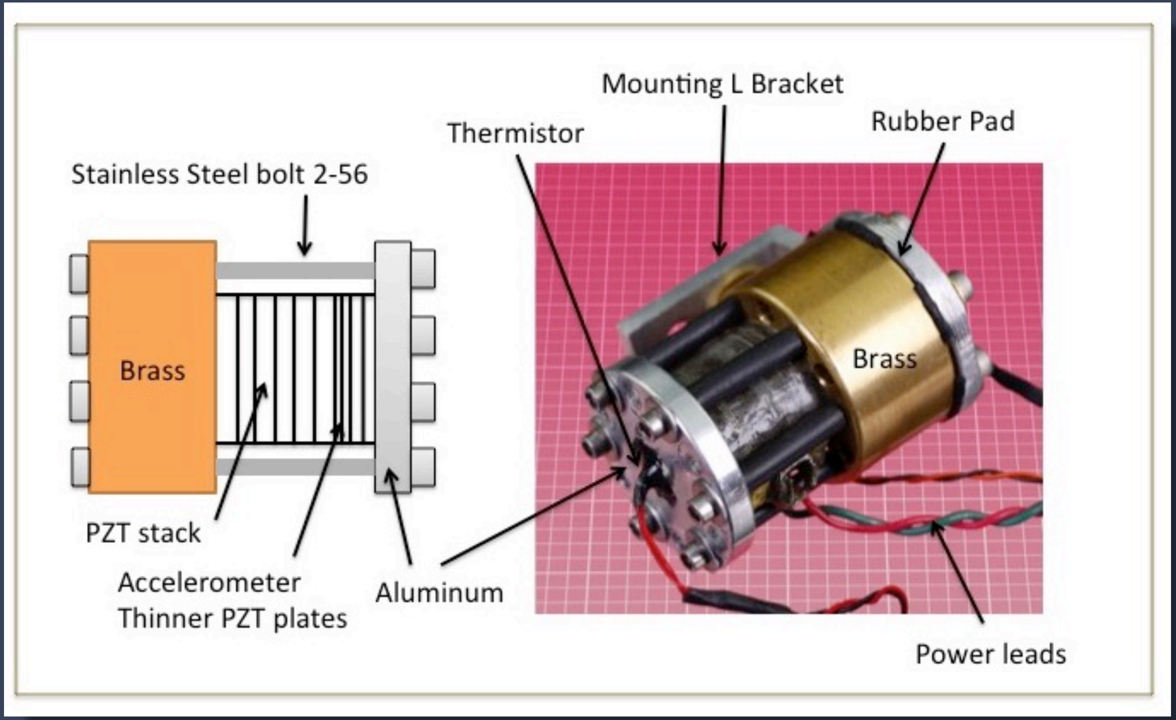
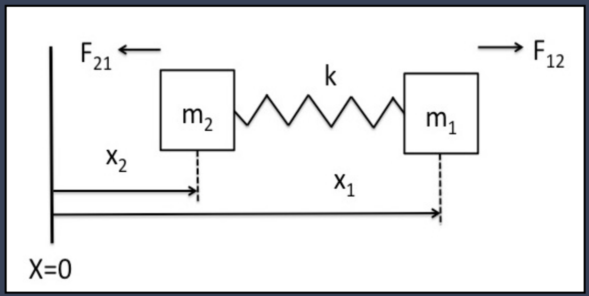
Drs. Heidi Fearn & J. F. Woodward

The *MEGA* drive



How to get a DC acceleration from oscillating masses ?



$$m_1\ddot{x}_1 = -k(x_1 - x_2 - L) + F_{12}$$
$$m_2\ddot{x}_2 = +k(x_1 - x_2 - L) + F_{21}$$

adding these equations gives,

$$m_1\ddot{x}_1 + m_2\ddot{x}_2 = -k(x_1 - x_2 - L) + F_{12} + k(x_1 - x_2 - L) + F_{21}$$
$$F_{12} = -F_{21}$$
$$\Rightarrow m_1\ddot{x}_1 + m_2\ddot{x}_2 = 0.$$

The COM of this mass-spring arrangement is given by

$$x_{com} = \left(\frac{m_1x_1 + m_2x_2}{m_1 + m_2}\right).$$

The acceleration of the COM, for masses taken to be constant, is therefore

$$a_{com} = \ddot{x}_{com} = \left(\frac{m_1\ddot{x}_1 + m_2\ddot{x}_2}{m_1 + m_2}\right) = 0$$

$$a_{com} = \ddot{x}_{com} = \left(\frac{1}{m_1+m_2}\right)\left[2\left(\dot{m}_1\dot{x}_1 + \dot{m}_2\dot{x}_2\right) + \left(m_1\ddot{x}_1 + m_2\ddot{x}_2\right) + \left(\ddot{m}_1x_1 + \ddot{m}_2x_2\right)\right]$$
$$-\left(\frac{2}{(m_1+m_2)^2}\right)\left[\dot{m}_1 + \dot{m}_2\right]\left[\left(m_1\dot{x}_1 + m_2\dot{x}_2\right) + \left(\dot{m}_1x_1 + \dot{m}_2x_2\right)\right]$$
$$-\left(\frac{1}{(m_1+m_2)^2}\right)[m_1x_1 + m_2x_2][\ddot{m}_1 + \ddot{m}_2] + \left(\frac{2}{(m_1+m_2)^3}\right)[m_1x_1 + m_2x_2][\dot{m}_1 + \dot{m}_2]^2$$

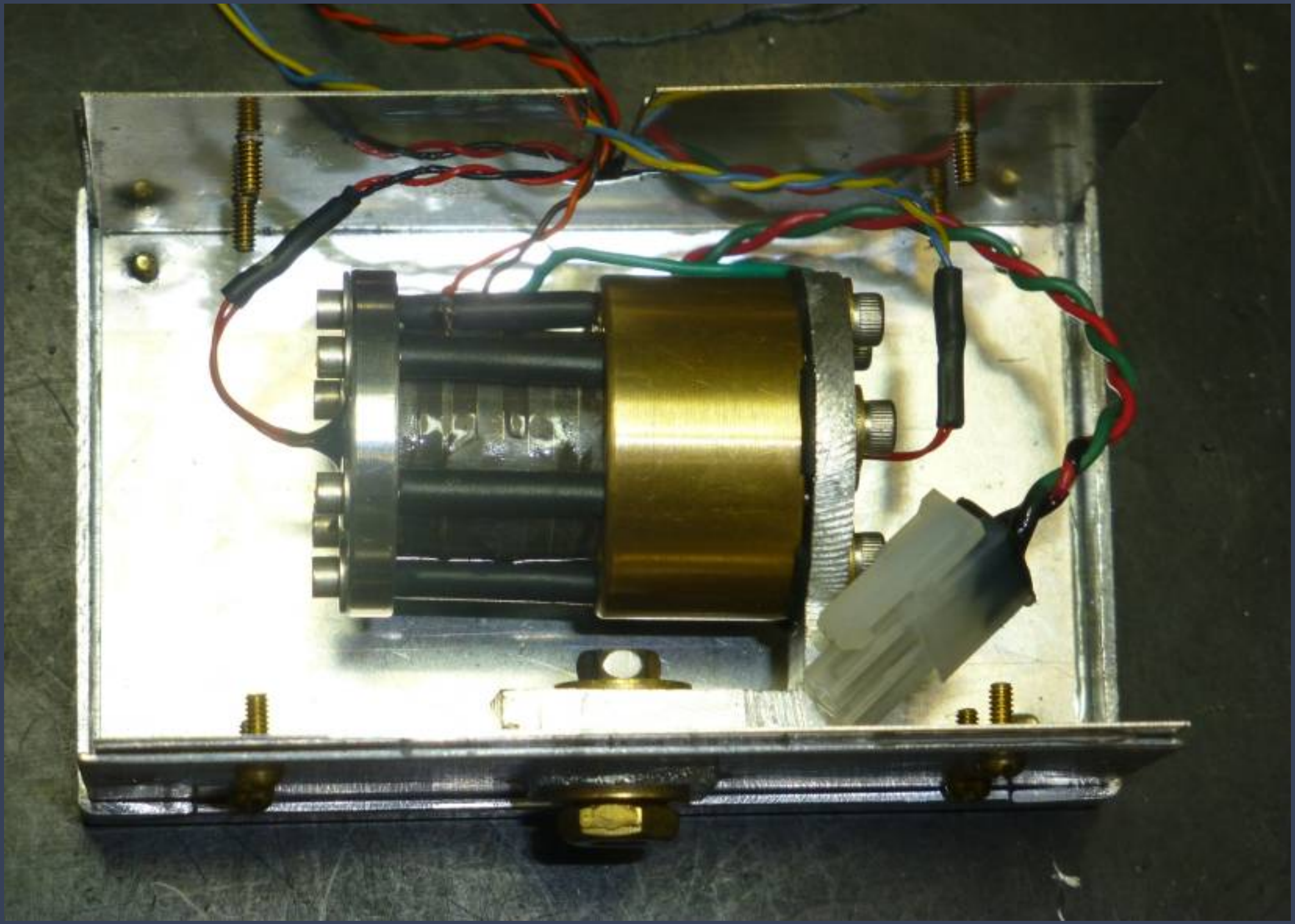
Using $(m_1\ddot{x}_1 + m_2\ddot{x}_2) = 0$ from Eq. (2), the total mechanical momentum p is given by,

$$p = m_1\dot{x}_1 + m_2\dot{x}_2$$
$$\dot{p} = \left(\dot{m}_1\dot{x}_1 + \dot{m}_2\dot{x}_2\right) + \left(m_1\ddot{x}_1 + m_2\ddot{x}_2\right) = \left(\dot{m}_1\dot{x}_1 + \dot{m}_2\dot{x}_2\right)$$

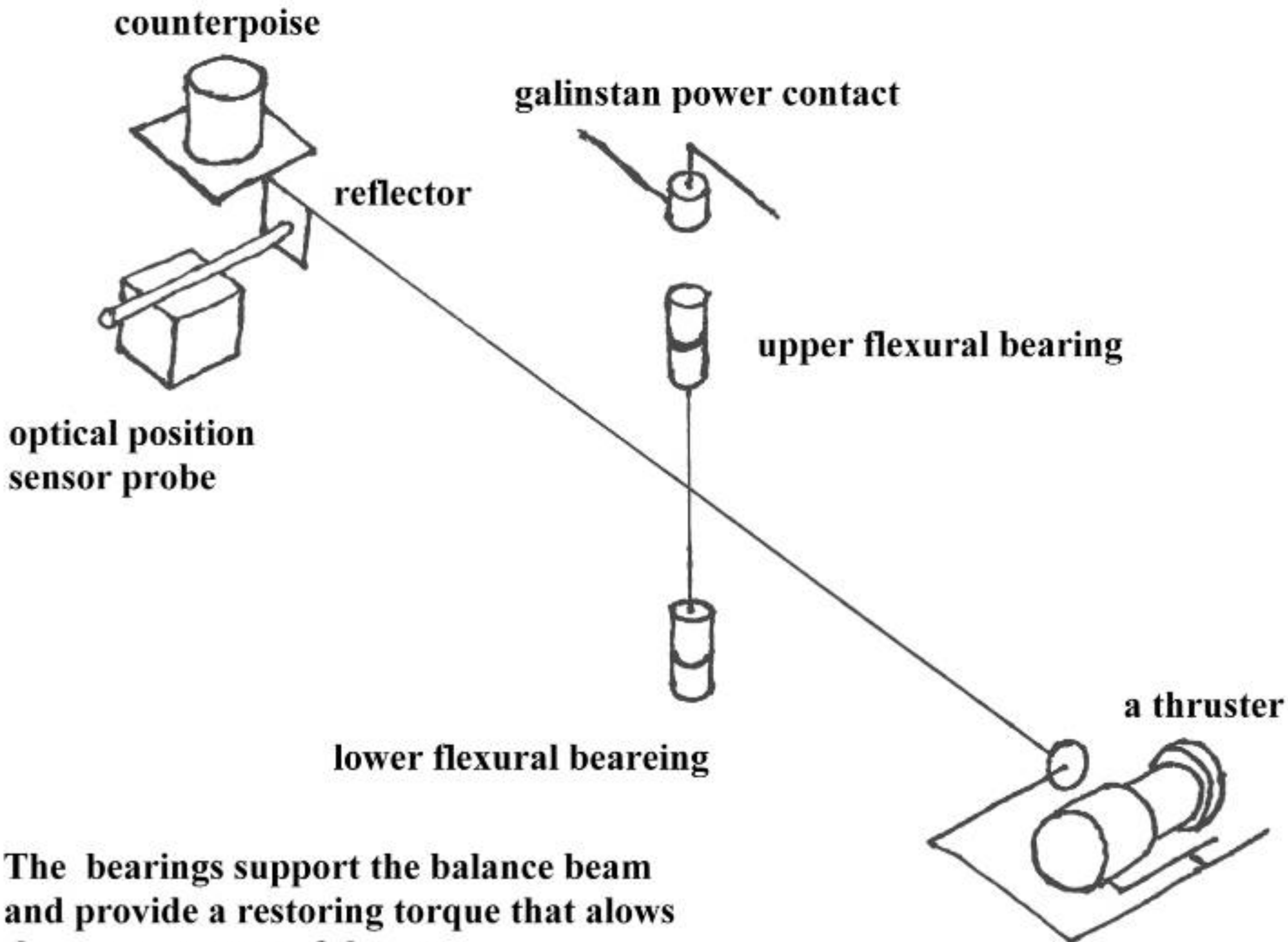
$$p = m_1\dot{x}_1 + m_2\dot{x}_2$$
$$\dot{p} = (\dot{m}_1\dot{x}_1 + \dot{m}_2\dot{x}_2) + (m_1\ddot{x}_1 + m_2\ddot{x}_2) = (\dot{m}_1\dot{x}_1 + \dot{m}_2\dot{x}_2)$$

We will take the force to be approximated by $F = \dot{m}\dot{x}$ for Eq. (6) where the extension of the stack with six, 2-56 stainless steel bolts, is $\Delta x \sim 5\mu m$ and the resonant frequency of operation is ~36 kHz, so the period of oscillation is $\Delta t \sim 2.75 \times 10^{-5}$ seconds. So $\dot{x} = \Delta x / \Delta t = 0.18$ m/s. Using the first term in Eq. (18) the value of $\delta m \sim 6.27 \times 10^{-6}$ kg. Using Power, P = I V, current I = 0.5 A ,V=200 volts, density PZT, $\rho = 7.9 \times 10^3$ kg/m^3 and $G = 6.674 \times 10^{-11}$ m^{3}kg^{-1}s^2. We find the force $F \approx 1.09 \mu N$. The order of magnitude of this force is correct.

