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Publication Date
2005-11-30

November 30. 2005

DARHT Tech Note # 446
LBNL Report # 59199

Transverse Impedance Measurements of the Modified DARHT-2 Accelerator Cell Design

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1. Introduction

The DARHT-2 accelerator cells have been redesigned to make their high voltage performance more robust. At the outset of the DARHT-2 development program about 8 years ago, an extensive campaign was mounted to minimize the transverse impedance of the original cell design. Since the initial spec on the machine was a beam current of 4 kA, the control of beam-breakup (BBU) amplification with a 2 microsecond pulse length was considered to be one the most critical issues in the design. Even after advances in detector technology allowed the beam current requirement to be lowered to 2 kA, the goal for the standard cell impedance was kept at ~ 300 ohms/meter to allow for the possibility of future beam current upgrades to 4 kA without any modifications in the cells.

The results of this campaign to minimize the transverse impedance are described in detail in Reference 1. After several iterations in the design of ferrite dampers and the anode finger stock shape, the measured (peak) impedance of the original standard cell was determined to be about 280 ohms/meter. (As a reference point, the measured impedance of the DARHT-1 cell is about 880 ohms/meter). This impedance provided such a wide safety margin against BBU amplification at 2 kA that it was felt that the cell redesign could focus on voltage holding without any detailed considerations of impacts on the transverse impedance. Now that a baseline design for the DARHT-2 cell has been established and tested, however, it was felt that a measurement of its impedance would be prudent. The results of these impedance measurements are presented in this note. The objective was mainly to do a "quick check" to ensure that there were no surprises, and to provide an estimate of the BBU frequencies and growth rates to the experimental test program. The "bottom line" is presented in Fig. 9 in the Conclusions Section.

2. The New Cell Design

The modification expected to have the greatest potential impact on the transverse impedance is the new cathode cap geometry. In Fig. 1 sketches of the cross section in the gap region of the original cell and the new baseline design are shown together with the corresponding electrostatic field potential plots. The angles of the equipotentials along the insulator-vacuum interface in the cathode region are substantially improved by the new cathode cap shape, and by the shaving of a small amount of material off of the vacuum side of the Mycalex insulator.

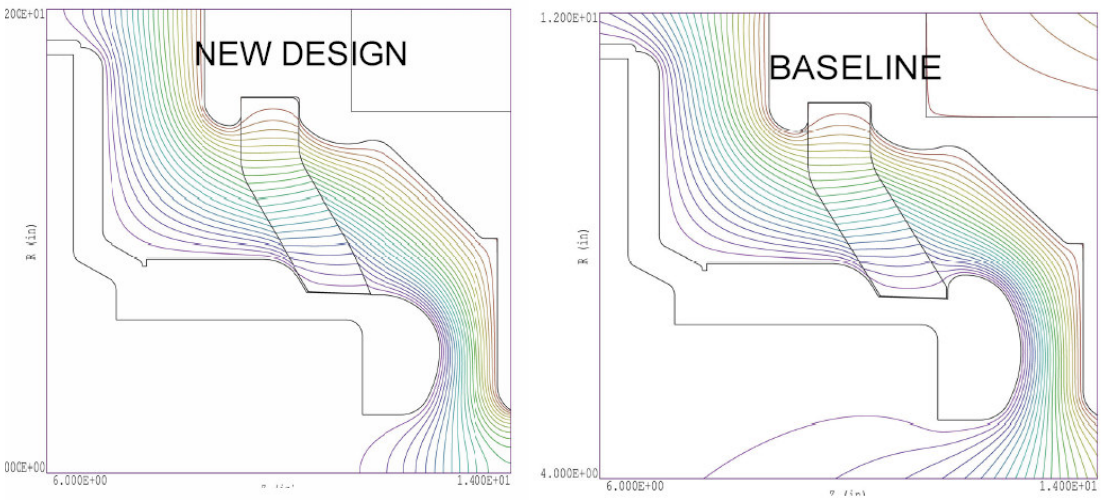

Fig. 1 Cathode region geometry of the new design and the original baseline cell design. (The equipotential plots are shown for the case when this section was mounted in the insulator test stand.)

Other changes in the new cell design include increases in the length of the "hockey pucks" that help support the high voltage plate, and a 1" extension in the separation between core # 4 and the high voltage plate. One would not expect these changes in the oil region to have significant effects on the RF impedance.

