Design Considerations for HIFU Transducers

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Introduction

Intent of this workshop is to outline some design considerations and guidelines for various types of transducers intended to be used for HIFU applications:

- Medical: Ablation, drug delivery, etc
- Industrial: droplet jets, descaling, etc
- Consumer: drug delivery, atomization, etc

“ Invention is 10% inspiration and 90% perspiration” Thomas Edison

Bio

- 1982: BSE - Purdue University
- 1982 – 1999: Etalon, Inc
- 1999 – 2007: Piezotech, LLC
- 2007 to present: Better UltraSonic Technologies
- 26 years of piezo and ultrasound transducer design, manufacture and marketing
- 17 years of medical HIFU

Outline

- Define Your Application
- Select best transducer configuration
- Determine Frequency and Sound Field
- Determine Power Requirements
- Select Piezo Material
- Determine Best Matching Layers
- Select Adequate Interconnects
- Tune Electrical Impedance

Outline

- Consider Thermal Management
- Model, Model, Model
- Consider MRI Compatibility
- Test and Characterize Performance, Life and Safety

- Consider Other Uses
- References
- Questions / Discussion

Define Your Application

- Assuming Medical
- Extracorporeal – Laparoscopic – Endocavity
  - Low F, long FL; High F, short FL; Mid, FL
- Durable – Disposable
- Biocompatibility of contact materials needs to be Class VI
- Imaging Modality
  - Integral to HIFU F
  - Integrated with HIFU
  - Other Modality: MRI, PET, CT, etc
  - Compatibility issues?

Define Your Application

- Identify Target Tissue(s) and Properties
- Identify Target Depth
- Identify any Intervening Materials and Properties
- Determine Treatment Volume Estimate
- Minimum Site Intensity (I_s)

Define Your Application

- Determine Treatment Time
  - (ref's: 10,11,12,51,52)
  - +70 C = 1 S, +56 C = 3 S, +43 C = 7200 S
  - After L. Crum, Therapeutic Workshop, 2007 US Symposium
- Consider Best Packaging

Select Best Transducer Configuration

- Single Element
  - Flat piezo element with Lens: low cost, less eff.
  - Cylindrical segment: medium cost, line focus
  - Spherical section: high cost, point focus, requires controlled scanning
- Multi-Element
  - Annular Array: medium to high cost, point focus, allows movement of focus along beam axis
  - Linear Array: expensive, can be concave, convex, phased, allows focusing along beam axis and transducer length, requires controlled scanning on transducer width for 3D

Select Best Transducer Configuration

- 2D Array: very expensive, phasing allows focusing in 3D
- CAUTION: Arrays create grating lobes – points of focus other than those intended- that can create hot spots/ lesions outside of the intended treatment area
- References: 13 – 22, 37

Determine Frequency and Sound Field

- Application is defined – how (ex, lap, endo), depth, intervening matl's, vol., I_s , Thermal
- Can calculate Frequency, F; Aperture, D; Focal Depth, FL; and Power, Po

- Frequency
  - Mainly dependent on depth to target due to intervening tissue attenuation
  - Typical is α = .5 to 1.5 dB/cm-MHz, 1 dB/cm-MHz is used

Determine Frequency and Sound Field

Example

Let z = 6 cm, F = 1 MHz

Loss to target = - 1 dB/cm-MHz * 1 MHz * 6 cm

= - 6 dB = 10 log (P/Po)

Based on assumptions and estimates made, the Site Intensity, I_s, needs to be estimated

Is typically between 1 kW/cm^2 and 10 kW/cm^2

For simplicity, let I_s = 1 kW/cm^2

Determine Frequency and Sound Field

Need to set an Aperture, D, as well; may be affected by packaging or anatomy, etc

Typically, F number = 1 = D/FL but can be from about .7 to 2 effectively

Since FL = 6cm, then D = 6 cm as well

Assume element geometry is the concave section of a sphere

From I_s, calculate Po

I = P/area where ba = area

Determine Frequency and Sound Field

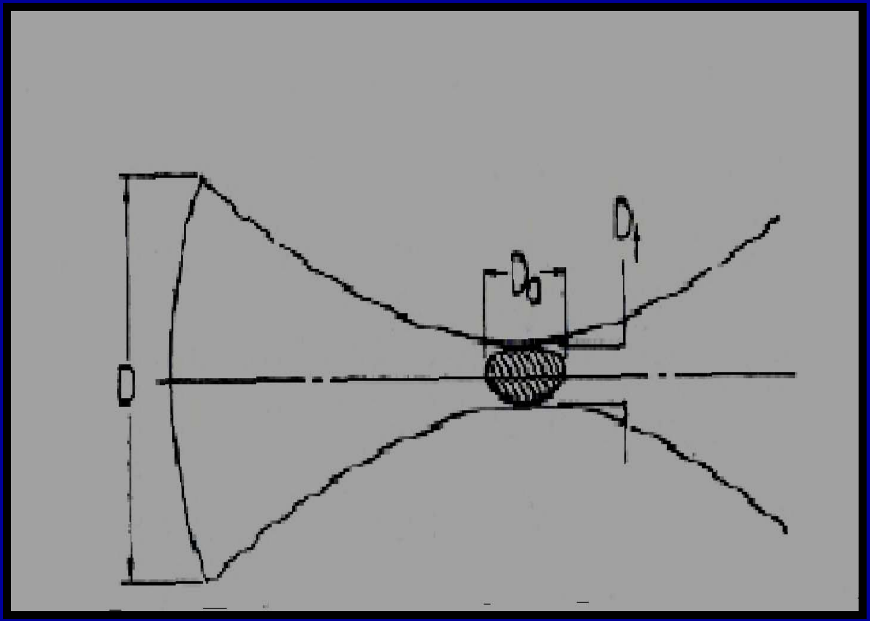
Calculate Focal beam Dia., Dt, Beam Area, ba, and Focal Zone Length, FZL (Da)

Dt = FL*c/(F*D), cm

ba = π*d^2/4, cm^2

Da = FZL ~ 10 d, cm

Vol = ba * FZL, cm^3



Determine Frequency and Sound Field

$Dt = 6*.15/(1*6) = .15$ cm

$ba = \pi * .15^2/4 = .018$ cm^2

$Da = 10 * .15 = 1.5$ cm

This is an iterative process based on requirements of the application

Determine Power Requirements

Calculate Site Power, P_s, from I_s and ba

$$P_s = I * ba = 1000 * .018 = 18\ W$$

Calculate Power, Po, from loss and P_s

$$Loss = -6\ dB = 10 \log (P_s/Po)$$

$$Po = P_s/10^{-.6} = 18 / .25 = 72\ W$$

Determine Power Requirements

Calculate Surface Intensity, Ia, on piezoelement

surface area, sa = $\pi * D^2 / 4 = 29 \text{ cm}^2$

Ia = Po / sa = 72 / 29 = 2.55 W / cm^2

this is well within limits of piezo materials
Pmax = sa * Is = 29 * 10 = 290 W

The power and intensity limits need to be balanced against the possibility of damaging tissue between the transducer and target site.

Select Piezo Material

Limit to "high drive" types

Assume 50 ohm source and desired load

Calculate capacitance

$$C = 1/ \omega * Z$$

Where C is Farads, Z is impedance, $\omega = 2*\pi*F$

$$C = 3200 \text{ pF}$$

Select Piezo Material

Calculate dielectric constant, K

$$K = C * t / (sa * \varepsilon_o)$$

where t = thickness = .21 cm;
and $\varepsilon_o = 8.85 \times 10^{-14}$ F / cm

$$K = 260$$

Select Piezo Material

Type	PZT5	PbT	PZT 2a	PZT 2b	PZT8	PZT4	PZT 4D	PZ52 K320	PZ56 K340
Prop									
$K3^T$	1700	215	350	550	1000	1300	1450	1500	2900
$K3^S$	830	160	225	310	600	665	710	865	1500
K33	.70	.51	.63	.65	.62	.70	.71	.60	.65
Kt	.50	.51	.50	.52	.44	.45	.50	.50	.50
Qmr	75	0	>900	>750	1000	500	1000	2000	1600
Qmt	50	300	220	200	200	100	400	400	400

Select Piezo Material

	PZT 5A	PbT	PZT 2a	PZT 2b	PZT8	PZT4	PZT 4D	PZ52 K320	PZ56 K340
loss	.020	.015	.004	.004	.004	.008	.004	.002	.004
V/cm	450	10 k	8 k	8 k	10 k	3.9 k	>5 k	>10k	5 k
V/cm 100C	400	8 k	7 k	7 k	8 k	3.3 k	3.5k	10 k	4 k
W / cm^2	<1 >1	>25 >50	>10 >25	>10 >25	>20 >40	> 5 > 10	>10 >25	>25 >50	>10 >20
Tc,C	350	350	350	330	300	325	300	320	200
d33	350	70	150	180	225	285	350	320	400
Z,MR	35	35	35	35	35	35	35	35	35
Vend	lots	E F PT M	F M PT	F M PT	lots	lots	lots	FP PT	FP PT

Select Piezo Material

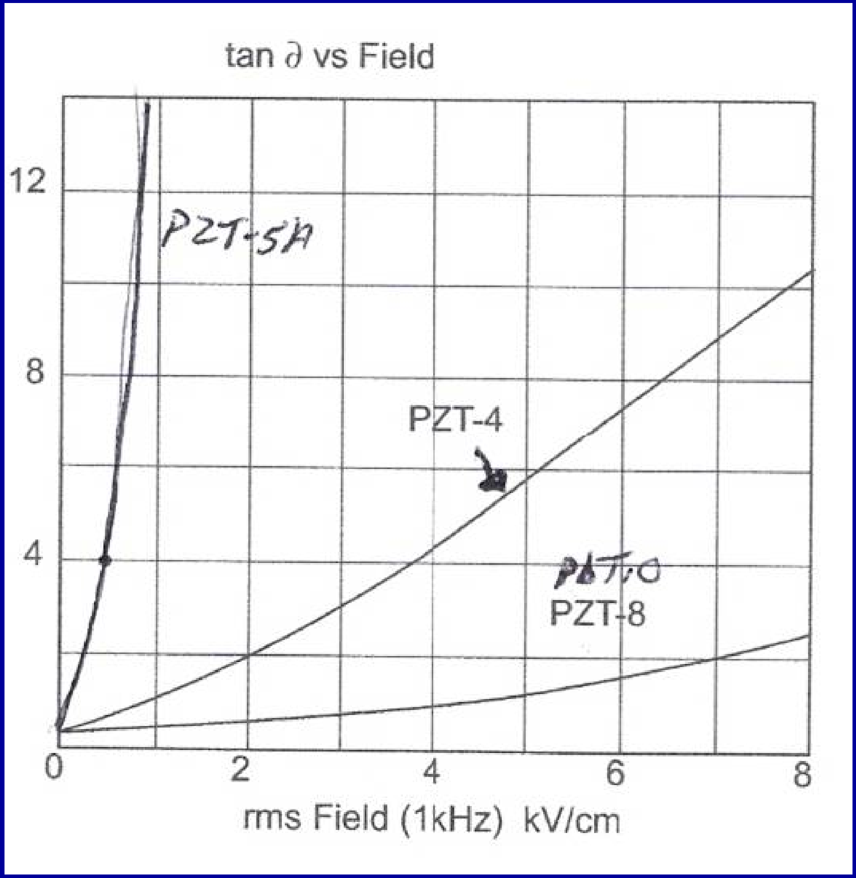
Calculate Power and Voltage Limits

$Po = 2*\pi*F*E^2*k^2*\varepsilon_{33}^T*Qm$, W/cm^3

where E is V/cm,

ε is F/cm

$Pd = 2*\pi*F*E^2*\varepsilon*lf$



(ref. 2)

Select Piezo Material

Need to balance Surface Intensity with applied Voltage using

$$Po = V^2/R$$

where V = drive volts, rms

$V = (Po*R)^{1/2} = (72*50)^{1/2} = 60$ Vrms

Vmax = t * E = .21 * 8000 = 1680 Vrms

$Pmax = Vmax^2/R = 56$ kW

Vmax real = $(290*50)^{1/2} = 120$ Vrms

Select Piezo Material

Composites (36)

Can be made from any PZT, no gain for PbT

Pros: increase k, vary volume % ceramic →
K, Za, Ze
minimal lateral modes,
minimal side lobes
Base for 2D array
30 W/cm^2 reported

