JLab Positron Technical Note #001

Some Practical Considerations for a Positron Source
and Positron Beam Operations at CEBAF

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(Ed. J. Grames)

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Introduction - Joe Grames

Users are expressing interested to receive beams of polarized and unpolarized positrons at CEBAF, with beam qualities and modes of operation as similar as possible to 12 GeV electron beam operations. In response to a 2017 Letter of Intent "*Physics with Positron Beams at Jefferson Lab 12 GeV*" (LOI12-18-004) the PAC46 committee agreed that the development of positron beams (both polarized and unpolarized) would provide important new research capabilities for CEBAF and its 12 GeV program.

The capability for positron beams depends on the integration of a new positron beam source, the ability to reliably reverse the polarity of CEBAF magnets that recirculate and transport the beams, and the diagnostic and safety system capabilities that are similarly required for electron beam operations. The 2017 Jefferson Laboratory Accelerator Advisory Committee (JLAAC) reviewed the status of positron development at Jefferson Lab and made two recommendations to the director.

- R26: Make an initial overall layout of what a full positron complex would look like at CEBAF including injectors, targets, capture regions, electron dumps, diagnostics, and new halls to see if an important design item has been missed.

- R27: It would be a good time to re-verify if the following possibility is not better: Making polarized positrons from a 1.5 GeV polarized electron beam (i.e. a single pass in the north linac) and sending this beam into a target or through a helical undulator to make polarized gammas.

In response an FY21 LDRD proposal is being developed to (a) evaluate the critical design parameters (energy, production target, collection) for a suitable positron source, and (b) define a proof-of-principle "PEPPo-II" experiment to test a proto-type source concept. 'Filling in the blanks' regarding the many necessary and practical issues related to CEBAF positron operations is beyond the scope of the LDRD, but nonetheless is important and timely.

Motivated by the JLAAC recommendations to inform laboratory management this note collects comments made by system owners and technical experts over the period March – May 2020 about the possibility of positrons at CEBAF.

Radiological Considerations – Keith Welch

You mentioned two potential approaches of producing the positrons. One being a separate "space" (new enclosure) to house the positron source. The other was to house the source in the existing injector segment. At the very high level, the first option would be the "safest" from a radiological standpoint, as it would allow shielding to be applied as part of the initial facility design, and allow the shielding and other radiological controls to be optimized integral part of the design, rather than more of a retrofit. But that's not to say acceptable approaches could not be found for the other option.

Concerning energy and power: at energies above the photo-neutron production threshold (10-15 MeV or so), any design will have to address the shielding of neutrons (as well as photons) and the

activation of materials, coolant, air, and potentially groundwater. A 100 kW, 100 MeV system would involve significant shielding, and very high levels of activation in the targets and surrounding materials, plus significant activation of cooling water used in and around the targets, and air activation in the vault. As Pavel mentioned in our discussion, the Hall D Tagger dump offers a fair approximation of the shielding requirements. Think in terms of several meters of iron and concrete.

I don't have any way to hazard a guess at the cost of the radiological "part" of such an installation. The shielding would be part of the civil construction, so the costs would be integral to that. Again, the shielding requirement is a function of not only power, but energy. Also maintenance becomes a significant issue if the energy is high. The activation would produce a radiological "footprint" something like one of the beam dumps in Hall A or C. In other words, this injector would in effect create a new "radiological facility" analogous to the Hall A dump, including cooling water systems. If the energy was kept at or below say 15 MeV, the activation issues would not be significant (though there may be a few activation products, mostly short lived). 10 MeV is even safer. At any rate, material selection could be considered to avoid materials that are activated at lower energies.

At higher energies, the "radiological cost" would eventually be dominated by long term maintenance activities, which would be impacted by the activation issues. A high energy system would benefit the most from being separated from the existing beam enclosure.

Beam Power Considerations – Pavel Degtiarenko

If the total electron beam power for the positron source is expected to be around 100 kW, I think that the reasonable way to produce and capture positrons should be the two-stage, as we have discussed earlier. As I understand, the efficiency of the positron capture requires all the capture hardware as close to the positron emission spot as possible. The two-stage solution would allow to separate the functions of main energy dissipation, and the positron production. The first stage (a radiator and a subsequent beam dump) would absorb main energy, and the e+ production stage would see only a few percent of it.

I think a single stage combining the e+ capture hardware with the need to absorb and shield 100 kW would be difficult. It will have to be a noticeably large vacuum volume with magnetic field as I understand. Having to absorb and dissipate 100 kW in it, and having to shield it would make the design really difficult in my opinion. The alternative "Compact Photon Source" (CPS) solution will be easier in that respect, separating the production of the bremsstrahlung photon beam and dissipating the bulk of energy -- from the positron production target that would see few percent of the total power. It will provide more comfortable heat and radiation conditions for the e+ capture hardware.

The design choices for the CPS may include magnetic field removal of the spent electron beam, as in the current version being developed for Physics experiments, - or may be trying to utilize electron scattering and narrow collimation to absorb the bulk of energy inside the CPS shielding. The second solution would keep some positrons produced forward in the radiator - but it will

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increase also the flux and power of forward-going electrons significantly, so it should be optimized and checked for the figures-of merit.

Personnel and Machine Protection – Jerry Kowal

Here are observations from the SSG perspective regarding CEBAF positron beam as discussed.

From the Personnel Safety System perspective,

1. We'll have to address problem with reversing current powering transport dipoles to experimental halls (A, B or C, whichever hall will take part in the positron experiment). Depending where the proposed by DC group switchgear will be installed, we may need to replace the current transducers, providing feedback to BELLs system. Presently these are unidirectional devices and it might be fine if they are installed before the switchgear. But they are installed after switchgear, then current transducers will have to be replaced (and software changes made). It's not a big expense estimated at $3k for each dipole, which needs to be inverted.

