The NASA Space Radiation Laboratory at Brookhaven National Laboratory

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K.A. Brown

Collider Accelerator Department, BNL

BROOKHAVEN
NATIONAL LABORATORY

Outline

The NASA/BNL Space Radiation Program

Sampling of experiments

The NSRL Facility

Operations

Beam Characteristics

Uniform Beams

Dosimetry

Large Dynamic Range Camera Imaging System

Solar Particle Simulator

Summary

The NASA/BNL Space Radiation Program

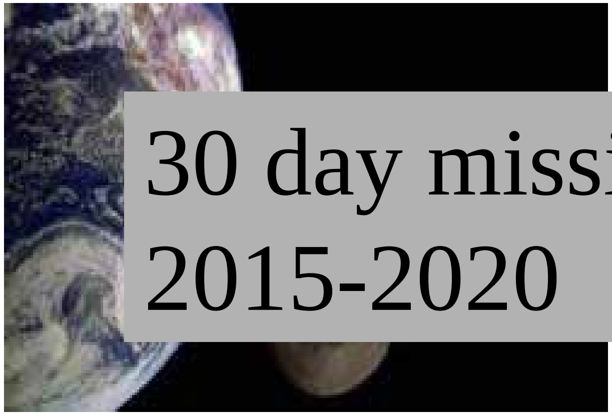
"Because astronauts are spending more time in space, the National Aeronautics and Space Administration (NASA) is working with Brookhaven National Laboratory and others here on Earth to learn about the possible risks to human beings exposed to space radiation. To study the radiobiological effects using beams that simulate the cosmic rays found in space, a new, $34-million NASA Space Radiation Laboratory (NSRL) has been established at Brookhaven Lab."

http://www.bnl.gov/medical/NASA/NSRL_description.asp

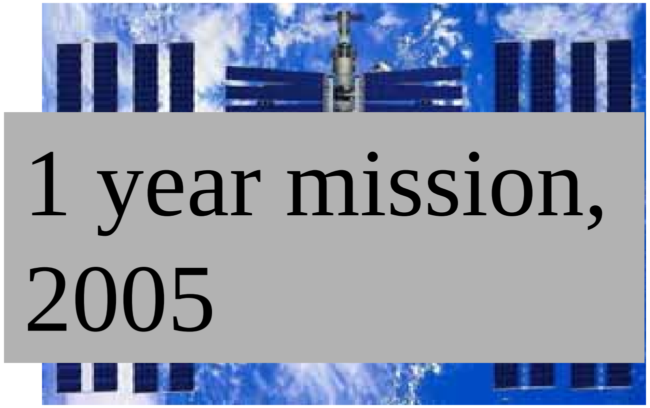
Human Environments in Space

Present

Future



30 day mission, 2015-2020



1 year mission, 2005

30 month mission, 2025-2030

Radiation Doses on Earth and in Space

1y in Houston	100 mrem
1y in Denver	200 mrem
1y in Kerala, India	1,300 mrem
Apollo 14	1,100 mrem (9-day to the Moon)
Skylab 4	18,000 mrem (87-day in orbit)
Shuttle mission 41-C	5,600 mrem (18-day in orbit)
Mission to Mars	130,000 mrem (30 month)
at solar minimum	30,000 mrem in 1.5 y on Mars
	80,000 mrem in 1 y in space,
	+20,000 mrem from a solar flare

Chest X-ray	50 mrem
PET scan	1,000 mrem
Treatment of brain cancer	500,000,000 mrem (to normal brain)

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The NASA/BNL Space Radiation Program

NSRL became operational during summer 2003

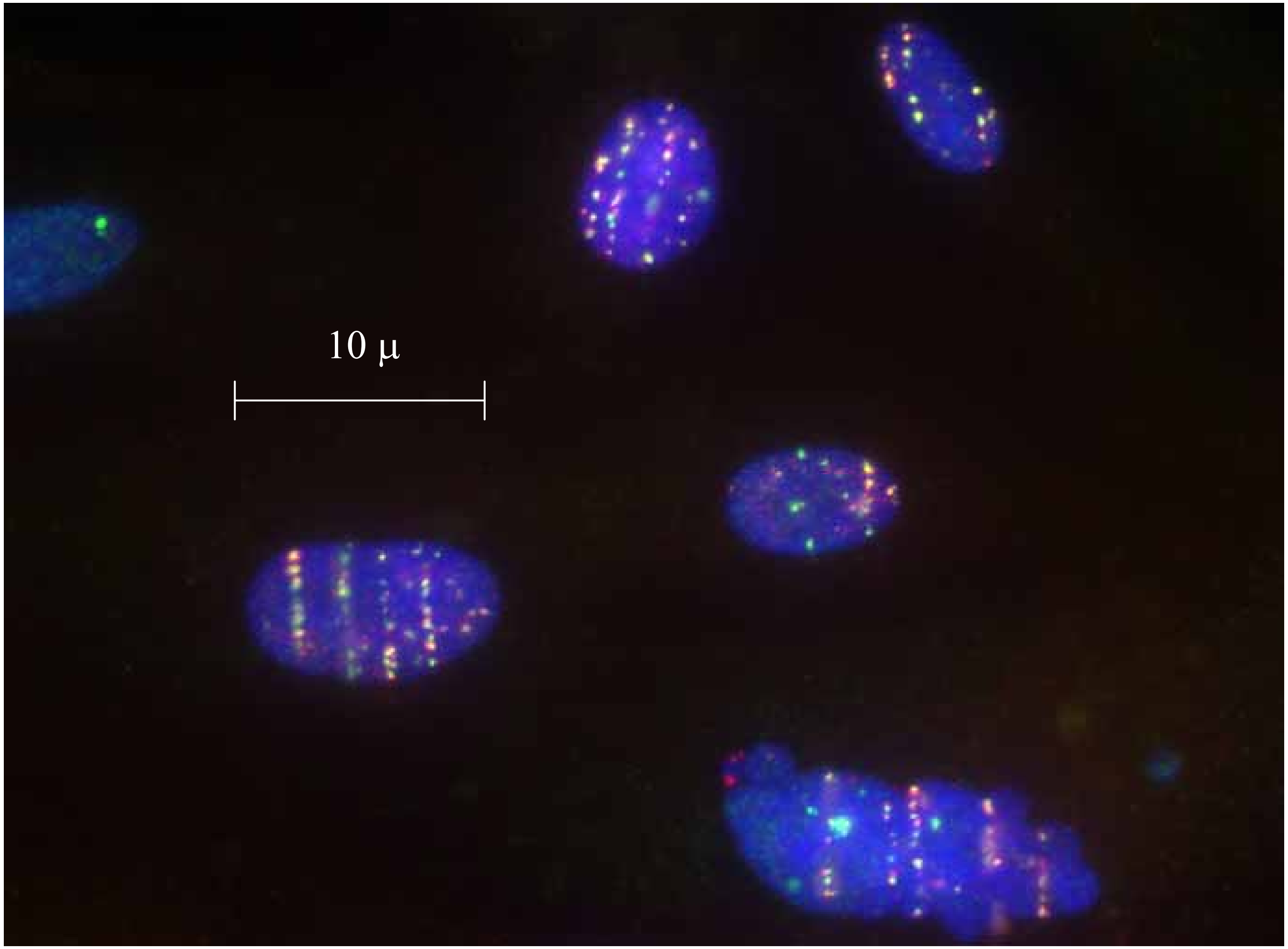
> 100 experimenters from 24 institutions (U.S. and abroad)

Brookhaven researchers and other NASA-sponsored scientists irradiate a variety of biological specimens, tissues, and cells, as well as DNA in solution. Other experimenters use industrial materials as samples, studying their suitability for space suits and spacecraft shielding.

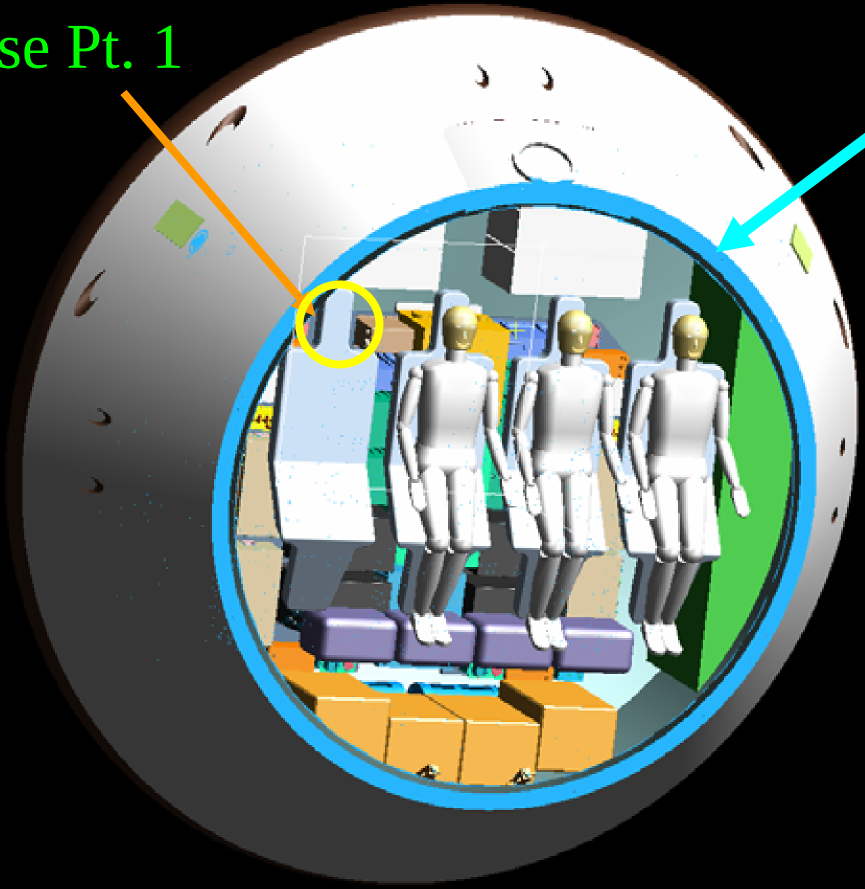
Sampling of experiments

- Effect of Deep Space radiation on Human Hematopoietic Stem Cells
- Risk Assessment and chemoprevintion of HZE-induced CNS damage
- Heavy Ion Induced Chromosome Damage and Biomedical Countermeasures
- DNA damage clusters in low level radiation responses of human cells.
- Complex Space Radiation-induced DNA damage Clusters in Human Cell Transformation: Mechanisms, relationships and Mitigation.
- Induction of Bystander Effects by High LET Radiation in Cells
- Gene Expression in the Nematode C. elegans following Irradiation with Charged Particles
- Heavy Ion Particle Impact on Simulated Martian Regolith
- MSL/RAD Technology Demonstration Model Characterization
- Spacecraft shielding and components experiments
- Ion fragmentation experiments

1 GeV Fe tracks in cells.

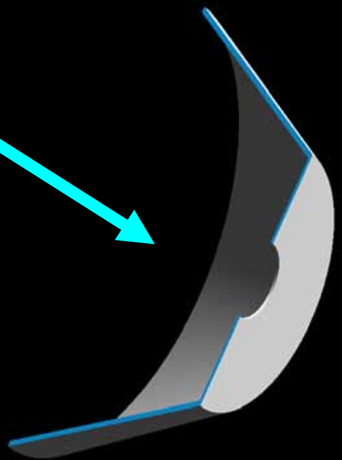


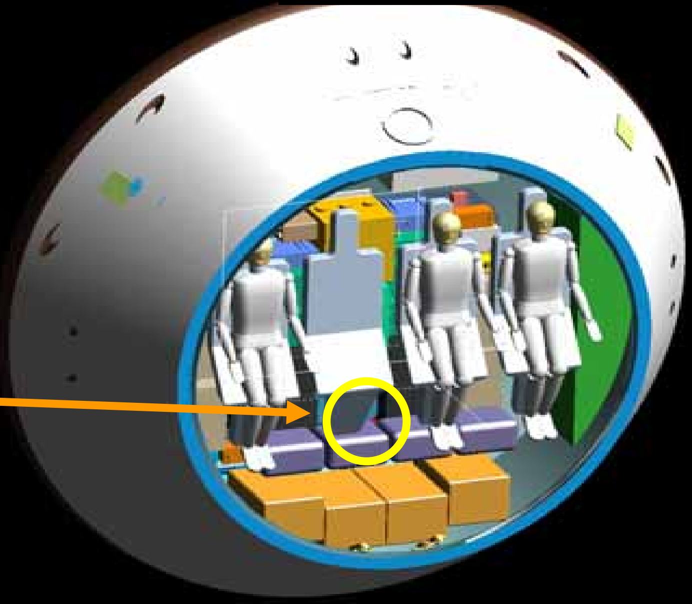
Local Polyethylene Shielding Study



Dose Pt. 1

Polyethylene radiation shield





Dose Pt. 2

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Heavy Ions

Charged

Ionizing Radiation

Outer-Space is full of them

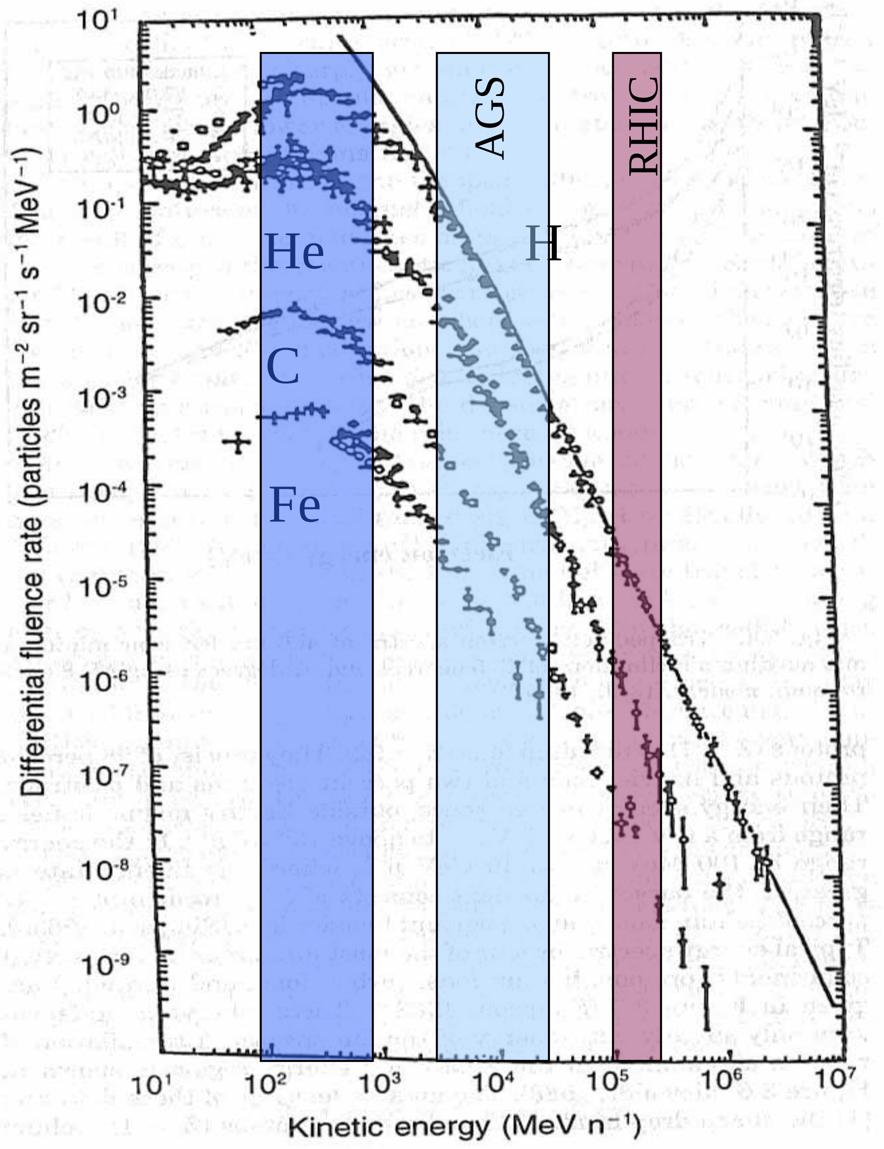

Fig. 3.5. Typical energy spectra for protons, helium ions, carbon ions, and iron ions from "top to bottom," respectively, at solar minimum. The solid line is the local interstellar spectrum (Simpson, 1983a).

