VIP0L0430 1.664e-09 ENABLED ON RF PERMIT
VIP0L0440 1.483e-09 ENABLED ON RF PERMIT
VIP0L04A 1.387e-10 ENABLED ON VALVE PERMIT
VIP0L0420 1.645e-09 ENABLED ON RF PERMIT
VIP0L0450 1.389e-09 ENABLED ON RF PERMIT
VIP0L04E 6.193e-11 ENABLED ON VALVE PERMIT

VINJDIG11 1.15e+02

	Com	Value
VIP2I01 Gun 2 Cathode		1.87e-09
VIP3I01 Gun 3 Cathode		1.99e-11
VIP1I01 Y Chamber		6.69e-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		6.20e-09
VIP0I01 A1 Aperature		4.62e-09
VIP0I02 A2 Aperature		4.87e-09

Glassman Gun Current report IGL1I00POTread 0.23702

DIG 02	7.33e-01
DIG 07	4.88e-01
DIG 03	4.88e-01
DIG 04	5.13e-01

DIG 04	5.13e-01
0L02	5.67e+00
DIG12	1.59e+01
0L03	8.06e+00
2D00A	6.15e+00
DIG 05	0.00e+00
DIG 06	0.22
DIG 08	1.95e+00

VPI0L04 78.11