Wireless (RF) Power "Harvesting" *in Large-Area Electronics*

EnerHarv 2024
PSMA International Workshop | 26-28 June, 2024 | Perugia, Italy

Dr Mahmoud Wagih

Lecturer (Ass't Prof.) and UK IC Research Fellow – Univ. of Glasgow
Visiting Fellow – Univ. of Southampton
Founder – RX WaTT Ltd.

GREENElectronicsLab.org

University of Glasgow
Royal Academy of Engineering
UKRI Engineering and Physical Sciences Research Council
Government Office for Science – UK IC Postdoctoral Research Fellowship Programme
dstl – The Science Inside
The Royal Society

My commercial experience:

Are we (really) expecting 1 Trillion Devices?!

Mahmoud.Wagih@Glasgow.ac.uk

RX WaTT

My commercial experience:

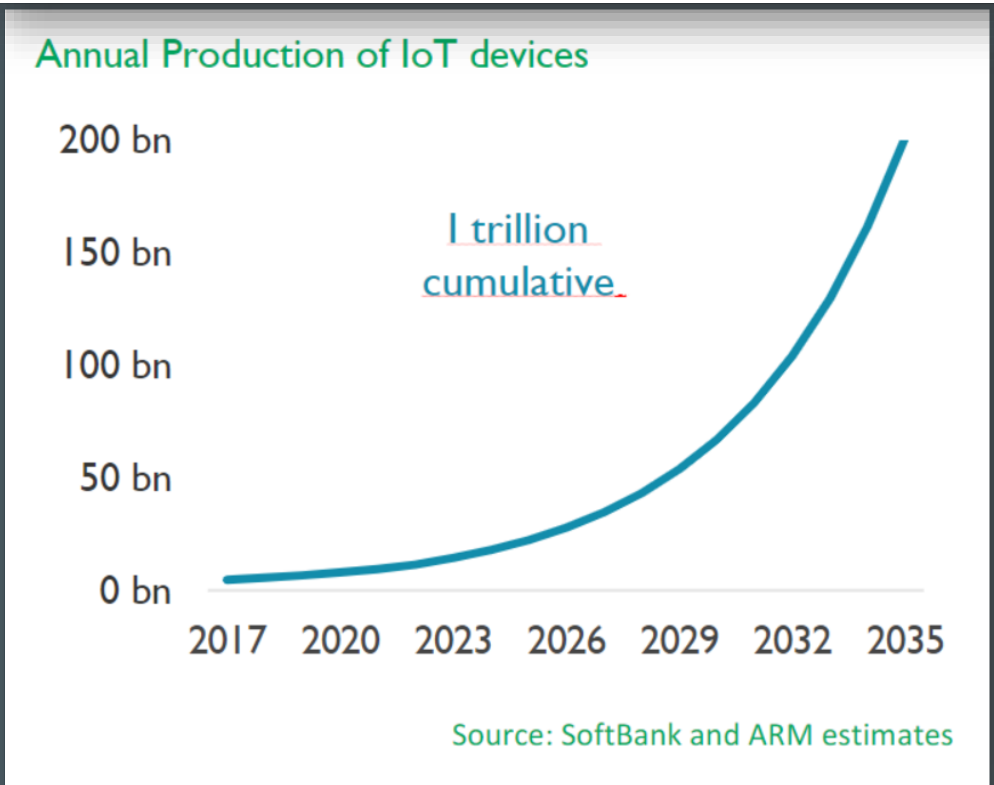
ing

GSMArena.com

Arm will reportedly lay off 15% of its workers following a failed Nvidia acquisition

Arm will reportedly lay off 15% of its workers following a failed Nvidia acquisition ... Last month, Nvidia officially confirmed that its acquisition of Arm was...

Mar 15, 2022



Point of View

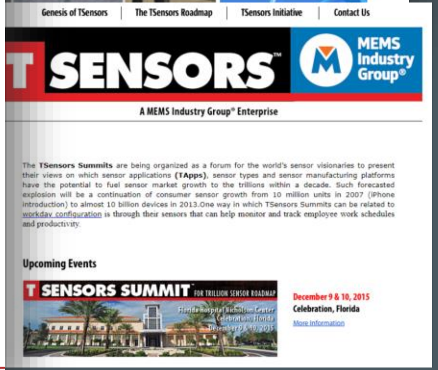
The Internet of Everything
How More Relevant and Valuable Connections Will Change the World

Dave Evans

The Trillion Sensors (TSensors) Foundation for the IoT

Dr. Janusz Bryzek
Chairman and CEO, TSensors Summit

TSensors Summit



Mahmoud.Wagih@Glasgow.ac.uk

Audience Guess:

How Many “Energy Harvesting”-Powered Devices?

“1 billion
harvester a year [2020-2040]”

– IDTechEx Report

“38 billion
RFID tags in 2023 [alone]”

– IDTechEx Report

Enabled by wireless power

Mahmoud.Wagih@Glasgow.ac.uk

1960s Wireless Power: Tesla or Brown?

1230 IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. MTT-32, NO. 9, SEPTEMBER 1984

The History of Power Transmission by Radio Waves

WILLIAM C. BROWN, FELLOW, IEEE

Abstract—The history of power transmission by radio waves is reviewed from Heinrich Hertz to the present time with emphasis upon the free-space microwave power transmission era beginning in 1958. The history of the technology is developed in terms of its relationship to the intended applications. These include microwave powered aircraft and the Solar Power Satellite concept.

into motion a number of activities that were to rapidly become the foundation of the technology of microwave power transmission.

The style of treatment used by the author to present the history varies with the time period. The early history, of

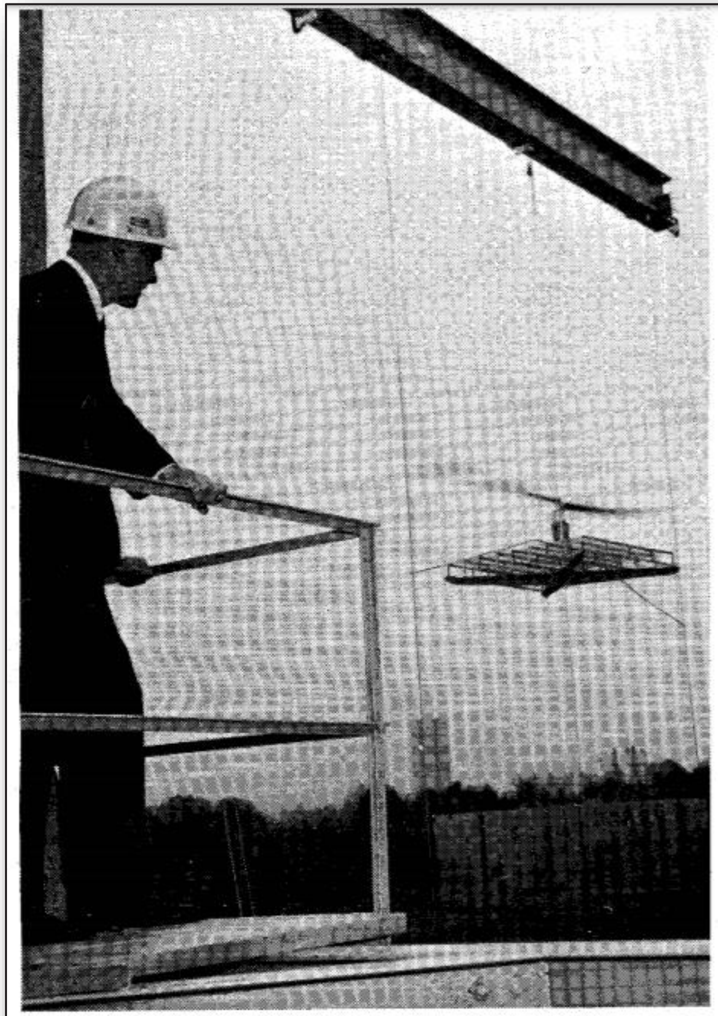


Fig. 5. Microwave-powered helicopter in flight 60 ft above a transmitting antenna. The helicopter was demonstrated to media in October 1964. A 10-h sustained flight was achieved in November of that same year.

"… dispel the *widespread but incorrect assumption* that power density always fell off as the square of the distance"

–W. C. Brown, 1984

RF Power Transmission

All electrical power, *no transduction* – **any electronic material can be used**

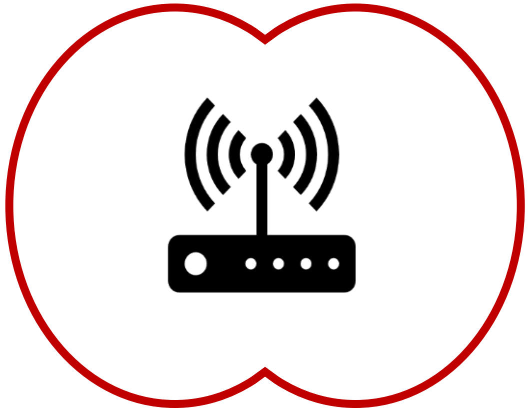
RF radiation spreads spherically

- Power proportional to 1/distance^2 in free space.

$$P_{\mathrm{RX}}(t) = S A_{\mathrm{Effective}} \; [\mathrm{W}]$$

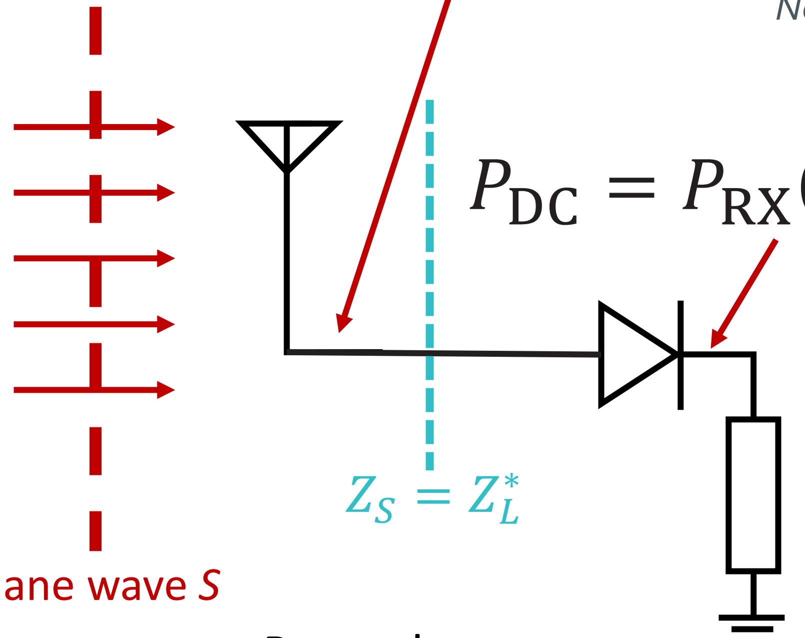
Not physical

Limited by regulations (4 W unlicensed)



Power transmitter

$$S(t) = \frac{P_{\mathrm{TX}} G_{\mathrm{TX}}}{4\pi d^2} \; [\mathrm{W/m^2}]$$



$$P_{\mathrm{DC}} = P_{\mathrm{RX}}(t) \times \mathrm{PCE}$$

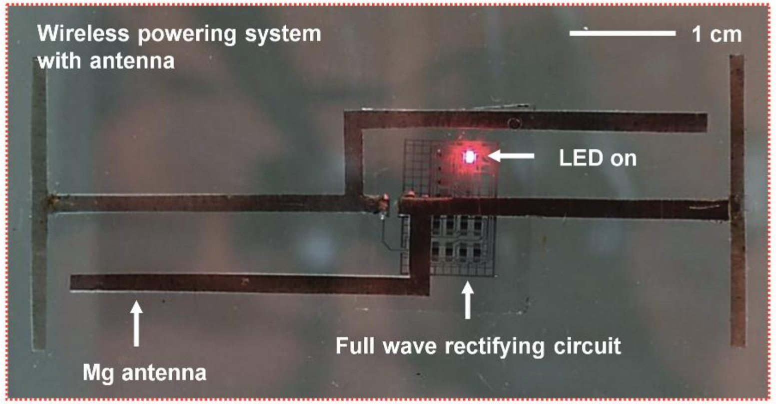
Power Conversion Efficiency

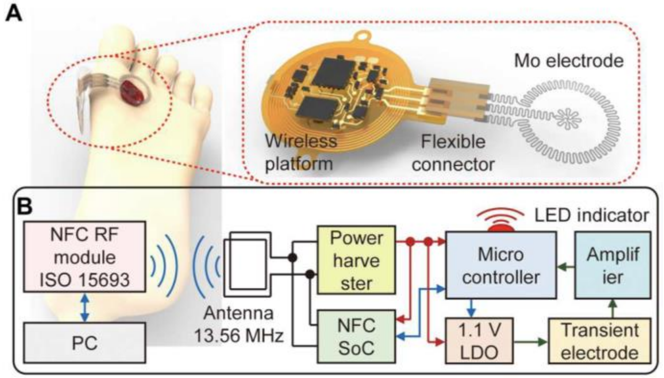
Power harvester (RECTifying antENNA)

Wagih et al. "Rectennas for RF Energy Harvesting and Wireless Power Transfer: A Review of Antenna Design" ***IEEE Antennas Propag. Mag.*** 2020. DOI: 10.1109/MAP.2020.3012872

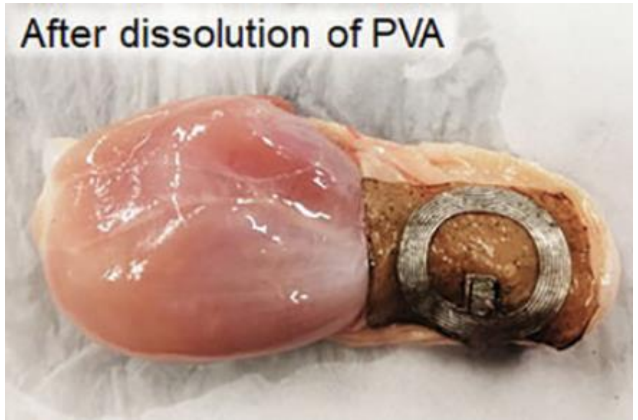
Mahmoud.Wagih@Glasgow.ac.uk

RF Power Transmission in:

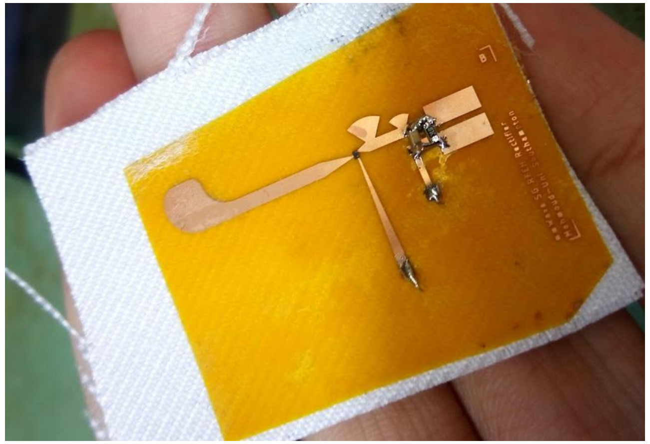


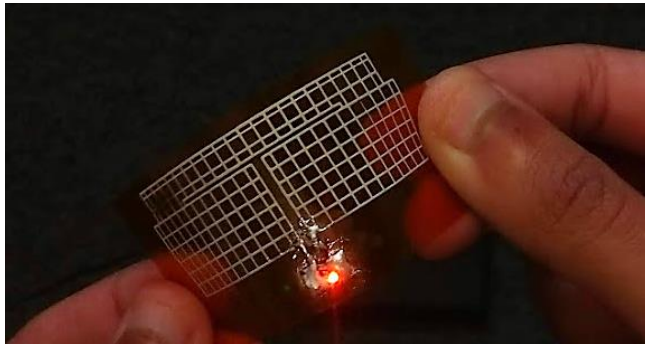


Bio-resorbable



Liquid



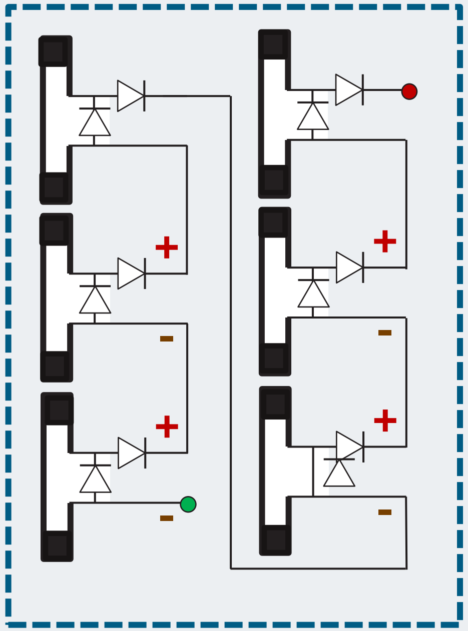


Flexible/Printed

Wagih and Beeby “Materials for Rectennas” in “Roadmap on Energy Harvesting Materials” ***JPhys Materials*** 2023

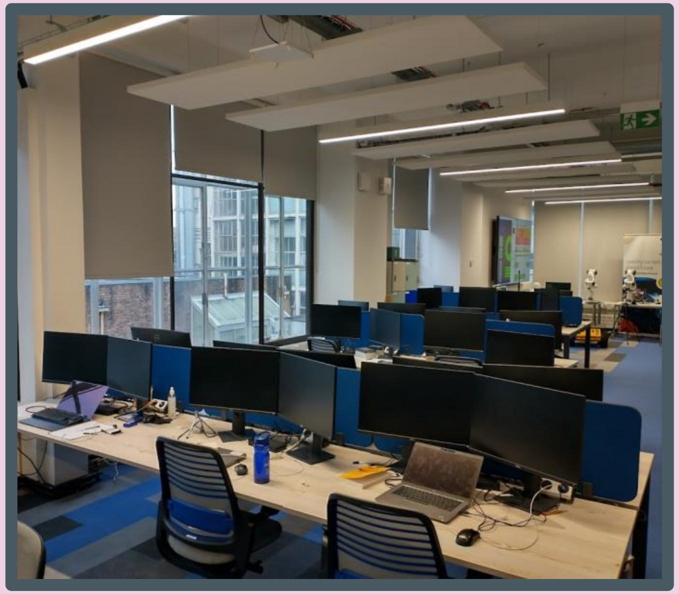
Mahmoud.Wagih@Glasgow.ac.uk

My RF Power Highlights



1. Enabling Principles

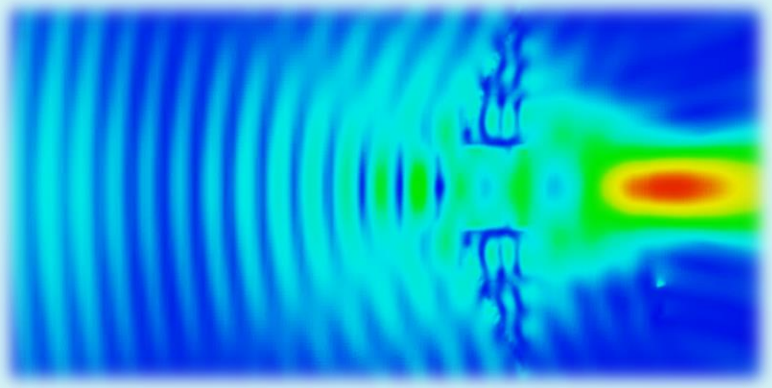
State-of-the-Art



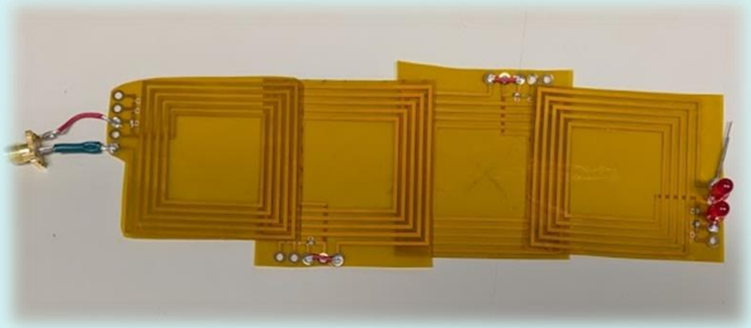
2. Practical Deployment

Use-case-Driven Testing

3. Generation-after-Next



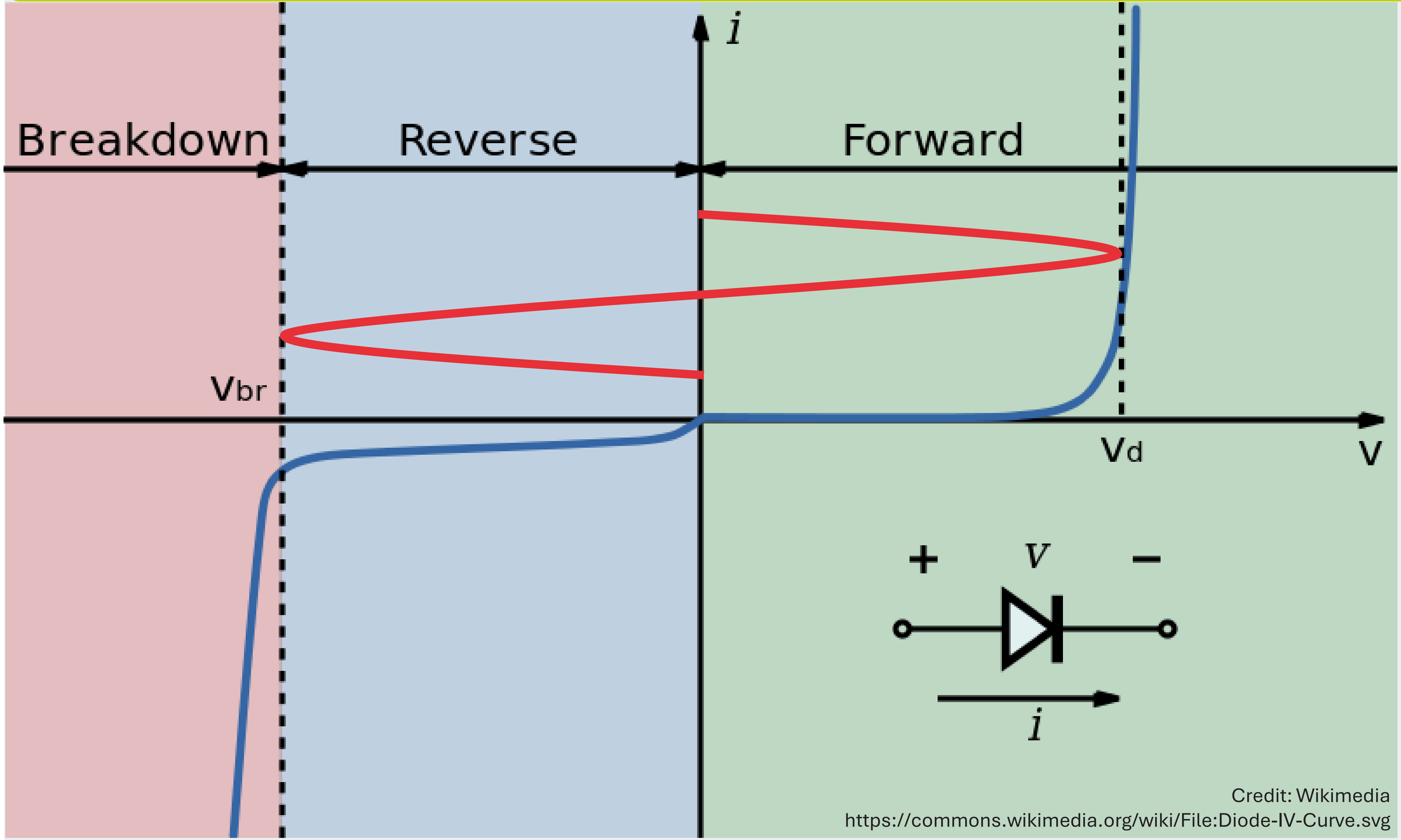
Quasioptic GHz Power



Near-Field
Beyond 1 m

Mahmoud.Wagih@Glasgow.ac.uk

Performance Limits? Diode Loss

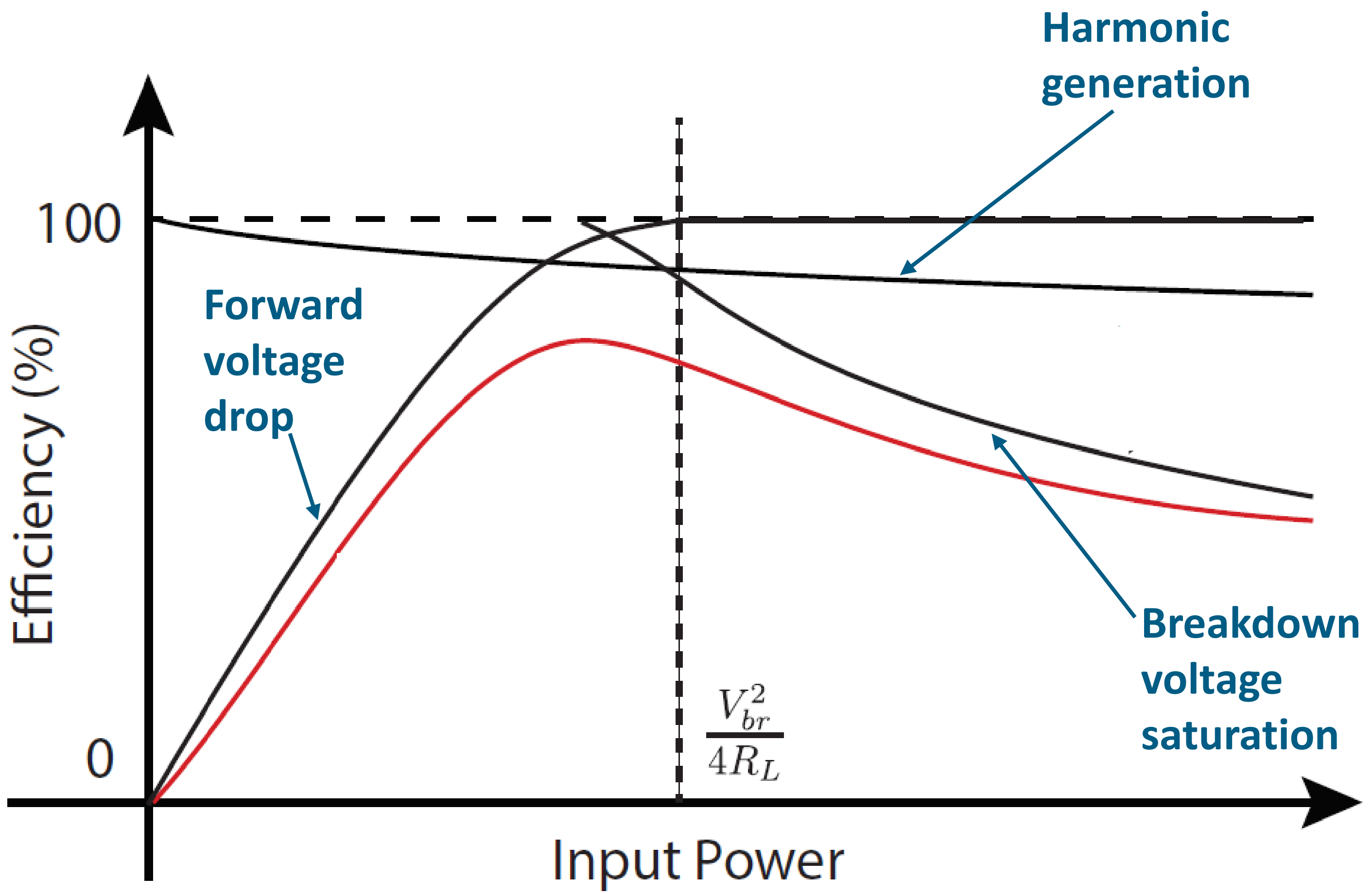


Credit: Wikimedia
https://commons.wikimedia.org/wiki/File:Diode-IV-Curve.svg

Breakdown and forward voltage bounds

Mahmoud.Wagih@Glasgow.ac.uk

Performance Limits?