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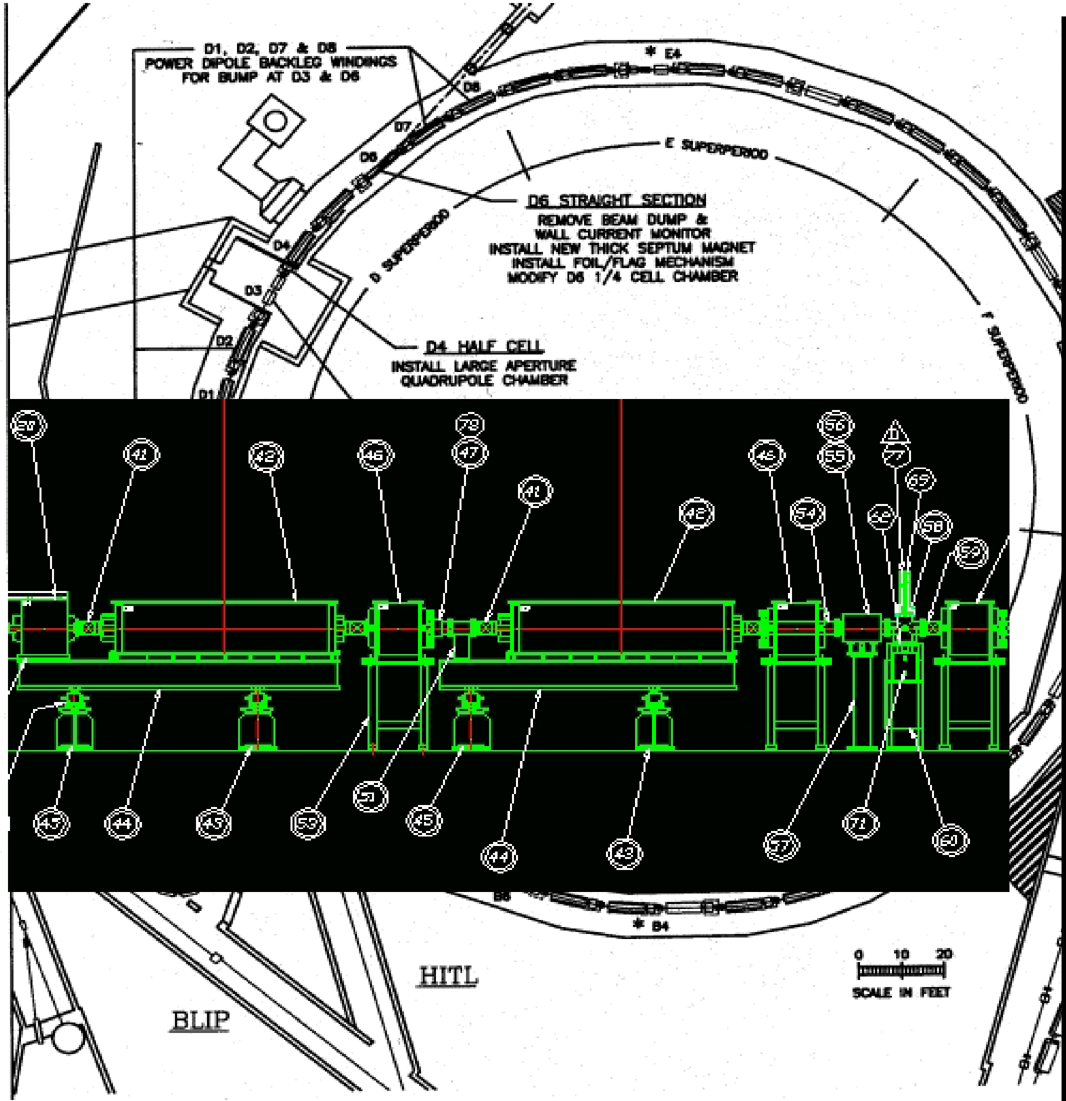
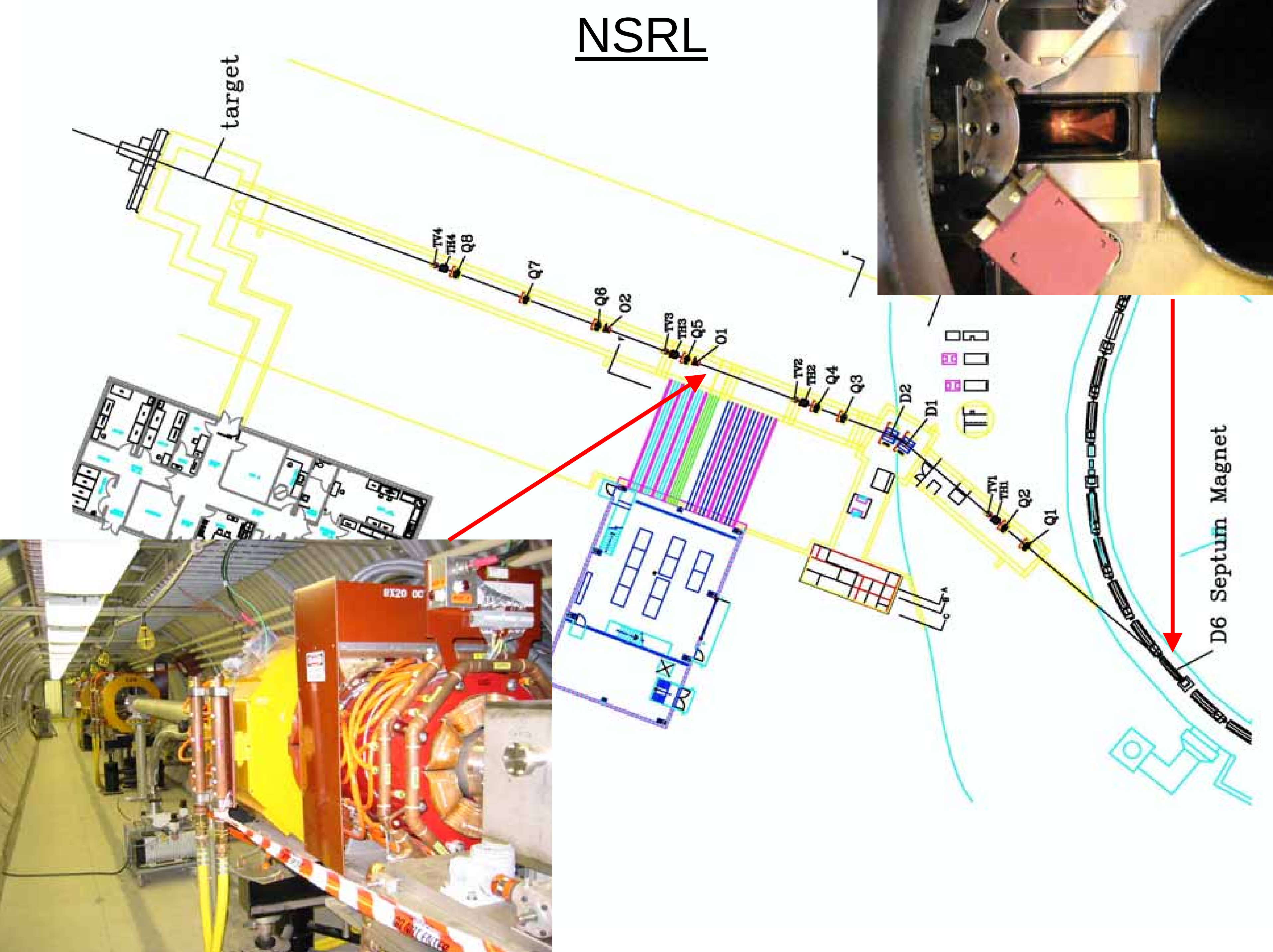
Booster Parameters

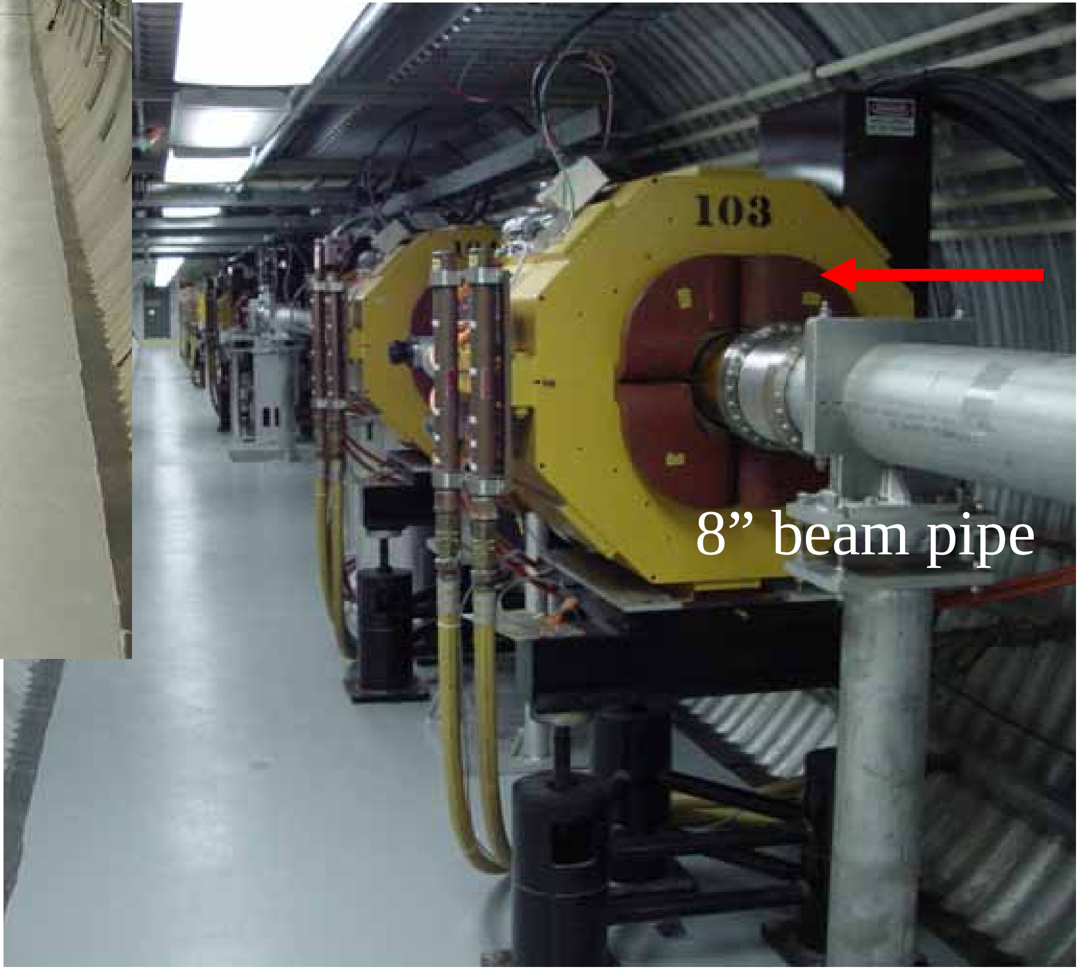


Parameter	Value
Circumference	201.78 (1/4 AGS) m
Ave. Radius	32.114 m
Magnetic Bend R	13.8656 m
Lattice Type	Separated Function, FODO
No. Superperiods	6
No. of Cells	24
Betatron Tunes,X,Y	4.82, 4.83
Vacuum Chamber	70 x 152 mm Dipoles 152 mm (circular) Quads
Max. Rigidity	17 Tm
Injection Rigidity	2.2 Tm (200 MeV protons)
Acceleration Rate	8.9 T/s (7.5 Hz)

NSRL


target
TV4
TH4
Q8
Q7
Q6
O2
TV3
TH3
Q5
O1
TV2
TH2
Q4
Q3
D2
D1
TV1
TH1
Q2
Q1
D6 Septum Magnet

R-Line: From Booster to NSRL



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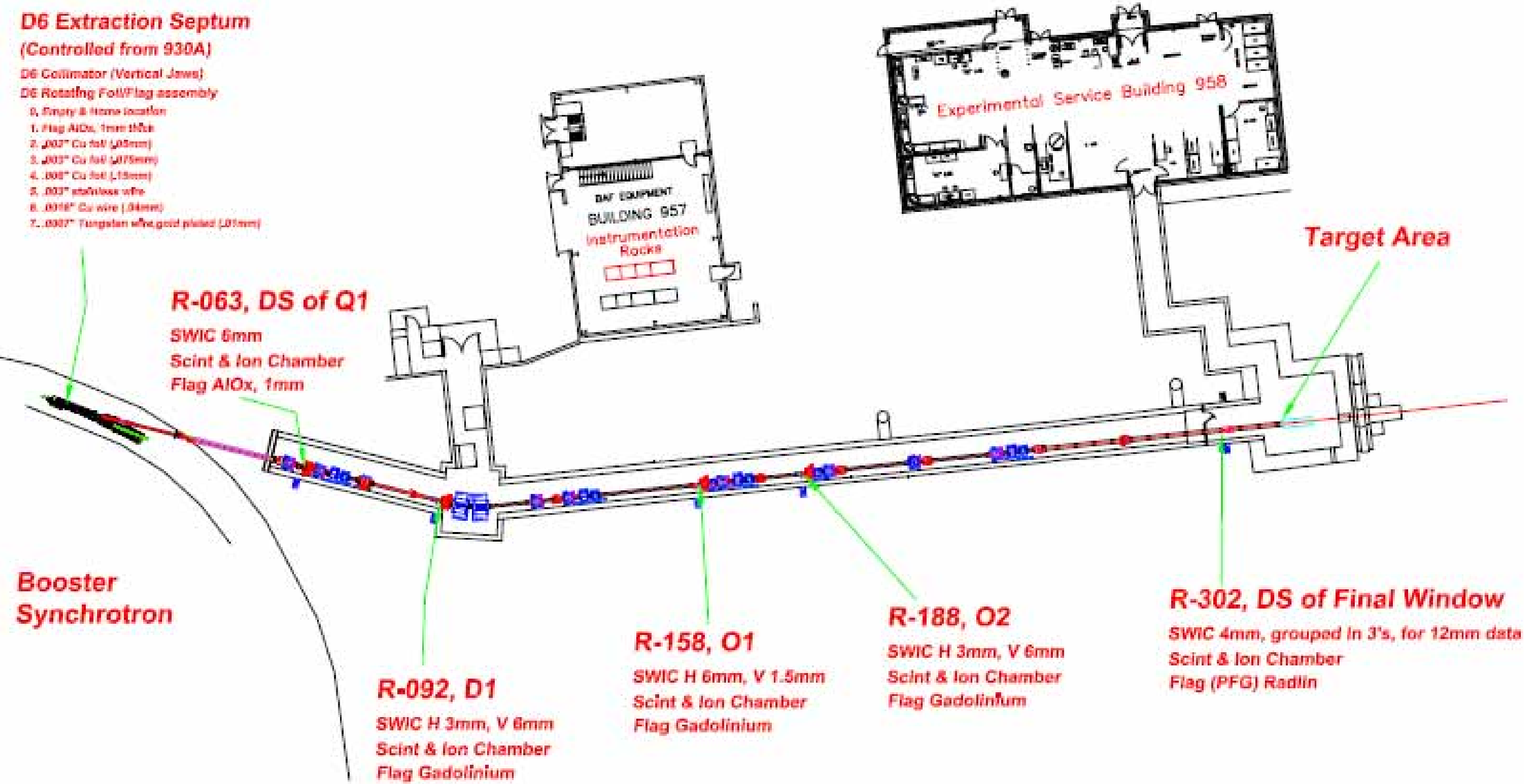
Instrumentation Layout



D6 Extraction Septum

(Controlled from 930A)

D6 Collimator (Vertical Jaws)

D6 Rotating Foil/Flag assembly

0. Empty & Home location
1. Flag AlOx, 1mm thick
2. .002" Cu foil (.05mm)
3. .003" Cu foil (.075mm)
4. .006" Cu foil (.15mm)
5. .003" stainless wire
6. .0016" Cu wire (.04mm)
7. .0007" Tungsten wire,gold plated (.01mm)

R-063, DS of Q1

SWIC 6mm
Scint & Ion Chamber
Flag AlOx, 1mm

Target Area

Booster Synchrotron

R-092, D1

SWIC H 3mm, V 6mm
Scint & Ion Chamber
Flag Gadolinium

R-158, O1

SWIC H 6mm, V 1.5mm
Scint & Ion Chamber
Flag Gadolinium

R-188, O2

SWIC H 3mm, V 6mm
Scint & Ion Chamber
Flag Gadolinium

R-302, DS of Final Window

SWIC 4mm, grouped in 3's, for 12mm data
Scint & Ion Chamber
Flag (PFG) Radlin

NSRL Target Room

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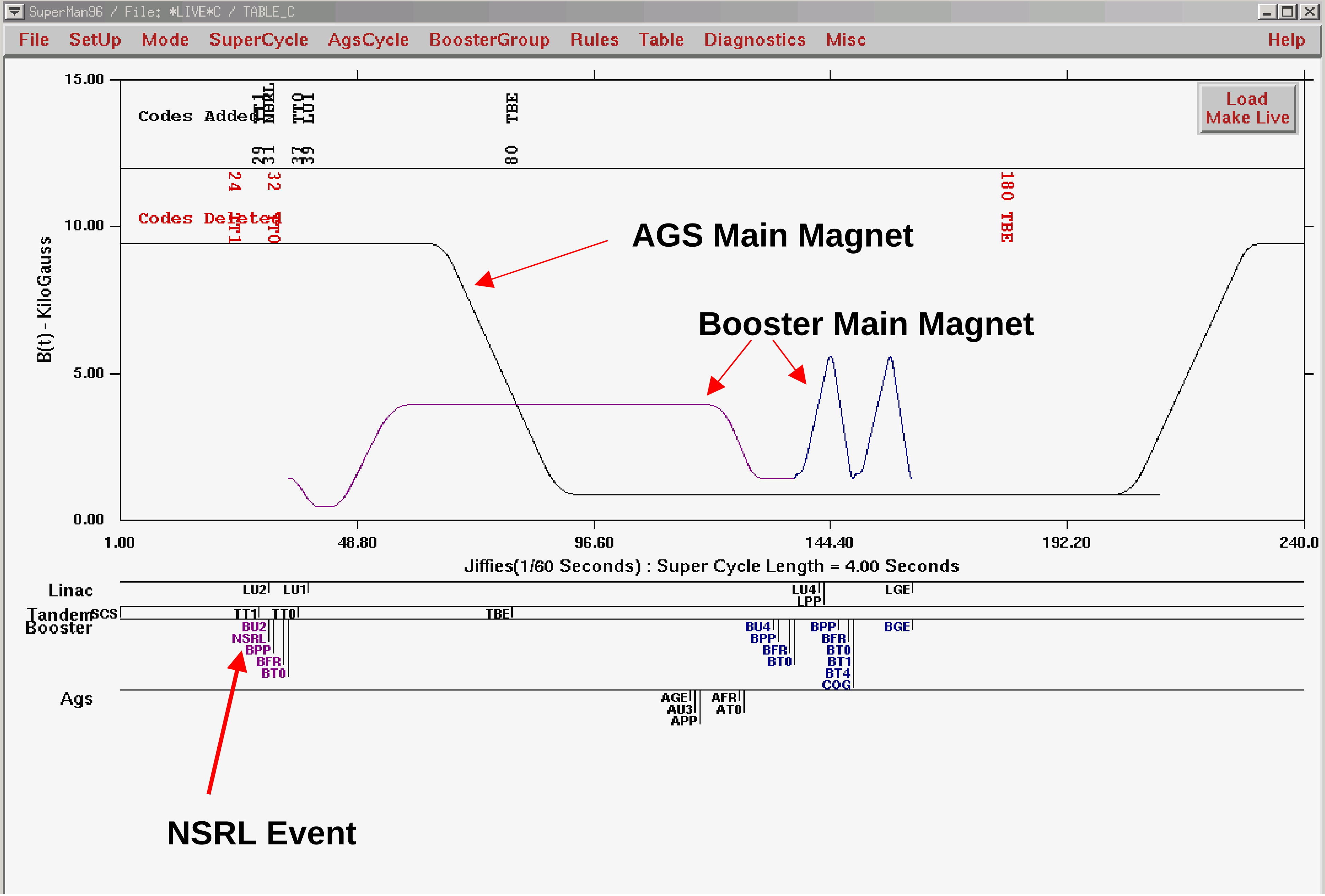
Beams delivered, NSRL-5 to NSRL-7

Ion	Energy (MeV/n)	Intensity
p	1000	3.4×10^{10}
C	290	1.2×10^{10}
O	1000, 600	4.0×10^{9}
Si	600, 300	3.0×10^{9}
Cl	500	2.0×10^{9}
Ti	1100	8.0×10^{8}
Fe	1000, 600, 300	2.0×10^{9}