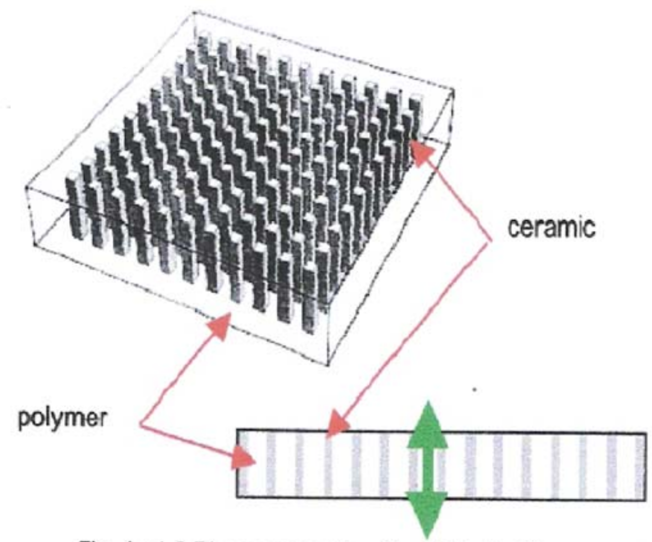


Fig. 1 : 1-3 Piezocomposite after W. A. Smith

Select Piezo Material

Cons

- More expensive
- Less solid ceramic → less real power
- ~ 1/3 thinner for same F → less Voltage
- Have to manage heat effectively

Select Piezo Material

Single Crystals

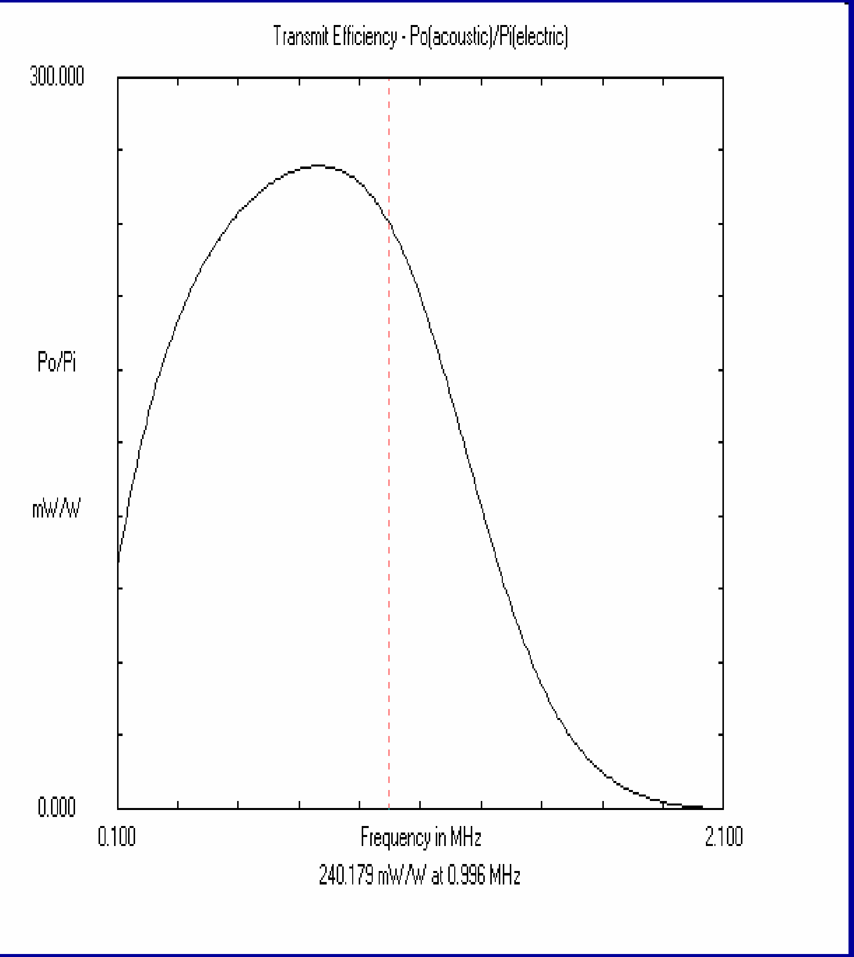
- Large k = .7 to .9+
- Low loss, < 1 % typically

But

- High K → low Ze, ok for array elements
- Low Tc w/ phase change near 25 C
- can they be focused?
- very expensive: $1/mm³ = $1000/cm³

Determine Best Matching Layer(s) (3, 17)

1. None
   a. Ok if therapy only
   b. Still needs coating to protect electrode, leads, seal, etc
   c. Can get > 50 % eff. If properly designed
   d. Very narrow BW
   e. Use PLL to stay on Fo
   f. Ex - CV



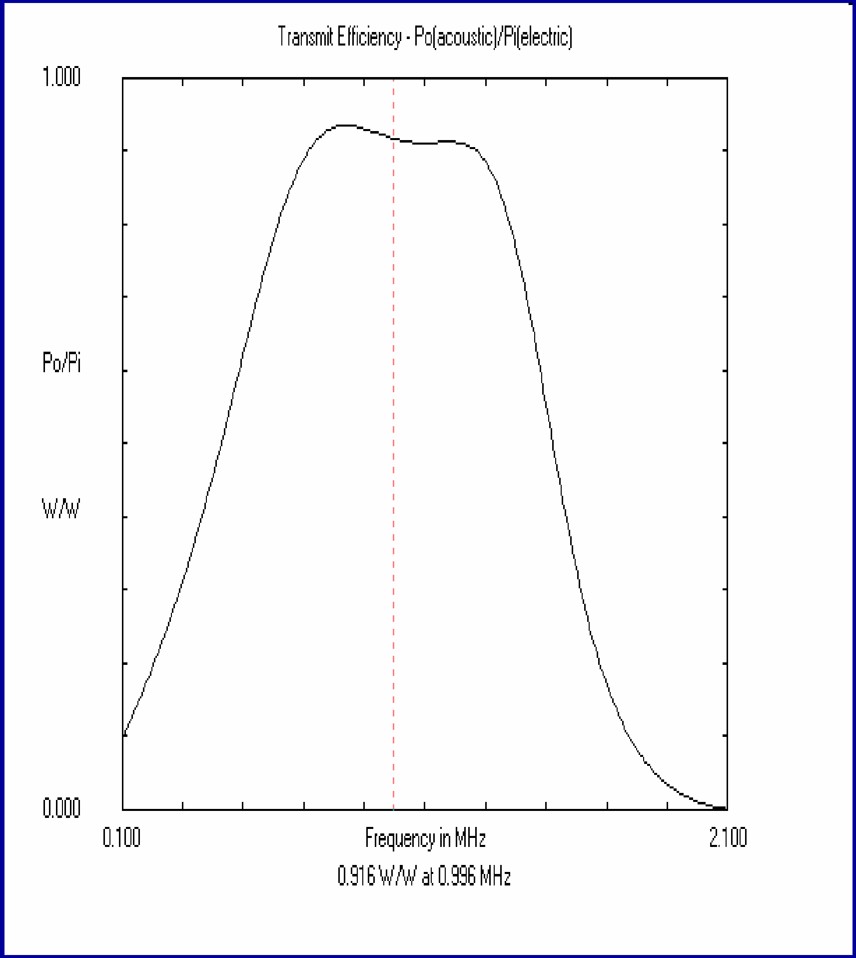
Determine Best Matching Layer(s)

2. Single λ/4

2 Main Equations

a. Geometric Mean

$$Zml = (Zl*Zx)^{1/2}$$
$$= 7.2\ MR$$



Determine Best Matching Layer(s)

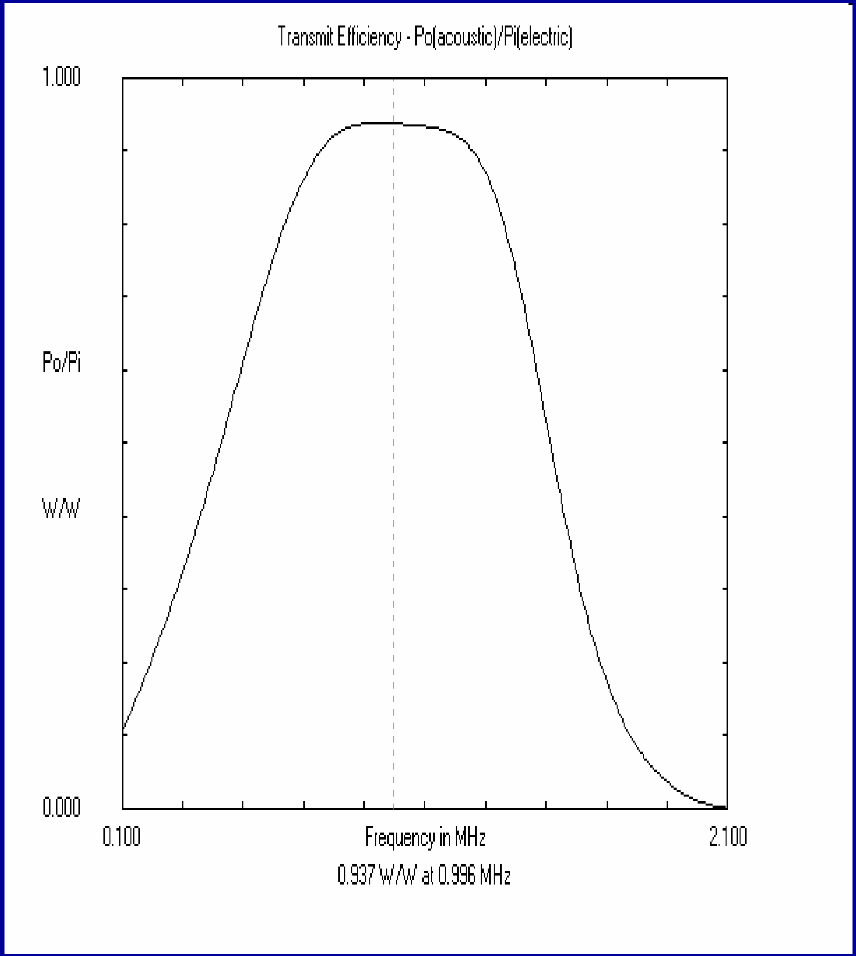
b. After DeSilet, et al

$Zml = Zl^{2/3} * Zx^{1/3}$

$= 4.3$ MR

used KLM, sets Qm = Qe to max. BW, min. PL

Not always best for max Po



Determine Best Matching Layer(s)

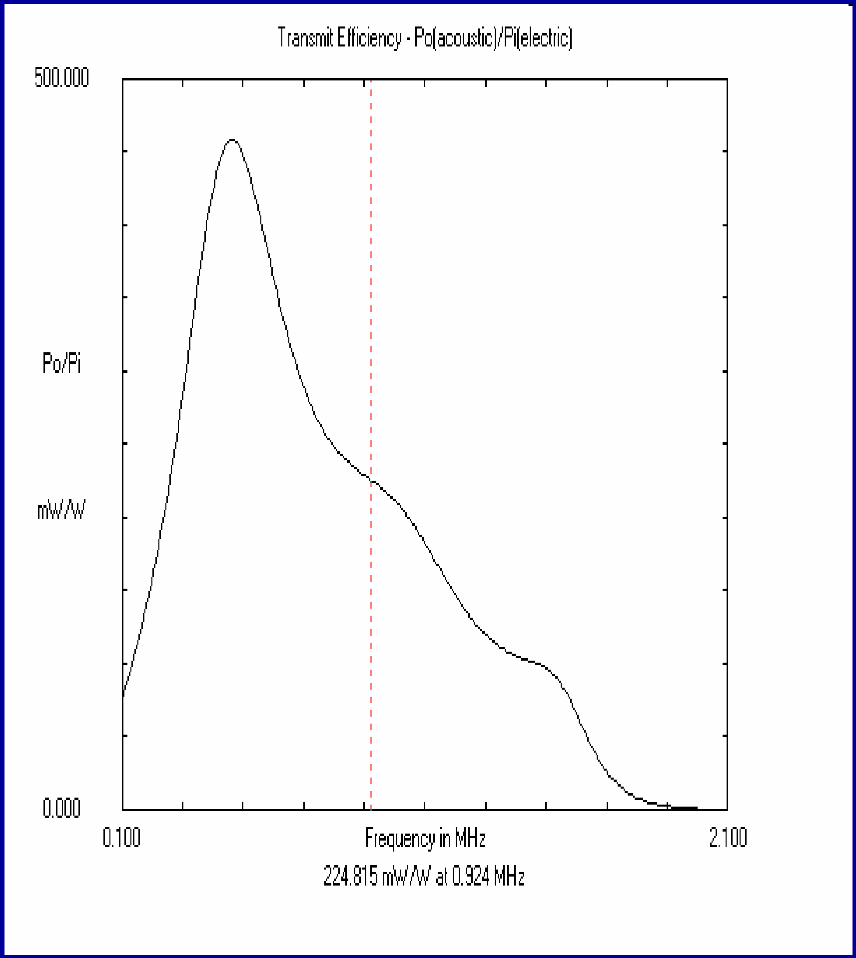
3. Single λ/2

same eq's.

