Transcranial Magnetic Stimulation

Physics, devices, & modeling

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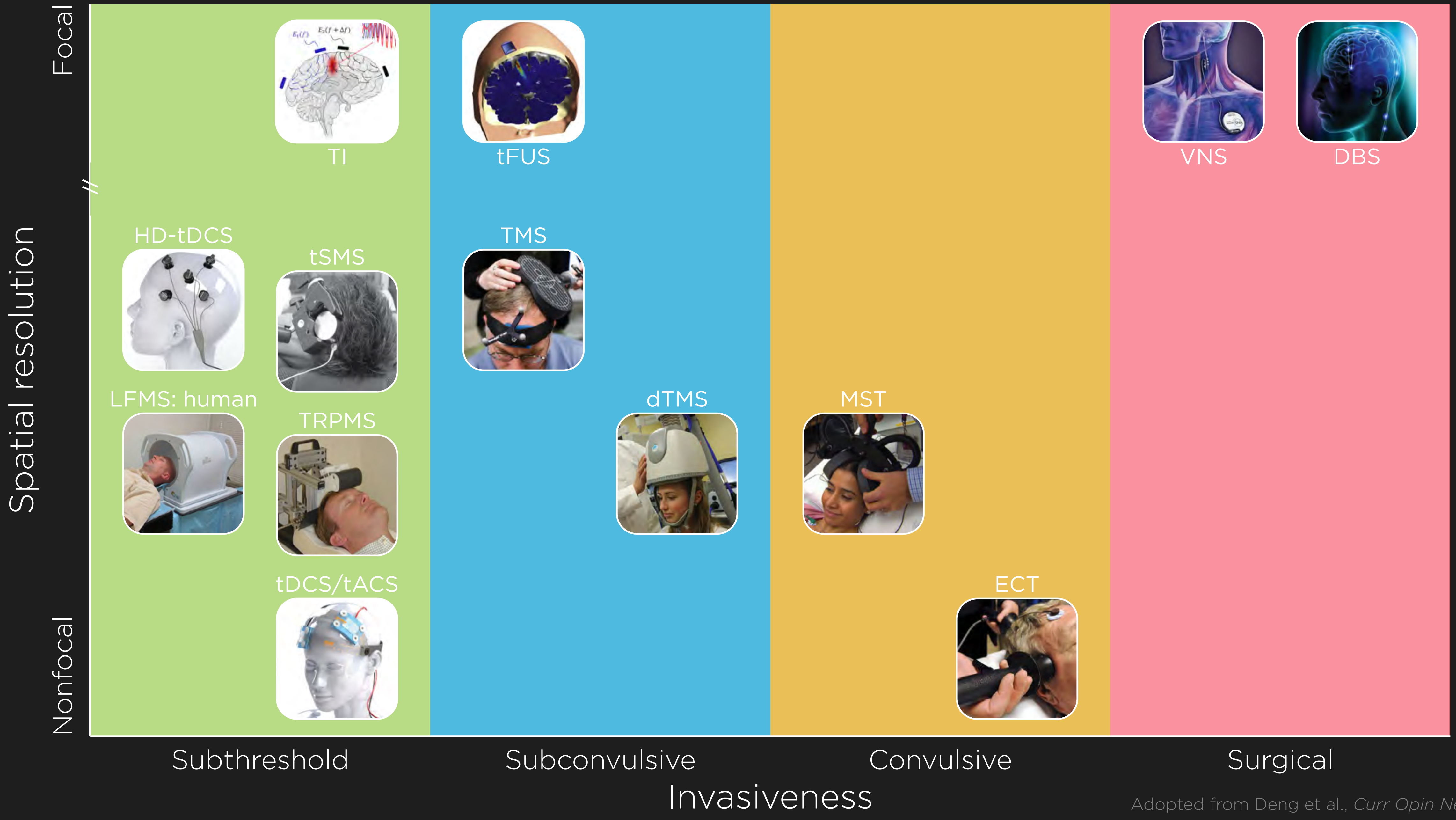
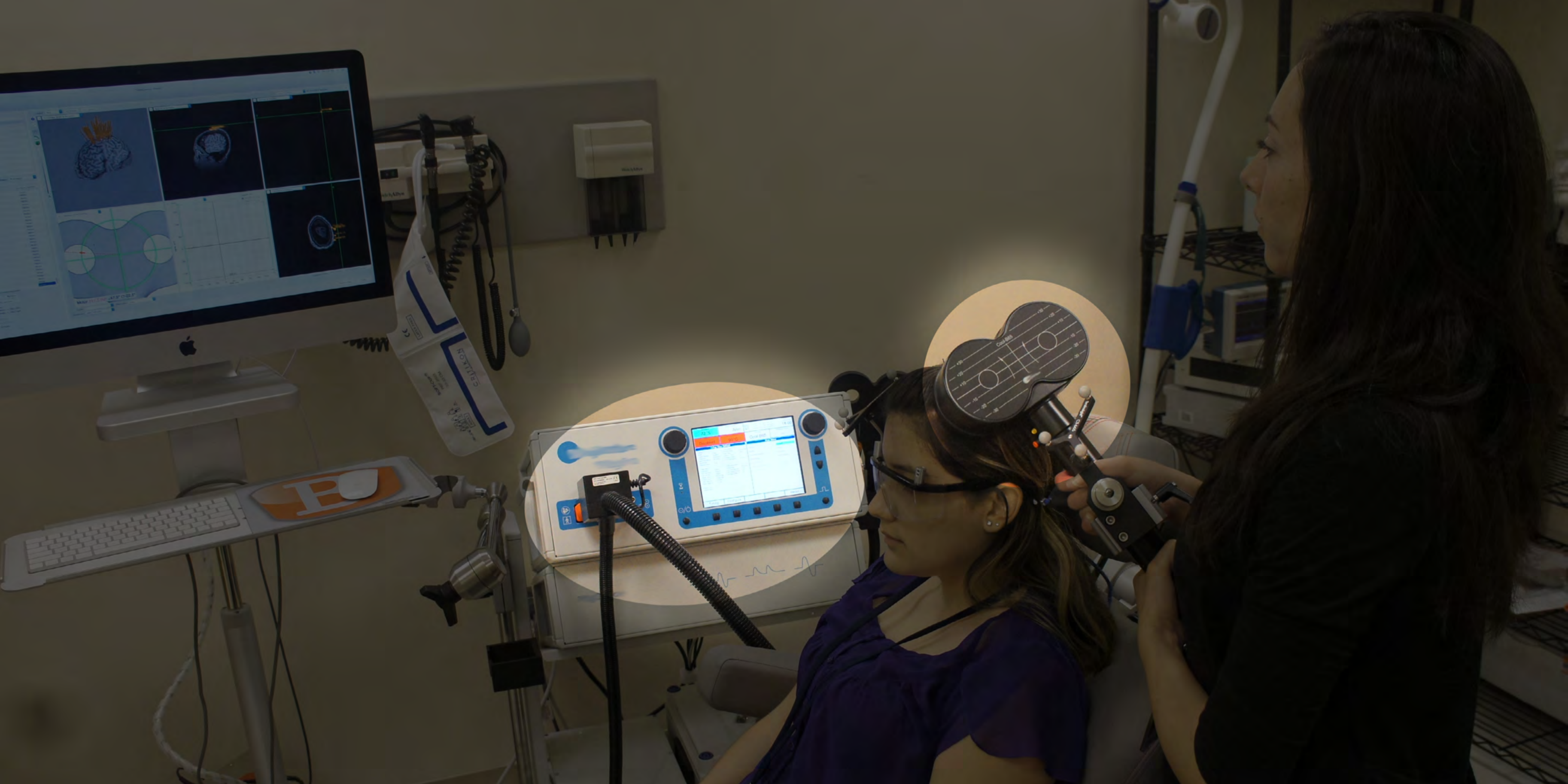