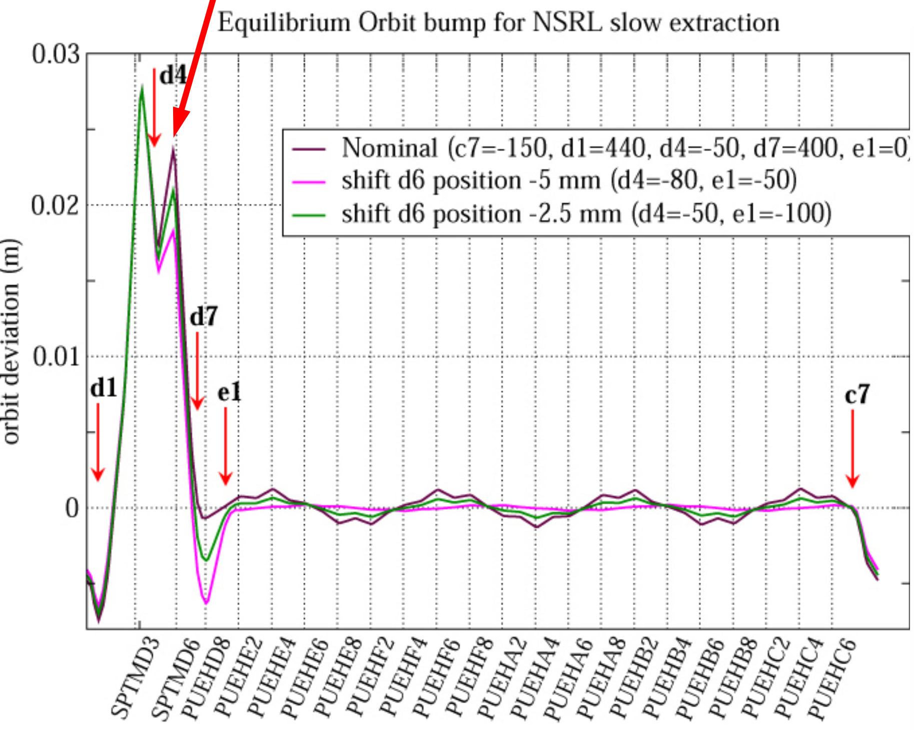


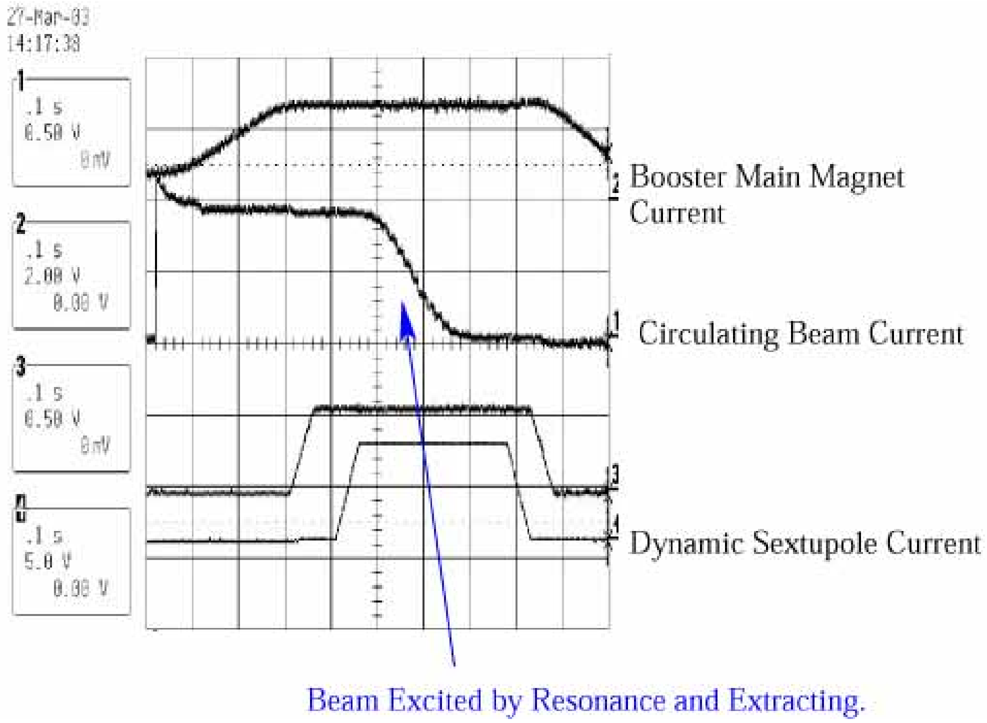
AGS Main Magnet

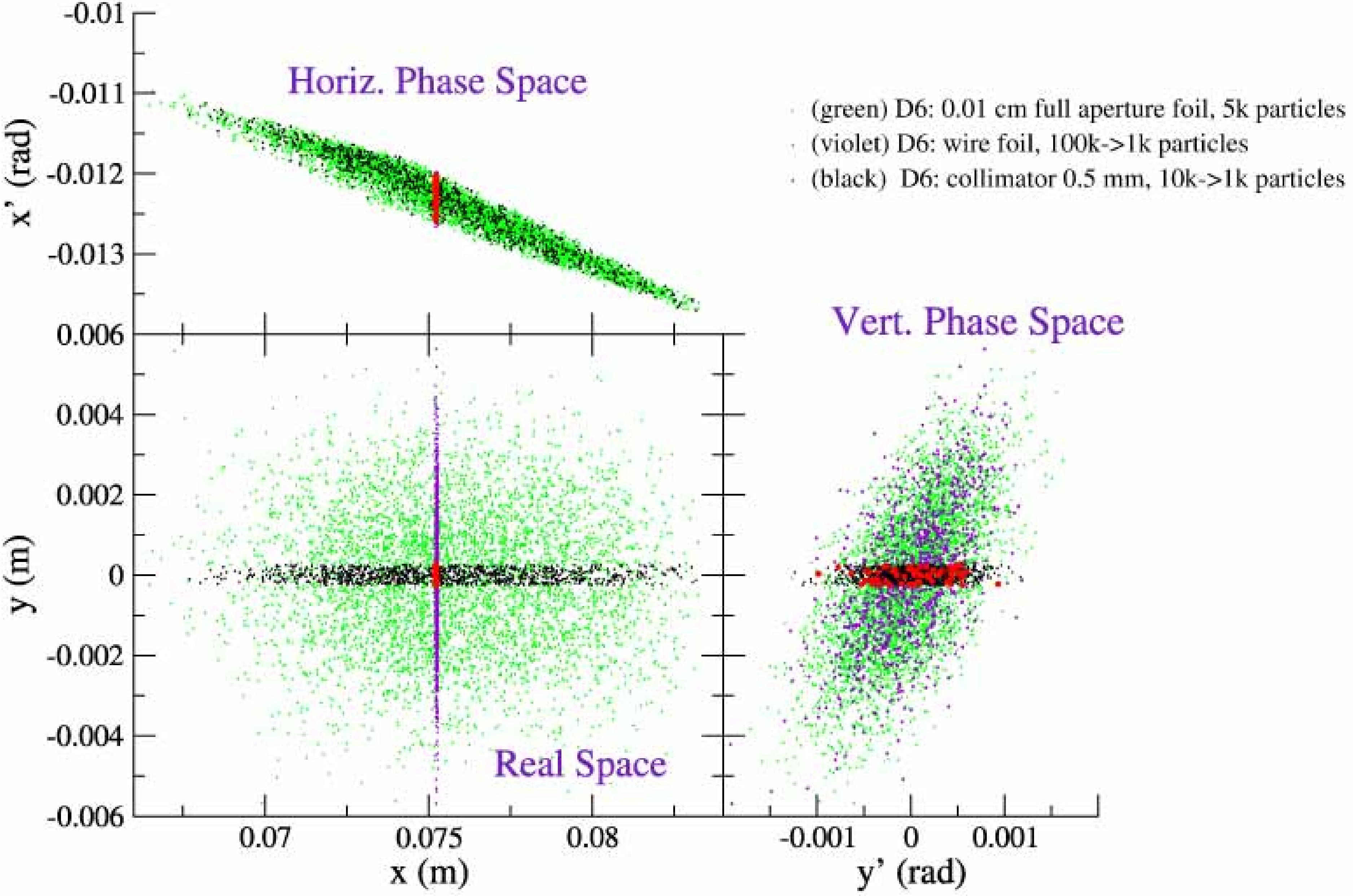
Booster Main Magnet

NSRL Event

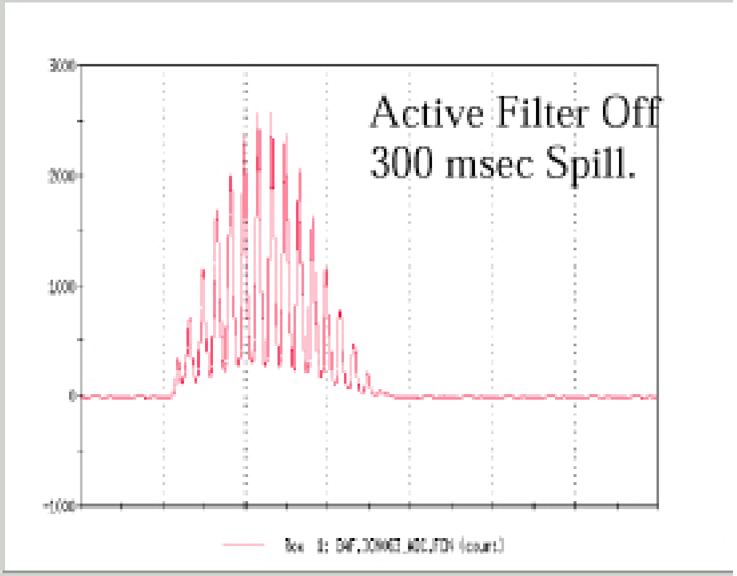
Extraction Point

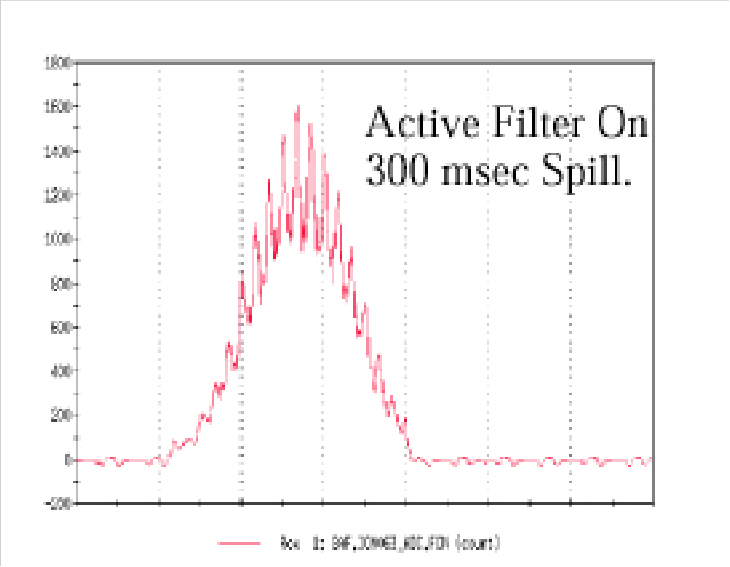




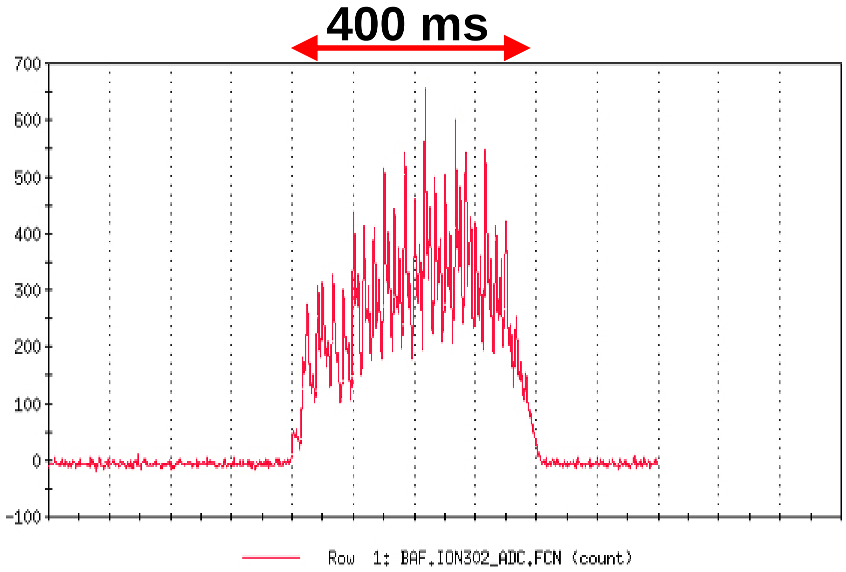

Horiz. Phase Space
(green) D6: 0.01 cm full aperture foil, 5k particles
(violet) D6: wire foil, 100k->1k particles
(black) D6: collimator 0.5 mm, 10k->1k particles
-0.01
-0.011
-0.012
-0.013
0.006
x' (rad)
Vert. Phase Space
0.004
0.002
0
-0.002
-0.004
-0.006
y (m)
Real Space
0.07
0.075
0.08
x (m)
-0.001
0
0.001
y' (rad)

2 GeV Protons

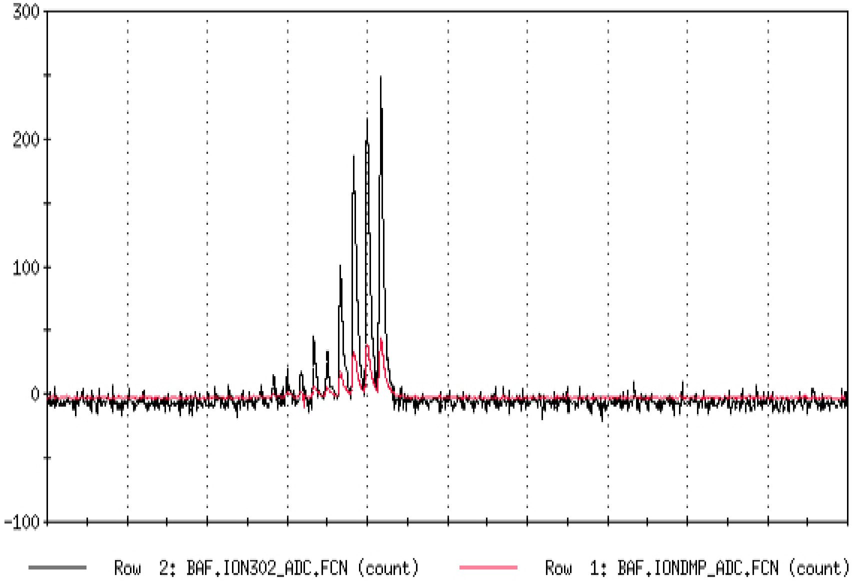




300 MeV/n Carbon



Spill Servo
And Active
Filter On.



Dosimetry
Beam Cutoff

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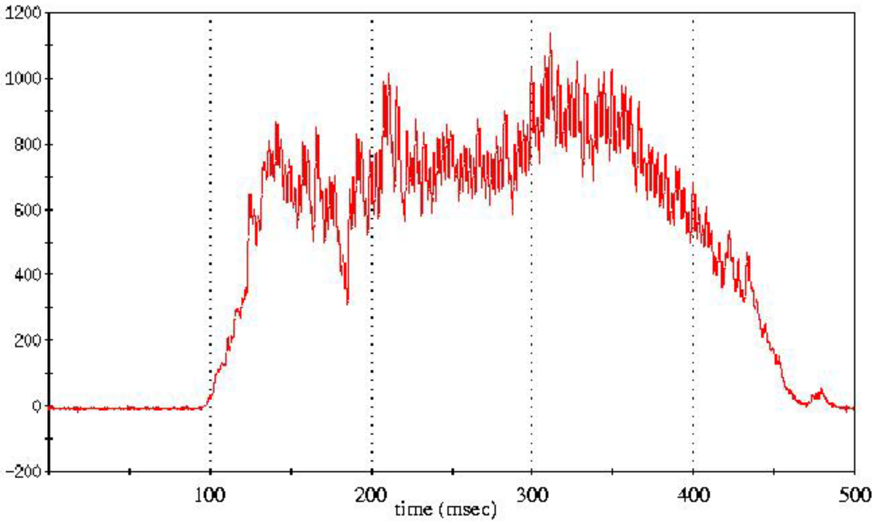
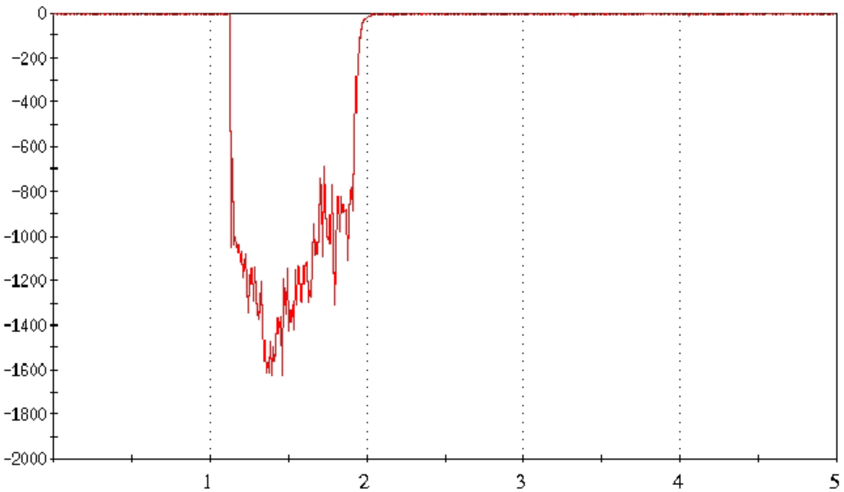
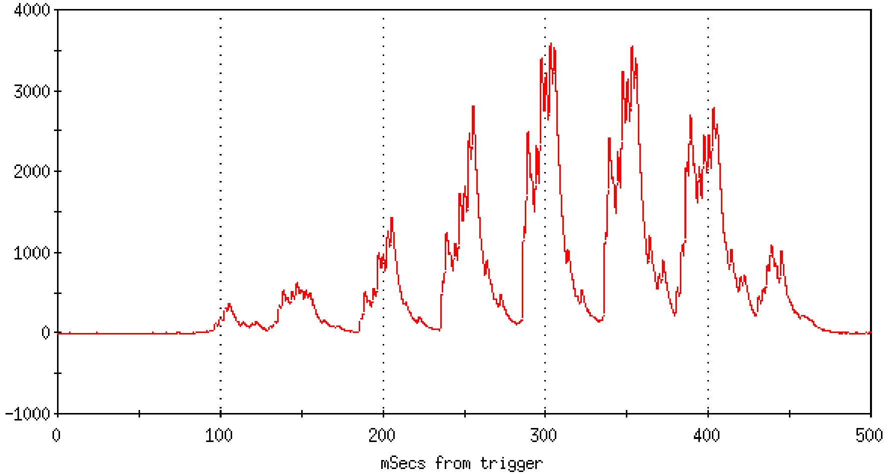
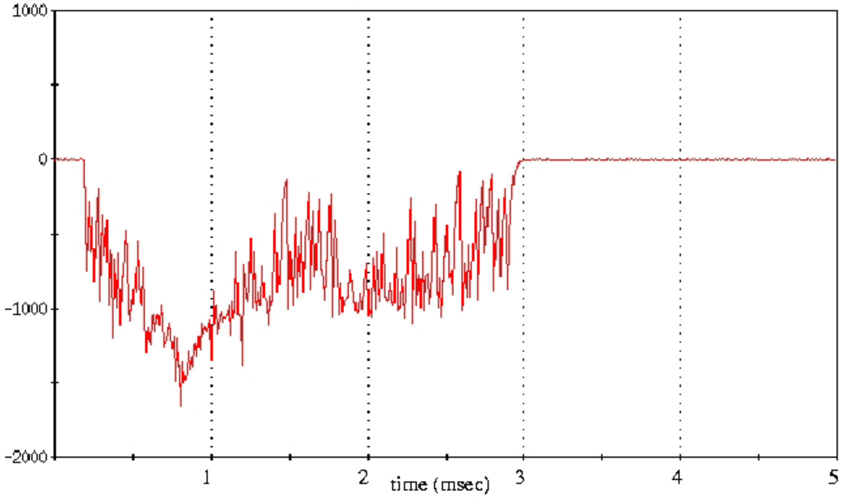
Beam Spills Delivered