Credit: Jo Bito, GaTech
https://smartech.gatech.edu/handle/1853/60157

Breakdown and forward voltage bounds

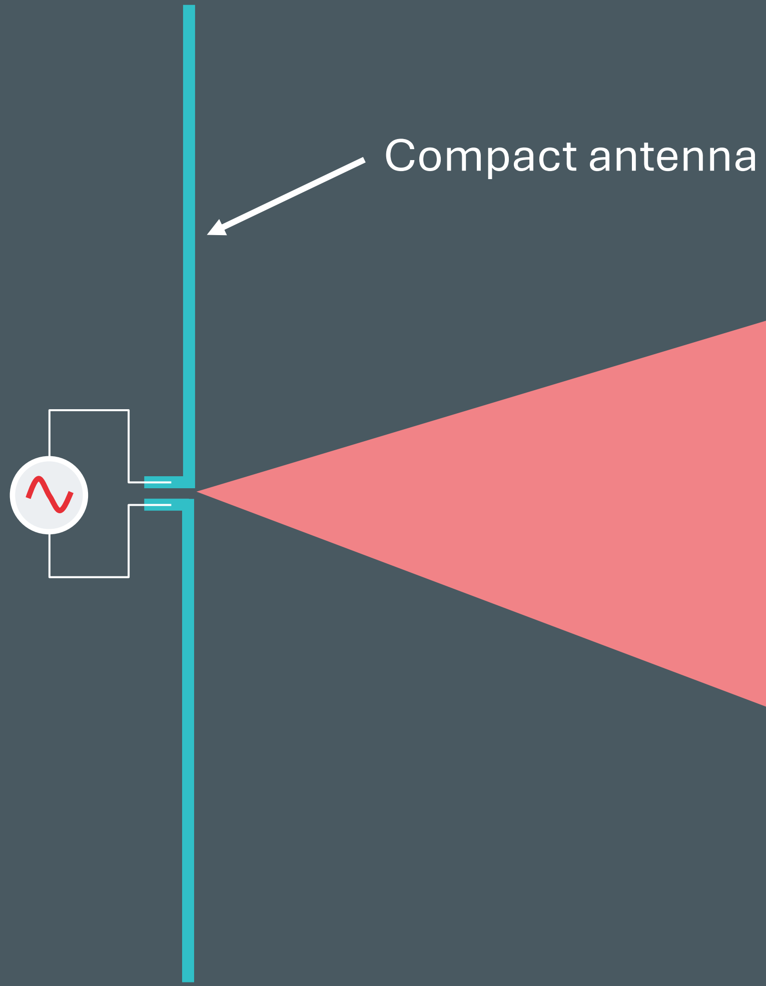
Mahmoud.Wagih@Glasgow.ac.uk

Practical RF Energy Harvesting Using

Arrays of "Small" Antennas?

Mahmoud.Wagih@Glasgow.ac.uk

Re-Introducing the Century-Old Dipole



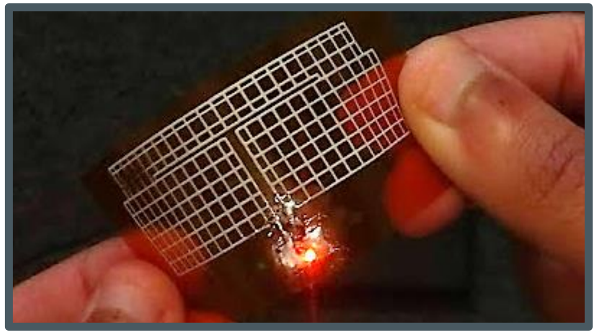
"The wire antenna can capture much more power than is intercepted by its physical size! This should not come as a surprise.

So electrically, *the wire antenna looks much bigger than its physical stature.*"

— Constantine A. Balanis

Antenna Theory & Design 2nd Edition pp. 90-91

$$A_{effective} = Gain\frac{\lambda^2}{4\pi}$$



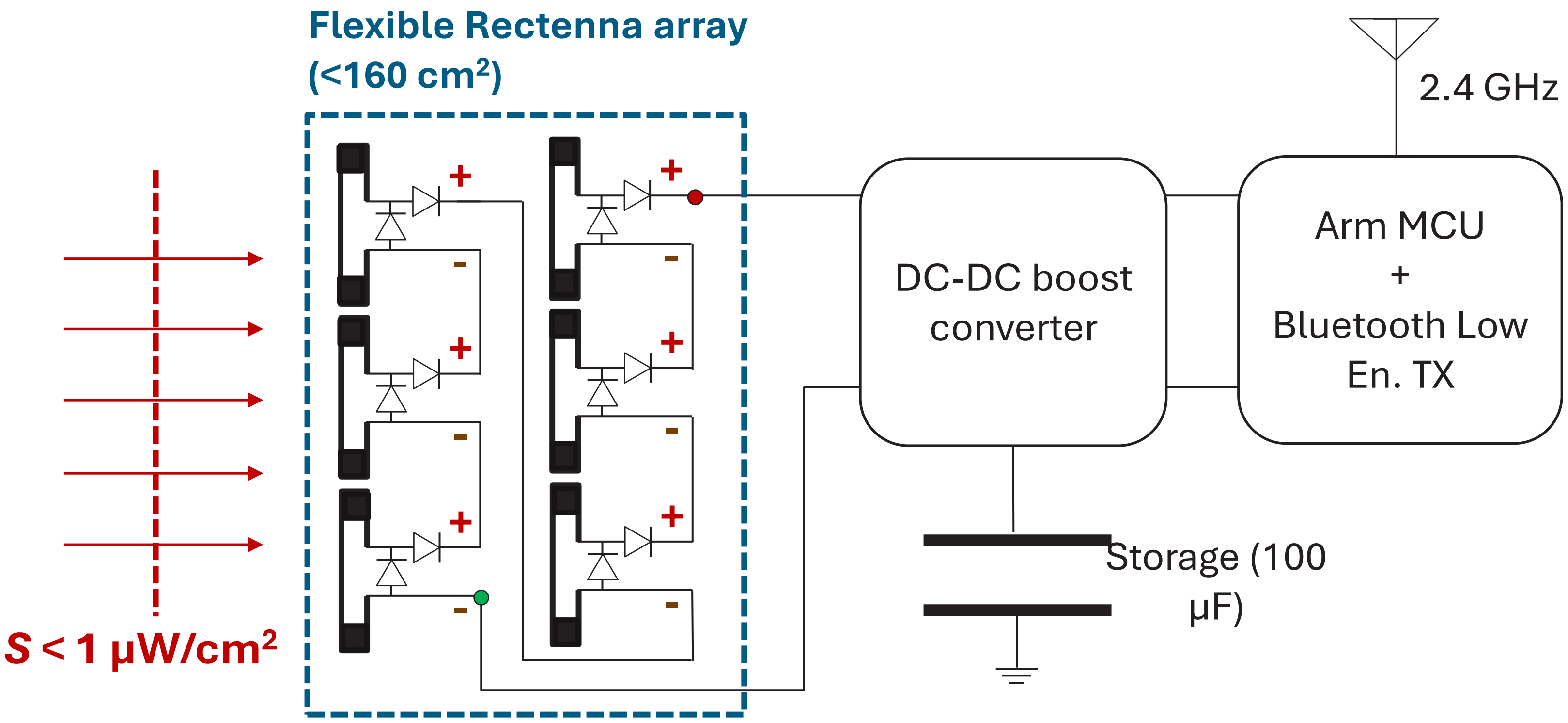
IEEE Open J. Antennas Propag. 10.1109/OJAP.2020.3038001

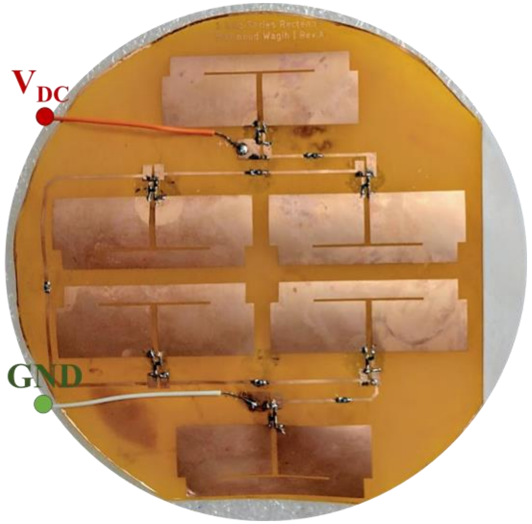
Mahmoud.Wagih@Glasgow.ac.uk

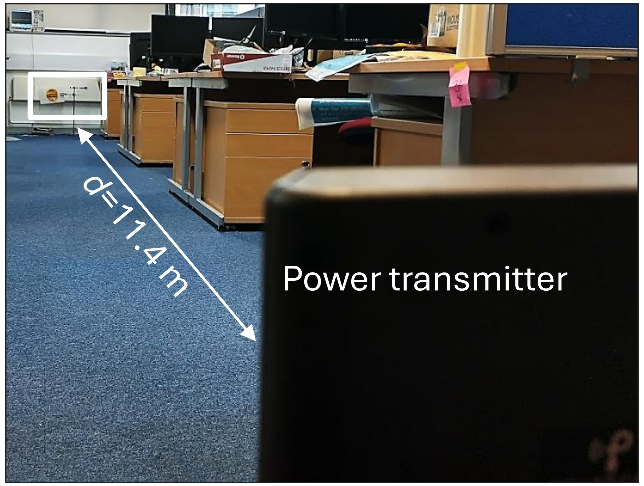
Scaling Tightly-Coupled **Dipoles**

"Antenna array elements should be spaced by λ/2" **?**

- Tightly coupling small 900 MHz rectennas
- DC combining with RF blocking
- 2D on a flexible substrate







Wagih and Beeby "Thin flexible RF Energy Harvesting Rectenna Surface" ***IEEE Trans. Microw. Theory Techniq.*** 2022

Scaling Tightly-Coupled Dipoles

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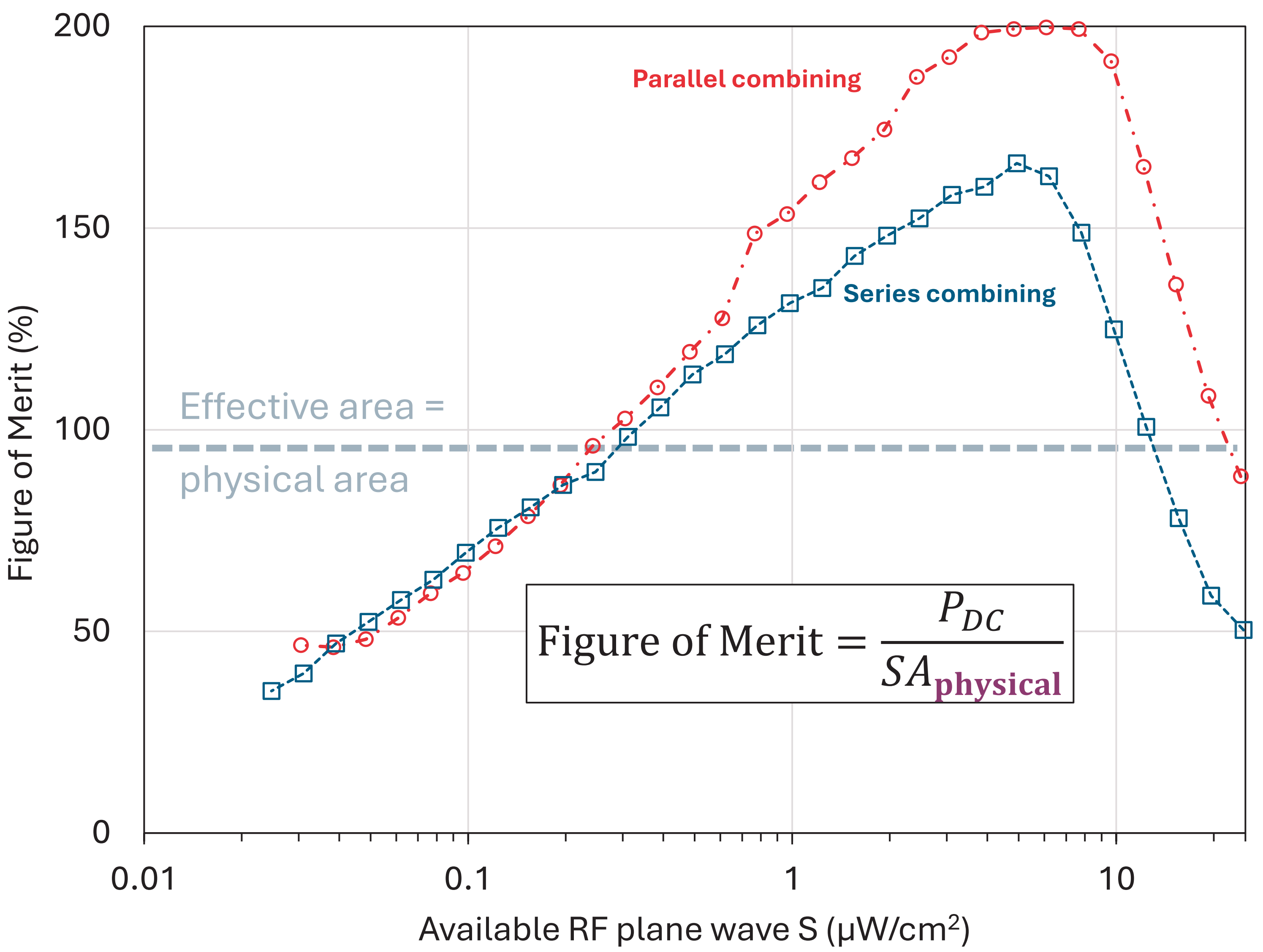
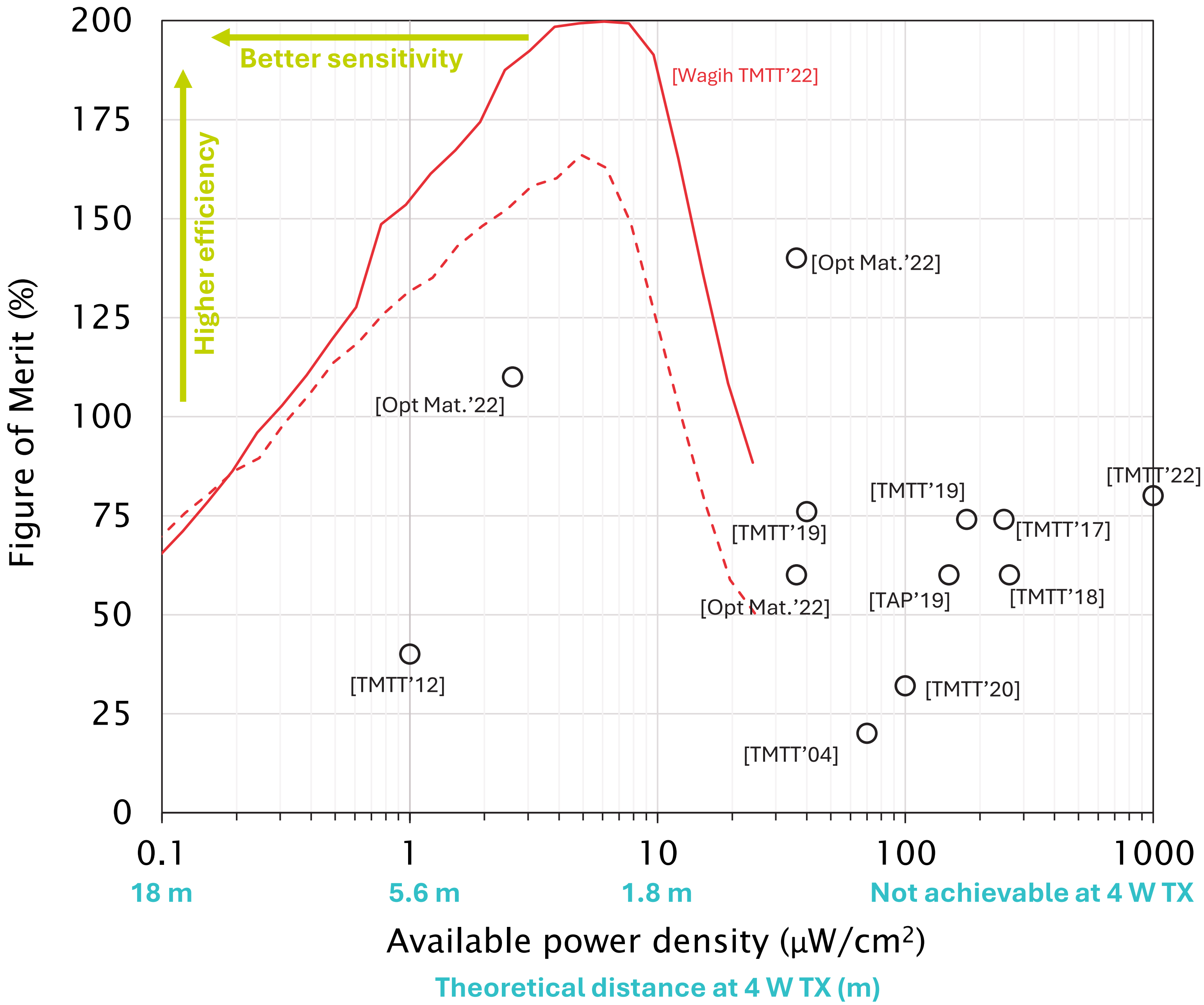


