Preconference Workshop: EMF exposure from 5G equipment: the state of art of research and standardization

EMF Exposure Limits above 6 GHz

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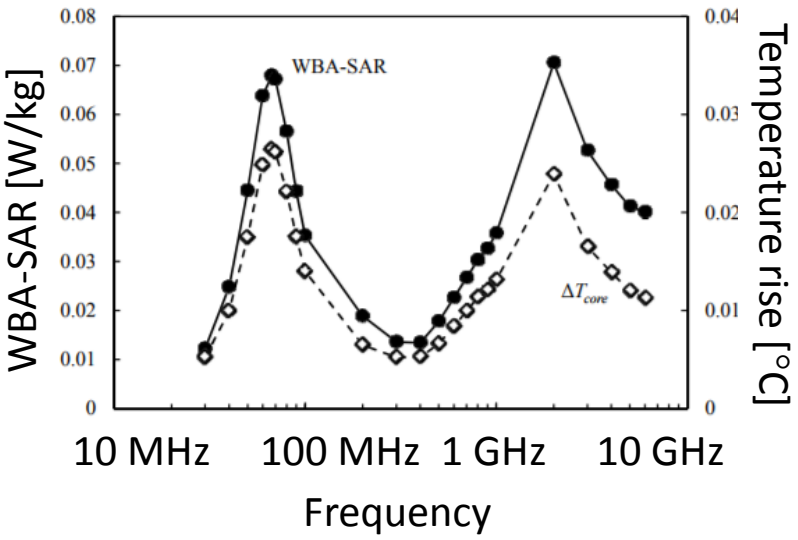
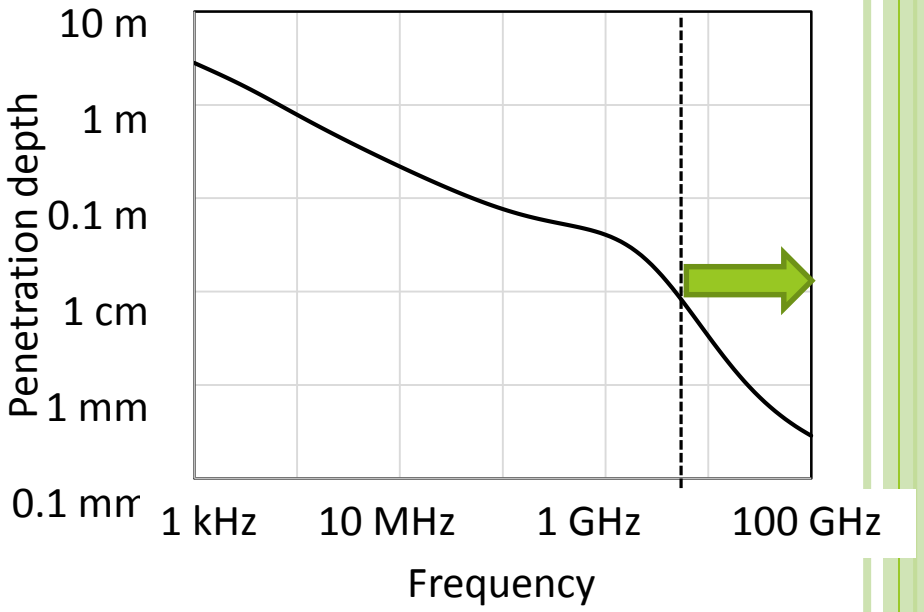
(As individual)

✓ Power absorption in biological tissues from 100 kHz to 300 GHz

- In frequency band between 30 MHz and 130 MHz, the resonance occurs over the body, corresponding to 0.4-0.45 wavelength in free space.
- From a few hundreds megahertz to GHz region, (weak) partial-body resonance may occur.
- Above a few gigahertz (3 or 6 GHz) power absorption is superficial (skin).



Whole-body averaged SAR for exposure at the field strength of the ICNIRP Reference level.



With the increase of frequency, the penetration depth becomes shallower.

Above 6 GHz, skin surface heating is dominant.

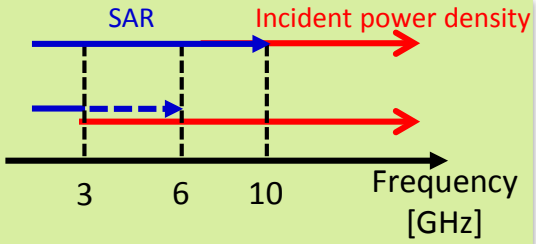
✓ On human protection above 6 GHz

Physical Quantities in Standards

- **SAR** Specific Absorption Rate [W/kg]
  Averaged over 10 g of tissue
- **Incident Power Density** [W/m^2]
  Averaged over a specific area

1. SAR applicable frequencies

- ICNIRP guidelines†
- IEEE standard††



2. Incident Power Density (Basic Restriction: 10 [W/m^2])

- ICNIRP guidelines†
  20 [cm^2] (10 - 300 GHz)
- IEEE standard††
  - $100\lambda^2$ [cm^2] (3 - 30 GHz)
    (λ[cm] : wavelength)
  - 100 [cm^2] (above 30 GHz)

Definition are different in guidelines/standard

Only a limited numbers of papers were available for frequencies higher than 6 GHz. mmW use was not expected = Scientific rationale is needed.

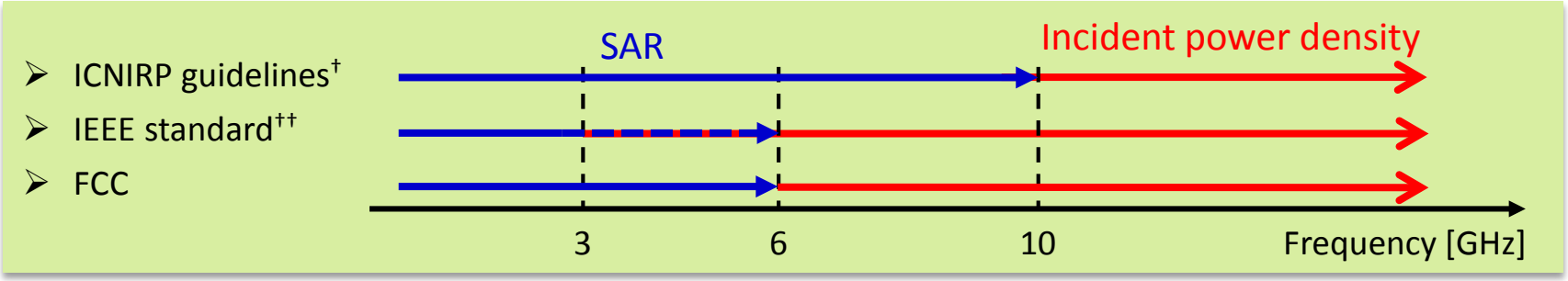
➡ Necessity of reassessment of physical quantities and limit

