Optical Readout TPC (O-TPC) For a Study of Stellar Helium Burning at HIγS

Moshe Gai
UConn and Yale
http://astro.uconn.edu

1. **The Collaboration**
2. **The Experiment (Briefly):**
   Oxygen Formation in Stellar Helium Burning
   $^{12}C(\alpha,\gamma)^{16}O$ Reaction With Real Photons
3. **The Detector (O-TPC)**
4. **Performance of O-TPC**
5. **Future Developments**

TUNL, Duke, 12 July 2007

The Laboratory for Nuclear Science At Avery Point

The O-TPC at HIγS Collaboration:

UConn :*
M. Gai
T.J. Kading
L. Weissman
A.H. Young
P.N. Seo (anticipated)
Unnamed Grad Student

Yale:**
G.F. Burkhard
D.F. Rubin

PTB, Braunschweig: ***
B. Bromberger
V. Dangendorf
K. Tittelmeier

Weizmann, Israel:**
A. Breskin
R. Chechik
M. Klin

UCL, LLN, Belgium:***
Th. Delbar

TUNL, Duke:*
M.W. Ahmad
S. Stave
H.R. Weller

UHartford:
J.E. McDonald

GCSU:
R.H. France III
NGCSU:*
R.M. Prior
M.C. Spraker

* Supported by US Department of Energy

** Supported by the American Committee on Weizman
Yale-Weizmann Collaboration

*** In Kind Contribution, Optical Readout System

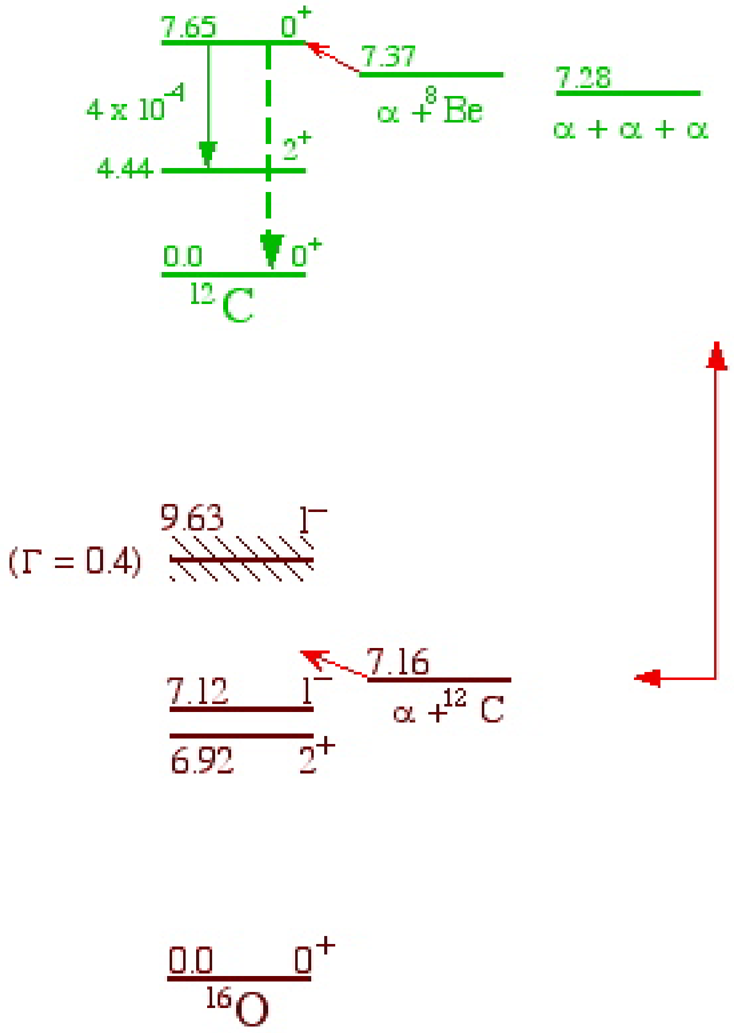

Laboratory for
Astrophy
1084 She

HELIUM BURNING IN (MASSIVE) STARS

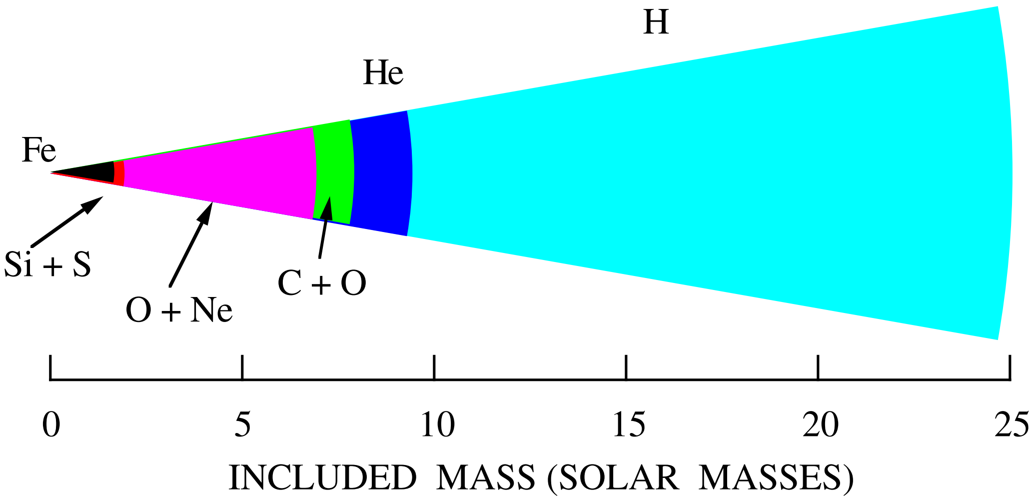
I. $3\alpha \rightarrow {}^{12}C$

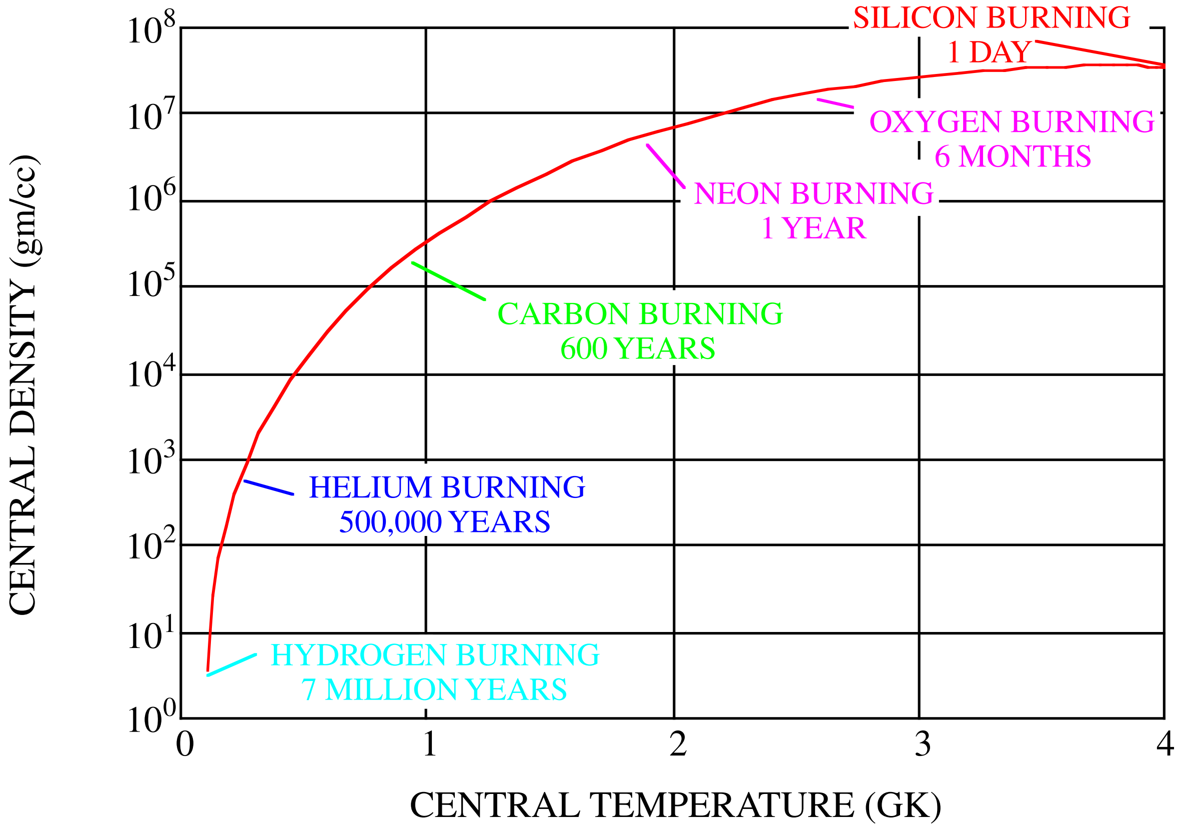
II. $\alpha + {}^{12}C \rightarrow {}^{16}O$

1. Energy
2. ${}^{12}C/{}^{16}O$
3. Heavier Elements

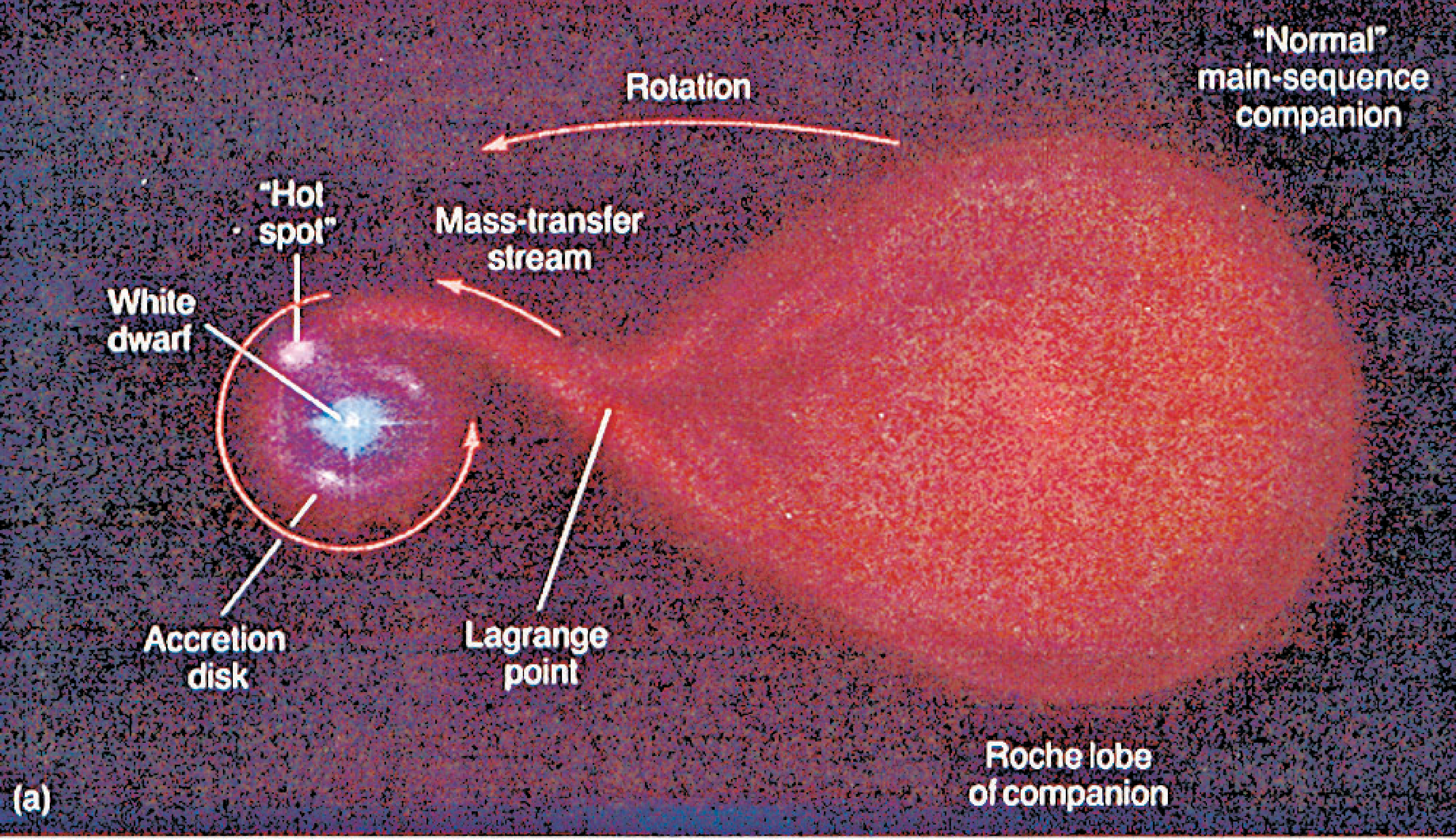


III. $\alpha + {}^{16}O \rightarrow {}^{20}Ne$ (NEGLIGIBLE)





Brown & Bethe - 1985 (x10)

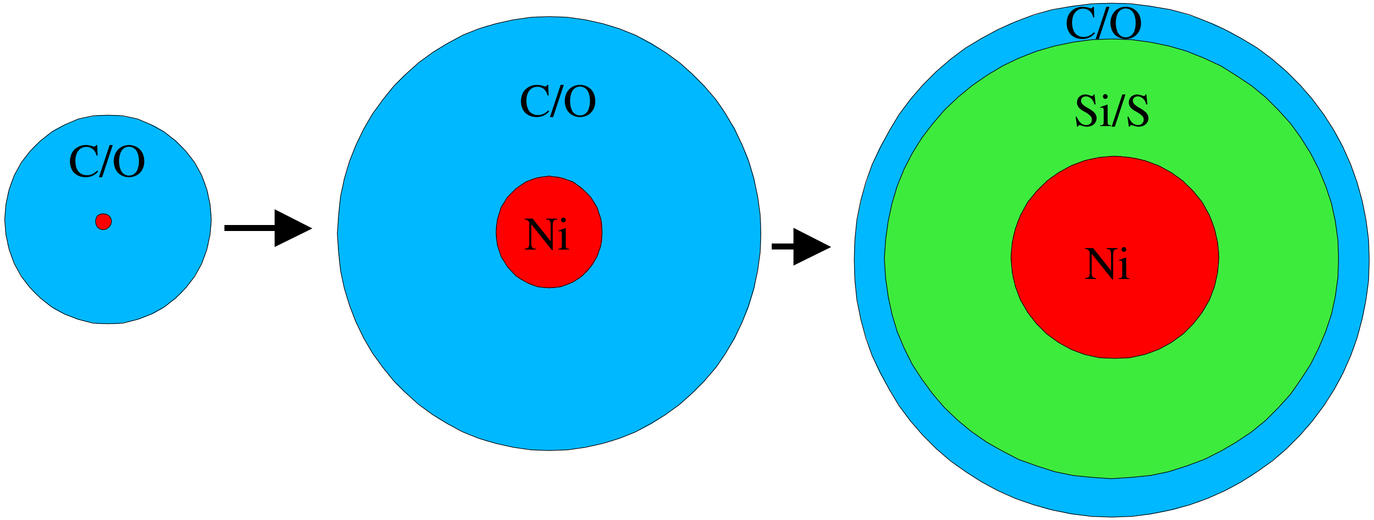

"Normal" main-sequence companion
Rotation
"Hot spot"
Mass-transfer stream
White dwarf
Accretion disk
Lagrange point
Roche lobe of companion
(a)

Explosion of a White Dwarfs (Defl., Delayed Det. & Merger)

Initial WD **Deflagration phase(2...3sec)** **Detonation phase (0.2...0.3 sec)**

preexpansion of the WD

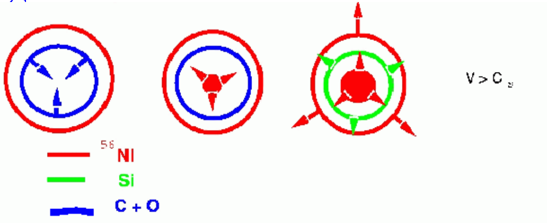
hardly any time for further expansion



Deflagration: Energy transport by heat conduction over the front, v <<v(sound)=> ignition of unburned fuel (C/O)
Detonation: ignition of unburned fuel by compression, v = v(sound)

Rem1: Pre-expansion depends on the amount of burning. The rate of burning hardly changes the final structure for DD-models (Dominguez et al. ApJ 528, 590)

Rem.2: HeDs
(sub-MCh)



- disagree with LCs and spectra

(Nugent et al. 96, Hoeflich et al. 96)

Peter Hoeflich (2002)

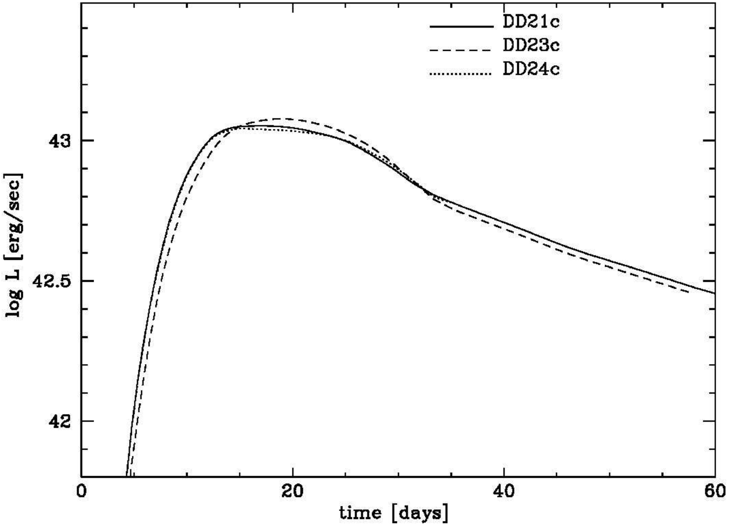
INFLUENCE ON LIGHT CURVES (0-60 Days)

DD21c: C/O=1/1; Z=0.02 (solar)

DD23c: C/O=2/3; Z=0.02 (solar)

DD24c: C/O=1/1; Z=0.0067 (solar/3)

Bolometric Light Curves



C/O Ratio of the WD

- Maxima ≈ 2-3 days later (i.g. 1-5 days)
- Peak to 'Tail' ratio changes by ≈ 0.3^m

Metalicity Z - negligible

OFF SET in M(dM15)
dM(V) ≃ 0.1 dt(rise)

The chlorine detector must be maintained in low-level operation until the chlorine and gallium detectors can be operated at full level simultaneously. Otherwise endless conjecture concerning time variations in the solar neutrino flux will ensue. Moreover, the results of the gallium observations may uncover information that has been overlooked in the past chlorine observations.

The CNO cycle operates at the higher temperatures which occur during hydrogen burning in main sequence stars somewhat more massive than the sun. This is the case because the CNO cycle reaction rates rise more rapidly with temperature than do those of the *pp* chain. The cycle is important because ^{13}C, ^{14}N, ^{15}N, ^{17}O, and ^{18}O are produced from ^{12}C and ^{16}O as seeds. The role of these nuclei as sources of neutrons during helium burning is discussed in Sec. V.

