



Human health aspects of radar operation

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Disclaimers



1. Supported by:



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2. Thank you to:

a) Gregory Barshtein and Yuri Feldman, Anna Bogdanova that taught me everything I know in this domain.

Noa Betzalel conducted endless CST simulations

Anna Grinbaum, Timur Safin and Keril Zayde that made all experiments and built the system

3. Disclaimers:

- We do not investigate the health effects, but the electro-bio-physical phenomena.
- Observed phenomena are statistically significant.
- However, further work is needed to investigate mechanisms leading to these phenomena.

BACKGROUND



Electromagnetic Exposure

- RF-based consumer applications increases human exposure to electromagnetic fields (EMF).
- Human sensitivity to EM exposure is known:
 - Skin responses
 - Musculoskeletal pain
 - Headaches
 - Dizziness

- EM waves penetrate upper human skin layers

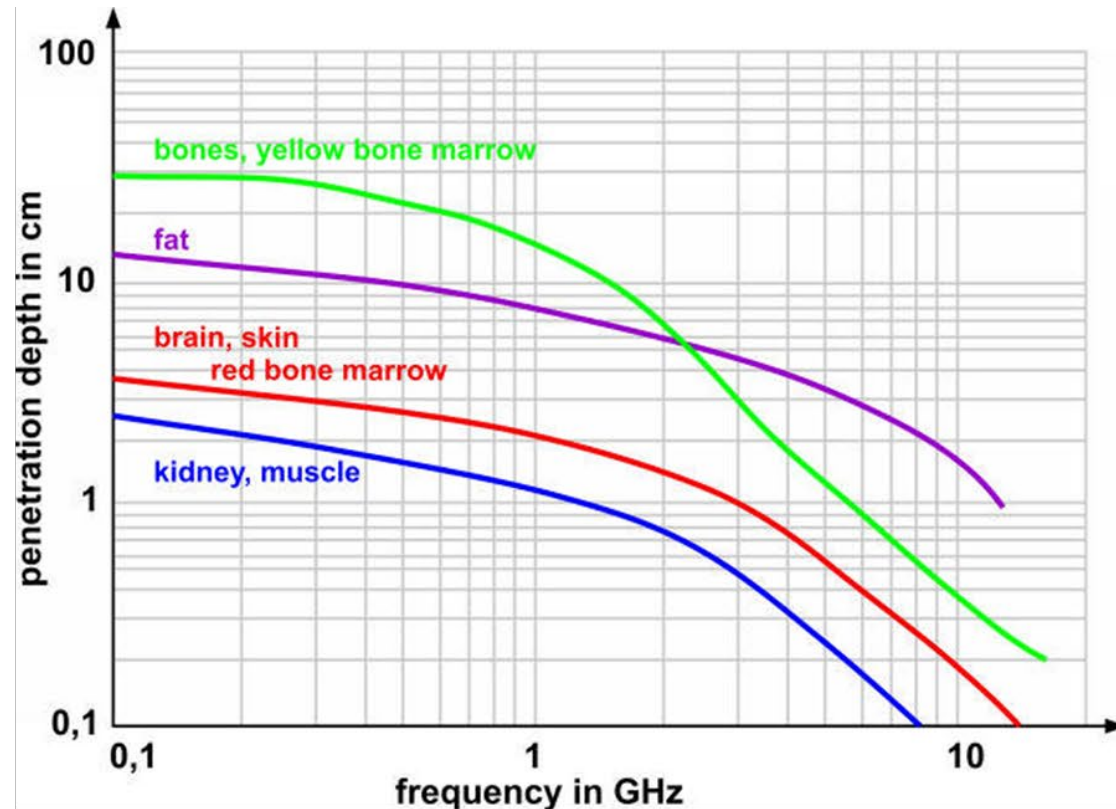


[1] Jamshed, Muhammad Ali, Fabien Heliot, and Tim WC Brown. "A survey on electromagnetic risk assessment and evaluation mechanism for future wireless communication systems." *IEEE Journal of Electromagnetics, RF and Microwaves in Medicine and Biology* 4.1 (2019): 24-36.

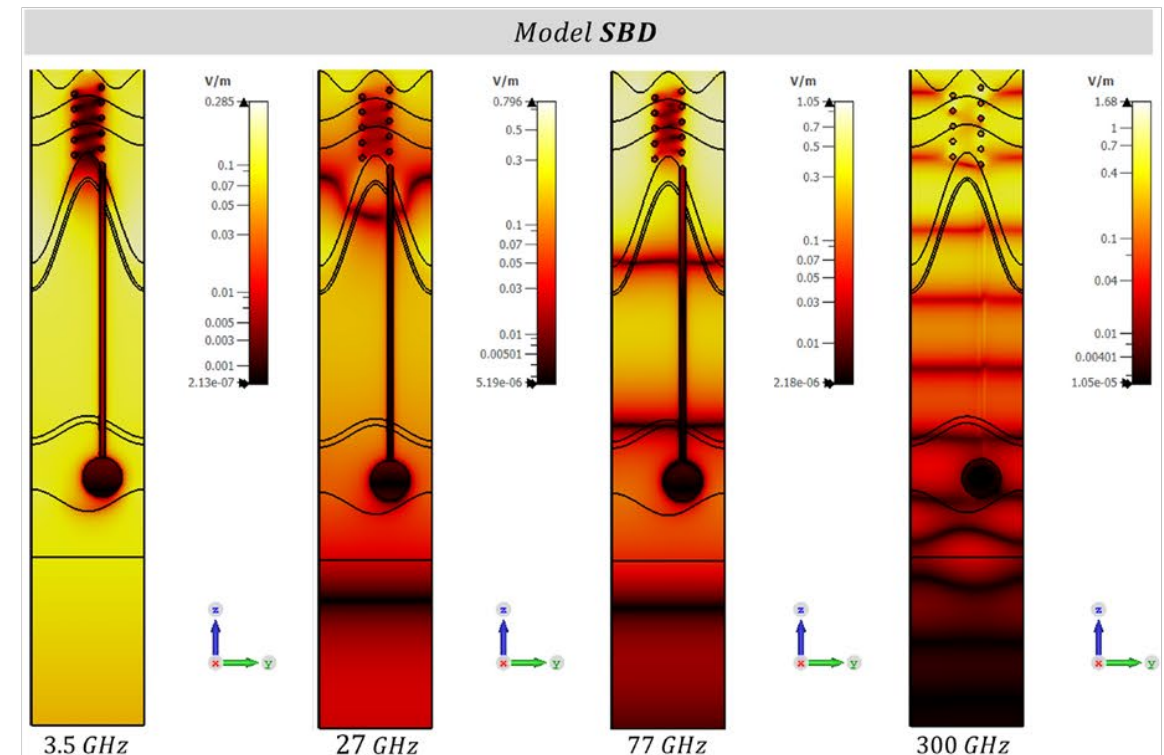
[2] Dieudonné M. Electromagnetic hypersensitivity: a critical review of explanatory hypotheses. *Environmental Health : a Global Access Science Source*. 2020 May;19(1):48. DOI: 10.1186/s12940-020-00602-0. PMID: 32375774; PMCID: PMC7201940.

[3] Yael Stein, Iris G. Udasin, "Electromagnetic hypersensitivity (EHS, microwave syndrome) – Review of mechanisms," *Environmental Research*, Vol. 186, 2020,

Human Skin Penetration Depth



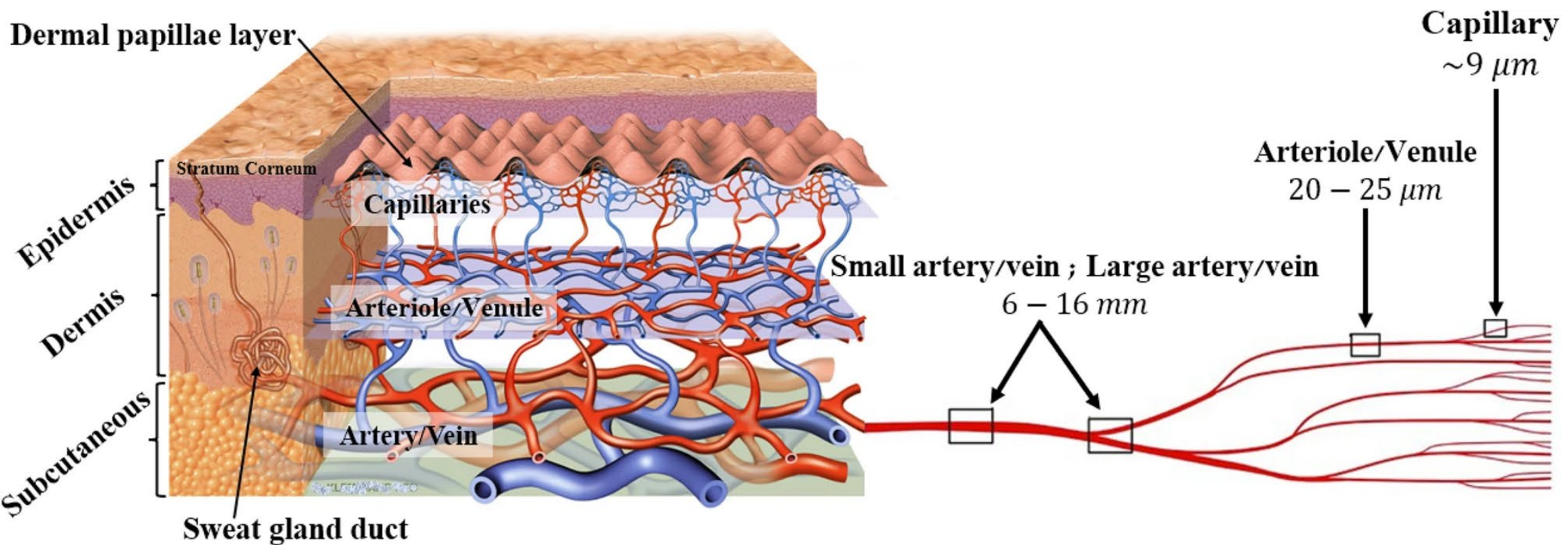
<https://www.emf-portal.org/en/cms/page/home/effects/radio-frequency#:~:text=The%20average%20depth%20of%20penetration,about%200.2%20mm%20and%20less.>



Betzalel, N., Feldman, Y. & Ben Ishai, P. The modeling of the interaction of pulsed 5G/6G signals and the fine structure of human skin. *Sci Rep* **15**, 28651 (2025).
<https://doi.org/10.1038/s41598-025-13777-8>

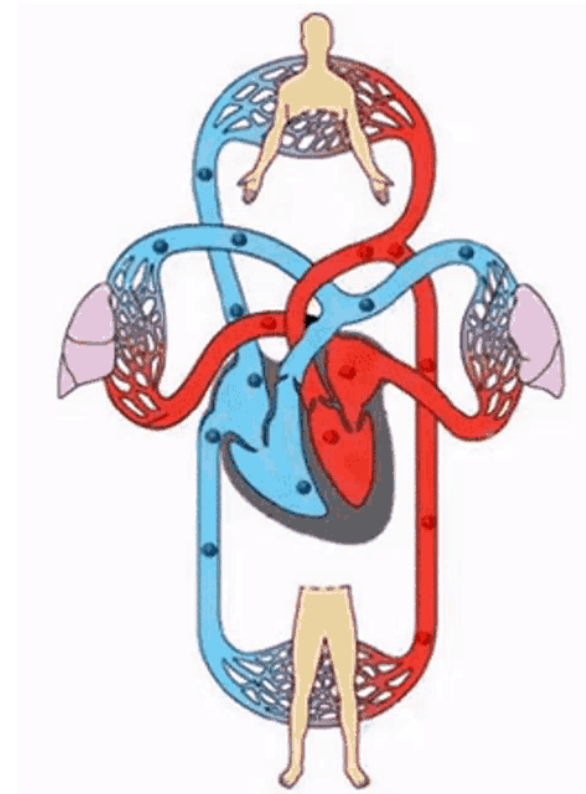
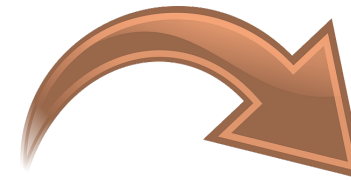
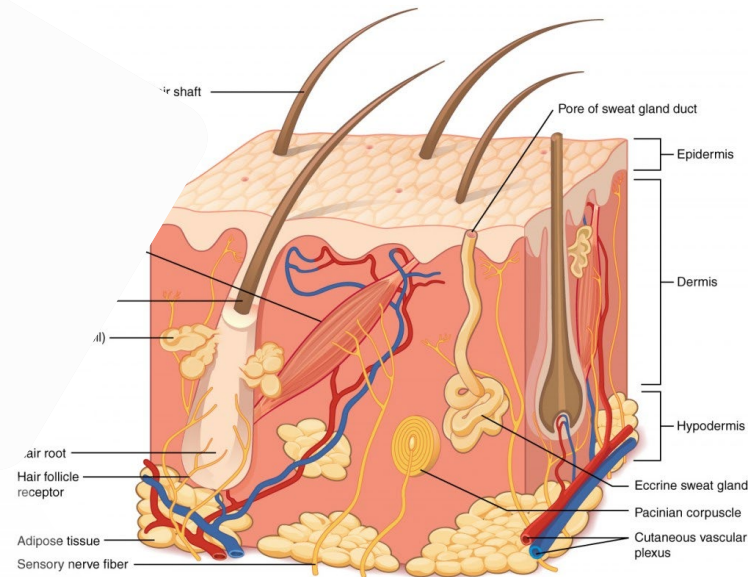
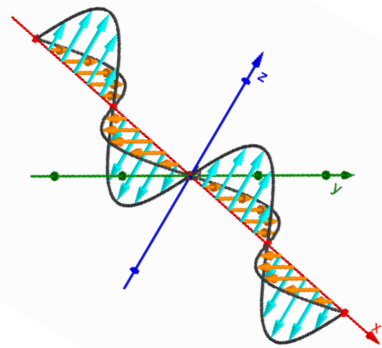
What can EM interact with?

- **EMF penetrates upper skin layers**

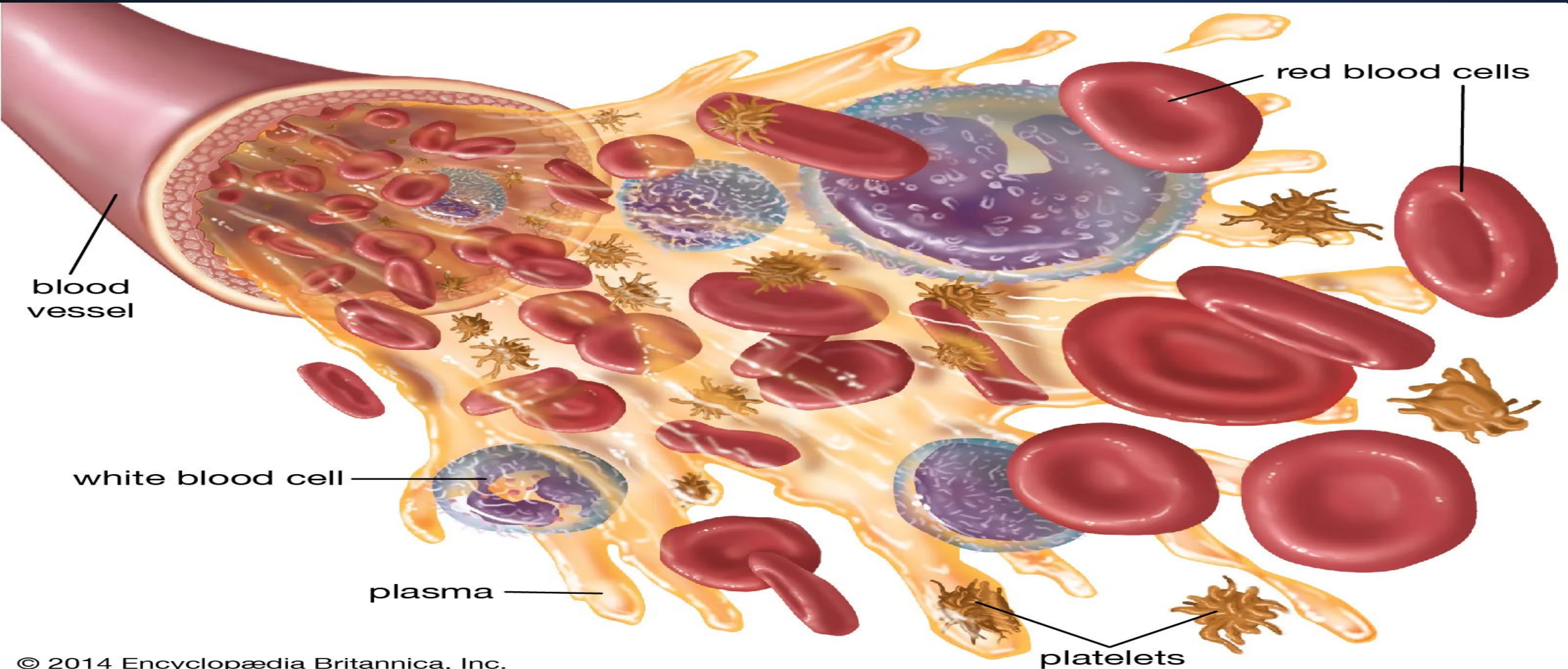


EM interaction at Epidermis

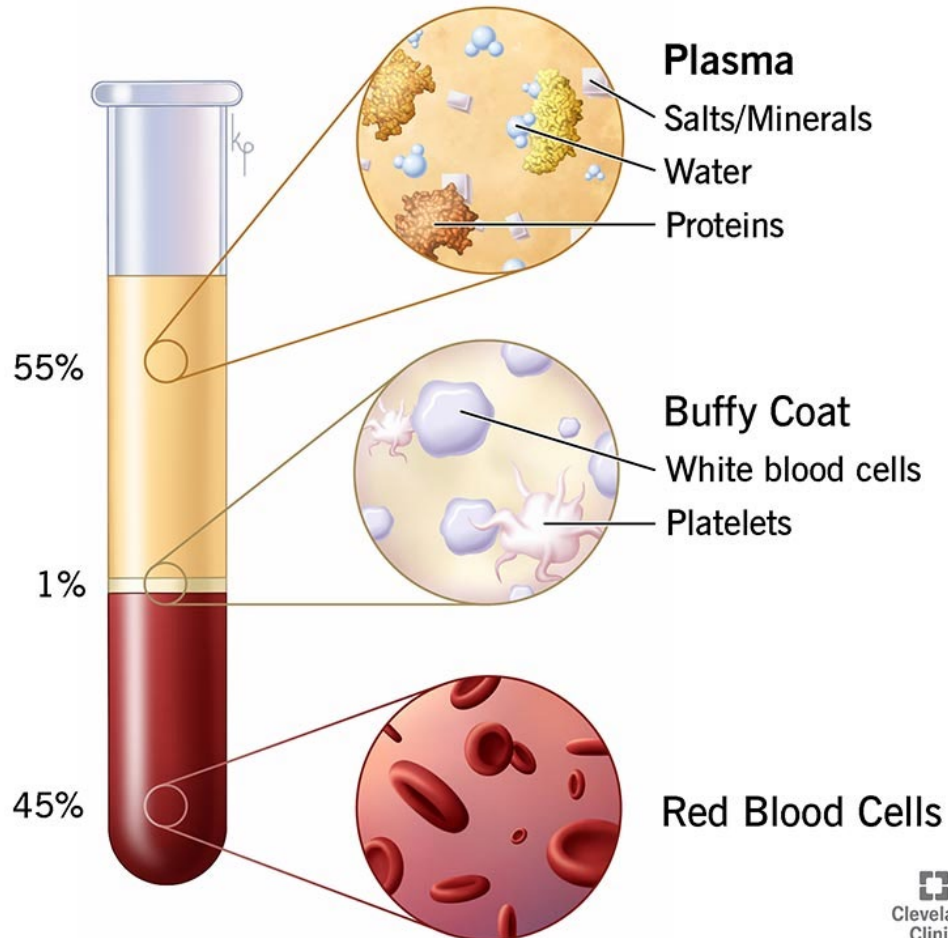
- Interacting with the capillary network.
- Inducing nonthermal effects on the circulating blood.
- Effects may be transferred into internal organs.



What is Blood?



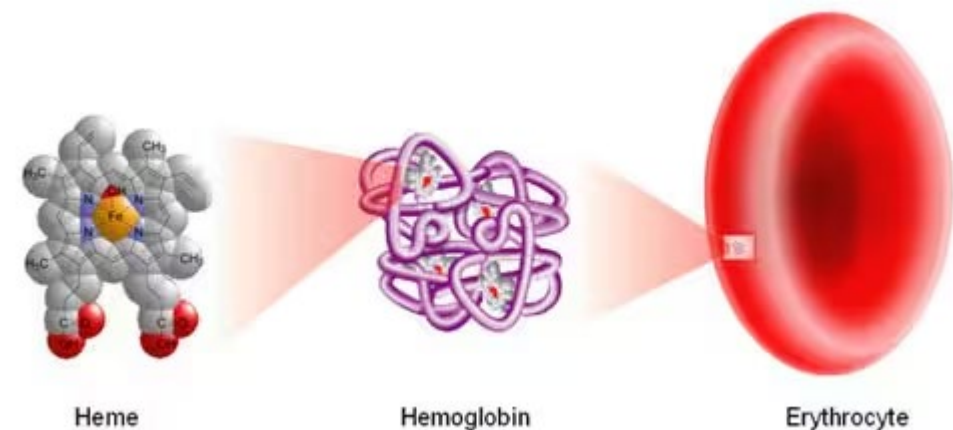
Blood components




Cleveland
Clinic
©2021

EM exposure targets:

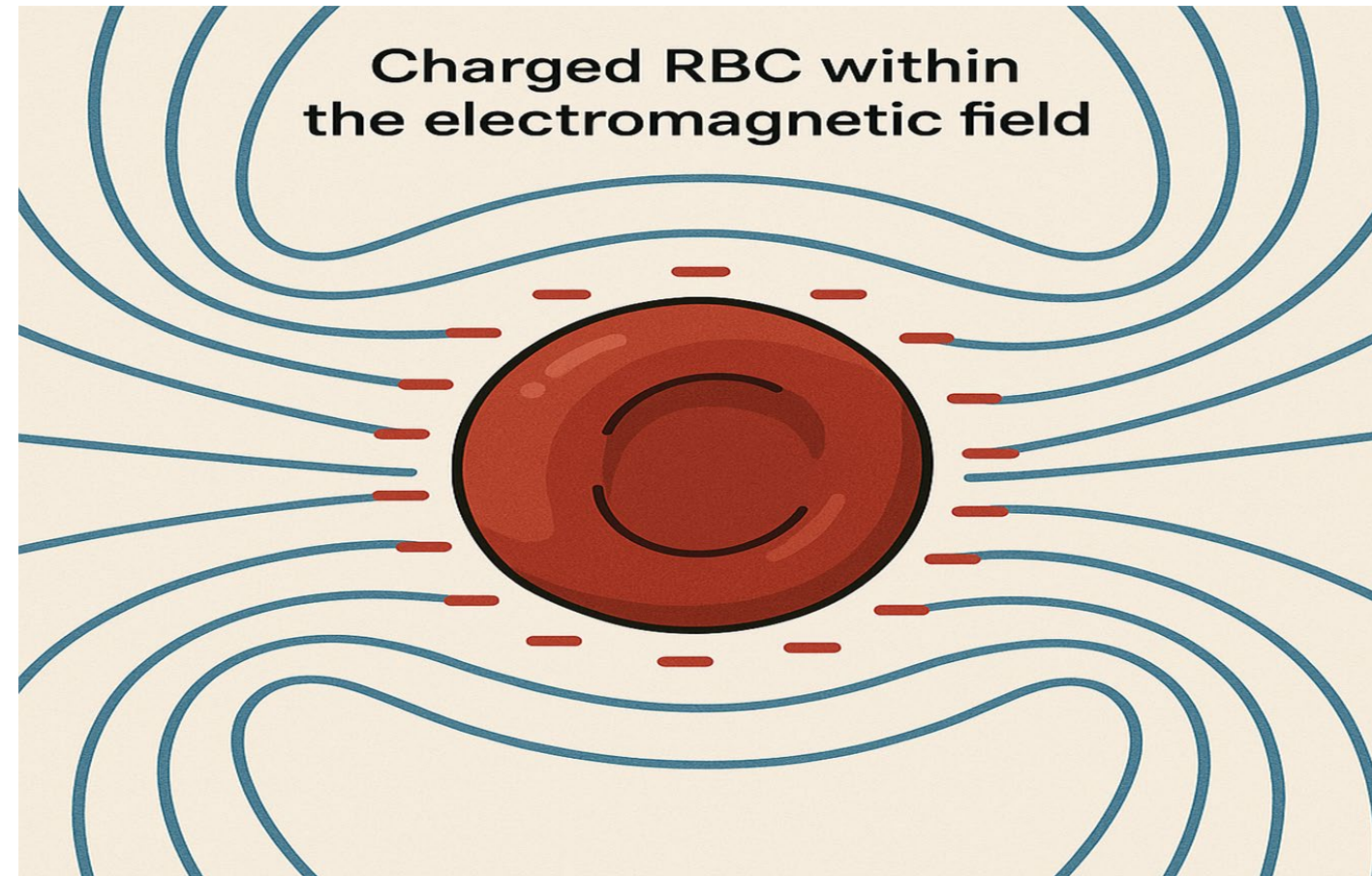
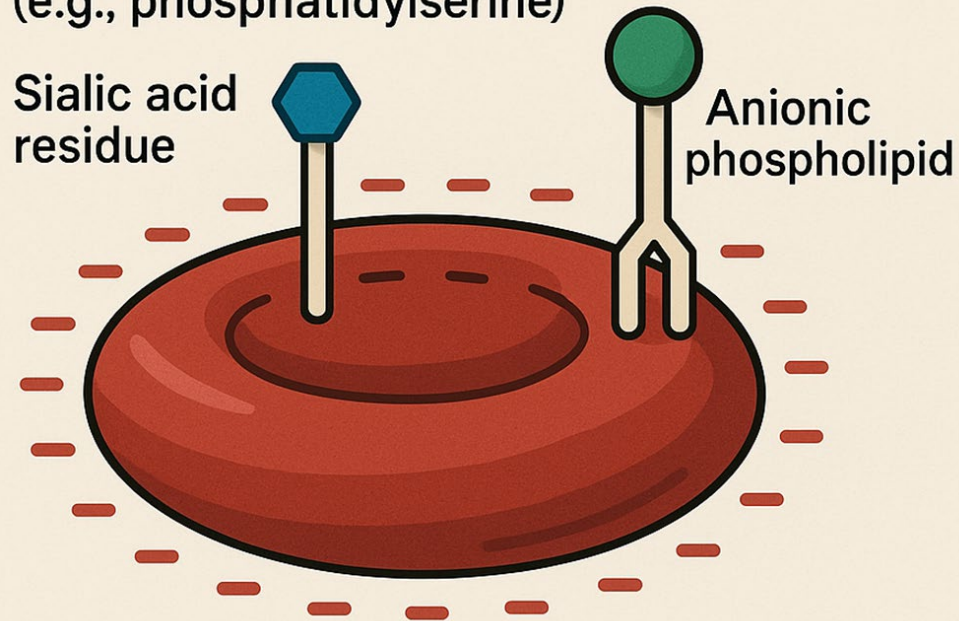
- **45% erythrocyte (red blood cells)**
Transfer oxygen
- **4% Protein (Albumin, Globulins)**
Protect from diseases , transport



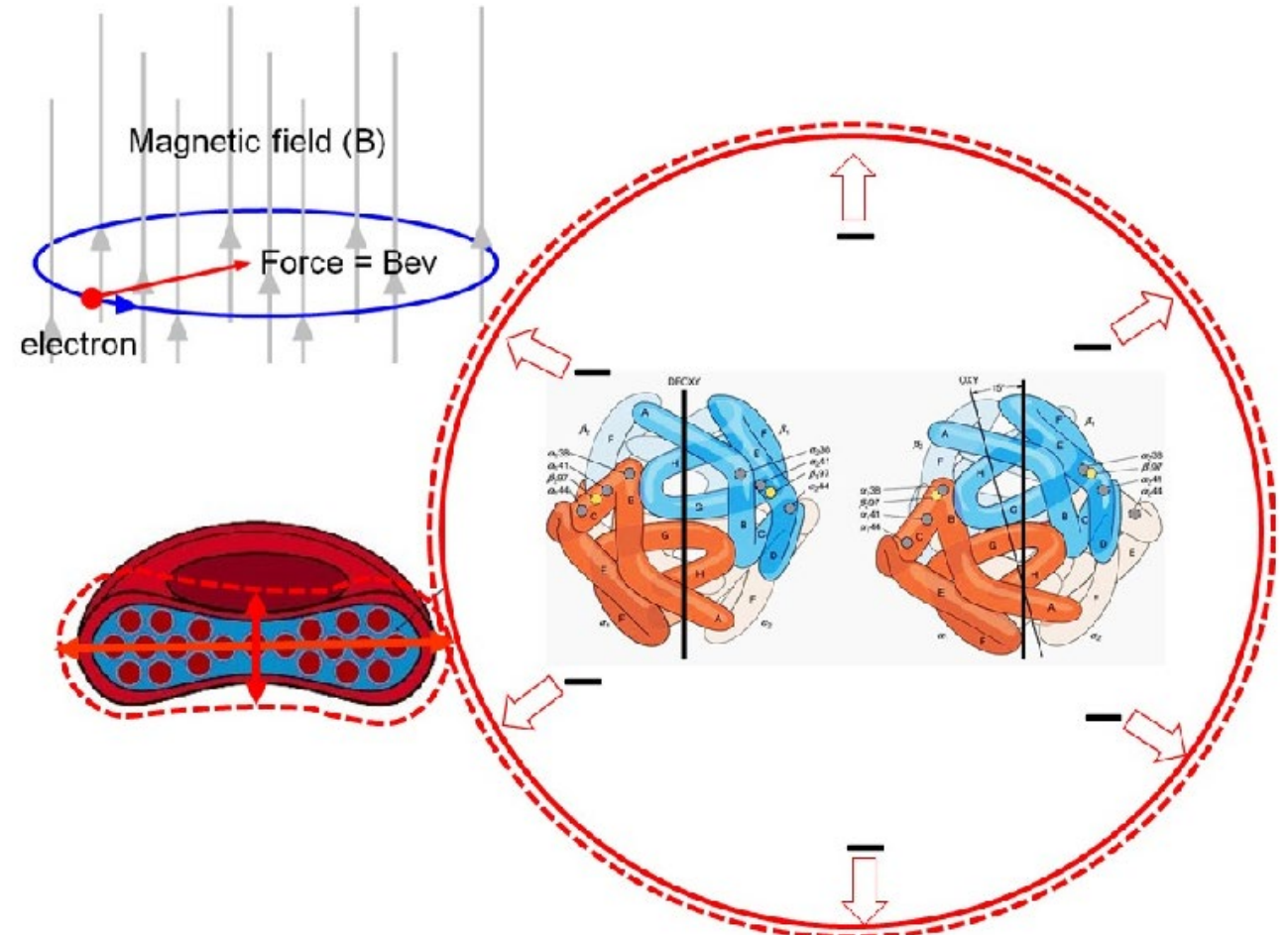
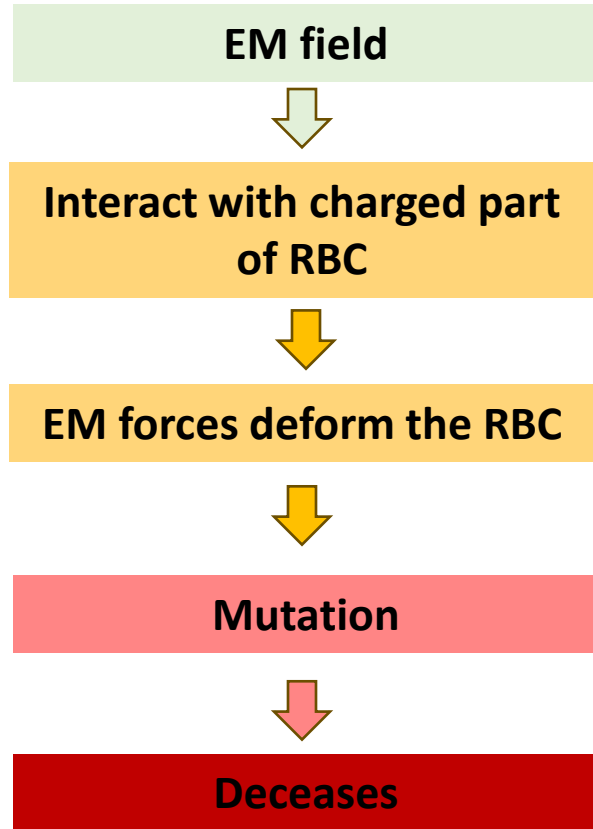
Electro-Magnetic Structure of RBC

The outer membrane of an RBC is covered with negatively charged molecules, especially:

- Sialic acid residues on glycoproteins
- Anionic phospholipids (e.g., phosphatidylserine)

