ARDB Technical Note No. 61   **Draft for Comment**

9/28/96

Technical Note: Upgrade to South Final Focus Bunch Length Monitor

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Physicists for the SFF-BLM
"We Care About Bunch Length"   *Expires 6/28/97*

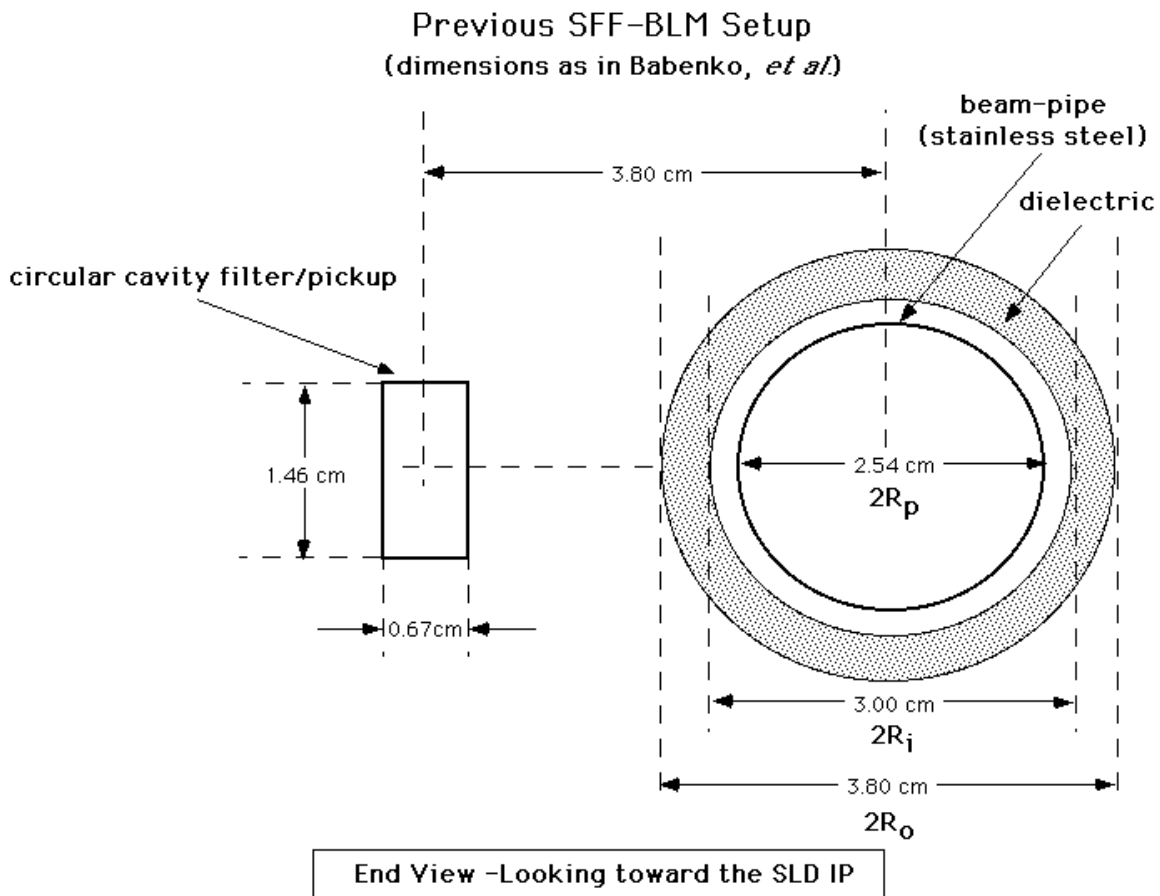**Technical Note: South Final Focus Bunch Length Monitor**

Distribution: When complete to - Ops, SFF Area Manager, Controls, AMRF

SFF-BLM Commissioner: F. Zimmermann x2626, Pager 719-6398

From: F. Zimmermann, D. Whittum

Summary

This reports the particulars of the South Final Focus Bunch Length Monitor (SFF-BLM) upgrade in progress as of 9/28/96.

Fig. 1. Previous SFF-BLM setup, end-view. [Correction, monitor is in contact with wrapping on the pipe, and facing down toward the floor. Additional observation: no dedicated return current path across dielectric. Probably sparking as is.]
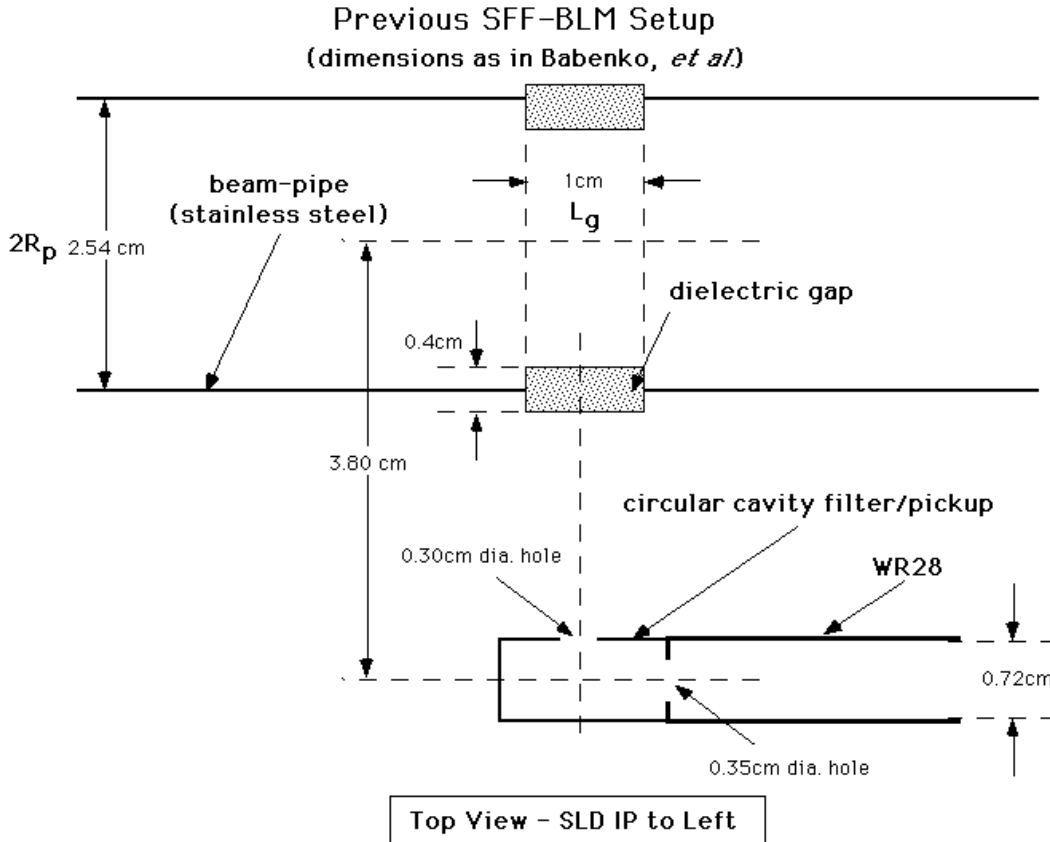
Fig. 2. Previous SFF-BLM setup, top view. [see correction, previous figure]

History

Recent references on this subject are Robert Holtapple's thesis[1] and the paper in the 1993 PAC Conference by E. Babenko, *et al.*[2] Additional technical notes are cited by Babenko.[3,4,5] [Attach these notes as an Appendix]. The SFF-BLM setup prior to upgrade is depicted in Figs. 1-2, with parameters as listed in Table 1. The central element of this setup is a dielectric gap in the beam-pipe, originally emplaced there for toroid Micro FF01 Unit 3920. This toroid is still present and has merely been displaced along the beam axis [how has it been performing?].

The signal-processing used in the previous setup is illustrated in Fig. 3. The function of the setup in Fig. 3 is to integrate the beam power spectrum over the pass-band of the cavity-filter (125MHz FWHM centered on 36GHz) and deliver this scalar quantity (in mV from the crystal detector) to a gated analog-to-

digital converter (GADC) and thence to the Solo Control Program (SCP) (in units of counts at 1 bit per [0.5 pC] of integrated signal from the crystal detector).

Table 1. Parameters for the previous SFF-BLM setup (from Babenko, *et al.*)

Symbol	Value	Parameter
L_g	~1cm	ceramic gap length
$2R_p$	2.54cm	beam-pipe diameter
$2R_o$	3.80cm	ceramic outer diameter
$2R_i$	3.00cm	ceramic inner diameter

This setup has suffered from unidentified sources of noise as a result of which the SFF-BLM has in the past not been a useful monitor of bunch length. The intent of the SFF-BLM upgrade is to eliminate this noise problem and provide a sensitive and reliable monitor of bunch length. The signal processing will be extended to either 1, 2, 3 or 4 channels (depending on cost) to enhance sensitivity to sub-mm bunch lengths. We recommend the 4 channel setup discussed below.

Possible Sources of Noise

Possible sources of "noise" in the old BLM setup are:

(1) pulsed noise from the passage of a several hundred Ampere peak current beam

(2) pickup from other electrical devices in the vicinity

(3) intermittent electrostatic charge-up & sparking of the dielectric gap

Items (1) & (2) are eliminated in the new setup discussed below. As for item (3), we understand that such gaps are normally coated with a flash of conductor [still getting info], so this should not be a problem could well be concerns even with the new setup. Regarding (1), it is also worth noting that, to reduce ground loop noise for other devices in the vicinity we could insure that a return current path is provided across the gap, with sufficiently high impedance that it does not shunt high frequency current away from the aperture of the BLM pickup. As is, it

appears that the return current path is entirely parasitic, *i.e.*, consisting of any cables that happen to be in the area. Peak current suggests that a fairly high ampacity return current path would be best, for example, a bus-bar. [discuss] For proper function of any gap monitor, this return current path should be physically well-separated from the image charge on the dielectric, to insure that our pickup receives the full benefit of the image displacement effect. [wondering at this point, what is the state of any conducting coating one the dielectric] [Add caution on ground loop pickup to waveguide itself, possibly carrying pulsed noise into the Laser Shack, provide for isolation.]