a. Geometric Mean

Zml = 7.2 MR

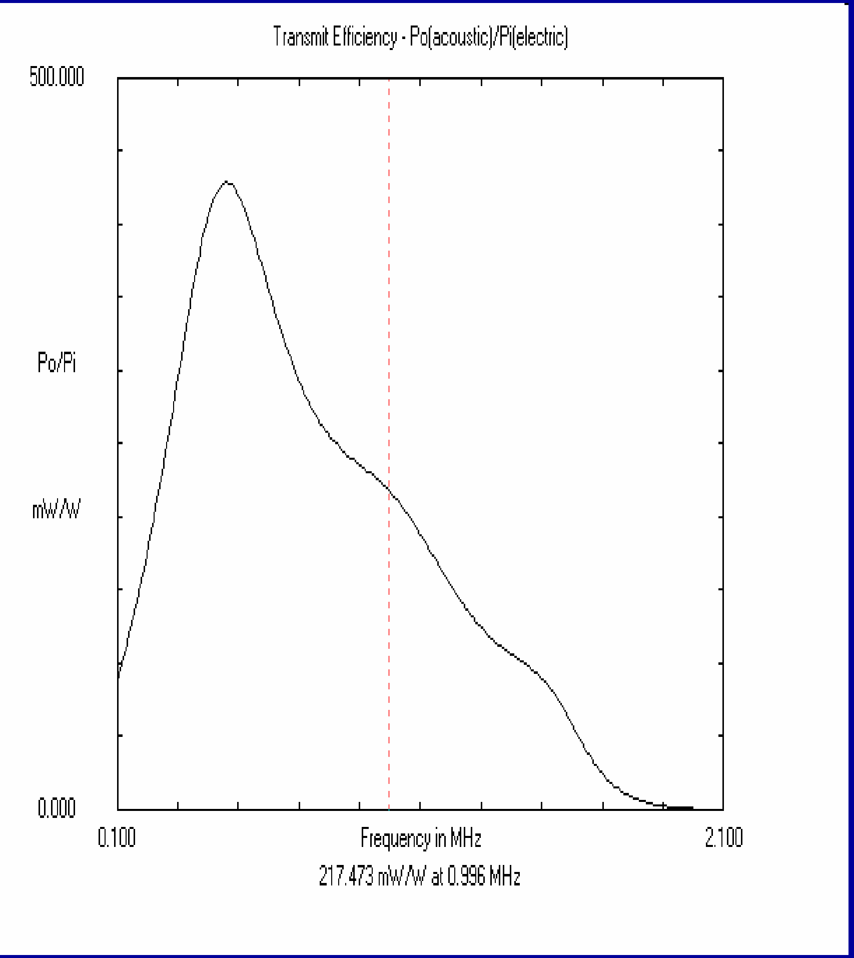
narrowband



Determine Best Matching Layer(s)

b. DeSilet

Zml = 4.3 MR

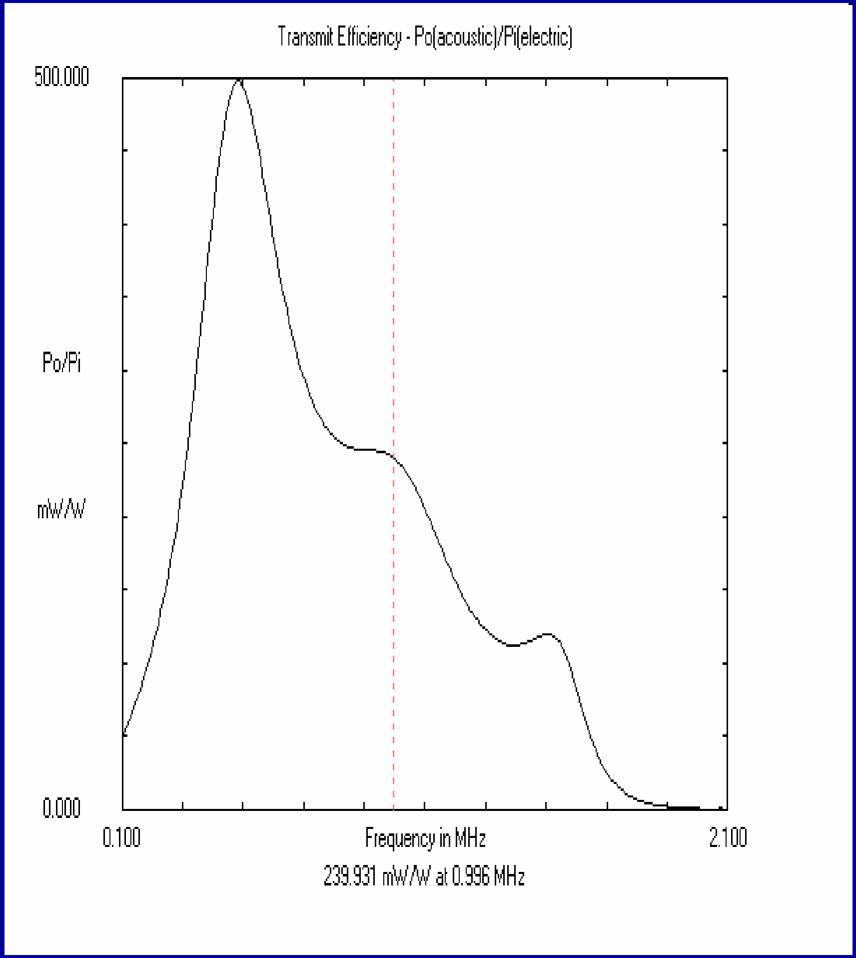


Determine Best Matching Layer(s)

c. Example from physiotherapy

Zml = 17.1 MR

Aluminum



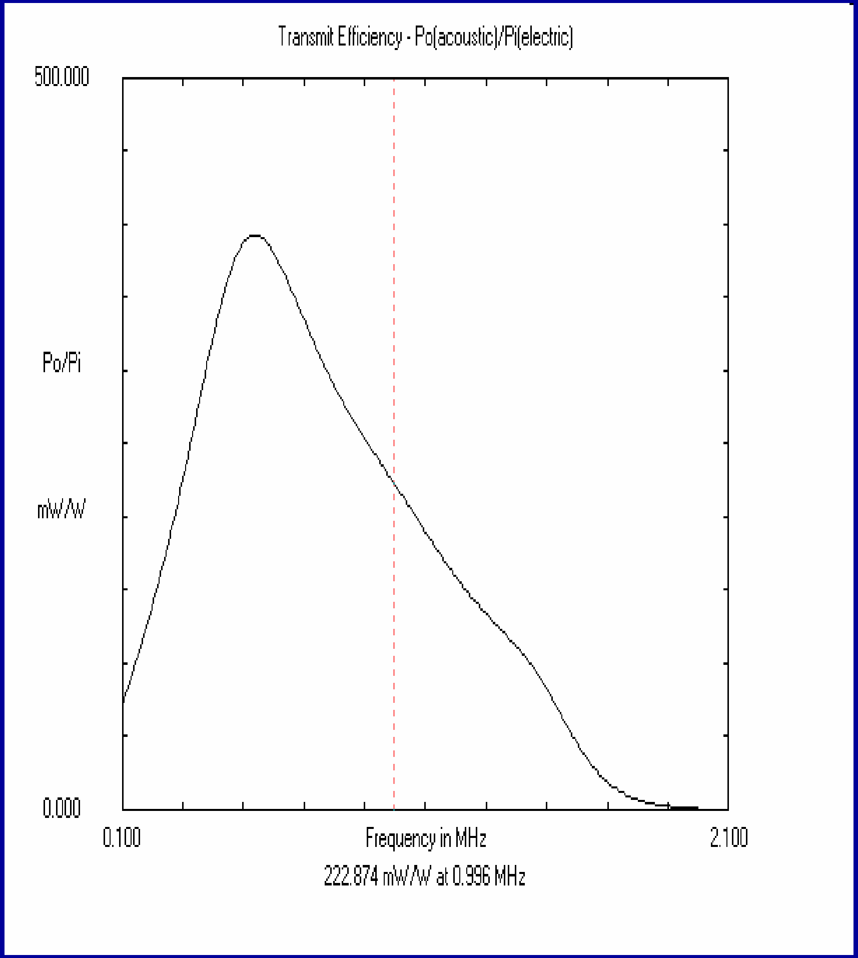
Determine Best Matching Layer(s)

4. Double λ/4
 3 Main Derivations
 Max. BW

 a. Geometric Mean

 $Zml1 = Zx^{2/3} * Zl^{1/3}$
 $= 12$ MR

 $Zml2 = Zx^{1/3} * Zl^{2/3}$
 $= 4.2$ MR



Determine Best Matching Layer(s)

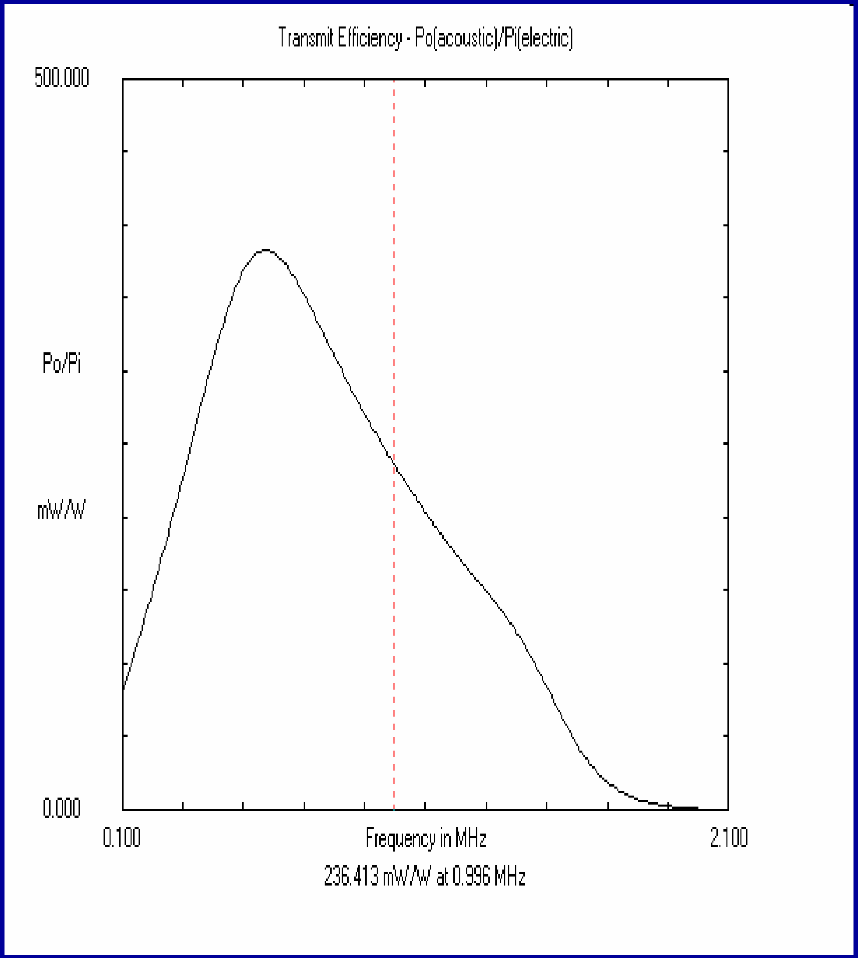
b. DeSilet

$Zml1 = Zx^{4/7} * Zl^{3/7}$

$= 9$ MR

$Zml2 = Zx^{1/7} * Zl^{6/7}$

$= 2.4$ MR



Determine Best Matching Layer(s)