2. Currently there are two proposals for generation of the positrons: conversion in the Injector or construction of separate Positron Injector. Building a separate positron Injector will require to treat it as a separate segment, where all necessary PSS controls would have to be installed. In essence it would be a duplication of existing Injector. In my estimation it would cost around $250k. On the other hand, if conversion takes place within existing Injector enclosure, even if the "converter" is placed in the separate shielded room, it would be less expensive. In this case I can imagine need for some equipment monitoring configuration of the Injector (electron or positron generation). The cost of such equipment may be in range of $50-100k

3. With regard to the ODH system, if we build a separate segment with equipment using significant quantity of cryogens, it may be necessary to install ODH system. Cost would be in the range of $50k. If all is housed within existing Injector, the cost, if any, should be below $5k (perhaps additional O2 head).

Form the Machine Protection System perspective,

1. In general, there would be no need to alter the existing equipment around the site. One exception is the injector. Similarly, to PSS considerations, building separate Positron Injector would require around $50-100k of investment. Installing additional MPS protection equipment in the existing Injector would require only around $10k.

The above numbers are rough estimations. They illustrate the effect the two proposals will have on the expenses associated with SSG maintained systems.

DC magnet power supply (re)configuration for positrons beams – Sarin Philip

<u>Trims Magnet Power supplies (~1900 units)</u>

All correctors and quadrupole magnets are bipolar power supplies able to drive positive or negative amperage. These can be used for electron/positron beam without any changes in hardware.

Some trim system magnets are used for 30Hz modulation, position modulation and Fast Feedback. It is expected that these will remain the same.

<u>ARC, spreader, recombiner, transport and extraction bending dipole magnets</u>

All of the bending dipole magnets in CEBAF proper are powered by uni-polar power supplies without polarity reversal switches, namely:

1. ARC1 to ARC10 (10 units)
2. RSEP8 and RSEP9 (2 units), recirculating septa in the West and East ARCs
3. Dogleg1 to Dogleg9 (9 units)
4. XSEP2,4,6,8,10 (5 units), extraction region magnets for each of 5 passes
5. YA 2,4,6,8,10 (5 units), extraction region thin septa for each of 5 passes
6. Hall A,B,C,D (5 units), magnets that transport beam into each of the halls
7. BSY Dump (1 unit), allows beam steered into the dump before Halls A, B, C
8. Hall A and Hall C Lambertson (2 units), beam to Hall A or Hall C

For these 39 units, the reversal of current would require manually reversing the power cables at the output terminals of each power supply. Adding reversal switches can be accomplished at the rate of ~$8k per unit and a firmware upgrade for controls. Most of the Arc magnets are in a series configuration, meaning the reversal of the power leads at the supply effectively reverses the field in all of the magnets powered by the individual power supply. See Figure 1 for a typical example.
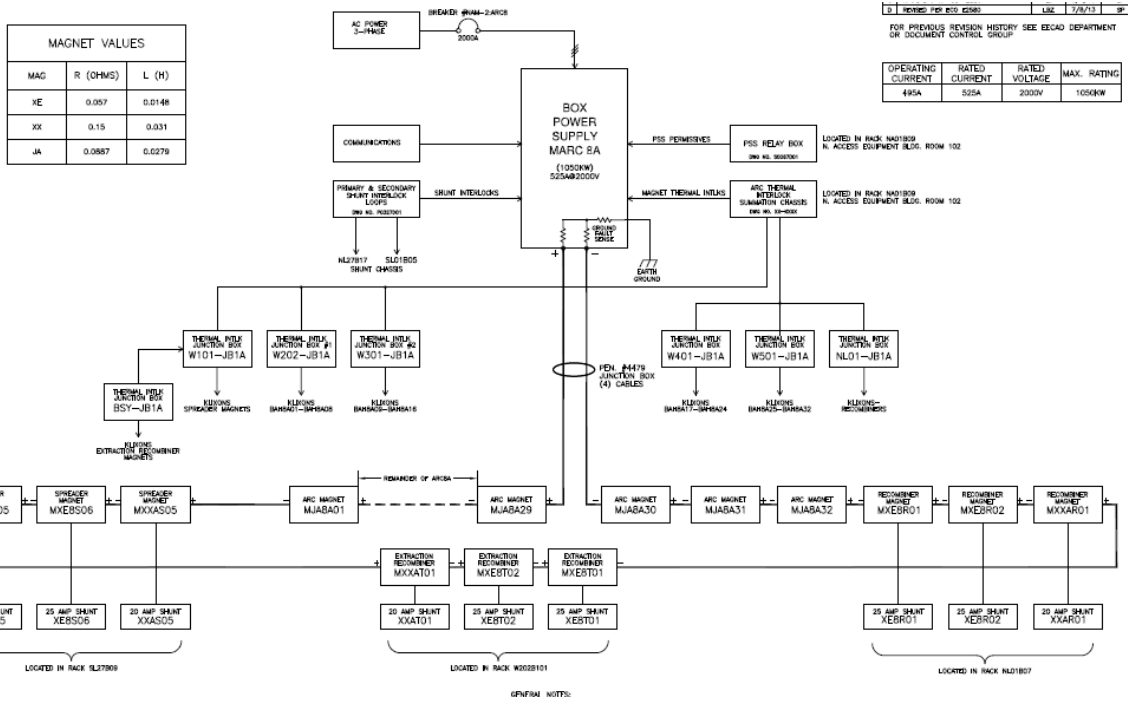
Figure 1: Typical box power supply for ARC magnets

Other considerations: The MPS/PSS system monitor the current on some of these power supplies and issue beam state monitor/ directives. The reversal of the currents would have to be coordinated with the SSG group so they have the correct signals for interpretation.