Signal Processing in the Previous SFF-BLM Setup
(NTS)
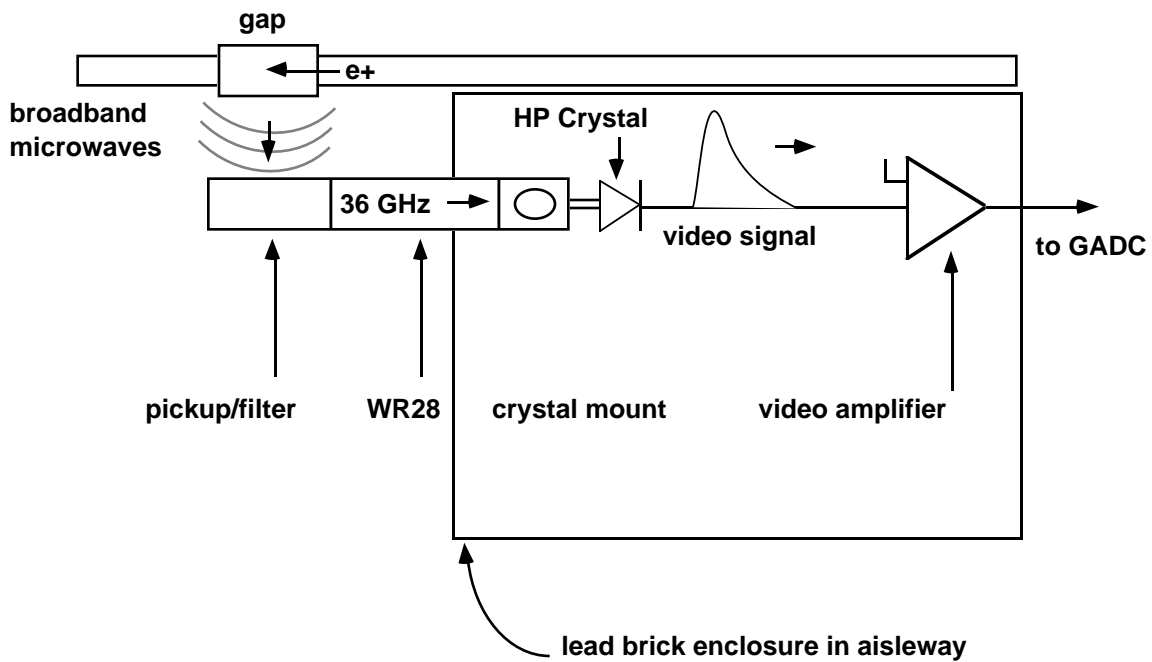
Fig. 3. Processing of the SFF-BLM in the previous SFF-BLM setup consisted of power detection in the pass-band of the filter-cavity, and took place within the accelerator housing, inside a small pile of lead bricks on the floor of the aisleway. Such a setup is in principle susceptible to pulsed "noise" and ionizing radiation induced "noise"

Waveguide Network

To permit study of the raw microwave signal during colliding beam operations, it was decided to install a waveguide network to transmit the microwave signal out of the accelerator housing. To control cost and reduce attenuation of the very high frequencies involved, it was decided to take the signal out in WR90 as this is plentiful on-site.
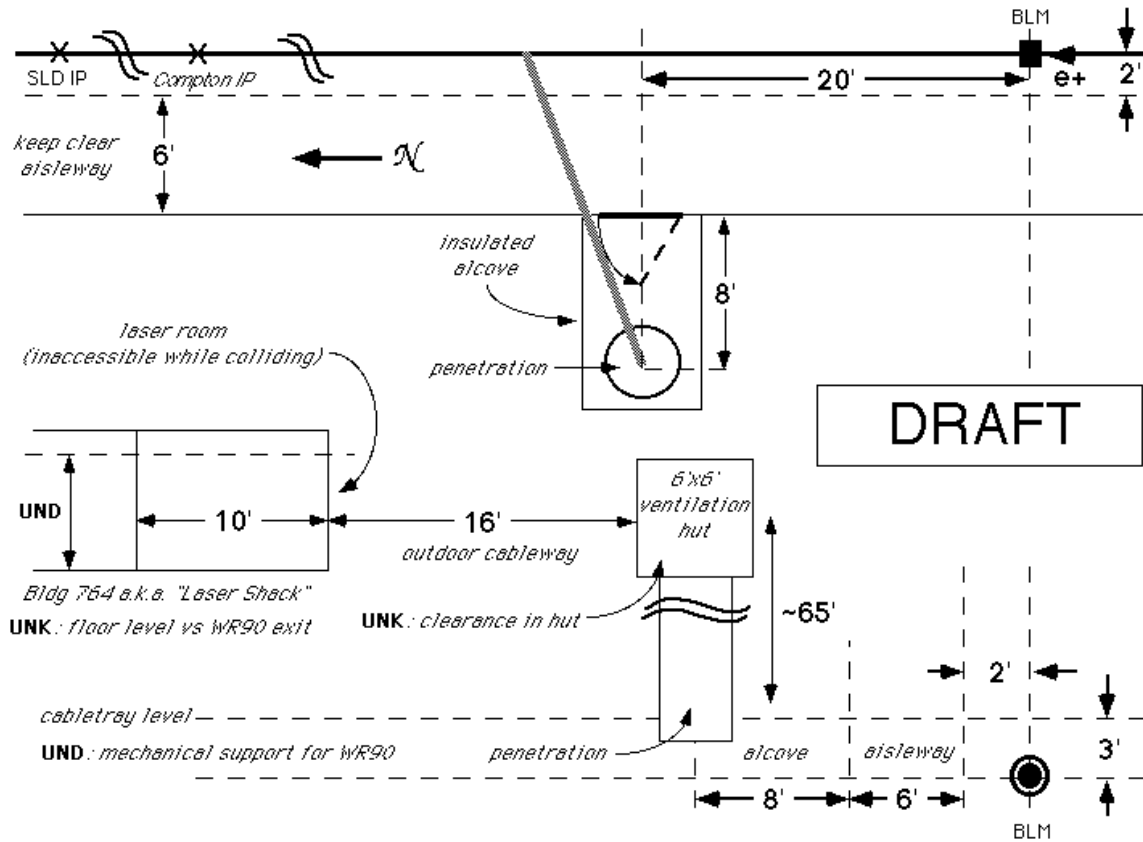
Space Available for SFF Bunch Length Monitor Waveguide Network - *NTS* - DRAFT - 9/28/96

Fig. 4. Space available for the waveguide network. Maximum length of straight WR90 the can be fit into penetration from below is more than 7', less than 8'.

The need for waveguide (as opposed to heliax cable) is dictated by the very high frequencies involved. At present WR90 is the most plentiful waveguide on site and it was selected primarily for this reason (it is in fact cheaper than heliax, since it is freely available). One disadvantage of the high

frequencies involved is the absence of test and measurement equipment on-site for 35 GHz signals. In fact, between 26.5 GHz and 75 GHz, there is no spectrum analyzer or network analyzer on site.
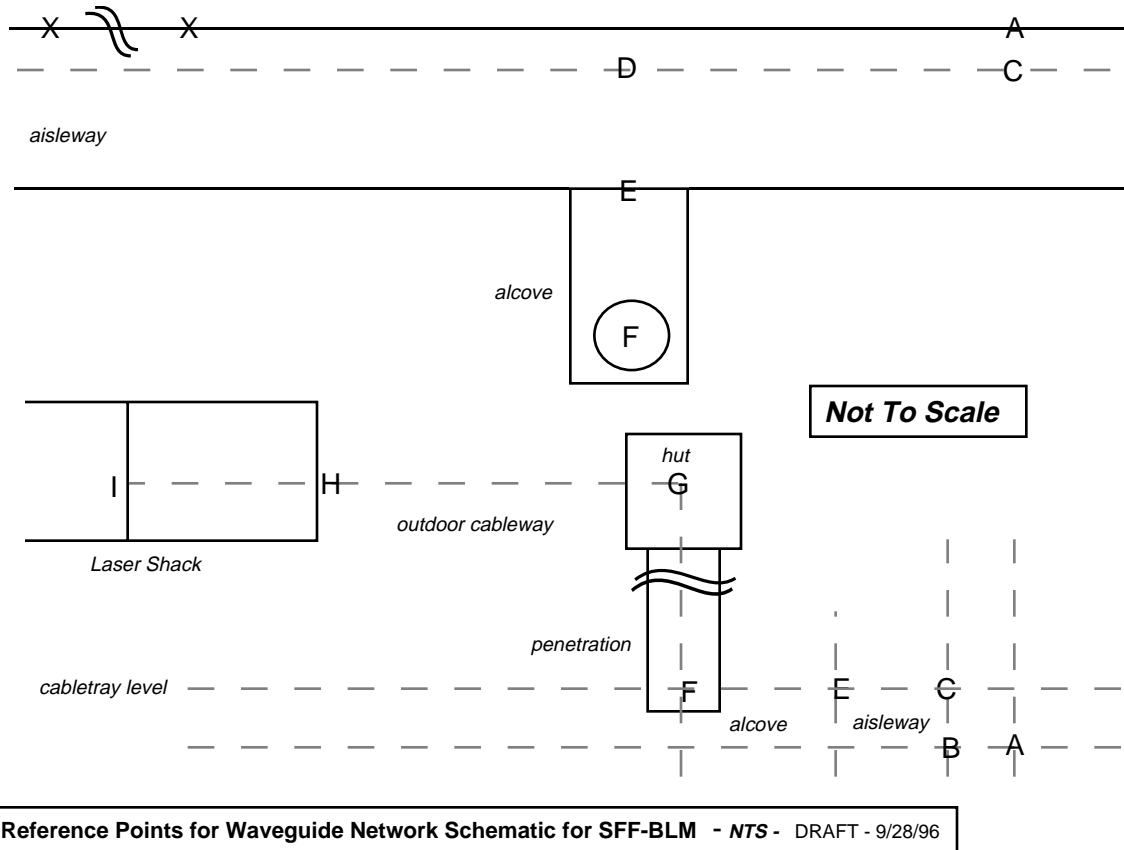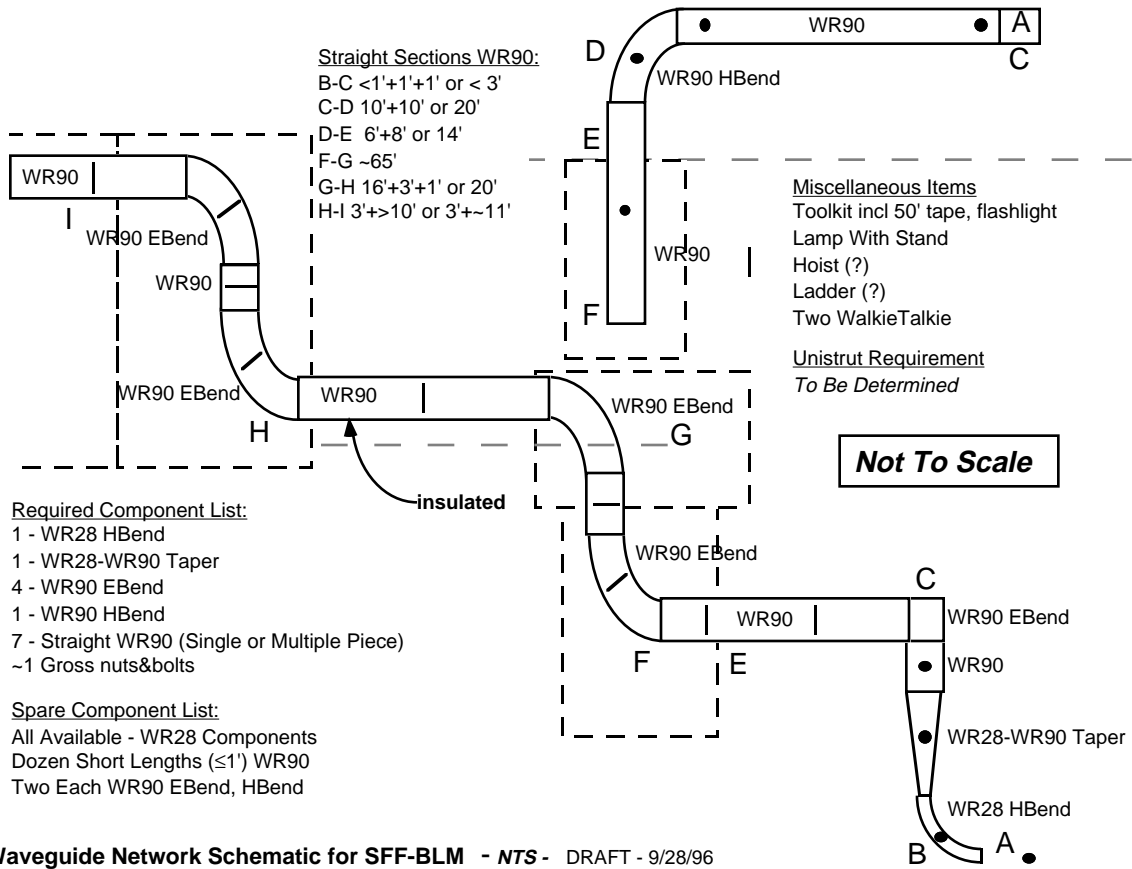

