Introduction to Bubble Chamber: Ops Training

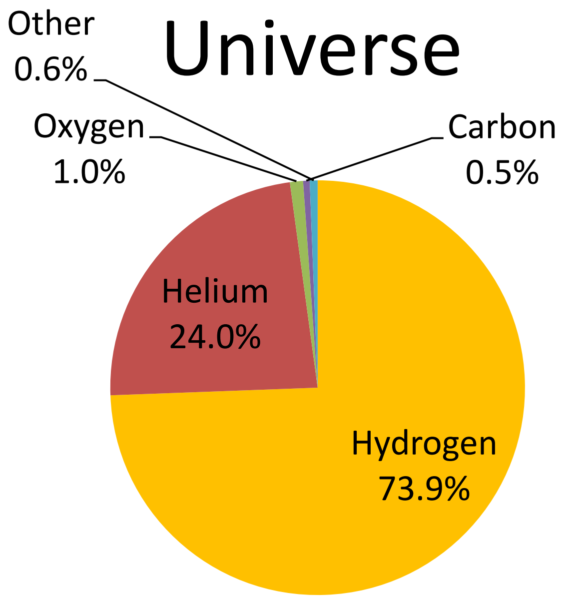
September 9, 2015

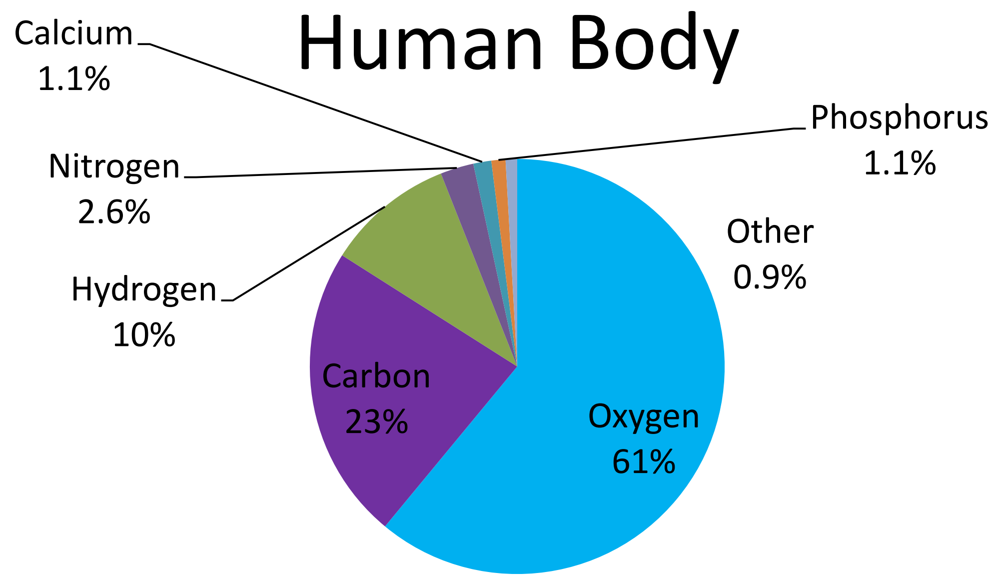
https://wiki.jlab.org/ciswiki/index.php/Bubble_Chamber

