# Helical resonator

By 王雯

# Goal

To trap ions within a Paul trap a high radio frequency voltage is applied to electrodes in order to provide the required electric potentials.

A helical resonator allows impedance matching between a radio frequency source and an ion tap enabling **high voltages** while reducing **the noise** injected into the system.

# Goal

high voltage: ***resonate frequency*** → impedance matching

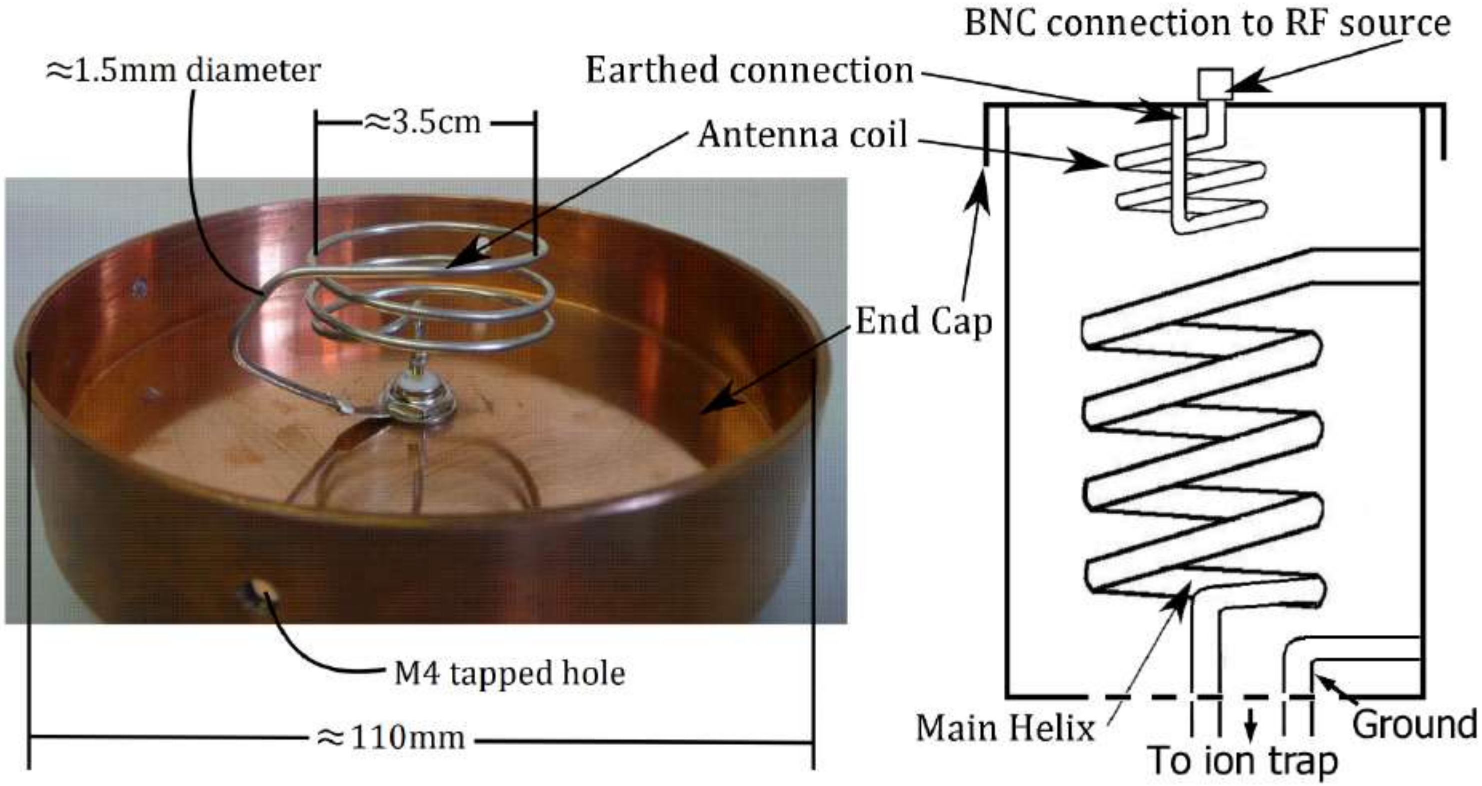
→ maximum power on load impedance

→ maximum voltage between the trap

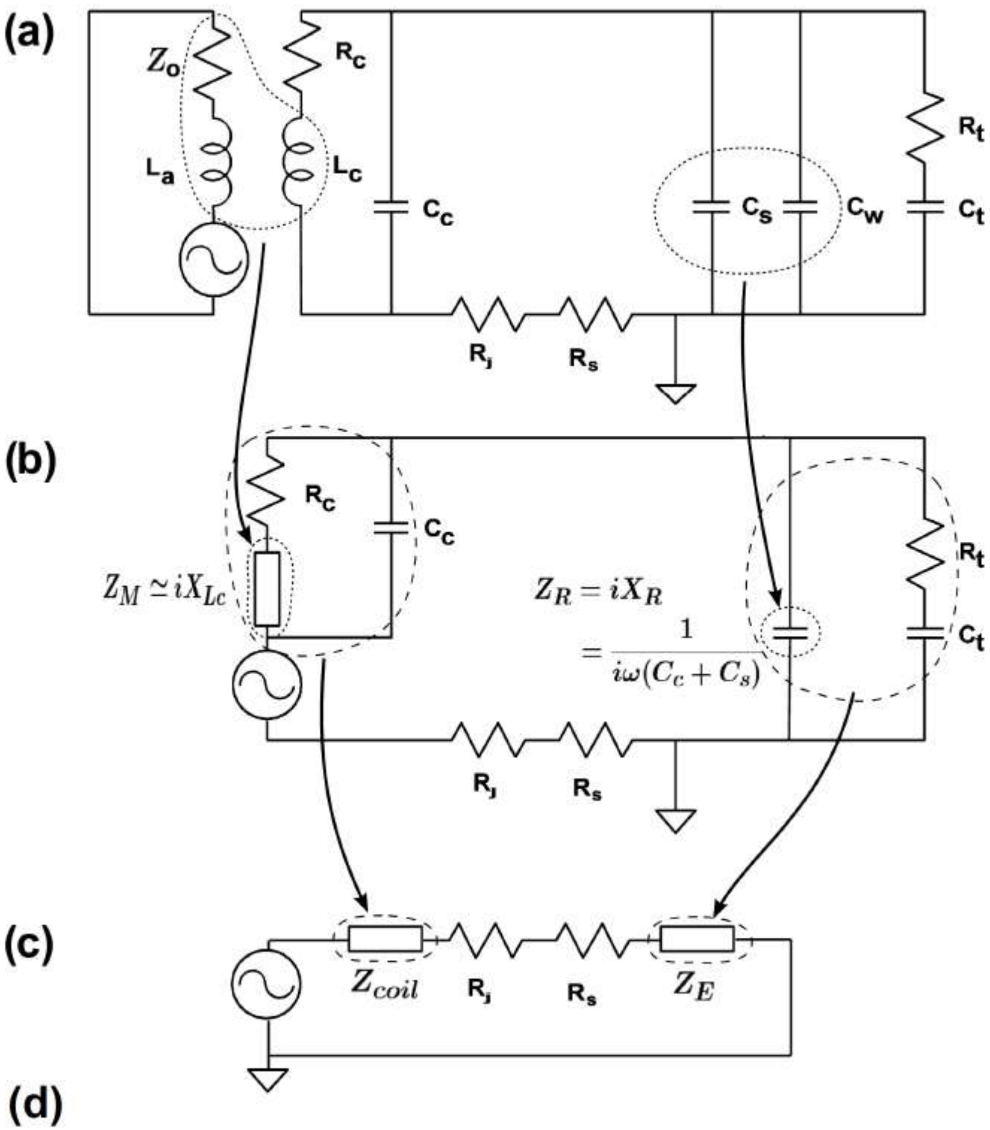
Less noise: ***high Q*** → frequency selectivity

→ less noise

# structure


≈1.5mm diameter
≈3.5cm
Antenna coil
End Cap
M4 tapped hole
≈110mm
BNC connection to RF source
Earthed connection
Main Helix
To ion trap
Ground

# Structure




- $Z_{coil}$ Equivalent impedance of the Helical coil due to:
  - $R_c$ Helical coil resistance
  - $C_c$ Helical coil self capacitance
  - $Z_M$ Helical coil total inductance due to:
    - $L_c$ Helical coil self inductance
    - $L_a$ Antenna coil self inductance
    - $Z_o$ RF voltage source impedance (typically $50\Omega$)
- $Z_E$ Equivalent impedance of the experimental system due to:
  - $R_t$ Ion trap resistance
  - $C_t$ Ion trap capacitance
  - $X_R$ Equivalent capacitance due to:
    - $C_s$ Capacitance of Helical coil to surrounding shield
    - $C_w$ Capacitance of the ion trap connecting wires
- $R_j$ Helical coil to shield junction resistance
- $R_s$ Shield resistance

# condition

At resonance： the imaginary part of the impedance is 0, which determines “b”.