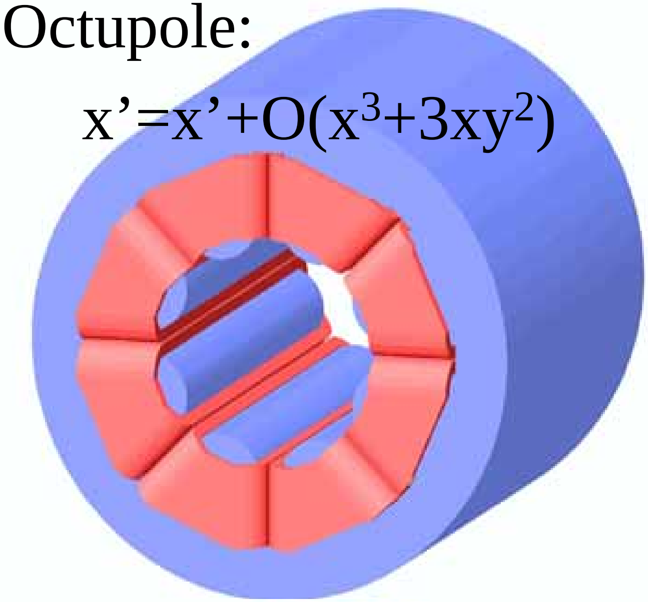


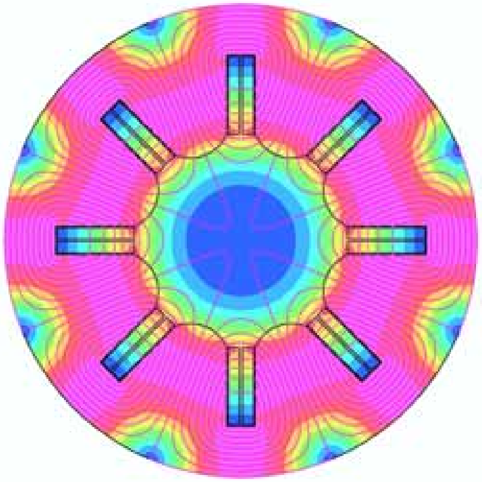


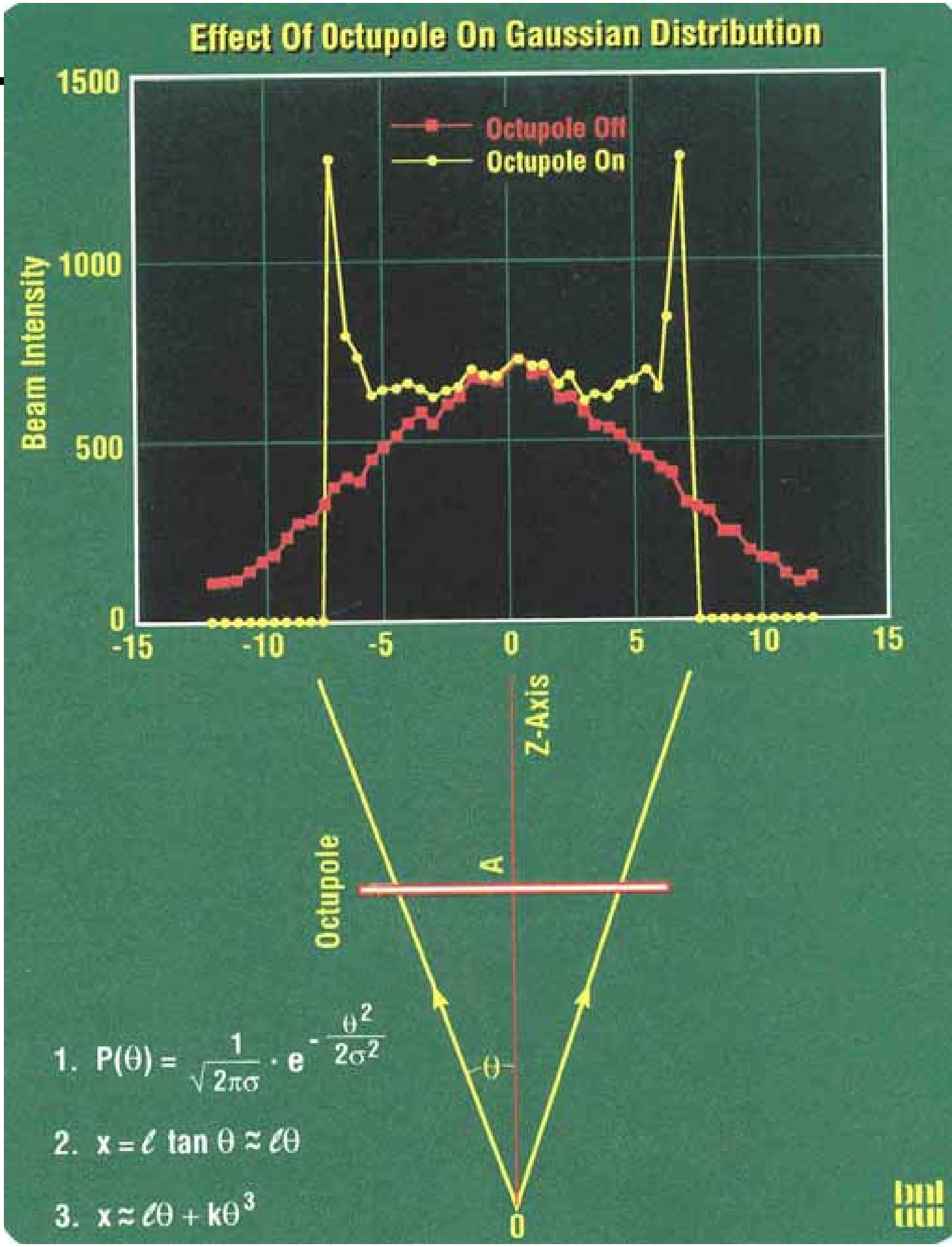
Uniform Beams

Octupole:

$$x' = x' + O(x^3 + 3xy^2)$$



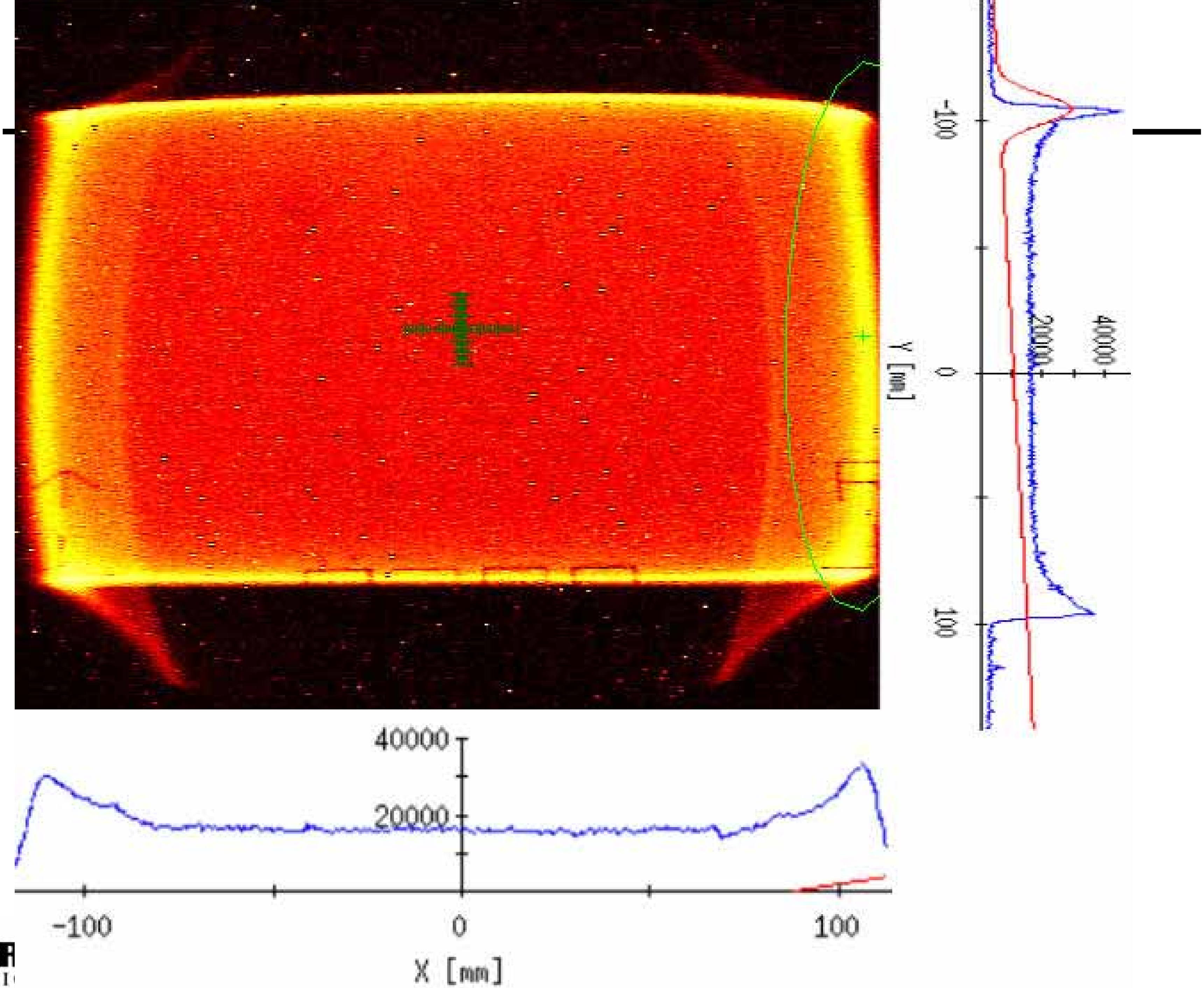


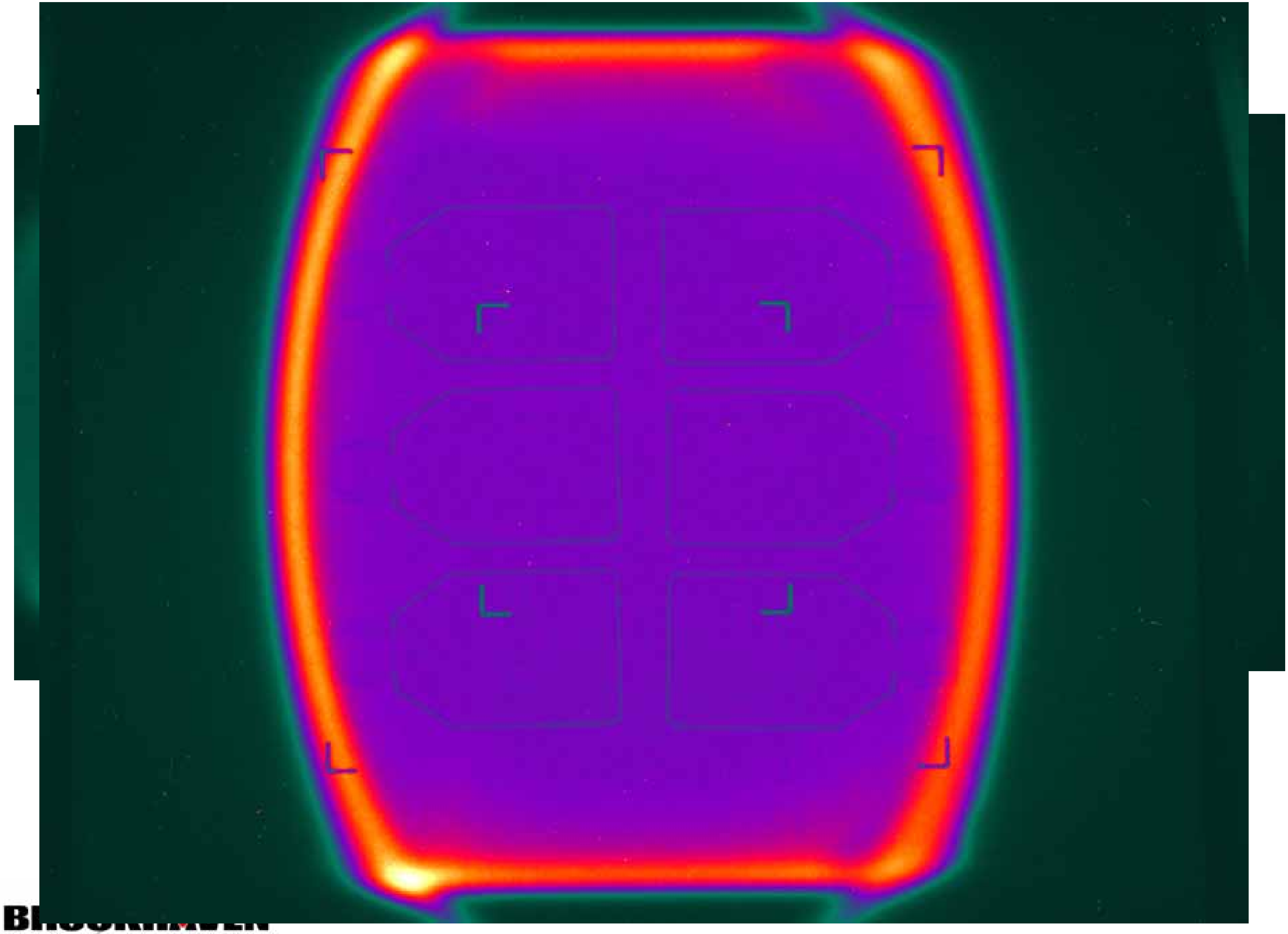


1. $P(\theta) = \frac{1}{\sqrt{2\pi\sigma}} \cdot e^{-\frac{\theta^2}{2\sigma^2}}$

2. $x = \ell \tan\theta \approx \ell\theta$

3. $x \approx \ell\theta + k\theta^3$


-100
100
20000
40000
Y [mm]
-100
0
100
X [mm]
0
20000
40000



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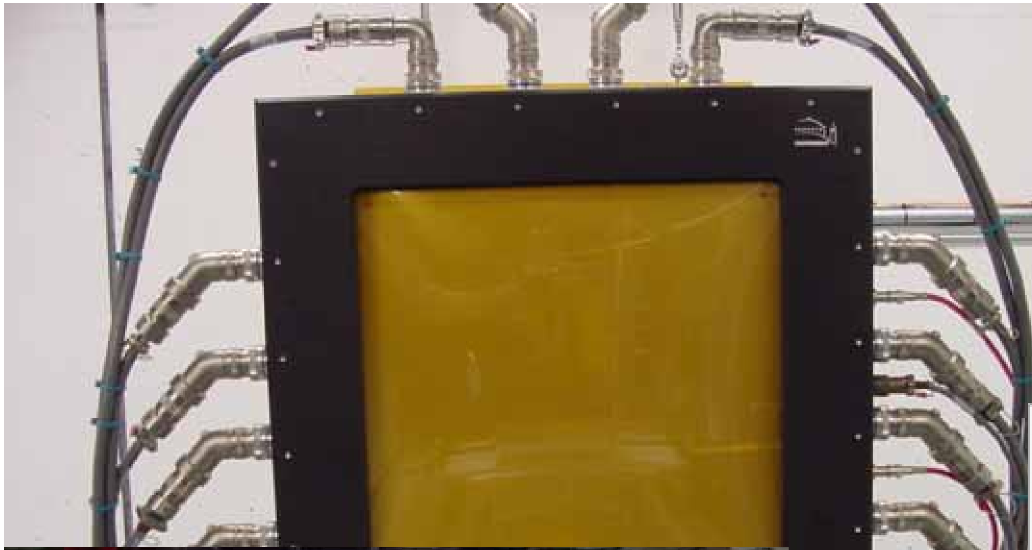
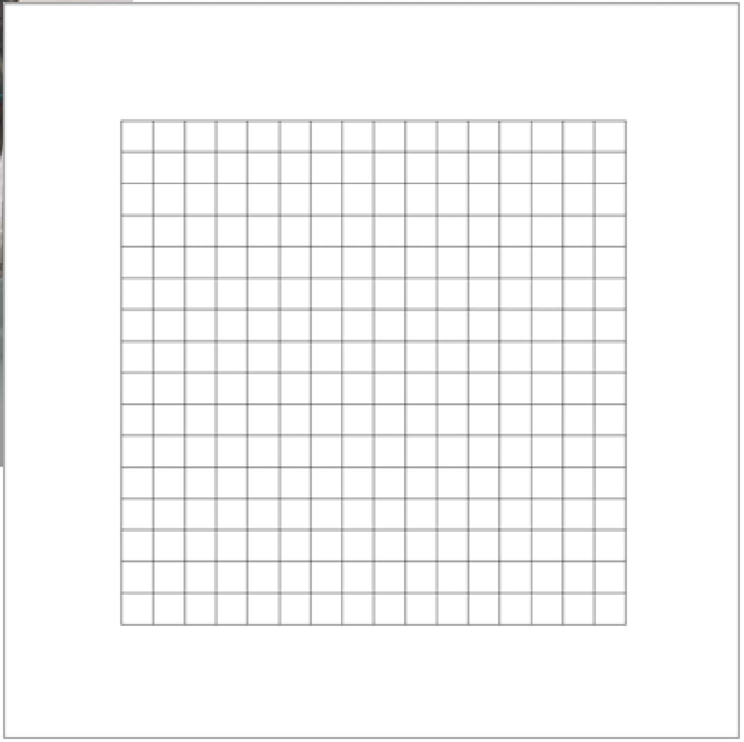
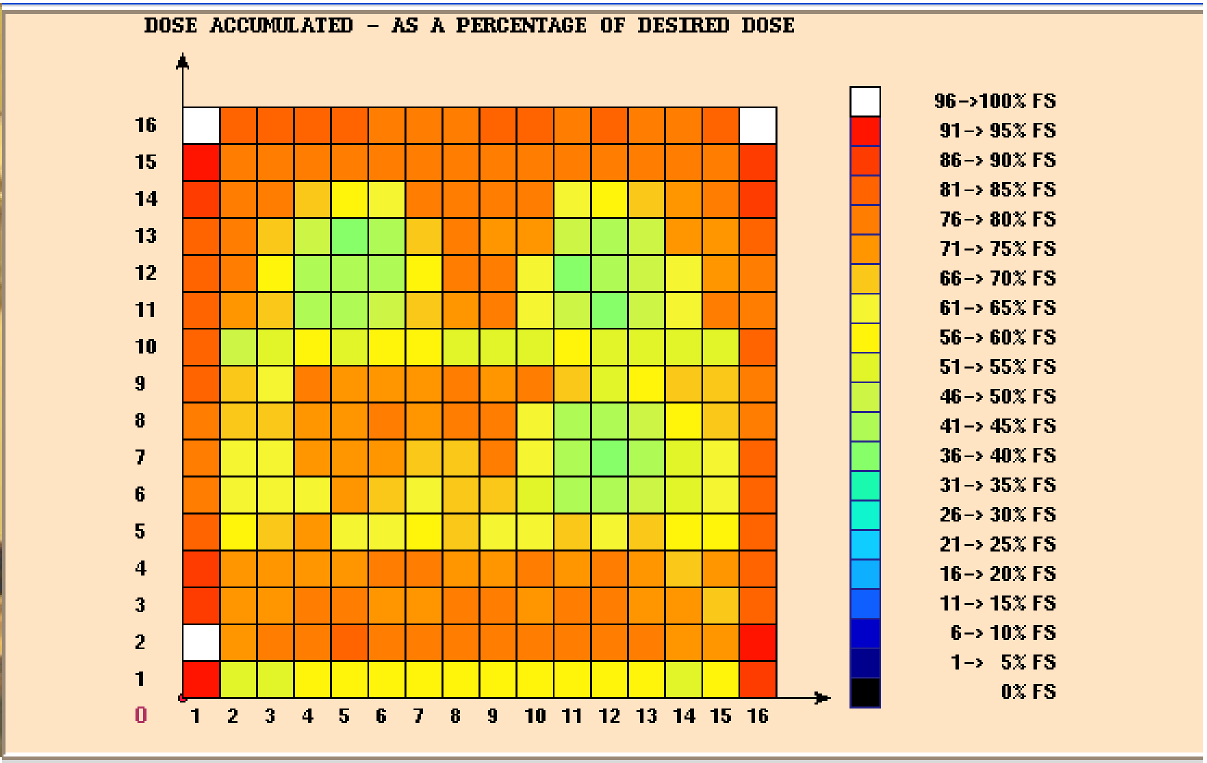
256-Element Ion-Chamber (Beam Imaging)