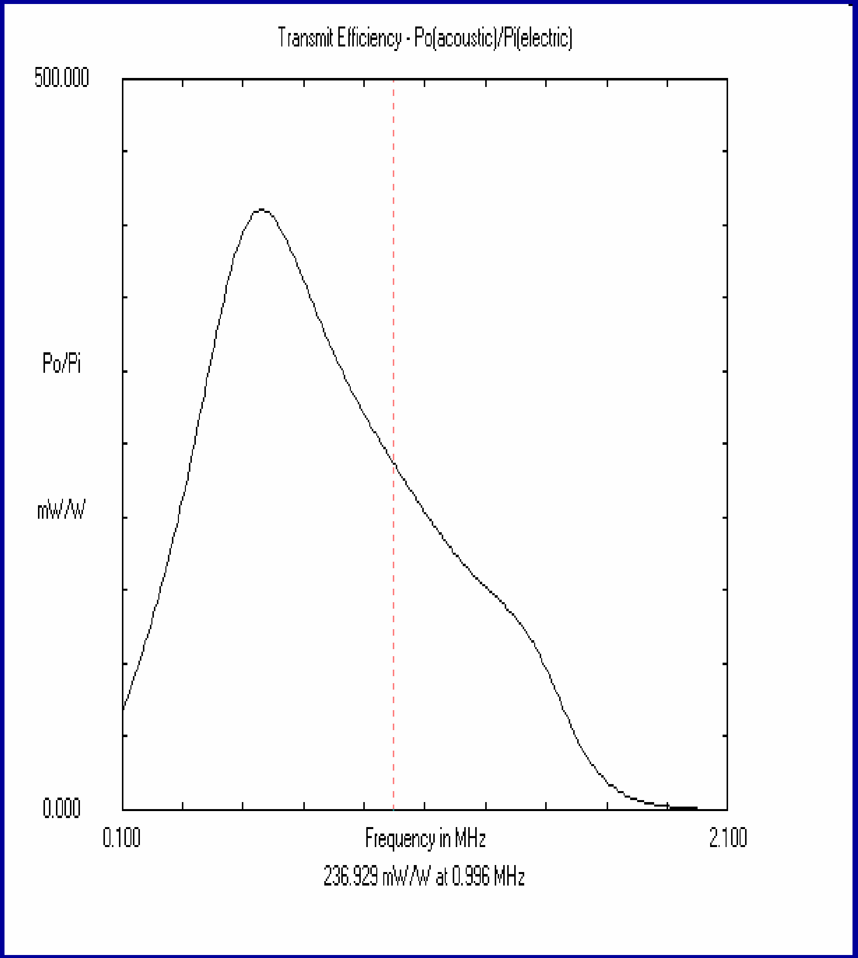
c. After Goll

$Zml1 = Zx^{3/4} * Zl^{1/4}$

$= 15.5$ MR

$Zml2 = Zx^{1/4} * Zl^{3/4}$

$= 3.5$ MR



Determine Best Matching Layer(s)

5. Materials (4)
   - a. Z = 1 to 10 MR:
     - polymers, carbon, magnesium
     - fillers: AlO, AlN, SiC, W, Others
   - b. Z = 10 to 15 MR:
     - glass, glass ceramic, fused silica
   - c. Z = 15 to 20 MR:
     - x-cut quartz, aluminum, silicon, indium

Determine Best Matching Layer(s)

6. Precautions

High Power, i.e. Surface Intensity →

High surface deformation & heat

- a. electrode: high adhesion to piezo
- b. ML: void free, high Tg, low α, some plasticity – Shore D 70 to 90
- c. May require use of chemical primers
- d. Mid to high thermal conductivity

Select Adequate Interconnects

1. Electrodes on element
   a. Fired silver frit
   b. Sputtered or electroless copper, gold, nickel, platinum, palladium, indium, tin, etc
   c. Needs to be solderable, preferrably nonmagnetic
2. Wires and Cables
   a. Foils: copper, tin, brass, nickel, silver
   b. Small gauge wires, solid or stranded, copper with tin, silver or gold plate, etc
   c. Cables: typ. Coax but can be twinax, triax, etc

Select Adequate Interconnects

3. Solders
   a. Pb/Sn, Sn/Ag, Pb/Sn/Ag, Sn/Ag/Cu, Au/In, etc.
   b. Conductive polymers
   c. Need to be somewhat pliable due to high mechanical stress
   d. Need to have high Ts / Tl due to high thermal stress
   e. Must be compatible with electrode and wire materials to prevent scavenging / leaching

Tune Electrical Impedance

Transducer can be modeled as a simple Lumped-element Circuit

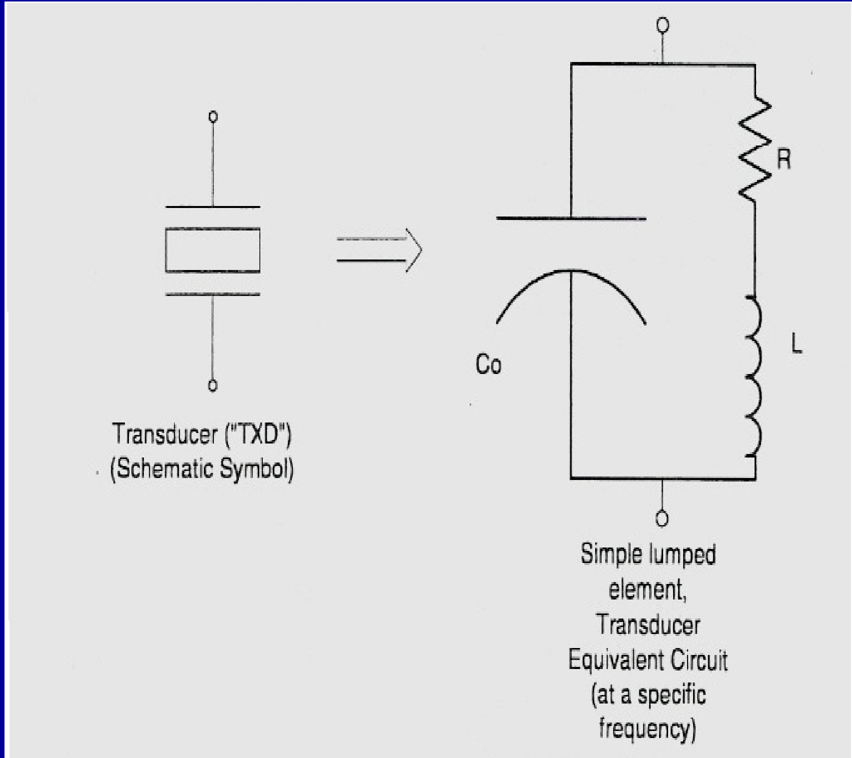


Figure 1: Lumped element representation of a piezoelectric transducer (near resonance)

(ref's 5, 6, 7, 8, 9)

Tune Electrical Impedance

1. Parallel eq. Circuit
   a. Parallel Inductor

$$Rp = Z / \cos\theta$$

$$Xp = Z / \sin\theta$$

$$Lp = Xp / \omega$$

Requires high saturation core & large wire gauge

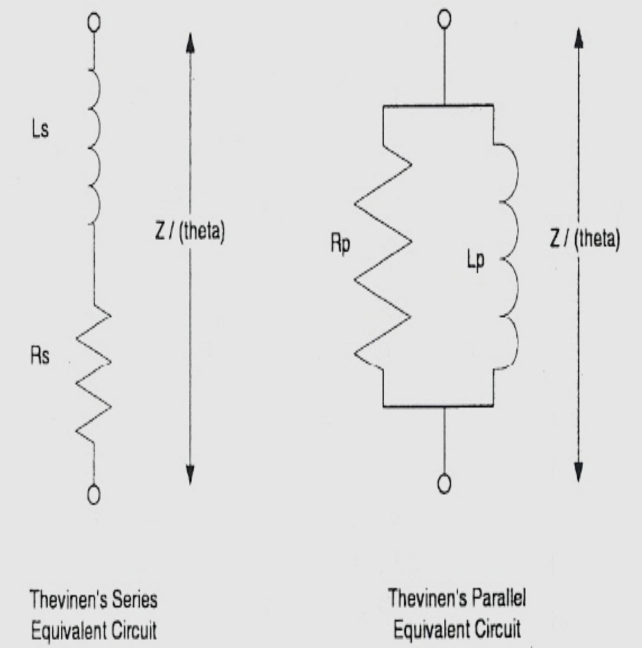


Figure 2: Thevinen's equivalent circuit representation for the impedance and phase angle

Tune Electrical Impedance

b. Transformer

$Zsec / Zpr = N^2$

set $Zsec = \omega * Xp$

or $Lp = Lsec = Xp / \omega$

$Zpr = Rs$

and $N = t_s / t_p = (\omega * Lp / Zpr)^{1/2}$

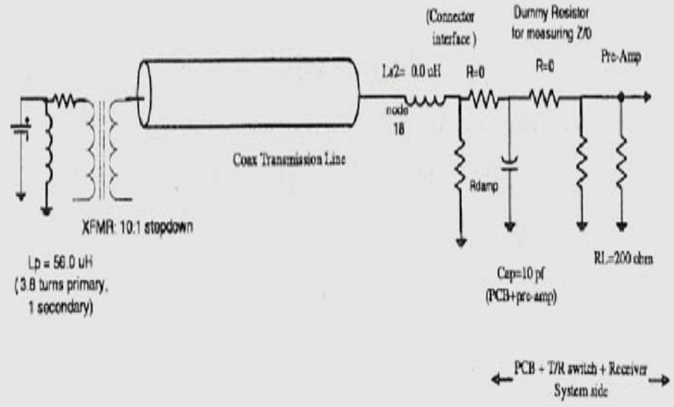


Figure 4: Broadband impedance matching (tuning) with "auto-transformer"

Tune Electrical Impedance

b. Transformer

can be toroid, C-core, E-core, balun, etc

be cautious with wire gauge and core material

typically high Q but can control with additional capacitance

$$Q = Rp / Xp$$

Tune Electrical Impedance

2. Series Eq. Circuit

Rser = Z * cos θ

Xser = Z * sin θ

Lser = Xser / ω

cancels reactance

Z = Rser

Z ≠ Rs unless design is right

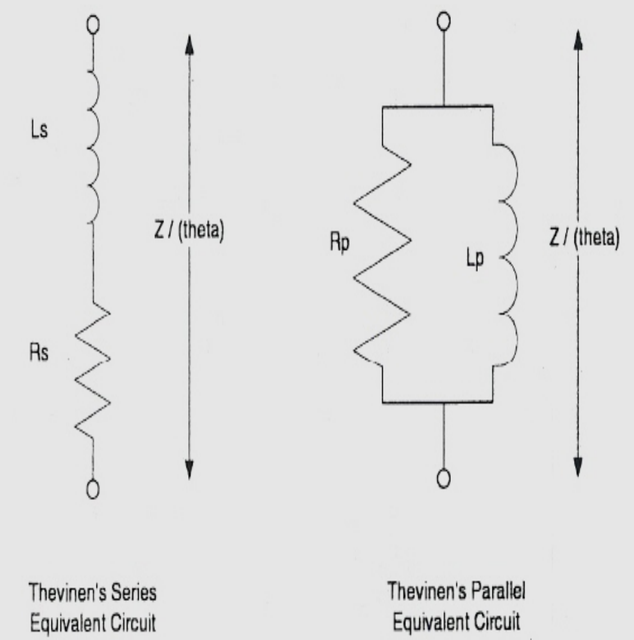


Figure 2: Thevinen's equivalent circuit representation for the impedance and phase angle

Tune Electrical Impedance

3. The L Network

Near lossless, max. power transfer, esp. if true conjugate of Zs; high or low pass choose by:

RL > Rs, RL < Rs

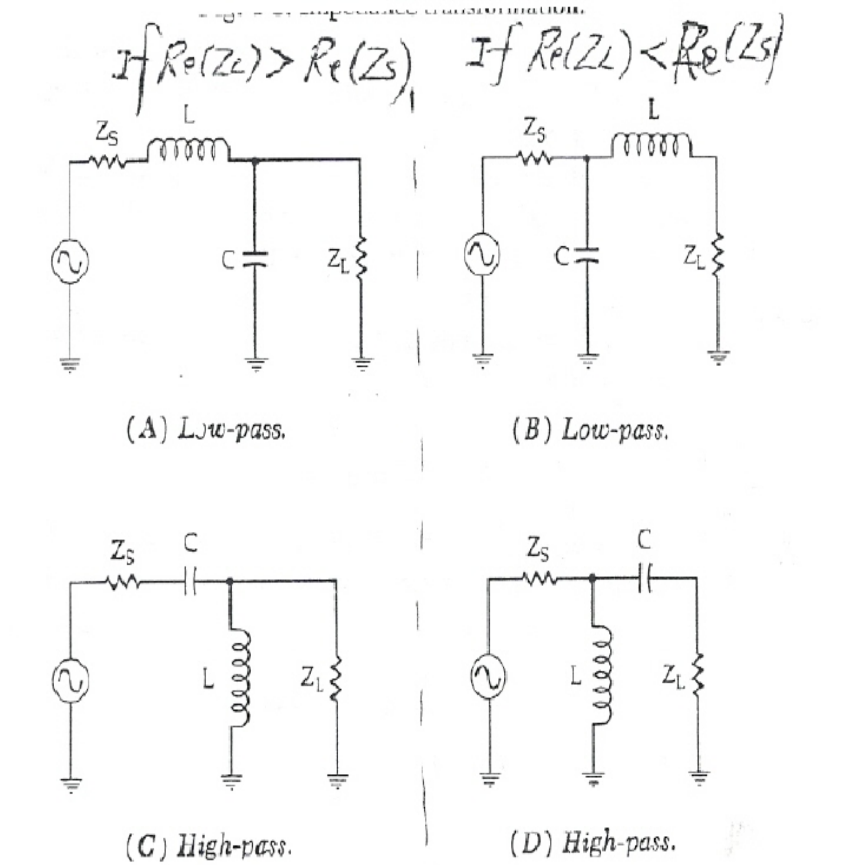


Fig. 4-4. The L network.

Tune Electrical Impedance

3. L Network

High pass preferred for harmonic content, Nonlinear component increases rate of tissue necrosis due to increased absorption at focus (ref. 9);

components should be rated for power and values are at F,

technique can be written as a program

and can be extended to more complex T and π networks

can easily adjust for stray cap. and ind.

Tune Electrical Impedance

3. L Network

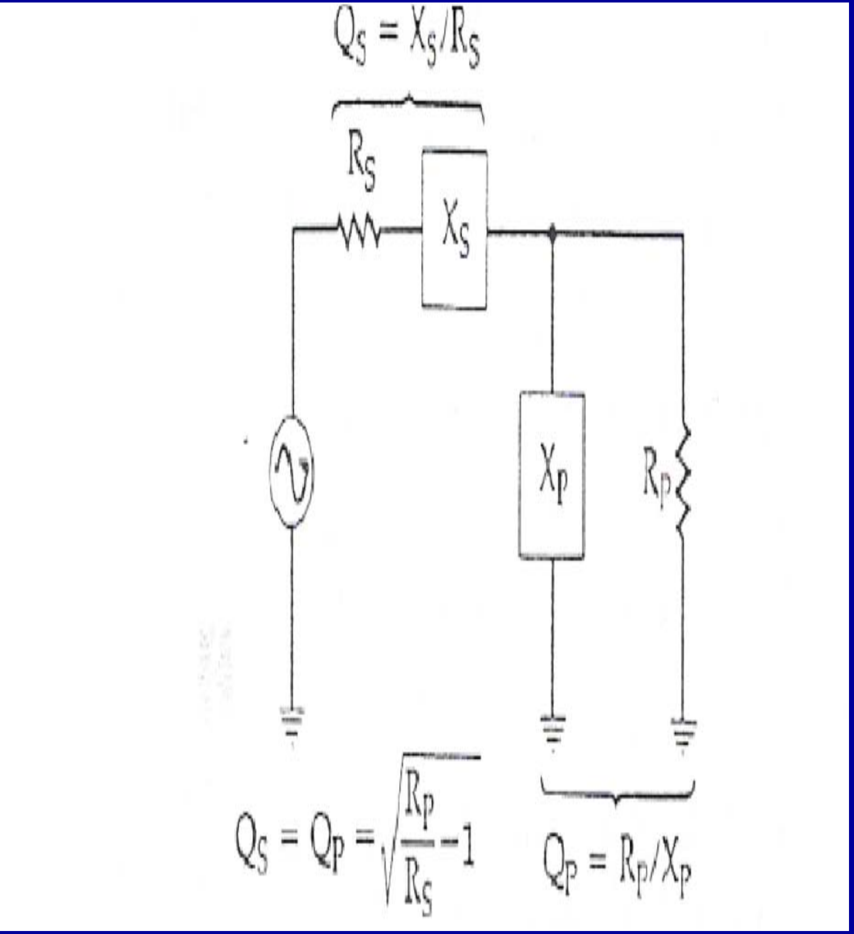
$Qs = Qp = (Rp/Rs – 1)^{½}$

$Xs = Qs * Rs$

$Xp = Rp / Qp$

$L = X / ω$

$C = 1/ (X * ω)$



Tune Electrical Impedance

Tuning Example

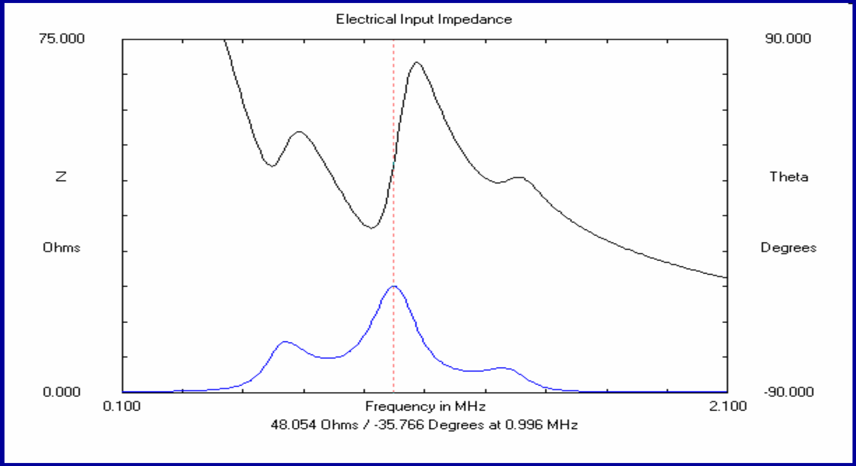
Double λ/4, Geo. Mean

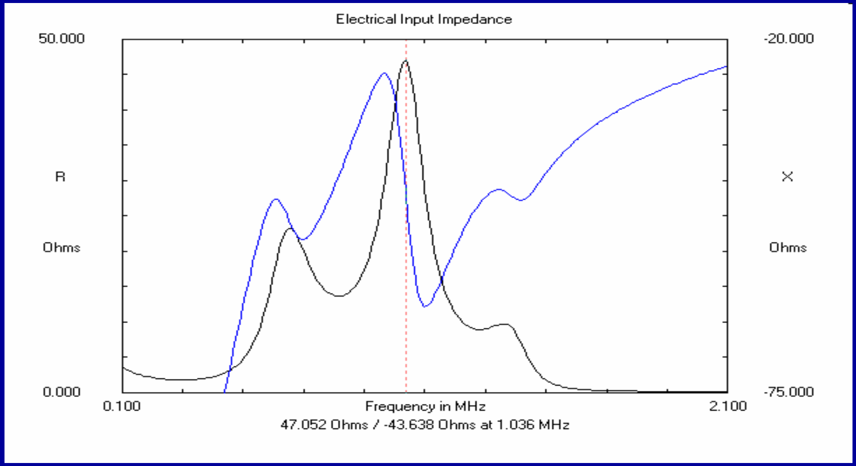
Use simple series L

$L_s = X_s / \omega =$

$43.64/6.28 \times 10^6 =$

6.95 μH



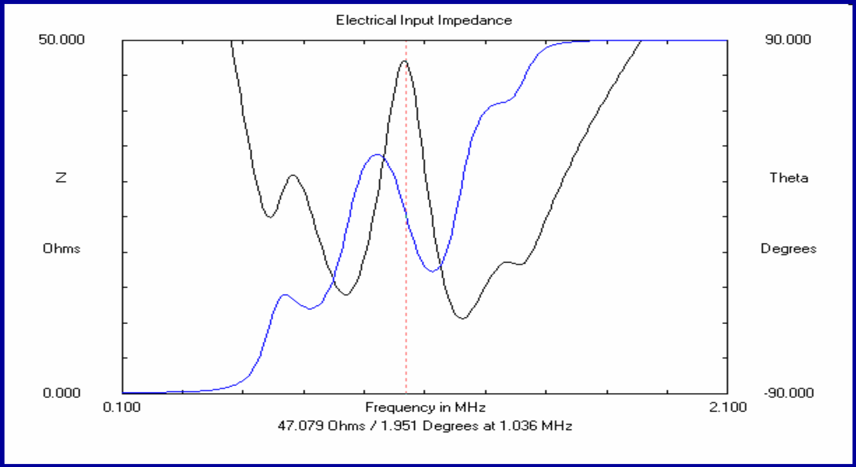


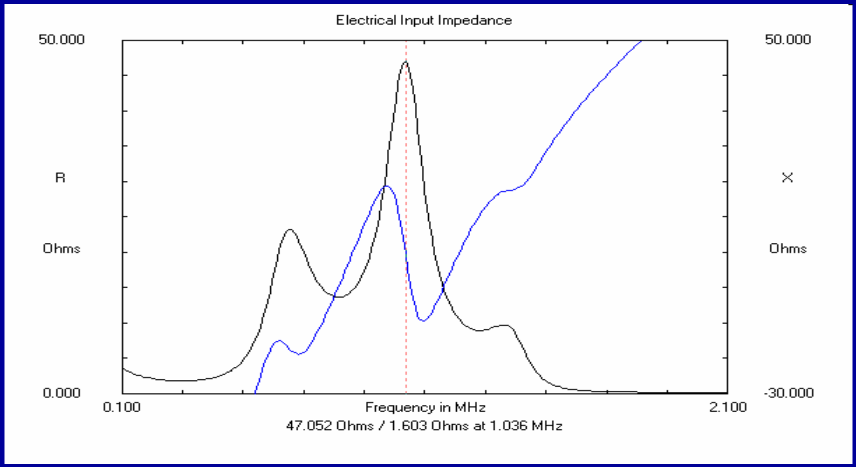
Tune Electrical Impedance

Results from implementing into model

Z <θ = 47.1 Ω < +2°

R + jX = 47 + j 1.6



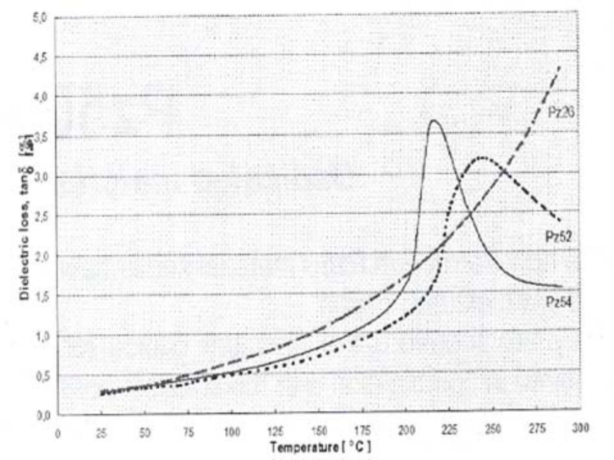


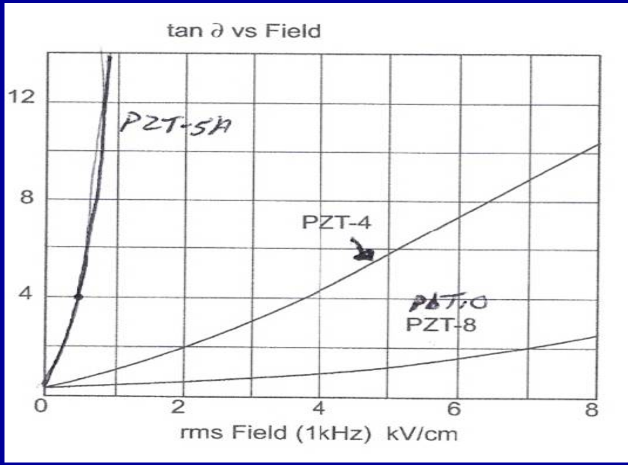
Consider Thermal Management

At high power, duty cycles – things will get hot!