Wagih and Beeby "Thin flexible RF Energy Harvesting Rectenna Surface" ***IEEE Trans. Microw. Theory Techniq.*** 2022

Scaling Tightly-Coupled **Dipoles**

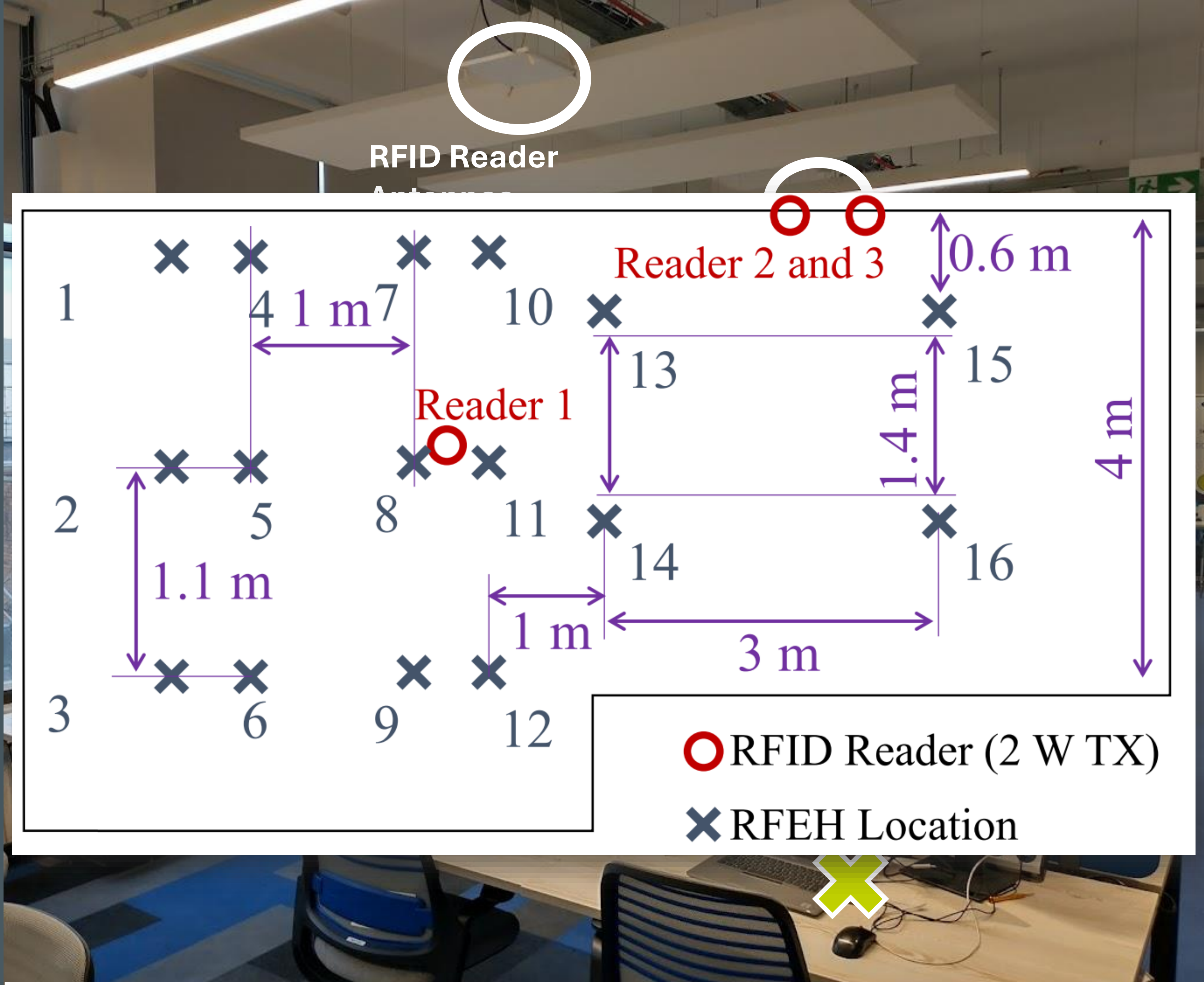
- Best reported “efficiency” relative to area
- Best sensitivity due to rectifier optimization
- Lowest cost, thinnest, 2D implementation



Wagih and Beeby "Thin flexible RF Energy Harvesting Rectenna Surface" ***IEEE Trans. Microw. Theory Techniq.*** 2022

Deploying Wireless Power:

An RFID "Grid"

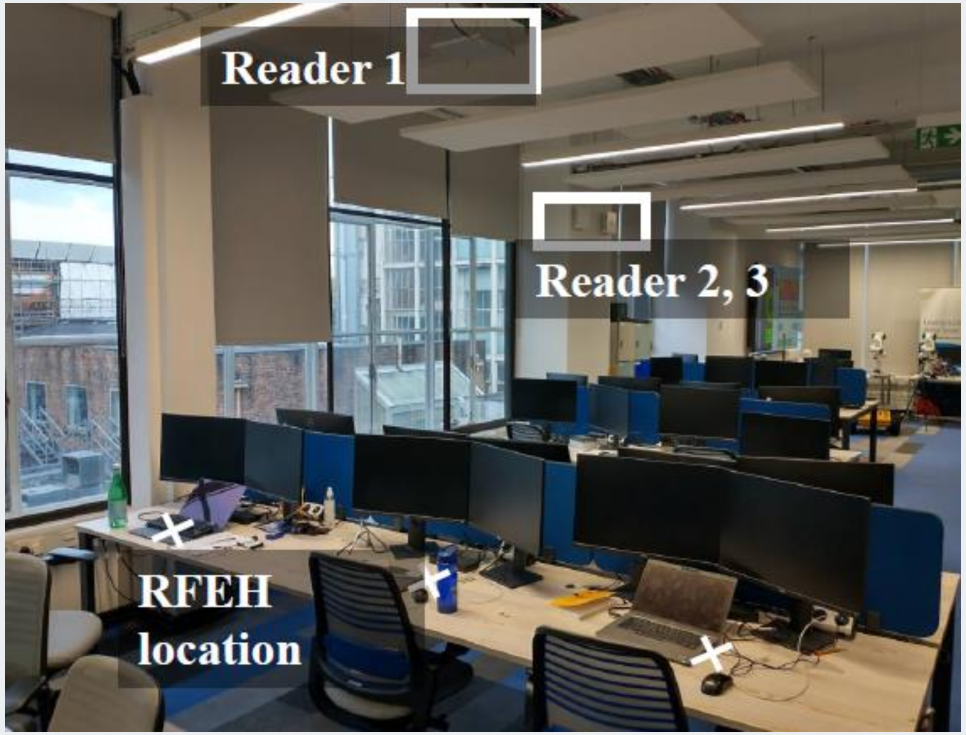


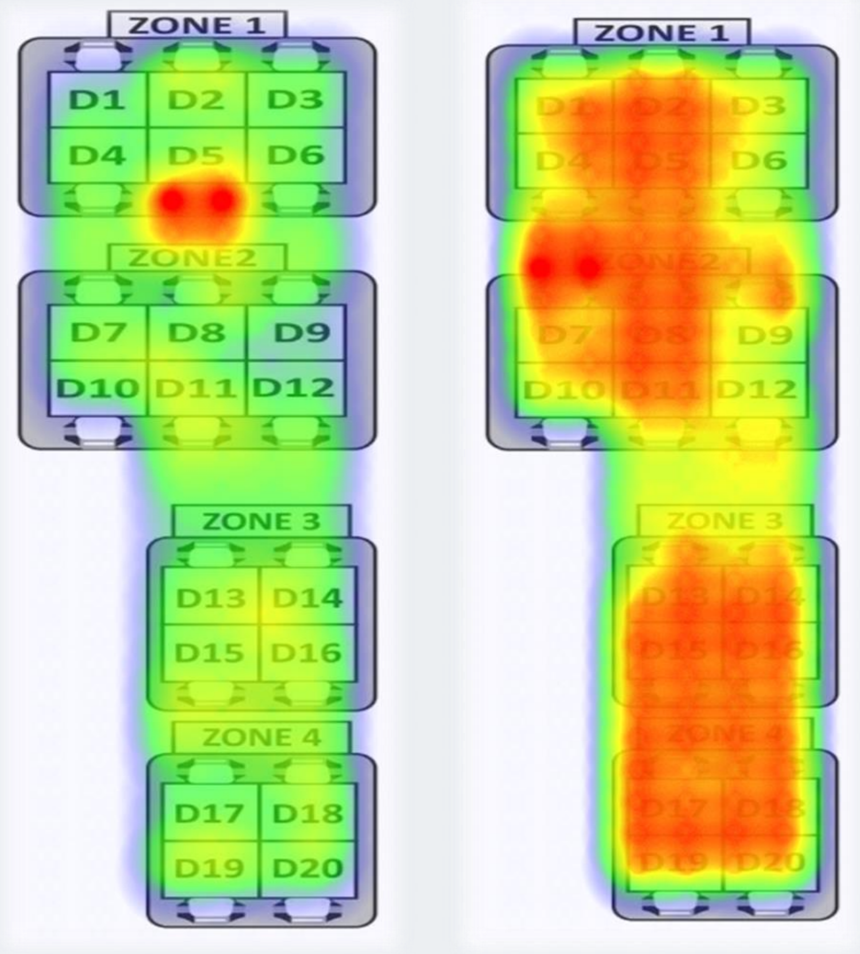
Wagih et al. "RFID-Enabled Energy Harvesting using Unidirectional Electrically-Small Rectenna Arrays" ***Euro. Conf. Antennas Propag*** 2023