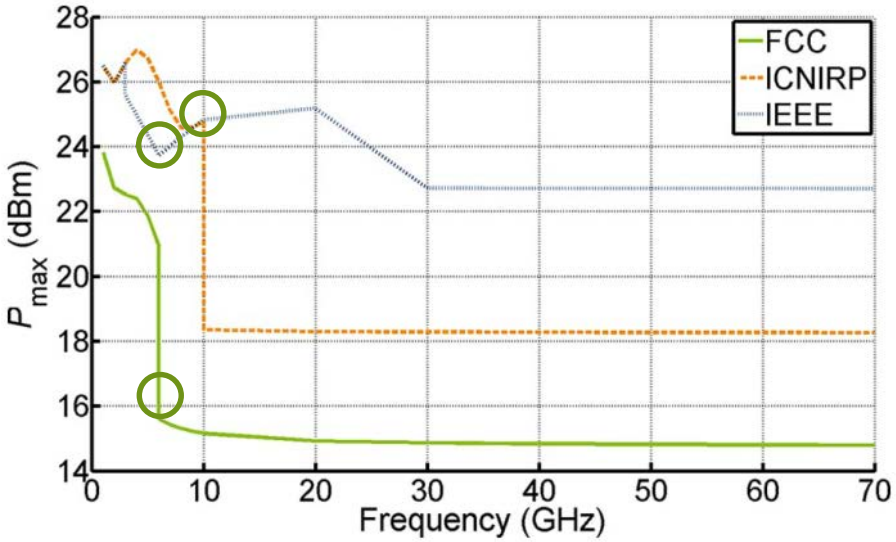
† ICNIRP: "Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300GHz)",Health Phys., vol.74, pp.494-522, 1998.

†† IEEE C95-1 : "IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3kHz to 300GHz", 2005.

✓ Gap at 3-10 GHz (Local SAR versus incident power density)

- SAR is internal physical quantities, while incident power density is external ones.
- As compared with local SAR, the number of papers investigating the relationship between temperature elevation and incident power density are limited.





Relation between incident power density and its averaging area should be discussed simultaneously.

D. Colombi et al, IEEE Antenna & Wireless Propagat. Letts., 2015.

* Note in the ICNIRP guidelines (for small area) was not considered.

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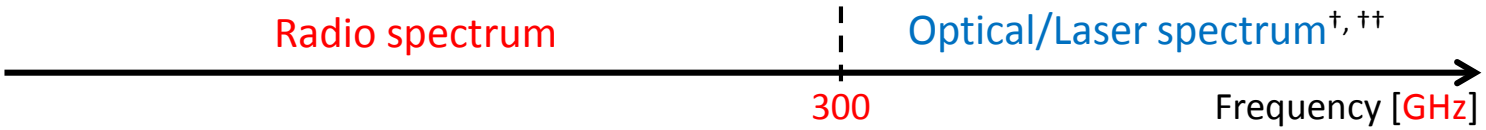
✓ Gap at 300 GHz (Radio-wave versus optical radiation)

1. ICNIRP has optical radiation guidelines (> 300 GHz) in addition to EMF guidelines (< 300 GHz). ANSI has also has a laser standard (under revision).
2. There are two guidelines in the optical regime of the ICNIRP: Incoherent visible and infrared radiation and laser radiation.

ICNIRP guidelines



Radio-wave

1. General public versus Occupational environment
2. Definition of Averaging time

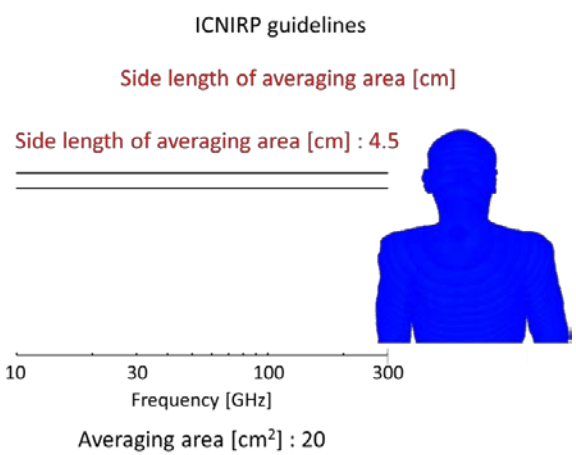
Optical Radiation

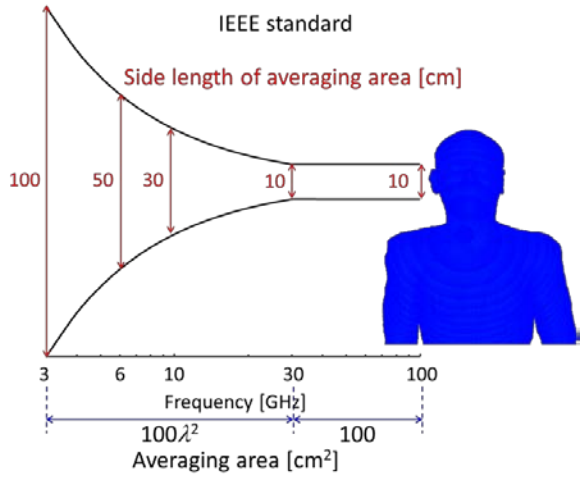
- No definition of environment†, ††
- No definition of averaging time
- Intense short-time exposure (< 10 sec) ††
- Averaging area (approximately 1 cm^2), depending on the frequency (wavelength)

It would be preferable if the RF guidelines match up with the optical guidelines.

† ICNIRP. Guidelines on Limits of Exposure to Laser Radiation of Wavelengths between 180 nm and 1,000 µm. Health Phys. 2013; 105(3): 271-95.
†† ICNIRP. Guidelines on limits of exposure to incoherent visible and infrared radiation. Health Phys. 2013; 105(1): 74-96.