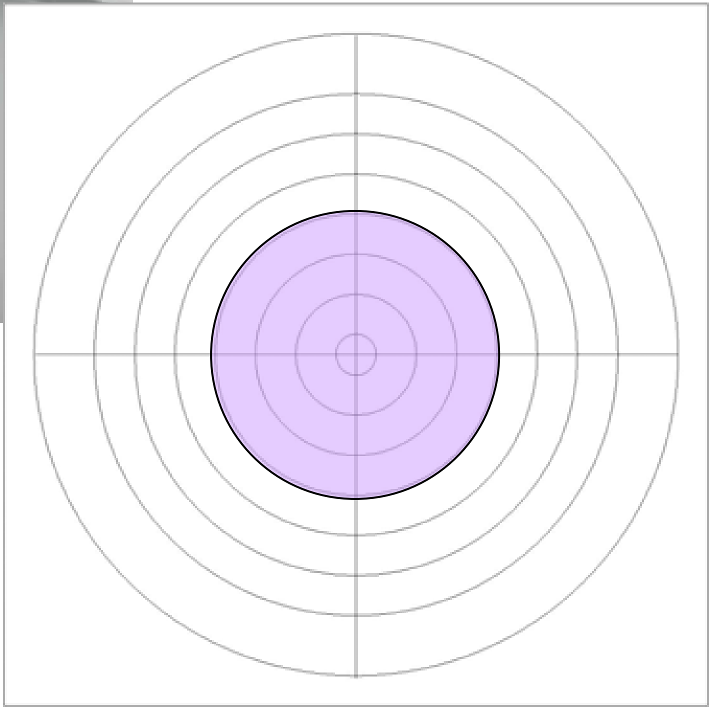


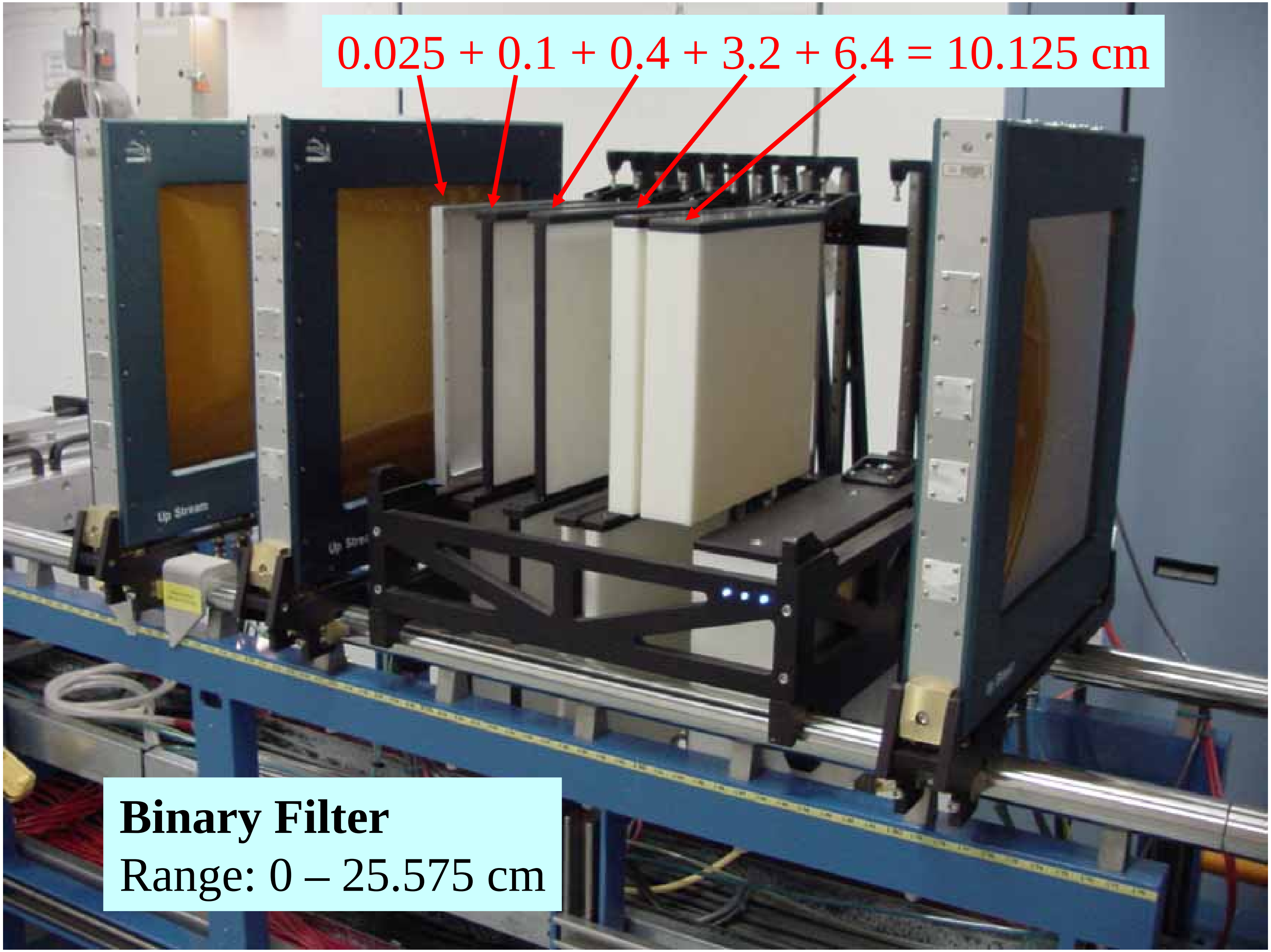
Beam Image on the 256-element IC

During E.Blakely’s experiment (NSRL-2).



32-Element Ion-Chamber (Dosimetry)

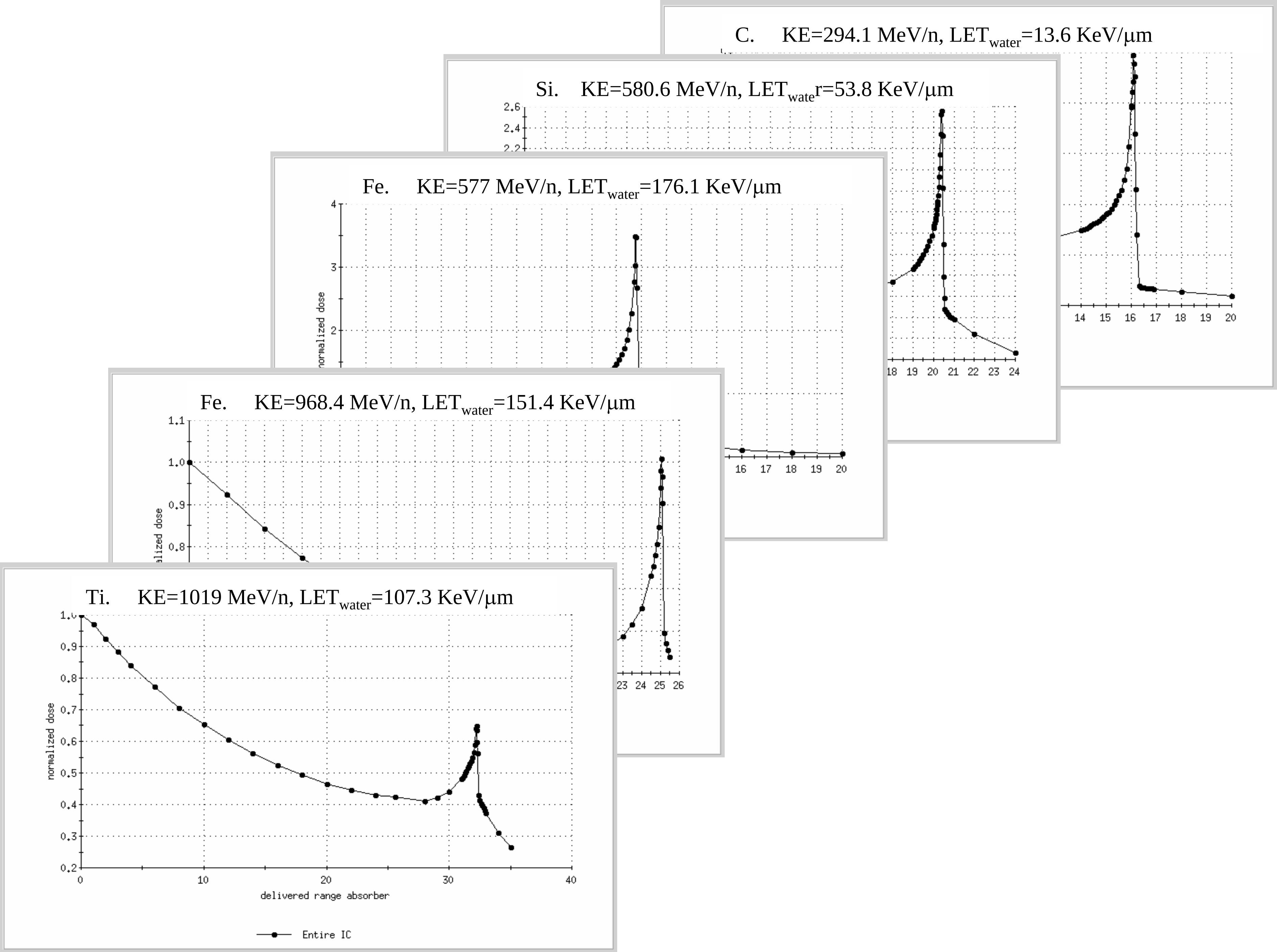




0.025 + 0.1 + 0.4 + 3.2 + 6.4 = 10.125 cm

Binary Filter

Range: 0 – 25.575 cm



C. KE=294.1 MeV/n, LET$_{water}$=13.6 KeV/μm

Si. KE=580.6 MeV/n, LET$_{wate}$r=53.8 KeV/μm

Fe. KE=577 MeV/n, LET$_{water}$=176.1 KeV/μm

Fe. KE=968.4 MeV/n, LET$_{water}$=151.4 KeV/μm

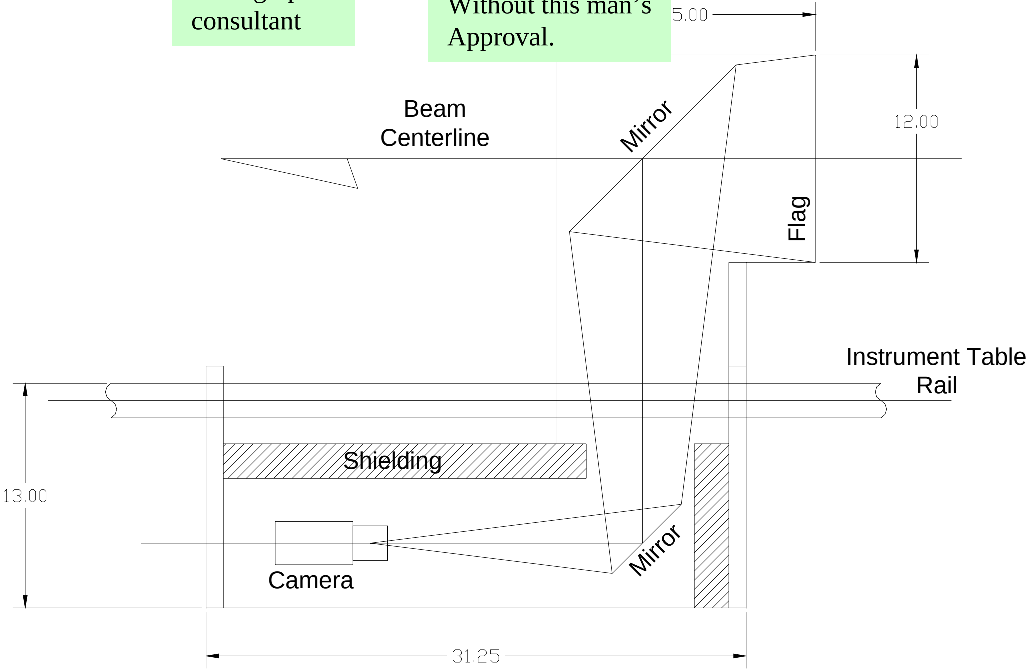
Ti. KE=1019 MeV/n, LET$_{water}$=107.3 KeV/μm


Adam Rusek

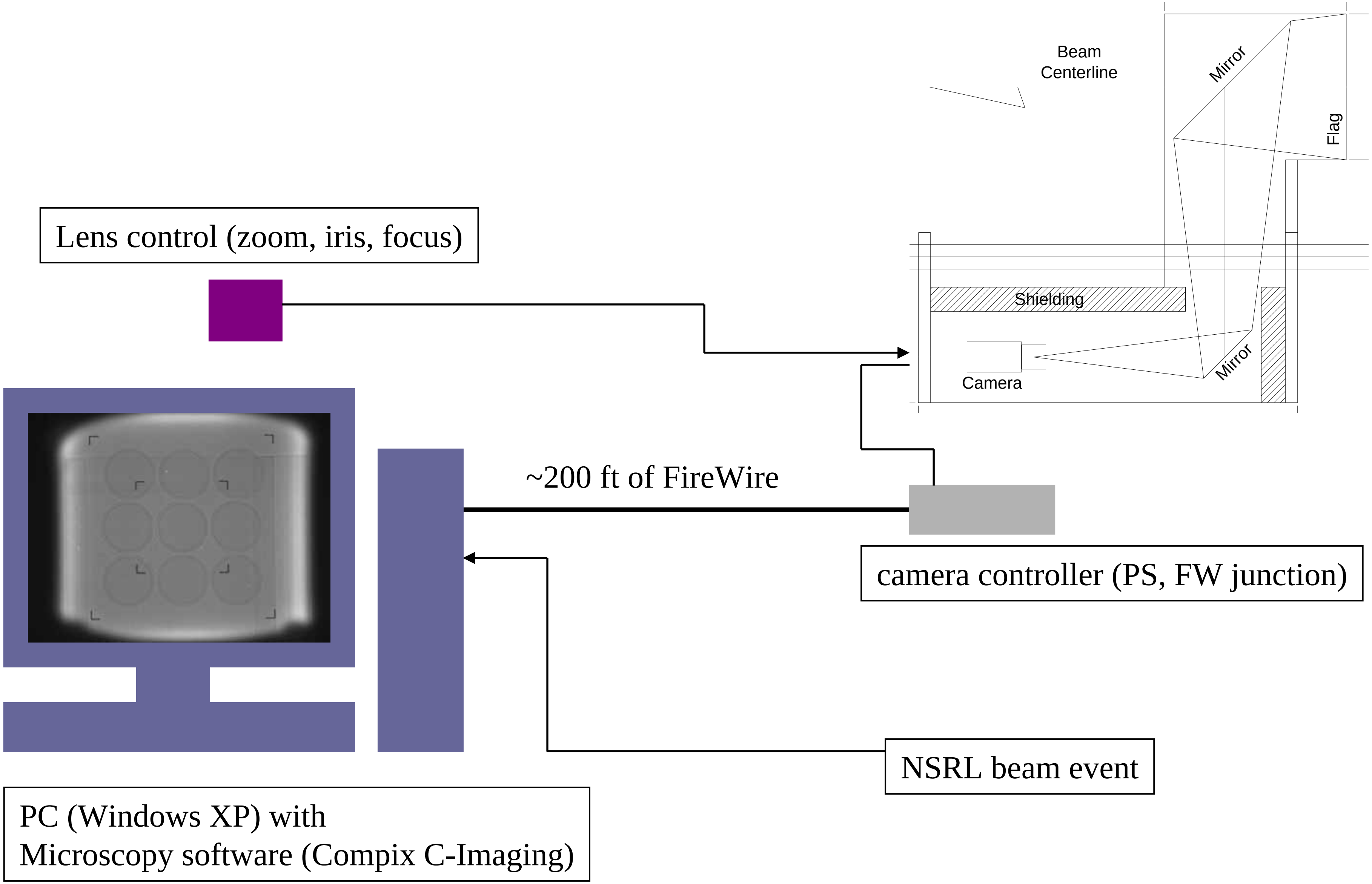

Kevin Brown
Photographic
consultant


I-Hung Chiang
Nothing happens
Without this man's
Approval.