V. THE SYNTHESIS OF ^{12}C AND ^{16}O AND NEUTRON PRODUCTION IN HELIUM BURNING

The human body is 65% oxygen by mass and 18% carbon, with the remainder mostly hydrogen. Oxygen (0.85%) and carbon (0.39%) are the most abundant elements heavier than helium in the sun and similar main sequence stars. It is little wonder that the determination of the ratio ^{12}C/^{16}O produced in helium burning is a problem of paramount importance in Nuclear Astrophysics. This ratio depends in a fairly complicated manner on the density, temperature, and duration of helium burning, but it depends directly on the relative rates of the $3\alpha \rightarrow {}^{12}$C process and the ^{12}C$(\alpha,\gamma)^{16}$O process. If $3\alpha \rightarrow {}^{12}$C is much faster than ^{12}C$(\alpha,\gamma)^{16}$O, then no ^{16}O is produced in helium burning. If the reverse is true, then no ^{12}C is produced. For the most part the subsequent reaction ^{16}O$(\alpha,\gamma)^{20}$Ne is slow enough to be neglected.

There is general agreement about the rate of the $3\alpha \rightarrow {}^{12}$C process, as reviewed by Barnes (1982). However there is a lively controversy at the present time about the laboratory cross section for ^{12}C$(\alpha,\gamma)^{16}$O and about its theoretical extrapolation to the low energies at which the reaction effectively operates. The situation is depicted in Figs. 4, 5, and 6, taken with some modification from Langanke and Koonin (1983), Dyer and Barnes (1974), and Kettner *et al.* (1982). The Caltech data obtained in the Kellogg Laboratory is shown as the experimental points in Fig. 4, taken from Dyer and Barnes (1974), who compared their results with theoretical calculations by Koonin, Tombrello, and Fox (1974). The Münster data are shown as the experimental points in Fig. 5, taken from

Helium Burning:

$3\alpha \rightarrow {}^{12}C$ Known

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

$\boxed{\boxed{C/O = ?}}$

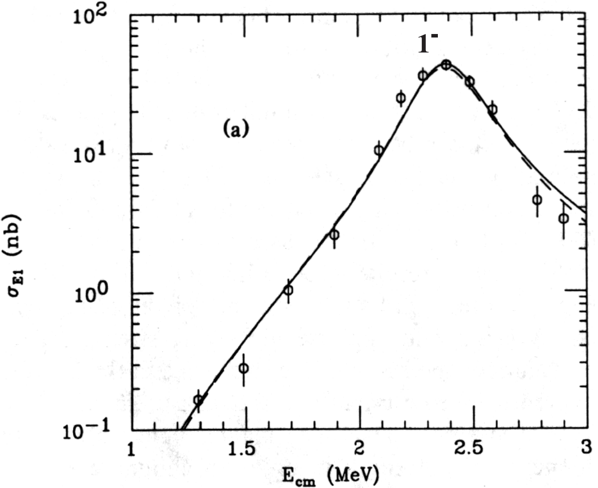
${}^{12}C(\alpha,\gamma){}^{16}O$ (E_{cm} = 300 keV)

$$\sigma(\alpha,\gamma) = S/E \times e^{-2\pi\eta}$$

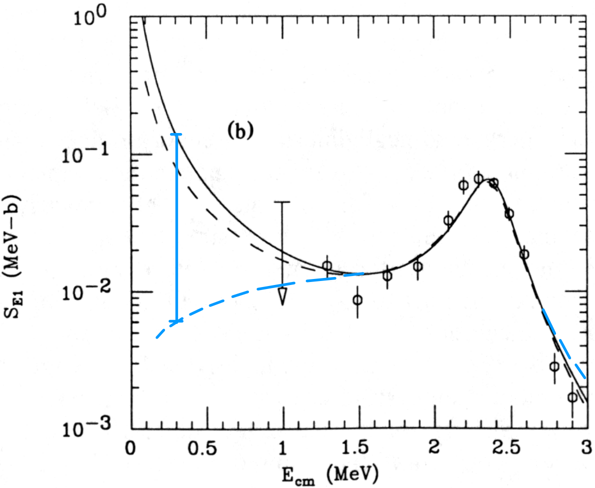
$$(\eta = e^2 Z_1 Z_2/\hbar\upsilon = Z_1 Z_2 \alpha/\beta)$$

Astrophysical Cross Section Factor (P and D waves)

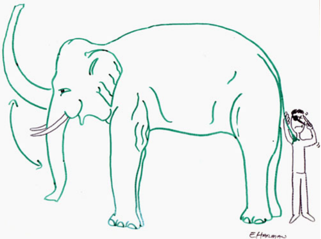
$$\boxed{\boxed{\begin{array}{c} S_{E1}(300) \\ S_{E2}(300) \\ \pm 15\% \end{array}}}$$



10^2
10^1
10^0
10^-1
σ_E1 (nb)
1⁻
(a)
1
1.5
2
2.5
3
E_cm (MeV)



10^{0}
10^{-1}
10^{-2}
10^{-3}
S_{E1} (MeV−b)
(b)
0
0.5
1
1.5
2
2.5
3
E_{cm} (MeV)



Eric T. Harman

Physics Today 55:12(2002)26

O-TPC at HIγS

(Detailed Balance)

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

$$\mathrm{E}_\gamma \quad = 8.0\text{ - }10.0\ \mathrm{MeV}\ (\pm 1\%)$$

$*\ \sigma(\alpha, \gamma_{cascade}) < 4\%$ at 300 keV

$$\sigma(\gamma, \alpha) \quad = \frac{(2S_1+1)(2S_2+1)}{2(2S_4+1)} \times \frac{k_\alpha^2}{k_\gamma^2} \times \sigma(\alpha, \gamma)$$

$$\sigma(\overrightarrow{\gamma}, \alpha) \quad = \frac{(2S_1+1)(2S_2+1)}{1(2S_4+1)} \times \frac{k_\alpha^2}{k_\gamma^2} \times \sigma(\alpha, \overrightarrow{\gamma_i})$$

but: $\sigma(\alpha, \overrightarrow{\gamma_i}) = \frac{1}{2}\sigma(\alpha, \gamma)$

$$= \frac{(2S_1+1)(2S_2+1)}{2(2S_4+1)} \times \frac{k_\alpha^2}{k_\gamma^2} \times \sigma(\alpha, \gamma)$$

$$= \frac{1}{2} \times (80 - 160) \times \sigma(\alpha, \gamma)$$

$$\boxed{= (40 - 80) \times \sigma(\alpha, \gamma)}$$

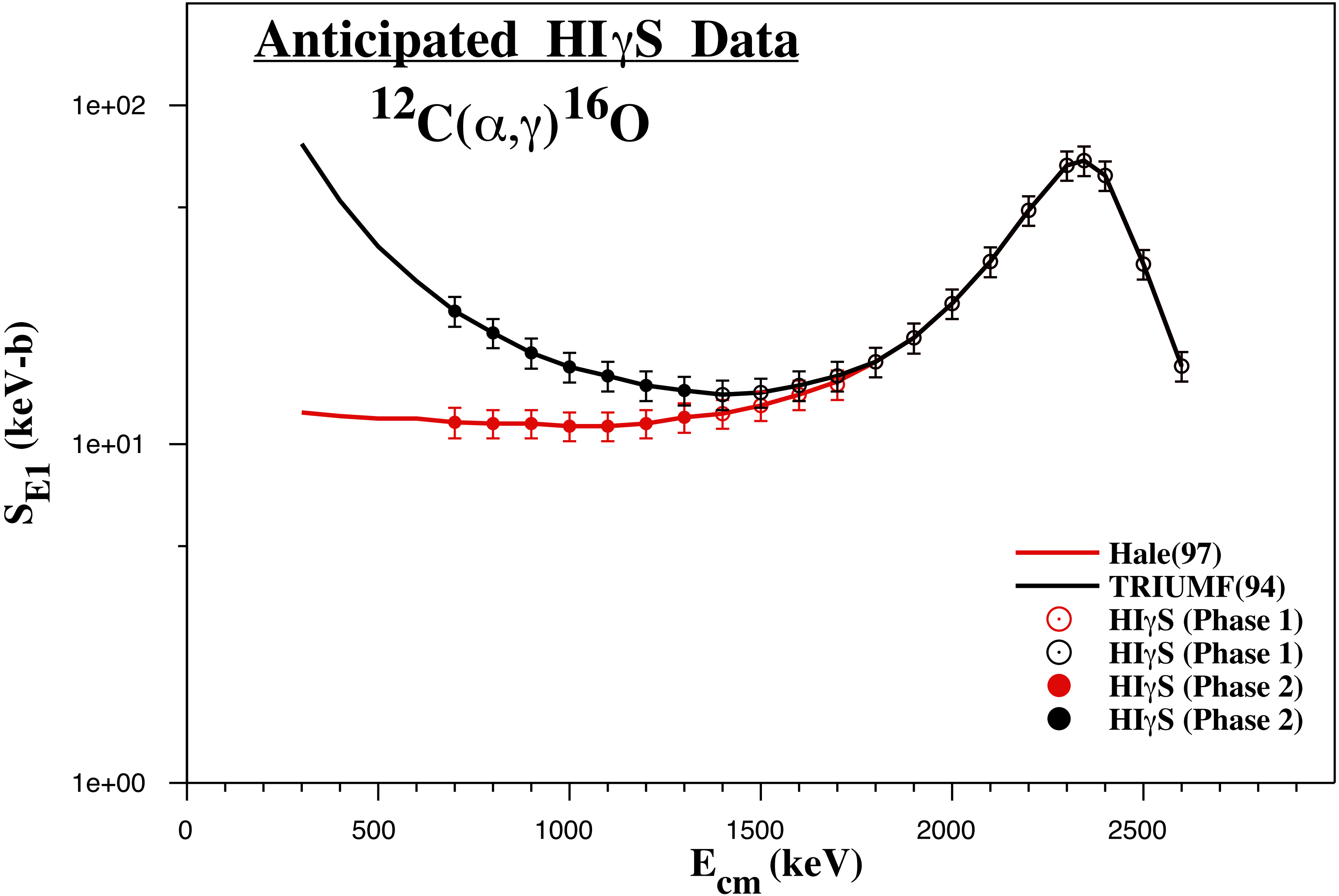
Luminosity = 1 nb^{-1} per Day

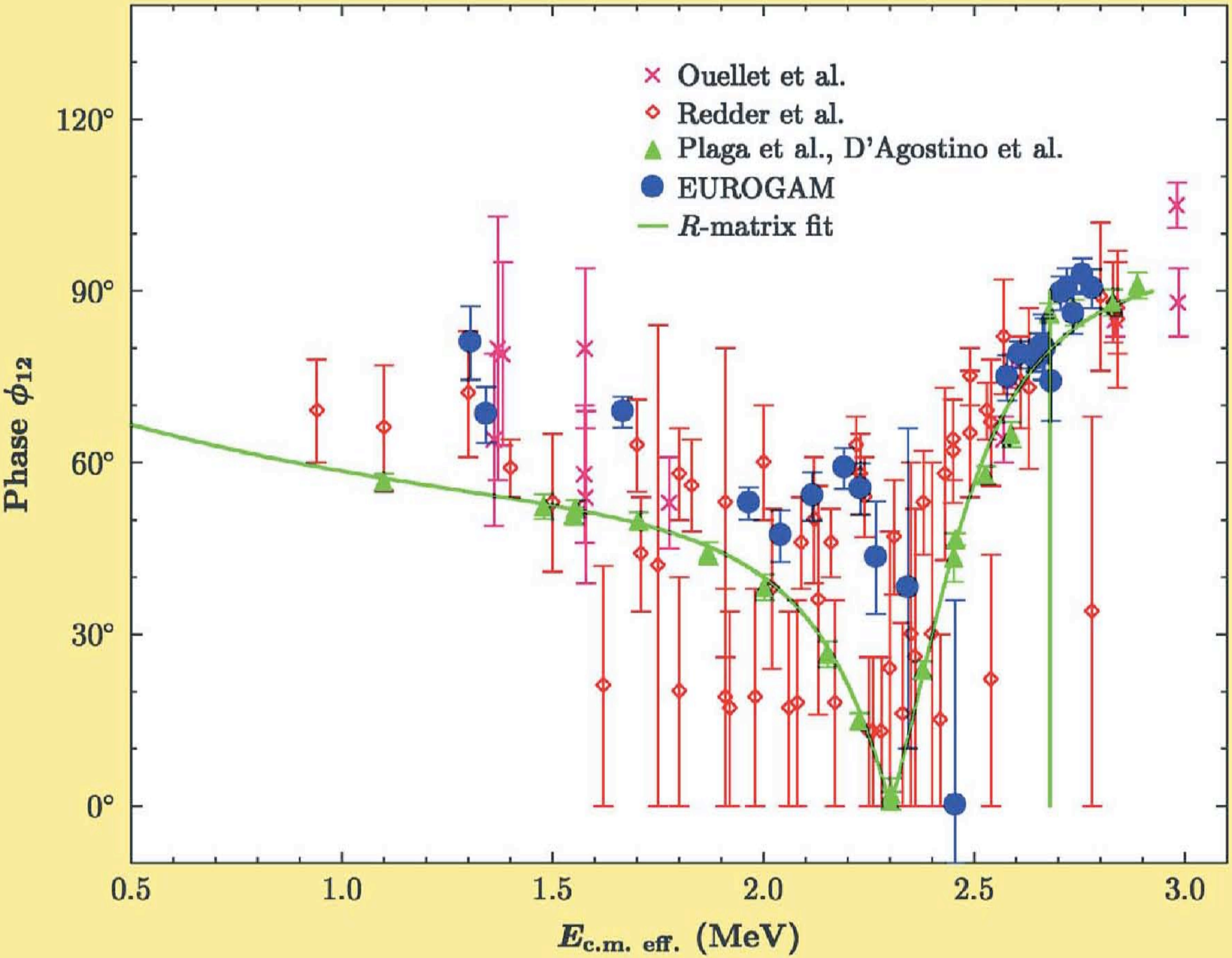
$\mathrm{I}_\gamma = 4.0 \times 10^7$ /sec (phase 1), $\Delta\mathrm{E} = 2\%$, Collimator = 1/2”

$\sigma_{\alpha\gamma}(1.3MeV) = 0.6\ nb,\ \sigma_{\gamma\alpha}(8.5MeV) = 30\ nb \rightarrow\ 30CPD$

Anticipated HIγS Data

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

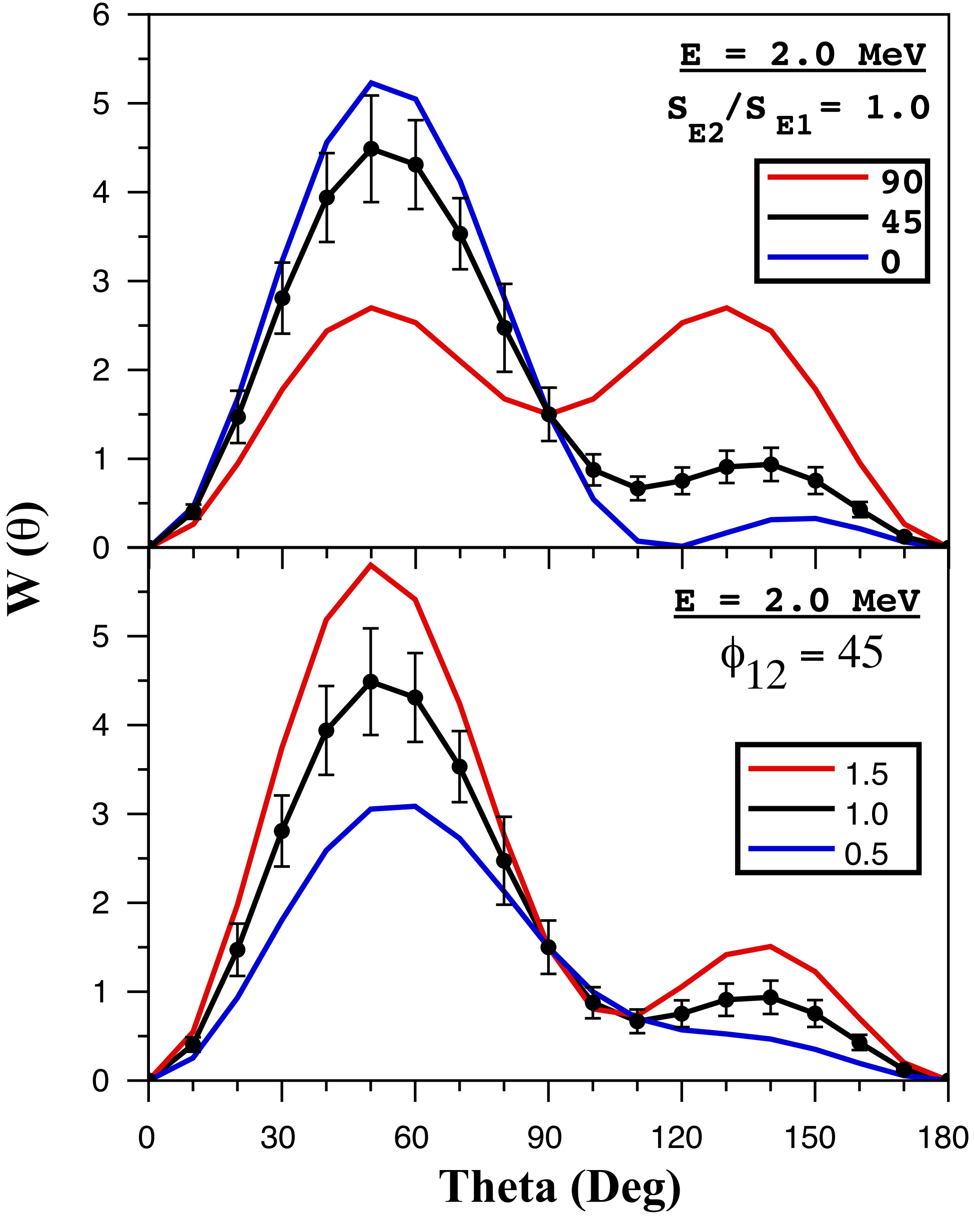


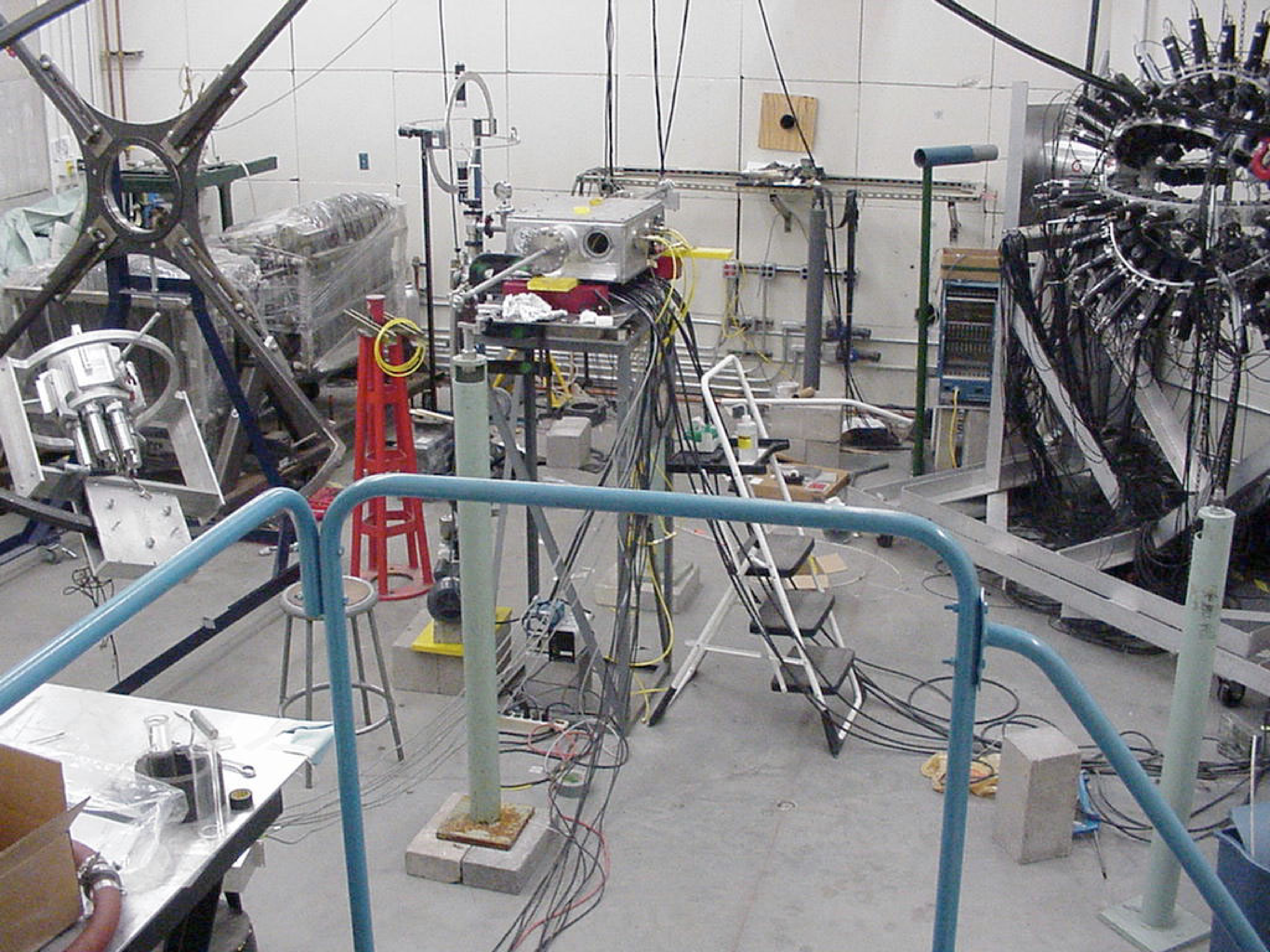

Ouellet et al.
Redder et al.
Plaga et al., D'Agostino et al.
EUROGAM
R-matrix fit
Phase ϕ_{12}
120°
90°
60°
30°
0°
0.5
1.0
1.5
2.0
2.5
3.0
$E_{\mathrm{c.m.\ eff.}}$ (MeV)