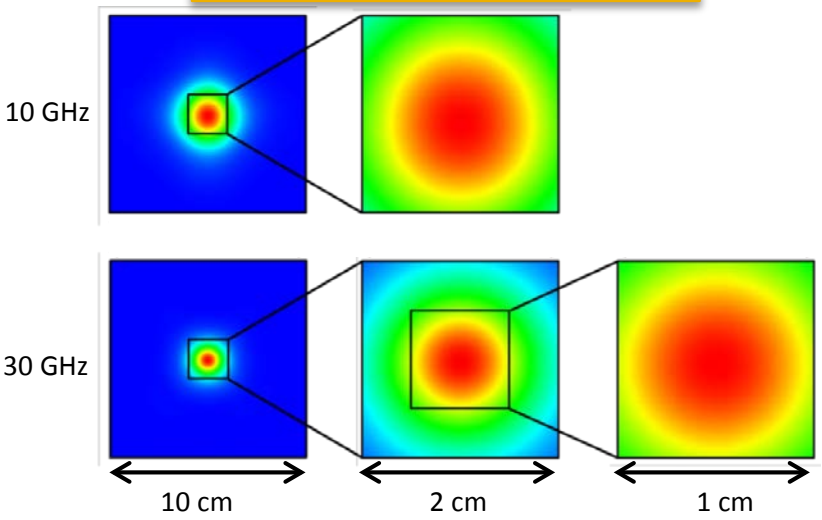
✓ Averaging area of Incident Power Density (1)

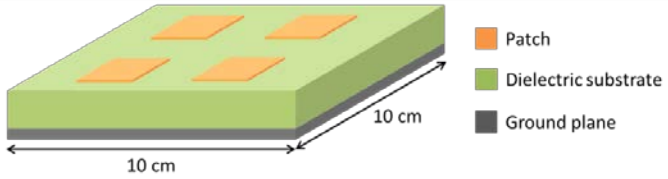




ICNIRP Guidelines†
Frequency independent

IEEE Standard C95.1††
Dependent on frequency from 3 to 30 GHz





Patch antenna array with 4 elements

Averaging area of incident power density
May not depend on the frequency (except for small beam)
Can be correlated with temperature rise

Distributions of power density for patch antenna array with 4 elements

† ICNIRP: "Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300GHz)",Health Phys., vol.74, pp.494-522, 1998.

†† IEEE C95-1 : "IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3kHz to 300GHz", 2005.

✓ Averaging area of Incident Power Density (2)

ICNIRP Guidelines

20cm^2 (Reference level 10 W/m^2). 20 times higher RL can be allowed for the area of 1 cm^2 (200 W/m^2).

IEEE Standard

3-30 GHz : 100λ^2 [cm^2] (λ : wave length in free space[cm])

> 30 GHz: 100 cm^2

Recent research papers

6 (10)-30 GHz : 4 cm^2, at higher frequencies: 1cm^{2†}

Circle with a diameter of 1.5 cm (approximately heat conduction distance in biological tissues) ††

Averaging area of incident power density :

Scientific results suggest the averaging area of 1-4 cm^2

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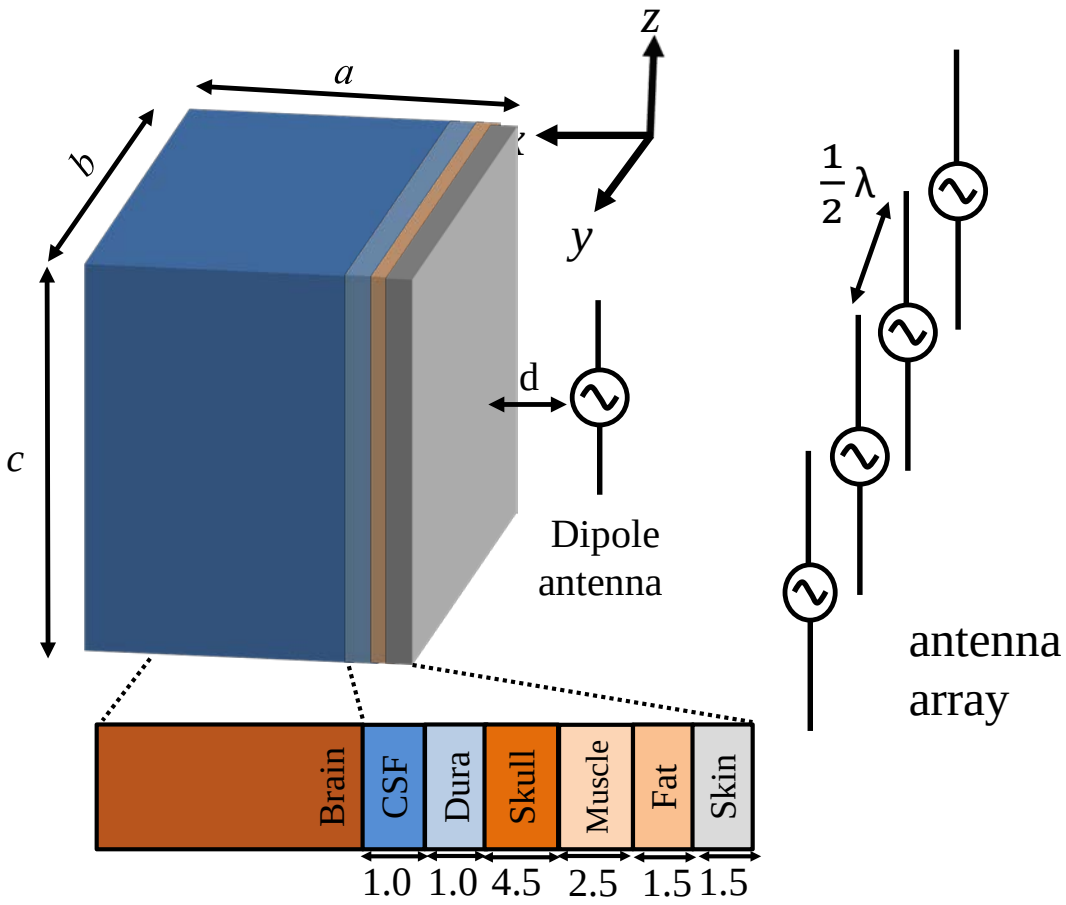
† Hashimoto Y, Hirata A, Morimoto R, Aonuma S, Laakso I, Jokela K, Foster K R. On the averaging area for incident power density for human exposure limits at frequencies over 6 GHz. Phys. Med. Biol. 2017; 62(8): 3124-38.