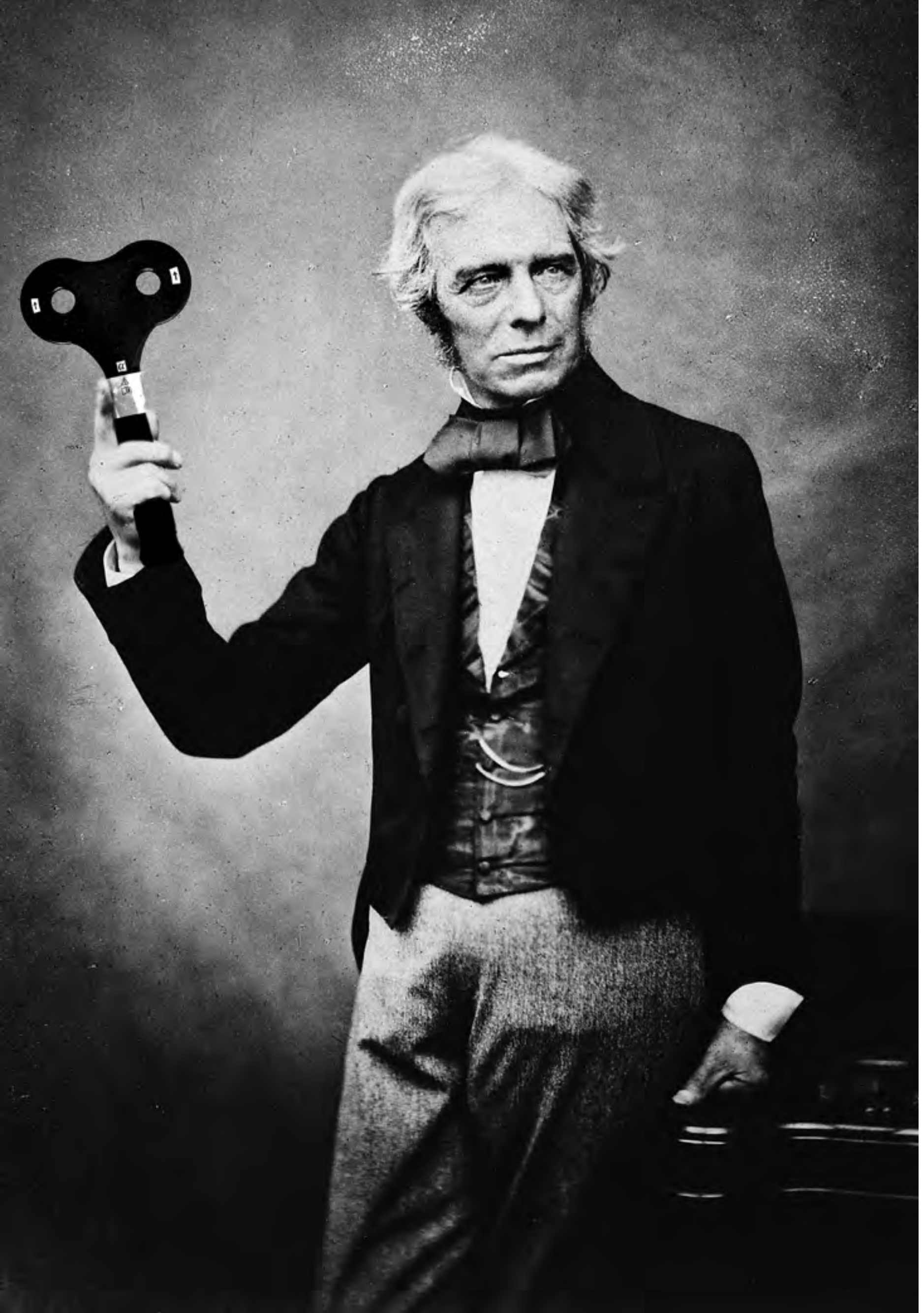
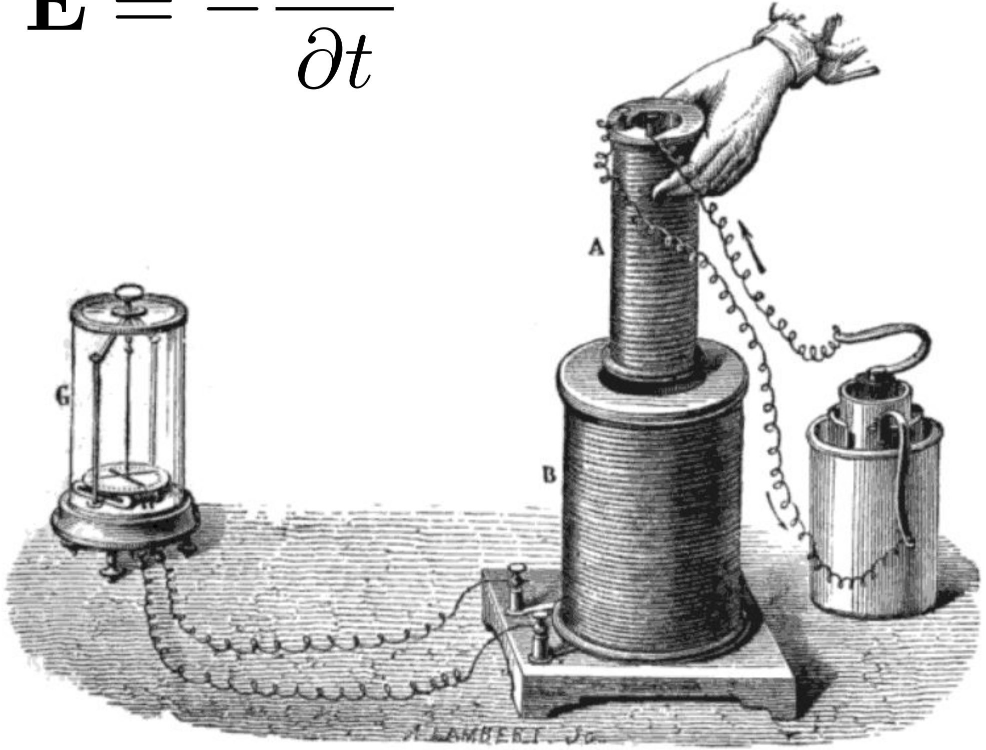


