Those Upsetting Ions-The Effects of Radiation on Electronics

Ethan Cascio

The Francis H. Burr Proton Therapy Center
at Massachusetts General Hospital

Basic Radiation Damage Mechanisms

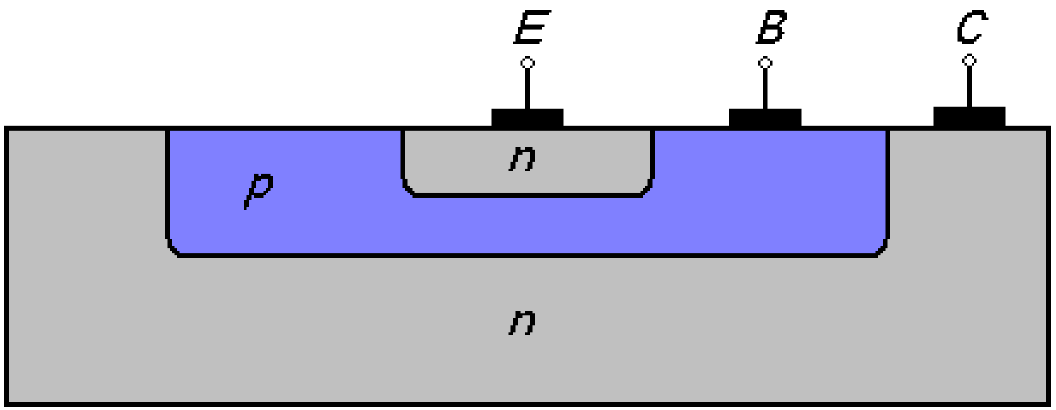
Transient Effects

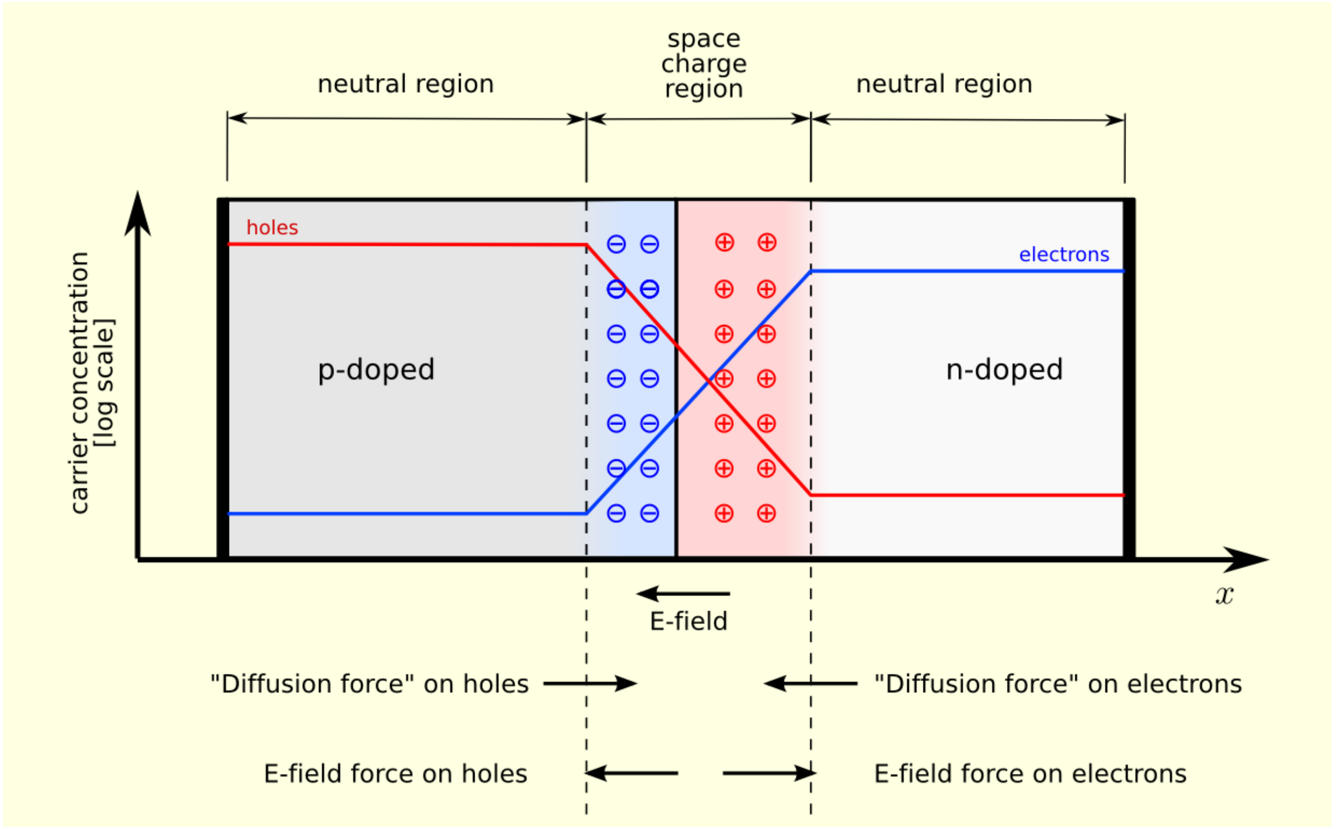
History of Awareness of these effects

HCL/MGH Test Program

MASSACHUSETTS GENERAL HOSPITAL
RADIATION ONCOLOGY

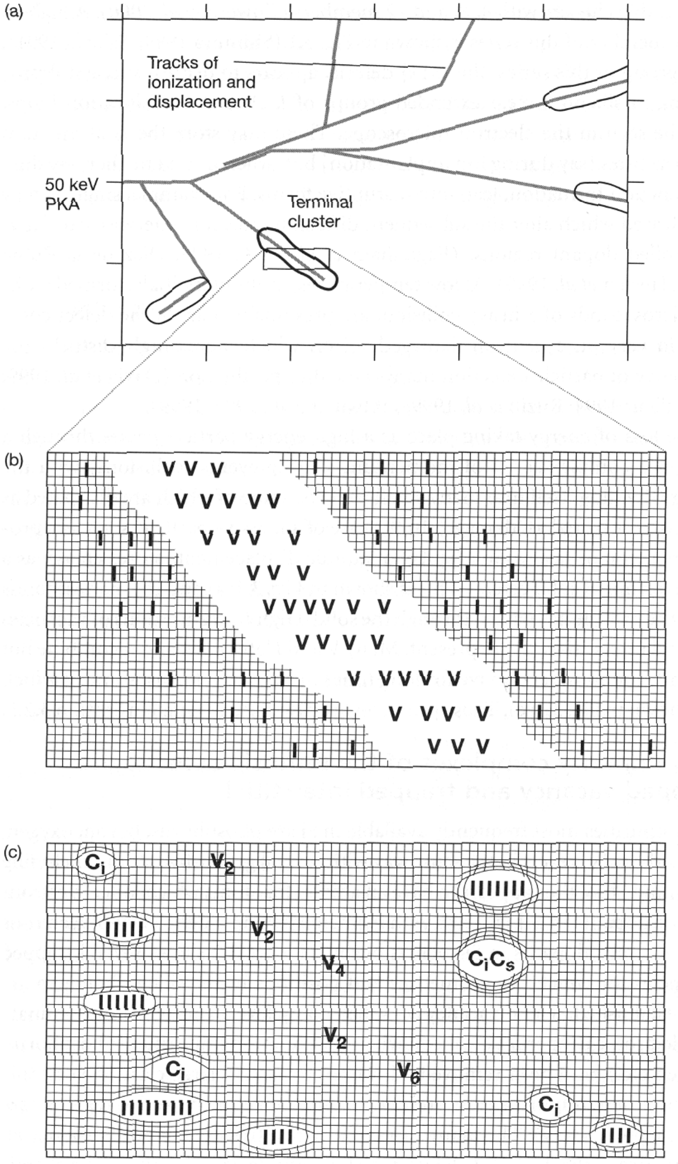
HARVARD MEDICAL SCHOOL


E
B
C
n
p
n


space
charge
region
neutral region
neutral region
holes
electrons
p-doped
n-doped
carrier concentration
[log scale]
x
E-field
"Diffusion force" on holes
"Diffusion force" on electrons
E-field force on holes
E-field force on electrons

