Beam Installation of the BB1-2 Cavity: Waveguide Adjustment and Cavity Positioning

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I. Introduction

It is important to place RF cavities in a collider in proper position and feed them with RF power with appropriate phase in order to i) keep the amplitude of accelerating voltage maximal and equal for electrons and positrons and to ii) maintain the interaction point (IP) at the right place inside a detector.

Four normal conducting copper 5 cell RF (NRF) cavities in CESR are grouped in pairs and fed by two klystrons (one klystron per pair of cavities) through the WR1800 waveguide. A magic T is used to evenly split RF power between the two cavities in a pair in the present configuration. Phasing between cavities in a pair is achieved by choosing the correct lengths of the feeding waveguides after the magic T. Phasing between cavity pairs is provided by electronic means at low power level.

In order to keep the RF voltage the same for electron and positron beams i) the distances between cavities in the ring must be equal to integer numbers of half RF wavelength, ii) difference in waveguide lengths after the splitter must be equal to integer number of half RF wavelength in the waveguide and has the same (or opposite, depending on the cavity input couplers relative polarization) parity as the number for the cavities in a pair plus some extra length to correct phase introduced by the splitter, and iii) phase between East and West RF should be adjusted to maximize the amplitude of RF voltage seen by particles. In order to maintain the IP one must position the cavity pairs on the distance equal to the integer number of half RF wavelengths from the point defined by the machine optics.

The problem is relatively simple when one has identical cavities and it was successfully accomplished in CESR on several occasions in the past. The sequence of installation in this case is: i) install cavities in the ring according to survey; ii) install waveguides and adjust their lengths using shims; iii) verify installation by measuring RF forward and reflected powers with and without beam (electron, then positron) and adjust waveguides and /or move cavities if necessary. The procedure of deducing the errors in cavities spacing and waveguide phasing was described by D. Morse in his unpublished note [1]. We enclose his note as an appendix to this paper for the reader's convenience.

The situation will be as simple as the present one with four superconducting RF (SRF) cavities in the ring. The current plan is to install only one SRF B-cell cavity, namely BB1-2, by replacing E2 NRF cavity for long term operation. That is why the installation process becomes more complicated. In this paper we consider issues related to the installation of the SRF cavities. Some reference numbers for the CESR RF are listed in Table 1.

II. RF Power Splitting

It would be much more convenient from the SRF cavity testing point of view (both, installation and operationally) to use a separate klystron to feed the cavity, but for different reasons, which are out of scope of this paper, it was decided to use an RF splitter and supply the SRF cavity with power in parallel with the E1 NRF cavity.

Design value of the SRF accelerating gradient is 6 MV/m (or 1.8 MV per cell) for the CESR Phase III Luminosity Upgrade Plan [3]. So, though SRF cavities should be capable to operate at as high as 10 MV/m accelerating gradient, it is desirable to keep gradients in the vicinity of 6 MV/m during the long term operation.

Table 1. CESR RF Related Reference Numbers

RF frequency [2]	499.765 MHz
RF wavelength, λ	59.9867 cm or 23.6168"
WR1800 wavelength, Λ	31.2913"
NRF:	
Total operating NRF voltage [2]	5 MV (6 MV available)
R/Q (per cell)	256 Ohm
Unloaded quality factor, Q_o	3.17×10^4
Coupling coefficient, β_o	5.0
No. of cavities	4
No. of cells per cavity	5
SRF:	
Accelerating gradient / voltage per cell	6 MV/m / 1.8 MV (CESR III requirement) 10 MV/m / 3 MV (should be available)
R/Q (per cell)	89 Ohm
Unloaded quality factor, Q_o	10^9
Coupling coefficient, β_o	5×10^3
No. of cavities	4 (CESR Phase III)
No. of cells per cavity	1

The present CESR RF control system was designed so that one of the cavities in a pair is a "master" and the other one is a "slave". This means that the control system uses a signal from an RF field level detector of the master cavity as an input for an amplitude feedback loop to keep the amplitude of the RF voltage constant and assumes that the cavities are identical and that therefore the slave cavity voltage is the same as the master cavity voltage. The latter postulate is not true anymore when we replace the E2 NRF cavity by the SRF BB1-2 cavity. To maintain the same level of the RF field the SRF cavity requires much less incident RF power without beam present. According to formulae

$$P_{wall} = \frac{(V_{acc} / N_{cell})^2}{R/Q \cdot Q_o}$$

$$P_{inc} = \frac{(1+\beta)^2}{4\beta} P_{wall} N_{cell}$$

to maintain the peak RF voltage at 1.5 MV level, one needs to provide forward power of approximately 100 kW for the NRF cavity , but only about 30 kW for the SRF cavity. The numbers will converge with increasing beam current, but even at 0.6 A total beam current we have forward power of 250 kW for the NRF case versus 210 kW for the SRF (see Figure 1).

These numbers mean that we can not use a 3 dB RF power splitter (magic T or 3 dB hybrid) if we want to keep both NRF and SRF voltages reasonably even. Calculations were performed to find splitting ratio which will be suitable for the Phase III requirements. Currently NRF cavities operate at the total voltage of 5 MV or 1.25 MV per cavity [2]. If we choose a 4 dB splitter and designate master status to the SRF cavity, then by keeping the SRF voltage at 1.5 MV we get beam current dependence of the NRF voltage shown in Figure 2. Thus, we see that for reasonably wide current range the total E1 + SRF voltage is in desirable range of about 2.5 MV. The 4 dB hybrid has been purchased and is in storage now.

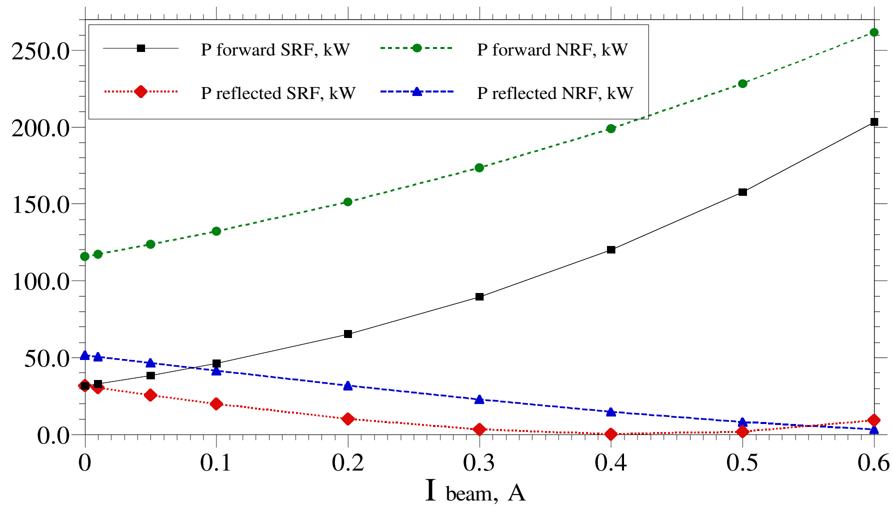


Figure 1. RF forward and reflected powers as functions of beam current for the CESR NRF and SRF cavities (at 1.5 MV per cavity).