Adopted from Deng et al., *Curr Opin Neurobiol*, 2015





$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

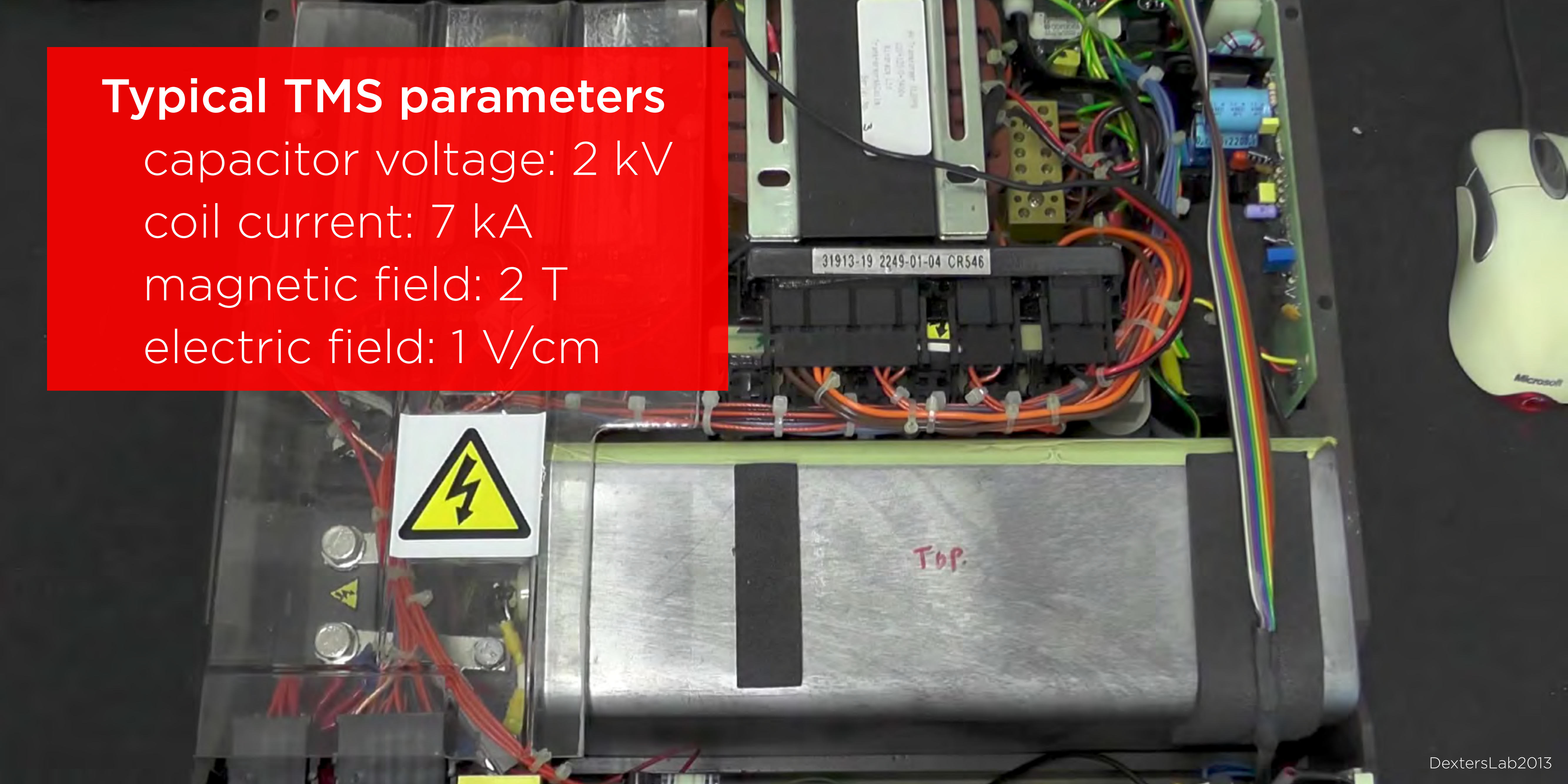


Faraday's experiment with induction.

Poyser, *Magnetism and Electricity*, 1892