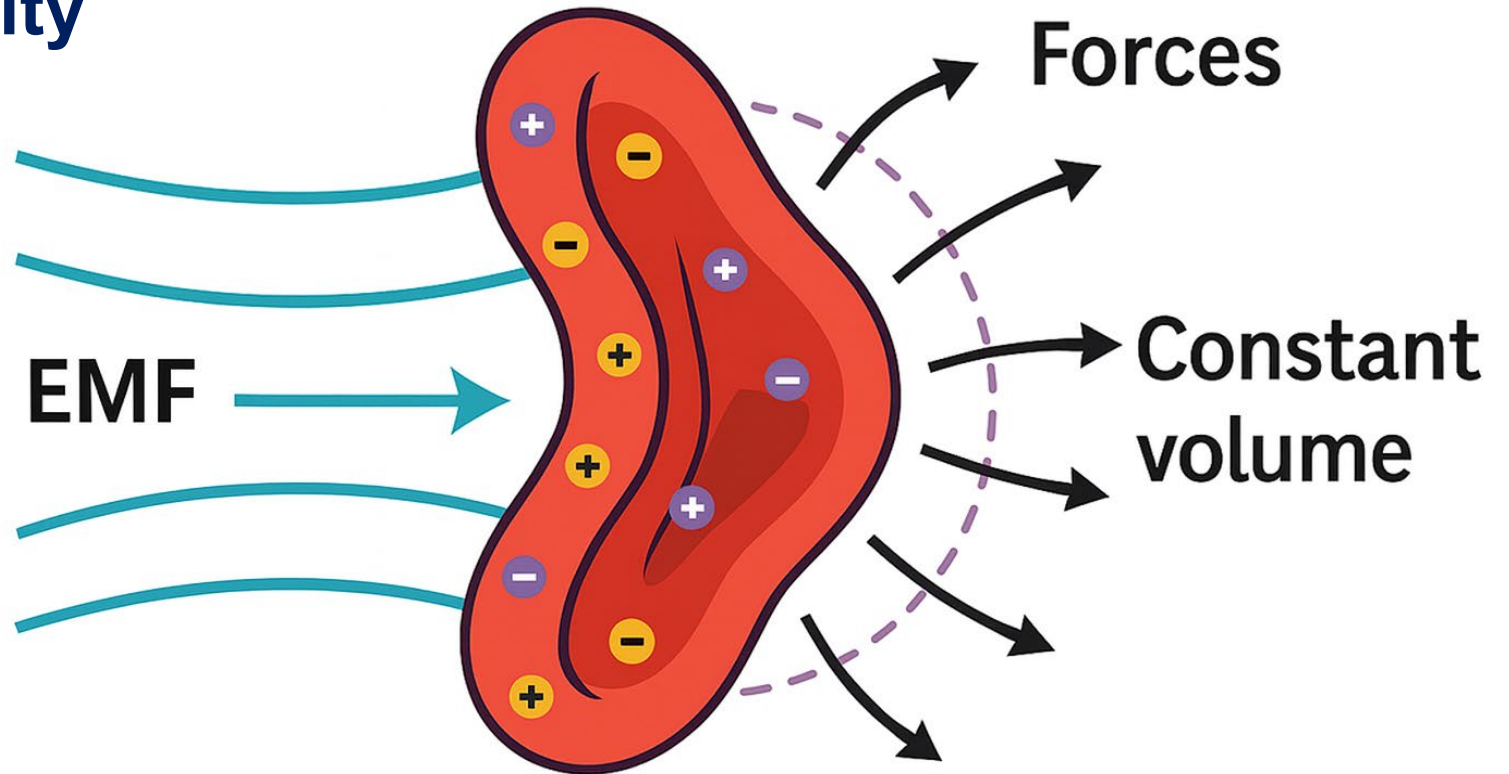


The Main Conjecture

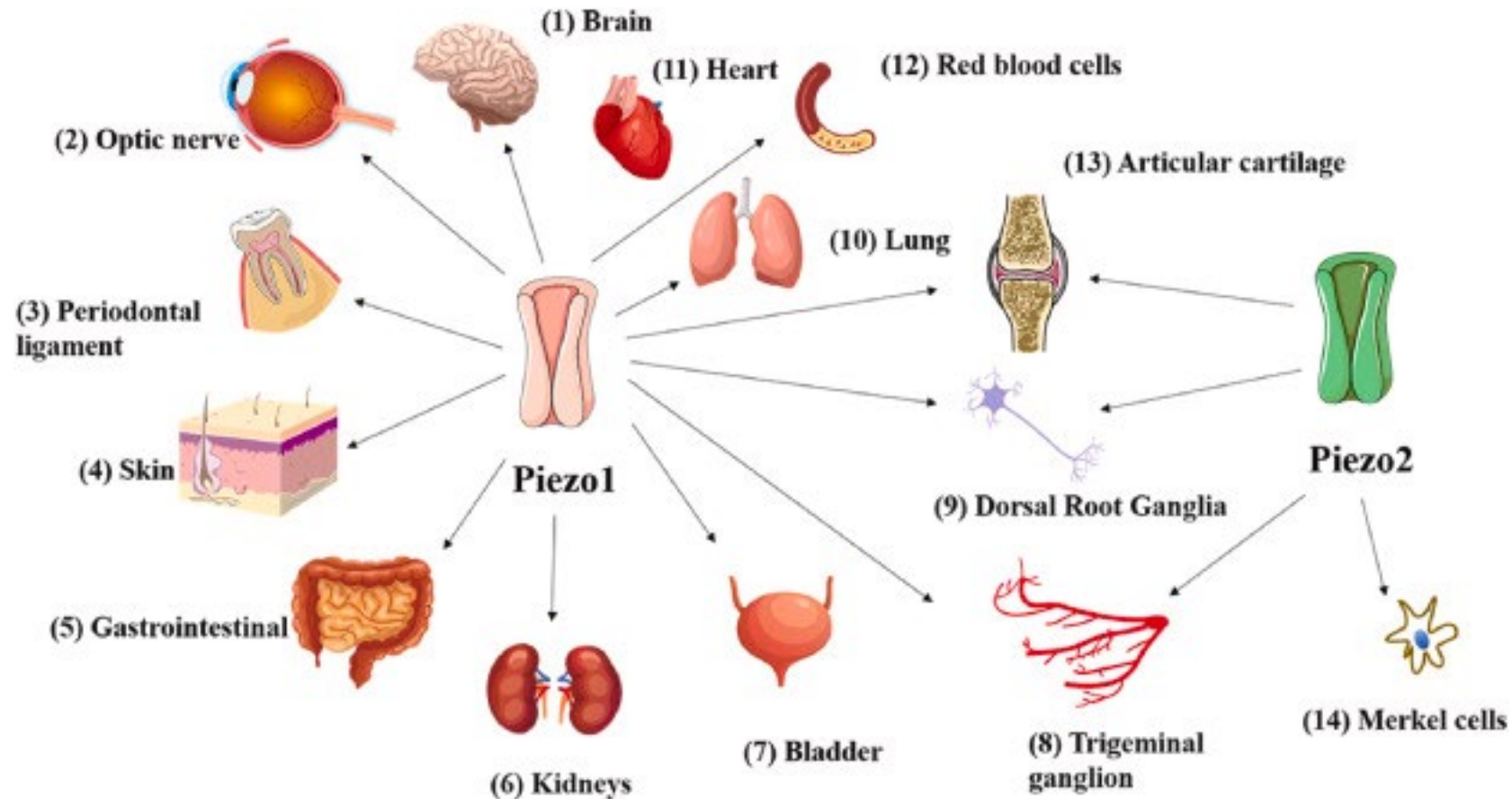


EMF Effect on RBC

- EMF $\rightarrow$ forces on membrane charges
- Affects RBC deformability



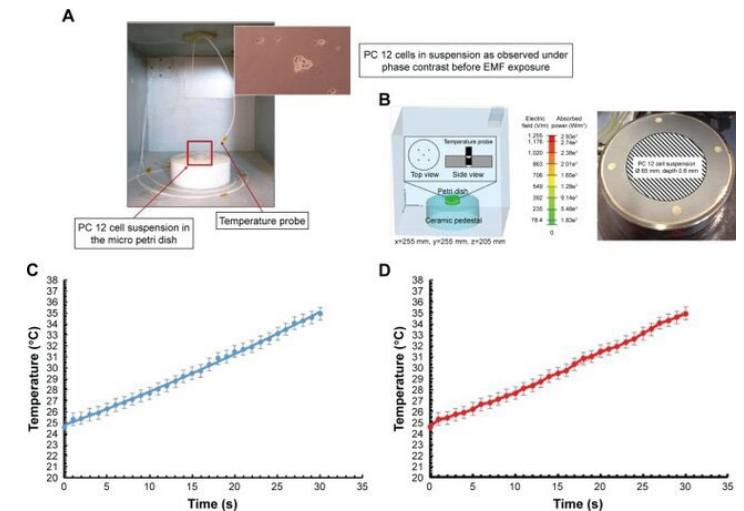
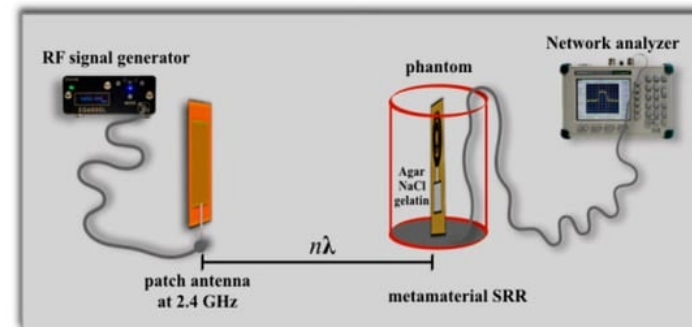
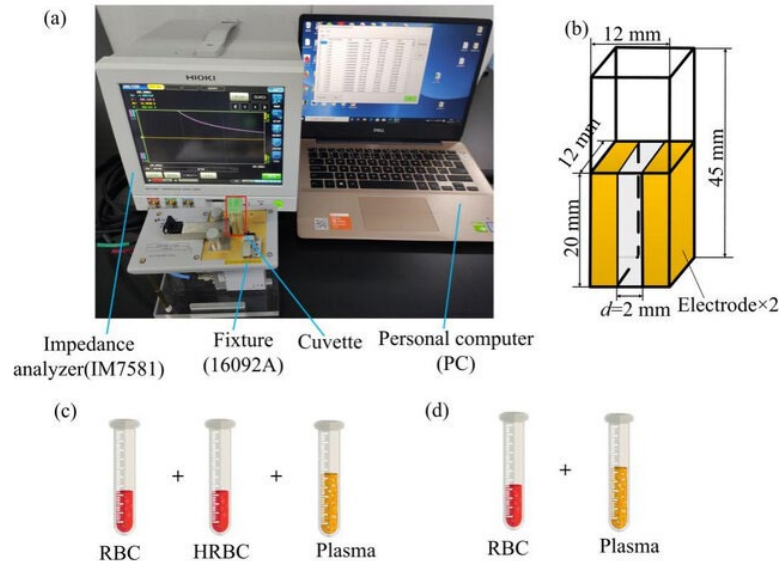
RBC Mutations are Associated with Diseases



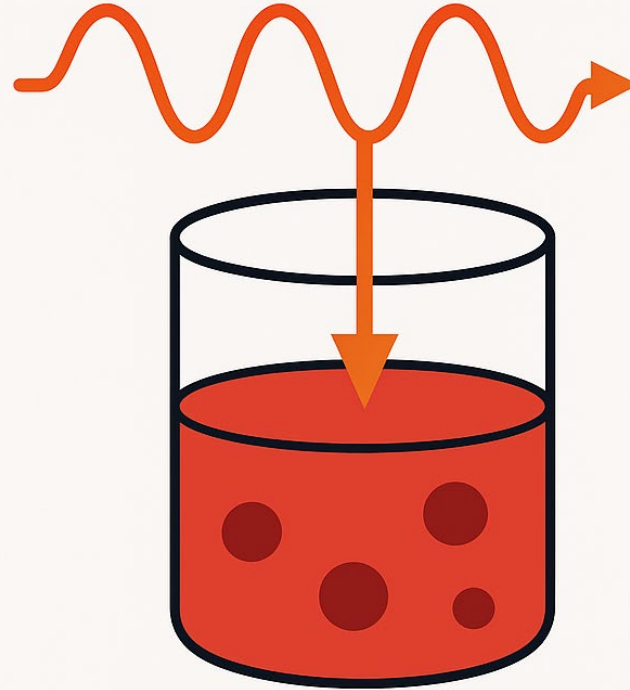
THE MAIN GOAL

Motivation and Existing Gap

- The existing EMF exposure systems expose only static blood.
- Cannot be indicative to practical circulating blood conditions.



The Challenge



Shallow Penetration
Small volume is exposed

The Main Focus

- **EMF exposure system design:**
 - **Part I: Near-field EMF exposure system**
 - **Part II: Far-field EMF exposure system**

Core Components Simulated

-  **Circulating blood system**
-  **Controlled EMF exposure**
 - Near-field (NF)
 - Far-field (FF) with modulation
-  **Fixed, small volume of exposed blood**
-  **Precisely controlled temperature**

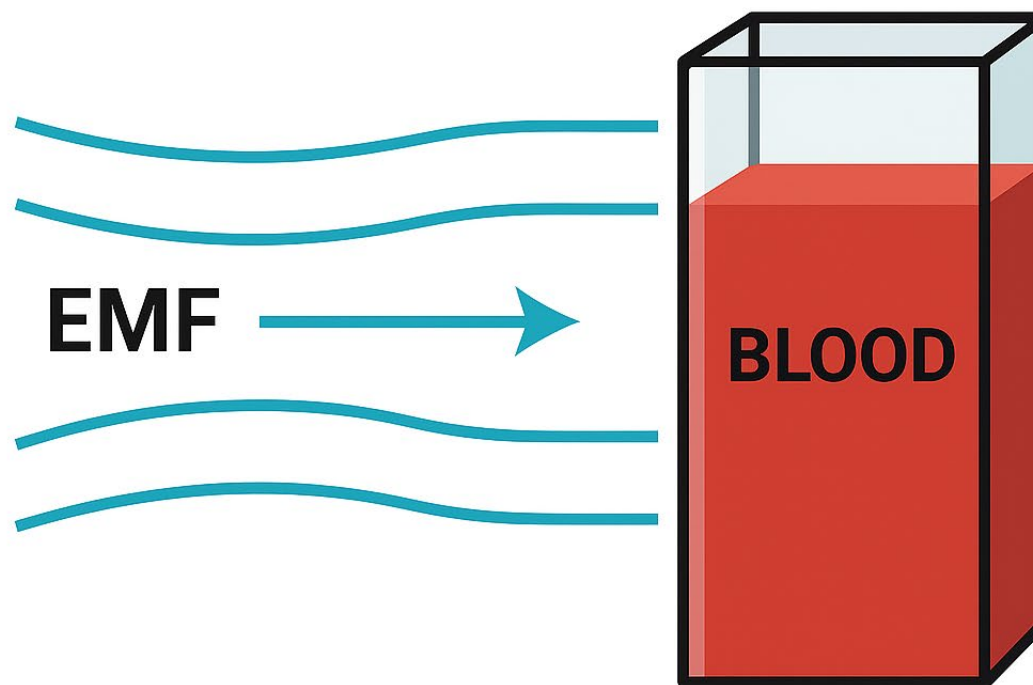
BIOLOGICAL TARGETS

-  **RBC (Red Blood Cell)**
-  **Albumin (Protein)**

The Main Goal

- Design exposure system to ensure: uniform EMF

**Achieve uniform EMF
within cuvette**



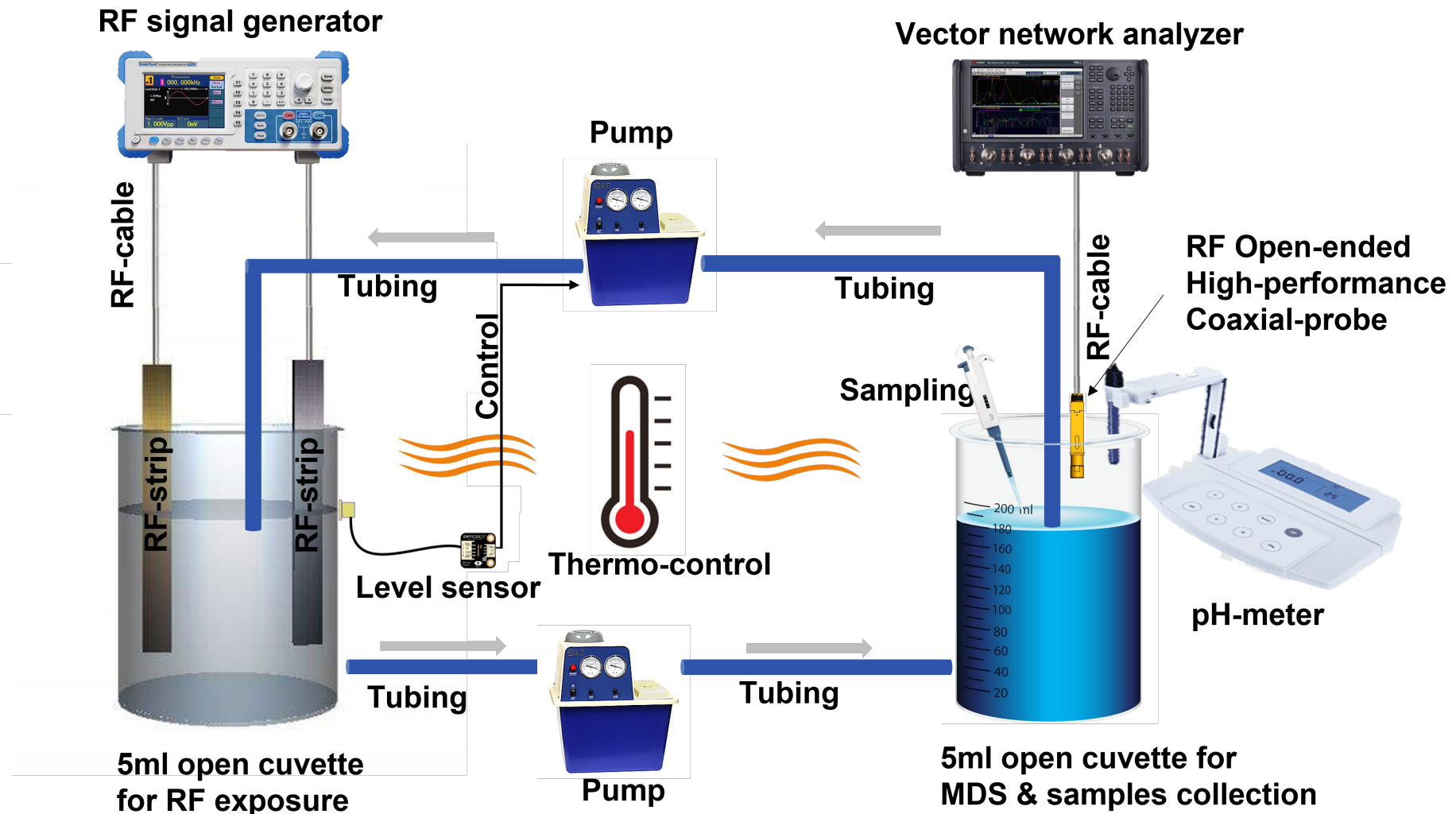
EMF System Design



Near-Field EMF Exposure System



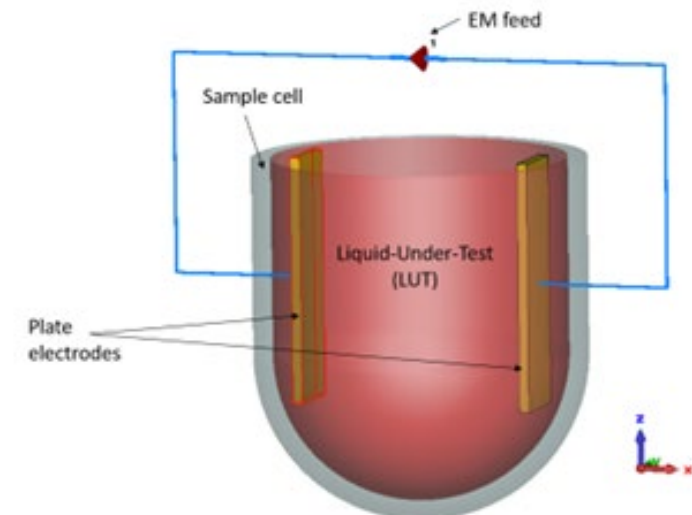
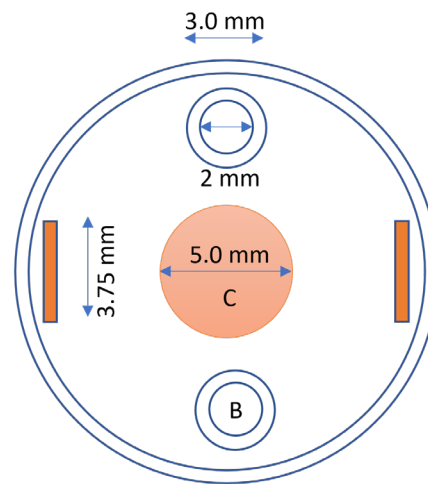
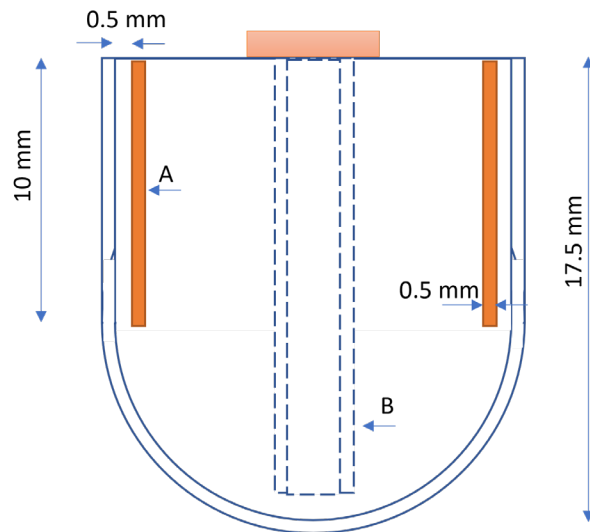
Near-Field EMF Exposure System



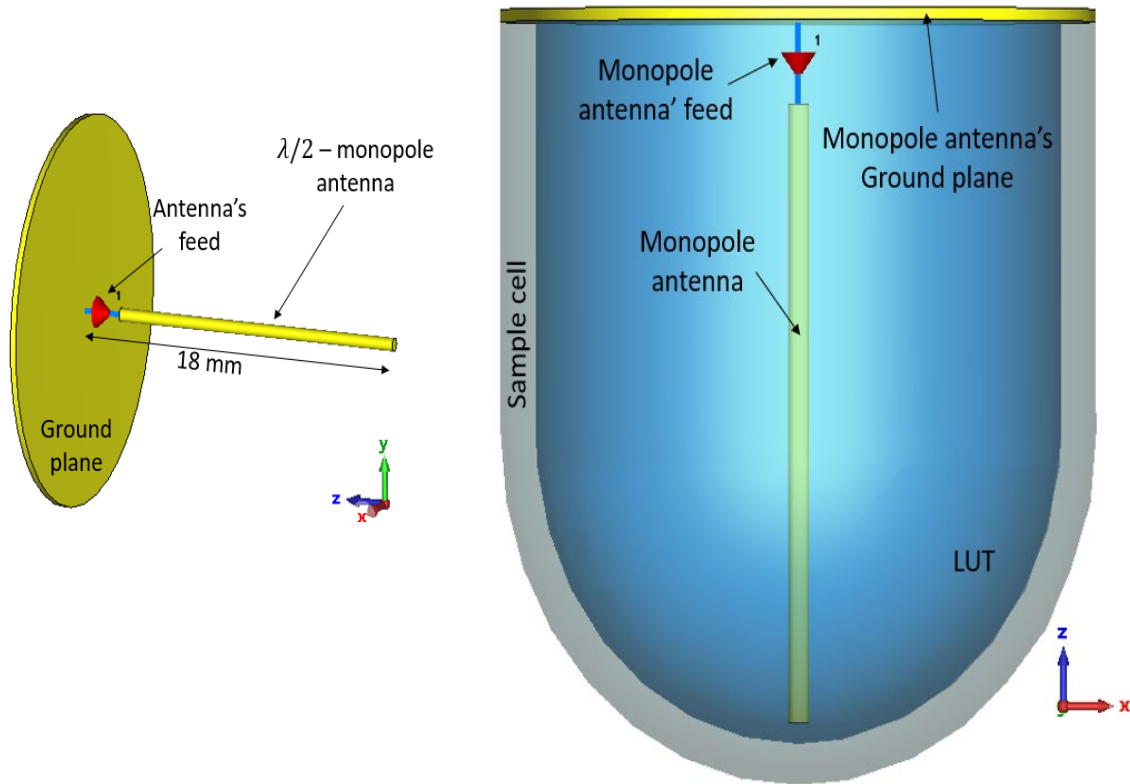
EM Simulation of the Exposure Cuvette



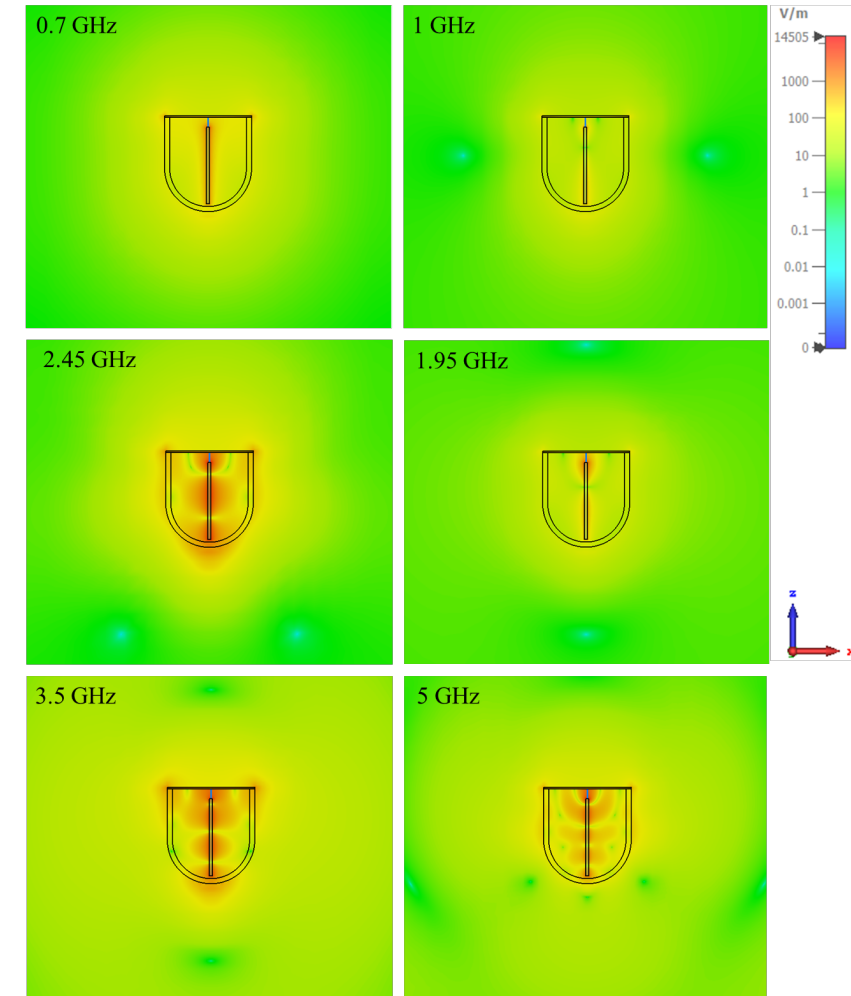
- CST simulation
- Gold-coted electrodes with electric conductivity of $4.561 \cdot 10^7 S/m$ and thermal expansion coefficient $14 \cdot 10^{-6} 1/K$
- Simulated frequencies: 0.7, 1, 1.95, 2.45, 3.5 GHz
- Average transmit power: 10dBm
- Cuvette of lead glass with permittivity 6 and conductivity $10^{-12} S/m$, permeability $1H/m$.



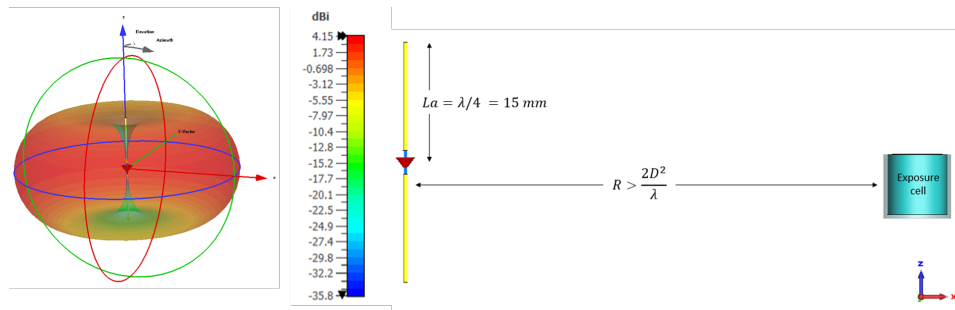
Monopole Antenna Within Exposure Cuvette



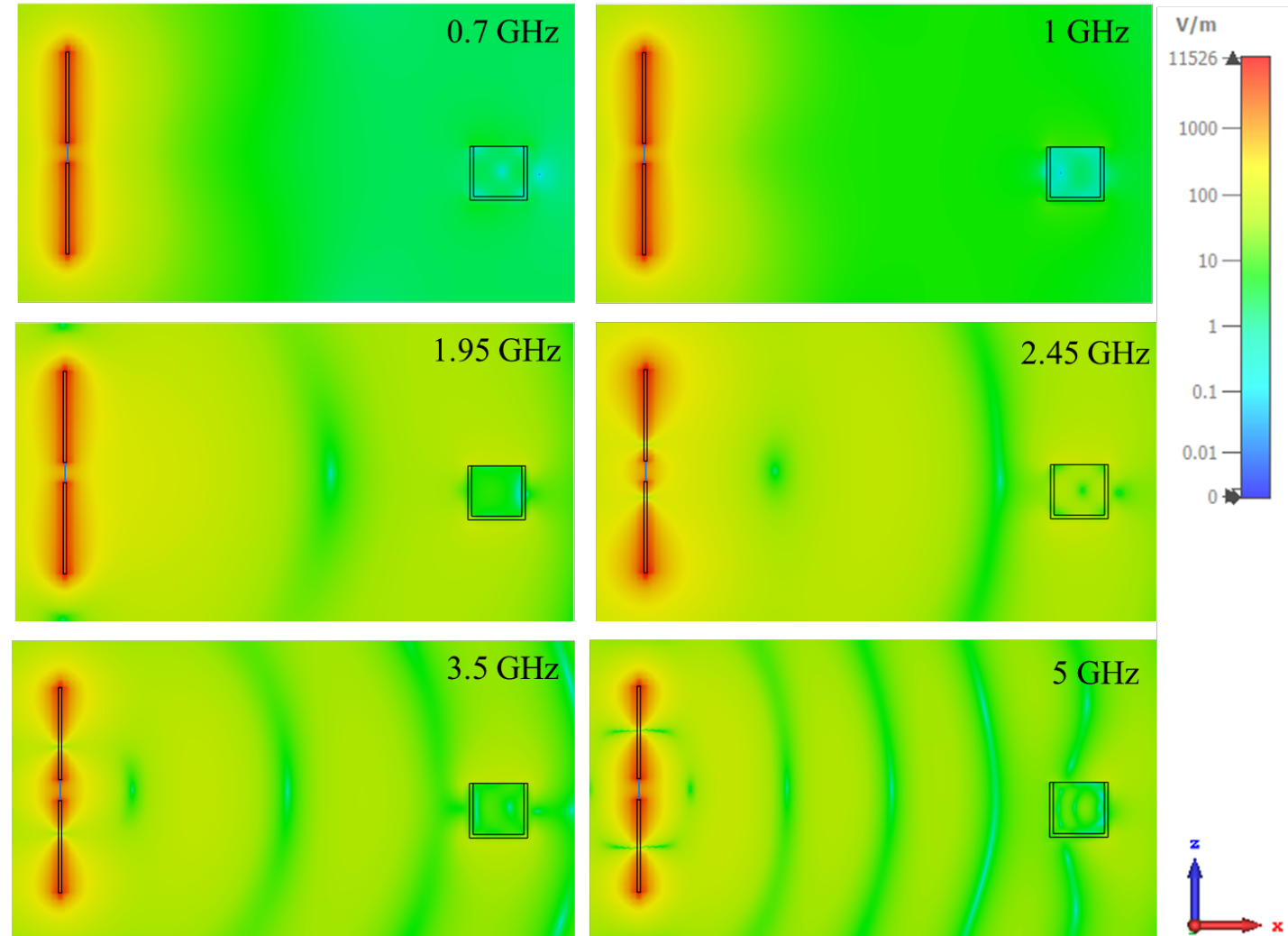
- Nonuniform distribution of the electromagnetic field.
- Significant variations with increasing frequency.



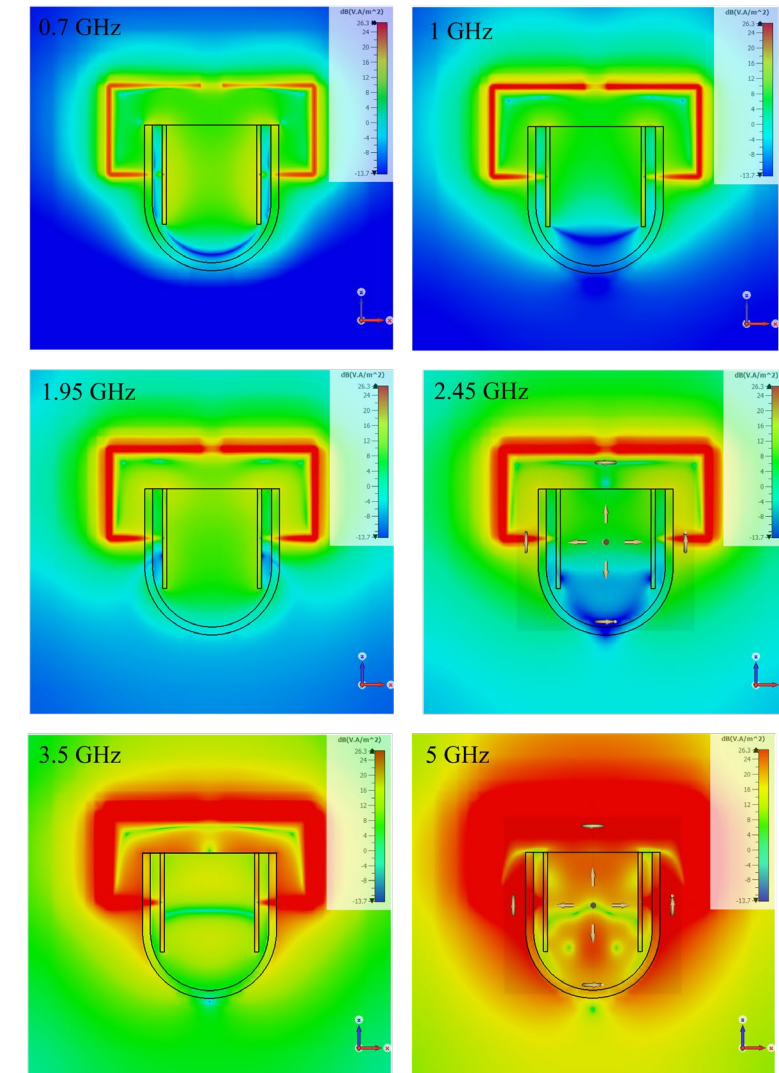
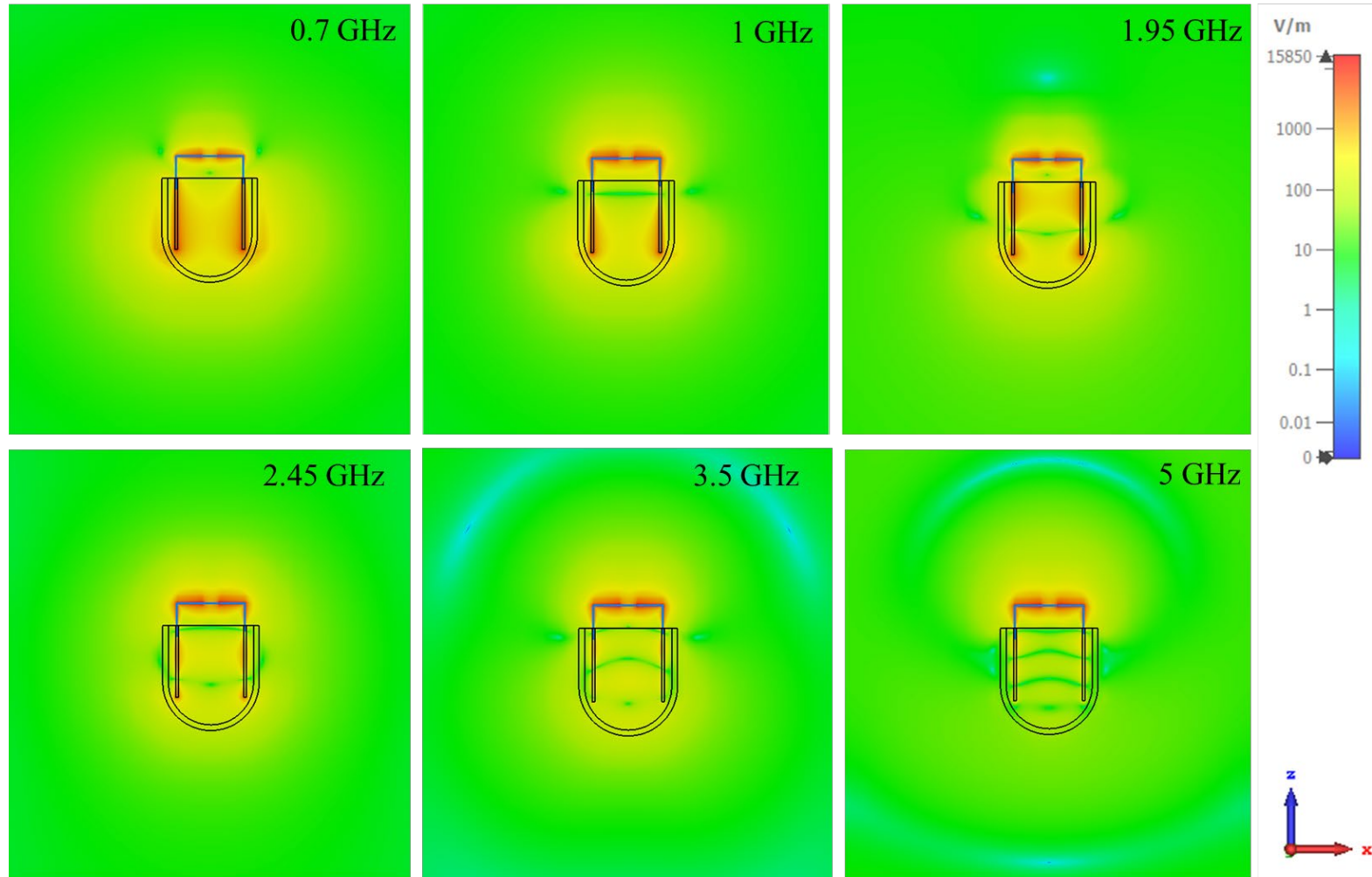
Dipole Antenna Outside the Exposure Cuvette



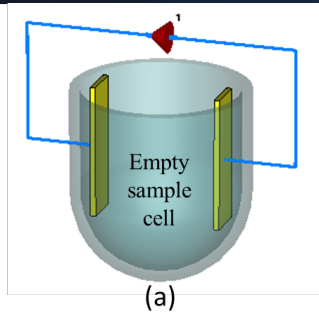
The standing wave pattern within the exposure cuvette compromises the EMF uniformity.