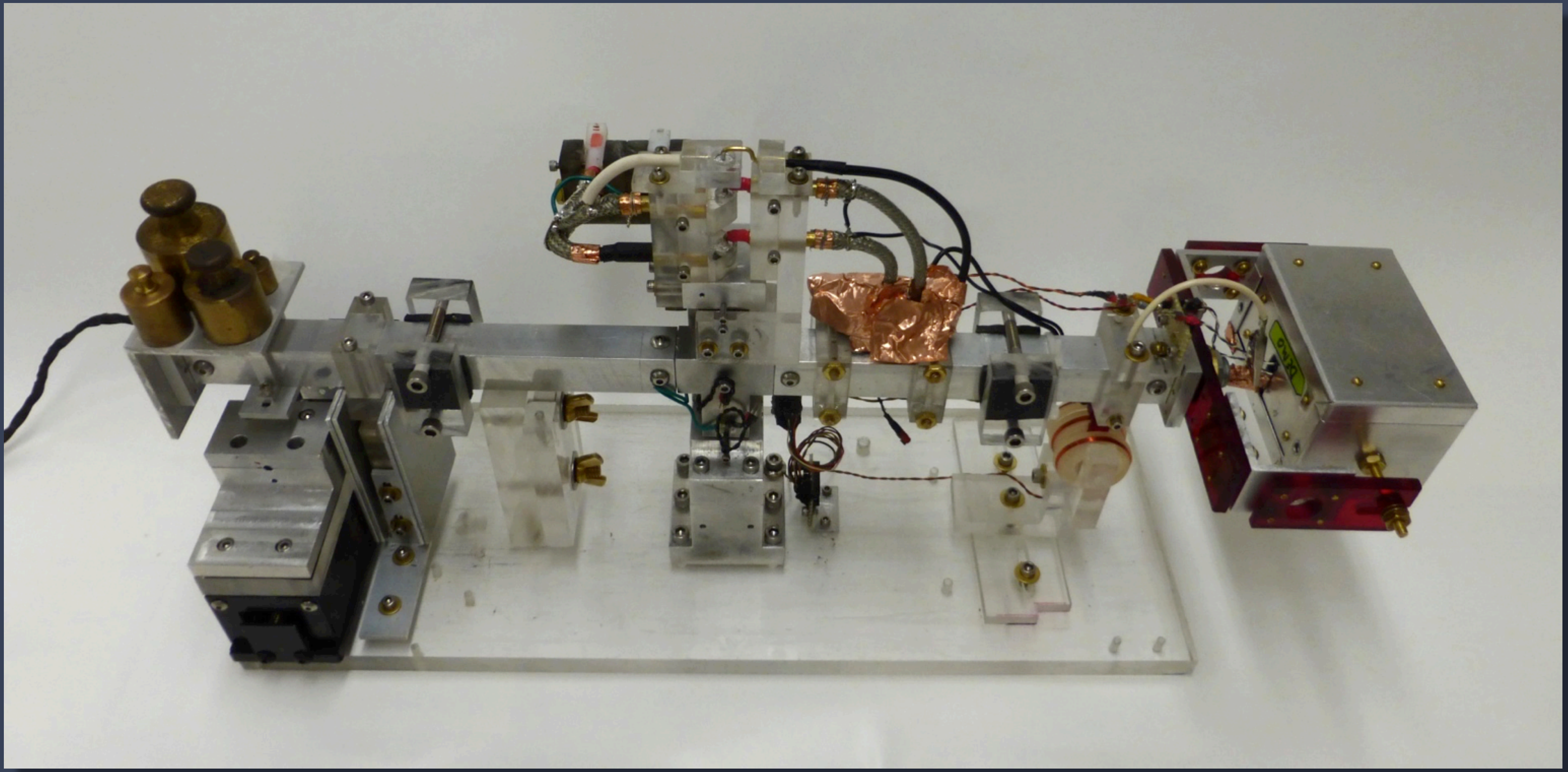
$$\delta m_0 = \frac{1}{4\pi G}\left[\frac{1}{\rho_0 c^2}\frac{\partial P}{\partial t} - \left(\frac{1}{\rho_0 c^2}\right)^2 \frac{P^2}{V}\right]$$



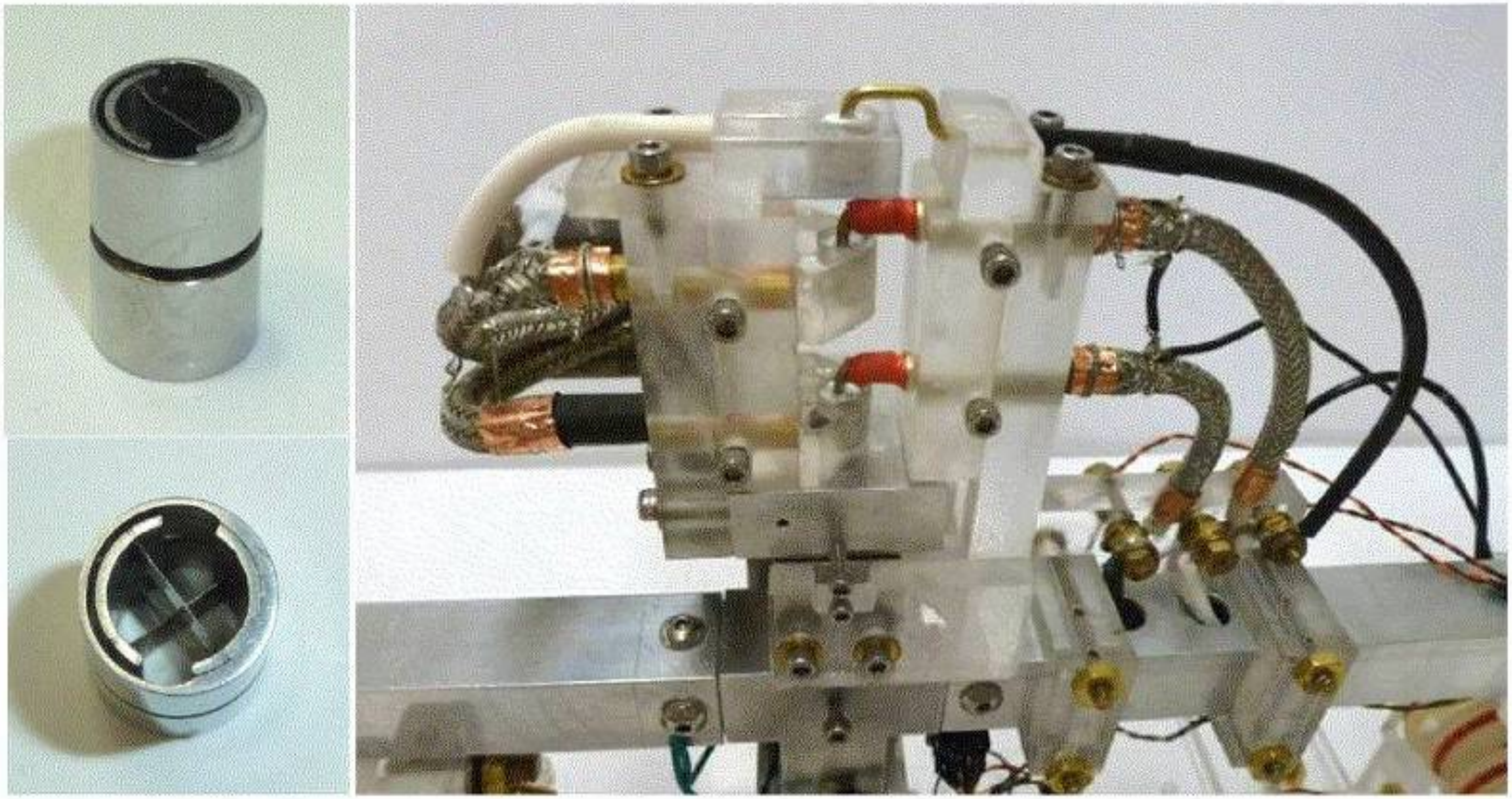
The MET being tested mounted in the half-shell of a mu metal lined Faraday cage.



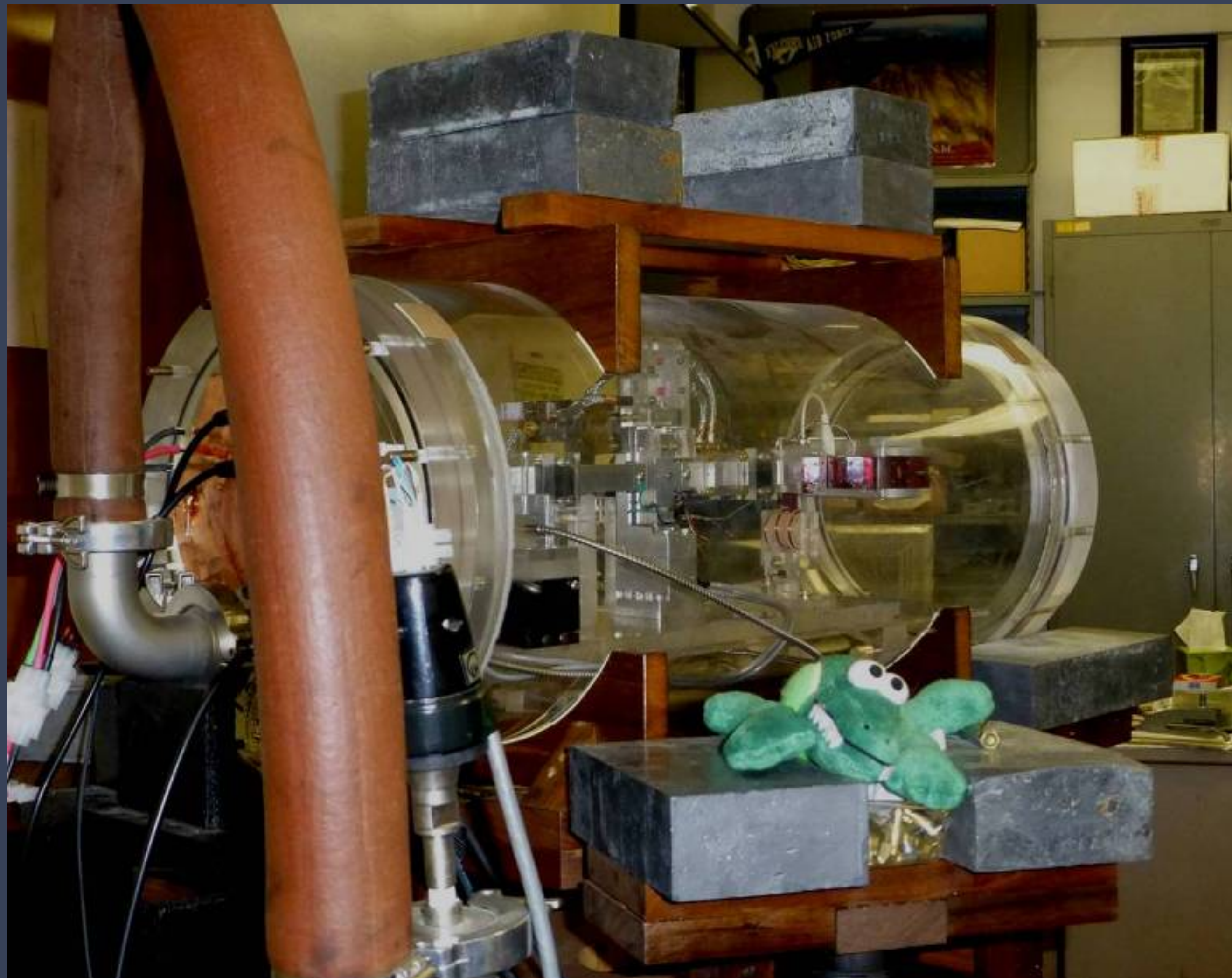
The bearings support the balance beam
and provide a restoring torque that alows
the measurement of thrusts.



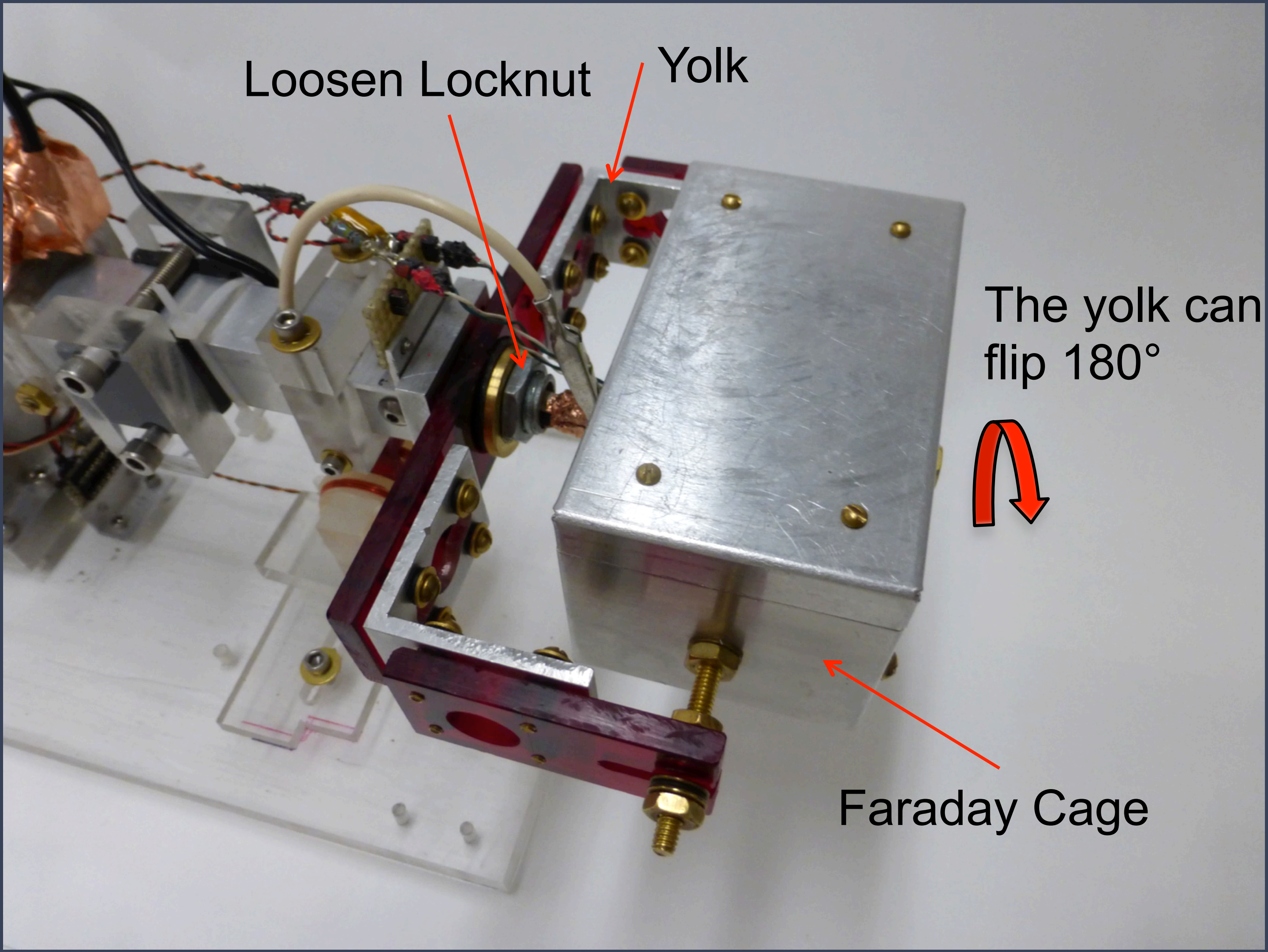
CSUF Balance beam.

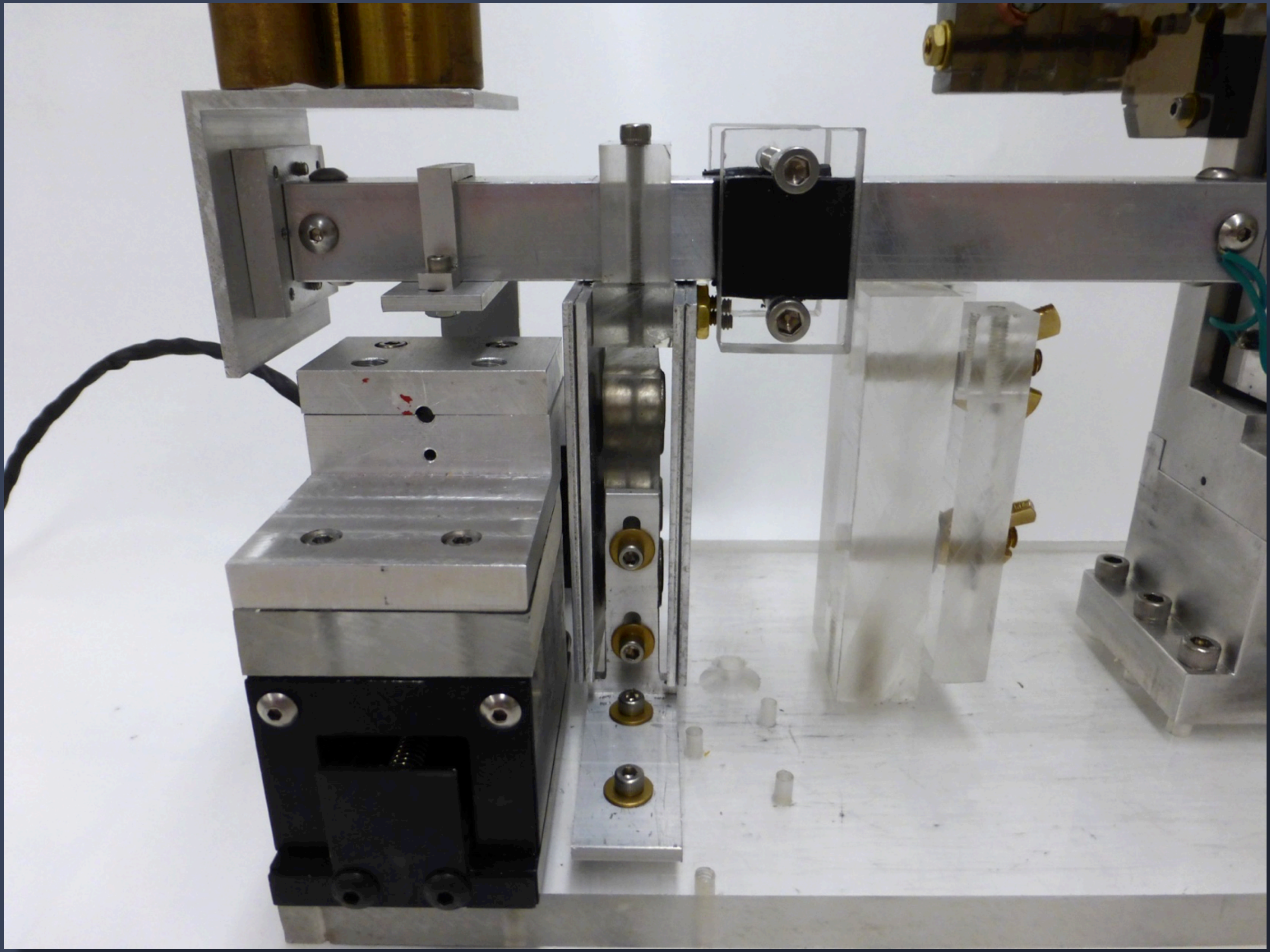


On the left, two views of a flexural bearing used to support the beam of the thrust balance. Note the crossed metal strips that provide restoring torque when the balance beam is displaced, causing the bearing parts to rotate. On the right, a closeup of the galinstan (liquid metal) contacts used to transfer power to the device in the Faraday cage.