$$X_{tot} = 0$$

High Q:

$$Q = \frac{X_{L_c}}{R_{ESR}}$$

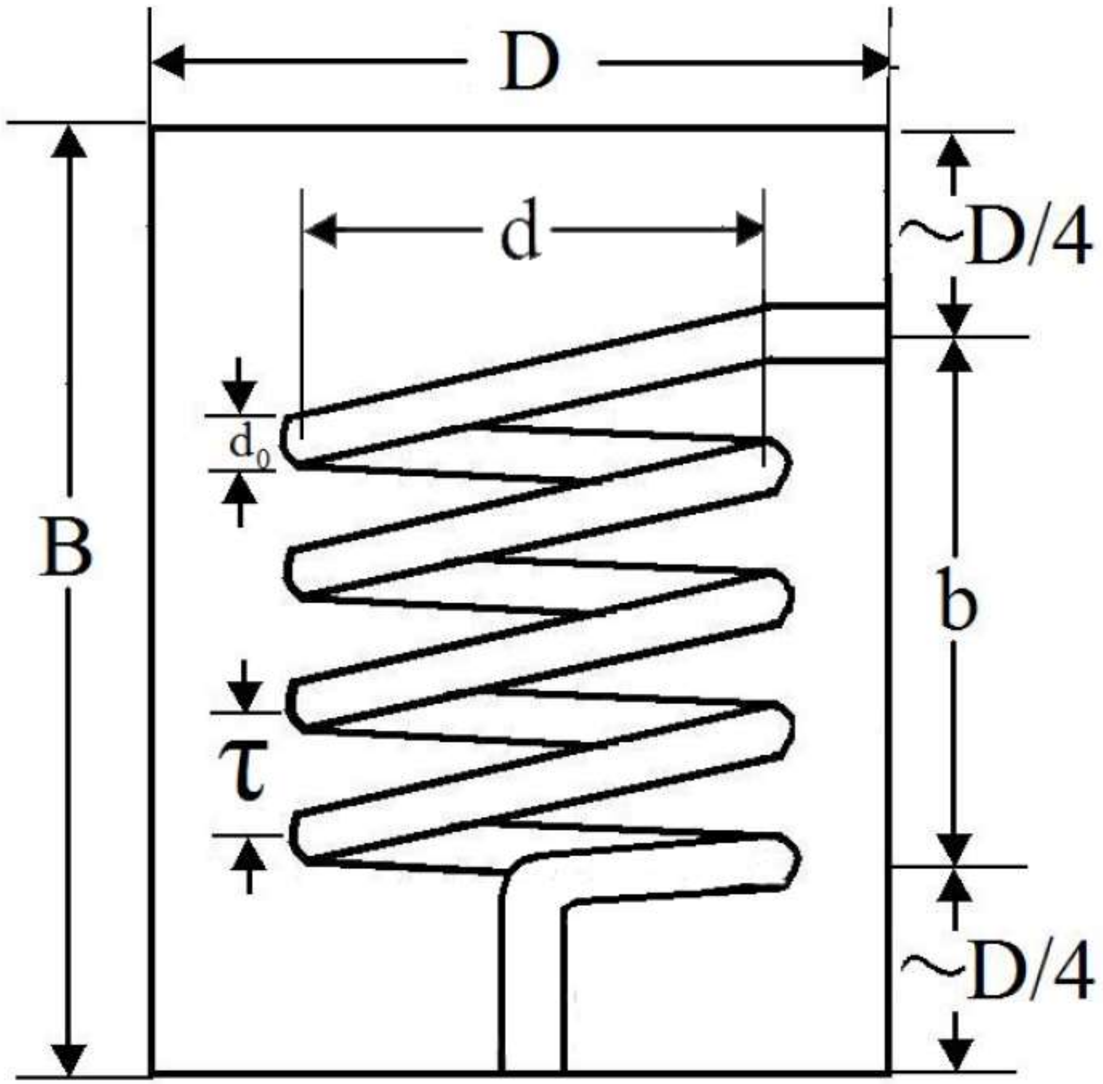
# Empirical formula

If b>d

$$C_C \simeq (Hd/100) \times 10^{-12}$$

$$C_s \simeq 39.37b\frac{0.75}{\log\left(\frac{D}{d}\right)} \times 10^{-12} = K_C\,(d, D)\,b$$

$$L_C \simeq 39.37b\frac{0.025d^2(1-\frac{d}{D})^2}{\tau^2} \times 10^{-6} = K_L\,(d, D, \tau)\,b$$



# resistance

$$R_n = \frac{\rho l}{C \delta_n}$$

$$\delta_n = \sqrt{(2\rho)/(\pi f_n \mu_0)}$$

$$R_0 = R_1 \sqrt{\frac{f_0}{f_1}}$$

Only valid: in a frequency regime where the solder joint is larger than the skin depth
and when the resistivity, $\rho$, is constant over the two frequencies used.

# Result of calculation

Resonate →

$$\boxed{b \simeq \sqrt{\frac{1}{K_C K_L (2\pi f_0)^2} + \frac{C_\Sigma^2}{4K_C^2}} - \frac{C_\Sigma}{2K_C}}$$

Size and frequency →

$$\boxed{Q = \frac{X_{L_c}}{R_{ESR}}.}$$

# Specific process of calculation

$b(d, d/D)$ - The coil length - by using equation $\boxed{27}$ and $K_c$ and $K_l$ from equation $\boxed{25}$ and $\boxed{26}$

$C_s(d, d/D)$ - The coil to shield capacitance - by substituting $b(d, d/D)$ into equation $\boxed{25}$

$C_c(d, d/D)$ - The coil self capacitance - by substituting $b(d, d/D)$ into equation $\boxed{25}$

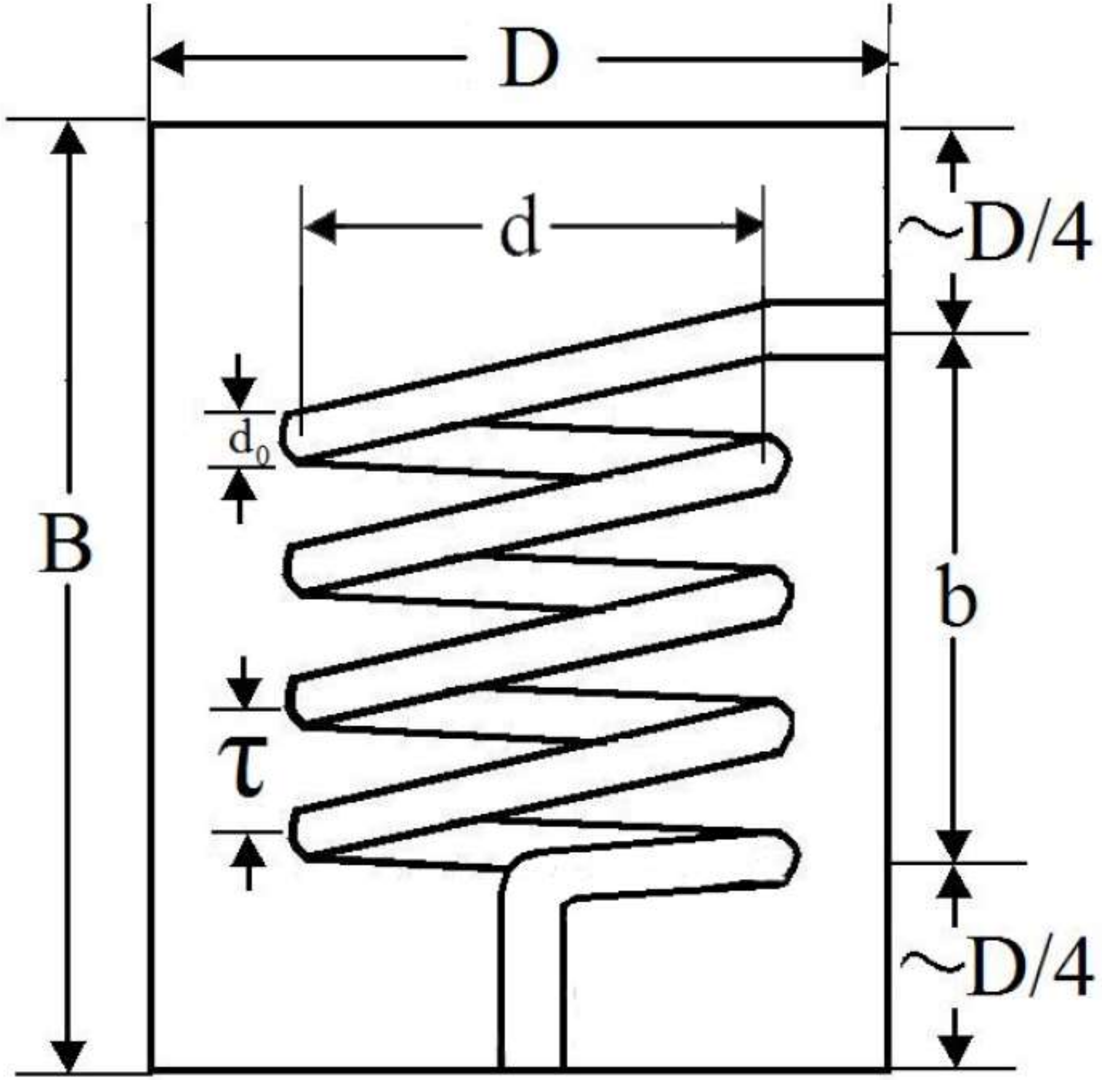
$R_s(d, d/D)$ - The shield resistance - by using equation $\boxed{34}$

