

## Characterization and Comparison of Control Units for Piezo Actuators to be used for Lorentz Force Compensation in the ILC

Sampriti Bhattacharyya and Roman Pilipenko

### Abstract

Superconducting accelerators, such as the International Linear Collider (ILC), rely on very high  $Q$  accelerating cavities to achieve high electric fields at low RF power. Such cavities have very narrow resonances: a few kHz with a 1.3GHz resonance frequency for the ILC. Several mechanical factors cause tune shifts much larger than this: pressure variations in the liquid helium bath; microphonics from pumps and other mechanical devices; and for a pulsed machine such as the ILC, Lorentz force detuning (pressure from the contained RF field). Simple passive stiffening is limited by many manufacturing and material considerations [1]. Therefore, active tuning using piezo actuators is needed. Here we study a supply for their operation. Since commercial power amplifiers are expensive, we analyzed the characteristics of four power amplifiers: (iPZD) built by *Istituto Nazionale di Fisica Nucleare (Sezione di Pisa)*; and a DC-DC converter power supply built in Fermilab (Piezo Master); and two commercial amplifiers, Piezosystem jena and Piezomechanik. This paper presents an analysis and characterization of these amplifiers to understand the cost benefit and reliability when using in a large scale, pulsed beam accelerator like the ILC.

### Introduction:

The International Linear Collider is one of the most important ongoing projects at Fermi National Accelerator Laboratory and it is playing most vital role among 100 universities and countries worldwide to make the linear collider a reality [2]. The technical idea behind the plan is to have 16000 superconducting cavities tuned to a resonant frequency. These cavities are subjected to different distortions like Lorentz force detuning which causes the cavities to drift from the resonant frequency. This can be compensated by installing piezoelectric actuator local to the cavity wall which in turn would be driven by supplies with the following characteristics.

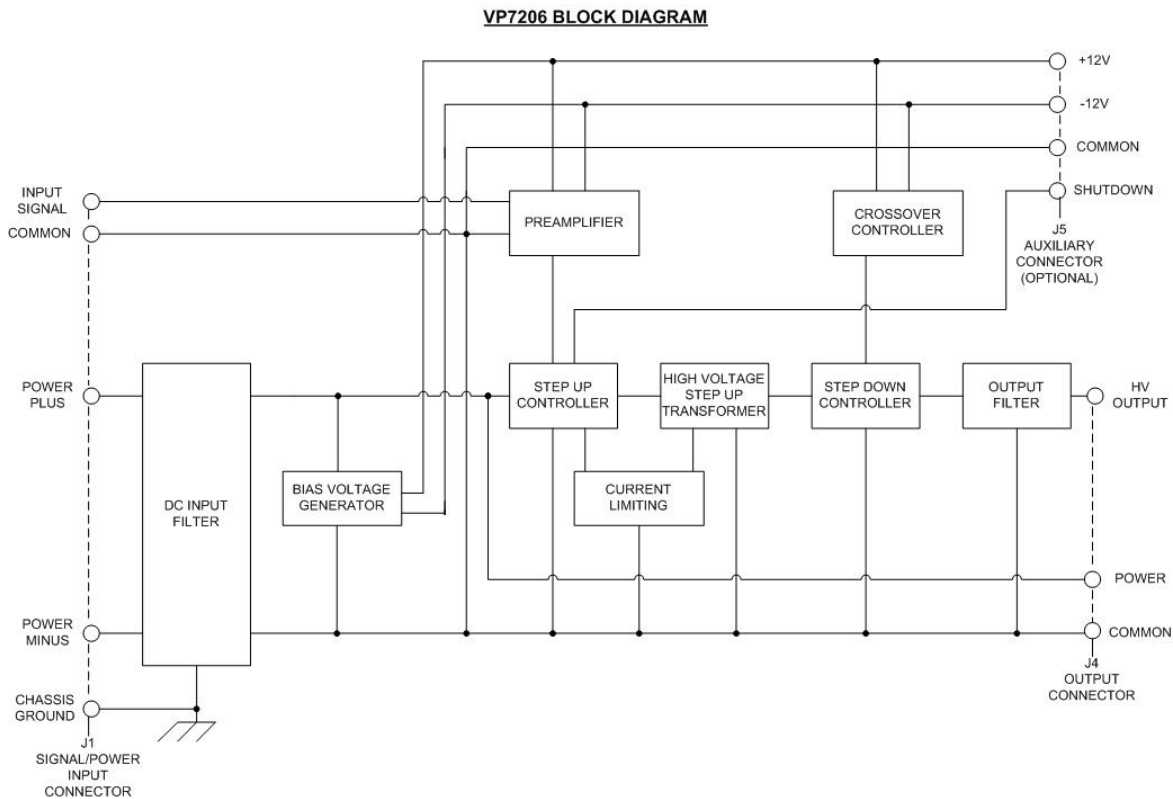
1. Relatively short pulse  
→ 1 KHz bandwidth
2. Can handle a DC offset
3. Low cost and high efficiency

The first system, iPZD, is made by the *Istituto Nazionale di Fisica Nucleare (Sezione di Pisa)*. A full Piezo Control Unit (PCU) includes 4 iPZD boards in a 6U-19" crate, together with power supplies. Each iPZD board has two independent channels allowing one PCU to control 8 actuators. The iPZD is designed specifically for piezo crystals at 2 – 4°K. The architecture is complementary MOSFET source followers for low output impedance, operated in class AB to reduce crossover distortion while maintaining high efficiency. The iPZD operates in closed loop below 30 Hz and transitions to open loop

for higher frequencies, allowing precise control of DC bias while maintaining high bandwidth. [3]

The second system we consider was assembled in-house using VP7206 “Piezo Master” units from Viking Industrial Products. The Piezo Master combines a switching amplifier with a step-up transformer to put out up to 200V (models also available for up to 800V). This allows high efficiency and a compact package. The amplifier is DC-coupled and has wide bandwidth. The output is rated for sourcing or sinking current, and for driving capacitive loads. It includes a current limit to protect the output stage [4]. Our system has 4 channels (instead of the 6 of the iPZD). A block diagram of a typical “Piezo Master” unit is reproduced (from the manufacturer) below.

The rest of the paper will deal with the analysis of these two systems and their characterization.



**Fig. 1** Schematic for a single PiezoMaster module

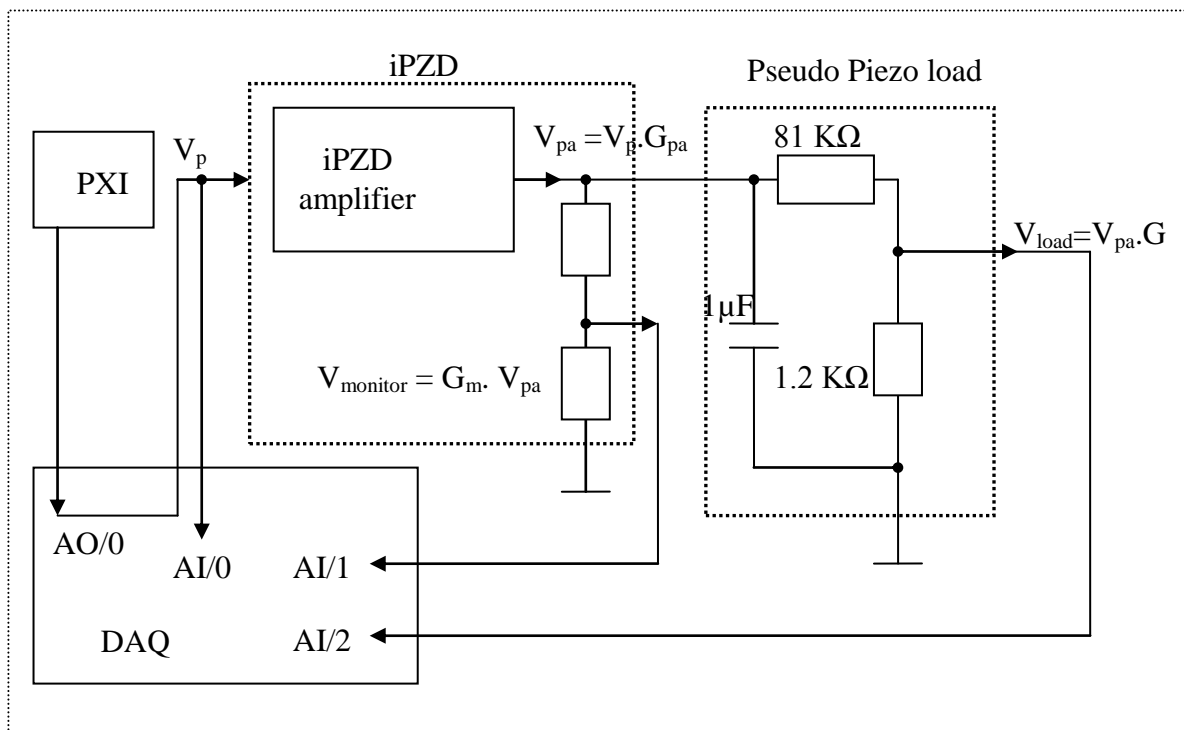
Schematic Source: <http://www.piezomaster.com/TechnicalInfo.htm>

