Nucleus - Nucleus Bremsstrahlung and measurement of charge* stopping at RHIC

* Perhaps also measurement of the time history of charge acceleration in the heavy ion collision

Berkeley Workshop Jan. 10 '99
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Because of the large extrapolation to RHIC it is very important to measure early in the RHIC era the basic "global" properties of the collisions

Perhaps the most fundamental of these global parameters is the measurement of

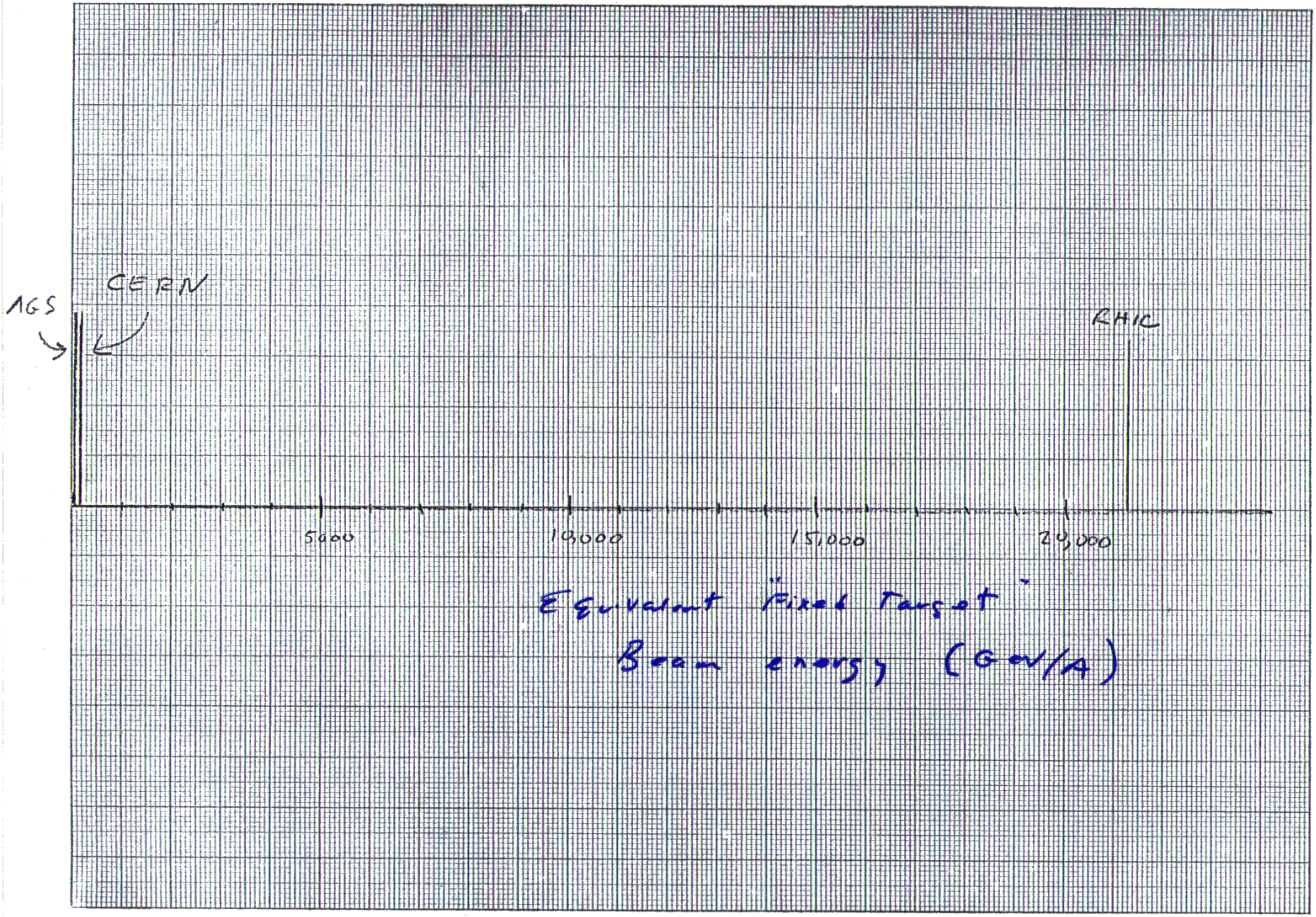
The Fraction of the initial kinetic energy of the ions which is converted to "Thermal" type of energies.

Or equivalently how much directed kinetic energy remains in the constituents of the ions after the collision

This is loosely referred to as the

"STOPPING" fraction.

The experiment(s) I will discuss today is (are) aimed at a clear measurement of ~~charge~~ stopping via the e.m. radiation created by the deceleration of charges....



AGS
CERN
RHIC
5000
10,000
15,000
20,000
Equivalent Fixed Target
Beam energy (GeV/A)

Basic "Idea"

I. When heavy high energy heavy ions collide there is a deceleration of the electric charges they carry and this leads to electromagnetic radiation (bremsstrahlung).

II. For wavelengths of this radiation which are large compared to the size of the region over which the ions interact with one another, this radiation is emitted coherently from all the individual charges and depends only on the initial and final velocities of the charges involved in the collision.

The coherence condition can obviously also be stated as the period of the radiation must be longer than the duration of the interacting phase of the collision.

III. For such long wavelength, coherent bremsstrahlung, the frequency spectrum $= 1/\hbar\omega = 1/E_\gamma$.

J. Kapusta, Phys. Rev. C, 15, 1580 (1977)

J.D. Bjorken and L. McLerran, Phys. Rev. D, 31, 63 (1985)

S. Jeon, J. Kapusta, A. Chikanian, and J. Sandweiss, to be published in Phys. Rev. C (1998)

PRC 58, 1666 (1998)

"Projectile" current

$$\mathbf{J}_{\mathrm{P}}(\mathbf{x},t)=v_0\sigma(r_\perp)\delta(z-v_0t)\theta(-t)\hat{\mathbf{z}}\,, \tag{1}$$

and by the "target" is:

$$\mathbf{J}_{\mathrm{T}}(\mathbf{x},t)=-v_0\sigma(r_\perp)\delta(z+v_0t)\theta(-t)\hat{\mathbf{z}}\,, \tag{2}$$

where $\sigma(r_\perp)$ is the charge per unit area at a distance $r_\perp$ from the central beam axis. For low frequency photons the nucleus-nucleus collision appears almost instantaneous. To the extent that the transverse rapidities of the outgoing charged particles are small compared to the beam rapidity one may then approximate the current after the collision as:

$$\mathbf{J}_{\mathrm{F}}(\mathbf{x},t)=\hat{\mathbf{z}}\sigma(r_\perp)\theta(t)\int_{-\infty}^{\infty}d\mathrm{y}\rho(r_\perp,\mathrm{y})v(\mathrm{y})\delta(z-v(\mathrm{y})t)\,. \tag{3}$$

Here ρ represents the charge rapidity distribution and is normalized as:

$$\int_{-\infty}^{\infty}d\mathrm{y}\rho(r_\perp,\mathrm{y})=2\,, \tag{4}$$

the 2 arising because the total charge is $2Z$.

The classical amplitude to emit electromagnetic radiation in the direction $\mathbf{n}$ with frequency ω is [6]:

$$\mathbf{A}(\mathbf{n},\omega)=\int dt\int d^3x\,\mathbf{n}\times(\mathbf{n}\times\mathbf{J}(\mathbf{x},t))\,e^{i\omega(t-\mathbf{n}\cdot\mathbf{x})}\,. \tag{5}$$

Here $\mathbf{J}=\mathbf{J}_{\mathrm{P}}+\mathbf{J}_{\mathrm{T}}+\mathbf{J}_{\mathrm{F}}$ is the total current. It is convenient to take $\mathbf{n}=(\sin\theta,0,\cos\theta)$. Then the distribution in frequency and direction is:

$$\boxed{\frac{d^2N}{d\omega d\Omega}=\frac{\alpha}{4\pi^2\omega}\sin^2\theta\left|\int dxdy\sigma(r_\perp)e^{-ix\omega\sin\theta}\left[\int d\mathrm{y}\frac{v(\mathrm{y})\rho(r_\perp,\mathrm{y})}{1-v(\mathrm{y})\cos\theta}-\frac{2v_0^2\cos\theta}{1-v_0^2\cos^2\theta}\right]\right|^2.} \tag{6}$$

We cannot go further without some knowledge of the distribution $\rho(r_\perp,\mathrm{y})$.

In Fig. 1 we plot the quantity $\rho(r_\perp,\mathrm{y})$ as computed in LEXUS [7] for central Au+Au collisions at 100 GeV per nucleon in the cm frame. LEXUS is a linear extrapolation of nucleon-nucleon scattering to nucleus-nucleus collisions. It is based on sequential nucleon-nucleon scatterings, as in free space, with energy loss taken into account. For $r_\perp=0$ this distribution has a broad maximum at $\mathrm{y}=0$, whereas for $r_\perp\approx R$, the nuclear radius, Thus all that matters, for these "soft" photons are the initial and final rapidities of the electric charges. The radiation is the coherent sum from all the sources. It is thus the *net* final charge rapidity spectrum that determines the bremsstrahlung. Negative and positive produced particles are all coherently summed.