$R_c(d, d/D)$ - The coil resistance - by using equation $\boxed{33}$

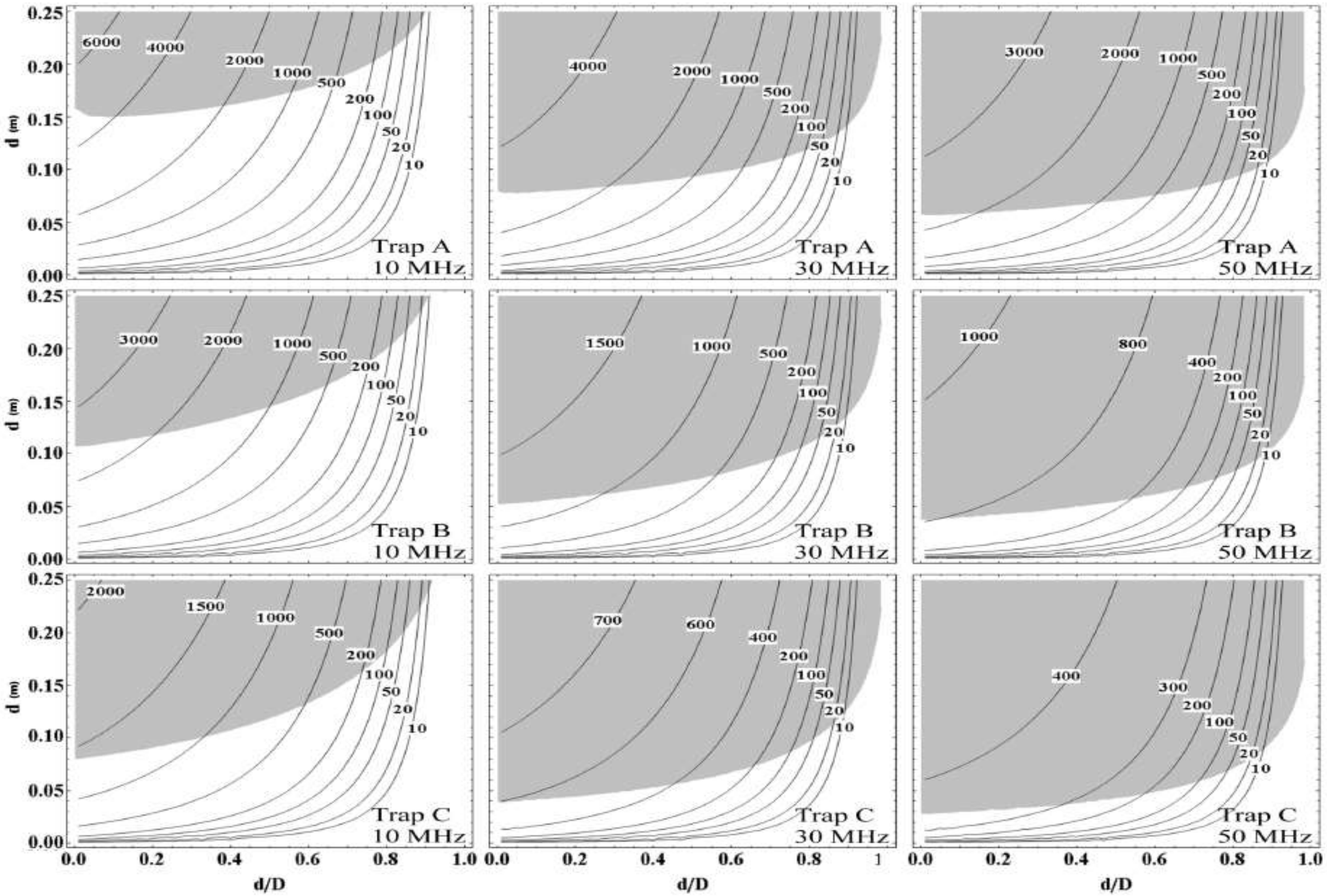
$R_{ESR}(d, d/D)$ - The total resistance - by using equation $\boxed{23}$

$L_c(d, d/D)$ - The coil inductance - by substituting $b(d, d/D)$ into equation $\boxed{26}$

$Q(d, d/D)$ - The $Q$ factor - by substituting $L_c(d, d/D)$ & $R_{ESR}(d, d/D)$ into equation $\boxed{21}$



# Result from the paper (？ )




| Trap | Resistance Ω | Capacitance pF |
|---|---|---|
| A | 0.1 | 5 |
| B | 0.1 | 20 |
| C | 0.1 | 50 |
| D | 5 | 5 |
| E | 5 | 20 |
| F | 5 | 50 |
| G | 15 | 5 |
| H | 15 | 20 |
| I | 15 | 50 |