Charlie Pearson
Engineering design



Beam Profile Camera System
Side Elevation View



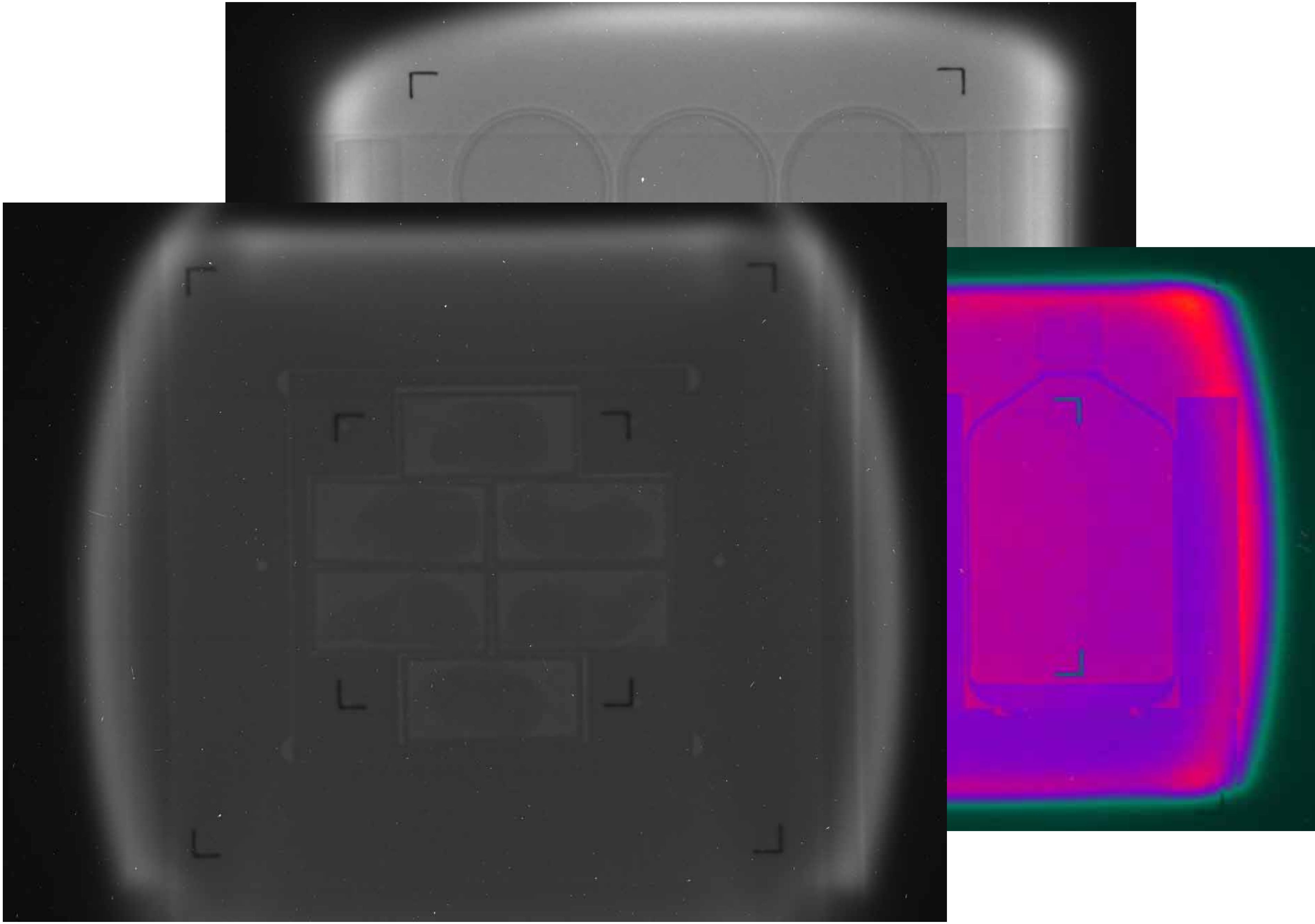
Lens control (zoom, iris, focus)

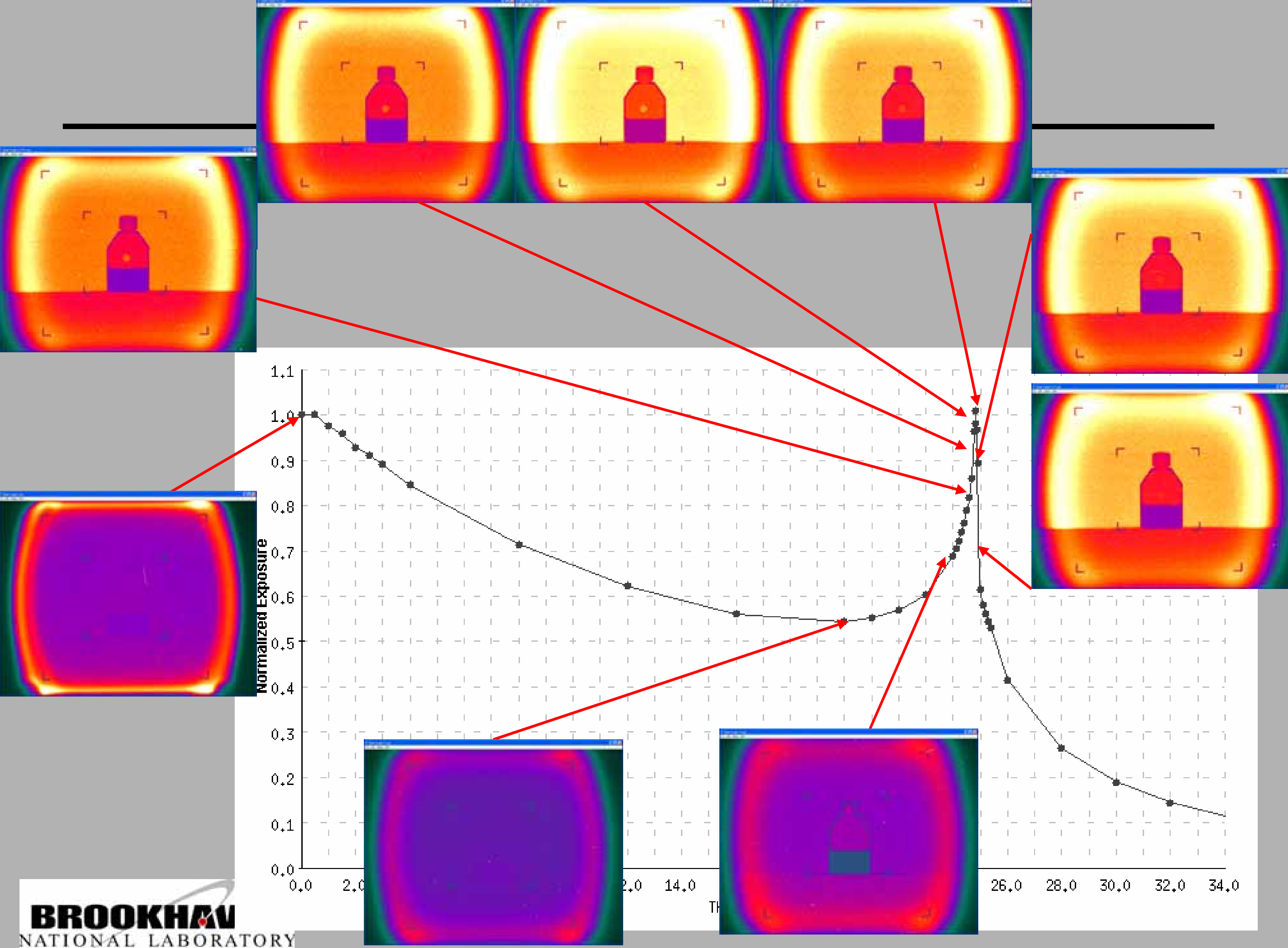
~200 ft of FireWire

camera controller (PS, FW junction)

NSRL beam event

PC (Windows XP) with
Microscopy software (Compix C-Imaging)




1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Normalized Exposure
0.0
2.0
14.0
26.0
28.0
30.0
32.0
34.0
Th

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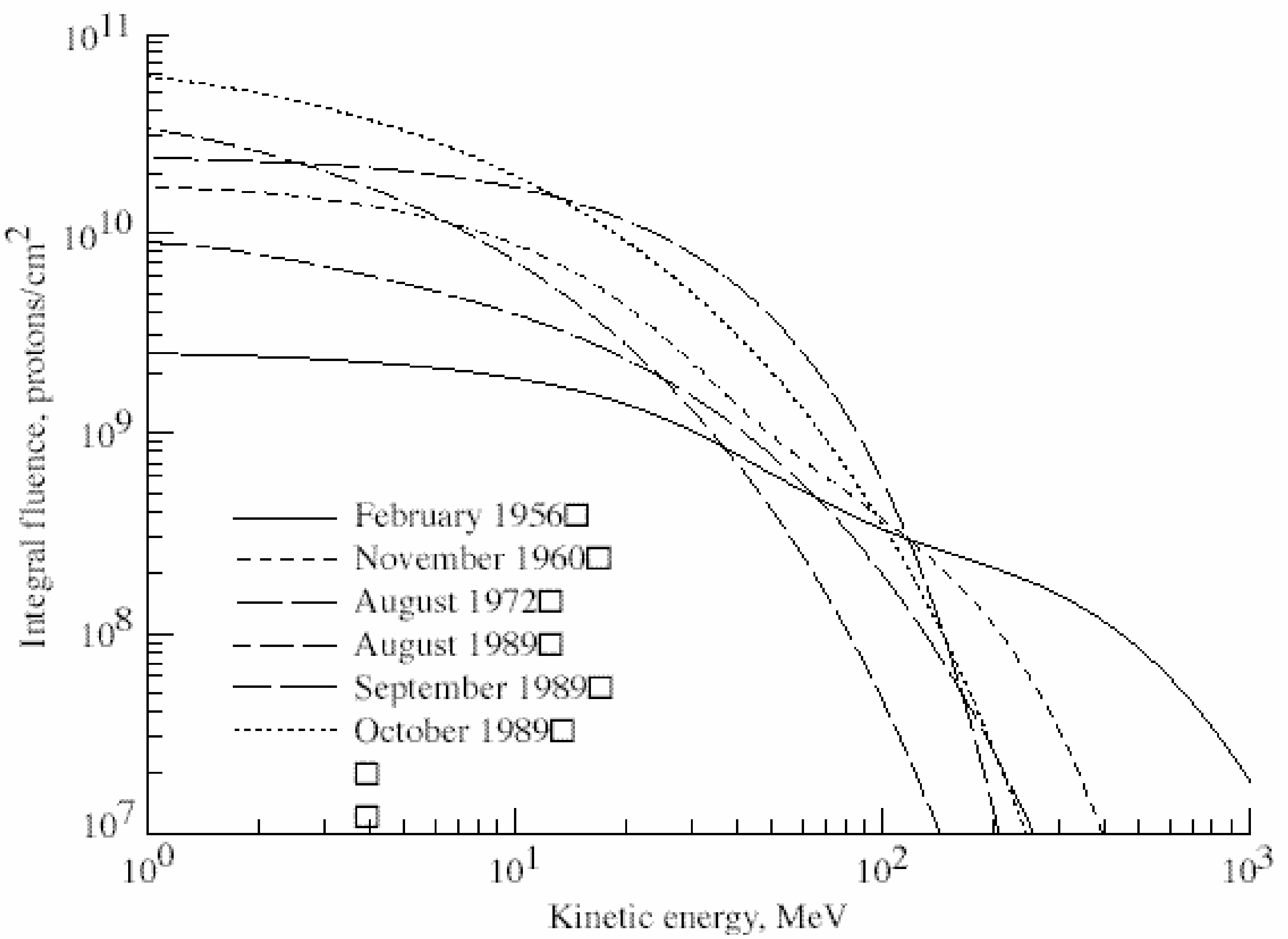
Solar Particle Simulator

The main motivation is to be able to reproduce energy spectra of the environment in space, particularly solar events.

NSRL Ground rules

- *Need to be able to irradiate a single sample over entire energy spectrum within as little as a 1 hour period.*
- *Need a clean beam, as clean as any current NSRL experiment now receives.*
- *Need to know the energy of the beam as well as any current NSRL experiment.*
- *Need to know the dose as well as any current NSRL experiment.*

Solar Proton Events

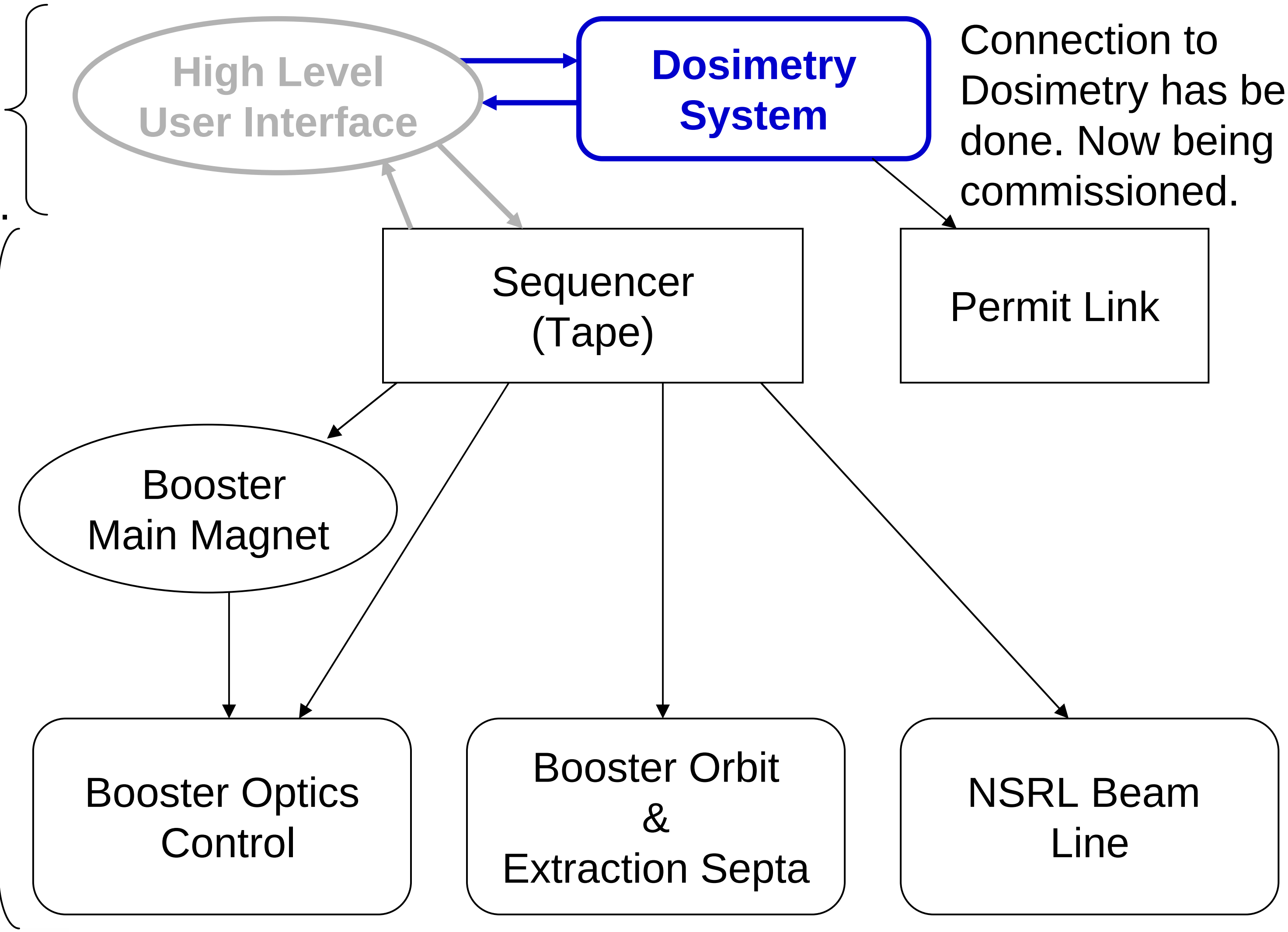


. Large solar proton event integral fluence spectra at 1 AU.

Actively Changing Energy at NSRL

A high level interface has been designed and constructed. Is now being commissioned.

Theses parts are working well and are commissioned.



Connection to Dosimetry has been done. Now being commissioned.