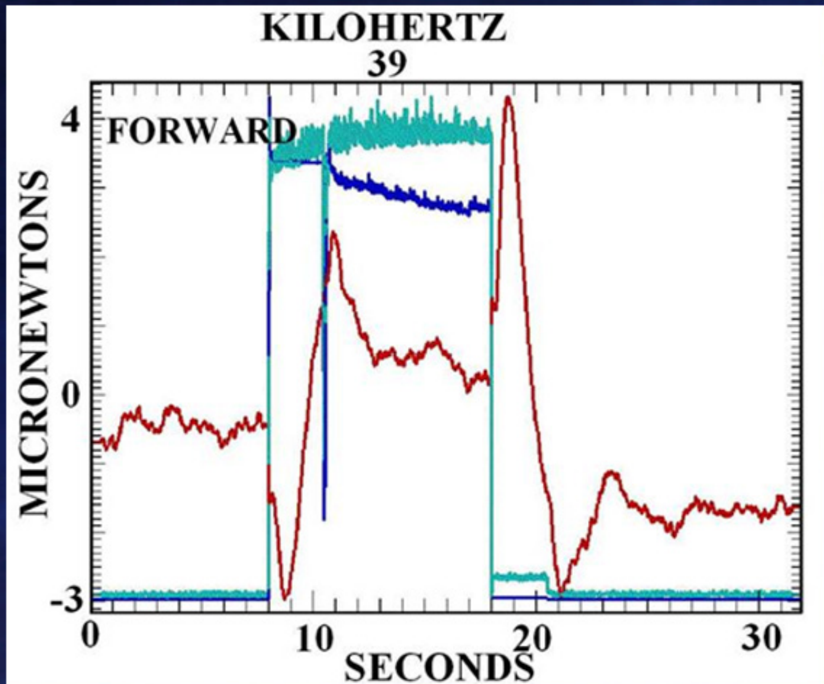


The thrust balance in the clear acrylic vacuum chamber. Feed-throughs
for the electronics are obscured by the vacuum line to the pump.

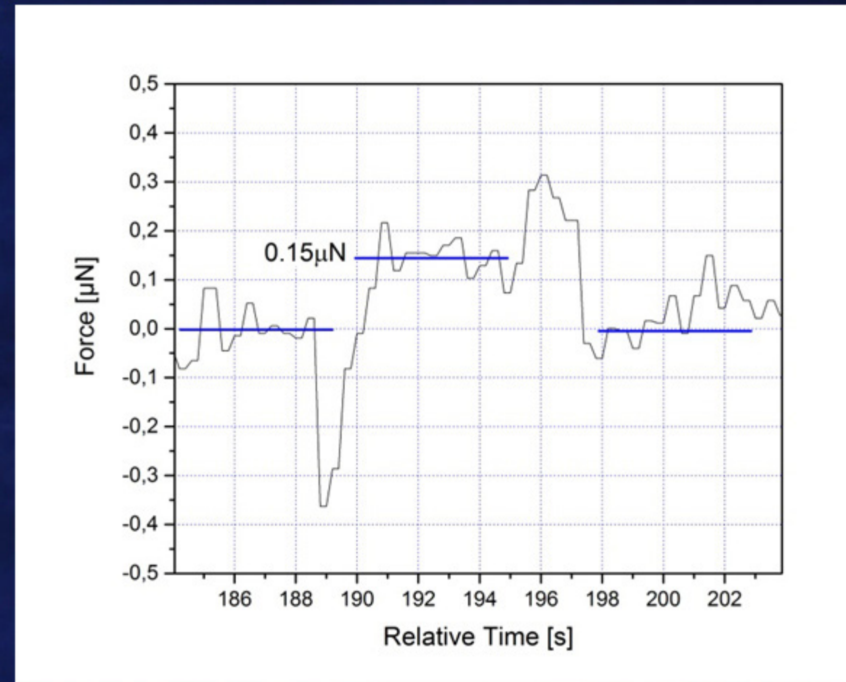

Loosen Locknut
Yolk
The yolk can flip 180°
Faraday Cage



Neodymium-boron magnetic damper.



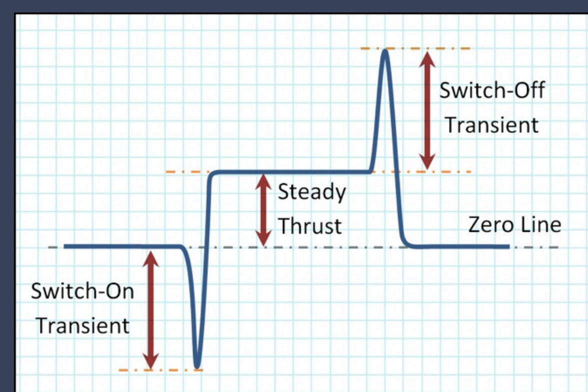
Thrust graph (red plot) (Woodward)



Thrust graph (Buldrini)

JFW Average of about 12 runs.

Slides taken from paper of
Nembo Buldrini- Estes Park Adv.
Propulsion Workshop. Sept 2016..
Free pdf book available ssi.org



The transients seem to give a higher thrust than the steady thrust shown… can we use this??

The on and off transients are in opposite directions can we overcome this problem?

YES.. Chirp the frequency…
start off freq. then chirp onto the resonant freq. or vice versa

Chirping with the demo device in preparation for a visitor.

19mm disc SM-111 PZT , 3/4” brass mass & 1/4” Aluminum end masses. Res. freq ~36 kHz.

Color code:

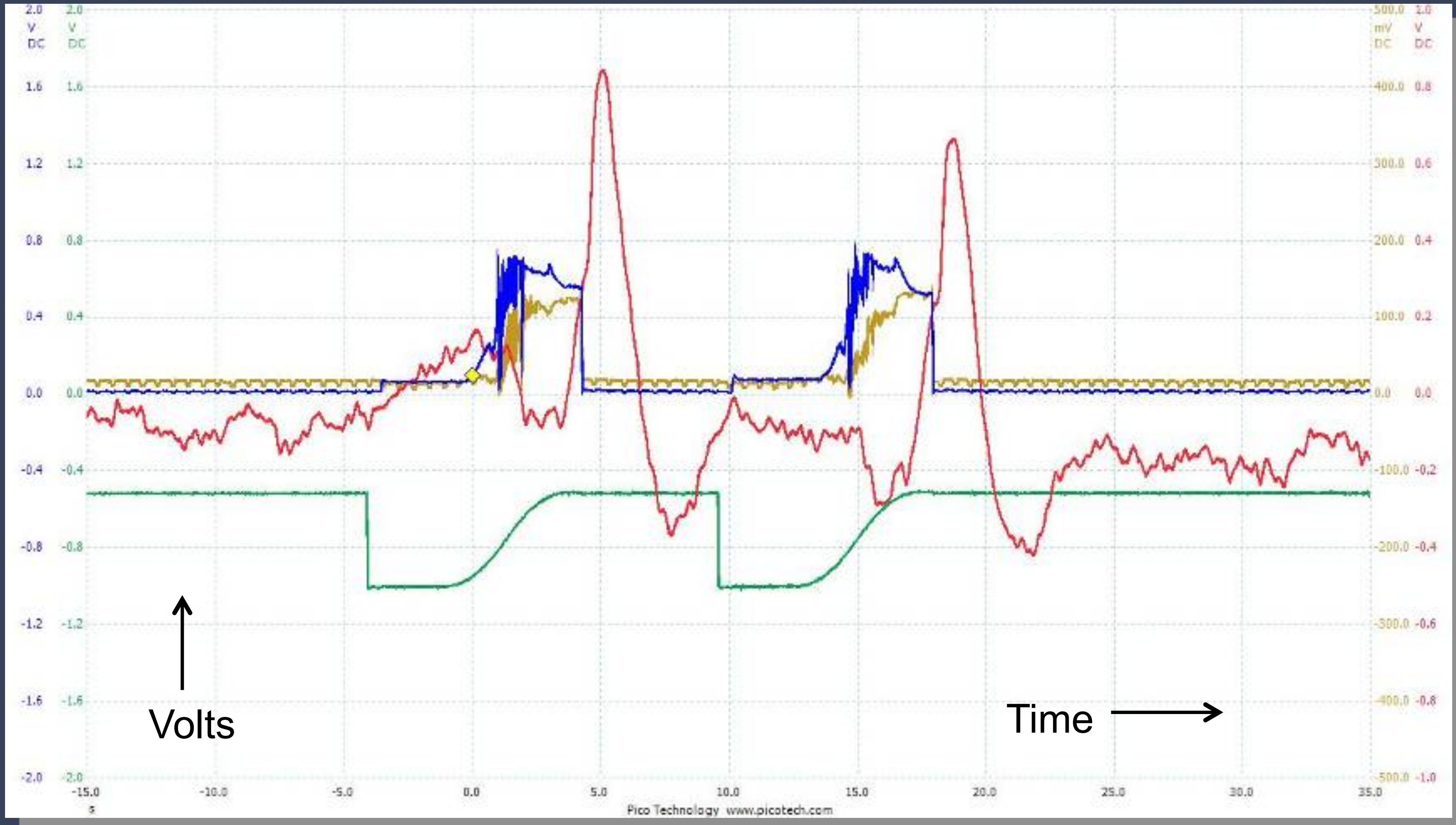
thrust: ······················ red

voltage: ······················ blue

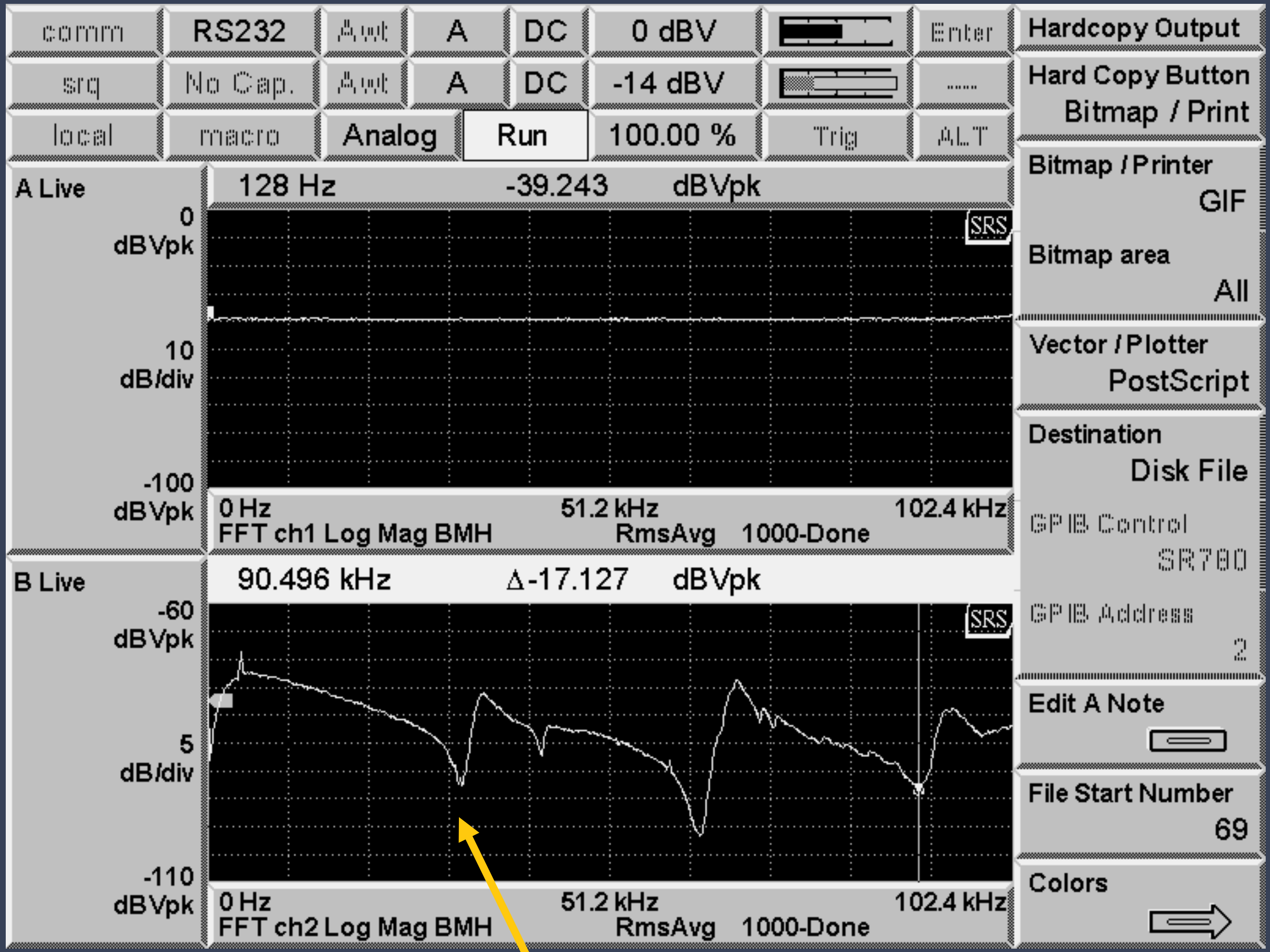
Strain Gauge: ·········· brown

VCO control voltage: ··· green

Picoscope 4424 data



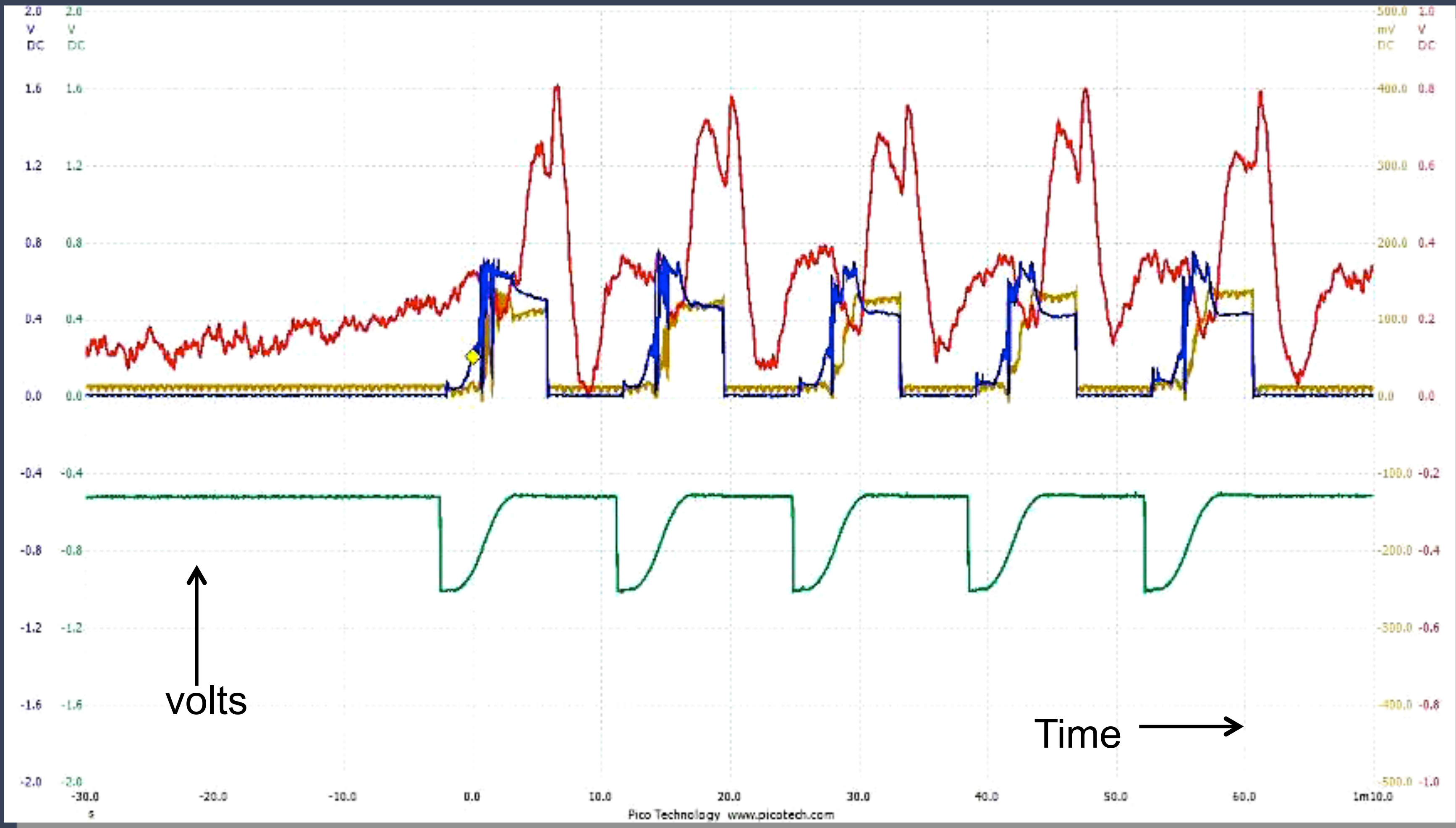
Green line shows INVERTED sweep of frequency. Starts high and sweeps down to resonance.