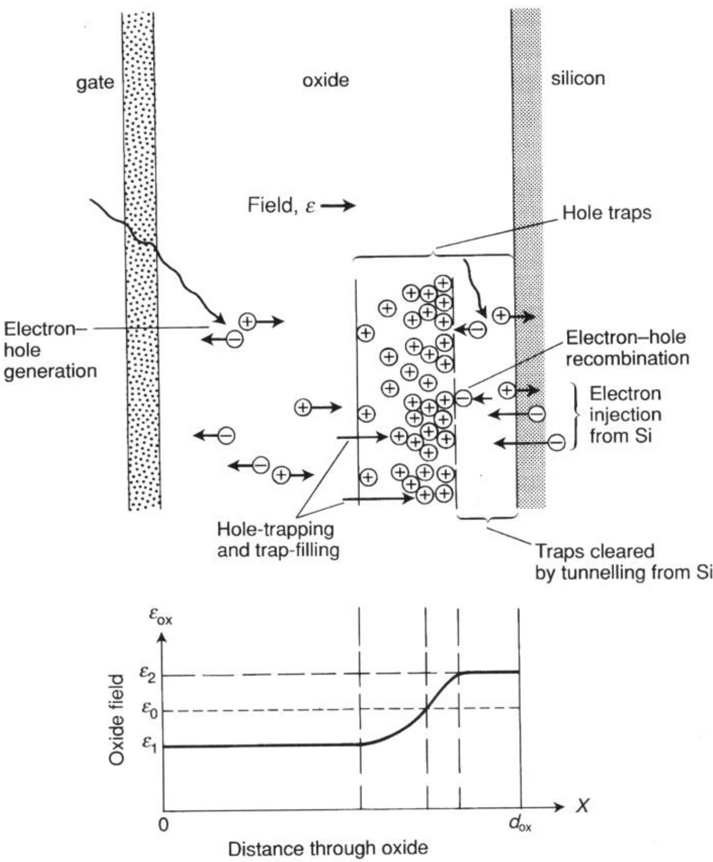
Atomic displacement damage in Si

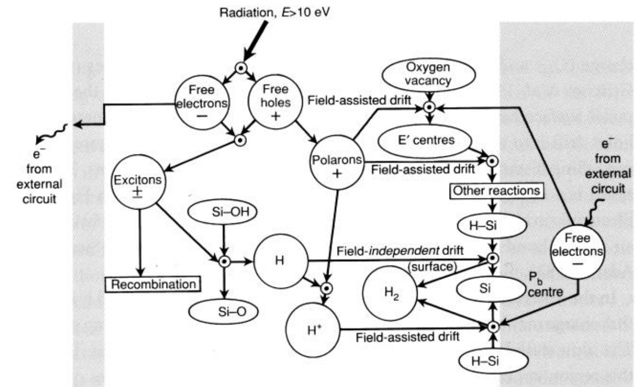
(mostly due to neutrons and Protons)

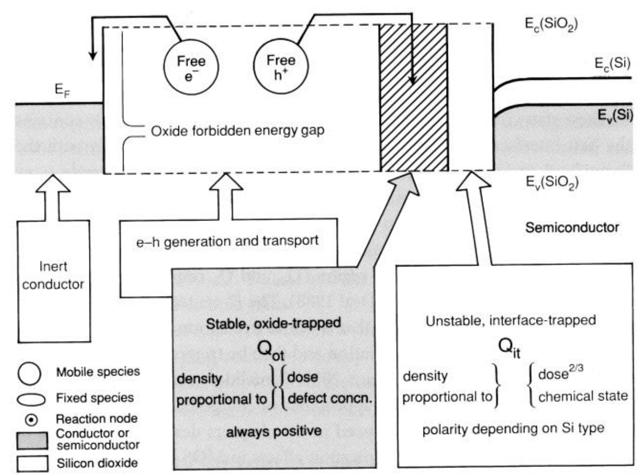


Minority carrier lifetime and mobility is reduced. This results in gain reduction in bipolor transistors & degradation of performance in LEDs and optical detectors.

Trapped Charge in Oxides







Trapped charge changes/degrades performance

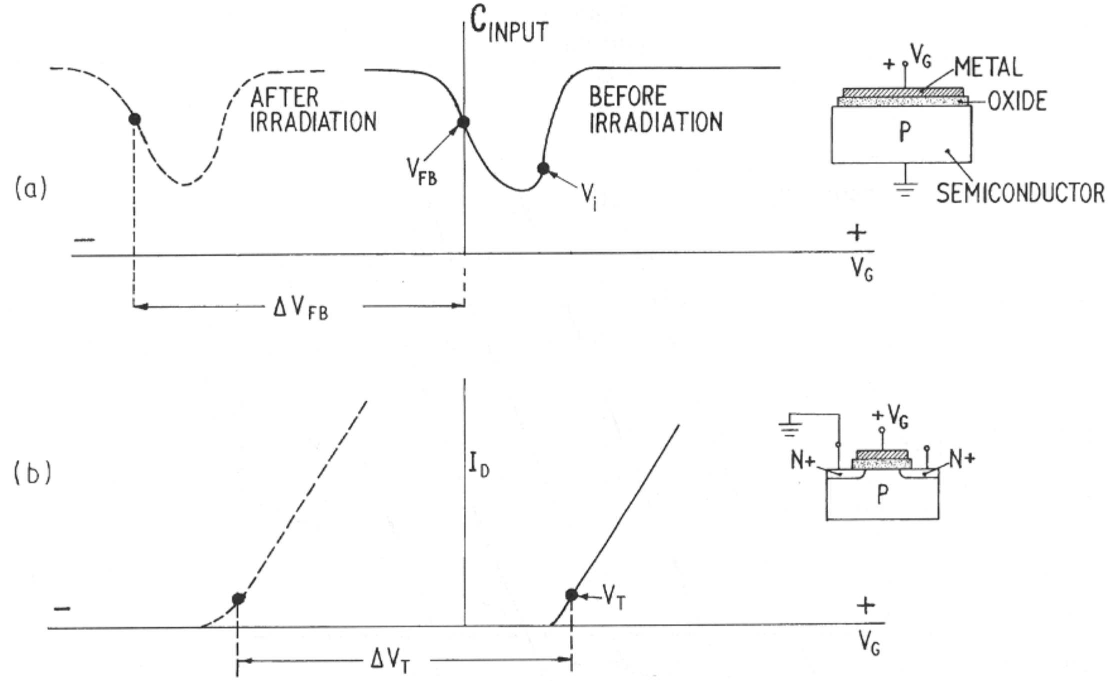
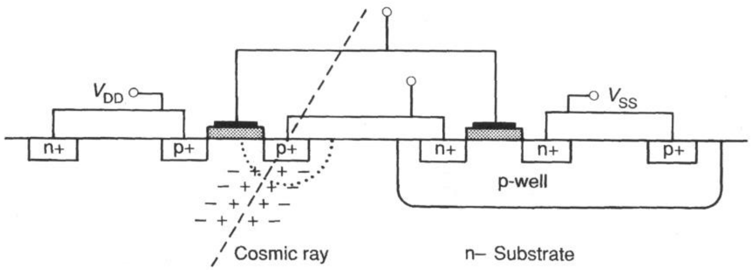
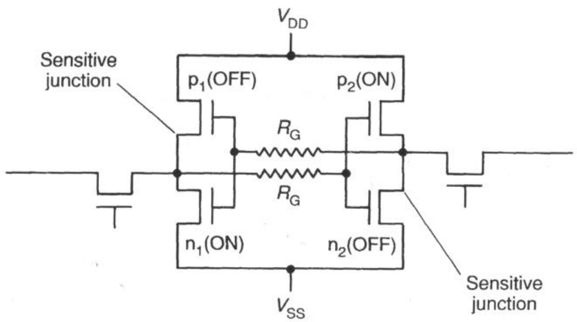


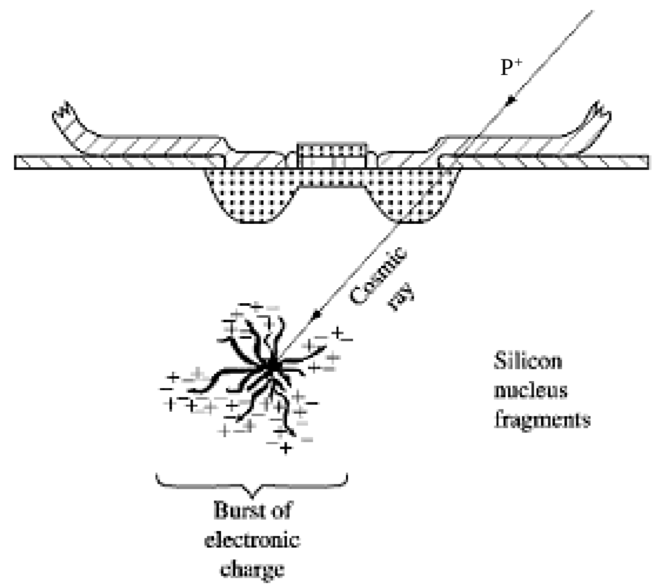
Fig. 4.4 MOS characteristics: typical variation of (a) capacitance and (b) drain current with gate voltage, showing the shifts in flatband and threshold voltages due to trapped charge (no interface states).