3. Measurement Technique

We attempted to replicate as closely as possible the test set up that was used to measure the impedance of the original cells, since the technique that was finally developed and optimized was the product of an extended campaign. (*Ref 1*) The main difficulties we encountered included trying to remember the details of that set up 5 – 6 years later, and working with a borrowed network analyzer. A new surrogate beam tube and a new anode mounting flange also had to be constructed.

The essence of the measurement technique is the use of a twin-lead transmission line placed along the axis of the beam tube to excite dipole (n = 1) RF fields in the cell. With the twin lead terminated in a matched load, a dipole traveling wave is created which has the exact same electromagnetic field structure as that of a relativistic beam oscillating in the transverse direction. The transverse impedance as a function of frequency is deduced from ratios of magnetic RF loop signals inside the accelerator gap to RF loop signals near the beam tube wall at a distance 15" away from the gap.

The original cell configuration with the anode fixture used to replicate the metal boundary condition of the finger stock in the actual cell is shown in Fig. 2. (The finger stock was not available at that time for the RF testing.) The new cell with the anode plate flange and the RF loop ports used in the present test is also shown in Fig. 2.

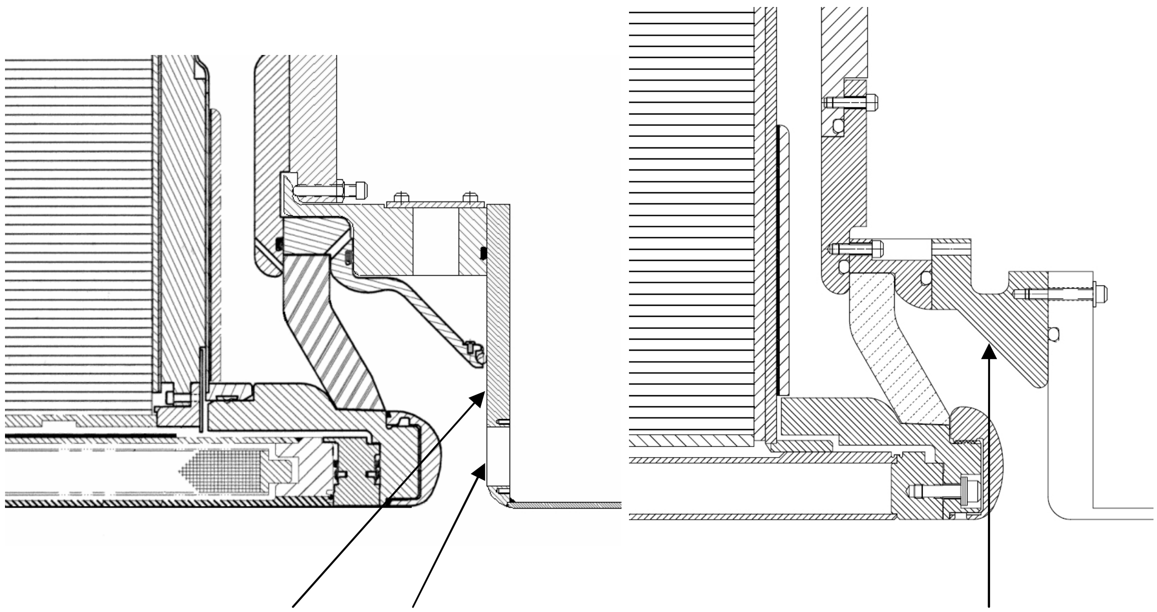

Fig. 2 The insulator and cathode cap regions in the new cell design and in the original cell

A photo of the test set up from the anode side is shown in Fig. 3. This photo shows the network analyzer, the balun used to excite the dipole mode on the twin lead, the balanced pair of RF loops inserted into the beam tube 15” from the gap to measure the dipole B theta at the beam tube radius, the “ferrite blockhouse” at the drive end used to damp any residual monopole RF wave on the twin lead, and the twin lead itself.

Without going into the details, it is worth mentioning that we went through several iterations in the set up before obtaining the data presented in the following section. In the first attempt, we deduced that the finger stock was not making good contact with the anode plate. The mode around 600 MHz had a high Q as a result. Poking metal objects into the region behind the finger stock fixture shifted the resonant frequency so it was clear that the RF fields were coupling into that region. When this was corrected the next set of measurements indicated a peak impedance (of the higher frequency mode around 600 MHz) about 35 - 40% higher than the “final measurements” presented in the following section. We determined that this measurement had significant errors at the higher frequency peak because of the mismatches discussed below.

