Bubble Chamber: Experimental Overview

August 18, 2015

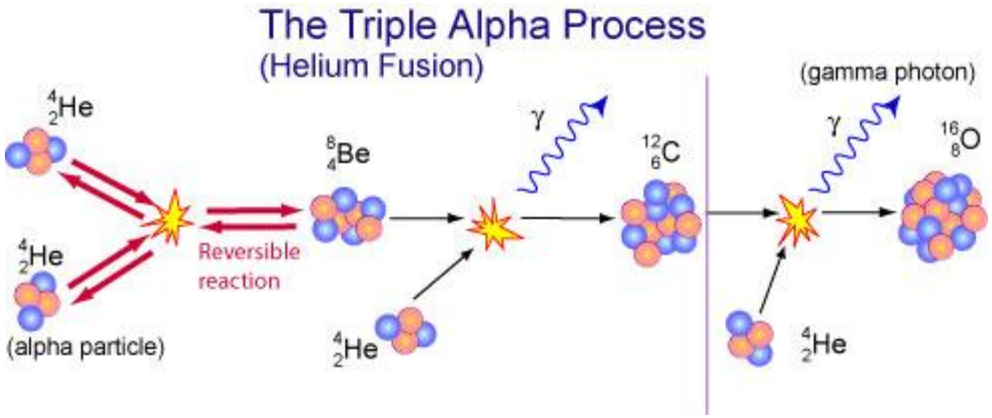
https://wiki.jlab.org/ciswiki/index.php/Bubble_Chamber

OUTLINE

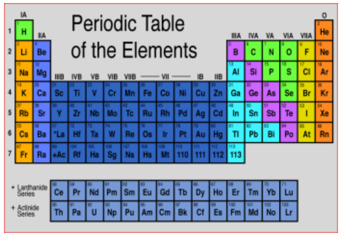
- Nucleosynthesis and $^{12}C(\alpha,\gamma)^{16}O$ Reaction
- Time Reversal Reaction: $^{16}O(\gamma,\alpha)^{12}C$
- Electron Beam Requirements
- Bremsstrahlung Beam
- Penfold-Leiss Cross Section Unfolding
- JLab Projected Results
- Test Beamline
- Bubble Chamber Test Plan

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

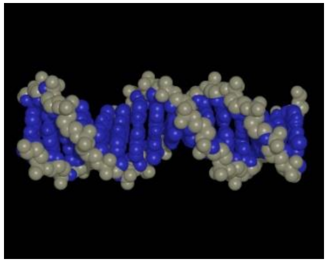
Stellar Helium burning



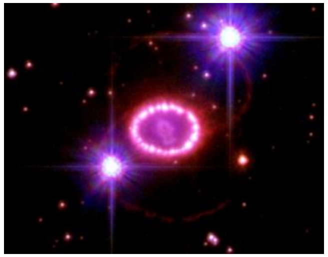
- The *holy grail* of nuclear astrophysics:



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/cm²)	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

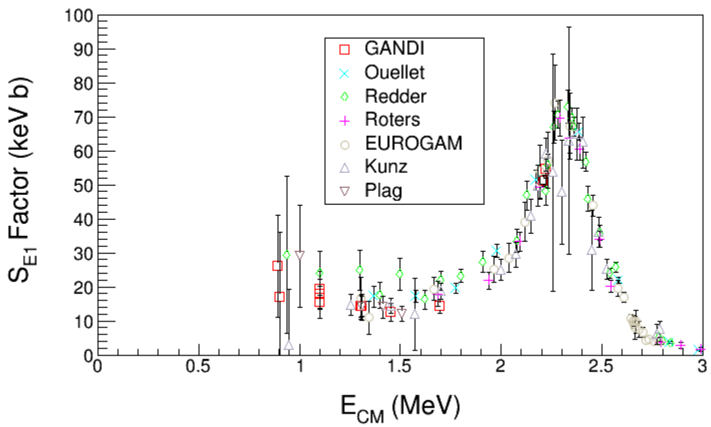
ASTROPHYSICAL S-FACTOR $^{12}C(\alpha,\gamma)^{16}O$

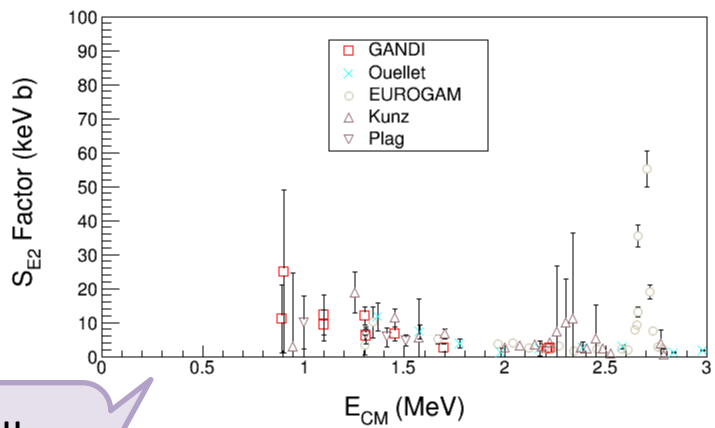
- Define *S-Factor* to remove both 1/E dependence of nuclear cross sections and Coulomb barrier transmission probability:

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

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

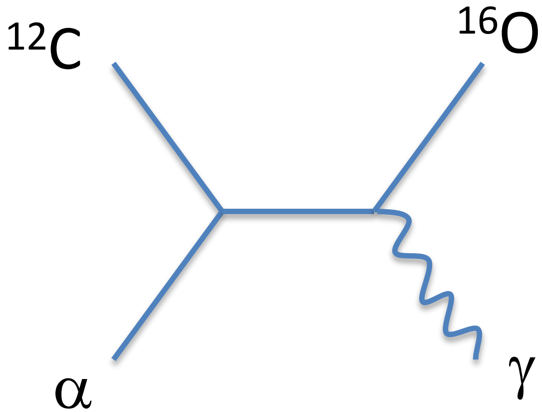
Author	S_{tot}(300) (keV b)
Hammer (2005)	162±39
Kunz (2001)	165±50