## The Code

We use a LabVIEW code for acquisition of data. The code is able to measure parameters like amplitude, offset, and frequency. We performed experiment by setting the range of the parameters (for example, keeping frequency constant, and applying constant offset, we could do an amplitude scanning and read out the various outputs from the DAQ). The program was coded so as to be able to calculate the gain and phase from the received data. A dc bias is necessary in the amplifier for the purpose of providing a slow compensation against various microphonic distortions.

## Characterization of iPZD Control Unit

The test set up for the iPZD characterization is shown in the schematic below:



**Fig. 2** Block Diagram for Test Set-Up for iPZD characterization

The pseudo piezo load we use has a capacitance of 1  $\mu\text{F}$ , representative of a piezo crystal at cryogenic temperature. The resistive dividers are to help us to find the monitor gain. For finding the phase and gain versus frequency characteristics we omit the resistors.

### Terminologies:

- $V_p$  driving signal set by the program.
- $V_{pa}$  output voltage of the power amplifier iPZD
- $V_{\text{monitor}}$  voltage across the resistive divider, amplified by the opamp
- $V_{\text{load}}$  Voltage across the resistive divider of the load which represents the piezo crystal.

- $G_m$  Gain of monitor of iPZD.
- $G_{pa}$  Gain of the Power Amplifier iPZD
- $G$  Gain of the load (model of piezo).

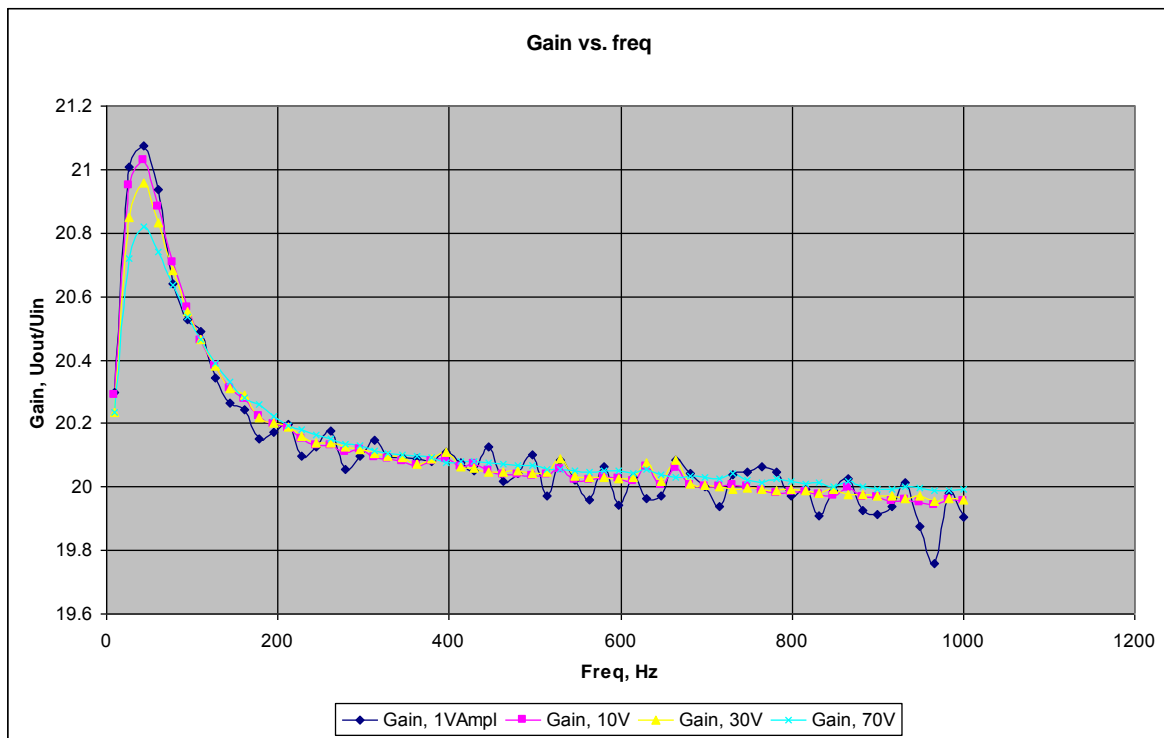
The first step was to measure the gain of the gain of the power amplifier and the monitor. We followed the following relation:

$$V_p G_{pa} = V_{pa} = V_{load} / G = V_{monitor} / G_m \dots\dots\dots (1)$$

From measurement, the gain of the load was found to be 1/68.5. Using the LabVIEW code, we did an amplitude scan at 100Hz and recorded the output of the load ( $V_{load}$ ) for input amplitudes  $V_p = .04V$  to 6V. Using equation (1) we could find  $V_{pa}$ , which when divided by the input voltage  $V_p$  gave us the gain of the iPZD amplifier. The approximate value of gain obtained from a series of test is approximately 20 for 100 Hz.

Similarly using (1) we found the monitor gain, dividing the output of the iPZD ( $V_{pa}$ ) by the output from the iPZD monitor ( $V_{monitor}$ ) to be approximately 88.

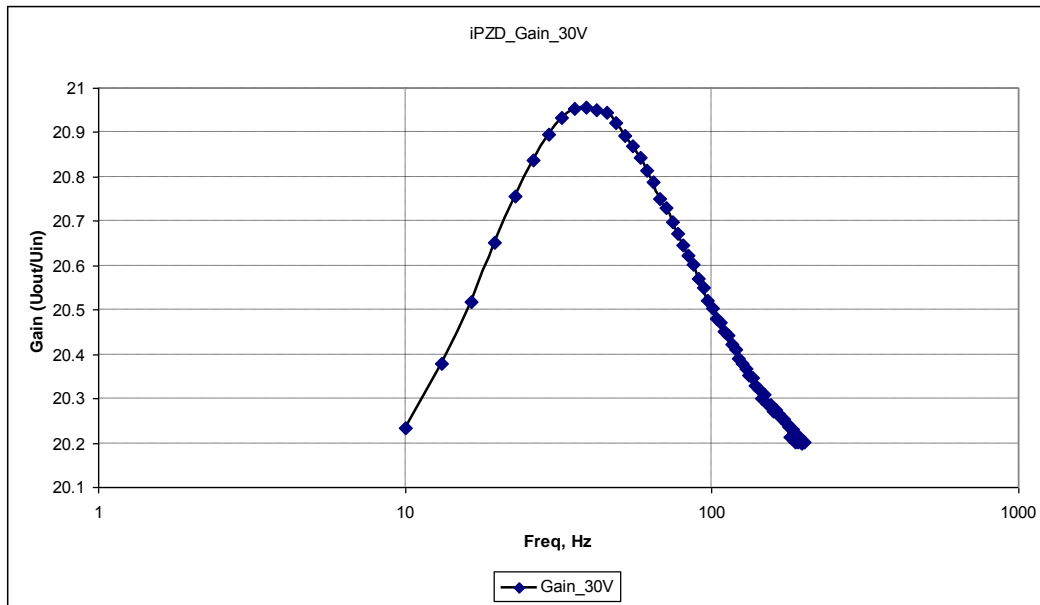
Our measurement of gain and phase was based on a frequency scan at output voltages,  $V_p$ , of 10V, 30V, and 70V. The results are shown as below.