Potential hardware cost: ~$315k

Labor estimate -- 2 persons, 45 minutes each: swapping terminals on each power supply and then conducting electrical testing to verify. Total hours will depend on how many power supplies will need to be re-configured. Adding reversal switches will require half an FTE of engineering labor for parts, drawings, configuration procurement, plus 1 FTE of technician labor to install the (39) reversing switches and associated wiring/cabinets etc.

Recirculation and Transport Shunt Modules

There are 109 modules used for shunting current around chosen magnets in the spreader, recombiner and transport regions. Reversal of the current in the magnet means each individual shunt module will need to have leads reversed on the termination upstairs at the chassis.

To reduce the number of reversing operations and to prevent failures/error, the polarity reversal would have to be an engineered solution. The system would have remotely controlled switches that can be configured into the correct state for electron or positron beam.

Hardware Cost: A ballpark estimate of ~$150k for the switch hardware, controls hardware/firmware, chassis, wiring.

Labor estimate: One FTE of (engineer + technician + software) labor to choose components, design the hardware. One FTE of technician labor to manufacture the switch boxes, install the hardware, test the configuration. Once the hardware is installed, it should be a few days of labor anytime one wants to configure for electron/positron beam.

End Station Magnets for CEBAF Operations

1. HallA has four Moller quadrupole magnets that have bi-polar current power supplies, which can be used without any changes.
2. The HallA Moller dipoles are powered by a uni-polar power supply that will need leads manually reversed upstairs. HallA's Compton dipole power supply would also need leads manually reversed upstairs. (2 units)
3. The ninth dipole in the HallA line may need its field readings calibrated for positive versus negative magnetic fields and for energy measurement.
4. HallC has 2 quadrupole magnet power supplies, one of them has bi-polar current capability, and the other will have a reversal switch added soon.
5. The HallC Compton Dipole will require manual reversal of leads at the power supply (1 unit)
6. HallD has the "Tagger" magnet which will need power leads reversed at the power supply (1 unit).

Adding a polarity reversal switches for the (4) identified units would limit the amount of manual cable swaps. These reversal switches are estimated to be ~ $8k per unit plus control firmware upgrade.

Potential hardware cost: ~$35k

Labor estimate: 2 persons, 45 minutes per power supply for manual reversal.

End Station Superconducting Magnets

Each of the physics halls have normal and superconducting magnets of various kinds that are not controlled by DC power. Their configuration needs should be examined by the various Halls.

Some examples would be the "Frascati" magnets in Hall B, Tagger and Moller magnets in Hall B, the detector magnets etc.

Hall D Permanent Tagger Dipole

Hall D permanent dipole to prevent beam into the Hall in case of Tagger magnet failure. This magnet may need to be rotated to get the same effect.

Hardware cost: Unknown.

Labor cost: Unknown. May be an installation task to rotate the magnet.

Reversal of CEBAF Magnetic Fields – Michael Tiefenback

On the issue: "What might you expect would be the scope and level of effort to operate the magnets at CEBAF to operate with either electrons or positrons, from the injector to the halls":

1) Operation: inverting polarity would require at the least a swap of power supply leads, but also all of the shunt units would require lead swap (at least as I understand it) because of the unipolar design of the shunt circuits. I am reluctant to speculate further on this at this time because Sarin Philip will provide you more information with much greater certainty than I can. The prospect of error at reconnection (as experienced on a ZA magnet recently) must be considered, and it would seem necessary to invest some design and fabrication work to assure that all connections remain correct through the multiple reconfigurations which might be executed.

Operational procedures would remain unchanged, as the magnet systems are blind to polarity of connection. For positrons with inverted magnet polarity, all "up/right" is positive and "down/left" is negative conventions would remain unchanged. Any portion of the accelerator used to create an electron beam to produce positrons as well as to transport positrons would require special attention procedurally.

2) Magnet calibration variation: The various magnets of the accelerator are a mix of bipolar and unipolar configurations. For the bipolar magnets, I have examined many of the "field maps," as we call the BDL vs. Current relationships, for parity invariance as an internal self-consistency validation. In some, such as the small BL dipoles of the injection chicane, the earth's background field seems to result in an apparent parity asymmetry, but only as a measurement artifact. For the bipolar magnets, observations are consistent with no change in magnetic field vs. current after unipolar operation.

The meter-scale dipole magnets are configured as unipolar systems, and have not been deliberately tested for a calibration change after polarity inversion. The remanent field of the various dipoles is in the 10 Gauss to 15 Gauss range, based upon sparse measurements of low-current field integrals. We have observed in unipolar operation that raising the "HMIN" minimum magnitude of hysteresis cycling current changes the BDL calibration on the rising current leg of the hysteresis cycle, which is where we operate the dipoles. This is a consequence of retaining greater residual magnetization of the iron when not reducing the drive current to the calibration curve level. Such operation has only been done when driven by hardware reliability problems (power supply tripping off at HMIN) when program schedule requirements. After correction of the power supply hardware, no persistent shift in the field vs. current calibration was apparent. The MBF (injector full-energy) spectrometer dipole has been operated in bipolar configuration.

The most stringent empirical test known to me at this time is the observation of fine reproducibility of the beam trajectory after dipole string power supply "trips" to zero current. The uncontrolled magnetic field of the dipoles, involving prospectively a flux reversal as the dipole field collapses, has not been seen to alter the beam trajectory after the multiple hysteresis cycles we execute by protocol after such an event. The observations known to me indicate that the magnet iron is magnetically "soft" enough at the fields in use in the CEBAF accelerator as to result in no persistent calibration shifts after field reversal and restoration.

A test in the magnet measurement lab could be fielded to validate this in a rigorous, quantitative fashion.

"The uncontrolled magnetic field of the dipoles, involving prospectively a flux reversal as the dipole field collapses, has not been seen to alter the beam trajectory after the multiple hysteresis cycles we execute by protocol after such an event."