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

Time Reversal Reaction

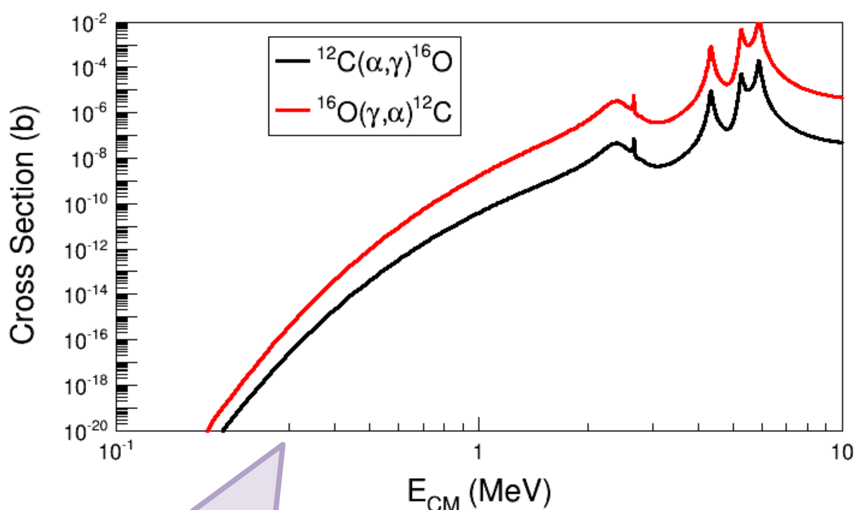


$$m_{^{12}C\alpha}c^2 = \frac{M(^{12}C)\cdot M(\alpha)}{M(^{12}C)+M(\alpha)} = 2796\ \text{MeV}$$

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

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

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



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

New Approach: Reversal Reaction + Bubble Chamber

beam	target	signal

$$\gamma + {}^{16}\text{O} \rightarrow {}^{12}\text{C} + \alpha$$

- 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 = $3.5 \times 10^{22}/\text{cm}^2$ (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})

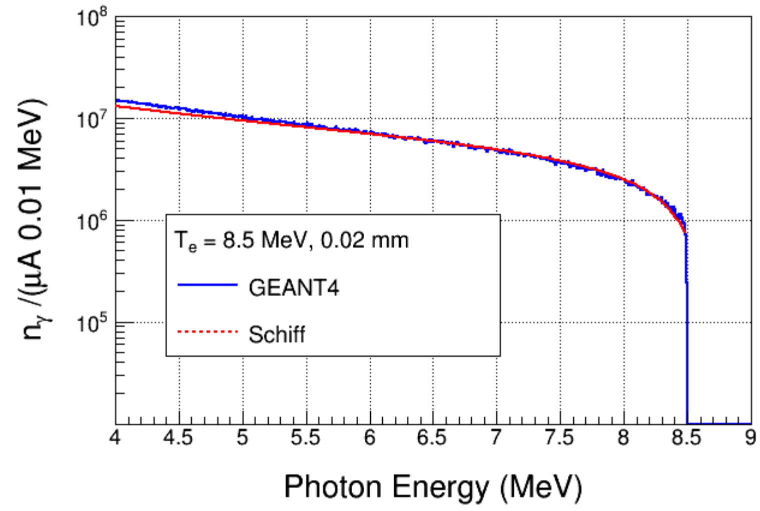
Electron Beam Requirements

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

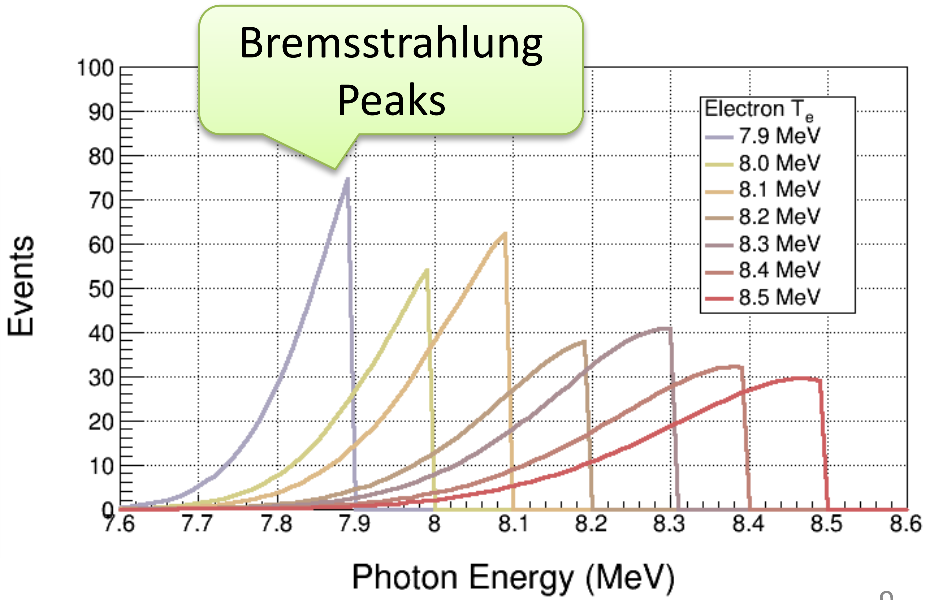
BREMSSTRAHLUNG BEAM

- 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)



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:

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

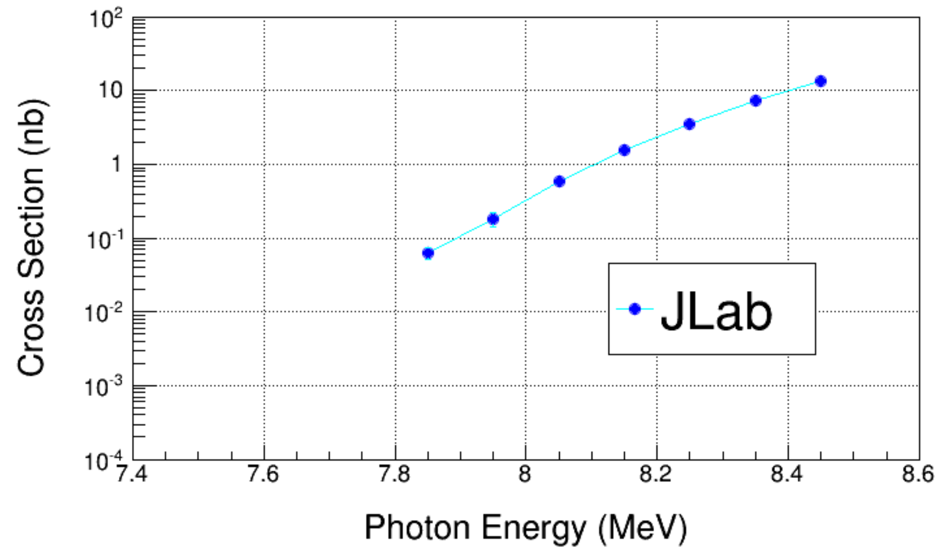
- Or, Matrix form:

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

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

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

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



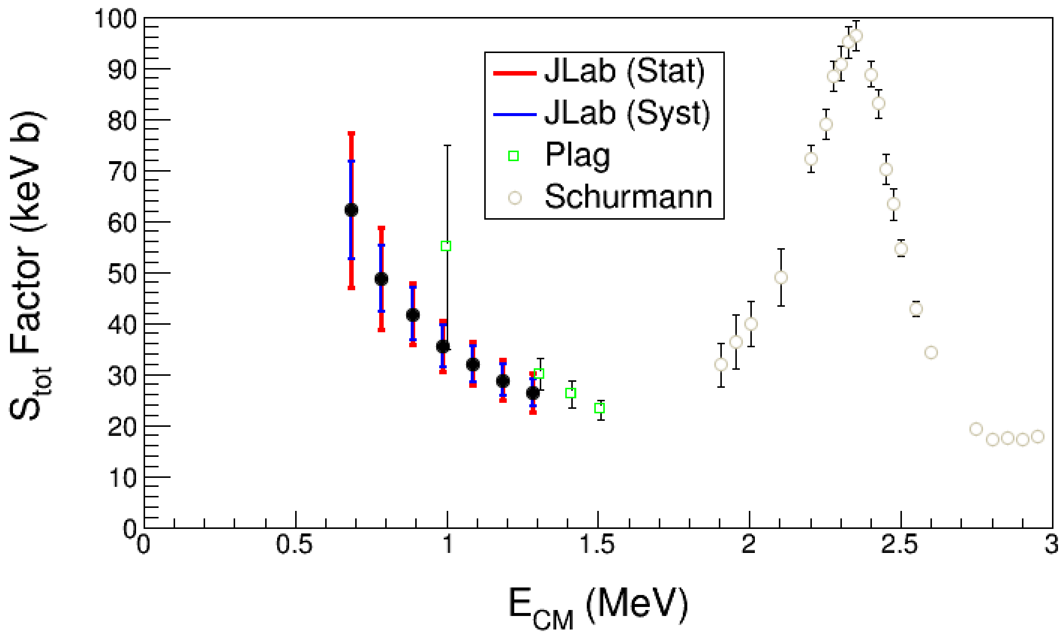
Absolute Beam Energy, δE	0.1%
Beam Current, $\delta I/I$	3%
Photon Flux, $\delta\varphi/\varphi$	5%
Radiator Thickness, $\delta R/R$	3%
Bubble Chamber Thickness, $\delta T/T$	3%
Bubble Chamber Efficiency, ε	5%

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

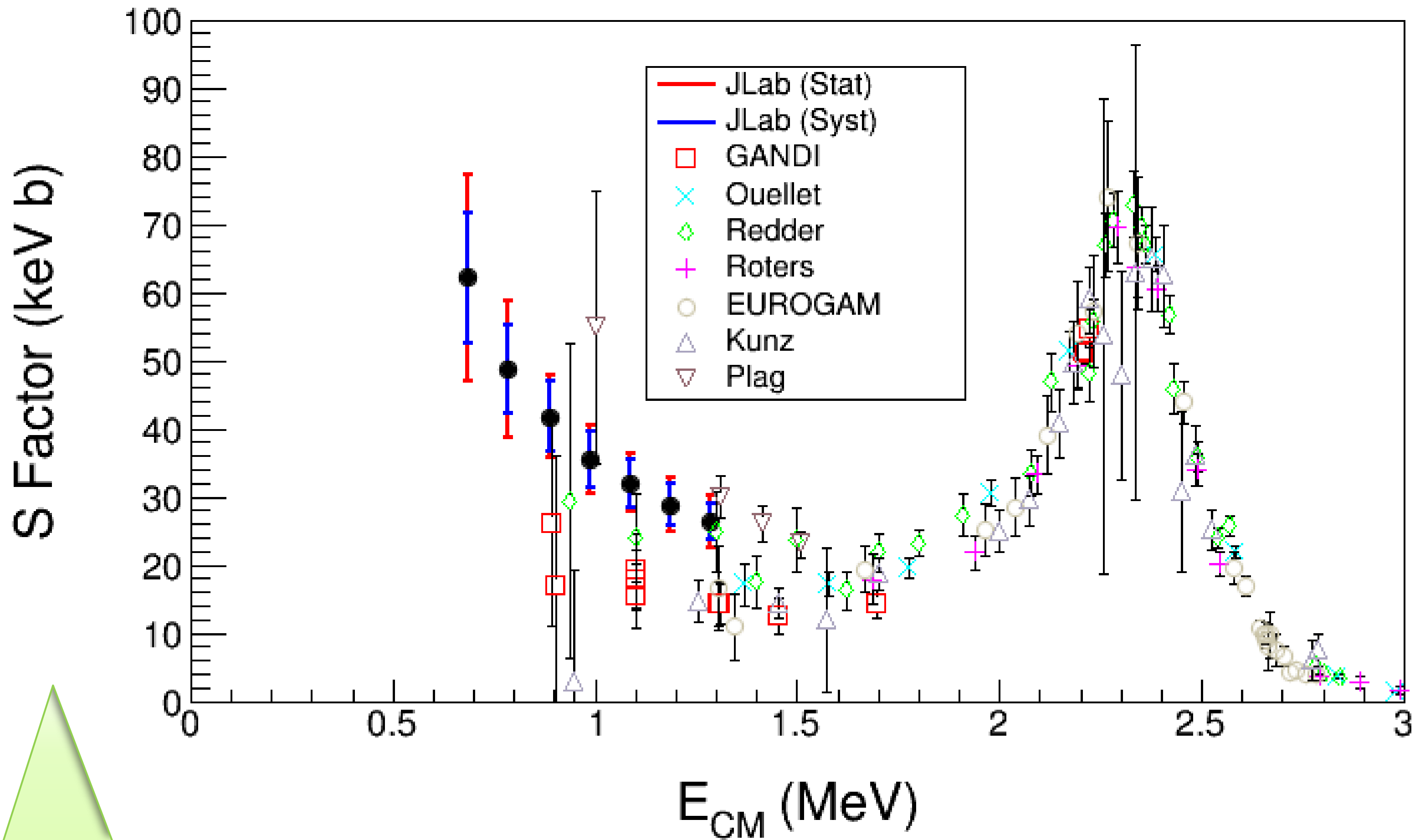
JLAB PROJECTED $^{12}C(\alpha,\gamma)^{16}O$ S-Factor