SR780 VNA

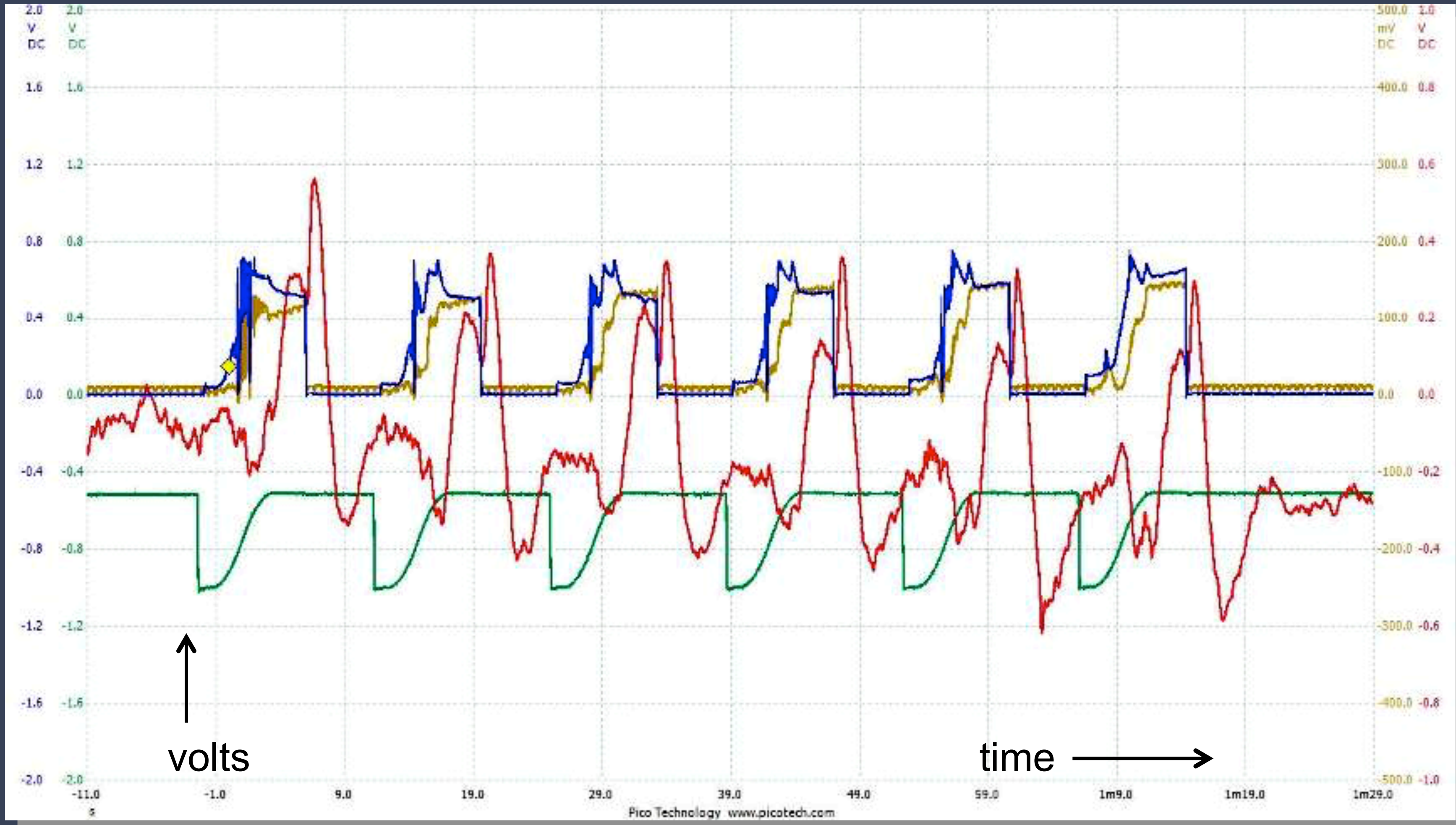
Spectrum of the device tested (response to white noise).
Arrow points to the 36 KHz resonance used. Standford Research 780 vector network analyzer (VNA).

Picoscope 4424 data··· (0.15 V per 1uN)



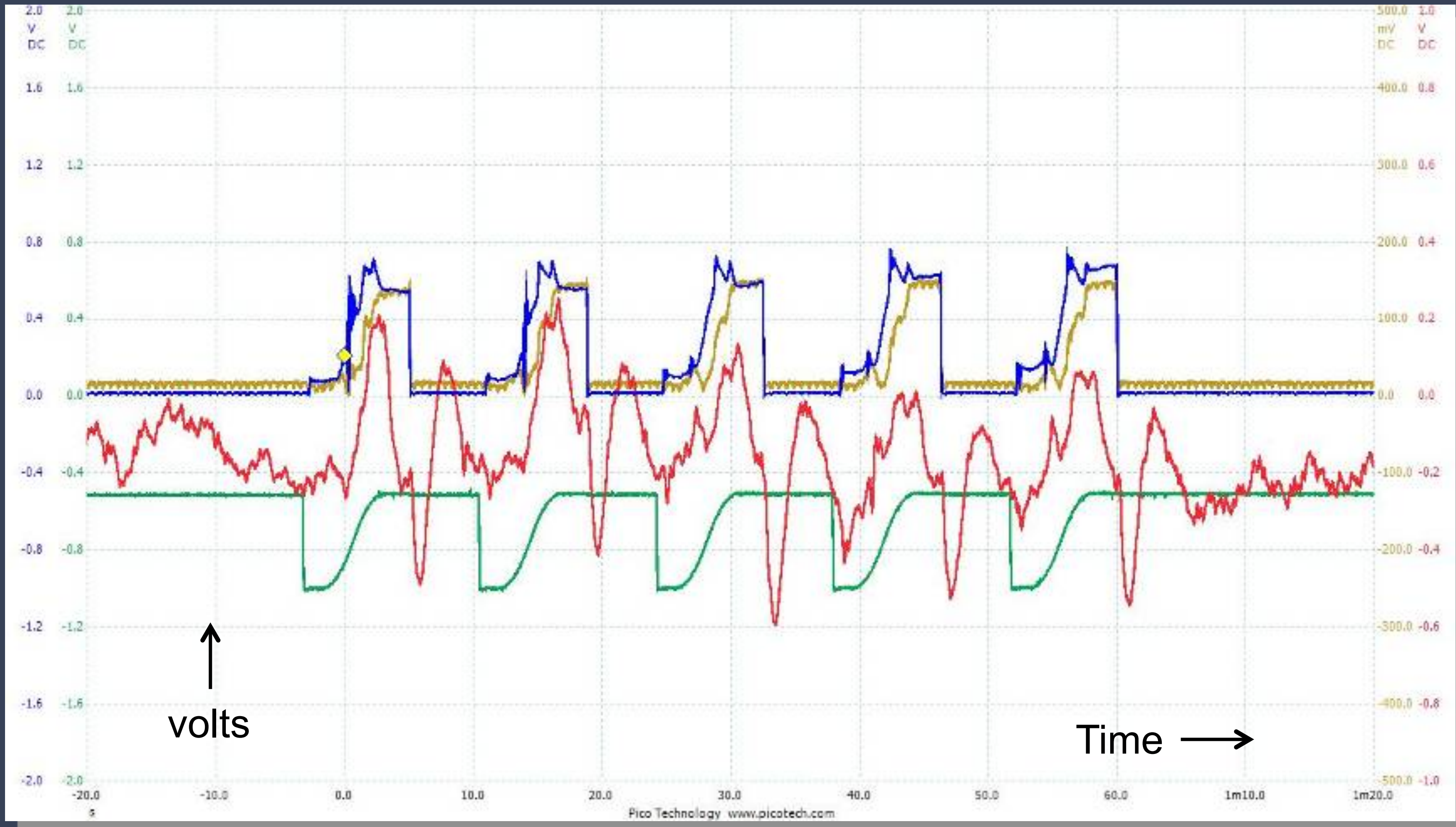
Several chirps taken sequentially. Green line is inverted. The chirp starts at high frequency come down to resonance.

Picoscope 4424 data (0.15 V per 1 uN)

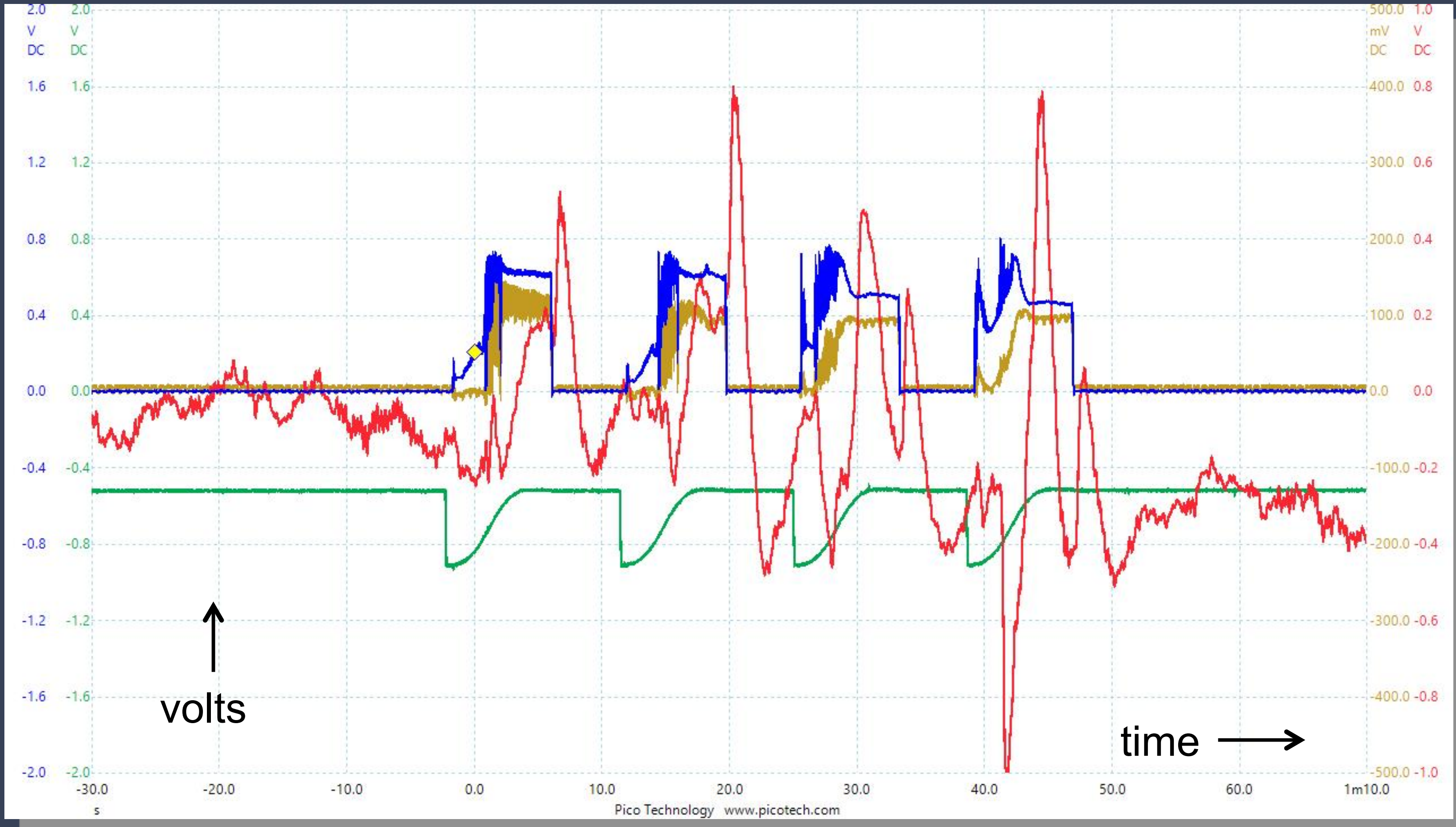


Shows some thermal drift.