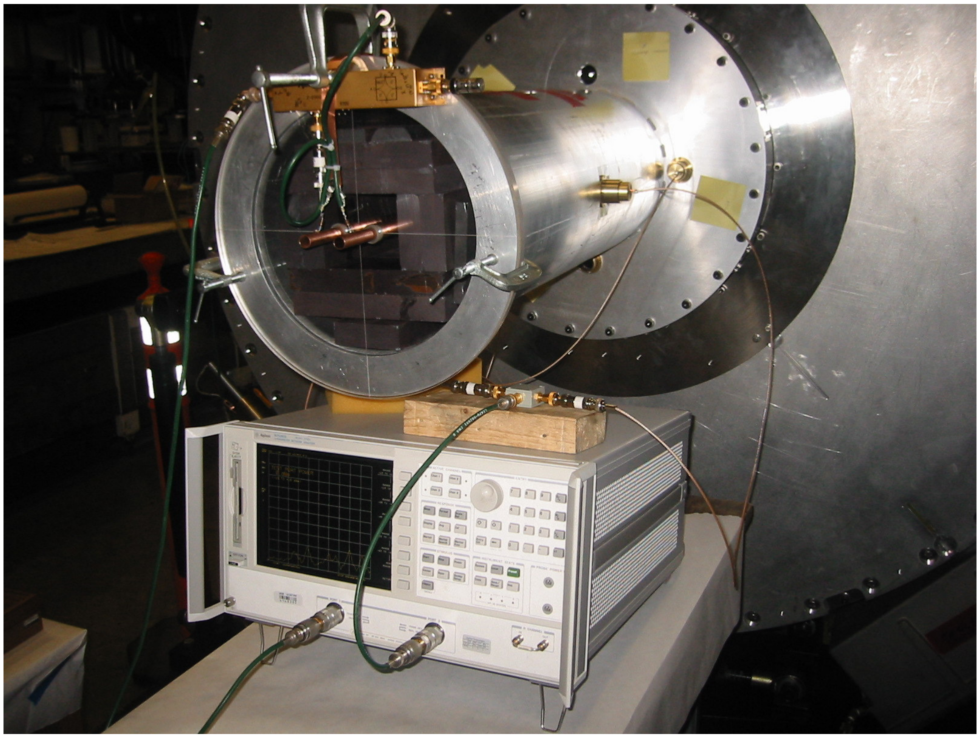

Fig. 3 Photo of test set up on the anode side (twin lead drive side)

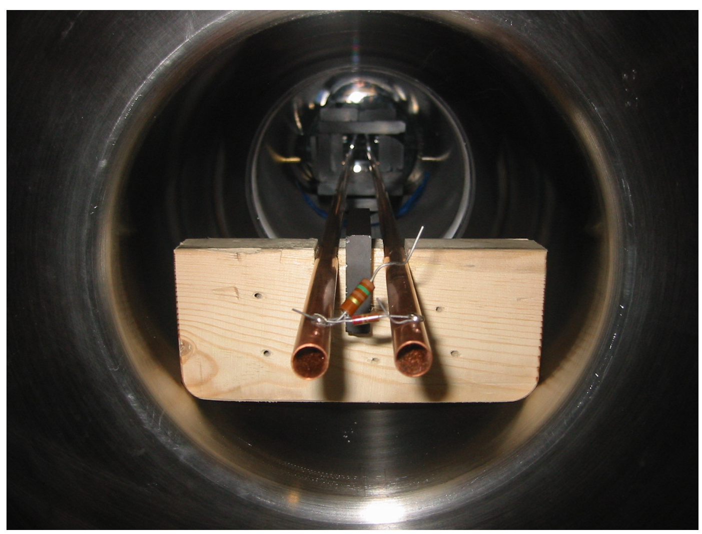

Fig. 4 Termination end with ferrite absorber

Sources of “errors” in the impedance technique we are using (requiring many iterations in the original set up to minimize, as discussed in Ref. 1) include mismatches in the twin lead, coupling to monopole “coax modes” on the twin lead, and mismatches in the drive circuitry. (It’s important to recognize that the induction cell itself puts a high RF impedance between “ground” on the drive side and “ground” on the termination side, and this complicates the RF drive techniques and the RF measurements.) In the set up used for the measurements presented in the following section we added the ferrite absorber block between the twin leads shown in Fig. 4 to improve the matching of the twin lead at higher frequencies. Since the impedance is deduced from a ratio of the radial RF magnetic field in the gap to the B theta field in the beam tube 15” away from the gap, a mismatch on the twin lead can put a "spurious" minimum in B theta vs. frequency that artificially increases the impedance.