Reference Points for Waveguide Network Schematic for SFF-BLM - *NTS* - DRAFT - 9/28/96

Fig. 5. Reference points for the waveguide network

Some dimensions remain to be determined: trailer height vs. the ventilation hut, clearance for lifting waveguide in the ventilation hut (will limit the longest piece of waveguide we can use in the penetration), exact depth of penetration. Several holes need to be punched, probably one in the siding of the ventilation hut, one in the wall of the Laser Shack, and one in the foam insulation downstairs to get into the alcove. This last hole needs to be repacked with insulation to insure temperature stability required by the Compton polarimeter setup that also uses this penetration.

Straight Sections WR90:
B-C <1'+1'+1' or < 3'
C-D 10'+10' or 20'
D-E 6'+8' or 14'
F-G ~65'
G-H 16'+3'+1' or 20'
H-I 3'+>10' or 3'+~11'

Miscellaneous Items
Toolkit incl 50' tape, flashlight
Lamp With Stand
Hoist (?)
Ladder (?)
Two WalkieTalkie

Unistrut Requirement
To Be Determined

Not To Scale

Required Component List:
1 - WR28 HBend
1 - WR28-WR90 Taper
4 - WR90 EBend
1 - WR90 HBend
7 - Straight WR90 (Single or Multiple Piece)
~1 Gross nuts&bolts

Spare Component List:
All Available - WR28 Components
Dozen Short Lengths (≤1') WR90
Two Each WR90 EBend, HBend

Waveguide Network Schematic for SFF-BLM *- NTS -* DRAFT - 9/28/96

Fig. 6. Sketch of waveguide component layout & parts required. [This is being modified to remove the WR28 downstairs and put all filtering functions upstairs. The result is that the WR28-WR90 taper and the WR28HBend are replaced with a WR90 horn, and a WR90 HBend.]

Preliminary Estimate for the Existing Pickup/Filter

At the preliminary stage we considered simply retaining the present pickup/filter and estimated signal levels for that. This setup was later revised to eliminate the pickup/filter and make use of a horn antenna, for broadband coupling; this has the advantage of permitting modifications to the filtering to be made outside the accelerator housing, during colliding beam operations. However, for completeness we note here the preliminary estimate made for the narrow-band pickup, as it puts a lower bound on the worst case signal level of all detection setups one might contemplate.

For the preliminary estimate, quantitative considerations were as follows. Holtzapple reports (private communication) that for the LI25 (sector 25) BLM,

with N_b=2.5x10^{10} particles per bunch, typical signal levels were 17mV on an HP crystal detector for which this corresponds to about 4dBm (dB relative to 1 mW). The network for this BLM station consists of 39 feet of WR28 for which we estimate an attenuation of 6dB, assuming copper [check, if brass, then 12dB]. This implies 10dBm into the waveguide from the cavity. This figure for power can be compared to the estimate of Babenko, *et al.*, for this LI25 BLM. They estimate 5.2dBm into the waveguide from the cavity at N_b=3x10^{10} (3.6 dBm at N_b=2.5x10^{10}). This suggests an uncertainty of about 6dB or about a factor of 4, perhaps due to cavity placement. For the SFF-BLM they estimate at 11dBm at N_b=3x10^{10} (9.5 dBm at N_b=2.5x10^{10}). Since the minimum detectable signal (1-2mV say) with good crystal detectors on-hand (as opposed to the HP crystals previously employed) is about -25dBm, we can immediately conclude that we have a margin of several 10's of dB without employing a 36GHz amplifier.

This margin is of concern for reasons of cost only. The thermal noise level into a 20GHz bandwidth is -96dBm, far below the signal levels of interest. [characterize noise environment in the Laser Shack, check particularly time sequence of "noise" in the Shack, if necessary, include in plan, small screen cage + chokes]. However, for signal levels below -25dBm, a Ka-band amplifier would be required, and these cost several thousand dollars. For example, the CTT Microwave Model LA-26408 is a 26-40GHz amplifier with 36dB gain, and noise figure of 5.0dB, WR28 connectorized, and costs $5225. It also requires a 12V, 610mA power supply---not a costly item, but adding to the complication of the setup and the possibilities for systematic errors/drifts etc. A narrower band amplifier would be cheaper, potentially about $1000. We exclude use of such an amplifier from our considerations, as it appears at present not necessary.

For this preliminary analysis of the effiicacy of the waveguide network, we took 10dBm as the power level coupled into the waveguide. Actual coupling does depend on the cavity Q_e, Q_w, and resonant angular frequency ω_0, and it is not clear that these were ever actually measured for the SFF-BLM cavity, insofar as no test & measurement equipment is available on-site for such a

measurement. More likely, Babenko, *et al.*, scaled down from their 25GHz cavity. (Test & measurement equipment on site is limited to 0-26.5GHz, and 75-100GHz).

The length of the WR90 network required by the geometry of the housing and available penetrations, is about 130 feet, corresponding to an attenuation at 35GHz of 8dB in brass or 4dB in copper. This implies a signal level at the output (in the Laser Shack) of 12dBm assuming copper WR90. Minimum detectable signal (1-2mV, say) with crystal detectors on hand is -25dBm. Thus we may expect a 37dB margin for the three unkowns at present:

(1) actual attenuation in the network (may differ due to surface roughness, cleanliness),

(2) mode conversion and reflection at the bends (unknown)

(3) details yet to be determined of the coupling geometry (~~whether we continue to employ the cavity, switch to a horn, or a rentrant cavity surrounding the beamline~~) (see calcluations on horn pickup).

As a worst case, if we assume 1dB loss per bend, and 10dB loss in coupling to the waveguide (due to infelicities in mounting for example), and an additional attenuation of 4 dB due to waveguide surface conditions (roughness, dirtiness) our 37dB margin comes down to about 15 dB at N_b=2.5x10^{10}. The minimum detectable signal in this worst case is reached for N_b=3x10^9.   [revise these comments to more precise forms after benchtesting & waveguide cleaning as necessary].

Detailed analysis of sensitivity to bunch length variations, at fixed charge per bunch is provided below, assuming a broadband coupling, as for a WR90 horn. Use of a horn ameliorates concerns about weak signals expressed in the previous paragraphs; we will most likely need a fair bit of attenuation upstairs.

Calibrations

To put firmer bounds on these uncertainties, we [will perform] bench tests with an HP8510C network analyzer. No equipment on site is available for tests at 35GHz, so we [will perform] measurements of insertion loss over the band of frequencies from 10GHz up to 25GHz, to permit extrapolation to 35GHz. We [will measure] insertion loss on several lengths of WR90, with identical couping flanges. Insertion loss includes three effects in principle:

(1) attenuation in the guide
(2) reflection at the couplers
(3)mode conversion in the guide.

Effect (1) scales with waveguide length and frequency. Variation of (2) with frequency is a bit complicated in overmoded guide; it is not expected to exhibit any particular scaling with length. However, for (3), rotation of the coupled-to mode, between hybrid modes could exhibit a length dependence.

The WR90 used in the above test [is] generally speaking rather clean, having been previously employed for some work at X-Band in the klystron department, and subsequently wrapped with aluminium foil. We [will perform] similar tests on never-used WR90 that had been stored in no particular conditions of cleanliness in the LI29 cage. Prior to the tests, we [will employ] an air-gun to blow the dust out.

Based on these results we decided that chemical cleaning/steam cleaning of the waveguide [was/was not] necessary.

Bunch Spectra

To understand BLM performance it is helpful to recall some features of bunch spectra and the particulars (frequencies, bunch lengths) for bunches produced for SLD.

Most Knobs Affect Bunch Length

It is good to appreciate that the bunch length for the e+ passing through the SFF is affected by a multitude of knobs that are in fact routinely and even casually tweaked by physicists and operators. A number of references are available on the subject of bunch length and longitudinal dynamics in the SLC, particularly, Robert Holtzapple's thesis, and works of Zimmermann[6] and Bane[7].

Starting in the south damping ring, equilibrium longitudinal phase-space (bunch length, energy spread) is determined by the gap voltage (V_{gap}). Prior to extraction, there may be bunch munching [...] (a phase-space rotation). In addition, the bunch is lengthened, and the synchronous phase is shifted by a current-dependent amount (at most 4 degrees of 714MHz) due to the broad-band impedance of the ring. In the RTL, longintudinal phase-space is sheared in energy by an amount depending on the the compressor voltage (V_c), and possibly translated in energy if the compressor phase (ϕ_c) is not at the zero crossing at beam time. Next, due to the bends in the RTL, the longitudinal phase-space is sheared in position ("compressed"), a transformation depending on the RTL R_{56}, and T_{566}. If the compressor-induced energy chirp is large, there is in addition collimation in the RTL. This collimation can shift the longitudinal beam centroid. In the linac, the energy distribution is again modified by an amount that depends on the DR phase with respect to the linac phase (DR-RF S-Band Loop), and by the phase-schedule along the linac (**BNS** phasing). The effect of wakefields on energy loss in the linac depends on bunch length explicity, so all previous knobs mentioned have some influence on the outgoing energy spectrum at LI30. In addition, wakefield modifications to the energy spectrum depend on the charge in the bunch. This charge is coupled to many dozen e- knob settings on the second to last machine cycle. In passing through the south arc, additional compression occurs, due to the arc R_{56} and is determined by the energy spectrum from the linac (*i.e.*, all previously mentioned knobs). Coming out of the arcs, the bunch passes through the SFF-BLM, and on

to the interaction region. [There is/is not some additional R_{56} between the BLM and the final focus.]