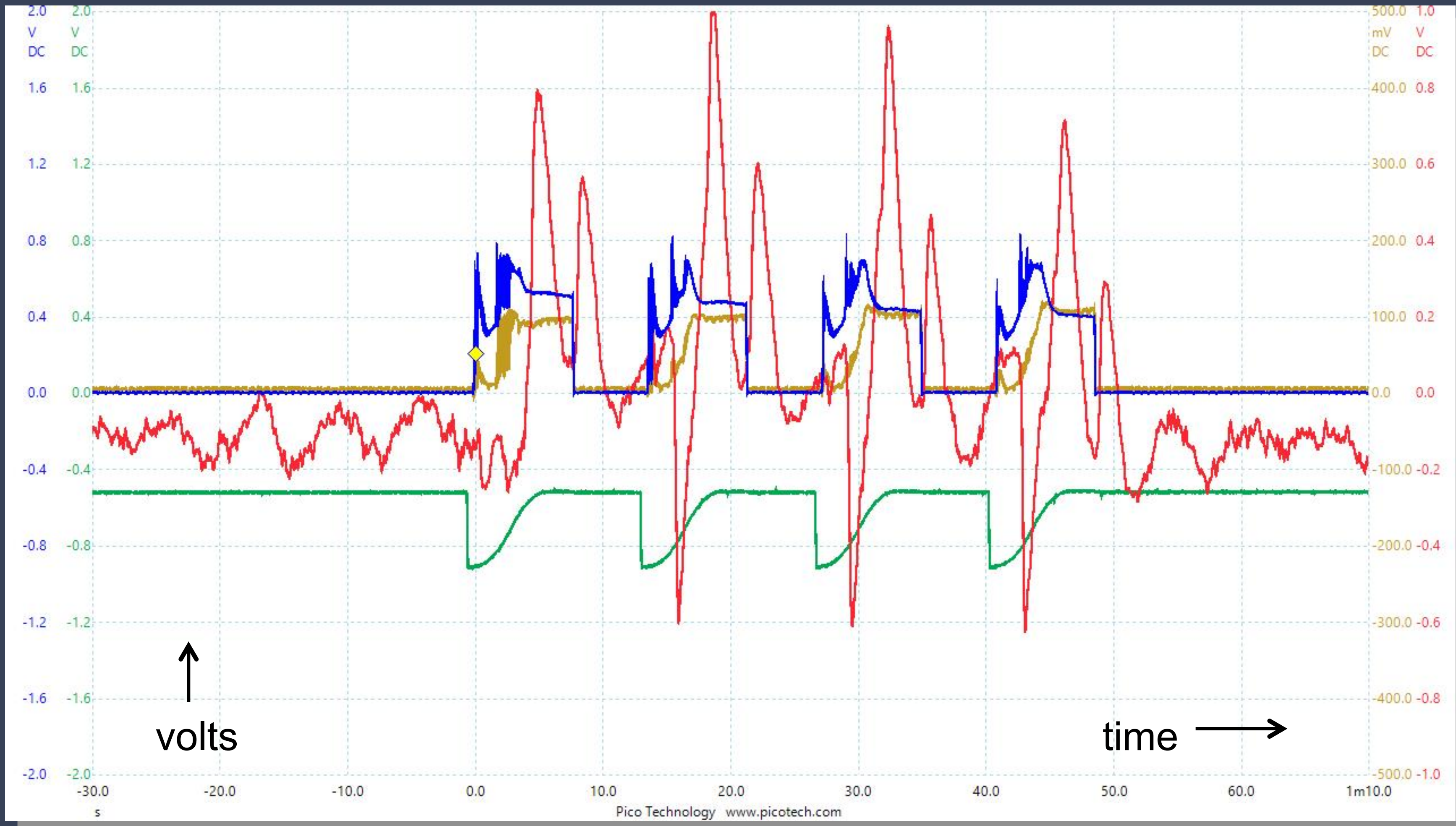
Picoscope 4424 data (0.15 V per 1 uN)



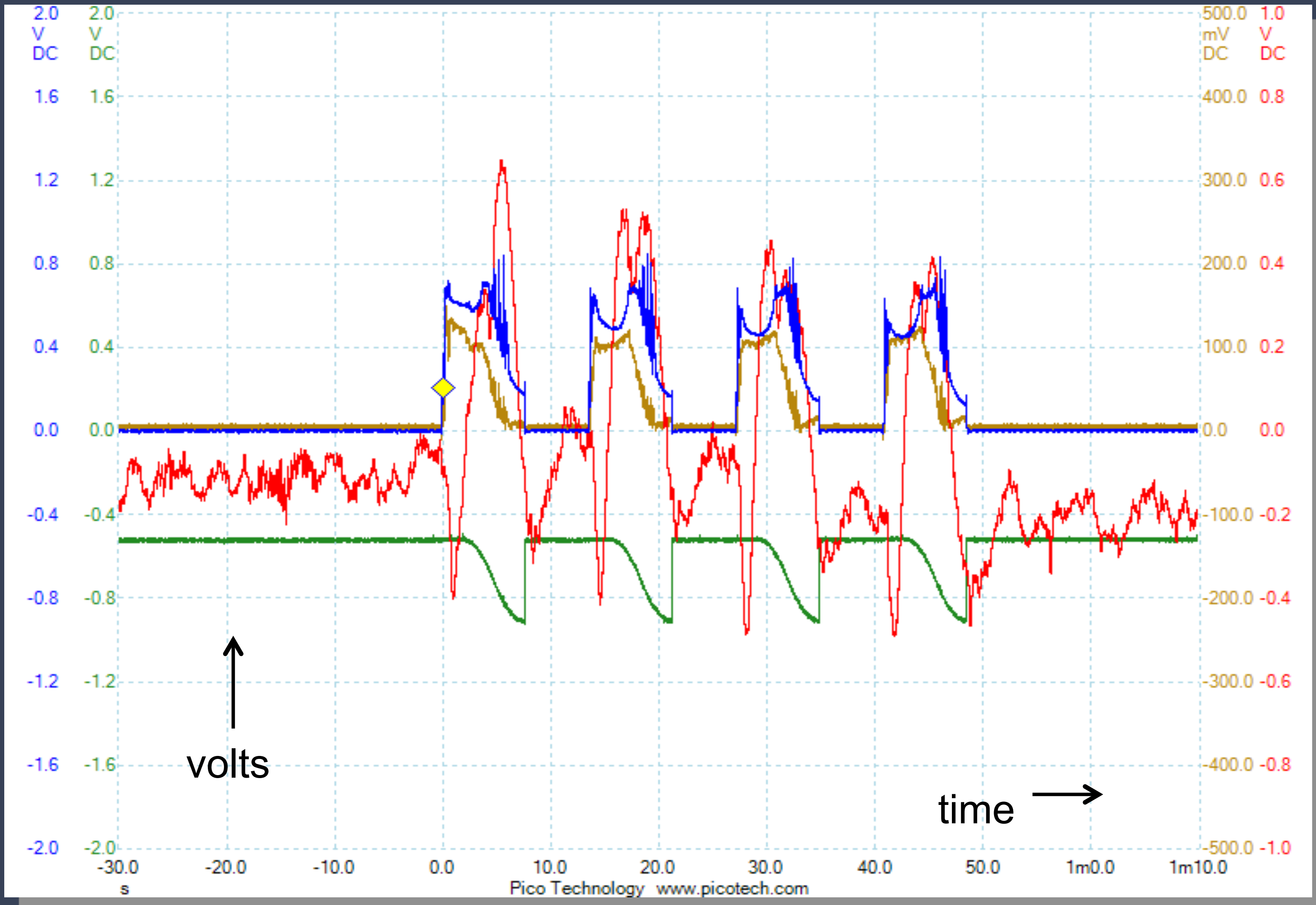
The direction of the device has been reversed.



The first two chirps are with 37.0 KHz as the chirped to frequency (the steady value of the VCO control frequency [green trace]. Realizing the error, the frequency was changed to 35.8 KHz between the second and third chirps. Resonance was 36.3 kHz.
Note the behavior in the third and fourth chirps where the resonant frequency is swept in the chirp.



Last run of the day. Various little tweaks to make things pretty.



Off switching transient is now suppressed. Chirp away from resonance to higher frequency. The switch on transient is apparent.

ssi.org webpage.. Workshop proceedings is available.

Estes Park Advanced Propulsion workshop, Sept 19-22, 2016.

One of the developments emerging at the workshop was that there are now three independent labs where Mach effects are seen (in addition to CSUF):

* **Nembo Buldrini, FOTEC, Austria**
* **George Hathaway, Toronto, Canada**
* **Martin Tajmar, TU Dresden, Germany**

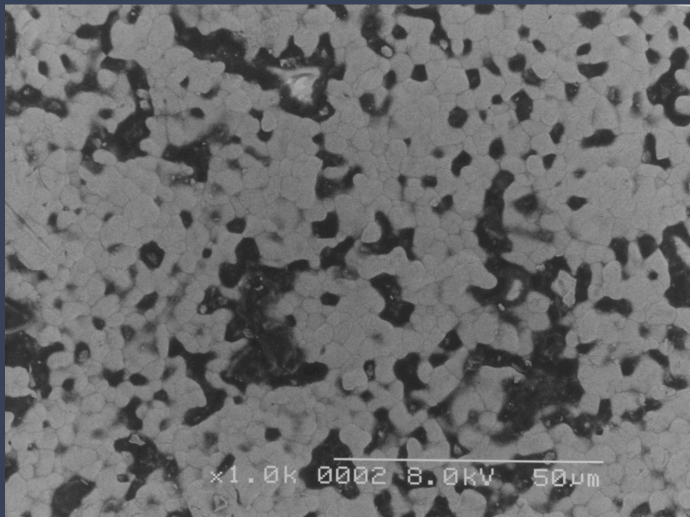
Are there improvements we can make ?

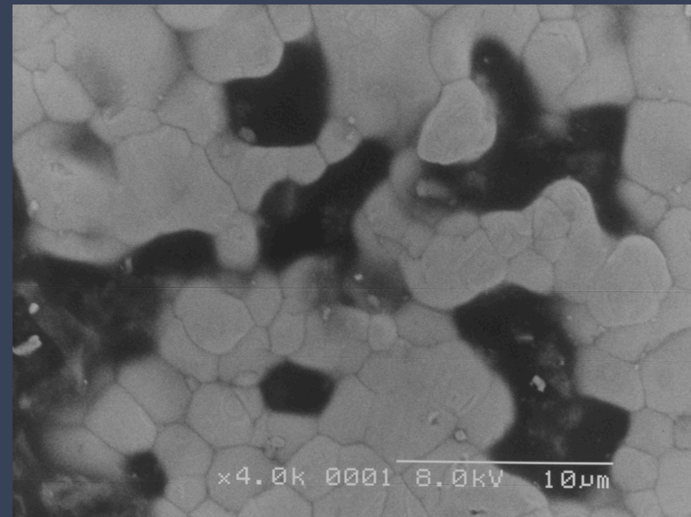
Scanning Electron Microscope

3/8” diam cylinder

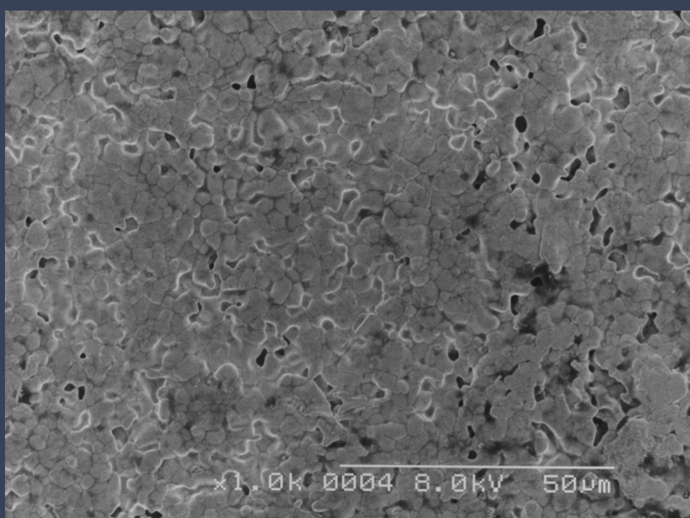
Improvements ?? The material we are using PZT **SM-111**

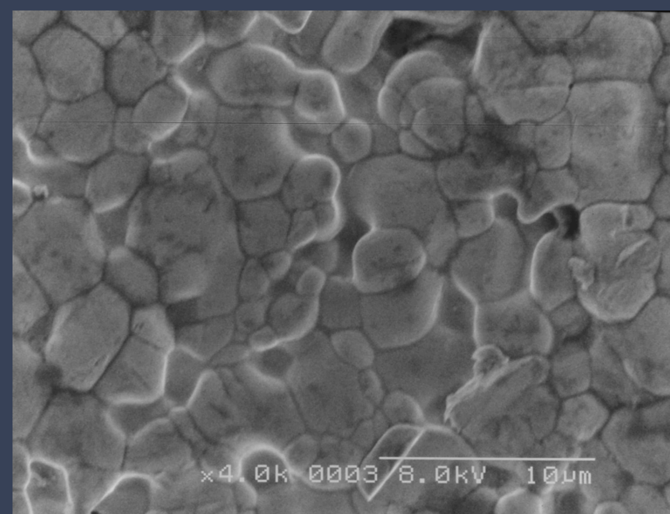
SEM photos of SM-111 material and APC material





SM-111
Seiner Martins
Q =1800
Q ~ 60 Tajmar



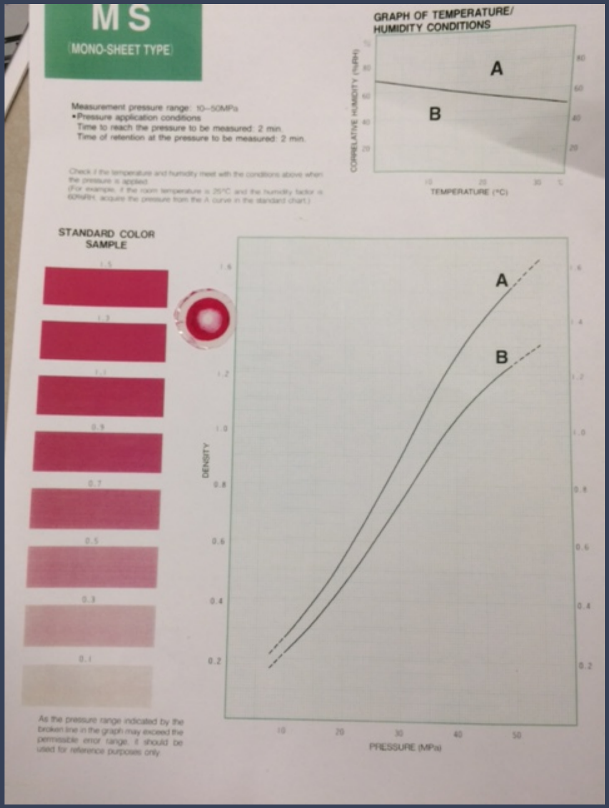


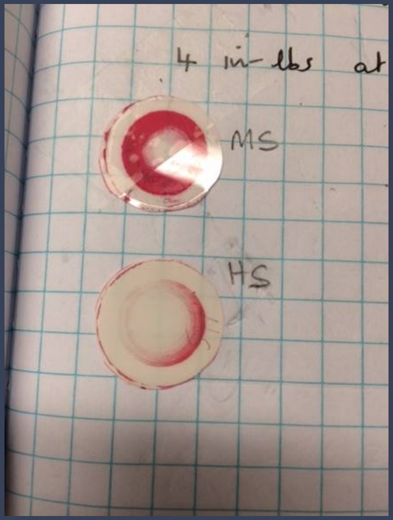
APC International Ltd.
844 material
Item #790
Discontinued.
Q =1500

Stiff- high Q
Large d_33

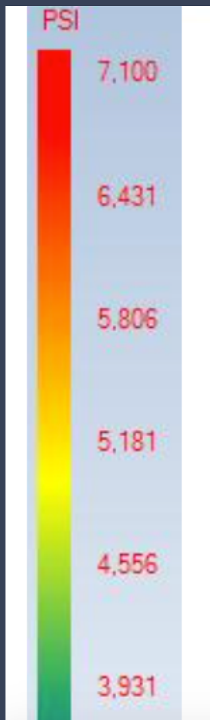
Crystals from TRS technologies…PIN-PMN-PT

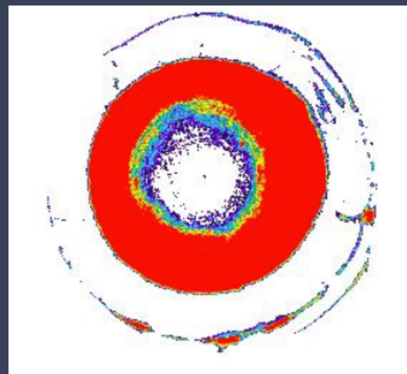
Fuji Film - Pressure sensitive film





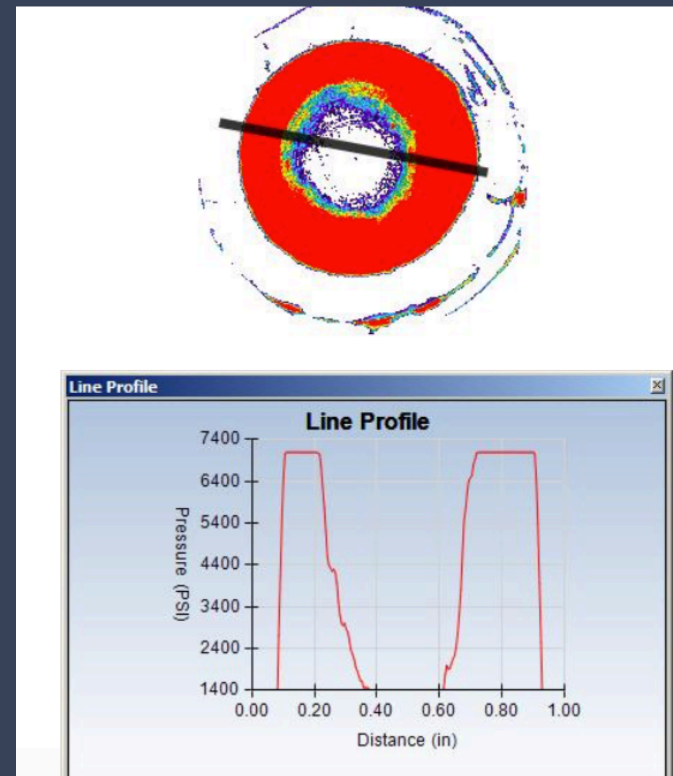
Improvements ??