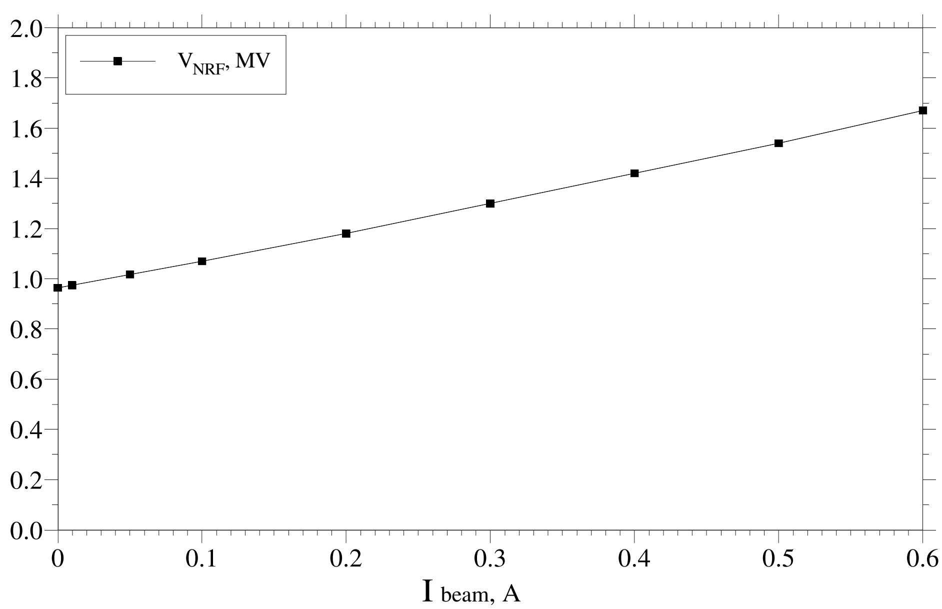


Figure 2. Dependence of the NRF voltage on beam current (SRF voltage at 1.5 MV, SRF cavity is master, NRF cavity is slave).

III. Waveguide Installation

A. Present configuration
Presently one waveguide is coming out of the LOE transmitter area through the hole in to the Adit where RF power splitting takes place via magic T. The waveguide configuration is presented in Figures 3 and 4. There is an elbow for the waveguide length adjustment.

B. Difference between magic T and 3 dB hybrid coupler
As it is known from the literature (see for example [4]), a scattering matrix for magic T is

$$S = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & -1 \\ 1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \end{pmatrix}$$

That is, if we use port 4, or E arm, (see Figure 5) as an input from the klystron, two output signals at ports 1 and 2 are out of phase. As we will see later the distance between two NRF cavities is equal to 7.5 of RF wavelength. That means that the difference in the lengths of two waveguide arms must be equal to integer number of the RF wavelength in the WR1800 waveguide. We get this difference to be equal to approximately 7 Λ from Figures 3 and 4.

On the other hand a scattering matrix for 3 dB hybrid is

$$S = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 1 & 0 & j \\ 1 & 0 & j & 0 \\ 0 & j & 0 & 1 \\ j & 0 & 1 & 0 \end{pmatrix}$$

That is, if we use port 3 as an input from the klystron, the output signals at ports 2 and 4 have a phase difference of 90^o. That means that difference in the waveguide lengths must be equal to an integer number of wavelengths plus 3/4 Λ. Phase relationships for the 4 dB coupler are the same.

C. Intermediate configuration
As far as NRF and SRF cavities are not identical, we can only make a rough guess about what should be the difference in the lengths of the waveguide arms for these cavities. That is why some intermediate step seems to be necessary. We propose to replace the magic T with 3 dB hybrid and adjust waveguide length and RF phase while there are still two NRF cavities in the ring. Then we will be sure that we established correct RF phase for the East transmitter and waveguide length for the E1 cavity.

D. SRF + NRF configuration
During this step we replace the E2 NRF cavity with the SRF cavity and 3 dB hybrid with 4 dB hybrid. The waveguide length for the SRF is still unknown, but we should be able to define it by low level network analyzer RF phase measurements and then make a fine adjustment after beam loading measurements [1].

If for some reason step C is not possible, then we replace the magic T by the 4 dB hybrid during BB1-2 installation, perform RF phase measurements, and then adjust cavity phasing/positions after beam loading measurements. New waveguide configuration is shown in Figures 6 and 7.