Bunch length for the (outgoing) e- passing through the SFF are influenced by the e- analogs of the above mentioned knobs, as well, in principle by any "R_{56}" due to the beam-beam effect with bunch offset. [this has/has not been estimated, include estimate]. It could also be added that the e- energy spectrum is influenced by the induced voltage in the linac from the e+ bunch 58 ns in front of it. This voltage depends for the most part on the e+ charge, and phasing (with respect to the e-). Thus some coupling of e+ knobs to e- bunch length is present. [quantify].
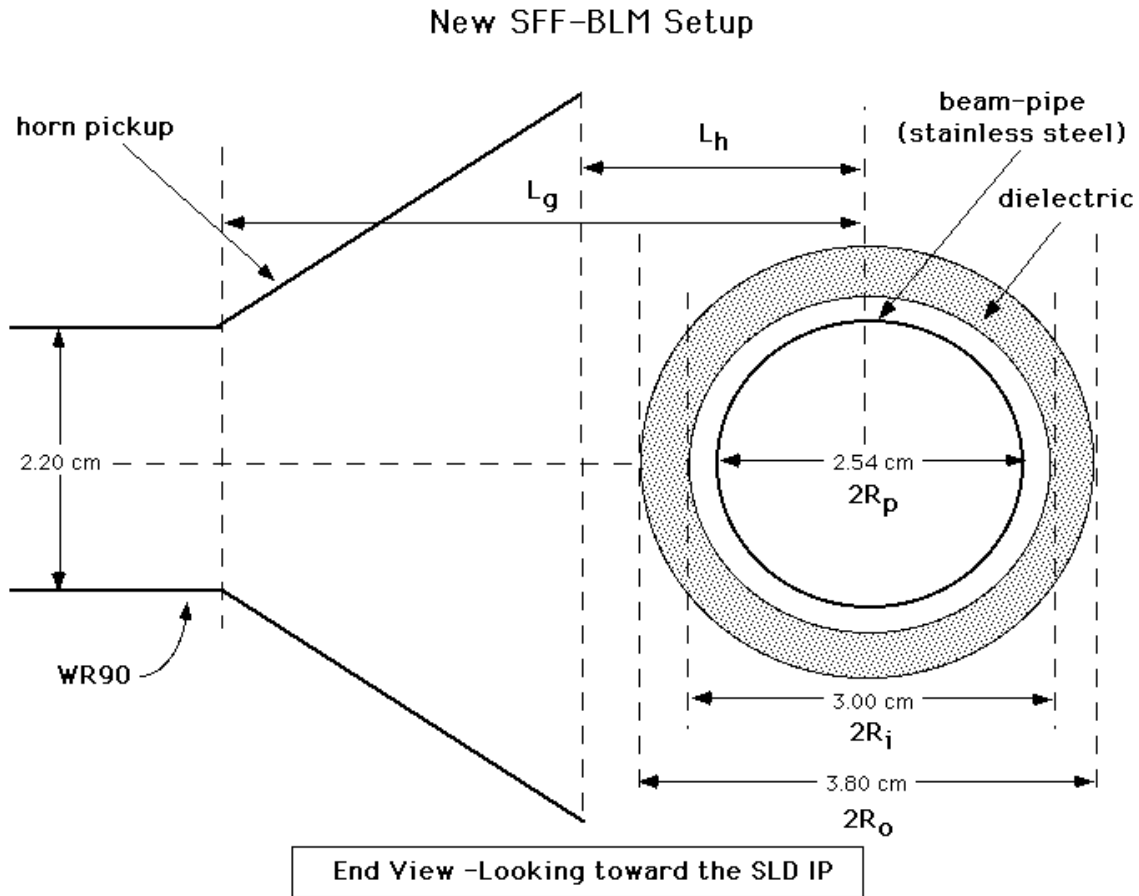
Fig. 7. New setup for the SFF-BLM making use of a horn pickup, end view.

The actual bunch distribution is not Gaussian in general, but to exemplify the scalings for the BLM, we provide curves corresponding to Gaussians. To aid the imagination, [consider an asymmetric Gaussian].

e+ Pickup & Coupling To Waveguide

We are strongly inclined to dispense with the narrow-band cavity pickup, and use instead a WR90 horn. The reason for this is simply that a setup with a broadband pickup is more versatile, permitting one to monitor a number of frequency bands. In addition, should later applications or projects require it, one can make extensive modifications to the detector circuit upstairs during colliding beam operations, with no modifications in or access to the accelerator housing. The setup we intend to implement is depicted in Figs. 7-9. The particulars of the horn will be decided by what is available on-site [so far 1 horn candidate].
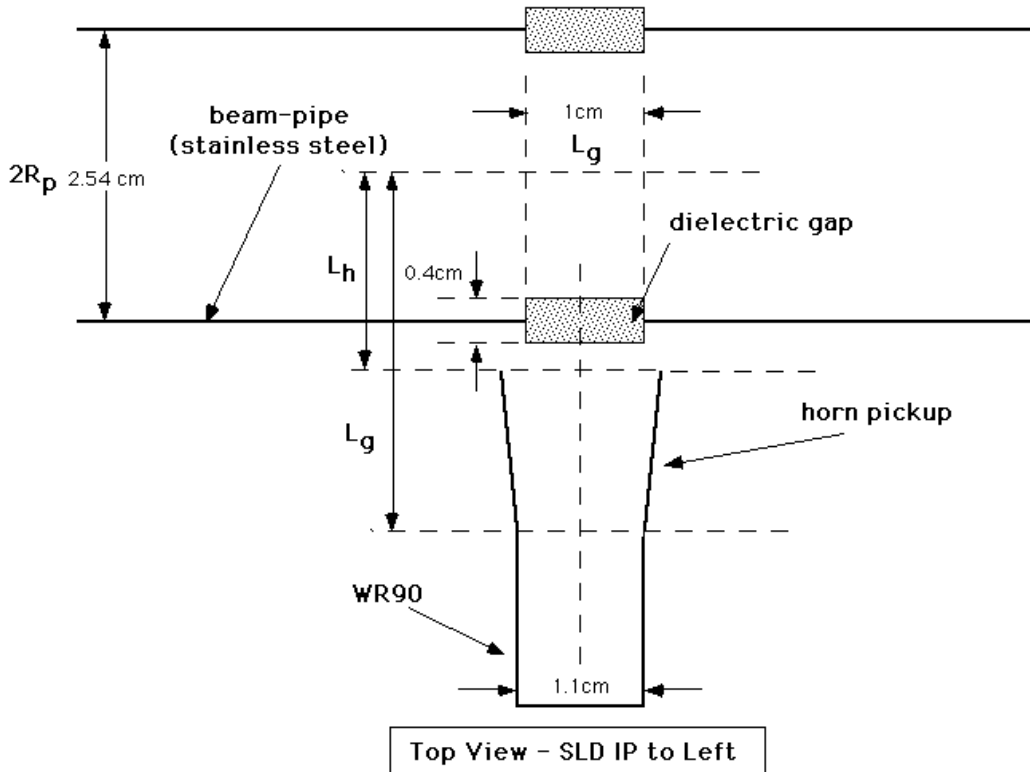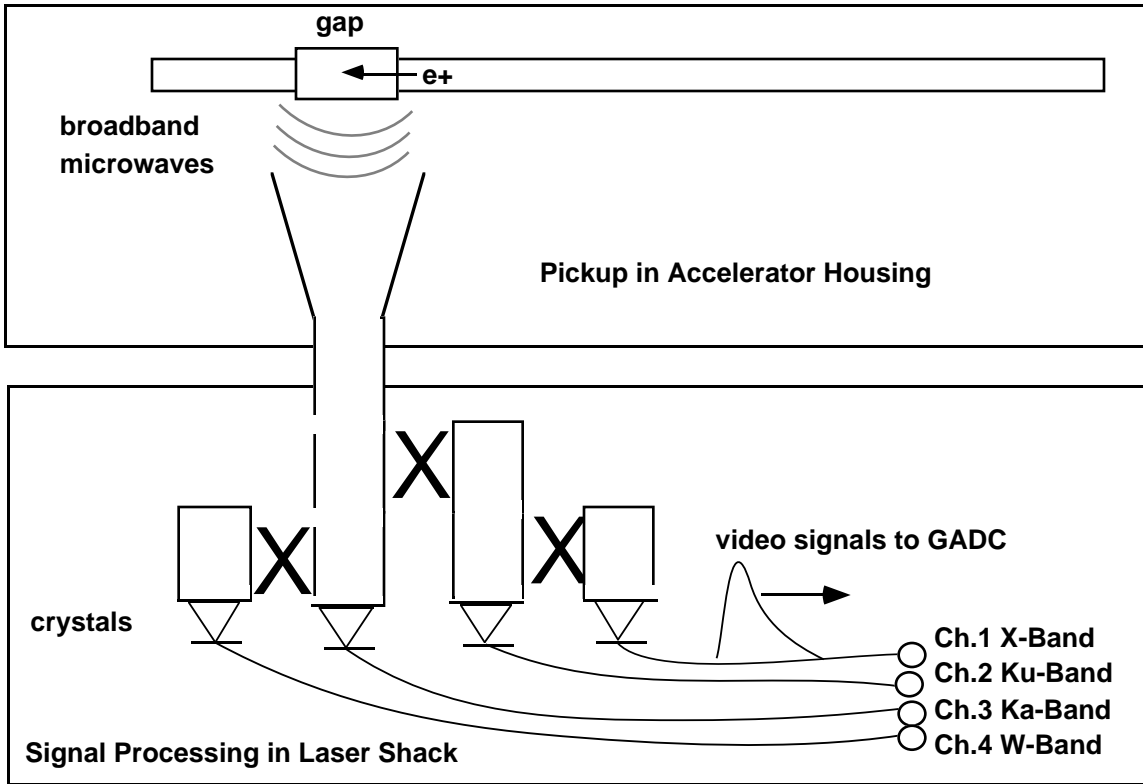

Fig. 8. New setup for the SFF-BLM making use of a horn pickup, top view.

Signal Processing in the New SFF-BLM Setup
(NTS)

Fig. 9. In the new setup for the SFF-BLM signal processing occurs outside the accelerator housing. Details are provided in the section on "signal processing" and Fig. 13 below.