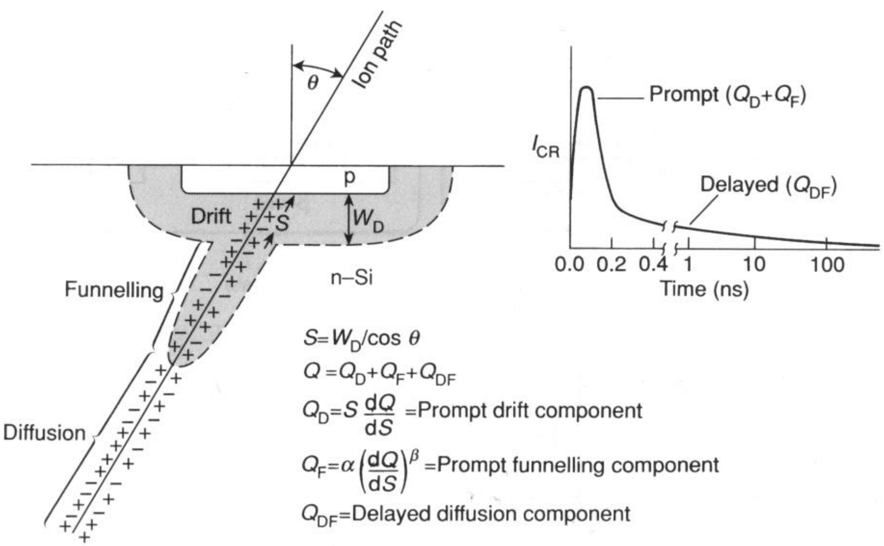
Transient Effects: Single Event Upset





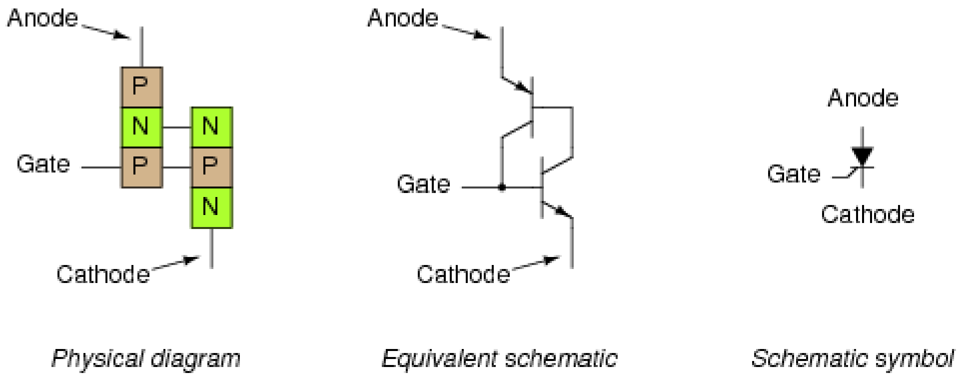
First identified as due to heavy ions in:
D. Binder, et. al., "Satellite Anomalies from Galactic Cosmic Rays," IEEE Trans. Nut. NS-22, 2675 (1975).



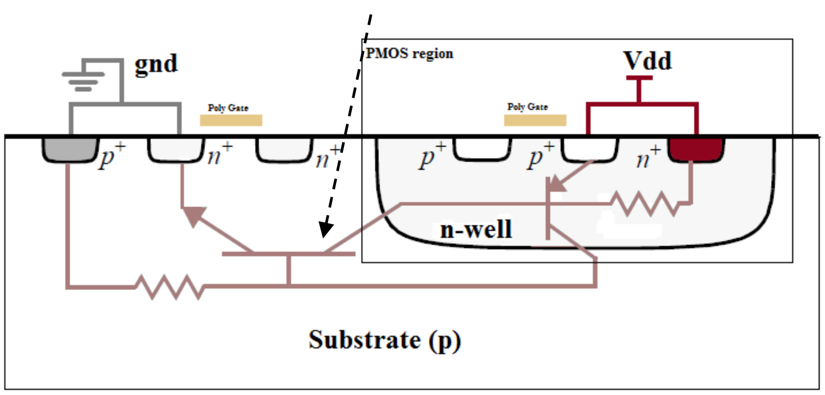


Single Event Latchup in CMOS Structures

Silicon Controlled Rectifier (SCR) or Thyristor



Parasitic equivalent structure in CMOS layout activated by ion strike



Single Event Burnout (SEB) in Power MOSFETs

This effect was first noticed in high power components used in railway power supplies. The mechanism is described thusly;

"*SEB is triggered when a heavy ion passes through a power MOSFET biased in the off state (blocking a high drain-source voltage). Transient currents generated by the heavy ion turn on a parasitic BJT inherent to the device structure. Because of a regenerative feedback mechanism, collector currents in the BJT increase to the point where second breakdown sets in, creating a permanent short between the source and drain and rendering the MOSFET useless.*" (From G. H. Johnson, J. M. Palau, C. Dachs, K. F. Galloway, and R. D.Schrimpf, "A review of the techniques used for modeling single-event effects in power MOSFETs*," IEEE Trans. Nucl. Sci, vol. 43, no. 2, pp.546–560, Apr. 1996*

The mechanism is essentially the same when triggered by the charged secondaries produced by a neutron or proton strike on a silicon nucleus.

Types of Radiation Damage/Effects:

1.Permanent or Long Term **Deterministic**

Displacement Damage

Trapped Charge

2. Transient **Stochastic**

Single Event Upset (SEU)

Single Event Latch Up (SEL)

Single Event ____ (Fill in the blank!)

IEEE Transactions on Nuclear Science, Vol.NS-22, No.6, December 1975

SATELLITE ANOMALIES FROM GALACTIC COSMIC RAYS

D. Binder, E. C. Smith, and A. B. Holman
Hughes Aircraft Company
Culver City, California 90230

Introduction

Anomalies in communication satellite operation have been caused by the unexpected triggering of digital circuits. Although the majority of these events have been attributed to charge buildup from high temperature plasmas,[1,2] some of the events appear to be caused by another mechanism. The purpose of this paper is to investigate interactions with galactic cosmic rays as an additional mechanism.

The satellite anomalies studied were caused by the triggering of flip-flop circuits. The particular mechanism assumed for the cosmic ray interaction was the charging of the base-emitter capacitance of critical transistors to the turn-on voltage. The charge is produced by the dense ionization track of an energetic, high-Z cosmic ray.

The following sections describe the determination of the number of sensitive transistors, the charge collection efficiency, the transistor parameters, and the energy spectrum of the penetrating cosmic rays. All these quantities were required as input data for a computer code called CRAC, developed for this problem. The code was used to calculate the solid angle in which cosmic rays supplied sufficient energy to turn on the transistors. The theoretical event rate was then calculated and compared with satellite data.

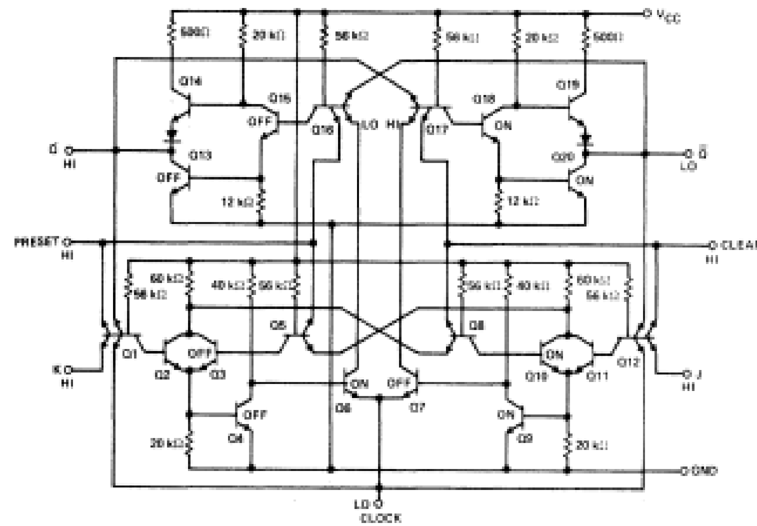
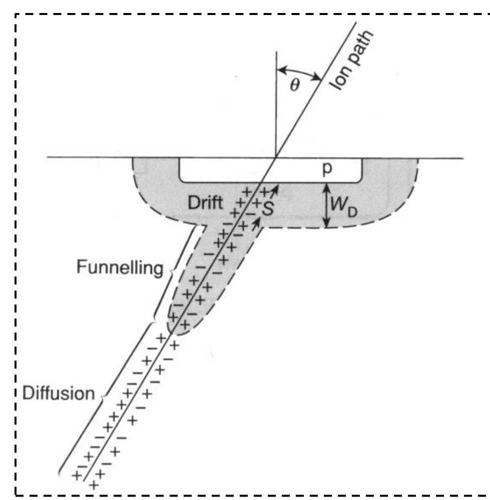


Figure 1. J-K Flip-Flop Circuit with Transistor States



IEEE Transactions on Nuclear Science, Vol. NS-26, No. 6, December 1979

SOFT ERRORS INDUCED BY ENERGETIC PROTONS

R.C.Wyatt, P.J.McNulty, and P.Toumbas
Clarkson College of Technology
Potsdam, N.Y. 13676

P.L.Rothwell and R.C.Filz
Air Force Geophysics Laboratory
Hanscom Air Force Base, MA 01731

1. Introduction

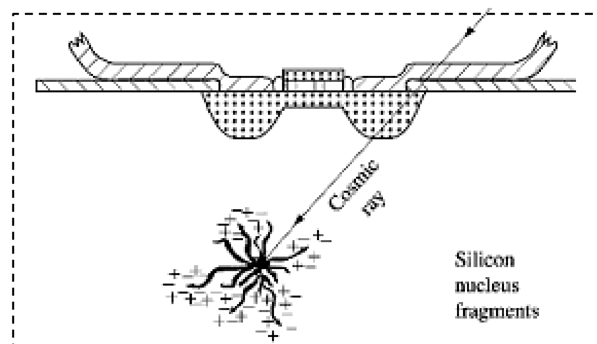
There has been considerable recent interest in the soft error phenomena in semiconductor memory devices.[1-5] Soft memory errors take the form of anomolous changes in the information stored in a memory device flown in space without observable damage to the device itself. Soft errors were first observed in bipolar digital components - J-K flip-flops.[1] The soft-error rates in satellite systems have increased significantly recently, presumably because of the increased use of large-scale integrated (LSI) devices.[2-5] The decrease in volume of a sensitive element implies a corresponding decrease in the stored charge and in the number of ion pairs necessary to induce a soft error.