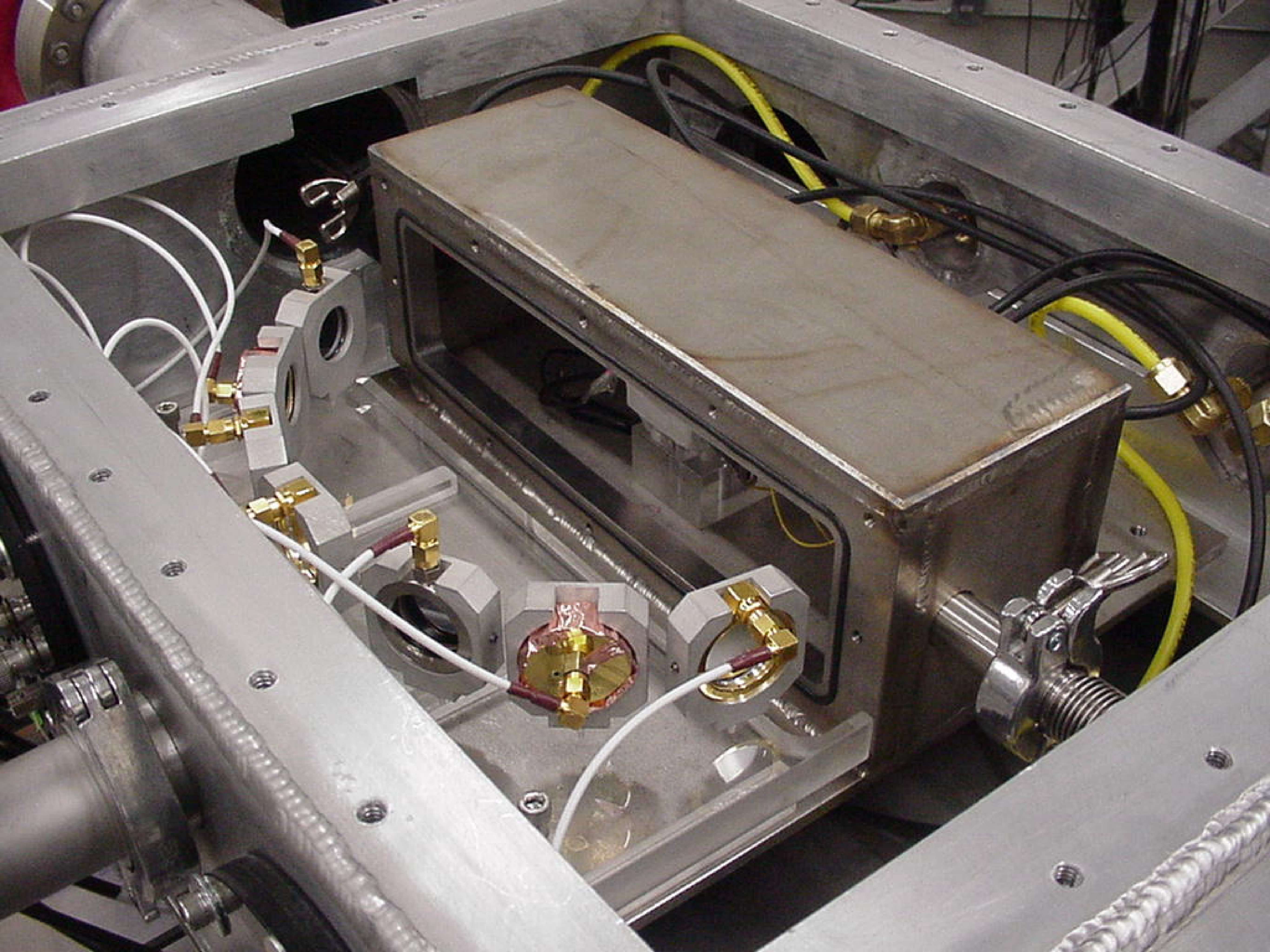
One tantalizing new problem that was posed by the new gamma-ray data [2] is the disagreement between E1/E2 mixing phases (ϕ_{12}) extracted from the measured gamma-ray angular distributions and the mixing phase predicted by theory:

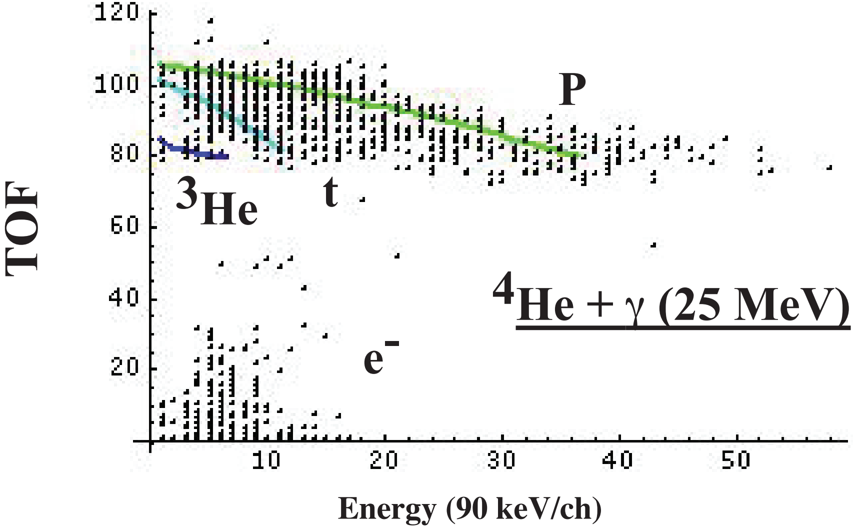
$$\phi_{12} = \delta_2 - \delta_1 + \arctan(\eta/2)$$

where δ_1 and δ_2 are the p and d wave elastic phase shifts and η is the Sommerfeld parameter. In Ref. [2] the disagreement is considered as a simple disagreement between data and the prediction of R-Matrix theory. But in fact the above relationship is rooted in the Watson theorem and unitarity. This disagreement is observed already at high energies, on the broad 1^- resonance located at 9.58 MeV where the capture cross-section is large, and it must be resolved.


E = 2.0 MeV
$S_{E2}/S_{E1} = 1.0$
90
45
0
E = 2.0 MeV
$\phi_{12} = 45$
1.5
1.0
0.5
W (θ)
Theta (Deg)
0
1
2
3
4
5
6
0
30
60
90
120
150
180

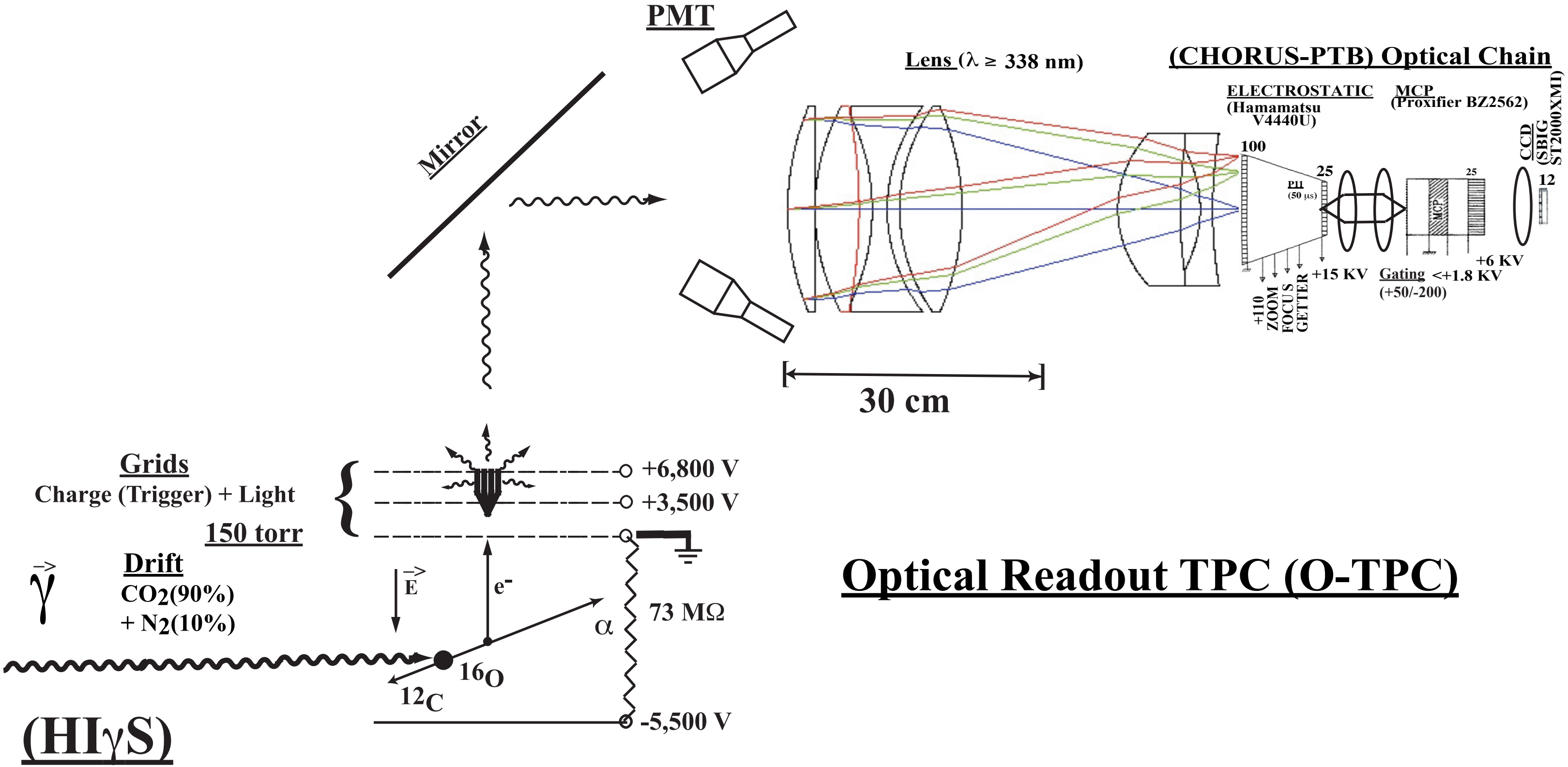


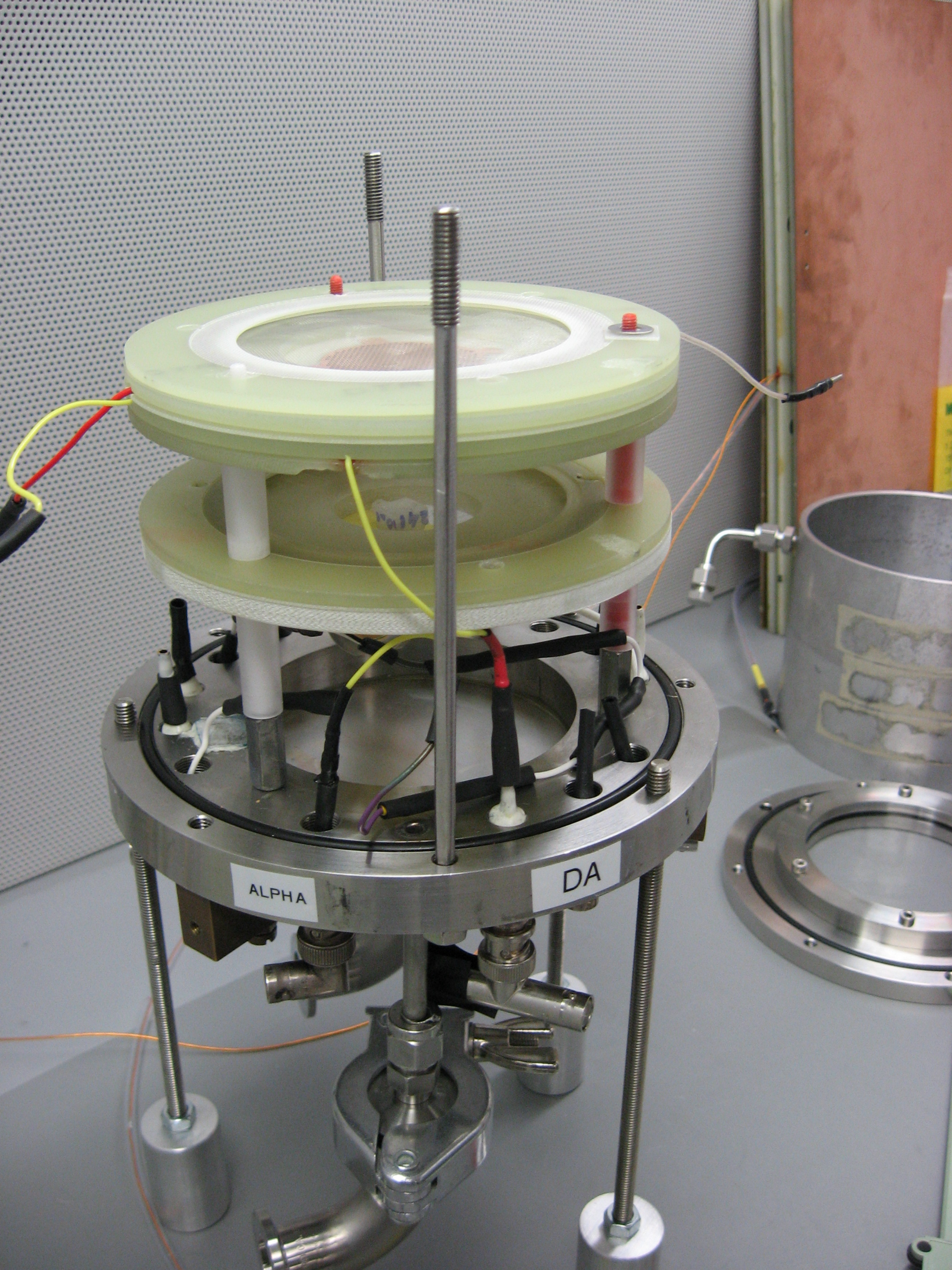


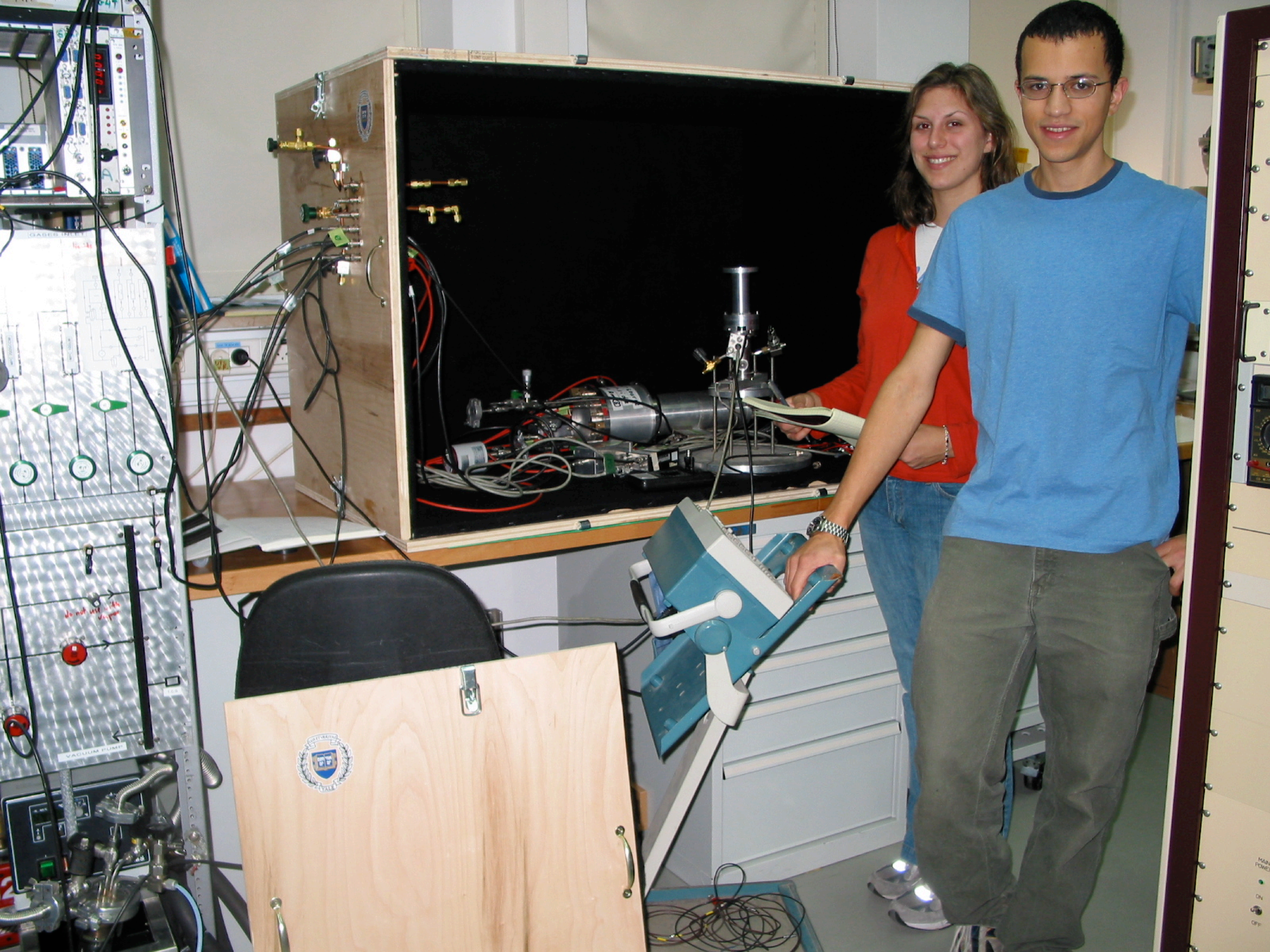


120
100
80
60
40
20
10
20
30
40
50
TOF
Energy (90 keV/ch)
P
t
3He
e-
4He + γ (25 MeV)