†† Foster K R, Ziskin M C, Balzano Q. Thermal modeling for the next generation of radiofrequency exposure limits: commentary. Health Phys. 2017; 113(1): 41-53.

✓ Computational Examples (exposure from dipole antenna and its array)



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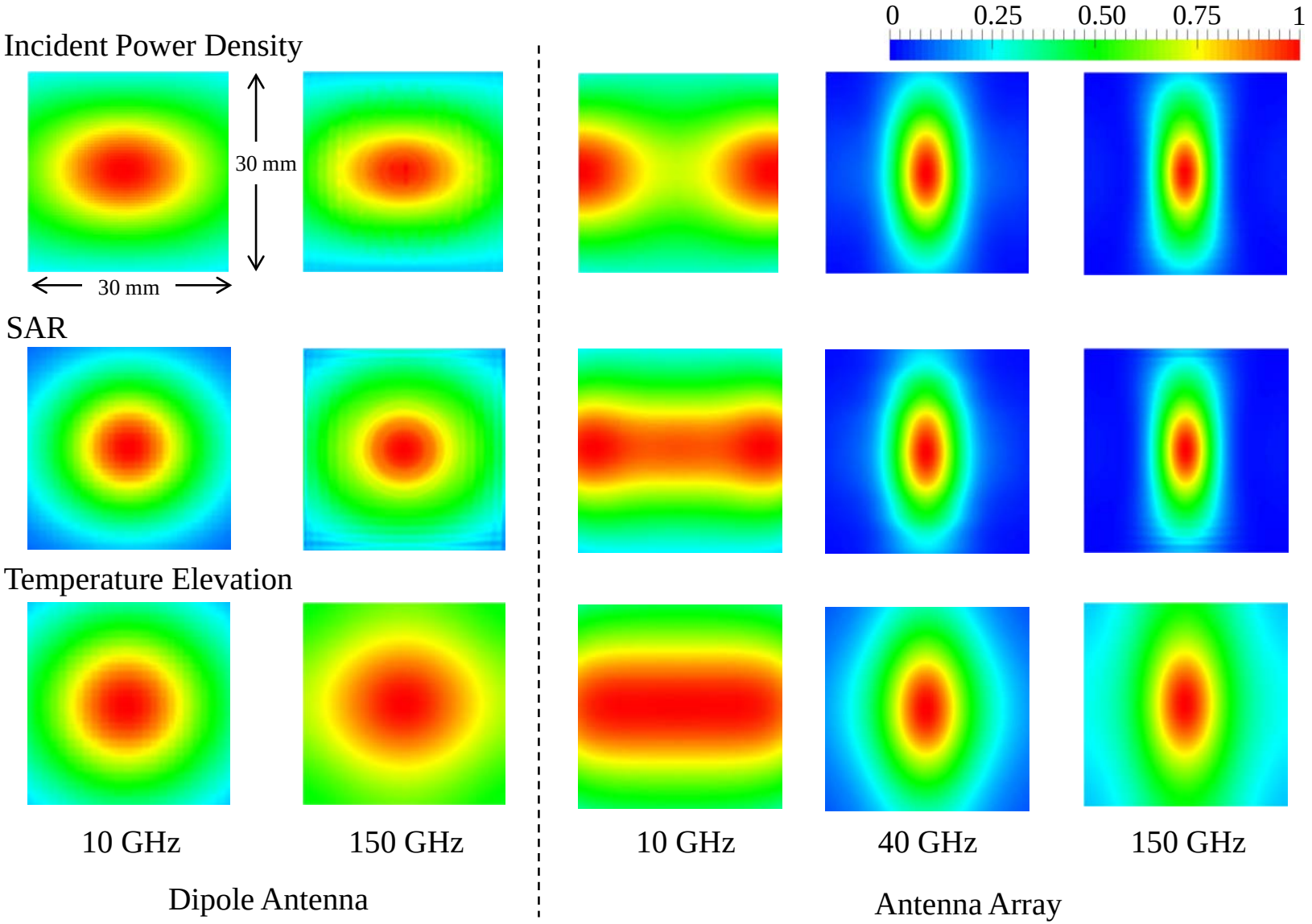
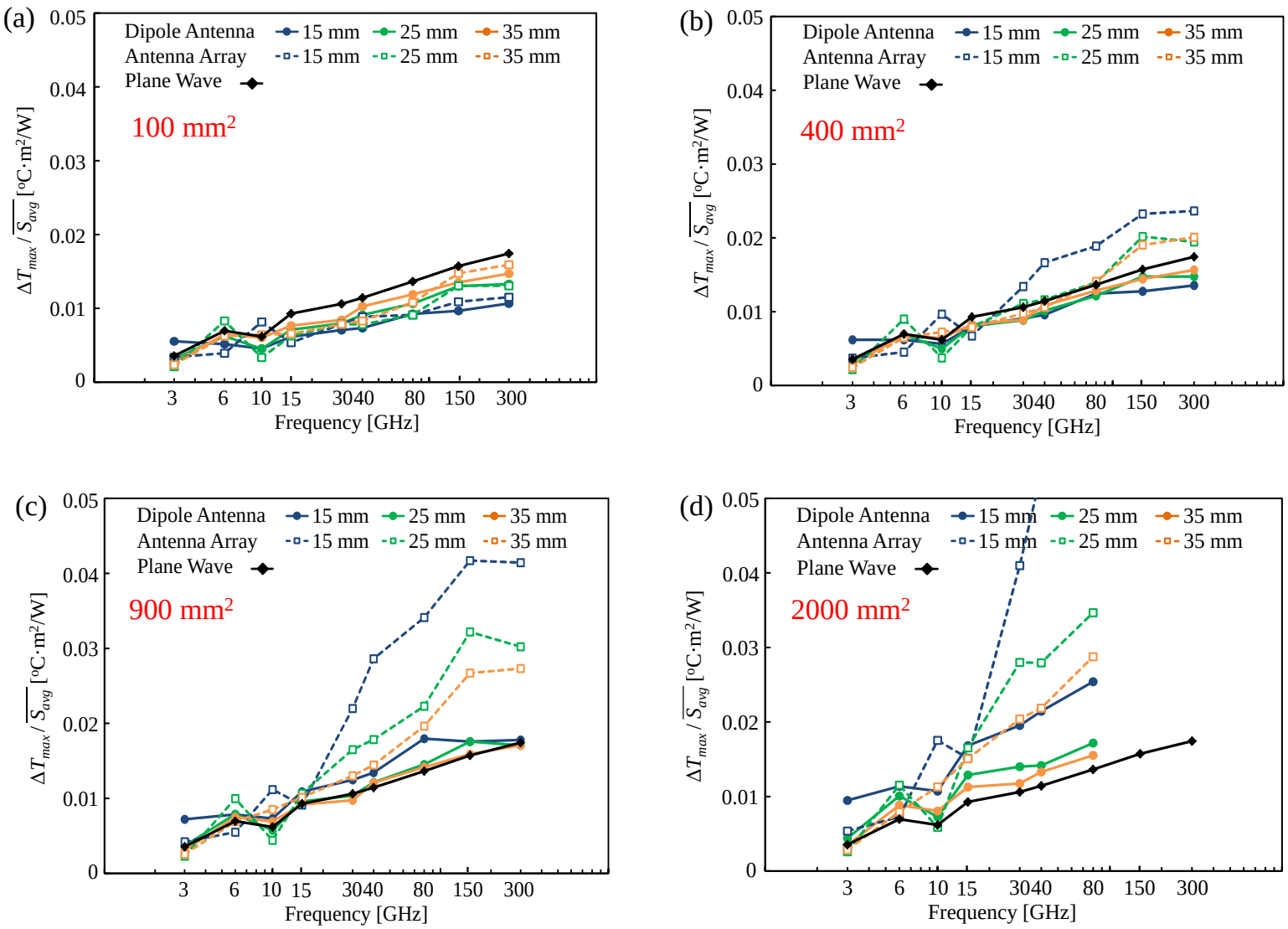
✓ Incident Power Density, SAR, and Temperature Distributions