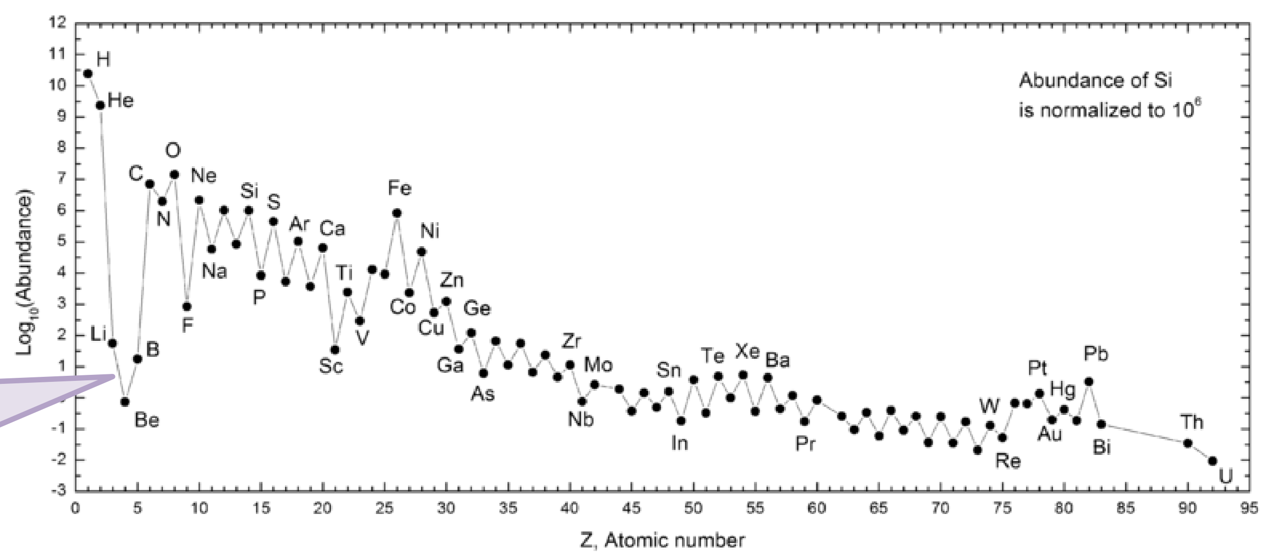
Outline

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

RELATIVE ABUNDANCE OF ELEMENTS BY WEIGHT



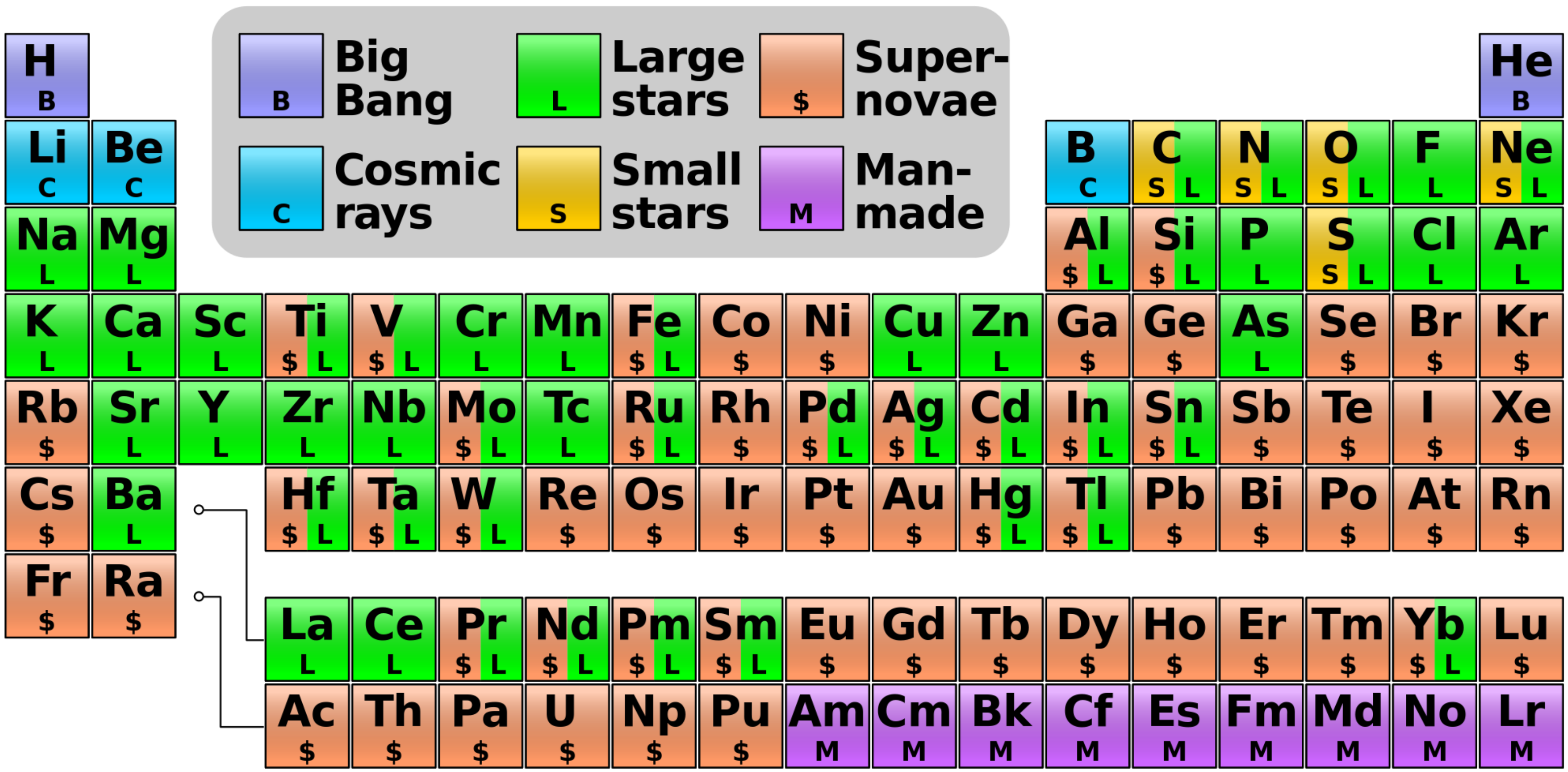




This region is bypassed by 3α process

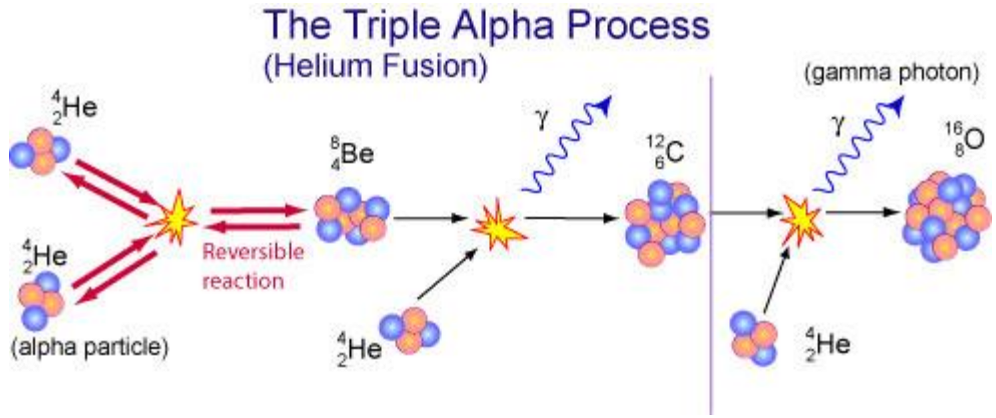
NUCLEOSYNTHESIS

- **Big Bang Nucleosynthesis:** quark–gluon plasma → p, n, He
- **Stellar Nucleosynthesis:** H burning, He burning, NCO cycle
- **Supernovae Nucleosynthesis:** Si burning
- **Cosmic Ray Spallation**

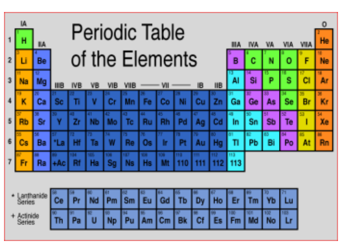


NUCLEOSYNTHESIS AND $^{12}C(\alpha,\gamma)^{16}O$

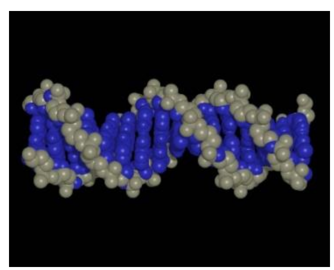
Stellar Helium burning



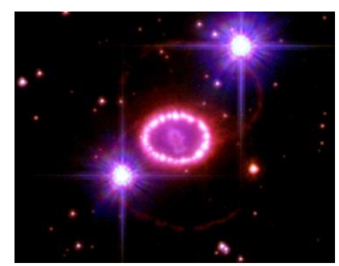
- The *holy grail* of nuclear astrophysics:



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

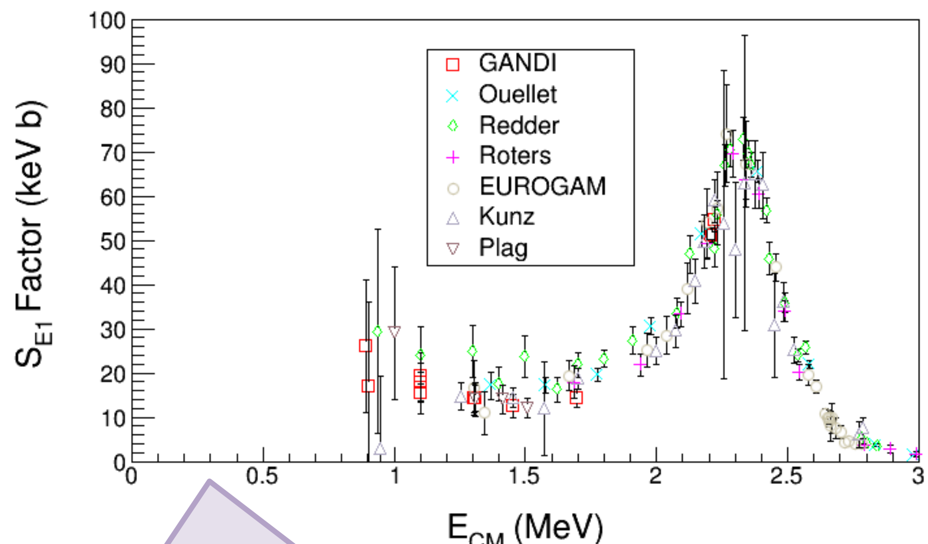
Heroic Efforts in Search of $^{12}C(\alpha,\gamma)^{16}O$

- 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 $^{4}He(^{12}C,^{16}O)\gamma$

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

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

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



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

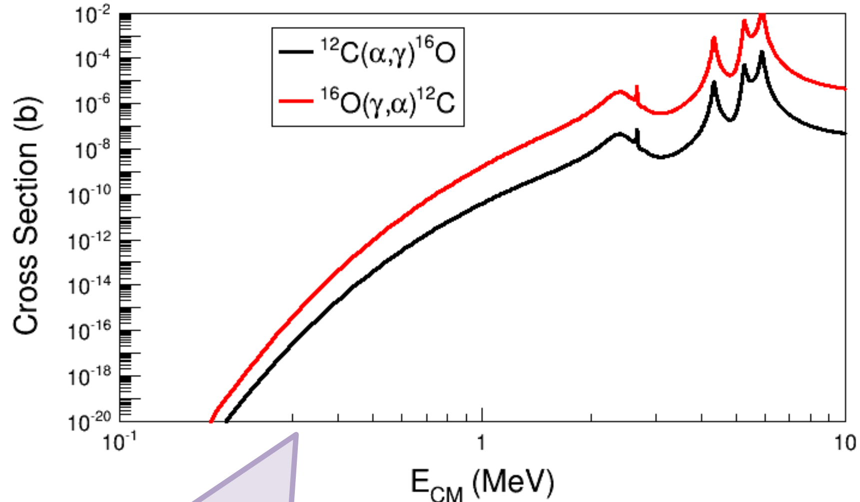
New Approach: Reversal Reaction + Bubble Chamber

beam | target | signal

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

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

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



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

- Extra gain (factor of 100) by measuring time reversal reaction
- Bremsstrahlung at JLab $\sim 10^9$ γ/s (top 250 keV)
- Target density up to 10^4 higher than conventional targets. Number of ^{16}O nuclei = 3.5×10^{22}/cm^2 (3.0 cm cell)
- 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})