This concerns prospective behavior in the event of a power supply trip and reduction in drive current faster than skin depth time scales of the solid iron dipoles. In such an occurrence, it may be possible for the total current in the windings to drop faster than the skin depth limited decay of the core dipole field. This would result in strong field nonuniformity across the pole tips, with the field near the center of the poles held up. To satisfy Ampere's Law, the field near the boundaries of the magnet might invert during the field collapse. I do not know whether the free-wheeling diodes in the power supplies extend the time scale for decay of current sufficiently to prevent such local flux reversal.

But such an event is why I consider power supply trips to have some prospect of violating the "thou shalt not" field polarity reversal part of the magnet construction specification.

What I was trying to do was to give the general statement that the iron of the magnets is "soft," and is reasonably expected to return to present calibrations after inversion and reversion. I also expect the calibration curves to be parity-invariant, so that inverting the current will invert the field as long as the hysteresis cycle is respected. I believe that we should be able to paste a Hall probe on the iron and verify this, as well as the restoration of calibration after inversion/reversion.

I tried to provide some plausibility justification (excisable, but present if desired) for the conclusions I have drawn over time.

I believe that, in order to have the best test and highest certainty of zero residual effect, we should take a typical magnet from the mag test lab and do a field probe test for restoration of field after polarity inversion.

If we do not do this, then there is some nebulous _chance_ of a shift in BDL integral for the dipoles at the part per thousand level. I do not believe that it will happen, but certainty is the better option, and the mag test should be made. I believe that we do not need a field map repetition, but only a local NMR core field measurement.

CEBAF Diagnostics for Positron Beams – John Musson

The JLAB UITF has become a unique test facility for evaluating injector configurations, beamline components, target elements, and EPICS routines. A proposal to produce and accelerate positrons has elicited concerns as to whether the beam diagnostics will be affected, and what activities might be needed to ensure beam current and position are properly measured. A similar proposal to employ

Jefferson Lab's CEBAF and LERF machines to produce positron beams briefly describes the application of existing RF-based beam diagnostics, with minimal re-configuration [1].

Since previous positron efforts have successfully employed DCT, cavity, and button-electrode-based BPM systems, it is our opinion that design for positron production can proceed, based on data obtained from the JLAB experience [2,3]. Following is a summary of diagnostics behavior and metrics.

BCM Resolution Analysis

Since electrons and positrons differ only by charge (and magnetic moment), polarity is an obvious difference in the electronic signals. Signal polarity is of little significance, since beam current is the result of a magnitude-only measurement of the high-Q cavitiy, which is phase-independent. Also, positron mass and beam size should result in identical beam loading, thereby producing the same cavity response for a given beam current.

The JLAB BCM "pillbox" cavity is a pretty old friend, with nearly 25 years of operational experience; there are currently 33 cavities employed in the CEBAF, providing detailed current information, time of flight measurements, and also as time-of-arrival sensors. The basic *"Cavity Facts,"* pertaining to expected performance are shown in Table 1.

Table 1. JLAB BCM Cavity Parameters

Parameter	Symbol	Value
Cavity Radius	a	7.74 cm
Unloaded Q	Q_0	3200
Loaded Q	Q_L	1600
External Q	Q_E	3200
Coupling Coefficient	β	1.05
Source Impedance	Z	50 Ω
Shunt Resistance	R_{sh}	180 Ω
R/Q		93 Ω
Material	*SS304*	Stainless Steel
Beam Pipe Radius	ρ	1.75 cm
Probe Type		Magnetic Loop

Parametric simulation for various expected beam currents has been performed, which agrees with actual beam-based measurements (to within 2 dB). Therefore, it is useful to rely on several rules of thumb, for which receiver electronics can be evaluated in the lab. Using this data, a nomograph is produced, which accurately predicts the RF output power (in dBm) for a large range of beam currents. Figure 1 is a composite of several JLAB beamline elements, of which the BCM cavity is shown in red. An extremely useful relationship to remember is I_{beam} = 1 uA results in -40 dBm.
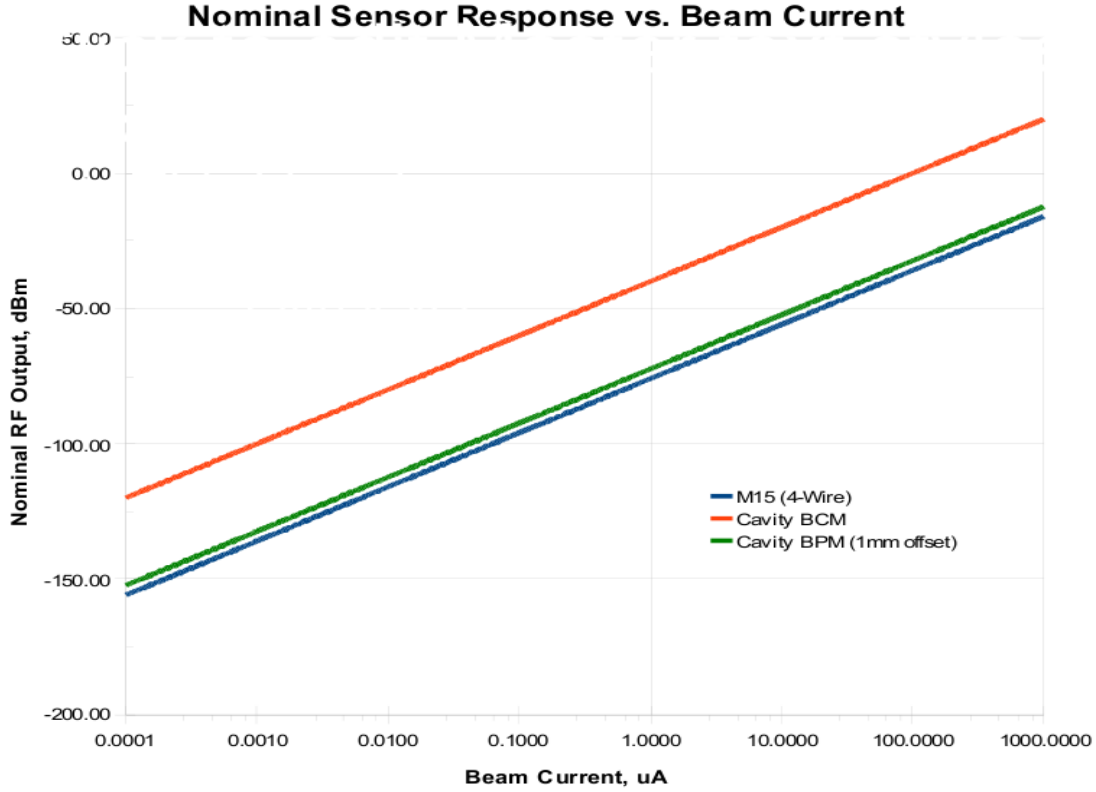
Figure 1. Nomograph of expected BCM cavity power output (red) for various electron/positron beam currents. If one can remember I_{beam} =1 uA results in -40 dBm of output power, then scaling simply follows as 20 log(I_{beam}).