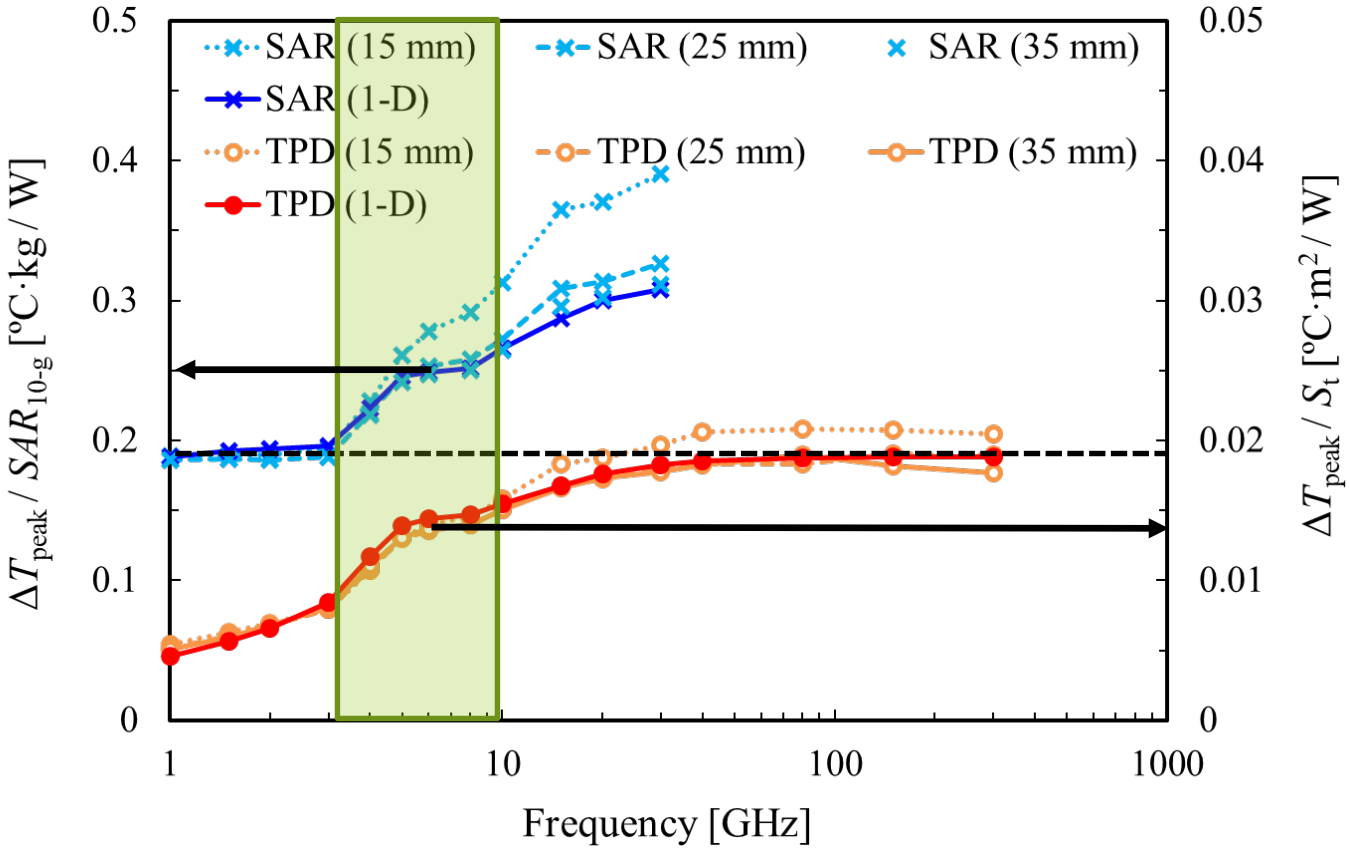


✓ Effect of Averaging Area on Heating Factor (Ratio of ΔT to Avg. Inc. Power Density)



✓ What is appropriate “dose” above 3-10 GHz.