It is also advantageous to have a simple analytic model with a variable charge rapidity distribution. To this end suppose that $\rho(r_\perp, \mathrm{y})$ is independent of $r_\perp$. Then

$$\boxed{\frac{d^2N}{d\omega d\Omega} = \frac{\alpha Z^2}{4\pi^2\omega}\sin^2\theta\,|F(\omega\sin\theta)|^2\left|\left[\int d\mathrm{y}\frac{v(\mathrm{y})\rho(\mathrm{y})}{1-v(\mathrm{y})\cos\theta} - \frac{2v_0^2\cos\theta}{1-v_0^2\cos^2\theta}\right]\right|^2 , \quad (7)}$$

where F is a nuclear form factor:

$$F = \frac{1}{Z}\int dxdy\,\sigma\left(\sqrt{x^2+y^2}\right)e^{-ix\omega\sin\theta}. \quad (8)$$

A solid sphere approximation should be adequate for large nuclei, in which case

$$\boxed{F(q) = \frac{3}{q^2}\left(\frac{\sin q}{q} - \cos q\right),} \quad (9)$$

where $q = \omega R\sin\theta$ and R is the nuclear radius. Actually, for the range of angles and frequencies of interest to us, the nuclear form factor is practically equal to one.

Given that the form factor is essentially unity, we note the important result that $\frac{d^2N}{d\omega d\Omega}$ factors into an energy dependent part and an angle dependent part. The rapidity dependence can be determined from the angular distribution over any part of the energy spectrum.

In addition we have an important check on the validity of the measurement (and the assumption of coherence) by verifying that the shape of the bremsstrahlung energy spectrum is independent of the angle at which the bremsstrahlung is observed.

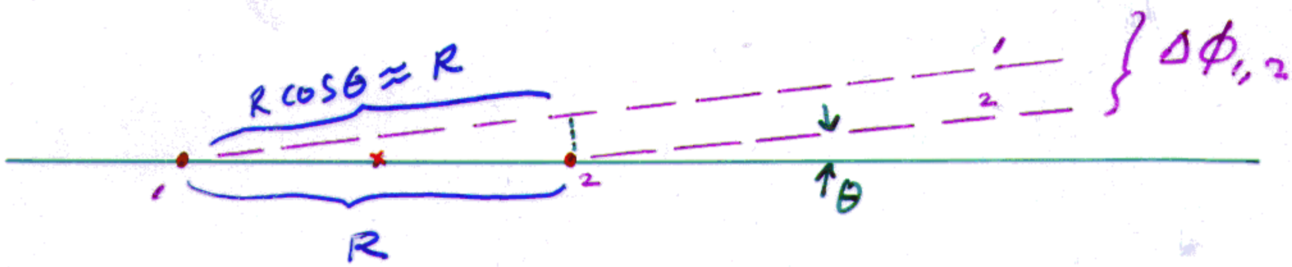
A simple illustrative case is that of a flat rapidity distribution for which the integral over rapidity can easily be performed.

$$\rho(\mathrm{y}) = \frac{\theta(\mathrm{y}_0-\mathrm{y})\theta(\mathrm{y}_0+\mathrm{y})}{\mathrm{y}_0} \quad (10)$$

Then the photon distribution is:

$$\begin{aligned}\frac{d^2N}{d\omega d\Omega} &= \frac{\alpha Z^2}{4\pi^2\omega}\sin^2\theta\,|F(\omega R\sin\theta)|^2 \\ &\times \left[\frac{2}{\sin^2\theta} - \frac{1}{\mathrm{y}_0\sin^2\theta}\ln\left(\frac{1+v_0\cos\theta}{1-v_0\cos\theta}\right) - \frac{2v_0^2\cos\theta}{1-v_0^2\cos^2\theta}\right]^2 . \quad (11)\end{aligned}$$

Coherence Conditions for BREMS



all charges move to their last acceleration points with $v = c$. If R is the max separation between last acceleration points, $\Delta\phi_{1,2}$ max occurs for case drawn with emission times t_1 & t_2.

since $\cos\theta \approx 1$ $\quad \Delta\phi \cong \dfrac{\omega R}{c}$

For coherence:

$$\Delta\phi < 1$$

$$\therefore \quad \frac{\omega R}{c} < 1$$

$$\therefore \quad E < \frac{\hbar}{R/c} \quad \text{or} \quad E < \frac{\hbar}{\tau_{coll.}}$$

For $\tau = 50$ Fermi/c
$E = 3.95$ MeV

we choose $E_{max} \sim 3$ MeV

so for BREM energies below 4 MeV, all charge accelerations add coherently to BREM.

AUTOMATICALLY accounts for $\Lambda, \Sigma^{\pm}, n, \bar{p}p$, etc. !

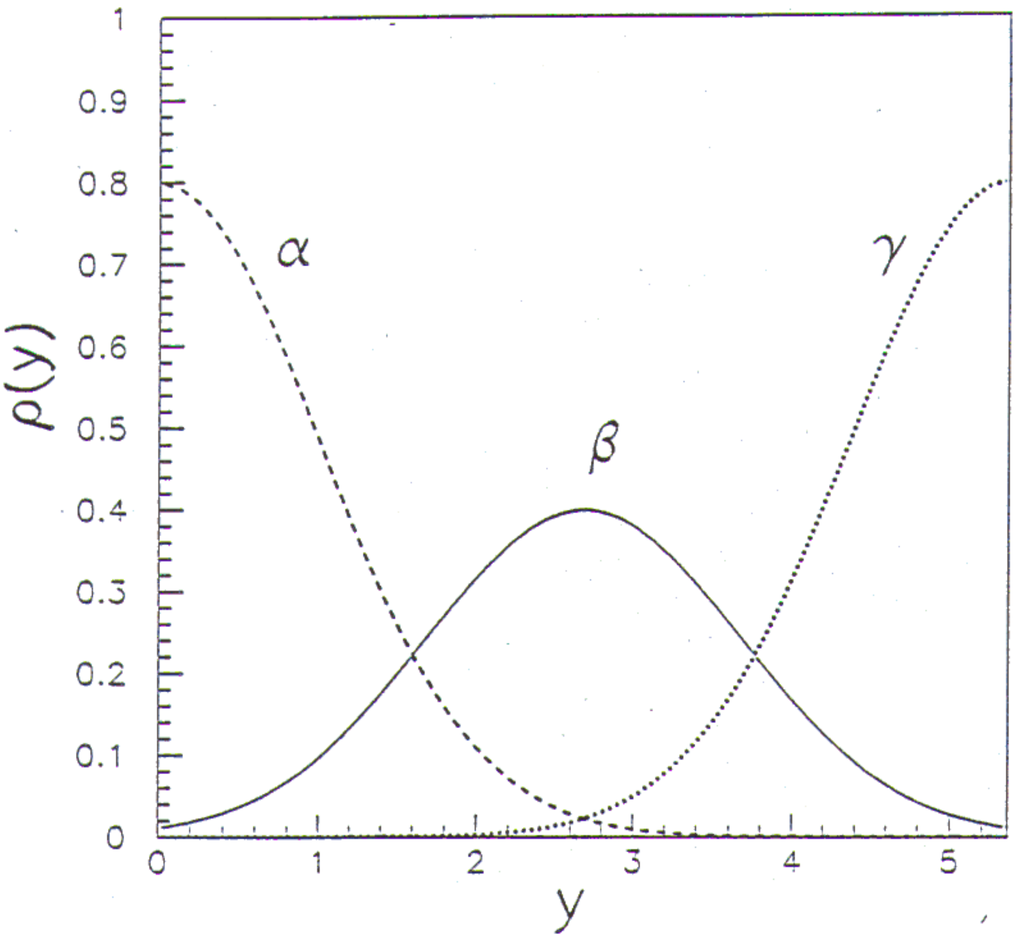


Figure 1: The final charge rapidity distribution (normalized to 2 as explained in the tesxt) for three different models of the chrge stopping. The curve α represents "full stopping", β "50% stopping", and γ "near transparency". Only the positive rapidity part of the distributions are shown. The full, symmetrical about midrapidity, distributions were used in the calculations.