The primary mechanism for the soft errors in LSI devices is believed to be the passage of a heavy cosmic-ray nucleus through a memory storage element where the energy deposited by the particle traversing the element creates a sufficient number of electron-hole pairs at or near the depletion region to neutralize the stored charge.[1-5] According to this hypothesis, all soft errors should be one to zero for memory elements in which the data is stored true and zero to one for elements which store information in complement form. Any devices of comparable geometry on the microscopic level should have equal probability of exhibiting soft errors. According to the primary mechanism LSI devices should be sensitive to heavily ionizing particles that have values of linear energy transfer (LET) above some threshold value.

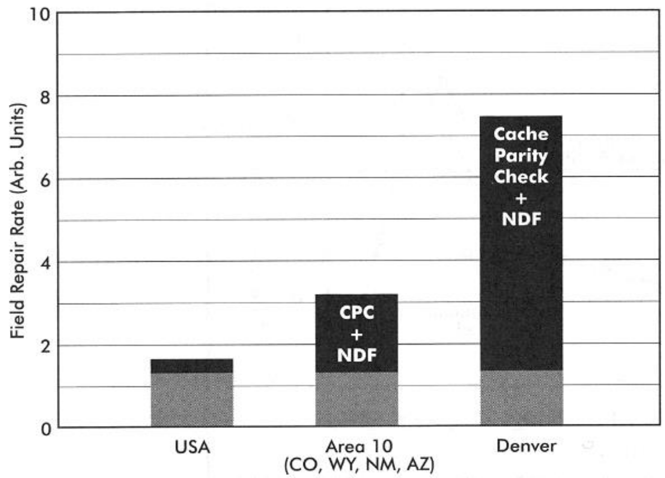
Nuclear interactions provide a possible alternative mechanism for the soft errors. The secondary particles (mostly protons and alphas) emerging from inelastic nuclear interactions may ionize a sufficient number of atoms along their trajectories to change the state of a nearby memory element. May and Woods have recently observed soft errors induced by alpha particles,[2] and Yaney et al report peak sensitivity for a maximum alpha energy of 3-4 MeV.[4] The recoiling nucleus can provide considerable local ionization loss. Bradford[5] has pointed out that nuclear reactions can contribute to the soft errors, especially for VLSI where the threshold energy that must be deposited for a soft error is expected to be below 1 MeV. Preliminary calculations by Farrell and McNulty[6] indicate that the nuclear recoil in inelastic

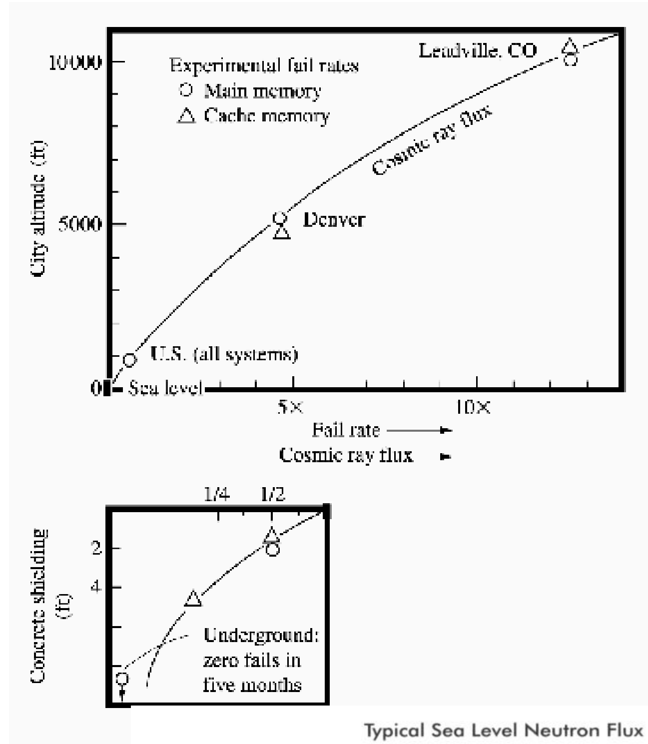
2. Experimental Procedures

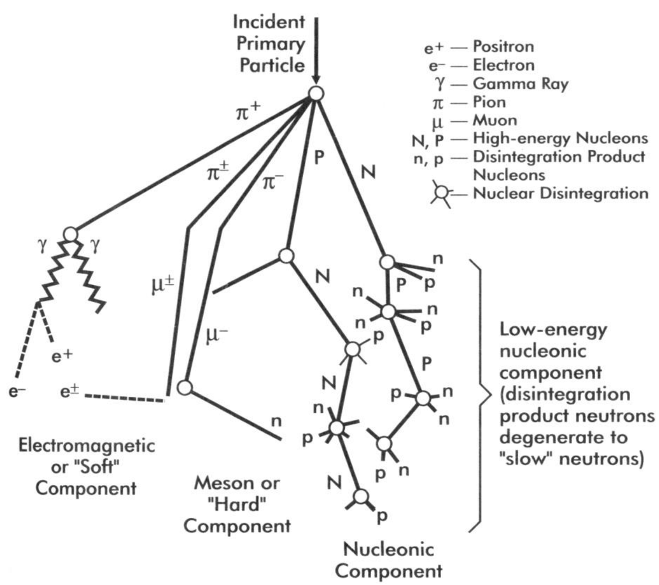
Two types of 4K x 1 dynamic RAM, Intel C2107B and National semiconductor MM-5280, were studied in these investigations. Both devices came in ceramic packages with metal lids, which were removed for low energy proton exposures. The energetic proton exposures were carried out at the Harvard Cyclotron and included energies of 18, 32, 51, 91, and 130 MeV. The energy of the protons was controlled by inserting lucite degraders in the beam. This introduced considerable spread in the beam energy for the lower energies, (FWHMs were ~17, 14, 10, 4 MeV for the 18, 32, 51, and 130 MeV beams, respectively.) The 0.95, 1.3, and

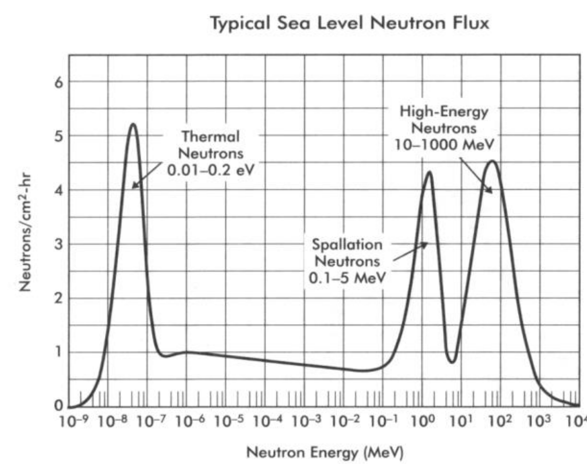


IBM Experiments to show that terrestrial neutrons are a significant source of failures (1982-1988)

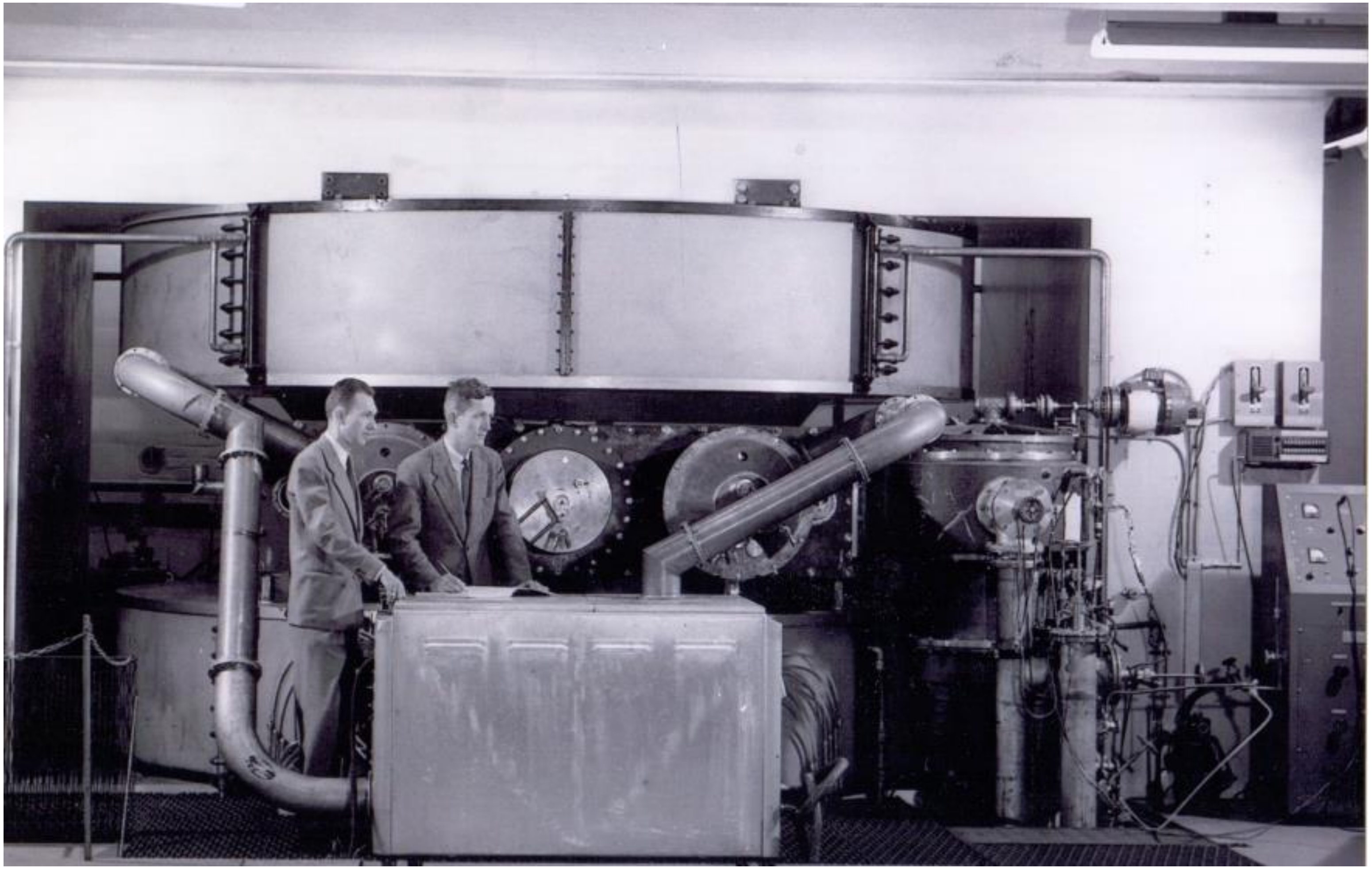








From "SER-History, Trends and Challenges", James F. Ziegler and Helmut Puchner (Cypress)