RFID Power Survey

License-free UHF RFID-compliant readers in office environment

→ *A computational node can be powered anywhere*



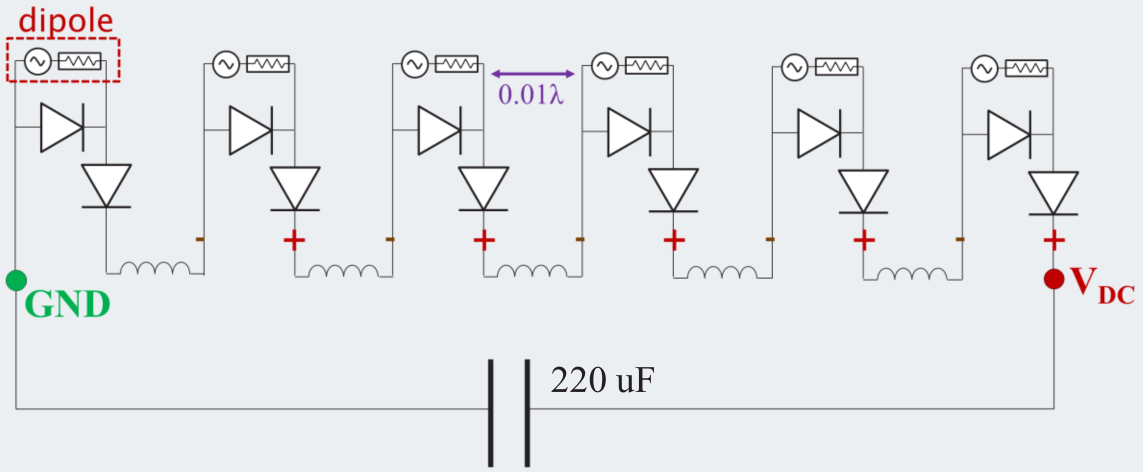


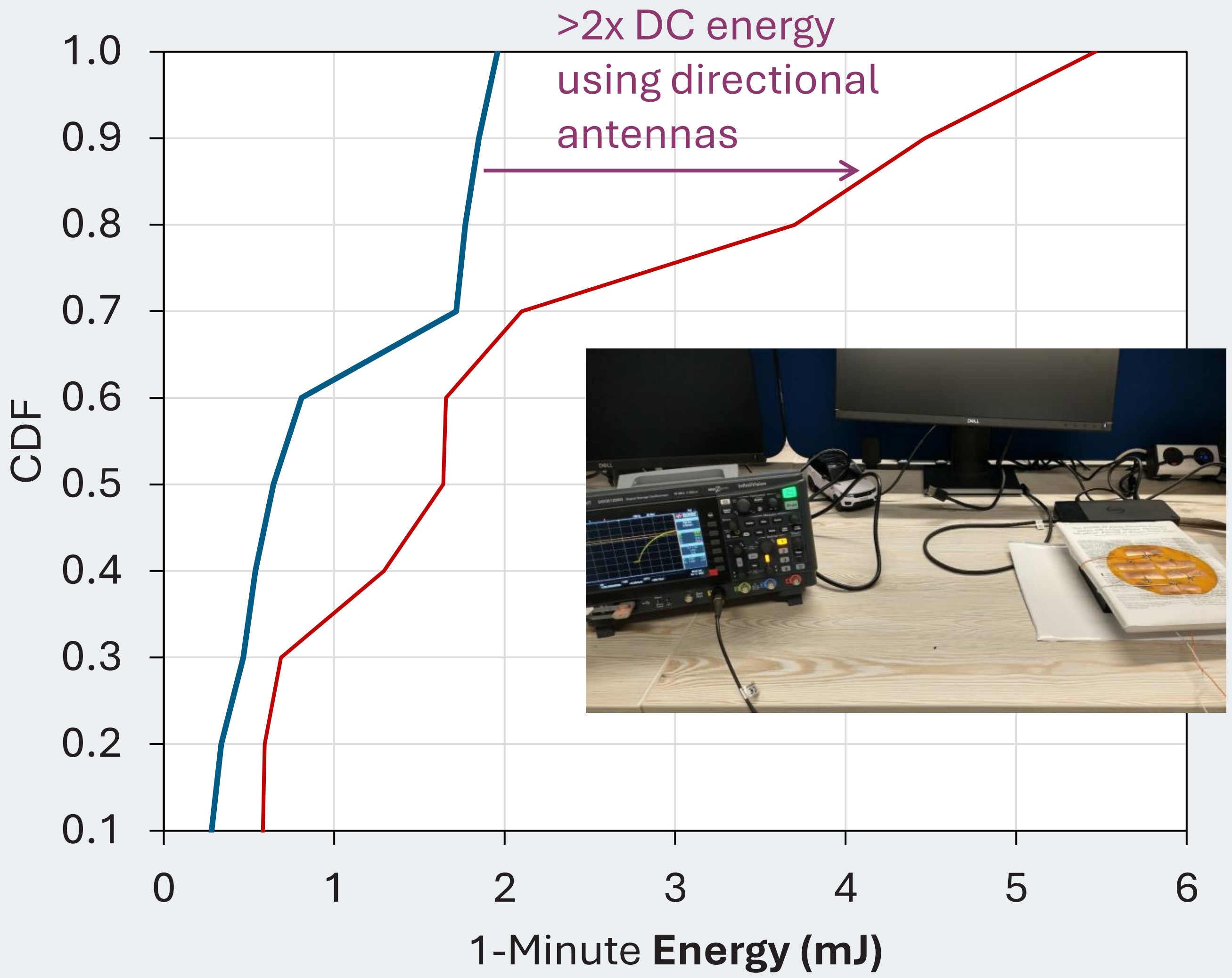
(a) Omnidirectional harvester (b) Unidirectional +3 dBi harvester

Wagih et al. "RFID-Enabled Energy Harvesting using Unidirectional Electrically-Small Rectenna Arrays" ***Euro. Conf. Antennas Propag*** 2023
Nesbit, Wagih et al. "Next-Generation IoT: Harnessing AI for Enhanced Localization and Energy Harvesting in Backscatter Communications" ***Electronics*** 2023

RFID Packets for Power *Capacitor Charging*

>1 mJ energy in 65% of tested locations at >1.6 V





Wagih et al. "RFID-Enabled Energy Harvesting using Unidirectional Electrically-Small Rectenna Arrays" ***Euro. Conf. Antennas Propag*** 2023

Focusing Wireless Power:

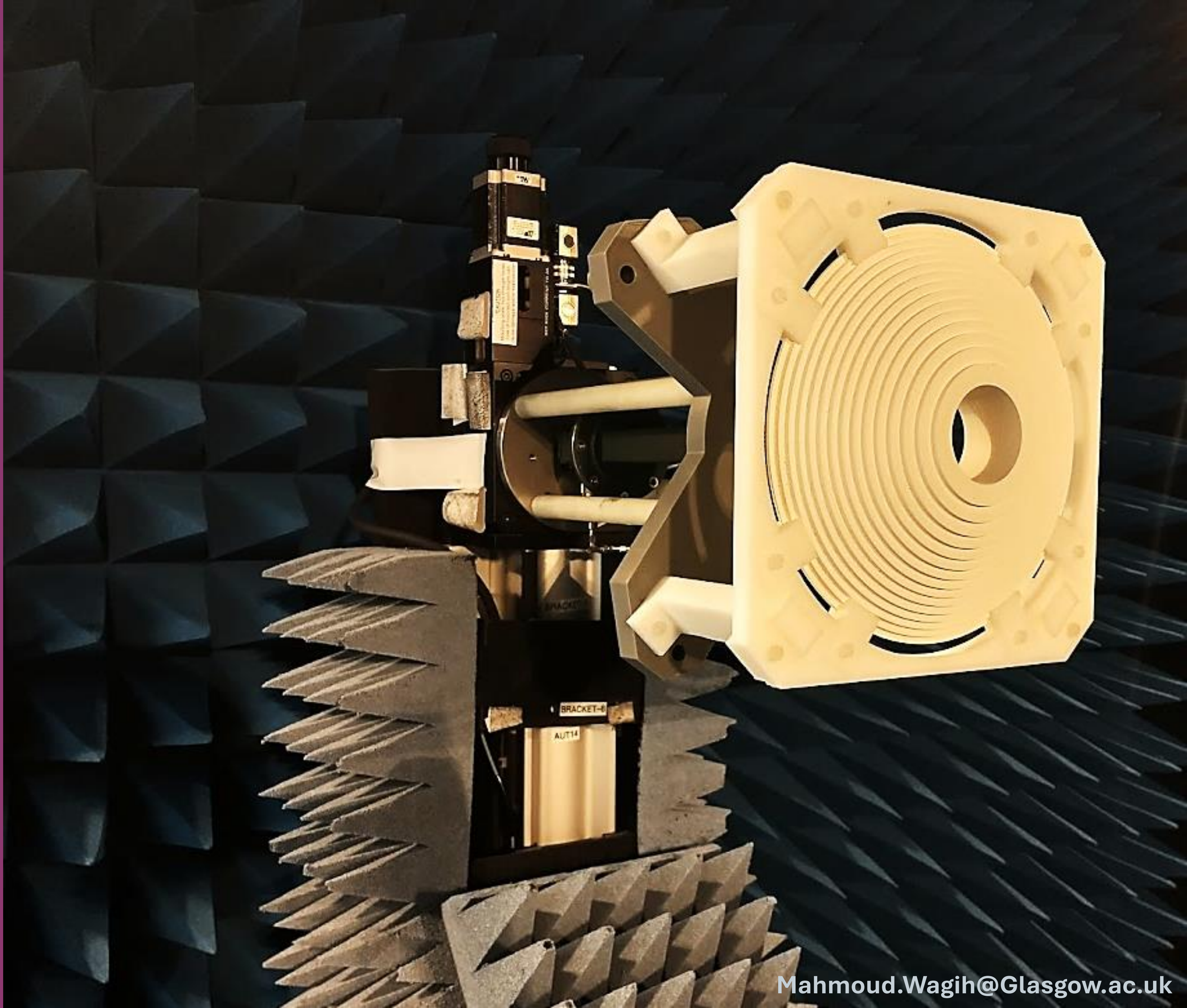
Quasi-Optic RF for
>30 m Safe Powering Range

M. Wagih, T. Whittaker, S. Mu, W. Whittow "Quasi-Optic, Radio Frequency Joint Wireless Power Transfer and Machine Learning-Enabled Sensing" (Under Review) *Nature Electronics*

Overcoming the Safety / Range Bottle-Neck?

Lens receiver

- Higher RX power than theoretical "single-ray" path-loss model

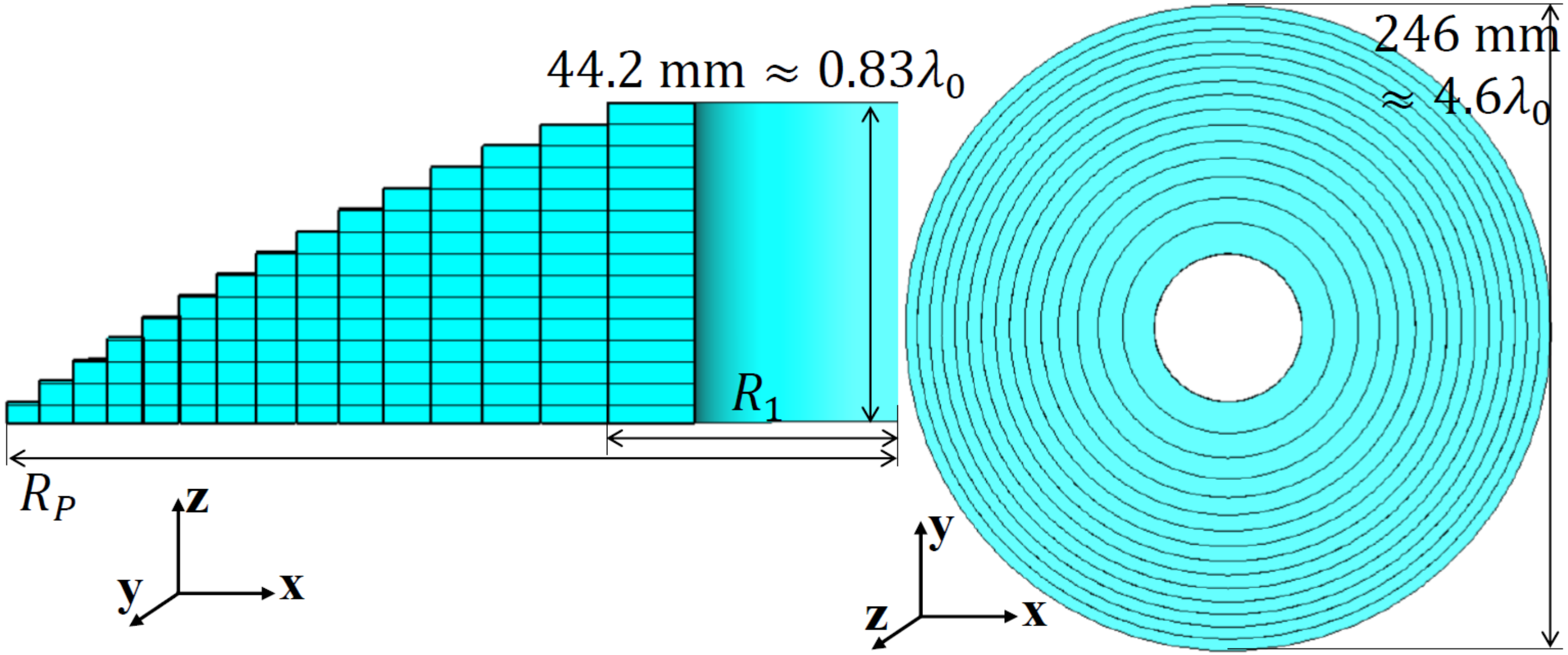


Mahmoud.Wagih@Glasgow.ac.uk

Fresnel Lens Design

- $5.3 \times \lambda^2$ aperture
  - ~50% simulated aperture efficiency.
- <30 cm diameter.
  - Printable on a standard FDM printer
- Low-loss Premix 4.4 filament