In this setup we need to be concerned with all modes above cut-off that are permitted by symmetry to couple, and the coupling of the beam, through the dielectric, to each of these modes. Generically, we may always describe the coupling to a mode by a coupling coefficient ε,

$$\tilde{V}_a(\omega,z) = \varepsilon_a(\omega)Z_a(\omega)\tilde{I}_b(\omega)\exp(j\omega t - j\beta_a z - \alpha_a z),$$

(1)

where *a* is the mode index. It is generally a fair bit of work to compute ε, or, as usefully, to measure ε on a scaled setup. We may go a fair distance in estimating sensitivity to bunch length in different frequency bands, with the assumption that ε is fairly flat as a function of frequency. Until further notice and regardless of any MAFIA calculations or bench calibrations, the signal resulting should be understood as an uncalibrated monitor, requiring calibration by some other technique. That is to say, the signals described below in each channel, have associated with them an overall multiplicative constant (four in all). In addition, to the extent that the coupling coefficient has any variation over the frequency band of interest, a possible systematic deviation from predicted bunch length dependence may arise. [we can characterize this systematic frequency dependence error reliably using a scaled model at lower frequency --- should do]. For present purposes we will provide some simple estimates of ε, below.

In Eq. (1) the angular frequency $\omega=2\pi f$, with *f* the frequency. Z_a is the characteristic impedance of the waveguide mode, introduced as a convenient normalization. The propagation constant β_a is determined from the mode cut-off β_{ca}, according to[8]

$$\beta_a = \left(\beta_0^2 - \beta_{ca}^2\right)^{1/2}.$$

(2)

The free-space propagation constant $\beta_0 = \omega/c$. The attenuation constant is α_a, and for rectangular guide may be found in Collin (the expression is rather lengthy in general). Typically we are interested in the fundamental mode of rectangular guide, TE_{10}, for which, $\beta_c = \pi/a$, with *a* the interior waveguide broad dimension. For WR90,

$$a = \frac{90}{100} inch \times 2.54 cm/inch = 2.286 cm.$$

(3)

For WR28, *a* is 28/90 of the value for WR90, etc. The small waveguide dimension *b* is typically near ~0.5*a*.

To compute the attenuation constant for TE_{10} (or any other mode) one must know the conductivity of the waveguide material. As two extreme cases we may consider copper, with σ=5.8x10^7 mho/m (5 x 10^{17} sec^{-1} in cgs units) and brass with σ=1.6x10^7 mho/m (1.4 x 10^{17} sec^{-1} in cgs units) - roughly 1/4 the conductivity of copper. Attenuation results from the slight penetration of the fields into the conductor and is determined from the penetration, or "skin" depth,

$$\delta = \left(\frac{2}{\omega\mu\sigma}\right)^{1/2} = \frac{2.2\mu m}{\sqrt{f(GHz)}},$$

(4)

where the numerical values correspond to copper. For brass, the skin-depth will be about twice as large. The surface resistance can be expressed as

$$R_s = \frac{1}{\sigma\delta} = 8.3 m\Omega\sqrt{f(GHz)},$$

(5)

where the numerical values correspond to copper. For brass, the surface resistance is about twice as large. Knowing the surface resistance, we may compute the attenuation,

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$$\alpha = \frac{R_s}{Z_0}\frac{\left(2b\beta_c^2 + a\beta_0^2\right)}{\left(ab\beta_0\beta_z\right)},$$

(6)

where Z_0=377Ω. These results apply to an ideal surface, in general surface roughness, oxidation or general dirtiness can increase attenuation. Note that attenuation in decibels through a length L of guide may be expressed as,

$$A(dB) = -10\log_{10}\frac{P(z)}{P(0)} = -10\log_{10}\frac{P(0)e^{-2\alpha z}}{P(0)}$$

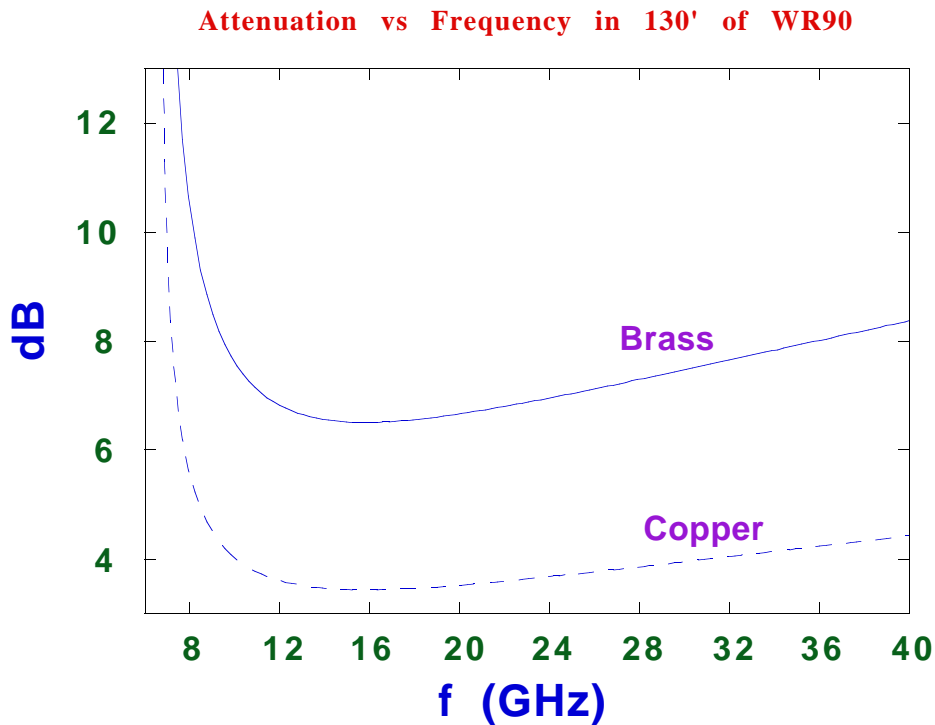$$= 10\log_{10}10^{-2\alpha z\log_{10}e} = 8.686\alpha z$$

(7)

Fig. 10. Attenuation in WR90 guide made of copper and WR90 made of brass.

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Note that waveguides cause dispersion so that different frequencies will arrive at different times. Arrival time of a narrow band signal with carrier frequency ω is determined from the group velocity

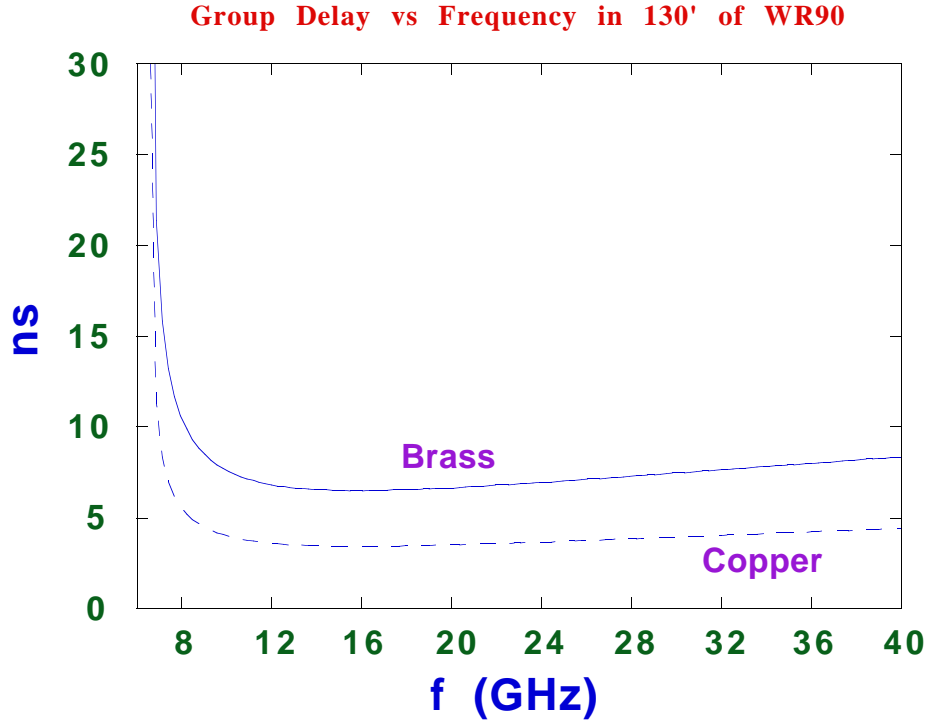$$v_g = \frac{d\omega}{d\beta_z} = c\left(1 - \frac{\beta_c^2}{\beta_0^2}\right)^{1/2}.$$

(8)

Since $v_g < c$, a wavepacket with carrier frequency ω travelling through a length L of waveguide is delayed with respect to a packet travelling the same distance in free space, by an amount equal to

$$T_g(\omega) = L\left(\frac{1}{v_g(\omega)} - \frac{1}{c}\right),$$

(9)

and we will refer to this as the group delay.

Group Delay vs Frequency in 130' of WR90

Fig. 11. Illustration of group delay with respect to transit at the speed of light, versus frequency. Signal timings above 8GHz are all within a few ns of eachother. Transit time at the speed of light over 130' is 132ns.

In terms of the voltage coefficient for each mode, we may compute the power spectrum at a point z in the waveguide,

$$P(\omega,z) = \sum_a \frac{\left|\tilde{V}_a(\omega,z)\right|^2}{2Z_a(\omega)}$$

$$= \left|\tilde{I}_b(\omega)\right|^2 \sum_a \frac{1}{2}\left|\varepsilon_a(\omega)\right|^2 Z_a(\omega)\exp(-2\alpha_a z)$$

$$= \frac{1}{2}R(\omega,z)\left|\tilde{I}_b(\omega)\right|^2$$

(10)

where the function R characterizes the net coupling of the beam to an idealized detector placed at z in the waveguide,

$$R(\omega,z) = \sum_a |\varepsilon_a(\omega)|^2 Z_a(\omega)\exp(-2\alpha_a z).$$

$$(11)$$

The Fourier transform of the beam current waveform is just

$$
\begin{aligned}
\tilde{I}_b(\omega) &= \int_{-\infty}^{+\infty} \frac{dt}{(2\pi)^{1/2}} \exp(-j\omega t) I_b(t) \\
&= \int_{-\infty}^{+\infty} \frac{dt}{(2\pi)^{1/2}} \exp(-j\omega t) \frac{Q}{(2\pi)^{1/2}\sigma_t} \exp\left(-\frac{t^2}{2\sigma_t^2}\right) \\
&= \frac{Q}{(2\pi)^{1/2}} \exp\left(-\frac{\omega^2\sigma_t^2}{2}\right)
\end{aligned}
$$

$$(12)$$

where in the last two lines, we take the case of a Gaussian bunch. (To be sure, bunches are usually not exactly Gaussian). The ideal detected power spectrum for a Gaussian bunch evidently takes the form,

$$P(\omega,z) = \frac{Q^2}{4\pi} R(\omega,z)\exp\left(-\omega^2\sigma_t^2\right).$$

$$(13)$$

Some impression of this scaling can be seen in Fig. 12, which assumes a broadband coupling, (ε constant with frequency) and takes into account attenuation in the waveguide.