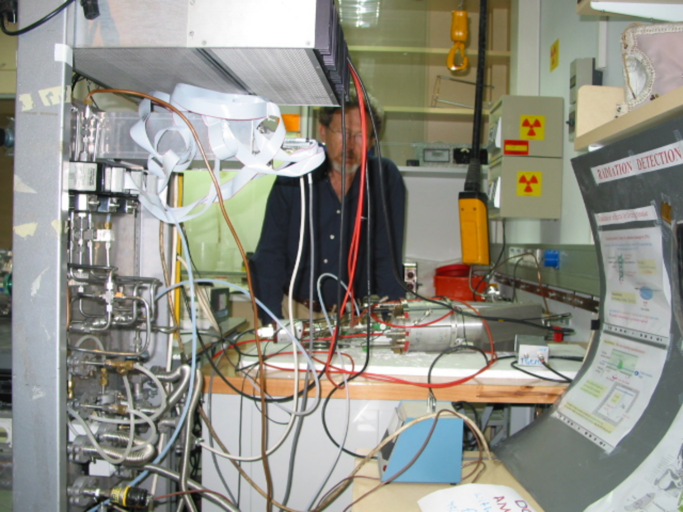
Optical Readout TPC (O-TPC)

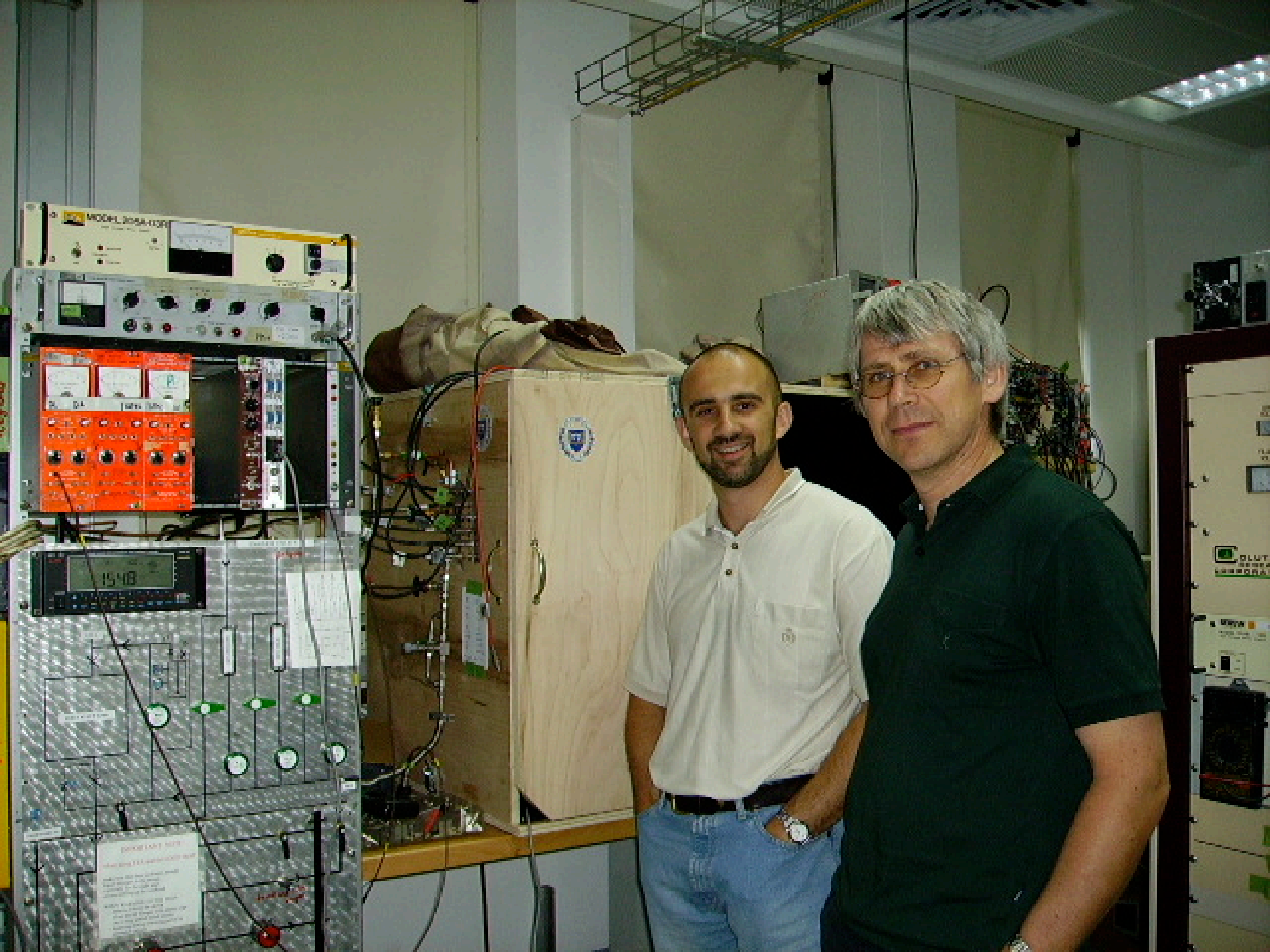



ALPHA
DA

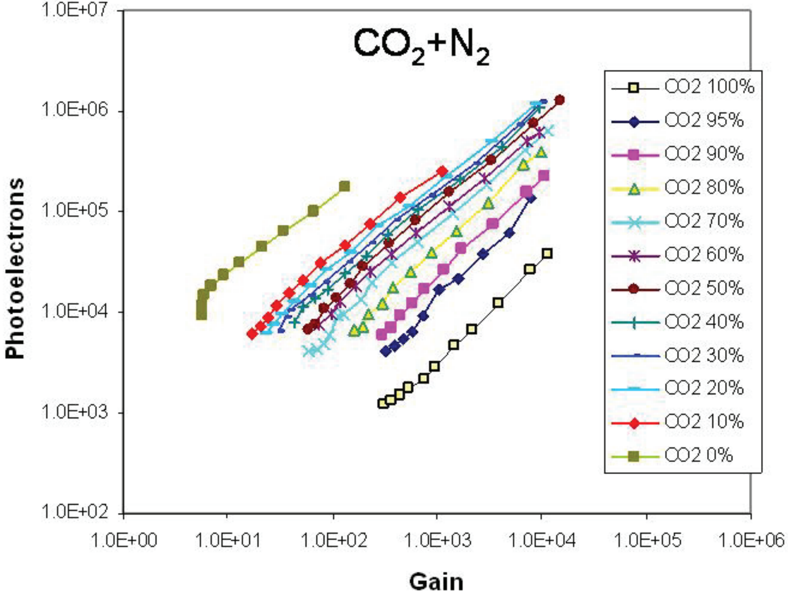

GASES INLET
VACUUM PUMP

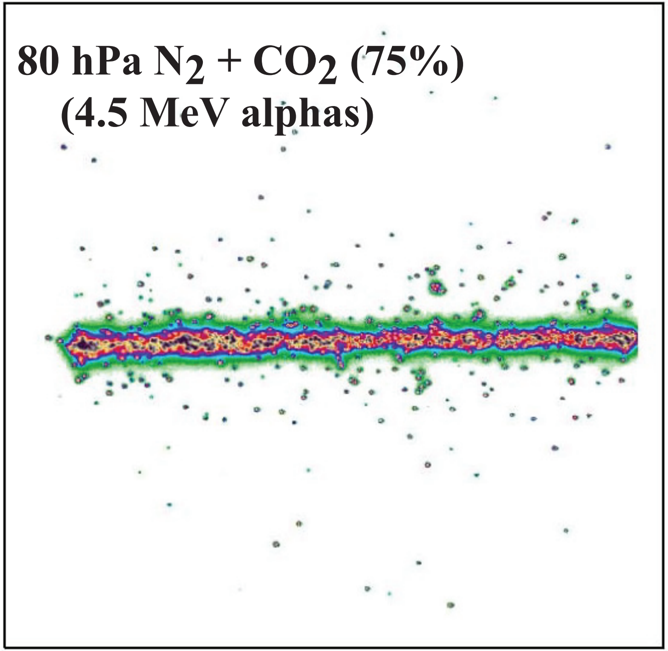

MODEL 205A-03R
Regular
IMPORTANT NOTE
DETECTOR
ANODE VOLTAGE
ION SOURCE PRESSURE
ANODE CURRENT
FILAMENT VOLTAGE
ANODE
FILAMENT CURRENT
FILAMENT
FOCUS
COLUTRON RESEARCH CORPORATION
ACCELERATION A2


RADIATION DETECTION

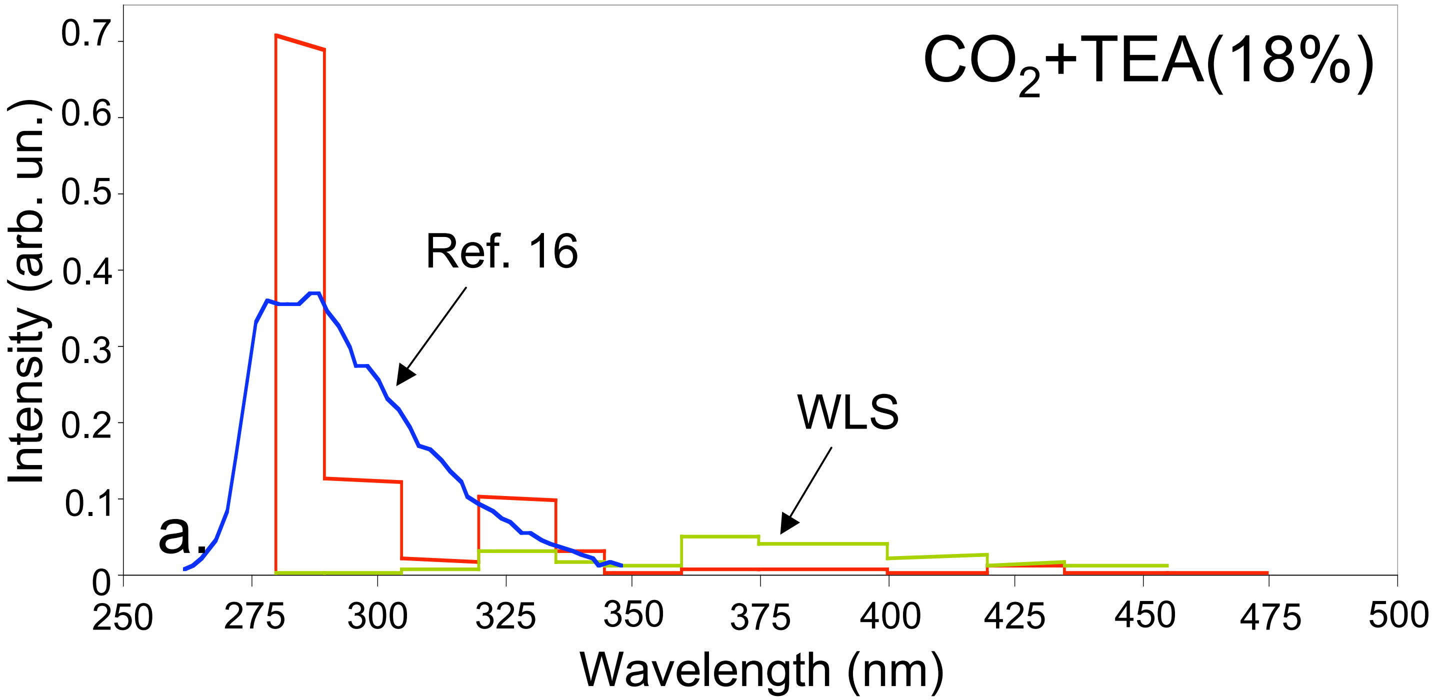


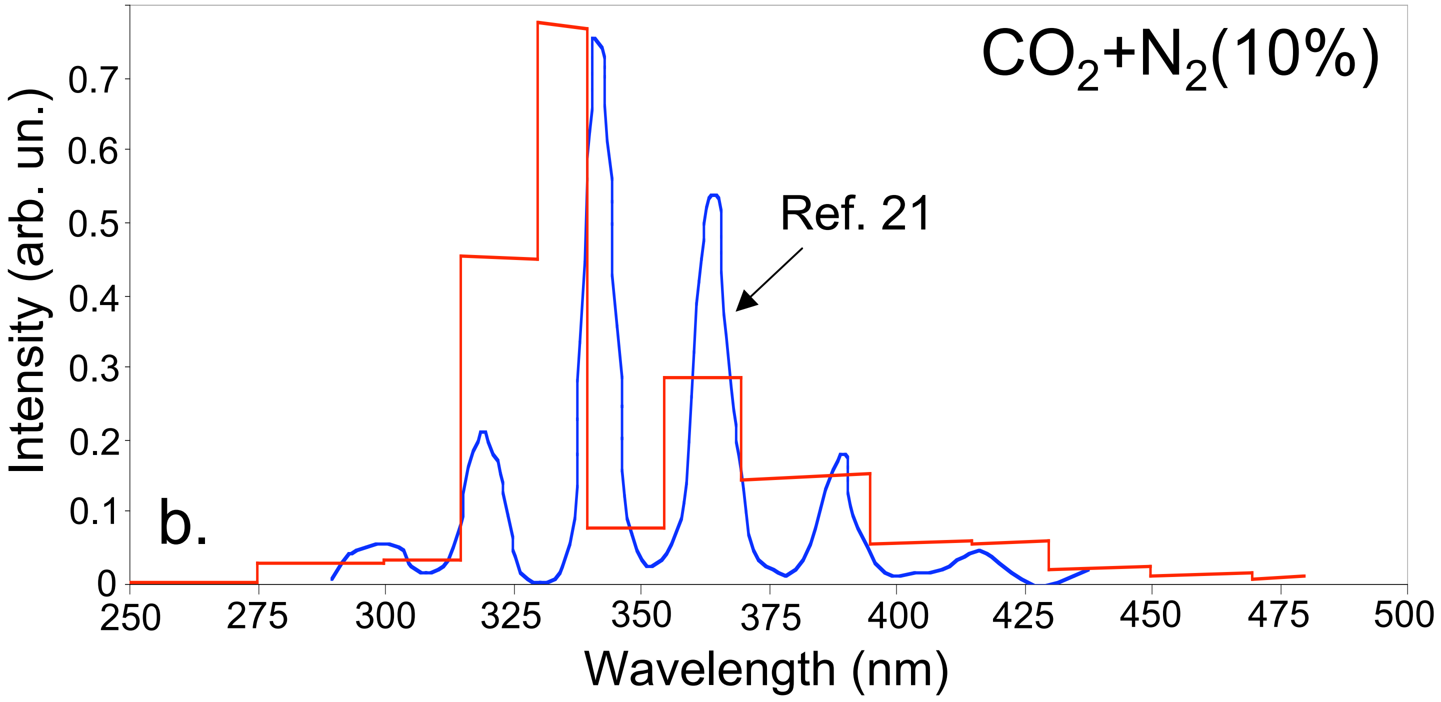
L. Weissman *et al.*; JINST 1(2006)05002



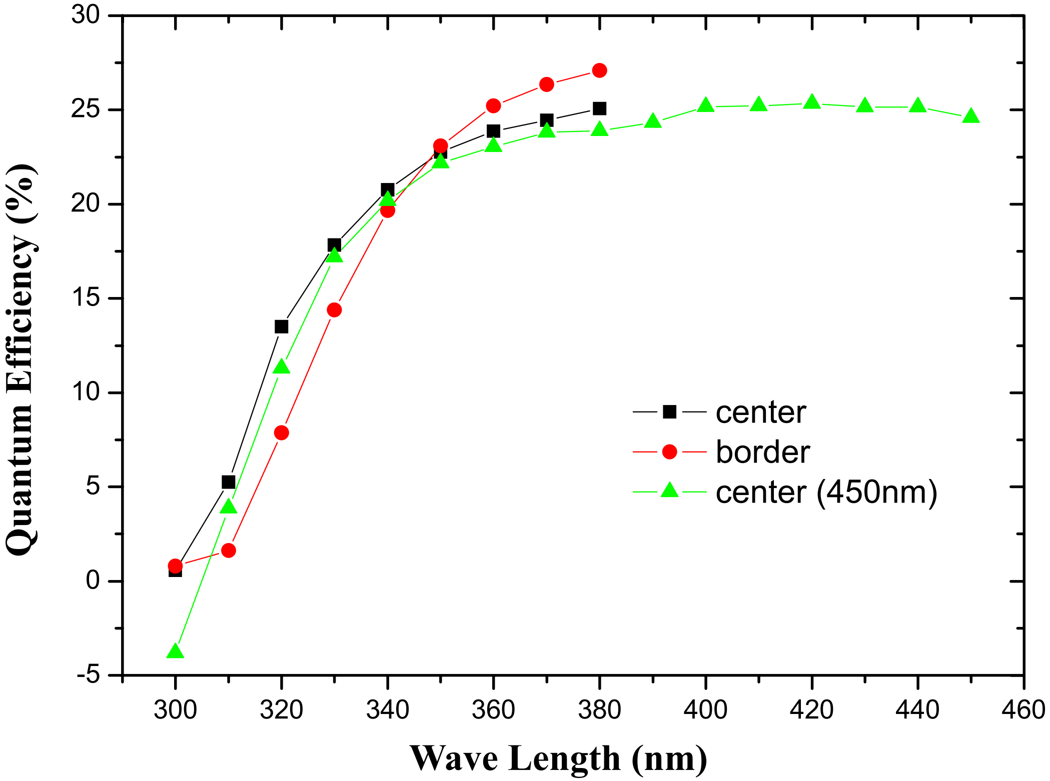


80 hPa N_2 + CO_2 (75%)
(4.5 MeV alphas)

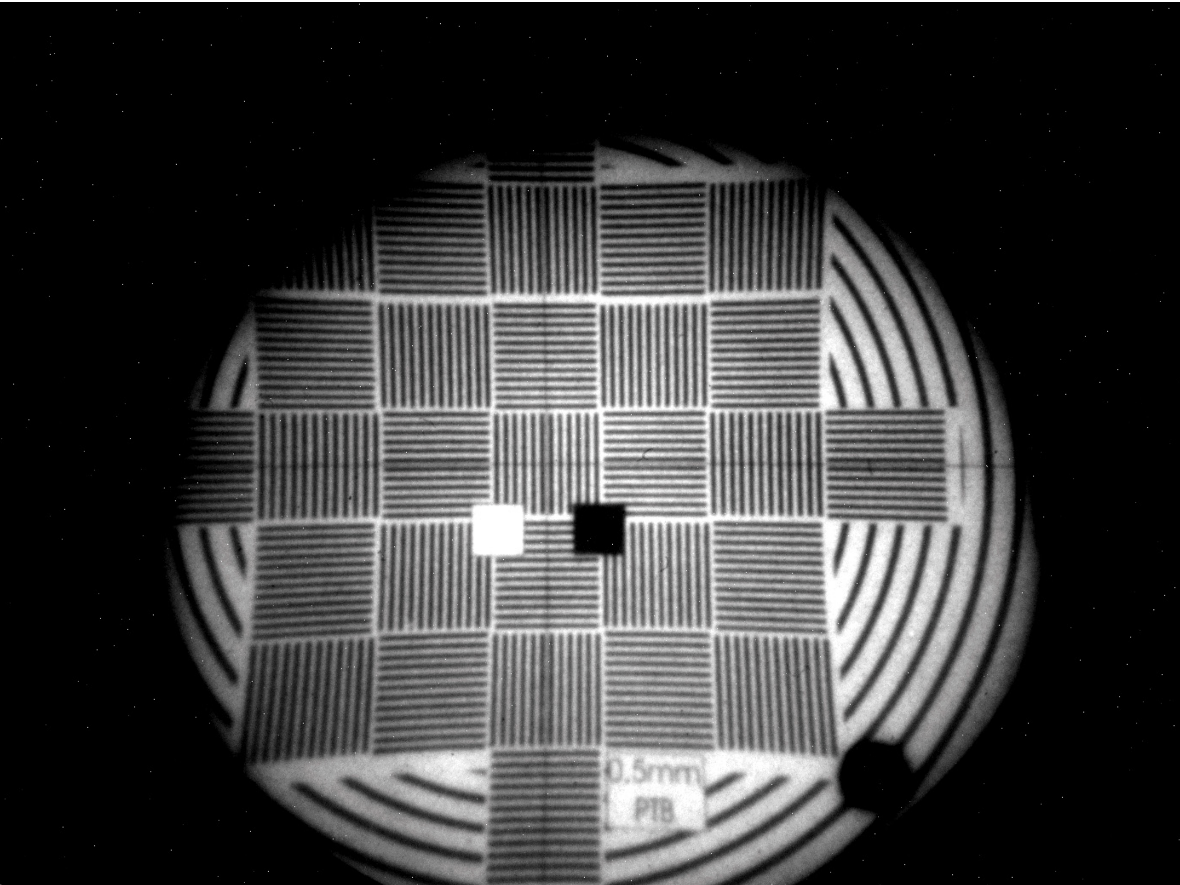

CO$_2$+TEA(18%)
Ref. 16
WLS
a.
Intensity (arb. un.)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
250
275
300
325
350
375
400
425
450
475
500
Wavelength (nm)


CO$_2$+N$_2$(10%)
Ref. 21
b.
Intensity (arb. un.)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
250
275
300
325
350
375
400
425
450
475
500
Wavelength (nm)

Quantum Efficiency of CHORUS BV55 Optical Chain/ PTB. March 2006.