To do:

1. Heat sink to thermal absorber
2. Thermal sensor
3. Coolant





Consider Thermal Management

Results:

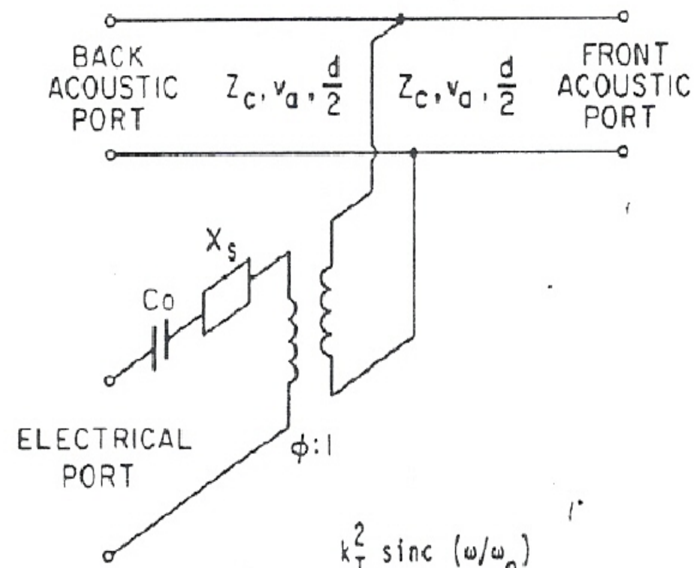
- Matching Layer and electrode delaminating, blistering, cracking
- Piezo cracking, depole arcing, breakdown
- Tuning Circuit and Wires burnout

FIGURE 1. Cracked transducer front face due to an excessive applied power (about twice the maximal acceptable excitation level)

MODEL, MODEL, MODEL

1. Equivalent Circuits
   a. Mason's Model – Lumped element – not used except for simple devices
   b. Redwood – modified Mason's Model
   c. KLM – implemented in most software today
   d. Fs vs. Fp Operation

(ref. 1, 23 – 27)



$$X_s = \frac{k_T^2 \operatorname{sinc}(\omega/\omega_0)}{\omega C_0}$$

$$\phi = k_T \sqrt{\frac{\pi}{\omega_0 C_0 Z_c}} \operatorname{sinc}\left(\frac{\omega}{2\omega_0}\right)$$

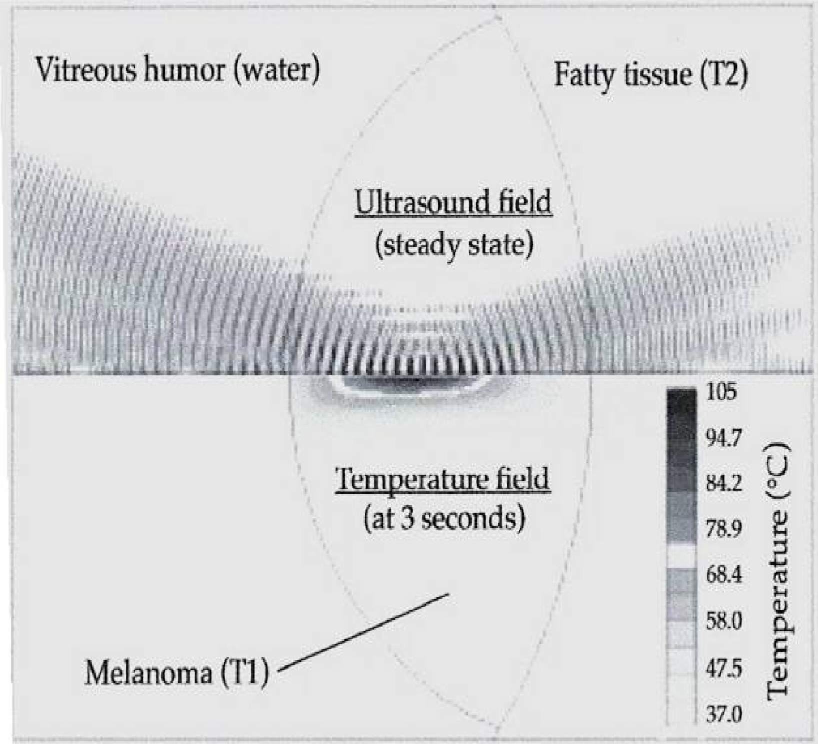
Figure 1. KLM model.

MODEL, MODEL, MODEL

2. Implementation
    a. Commercial SW Packages
        1. PiezoCAD – 1-D , Sonic Concepts
        2. ANSYS – FEA, Swanson
        3. COMSOL – FEA,
        4. PZFLEX – FEA, Weidlinger
    b. Write own in C, MatLab, MatCad, Spice

MODEL, MODEL, MODEL

3. What can be done
   a. Predictive: Po, BW, IL, Imp, Field, Thermal
   b. Parametric : include active & passive components, load losses
   c. FEA: 2 & 3D, defects, mode coupling, etc



'igure 5. Axisymmetric model of an ocular tumor, showing focused ltrasound beam (above) and temperature distribution at 3 sec below). Note focal temperature in excess of 100 °C. The transducer as a 4 cm aperture and 9 cm focal length.