4. Results of the Impedance Measurements

Measurements of the ratio of dipole radial and azimuthal RF magnetic fields in the gap to azimuthal RF fields in the beam tube are used to infer the dimensionless "eta parameter" defined in Ref. 1. The measured real and imaginary parts of η vs. frequency are shown in Fig. 5. These measurements are only valid below the cutoff frequency of the beam tube at 690 MHz. The data are also shown only from ~ 80 MHz and up because the signal levels made the ratios very noisy below that frequency, and the twin lead matching was also not optimized for the lower frequency region.

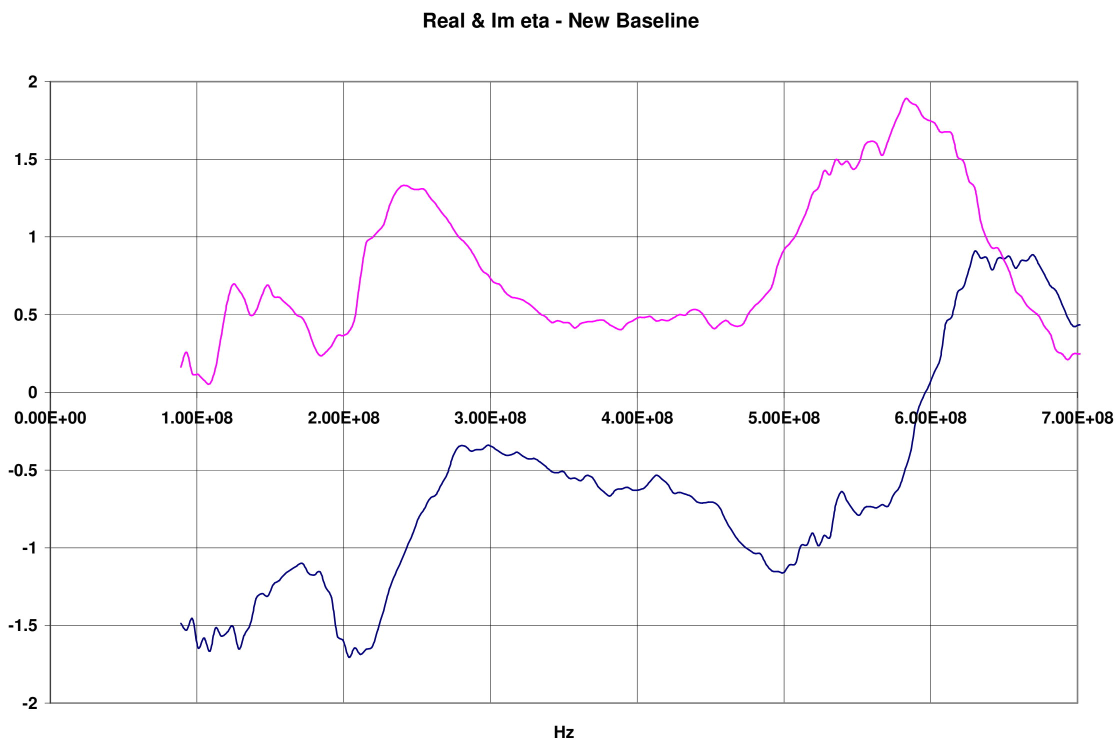

Fig. 5 Real (blue) and imaginary (magenta) parts of η vs. frequency.

The amplification of the BBU instability is proportional to the resistive part of the transverse impedance, which is equal to 189 Im (η) ohms/meter for the standard cell dimensions. This resistive impedance is shown in Fig. 6 for the "normal" case of drive cables connected to the cell (data in Fig. 5), and also for the case where the drive connections are all shorted out at the cable connection boxes (as illustrated Fig. 7). This latter case might occur, for example, when a cell has suffered a breakdown and the program wants to continue accelerator operations with that cell shorted out. The impedance is essentially unchanged by the shorting of the drive connections. (We believe the small differences in this data are more a reflection of the repeatability of the measurements than an actual difference.)