The Bubble Chamber

1 Cell is cooled then filled with room temperature gas

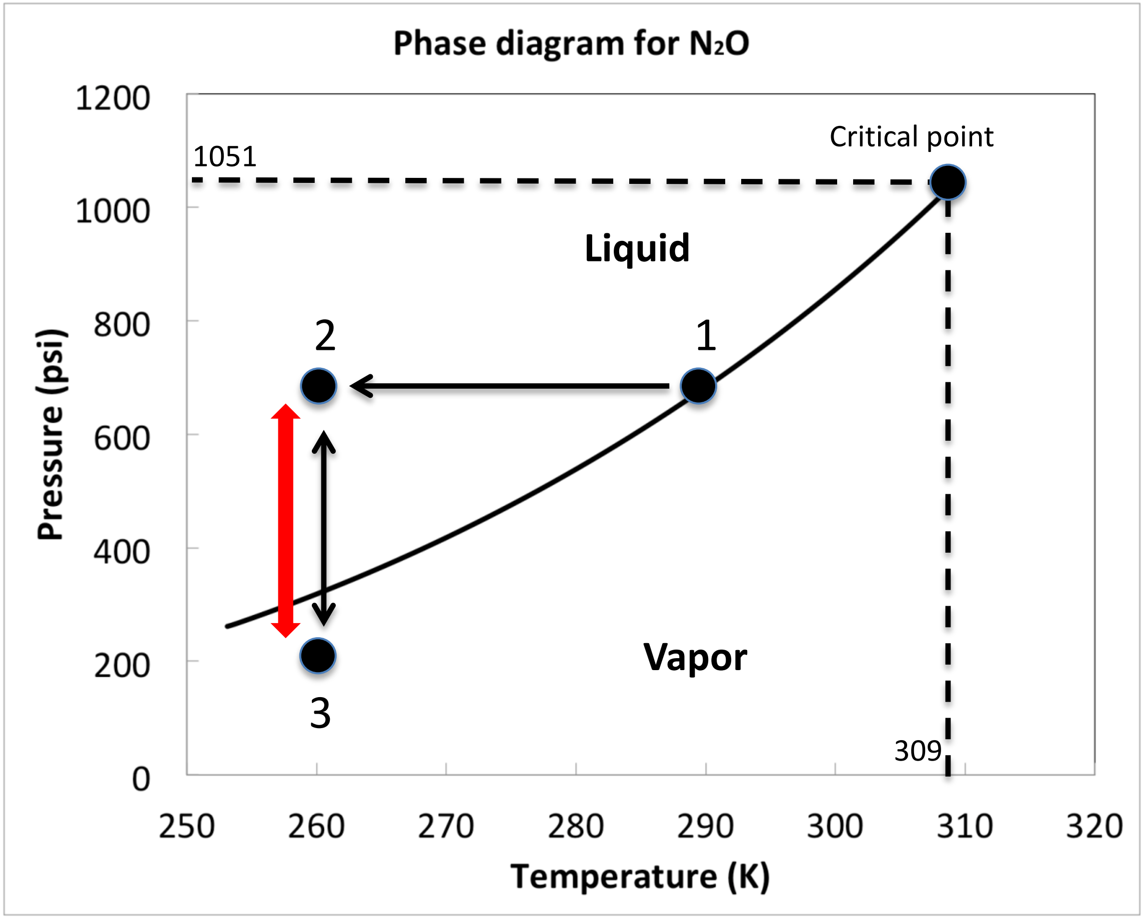
2 Gas is cooled and condenses into liquid

3 Once cell is completely filled with liquid, pressure is reduced creating a superheated liquid

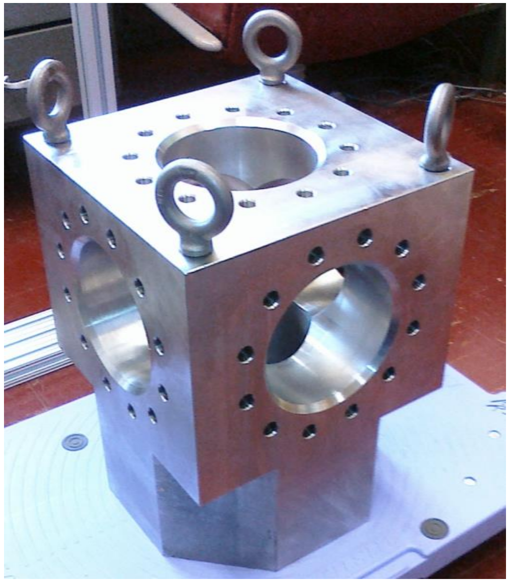
3 Nuclear reactions induce bubble nucleation

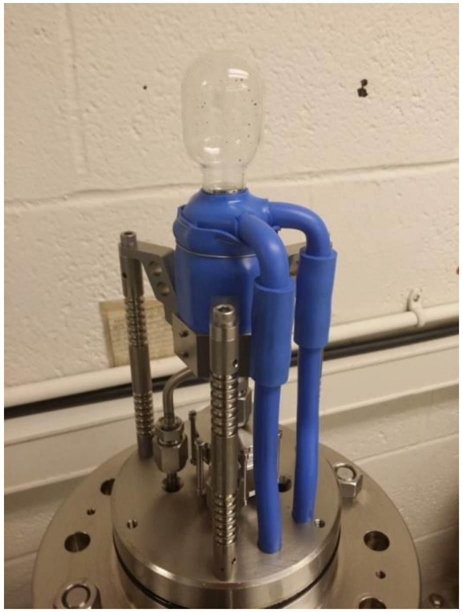
2 High speed camera detects bubble and repressurizes