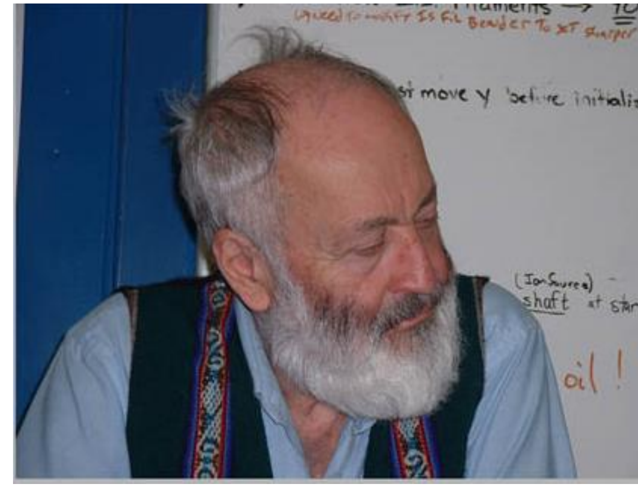


Harvard Cyclotron circa 1950

Andreas ("Andy") Koehler

1953

~1980



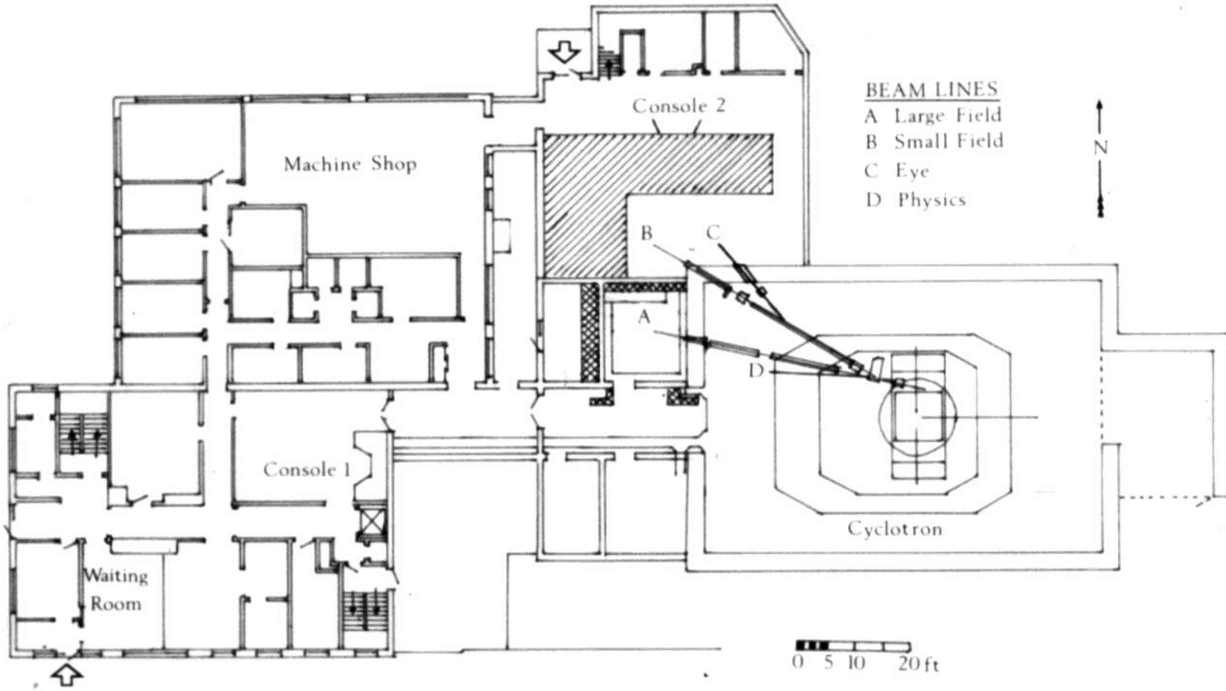
2002

Not much changed for the cyclotron equipment over the years

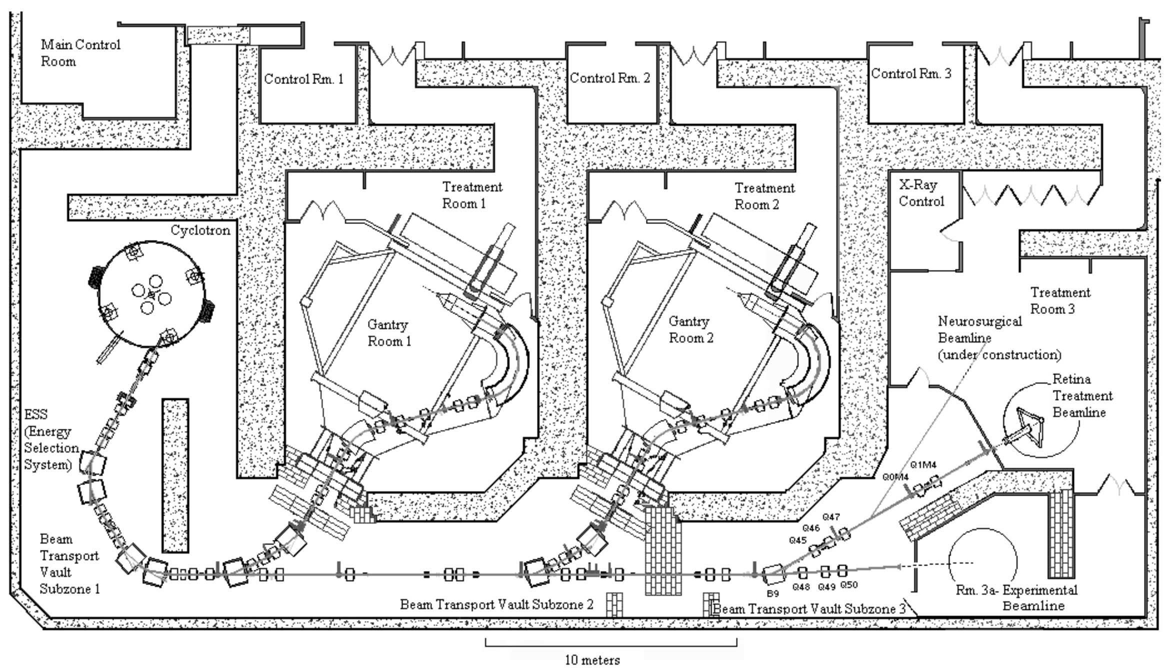
Mr. and Mrs. Robert Birge 1949

Ethan and Allison Cascio 1989

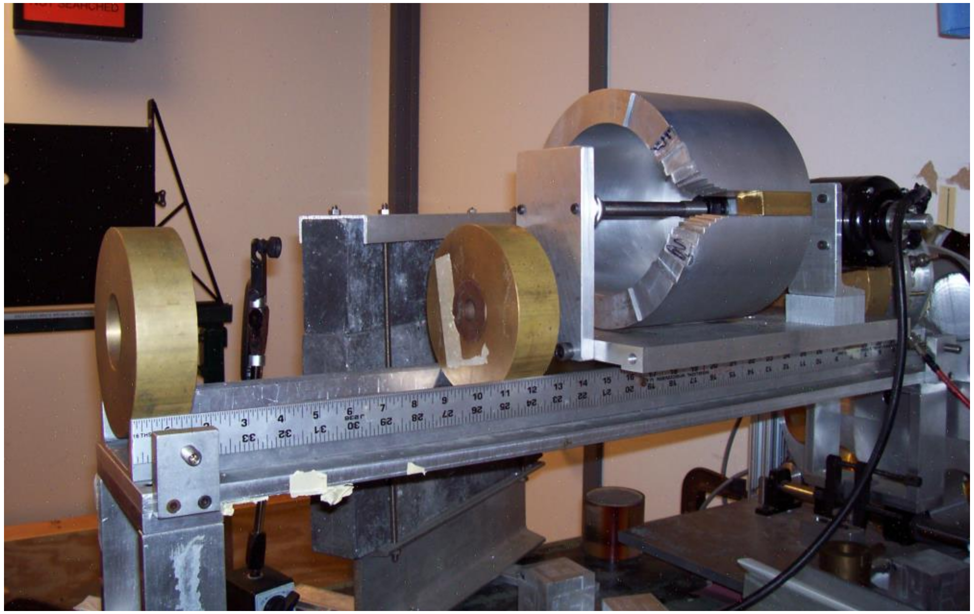