**Fig. 3** Gain vs. Frequency for Channel-5, iPZD for amplitudes 1V, 10V, 30V and 70V

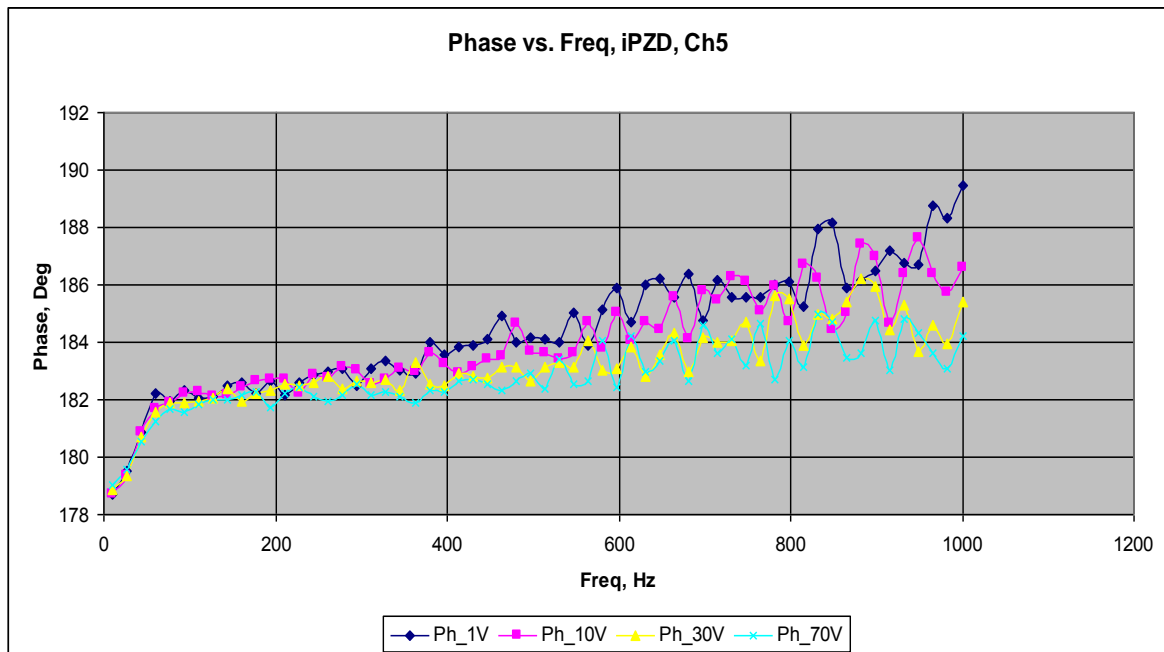
As clear from the graph, the gain of the iPZD is extremely stable with minimal variation. It is characterized by a peak in the 10-160 Hz region, but that accounts only 5% variation and can be corrected by software.

A clear representation of the peak is given in the plot below:



**Fig. 4** Bump in gain in the frequency region of 10Hz-160Hz

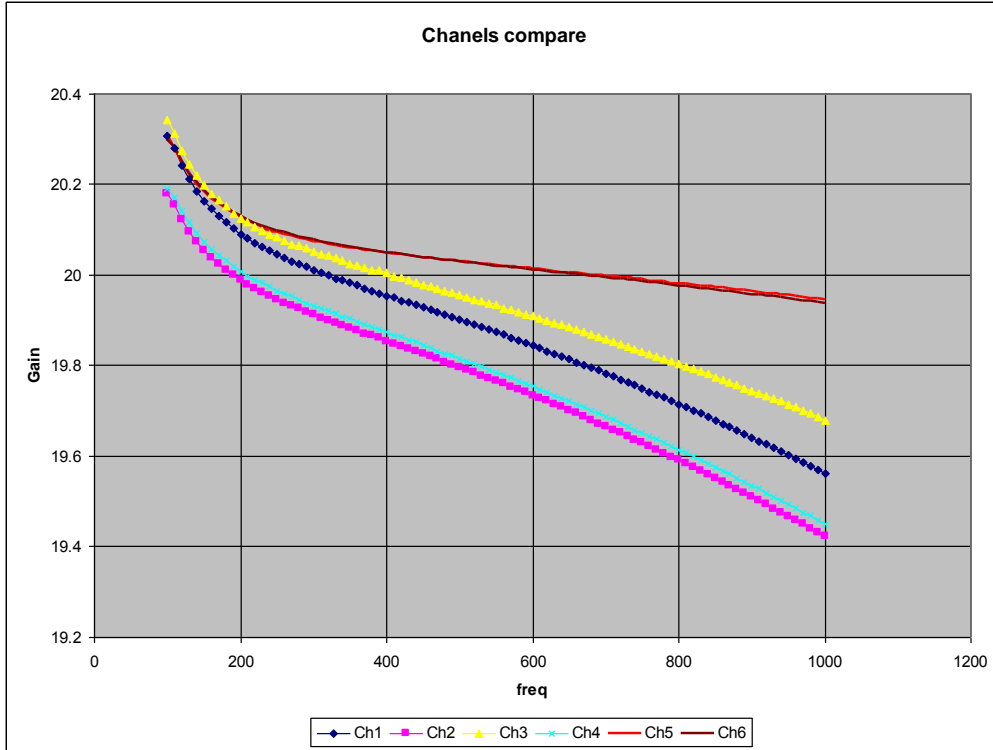
The phase analysis was done using the same code and it yielded the following results:



**Fig. 5** Phase vs. frequency for Ch-5, iPZD for amplitude 1V, 10V, 30V, 70V

As we see the phase characteristics meet our criteria and there is no phase reversal that could be otherwise problematic for our operation.