Gaussian Bunch Spectrum before & after 130' of WR90
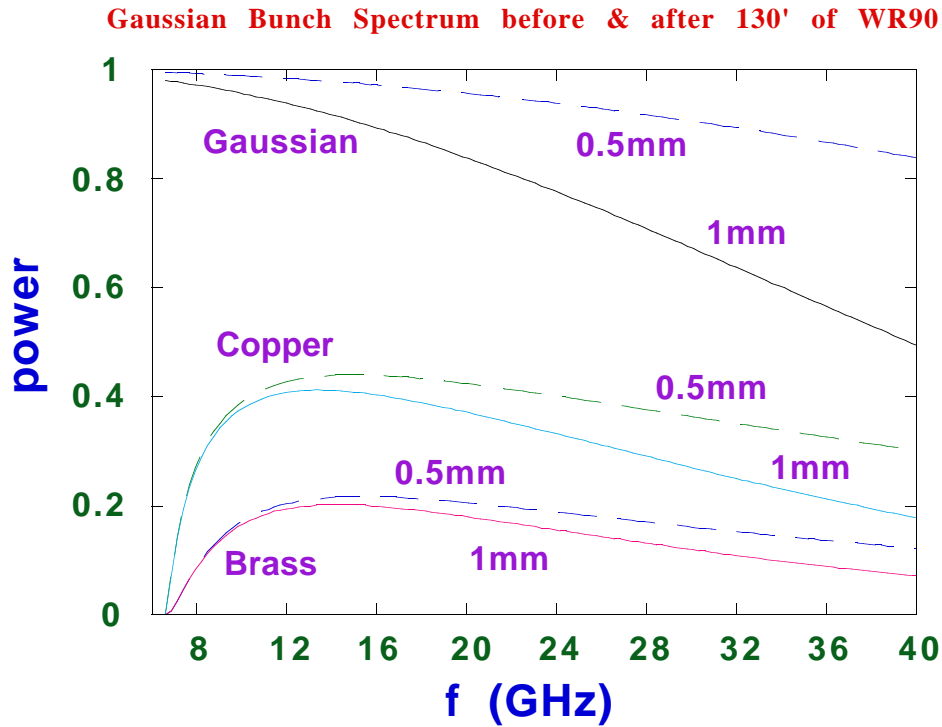
Fig. 12. Gaussian bunch spectrum, and the effect of waveguide attenuation in suppressing frequencies near cut-off, and causing a gradual roll off at high frequency.

Thus regardless of the coupling mechanism, power at a fixed frequency provides a monitor of bunch length. For practical purposes it is helpful to note

$$10\log_{10}P = -\left(13\frac{\sigma_z}{\lambda}\right)^2 + cons\tan t\,,$$

(14)

where $\sigma_z = c\sigma_t$ and λ is the free-space wavelength. ("Constant" here means independent of bunch length; the "constant" does depend on wavelength). To discern changes in bunch length by power-detection, one would prefer to use wavelengths of order $10\sigma_z$ or smaller. For example, varying σ_z. from a very small value to 0.1λ, produces a 1.7dB change in the power density at λ.. Viewing the entire spectrum one sees that the power spectrum is down by 50% at $\lambda \sim 7.5\sigma_z$.

from the value at very long wavelengths. Thus for a 0.5mm bunch length, one expects that 0.5cm wavelengths would be adequate. This corresponds to a frequency of ~60GHz. For a 1mm bunch, 30GHz should be adequate. In the SFF final focus a bunch length of 0.5mm is thought to be achievable, and this hints that frequencies up to the 60GHz range will be of interest.

[Note e+ specs (σ_x, σ_y etc at the BLM) optical functions, and any changes to them that might occur during startup & lattice debug. Be sure we have no collimation at the BLM, Note Babenko result for sensitivity to beam offset, note theoretical, decide on use of symmetric horn with T arrangement]

Signal Processing

Using freely available equipment, we may in principle monitor integrated power into the following channels.

        Ch.1   6.56 GHz - 12 GHz
        Ch2.   11.6 GHz - 19 GHz
        Ch3.   21.1 GHz - [upper limit set by attenuation]
        Ch4.   59.0 GHz - [upper limit set by attenuation]

For example, this may be accomplished with the setup depicted in Fig. 13. This setup would be placed at the top of the waveguide network, in the Laser Shack. In practice a sketch such as this will be revised based on attenuation and dynamic range issues, with the insertion of waveguide attenuators and limiters as necessary, during commissioning.
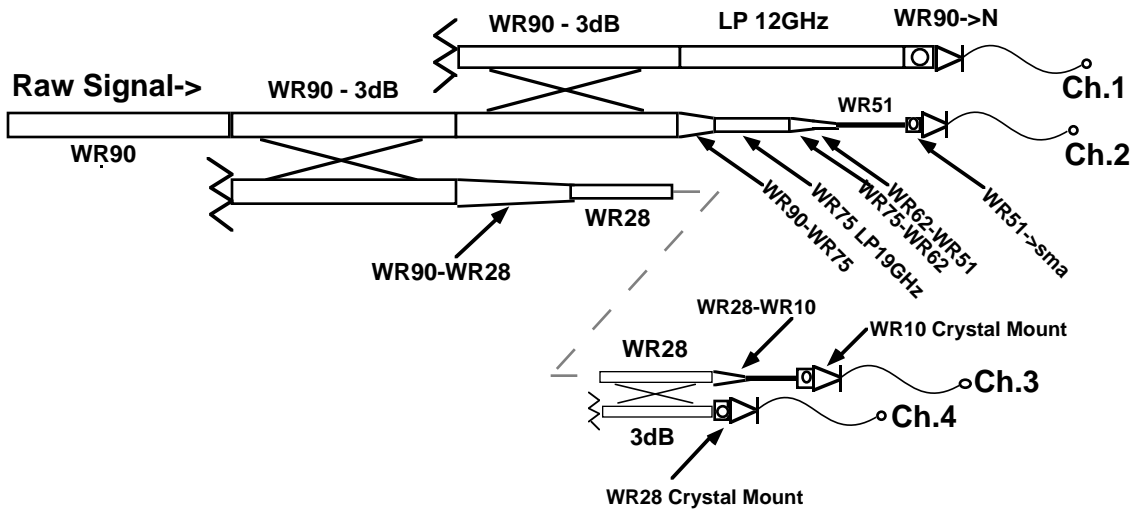
Comments
(1)Use symmetric splitters/tees where possible, for 3dB couplers.
(2)1 N-crystal, 1 sma crystal, 1 ea for WR28, WR10 mount

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Signal Processing for SFF-BLM

Fig. 13. In the Laser Shack, away from the noisy environment of the accelerator housing, the raw microwave signal from the BLM will be split into four channels and rectified on crystal detectors to produce video signals. Ch. 4 gives the greatest sensitivity to bunch length variations under 1mm.

Helpful facts to know in understanding this sketch are that WR10 has a cut-off at 59.0GHz and is resonably well-matched for 75-110GHz. WR28 has a cut-off at 21.1 GHz and is well-matched for 26-40GHz. WR51 has a cut-off at 11.6GHz (it is a relatively rare size of waveguide, in contrast to WR62 and WR42, but we just happen to have it on-site for Ku-band wakefield work). WR90 has a cut-off at 6.56 GHz, typically employed for 8-12 GHz. To appreciate cost issues, note that the WR51,WR62,WR75 and WR90 components are available on-site, thus Ch.'s 1,2,3 come for "free" so to speak.

The phrase "for free" assumes 3 free GADC channels, which is the case at present, and assumes that the current trigger to this GADC employed by SLD is consonant with the BLM signals or the BLM signals with RG-58 inserted for

delays. [confirm] For simultaneous e+,e- BLM acquisition, 2x3 channels would be required, or 2x4 for the 4 channel setup.

Without Ch.4 one has a monitor as functional as other BLM's on the linac, with adequate sensitivity for bunch lengths above 1mm, and 3dB sensitivity for a bunch length change from 0.5mm to 1mm. Note that, as dicussed previously, for channel 3, a WR28-WR90 taper is required. Aerowave Inc. sells such a taper for $450 and this is the base equipment cost for a minimal set-up.

For the W-Band Ch.4, an additional $2000 would be required; this includes $1150 for the crystal detector and mount[9], $450 for the WR28-WR10 taper, $150 for the WR28 EH untuned tee, and $250 for straight WR10. The bulk of the cost for this channel is in the vendor's cost for micromachining of the detector mount assembly (WR10 input, sma output). In case of diode burnout, the diode within the crystal detector can be replaced at the "factory" (Spacek Labs) at a much lower cost (~$200). In the case of diode burnout during operations, it is possible that, by that time (June '97), a spare could be found on-site for temporary use until a replacement arrives. Needless to say, commissioning of this channel would require special attention to the maximum signal level likely to be received, and would begin with plenty of additional attenuation inserted. It appears likely that attenuation could be inserted in the WR90 part of the line, so additional costs due to WR28 and WR10 waveguide fixed attenuators have been omitted. This is not an ideal arrangement, but it appears to be cost effective, and the curves of power versus bunch length indicate that power levels in all channels are within 5dB of eachother.

To help judge the utility of Ch.4, one can compare the response of a 3-channel circuit for integrated power versus bunch length as depicted in Fig. 14, with the response of a 4-channel circuit, as in Fig. 15.
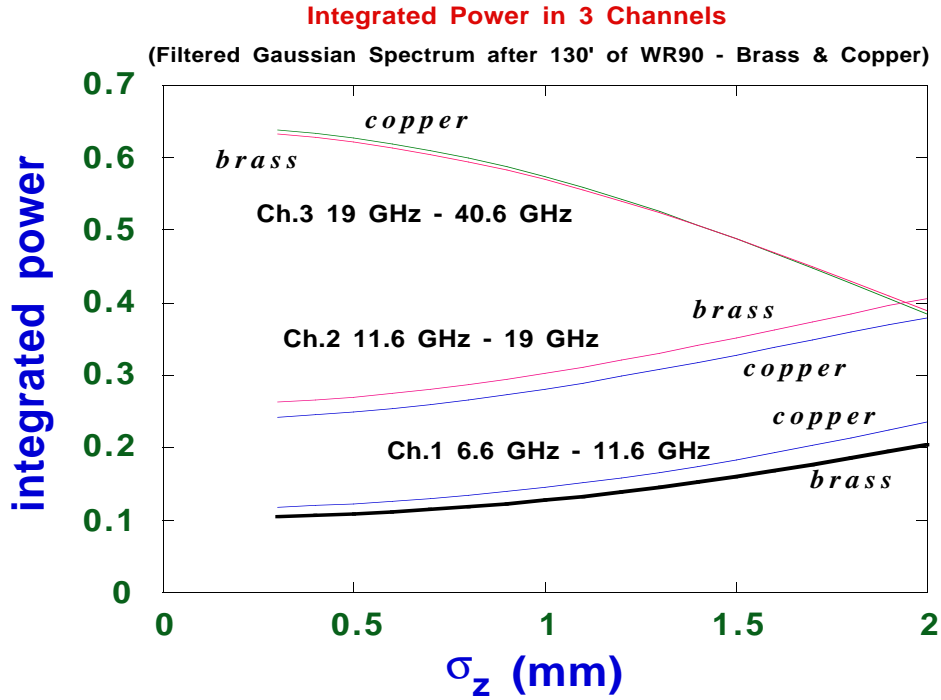
Integrated Power in 3 Channels

(Filtered Gaussian Spectrum after 130' of WR90 - Brass & Copper)

Fig. 14. Comparison of brass and copper networks, for a 3-channel power detection circuit.