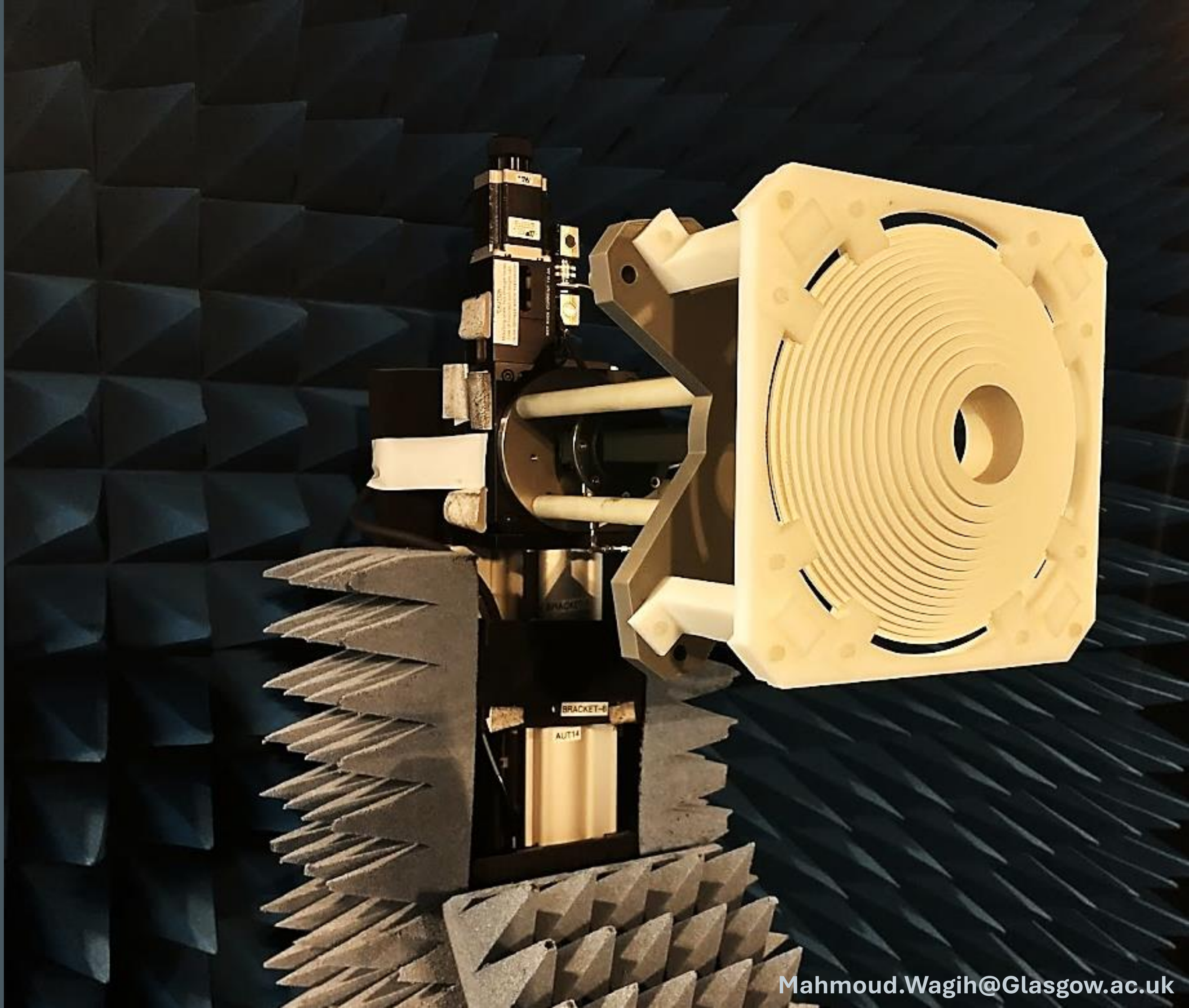
$$R_i = \sqrt{2Fi(\lambda_0/P) + (i\frac{\lambda_0}{P})^2} \qquad i = 2, 3, \ldots P$$



Mahmoud.Wagih@Glasgow.ac.uk

Fabricated Lens Prototype

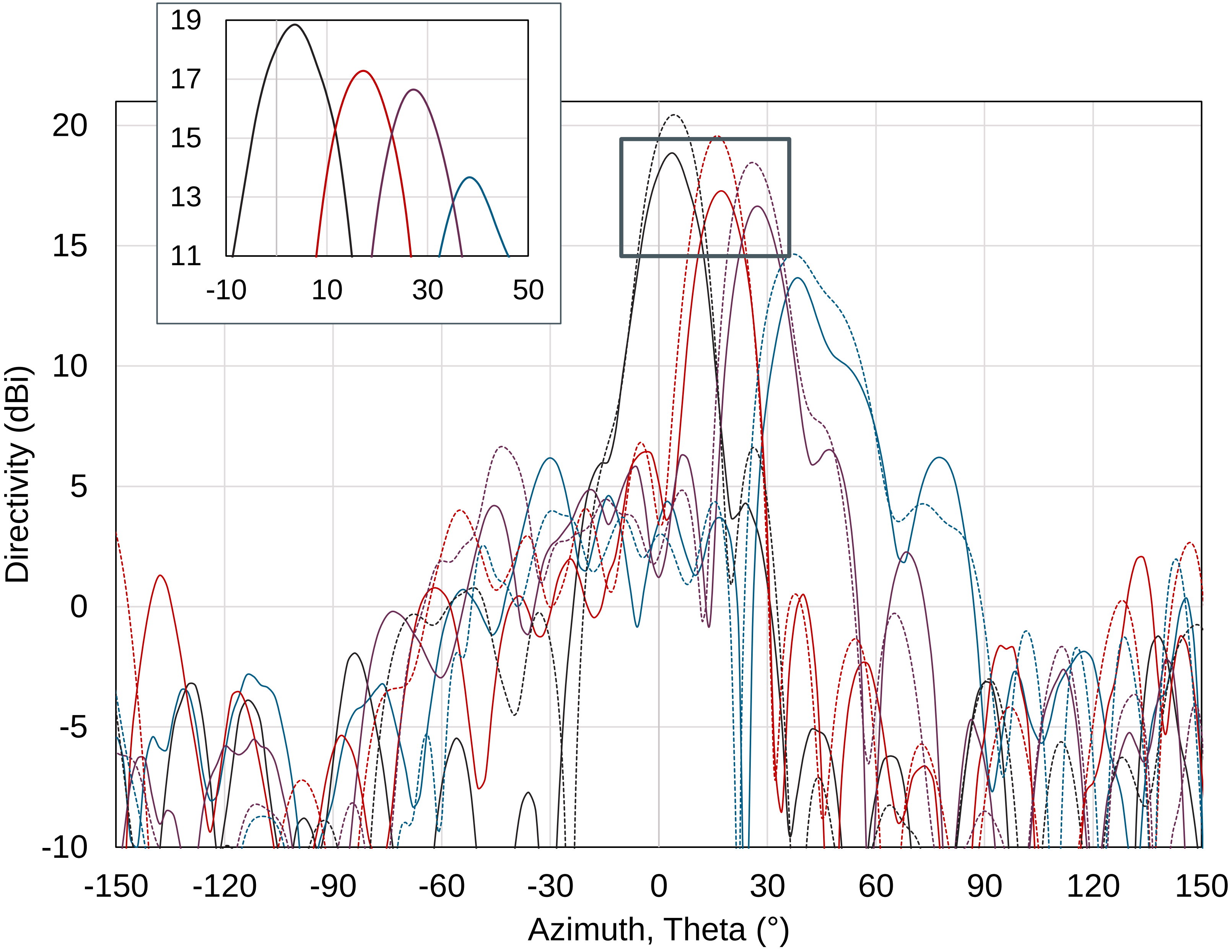
- Fresnel lens
- No dielectric grading
- Waveguide feed (WG12)
- ~2 kg prototype



Mahmoud.Wagih@Glasgow.ac.uk

Fabricated Lens Measurements

- 7 dBi planar Yagi-Uda feed
- Multiple feeding points to demonstrate the beam-steering
- ~15 mm feed spacing
- 18 dBi peak directivity
- 70° half-power beamwidth



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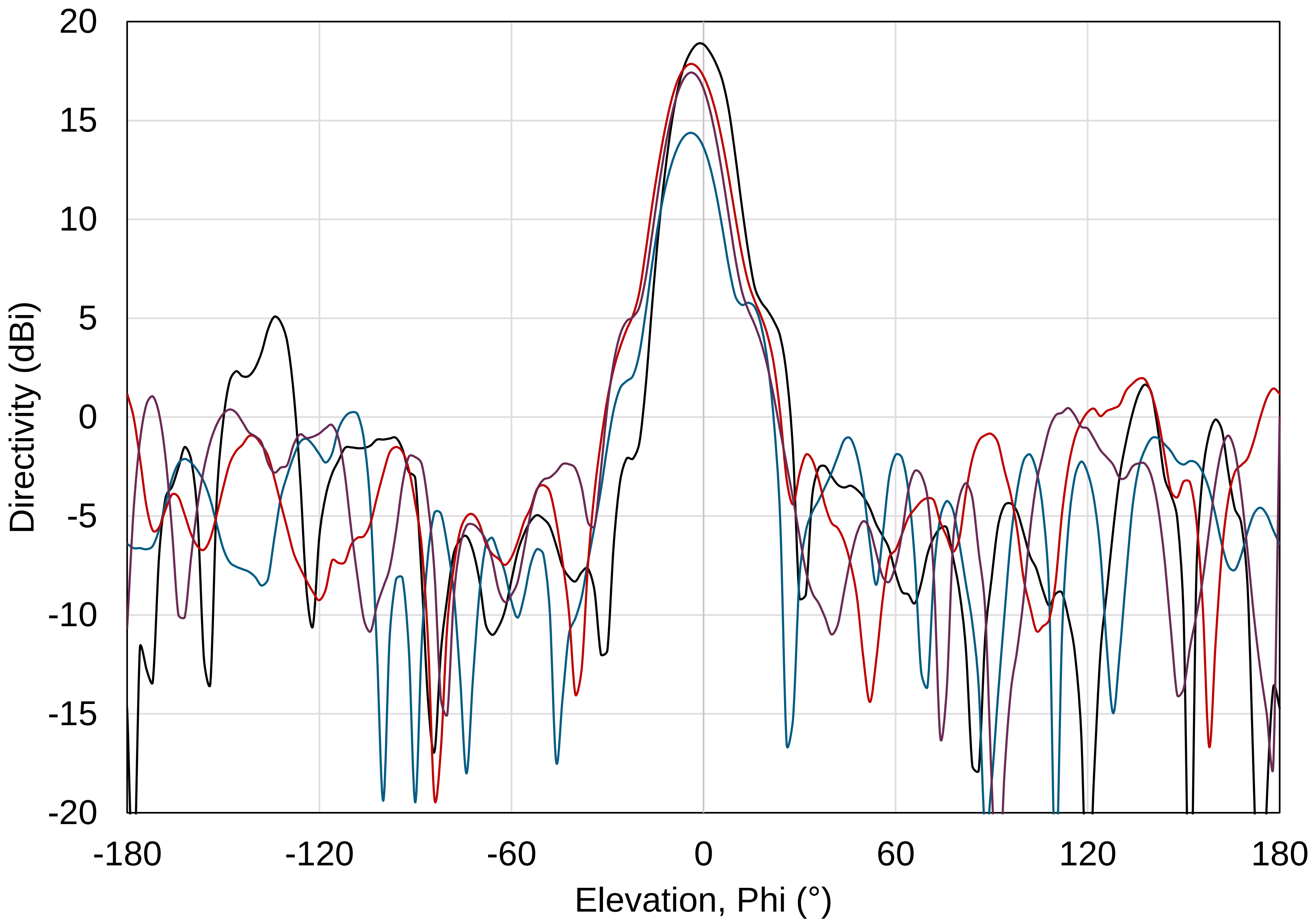

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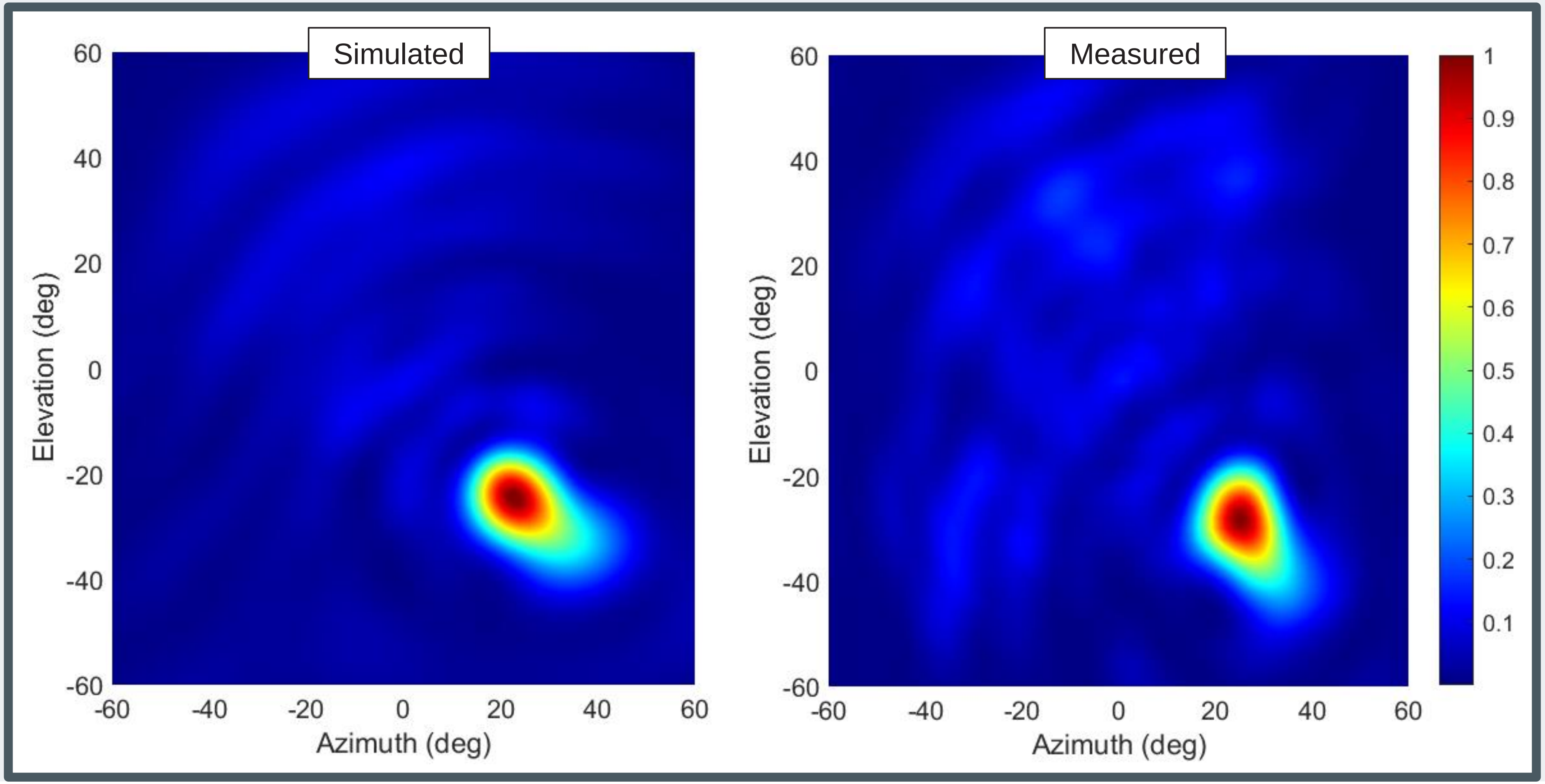
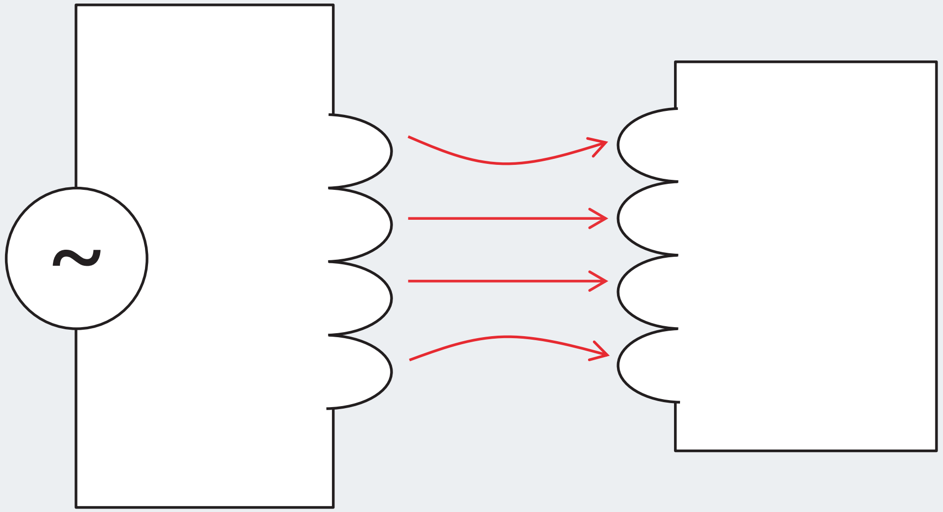
Azimuth and Elevation Steering