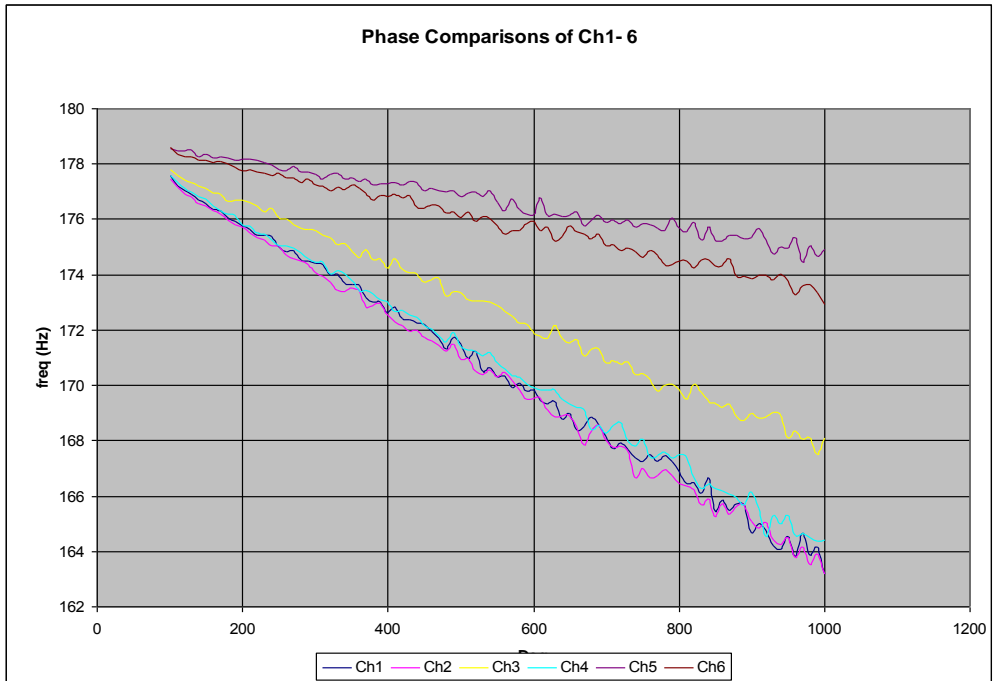
The iPZD has 6 channels which mean it can drive six piezo actuators at a time. The gain characteristics of the channels are described in the plot below.



**Fig. 6** Comparison of Gain vs. Frequency characteristic of Ch1-Ch6, iPZD

Channels 2 and 4 are seen to have similar behavior, as do channels 5 and 6. However it should be noted that the variation of gain is quite small over a wide frequency range.

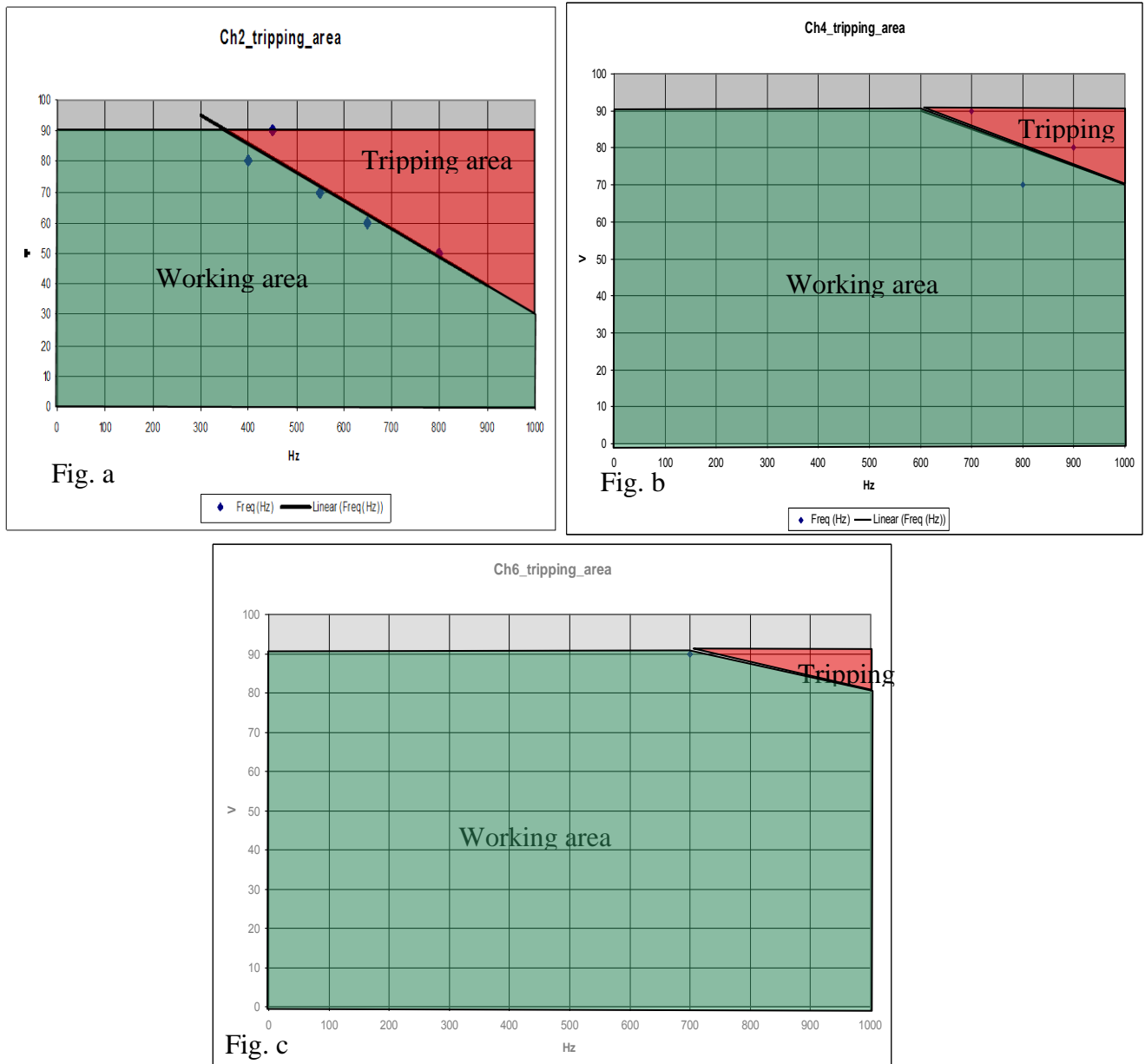
The following shows the phase comparison of the different channels.



**Fig.7** Phase comparison of Ch1-Ch6 of iPZD

It is interesting to note the present model of iPZD showed some strange even/odd channel behavior. An example of that is an experiment where we used amplitude of 80V and an offset of 75Volts. The result was that the even channels (2, 4, and 6) tripped while the odd channels (1, 3, and 5) did not. However the tripping takes place in high frequency/amplitude region and it does not impose any danger when working in the normal mode of 200-300Hz, 30V amplitude and offset of 90V.