Or with the working environment



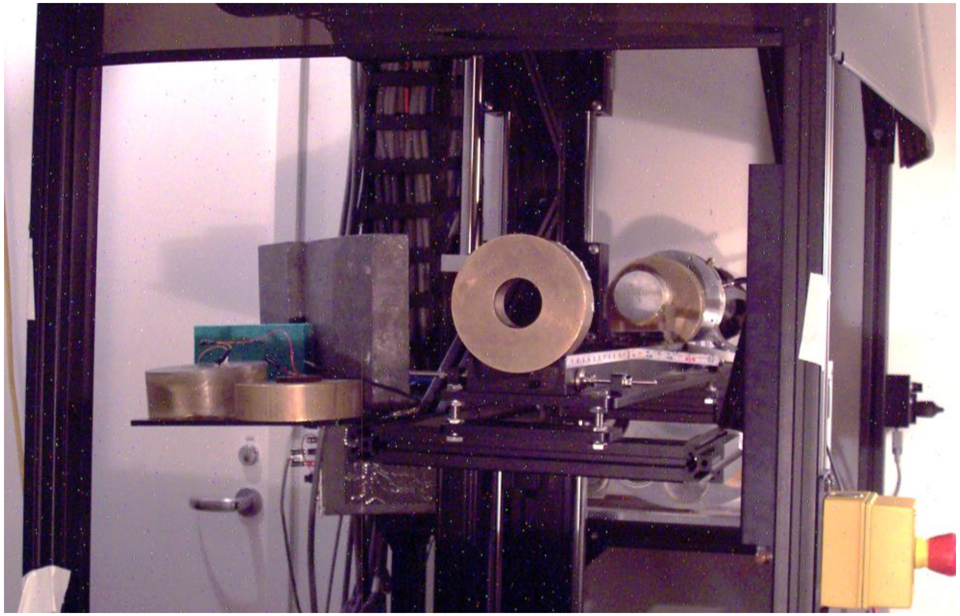
HCL layout



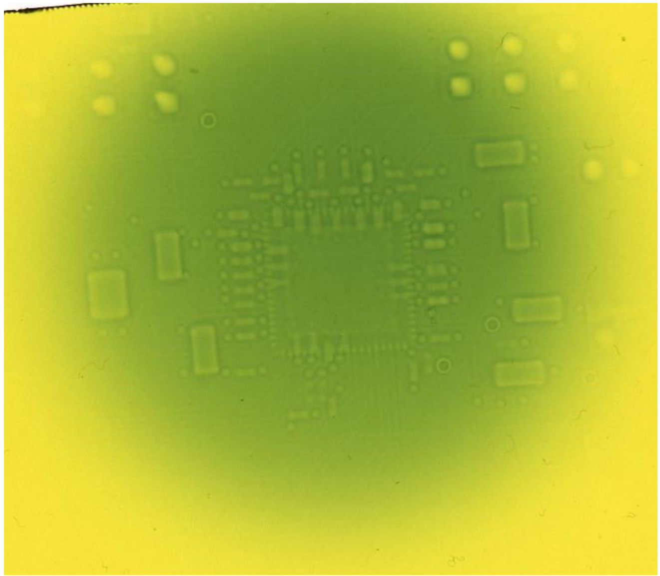
MGH layout



“physics” beamline (D) from HCL at MGH



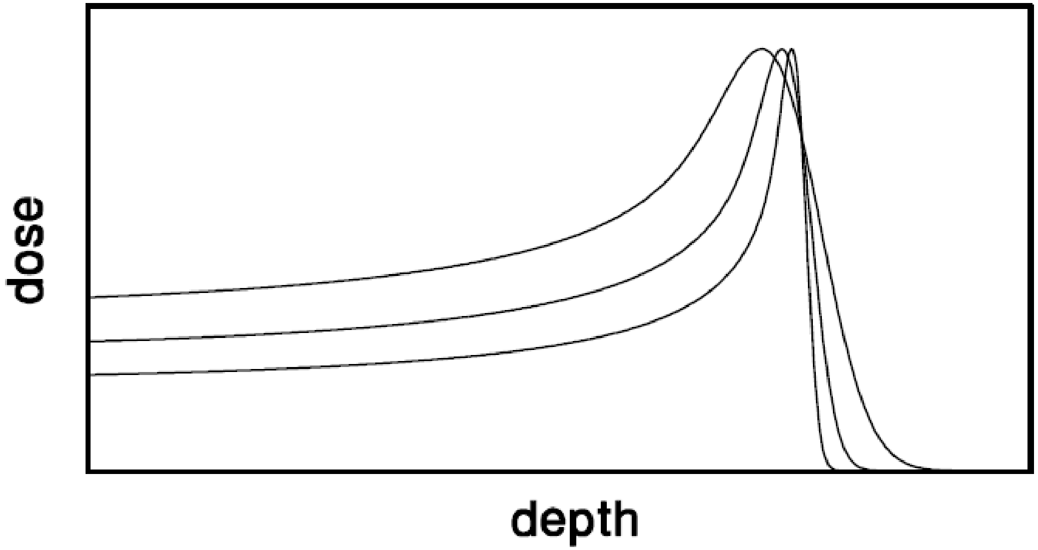
New (equivalent) beamline at MGH



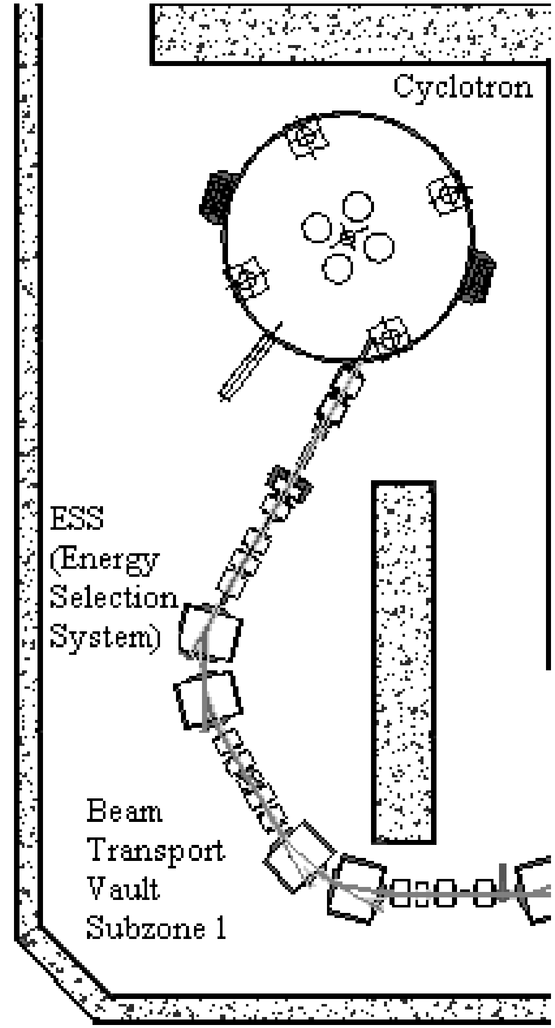
Chip under test illuminated by proton beam