- *x*=*y*=15 cm feed position -> 35° azimuth and elevation beam direction
- -5 dB directivity compared to the main beam



Near-Field Power Beyond few cms

Assisted
"Wireless" Power

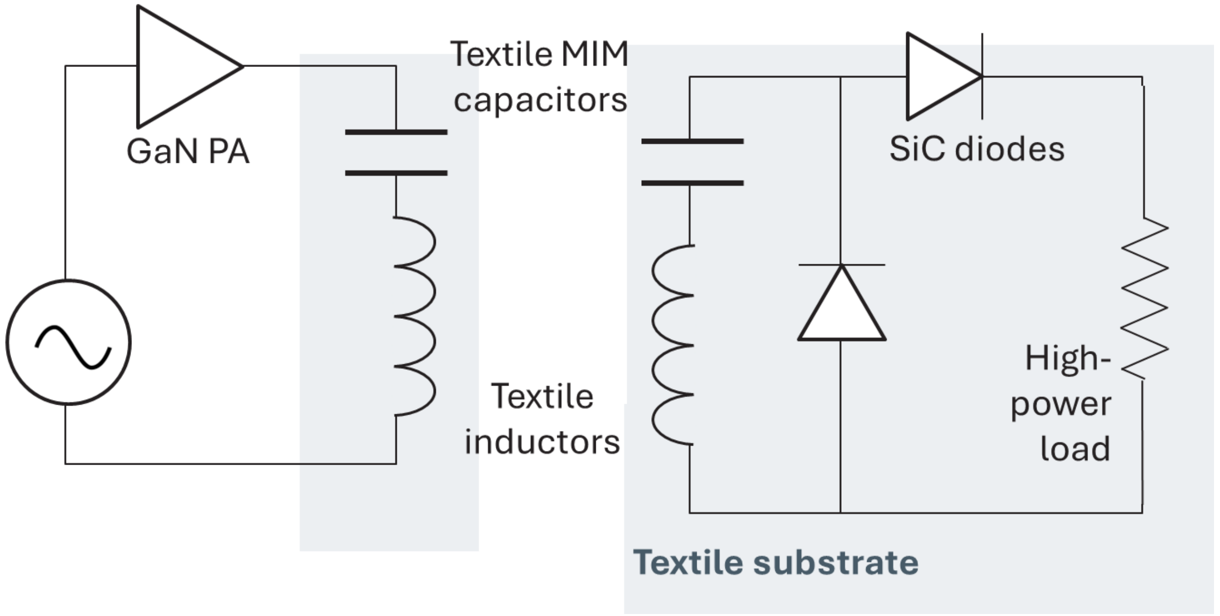


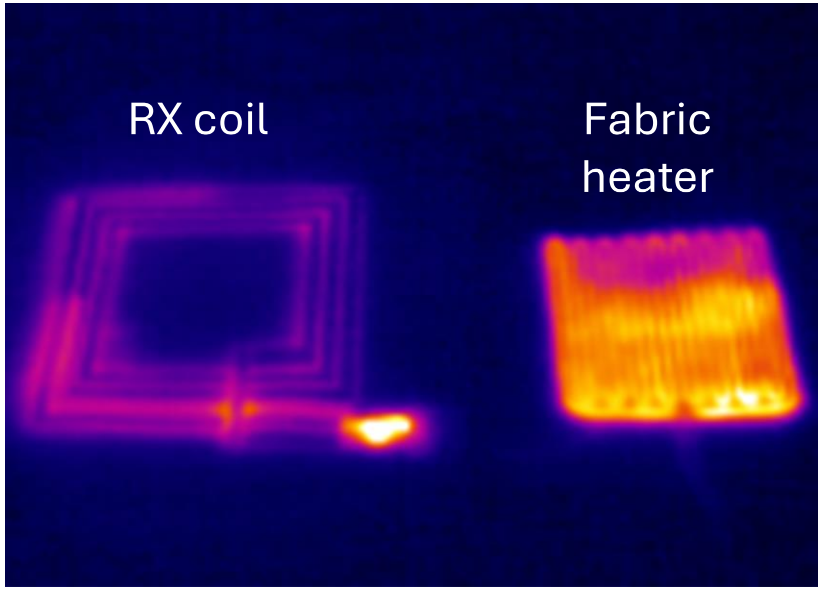
High-power;
Short-range?

Mahmoud.Wagih@Glasgow.ac.uk

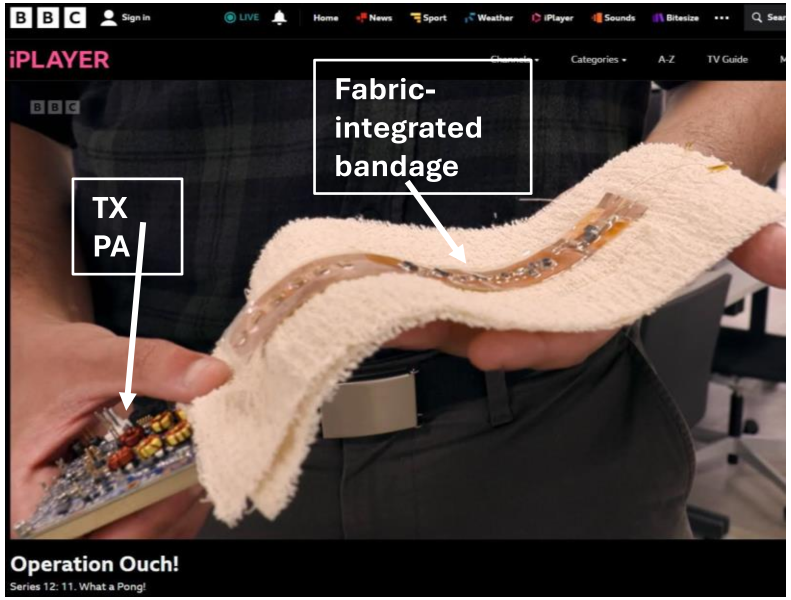
State-of-the-Art: **>1 W On-Body WPT**

- Near-field resonant coupling
- Enabler of novel applications





Wearable battery-free heater [1]



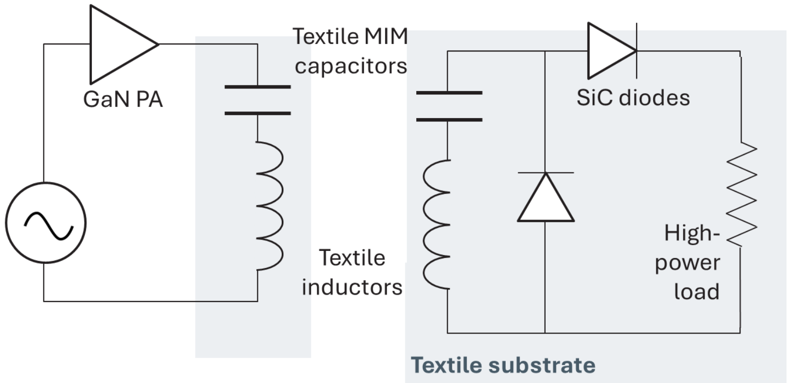
Anti-infective UV bandage [2]

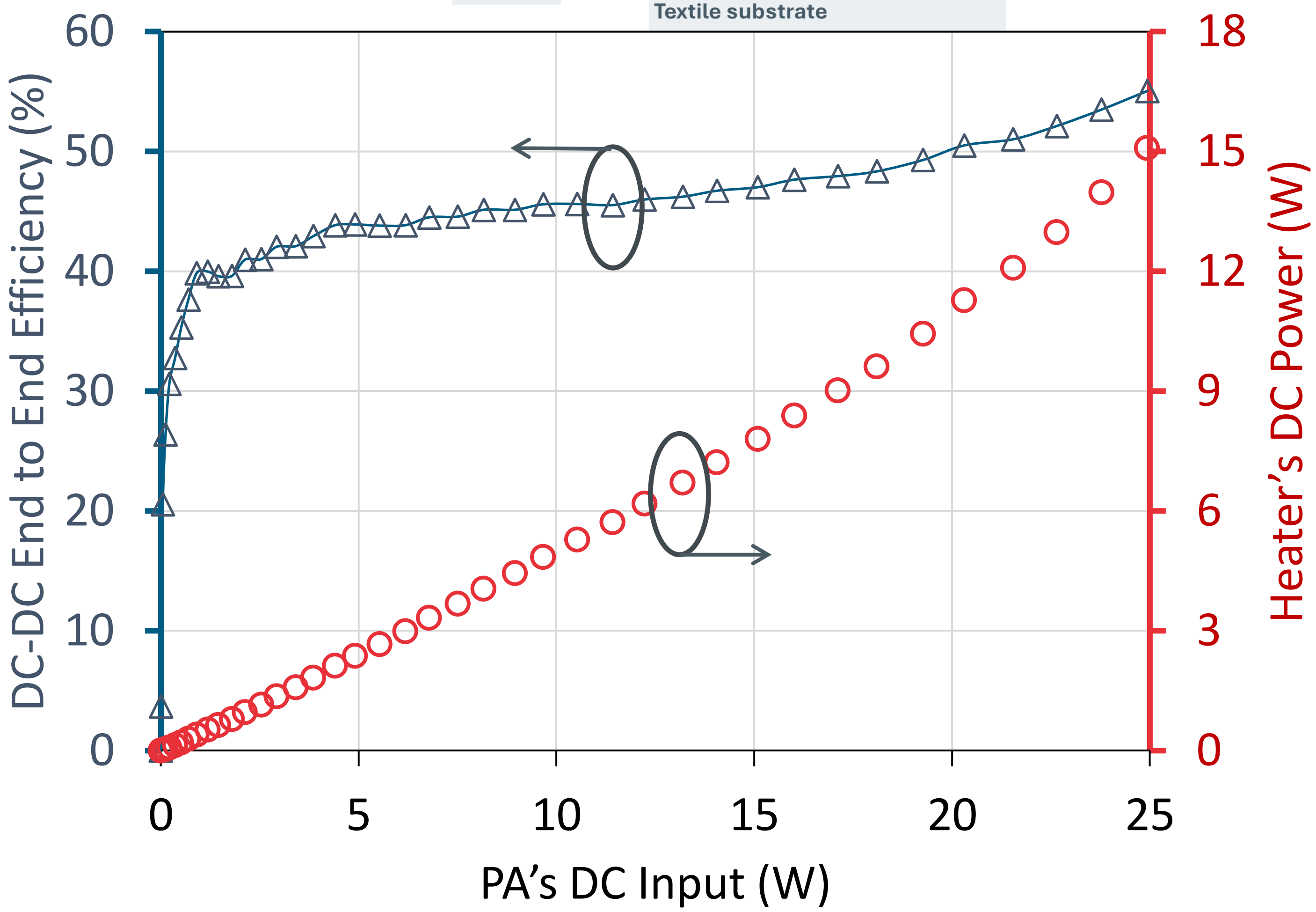
[1] Wagih et al. "All-Printed Textile-Based 6.78 MHz 15 W-Output WPT System and its Joule Heater," (2023) ***IEEE Trans. Industrial Electron.***
[2] Ullah, Wagih, Beeby et al. "Wirelessly Powered Anti-Infective Smart Bandage" (2023) ***IEEE Transactions on Biomed. Circuits & Sys.***