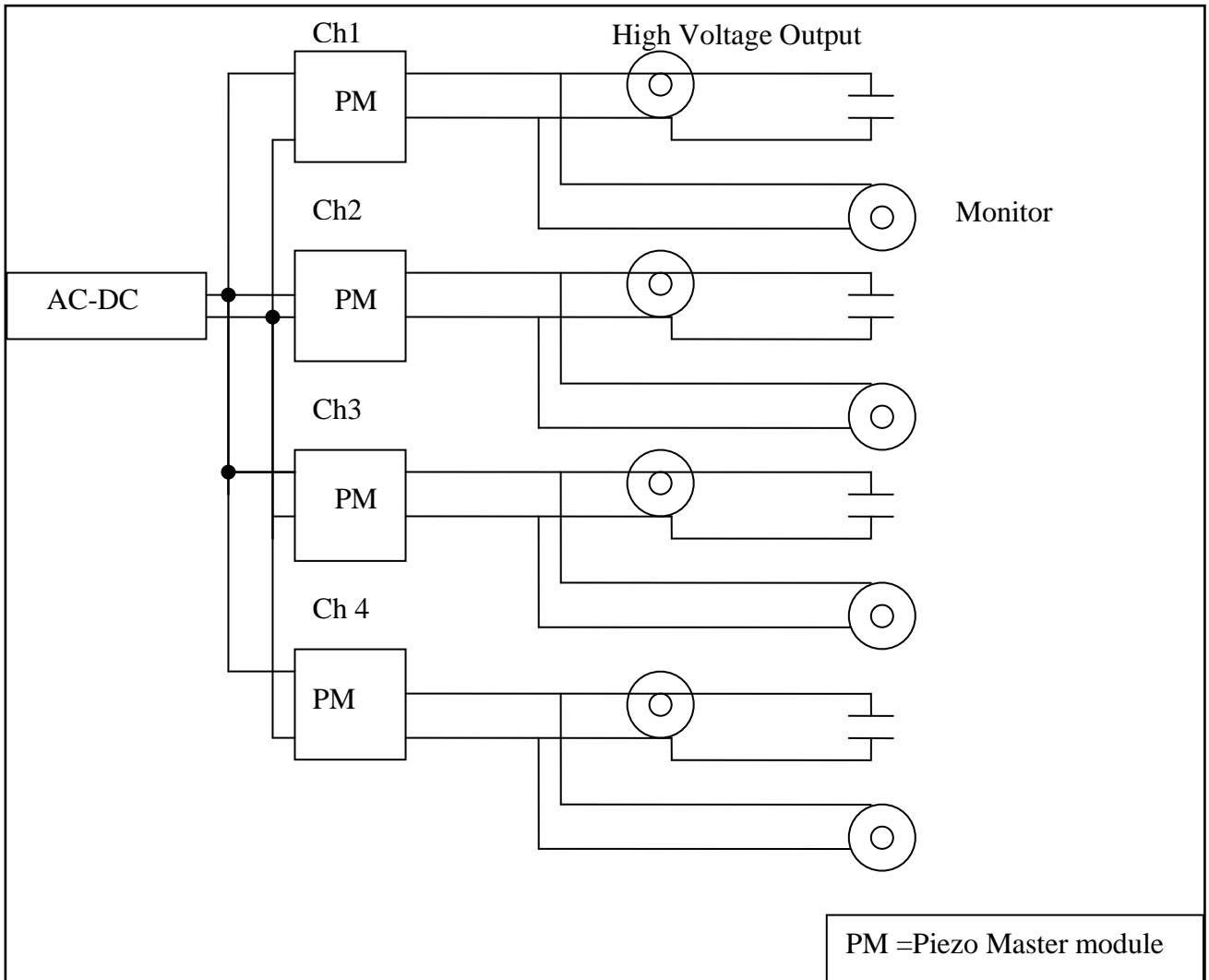
The following plots shows the working and tripping area of the “even” channels.



**Fig 8 a.** Tripping Characteristic of Channel 2 **b.** Tripping Characteristic of Channel 4  
**c.** Tripping characteristic of Channel 6

### Characterization of Piezo Master Control Unit

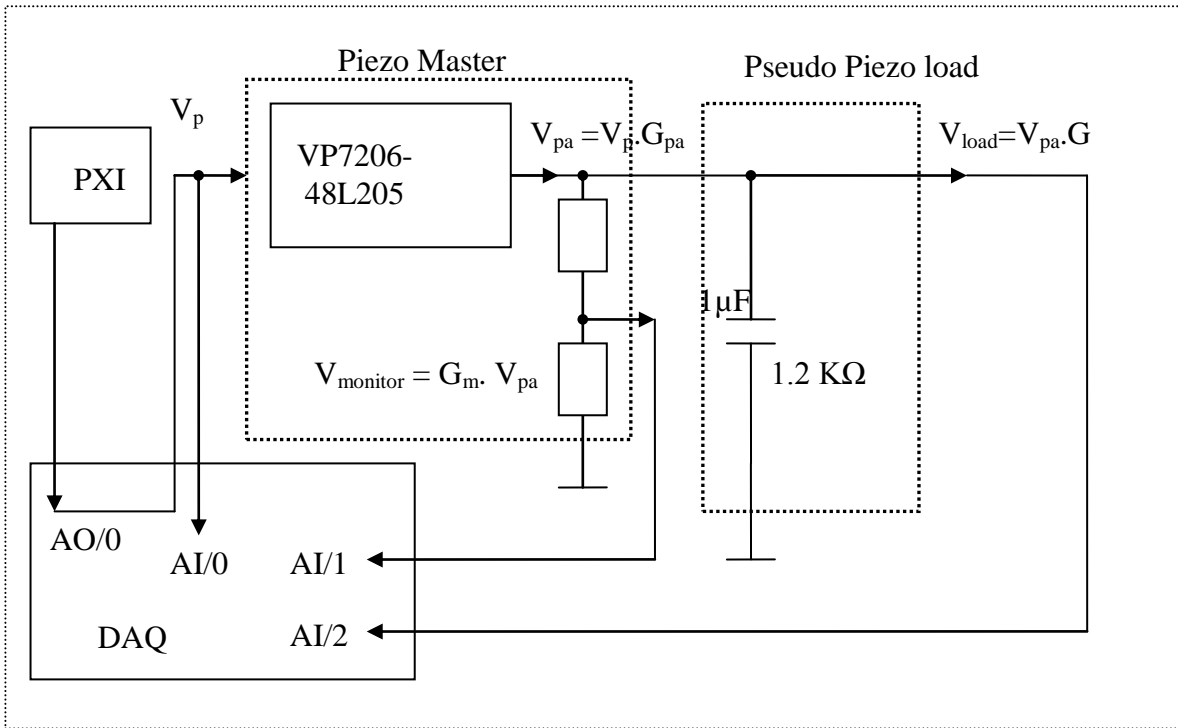
The Piezo Master control unit is a 4 channel actuator control unit assembled at Fermilab using Piezo Master modules VP7206-48L205 manufactured by Viking Industrial Products. Datasheet about the Piezo Master is available at <http://www.PiezoMaster.com/4205.htm> . This model has an output voltage range of 200Volts peak to peak. The schematic of the box (Fig. 9) is shown as below:



**Fig. 9** Block Diagram for Piezo Master Control unit containing 4 piezo master module

The experimental set up (Fig 10) for finding the gain and phase is similar to that we used in iPZD analysis. However in this case, we measured the monitor gain to be equal to 1/100 and the power amplifier has a gain of 50. So, we did not need any resistance in the load to determine the gain of the said two parameters.