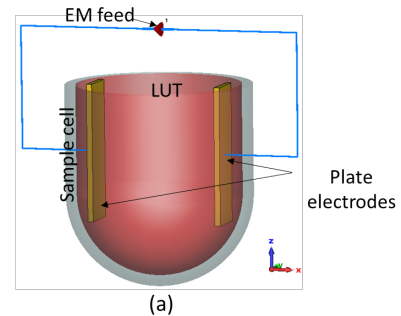
Cylindrical Electrodes E-Field & Power Flow



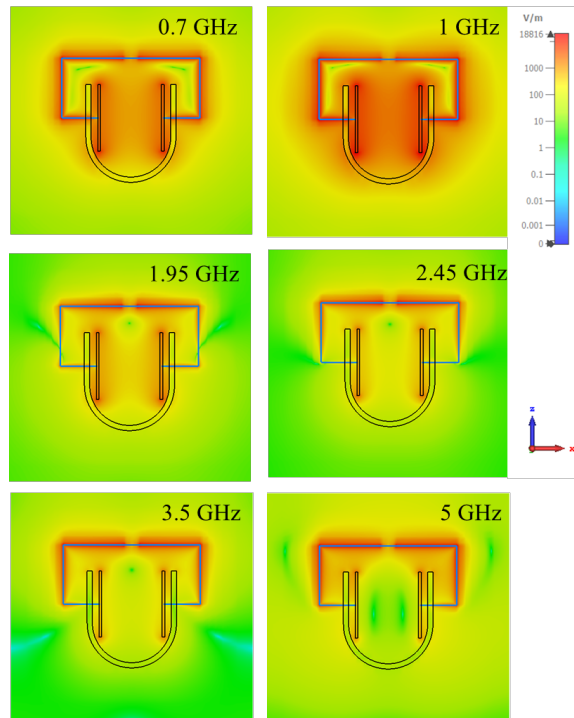
Plane Electrodes: Transverse Electromagnetic (TEM) Cell



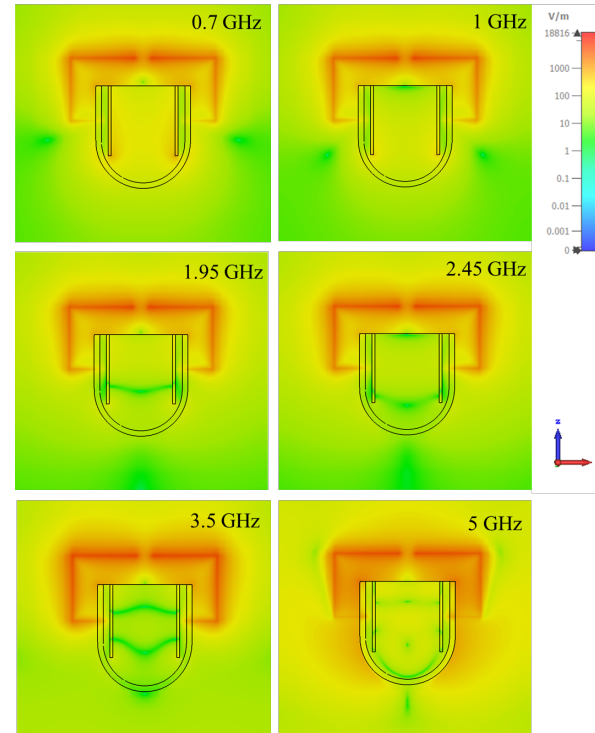
E-field



- H-field is relatively uniform
- Power flow is real and time-invariant

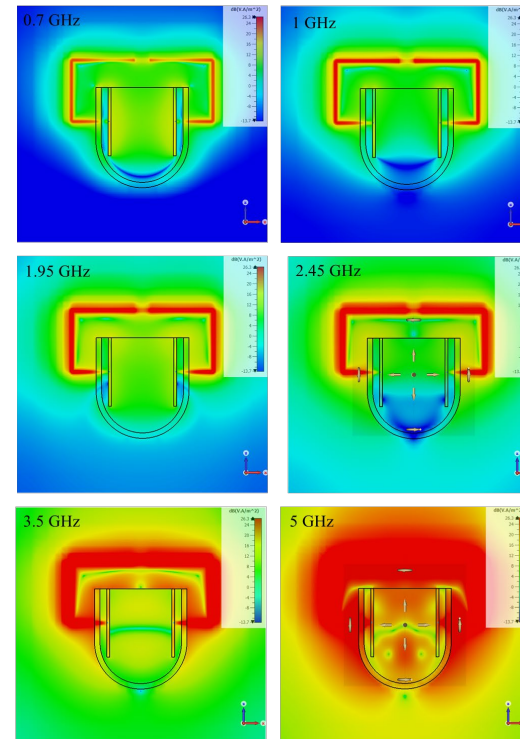


(b)

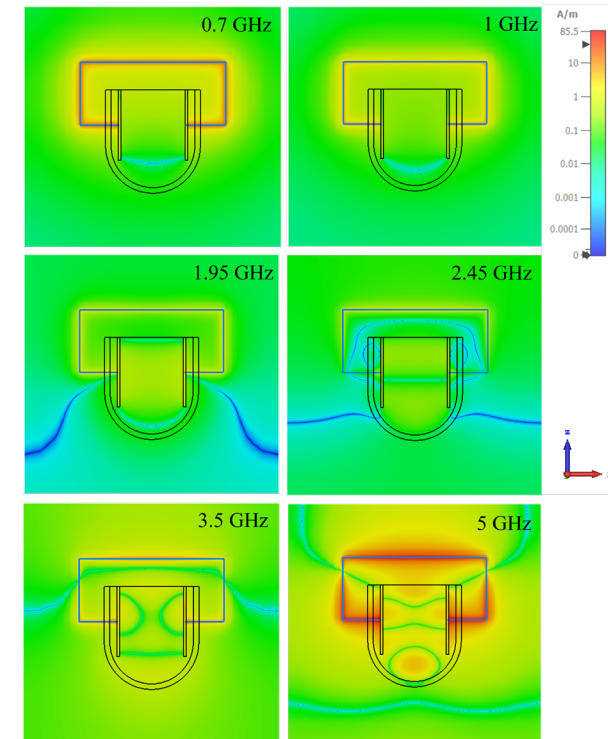


(b)

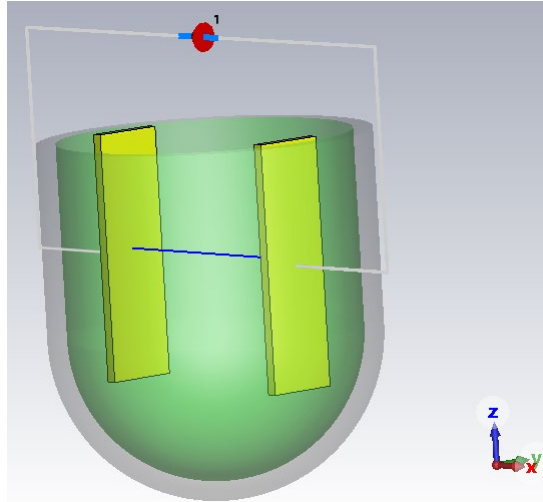
Power flow



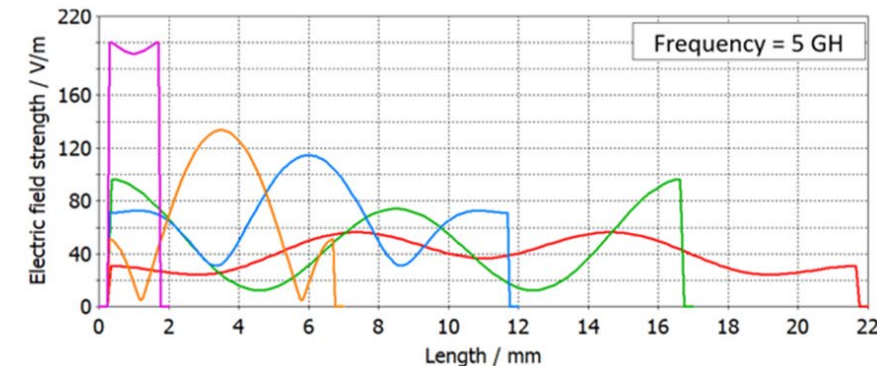
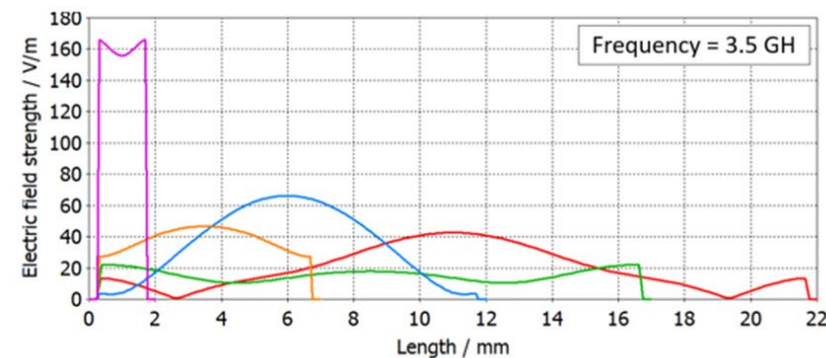
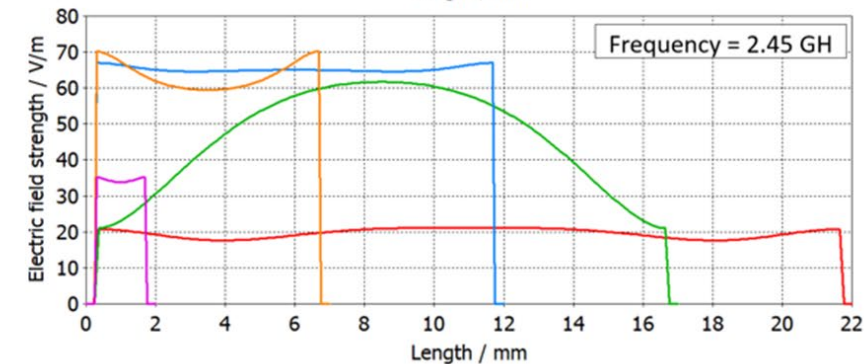
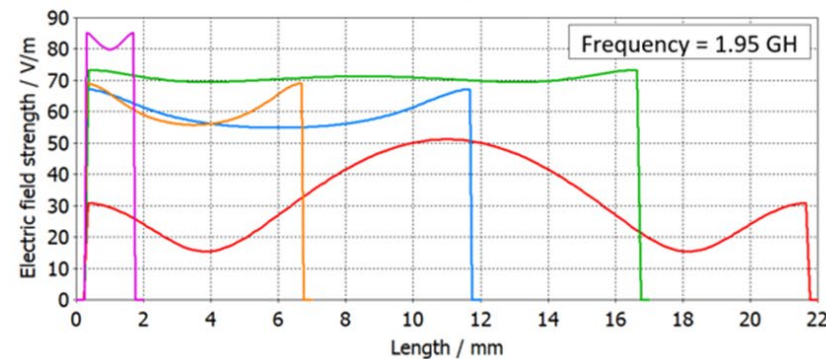
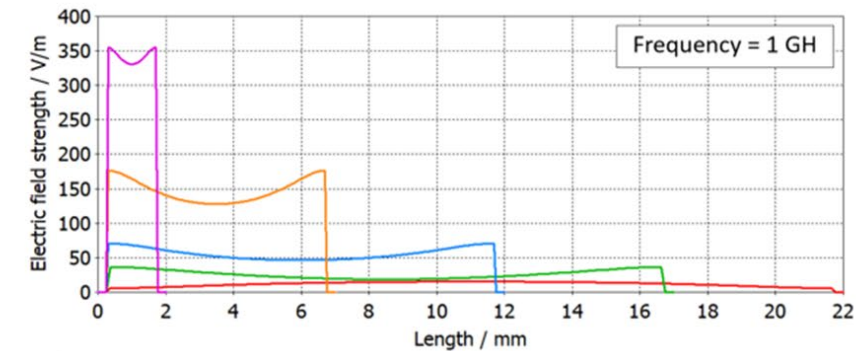
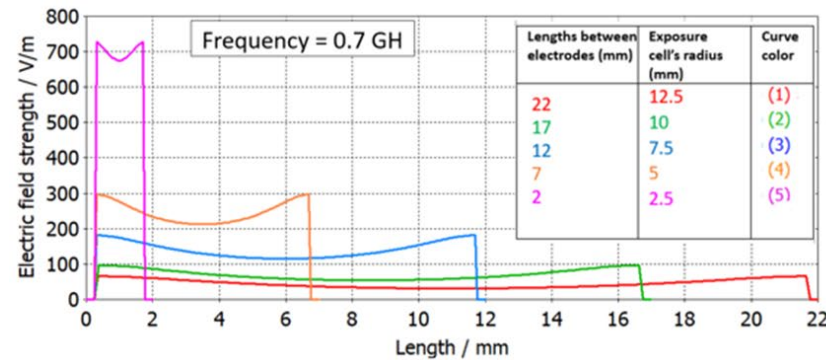
H-field



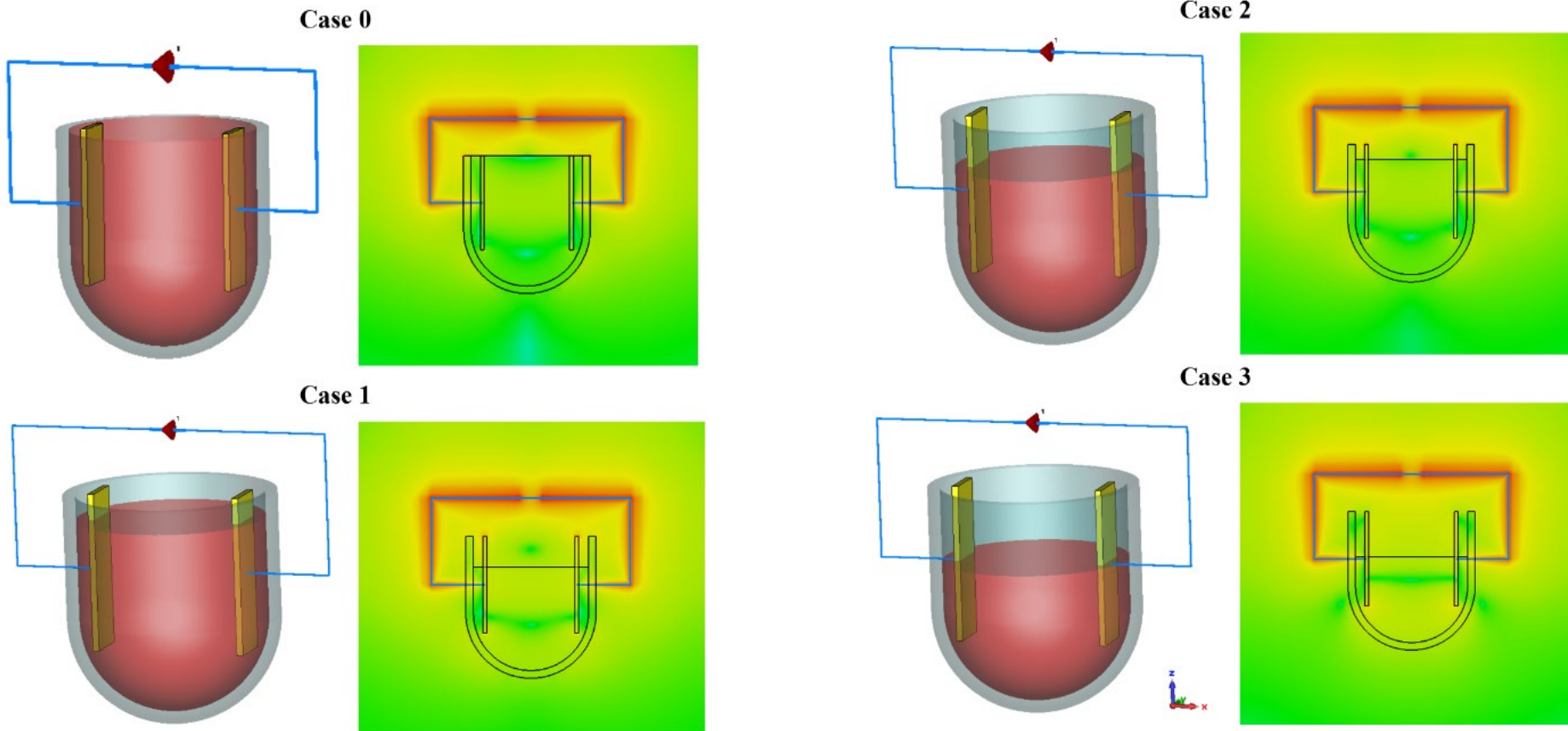
E-Field Uniformity



- The E-field uniformity degrades with increased frequency
- 7.5 mm diameter provides the E-field ~uniformity.



Influence of Suspension Level



The E-field uniformity degrades with the reduced suspension level

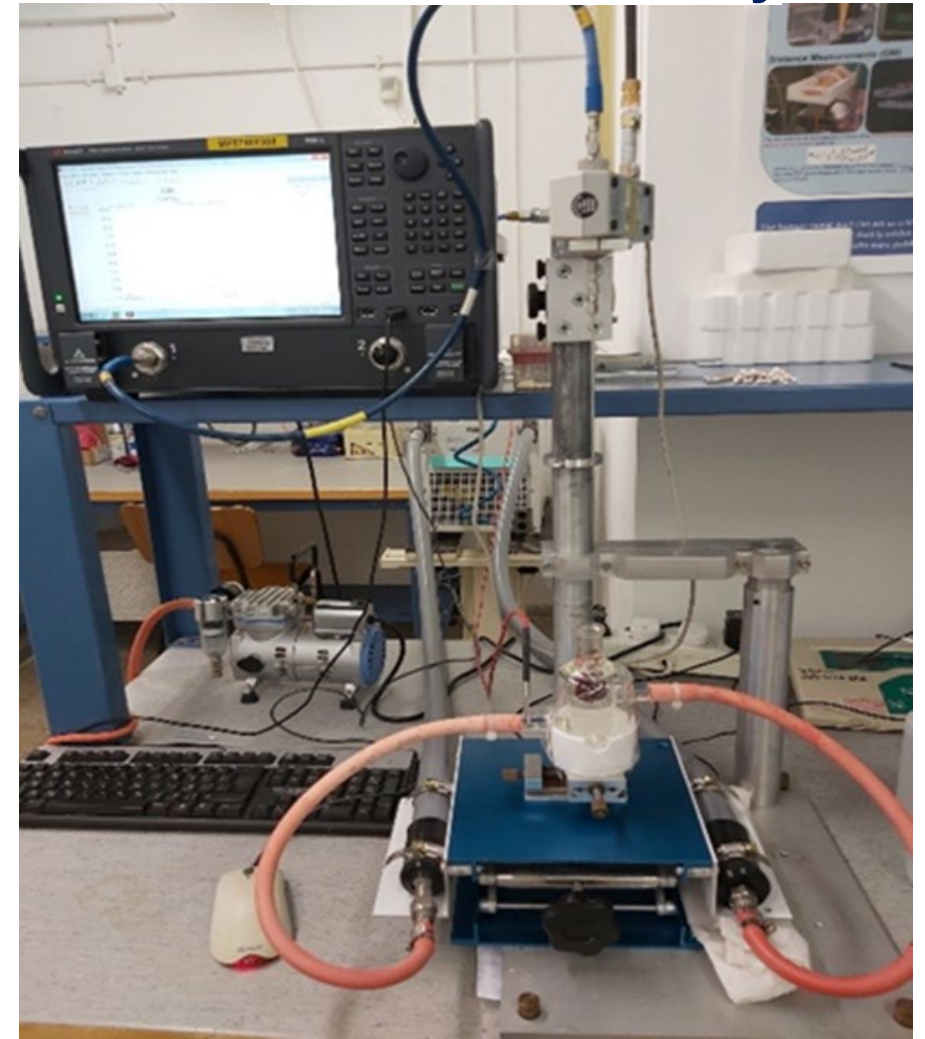
Near-Field EMF Exposure System



Zurich University



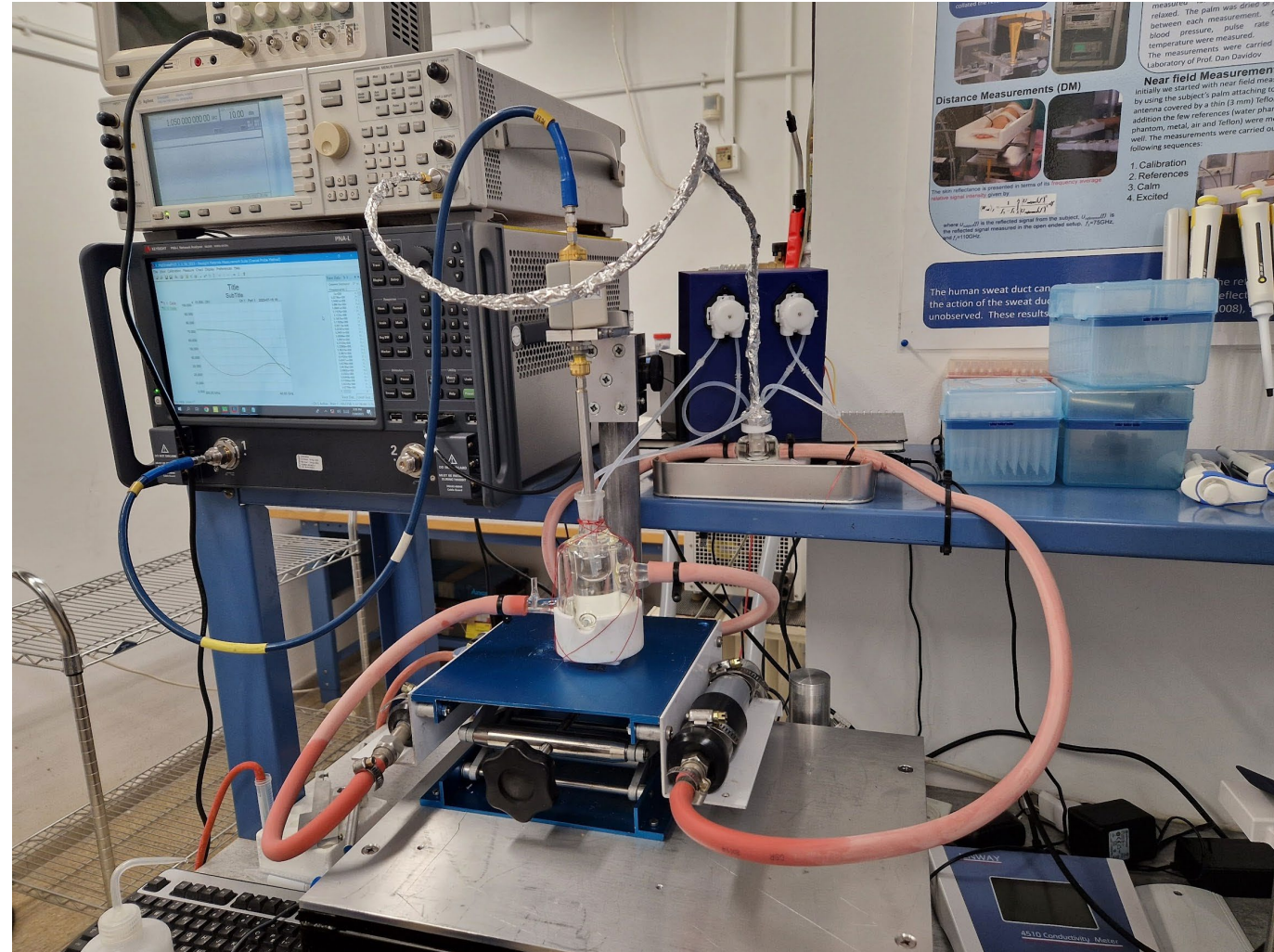
Hebrew University



Spectroscopy Measurement

Setup

- EMF frequency: 0.7-5 GHz
- EMF power: 10 dBm
- Plate electrodes
- Exposure time: 20 minutes
- Sample RBC volume: 5 ml
- Waveform:
pulse of 4.0 μsec , 50% duty cycle



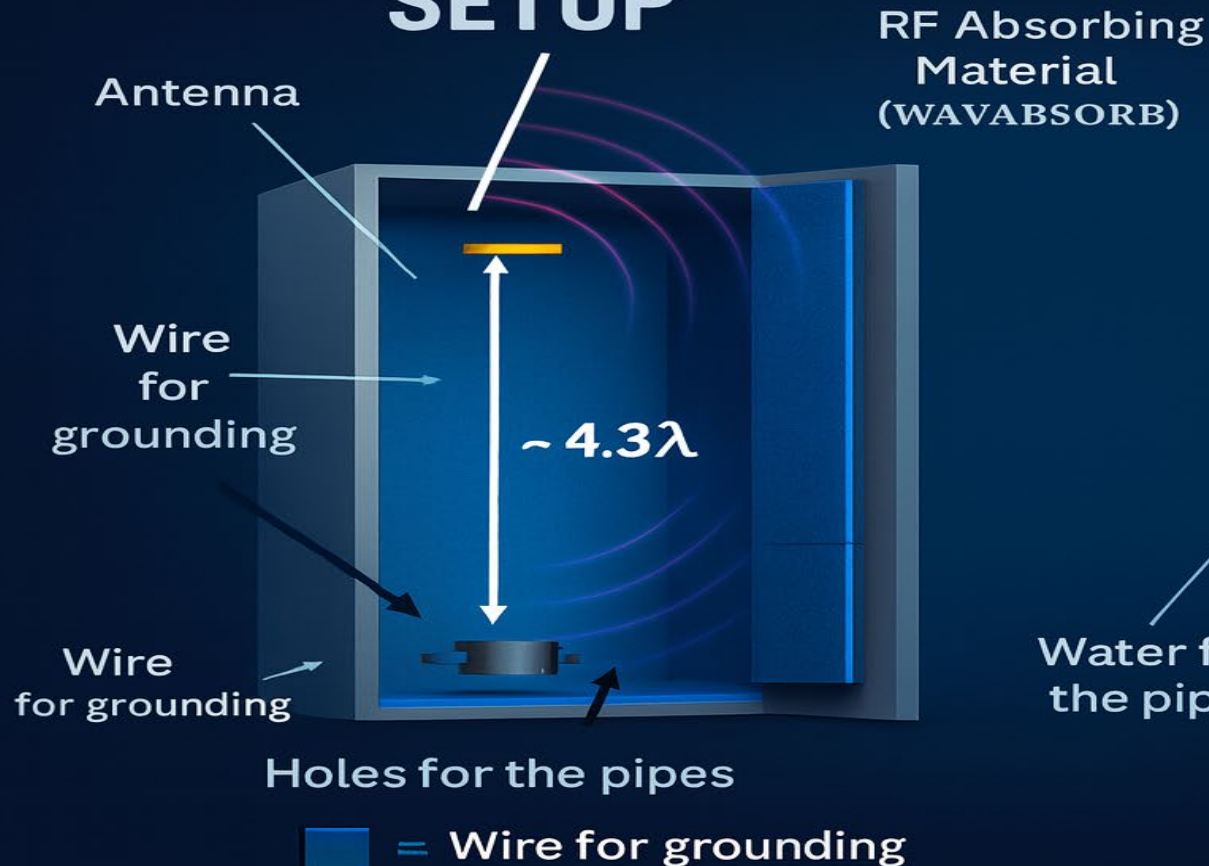
Far-Field EMF Exposure System



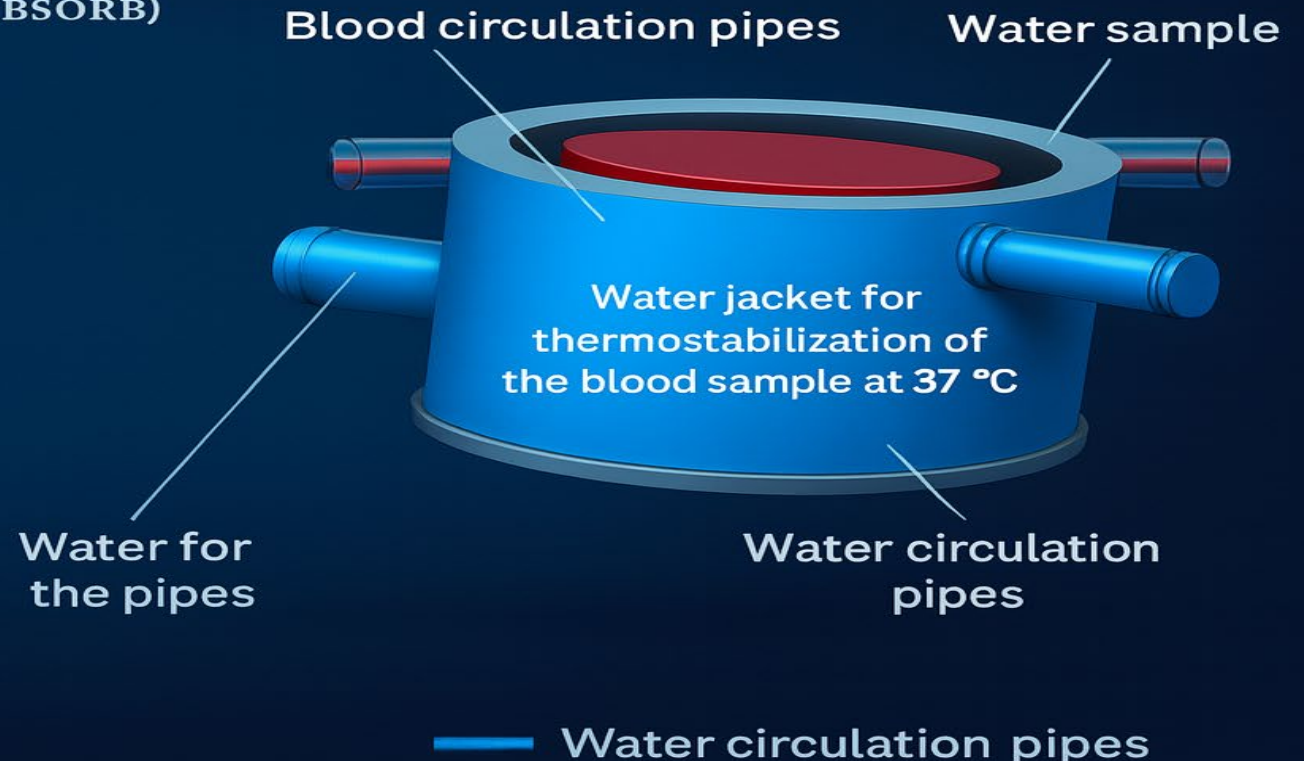
Far-Field EMF Exposure System -Design



EMF EXPOSURE SETUP



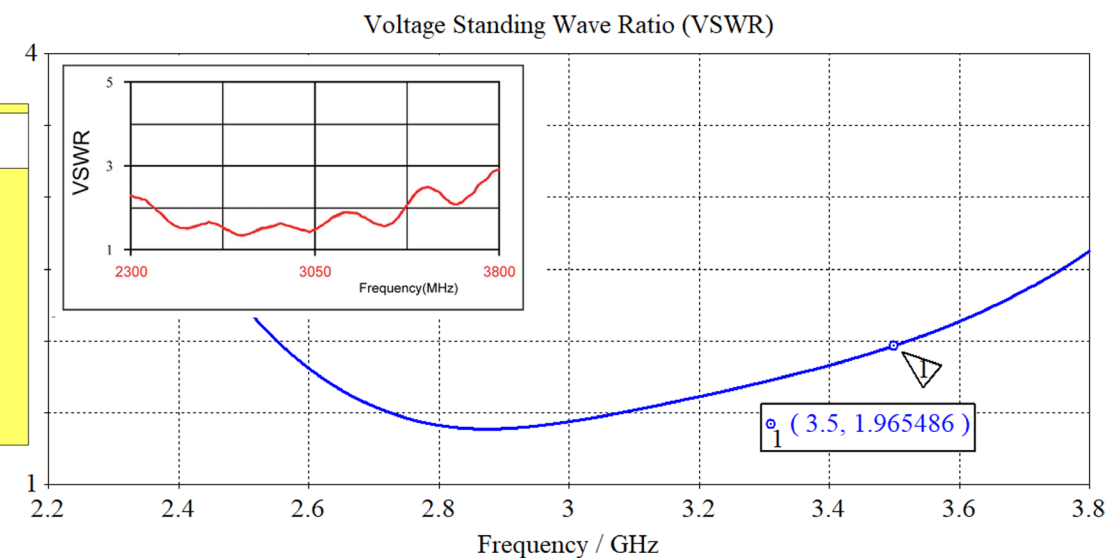
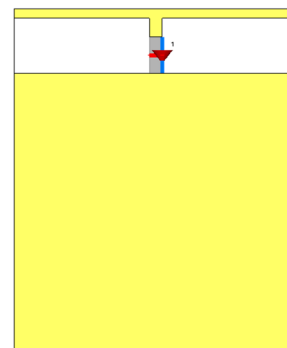
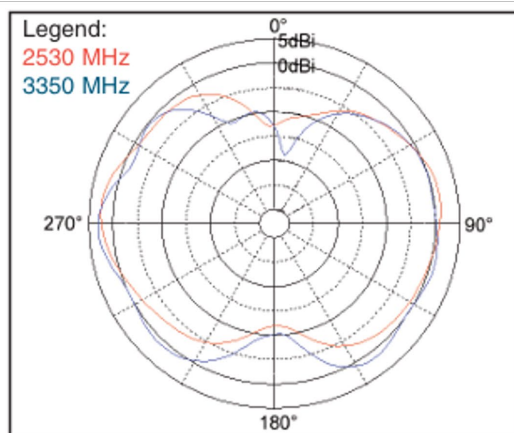
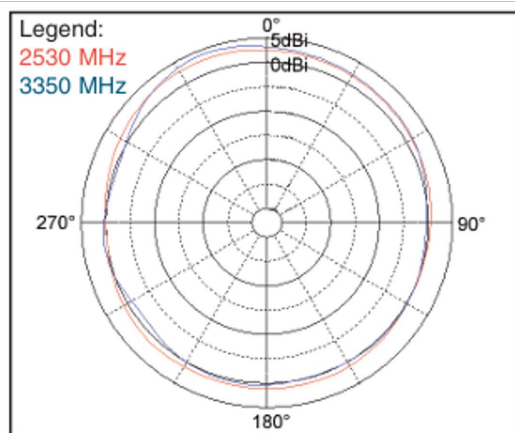
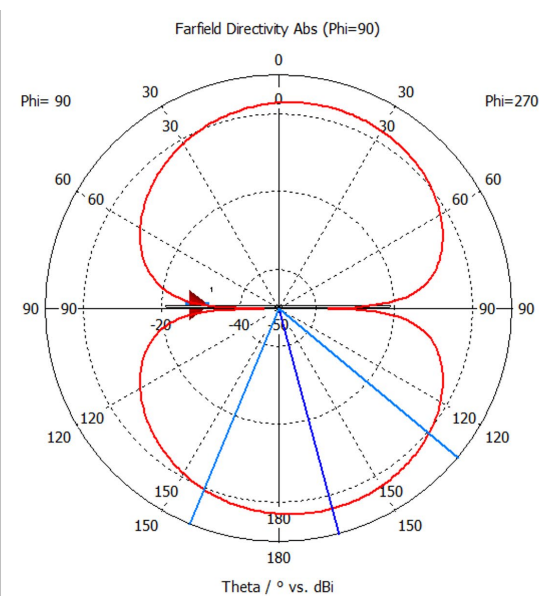
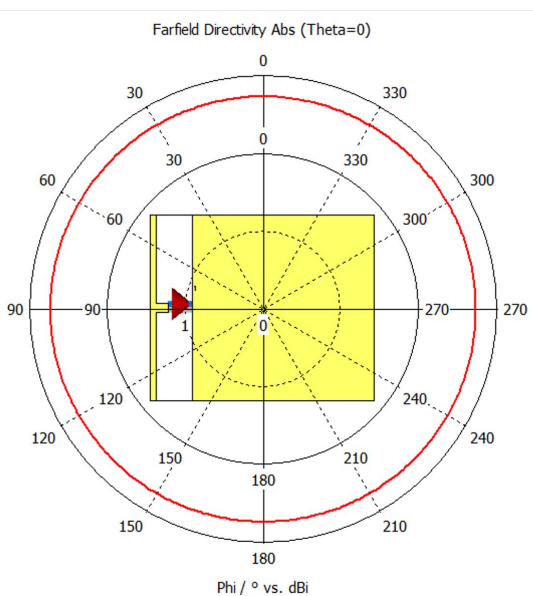
WATER-JACKETED CUVETTE