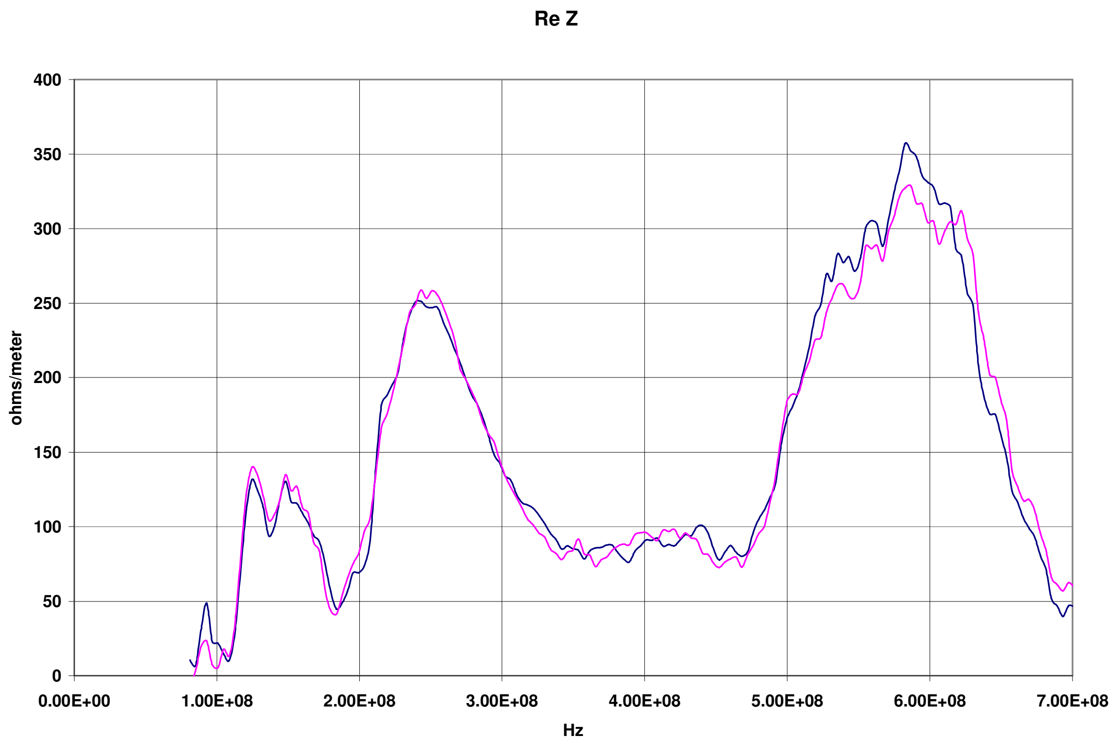

Fig. 6 Real part of the impedance vs. frequency. Blue curve is with the drive cables attached, and magenta curve is with the drive cables shorted.

The peak impedance of the lower frequency mode shown in Fig. 6 (about 240 MHz) is around 250 ohms/meter, essentially identical to the impedance of that mode measured on the original cell design (see Fig. 8). The peak impedance of the higher frequency mode around 580 MHz (325 – 350 ohms/meter), on the other hand, is about 15 to 25% higher than the impedance of this mode measured on the original cell (280 ohms/meter).

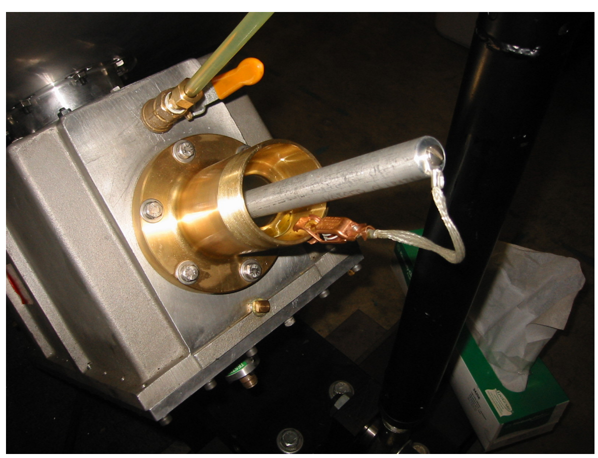

Fig. 7 Shorted drive connection

We might guess that the higher frequency (shorter wavelength) RF waves "propagating" from the gap region towards the insulator would be effected mainly by the cathode cap change. To test this hypothesis, the old cathode cap was installed on the test cell, with all the other design changes being the same. The measured impedance for this configuration is shown in Fig. 8 along with the impedance measurements on the original cell from Ref.1.