Knowing the sensor output allows one to quickly establish a linearity constant for I_{beam} *vs* V_{out}, which in the case of a standard, SS304 JLAB BCM cavity is

$$K = 447x10^{-6}\frac{uA}{uV},$$ electron and *presumably* positron beams.

For determination of resolution, noise power must be known so as to establish the confidence of the measurement from the resulting signal-to-noise ratio[*]. For this, the receiver electronics must be evaluated, as well as the amount of signal loss between the sensor and the receiver. If a perfect system is assumed (0 dB noise figure), and sitting in-situ at room temperature (290 K), then the noise power for the venerable 50 Ohm receiver, possessing a 1-Hz bandwidth is calculated using:

$$P_n = k_B TB = -174dBm - Hz,$$

where k_b is Boltzmann's constant, T is 290 K, and B is the bandwidth of 1 Hz.

Scaling for bandwidth is trivial, simply using the new bandwidth in place of 1 Hz. Receiver noise figure (in dB) can also directly added to the result. Scaling for other receiver impedances is less obvious, and requires going back a few steps in the noise power derivation (which is not done in

this report). Nevertheless, a nomograph is presented which does allow one to extend the calculation to systems other than 50 Ohms, as well as for various bandwidths. It is imperative that the user know that the BCM cavity is manufactured and tuned to 50 Ohms, so simply connecting it to a non-compliant receiver _will_ have additional consequences. The nomograph for noise power determination is shown in Figure 2.

* In actuality, a method of signal-plus-noise-over-noise (aka. SNNR) is used, especially since it is expected that usable signals will always be at least as great as the noise floor. It is also much easier to determine in the lab, and in situ.
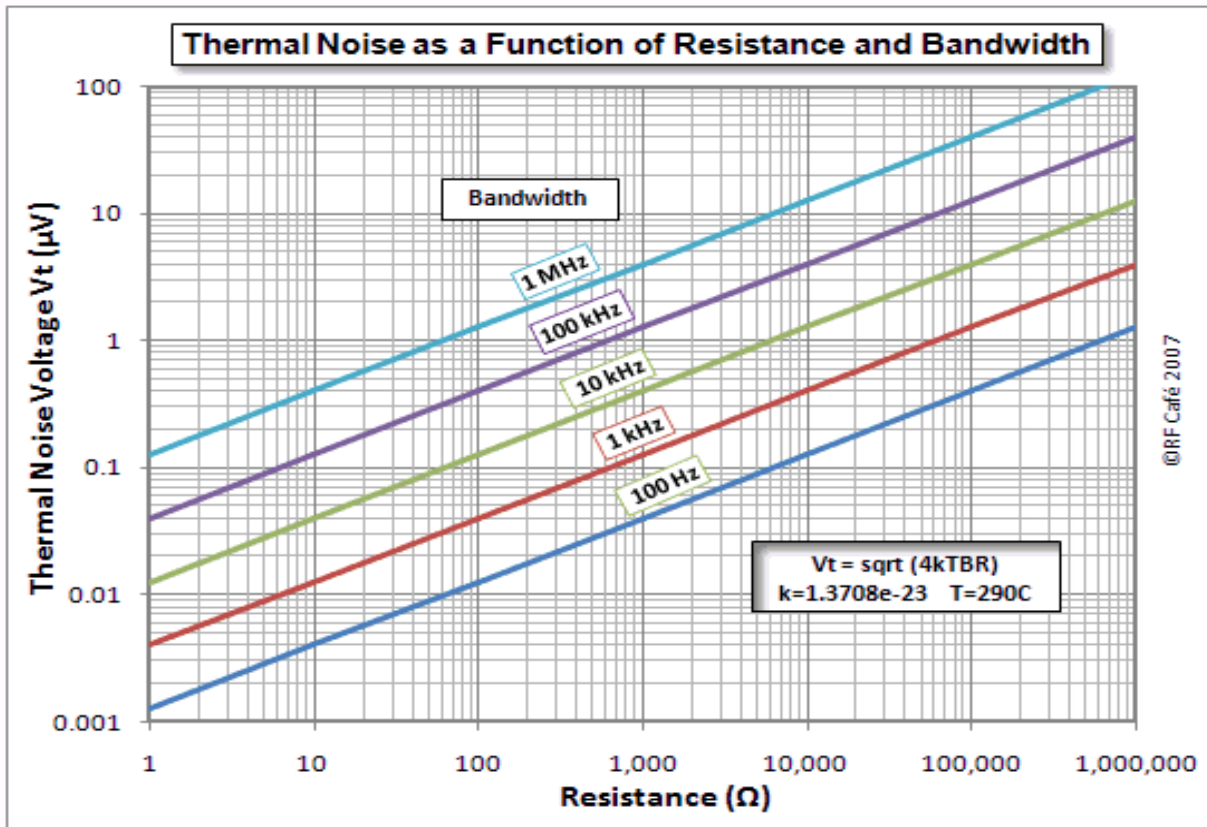
Figure 2. Thermal output voltage for various resistances and bandwidths, for systems other than 50 Ohm. It is assumed that the devices are maintained at 290 K.