Far-Field EMF Exposure System -Design

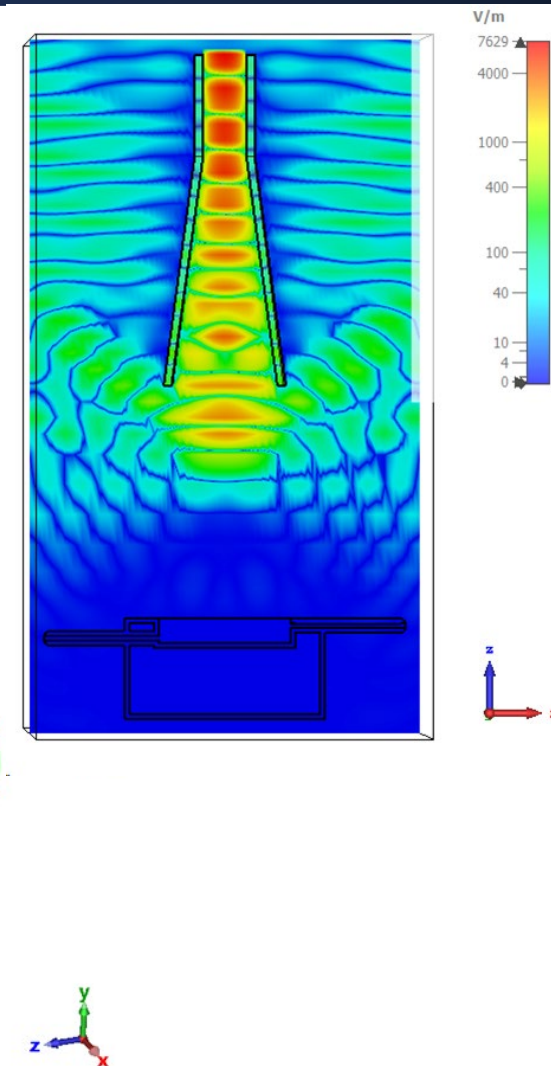
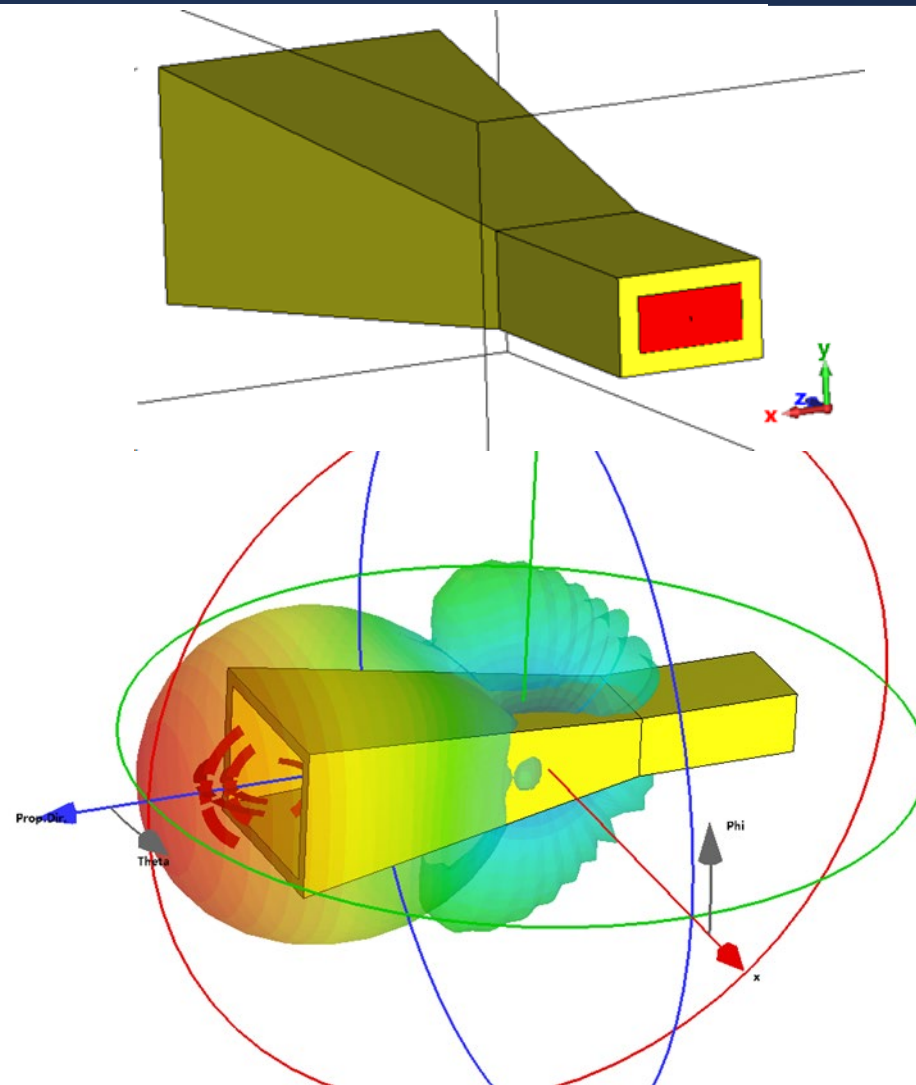
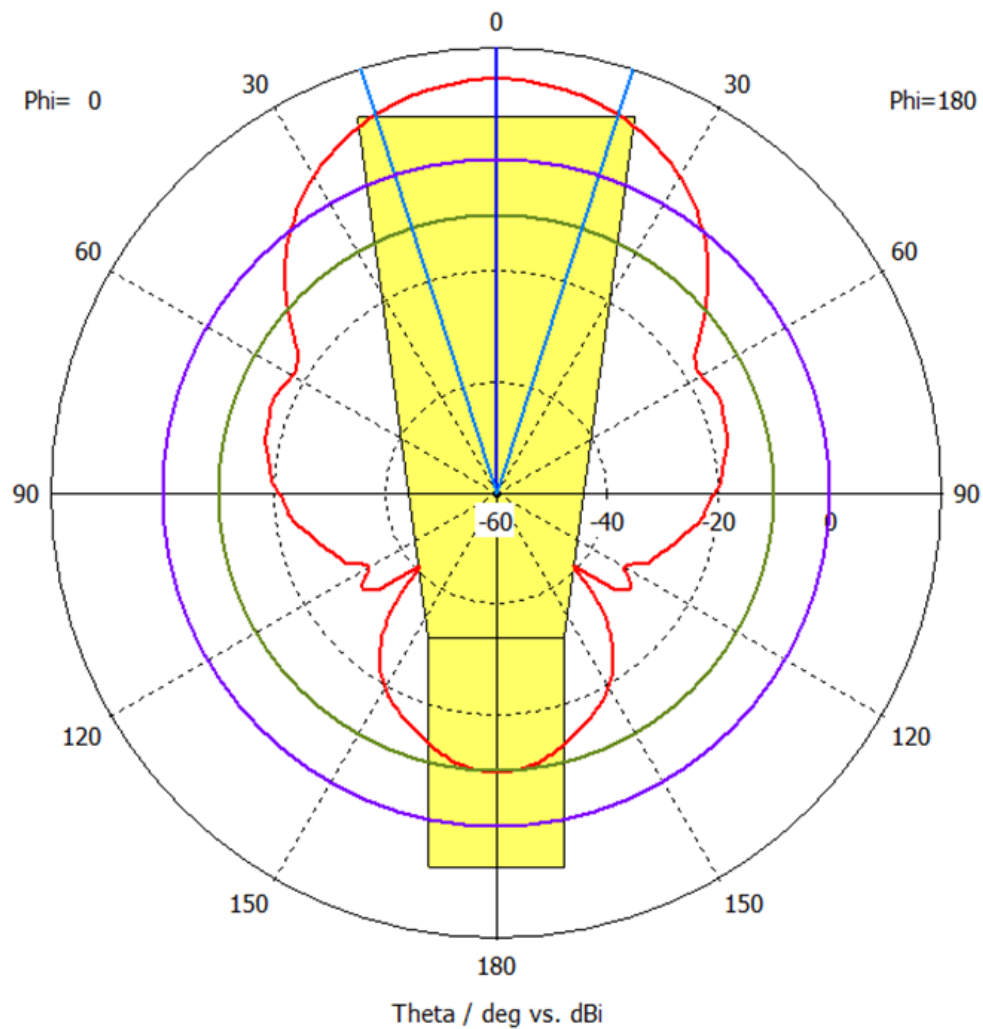


Antenna-Design



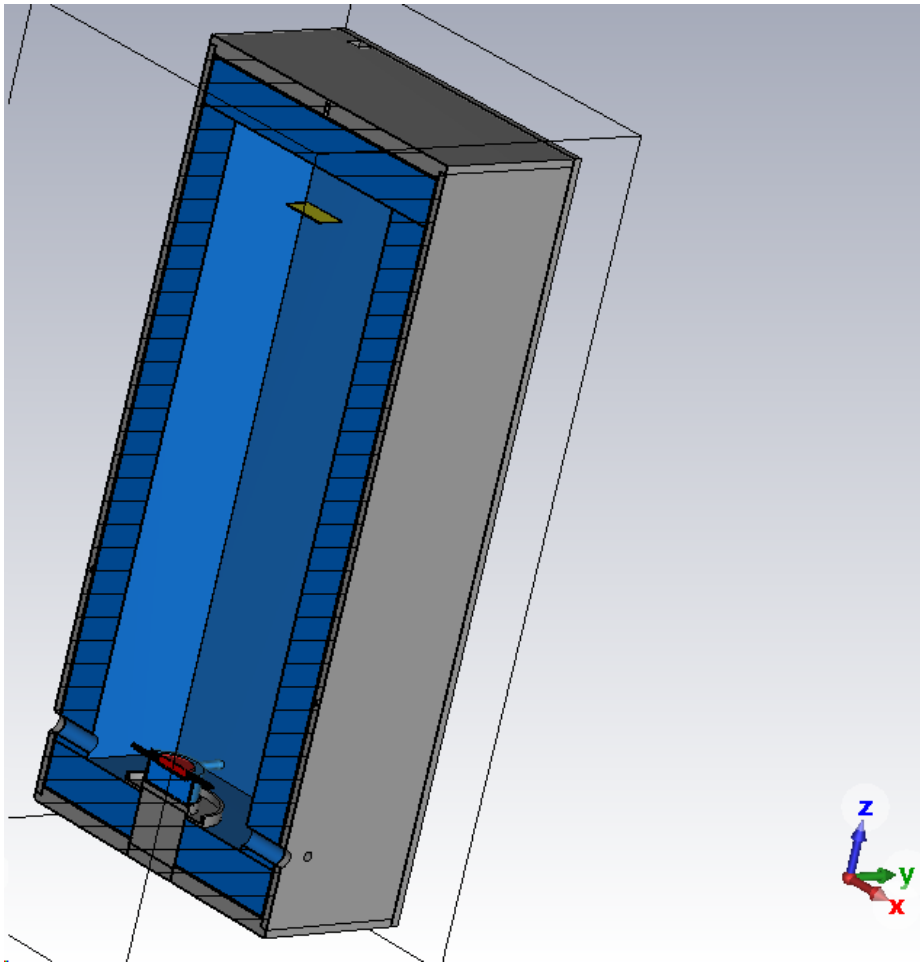
Antenna-Design

Farfield Directivity Abs (Phi=0)

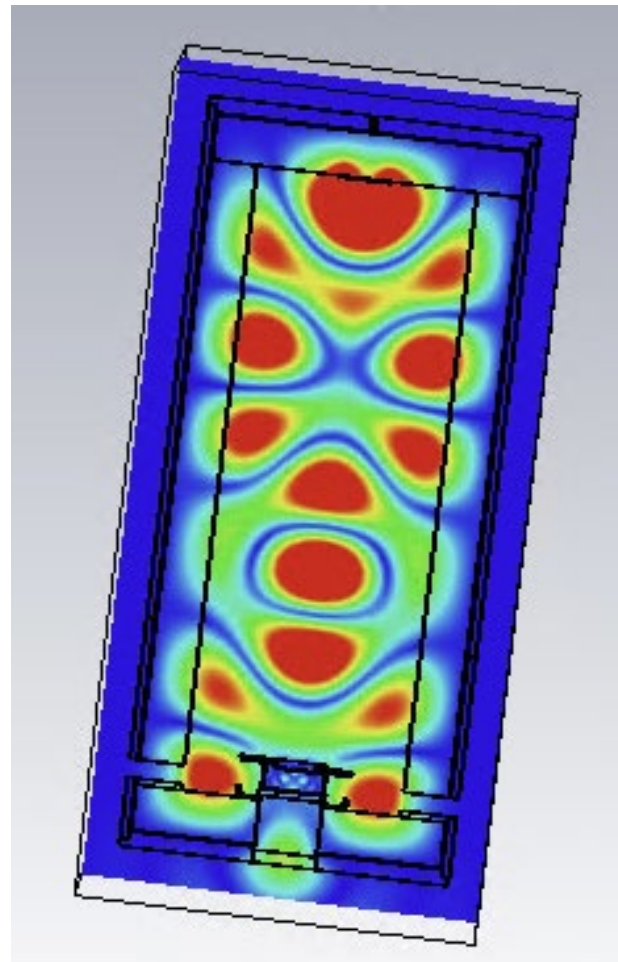


Chamber CST - Model

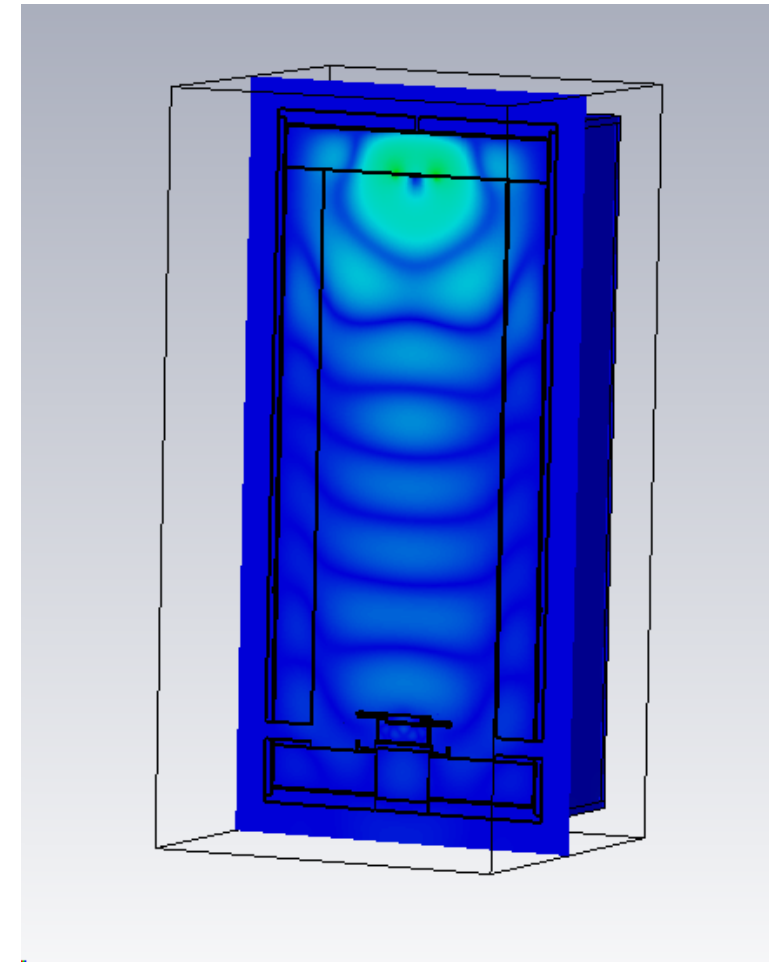
Chamber with absorption material



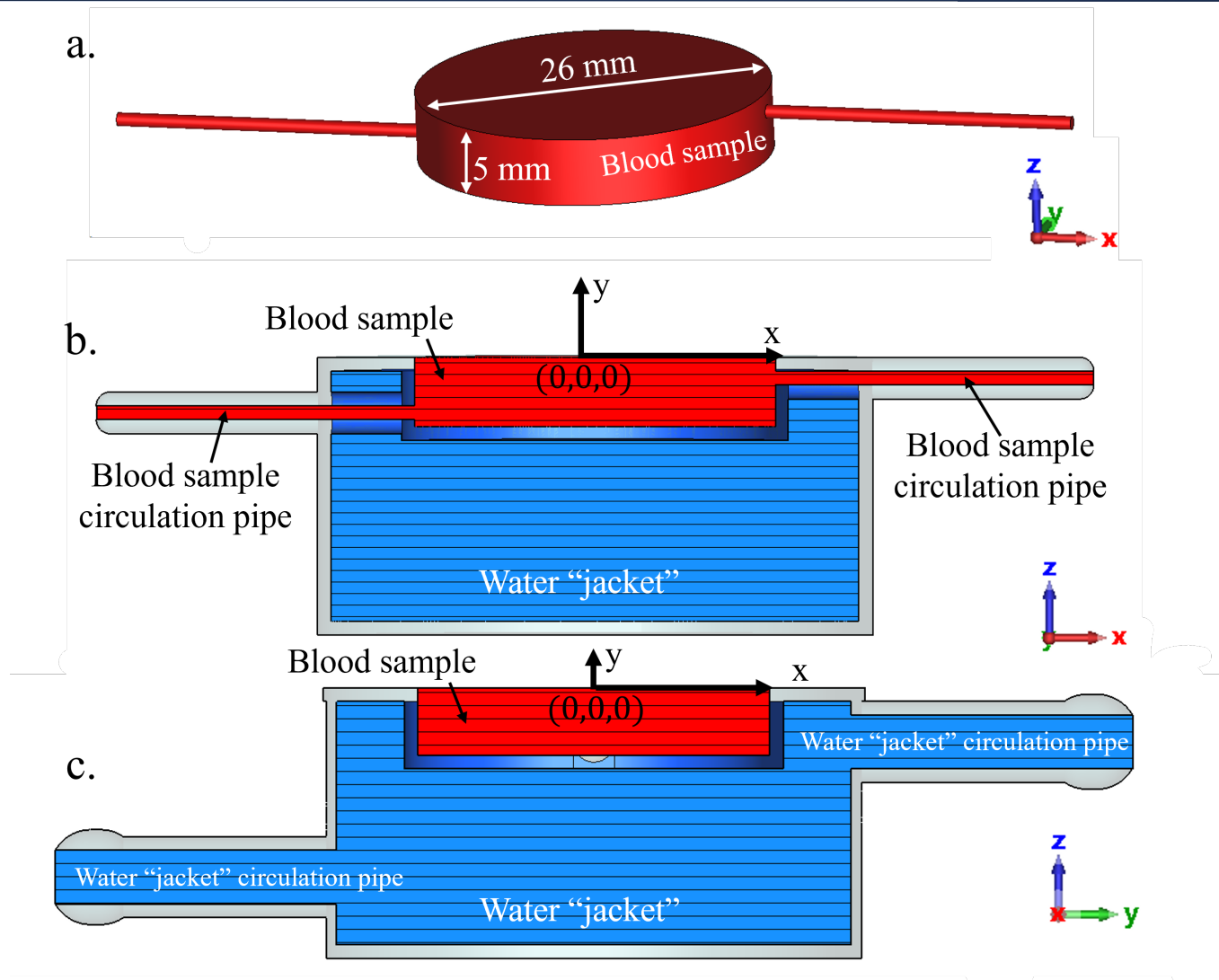
E-field free-space



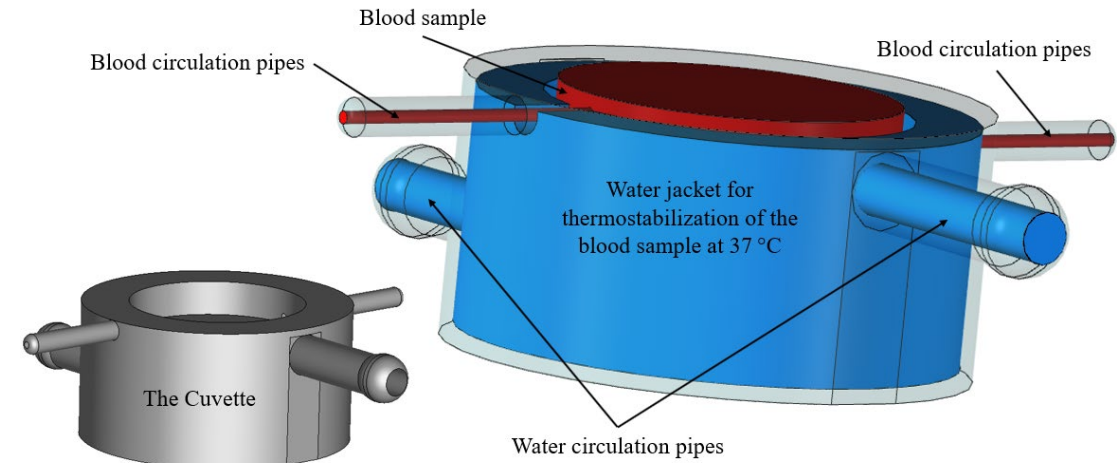
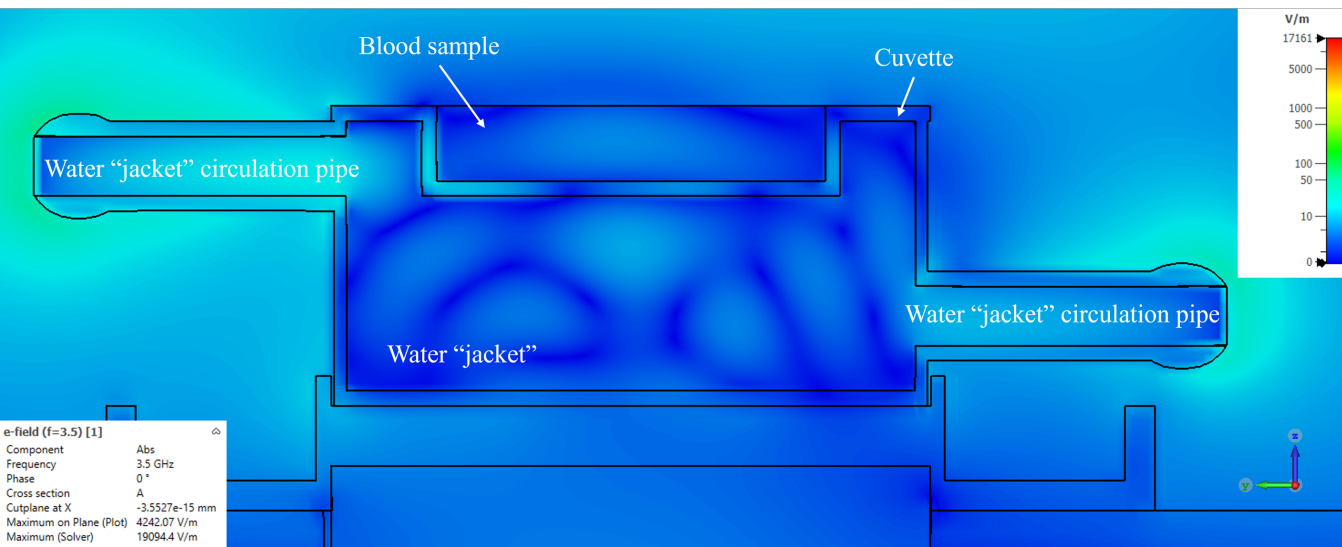
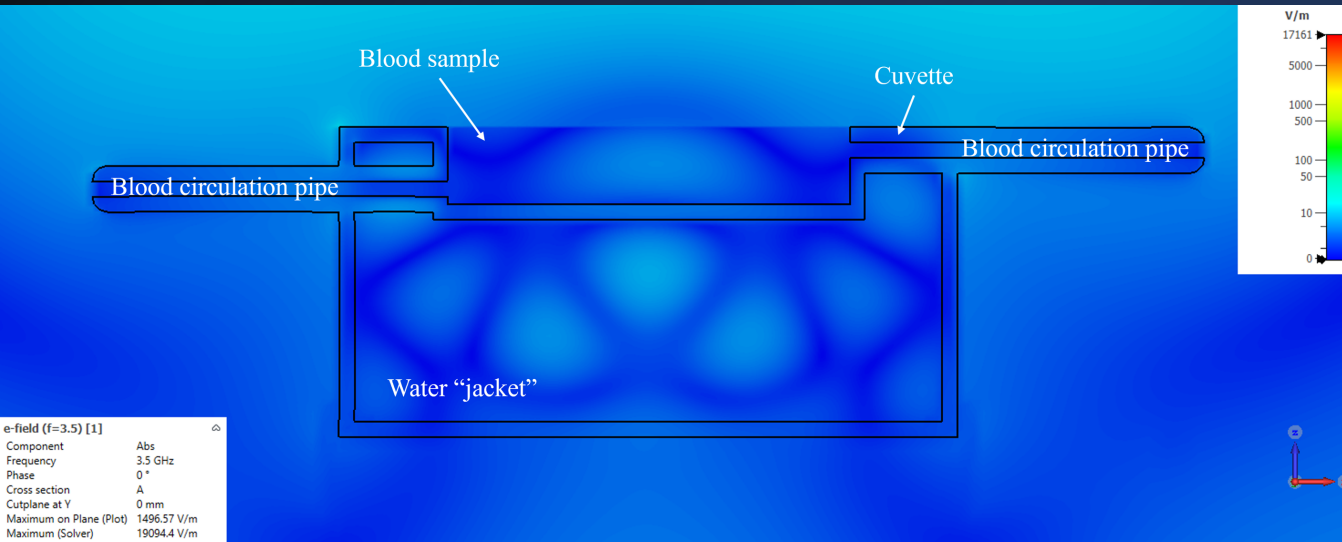
E-field with absorption material



Cuvette Design

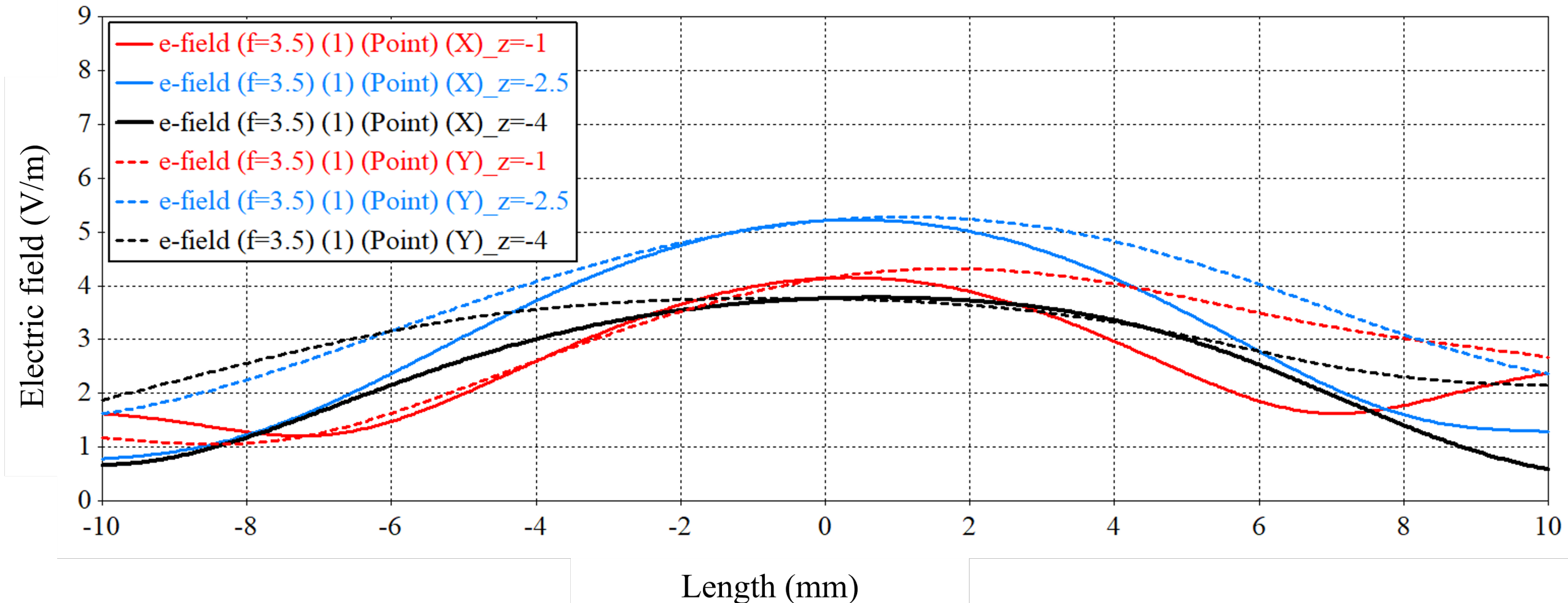


Cuvette Design



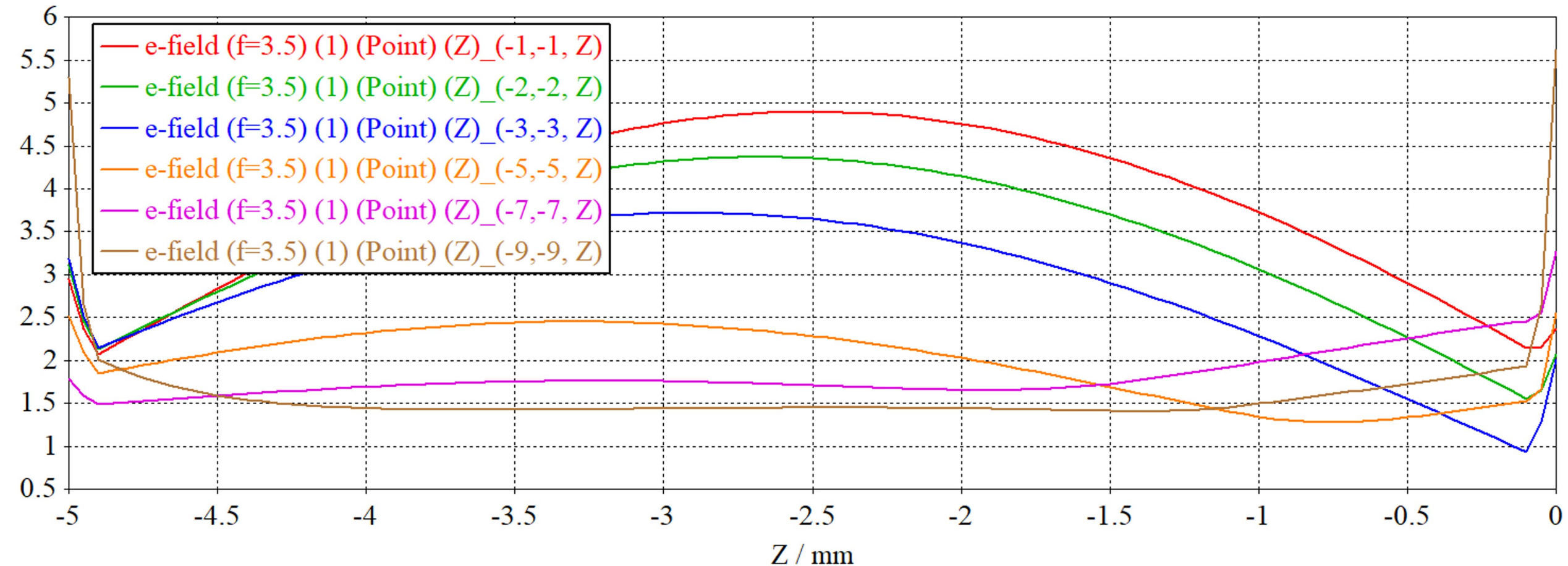
E-field Distribution in Cuvette

Electric field along X and Y directions at different depth of the cuvette

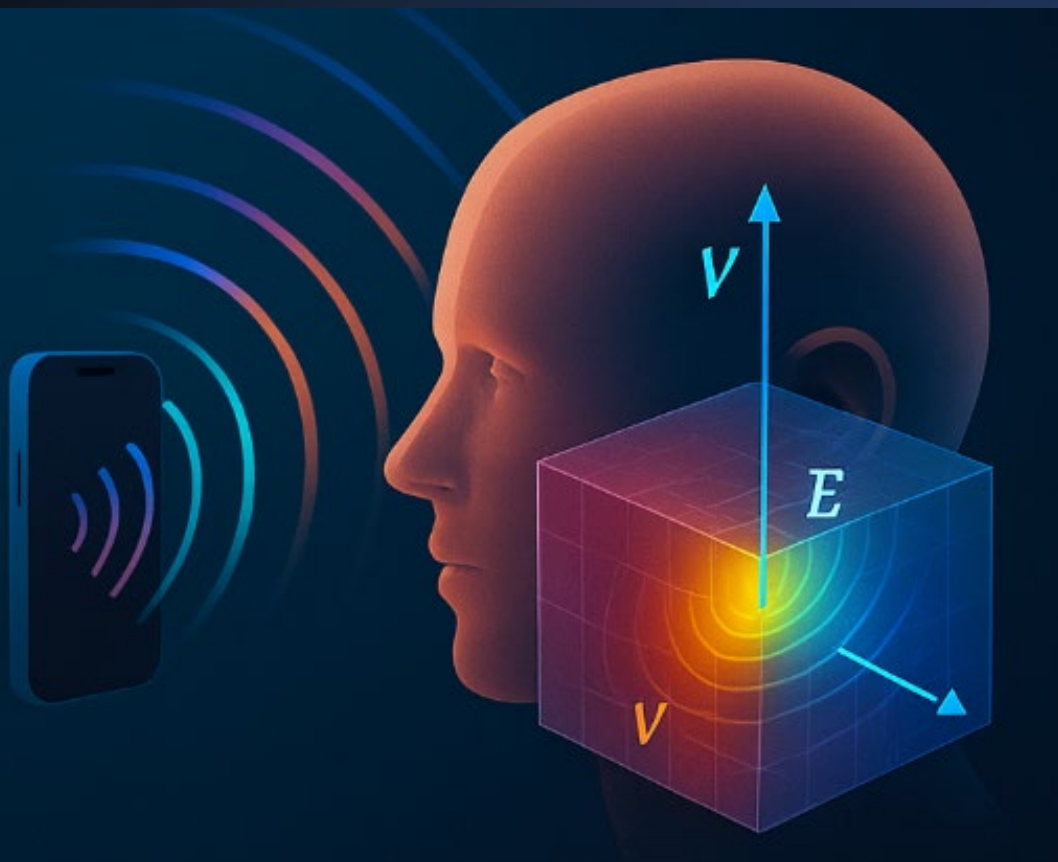


E-field Distribution in Cuvette

Electric field along Z direction at different (X,Y)



Specific Absorption Rate (SAR)



SAR- EMF energy absorption rate in tissue [W/kg]

$$\text{SAR} = \frac{1}{V} \int_{\text{sample}} \frac{\sigma(\mathbf{r}) |\mathbf{E}(\mathbf{r})|^2}{\rho(\mathbf{r})} d\mathbf{r}$$

σ : electric conductivity

$\mathbf{E}$: electric field

ρ : tissue density

V : sample volume



US (FCC)

SAR < 1,6 W/kg over 1g tissue



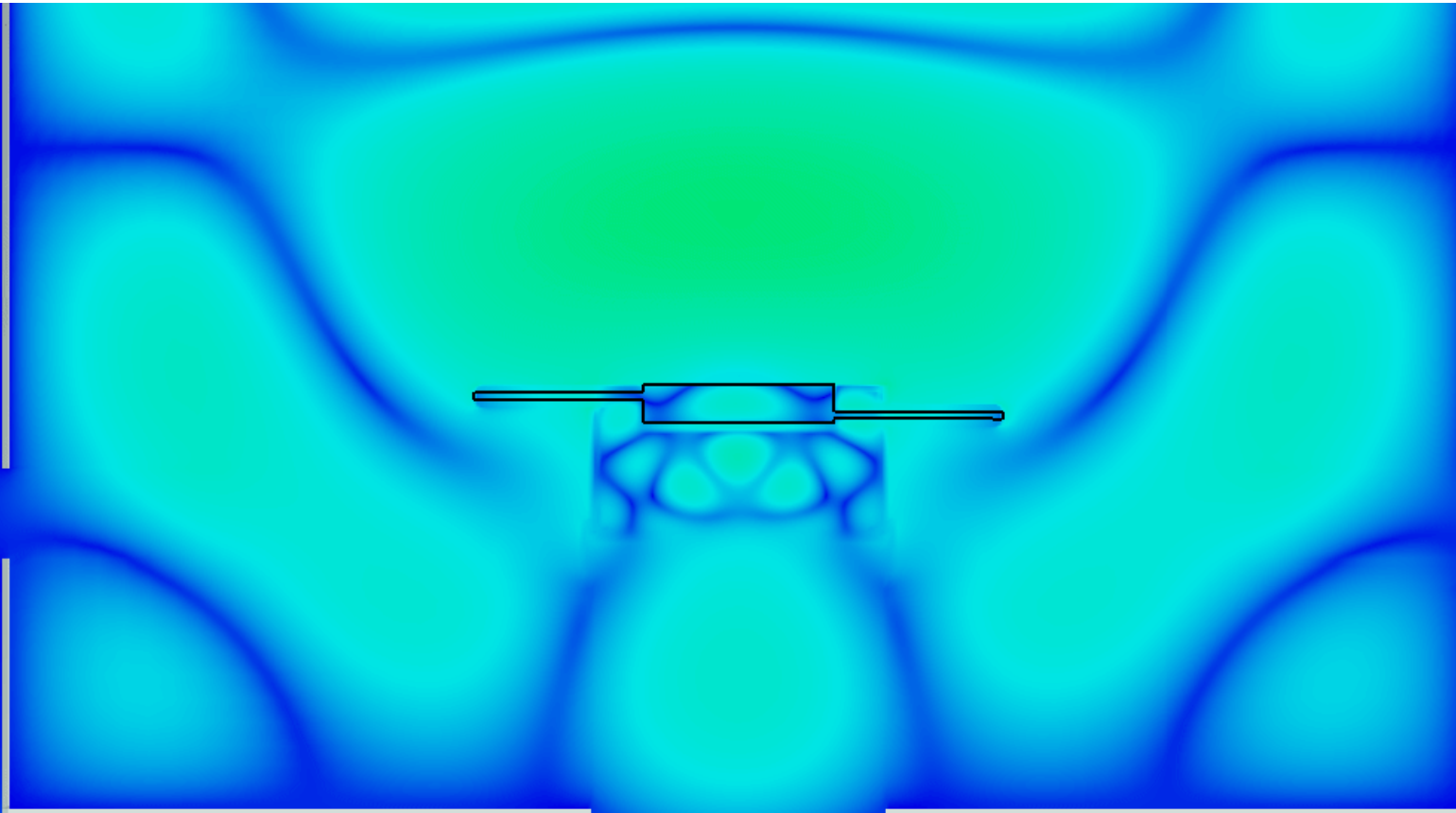
EU (CENELEC)

SAR < 2 W/kg over 10 g tissue

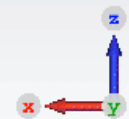
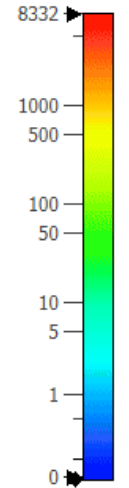
Far-Field EMF Exposure Cell CST Simulation: SAR