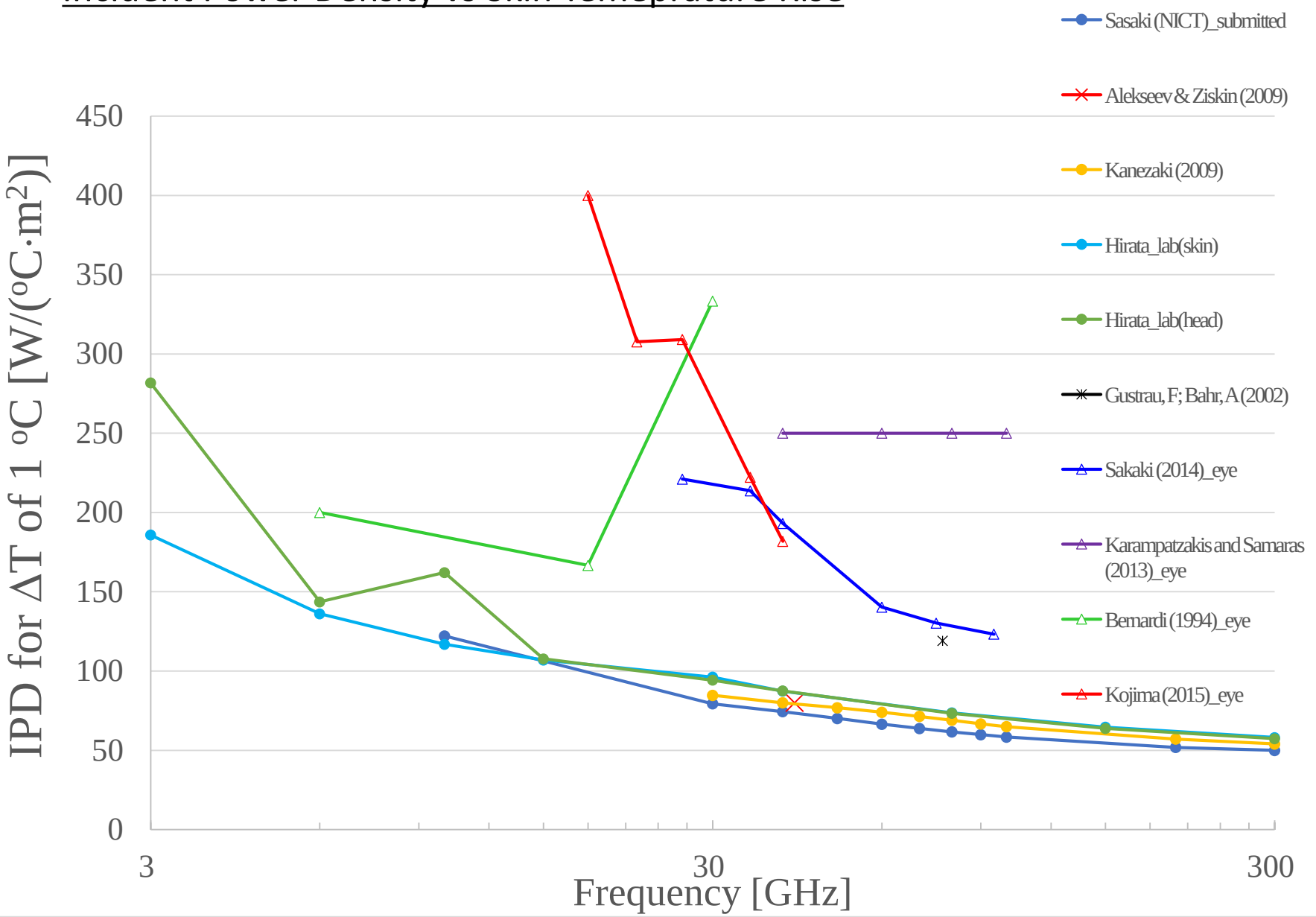
Heating Factor of dipole antenna for SAR (10 g) and Transmitted Power Density (4 cm^2)



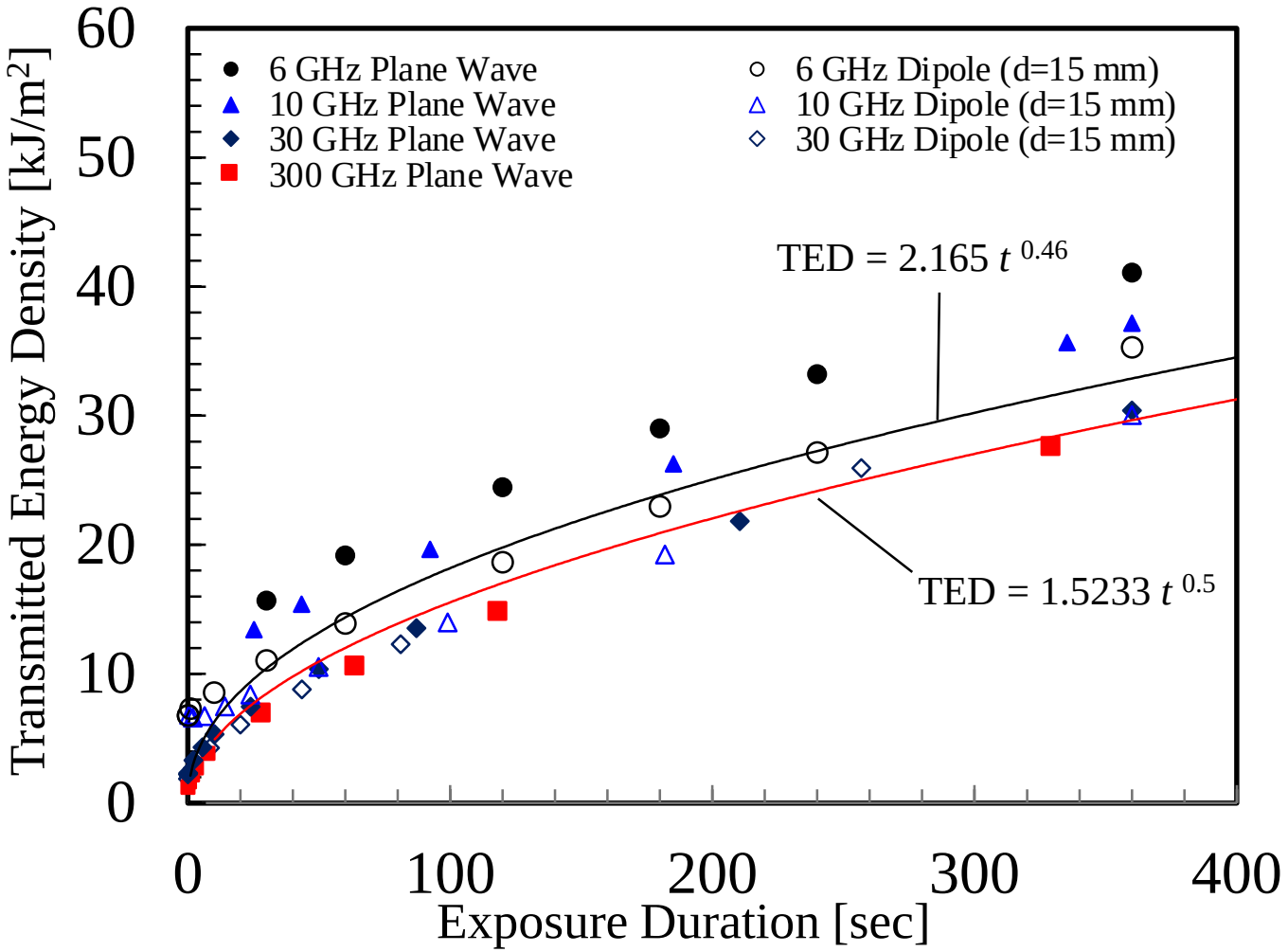
The boarder frequency is ~ 6 GHz. Above that transition, the power transmitted to the human (mainly in the skin) is good surrogate to estimate the temperature rise.