3 System depressurizes and ready for another cycle



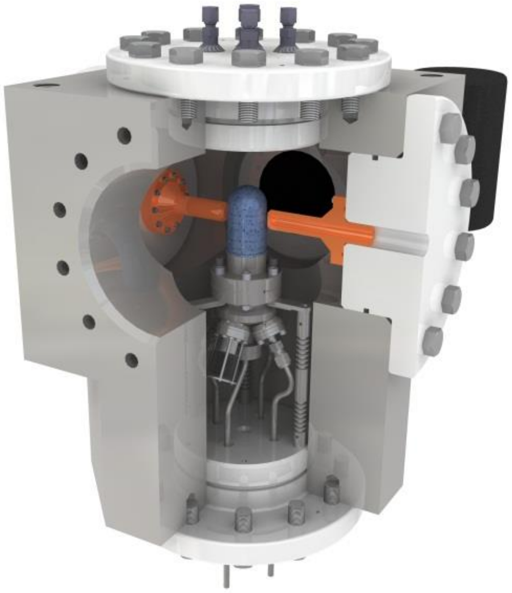
N_2O (Laughing Gas) Bubble Chamber

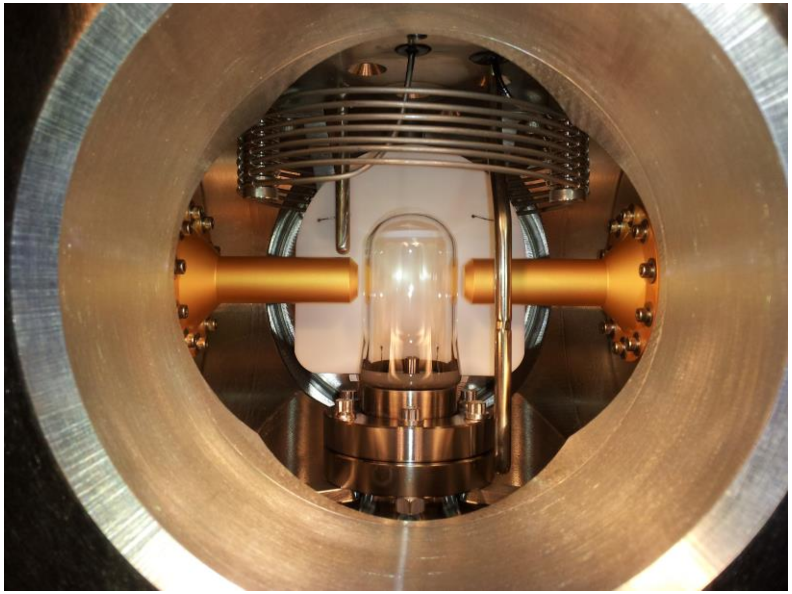




T = -10˚C

P = 50 atm





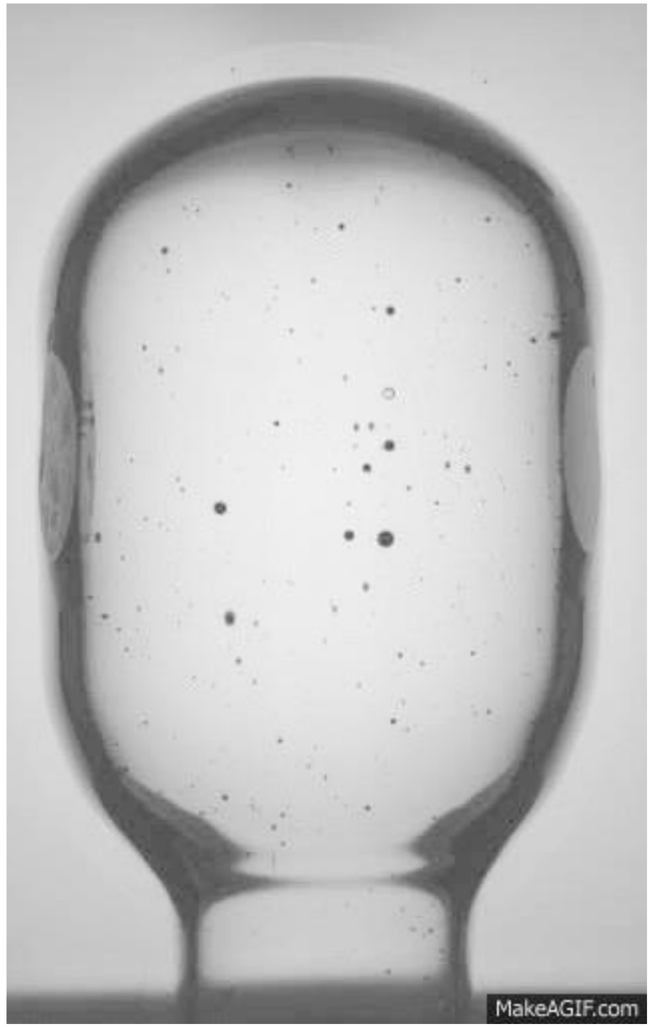
User Interface

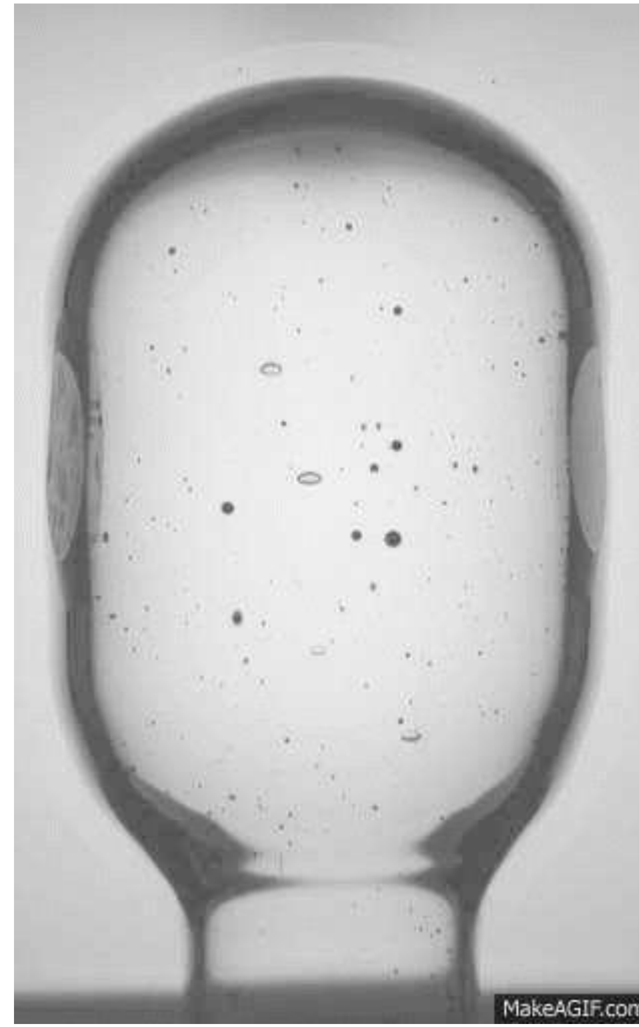
Bubble Growth and Quenching

3.0 cm

100 Hz Digital
Camera Δt = 10 ms

N_2O Chamber with PuC neutron source





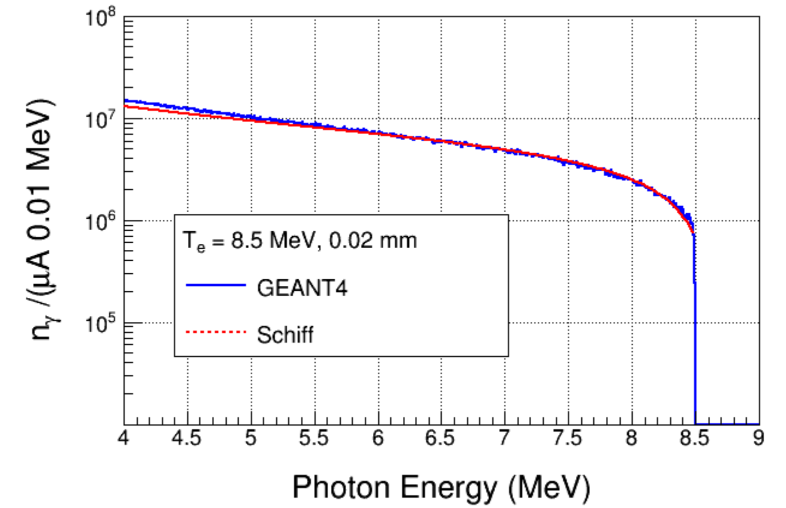
Electron Beam Requirements

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

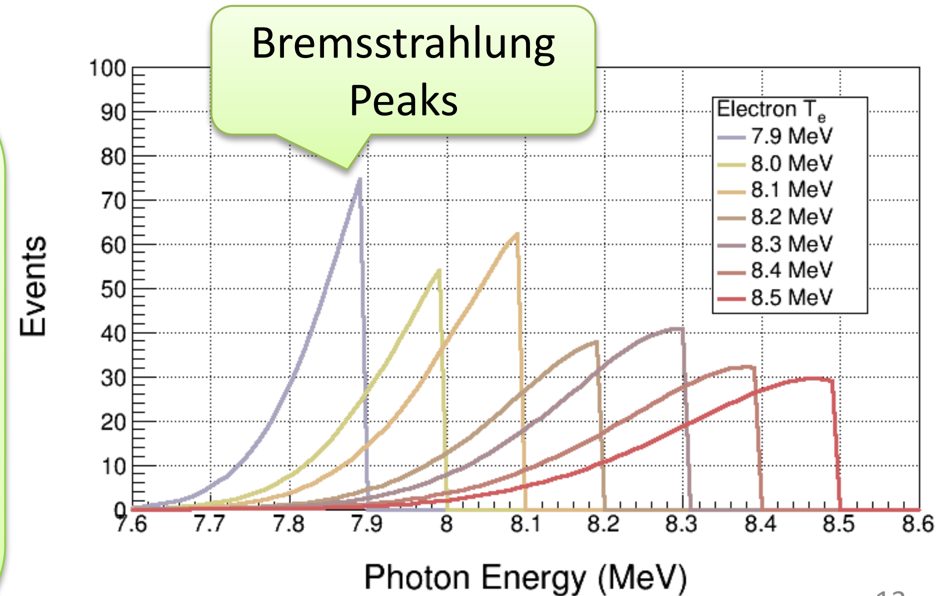
Bremsstrahlung Beam

- 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:

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

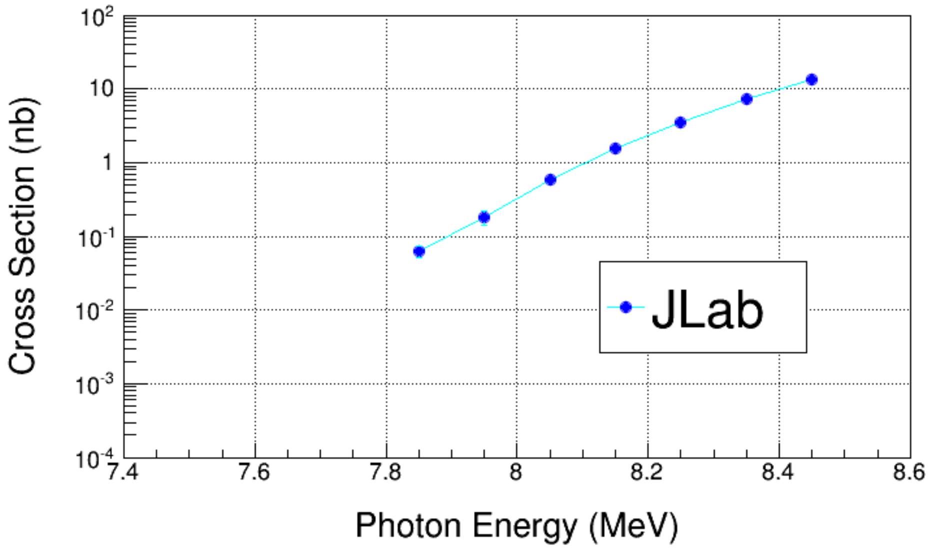
$$[Y] = [N] \bullet [\sigma]$$

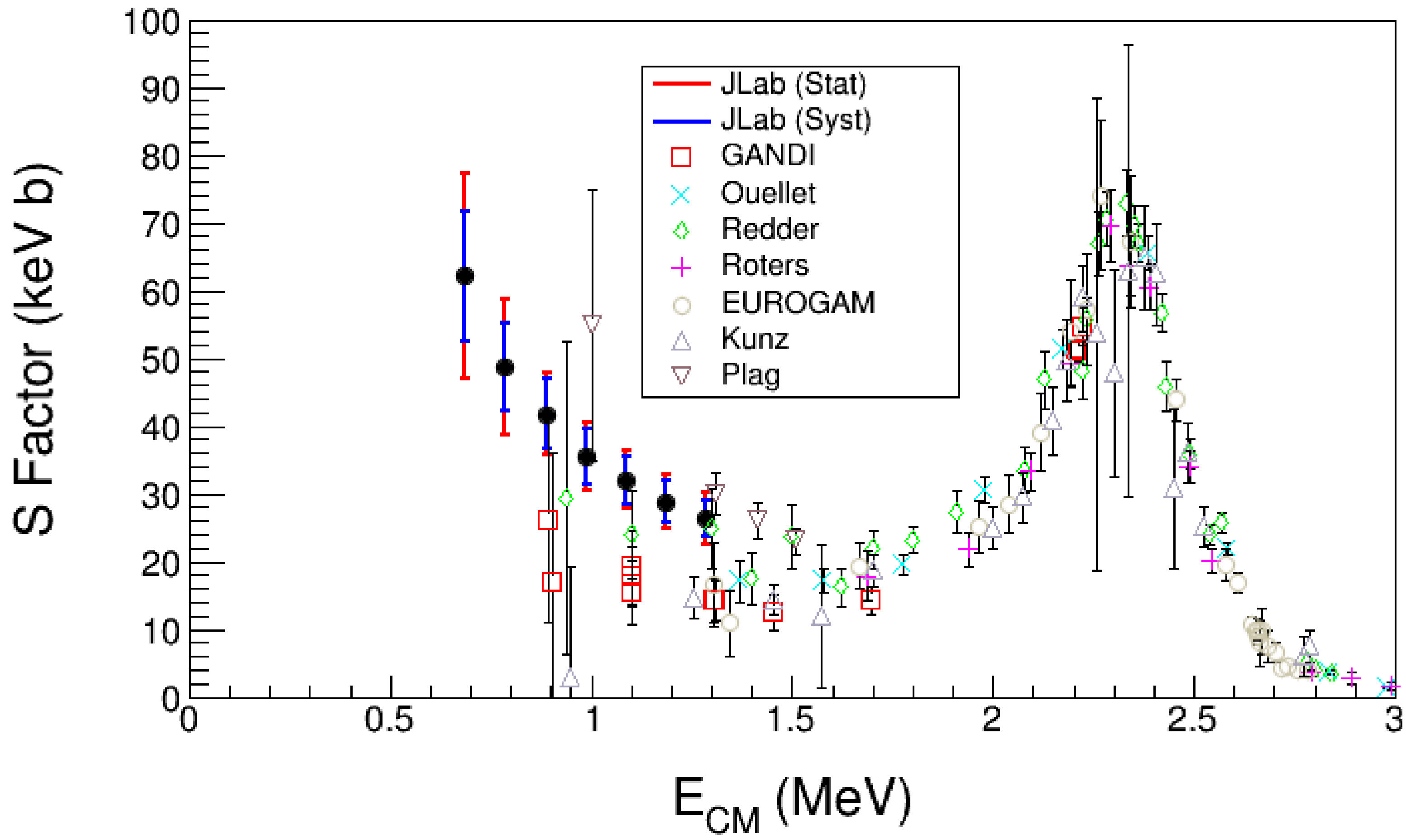
$$[\sigma] = [N]^{-1} \bullet [Y]$$

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)

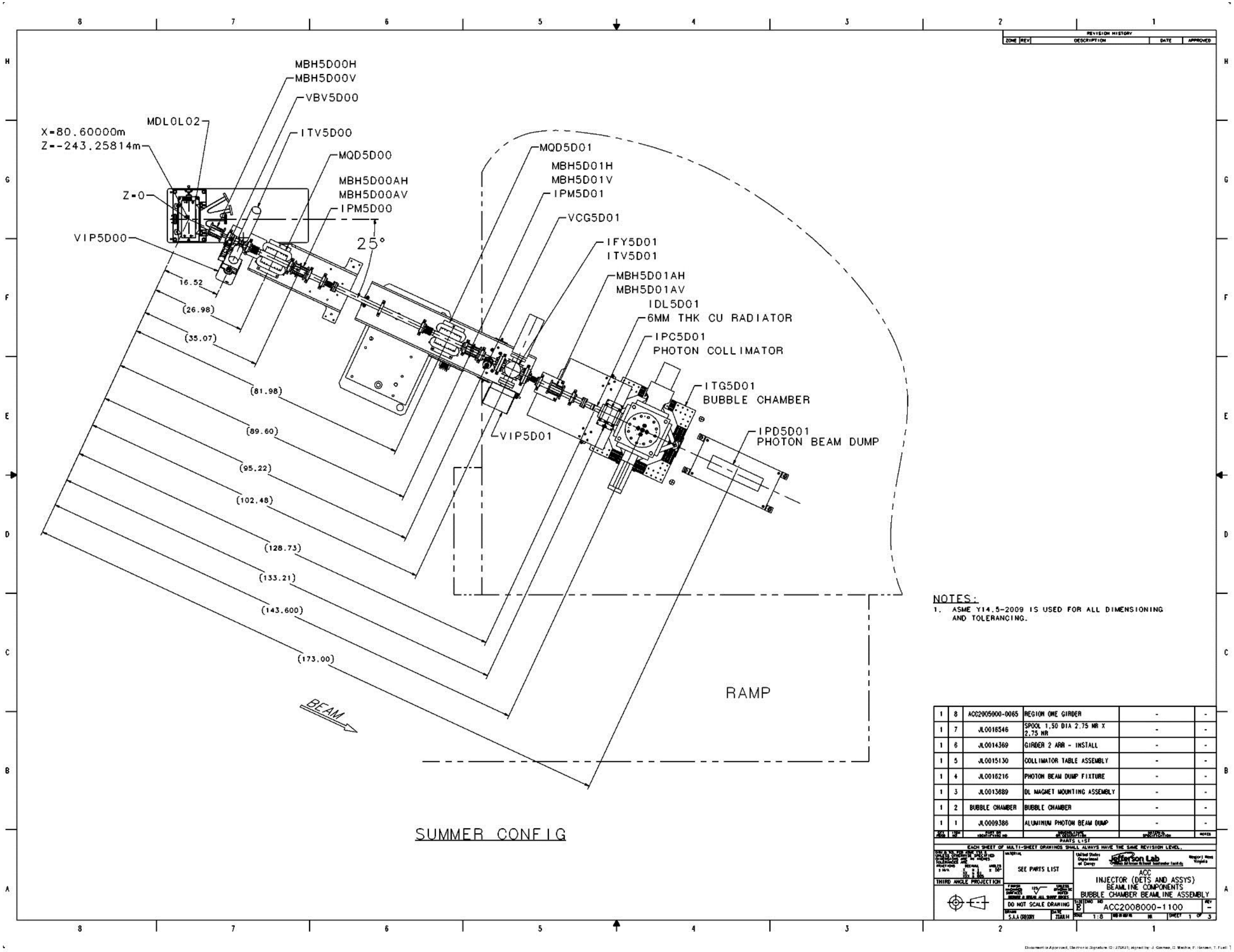
Electron Beam K. E.	Gamma Energy (MeV)	E_{CM} (MeV)	Cross Section (nb)	S_{tot} Factor (keV b)	Stat Error (%)	Sys Error (Total, %)
7.9	7.85	0.69	0.046	62.2	24.5	15.3
8.0	7.95	0.79	0.185	48.7	20.7	13.5
8.1	8.05	0.89	0.58	41.8	14.7	12.2
8.2	8.15	0.99	1.53	35.5	13.8	11.4
8.3	8.25	1.09	3.49	32.0	13.3	10.7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