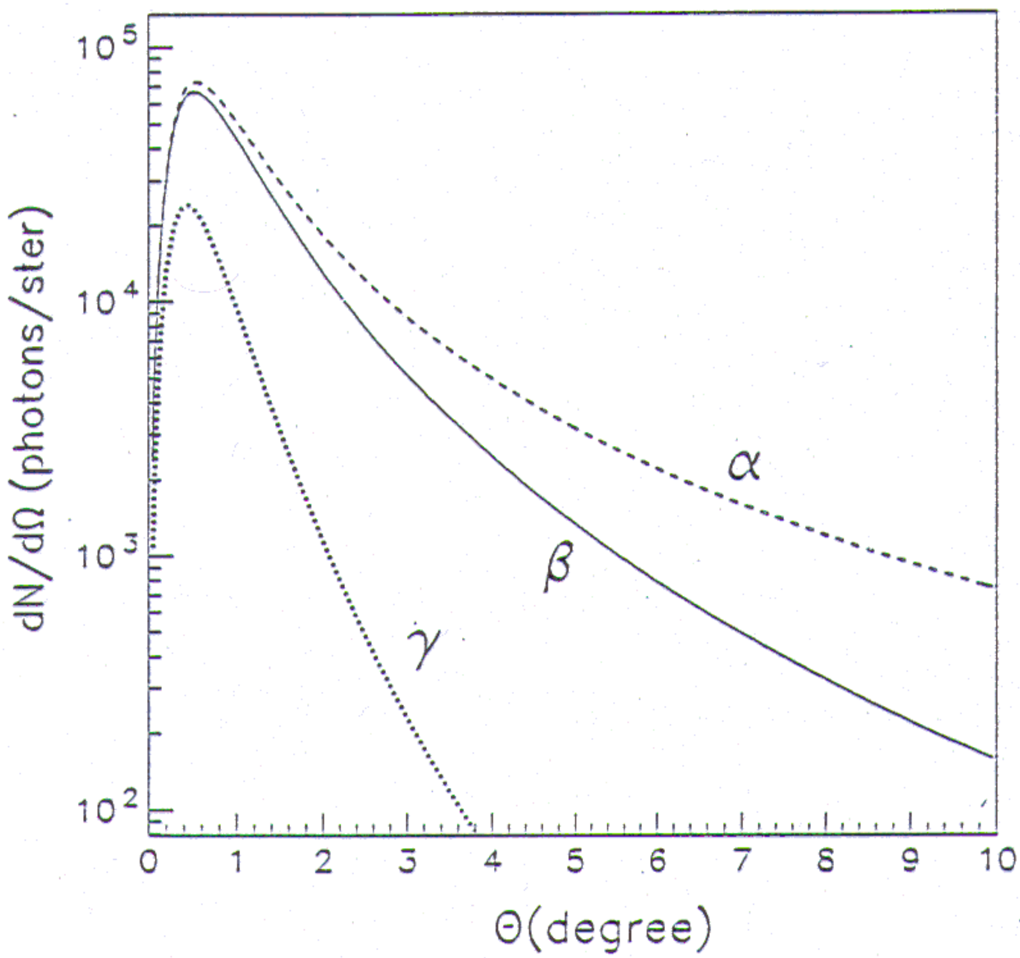
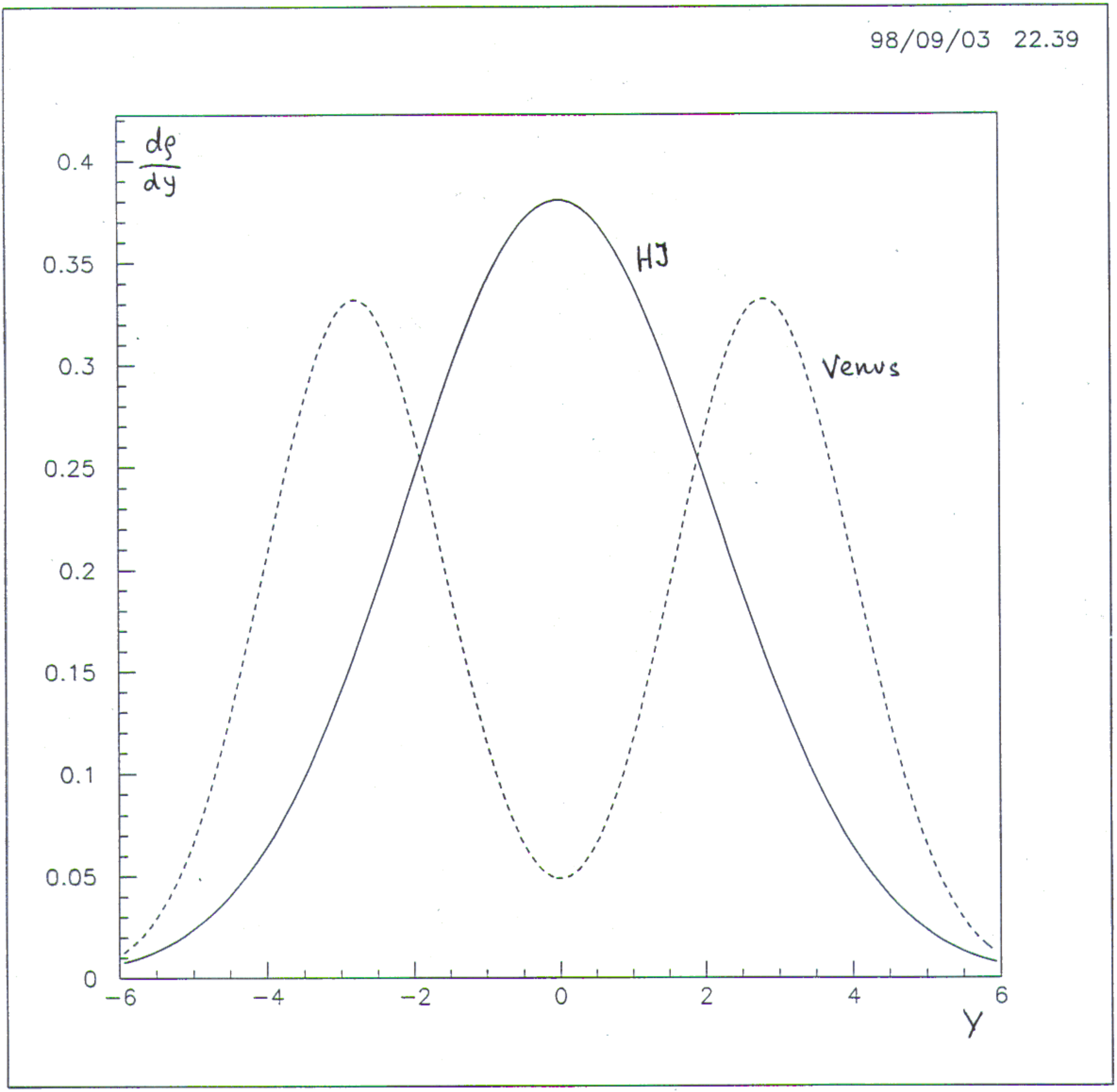
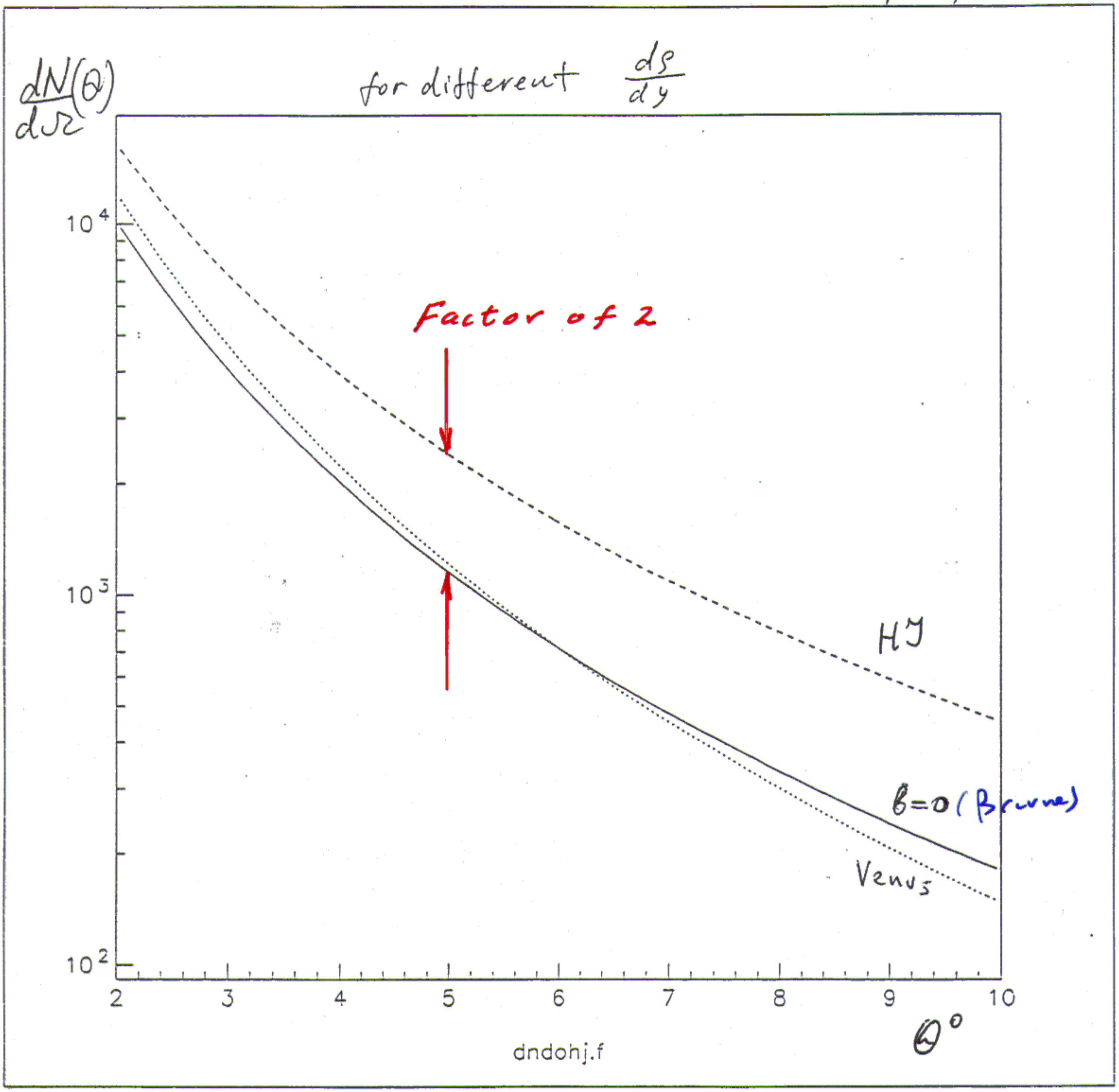


Figure 2: The number of bremsstrahlung photons with energies between 10 keV and 3 MeV, per steradian in the laboratory system for the three different stopping models α, β, and γ of figure 1.