- 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%

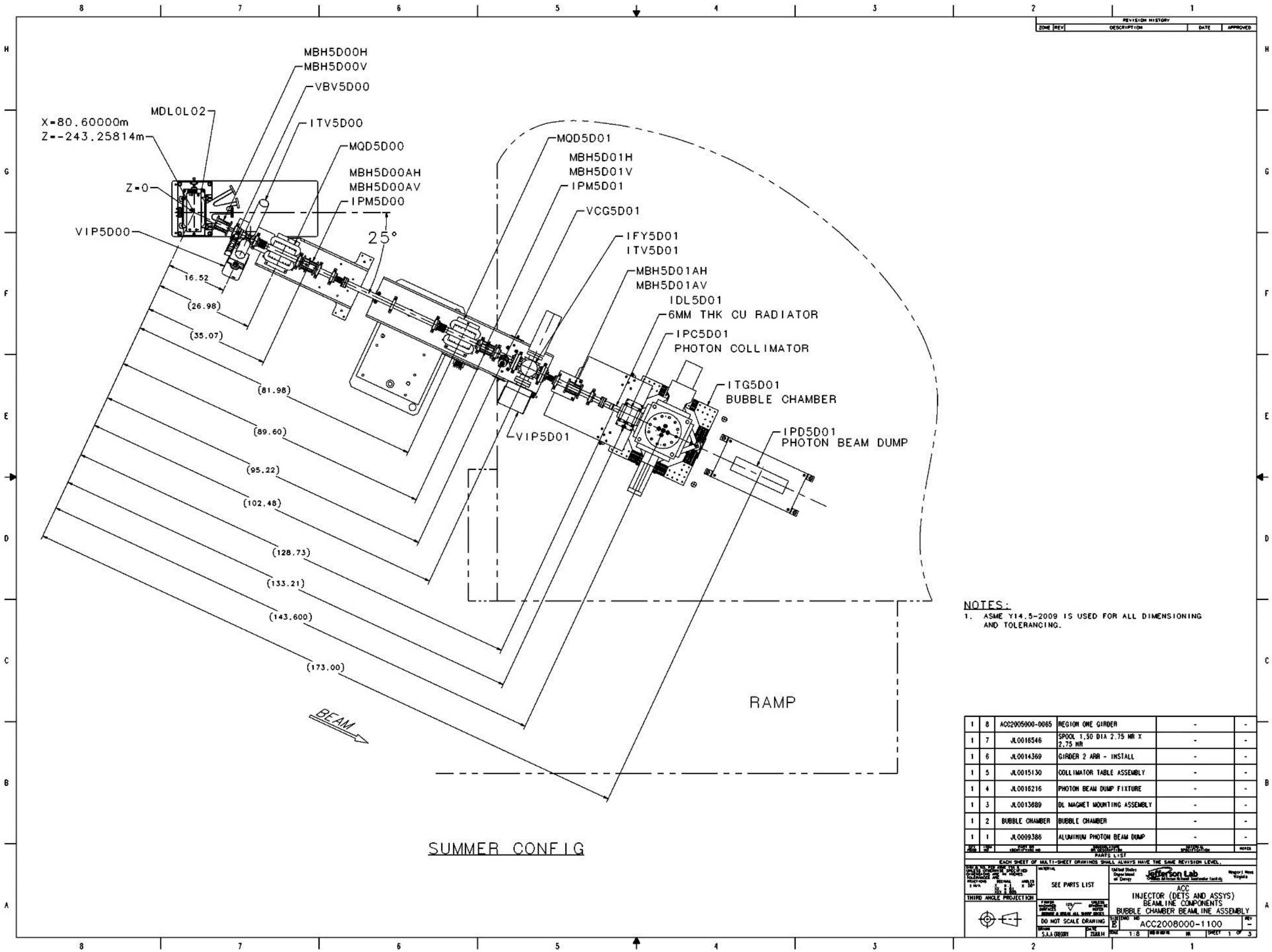
Physics (^{16}O Target)

Measure Backgrounds (^{17}O and ^{18}O Targets)