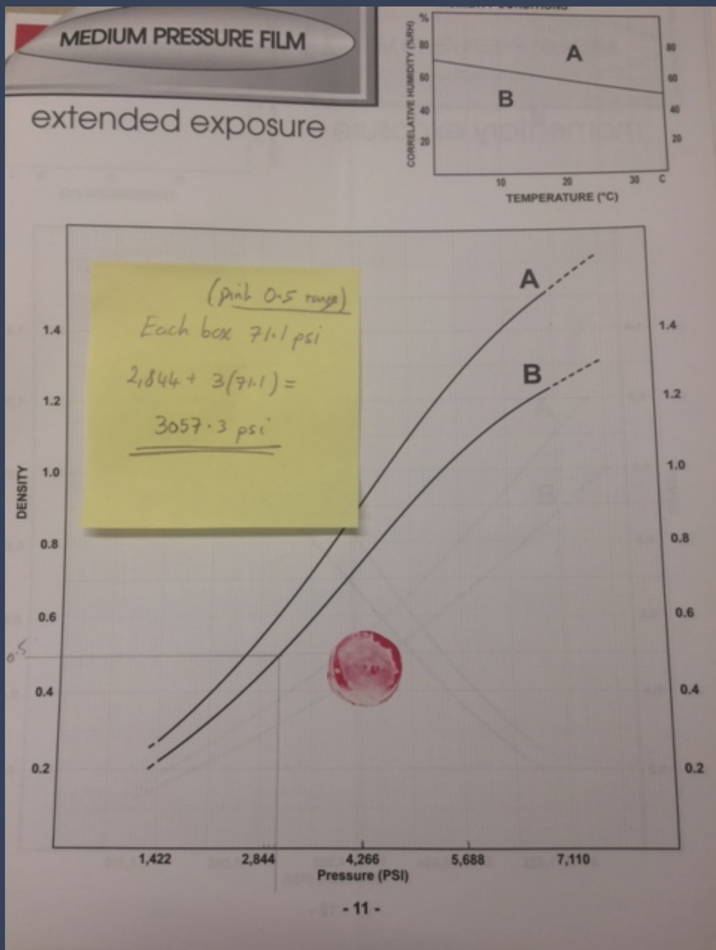
Statistics

Image:	MS Sample Pseudocolor Rep	
Avg Pressure	5,462.	PSI
Std. Deviation	2,188.	PSI
Contact Area	0.60	sq.in
Total Area	1.97	sq.in
Force	3,281.	lbf
Min Pressure	1,431.	PSI
Maximum	7,100.	PSI



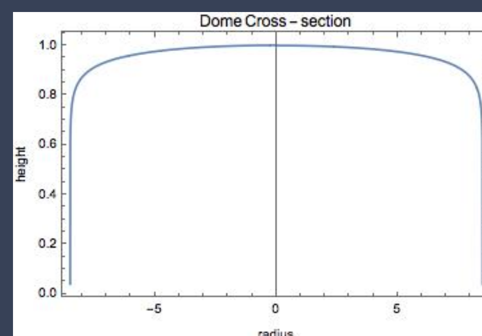
Fujifilm pressure sensitive Paper. Records pressure on the stack when clamped at 4 in lbs.

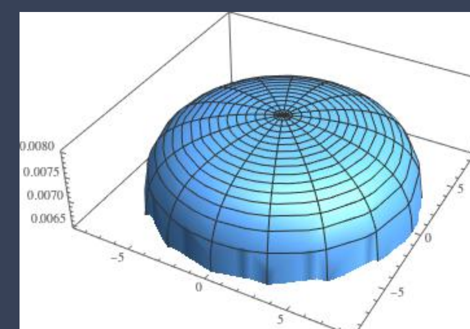
Possible solution: Kapton or lead gasket or Machine a dome on the brass and aluminum end masses.



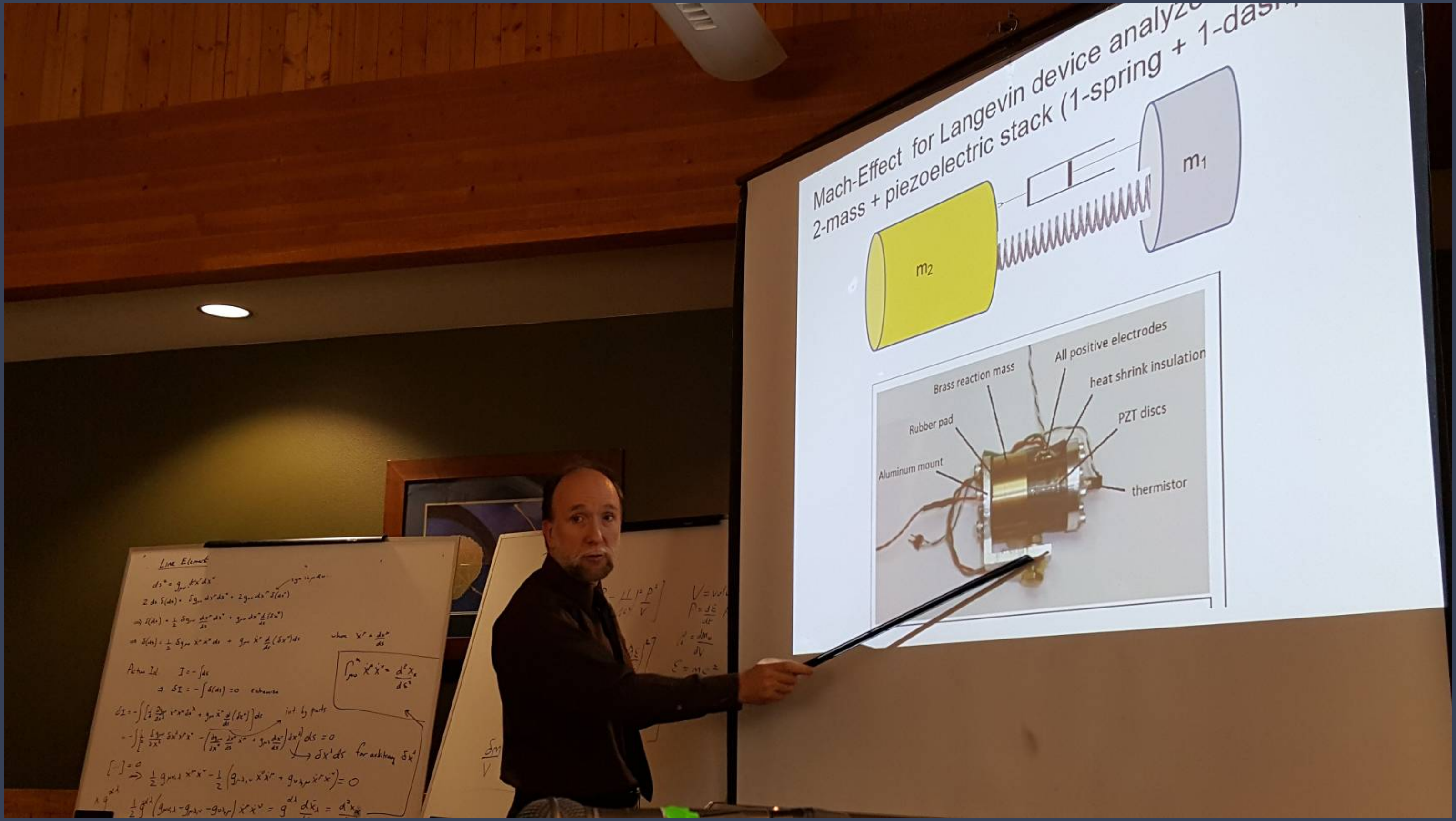
Dome shape profile;

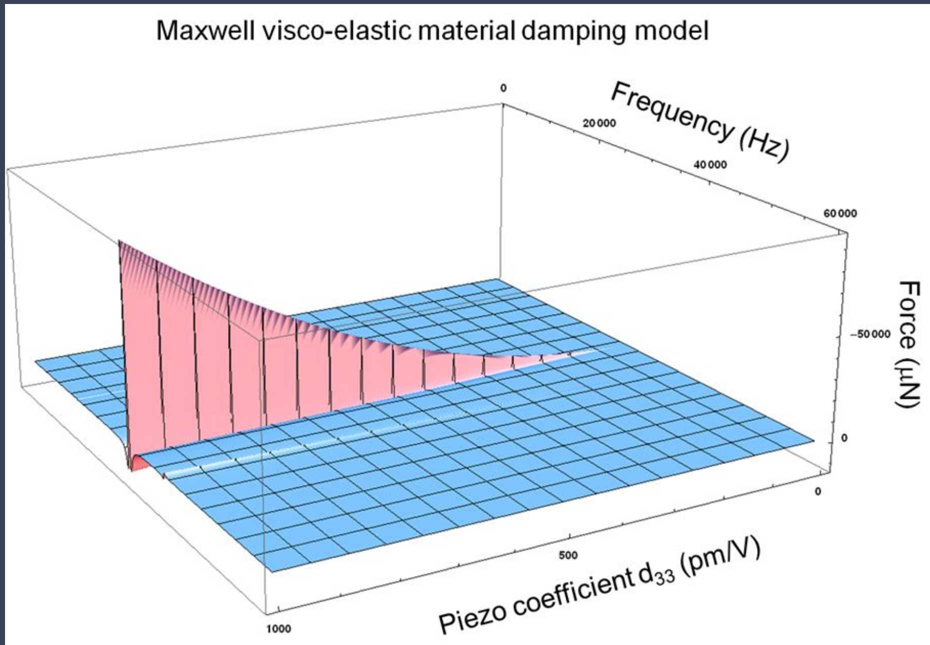
$$Ln\left(\sqrt{1-\frac{x^2}{R^2}}\right)$$

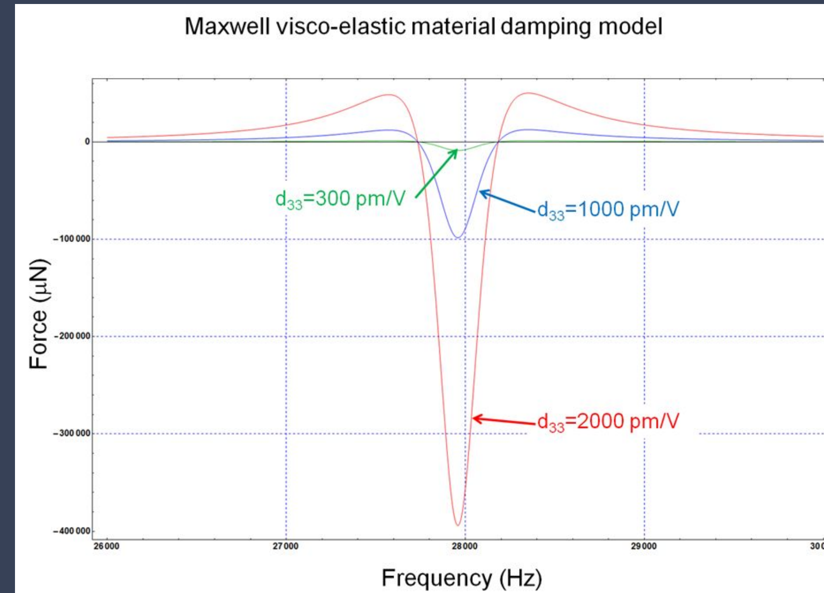


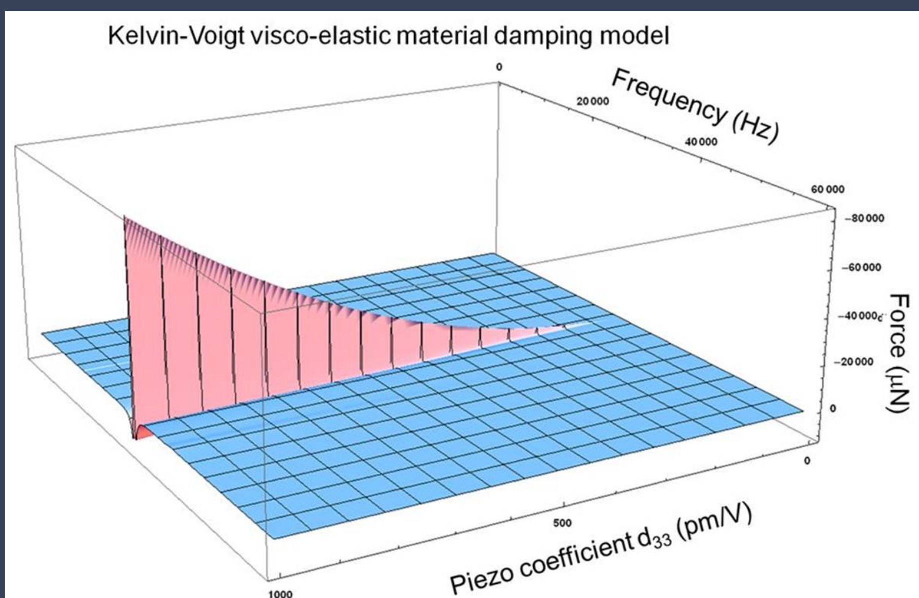


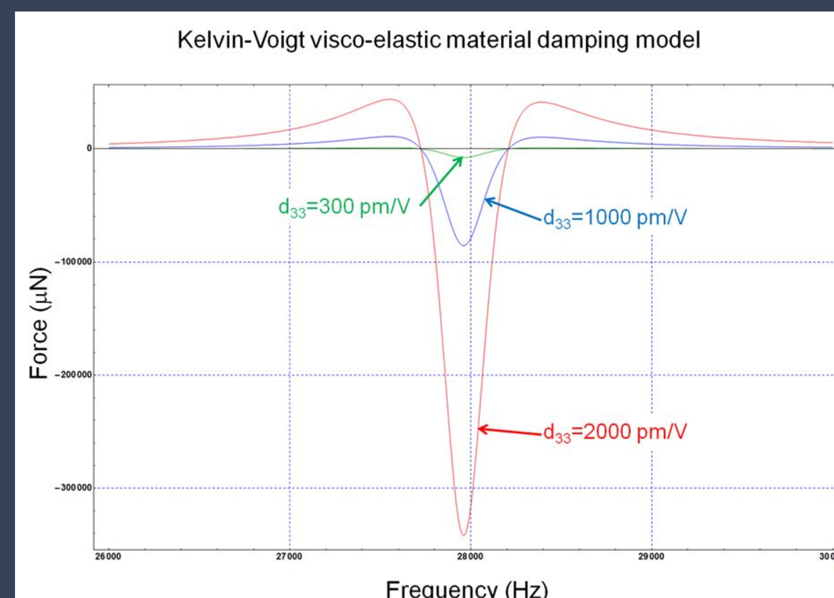
Results of the theoretical Modal by Jose Rodal 2016-2017




Maxwell visco-elastic material damping model
Frequency (Hz)
0
20000
40000
60000
Force (μN)
−50000
0
0
500
1000
Piezo coefficient d_{33} (pm/V)


Maxwell visco-elastic material damping model
Force (μN)
0
−100000
−200000
−300000
−400000
26000
27000
28000
29000
30000
Frequency (Hz)
d_{33}=300 pm/V
d_{33}=1000 pm/V
d_{33}=2000 pm/V


Kelvin-Voigt visco-elastic material damping model
Frequency (Hz)
0
20000
40000
60000
Force (μN)
−80000
−60000
−40000
−20000
0
0
500
1000
Piezo coefficient d_{33} (pm/V)


Kelvin-Voigt visco-elastic material damping model
Force (μN)
0
−100000
−200000
−300000
26000
27000
28000
29000
30000
Frequency (Hz)
d_{33}=300 pm/V
d_{33}=1000 pm/V
d_{33}=2000 pm/V