98/09/03 22.39
$\frac{d\rho}{dy}$
HJ
Venus
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
−6
−4
−2
0
2
4
6
Y

Sept 3, 98



$\frac{dN}{d\Omega}(\theta)$ for different $\frac{d\rho}{dy}$
Factor of 2
HJ
b=0 (Brown)
Venus
10^4
10^3
10^2
2
3
4
5
6
7
8
9
10
θ^0
dndohj.f

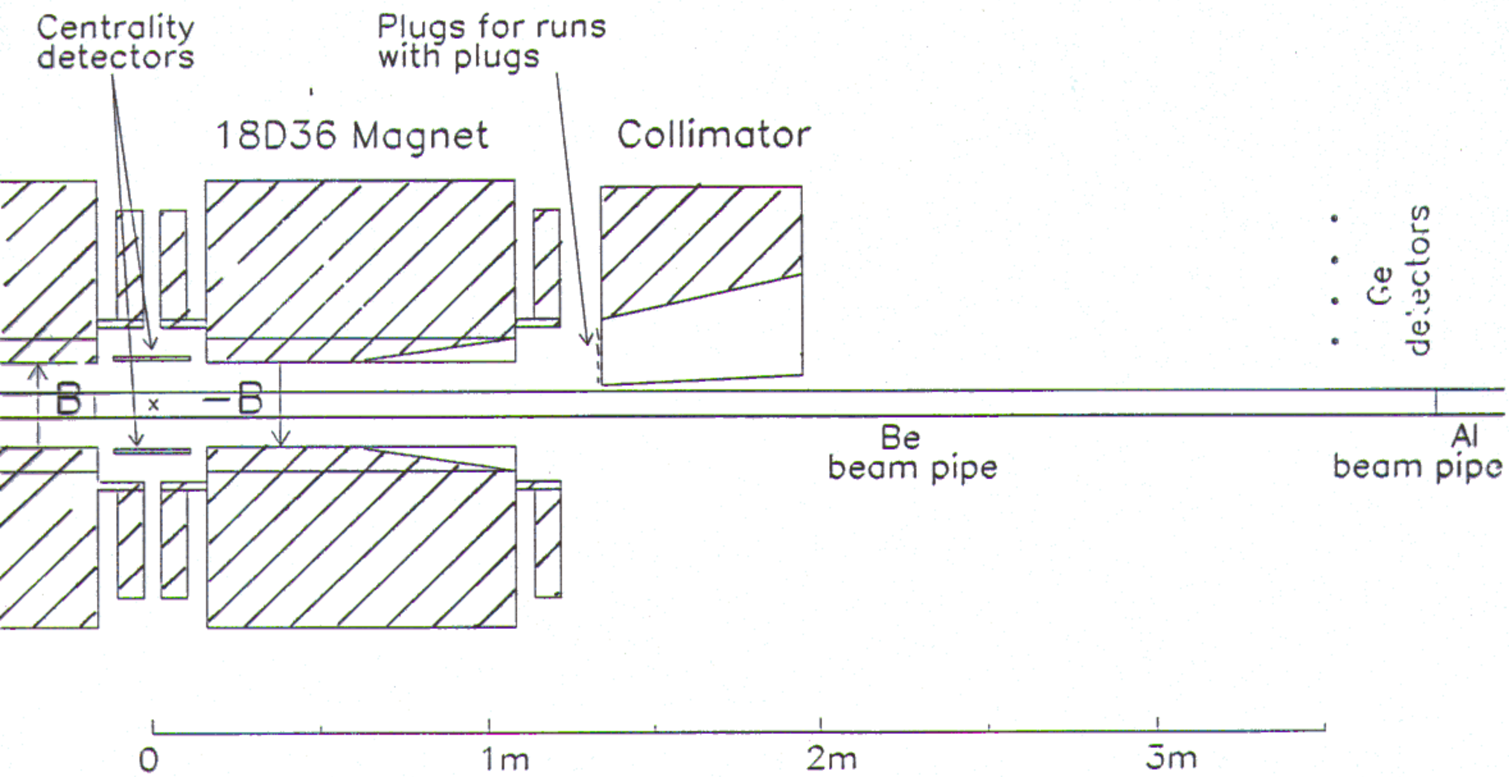
R-10

Measurement of Bremsstrahlung and Charge Stopping in Central RHIC Collisions

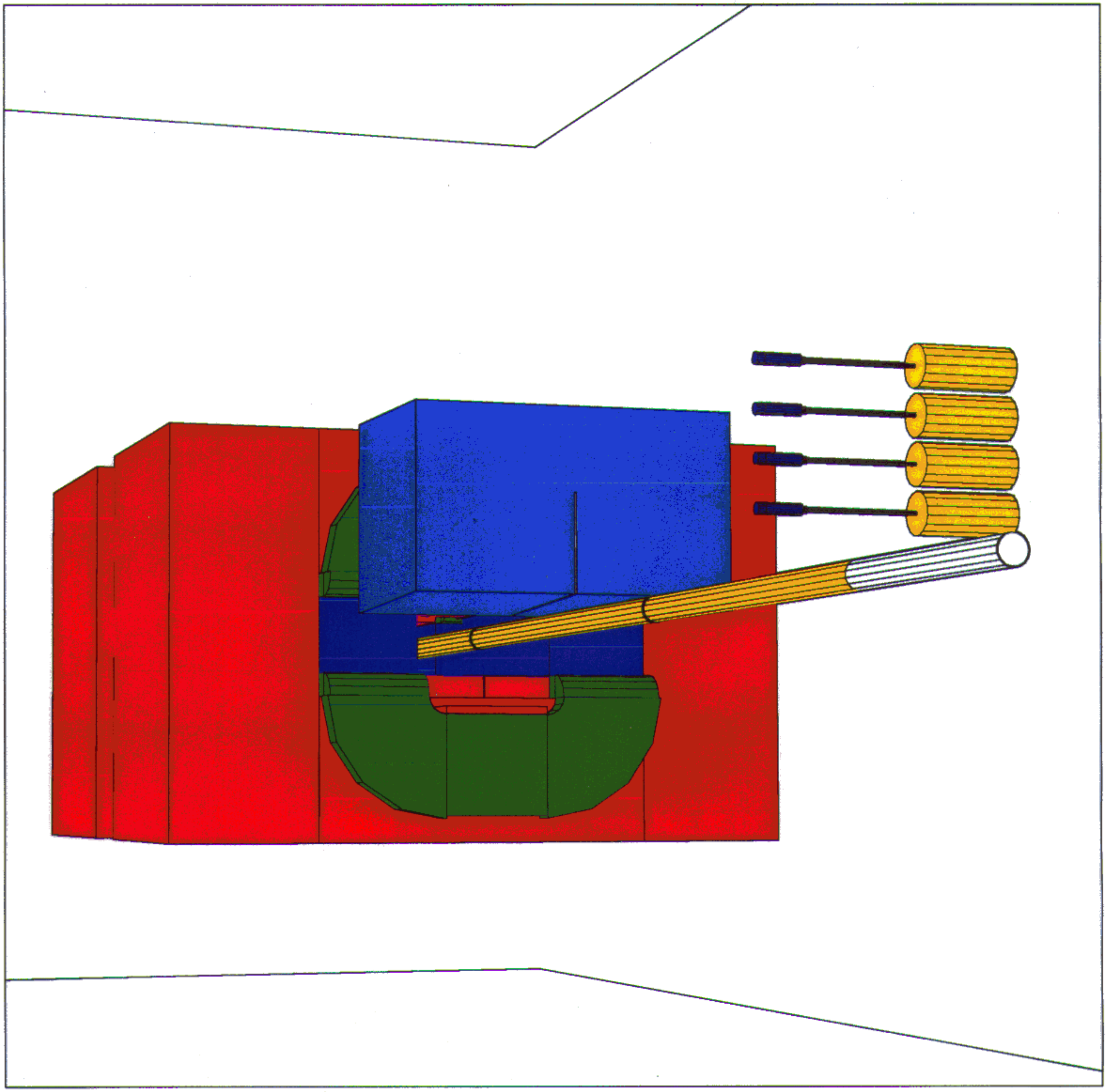
C. Beausang, A. Chikanian, R. Krueken, R. Majka, J. Sandweiss
Yale University