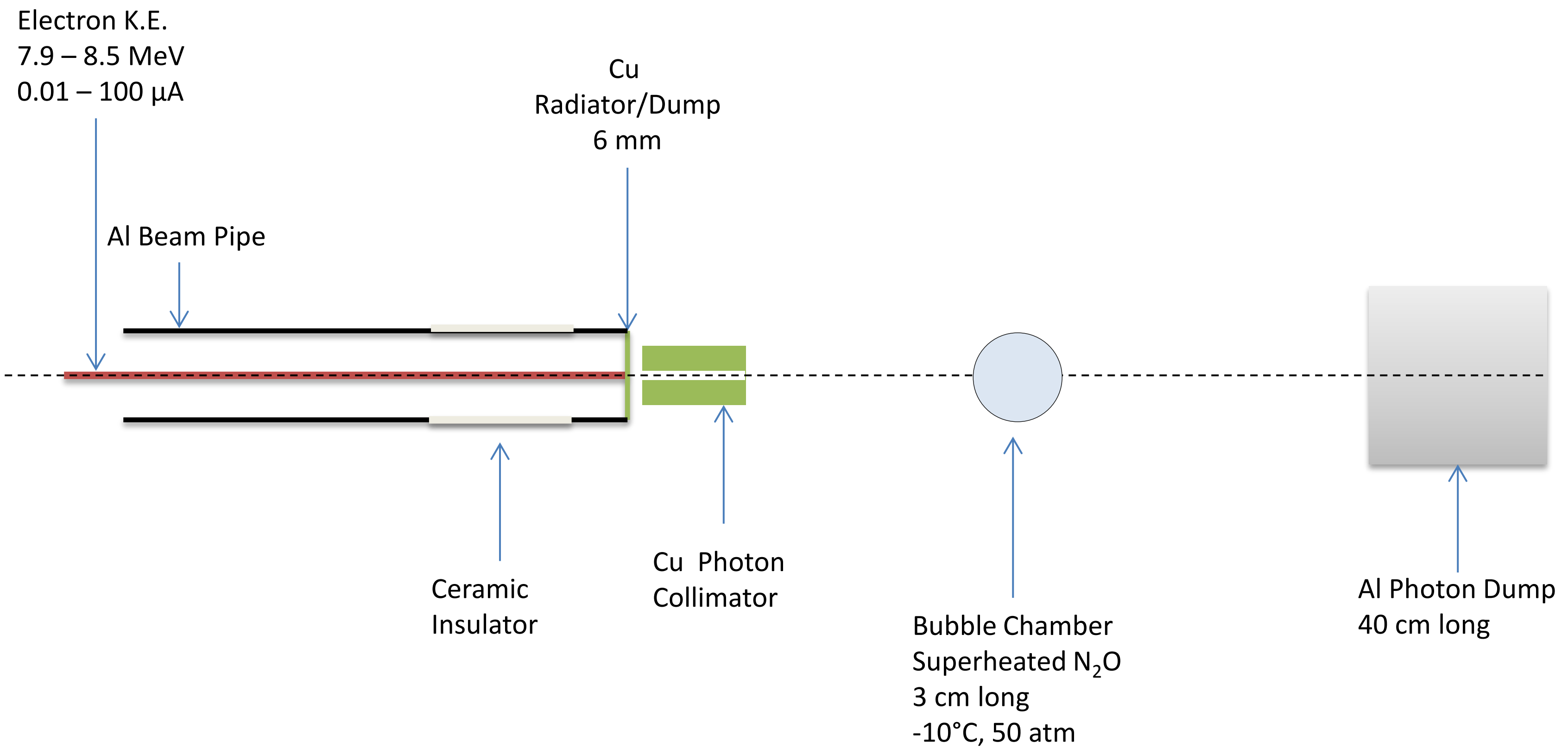
S Factor (keV b)
E$_{CM}$ (MeV)
JLab (Stat)
JLab (Syst)
GANDI
Ouellet
Redder
Roters
EUROGAM
Kunz
Plag
0
10
20
30
40
50
60
70
80
90
100
0
0.5
1
1.5
2
2.5
3