Created using
SIMULIA CST Studio Suite®



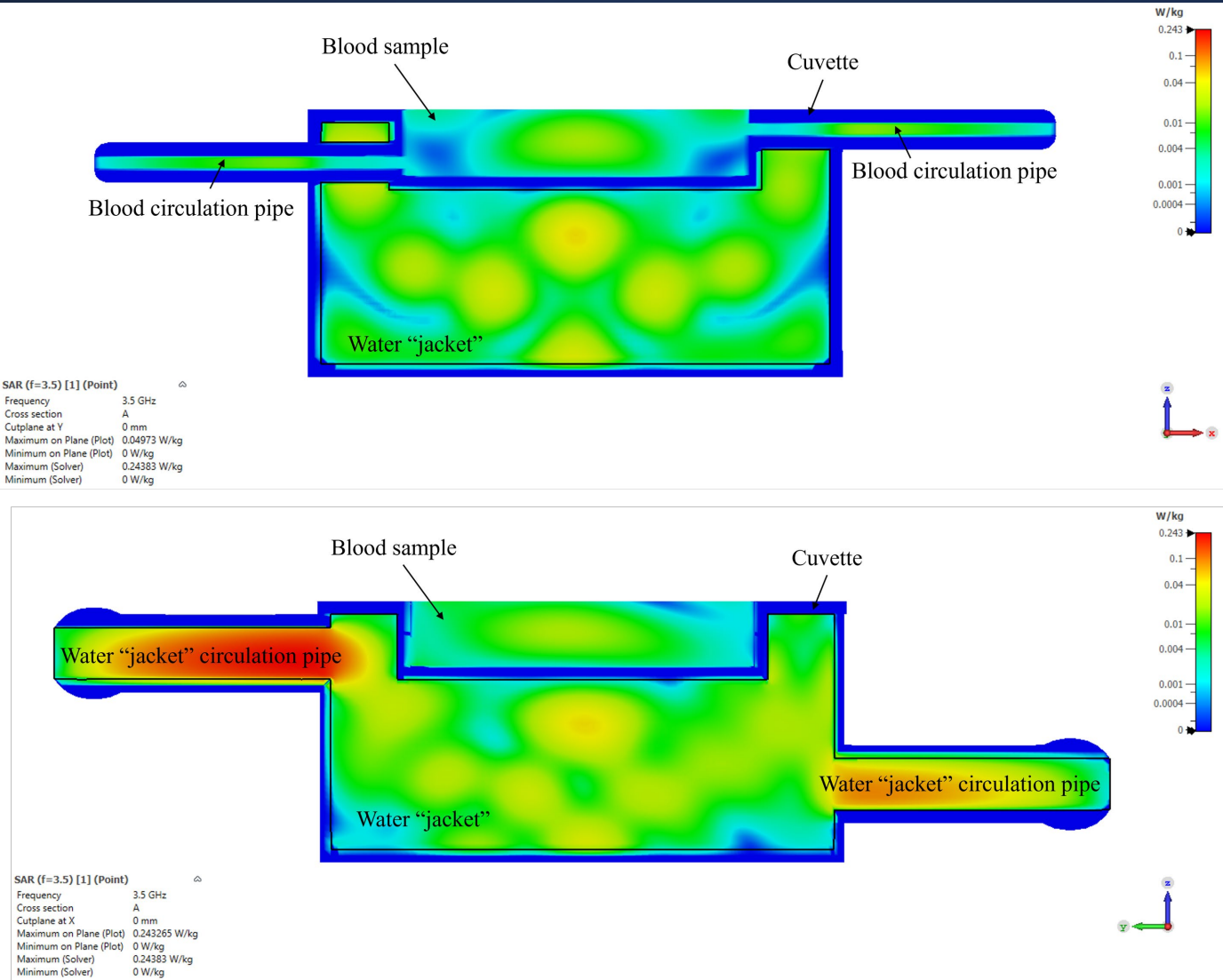
V/m



e-field (f=3.5) [1]

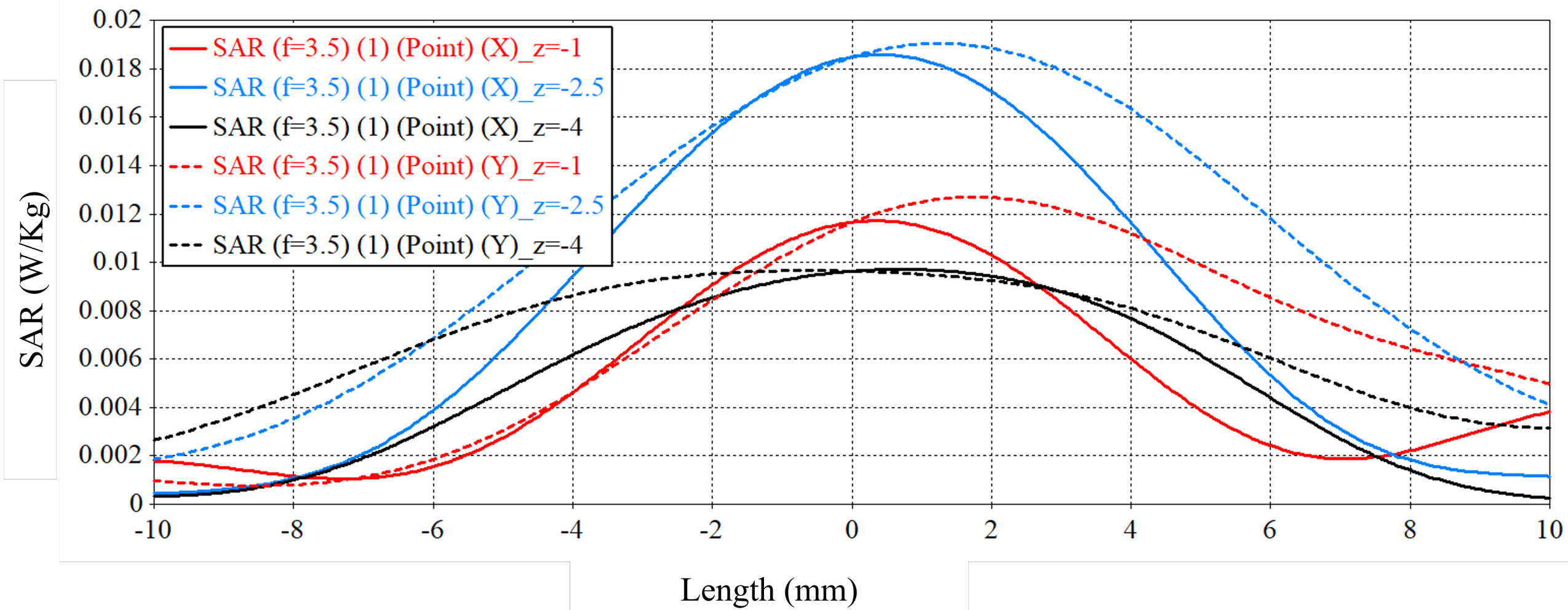
Component	Abs
Frequency	3.5 GHz
Phase	1 °
Cross section	A
Cutplane at Y	0 mm
Maximum on Plane (Plot)	766.917 V/m
Maximum (Solver)	9504.93 V/m

Specific Absorption Rate (SAR)



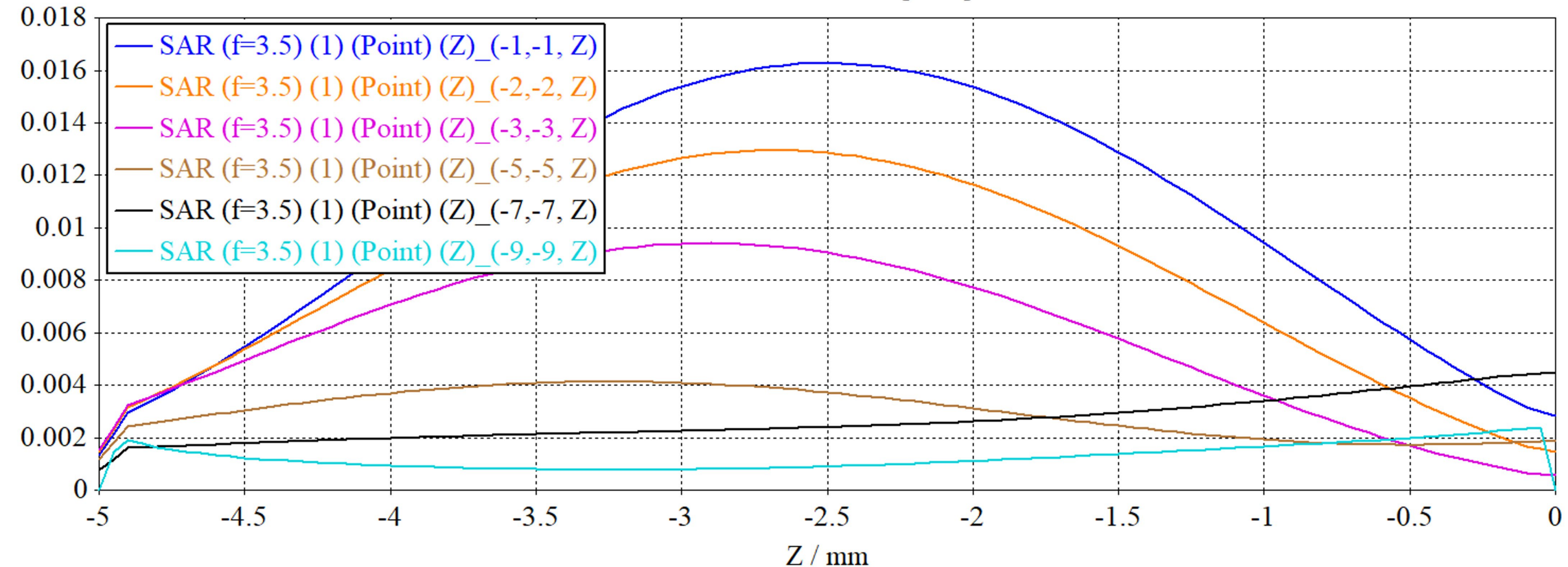
Specific Absorption Rate (SAR)

SAR along X and Y directions at different depths of the cuvette

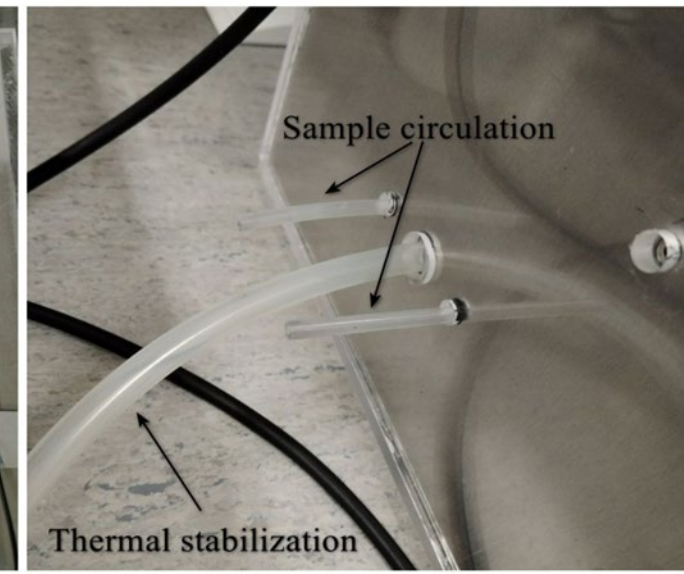
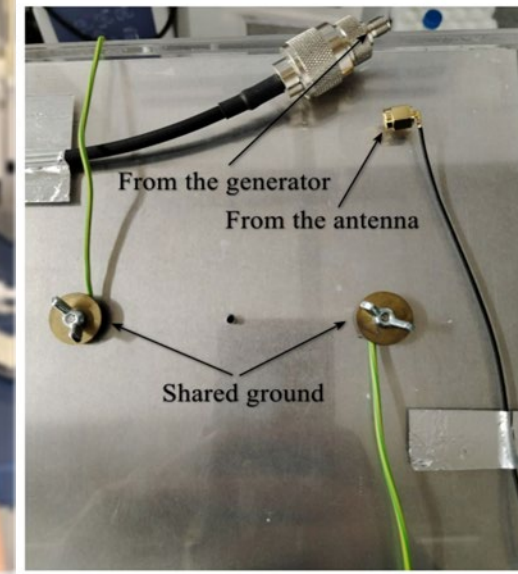
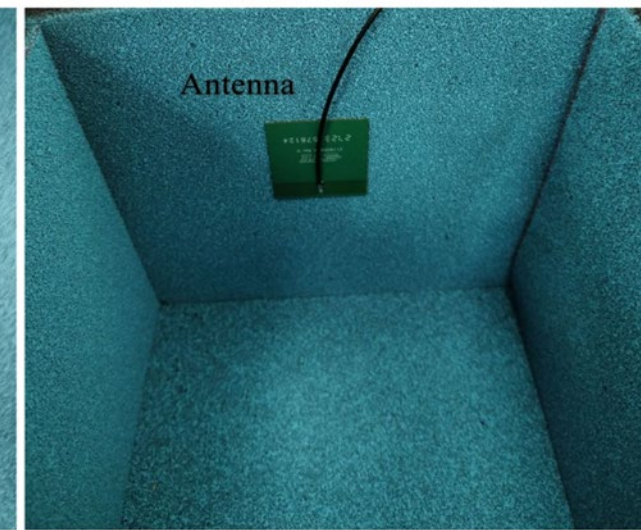
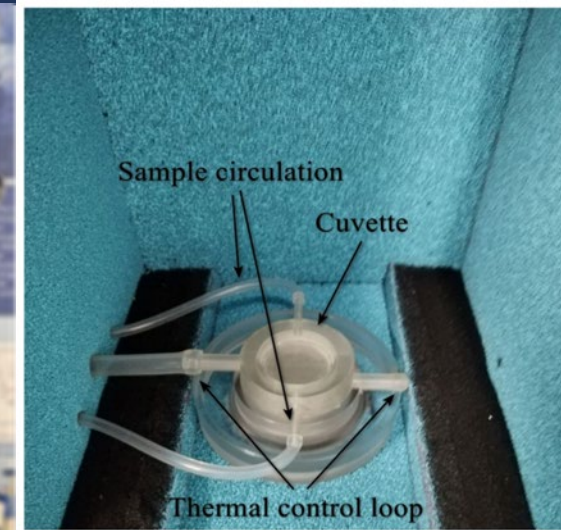
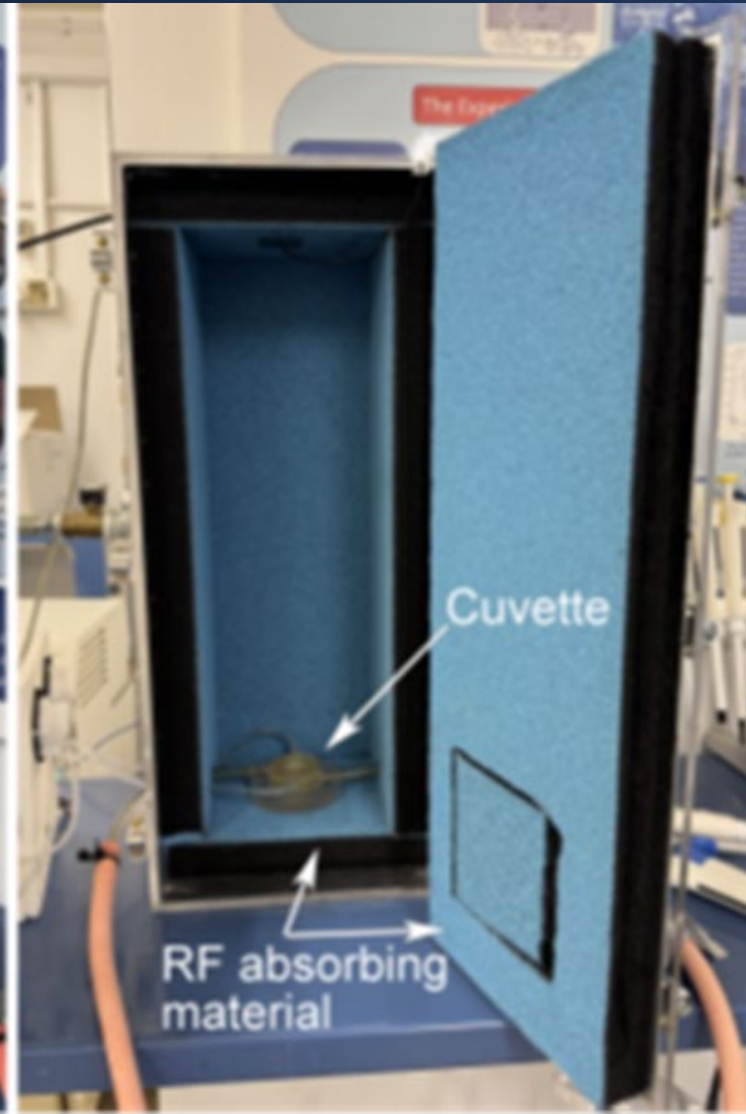
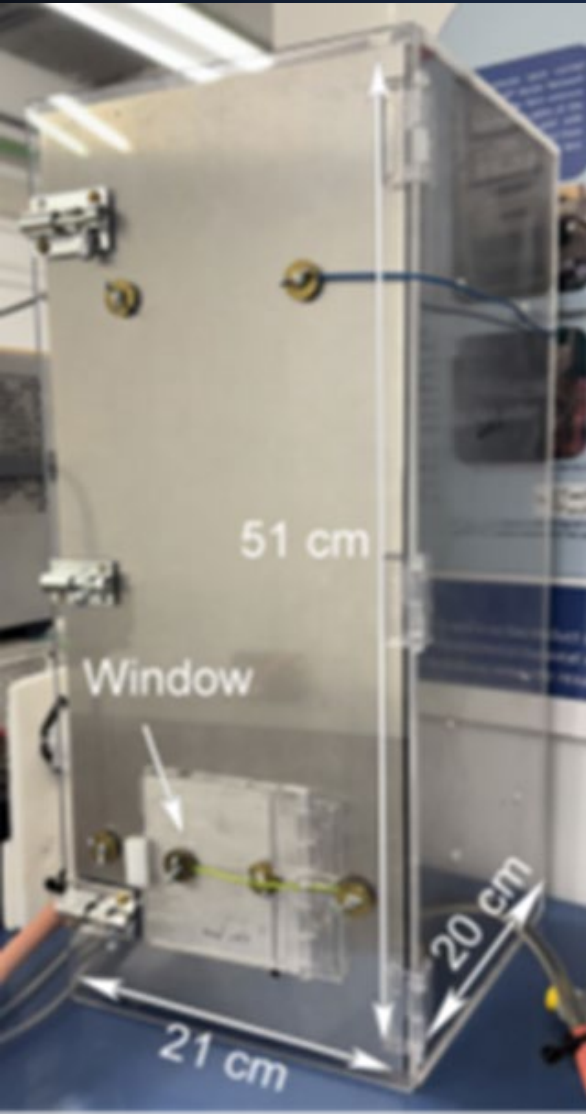


Specific Absorption Rate (SAR)

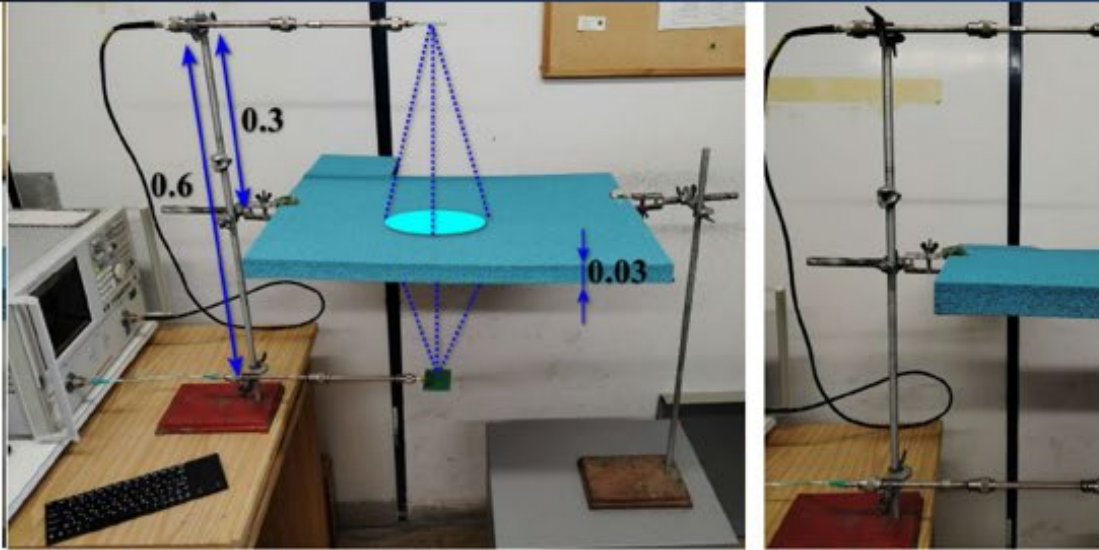
SAR along X and Y directions at different depths of the cuvette



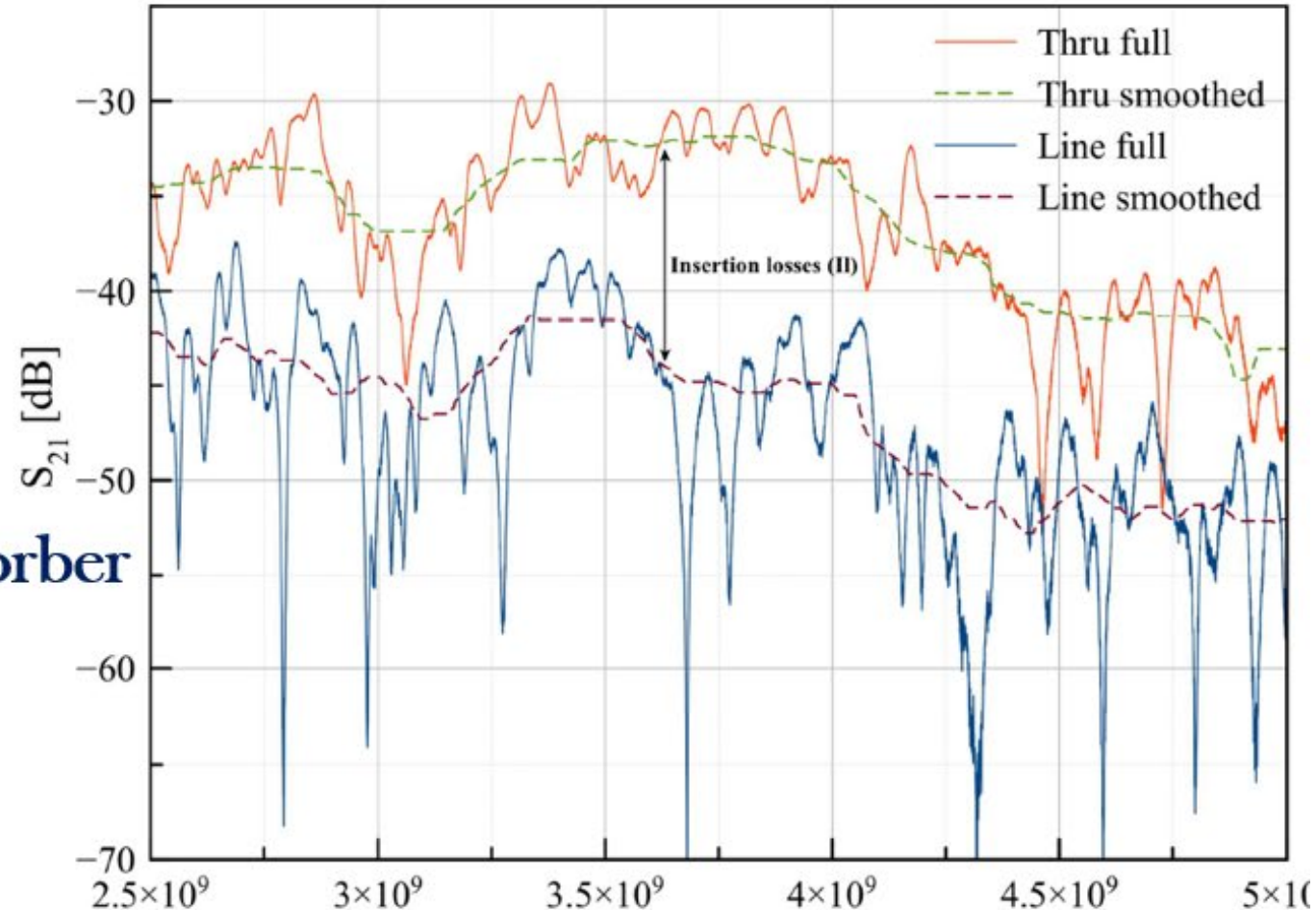
Far-Field EMF Exposure System-Implementation



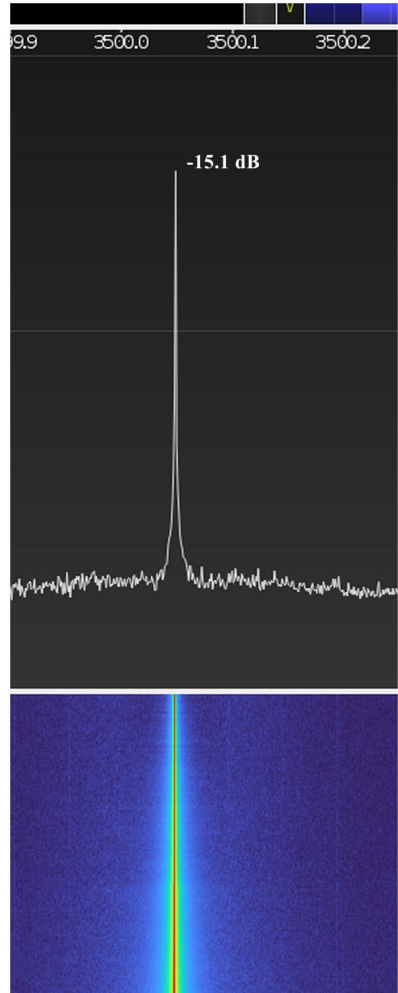
Absorption Material Characterization



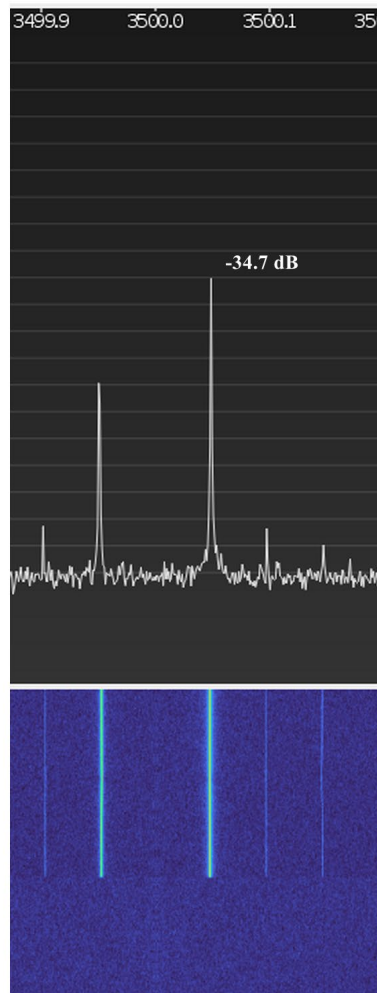
- Dielectric properties of a porous absorber
- Frequency range: 2.5–5 GHz
- Permittivity: 2.0
- Loss tangential: 0.5 dB
- Insertion loss: 9.5 dB



Far-Field EMF Exposure System Isolation

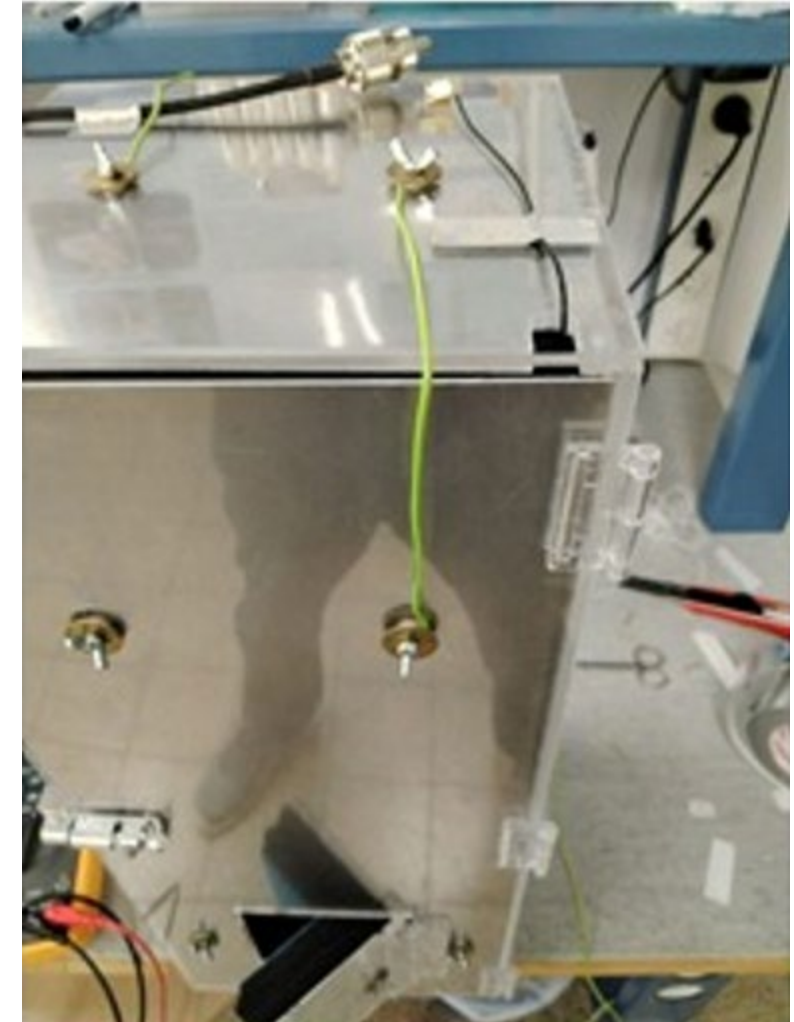


(b)

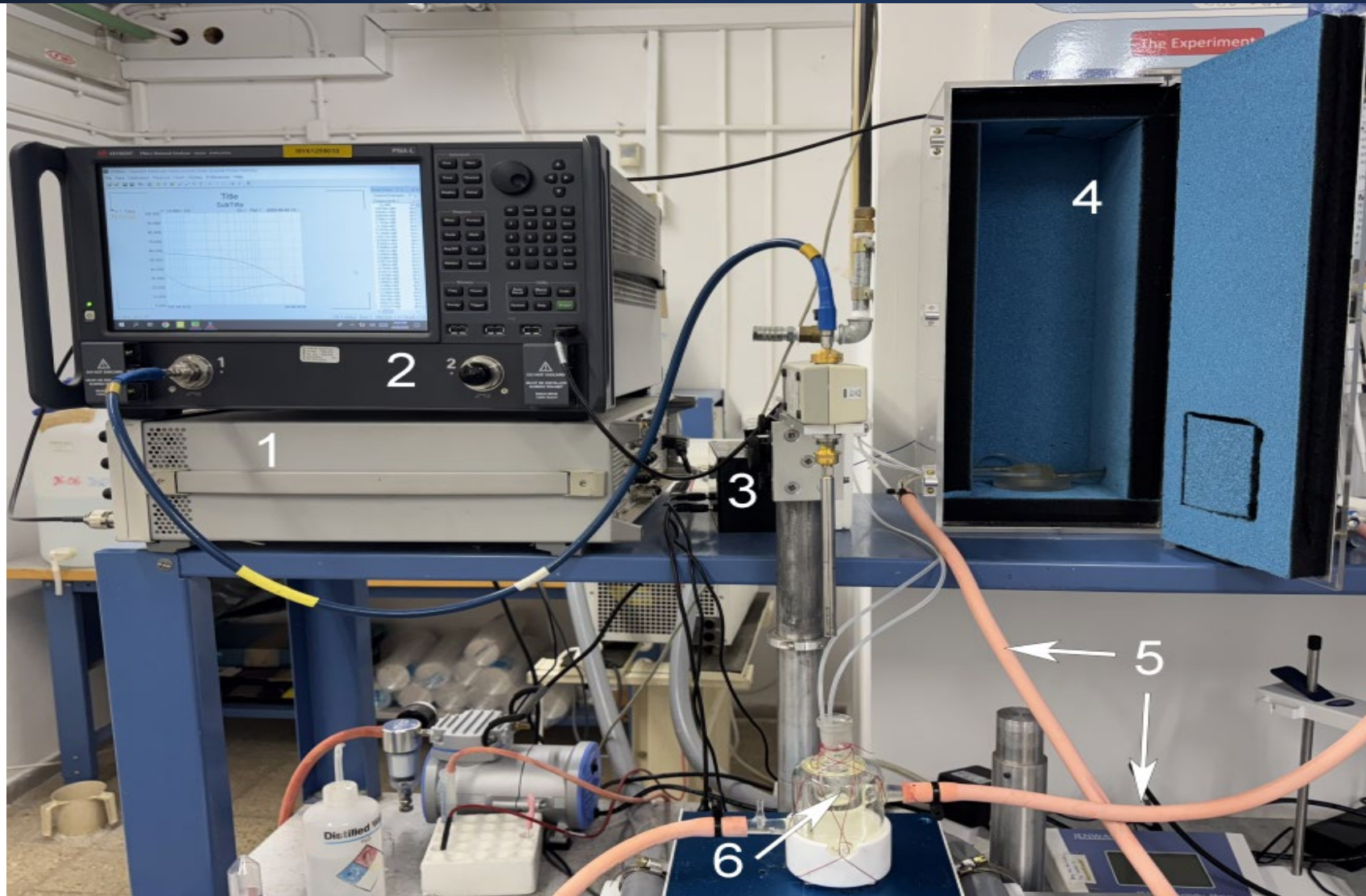


(a)

(a) Rx outside the chamber
(b) Rx inside the chamber



The AES logo (Association for the Development of Economic and Social Sciences) is on the left, and the AESS logo (Association for the Development of Economic and Social Sciences) is on the right.