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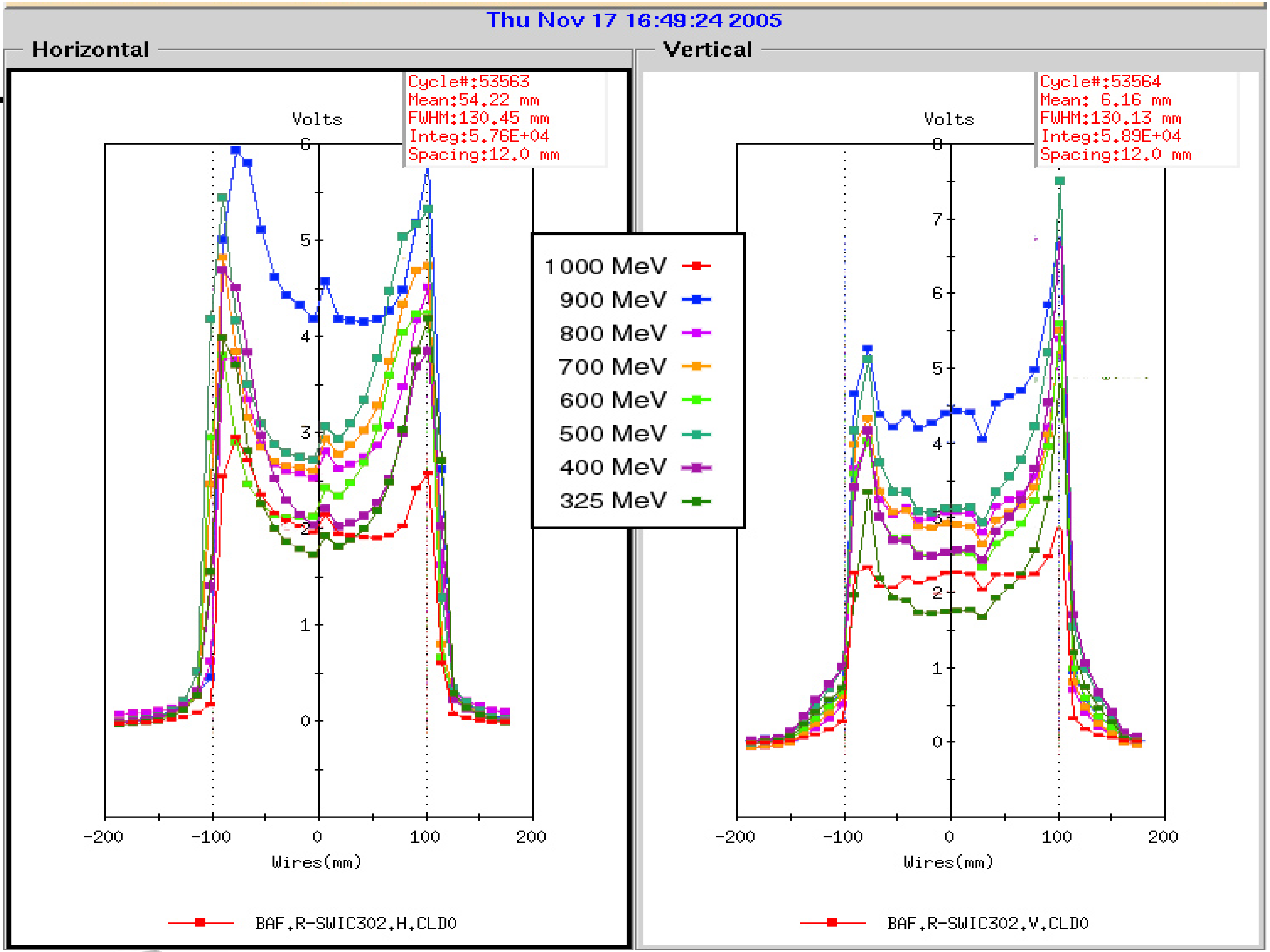

Thu Nov 17 16:49:24 2005

Horizontal

Cycle#:53563
Mean:54.22 mm
FWHM:130.45 mm
Integ:5.76E+04
Spacing:12.0 mm

Vertical

Cycle#:53564
Mean: 6.16 mm
FWHM:130.13 mm
Integ:5.89E+04
Spacing:12.0 mm

- 1000 MeV 🟥
- 900 MeV 🟦
- 800 MeV 🟪
- 700 MeV 🟧
- 600 MeV 🟩
- 500 MeV 🟩
- 400 MeV 🟪
- 325 MeV 🟩

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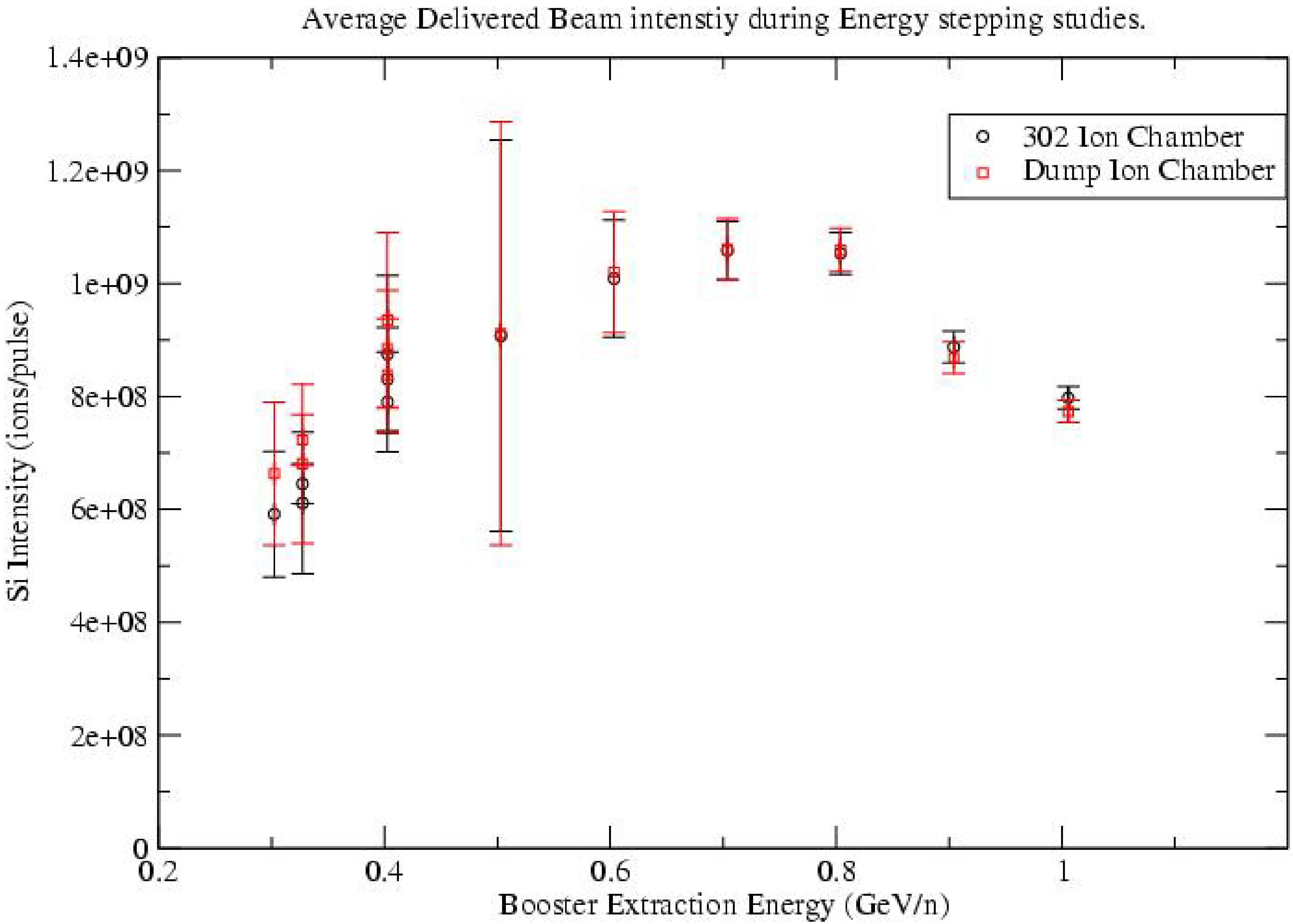
Average Delivered Beam intenstiy during Energy stepping studies.
Si Intensity (ions/pulse)
Booster Extraction Energy (GeV/n)
1.4e+09
1.2e+09
1e+09
8e+08
6e+08
4e+08
2e+08
0
0.2
0.4
0.6
0.8
1
○ 302 Ion Chamber
□ Dump Ion Chamber

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Current Capabilities

1. **Beam energies from 0.05 to 1 GeV/n with any ion that can be produced by a Tandem Van de Graff**
2. **Lowest intensities operated ~10^2 ions/cm^2/cycle**
3. **Smallest beams around 1 cm, smaller possible (not uniform, Gaussian). Largest beams around 20x20 cm^2 uniform**
4. **Mixed field of protons and ions on a single target**
5. **1 – 3 msec pulsed beams**
6. **Fast Extracted Beams (1 to 3 200 nsec pulses in 5 usec, or one 4 usec pulse)**
7. **Solar particle simulator**
    1. **Large range of ion energies over single irradiation**
    2. **Fast energy change**

Future Capabilities

EBIS (electron beam ion source) will provide

- All ions up to U, including noble gases
- Higher intensities for current ion set
- Multiple mixed field ions (more than 2 ions species/ irradiation)

Pulsed synchronized beams (with experimenter signals)

1. Synchronize beam with breathing, heart rate, EKG, ….
2. For low energy beams, allow for time of flight analysis

Supplemental

Slow Extraction Dynamics

Transverse fields in a normal sextupole are:

$$B_x(x,y) = -6B_s xy$$

$$B_y(x,y) = -3B_s(x^2 - y^2)$$

where,

$$B_s = -\frac{1}{6}\left(\frac{d^2B_y}{dx^2}\right)_0$$

A particle with a magnetic rigidity $B\rho$ receives (thin lens) kicks by a sextupole of length L,

$$\Delta x' = \frac{1}{2}\frac{L}{B\rho}\left(\frac{d^2B_y}{dx^2}\right)_0 (x^2 - y^2)$$

and,

$$\Delta y' = -\frac{L}{B\rho}\left(\frac{d^2B_y}{dx^2}\right)_0 (xy)$$

define the normalized sextupole strength as

$$S = \frac{1}{2}\beta^{3/2}\frac{L}{B\rho}\left(\frac{d^2B_y}{dx^2}\right)_0$$

The Kobayashi Hamiltonian

$$H = \frac{\varepsilon}{2}\left(X^2 + X'^2\right) + \frac{S}{4}\left(3XX'^2 - X^3\right)$$

where

$$X \equiv \frac{x}{\sqrt{\beta_x}} \text{ and } X' \equiv \frac{\alpha_x}{\sqrt{\beta_x}}x + \sqrt{\beta_x}x'$$

are the normalized phase space coordinates, and,

$$\varepsilon = 6\pi\delta Q = 6\pi\left(Q_{particle} - Q_{resonance}\right)$$

The first term in H describes particle motion in the linear unperturbed lattice (S = 0). The trajectories are circles with radius $\sqrt{2H/\varepsilon}$ in normalized phase space.

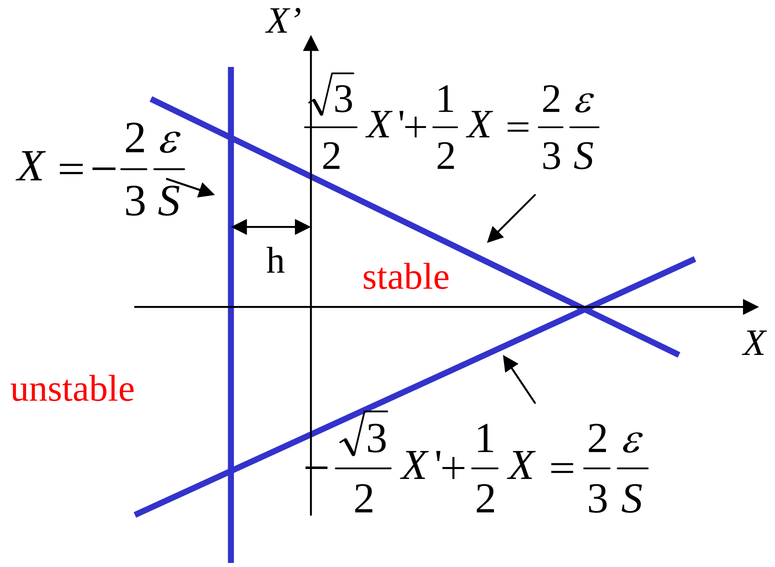
The second term (perturbative term) distorts the circle.

Slow Extraction Dynamics

when H has the value $\left[(2\varepsilon/3)^3/S^2\right]$ it factors into 3 terms,

$$\left(\frac{S}{4}X+\frac{\varepsilon}{6}\right)\left(\sqrt{3}X'+X-\frac{4\varepsilon}{3S}\right)\left(\sqrt{3}X'-X+\frac{4\varepsilon}{3S}\right)=0$$

The 3 lines define the boundries between stable and unstable regions of phase space. The size of the stable region is determined by the ratio ε/S.



$$\frac{\sqrt{3}}{2}X'+\frac{1}{2}X=\frac{2}{3}\frac{\varepsilon}{S}$$

$$X=-\frac{2}{3}\frac{\varepsilon}{S}$$

$$-\frac{\sqrt{3}}{2}X'+\frac{1}{2}X=\frac{2}{3}\frac{\varepsilon}{S}$$

$$\boldsymbol{h}=\frac{2}{3}\frac{\varepsilon}{\boldsymbol{S}}=\frac{4\pi}{\boldsymbol{S}}\delta\boldsymbol{Q}$$

The area of the stable region is

$$\mathrm{A}=3\sqrt{3}\boldsymbol{h}^2=\frac{48\sqrt{3}\pi}{\boldsymbol{S}^2}\left(\delta\boldsymbol{Q}^2\right)\pi$$

The area within a particular particles linear unperturbed motion is called the single particle emittance.

$$\boldsymbol{E}=\boldsymbol{a}^2\pi,\ \text{where}\ \ \boldsymbol{a}^2=\boldsymbol{X}_0^2+\boldsymbol{X}'^2_0$$

Particle motion remains stable as long as the particle motion lies within the stable triangle.

$$\boldsymbol{E}_{\boldsymbol{stable}}\leq\frac{48\sqrt{3}\pi}{\boldsymbol{S}^2}\left(\delta\boldsymbol{Q}^2\right)\pi$$

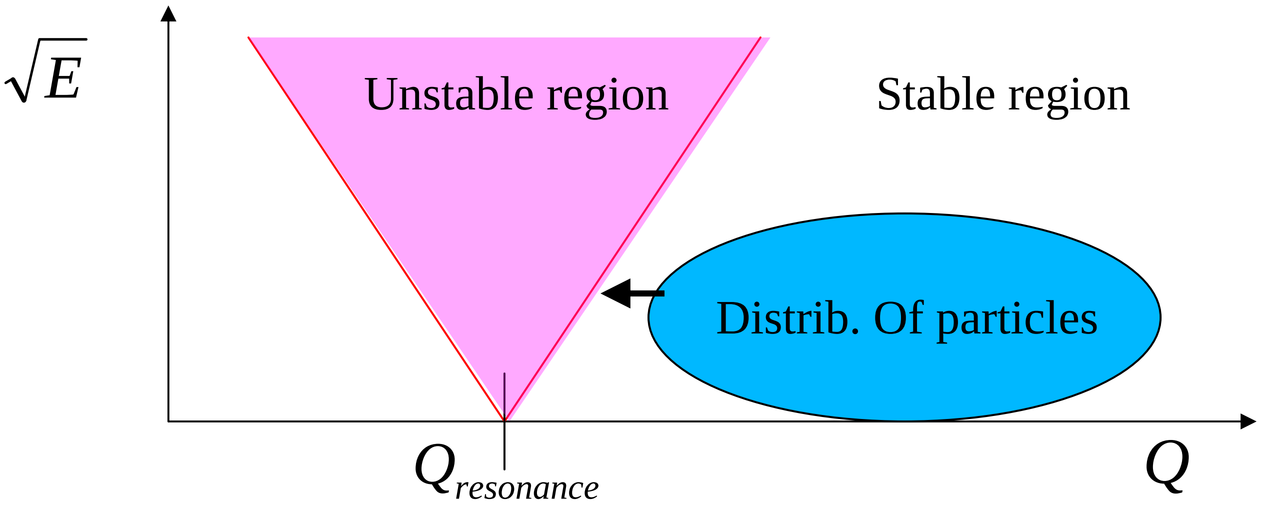
This criteria for stability can be rewritten in terms of absolute betatron tune, with

$$\delta\boldsymbol{Q}=\boldsymbol{Q}_{\boldsymbol{particle}}-\boldsymbol{Q}_{\boldsymbol{resonance}}$$

$$\boldsymbol{Q}_{\boldsymbol{resonance}}-\sqrt{\frac{1}{48\sqrt{3}\pi}}\boldsymbol{S}\sqrt{\frac{\boldsymbol{E}}{\pi}}<\boldsymbol{Q}_{\boldsymbol{particle}}<\boldsymbol{Q}_{\boldsymbol{resonance}}+\sqrt{\frac{1}{48\sqrt{3}\pi}}\boldsymbol{S}\sqrt{\frac{\boldsymbol{E}}{\pi}}$$

This can be shown graphically by plotting the action variable, $\sqrt{\boldsymbol{E}}$, as a function of betatron tune.