Contrast Transfer Function Mask, PTB, June 2006.



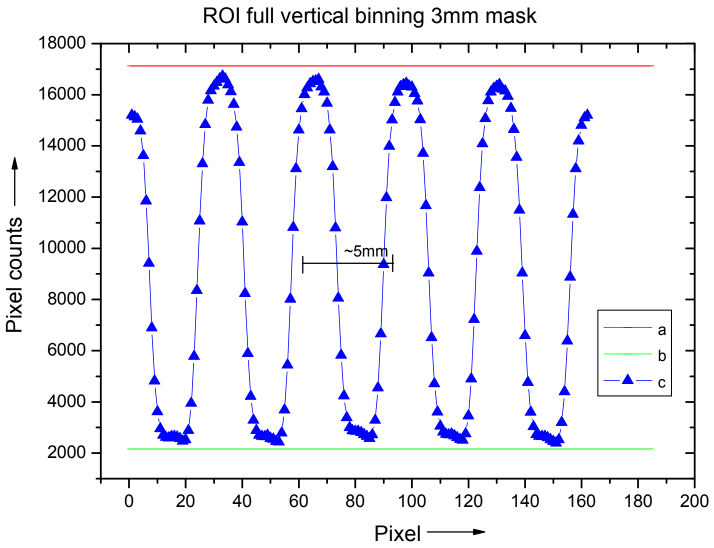
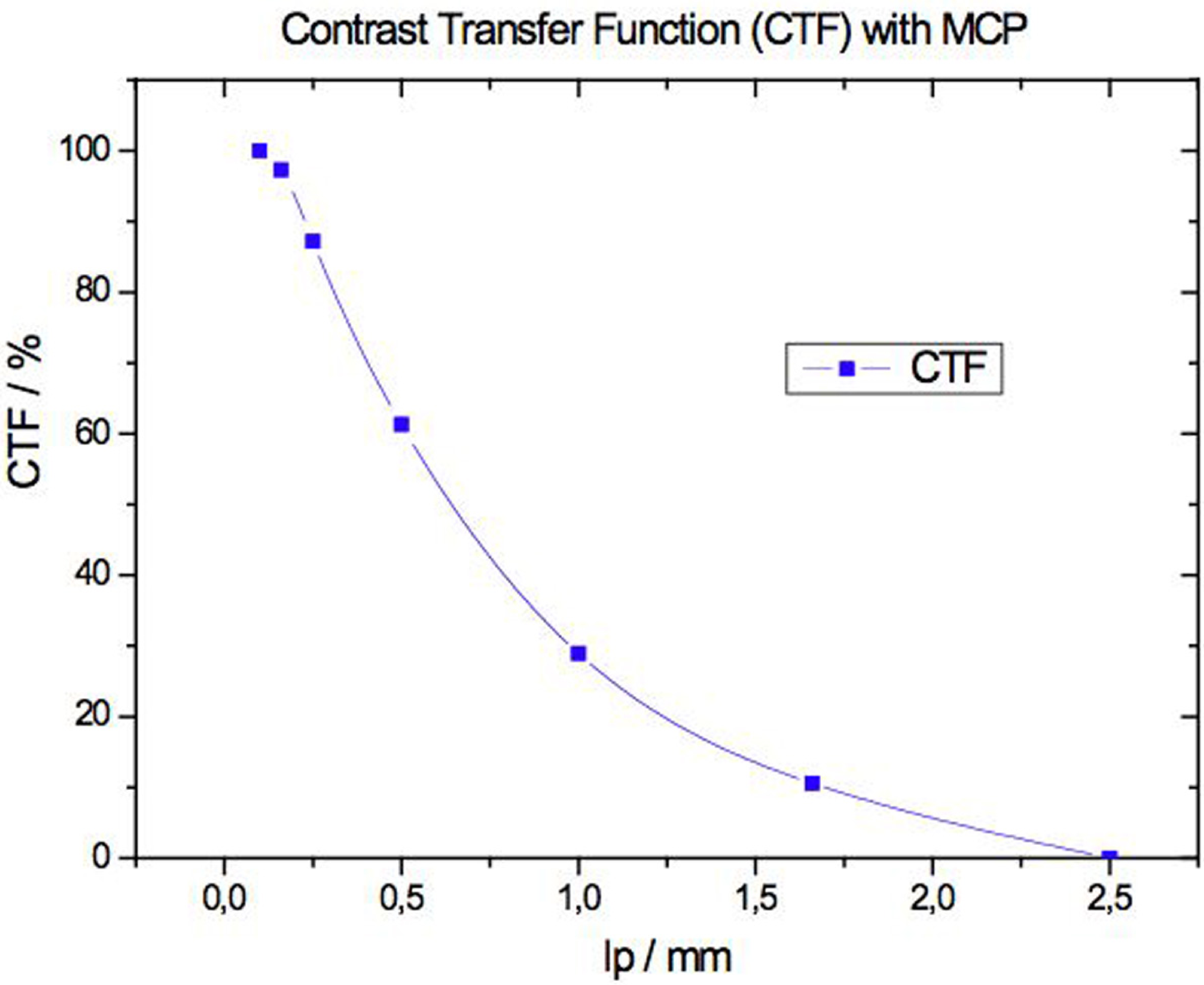
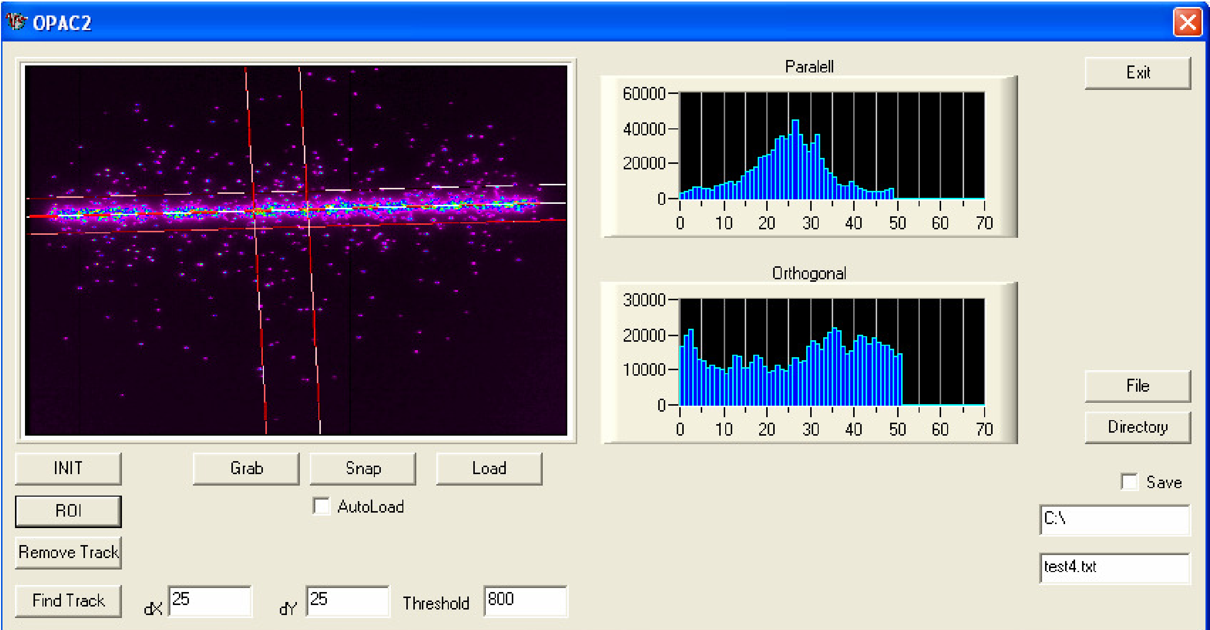


Fig.56: ROI full vertical binning of the 3 mm mask (a = white value; b = black value; c =pixel contents)


Contrast Transfer Function (CTF) with MCP
CTF / %
100
80
60
40
20
0
0,0
0,5
1,0
1,5
2,0
2,5
lp / mm
CTF


FRAGILE
Coca-Cola
YORK

Benjamin Bromberger - PTB (University of Braunschweig)