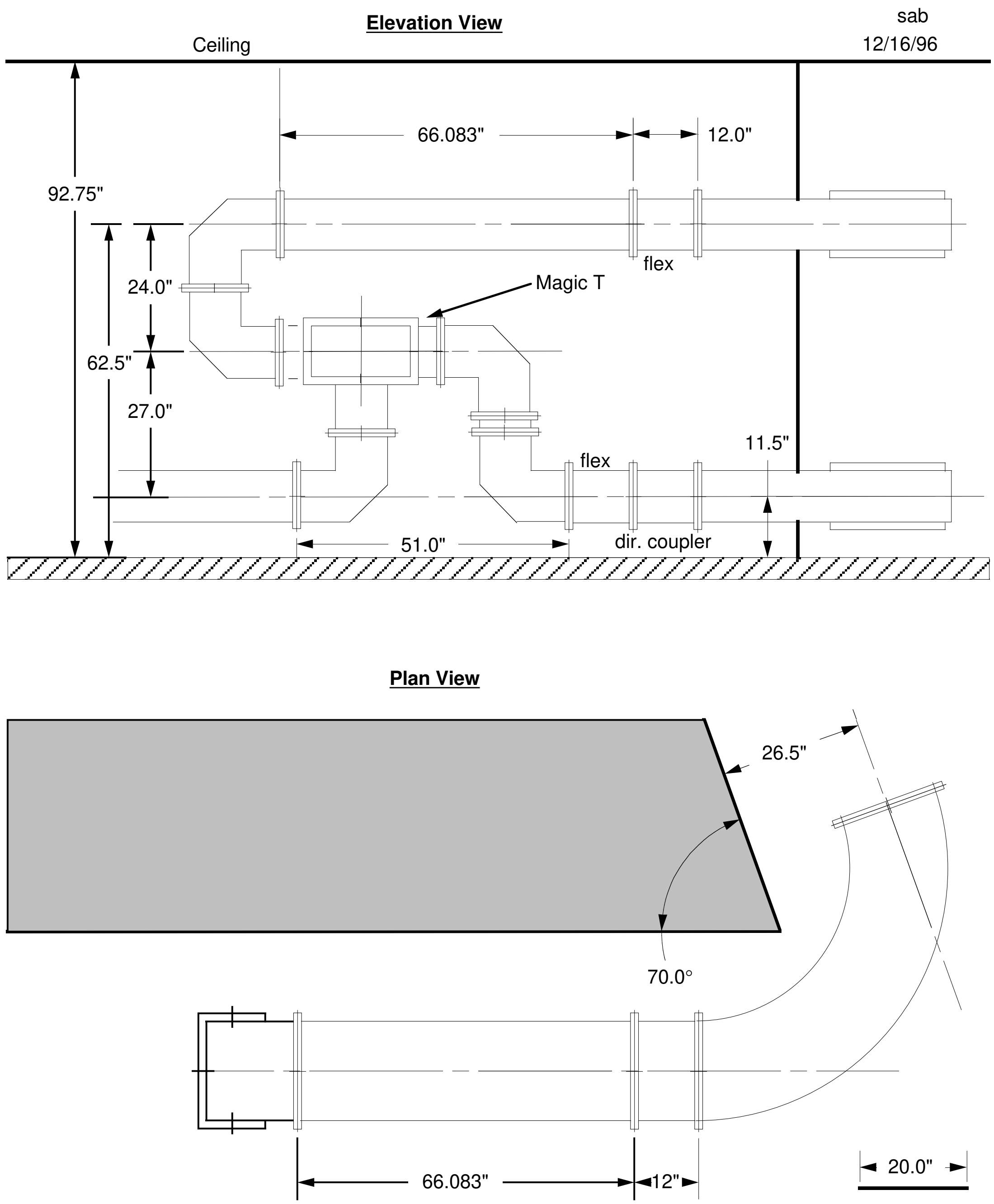


Figure 3. East flare waveguide run: Adit.

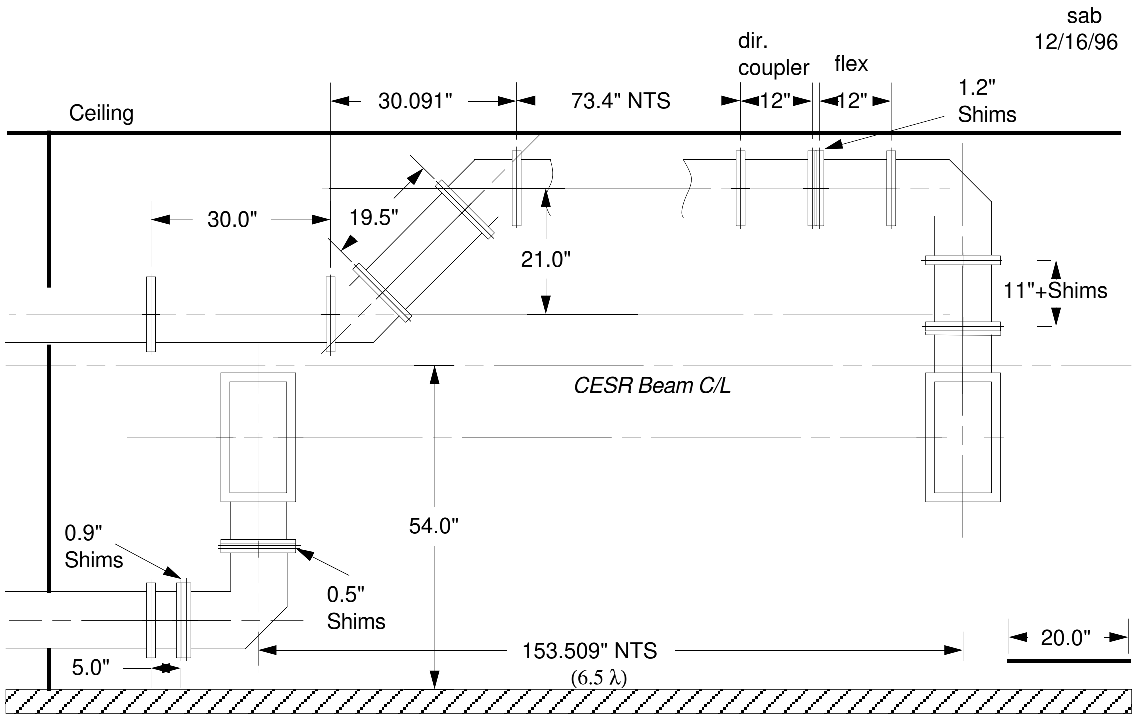


Figure 4. East flare waveguide run: CESR tunnel.

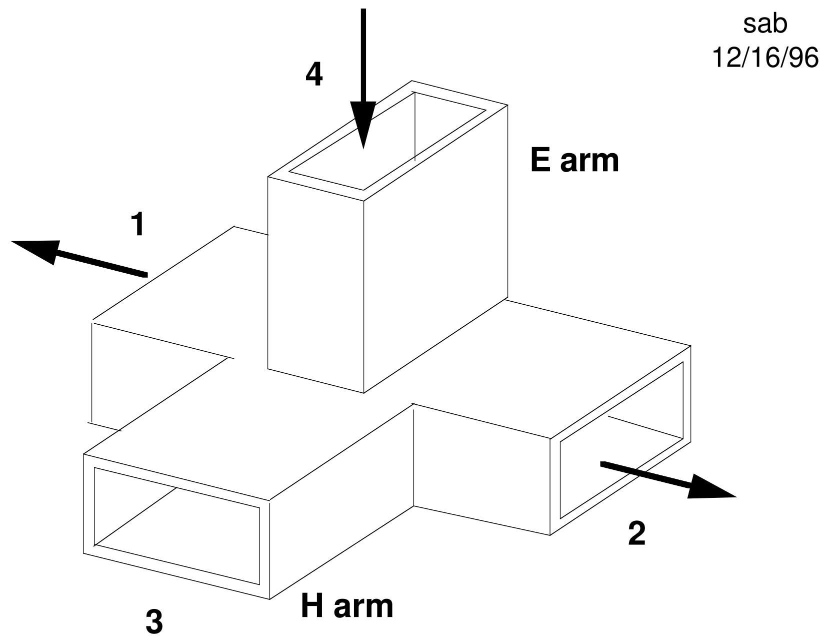
E. Final configuration

Finally, with two SRF cavities per pair, we will replace 4 dB hybrid with magic T or 3 dB hybrid. The main advantage of the magic T is more compact assembly and better amplitude balance between the output arms.