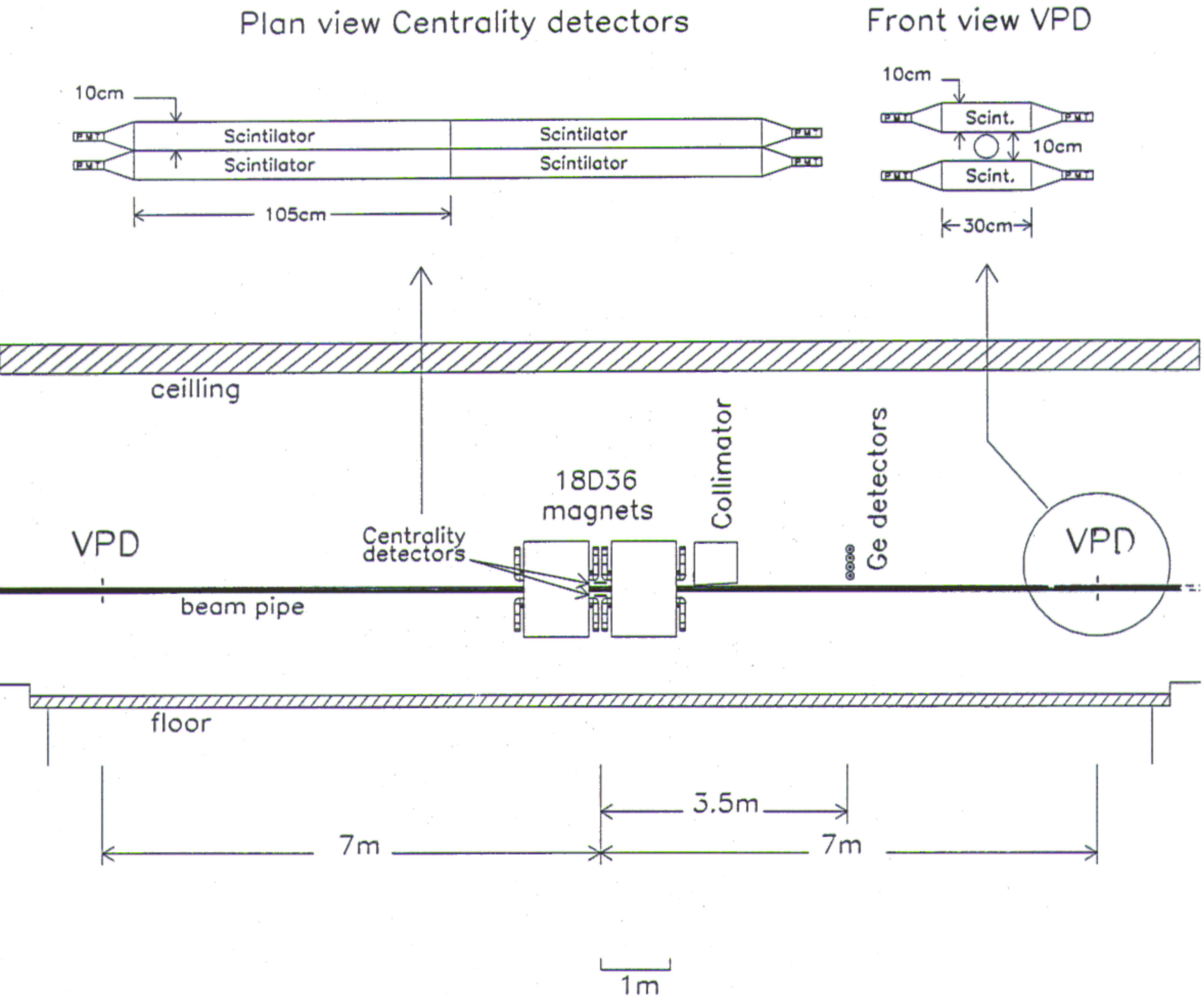
J.Kapusta
University of Minnesota

June 17,1998



Centrality detectors
Plugs for runs with plugs
18D36 Magnet
Collimator
Ge detectors
B
−B
Be beam pipe
Al beam pipe
0
1m
2m
3m




Plan view Centrality detectors
10cm
PMT
Scintilator
Scintilator
Scintilator
Scintilator
105cm
Front view VPD
10cm
Scint.
Scint.
10cm
30cm
ceilling
18D36
magnets
Collimator
Ge detectors
VPD
Centrality
detectors
VPD
beam pipe
floor
3.5m
7m
7m
1m

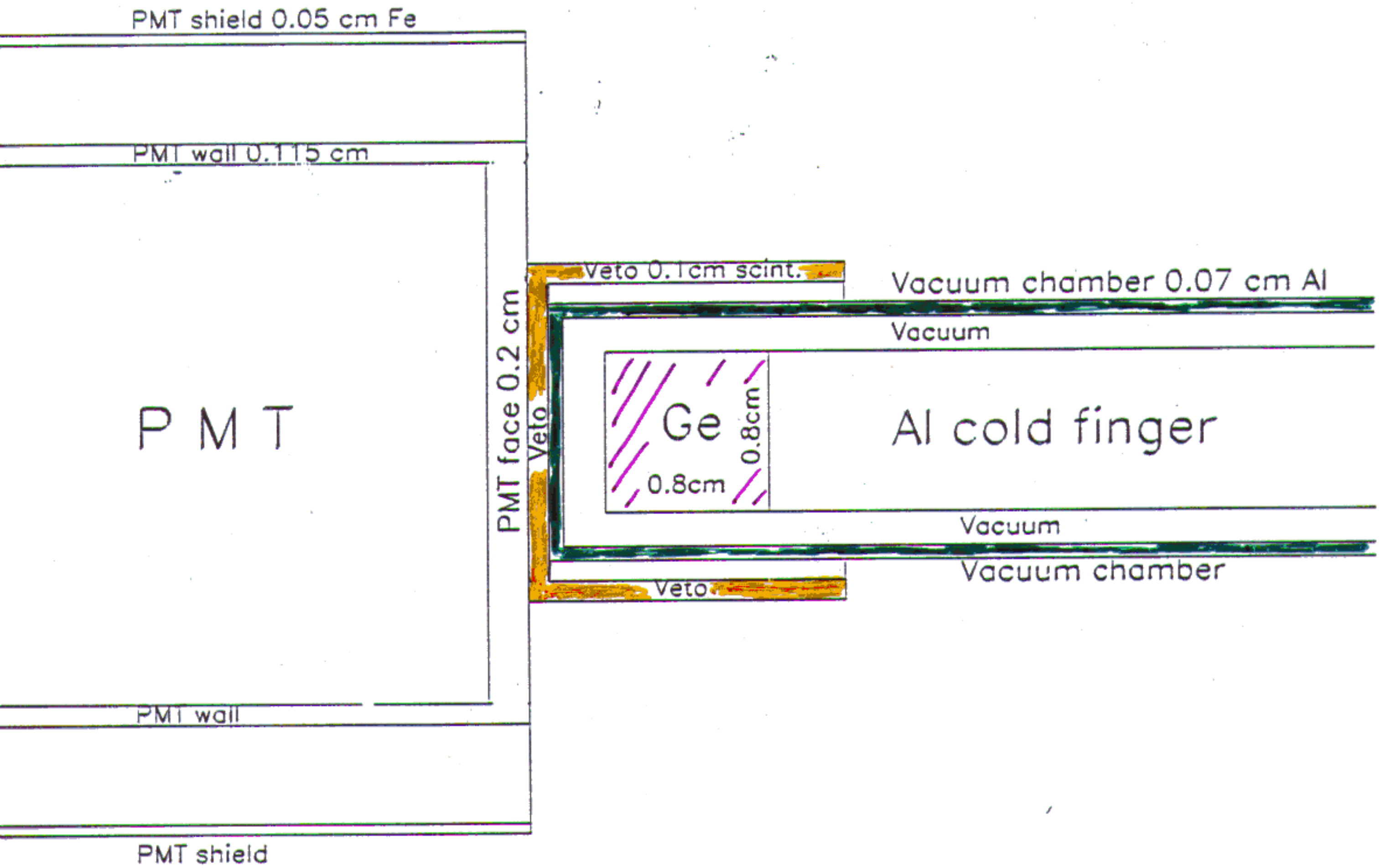


Figure 7: "Beam's eye" view of a Ge detector and scintillation veto counter.