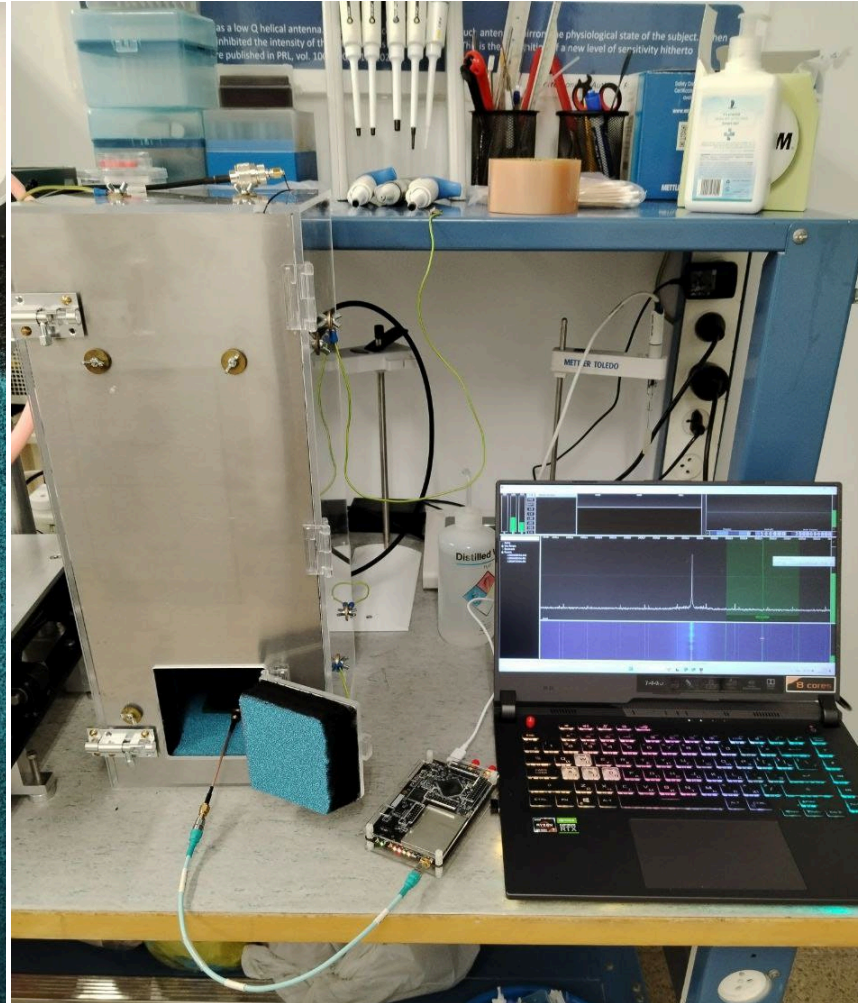
Far-Field EMF Exposure System Components



Chamber



Exposure System

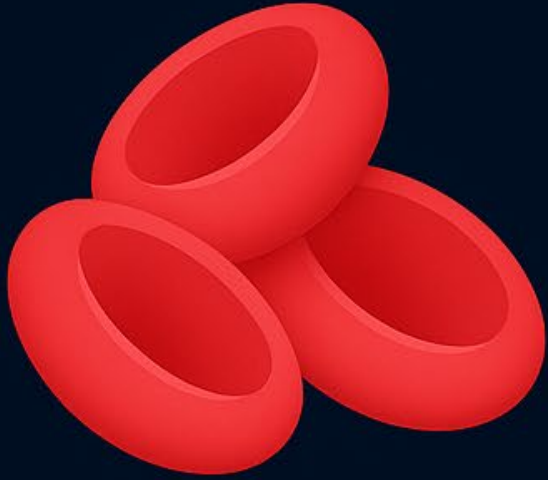


Cuvette

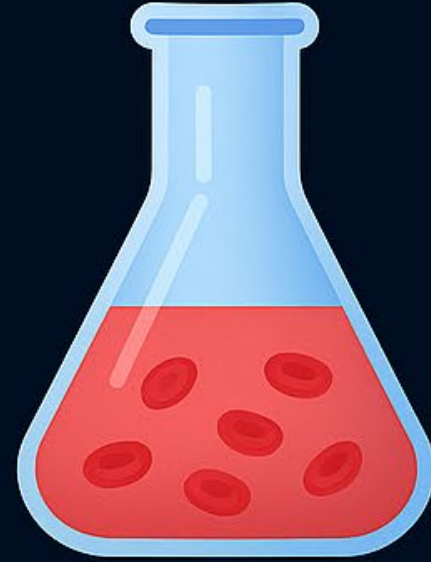


Experiments

Cell-Level Experiments

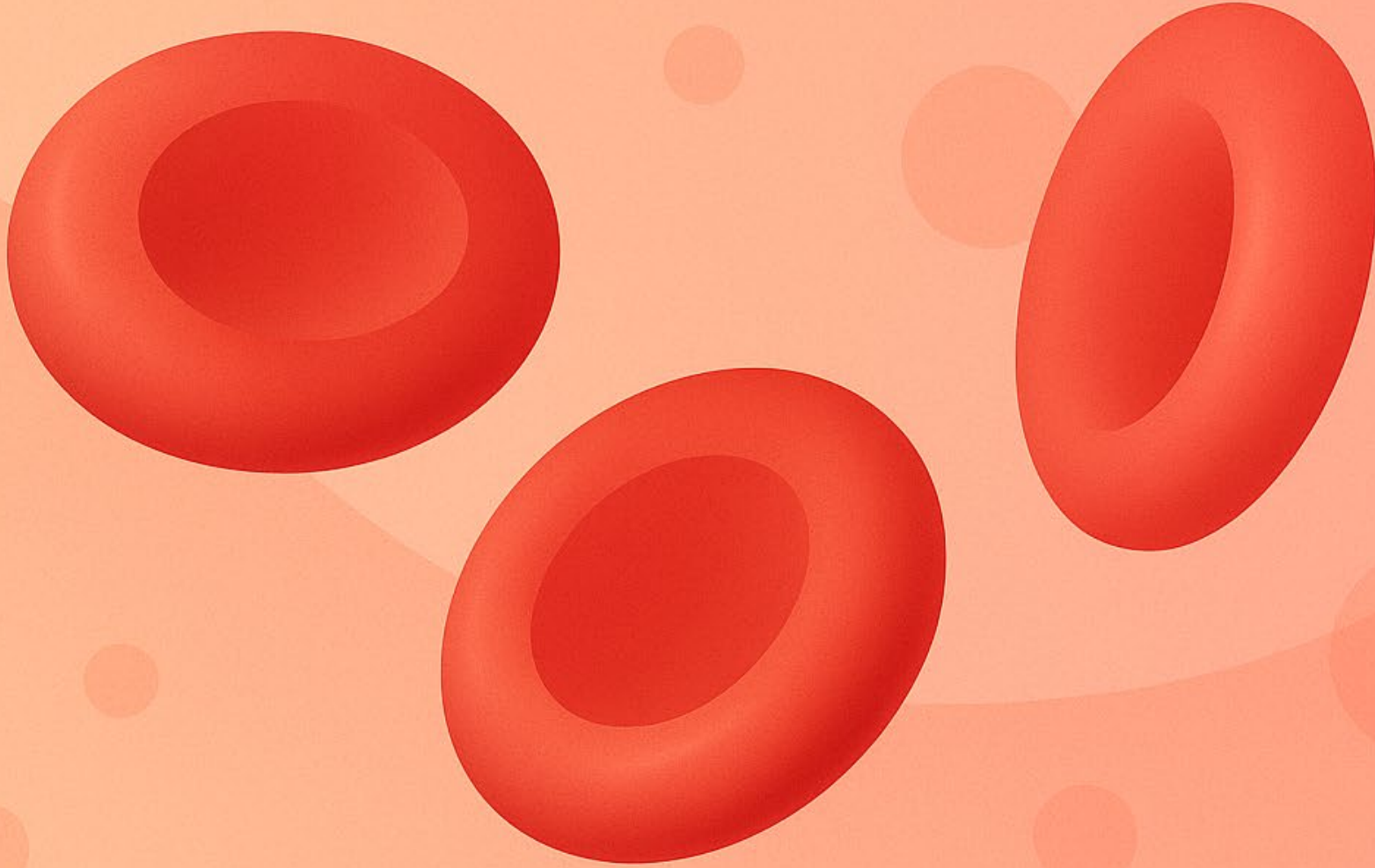


RBCs



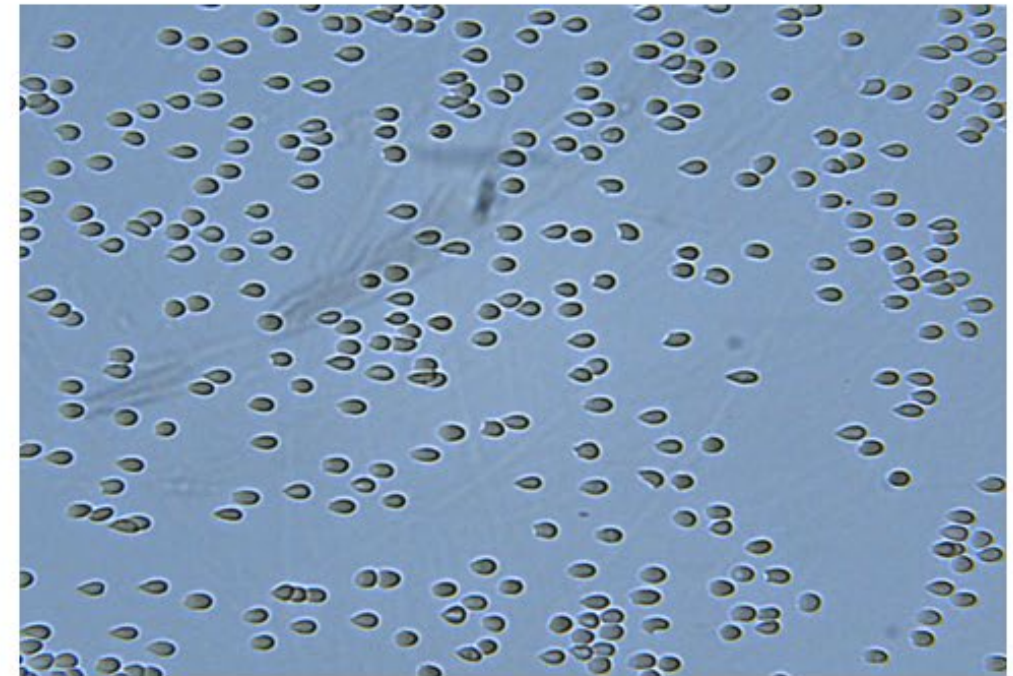
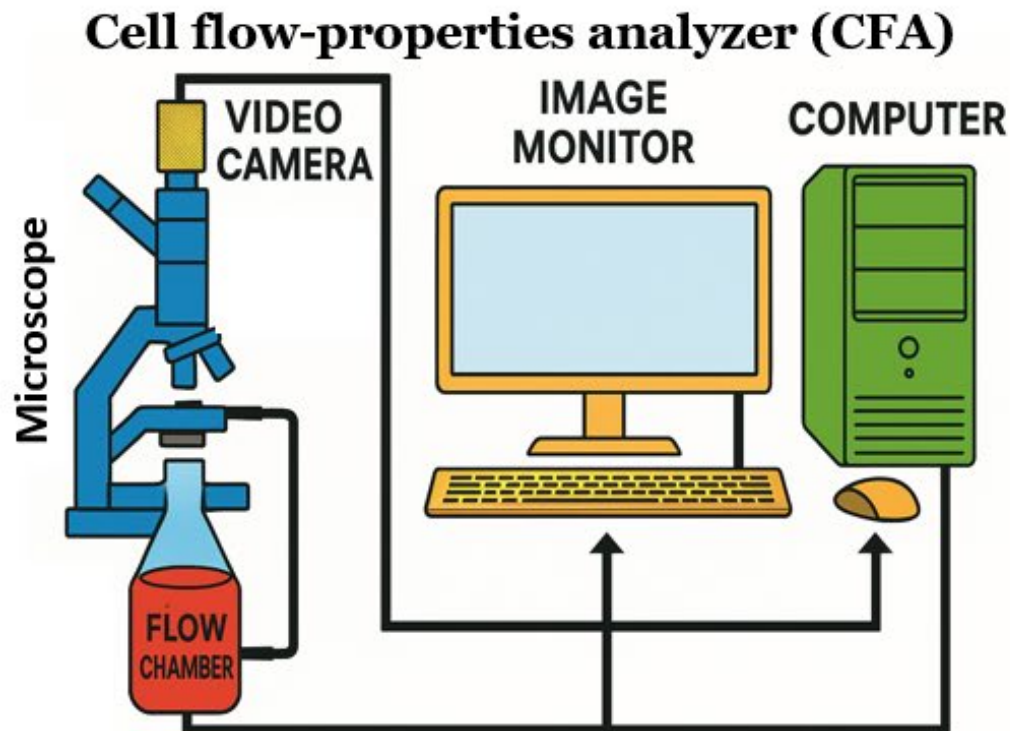
Sedimentation

RBC Deformability



RBC Deformability

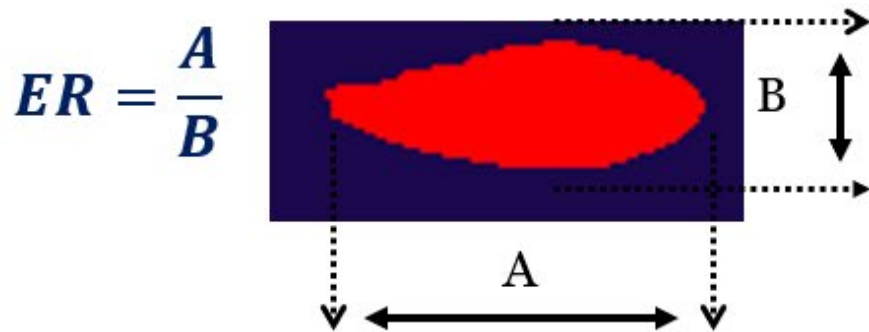
- RBC deformability investigated by computerized cell flow-properties analyzer (CFA).
- Visualization of the change in the RBC shape in a narrow-gap flow chamber under flow-induced shear stress (mimicking the conditions in micro-vessels).



RBC field in the CFA flow-chamber under a flow-induced shear stress

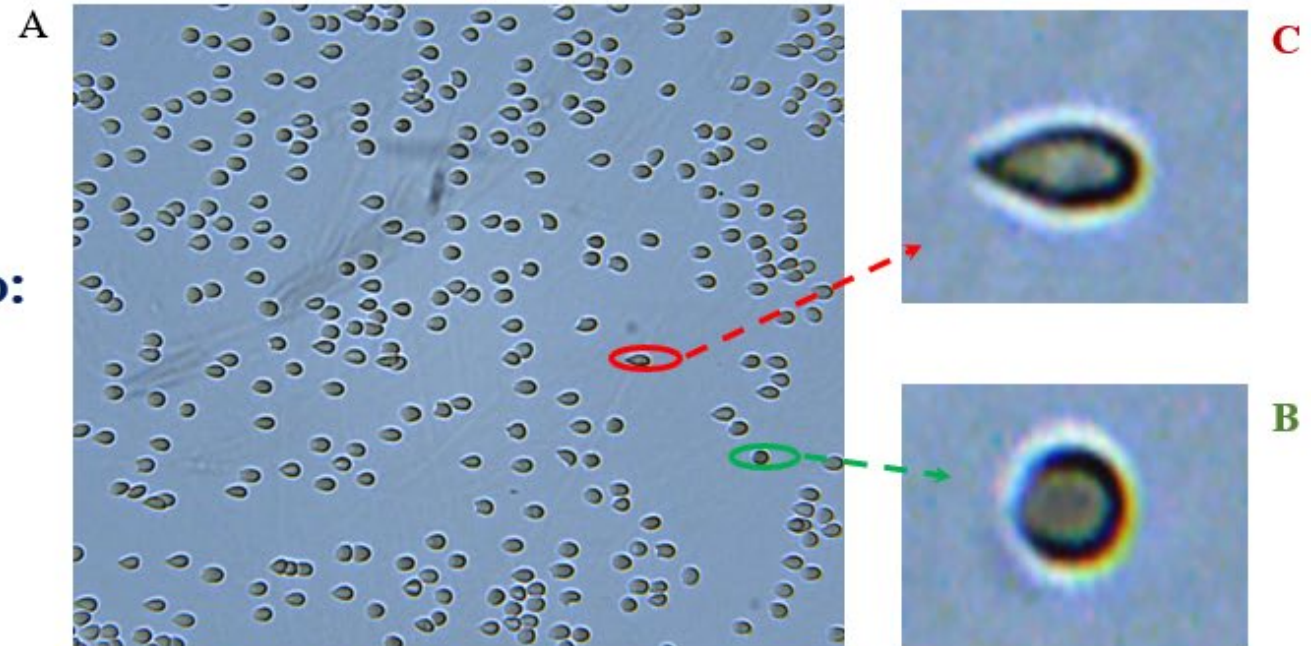
Experiment RBC Deformability Setup

- 0.5% Bovine serum albumin (BSA)
- Pumped into flow chamber
- The flow-induced shear stress of 3 Pa
- Deformability measure: elongation ratio:



- Average ER (AER)
- Median ER (MER)

Derived from 10,000 cells in 25 images



A. RBCs in the CFA under a flow-induced shear stress of 3 Pa

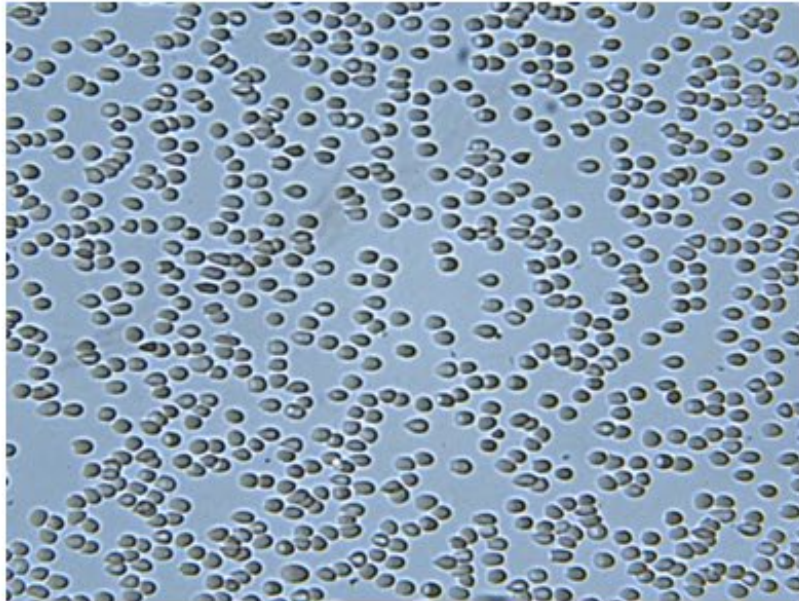
B. Undeformed cell (ER = 1)

C. Highly deformed cell (ER=2.3)

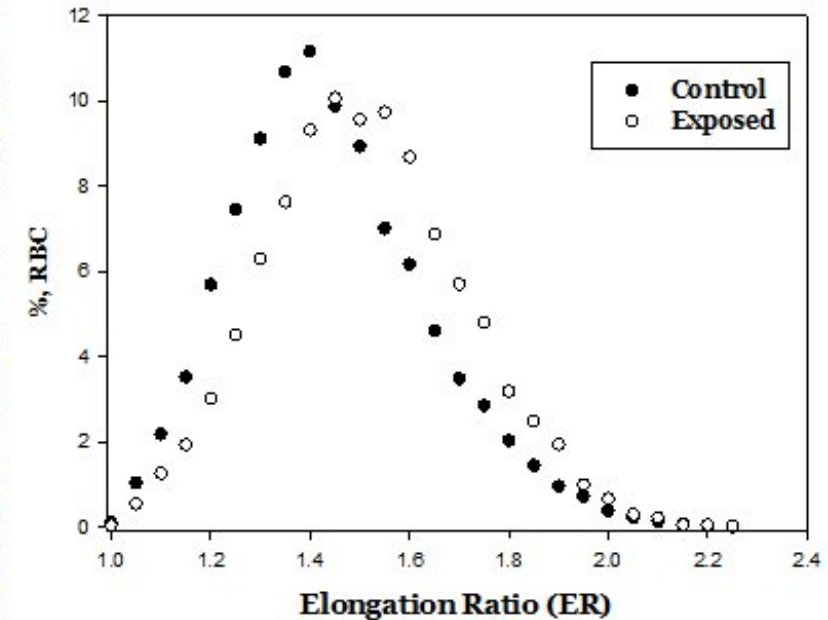
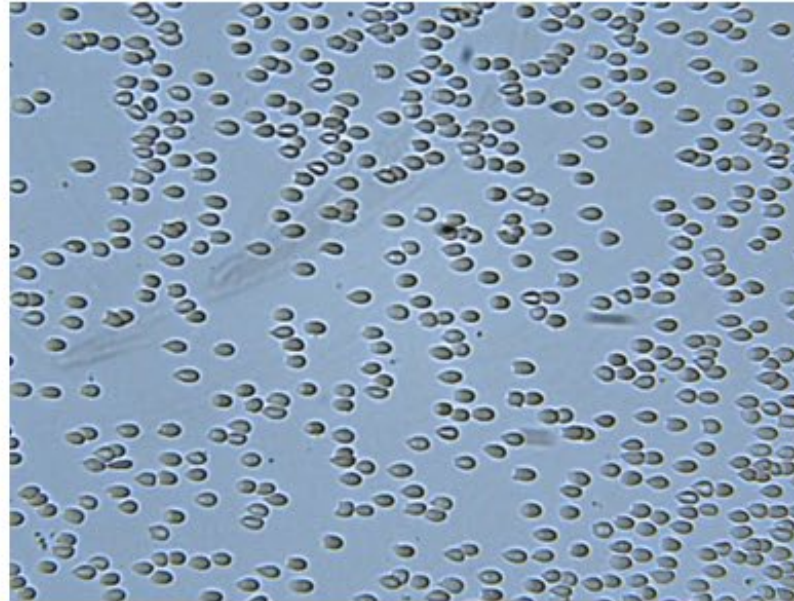
RBC Deformability

RBCs in the CFA under a flow-induced shear stress of 3 Pa
Deformability was measured 1 hour after exposure

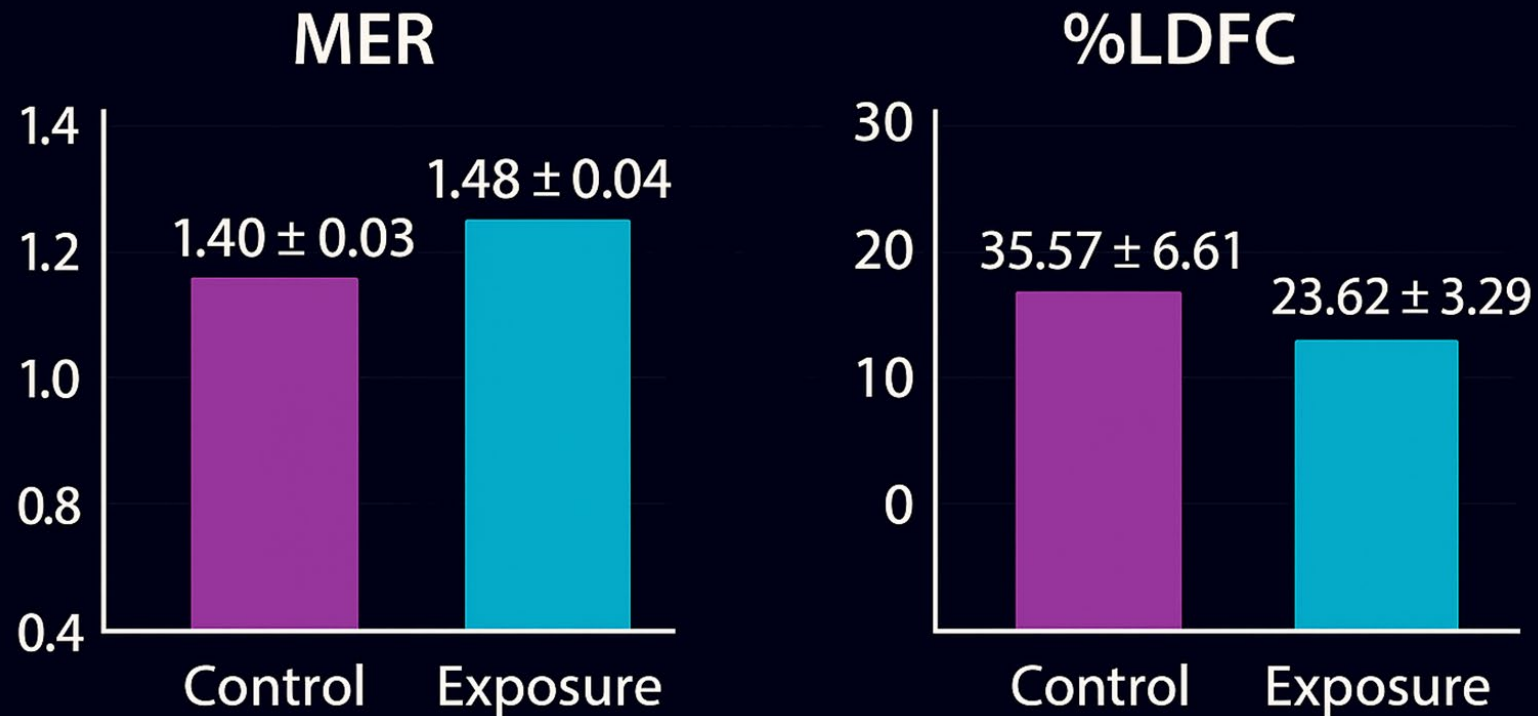
Control



Exposed during 40 min.



RBC Deformability



ER < 1.1

1.1 < ER < 1.3

ER > 2.5



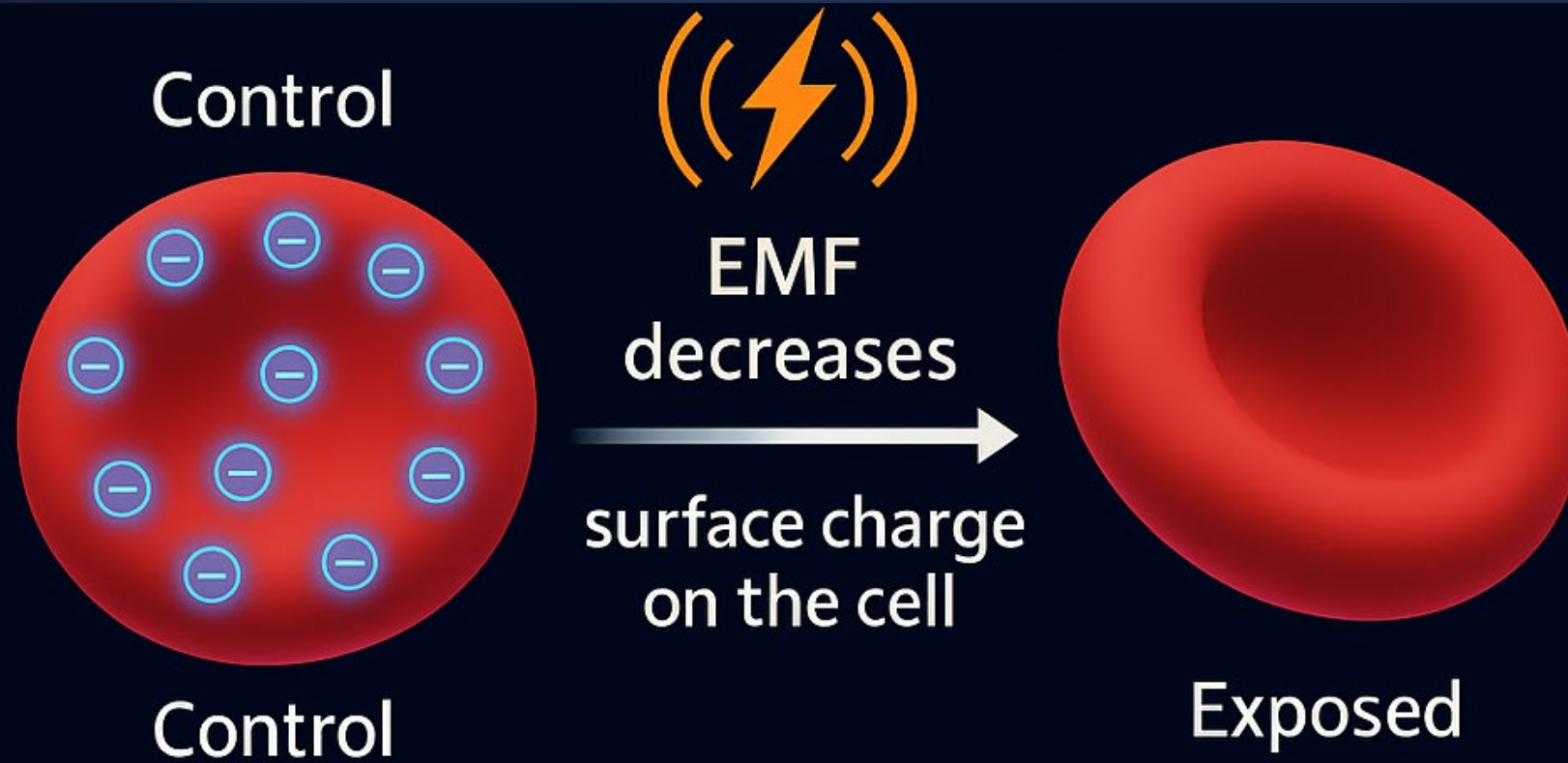
UDFC



LDFC

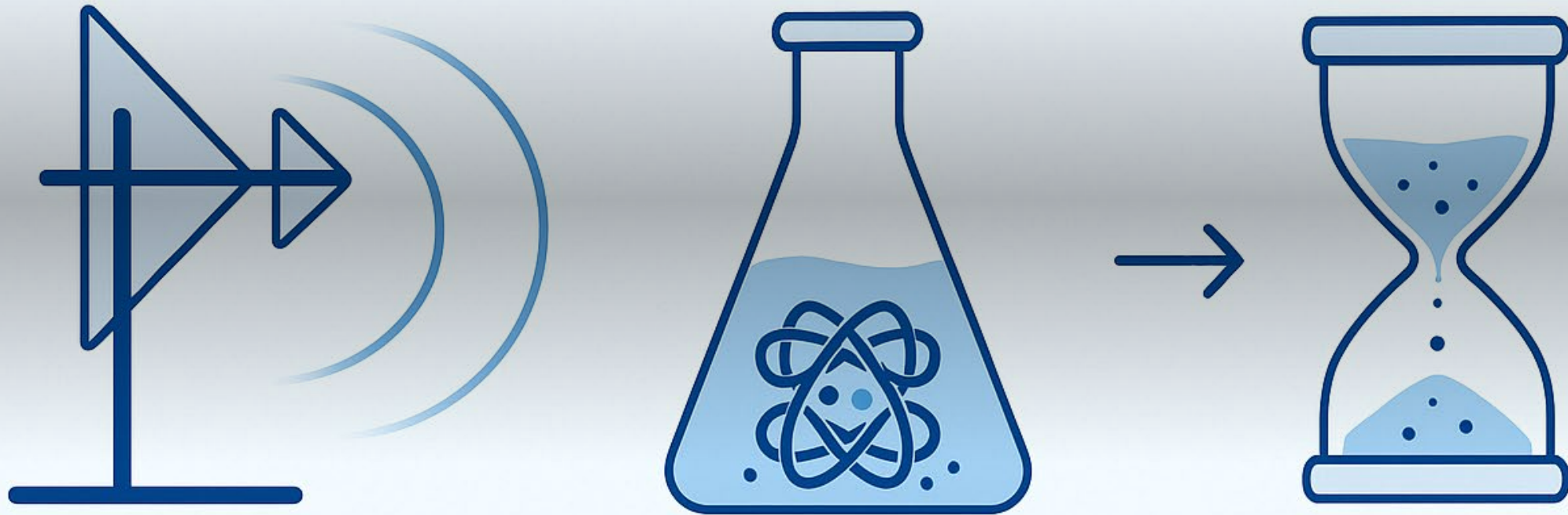


HDFC



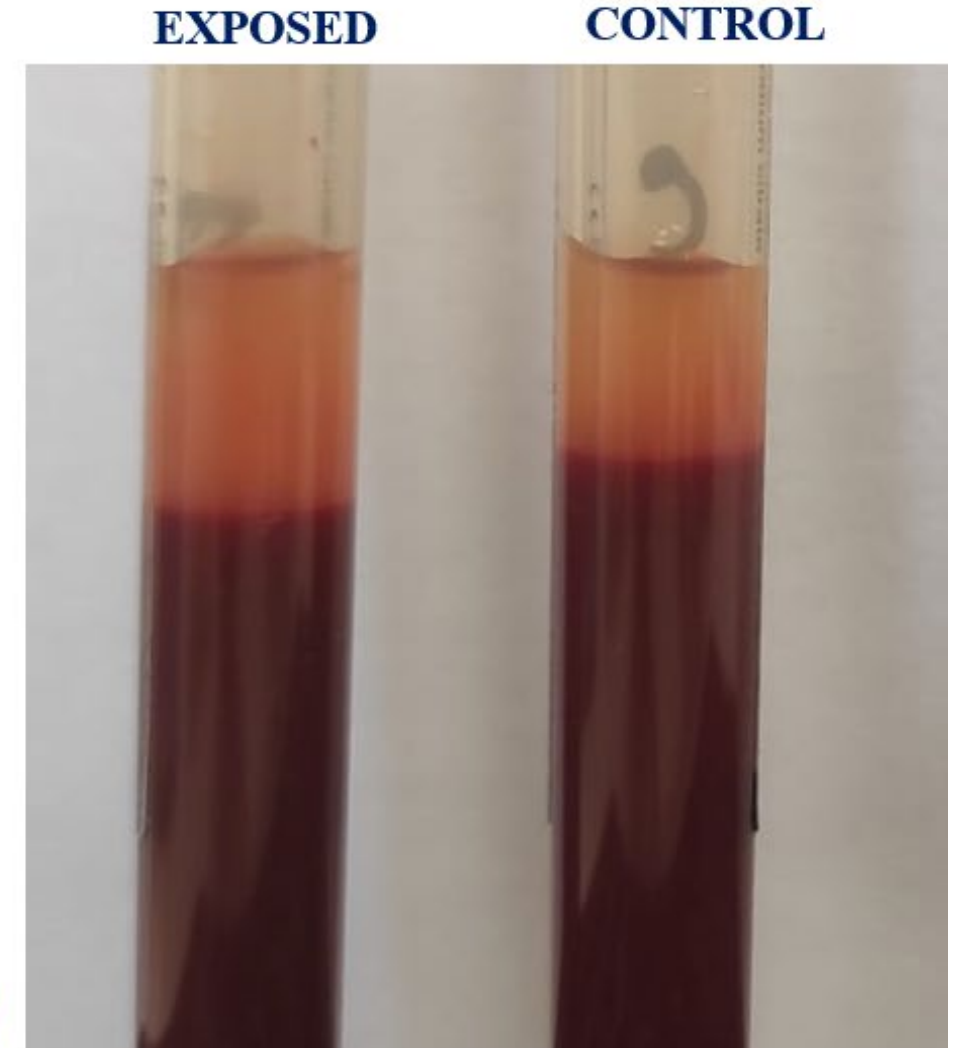
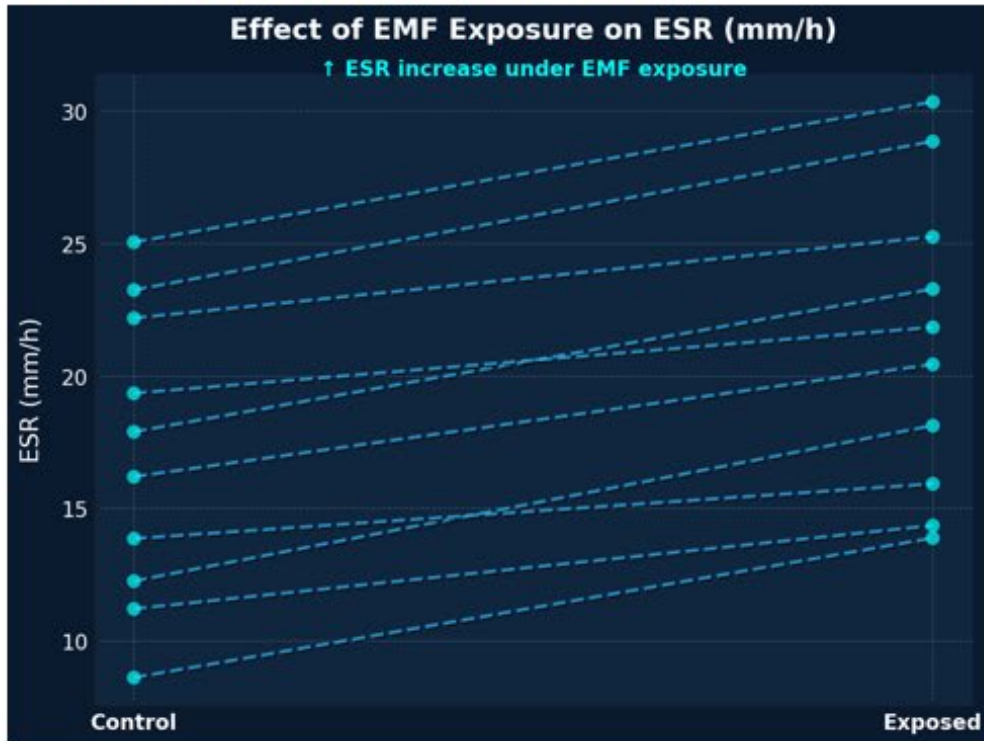
EMF decreases surface charge on the cell
RBC deformability increases.

Sedimentation Experiments



Experiment Erythrocyte sedimentation rate (ESR)

- 8 blood samples, Exposure (40 min)
- EMF at 2.5 GHz and 10 dBm

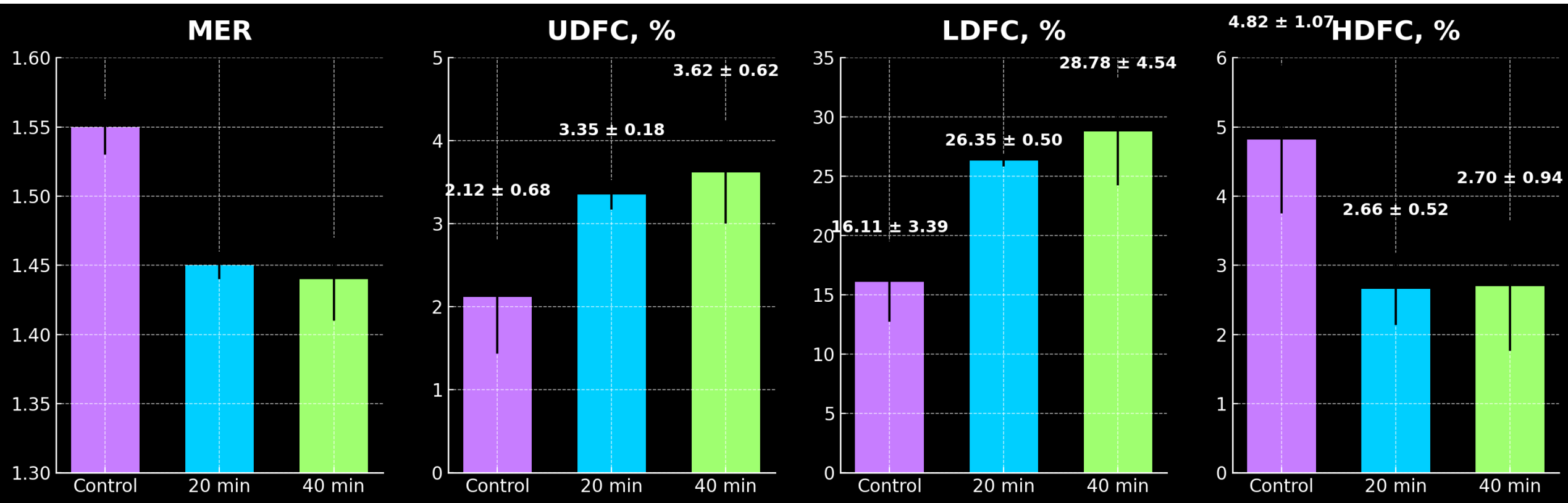


Observation: Exposure to EMF increased ESR

Explanation: Decrease in the surface charge on the cell

Experiment: Thermal Effects

RBC deformability parameters after incubation at 40°C.