# Result from the paper (？ )

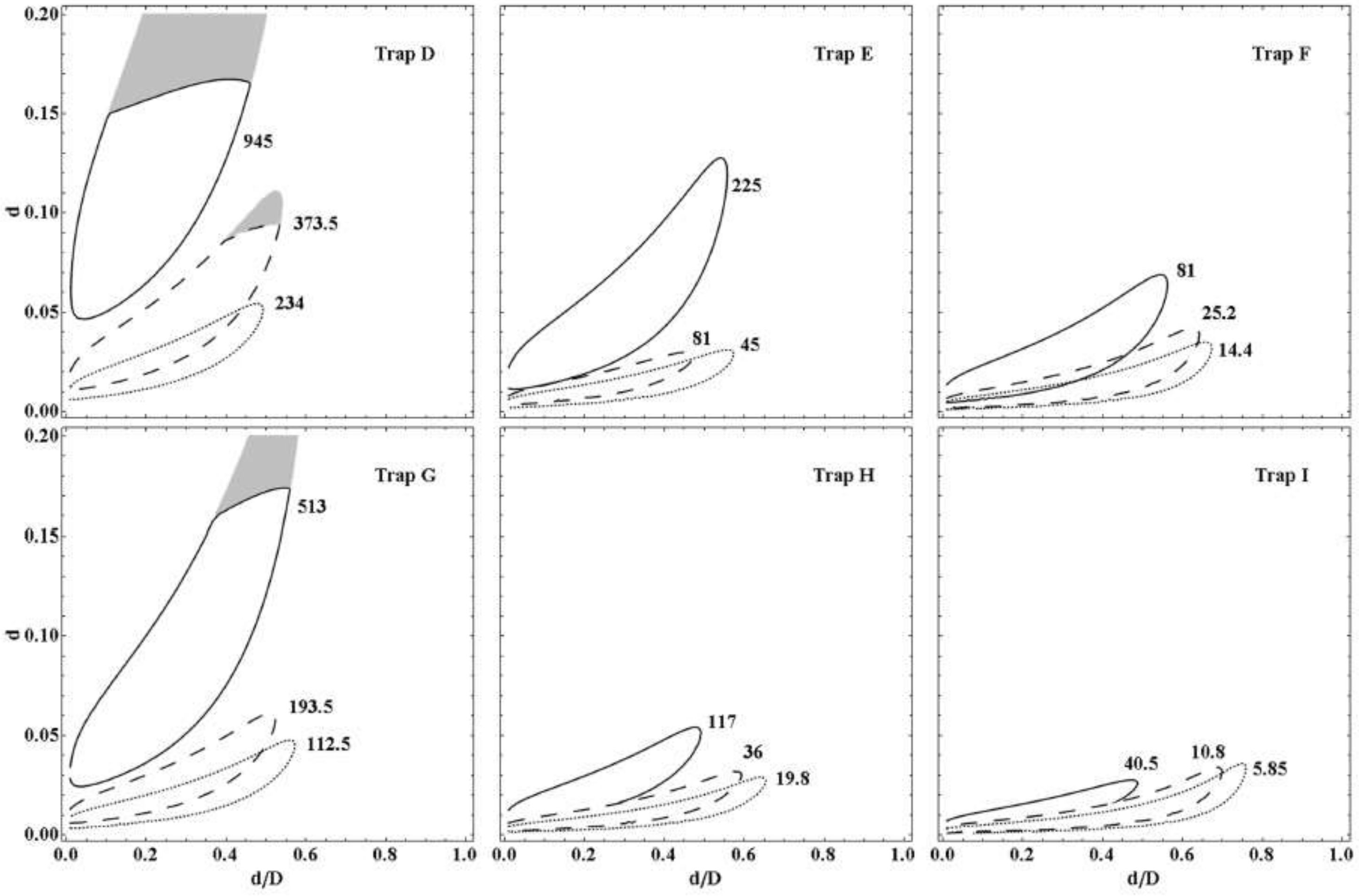



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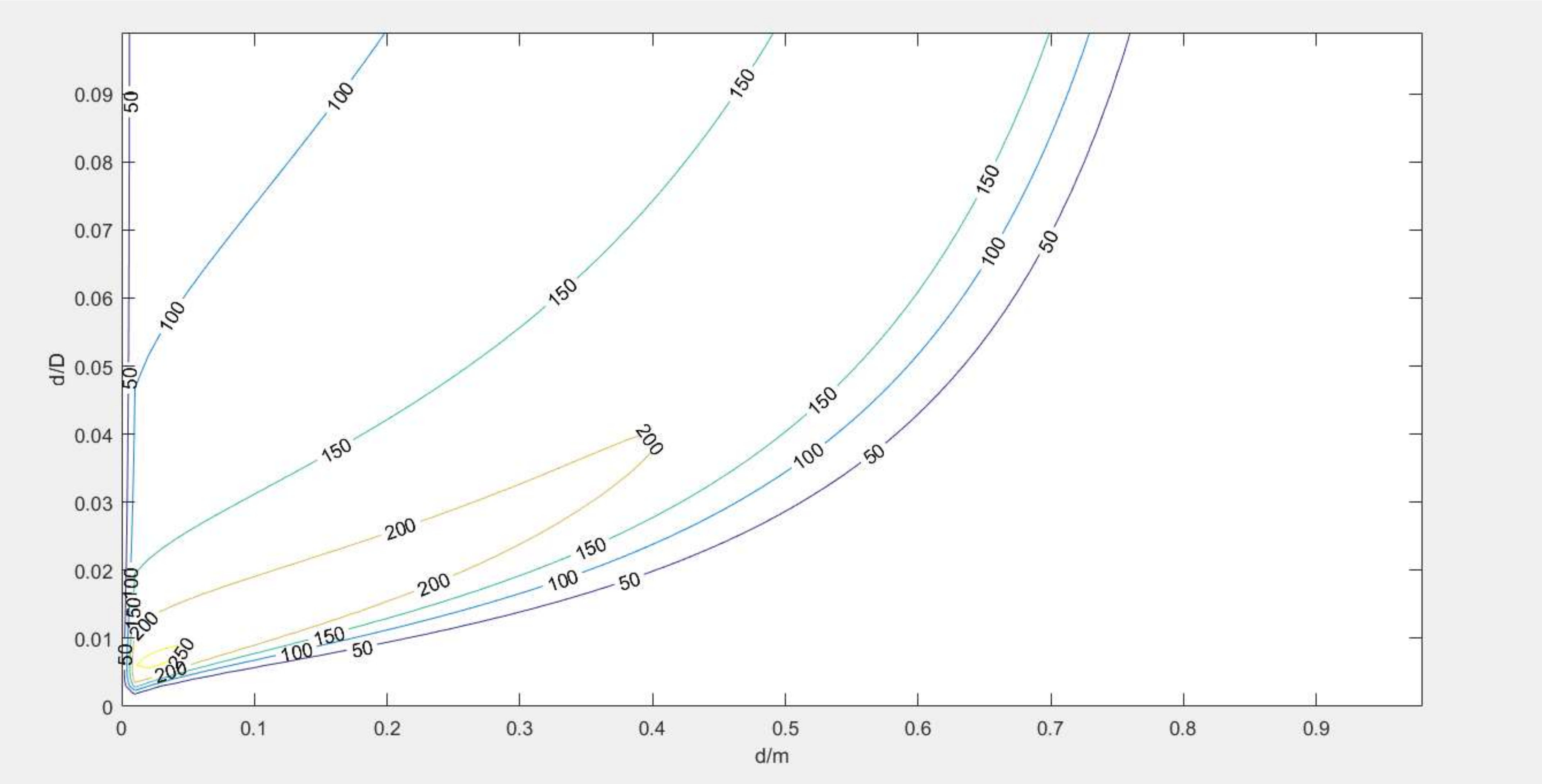
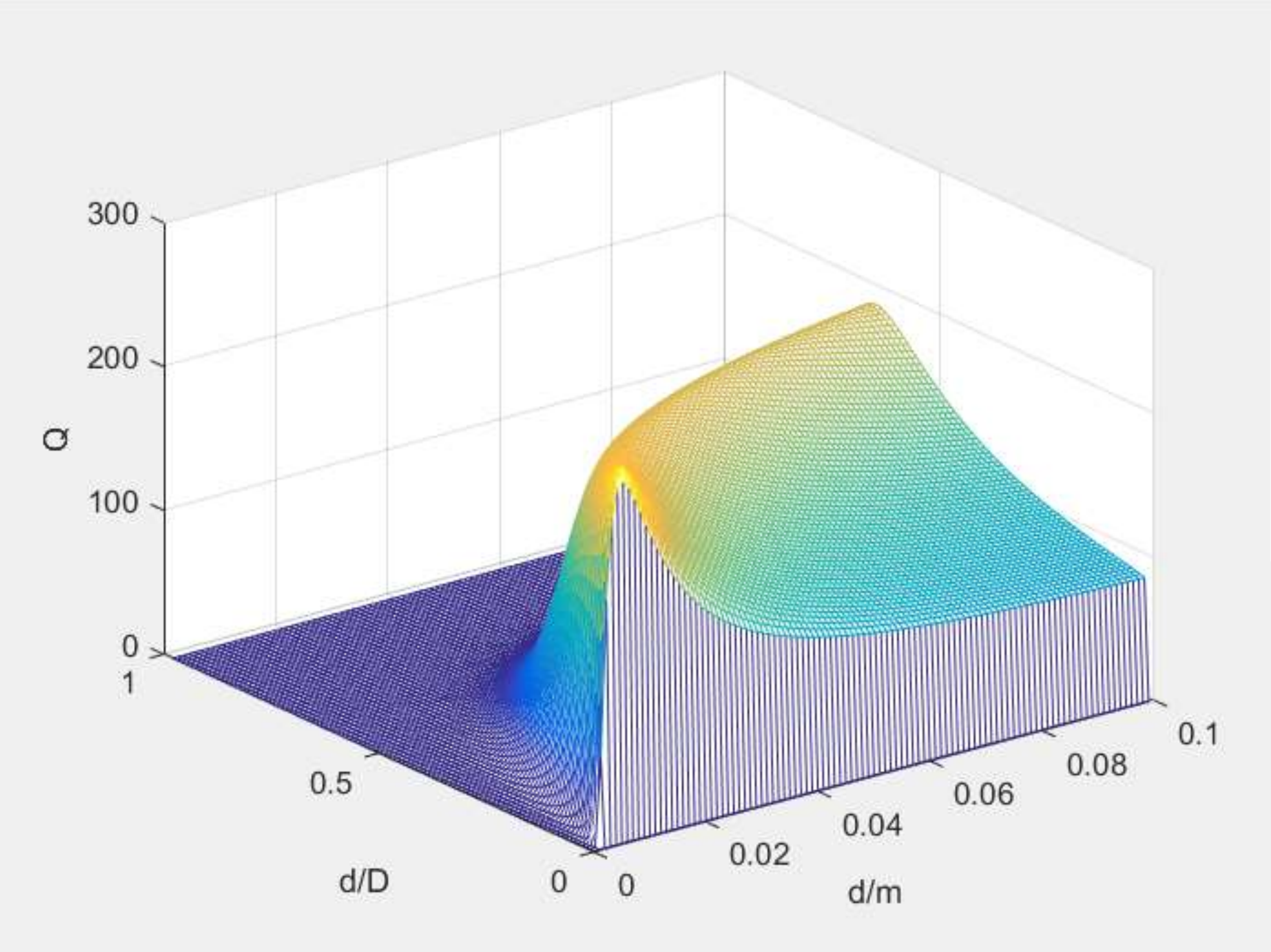
FIG. 11: Contour plots showing $Q_{90\%}$ for each set of paramters coresponding to traps D to I from table I for operating frequencies of 10 MHz (solid lines), 30 MHz (dashed lines) and 50 MHz (dotted lines). The grey areas indicate where $b/d < 1$ therefore invalidating the theory. The value of $Q_{90\%}$ is indicated next to the contour line.