II. Readout:

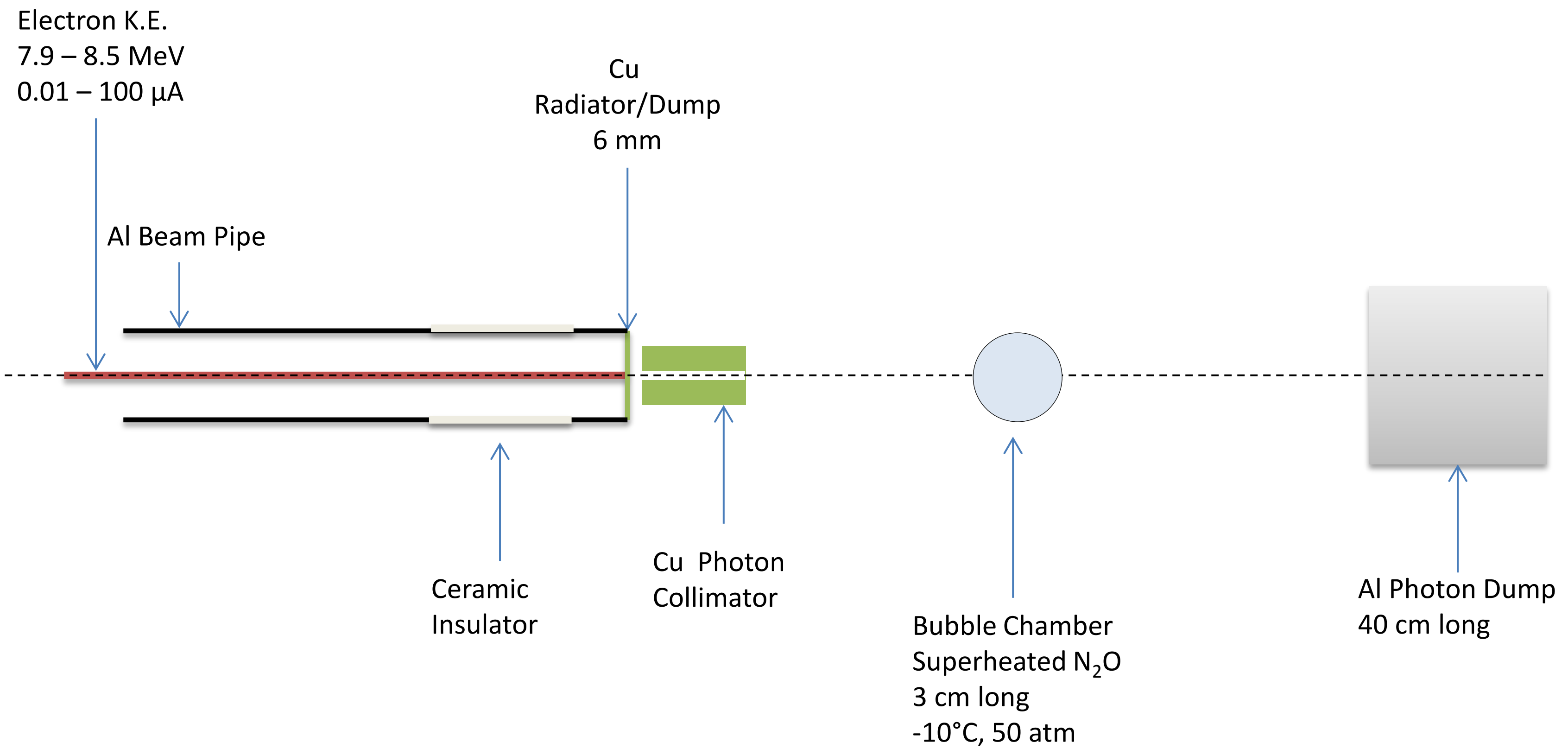
I. Fast Digital Camera
II. Acoustic Signal to discriminate between neutron and alpha events