Thermal effects



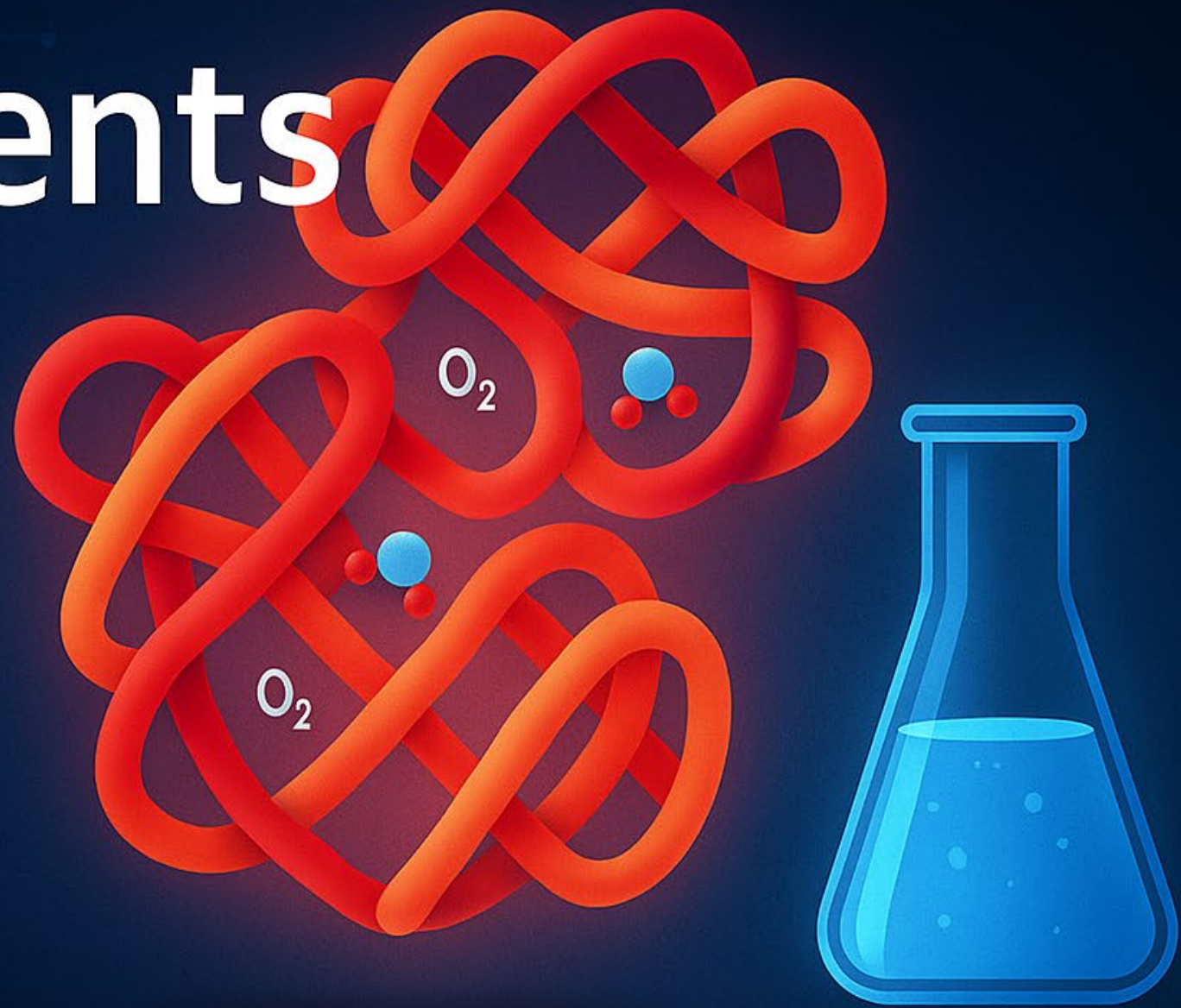
Reduction of
RBC deformability

Supporting EMF effects are not thermal



EMF exposure
increases
RBC deformability

Protein-Level Experiments

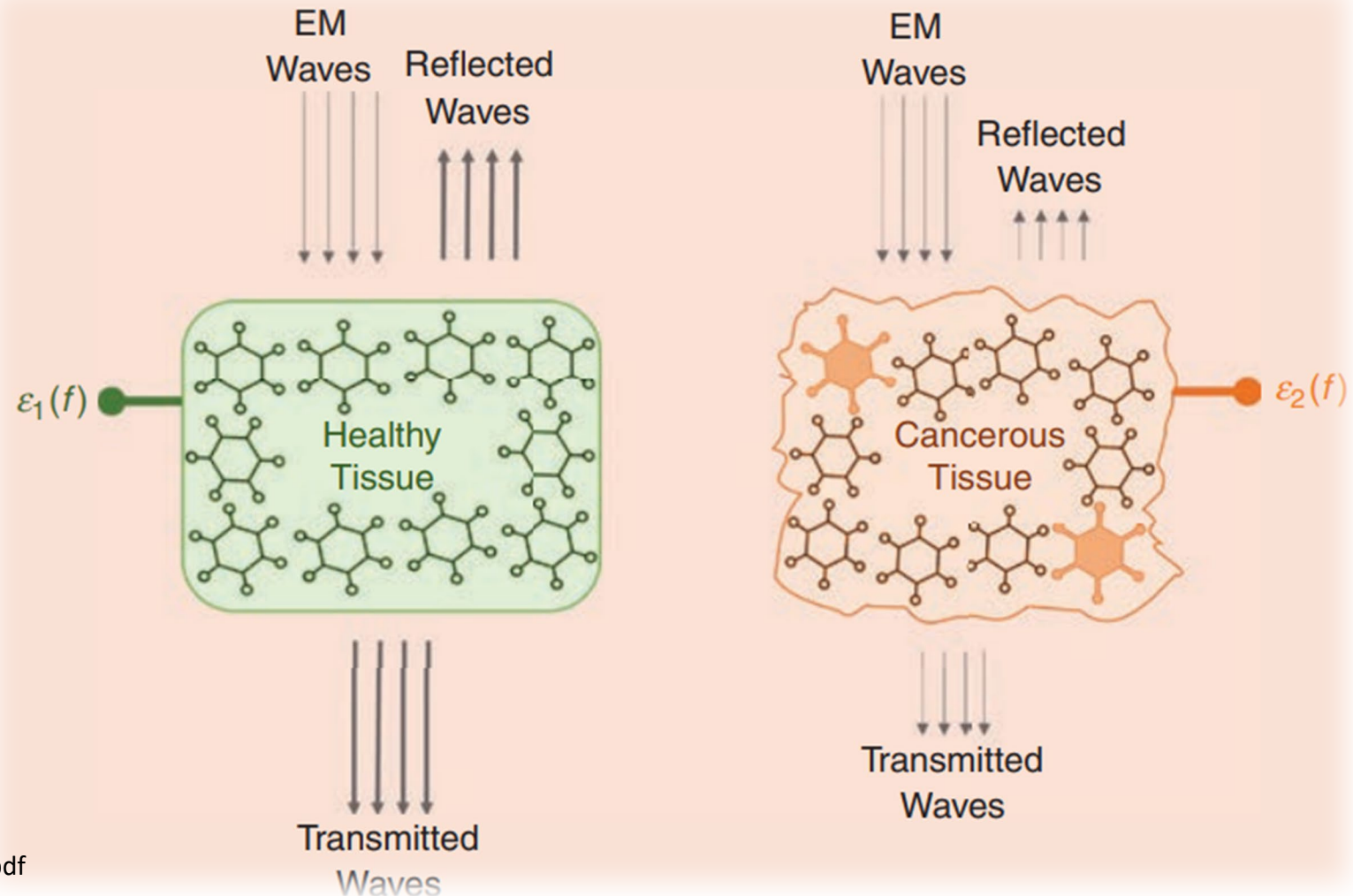




DIELECTRIC SPECTROSCOPY

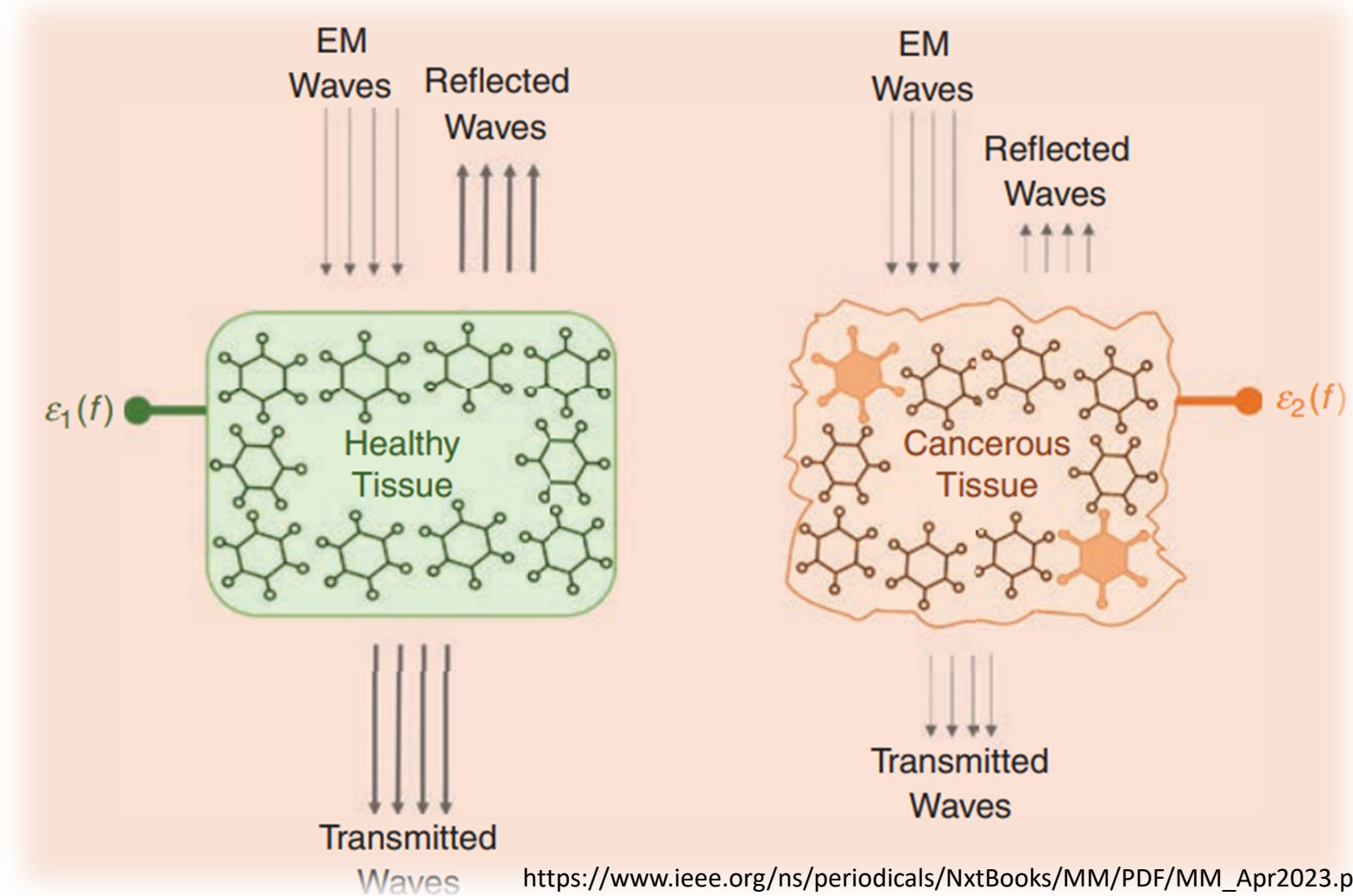
The Method: Dielectric Spectroscopy

- **DS - study the electrical properties of material**
- **Measuring response to EMF**
- **Information about:**
 - **material's structure**
 - **molecular dynamics**
 - **relaxational processes**



The Method: Dielectric Spectroscopy

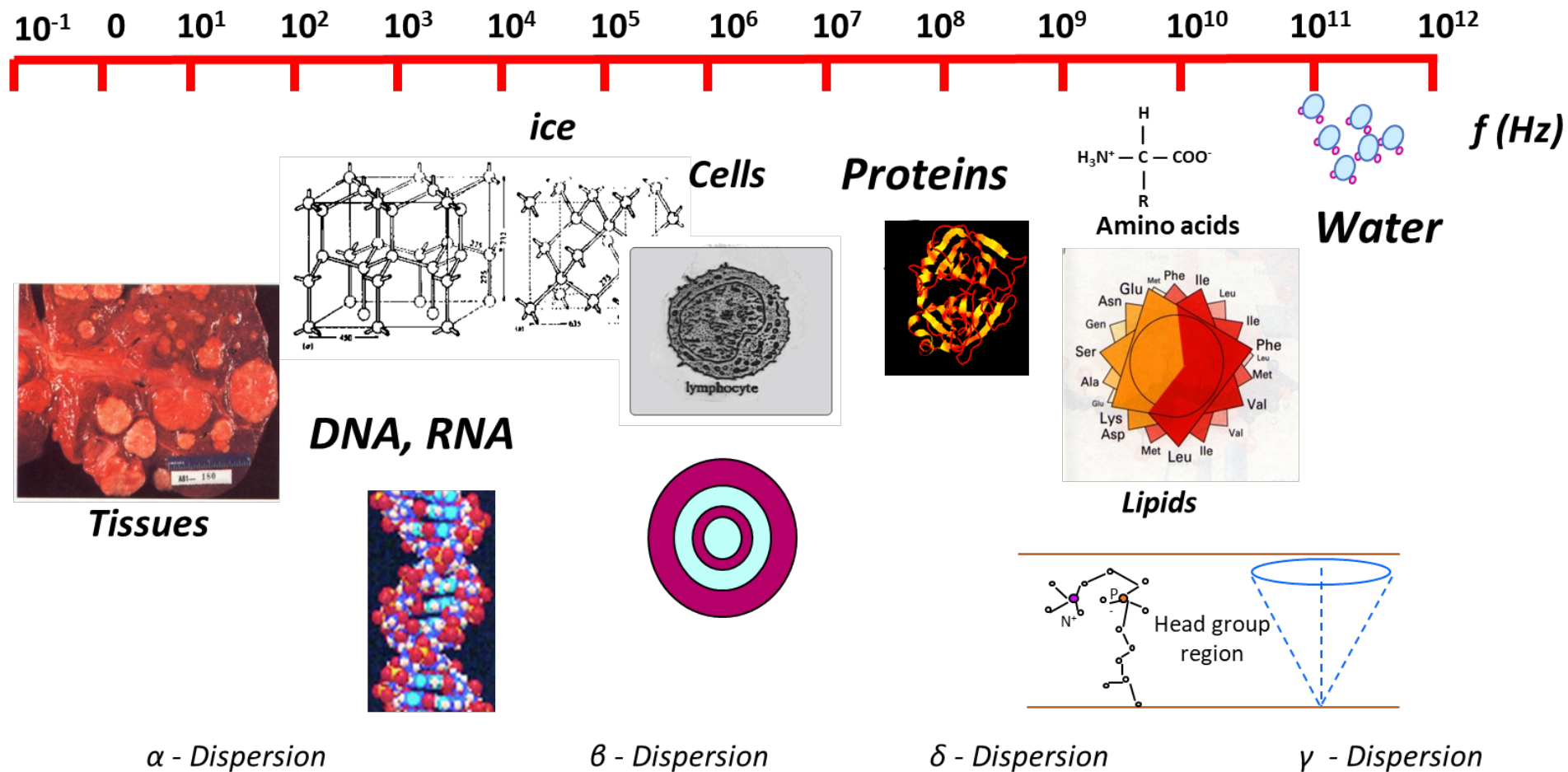
- **Complex permittivity:**
 $\varepsilon(f) = \varepsilon'(f) - j\varepsilon''(f)$
- **Determines - material's responds to EMF**
- **Calculated from reflection + transmission.**
- **Described by: S-parameters**
- **Measured by a VNA**



The Method: Dielectric Spectroscopy



- Complex permittivity spectrum of biological material = EM fingerprint



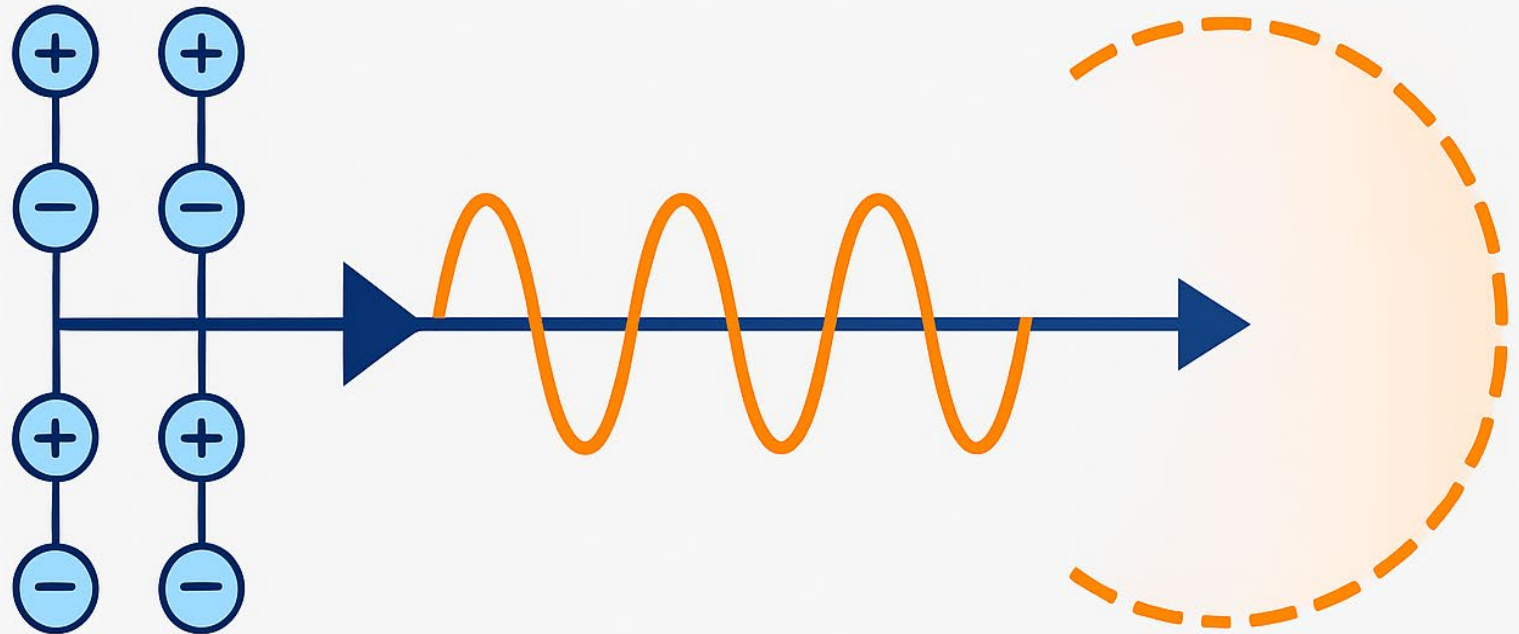
The Method: Dielectric Spectroscopy



Complex permittivity

$$\varepsilon(f) = \varepsilon'(f) - j\varepsilon''(f)$$

$\varepsilon(f)$ - electric dipole moments inside the material align to EMF



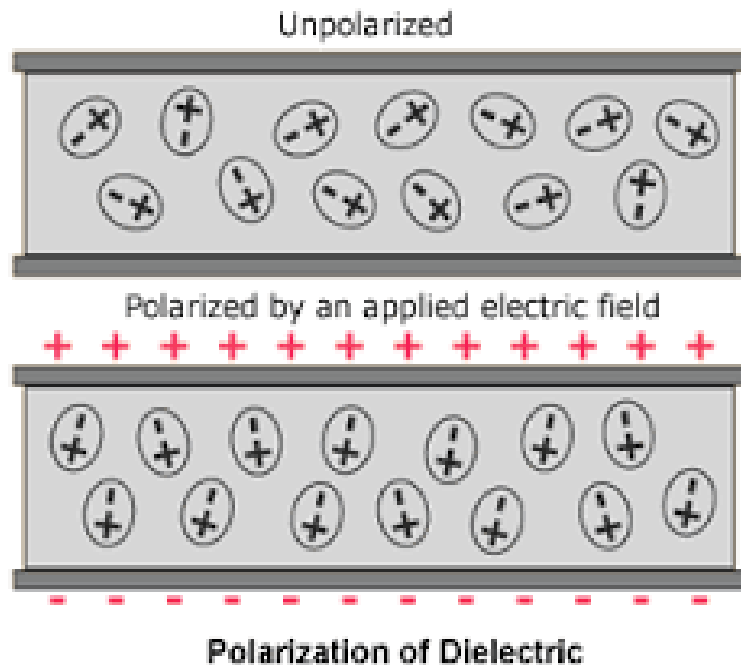
$\varepsilon'(f)$

EM losses (friction of charges aligning with the EM field)

The Method: Dielectric Spectroscopy

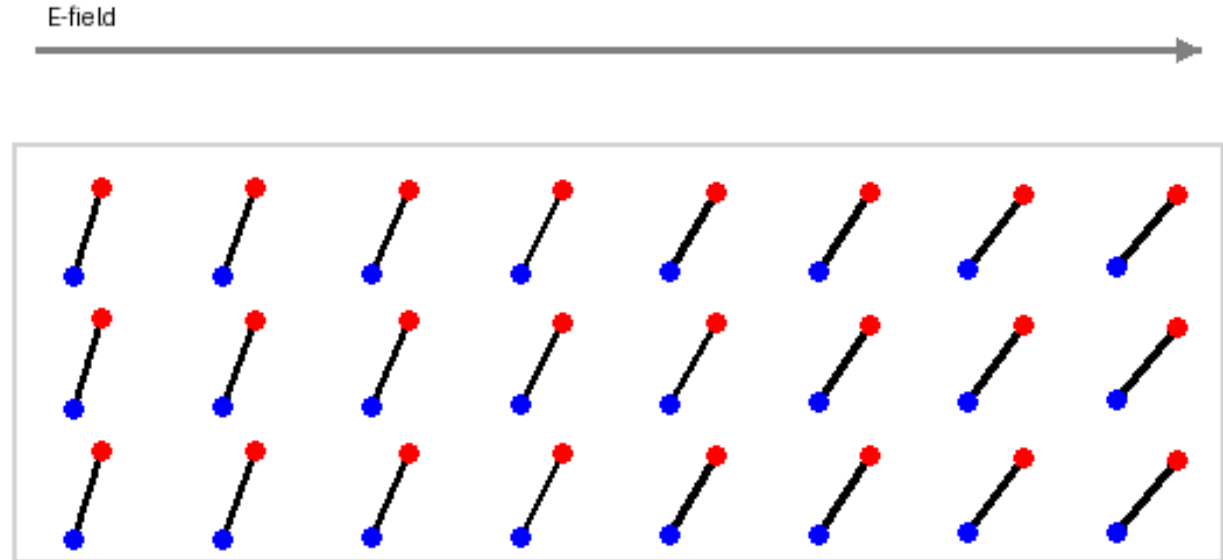


- EMF—induces polarization
- Polarization is described by complex permittivity:
Magnitude – polarization extent
Phase – polarization delay



Time- dependent fields: $E(t) = E_0 e^{-i\omega t}$

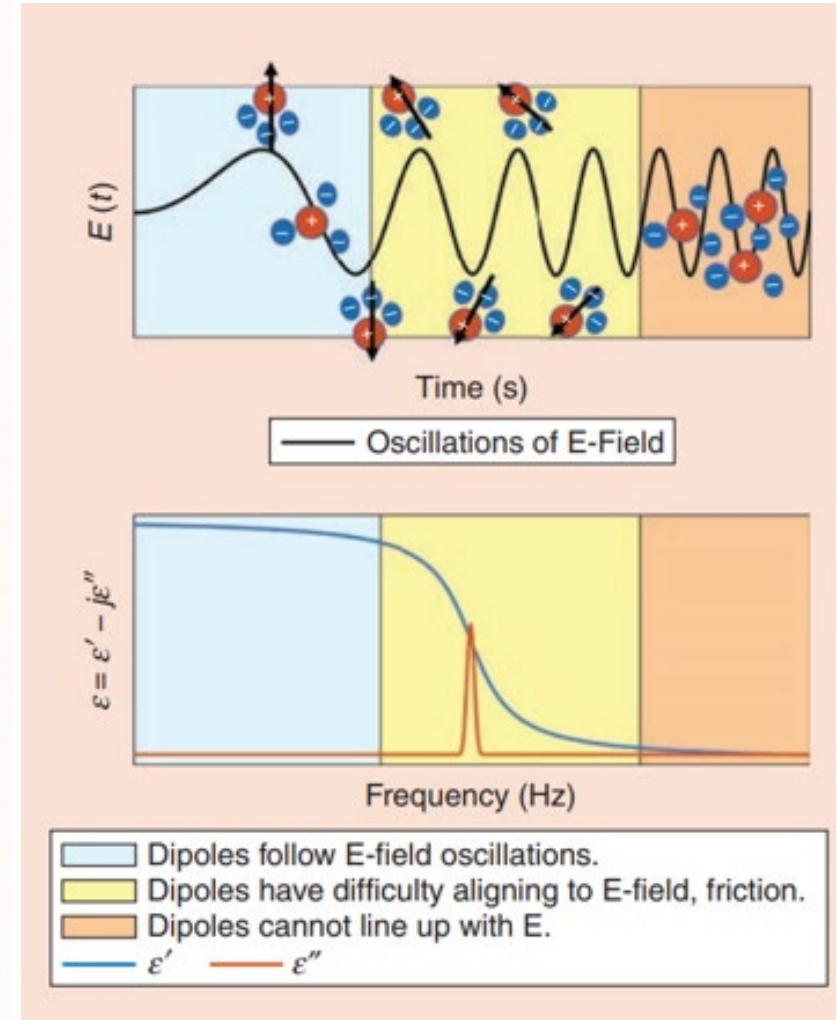
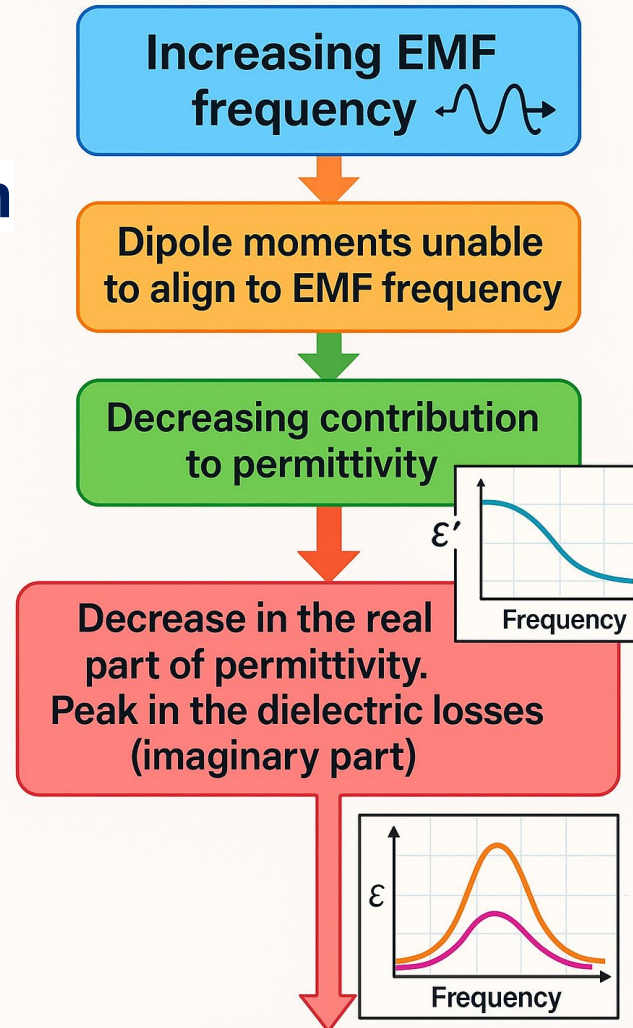
Polarization: $P(t) = \epsilon_0 \chi E(t)$



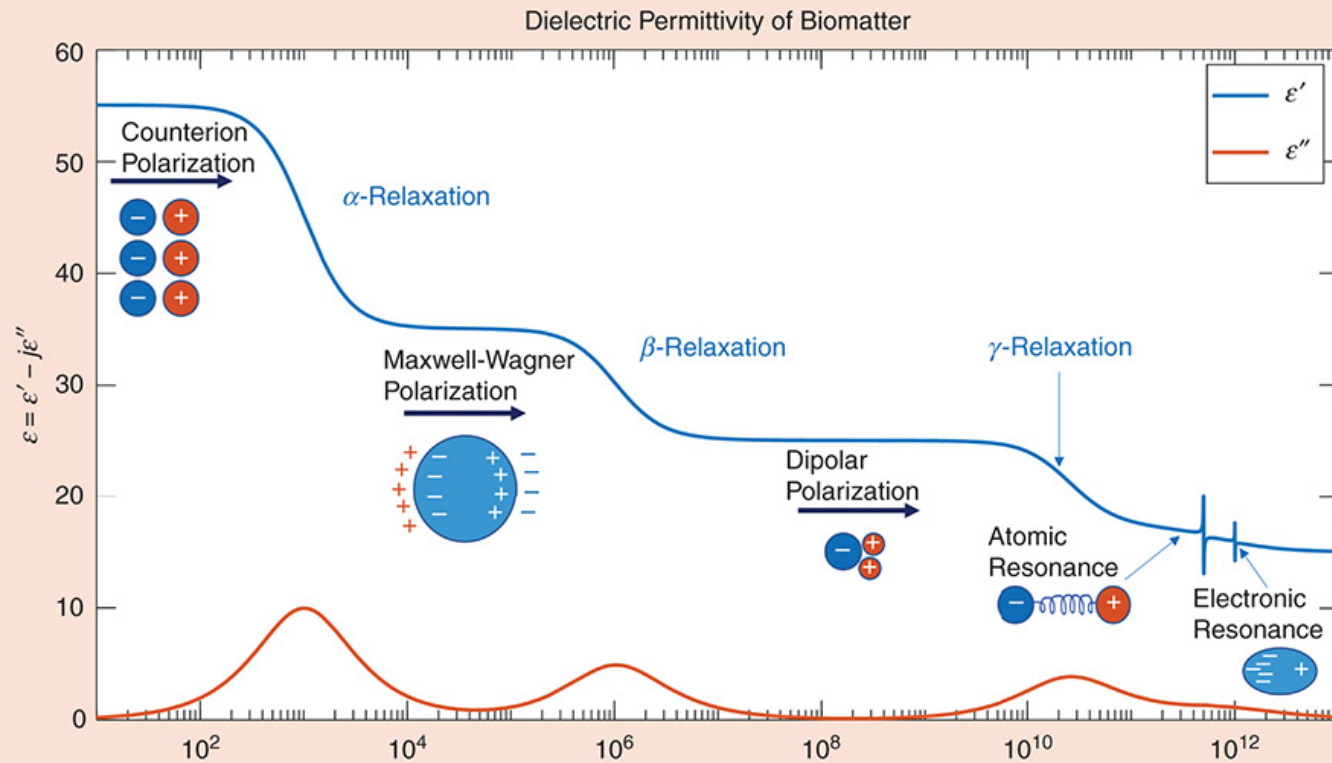
Relaxation Phenomena

Dielectric relaxation

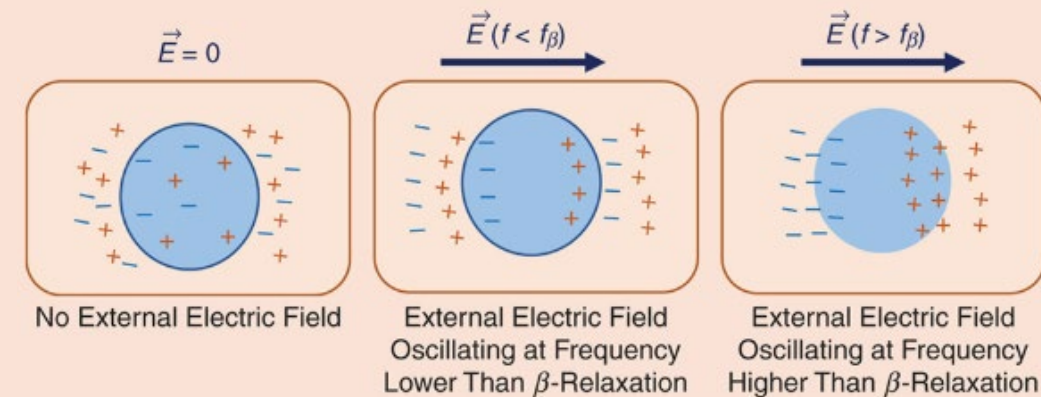
Time-dependent process
when material's polarization
adjusts to varying EMF



Relaxation Phenomena in BioMatter



β -dispersion



- α –dispersion: tangential flow of ions across cell surfaces
- β –dispersion: build-up of charge at cell membranes (Maxwell-Wagner effect)
- γ -dispersion is due to the dipolar rotation of small molecules (water) – the major part of any biomatter

Cole-Cole Model



Relation between relaxation and dielectric parameters

$$\varepsilon(f) = \varepsilon_{\infty} + \frac{\Delta\varepsilon}{1 + (jf\tau)^{1-\alpha}} + \frac{\sigma}{jf\varepsilon_0}$$

f Frequency

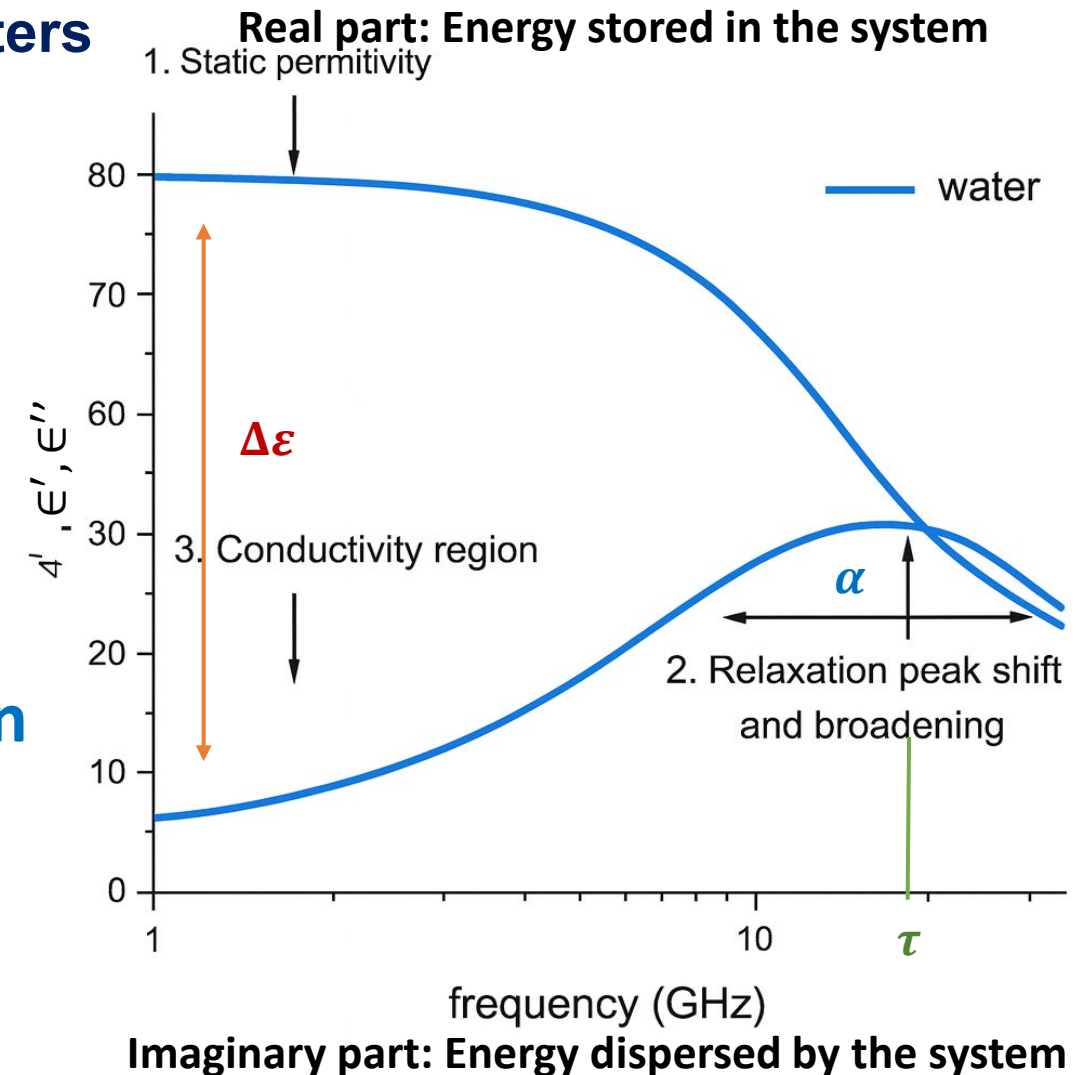
ε_0 Vacuum permittivity

$\Delta\varepsilon$ Dielectric strength

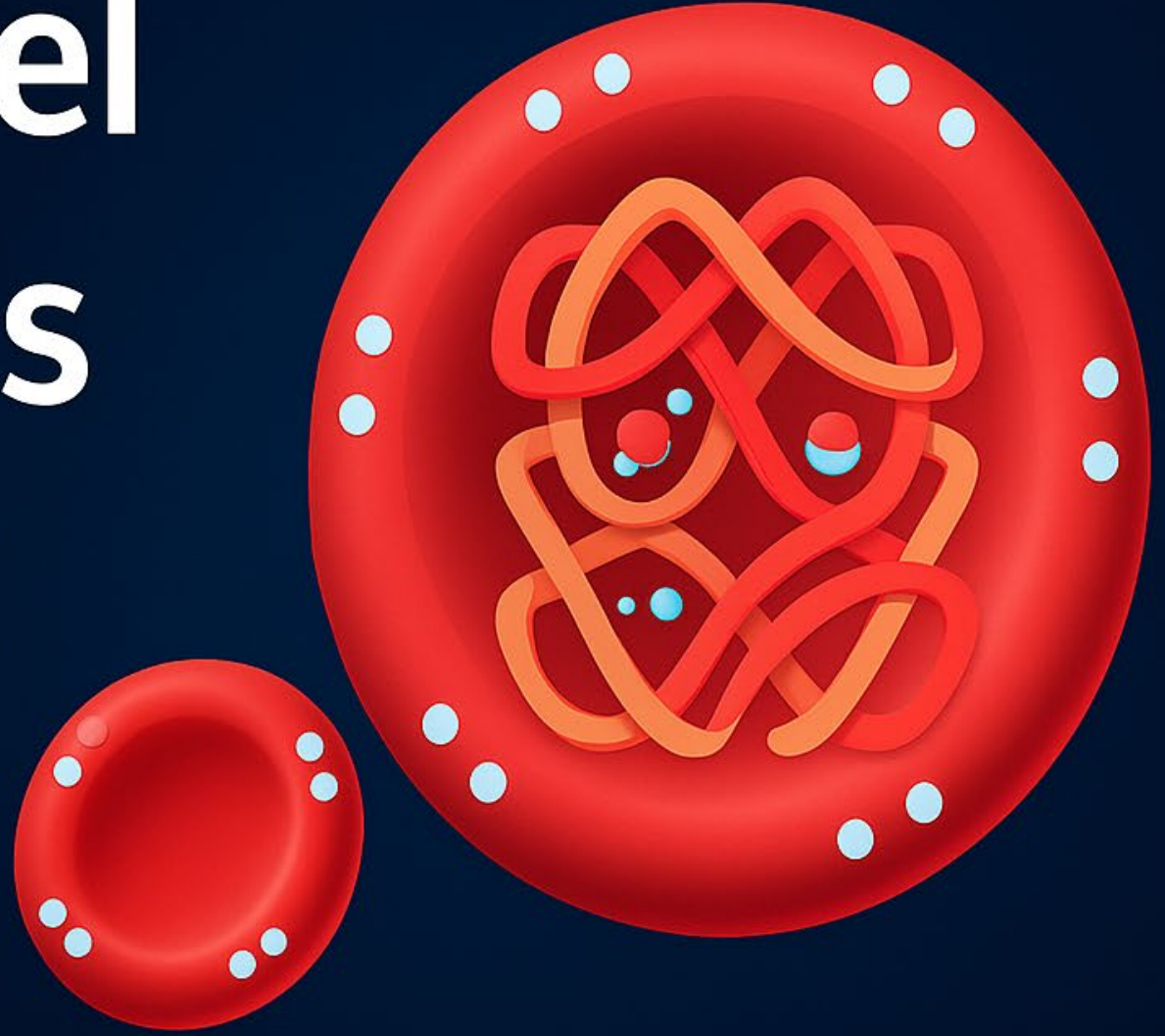
α Broadening of the relaxation distribution