Integrated Power in 4 Channels

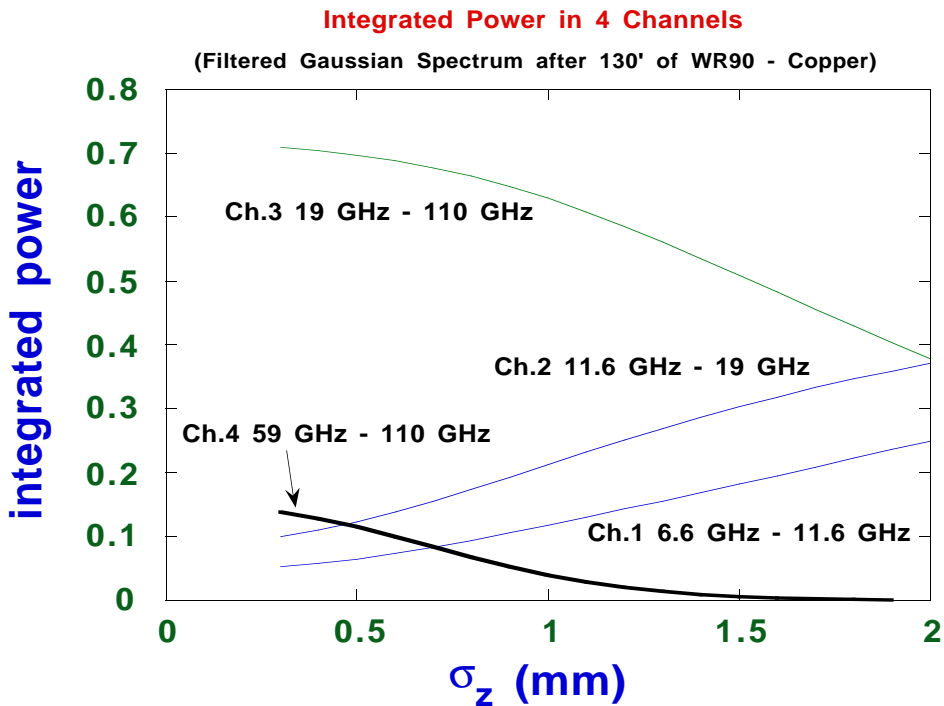**(Filtered Gaussian Spectrum after 130' of WR90 - Copper)**
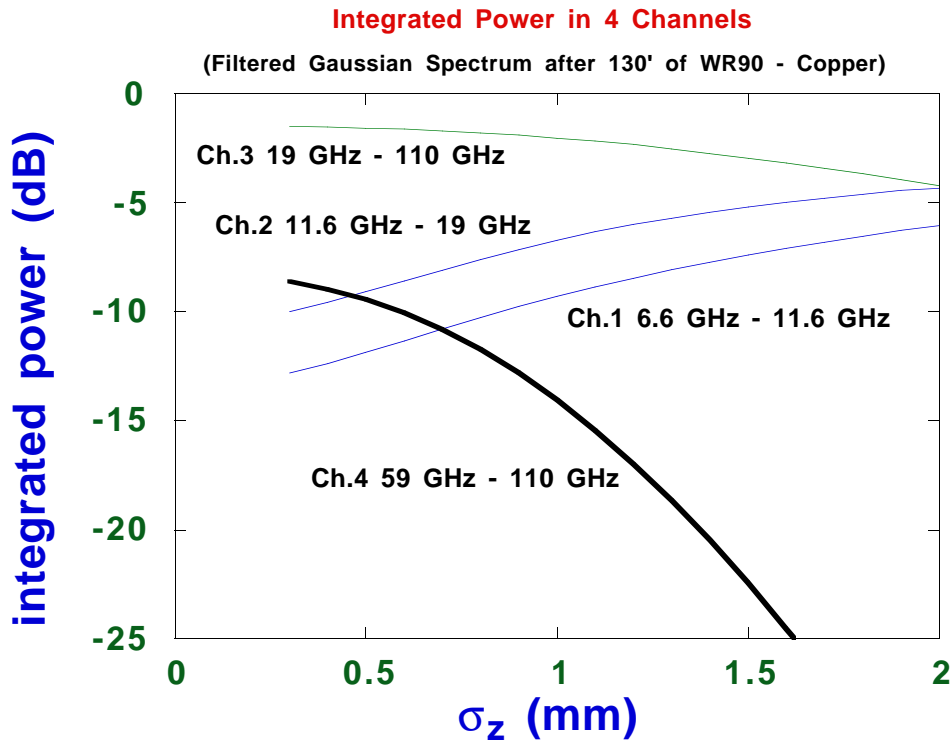
Fig. 15. There appears to be considerable advantage to a fourth, W-Band, channel, for bunch lengths under 1 mm. Channels are normalized to sum to unity.

The advantage of a fourth, W-Band channel becomes still clearer when these results are plotted with power in decibels as in Fig. 16.

Integrated Power in 4 Channels

(Filtered Gaussian Spectrum after 130' of WR90 - Copper)

Fig. 16. A fourth W-Band channel would have a sensitivity of about 5dB (a factor of 3 in power) to a bunch length variation from 0.5mm to 1.0mm. Other channels give a sensitivity of at most 3dB to this bunch length change. Channels are normalized to sum to unity.

Processing into four such channels can be accomplished with waveguide filters and couplers as indicated in Fig. 13. To rely on the 3-channel circuit one needs to decide whether 3dB is adequate sensitivity, in the presence of systematic effects that could tend to mask bunch length variations. Babenko's result for sensitivity to beam position indicates that this may not be a significant systematic. Jitter in charge could be removed "in the software" by normalizing the signal to the square of a toroid readout. A 3-channel circuit would likely be adequate, but not optimal.

[For commissioning purposes, note that crystal detector response must be calibrated and may require polynomial fitting to permit calculation of power. It

could result that the crystal detectors have an index of 2, *i.e.*, are power-detectors, but this should not be assumed.] .

Convolving group delays with the power spectra indicate expected pulsed signal delays in the range of 50ns between Ch.1 and the other channels. Thus at most 30ft of RG58 would suffice to delay Ch.1 into coincidence with the other channels. [provide table from spreadsheet, these are e+ delays only, include e- numbers].

Expected Spectra, Amplitudes, Waveforms, Counts

[Provide expected S_{12} for 10-25GHz debug with frequency synthesizing signal generator.]

[Provide spectra for comparison during debug with spectrum analyzer, beam-on conditions.]

[Provide time-domain waveforms for debug with crystal & scope. Include timings relative to presently used trigger for this GADC. Determine whether we need the BNC unit for gate width adjustment & coordinate with other users of this GADC. Two spare slots for BNS unit needed, confirm available.]

[Estimate GADC counts, & provide attenuators and instructions for use in case of saturation.]

Estimates for Horn Pickup, v0.0

The simplest estimate for the system starts from the far field radiation pattern of a dipole, corresponding to the image wall-current density displaced by the dielectric. An upper bound on the power spectrum coupled into the WR90 is then just the fraction intercepted by the geometric cross-section of the horn. This estimate errs by using far field expressions, taking source size small compared to a wavelength, neglecting reflections, neglecting the perturbing effect of the horn and the beam pipe on the radiation pattern, and neglecting reflections from the horn, or, particularly, failing to account for coupling of the radiation into each and every waveguide mode above cutoff. We can revisit these approximations later.

Taking a bunch charge Q_b, Gaussian bunch spectrum, with rms bunch lenth σ_t, net energy loss at all frequencies is, $E_l=k_lQ_b{}^2$, with loss factor

$$k_l \approx \frac{Z_0}{12\pi^{3/2}\sigma_t}.$$

for $L_g \gg \sigma_t$. This corresponds to 2V/pC for a 1mm bunch, roughly the equivalent of two S-Band accelerator cells (i.e. 2% of one 10' section). According to this estimate, a 5nC beam radiates 50μJ. Since this occurs in a transit time of 33ps (1cm gap), the peak power radiated into all angles is ~1 MW. If the horn dimensions are $W \times H$ (W in the E-direction), and the horn aperture is a distance L_h from the beam axis, then the angular half-apertures are ϕ in the x-y plane, and θ from the beam axis z, where

$$\tan\phi = \frac{H}{2L_h},$$
$$\tan\theta = \frac{W}{2L_h}.$$

In terms of these angles, the fraction of solid angle occupied by the horn is

$$f_h = \frac{3}{2\pi}\phi_h \sin\theta_h \left(1-\frac{1}{3}\sin^2\theta_h\right).$$

For example, if we dispense with the horn and simply prop WR90 against the dielectric liner,
then W=1.1cm, H=2.2cm, L_h=1.9cm (see Fig.1) and f_h=0.068. Energy deposited in the waveguide is then less than 3μJ (the entire portion of the spectrum below cutoff could be subtracted out of this and provide an improved upper bound). In

propagating through the guide and the splitter/filter setup, this energy is divided among the channels as indicated in Fig. 15 (where signals are normalized to sum to 1). Due to dispersion in the guide, as indicated in Fig. 11, pulses upstairs will be spread out over about ~1 ns, corresponding to a total peak power (sum of 4 channels) a bit less than 1 kW. This is plenty of signal and will require attenuation. Since we haven't yet decided the particulars of the geometry (it will depend on what we can find in the way of a WR90 horn or whether we just use straight guide), it is a premature to engage in more detailed calculations of the precise coupling. In any case, if precise calibration is required, the best method is bench test with a pulsed wire, using a scaled (lower frequency, longer pulse) geometry.