MODEL, MODEL, MODEL

4. An Example Using PiezoCAD

Single λ/4, Z = 4.3

No electrical tuning

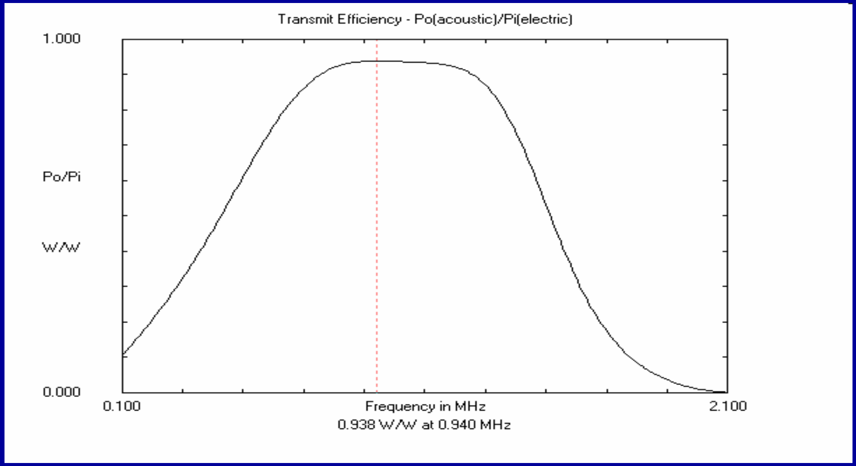
Z / θ = 49 / - 37 @ 1M

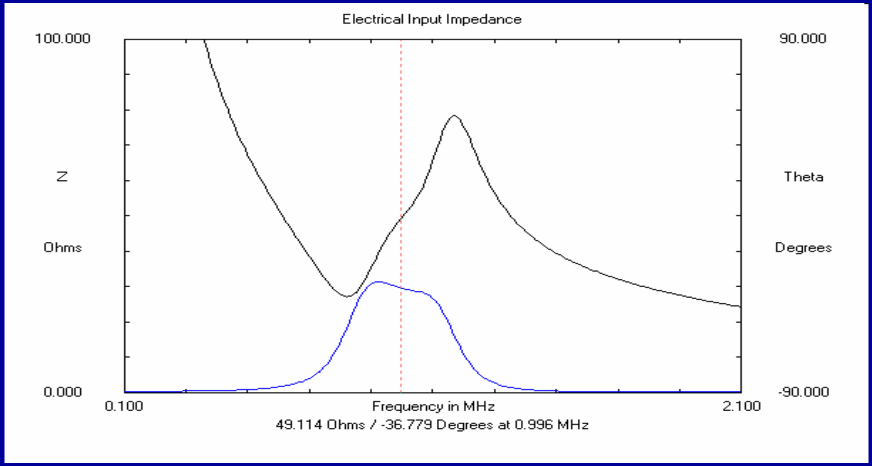
Po/Pi = .938 W/W @ .94

Rmax = 49 @1.116 M

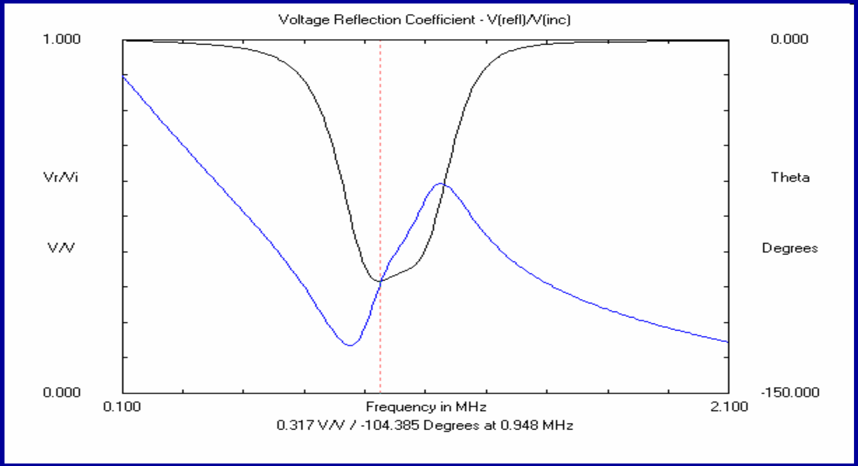
Gp @ .868 M

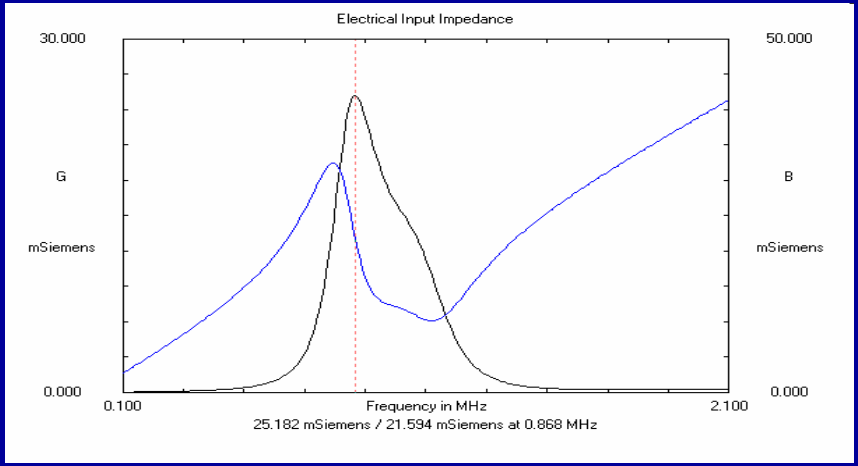
VRC = .317 V/V @ .95 M

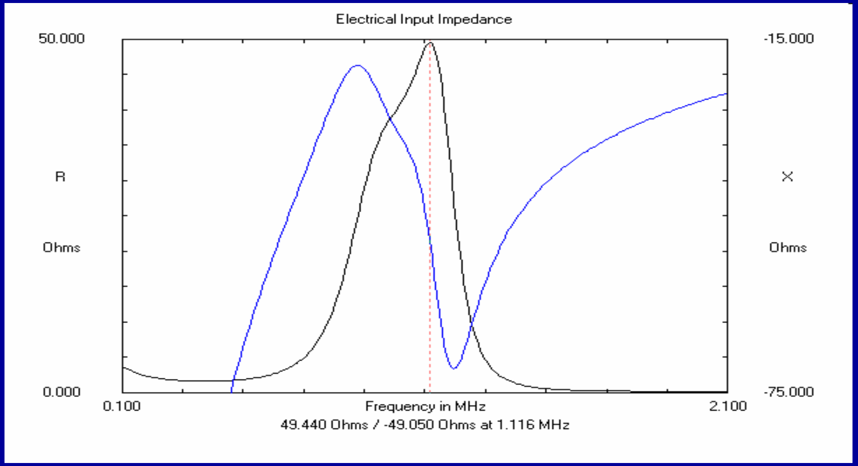




MODEL, MODEL, MODEL







MODEL, MODEL, MODEL

Adjust Matching Layer Thickness to affect F, R

Po/Pi = .944 W/W @ .97

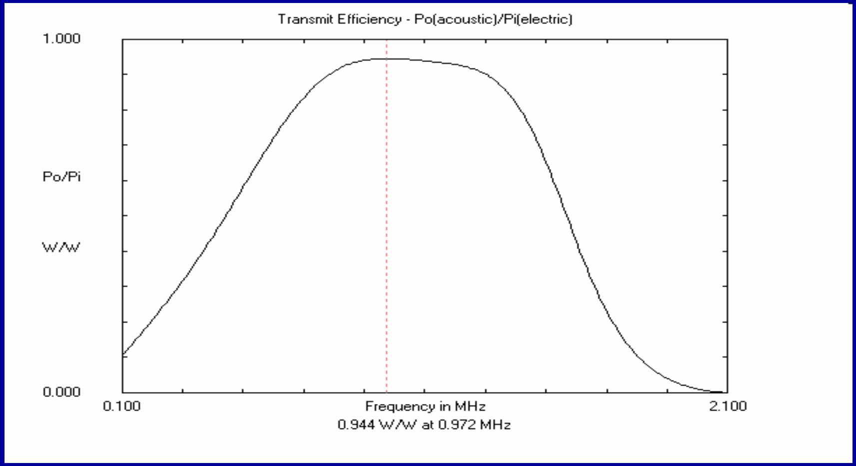
Z / θ = 69.5 / - 30 @ 1 M

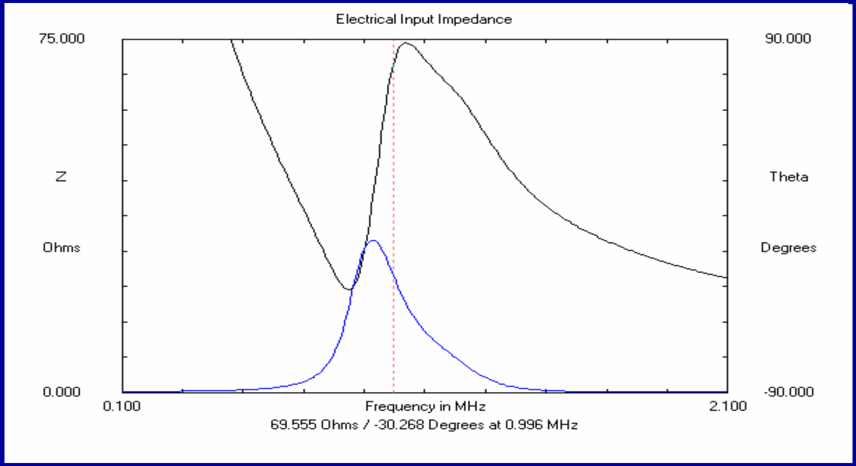
Gp @ .876 M

AND

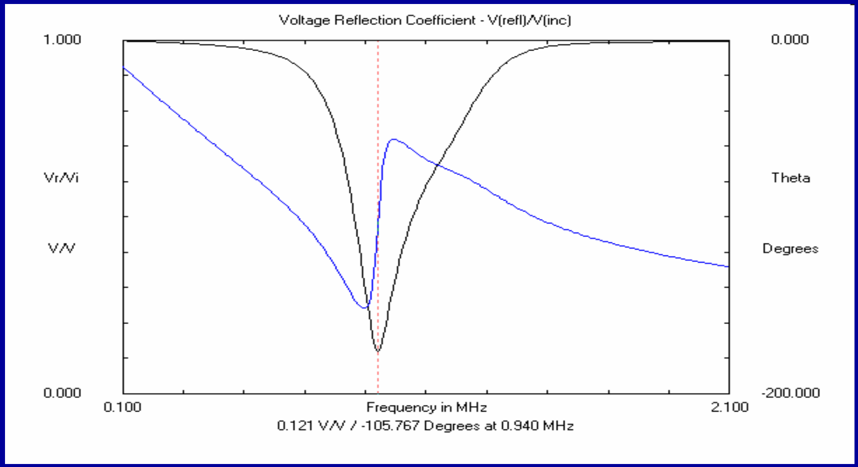
R max = 60 @ 1 M

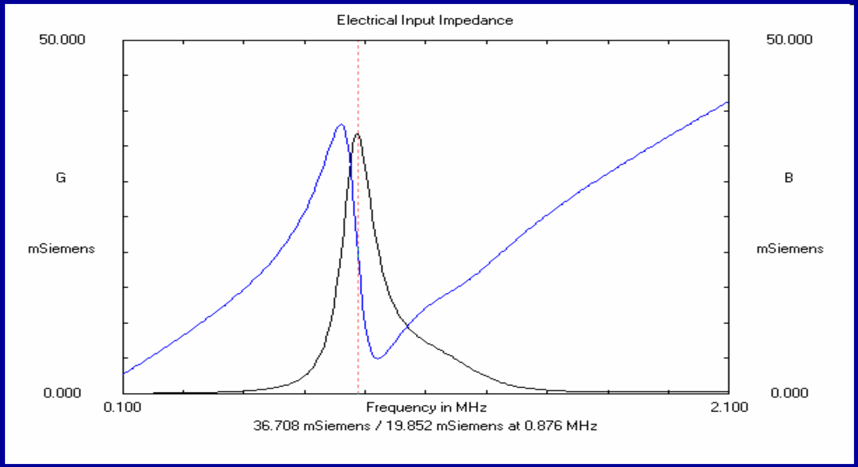
VRC = .121 V/V @ .94

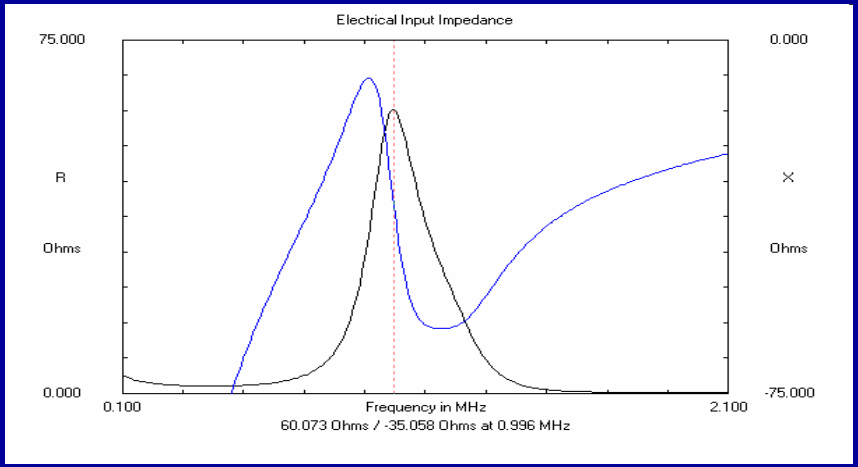




MODEL, MODEL, MODEL







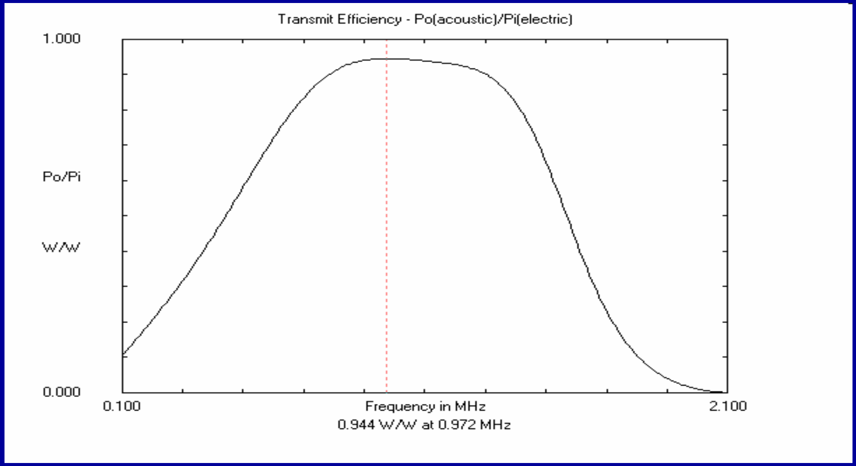
MODEL, MODEL, MODEL

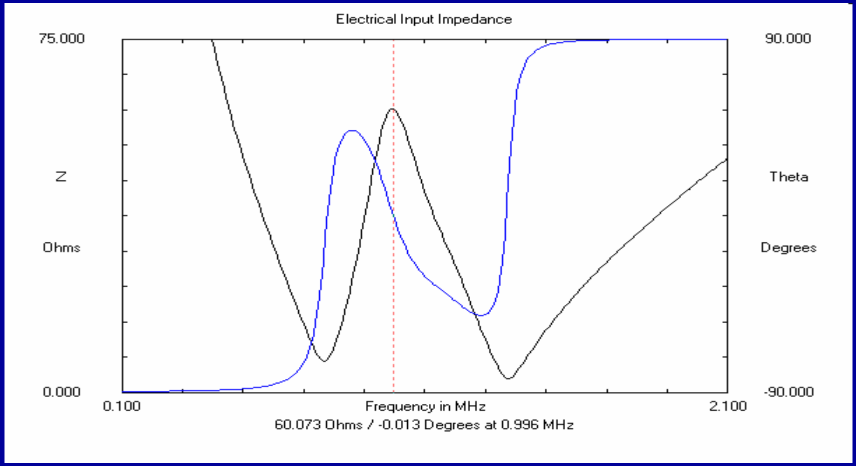
Add Tuning to cancel reactance

Series L = 5.6 µH @ 1 M

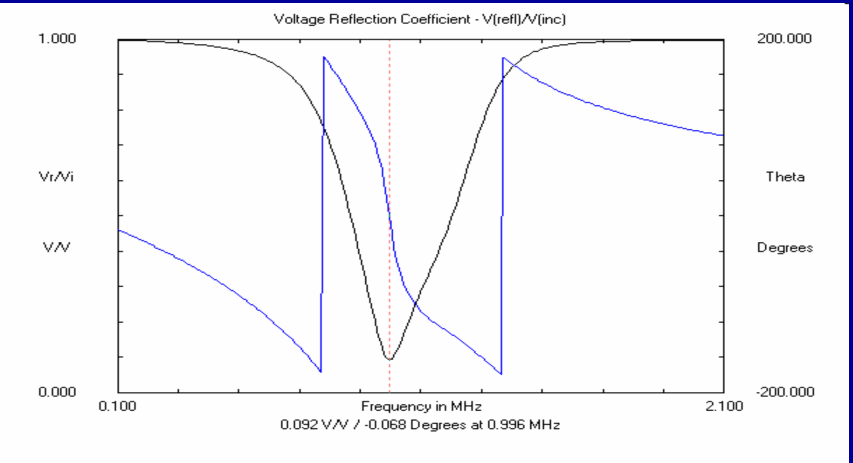
Results

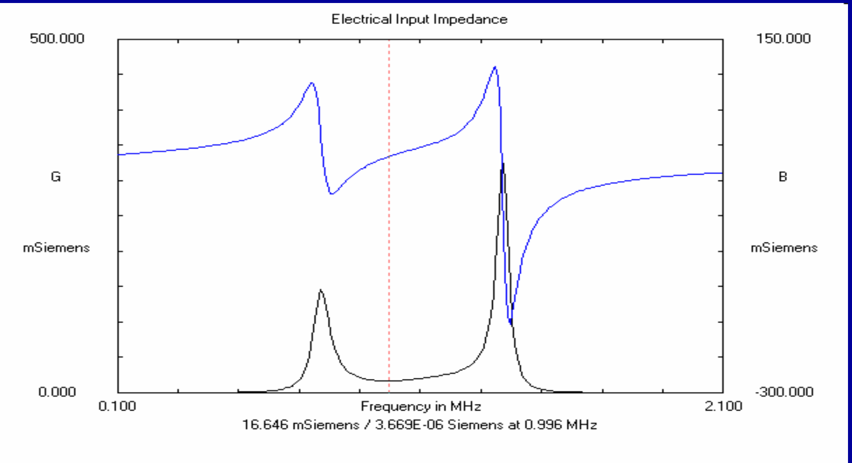
- **Po/Pi = .944 W/W @ .97**
- **Z / θ = 60 / 0 @ 1 M**
- **R max = 60 @ 1 M**
- **VRC = .09 V/V @ 1 M**
- **G shows typical split peaks**