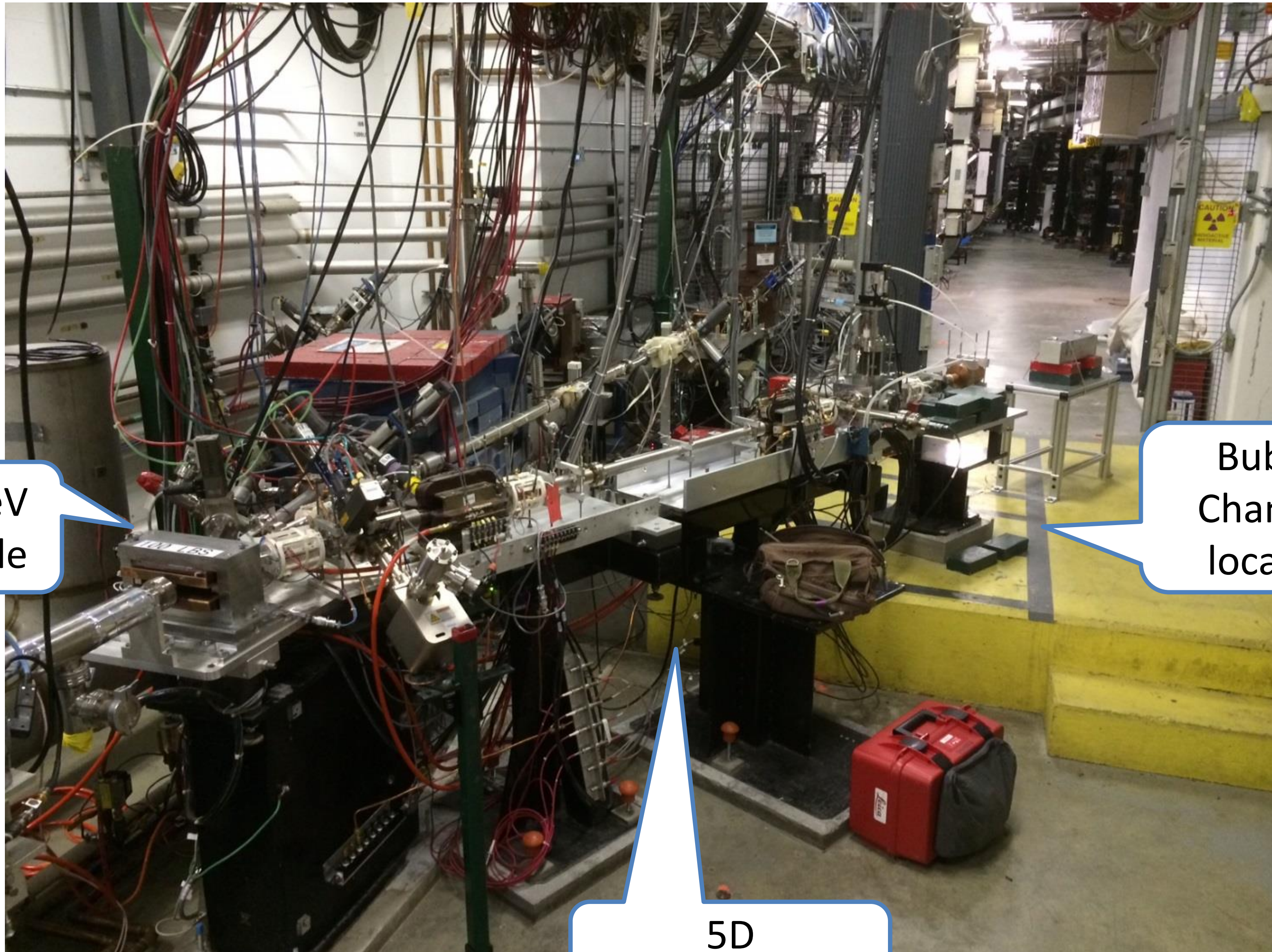
TEST BEAMLINE

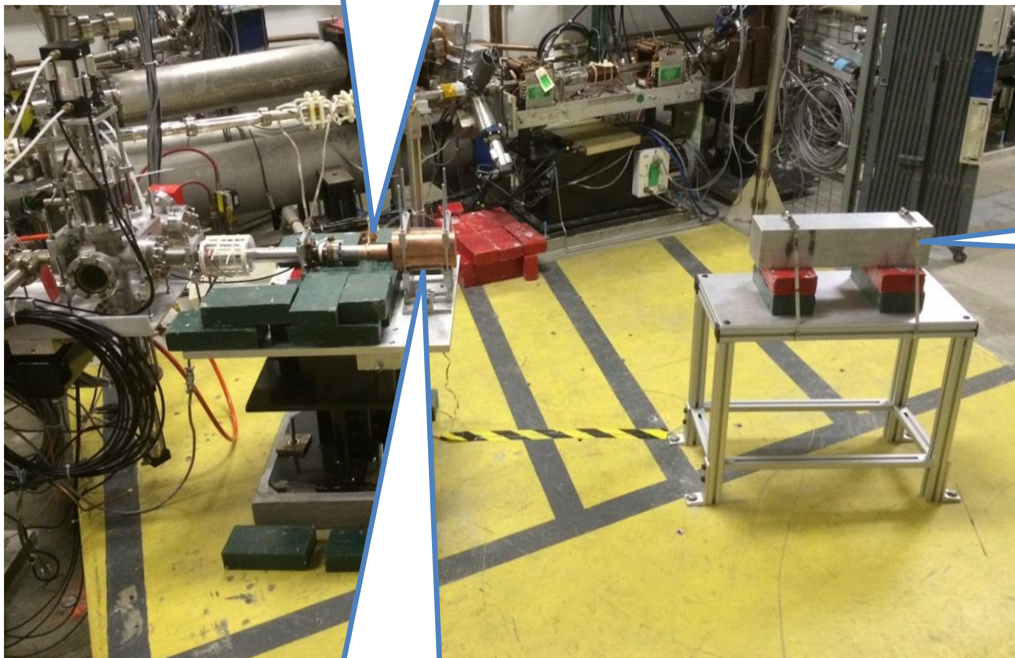


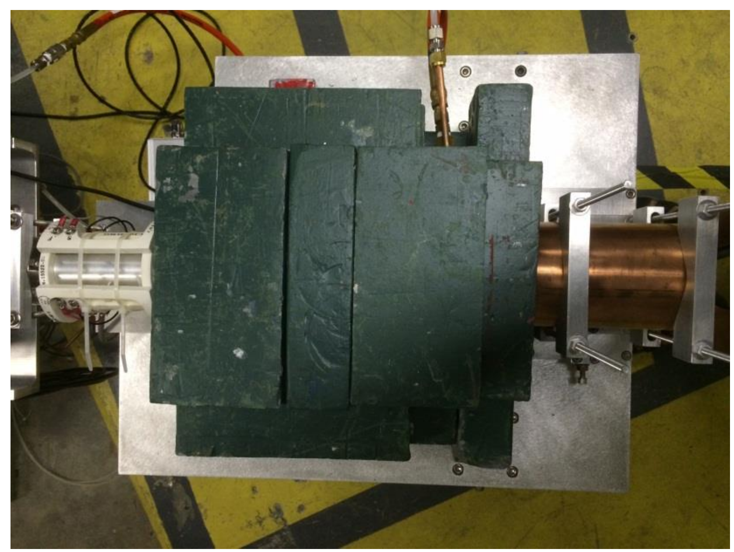
SCHEMATICS OF TEST BEAMLINE

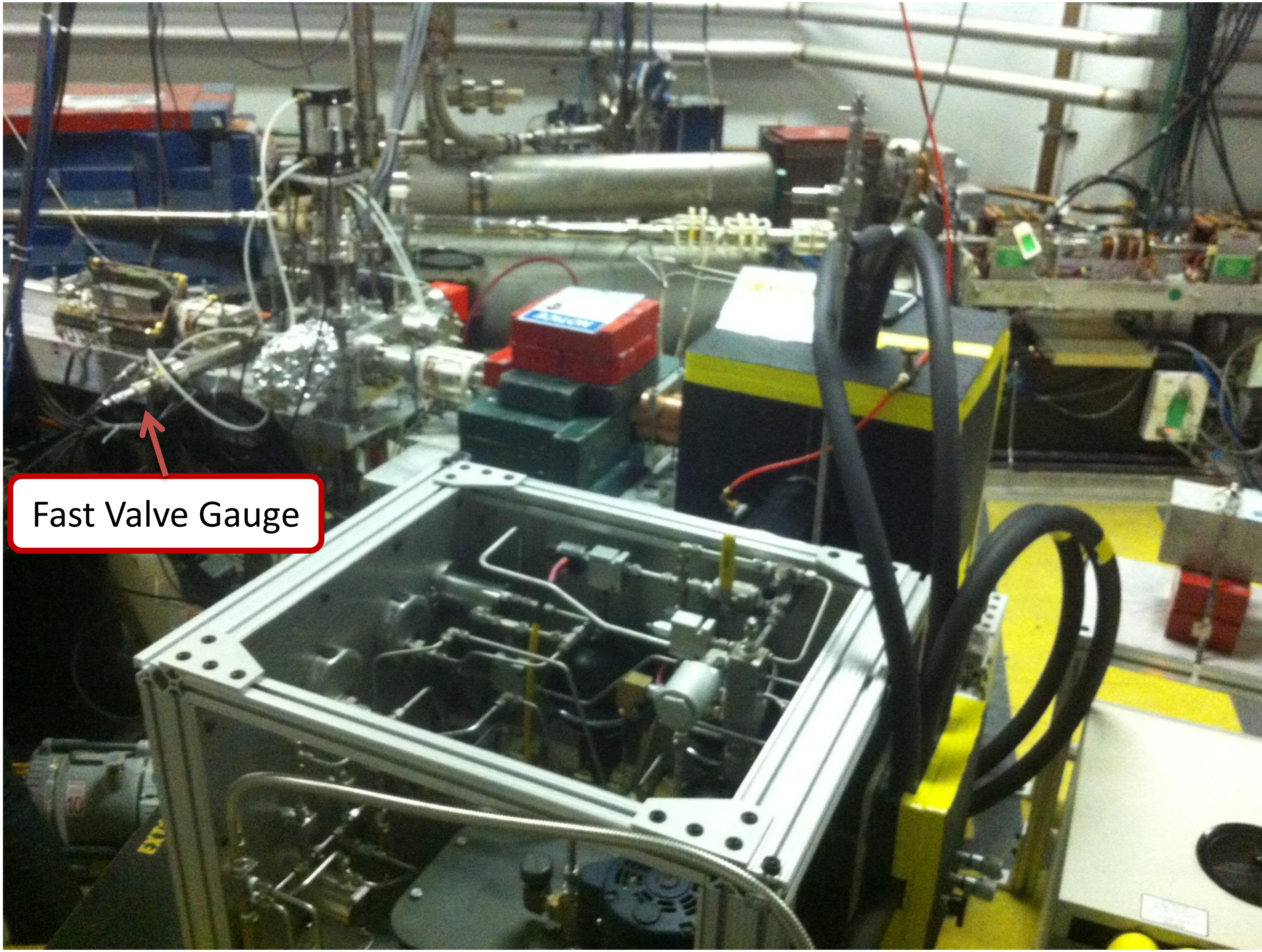
- Power deposited in radiator (100 μA and 8.5 MeV) :
  I. 6 mm: Energy loss = 8.5 MeV, P = 850 W
- Pure Copper and Aluminum (high neutron threshold):
  I. $^{63}C(\gamma,n)$ threshold = 10.86 MeV
  II. $^{27}Al(\gamma,n)$ threshold = 13.06 MeV