IV. Cavity Positioning

Results of recent survey of the East NRF cavity positions made by Scott Chapman [5] are in a very good agreement with cavity positions deduced from the RF power measurements with stored beam [6]. The results of Machine studies [6] are reported in the next section. We enclose summary and some analysis written by Joe Kirchgessner [7] as an Appendix B. We seem to be confident now that we know NRF cavities positions with precision good enough to install the BB1-2 cavity in place within limits provided by sliding joints. Some numbers related to cavities positions are given in Table 2. Note that WRF3 is W1 cavity and WRF4 is W2 cavity according to the RF group notation. Figure 8 illustrates relative cavity positions in the East flare for three different cases.

We should briefly mention the other possible method of determining cavity phase/position errors, namely, measuring the frequency of dipole synchrotron oscillations *(f_s)* at low beam current. With this method i) by maximizing f_s one can eliminate phasing errors; ii) non equal frequencies for electrons and positrons indicate an error in cavity positions. Though this method is not as straightforward in calculating those errors as RF power measurements, it can be useful when storing of reasonably high (for RF power measurements) beam current is not possible or as an indicator of phasing/positioning errors.



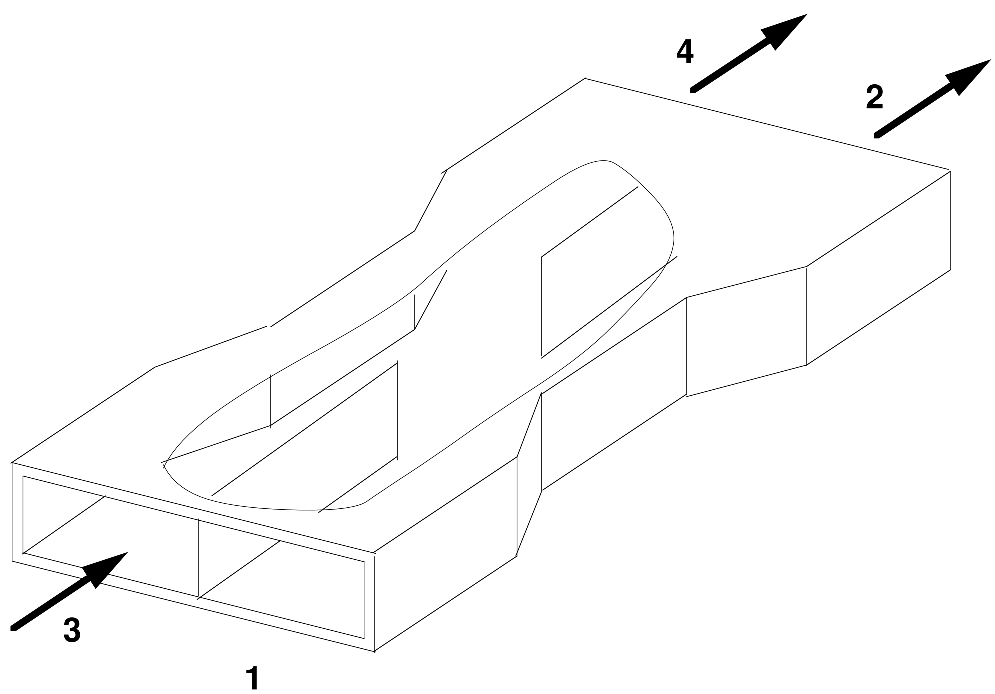


Figure 5. Outline drawings of a conventional magic T and a 3 dB hybrid coupler.