# Our result about trap D

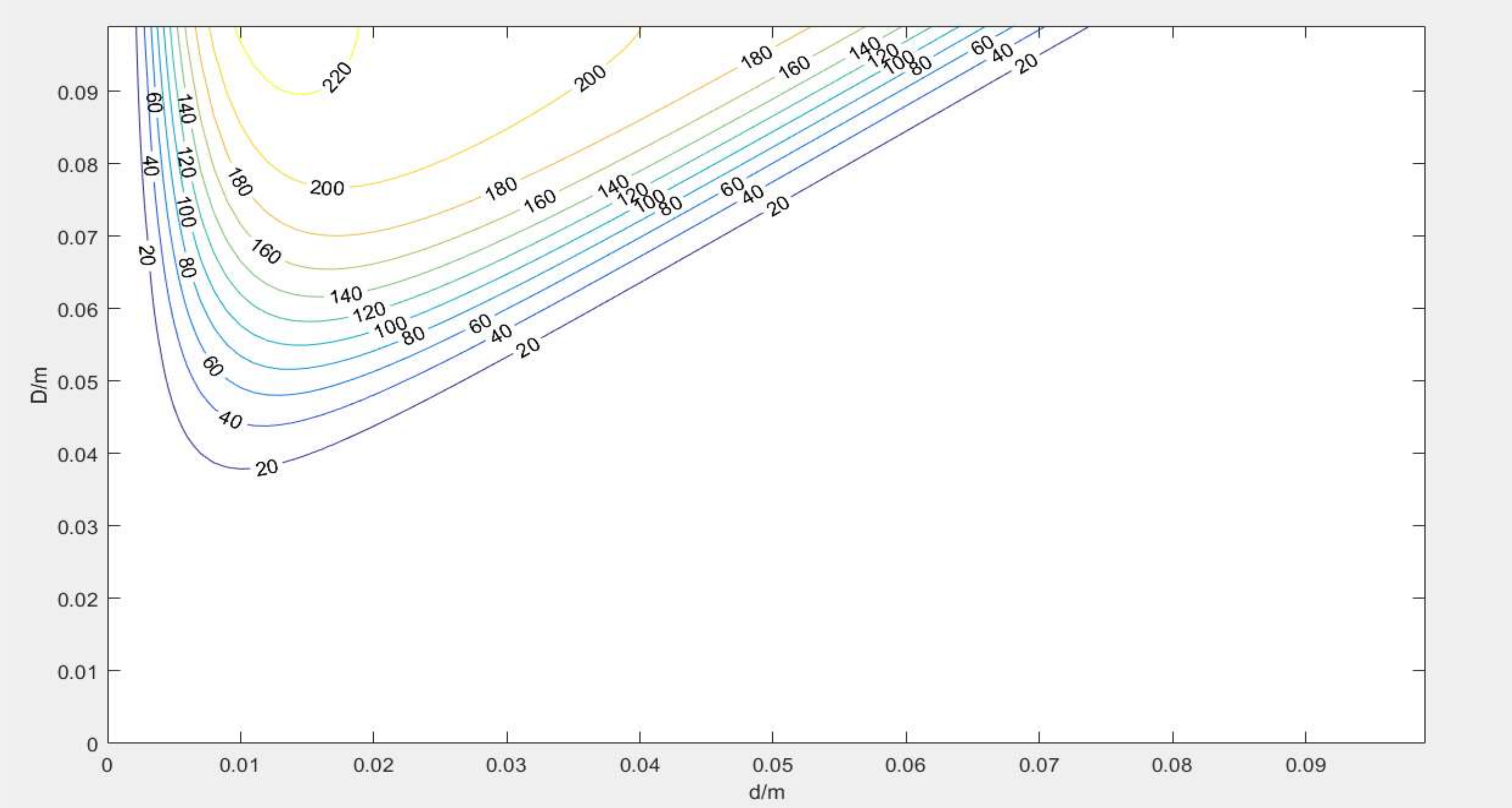


# Our result about trap D

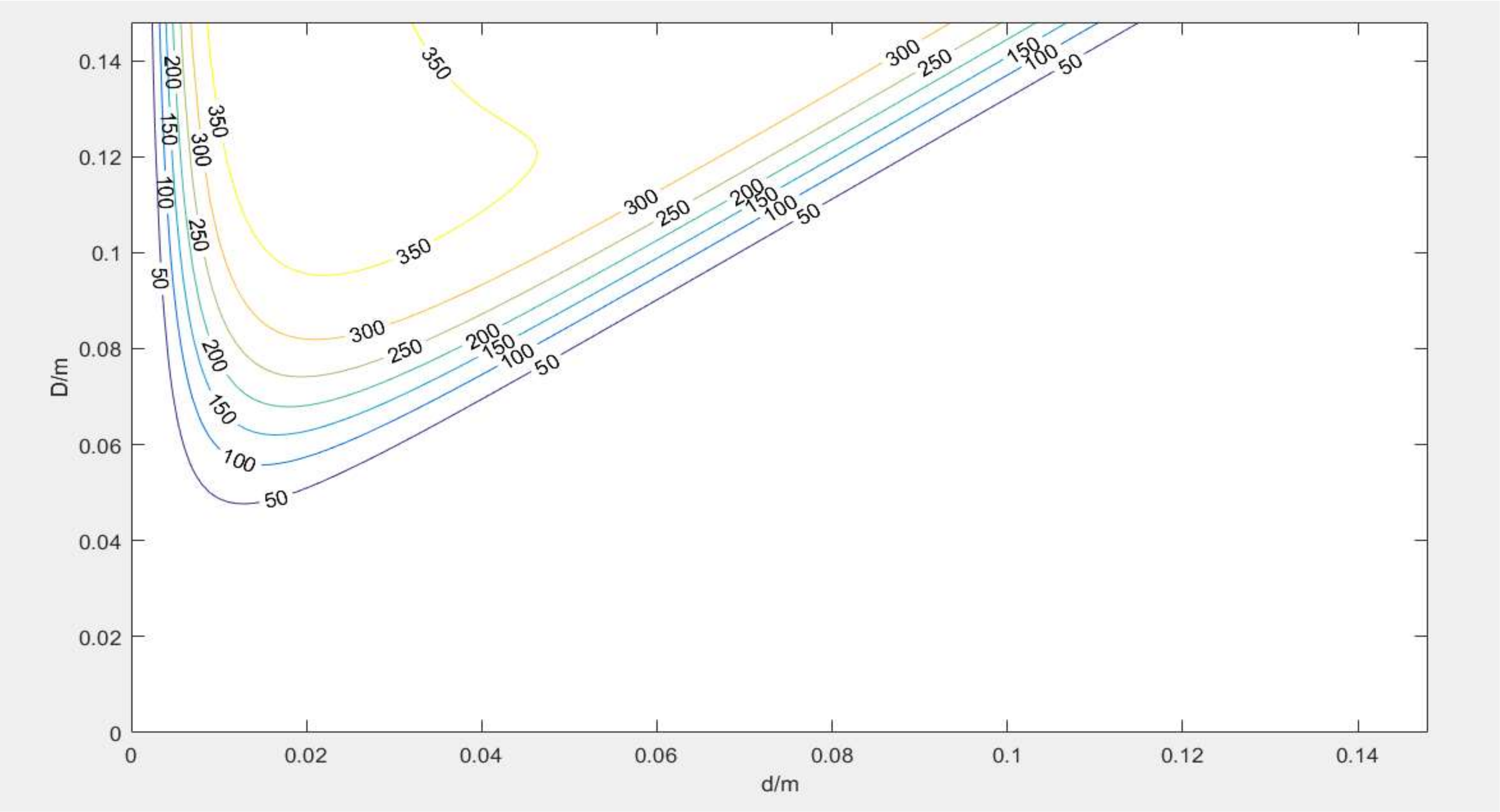


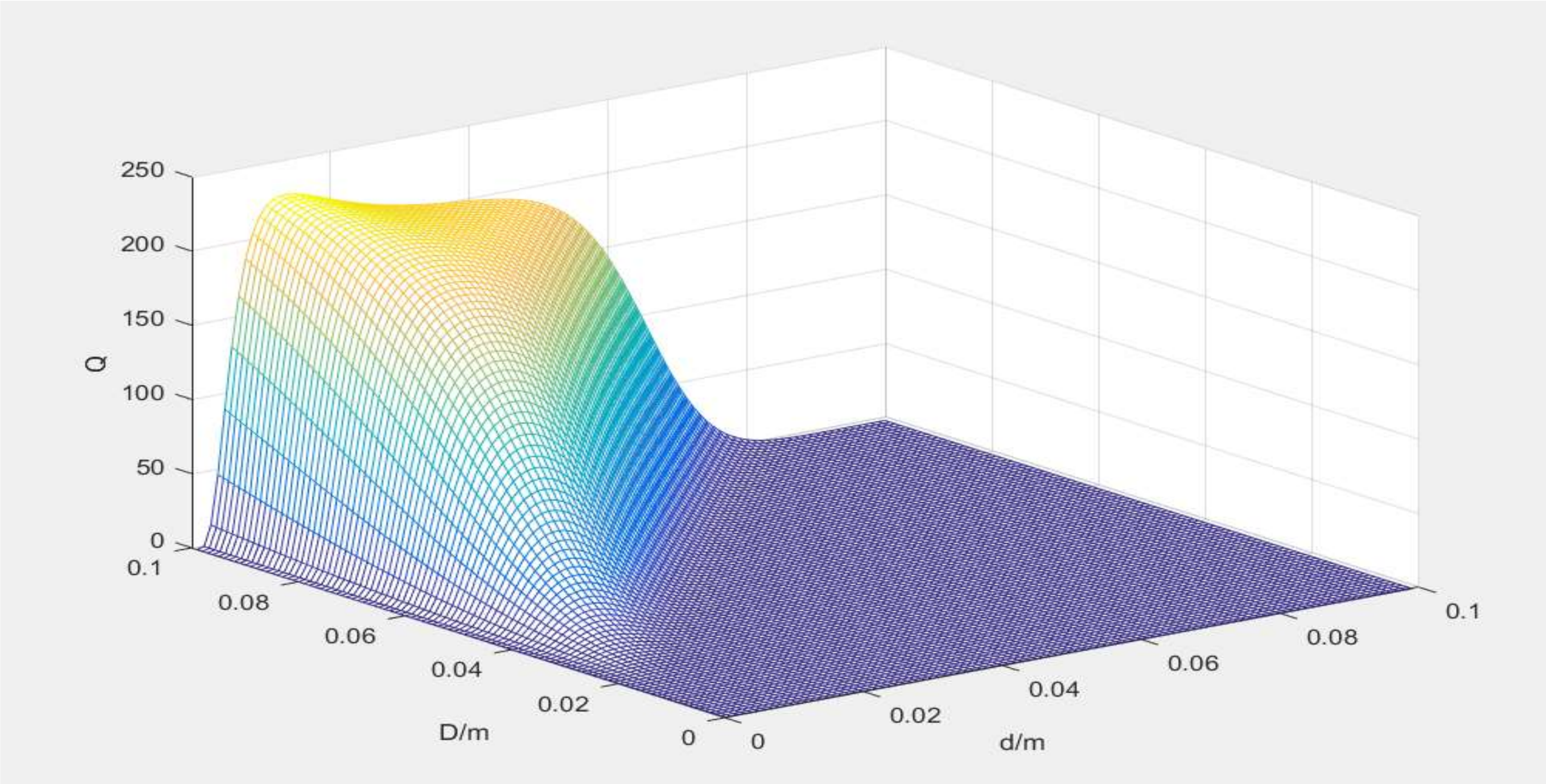

```
pho= 1.678E-8; %电阻率
f0=50E6; %频率
t= 0.01; %线圈相邻圈间距
d0=0.005; %线圈直径
Rj=0; %连接点电阻
Ct=5E-12; %trap的电容
Rt=5; %trap的电阻
Cw=0; %连接线电容
```