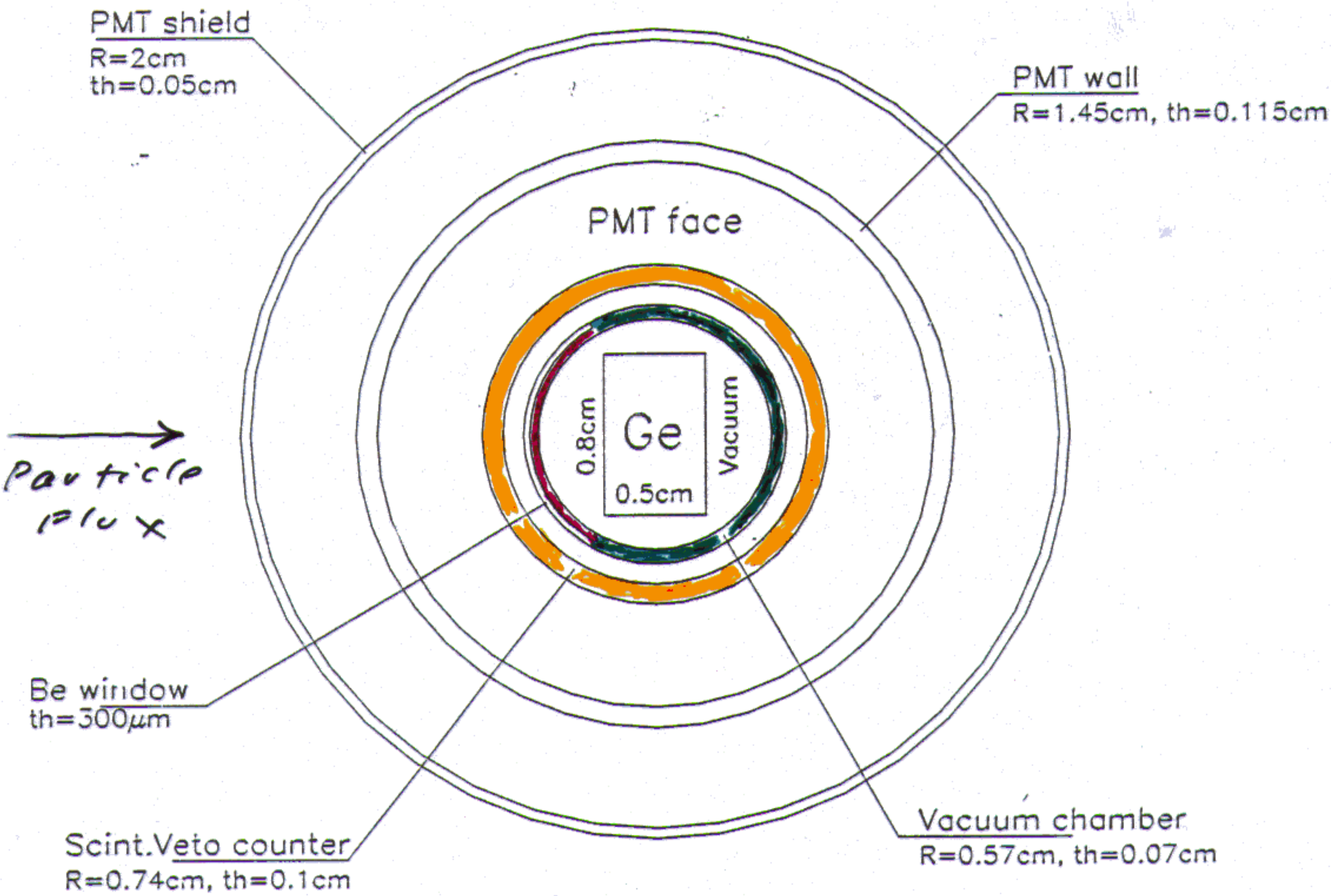


Figure 8: Cross section view of the detector assembly, showing the dimensions of the materials surrounding and near the detector.

Data Acquisition Strategy

The design Luminosity of RHIC = 1000 coll./s

Our (generously) estimated rate of detected events is (background + signal) .05 / collision (minbias)

Even at design Luminosity this corresponds to 50 ev/s
(NOT challenging !)

So, we will record all minbias events and record the multiplicity (centrality) signals - indeed, record all detectors -

Sort, off-line so all centralities measured simultaneously.

In the following, we focus on central collisions since the main goal of the experiment is to measure "charge stopping" in central collisions.

However, other centrality data will be recorded and, of course, analyzed.

Experiment- "Problems"

1. • Signal is just a soft photon.

   • predictable spectrum but
   • no peak! $(\approx 1/E_\gamma)$

   • Energy range $10\,\text{keV} \le E_\gamma \le 3\,\text{MeV}$ (200 keV)

   fits BREM physics (yield, coherence)

2. • Background can be estimated for purposes of exptl. design but not to the precision needed for measurement.

   $\boxed{\text{Background must be measured}}$

3. • RHIC collisions produce many particles. Must be sure detectors are not always "busy" with background particles.

   i.e. worry about live time!

Experiment - "Solutions"

1. Use small detectors
   ($.8 \times .8 \times .5\ cm^3$ Ge crystals).
   Large enough to contain most of Compton electrons produced by 3 MeV γ's, but not much more.

   Can measure energy deposited in Ge and compare distribution with calculation (folding photoabsorbtion and Compton). Calculation can be checked using sources.

   Shape of $\frac{dN_\gamma}{dE_{dep}}$ is independent of θ. So all 4 detectors should see same shape and it should agree with calculation.

2. Surround detector crystal with Scintillation ctr. veto. charged particles, pair production and Compton scatters of higher energy γ's will "self veto".

3. Remove charged particle flux at detectors with Magnet + Collimator

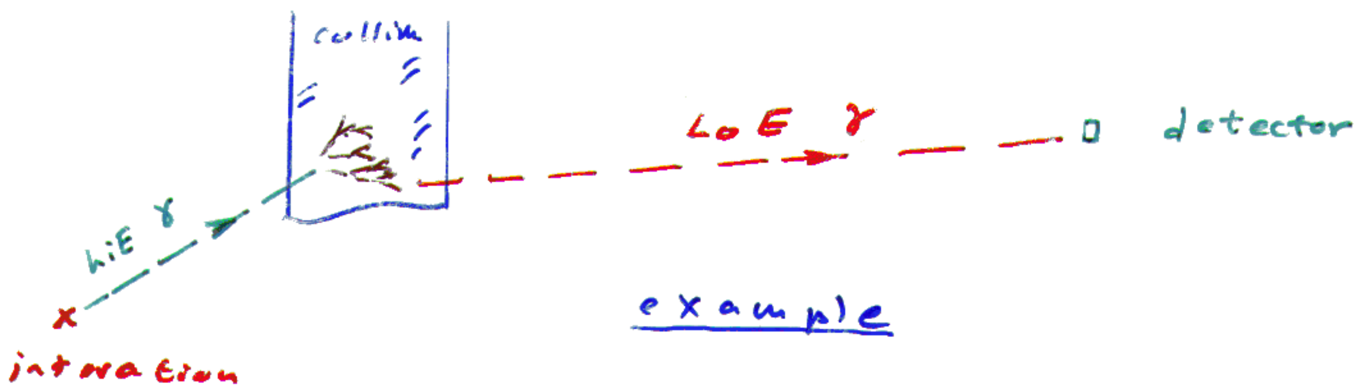
Backgrounds

1. $\pi^0 \to \gamma + \gamma$ yielding E_γ in our range (10 keV → 3 MeV).

   Since $M(\pi^0) = 140$ MeV this almost never happens.
   (HIJET π^0/BREM = 2×10^{-5})

   • Negligible !

2. Backgrounds due to energetic γ's produced at interaction, aiming in "general" direction of detector, showering in material and ultimately creating a low E γ which we detect.



example

$\boxed{\text{This is the Dominant Background type}}$

3. Backgrounds due to other processes.
   eg $\Lambda \to n\,\pi^0 \to \gamma + \gamma \to$ shower $\to$ LoE γ

4. Nuclear decays (γ, n) following hadr. inter.
   [GEANT does not do these !]

Background Rates

STD. - HIJET

SOFT - all particles "produced" by HIJET doubled in number but each with ½ momentum.