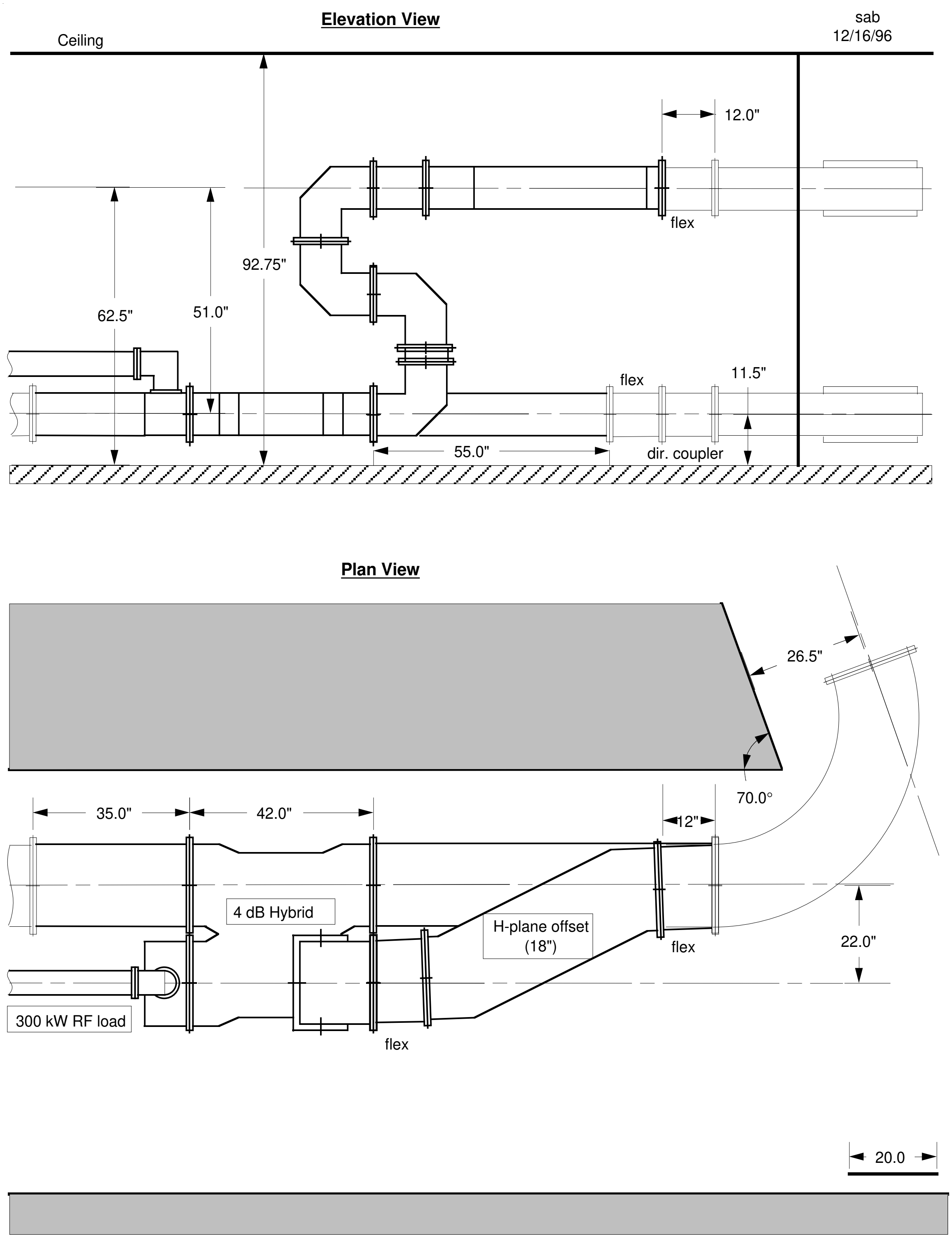


Figure 6. East flare waveguide run with hybrid coupler: Adit.

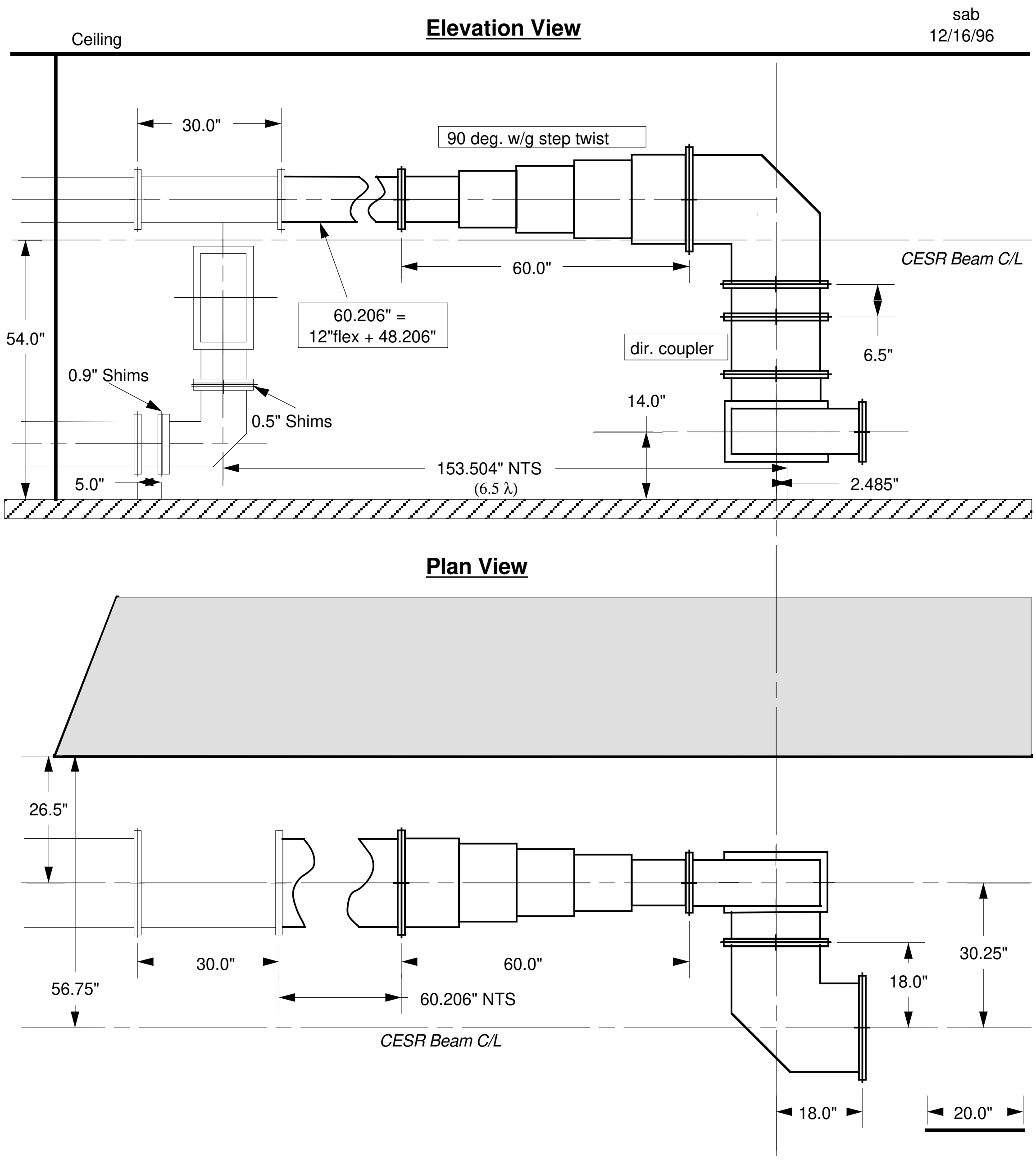


Figure 7. East flare waveguide run with hybrid coupler: CESR tunnel.

Table 2. CESR NRF and SRF cavities positions related numbers.

	Distance m	Distance inches	λ/2's
ERF1 c/l to ERF2 c/l	3.899	153.509"	13
ERF1 c/l to ESRF2 c/l	3.299	129.892"	11
ERF1 c/l to vertex	49.189	1936.577"	164
ERF2 c/l to vertex	45.290	1783.068"	151
WRF3 c/l to vertex	45.290	1783.068"	151
WRF4 c/l to vertex	49.189	1936.577"	164
ESRF1 c/l to vertex	48.589	1912.960"	162
ESRF2 c/l to vertex	45.890	1806.685"	153
WSRF3 c/l to vertex	44.690	1759.451"	149
WSRF4 c/l to vertex	47.389	1865.727"	158