☐ AutoLoad

☐ Save

C:\

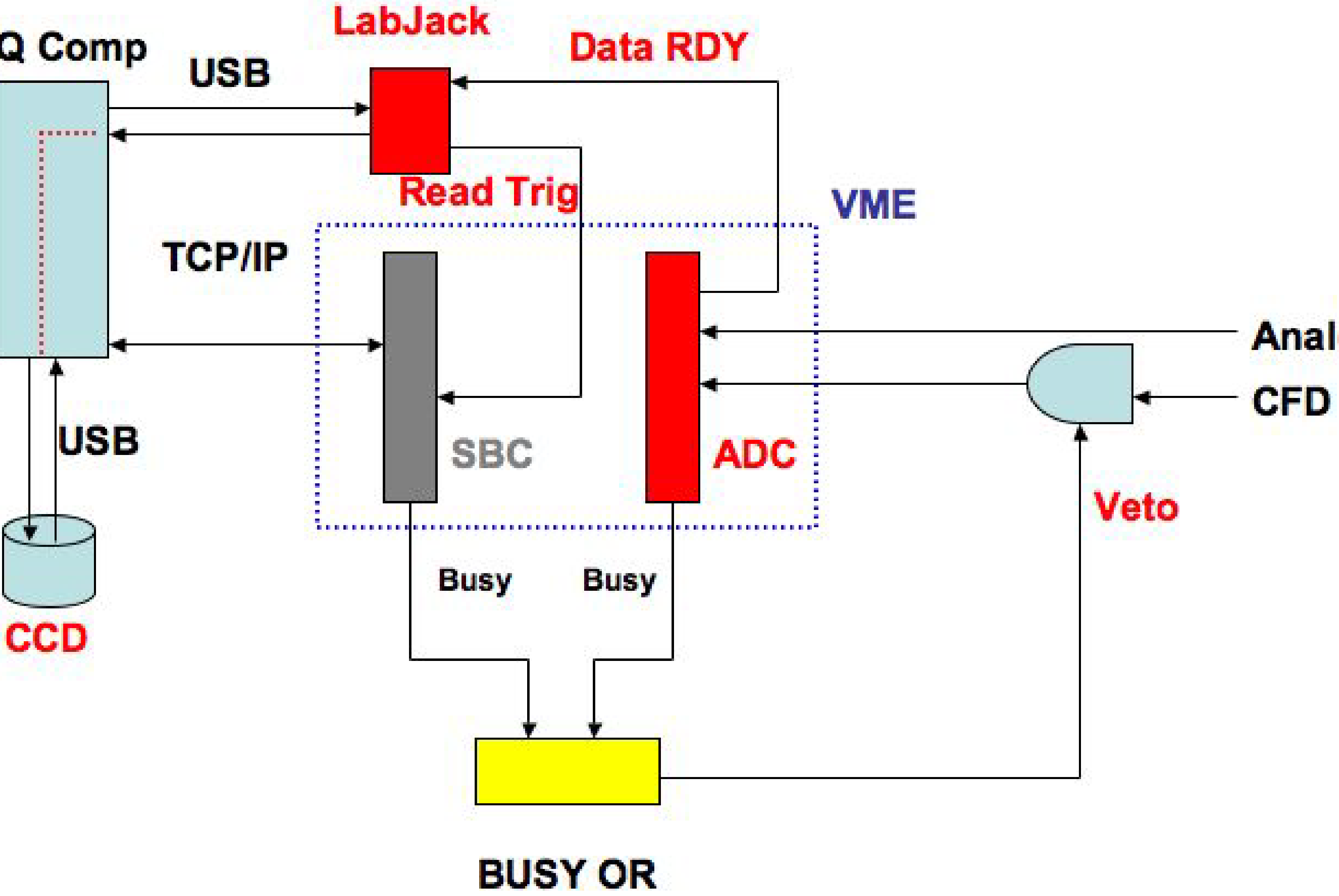
test4.txt

dX 25

dY 25

Threshold 800

Triggered Readout of OTPC System

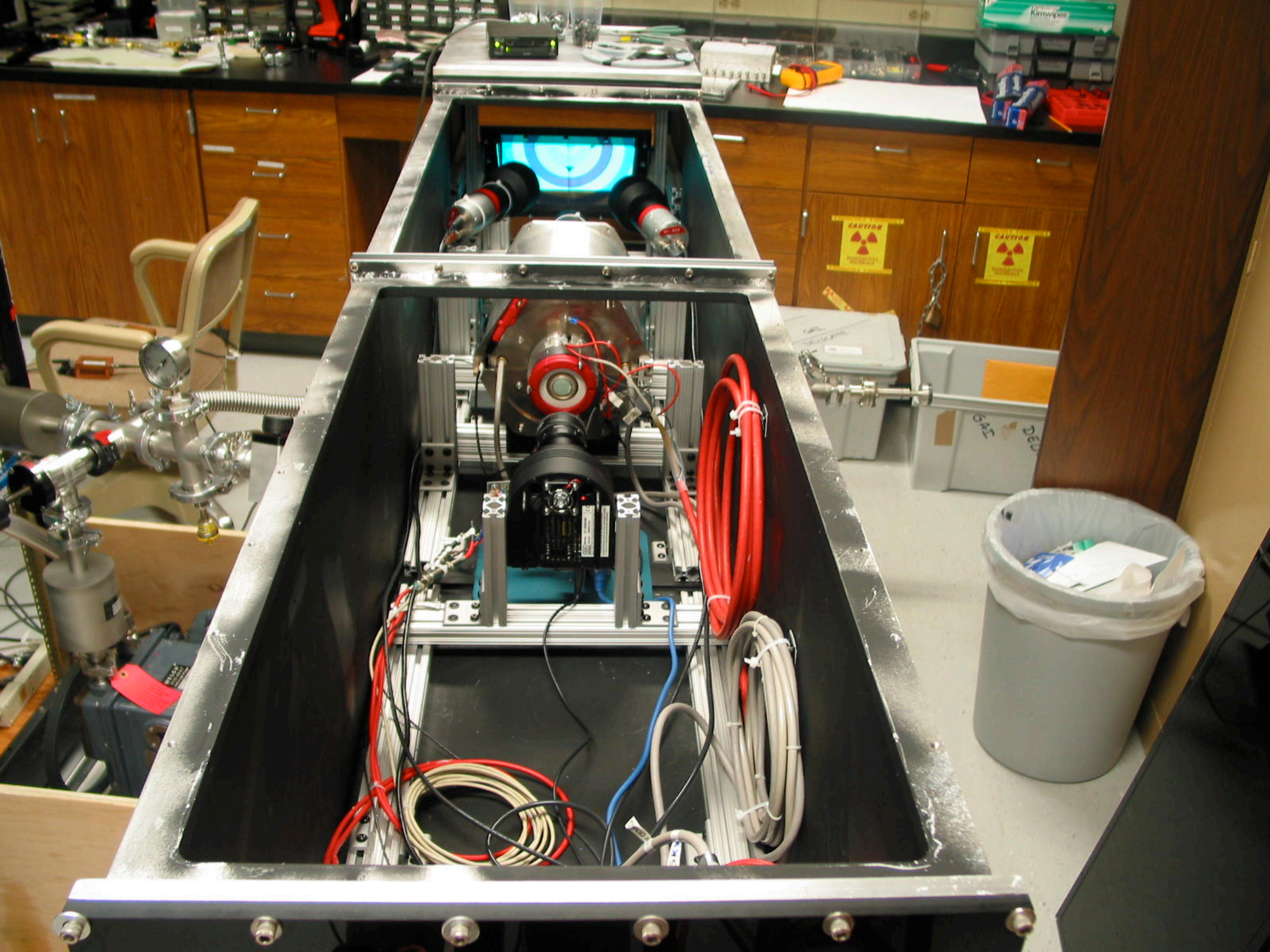


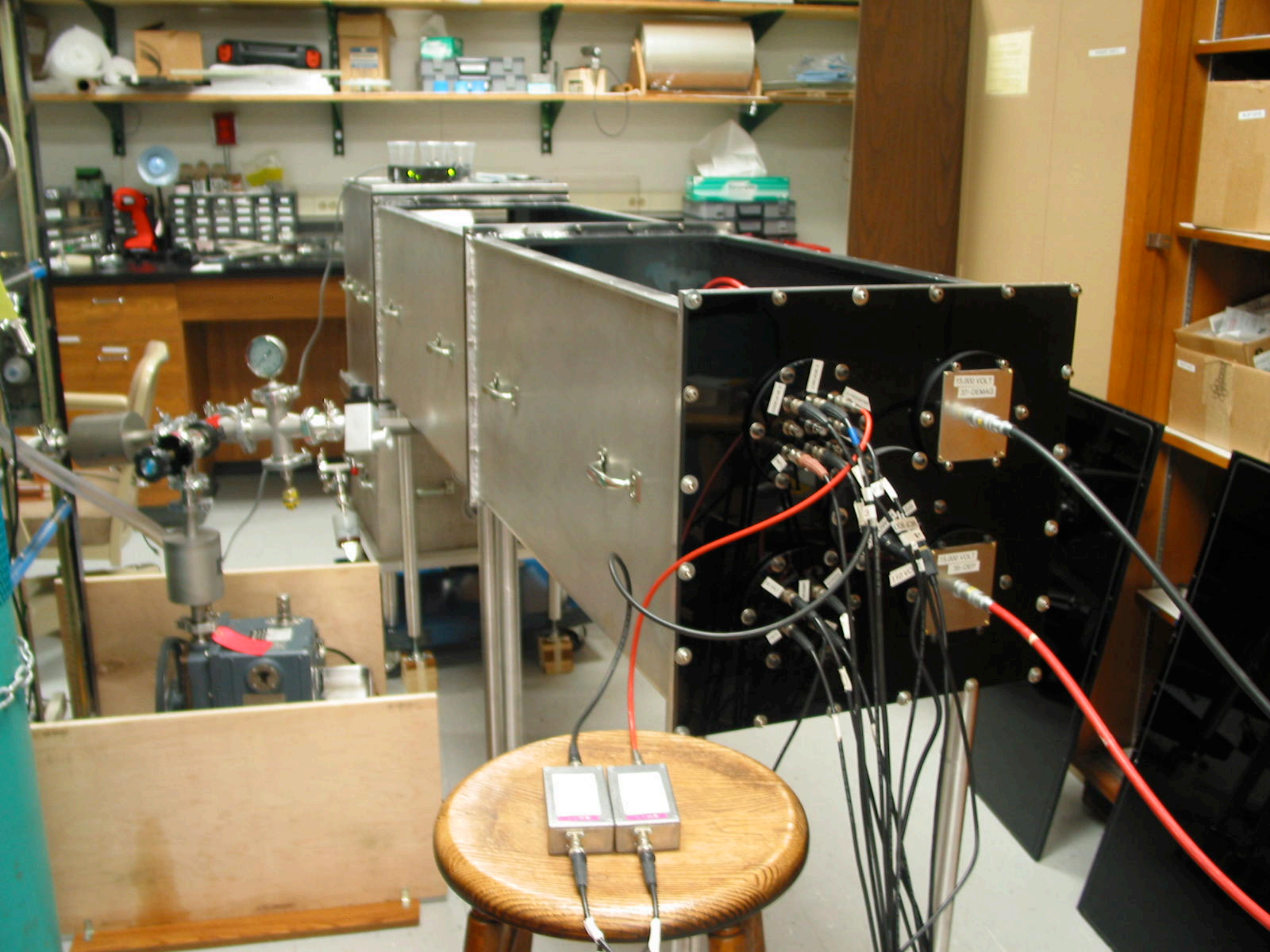
The Entire System

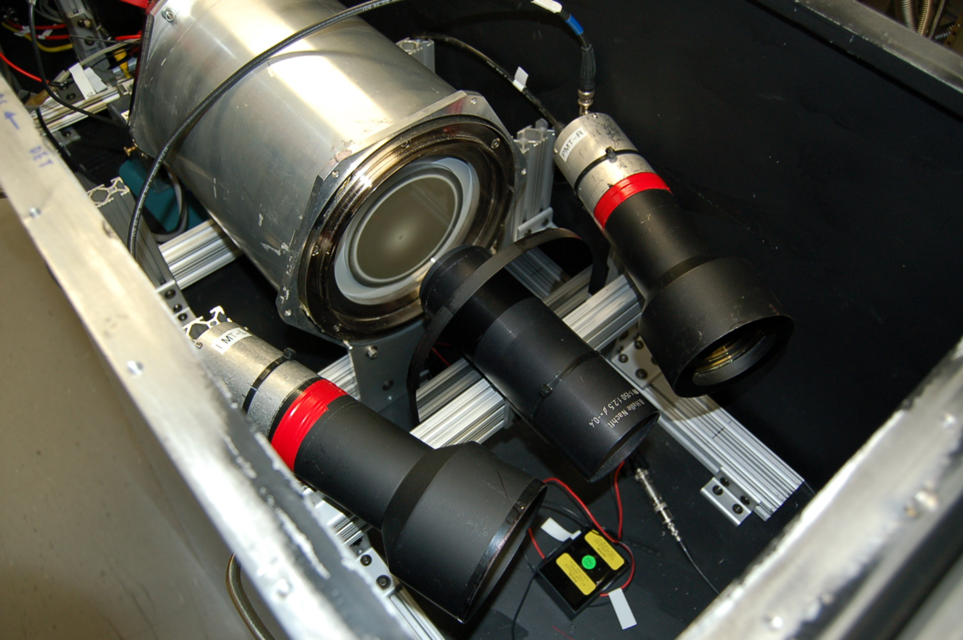
nature
Radiations
102
LABORATORY
No Food In Lab
No Food In Lab
CLASSIC