Dosimetry control unit from HCL at MGH with additions

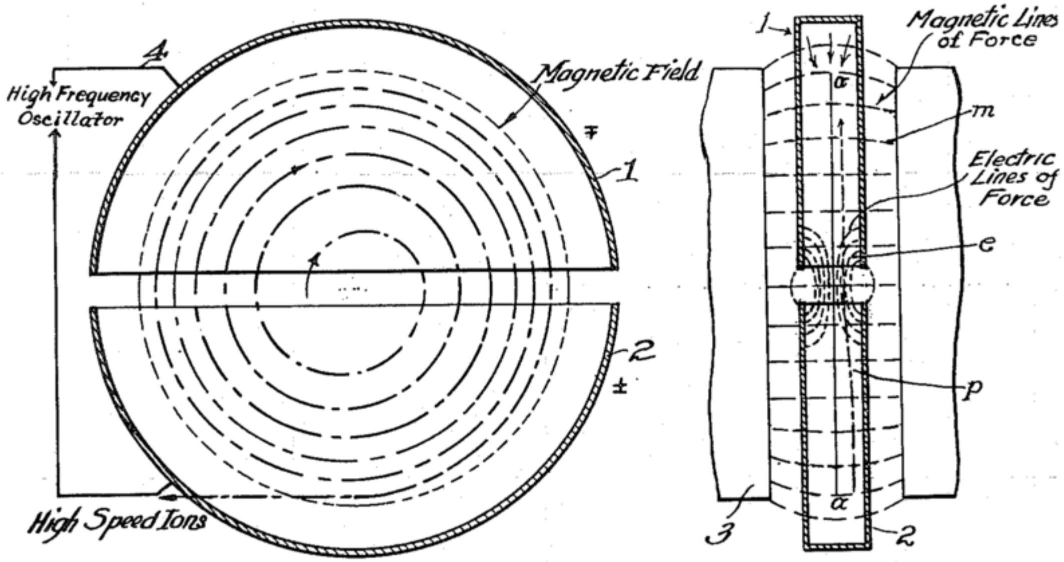
Recent replacement units at MGH



Effect on Bragg Peak distal fall off of increasing energy spread



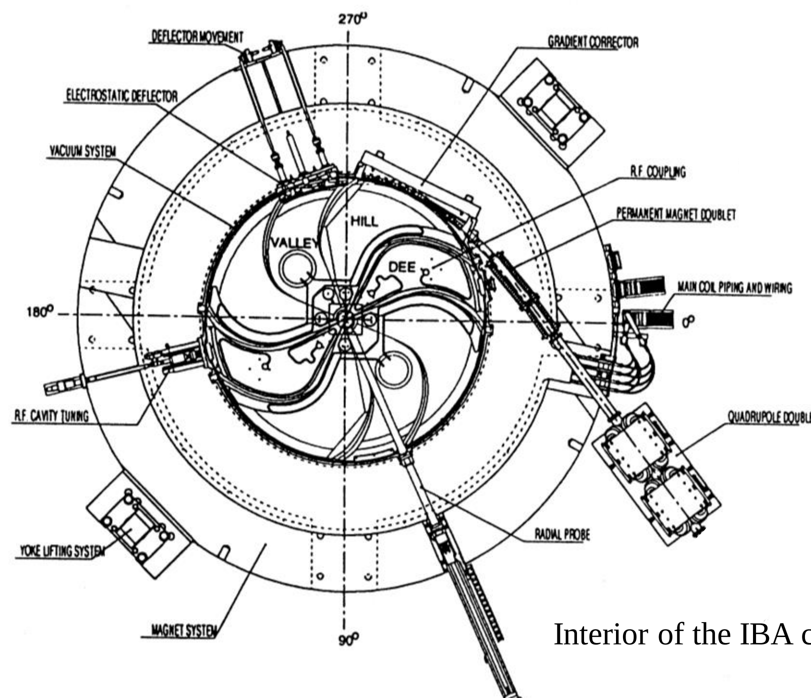
System at MGH for reducing energy spread of beams transported to the treatment rooms



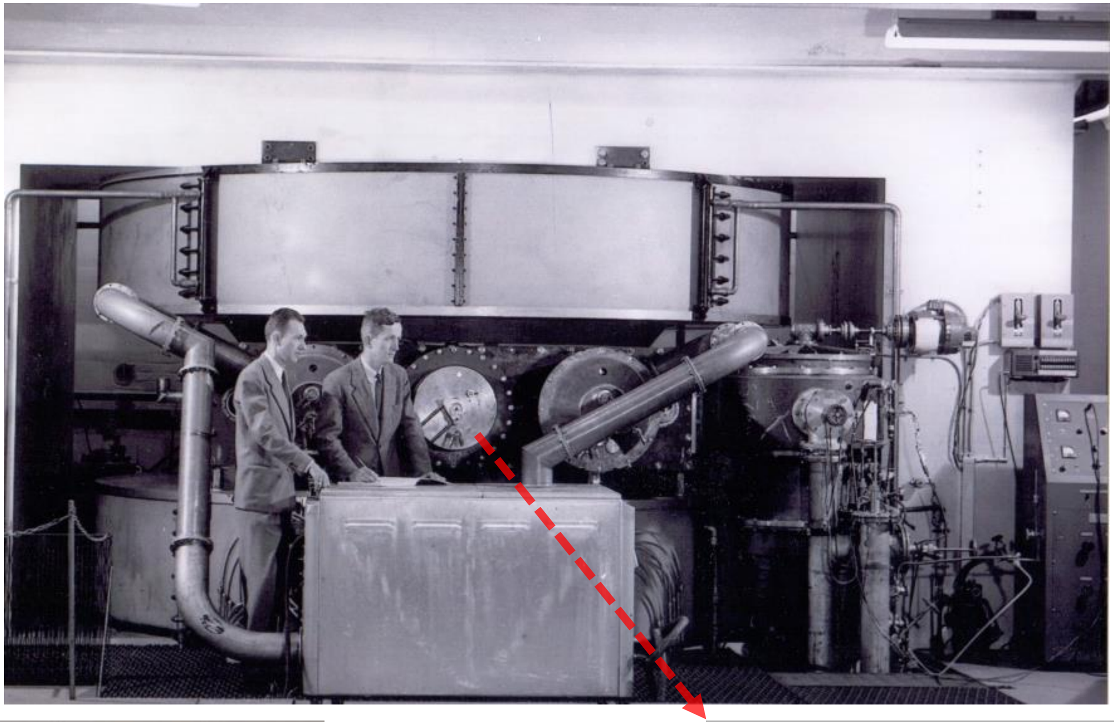
$$F = qB/2\pi m$$

$$m_{rel} = \frac{m}{1 - \sqrt{v^2/c^2}}$$

Drawing from Ernest Lawrence’s original patent for the Cyclotron (1934)



Interior of the IBA cyclotron at MGH



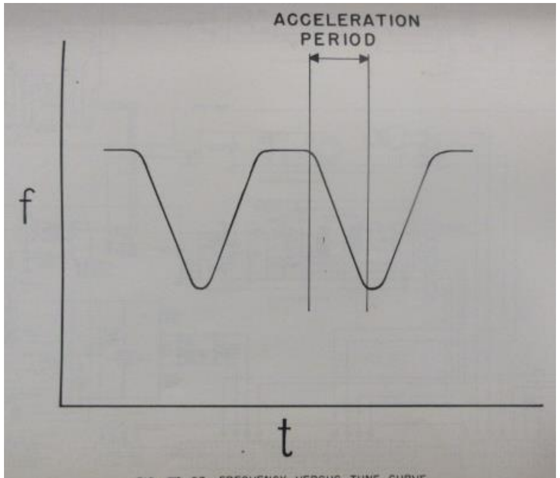
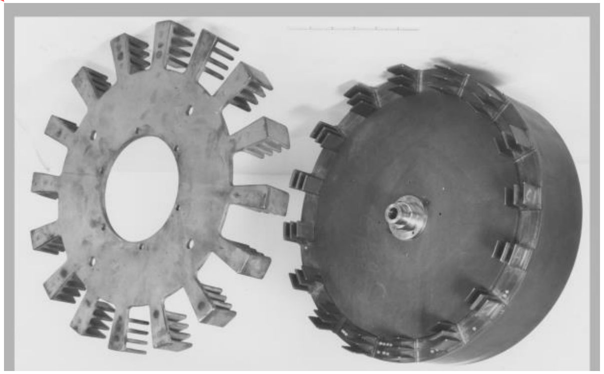


FIG. IV-23 FREQUENCY VERSUS TUNE CURVE.

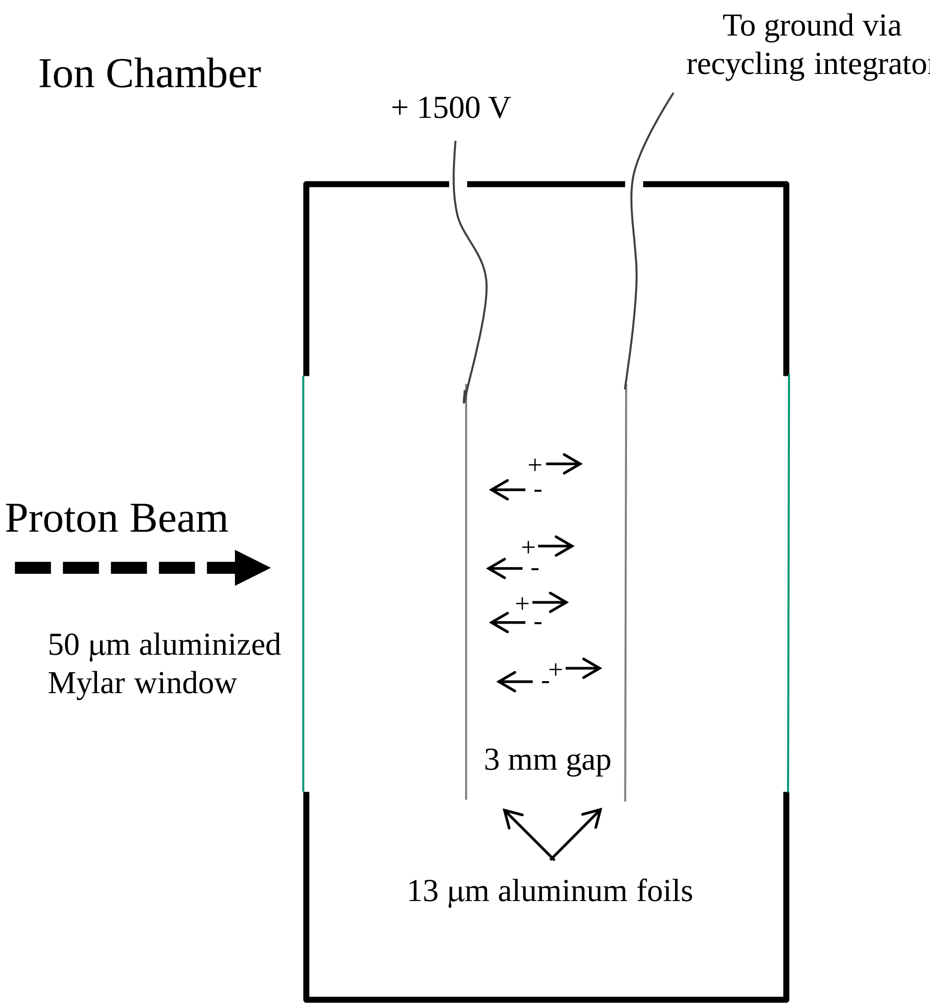


Rotating Condenser

From "**The Harvard University 95 Inch Cyclotron**
Design, Construction, and Preliminary Operating Instructions"

July 1950, Office of Naval Research

One issue is “recombination” signal loss in the monitor ion chamber. If the flux density is too high some of the ion/electron pairs will re-combine before they can be collected in the signal foil. Narrow gap between the foils is best way to avoid this. HCL ion chambers were built with very narrow gap due to low duty cycle/high instantaneous beam current.