τ Relaxation time

σ Conductivity



Protein-Level Experiments inside RBC

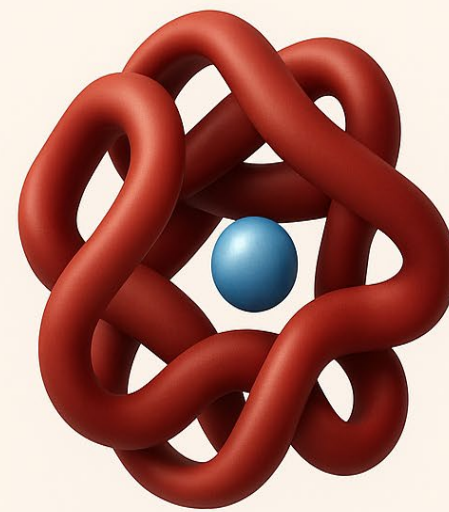


EMF exposure of MetHb solution



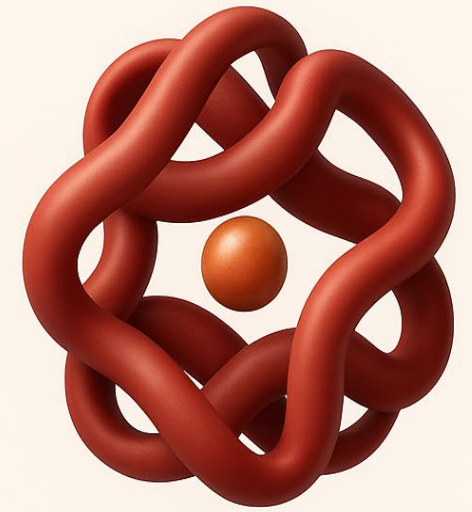
Effect of EMF exposure of MetHb solution

- Dielectric measurement of MetHb solution before/after EMF exposure
- MetHb provides a controlled biochemical state allowing:
 - Isolate EMF effects
 - Compare with normal Hb or RBC response
 - Measure changes in:
 - Absorption
 - Relaxation



Hemoglobin
Hb
Fe²⁺

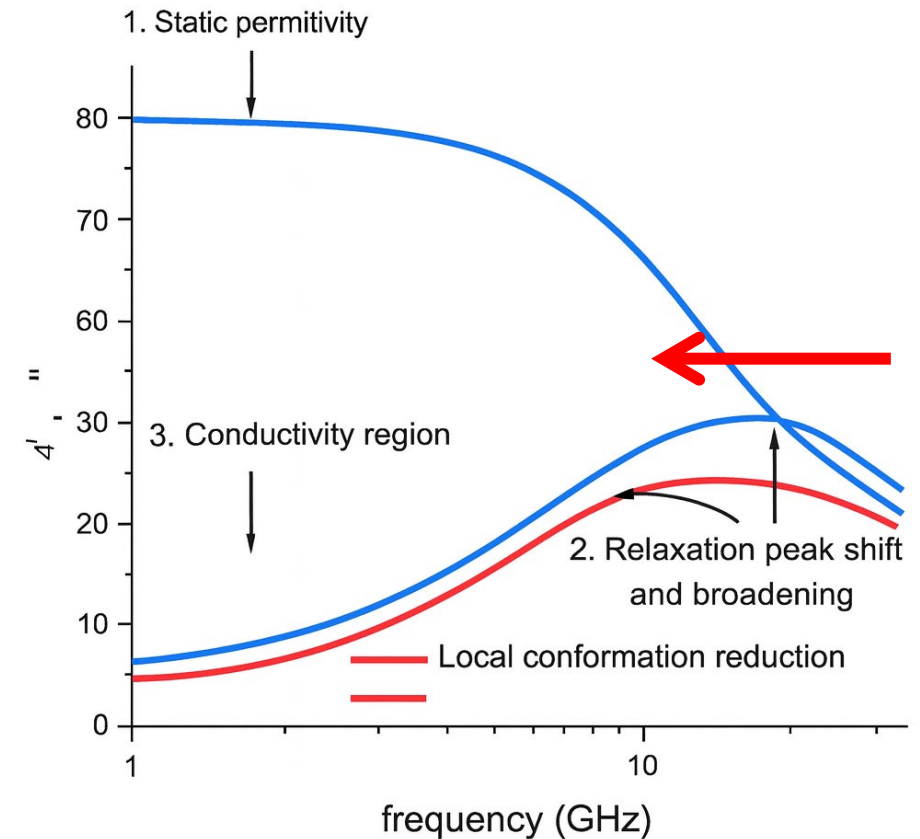
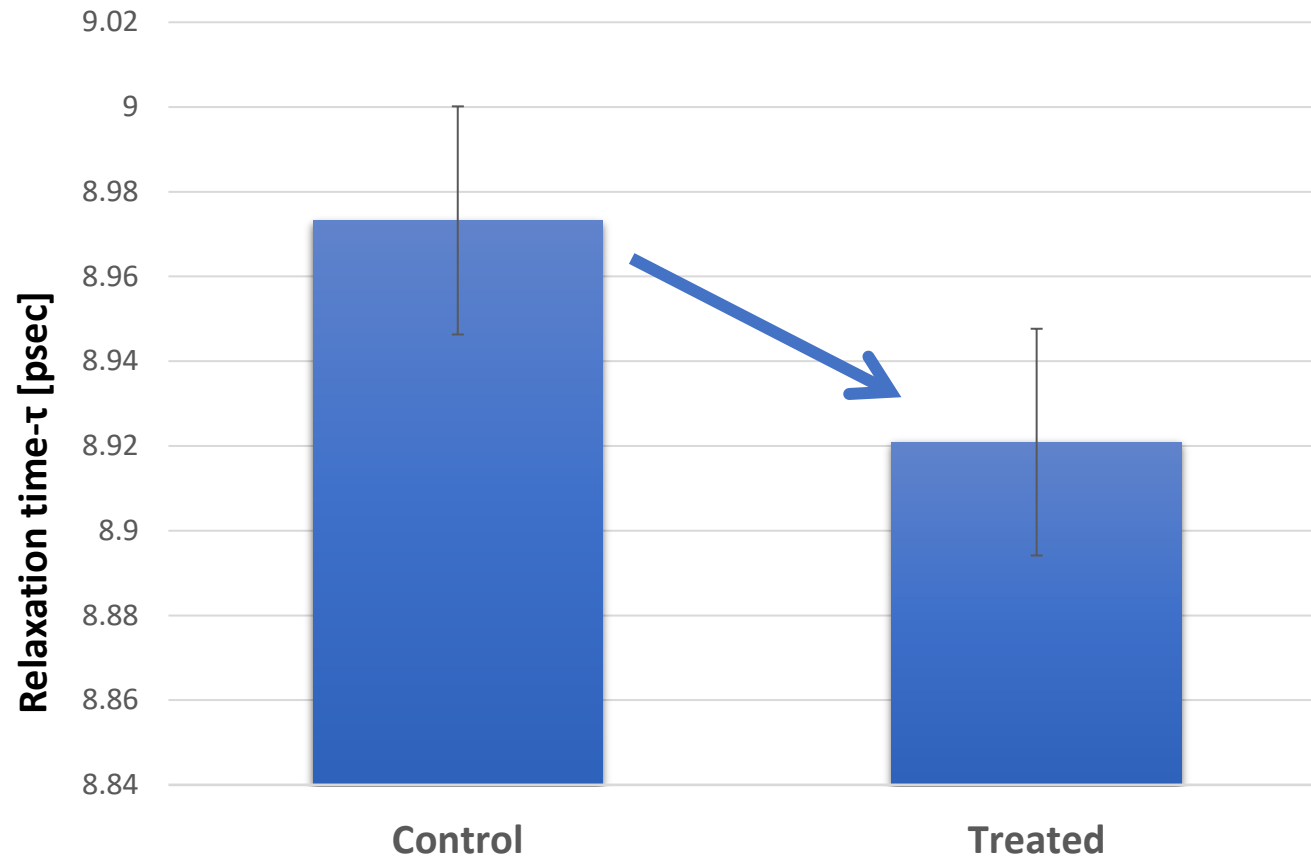
Oxidation

A thick grey arrow pointing from the Hemoglobin structure to the Methemoglobin structure.


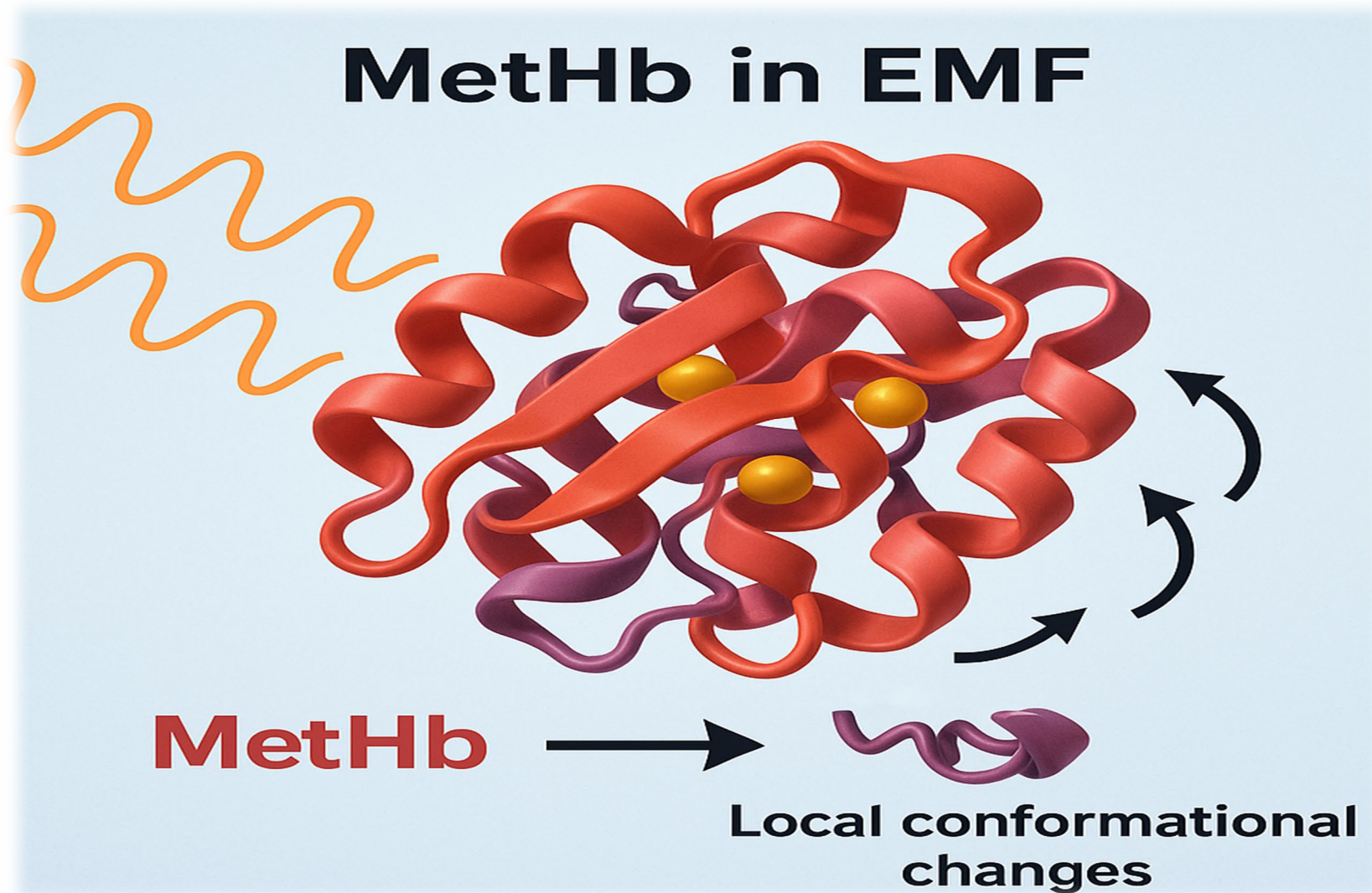
Methemoglobin
MetHb
Fe³⁺

Dielectric Relaxation Time

$$\epsilon(f) = \epsilon_{\infty} + \frac{\Delta\epsilon}{1 + (jf\tau)^{1-\alpha}} + \frac{\sigma}{jf\epsilon_0}$$



Possible Reason



HEMOGLOBIN EXPERIMENTS



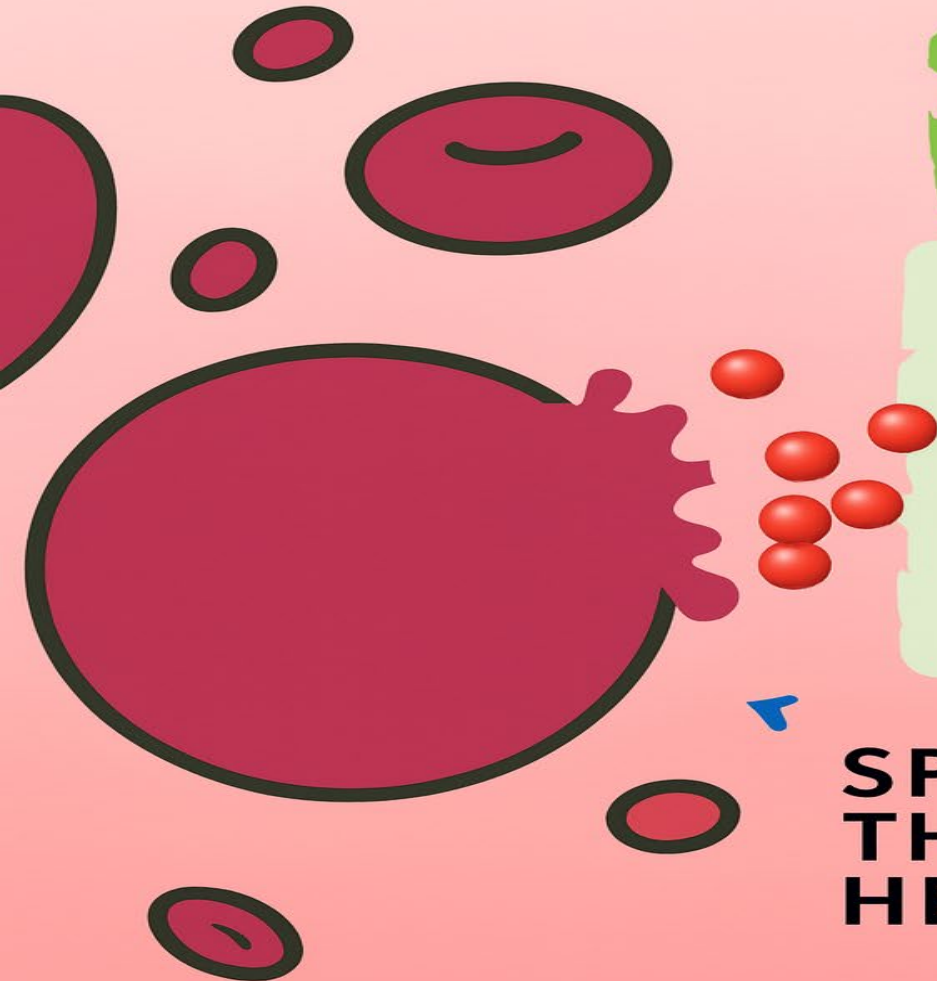
Experiment Hemolysate



What is Hemolysis?

Hemolysis is the lysis of red blood cells resulting in the release of hemoglobin.

SPHERE-SHAPED RED BLOOD THAT HEMOLYSED, RELEASING HEMOGLOBIN INTO BLOOD



Hemolysis

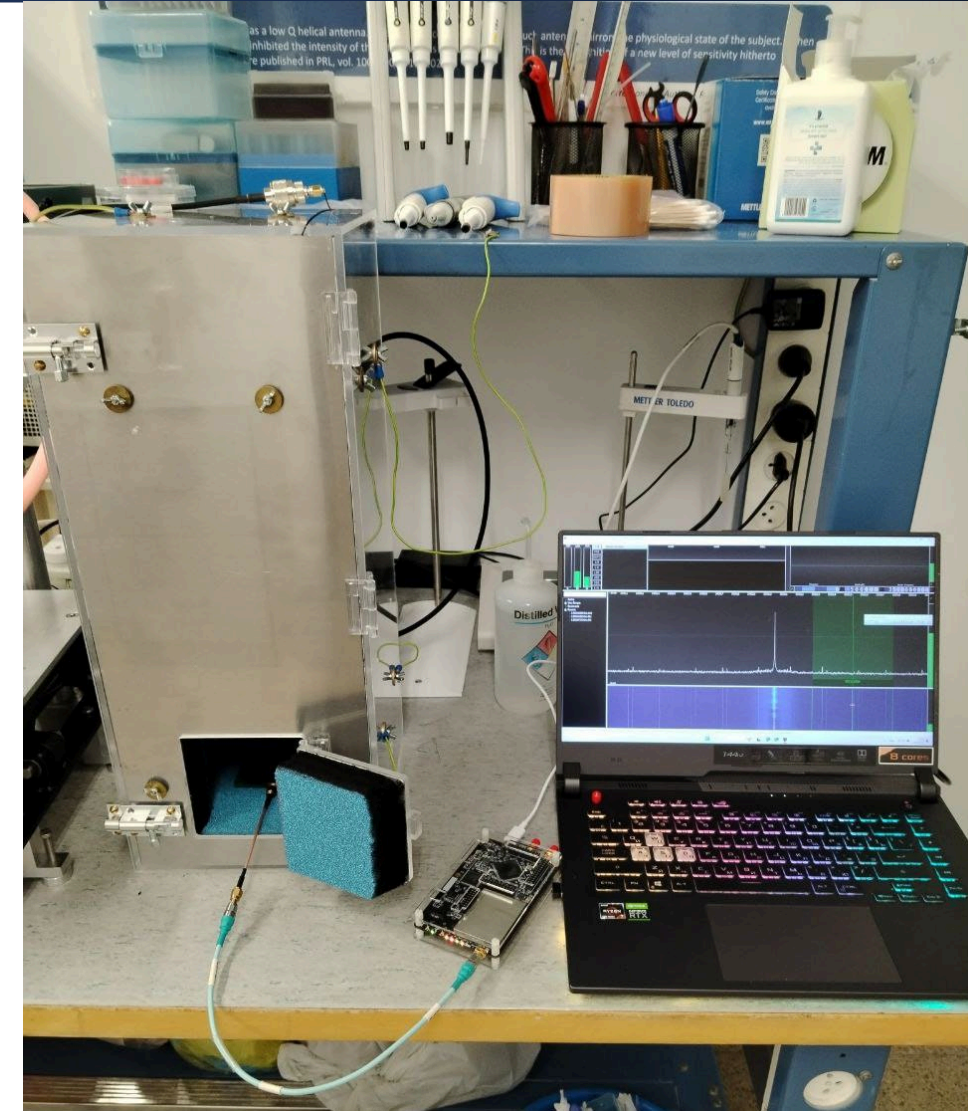


Experiment Hemolysate- Setup



- Exposure for 40 min
- Circulating hemolysate
- Temperature-controlled
- Unmodulated EMF
- High hemoglobin concentration:
 - Centrifugation removed plasma from blood
 - cell concentrate was hemolyzed.

Hemoglobin concentration: $20.5 \pm 1.2\%$.

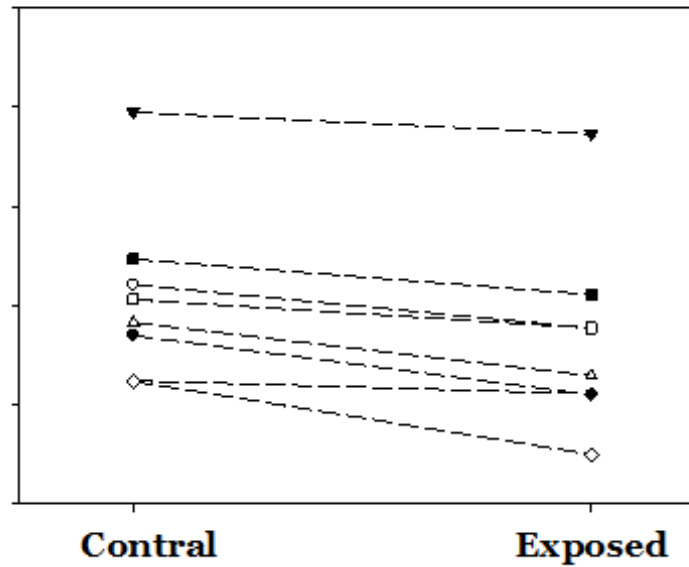
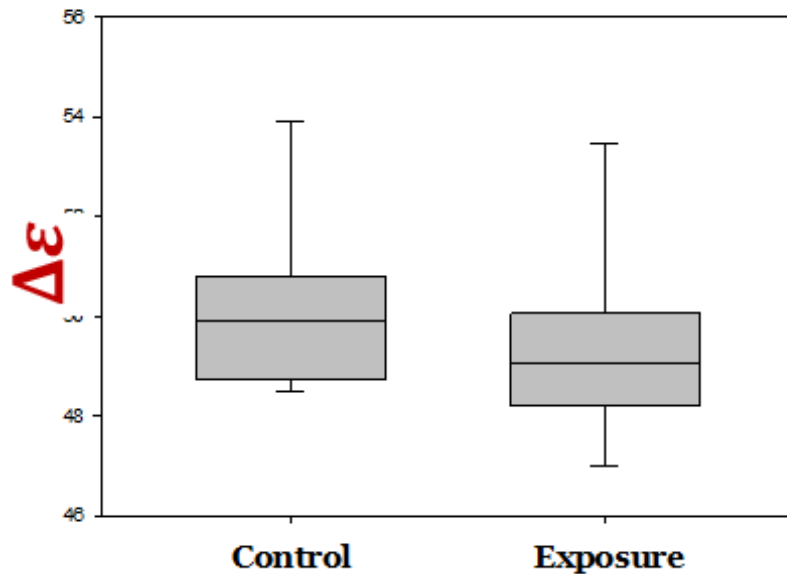


Experiment Hemolysate- Dielectric Strength

- Exposure for 40 min
- Circulating hemolysate
- Temperature-controlled

$$\varepsilon(f) = \varepsilon_{\infty} + \frac{\Delta\varepsilon}{1 + (jf\tau)^{1-\alpha}} + \frac{\sigma}{jf\varepsilon_0}$$

Dielectric strength



Indicate:

- altered hemoglobin conformation due to affected molecular dipoles
- redistribution of ions and increased ionic mobility

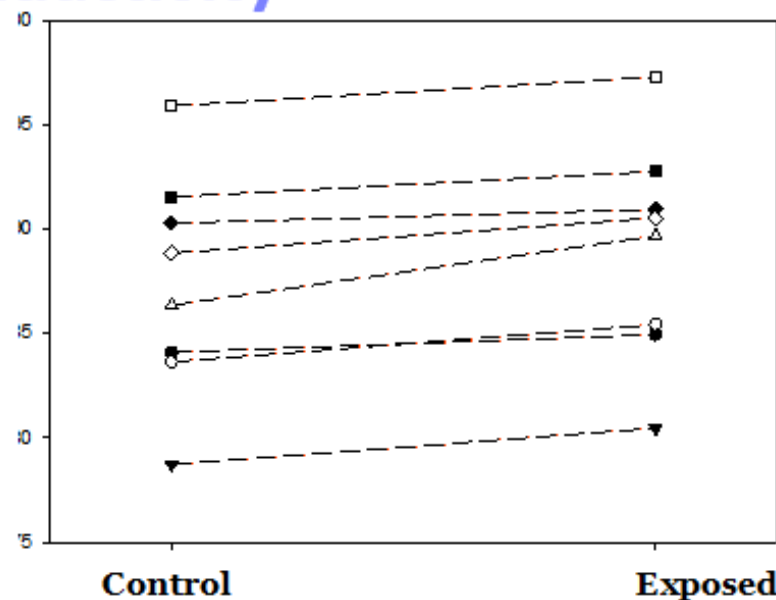
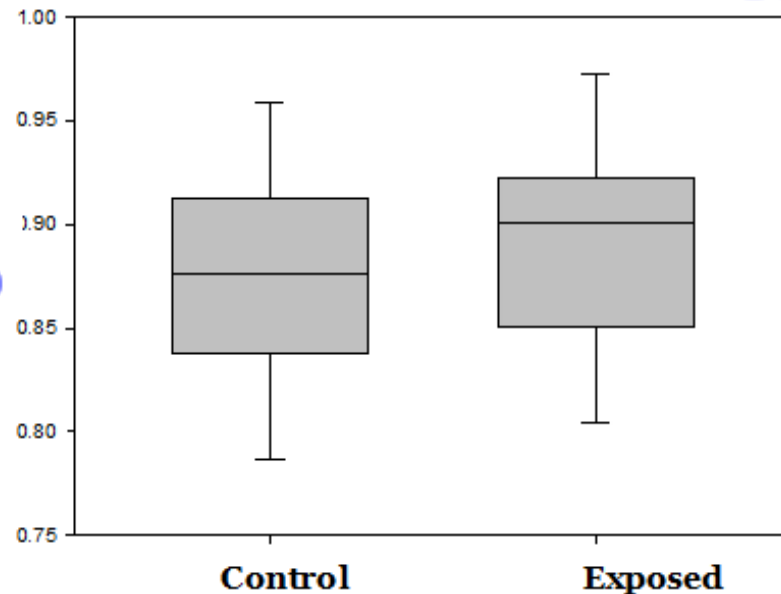
Decrease in dielectric strength ($\Delta\varepsilon$)

Experiment Hemolysate- Conductivity

- Exposure for 40 min
- Circulating hemolysate
- Temperature-controlled

$$\varepsilon(f) = \varepsilon_{\infty} + \frac{\Delta\varepsilon}{1 + (jf\tau)^{1-\alpha}} + \frac{\sigma}{jf\varepsilon_0}$$

Conductivity



Indicate more mobile ions

More mobile ions →
 - increased permeability
 - ion release

Increase in conductivity (σ)

Experiment PBS (Control)

Phosphate-Buffered Saline (PBS) - salt water with a stable pH similar to the body

P-value	PBS Control (n = 5) 40 min incubation	PBS Exposure (n = 5) during 40 min
$\Delta\epsilon$ decreases	70.43 $\pm$ 0.98	70.18 $\pm$ 0.79
σ increases	1.61 $\pm$ 0.06	1.56 $\pm$ 0.03

Exposure of PBS (Control) to EMF does not impact:

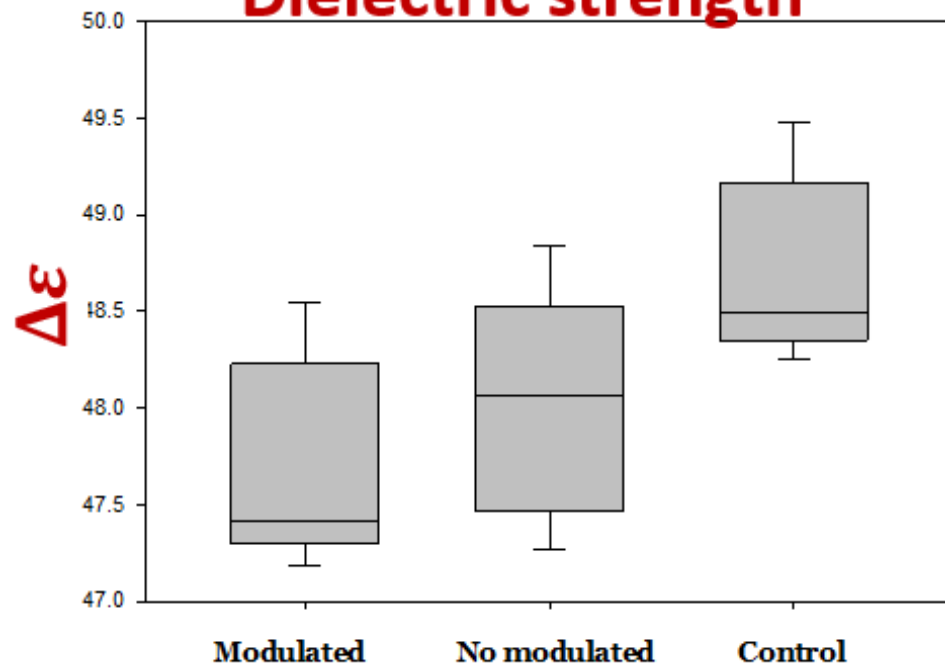
- dielectric strength ($\Delta\epsilon$)
- electrical conductivity (σ).

Modulation Impact

Pulse-modulated signal 50% duty cycle

$$\varepsilon(f) = \varepsilon_{\infty} + \frac{\Delta\varepsilon}{1 + (jf\tau)^{1-\alpha}} + \frac{\sigma}{jf\varepsilon_0}$$

Dielectric strength



Modulation increases dielectric strength decrease

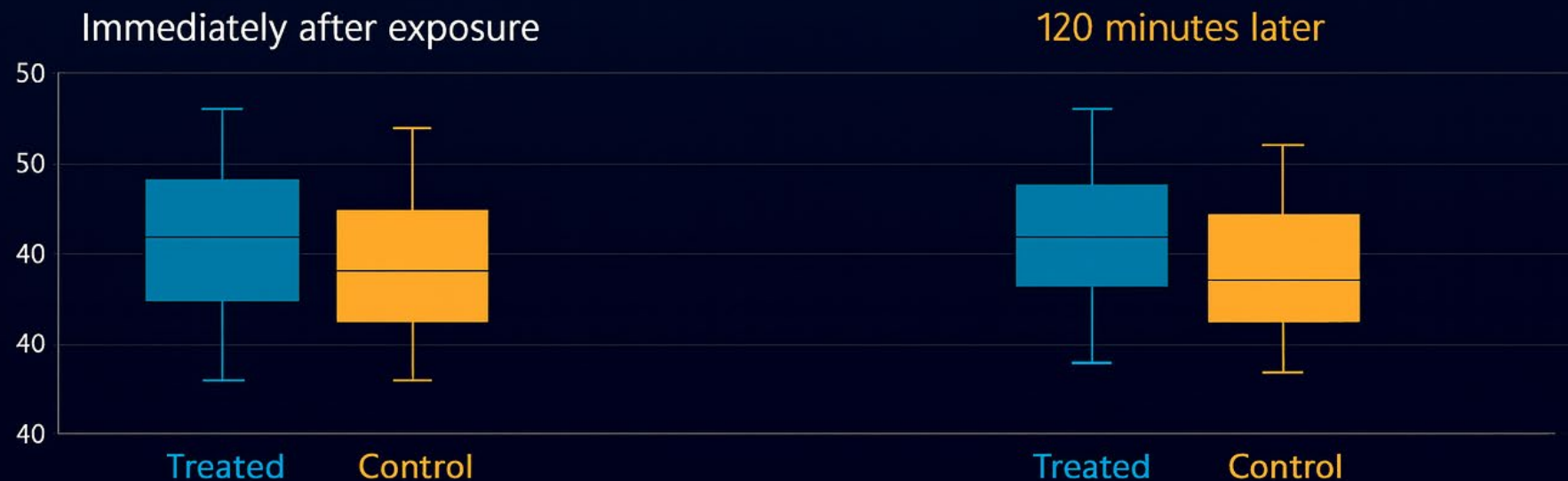
Explanation:

- increasing ions release and redistribution
- inducing greater structural perturbation

Irreversibility of EMF Effects

The effect of the electromagnetic field on the dielectric properties of the hemolysate is not reversible.

To assess this hypothesis, we compared the dielectric features of treated and control samples at two time points: immediately after exposure and 120 minutes later.



Protein Level Experiments Outside RBC (Plasma)



Albumin Solution Exposure



Parameter	$\Delta\epsilon$	τ , psec	α	σ , S/m
Control	61.09 ± 0.082	8.13 ± 0.002	0.978 ± 0.002	1.39 ± 0.017
Exposure	59.21 ± 0.221	8.14 ± 0.026	0.988 ± 0.002	1.45 ± 0.107
T-test	8×10^{-12}	NS	8.5×10^{-11}	3.5×10^{-10}

Exposure of the protein solution to RF-EMF leads to the loss of some of the absorbed ions by the protein molecules.

Albumin Solution Exposure



$\Delta\varepsilon$



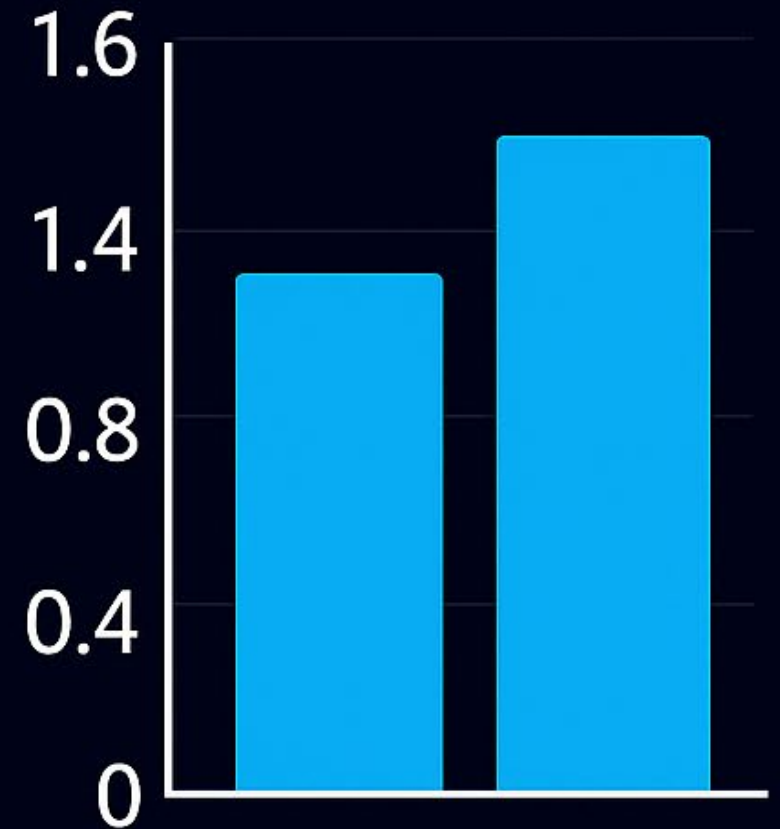
Control Exposure

α



Control Exposure

σ



Control Exposure

Conclusion



Developed uniform, temperature-controlled EMF exposure systems (near-field & far-field) enabling realistic, reproducible blood-level experiments.



RBC Results: EMF exposure increased RBC deformability & ESR → indicating **reduced surface charge on the membrane**. Heating produced the opposite trend → confirms non-thermal origin.



Protein/Hemolysate Results: EMF exposure decreased dielectric strength ($\Delta\epsilon$) and **increased** conductivity (σ) in hemolysate, MetHb, and plasma proteins → suggests **enhanced ionic mobility** and subtle conformational changes.



Pulse-modulated EMF induced stronger and **partially irreversible** bio-physical changes.



Overall: Weak RF fields can **modify electro-bio-physical properties of RBCs and blood proteins** under controlled conditions. These findings **do not claim** health effects, but demonstrate biologically meaningful EMF-blood

Next Steps



- **Build the model explaining ionic changes within EMF**
- **Predict the health effects of the EMF exposure**

Questions?