5 MeV Dipole
Bubble Chamber location
5D Spectrometer


Cu Electron Radiator/Dump
Al Photon Dump
Cu Photon Collimator

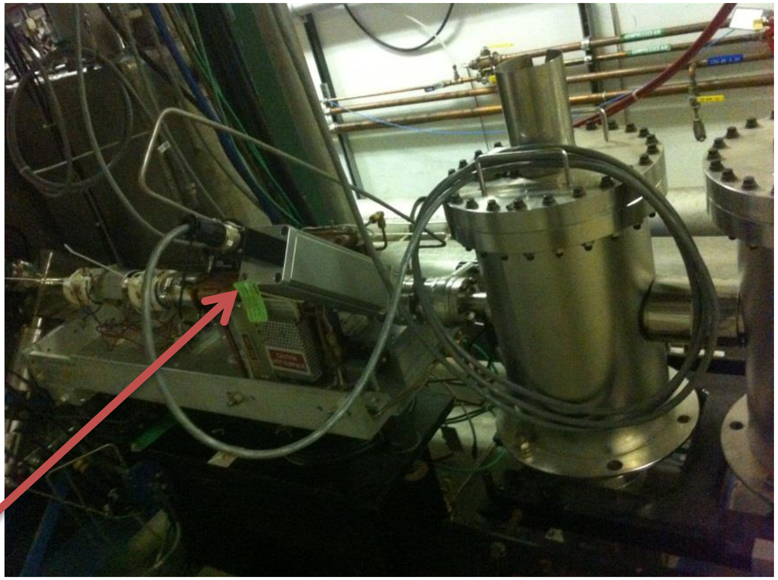



Fast Valve Gauge

New Beamline Elements

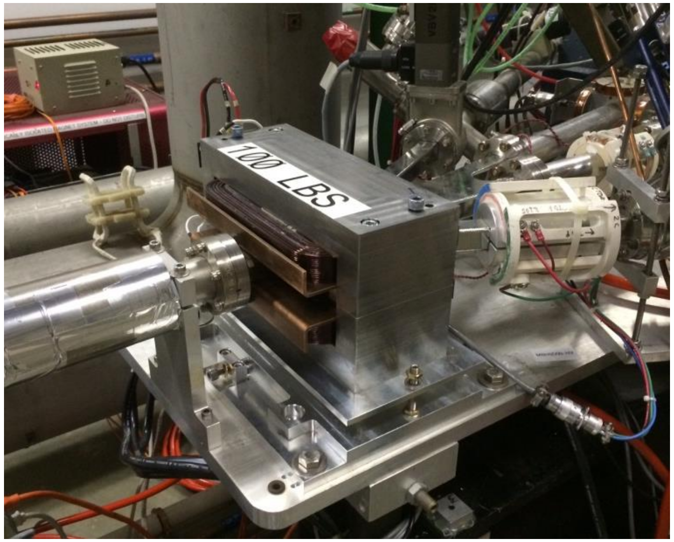
- New Beamline elements installed in support of Bubble Chamber experiment:

I. Fast Valve after ¼ Cryounit

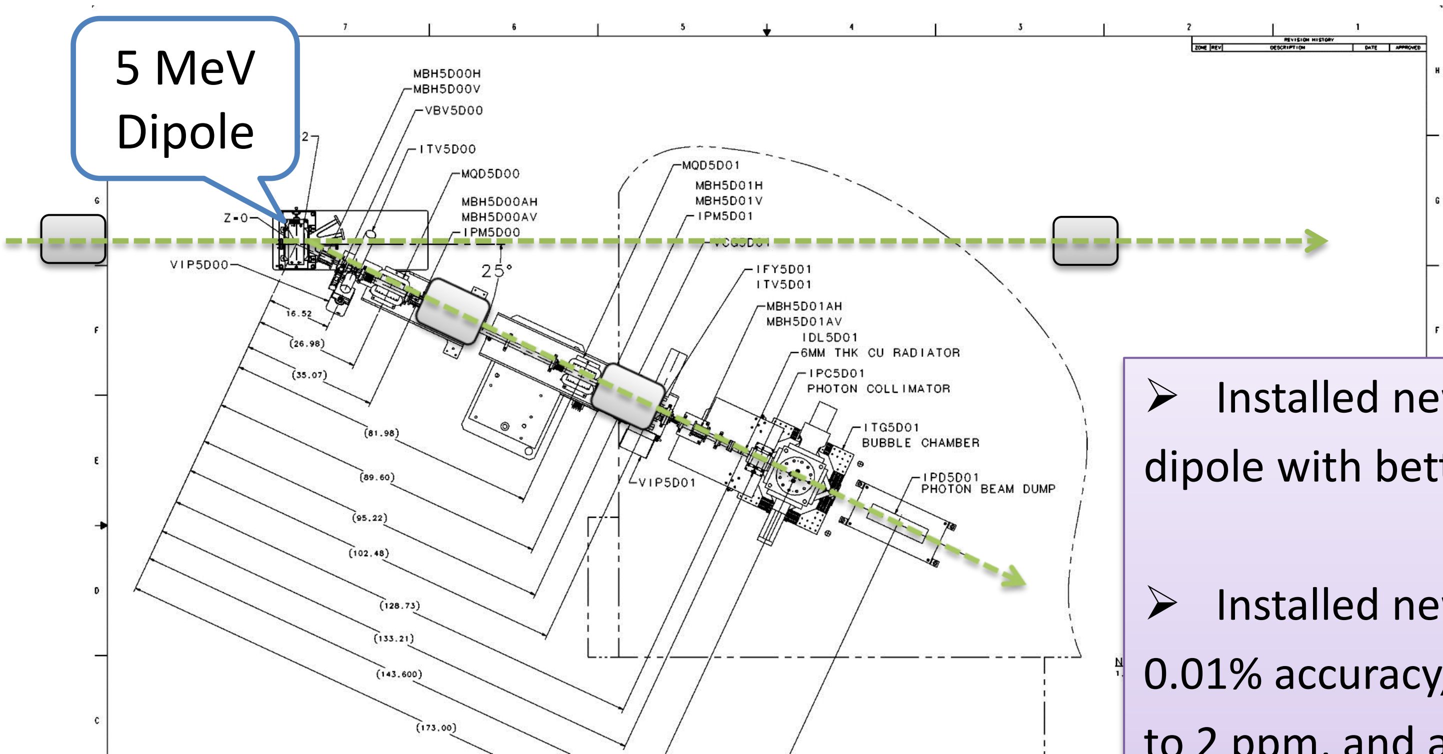


Protect ¼ Cryo-unit from vacuum failure

II. New MDL0L02 Dipole Magnet



MEASURING ABSOLUTE BEAM ENERGY



Beam Position Monitor (BPM)

Electron Beam Momentum

$$p = \frac{\int B dl}{\theta}$$

- 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 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).

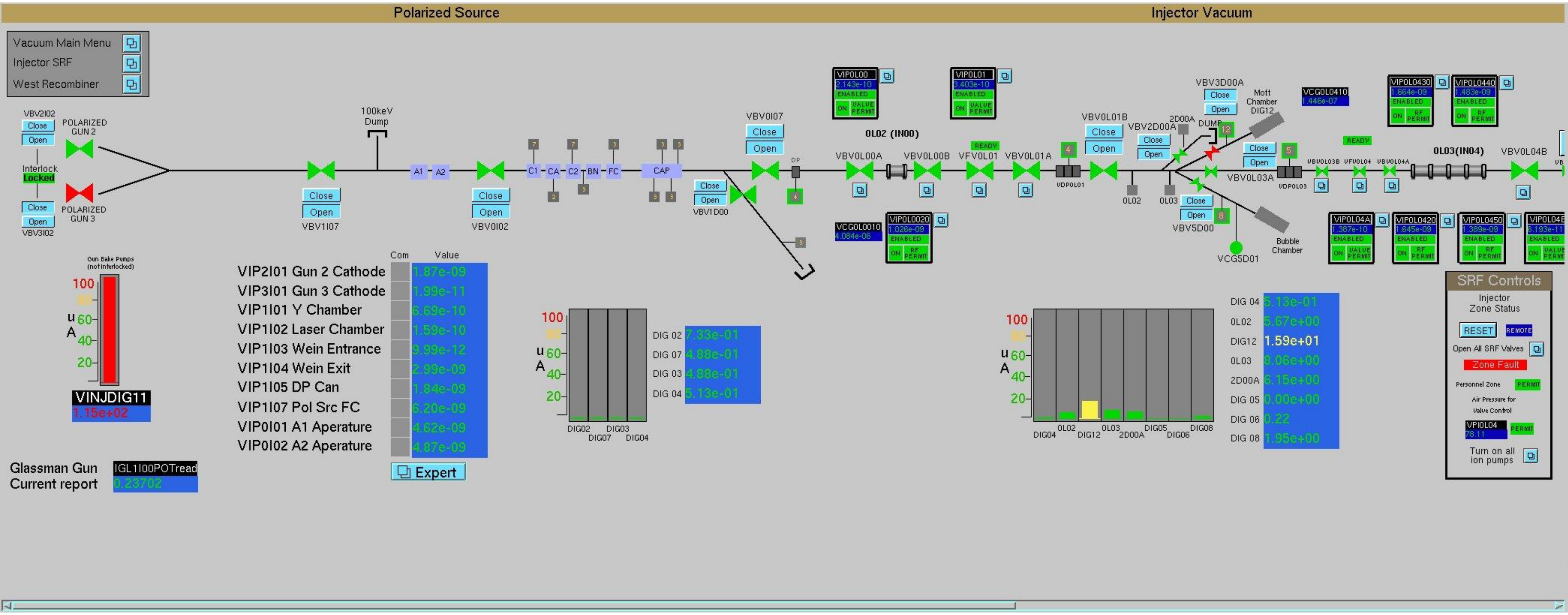
4. Fill with C_2F_6 – test bubble chamber systems operation. This is planned later in September after first beam test.

5. With beam (planned in October, 2015)

   I. Measure few data points of from $^{19}F(\gamma,\alpha)^{15}N$ to perform a Penfold-Leiss unfolding
   II. Compare measured cross section to our Duke 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
- No background reactions from carbon

BACKUP SLIDES


Polarized Source
Injector Vacuum
Vacuum Main Menu
Injector SRF
West Recombiner
POLARIZED GUN 2
POLARIZED GUN 3
Interlock
Locked
100keV Dump
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
Expert
VINJDIG11
1.15e+02
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
SRF Controls
Injector Zone Status
RESET
Open All SRF Valves
Zone Fault
Turn on all ion pumps
Mott Chamber
Bubble Chamber
0L02 (IN00)
0L03(IN04)