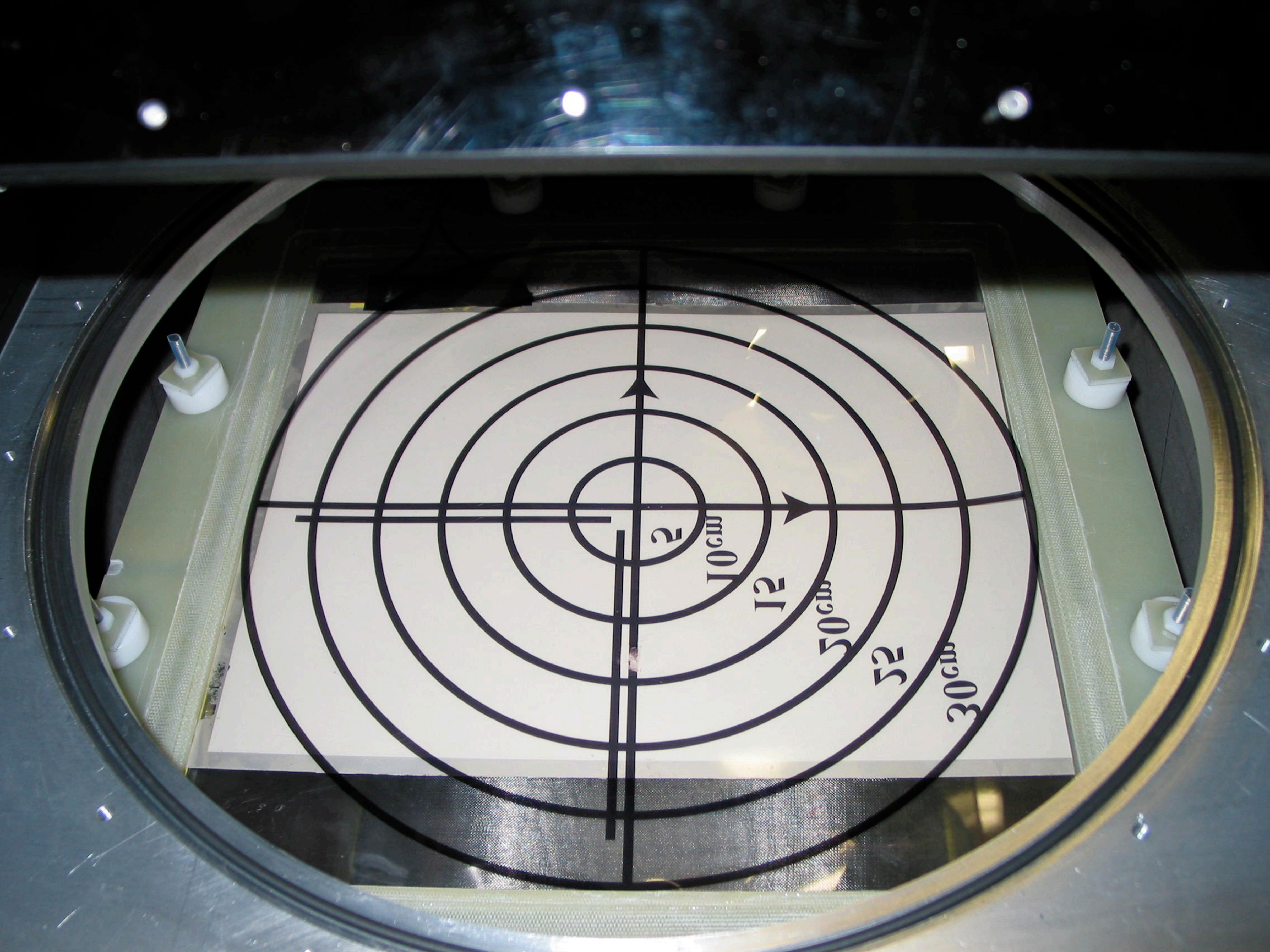

Belden

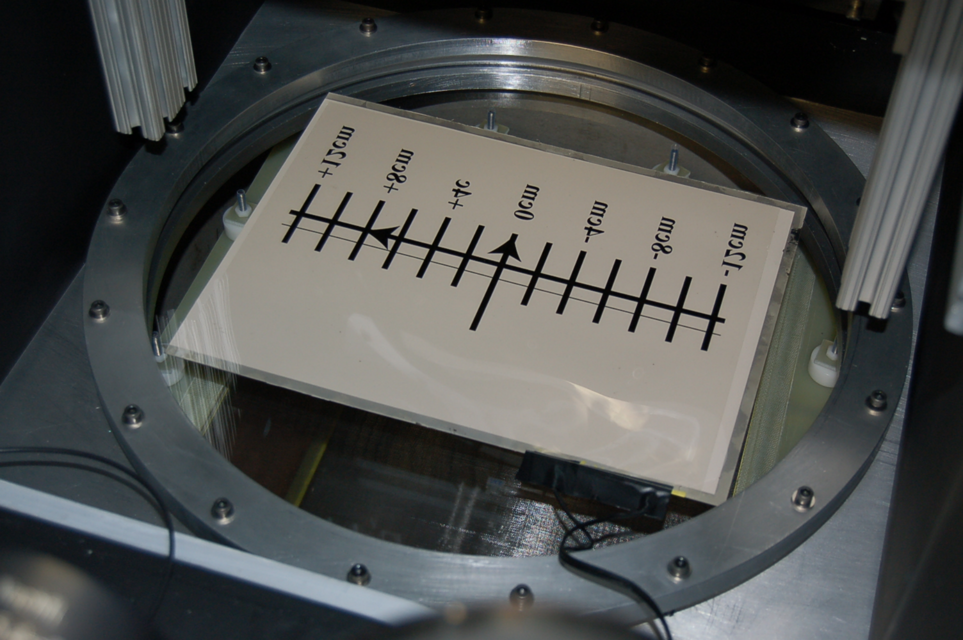

1514
3
2
1
DETECTOR
N2
CO2
IMPORTANT NOTE
VACUUM PUMP
UCONN


Kimwipes
CAUTION
CAUTION

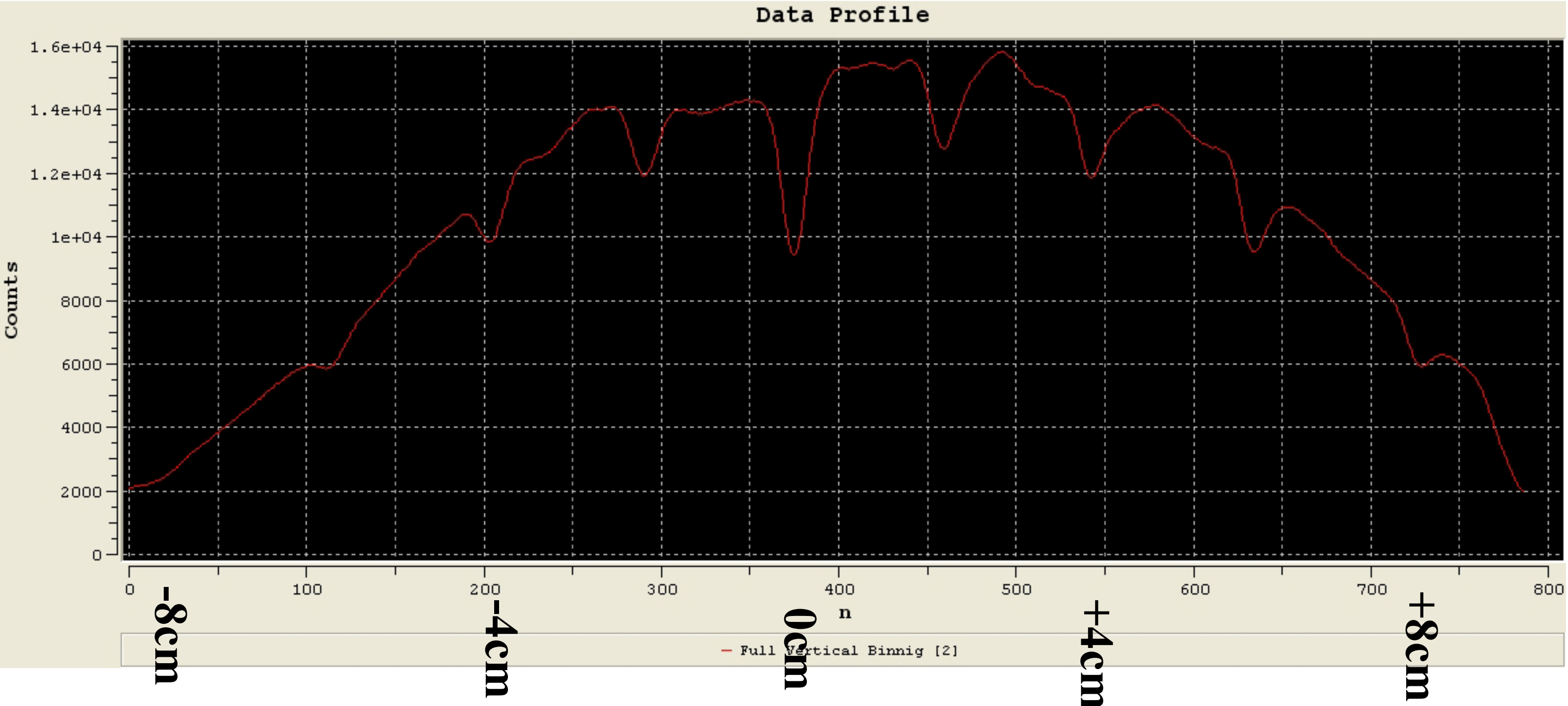

15,000 VOLT
37-DEMAG
15,000 VOLT
38-DEF

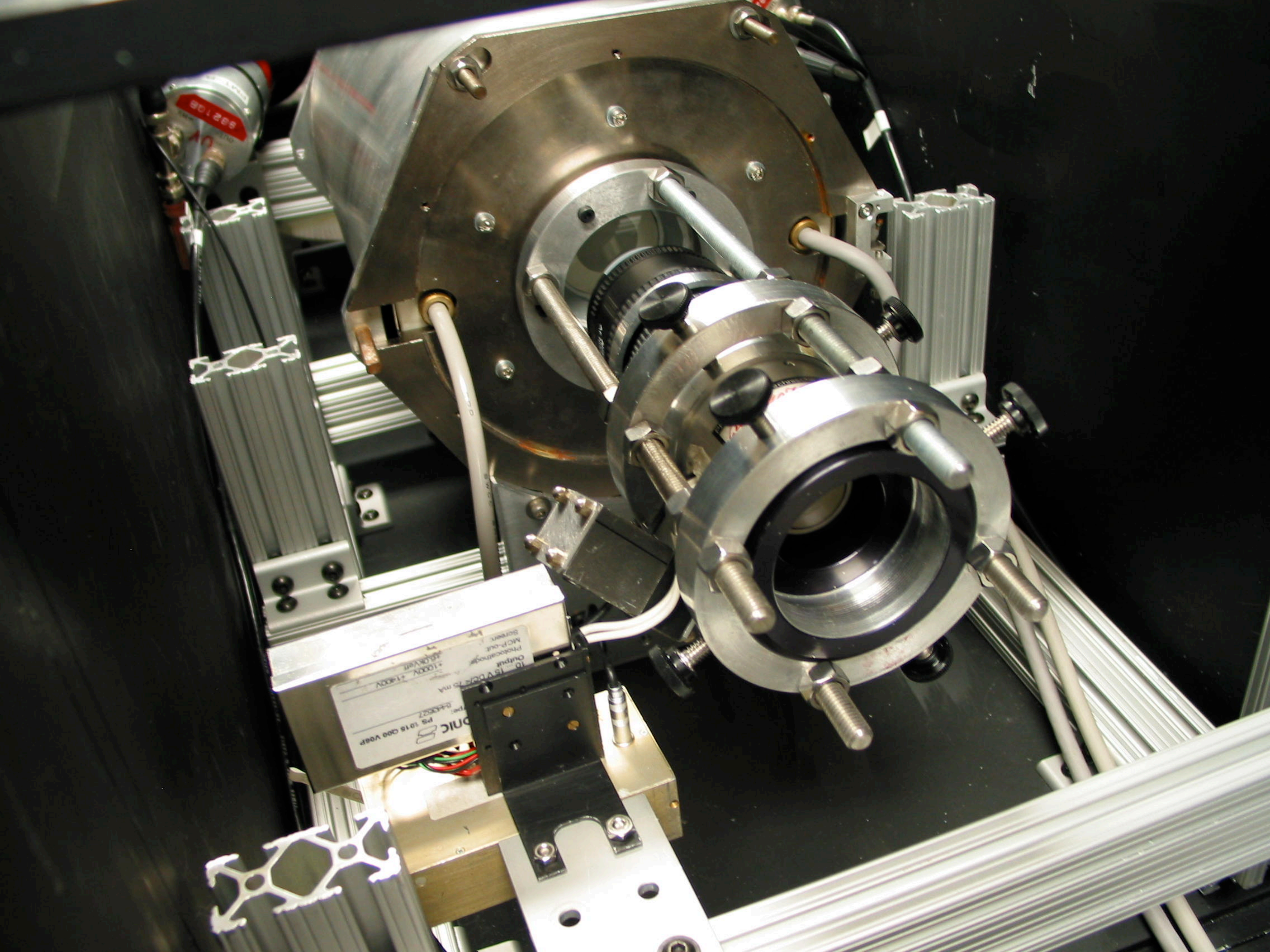

PMT-R
PMT-L
DET
B.Halle Nachfl.
M 1:150 f:2,5 ø-0,4

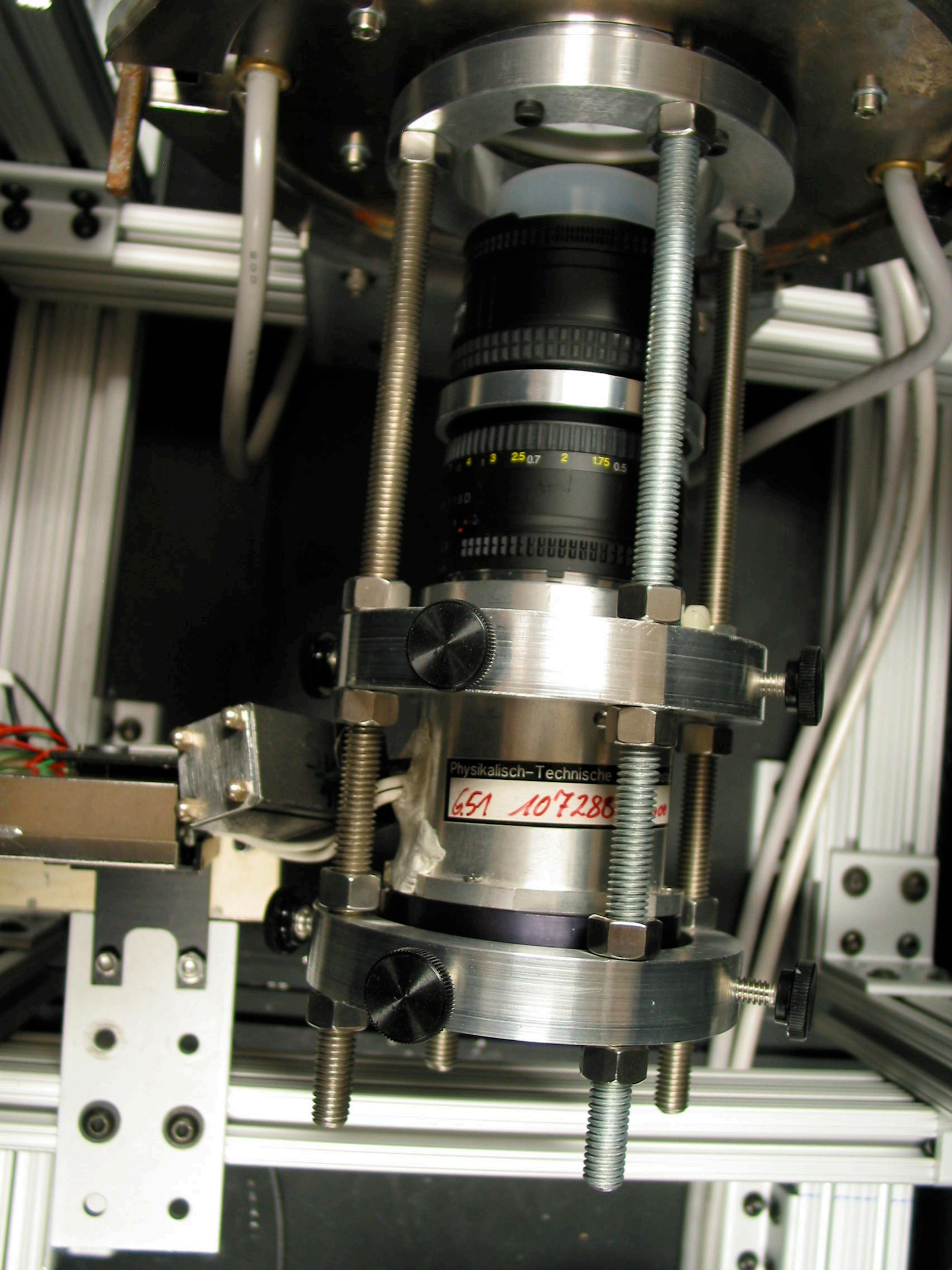

5
10cm
15
20cm
25
30cm

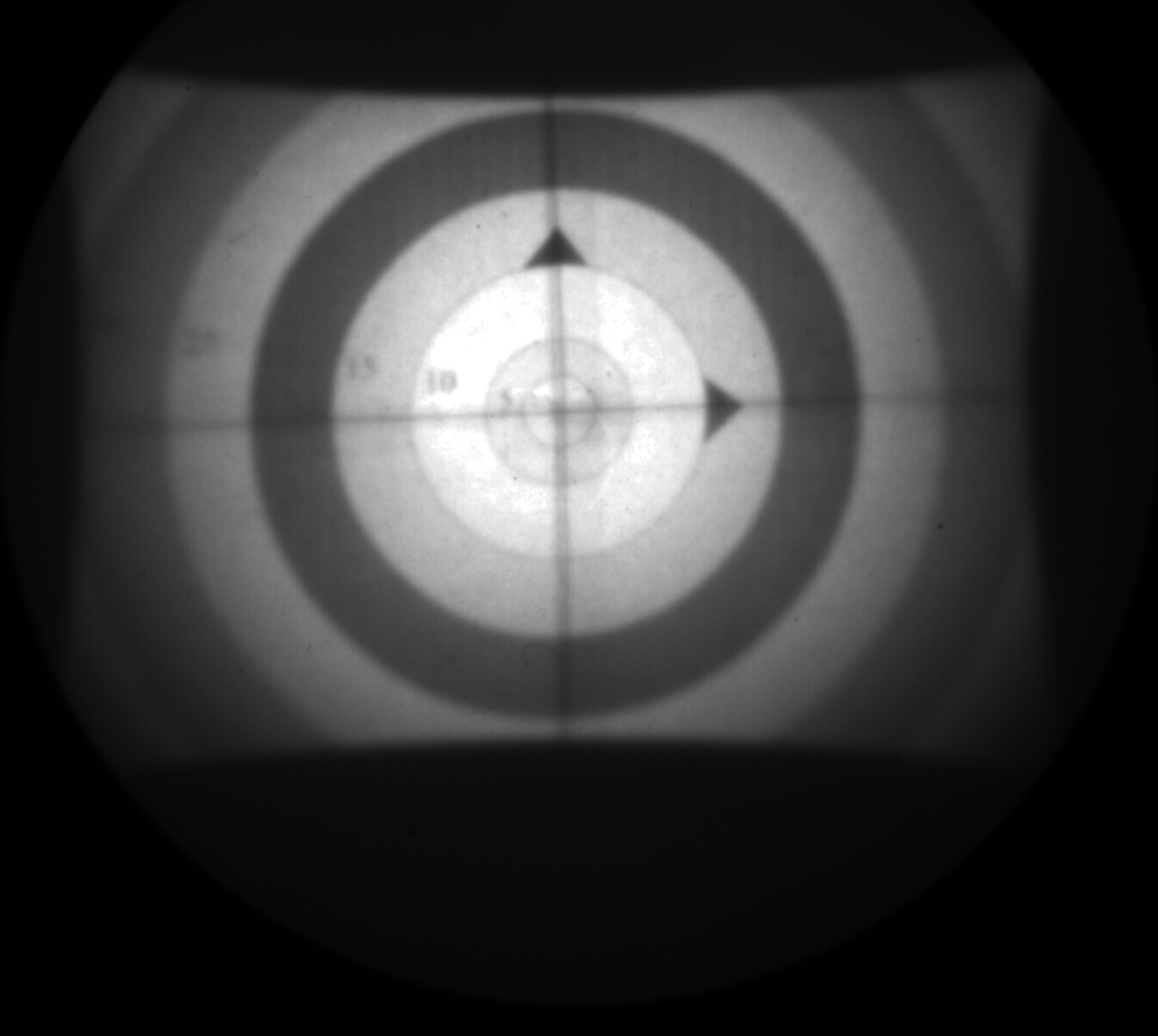

+12cm
+8cm
+4c
0cm
-4cm
-8cm
-12cm

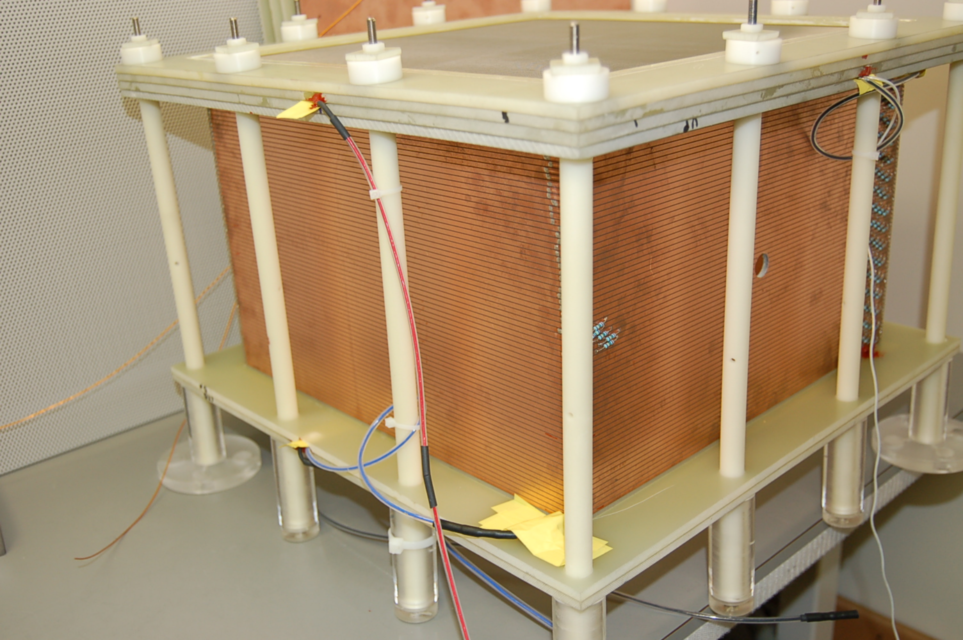
Lens Fiducial Circle (D ~ 15cm) at 85 cm Distance






4
3
2.5
0.7
2
1.75
0.5
Physikalisch-Technische
G51 107288

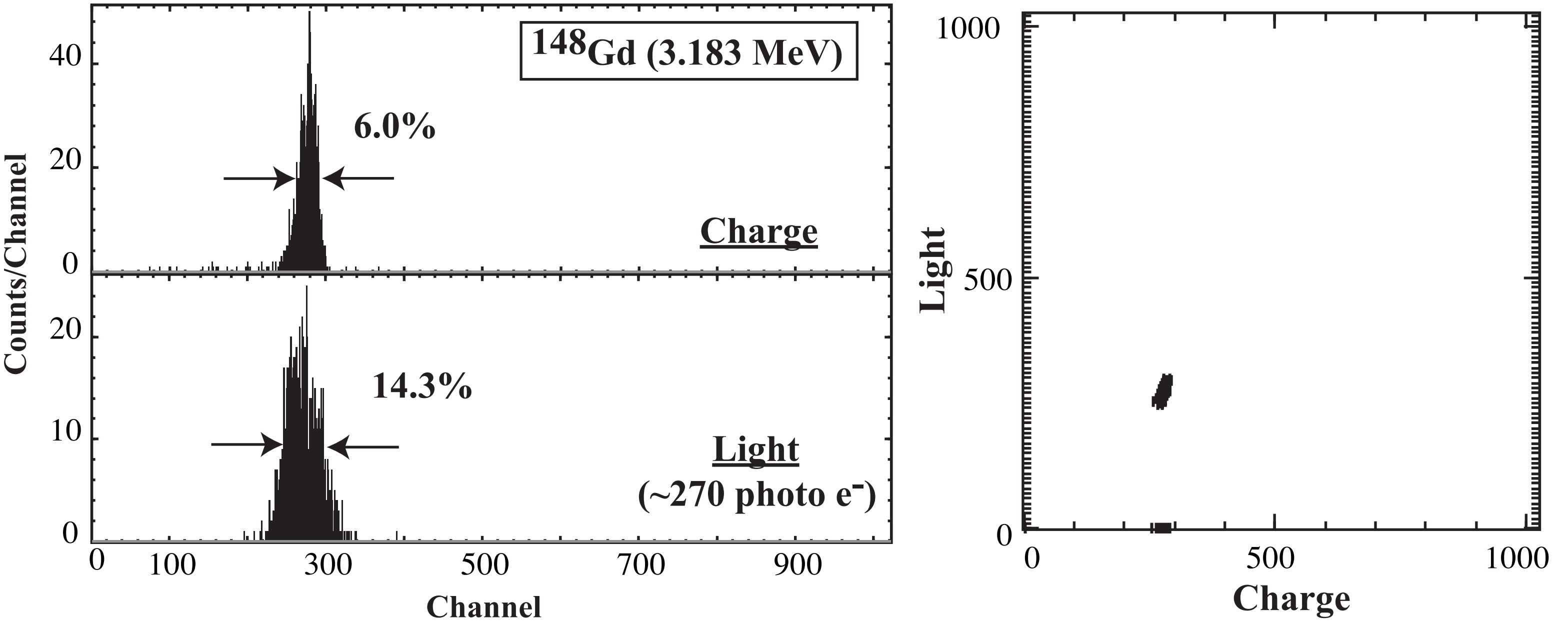

20
15
10
5

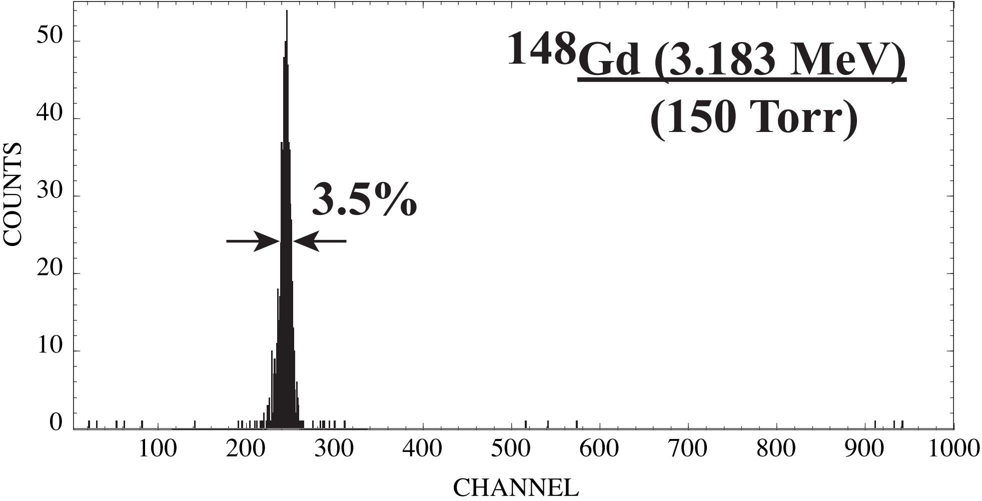


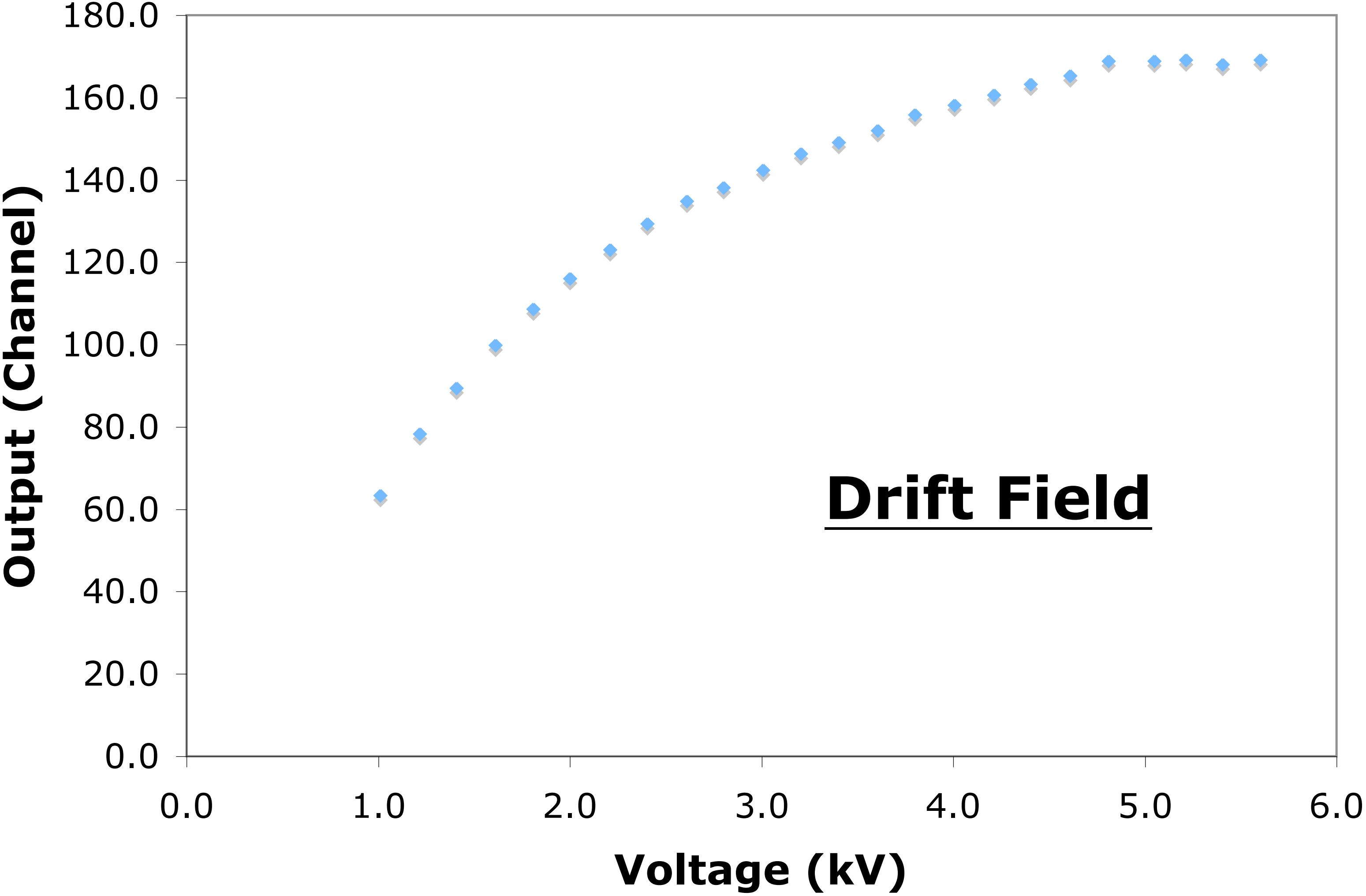

CHAMPION
Kimwipes
Reynolds Wrap

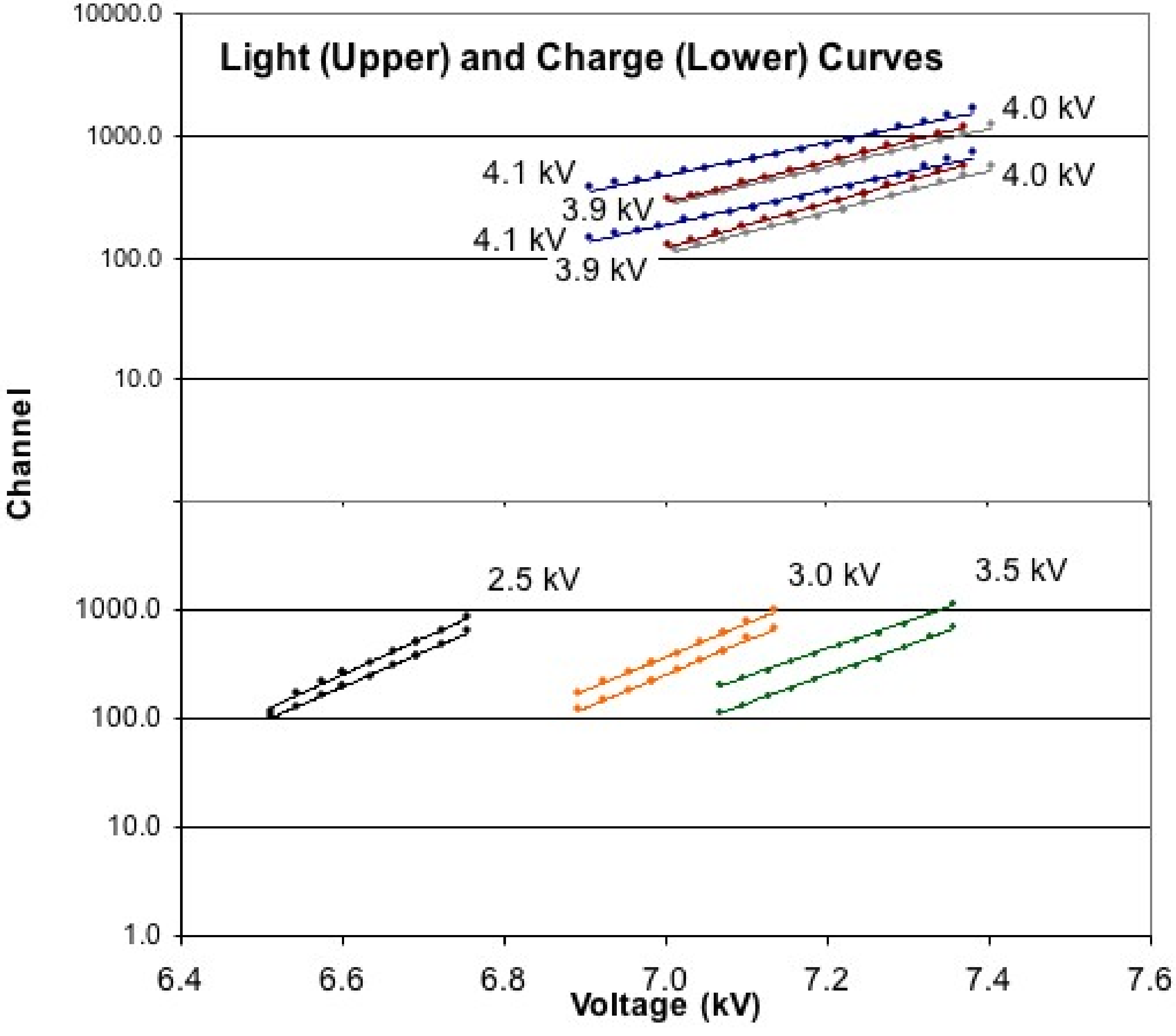

No Food
In Lab
UCONN
9 PIN SUB-D

O-TPC: CO_2(90%) + N_2(10%) at 100 Torr

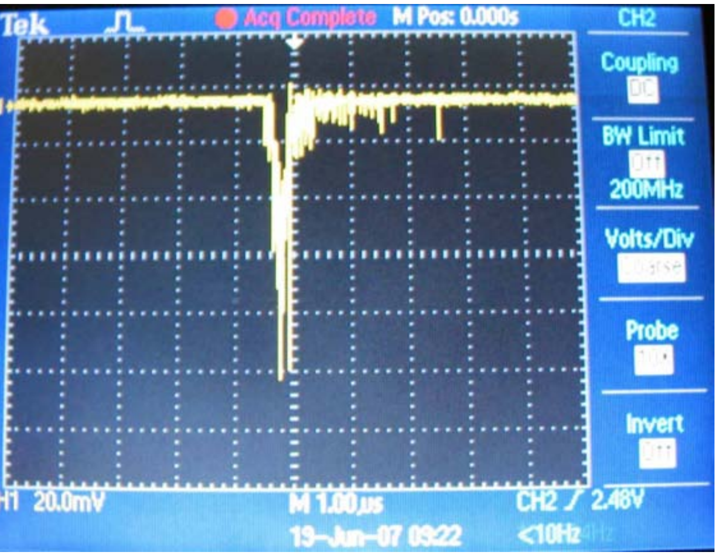



148Gd (3.183 MeV)
(150 Torr)
3.5%
COUNTS
0
10
20
30
40
50
100
200
300
400
500
600
700
800
900
1000
CHANNEL