Precision Al absorber set from HCL

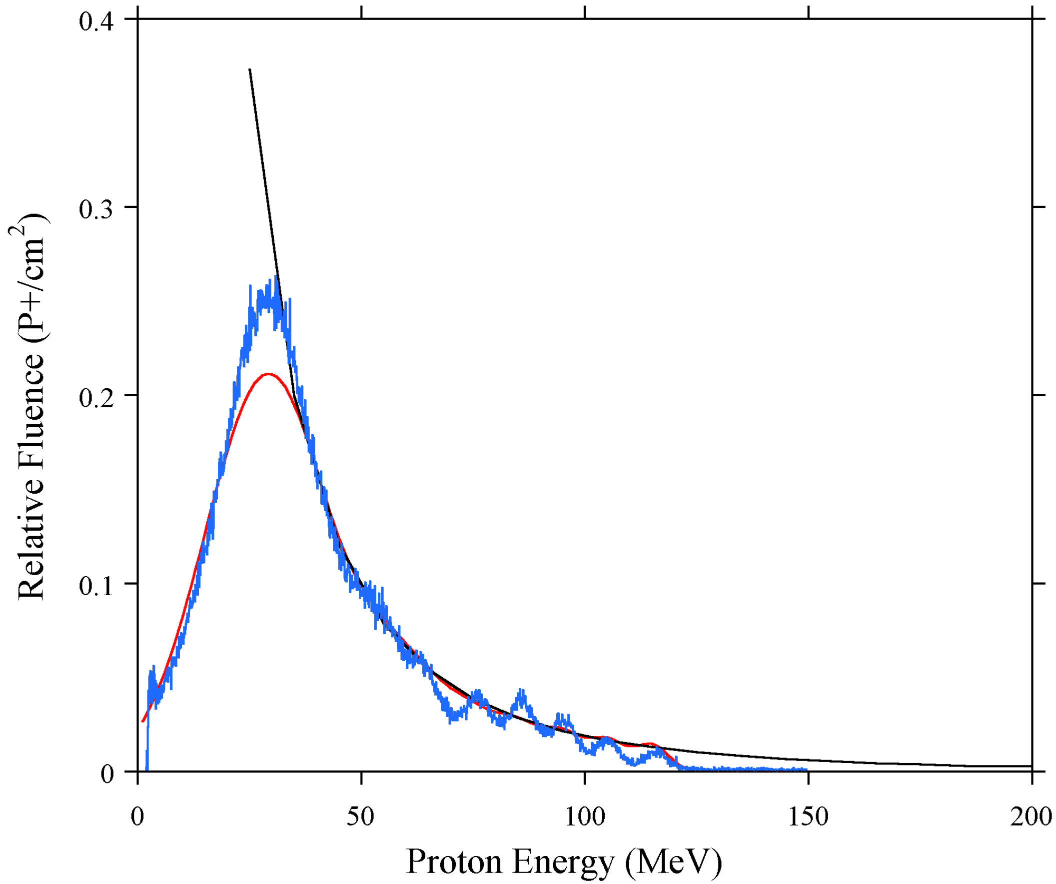
Measurements of areal density (weight/area) of pieces from 1967

No.	Avg. Dia.	Area	Weight (1)	Weight / Area	Avg. Thickness	Density
1	2.7228 in	37.57 cm^2	25[illegible].8764 gm	✓6.784 gm/cm^2	0.9851 in	2.711 gm/cm^3
2	2.7224	37.56	25[illegible].8486	6.785	0.9852	2.711
3	2.7222	37.54	25[illegible].9921	6.792	0.9858	2.713
4	2.7181	37.43	6[illegible].7517	✓1.676	0.2433	2.712
5	2.7182	37.43	6[illegible].9392	✓1.682	0.2441	2.713
6	2.7180	37.43	6[illegible].1242	1.686	0.2448	2.711
7	2.7180	37.43	6[illegible].2260	1.689	0.2452	2.712
8	2.7175	37.42	16.2887	✓0.4353	0.0633	2.707
9	2.7176	37.42	1[illegible].3171	0.4360	0.0634	2.708
10	2.7176	37.42	1[illegible].2491	0.4342	0.0632	2.705
11	2.7174	37.42	1[illegible].3185	0.4361	0.0634	2.708
12	2.7192	37.47	8.1287	✗0.2169	0.0316	2.70
13	2.719[illegible]	37.48	8.1414	0.2172	0.0318	2.69
14	2.719[illegible]	37.47	8.1570	0.2177	0.0318	2.70
15	2.7192	37.47	4.2796	✗0.1142	0.0167	2.69
16	2.7192	37.47	4.2500	0.1134	0.0166	2.69
17	2.7192	37.47	4.2591	0.1137	0.0166	2.70

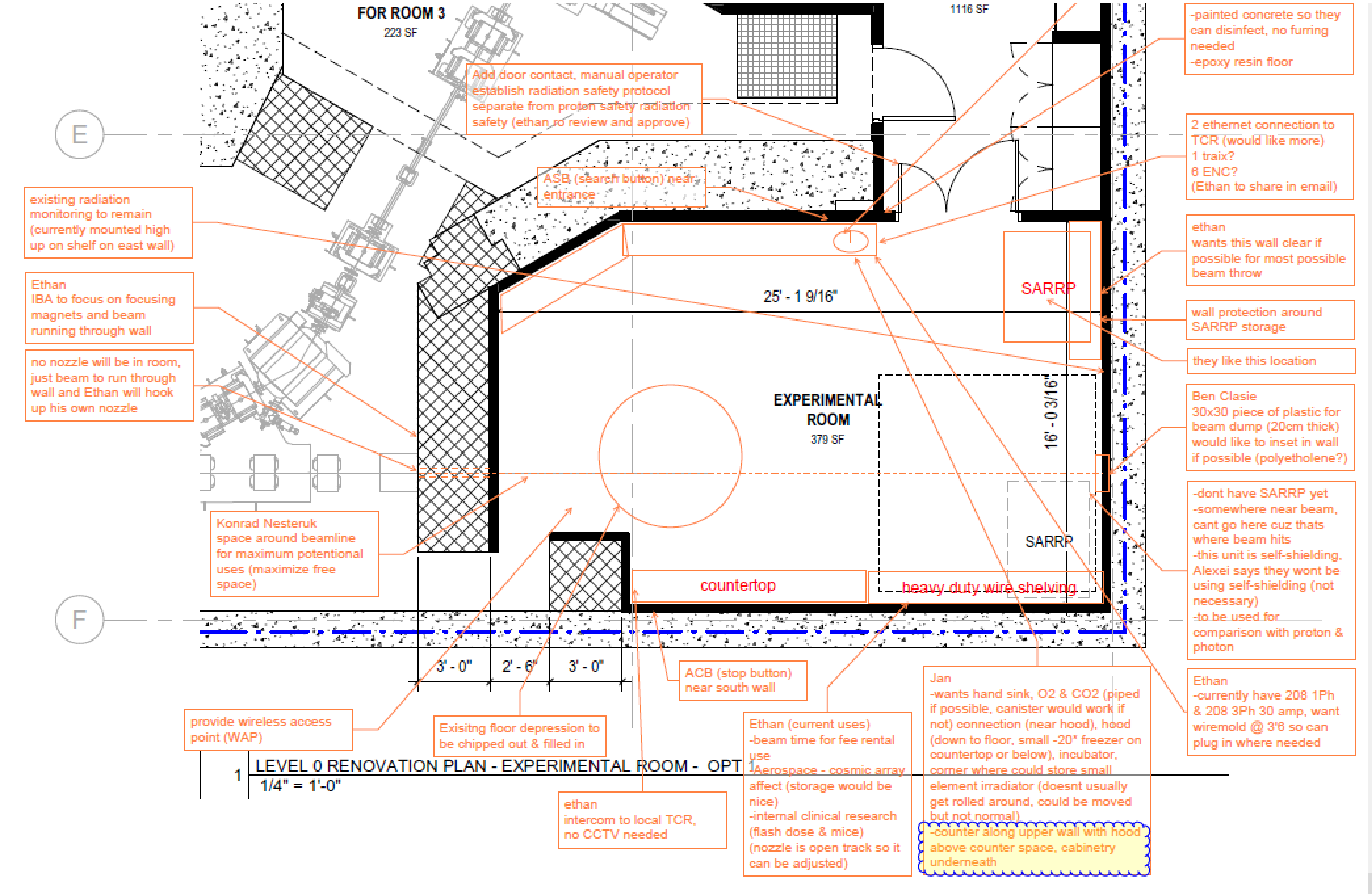
(1) Massachusetts Dept. of Labor and Industries, Division of Standards.

ALUMINUM ABSORBERS (RECALCULATED) 11 Dec 67.

Measurement of energy spectrum of solar flare wheel (<125 MeV) done with "Harshaw NaI(T1) Integral Line Scintillation Detector"



From E. W. Cascio and S. Sarkar "A Solar Flare Simulation Wheel for the Radiation Test Beamline at The Francis H. Burr Proton Therapy Center", IEEE Transactions on Nuclear Science, Vol. 55, NO. 6 (2008)



Markup plan for experimental/test room post Burr 2.0