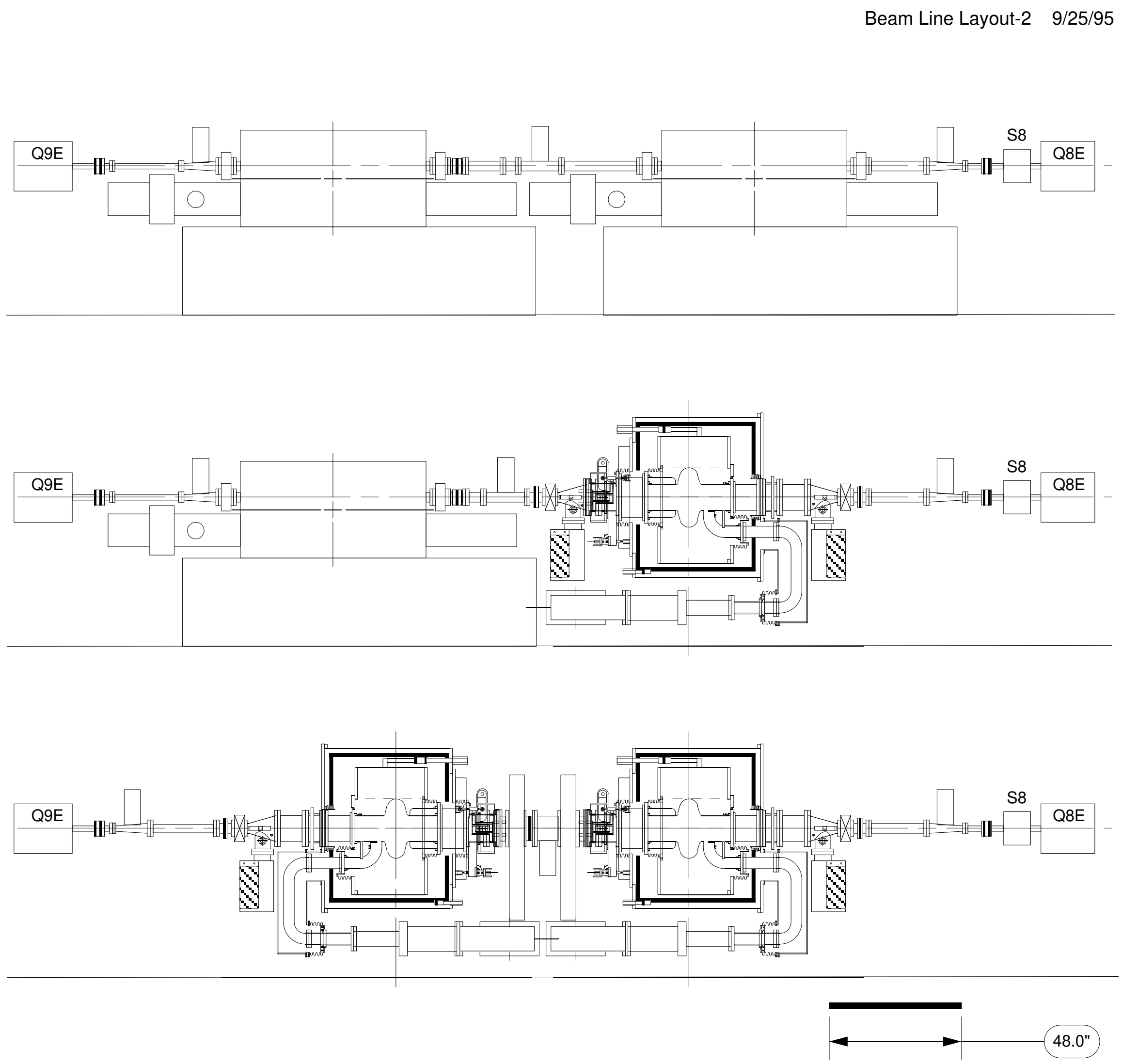


Figure 8. Relative cavity positions in the East flare.

V. Machine Studies of March 6, 1996 [6]

These Machine studies were dedicated to the RF power measurements needed for the RF cavity spacing and phasing calculations [1]. We used a standard CESR DTP program to acquire measured data. The DTP control file name is `RF_PHASE_SPACE.CTL`. The parameters measured and recorded in data files are the time, the total current measured by CERN current monitor, the electron and positron currents, the reflected and forward power for each cavity measured by RF power meters, and the RF field level in each cavity measured by crystal detector.

At first we recorded a zero offset of all measured quantities into the file `ZERO_3_6_96.16-16`. Then we calibrated crystal detectors by measuring RF powers without presence of the beam in the machine (file `RF_NO_BEAM_3_6_96.16-18`). One can find calibration curves in Appendix C. And finally we performed measurements with reasonably high beam current: at first with 200 mA of electrons then with 193 mA of positron beam. The results are stored in the files `ELECT_3_6_96.16-49` and `POS_3_6_96.16-53` correspondingly. All data files are located in the directory `USER$DISK:[CESR.MS.RFCAV]` on CESR24.

In our calculations we used measured values of the shunt impedances: 41.2 MOhm (W1), 31.6 MOhm (W2), 35 MOhm (E1 and E2). Table 3 lists some massaged data relevant to the cavity spacing and phasing calculation. The net results of the Machine studies measurements are that 1) the E2 cavity has an offset of about 0.48 cm in its position in north direction and 2) the West cavities have relative phase error of about 3.24^o which may indicate necessity to slightly adjust the length of the waveguide.

VI. Conclusion

Some problems related to the beam installation of the SRF cavity, BB1-2, in CESR were addressed in this paper. We hope that this note will serve as a reference for the installation of the BB1-2 cavity and as a guide for all subsequent installations.

Table 3. Data for the spacing and phasing calculations.

Cavity	$I\ e^-$ mA	$I\ e^+$ mA	P_{refl} kW	$P_f - P_r$ kW	Field kW	P_{diss} kW	P_{beam} kW	V_a MV	V MV	V_a/V	α deg.
W1	200.1		21.95	125.9	54.0	51.41	74.54	.3725	1.455	.2560	75.17
		193.5	24.45	118.5	54.0	51.41	67.04	.3465	1.455	.2381	76.23
W2	200.1		22.52	136.1	71.2	76.21	59.87	.2992	1.552	.1928	78.88
		193.5	22.59	130.1	68.8	73.69	56.42	.2916	1.526	.1911	78.98
E1	200.1		15.20	133.1	82.0	69.82	63.28	.3162	1.563	.2023	78.33
		193.5	18.74	120.5	82.0	69.82	50.64	.2617	1.563	.1674	80.36
E2	200.1		26.26	127.7	85.7	79.68	48.06	.2402	1.670	.1438	81.73
		193.5	15.52	129.0	72.2	67.21	61.77	.3193	1.534	.2082	77.98

VII. References

1. D. Morse. "Cavity Spacing and Phasing Measurements," Note of 3/11/93, unpublished, also, Appendix A.
2. CESR Parameters. http://w4.lns.cornell.edu/public/CESR/info/cesrinfo.html
3. S. Belomestnykh, et al. "Superconducting RF System for the CESR Luminosity Upgrade: Design, Status, and Plans," *Proceedings of the Fifth European Particle Accelerator Conference*, Barcelona, Spain, June 1996, Vol. 3, pp. 2100-2102.
4. R. K. Cooper. "High Power RF Transmission," *CERN Accelerator School: RF Engineering for Particle Accelerators,* Oxford, UK, April 1991, CERN 92-03, Vol. 1, pp. 245-268.
5. S. Chapman. Private communication.
6. S. Belomestnykh, R. Kaplan. Machine studies of March 6, 1996.
7. J. Kirchgessner. "Final Look at East Cavity Positions," Minutes of the SRF Meeting, March 20, 1996, *Report SRFM 032096*, Laboratory of Nuclear Studies, Cornell University, Ithaca, NY, also, Appendix B.