Frequency independent BR/DRL can be derived from the heating factor.

✓ Incident Power Density vs Skin Temeprature Rise

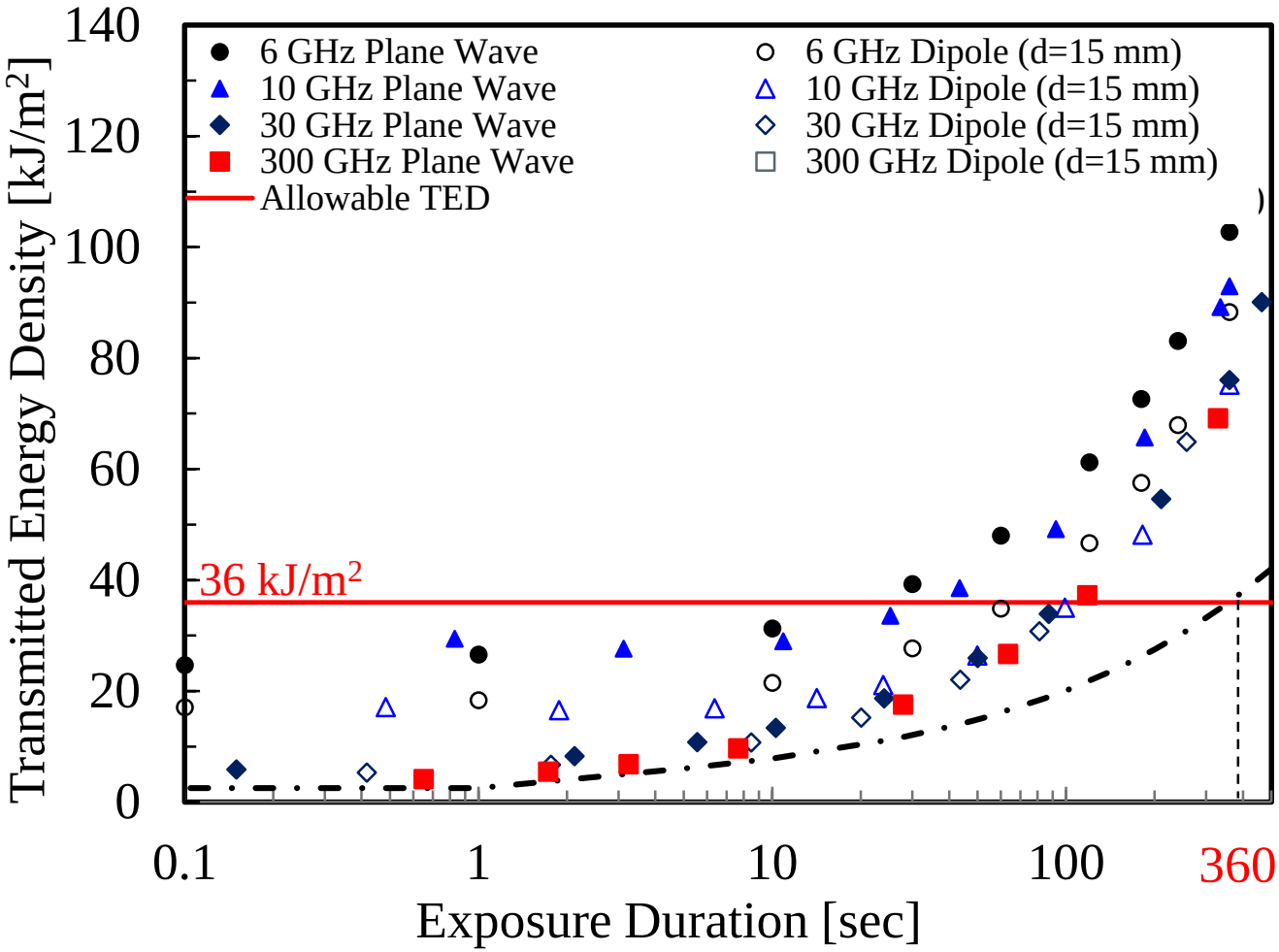


✓ Transmitted Energy Density (TED) required for ΔT of 1 °C



The transmitted energy density required to certain temperature rise may follow the function of $t^{0.5}$ as suggested in Foster et al (2017).