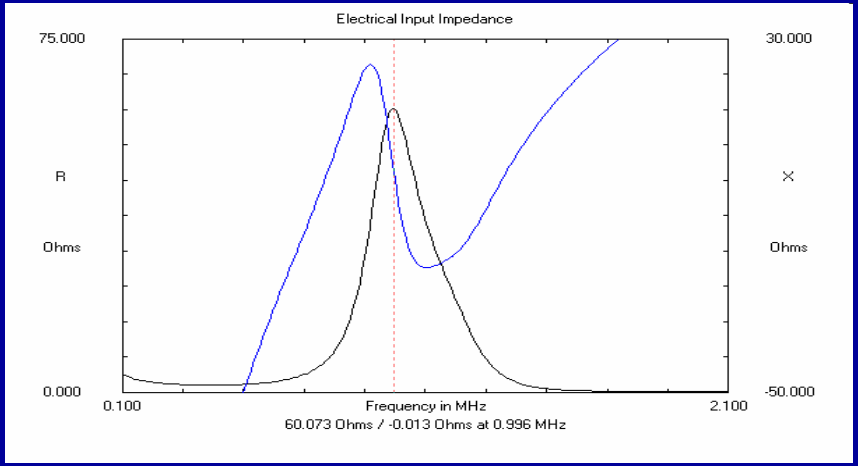




MODEL, MODEL, MODEL







Consider MRI Compatibility

1. Material Selection
   a. Compatible: polymers, carbon & graphite, copper, brass, BeCu, glasses & ceramics: fused silica, quartz, Macor, ZrO, AlO, AlN, SiN, Wood
   b. Safe: Aluminum, Titanium, Gold, Platinum, Palladium, Silver, some Stainless Steels, most piezo materials – some contain iron, nickel, gadolinium – be sure of trace additives
   c. Dangerous: magnetic / para-magnetic materials – iron and compounds, nickel, gadolinium, some piezo's

(ref's: 28,29)

Consider MRI Compatibility

2. Design Issues

   a. long cable runs from source, typ 7 to 10 M, signal losses

   b. can not electrically tune @ the transducer with coils, chokes, transformers

   c. avoid internal wire loops – can cause stray inductances

   d. exercise caution with fillers in polymers – know purity

Consider MRI Compatibility

3. Verification of Product

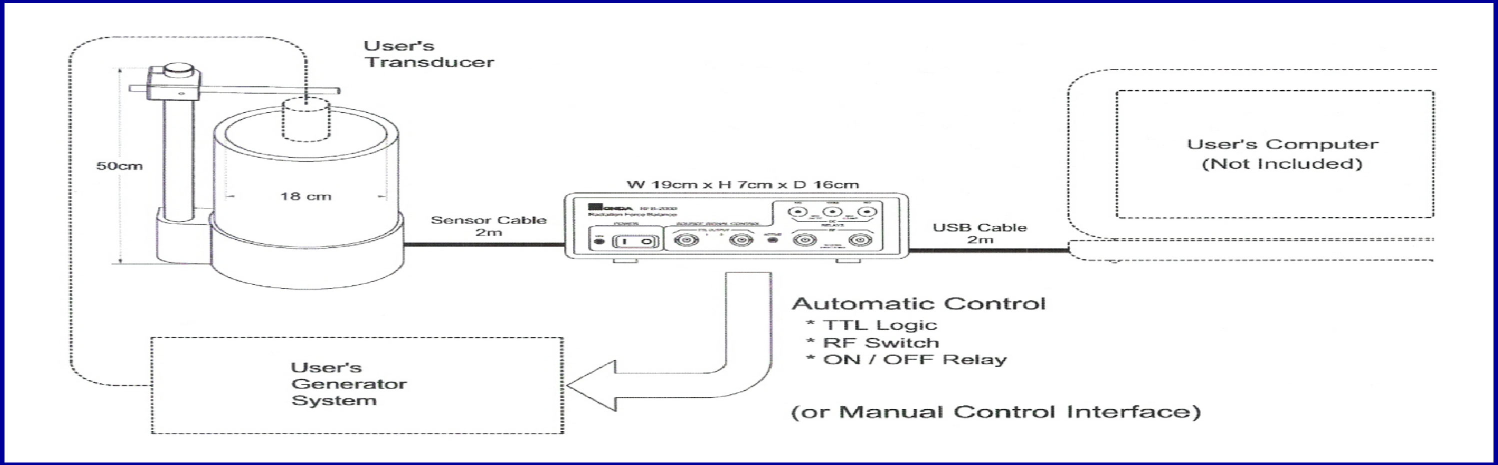
   ASTM, ANSI, ISO, IEC, NEC, FDA and others all publish standards for Testing Methods, Labeling Requirements, Definitions, etc.

   www.mrisafety.org

Test and Characterize Performance, Life and Safety ref (4, 30 – 35, 57)

1. Attended the preceding workshop “Acoustic Output Measurements”, Mark Hodnett, NPL
2. Standards Bodies: IEC, FDA, AIUM, ANSI, NEC, NEMA, etc.
3. Testing – parameters, output, linearity, repeatability, life expectancy, safety

   a. Output Power – TAP Meter, RF Amp, FG, PC, O’scope



Test and Characterize Performance, Life and Safety

3. Testing
   - b. Sound Field
     1. Scanning Tank with Hydrophone: 5 – 6 axis of freedom, can map in 3D, low power BUT new high power hydrophones being developed

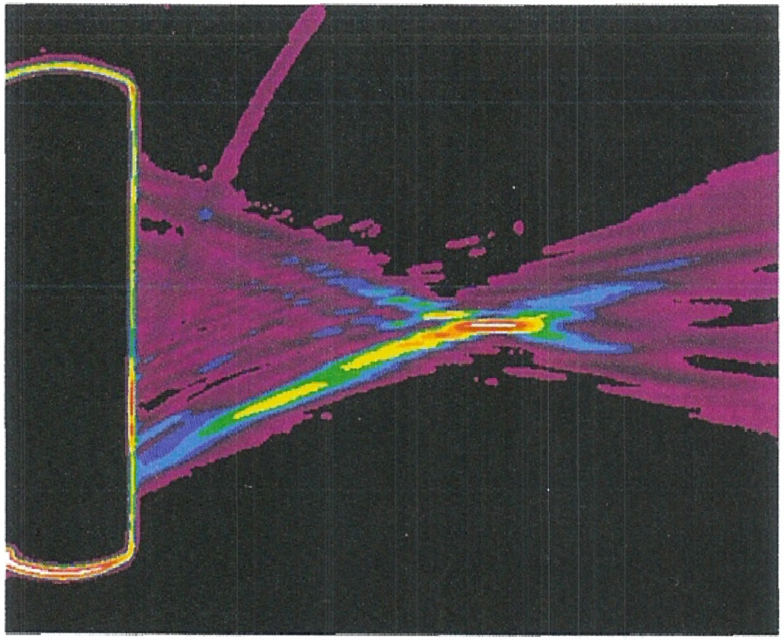
Test and Characterize Performance, Life and Safety

3. Testing
   b. Sound Field
      2. Schlieren Optical

High resolution,

can identify flaws or non-uniformities at low & high power,

Software can do 3D



Highly focused beam showing anomalous sidelobe caused by a crack in the radiating surface.

Test and Characterize Performance, Life and Safety

3. Testing
    b. Sound Field
        3. Acoustic Streaming (57)
            similar to Schlieren but uses suspended particles to map velocity profiles

        4. Phantoms
            several sources for HIFU phantoms,
            reasonably clear and closely mimic tissue, can visualize treatment

Test and Characterize Performance, Life and Safety

3. Testing
   - c. Environmental
     1. Thermal Conditions: storage, shipping, operating
     2. Hermiticity: IP rating, splash, immersion, etc., gas sterilization
     3. ESS/ Burn-in: validate to full spec
     4. Accelerated Life
     5. FMEA
   - d. Electrical Safety
     1. HiPot
     2. Insulation Resistance
     3. Current Leakage
     4. EMI/ EMS

Test and Characterize Performance, Life and Safety

4. Safety

   a. use common sense

   b. always operate loaded

   c. Always make sure source is off when connecting or disconnecting

   d. always use degassed water

   e. know limits

   f. always have path to ground

   g. NO BODY PARTS!

FIGURE 1. Cracked transducer front face due to an excessive applied power (about twice the maximal acceptable excitation level)

Consider Other Uses ref (38 – 41)

1. **Industrial**
   a. **Droplet Jetting: basically same as HIFU , must know material properties; ex. Ink jets, coating**
   b. **Nebulize / Atomize: chemical analyzers, FUSION**

$$d = .34 * (\pi^3 * T / (\rho * F^2)^{1/3}$$

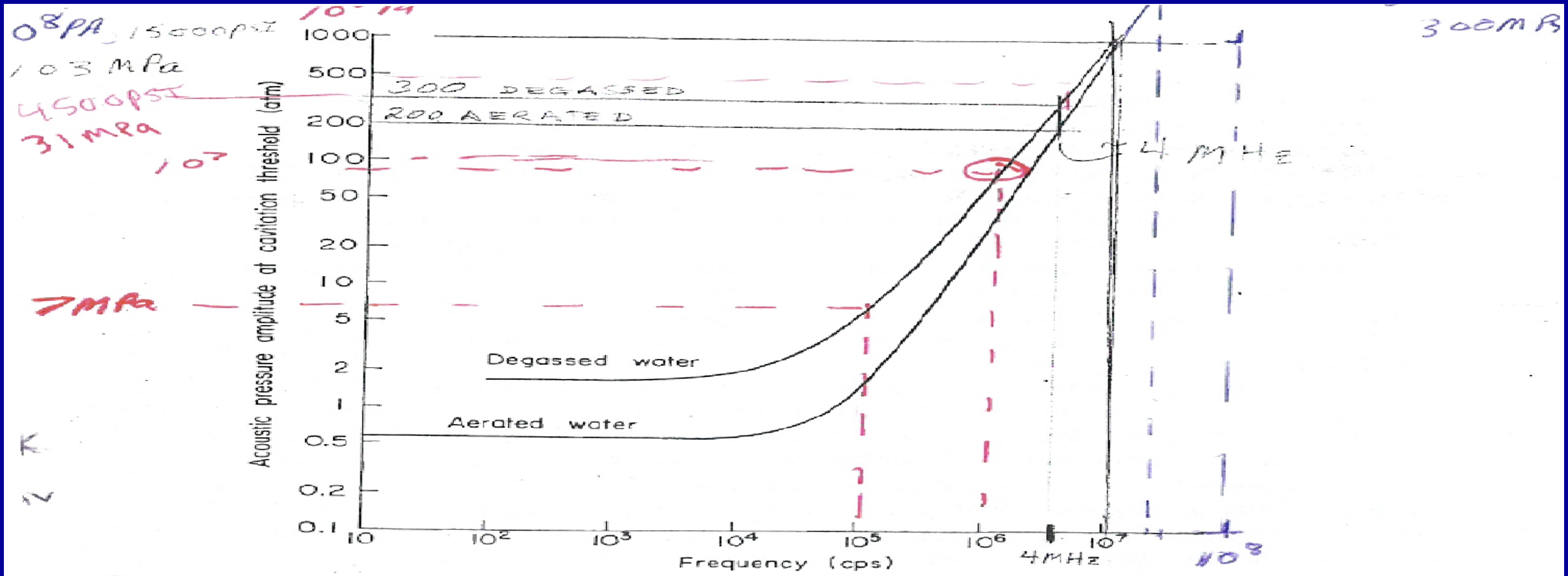


FIG. 33. Variation of the acoustic intensity cavitation threshold with frequency for both degassed and aerated water (after Esche).

Consider Other Uses

1. Industrial
   c. Megasonic Cleaning – uses streaming
   d. Descaling – think Lithotripsy
   e. Pumps – streaming
2. Pharma / Consumer
   a. Cosmetic – skin / wrinkle enhancement
   b. nebulizers – inhalable drugs – asthma, diabetes
   c. needleless injection – drugs that are to large

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