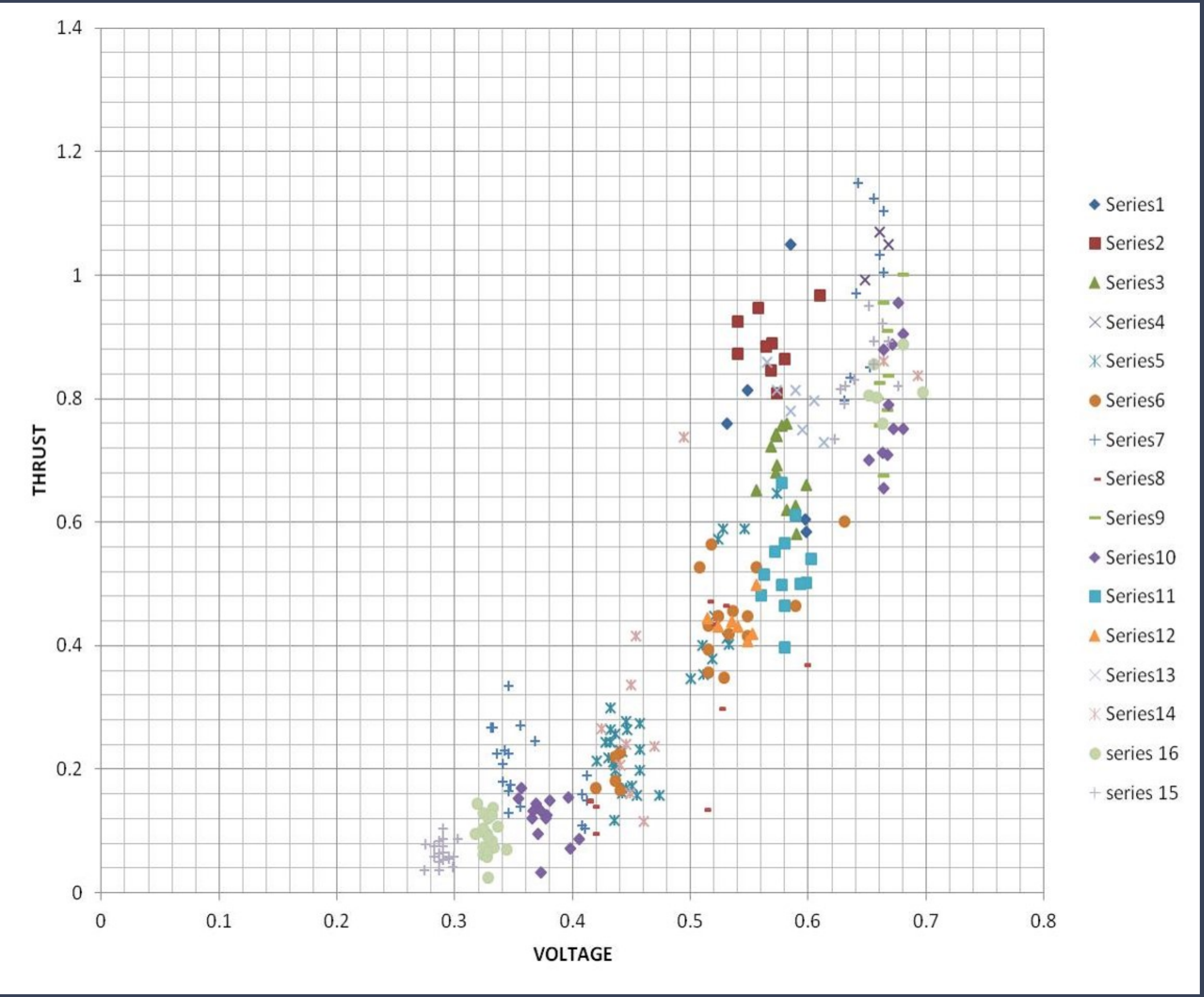
Voltage to the fourth power law scaling…

- Runs were performed from Aug – mid Sept for both the forward and reversed directions of the device.

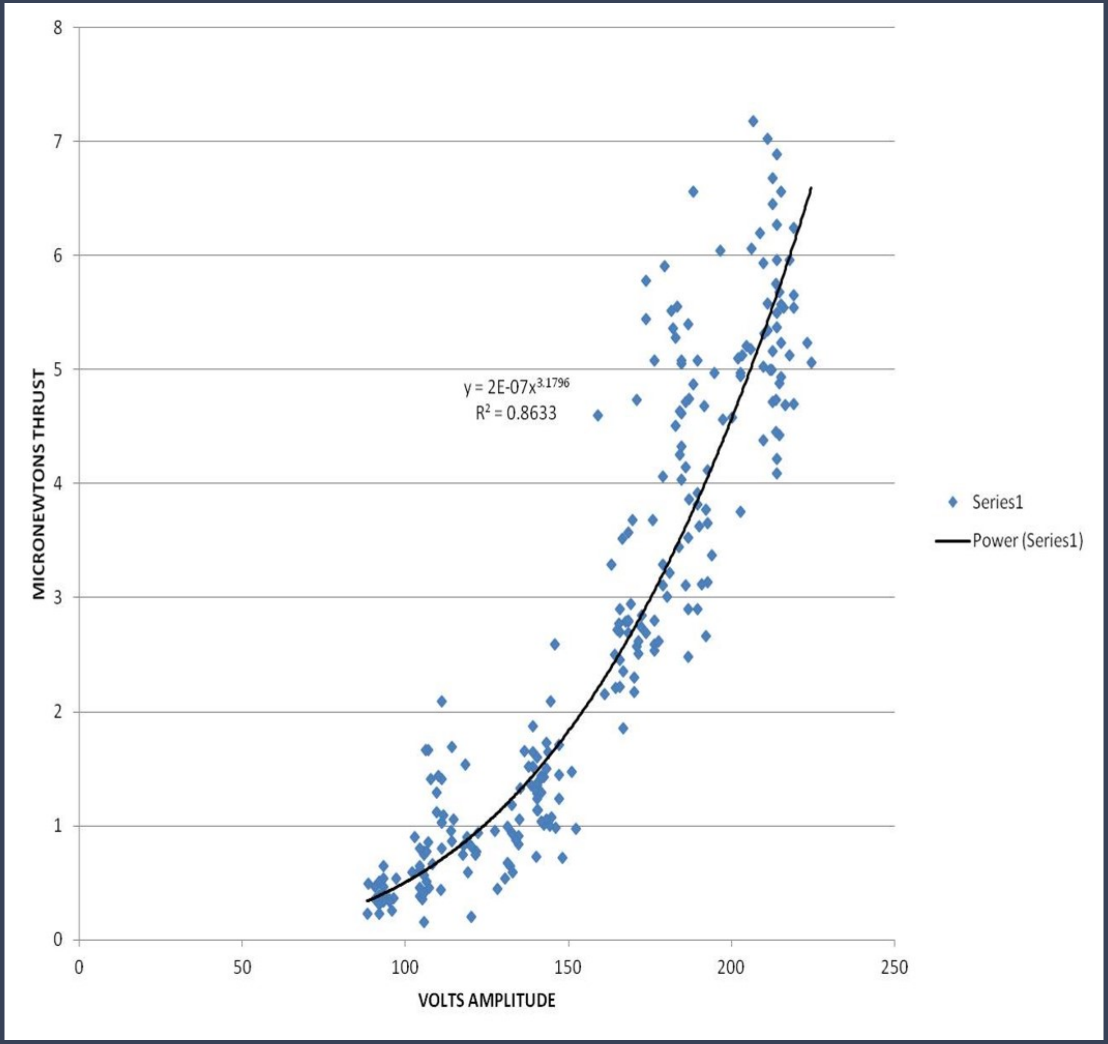
- Thrust versus applied voltage data were recorded and plotted each day as a series. The forward direction are shown on the next slide.. The clustering is due to particular amplifier settings.

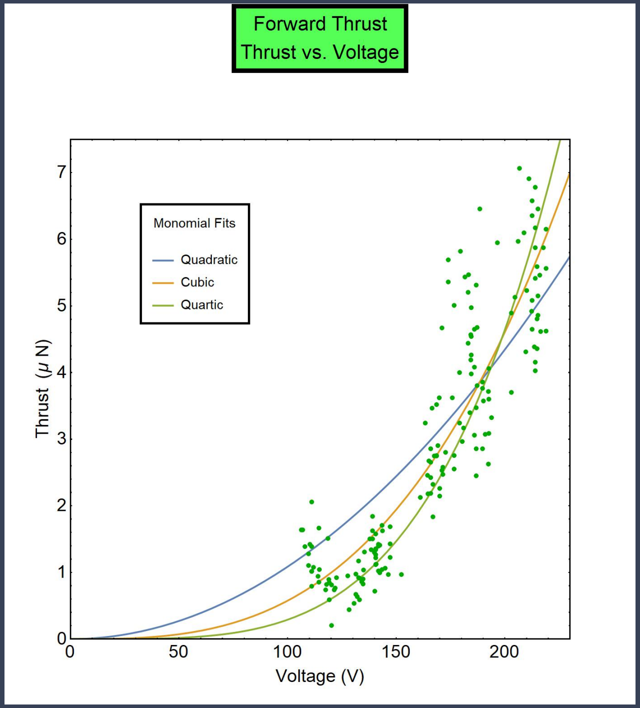
- Mass fluctuation goes as rate of change of power V^2/R and electrostriction goes as electric field squared or V^2/d^2 hence $V\uparrow 4$ law.

Forward runs (thrust 0.15volts = 1 uN)

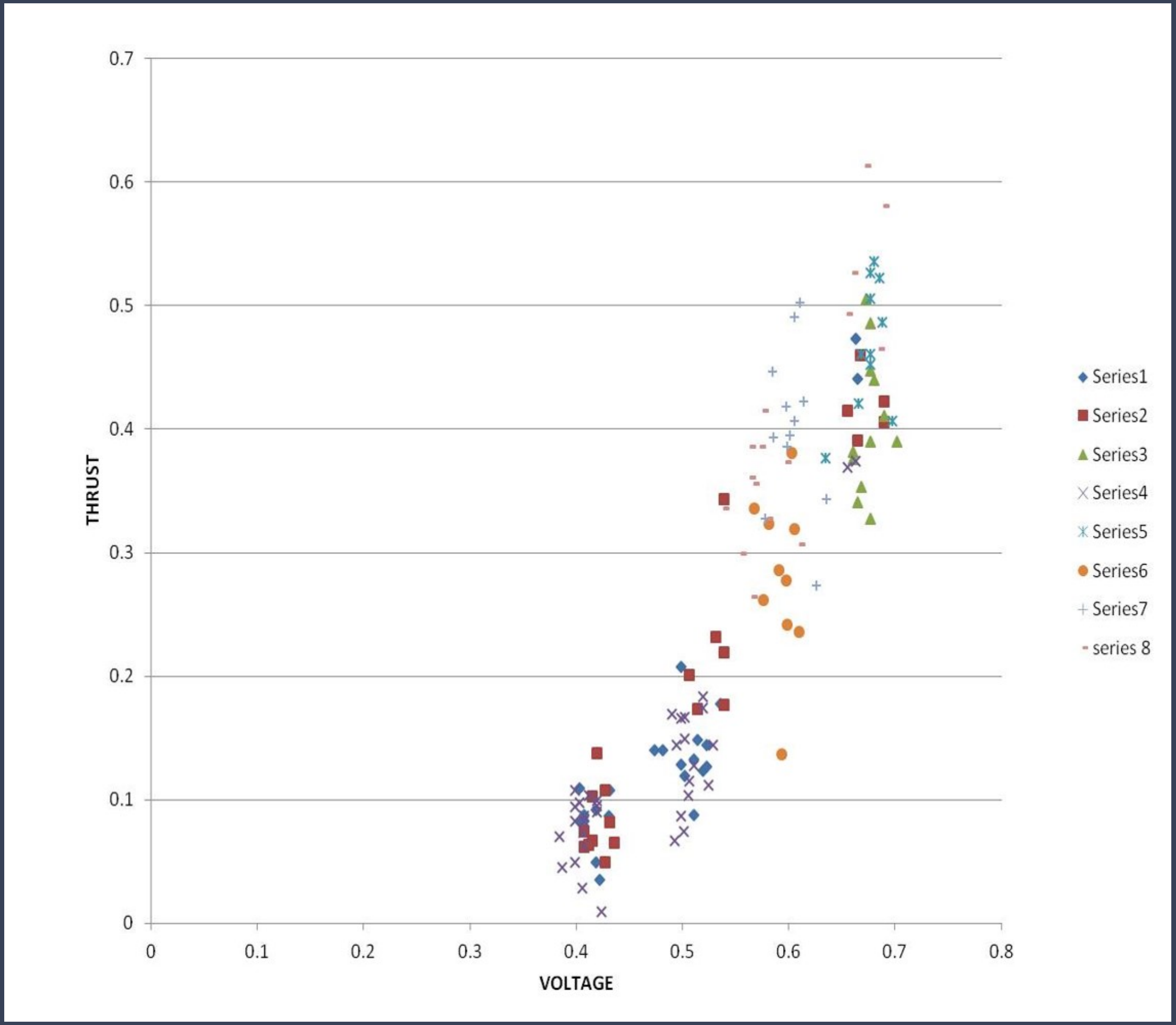


Forward runs

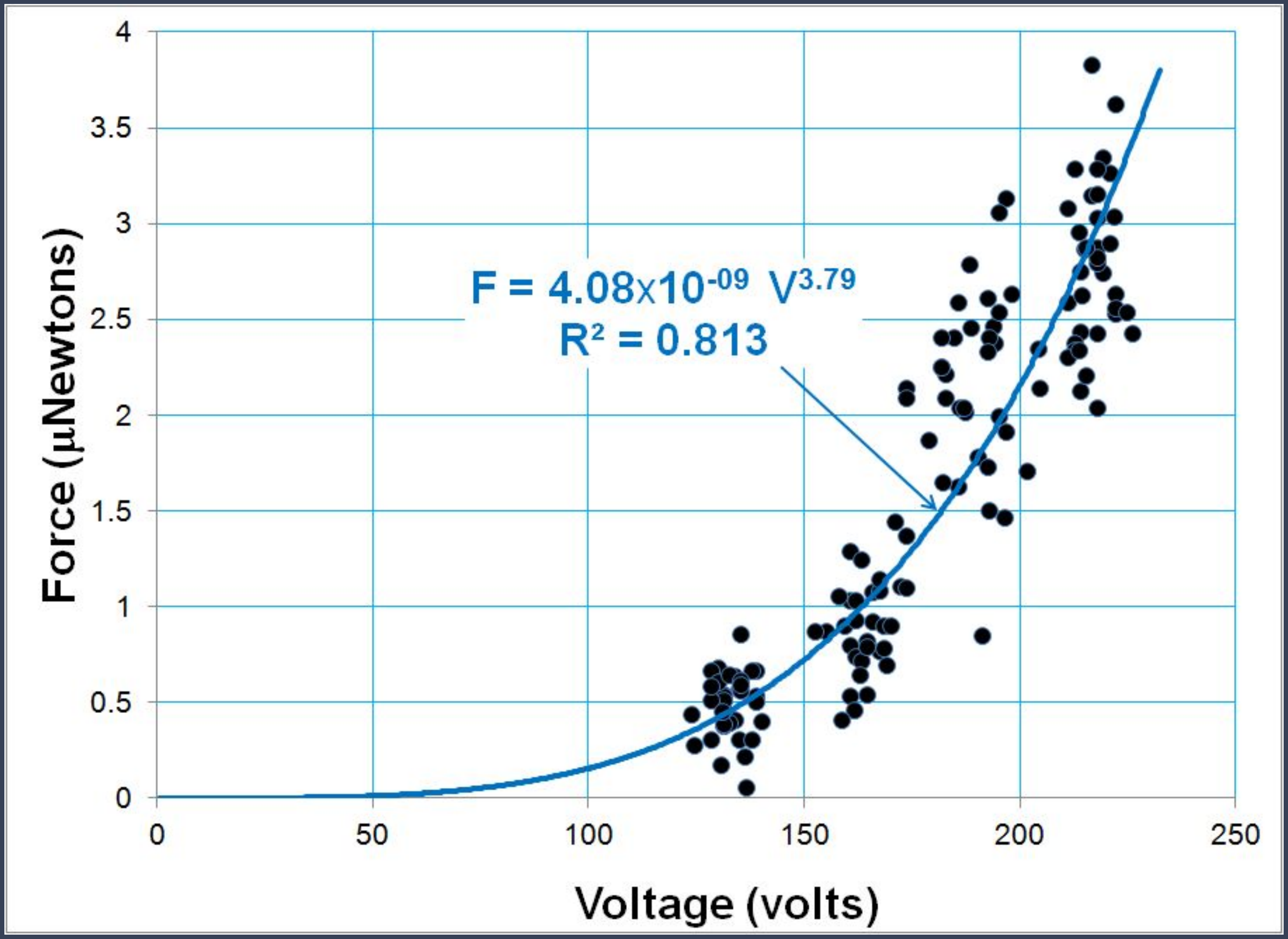




Reversed runs (0.15 volts = 1 uN)



Reversed runs



The New "tiny" Lab

My esteemed collaborators on NIAC-

- Dr. Marshall Eubanks, Astrophysics, coms./nav. & probe design.
- Gary Hudson (ssi.org) coms./nav. & probe design.
- Dr. Bruce Long, EE, power supply & probe design.
- Paul March, EE, power & freq. feedback control, cooling, EM drive work.
- Dr. José Rodal, theoretical model & probe design.
- Nolan van Rossum BS., student CAD design.
- Dr. James F. Woodward, theory and experiment, +40 years of work.