VIII. Appendix A

Cavity Spacing and Phasing Measurements

by D. Morse

IX. Appendix B
<u>Final Look at East Cavity Positions</u> 3/13/96, J. Kirchgessner

It seem that the final word is in that would allow us to locate the ESRF2 relative to the ERF2 cavity and to Q8E. We can also now specify the length of the SRF cavity beam line spool piece (6055-026) and the length of the "between the cavities" beam tube and pumpout section so that it can be designed and made (so called Dave Sagan {DS} piece).

As seen before from Scott's measurements;

• ERF1 c/l to ERF2 c/l = 153.320"
• ERF2 c/l to north face of SE DS piece = 41.704"
• ERF2 c/l to north face of Q8E = 103.998"
• ERF1 length, flange face to flange face = 70.891"

ERF1 c/l to ERF2 c/l should be 153.509" (13 x 11.808354)
So they are too close together by 0.188" (4.78 mm)

Beam measurements showed the distance between the electrical center of ERF1 and the electrical center of ERF2 to be close by 4.8 mm in almost perfect agreement with the physical c/l spacing. In other words it seems that the electrical center of the cavities lies at the mechanical center.

Further measurements show that ERF1 is in the correct location and ERF2 is too far north by .188". More details of these measurements are given in SRFM031396 and will probably be written up in even more detail by Sergey and Roger.

So if the ERF2 were moved to the correct location then the numbers should be:

•• ERF1 c/l to ERF2 c/l = 153.508"
•• ERF2 c/l to north face of SE DS piece = 41.516"
•• ERF2 c/l to north face of Q8E = 103.810"
•• ERF1 length, flange face to flange face = 70.891" (the same)

Since the ESRF2 cavity c/l is to be 2 x 11.808354" further north than the ERF2 cavity then,

••• ERF1 c/l to ESRF2 c/l = 129.892"
••• ESRF2 c/l to N face of SE DS piece = 65.133"
••• ESRF2 c/l to N face of Q8E = 127.427"
••• ERF1 S flange face to N face of SE DS piece=
153.508+41.516-70.891/2=159.579", so
••• ESRF2 c/l to ERF1 S flange face = 159.579-65.133 = 94.446"

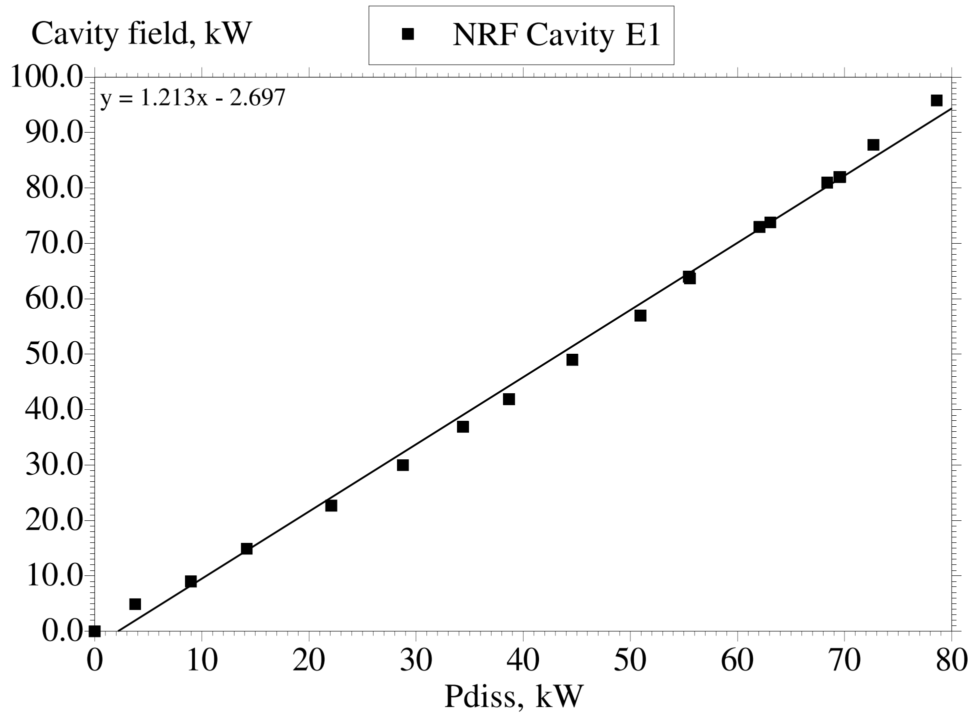
Since the distance from the ESRF2 c/l to the north face of SE DS piece = 65.133" and this includes the spool piece +54.300" (the other parts), then the spool piece length = <u>10.833"</u>