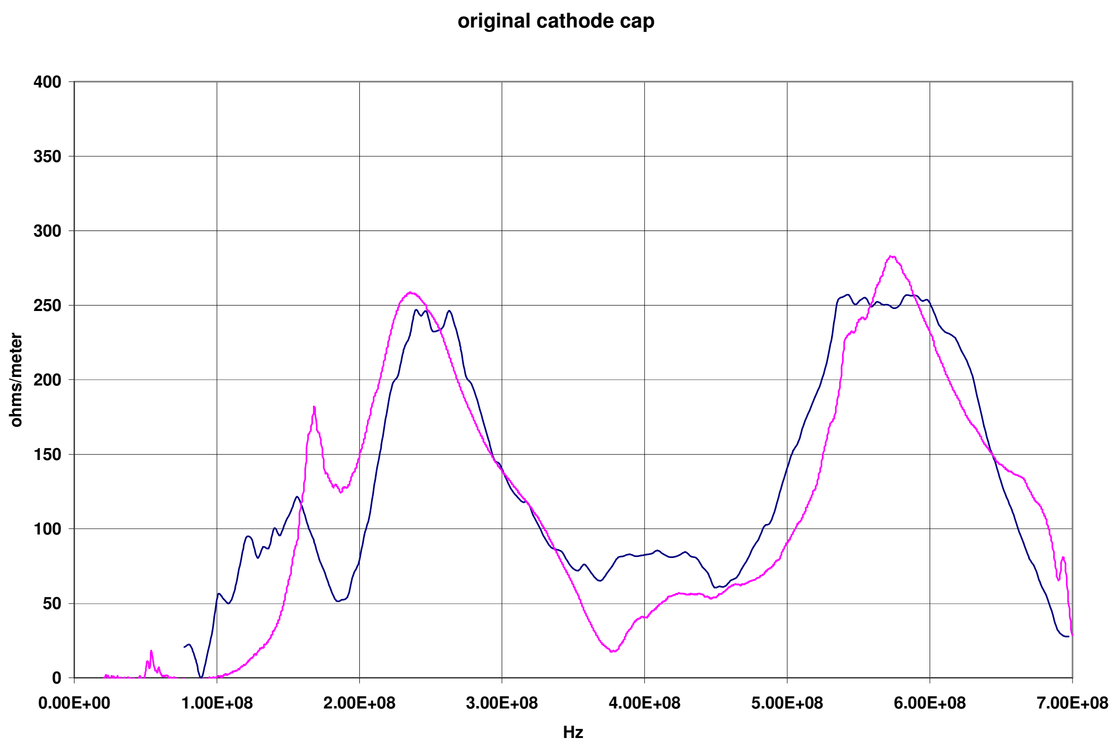

Fig. 8 Real part of the impedance measured with the old cathode cap installed on the test cell (blue), along with the impedance measurement on the original cell from Ref. 1 (magenta)

The two cases shown in Fig. 8 exhibit essentially the same peak impedance for both modes within the error bars of our measurement, so we believe the increase in the peak impedance of the upper frequency mode measured in the test cell (e.g., Fig. 6) is indeed due to the new cathode cap design.

As far as the more detailed features are concerned, we note that:

- The “flat top” on the upper frequency peak in the test cell data in Fig. 8 is correlated with a positive “bump” in the B theta signal vs. frequency due to slight mismatches, i.e., we expect the curve would be more rounded like the original impedance measurement with better matching of the twin lead drive.

- The relatively high Q lower frequency “sideband” seen on the original cell data in Fig. 8 appears to be much broader (or even absent) in the new cell. (The frequency digitizing steps used in the test cell data set shown in Fig. 8 would have broadened it somewhat, but this high Q feature isn't evident even with the finer step sizes used in other data sets.) We might speculate that changes in the oil region, like the 1" extension, are responsible for this modification since this little peak in impedance in the original cell has a very low Z/Q (i.e., the RF energy in the mode is mainly stored in regions away from the gap).

- As mentioned earlier, the matching of the twin lead was not optimized in the low frequency region in the test cell experiments, and the data below about 100 MHz also becomes very noisy. With the ferrite block removed, we looked carefully at the imaginary part of η data in the frequency region up to 100 MHz and found that it is zero to within the error bars of the experimental noise.