It may be helpful to record some notes on modes, and multimode effects, as well as pulse shapes. First, note that even though we are only interested in power detection, guide length variations due to temperature variations may be observable. We don't have enough experience with such highly overmoded guide to be confident one way or the other; adding to the concern is the fact that 16' of the waveguide will be outdoors. The problem is that our crystal detector mounts will be looking into the vector sum of all modes at the pickup point. Thus the phase of one mode with respect to another enters into the result. This phase depends on the waveguide length. It will be interesting to see if diurnal variations are noticeable; however, probably one could not discern whether to attribute these results to actual diurnal variations in beam conditions, or to the network. If this becomes an issue, we could provide a setup for in situ waveguide length measurement via phase comparison of a test signal injected upstairs, with its reflection from the open horn downstairs. Such a setup, depicted in Fig. 17, could be mounted in such a way as to permit bunch length signal acquisition to take place simultaneously with acqusition of the network monitor signal.
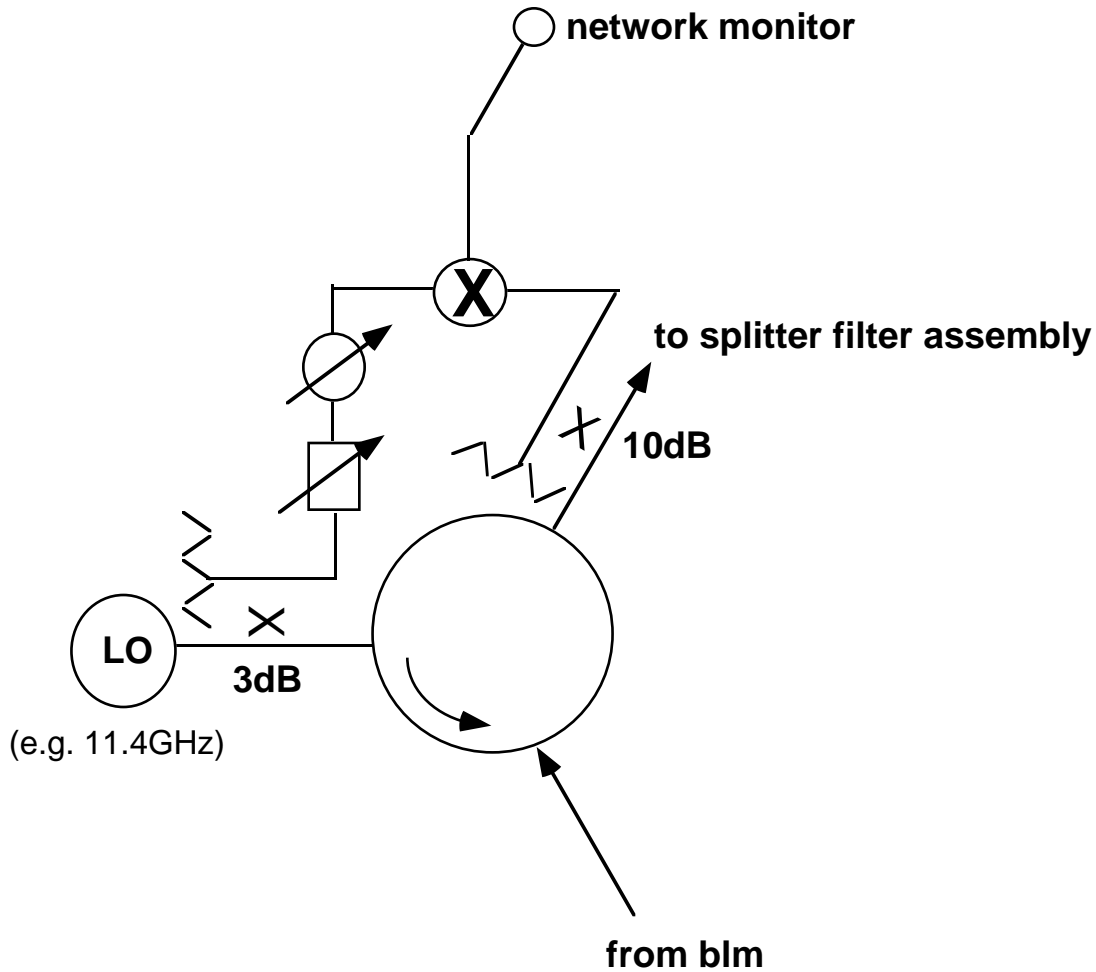
Setup for Monitor of Length Variations in WR90 Network, with Simultaneous Operation of BLM

Fig. 17. It may be of interest to monitor the waveguide network for length variations. LO would operate CW, and monitor signal would be gated between beams. Meanwhile, beam induced signals from downstairs pass into the previously described splitter/filter assembly, with some additional frequency dependent insertion loss due to the circulator. Should add a notch filter to Ch.1 to remove the LO signal from Ch.1 if signal level requires it.

This monitor is still subject to any drifts in the LO frequency. Roughly ppm of LO frequency drift will limit waveguide temperature drift resolution by comparison with 17ppm/$^\circ$C for copper for temperature variations uniform along the guide. Or, if say 16' of waveguide out of 130' varies only, then compare to

17ppm/°Cx16/130=2ppm/°C. If outdoor temperature variations are 20°C, one would need an LO stable compared to 40ppm to discern this. Since the LO itself can be held to constant temperature within 1°C, this is not hard to achieve. This could be much ado about nothing, however, as one should note that if we were working in fundamental mode guide, this would not be an issue at all for our power detection setup.

Next we enumerate the modes above cut-off up to 110GHz, and their attenuations in 130' of WR90 (copper)

Considerations for e- Pickup

[Timing, Cross-talk, charge-up effects]

Options are

(1)simultaneous acquisition of e- and e+ signals

~~(2) acquisition of one or the other at a time, requiring a dBedit to change trigger timing & coordination with other users of the GADC~~

We'll go with option (1). Check cross-talk by dumping one beam or another and observing changes in waveforms.

Clearly (1) is preferable. This requires 2 x 4 GADC channels [check availablility] for a 4-channel setup. [Get exact length from SLD IP to BLM. ~~Note delay cable lengths for the e- signal,~~ note lose 3dB on all signals for simultaneous acquisition.] Will try to avoid delay cable, see comments below under "Signal Processing, Timing, Triggers, Etc.**".**

Effects Due to Satellite Bunch , Muons, Background, Halo, Beam Offset

[Enumerate, quantify, indicate waveforms & amplitudes that might be expected upstairs. if collimators are moved out, halo appears, radial distribution changes -- what is the result]

Signal Processing, Timing, Triggers, Etc.

At present the plan is to process the raw microwave signal as follows. Attenuation and filtering will be determined empirically during commissioning. Equipment required will be the red rf toolbox, with spectrum analyzer & scope. Following attenuation and filtering, the signal will be rectified on a crystal detector. Spare attenuators and a spare crystal should be stored adjacent to this setup, with instructions for replacement in the case of crystal burnout (add 20dB, replace crystal, if unsatisfactory signal, replace 20dB attenuator with 10dB attenuator, if still unsatisfactory, page commissioner).

The video output of the crystal detector should appear roughly as depicted in Fig. xx for the four cases, $\sigma_z=0.5$mm and $\sigma_z=1$mm, at $N_b=2.5 \times 10^{10}$, and $N_b=4 \times 10^{10}$. [replace with polaroids when commissioned] ~~This output will go to a LeCroy 2249A (12 channel, single trigger) GADC, unit no. ____, channel ____, in crate ____, for micro ____. Trigger to this GADC is ____. [May need to add delay --- this needs to be checked and sorted out].~~

It is important to note that this raw signal must be normalized by charge in order to extract a bunch length analog. This will be performed in software [add details].

Comments added 10/2/96 after further coordination with Mike Woods, inspection of the ventilation hut, and discussion of signal logistics in the Laser Shack:

Signals will go to FB69, crate 09. SLD has a spare LeCroy 2249A (12 channel, 1 trigger) and a BNC 8010 (takes trigger, produces two adjustable width, delay, height triggers) that we can use, they are in a cabinet there. (Won't be using the existing 2249W in slot 15, with 4 channels free, as it is not

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necessary, and it is unlikely anyway that the trigger for that unit is consonant with our trigger needs.) Spare slots in this crate are 3,4,5,6,7,8,9,10,13,14,16,17. Mike Woods will patch in a trigger signal for us (all his STB 233-001-M1 channels are used) (trigger crate,slot and channel TBA). He will check to see if an additional 2249A is available (if so we need no delay cable for e- signal, separate triggers can then be generated via the 8010 for the e- signal and the e+ signal). Bldg. 764 could use a lab bench, we'll look into that; some portion of that bench would be a good place to setup waveguide split/filter assembly for purposes of debugging. Once operational the assembly could be moved out of the way (onto a shelf on a rack for example). WR90 should avoid the laser room itself, come in under the floor of the trailer, and up through a new hole (we will make) in the floor, under a rack, position to be chosen later. [forgot to check on any pulsed noise typical of this room during laser operations]

Inpsected ventilation hut. Nixed the idea of taking the roof off, not necessary. Max length of straight WR90 can fit in the hatch and into the penetration is >6' and <7'. Avoid bumping the laser pipe assembly during WR90 installation.

Estimate of Signal Levels with Horn Pickup

Options Not Employed

For the record it may be helpful to note other options for the upgrade of the SFF-BLM, and the reasons they are not employed.

Option 1 - Add additional lead to the exisiting setup

Problems: This still would not permit study of the raw signal, would not permit revision to or repair of detector apparatus during collisions, could still end up suffering from electromagnetic pulsed noise or ionizing radiation induced signals

Option 2 - Move setup to the Compton Alcove

Problems: The alcove is 20' down the beamline, and 6' across the aisle and thus very close, making this an interesting option. However this option has all the problems of Option 1, with the possible exception of a much reduced ionizing radiation background.

Option 3 - Employ a high frequency amplifier in the new setup

Problem: This is actually a fine idea. However, it appears as yet to be unnecessary. In addition, a 35GHz amplifier will cost about $5000, which is enough that one would prefer not to buy one unless some tangible benefit could be forseen. In principle, this could later become of interest for some as yet unforseen reason (*e.g.*, lower N_b operation somewhere in the complex, LCLS, FFTB applications, etc.).

Option 4 -VXI Acquisition of Spectra

This option may in principle be implemented later, upstairs, without modification to the waveguide network. [check on possibility of vxi crate etc in the vicinity] Problems: Maximum frequency is limited by spectrum analyzers on-hand, 26.5 GHz (unless we block downconvert or lease HP's 50GHz model), spectra acquired over several shots (systematics due to jitter). Advantages: software already written for this type of acquisition (M. Seidel), if jitter is not an issue, such spectra could provide much more detailed information on the bunch distribution than a 3 or 4 channel set-up.

Acknowledgements

Thanks to Bob Siemann and Al Menegat for helpful comments.

References

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[3] A. Kulikov, *et al.*, "A Monitor of Single Bunch Lengths", SLAC internal note, April 1986 (unpublished).

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[5] L. Merminga, *et al.*, "Bunch Length Measurement in the Linac", SLC Experimental Report 116, January 1990 (unpublished).

[6] F. Zimmermann, "Simulation Studies of the SLC Bunch Compressor", SLAC-PUB-7138, EPAC '96

[7] K.L.F. Bane, "Simulating Longitudinal Phase Space in the SLC from the Damping Rings to the Final Focus", SLAC/AP-80 (Sept. 1990).

[8] For this and other waveguide formulae, see R.E. Collin, **Foundations for Microwave Engineering** (McGraw-Hill, Singapore, 1966).

[9] Spacek Model No. DW-2 WR10 broadband detector specs are 500mV/mW typical, with ±1dB flatness, output to sma female. It is likely that we could check these specs on the bench, as ARDB is developing the capability to perform W-Band measurements.