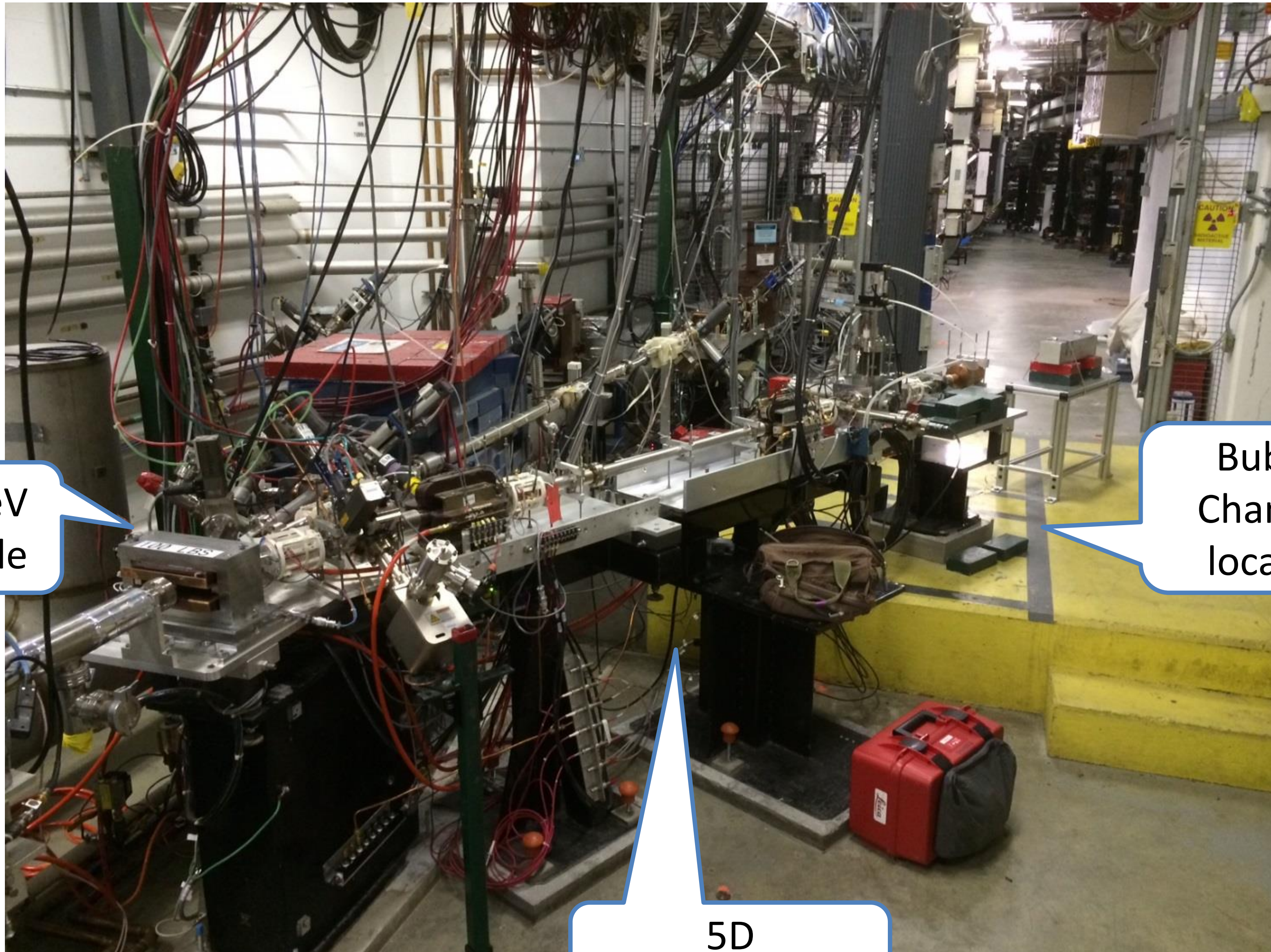
TEST BEAMLINE



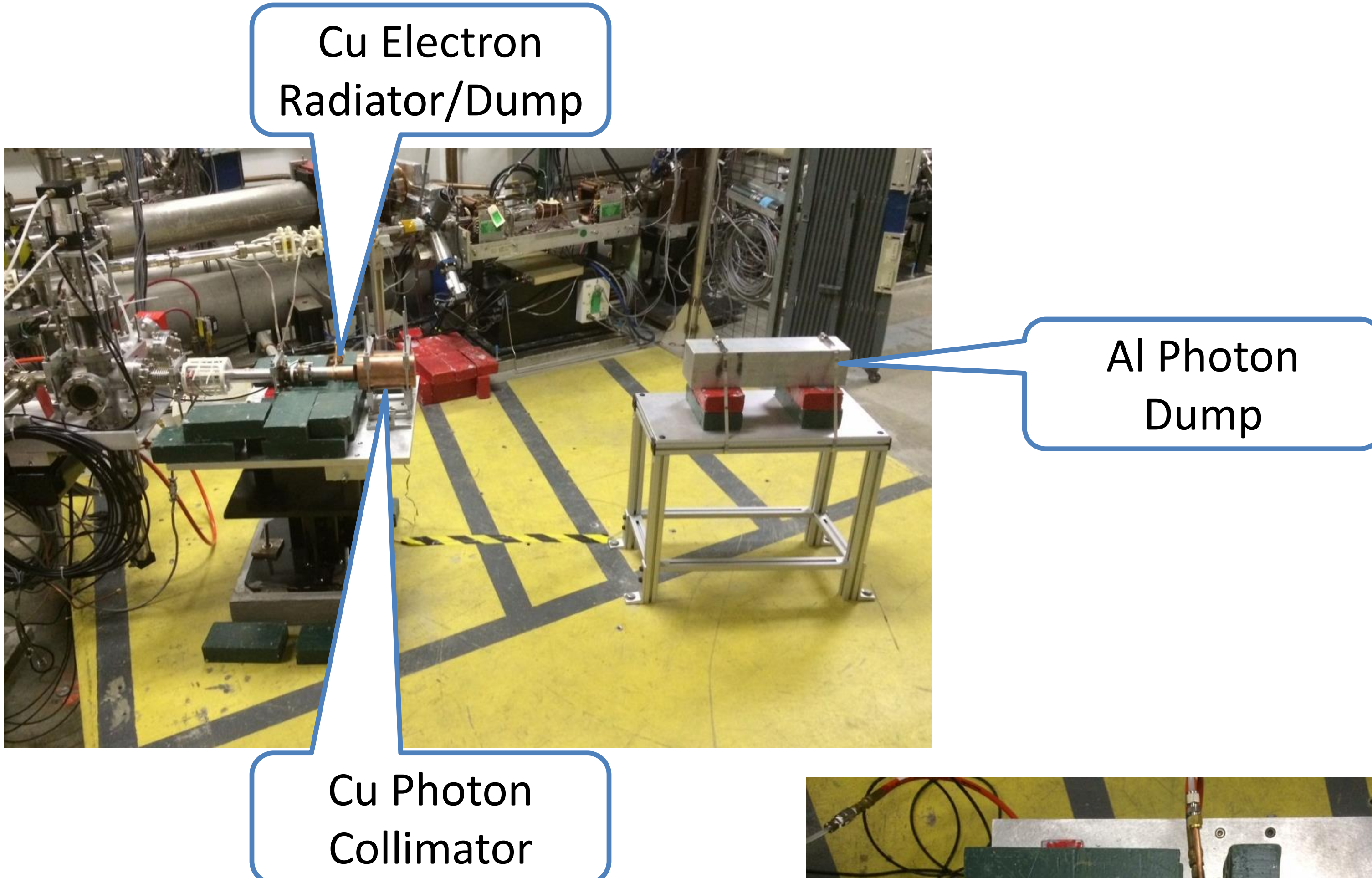
Schematics of Test Beamline

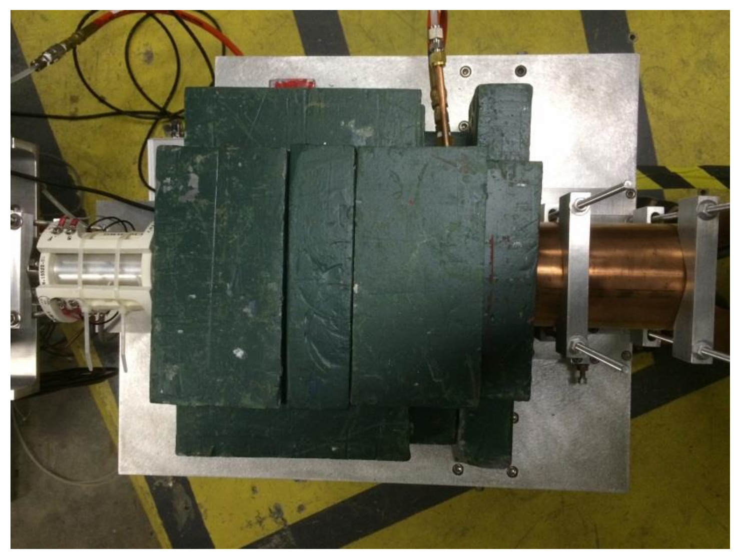
- Power deposited in radiator (100 µA and 8.5 MeV) :
  I. 6 mm: Energy loss = 8.5 MeV, P = 850 W
- Pure Copper and Aluminum (high neutron threshold):
  I. $^{63}C(\gamma,n)$ threshold = 10.86 MeV
  II. $^{27}Al(\gamma,n)$ threshold = 13.06 MeV