Finally, it is a simple matter to apply the resulting noise voltage to the derivative of the previous I_{beam} vs V_{out} relationship, to get an ultimate resolution of [4]:

$$\sigma = \delta I_{beam} = \frac{\delta V_{noise}}{K} \approx 1pA$$

In reality, cable losses, receiver noise figure, finite bit resolution and the fact that we intentionally wound the receivers for the larger signals of CEBAF impact the ultimate sensitivity. The JLAB experience contains solid data for a minimum detectable signal of $\leq$ 500 pA (1 Hz detection bandwidth), implying a composite noise figure of 27 dB (Grames/Musson...see ELOG #????).

Since the JLAB digital diagnostics receivers (ca. 2020) possess a 4dB noise figure, much improvement to resolution is expected.

Preliminary simplistic MAFIA data has recently been re-examined, using Microwave Studio, and contains the tuning and probe structures, which were originally too complicated to consider.

Fortunately, the fundamentals were verified, as well as sensitivities to beam position, manufacturing and temperature. Of greatest relevance, for recent physics experiments, is the change in signal output as the beam moves away from boresight. For machine protection and most physics data collection, the TM010 mode of the pillbox cavity has a relatively flat first Bessel function, so the effect has been largely ignored for the first 1 cm of beam displacement. Sensitive parity experiments, combined with larger-than-normal raster patterns motivated the study of displacement sensitivity. To first order, the change in output voltage for 10 um from boresight is 11×10^{-9}. Since this is a recent model-based determination, it is hoped that beam-based measurements will confirm this value, as well as extrapolate to larger (1 cm) displacements.

Cavity thermal effects are by far the largest offender for sensitive cavity measurements. At this time (quarantine 2020), the model data exists, but is deeply buried behind the virtual walls of JLAB, and will be available, someday. Also, physical measurements using the environmental oven were underway, to verify the larger-than-expected effects, as a result of the tuner mechanism. Typical temperature regulation is +/- 0.2° C, which maintains operational specifications.

BPM Analysis

Low-Q BPM sensors are somewhat problematic, since they often rely on a directional characteristic. For example, button electrodes are frequently used in machines with high beam currents, which have no directivity, whatsoever. However, UITF striplines are shorted 1/4-wave electrode structures, with an intrinsic impedance of 50 Ohms. This results in a much more directional behavior, and closely resembles the standard directional coupler, used for RF laboratory measurements. The M15 BPMs at CEBAF are open-wire, 200-Ohm structures which, when used with the standard 50 Ohm receiver, have moderate directivity, but are not fully reliant on that quality. It is shown [5] that, regardless of how the BPM is installed, usable signal is available. Nevertheless, to mitigate this problem, the CEBAF proposal intends to run the positron beam in the reverse direction (for additional reasons), which would allow the BPM sensors to perform identically to the conventional electron beam stimulus. While this is not an option for the UITF proposal, several options are available. Regardless of which BPM sensor or configuration is considered, the difference in how the beam current couples to the electrode, known as transfer impedance, Z_t, is easily investigated using the BPM Characterization Test Stand.

With respect to electronics, BPM detection is a relative measurement (aside from any 4-wire applications), so as long as the change in response is common to all four sensor electrodes (antennas), then a calculated position should be available. It is likely that, for any units which have had field mapping and bench calibrations, the relationship between electrical and physical centers would be altered. Reversing the necessary BPM sensors within the beamline is an obvious solution if it appears that sensitivity or orthogonality is compromised.

Assuming nearly-identical behavior for electron and positron beams, the BPM resolution follows as before, by establishing a sensor output, calculating expected noise voltage, and applying to the position calculation algorithm. Here, however, the algorithm may have several forms, which affects the sensitivity a given SNR has on the result. For our common difference-over-sum algorithm, it is a matter of applying the derivative, which can then be reduced to an expression of SNR [4].

For one-dimension:

$$X = \frac{a}{2} \cdot \frac{V_L - V_R}{V_L + V_R}$$

where V_L, V_R, and a represent the left-hand electrode voltage, right-hand electrode voltage, and beampipe radius, respectively. The derivatives become

$$\frac{\partial X}{\partial V_L} = \frac{a \cdot V_R}{(V_R + V_L)^2}$$

$$\frac{\partial X}{\partial V_R} = \frac{-a \cdot V_L}{(V_R + V_L)^2}$$

resulting in resolution (looking only at X-position)

$$\sigma_X = \frac{a}{(V_R + V_L)^2} \cdot \sqrt{V_L^2 \delta V_R^2 + V_R^2 \delta V_L^2}$$

for which, at boresight, the electrode voltage amplitudes are nearly equal ($V_L \sim V_R = V$).