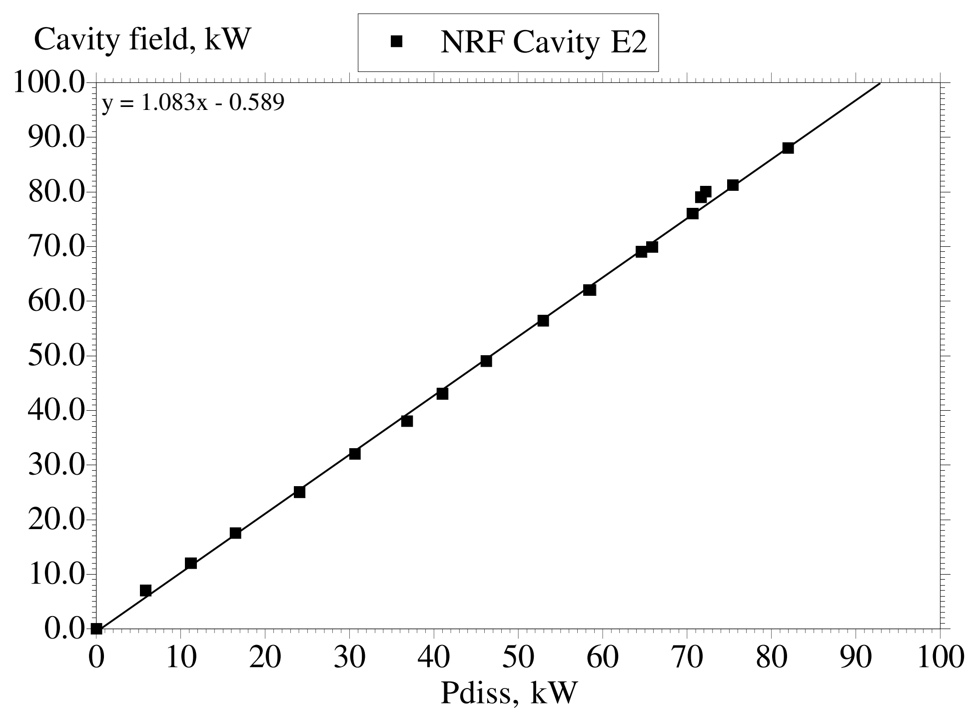
Since 94.446 = 57.882 (east SRF cavity 1/2 length) + 5.5" (old cavity gate valve) + 6.00' (new sliding joint length) + the yet to be designed and made east "between cavities" piece, then the length, face to face, of the yet to be designed east DS "between cavities" piece= <u>25.064"</u>

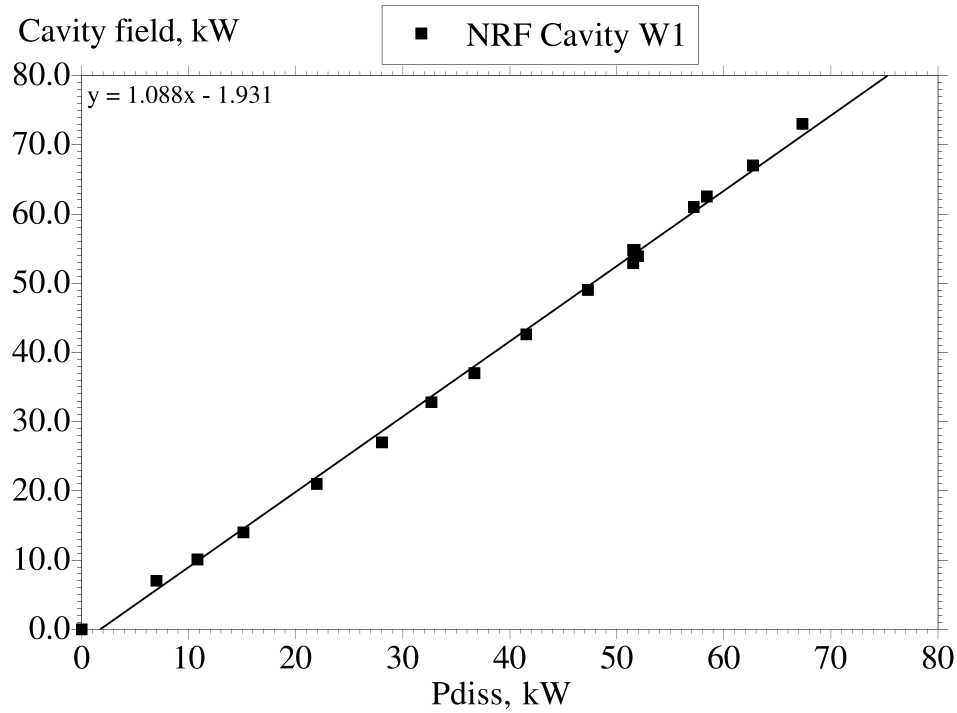
Note that the reference distance from the SRF cell c/l is 25.375" from the flange crack on the vac vessel. The SRF flange crack to the north face of Q8 is then 127.427-25.375= <u>102.052"</u>

X. Appendix C

Calibration of the RF Cavity Crystal Detectors






Cavity field, kW
NRF Cavity W1
y = 1.088x - 1.931
80.0
70.0
60.0
50.0
40.0
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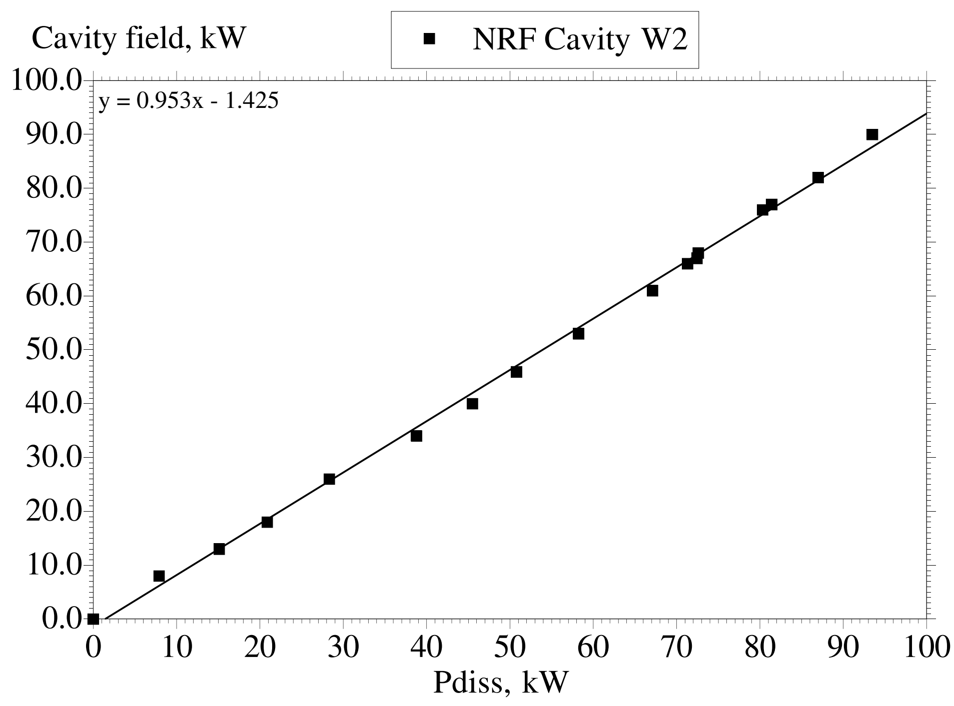
20.0
10.0
0.0
0
10
20
30
40
50
60
70
80
Pdiss, kW


Cavity field, kW
NRF Cavity W2
y = 0.953x - 1.425
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70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0
10
20
30
40
50
60
70
80
90
100
Pdiss, kW