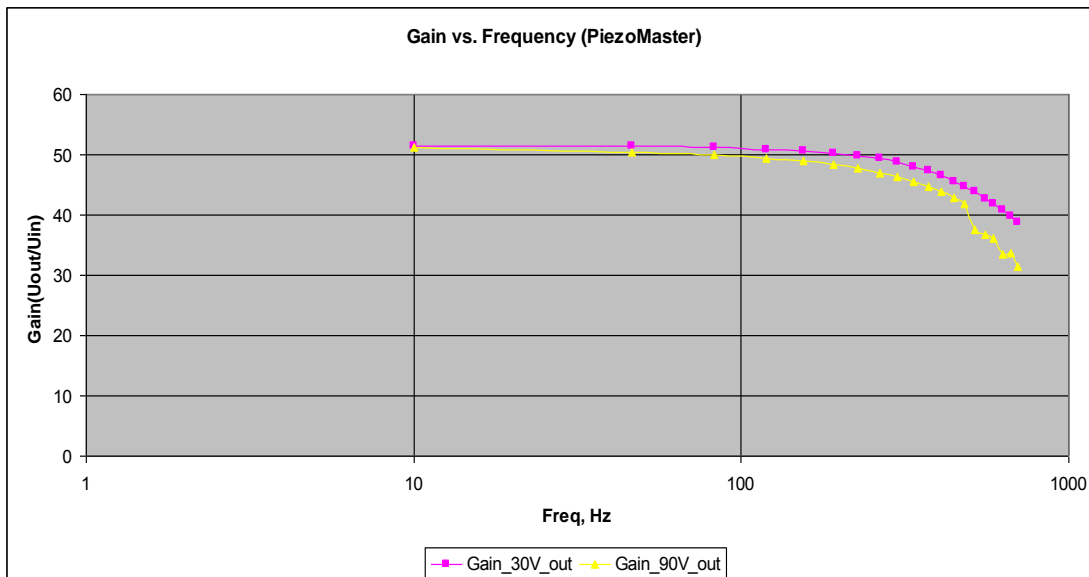




**Fig. 10** Block Diagram for Test Set Up for Piezo Master Characterization

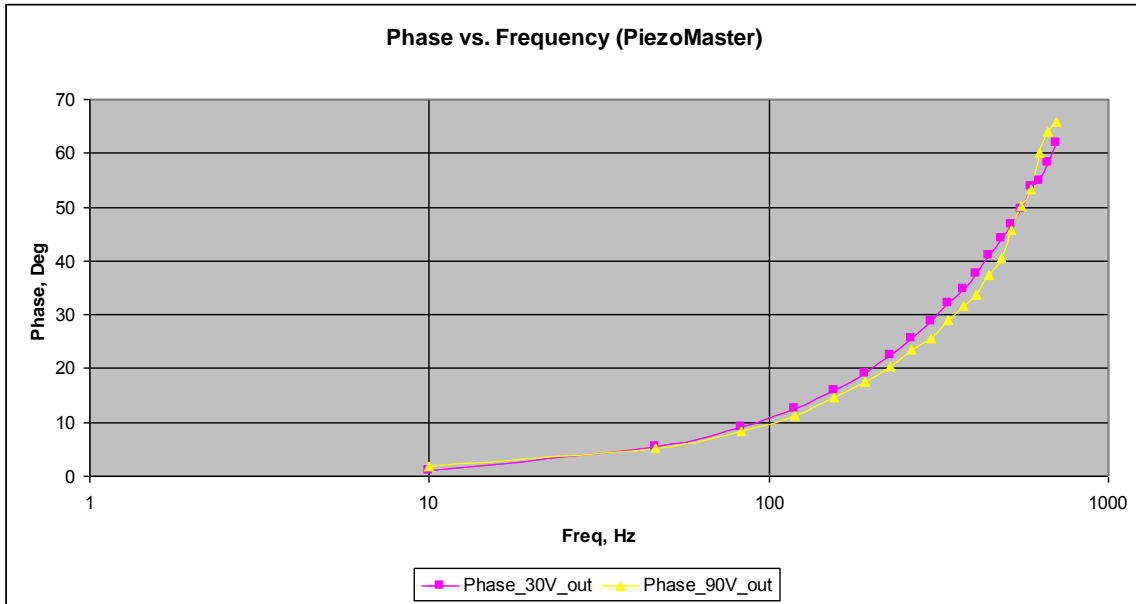
We used the same LabVIEW code to characterize the phase and gain for the Piezo Master which yielded the following results.

The following plot shows the gain characteristic of the Piezo Master. As we can see the Piezo Master has a smaller working bandwidth, i.e. its gain changes considerably within the frequency of 100Hz-1000Hz.



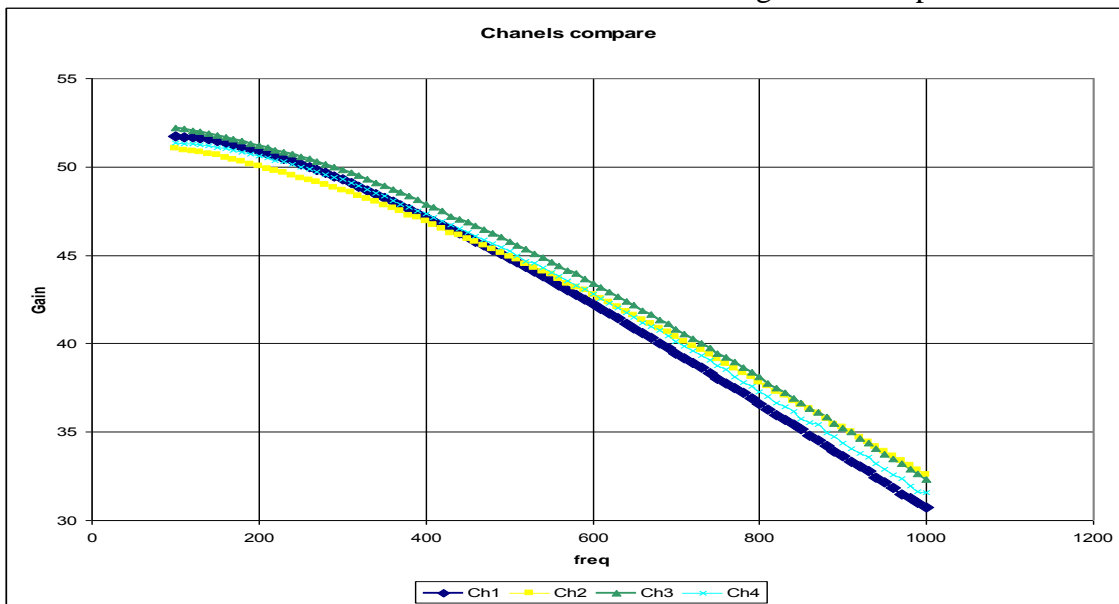
**Fig. 11** Gain vs. Frequency for Ch-2, Piezo Master at amplitudes 30V and 90V

The phase though shifted considerably did not undergo any reversal and hence is suitable for working in the required mode for the accelerator without any problem.



**Fig. 12** Phase vs. Frequency for Ch2, Piezo Master

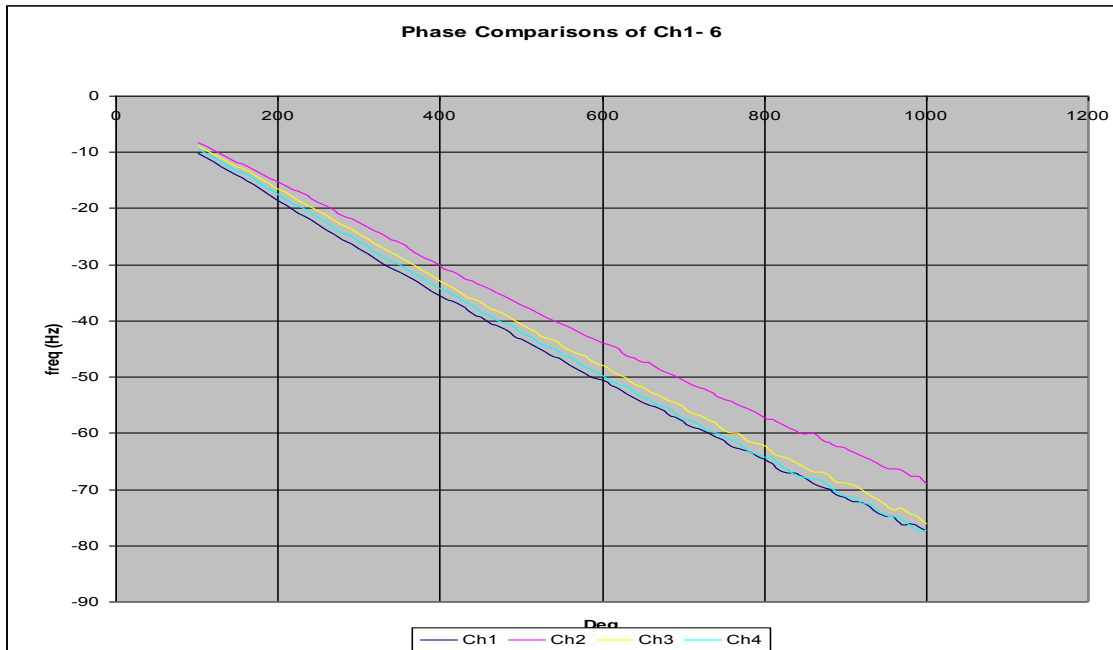
The Piezo Master has 4 channels and their characteristic is given in the plot below.



**Fig 13** Comparison of Gain vs. Frequency of Ch1-Ch 4, Piezo Master

As we can see the channels in the Piezo Master are more alike to each other than the channels in iPZD. However the variation of gain is quite large as compared to the iPZD. For example, in Channel 2, it changes from 52 to 32, whereas in Italian PIEZO, it changes from 20.2 to 19.4 for same range.