# Our result of trap D



# Larger range





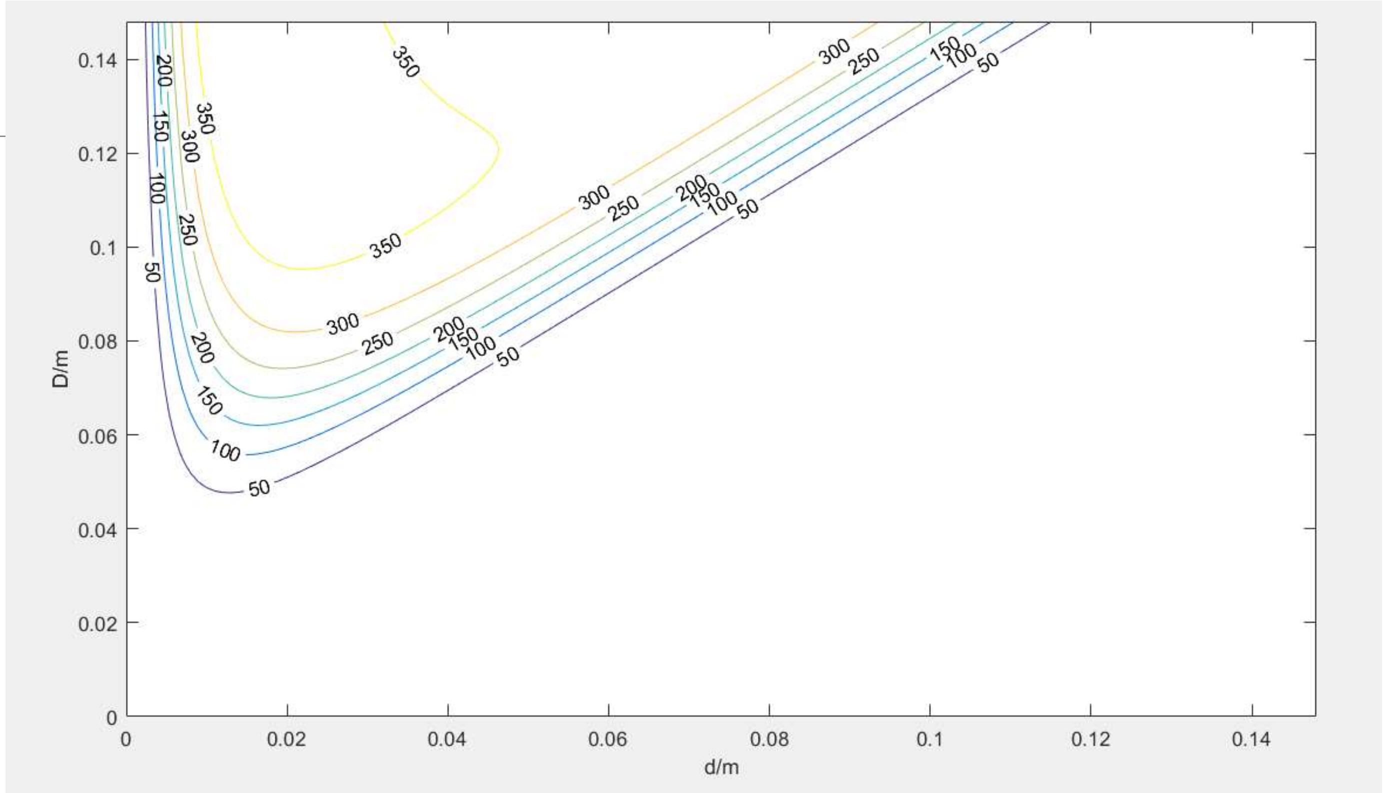
Q
250
200
150
100
50
0
0.1
0.08
0.06
0.04
0.02
0
D/m
0
0.02
0.04
0.06
0.08
0.1
d/m

# About the design

$$\boxed{b \simeq \sqrt{\frac{1}{K_C K_L (2\pi f_0)^2} + \frac{C_\Sigma^2}{4K_C^2}} - \frac{C_\Sigma}{2K_C}}$$

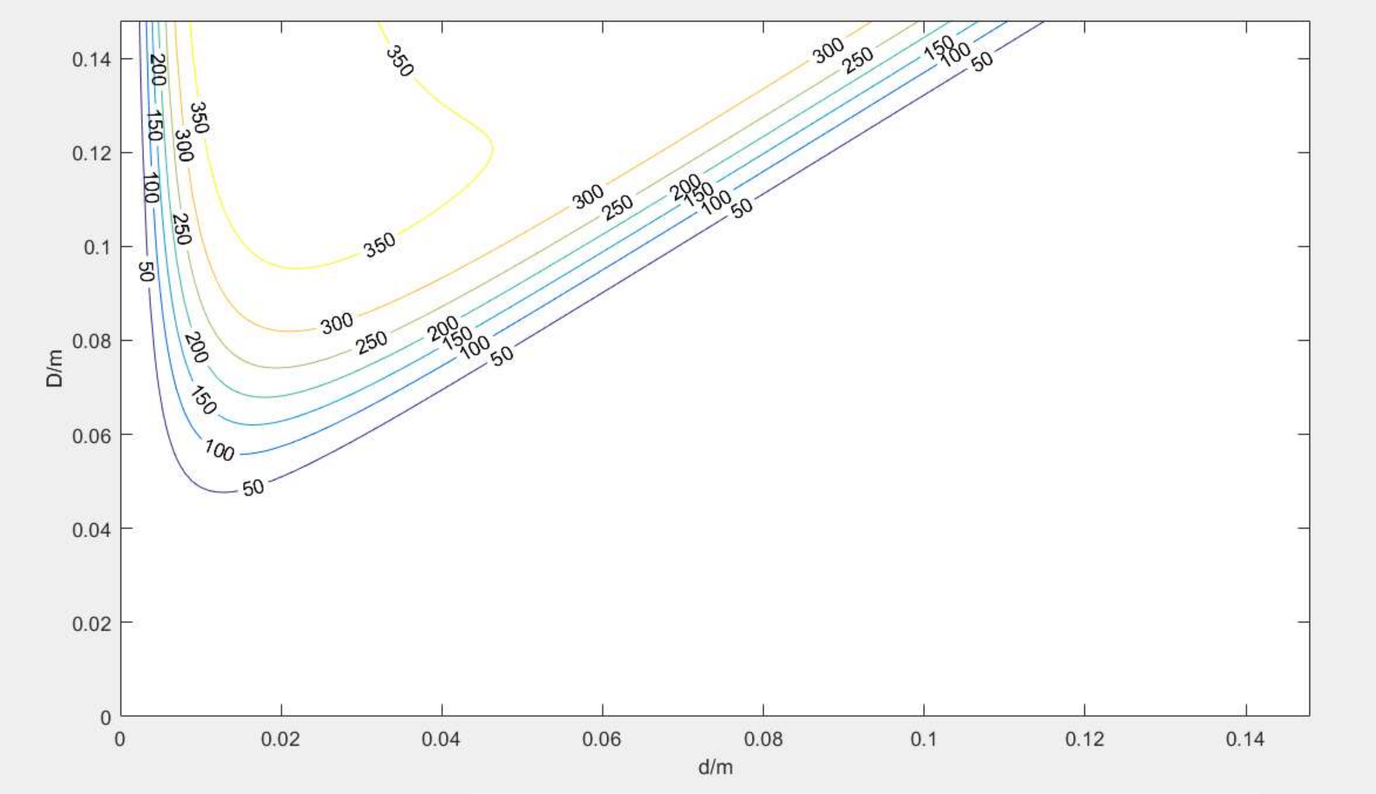
$$K_L \approx d^2 \cdot const$$

$$\rightarrow \mathrm{b} \cdot \mathrm{d} \approx \frac{1}{f_0} \cdot const$$



# About the design

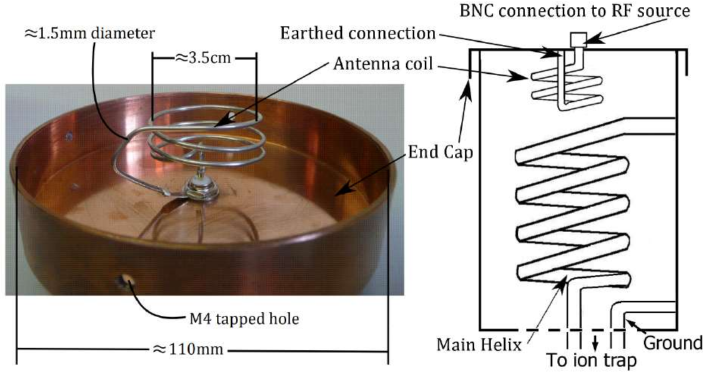
$$b \cdot d \approx \frac{1}{f_0} \cdot const$$
$$h = b + D/2$$




We want small size and a high Q:

So we choose a D less than 12cm so that we can choose a larger d and at the same time a Larger Q

★Notice: Although a larger D will be more likely to bring a higher Q, It also may make h bigger and make the whole size bigger.