State-of-the-Art:
>1 W On-Body WPT

- Near-field resonant coupling
- Enabler of novel applications

Maximum range is <5 cm, to a single direction / receiver





[1] Wagih et al. "All-Printed Textile-Based 6.78 MHz 15 W-Output WPT System and its Joule Heater," (2023) ***IEEE Trans. Industrial Electron.***
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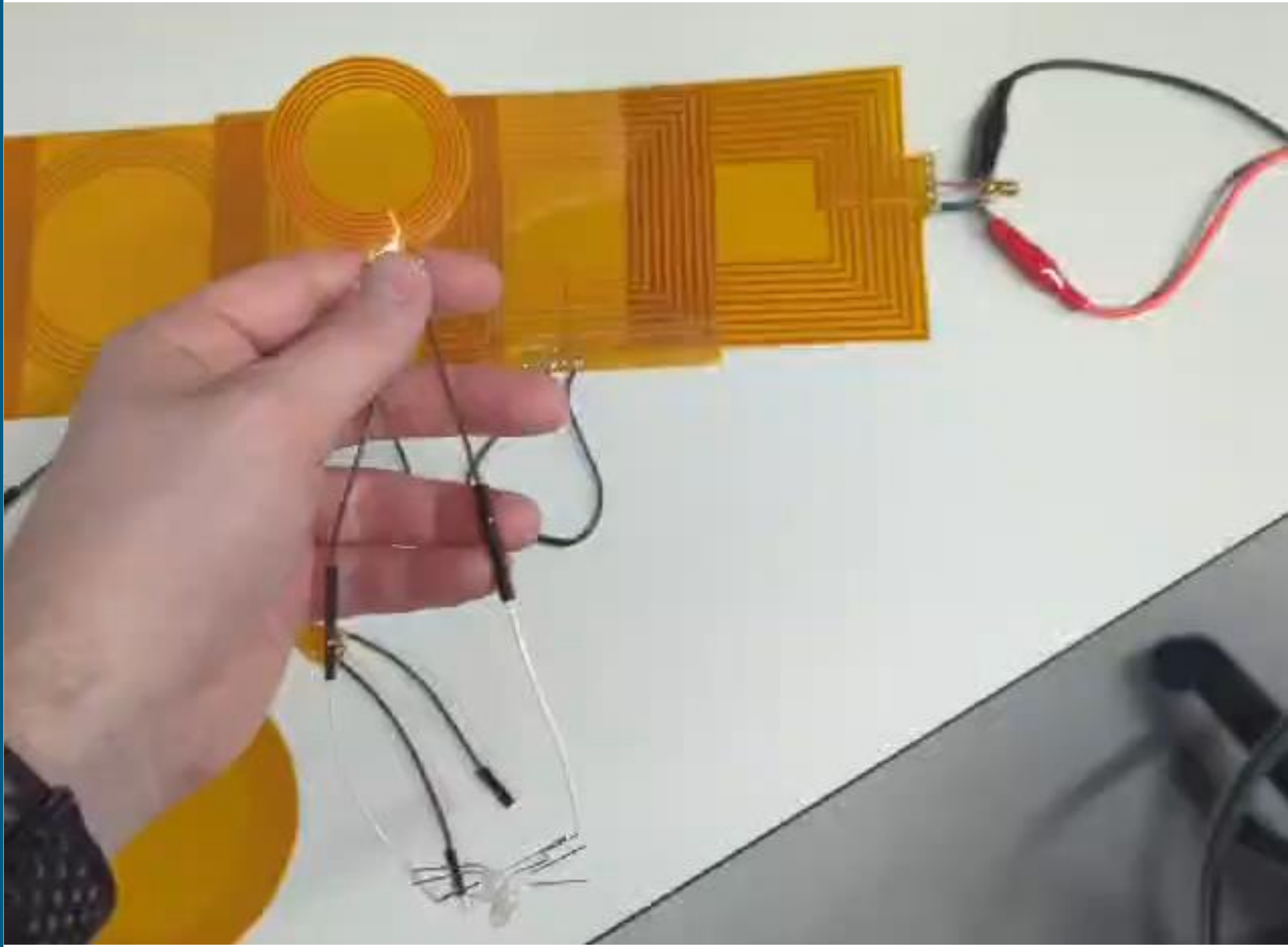
>1 W Power On-Body, 1 m Away?

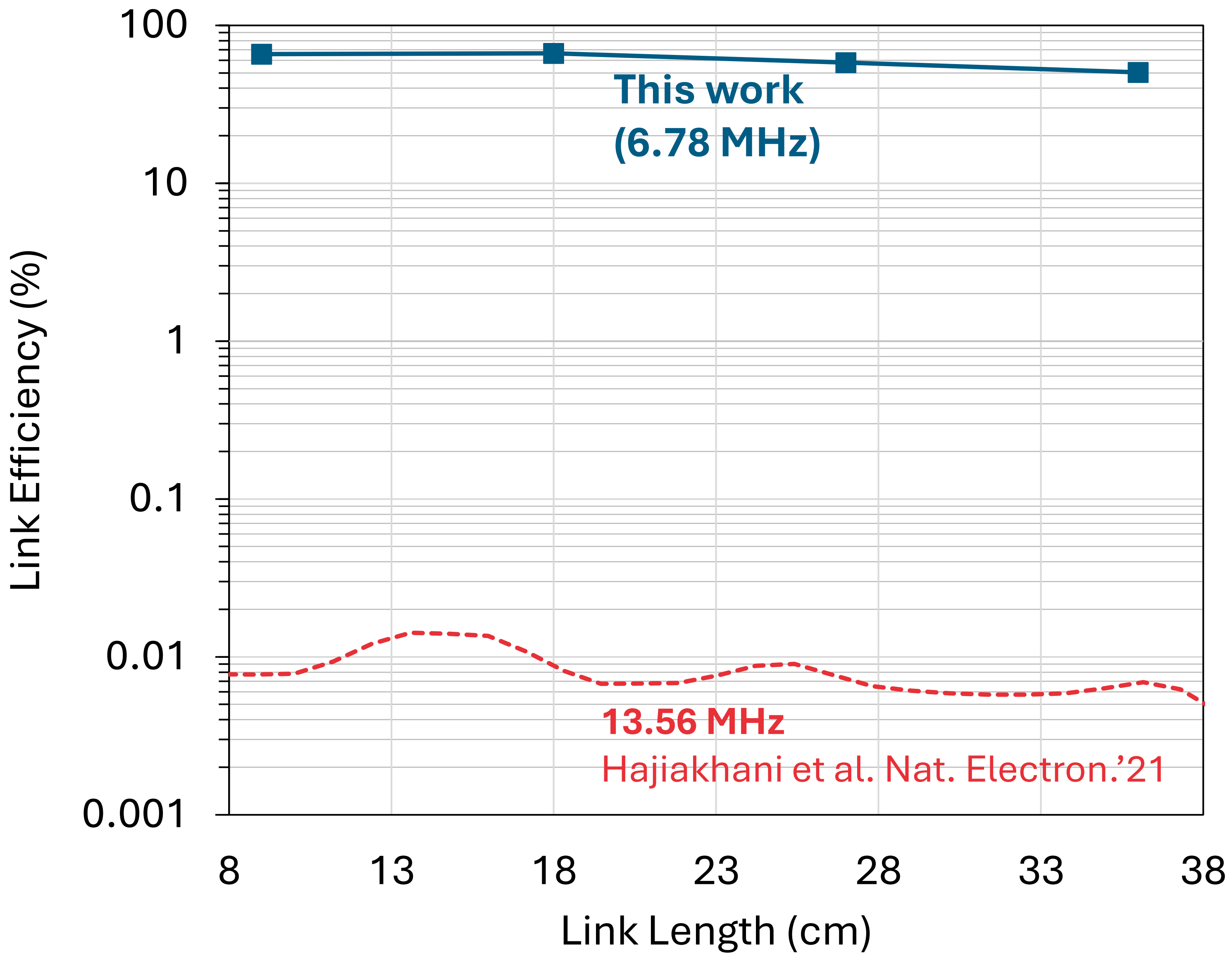
- Free positioning receivers
- 6.78 MHz AirFuel-compliant system
- Safe and high-power handling



Bruce & Wagih "Body-Scale, Steerable Self-Multiplexed Wireless Power and Data Grids" *Unpublished*

>1 W Power On-Body, 1 m Away?

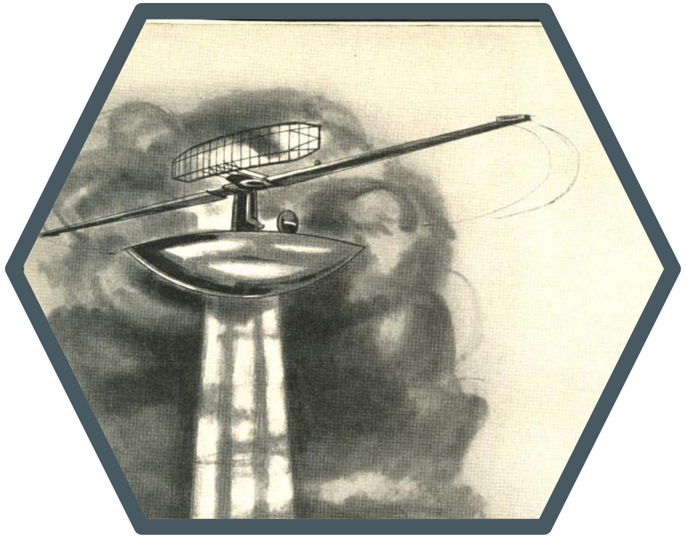
- Free positioning receivers
- 6.78 MHz AirFuel-compliant system
- Safe and high-power handling
- >15 dB higher efficiency than state-of-art



Bruce & Wagih "Body-Scale, Steerable Self-Multiplexed Wireless Power and Data Grids" *Unpublished*

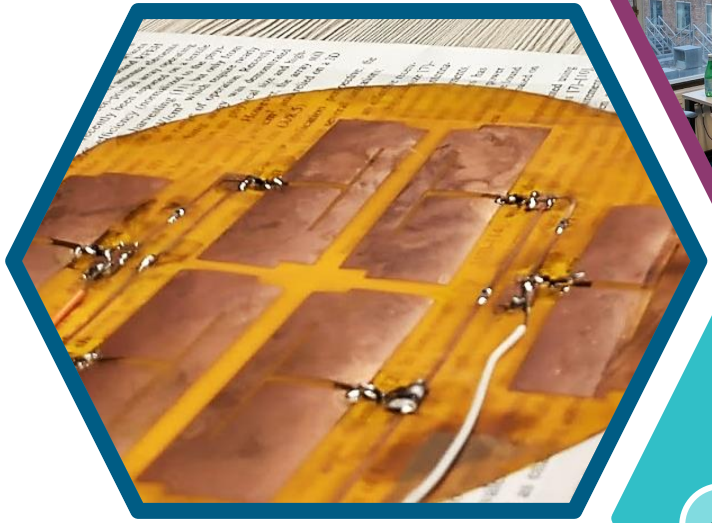
Summary:

>10% WPT efficiency in 1960s

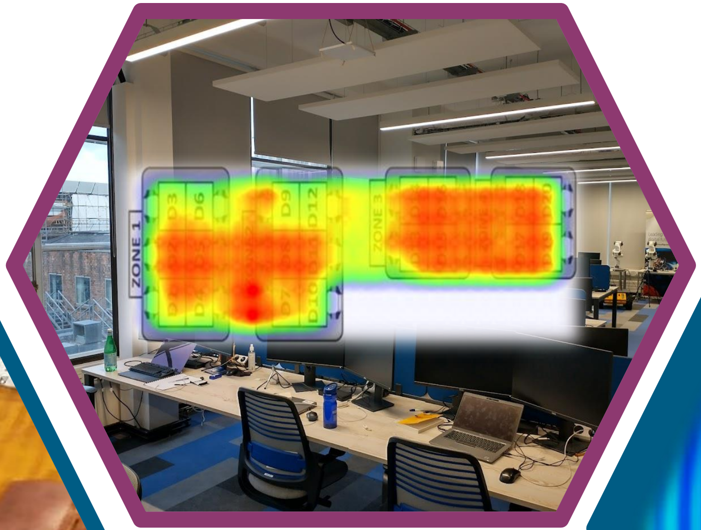


Small arrays

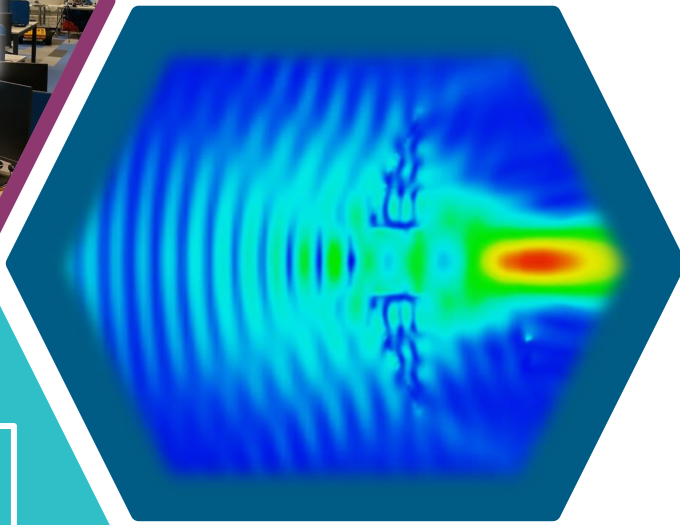
Antenna-circuit co-design

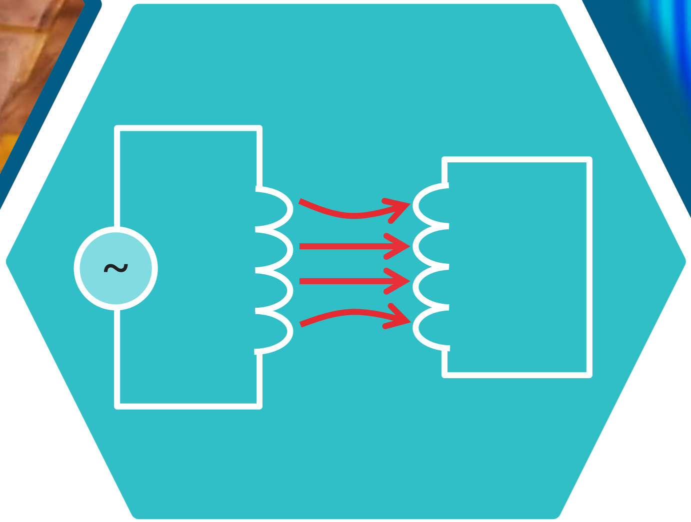


Practical RFID Grids



Focused Power @30m





>1 W in Near-Field

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Mahmoud.Wagih@glasgow.ac.uk