The plot for phase comparison of the four channels is as follows:

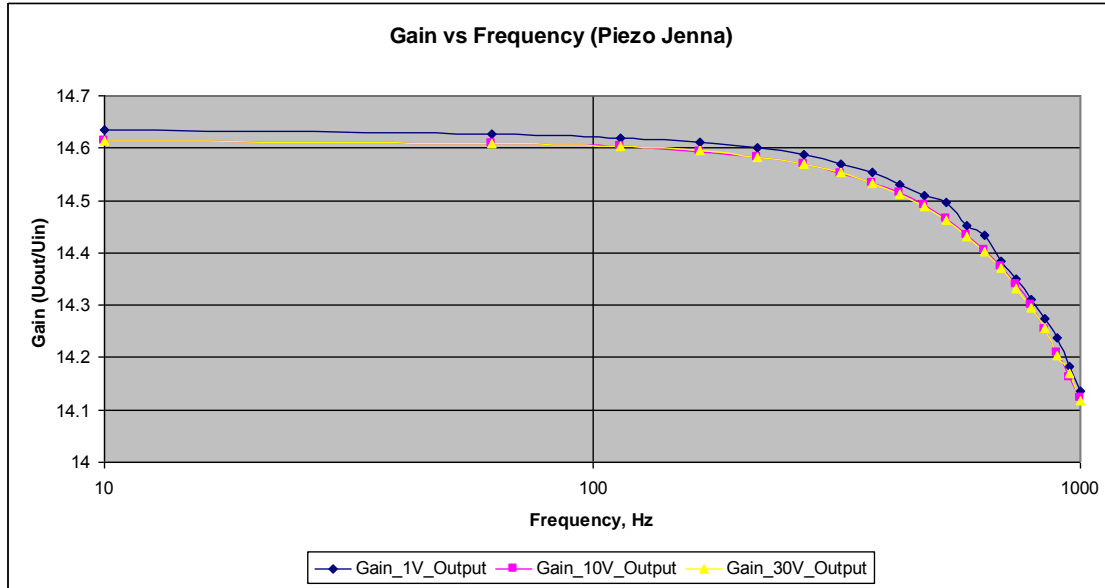


**Fig.14** Phase comparison of Ch1- Ch4, Piezo Master

### Commercial Amplifiers:

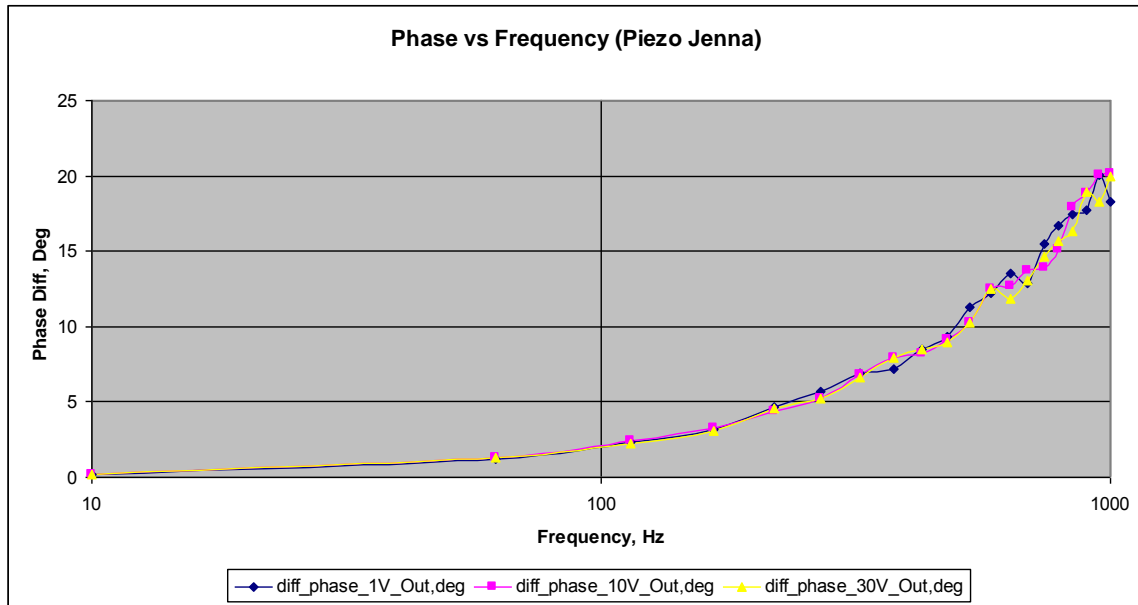
In our experiment we tried to understand the performance of the in house built actuator controllers with respect to the commercial ones. For this purpose we further analyzed two piezo control units, the Piezोजना (manufactured by Piezosystem Jena) and PiezoMechanik (manufactured by GmbH) each of which has a single channel. These controllers are much more expensive than the previous two units, but also have more precision than any of the in house built ones. The Piezo Jena has an amplifier gain of 15 and a monitor gain of 1/10. The Piezomechanik has an amplifier gain of 50 (and it can also be changed to 100) and a monitor gain of 1/15.

The graphs below show the phase gain characteristics of the PiezoJena amplifier.



**Fig. 15** Gain vs. Frequency, PiezoJena

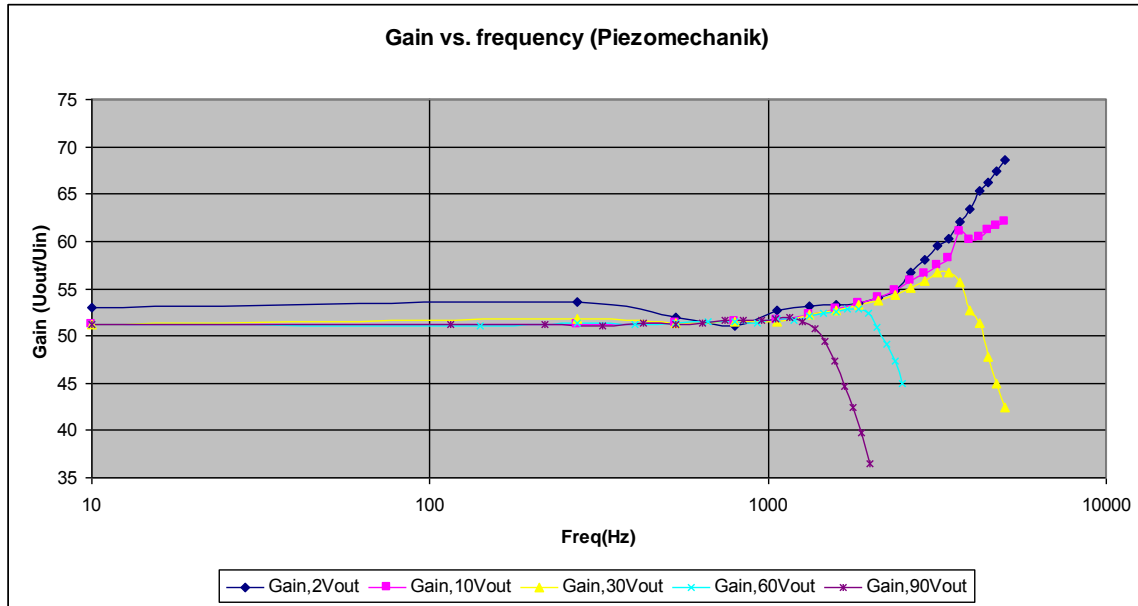
As we can see the PiezoJena has a working region of 10Hz to 700Hz. It is quite similar in its characteristics to the iPZD, both having very small variation in the gain. However unlike iPZD, this does not suffer any sharp peak in the low frequency region.