5. Conclusions

The measurements indicate that the peak impedance of the new cell design has increased by ~ 20% compared to the original design (see the comparison between the two presented in Fig. 9). This impedance increase is reasonable considering the fact that the distance from the new cathode cap to the finger stock fixture has increased by a similar amount. Replacement of the cathode cap with the old design resulted in essentially the same value of the peak impedance as before, giving us additional confidence in the measurements.

The data from this experimental series was not as clean or "nice looking" as the final measurements made on the original cell (Ref. 1). The earlier measurements were made with a more capable (and expensive) network analyzer, and they were also the end product of many iterations optimizing the matching of the twin lead and drive circuitry.

The BBU growth through the machine with the new cell design should continue to be minimal. With a 2 kA beam, 68 standard cells, an average B of 1 kG, and a 350 ohms/m peak value of the impedance, the estimated amplification factor is about 1.5 e-folds.

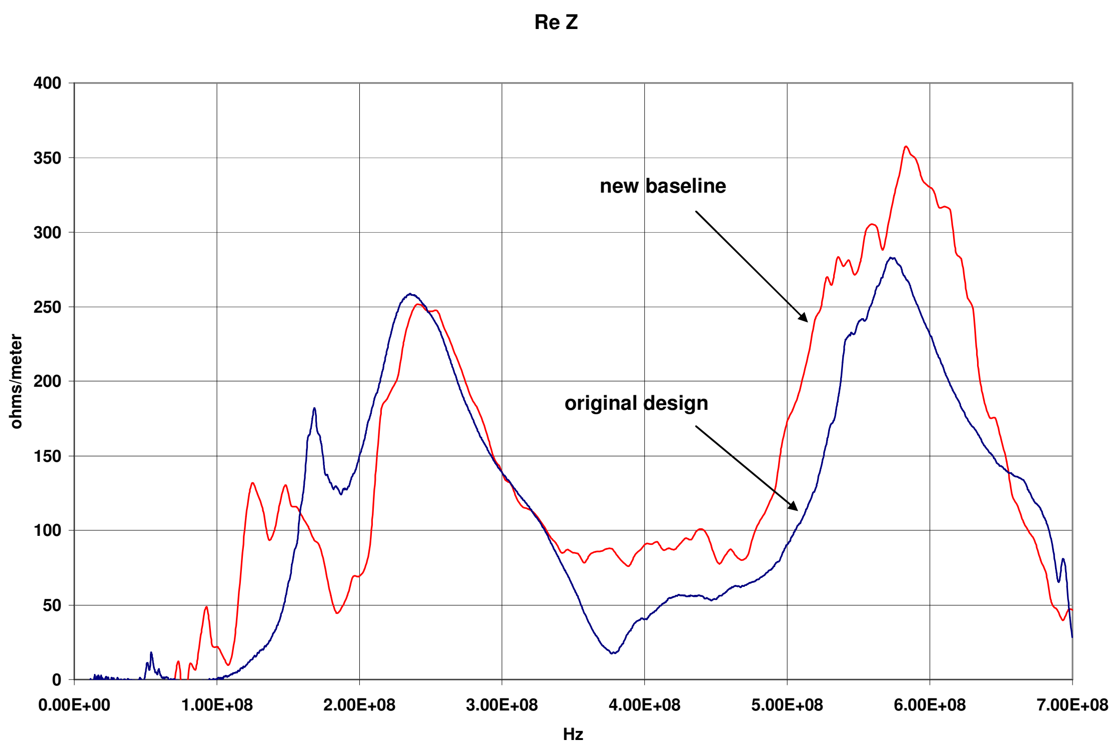

Fig. 9 Real part of the impedance measured on the new standard cell (red), along with the impedance measurement on the original standard cell from Ref. 1 (blue)

Acknowledgements

The excellent support of Ken Chow and the mechanical team in the design and assembly of the experimental hardware is appreciated.

References

1. "Campaign to Minimize the Transverse Impedance of the DARHT-2 Induction Linac Cells", Richard Briggs (SAIC) and William Fawley (LBNL), DARHT Tech. Note 424, LBNL-56796 (REV 1), March 15, 2005

(see also "Transverse Impedance Measurements of the DARHT-2 Accelerator Cell", R. Briggs, D. Birx, S. Nelson, L. Reginato and M. Vella, 2001 Particle Accelerator Conference, Paper TPH079, May 2001.)