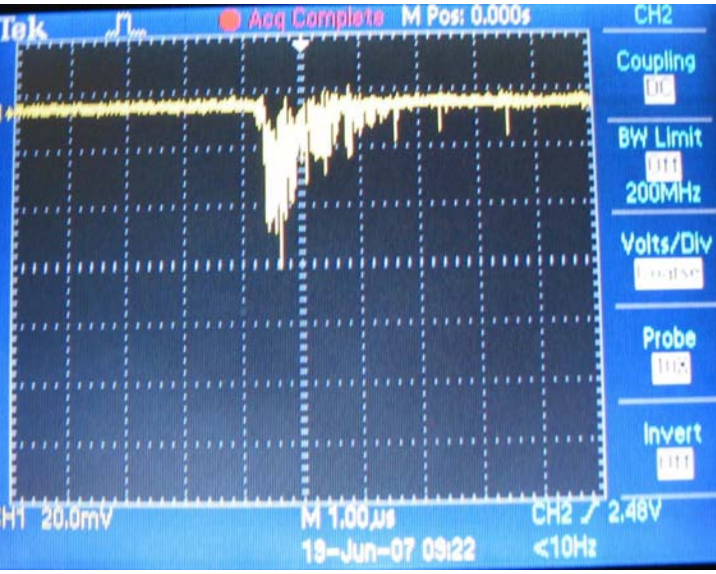

180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
Output (Channel)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
Voltage (kV)
Drift Field


Light (Upper) and Charge (Lower) Curves
Channel
1000.0
1000.0
100.0
10.0
4.1 kV
3.9 kV
4.1 kV
3.9 kV
4.0 kV
4.0 kV
2.5 kV
3.0 kV
3.5 kV
1000.0
100.0
10.0
1.0
6.4
6.6
6.8
7.0
7.2
7.4
7.6
Voltage (kV)

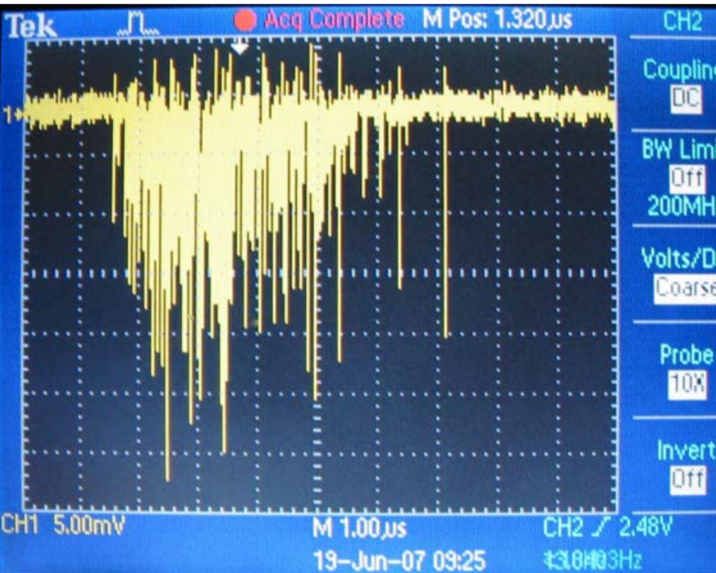
Horizontal Track



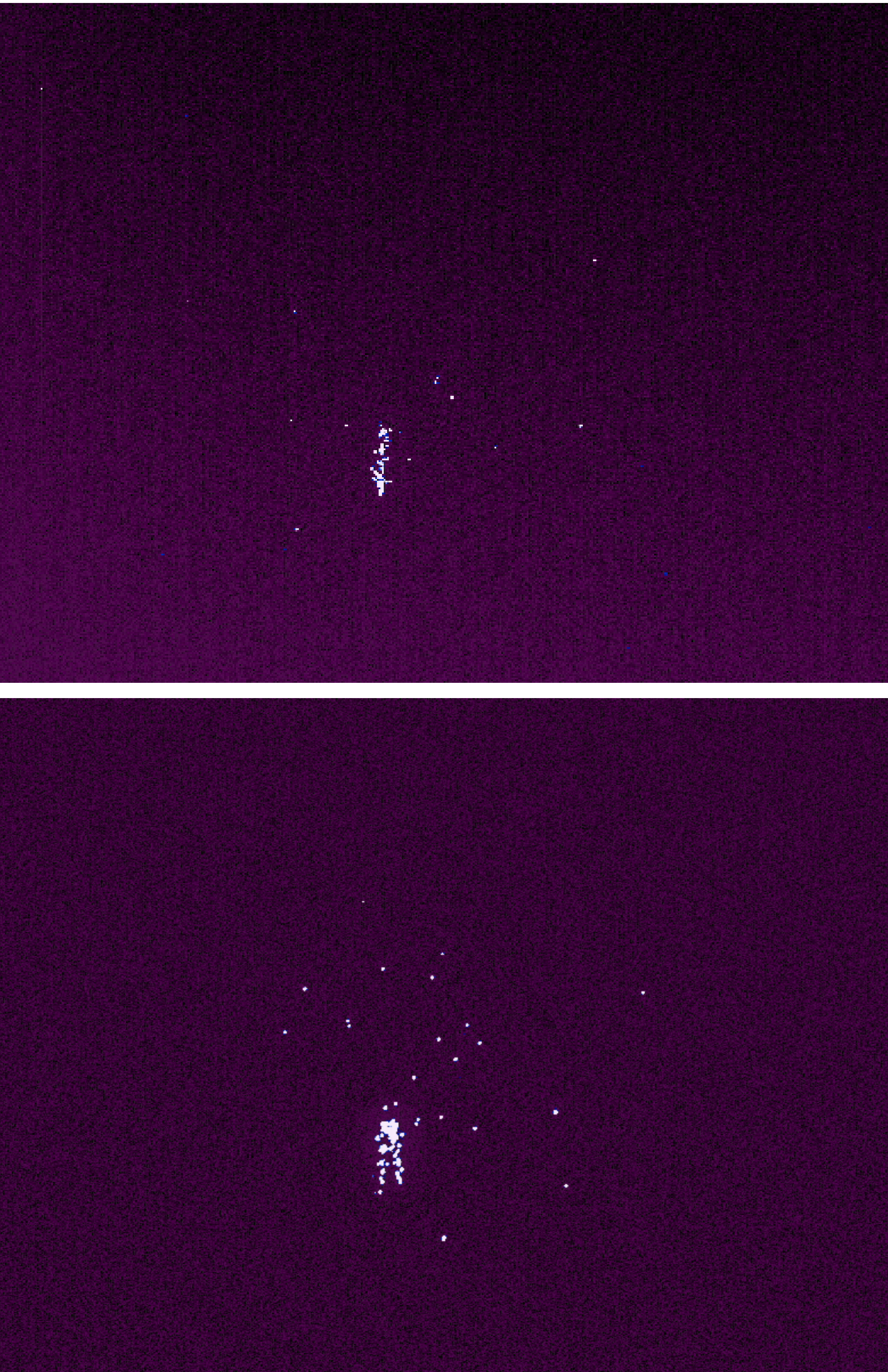
Slightly Tilted Track

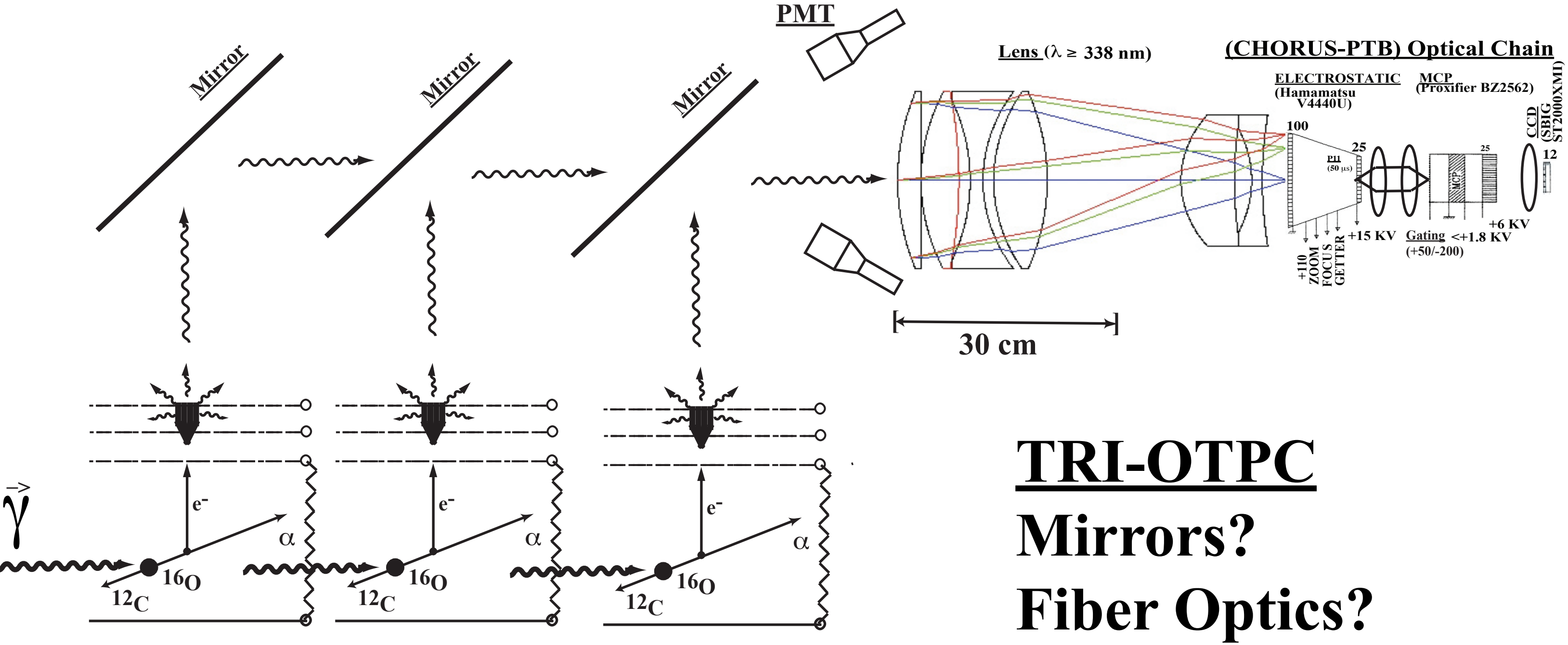


Very Tilted Track



Tracks From ^{148}Gd (3.181 MeV)

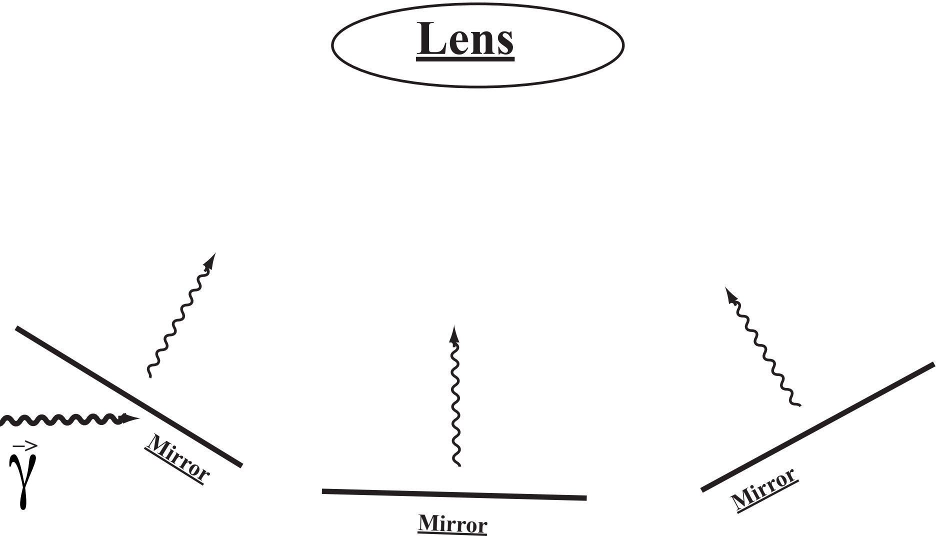




TRI-OTPC

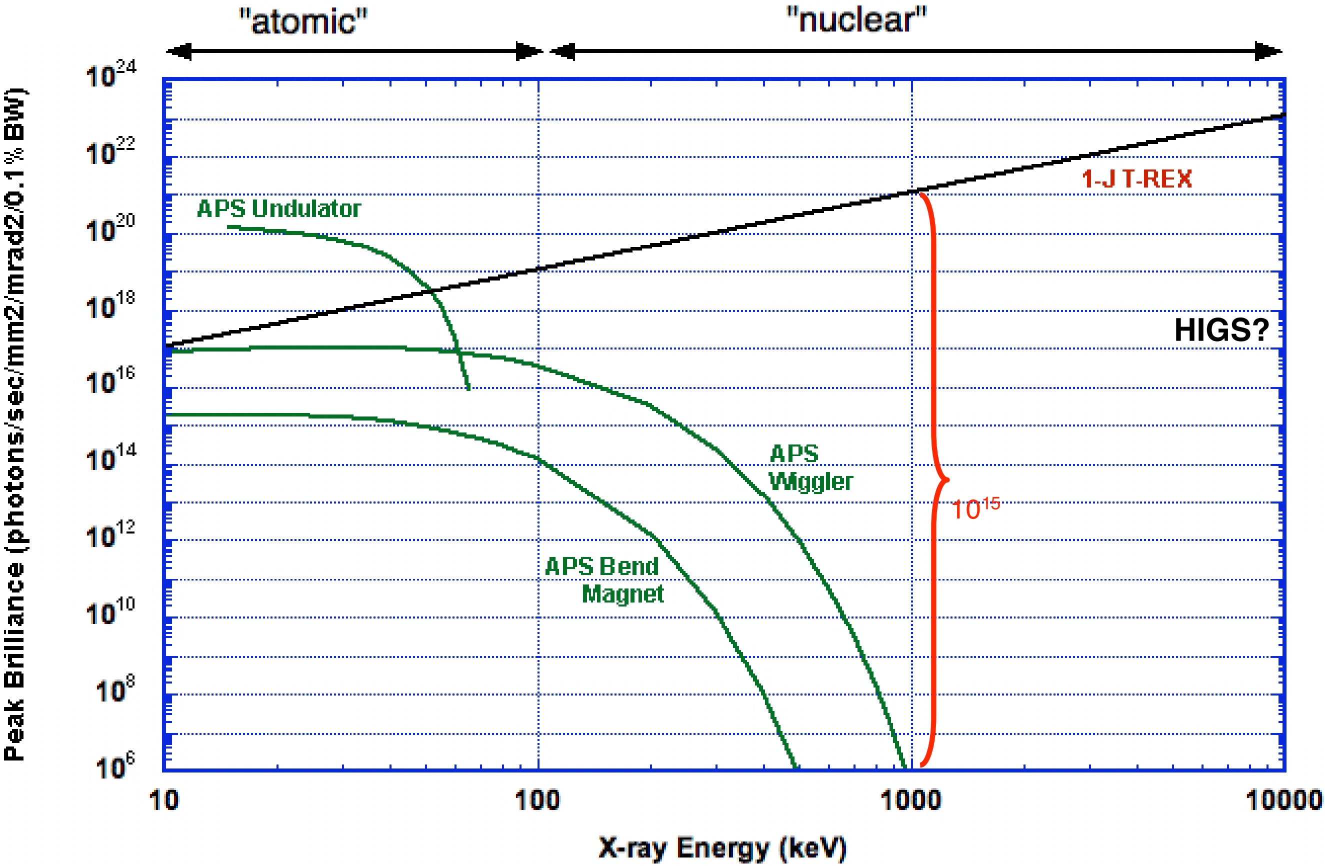
Mirrors?

Fiber Optics?

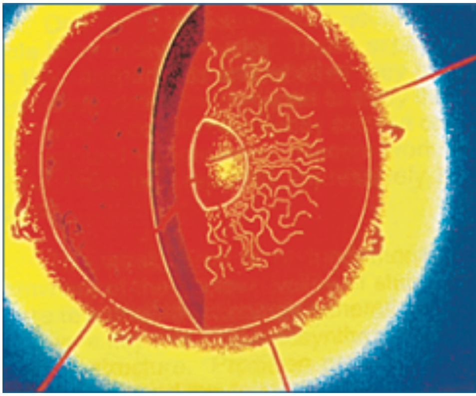


TOP VIEW

Laser power, low emittance, low bandwidth puts T-REX at the forefront of high brightness



We estimate T-REX peak brilliance at 1 MeV exceeds synchrotrons by 15 orders of magnitude



University of Connecticut
Laboratory for Nuclear Science
at Avery Point

August, 2007: O-TPC moves to TUNL
(We need a clean room)

September, 2007: O-TPC calibrated at TUNL
DAQ system tested

Fall, 2007: One shift test
Phase 1:
First week of data
Break
Second week of data

Supplementary Request
(DOE ~$40K)

January 21, 2008: End of my sabbatical leave!!!

Summer 2008: Please Consider an upgrade of
HIγS ala T-REX (LLNL)