Finally,

$$\sigma_X = \frac{a}{2} \cdot \frac{\sqrt{2}\sigma_v}{2V} = \frac{a}{2\sqrt{2}} \cdot \frac{1}{\sqrt{SNR}}, \text{ where } SNR = \frac{P_s}{P_n} = \frac{V_s^2}{V_n^2}. \quad \text{(dimensions are same as } a)$$

For a JLAB M15 or stripline, the expected output can be obtained from Figure 1 (above), and the noise voltage calculated or obtained from Figure 2, with a resulting SNR. For example:

The typical output power for 100 nA is -102 dBm. Expected noise power for a receiver having a 10 dB noise figure and 10 Hz bandwidth is -154 dBm. So, the resulting 52 dB SNR predicts a resolution (or minimum detectable motion) of:

$$\sigma \sim 10 \text{ um, for } I_{beam} = 100 \text{ nA, and } B = 10 \text{ Hz.}$$

Note that the resolution scales inversely with current, and as the square-root of bandwidth. So, at 10 nA, 1 Hz, the expected resolution becomes 10 um x $(0.1)^{-1}$ x sqrt (0.1) ~ 30 um.

Figure 3 demonstrates this effect using actual bench measurements. The 100 nA, 100 Hz map shows considerable noise (step size = 250 um), while the reduction to 70 nA is tempered by a reduced bandwidth of 10 Hz, for a total improvement of 0.7 * 3.1 = 2.2 in resolution.

(a)   (b)
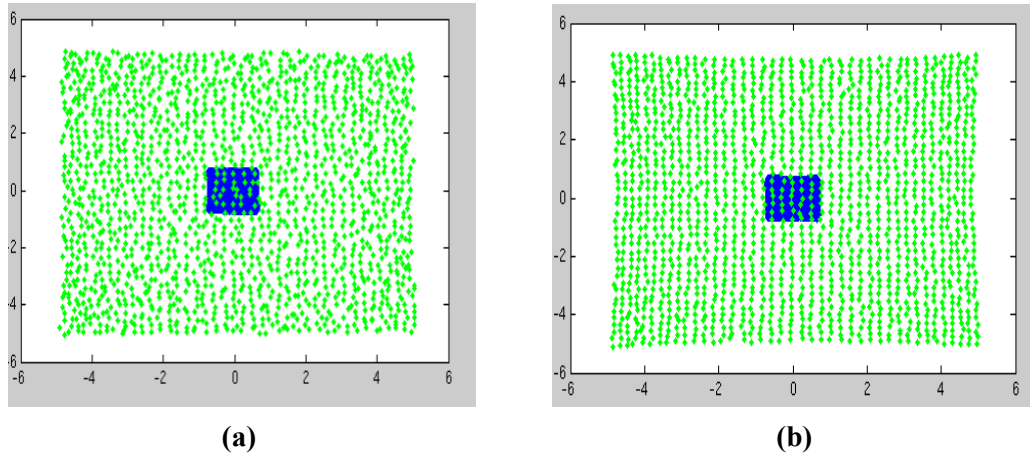
Figure 3. Comparison of measured stripline BPM field maps for (a) Ibeam = 100 nA, B = 100 Hz, and (b) Ibeam = 70 nA, B = 10 Hz. Reduction of beam signal is tempered by the narrower bandwidth, for 2.2x improvement in resolution. Scales are in mm, step size = 250 um.

To see how the SNR affects position convergence, Hall D was used to measure the position performance vs current (black trace) for four stripline BPMs. An ultimate usable floor of 10 nA (1 Hz) is demonstrated, and has subsequently been used for position locks during the past several experimental runs, as shown in Figure 4.

A final reminder that resolution is not accuracy. The User is responsible for determining the confidence limits, for which there are many methods (we at I&C are happy to help). Fortunately, for most applications, the beam SNR is high enough so as to swamp the other sources of error. The specification of 100 um is a relatively easy target for the currents commonly selected for most experiments.

Summary

While a full tutorial is far beyond the scope of this report (but fully available on request), it is hoped that the data can be used to provide design guidance for the proposed positron experiment. Also, the "iron cross," involving resolution, dynamic range, and measurement bandwidth (hence output data rate) is made apparent, such that decisions of optimization and cost-benefit can be evaluated.
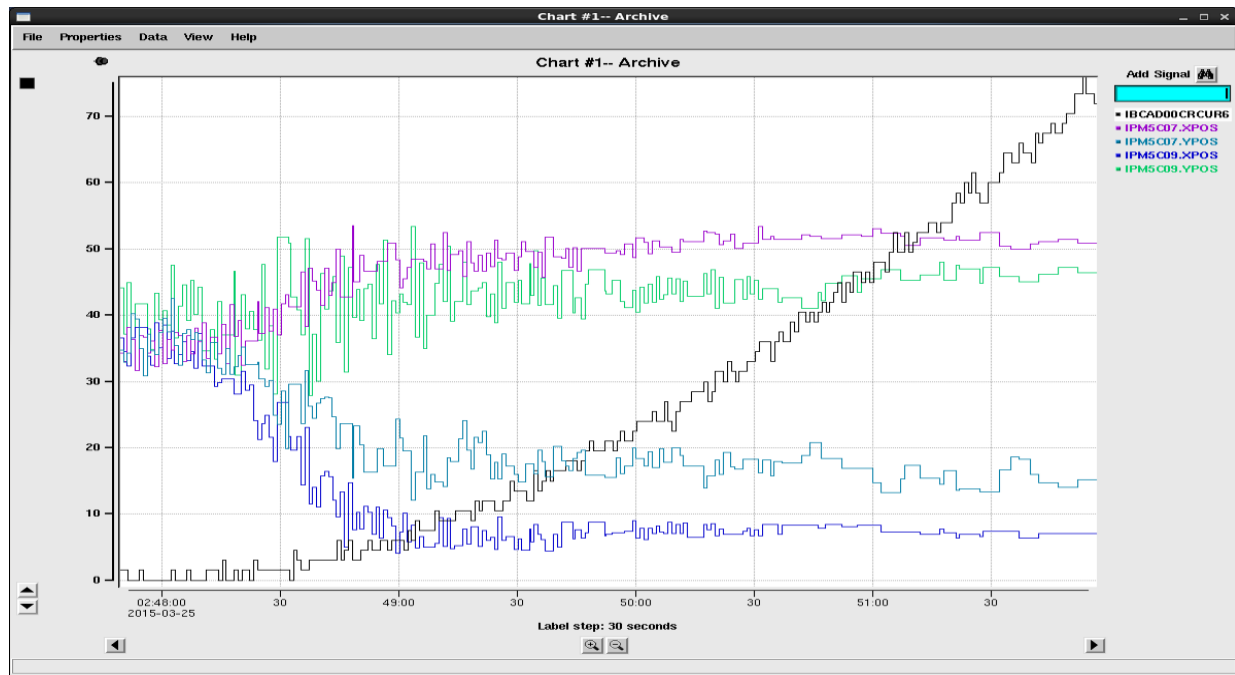
Figure 4. Hall D convergence test to establish usable lower-limit of stripline BPMs, using digital diagnostic receiver. Current ramp (black trace) is in nA, while the four BPMs show convergence at ~ 10 nA. Detection bandwidth was 1 Hz. Left-hand vertical scale is beam current, in uA. Position is masked, so is in Arbitrary Units.