HARD - all particles "produced" by HIJET doubled in momentum but halved in number

For "E_γ" cuts 10 KV → 200 KV (Ge signal)

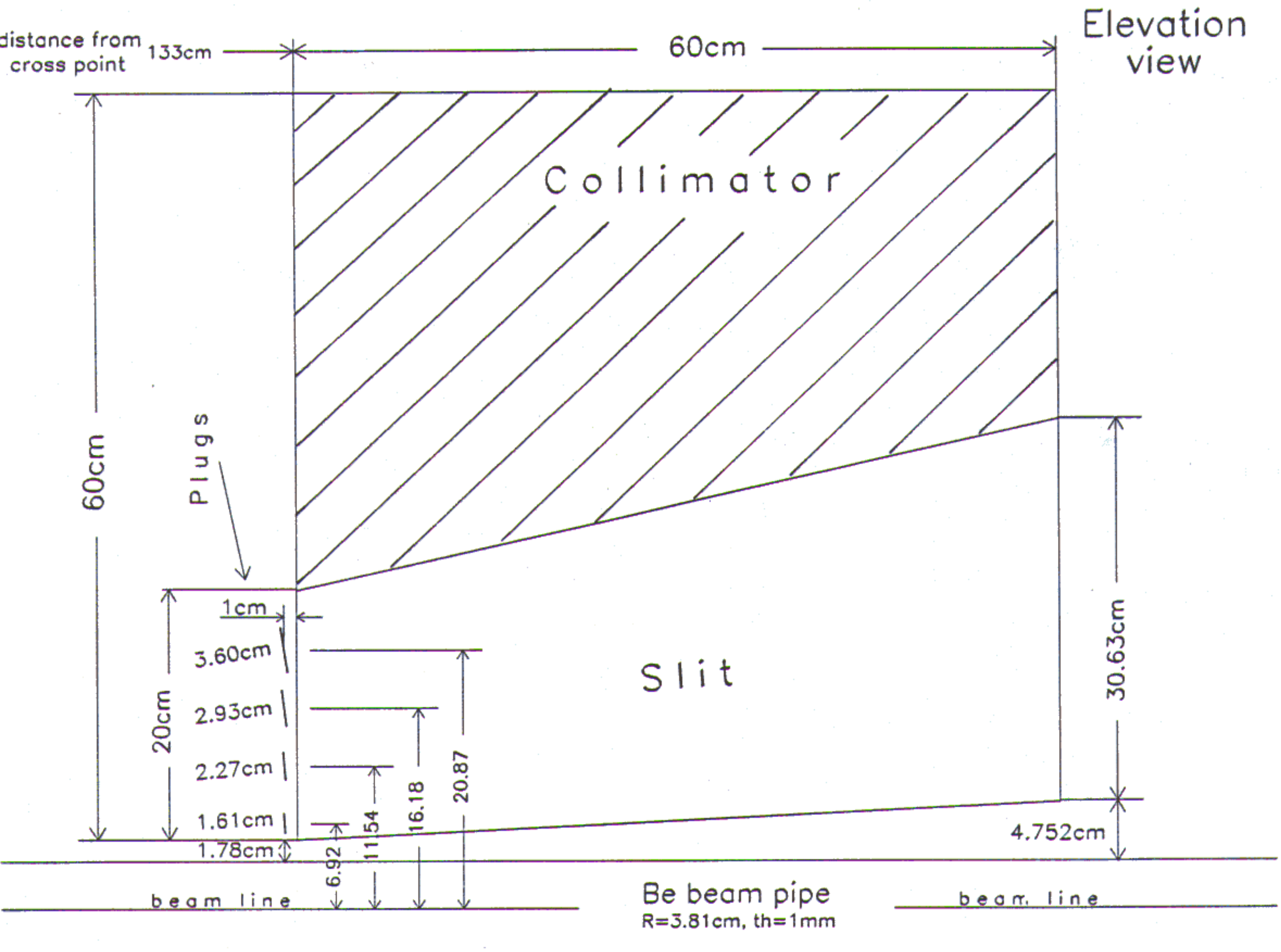
Rate / central ev.	Det. 1	2	3	4
BREMS	4.02×10^{-3}	1.32×10^{-3}	$.58 \times 10^{-3}$	$.3 \times 10^{-3}$
Background [SOFT SPECT.]	8.04×10^{-3}	5.68×10^{-3}	4.03×10^{-3}	2.37×10^{-3}

No calculation yet for HARD or STD SPECT. for 10 KV → 200 KV.

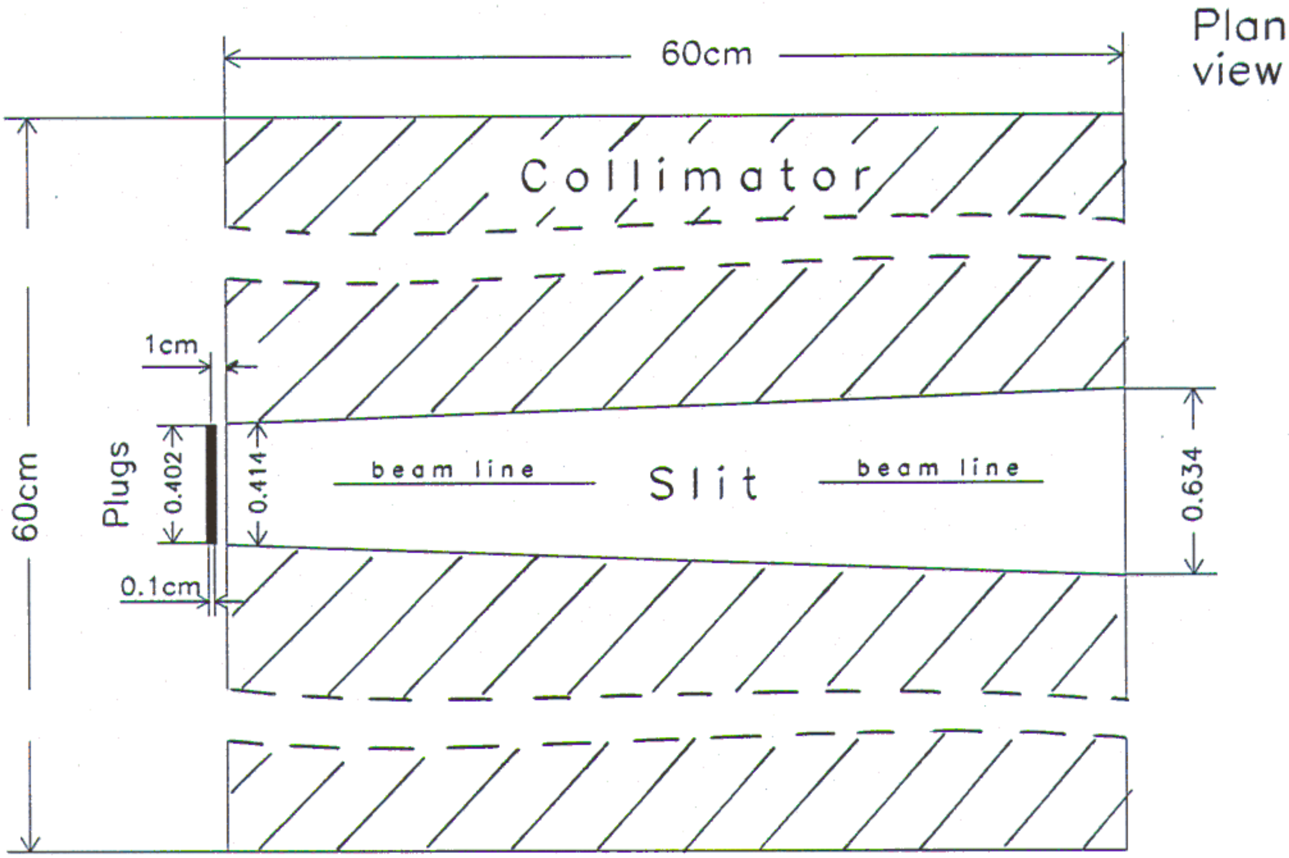
For 10 KV → 3 MeV SOFT is WORST CASE.