The End

Like Columbus, who found the New World while seeking a way to the Old, explorers who make landfall on unexpected continents of ideas are often unprepared to accept what they have found. They keep on seeking what they set out to find.

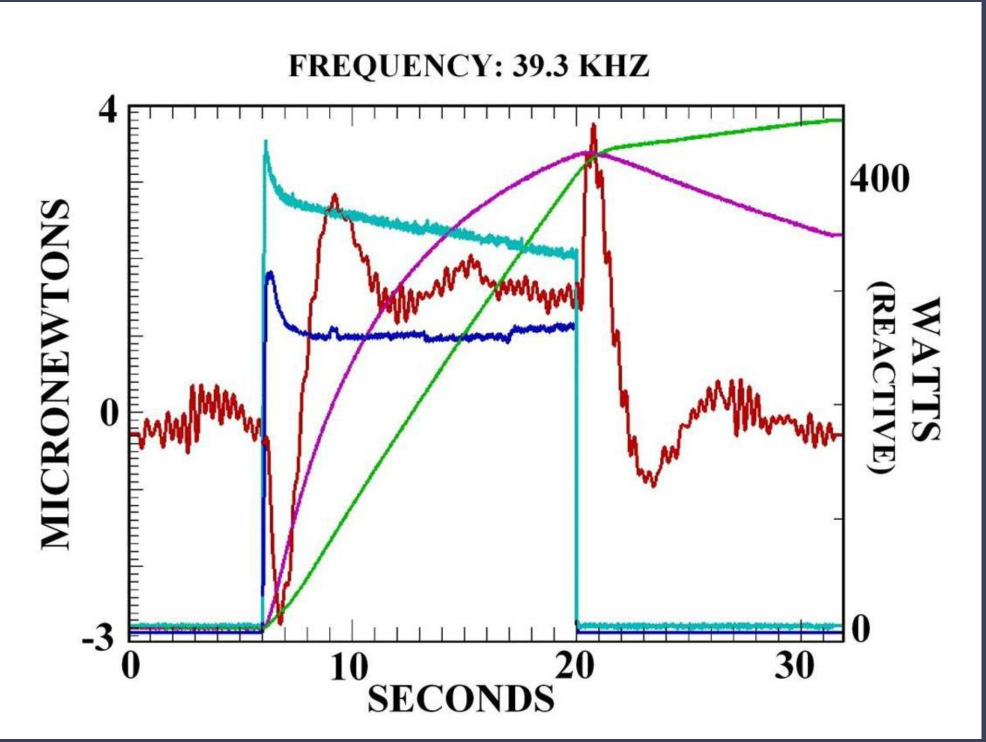
Frank Wilczek

Wrong theories are not an impediment to the progress of science; they are a central part of the struggle.

Freeman Dyson

Mach Effects for In-Space Propulsion:
An Interstellar Mission

Dr, Heidi Fearn, Dr. José Rodal, Dr. Marshall
Dr. Bruce Long, Dr. James F. Woodward, Paul March and Gary C Hudson



5.2 HN-theory field equation → mass change formula

Let's define the HN-field equation (in a smooth fluid) as follows (which agrees with Eq.(16) in reference [4]) by grouping terms together;

$$
\begin{aligned}
R_{\alpha\beta} - \frac{1}{2} g_{\alpha\beta} R &= -8\pi G (T_{\alpha\beta} + \delta T_{\alpha\beta}) \quad \text{where} \\
-(8\pi G)\delta T_{\alpha\beta} &= \frac{2}{m}(g_{\alpha\beta} g^{\mu\nu} m_{;\mu\nu} - m_{;\alpha\beta}) + \frac{4}{m^2}(m_{;\alpha} m_{;\beta} - \frac{1}{4} m_{;\gamma} m^{;\gamma} g_{\alpha\beta})
\end{aligned}
\tag{90}
$$

Now we expand the terms out. Let us put back in c and not set it equal to one, which can be confusing. The terms in μ, ν mix the time and spatial derivatives in an unexpected way.

Consider first the T_{00} and T_{jj} terms separately, using flat metric (+1,-1,-1,-1),

$$
\begin{aligned}
-\frac{8\pi G}{c^4}\delta T_{00} &= \frac{2}{m}\left[g_{00}\left(\frac{g^{00}}{c^2}\frac{\partial^2 m}{\partial t^2} + g^{jj}\frac{\partial^2 m}{\partial x_j^2} \right) - \frac{1}{c^2}\frac{\partial^2 m}{\partial t^2} \right] \\
&+ \frac{4}{m^2}\left[\frac{1}{c^2}\left(\frac{\partial m}{\partial t}\right)^2 - \frac{g_{00}}{4}\left(\frac{1}{c^2}\left(\frac{\partial m}{\partial t}\right)^2 - \left(\frac{\partial m}{\partial x_j}\right)^2 \right) \right] \\
&= \frac{2}{m}\left[\cancel{\frac{1}{c^2}\frac{\partial^2 m}{\partial t^2}} - \frac{\partial^2 m}{\partial x_j^2} - \cancel{\frac{1}{c^2}\frac{\partial^2 m}{\partial t^2}} \right] \\
&+ \frac{1}{m^2}\left[\frac{4}{c^2}\left(\frac{\partial m}{\partial t}\right)^2 - \frac{1}{c^2}\left(\frac{\partial m}{\partial t}\right)^2 + \left(\frac{\partial m}{\partial x_j}\right)^2 \right] \\
&= -\frac{2}{m}\frac{\partial^2 m}{\partial x_j^2} + \frac{1}{m^2}\left(\frac{\partial m}{\partial x_j}\right)^2 + \frac{3}{m^2 c^2}\left(\frac{\partial m}{\partial t}\right)^2
\end{aligned}
\tag{91}
$$

$$
\begin{aligned}
-\frac{8\pi G}{c^4}\delta T_{jj} &= \frac{2}{m}\left[g_{jj}\left(\frac{g^{00}}{c^2}\frac{\partial^2 m}{\partial t^2} + g^{jj}\frac{\partial^2 m}{\partial x_j^2}\right) - \frac{\partial^2 m}{\partial x_j^2}\right] \\
&+ \frac{4}{m^2}\left[\left(\frac{\partial m}{\partial x_j}\right)^2 - \frac{g_{jj}}{4}\left(\frac{1}{c^2}\left(\frac{\partial m}{\partial t}\right)^2 - \left(\frac{\partial m}{\partial x_j}\right)^2\right)\right] \\
&= \frac{2}{m}\left[-\frac{1}{c^2}\frac{\partial^2 m}{\partial t^2} + \cancel{\frac{\partial^2 m}{\partial x_j^2}} - \cancel{\frac{\partial^2 m}{\partial x_j^2}}\right] \\
&+ \frac{1}{m^2}\left[4\left(\frac{\partial m}{\partial x_j}\right)^2 + \frac{1}{c^2}\left(\frac{\partial m}{\partial t}\right)^2 - \left(\frac{\partial m}{\partial x_j}\right)^2\right] \\
&= -\frac{2}{mc^2}\frac{\partial^2 m}{\partial t^2} + \frac{3}{m^2}\left(\frac{\partial m}{\partial x_j}\right)^2 + \frac{1}{m^2c^2}\left(\frac{\partial m}{\partial t}\right)^2
\end{aligned} \tag{92}
$$

where $j = 1, 2$ or 3. Now take the trace of $T_{\alpha\alpha}$ where $\alpha = 0, 1, 2, 3$ by adding the last two equations.

$$
\begin{aligned}
-\frac{8\pi G}{c^4}\mathrm{Tr}(\delta T_{\alpha\alpha}) &= -\frac{2}{m}\frac{\partial^2 m}{\partial x_j^2} + \frac{4}{m^2}\left(\frac{\partial m}{\partial x_j}\right)^2 + \frac{4}{m^2c^2}\left(\frac{\partial m}{\partial t}\right)^2 - \frac{2}{mc}\frac{\partial^2 m}{\partial t^2} \\
\frac{1}{c^2}\mathrm{Tr}(\delta T_{\alpha\alpha}) &= \frac{1}{4\pi G}\left[\left\{\frac{1}{m}\frac{\partial^2 m}{\partial t^2} - \frac{2}{m^2}\left(\frac{\partial m}{\partial t}\right)^2\right\}\right. \\
&+ \left.\left\{\frac{c^2}{m}\frac{\partial^2 m}{\partial x_j^2} - \frac{2c^2}{m^2}\left(\frac{\partial m}{\partial x_j}\right)^2\right\}\right]
\end{aligned} \tag{93}
$$

Maxwell---Linear Gravity in S.I.

$$\nabla \cdot E = \frac{\rho}{\varepsilon_0} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \nabla \cdot E_g = -4\pi G \rho$$

$$\nabla \cdot B = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \nabla \cdot B_g = 0$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \ldots\ldots\ldots\ldots\ldots\ldots \nabla \times E_g = -\frac{\partial B_g}{\partial t}$$

$$\nabla \times B = \mu_0 J + \varepsilon_0 \mu_0 \frac{\partial E}{\partial t} \ldots\ldots \nabla \times B_g = -\frac{16\pi G}{c^2} J_g + \frac{4}{c^2} \frac{\partial E_g}{\partial t}$$

$$E = -\nabla \phi - \frac{\partial A}{\partial t}$$

$$B = \nabla \times A$$

$$\nabla^2 \phi - \frac{1}{c^2} \frac{\partial^2 \phi}{\partial t^2} = 4\pi G \rho$$

$$E_g = -\nabla \phi_g - \frac{\partial A_g}{\partial t}$$

$$B_g = \nabla \times A_g$$

$c \rightarrow c/2$

Woodward's Approach:

In 1953 Dennis Sciama [1]
the "gravelectric" field is given by:

$$\mathbf{E}_g = -\nabla\phi - \frac{1}{c}\frac{\partial \mathbf{A}_g}{\partial t}$$

where $\mathbf{E}_g$ is the gravelectric field strength, F_g/m and Φ and $\mathbf{A}_g$ are the scalar and three-vector potentials of the field.

This A_g is fully consistent with the modified PPN approx, where a Lorentz transformation is used on the flat space-time metric, Nordvedt [2,7], Sultana & Kazanas [3], Cook [4].

Woodward:
In analogy with electrodynamics where the force per unit charge is given by the electric field, and

$$\mathrm{Div}\, E = 4\pi\rho$$

where ρ is the charge per unit vol. in Gaussian units.

4-force/mass
$$F^{\mu} = -\left(\frac{c}{\rho_o}\frac{\partial \rho_o}{\partial t}, E_g\right)$$

The Divergence of the force/mass for the gravitational field Is given by ,

$$\partial_{\mu} F^{\mu} = 4\pi G \rho$$

where ρ is mass per unit vol. (metric - +++). Expanding…

MORE MATH THAN YOU WANTED TO SEE...

$$-\frac{1}{c^2}\frac{\partial}{\partial t}\left(\frac{1}{\rho_o}\frac{\partial E_o}{\partial t}\right)-\nabla\cdot E_g = 4\pi G\rho$$

where E_o is energy density and $E_o = \rho_o c^2$

$$-\frac{1}{\rho_o c^2}\frac{\partial^2 E_o}{\partial t^2}+\left(\frac{1}{\rho_o c^2}\right)^2\left(\frac{\partial E_o}{\partial t}\right)^2-\nabla\cdot E_g = 4\pi G\rho$$

$$-\nabla\cdot E_g = \nabla^2\phi$$

$$E_o = \rho_o\phi$$

$$-\frac{1}{\rho_o c^2}\frac{\partial^2 E_o}{\partial t^2} = \frac{1}{c^2}\frac{\partial^2\phi}{\partial t^2}-\frac{2}{\rho_o c^2}\frac{\partial\phi}{\partial t}\frac{\partial\rho_o}{\partial t}-\frac{\phi}{\rho_o c^2}\frac{\partial^2\rho_o}{\partial t^2}$$

$$\nabla^2\phi - \frac{1}{c^2}\frac{\partial^2\phi}{\partial t^2} - \frac{2}{\rho_o c^2}\frac{\partial\phi}{\partial t}\frac{\partial\rho_o}{\partial t} - \frac{\phi}{\rho_o c^2}\frac{\partial^2\rho_o}{\partial t^2} + \left(\frac{1}{\rho_o c^2}\right)^2\left(\frac{\partial E_o}{\partial t}\right)^2 = 4\pi G\rho$$

$$E_o = \rho_o c^2$$

$$\left(\frac{1}{\rho_o c^2}\right)^2\left(\frac{\partial E_o}{\partial t}\right)^2 = \left(\frac{1}{\rho_o c^2}\right)^2\left(\rho_o\frac{\partial\phi}{\partial t} + \phi\frac{\partial\rho_o}{\partial t}\right)^2 =$$

$$\frac{1}{c^4}\left(\frac{\partial\phi}{\partial t}\right)^2 + \frac{2\phi}{\rho_o c^4}\frac{\partial\phi}{\partial t}\frac{\partial\rho_o}{\partial t} + \left(\frac{\phi}{\rho_o c^2}\right)^2\left(\frac{\partial\rho_o}{\partial t}\right)^2$$

$$\nabla^2\phi - \frac{1}{c^2}\frac{\partial^2\phi}{\partial t^2} = 4\pi G\rho + \frac{\phi}{\rho_o c^2}\frac{\partial^2\rho_o}{\partial t^2} - \left(\frac{\phi}{\rho_o c^2}\right)^2\left(\frac{\partial\rho_o}{\partial t}\right)^2 - \cancel{\frac{1}{c^4}\left(\frac{\partial\phi}{\partial t}\right)^2}$$

$$\nabla^2\phi - \frac{1}{c^2}\frac{\partial^2\phi}{\partial t^2} = 4\pi G\rho + \left[-\frac{1}{m^2}\left(\frac{\partial m}{\partial t}\right)^2 + \frac{1}{m}\frac{\partial^2 m}{\partial t^2}\right]$$

Note the transient terms on the RHS of the eqn.

Last of the math!

$$\delta\rho_o(t) \approx \frac{1}{4\pi G}\left[\frac{\phi}{\rho_o c^4}\frac{\partial^2 E_o}{\partial t^2} - \left(\frac{\phi}{\rho_o c^4}\right)^2\left(\frac{\partial E_o}{\partial t}\right)^2\right]$$

$$\phi = c^2$$

$$\delta\rho_o(t) \approx \frac{1}{4\pi G}\left[\frac{1}{\rho_o c^2}\frac{\partial^2 E_o}{\partial t^2} - \left(\frac{1}{\rho_o c^2}\right)^2\left(\frac{\partial E_o}{\partial t}\right)^2\right]$$

$$\rho_o = m_o / V$$

$$E_o = \varepsilon / V$$

$$\frac{\partial \varepsilon}{\partial t} = P$$

$$\frac{\delta m_o(t)}{V} \approx \frac{1}{4\pi G}\left[\frac{1}{\rho_o V c^2}\frac{\partial^2 \varepsilon}{\partial t^2} - \left(\frac{1}{\rho_o c^2 V}\right)^2\left(\frac{\partial \varepsilon}{\partial t}\right)^2\right]$$

thus can write δm in terms of Power P…

THE “MACH EFFECT” EQUATION

QUANTIFIES THE MAGNITUDE OF THE PREDICTED MASS FLUCTUATIONS IN ACCELERATED OBJECTS:

$$\delta m_0 \approx \frac{1}{4\pi G}\left[\boxed{\frac{1}{\rho_0 c^2}\frac{\partial P}{\partial t}} - \boxed{\left(\frac{1}{\rho_0 c^2}\right)^2 \frac{P^2}{V}}\right]$$

- The linear term in *P* [the power delivered to a capacitor] is the “impulse engine” term.
- The quadratic term in *P* is the “wormhole” term (because it is always negative), normally a factor of $1/c^2$ smaller than the impulse engine term.
- Note, however, that this is only true for extended objects undergoing “bulk” accelerations.