Below, Table 2 provides the results for BCM and BPM parameters, tabulated in the simplest form, possible. Figure 5 follows some rules of thumb, and is useful for BPM resolution approximations. Power levels represent dB-milliwatts, into 50 Ohms. A temperature of 290 K is assumed, with 1 Hz bandwidth. Please use as a guide, but understand that many other performance issues have been eliminated, and will be made available as necessary. A comfortable design margin has been included.

Table 2. Summary of Expected BCM and Stripline/M15 BPM Performance (JLAB Experience)

Ibeam	BCM	σ_{BCM}, 1Hz	BPM	σ_{BPM}, 1 Hz
10 nA	-80 dBm	<= 500 pA	-120 dBm	30 um
100 nA	-60 dBm	<= 500 pA	-100 dBm	3 um
1uA	-40 dBm	<= 500 pA	-80 dBm	0.3 um
10 uA	-20 dBm	<= 500 pA	-60 dBm	0.03 um
100 uA	0 dBm	<= 500 pA	-40 dBm	0.003 um

Rules of Thumb

$$P_{BCM} = -40 \text{ dBm} + 20\log(I_{beam}, uA), \text{dBm}$$
$$SNR_{BCM} \sim -164 - P_{BCM} + 10\log(\text{bandwidth, Hz}), \text{dB}$$

$$P_{BPM} = -80 \text{ dBm} + 20\log(I_{beam}, \text{uA}), \text{dBm}$$
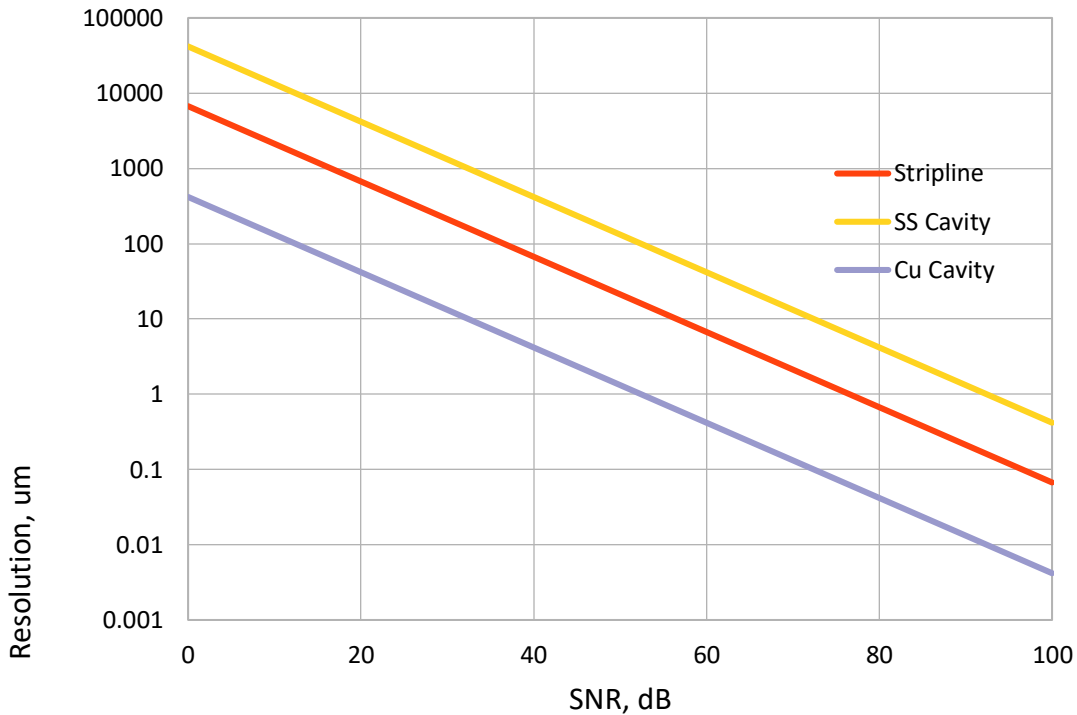$$SNR_{BPM} \sim -164 - P_{BPM} + 10\log(\text{bandwidth, Hz}), \text{dB}$$

For the JLAB experience,

$$\sigma_{BPM} \approx \frac{0.3um \cdot uA}{\sqrt{\text{Hz}}}$$

$$P_{dBm} = 10 * \log(\frac{P}{1mW})$$

$P = \frac{V^2}{R}$, where R=50 Ohms for most detection electronics.

Resolution vs SNR

Figure 5. Nomograph for (optimal) stripline BPM resolution approximation (red). Temperature is assumed to be 290 K, and measurement bandwidth = 1 Hz. Resolution scales as $1/I_{beam}$, and as the square-root of bandwidth.

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