**Fig.16** Phase vs. Frequency, PiezoJena

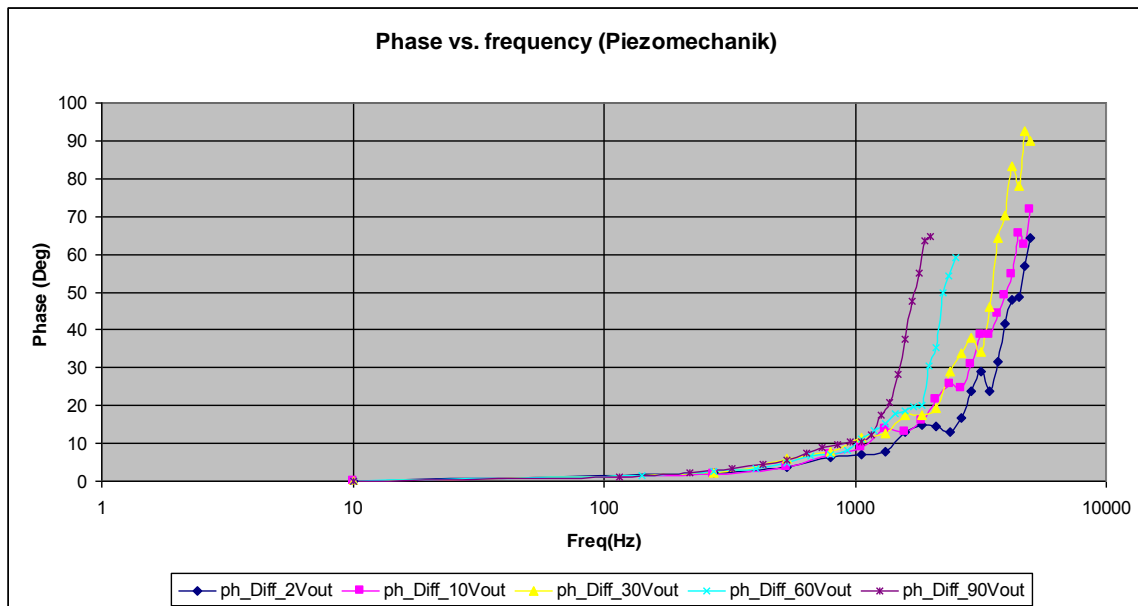
The above plot showing the phase versus frequency of piezojena shows that it suffers no considerable phase shift or reversal.

The plot below shows the gain characteristics of Piezomechanik. Its gain is very similar to the Piezo Master, but with a bandwidth extending to over 1000Hz. It appears non linear (gain varies with amplitude) for frequencies over 1000Hz.



**Fig. 17** Gain characteristics of PiezoMechanik

The phase versus frequency of the Piezomechanik is as below.



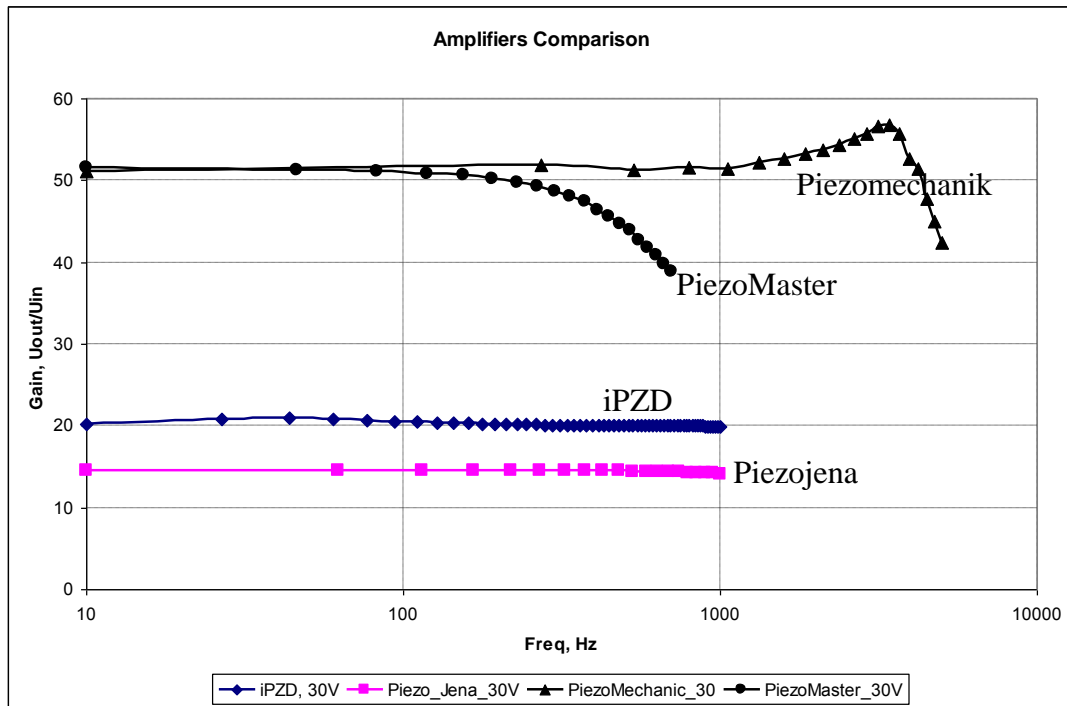
**Fig. 18** Phase vs. Frequency Characteristic of Piezo Mechanik

## Comparison

When choosing piezo actuator control units for large scale projects like the ILC, we take into consideration the following two criteria:

1. Performance in the desired working region
2. Cost effectiveness

Based on our extensive experimental analysis we made a comparison of the different control units that we dealt with. We found that the Piezोजना and the iPZD have a strong similarity as far as consistency of the gain goes and the Piezomechanik and Piezo Master also exhibited similar characteristics.



**Fig. 19** Comparison of gain characteristics of iPZD, Piezo Master, PiezoJena and PiezoMechanik

We evaluated the amplifiers based on some specific parameters. The comparison chart is given as below:

Parameter	iPZD	Piezo Master	Piezोजना	Piezomechanik
Amplifier Gain (for our tests)	20	50	15	50
Working region	1600Hz. Has a bump in gain accounting for 5% variation.	Upto 400Hz. Its gain falls off sharply at higher	Upto 700Hz. Gain variation is very less.	It has the largest working bandwidth,

	Overall gain variation is very less.	frequencies. Gain variation is larger.		i.e. 10Hz to over 1000Hz. Over 1000Hz the gain changes sharply.
Channel	6 in number. Channel characteristics vary. Even channel trips in the high frequency/amplitude region.	4 in number. Channels are more similar to each other.	Single channel.	Single channel.
Cost/channel	1500\$	500\$	3000\$	7000\$

## Conclusion

Both iPZD and Piezo Master met the criteria for operation at the ILC and also proved to be much more economical compared to commercial amplifiers. Neither of them are however suitable for high frequency operation, which we do not require for the ILC. Moreover from our experiments we have found the Piezo Master is more robust than iPZD though its gain drops rapidly above ~400Hz, we have protection from high frequency reactive current flow. Its internal over current protection allows it to avoid any damage due to short connection. Combining the commercially-built Piezo Master modules with minimal in-house engineering and assembly has proved to be extremely cost effective for large scale production. We believe that with further work there would be more sophistication and modification implemented in our present in house built control units.

## REFERENCES

- [1] S. N. Simrock, DESY, Hamburg, Germany “Lorentz Force Compensation of Pulsed SRF Cavities” Proceedings of LINAC 2002, Gyeongju, Korea.
- [2] <http://www.linearcollider.org/cms/?pid=1000000> –Official website for International Linear Collider.
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- [4] <http://www.piezomaster.com/TechnicalInfo.htm>