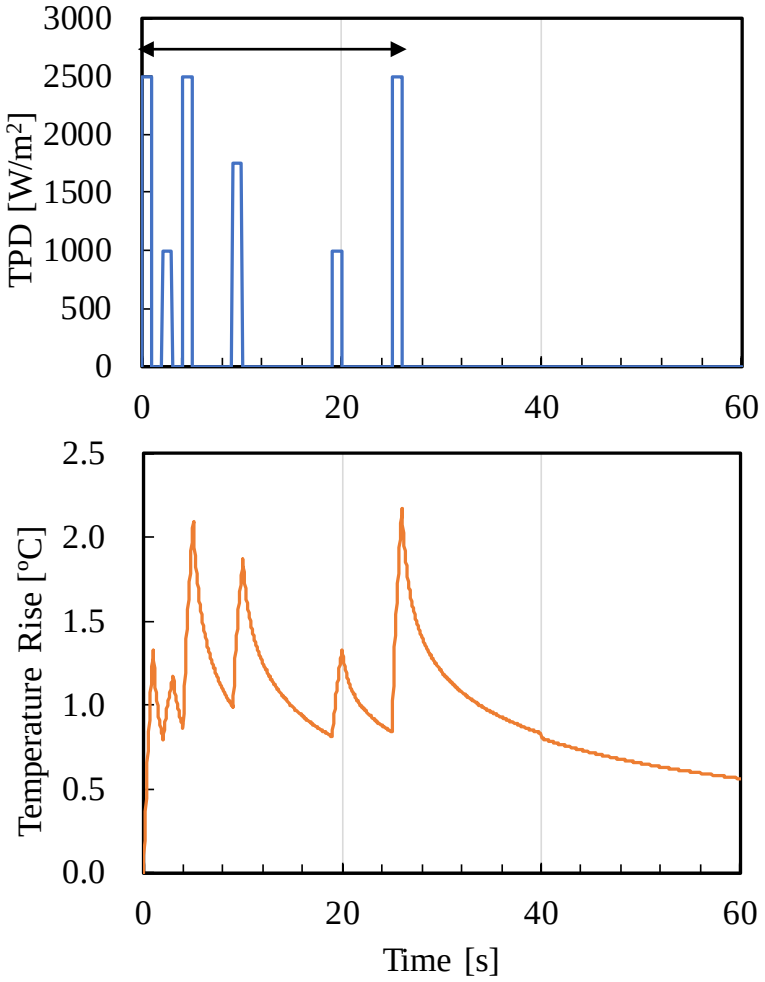
✓ Can TED match up for CW exposure?



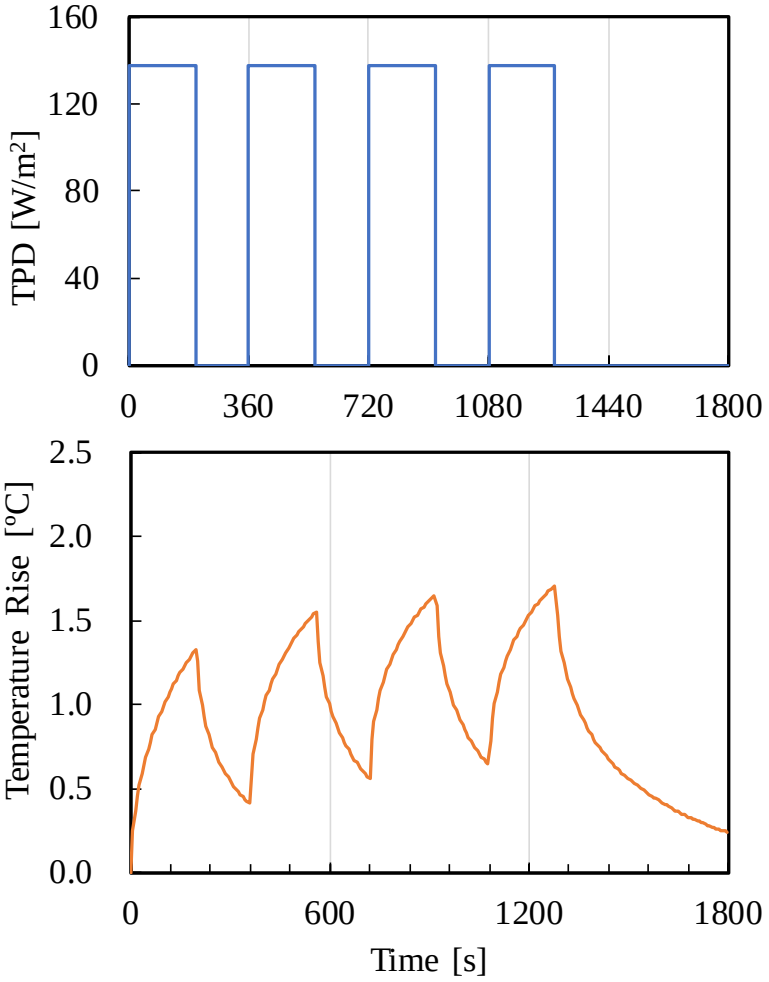
Regression curve for the allowable TED matches up that of 36 kJ/m^2 at 6 min.

Temperature Rise for Multi-pulse Exposure

a) 300 GHz Plane Wave (1-sec pulse)



b) 300 GHz Plane Wave (200-sec pulse)



Amplitude of multiple pulses was set so as to satisfy the TED regression curve.

Summary

- Transmitted power density (TPD) is a good metric to estimate the temperature elevation in the skin at frequencies above 3-10 GHz.
- 2cm*2cm is appropriate averaging area for of IPD/TPD; at higher frequencies, smaller averaging area may be needed.
- Transmitted power density (TED) is a good metric to estimate brief exposure; if matching up with CW exposure at 6 min, computation suggests it applicability for different pulse patterns.
- In international standard/ guidelines, the ambient condition etc is included in reduction/safety factor.

Our publication above 6 GHz

- R. Morimoto, I. Laakso, V. De Santis, and A. Hirata, “Relationship between peak spatial-averaged specific absorption rate and peak temperature elevation in human head in frequency range of 1-30 GHz,” Physics in Medicine and Biology, vol.61, no.14, pp.5406-5425, 2016.
- R. Morimoto, A. Hirata, I. Laakso, M. C. Ziskin, and K. R. Foster, “Time constants for temperature elevation in the human models exposed to dipole antennas and beams from 1 to 30 GHz,” Physics in Medicine and Biology, vol.62, no.5, pp.1676-1699, 2017.
- Y. Hashimoto, A. Hirata, R. Morimoto, S. Aonuma, I. Laakso, K. Jokela, and K. R. Foster, “On the averaging area for incident power density for human exposure limits at frequencies over 6 GHz,” Physics in Medicine and Biology, vol.62, no.8, pp.3124-3138, 2017.
- I. Laakso, R. Morimoto, J. Heinonen, K. Jokela, and A. Hirata, “Human exposure to pulsed fields in the frequency range from 6 to 100 GHz,” Physics in Medicine and Biology, vol.62, pp.2017.
- Manuscripts on TPD and brief exposure are in preparation.