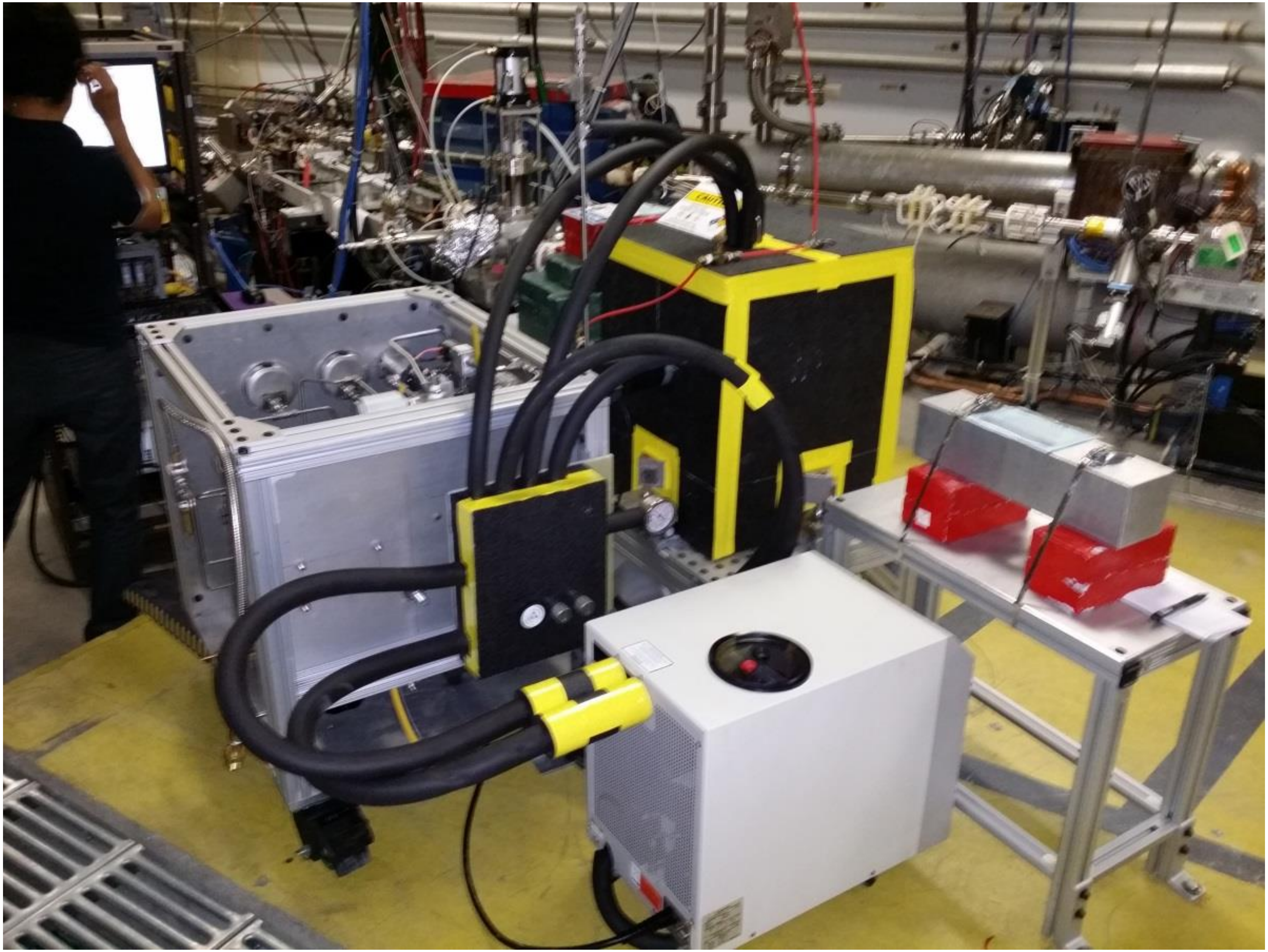




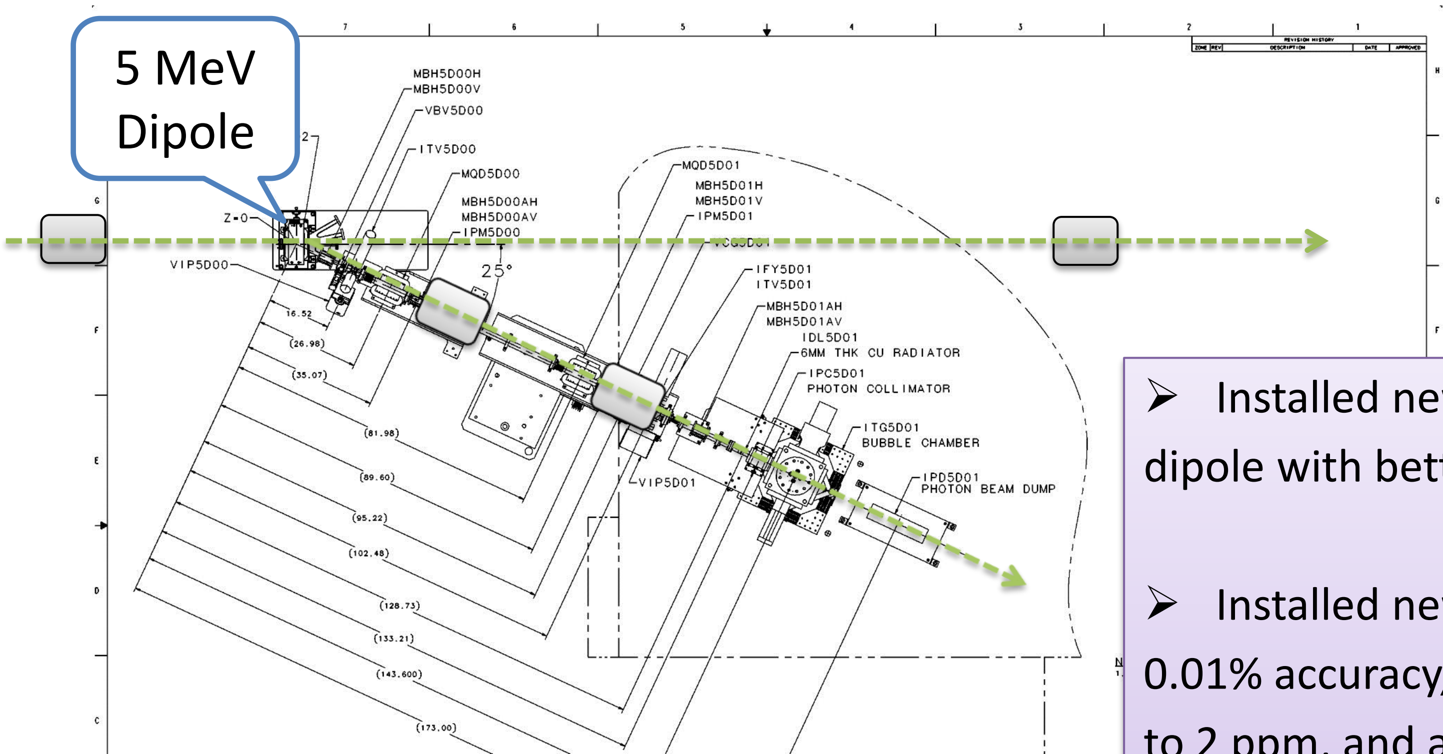
5 MeV Dipole
Bubble Chamber location
5D Spectrometer


Cu Electron Radiator/Dump
Al Photon Dump
Cu Photon Collimator





MEASURING ABSOLUTE BEAM ENERGY



- 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

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

Test Beamline Commissioning

- Beamline was ready since Fall 2014
- Approved to run 10 µA CW and total energy of 10 MeV
- Completed hot checkout and beam checkout
- Beam Studies completed so far:
  I. Delivered 10.0 µA and 9.65 MeV (kinetic) 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 run at 100 µA

Bubble Chamber Test Plans

1. Fill with natural N_2O – test bubble chamber systems operation

2. Study Chamber with beam (1:00 – 11:00 pm, Sept 10 – 18)

3. Background measurements

4. Fill with C_2F_6 – test bubble chamber systems operation

5. With beam (planned in Oct 16 – 22, 2015)

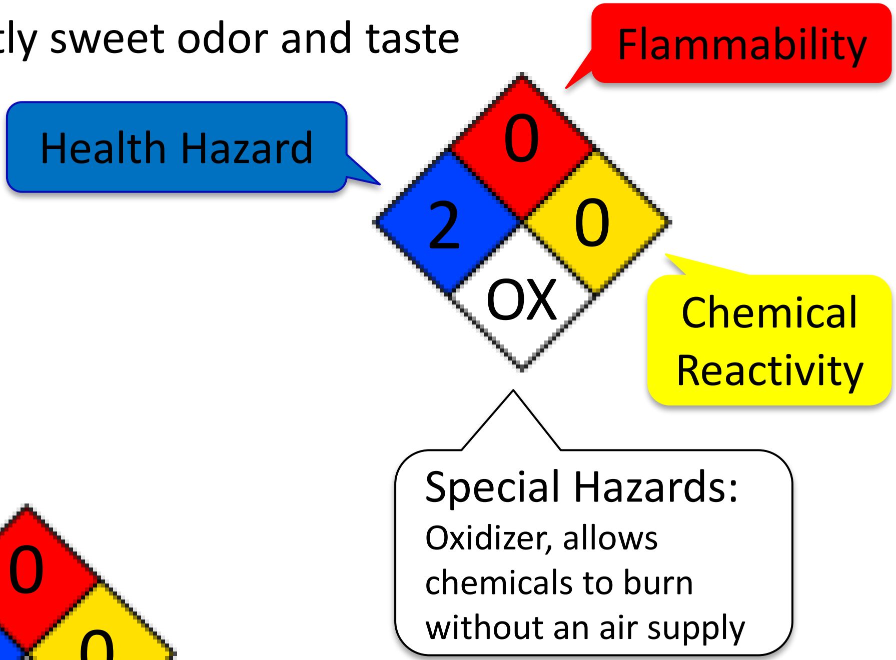
    I. Measure $^{19}F(\gamma,\alpha)^{15}N$ (Q = +4.013 MeV)

    II. Compare measured cross section to our HIGS data

➢ Fluorine is suitable for a first Penfold-Leiss unfolding:
  - Only one stable natural isotope (^{19}F)
  - Low electron beam kinetic energy (4.6 – 5.2 MeV) – below threshold of any background reaction

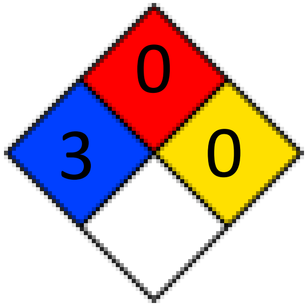
Bubble Chamber Safety Reviews

- Superheated liquid: N_2O, Nitrous oxide (laughing gas)
  I. Colorless, non-flammable gas, with slightly sweet odor and taste



- High pressure system:
  I. Design Authority: Dave Meekins
  II. T = -10˚C
  III. P = 50 atm

- Buffer liquid: Mercury
  I. Closed system
  II. Volume: 150 mL



- Bubble Chamber Safety Review was on Aug 18, 2015

- Temporary Operational Safety Procedures (**TOSP**) is approved