# My design

```
f0=4e+007
d=0.053m
D=0.103m

Q=528.535
b=0.131594m
h=0.183094m
检验信息:
b=0.131594m 满足b>d, valid!
趋肤深度为1.45781e-005m<1mm. 足够小!

resonator尺寸信息:
height=18.3094cm
Diameter=10.3cm

Vpeak=1323.21
```

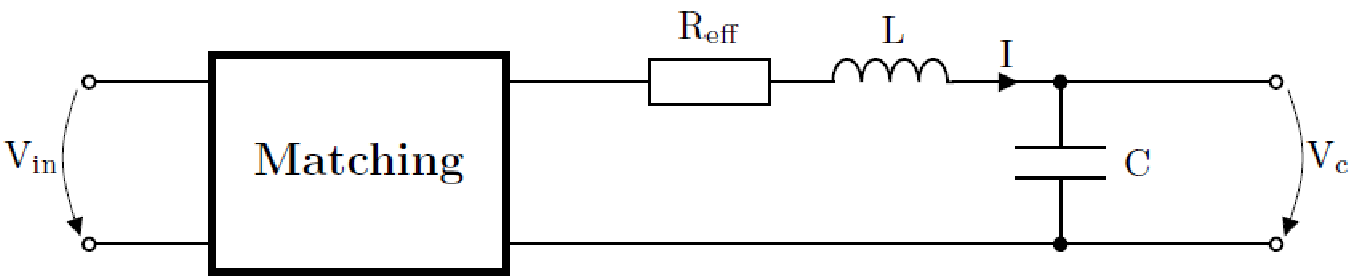
```
f0=5e+007
d=0.055m
D=0.103m

Q=679.268
b=0.0993721m
h=0.150872m
检验信息:
b=0.0993721m 满足b>d, valid!
趋肤深度为1.30391e-005m<1mm. 足够小!

resonator尺寸信息:
height=15.0872cm
Diameter=10.3cm

Vpeak=1395.72
```

# The end

About this design

# Another design

OF RESONATORS WE MAY BE INTERESTED IN

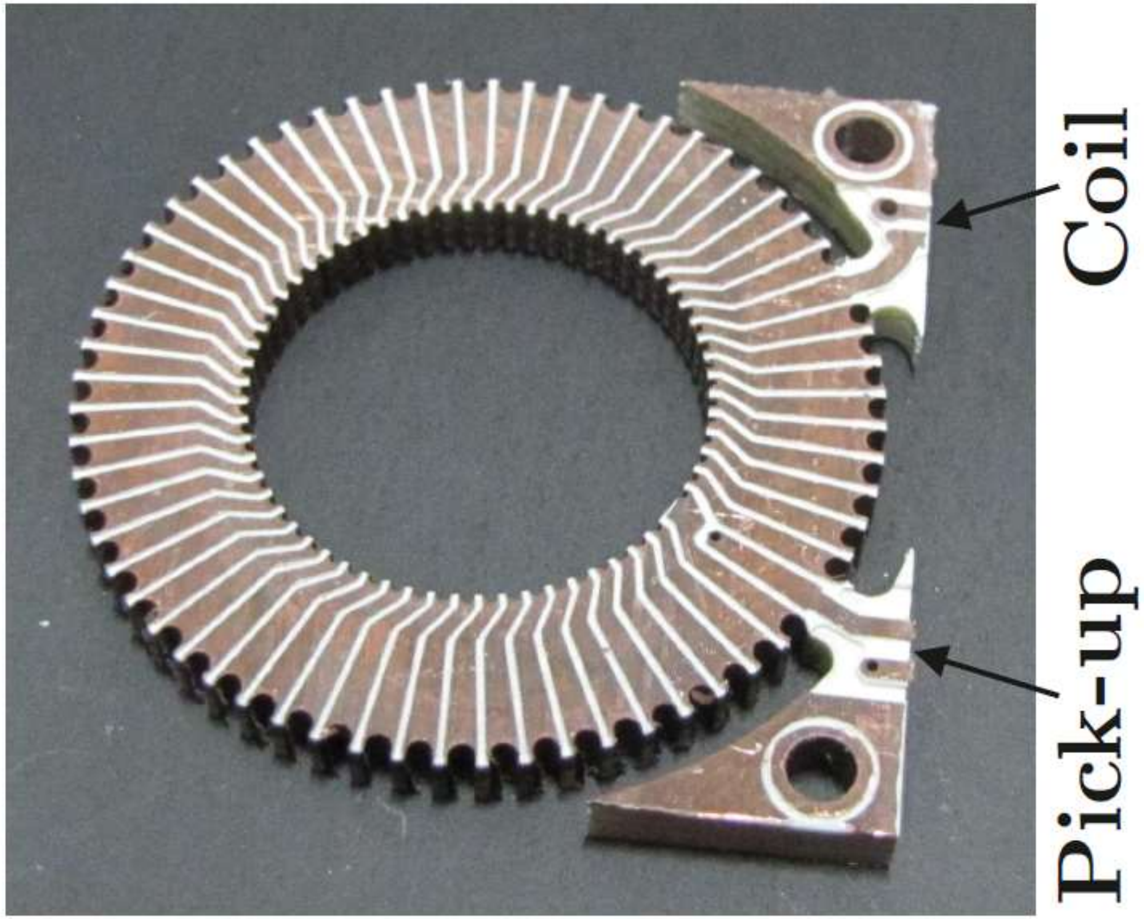



An ***RLC***-series-resonator driven through a ***matching*** network

Coils produced with machines are desirable because the production process is reproducible. Furthermore, we prefer toroid coils as they guide the magnetic field in their center, making them less Sensitive to their environment.