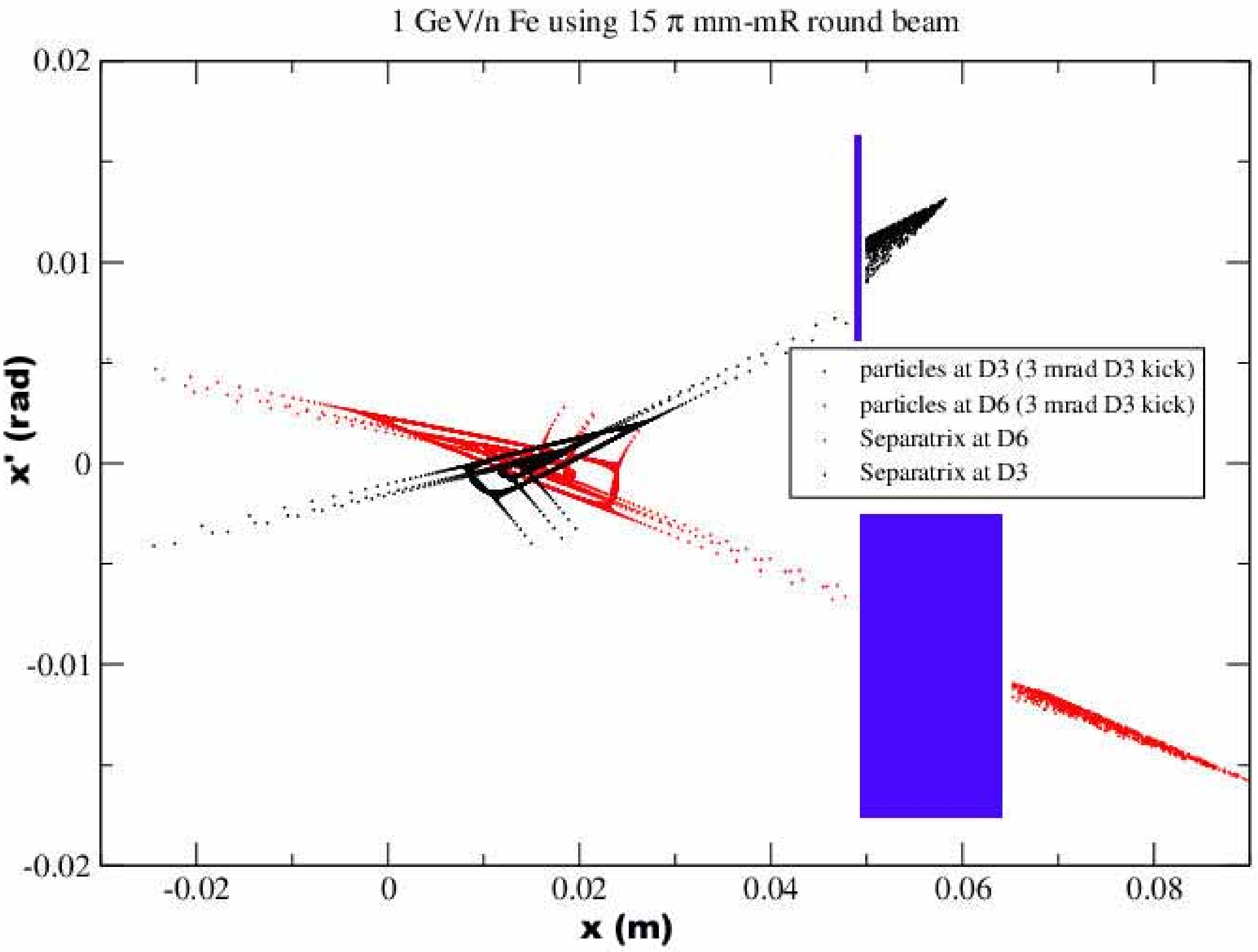
Slow Extraction Dynamics



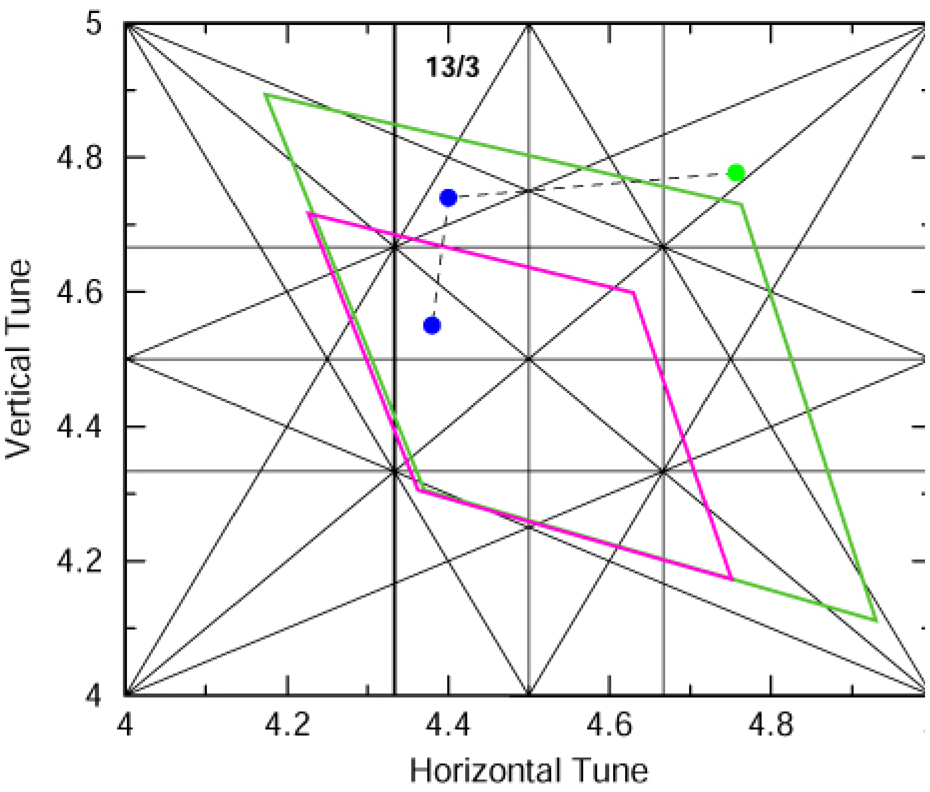
Extraction Methods:

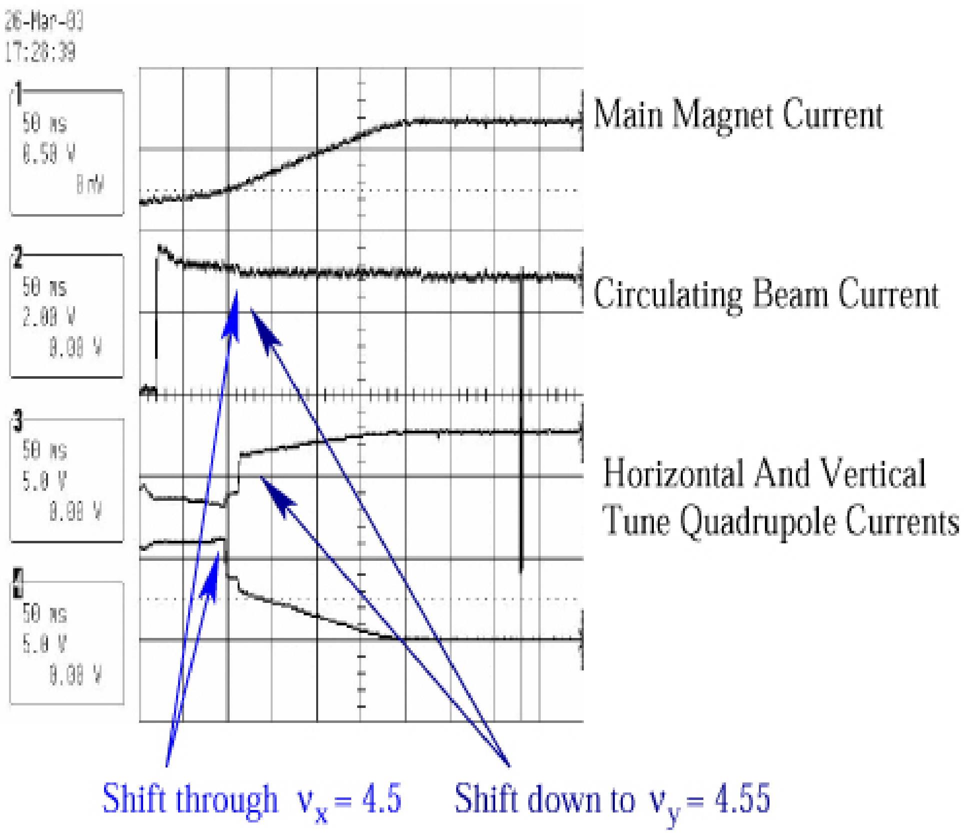
1. Widen stopband by increasing S
2. Move particles into resonance by changing betatron tune (AGS).
3. Increase particle amplitudes until it encounters the unstable region (rf knockout method).

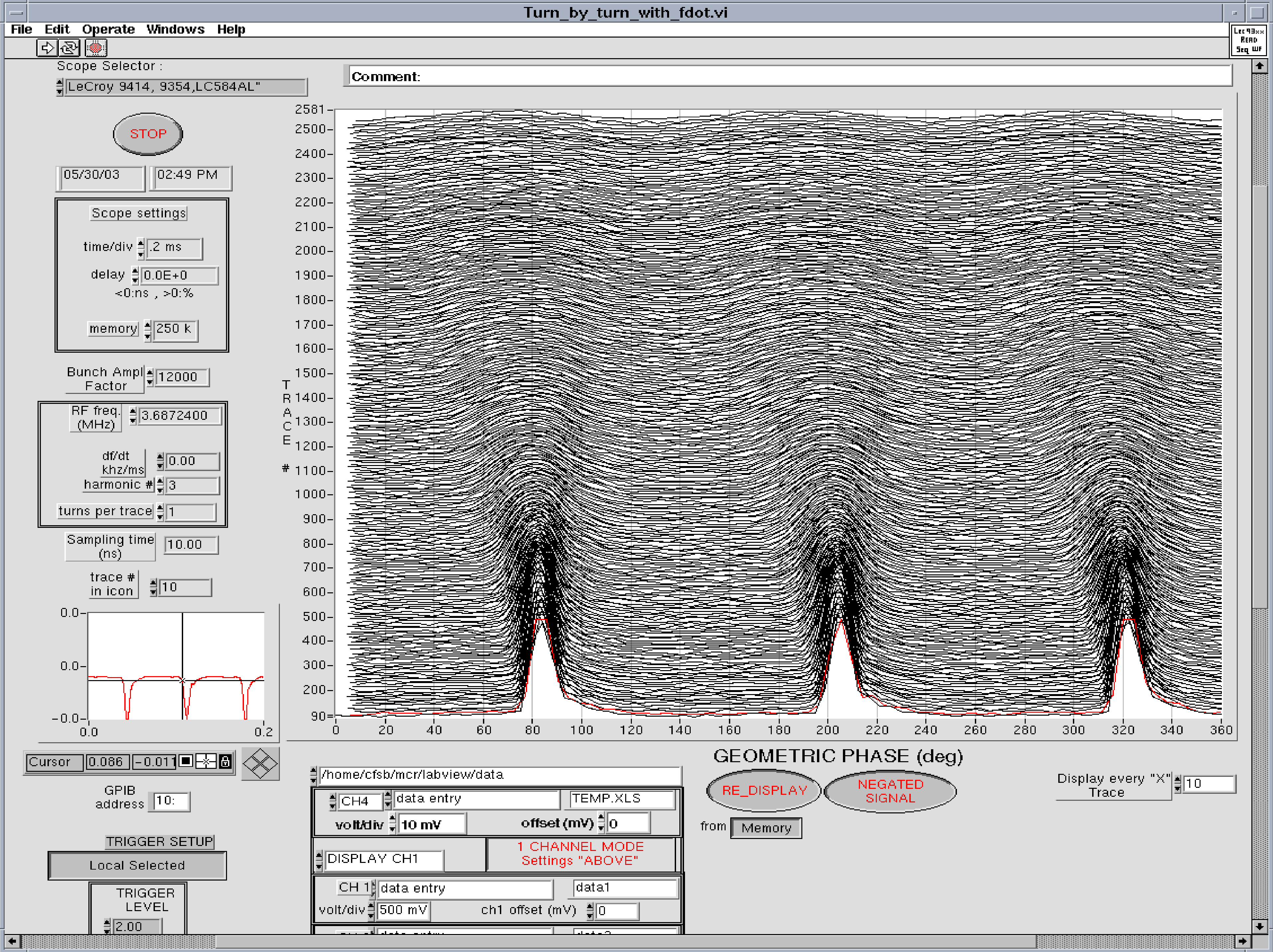
Booster Resonant/Slow Extraction



Injection, Acceleration, and Tune Space Manipulations







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Comment:

05/30/03 02:49 PM

Scope settings

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memory 250 k

Bunch Ampl Factor 12000

RF freq. (MHz) 3.6872400

df/dt khz/ms 0.00

harmonic # 3

turns per trace 1

Sampling time (ns) 10.00

trace # in icon 10

Cursor 0.086 -0.011

GPIB address 10:

TRIGGER SETUP

Local Selected

TRIGGER LEVEL 2.00

/home/cfsb/mcr/labview/data

CH4 data entry TEMP.XLS

volt/div 10 mV offset (mV) 0

DISPLAY CH1

1 CHANNEL MODE Settings "ABOVE"

CH 1 data entry data1

volt/div 500 mV ch1 offset (mV) 0

Display every "X" Trace 10

from Memory

Energy Measurement in an Accelerator

Energy

$\beta = (2\pi R_{booster} f_{rf})/(h c)$

$\gamma = 1/(1-\beta^2)^{1/2}$

$K.E. = (\gamma - 1)mc^2$

Uncertainty

$d\beta^2 = (2\pi f_{rf} / hc)^2 dR^2 + (2\pi R/hc)^2 df_{rf}^2$

$d(K.E.) = mc^2 \beta (1-\beta^2)^{-3/2} d\beta$

Symbols:

h = harmonic #

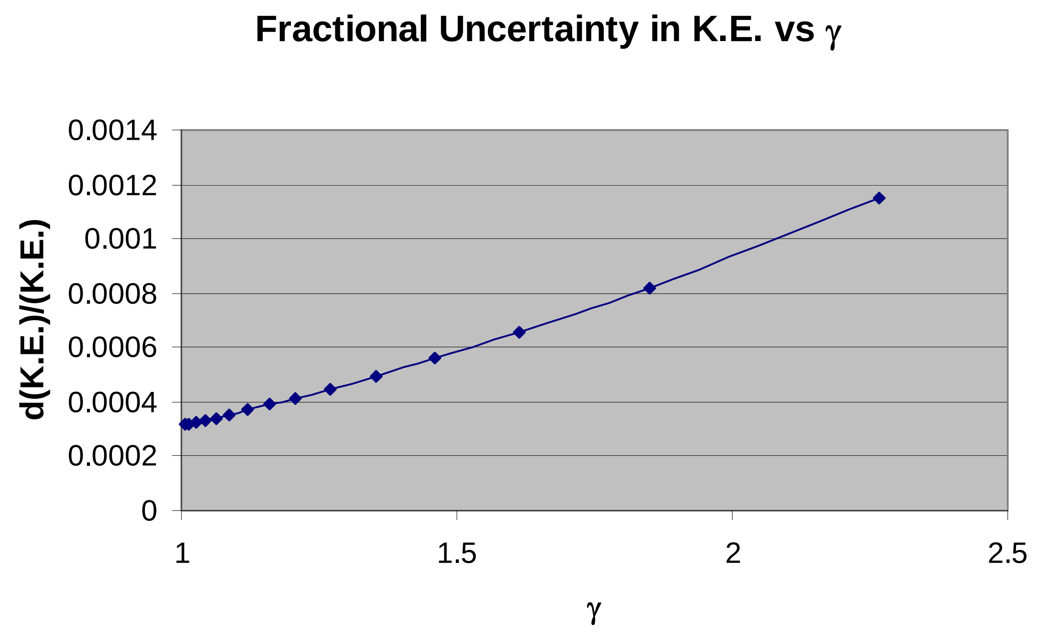
c = 2.99792458×10^8 m/s

$R_{booster}$ = R = 32.113 m

f_{rf} = accelerating frequency

Values used in figure:

dR = 5 mm df_{rf} = 10 Hz h = 3



Spill and Ripple

Time Structure Formalism

definitions:

Q = horizontal betatron tune

ξ = horizontal chromaticity = $\frac{dQ/Q}{dp/p}$

I_m = current in the Main Dipoles and Quadrupoles

N = number of particles ($\frac{dN}{dQ}$ represents the particle distribution in tune space

T = period over which particles are extracted

Low frequency duty factor:

$$D_f = \frac{[\int_T S(t)dt]^2}{T \int_T [S(t)]^2 dt} \quad \Rightarrow (\frac{f_{av}}{f_{rms}})^2 \quad in\ general$$

where

$$S(t) = \frac{dN}{dt} = \frac{dN}{dQ}\frac{dQ}{dt}$$

if there is no ripple,

$$S(t) = \frac{dN}{dQ}\dot{Q}_0$$

where $\dot{Q}_0$ is the rate at which particles move into resonance.

$$\dot{Q}_0 = \frac{Q\xi}{I_m}\frac{dI_m}{dt}$$

Spill and Ripple

If there is ripple on the magnet power supplies;

$$S(t) = \frac{dN}{dQ}(\dot{Q}_0 + \dot{Q}_v)$$

where $\dot{Q}_v$ is the variations in the rate at which particles move into resonance.

$$\dot{Q}_v = \frac{Q\xi}{I_m L_m}\sum_h V_h$$

L_m is the total inductance of the main dipoles and quads and V_h is the sum of the 60 Hz harmonics amplitudes (in volts).

Reducing Time structure using RF Phase Displacement

$$S(t) = \frac{dN}{dQ}\dot{Q}_0(1 + \frac{\dot{Q}_v}{\dot{Q}_0})$$

For 1 particular frequency we can write the duty factor as

$$D_f = \frac{1}{1 + \frac{1}{2}(\frac{\dot{Q}_v}{\dot{Q}_0})^2} = \frac{1}{1 + \frac{1}{2}(\frac{\omega\delta Q}{v_0})^2}$$

where

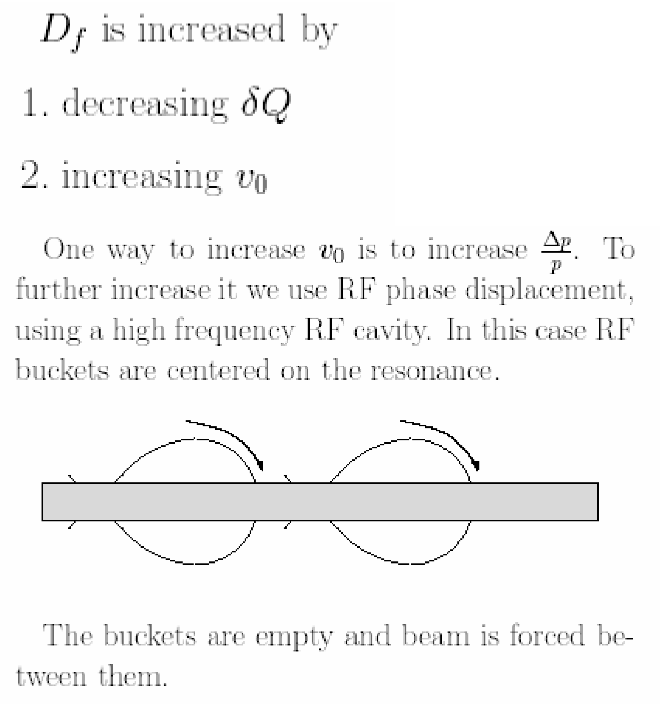
ω = frequency

δQ = relative ampl. of that freq. in tune space

v_0 = speed that beam crosses resonance

$$v_0 = \frac{\Delta p}{p}\frac{1}{T}$$

Spill and Ripple

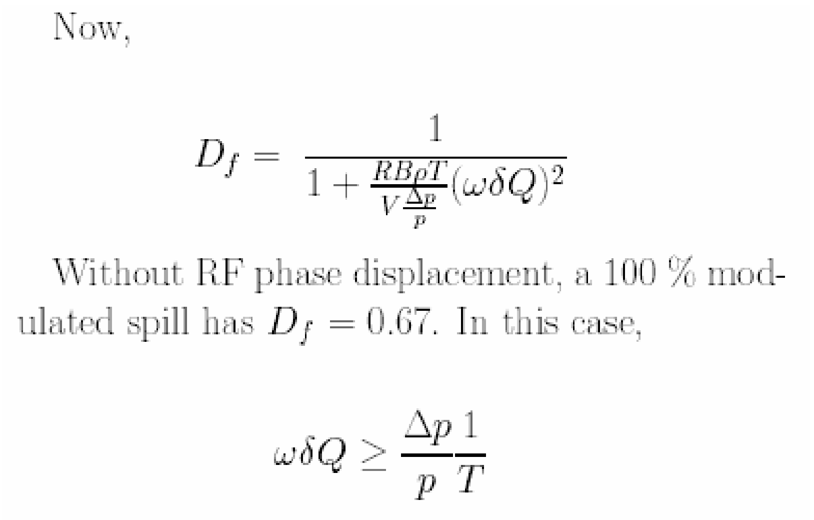


D_f is increased by

1. decreasing δQ
2. increasing v_0

One way to increase v_0 is to increase $\frac{\Delta p}{p}$. To further increase it we use RF phase displacement, using a high frequency RF cavity. In this case RF buckets are centered on the resonance.

The buckets are empty and beam is forced between them.



Now,

$$D_f = \frac{1}{1 + \frac{RB\rho T}{V\frac{\Delta p}{p}}(\omega\delta Q)^2}$$

Without RF phase displacement, a 100 % modulated spill has $D_f = 0.67$. In this case,

$$\omega\delta Q \geq \frac{\Delta p}{p}\frac{1}{T}$$

Spill and Ripple