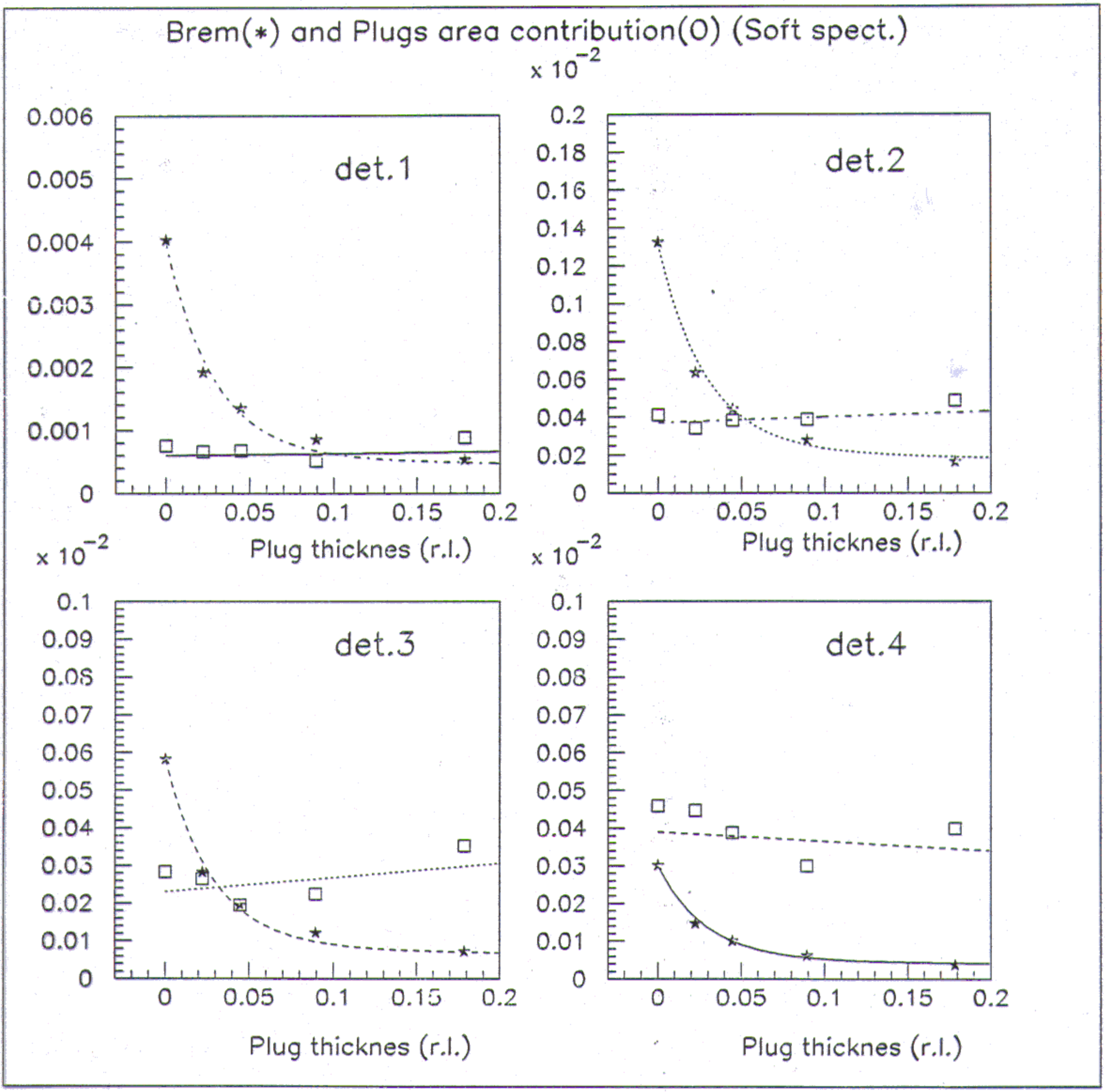
Plan of the Bremsstrahlung Experiment

- The "name" of the game is the experimental measurement of the background in a manner that is adequately insensitive to the spectrum of particles (unknown at the time of the experiment) that RHIC collisions produce.
- Basic Scheme :
  - $N_{T,0}$ central events with no plug.
    The Ge detector (with veto) measures the bremsstrahlung +the background
  - $N_{T,1}$ central events with plug set 1.
    Since the brem signal is highly attenuated, this run measures mainly background
  - $N_{T,2}$ central events with plug set 2.
    This run is used to lessen the sensitivity of the background measurement to the (unknown) RHIC spectrum.



distance from cross point
133cm
60cm
Elevation view
Collimator
60cm
Plugs
1cm
3.60cm
2.93cm
2.27cm
1.61cm
1.78cm
20cm
6.92
11.54
16.18
20.87
Slit
30.63cm
4.752cm
beam line
Be beam pipe
R=3.81cm, th=1mm
beam line


60cm
Plan view
Collimator
1cm
Plugs
0.402
0.414
beam line
Slit
beam line
0.634
60cm
0.1cm



Brem(*) and Plugs area contribution(O) (Soft spect.)
x 10^-2
det.1
det.2
det.3
det.4
x 10^-2
x 10^-2
Plug thicknes (r.l.)
Plug thicknes (r.l.)
Plug thicknes (r.l.)
Plug thicknes (r.l.)

Nominal 6 weeks @ 100 hrs. / week

1% of design luminosity = 10 ev/s

Livetime and "diamond cut" (50%) included.

Run plan 7/8/1 No plug / $\frac{1}{8}$" "Pb." / 1mm Pb.

SOFT π SPECTRUM

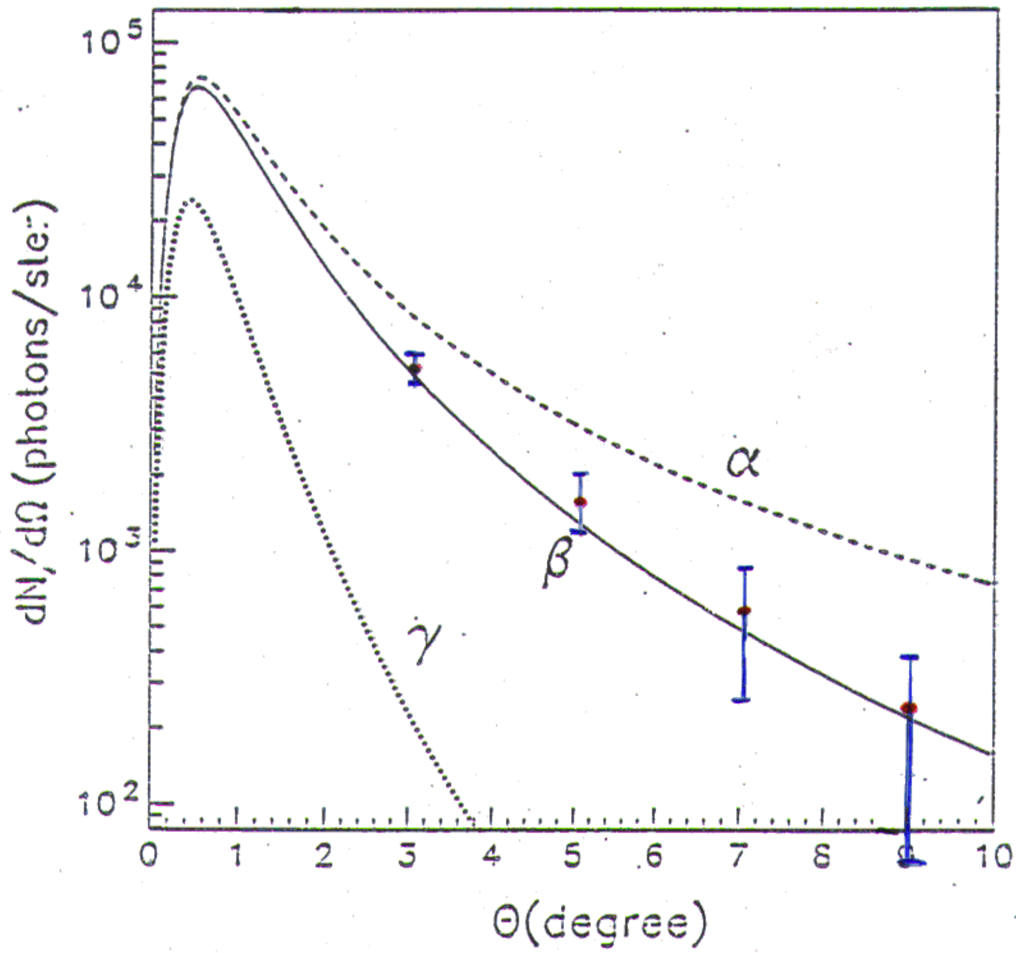


Figure 2: The number of bremsstrahlung photons with energies between 10 keV and ~~3 MeV~~ 200 keV, per steradian in the laboratory system for the three different stopping models α, β, and γ of figure 1.

Role of the Bremsstrahlung Measurement

- The experiment will measure the average charge stopping in in an unambiguos and global fashion.

- every decelerated charge contributes (coherently) to the spectrum of Bremsstrahlung.

- This global measurement will be an important overall constraint on the understanding of RHIC collisions.

- It relates to a fundamental property: How much energy is deposited in the central region?

- Similar information will be provided by other expts. ($p, \bar{p}$ spectra, etc.). However, these measurements are not global (finite acceptance, hyperons not measured, etc.). The information they provide will be enhanced by the results of Brems. expt.

Future

- Unfortunately (!), R-10 was **not** approved by BNL
  (too much cost for the "benefit")

  [equipment (detector) cost ~ 120 K\$
  BNL set up cost ~ 600-750K\$)

- So ....

  we are studying a more ambitious experiment which would be done year 1+2 (3?)

  The idea is to extend the Bremsstrahlung measurement to higher energy and coverage to measure the deviation from the coherent radiation

  Simply put the E_γ at which the deviation occurs signals the size of the region of acceleration.

  More exactly one uses $\frac{d^2N}{dE_\gamma d\Omega}$ to "fit" the temporal history of the acceleration.

The e.m. radiation from a charge, e, with an acceleration history $\dot{\vec{\beta}}(t)$ is:

$$\frac{d^2 I}{d\omega\, d\Omega} = \frac{e^2}{4\pi^2 c} \left| \int_{-\infty}^{\infty} \frac{\hat{n} \times [(\hat{n} - \vec{\beta}) \times \dot{\vec{\beta}}]}{(1 - \vec{\beta} \cdot \hat{n})^2} e^{i\omega(t - \frac{\hat{n} \cdot \vec{r}}{c})} dt \right|^2$$

$\hat{n}$ is unit vector to detector

$\vec{r}$ ranges over the collision

"low" ω neglect phase factor $\Rightarrow$ R-10

higher ω measure effect of phase ...

Basic Approach of expt :

Add pair Spectrometer to R-10 (also then have "acess" to polarization of γ's).

Experiment design at an early stage but has passed "first order" tests.