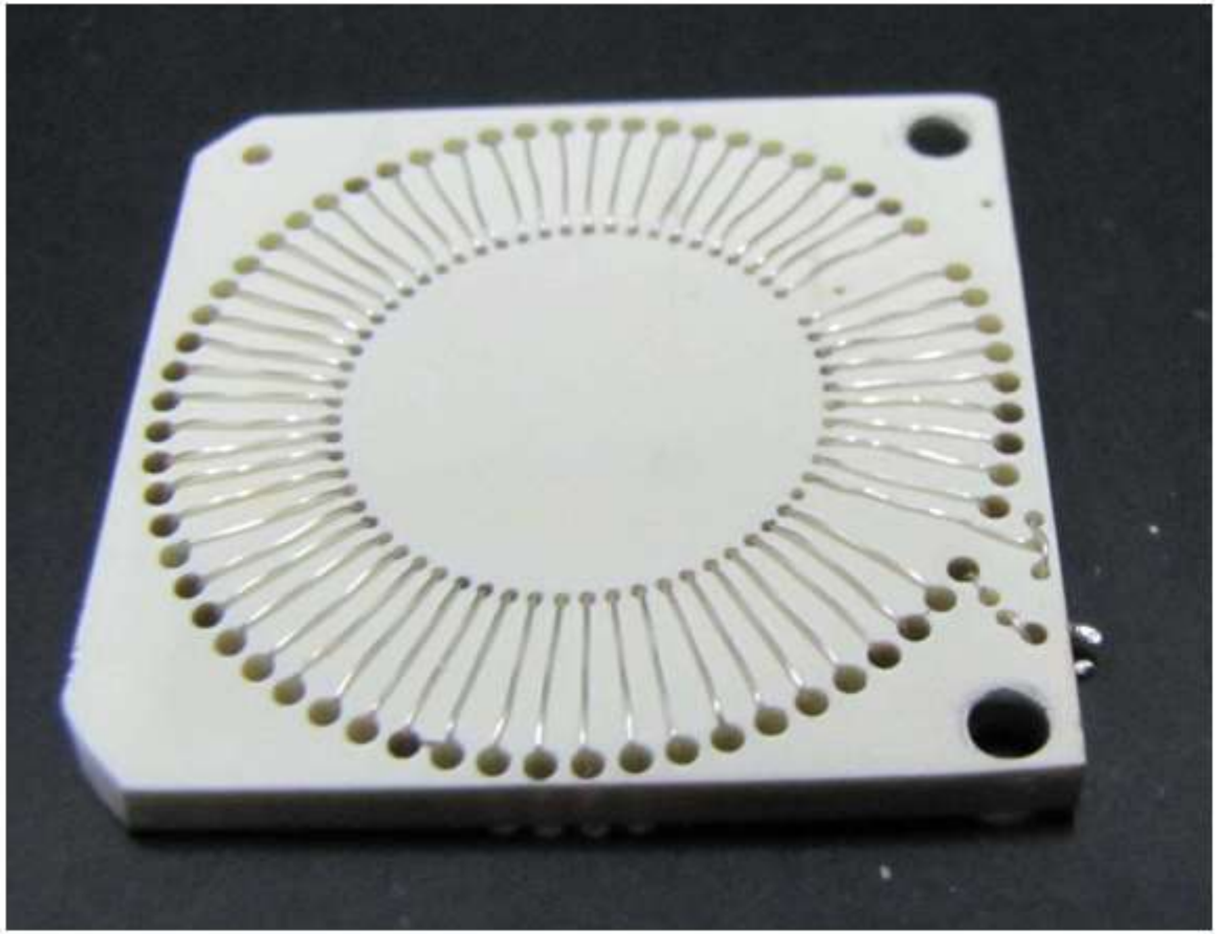
# Different designs

1.PCB coils



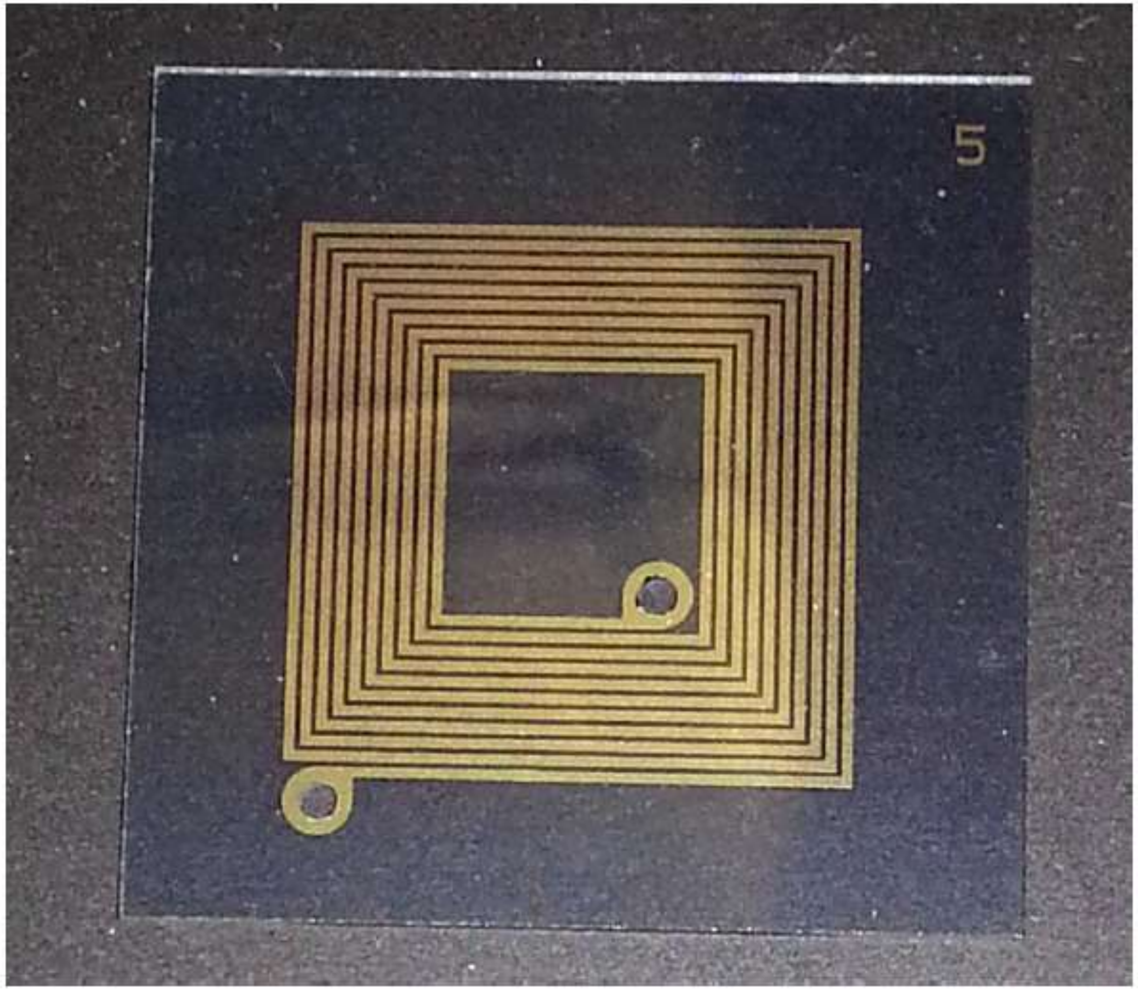
# Different designs

2.wire coils

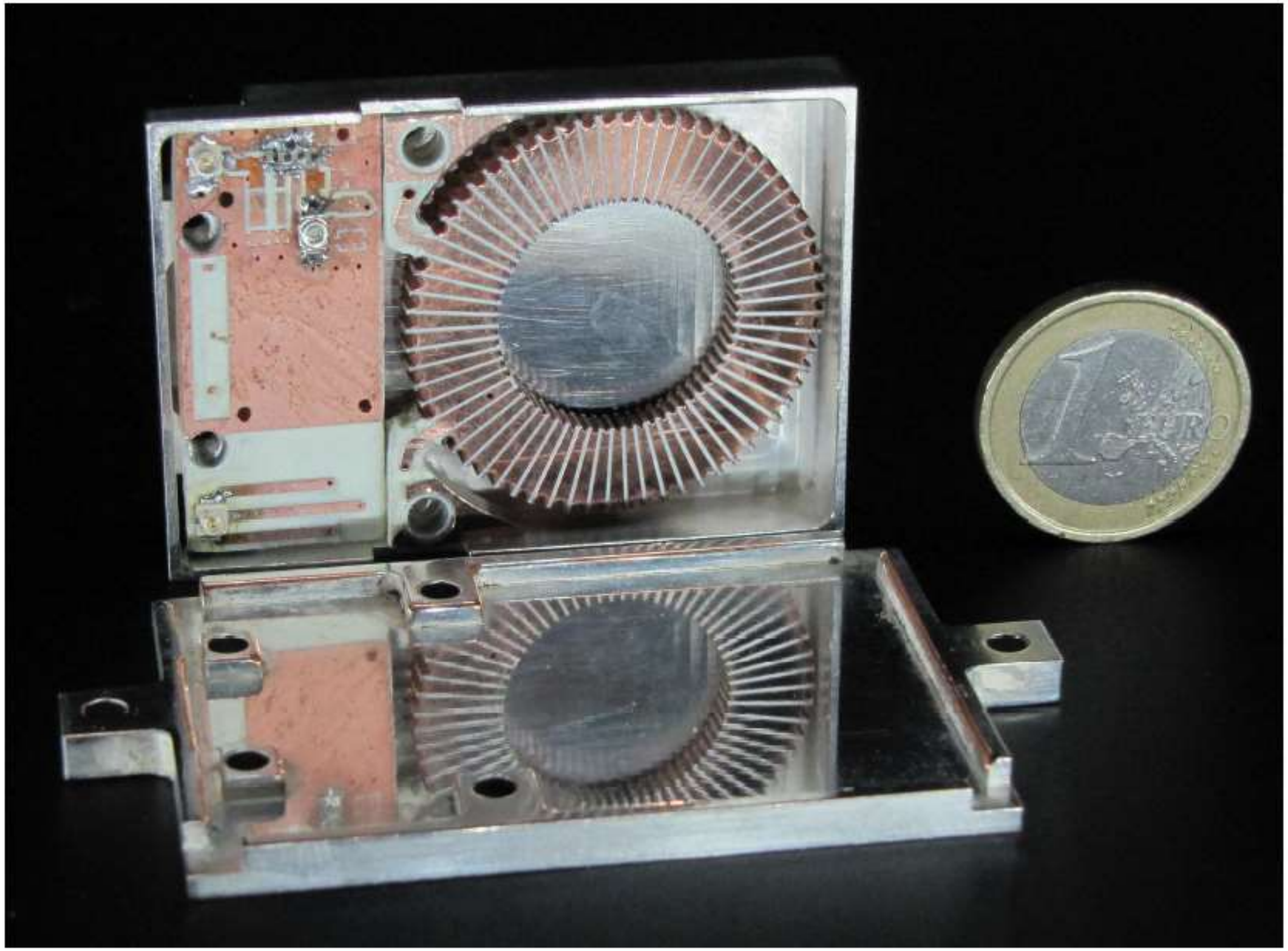


# Different designs

3.Spiral coils



# Small size



# effective

| Name | T | $f_{res}$ | $G_V$ | $Q_{coil}$ |
| --- | --- | --- | --- | --- |
| PCB coil | 295K | 42.4MHz | 19.4 | 60 |
| PCB coil | $\sim$80K | 42.8MHz | 27.1 | 115 |
| PCB coil | $\sim$10K | 42.9MHz | 41.5 | 208 |
| Wire Coil | 295K | 36.8MHz | 25.2 | 89 |
| Wire Coil | $\sim$80K | 37.2MHz | 36.5 | 184 |
| Wire Coil | $\sim$10K | 37.9MHz | 58.9 | 624 |
| HTS Coil | $<$88K | 44.3MHz | 92.1 | 1172 |

$$G_V = \frac{V_c}{V_{in}}$$

# Reference

[1] Siverns J D, Simkins L R, Weidt S, et al. On the application of radio frequency voltages to ion traps via helical resonators[J]. Applied Physics B, 2012, 107(4):921-934.

[2] Matthias F. Brandl, Philipp Schindler, Thomas Monz, Rainer Blatt, Cryogenic resonator design for trapped ion experiments in Paul traps, arxiv:1601.06699

# The end

THANK YOU