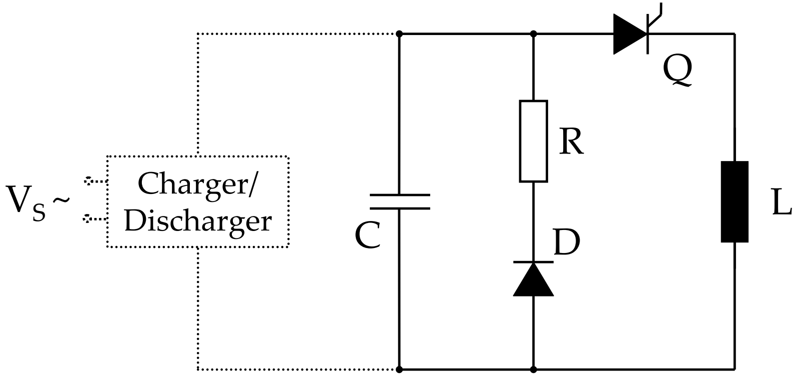
Typical TMS parameters

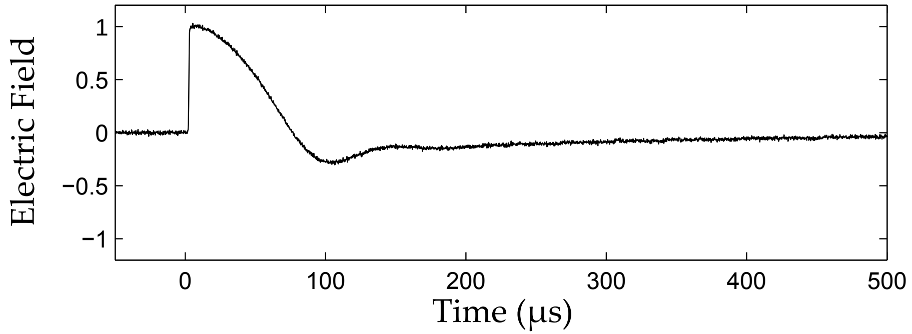
- capacitor voltage: 2 kV
- coil current: 7 kA
- magnetic field: 2 T
- electric field: 1 V/cm

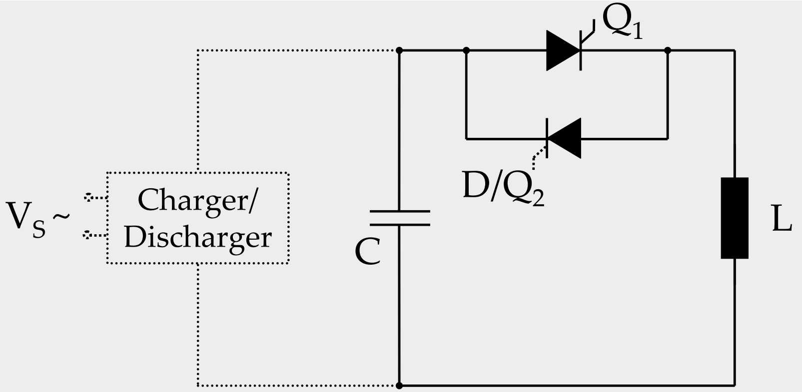


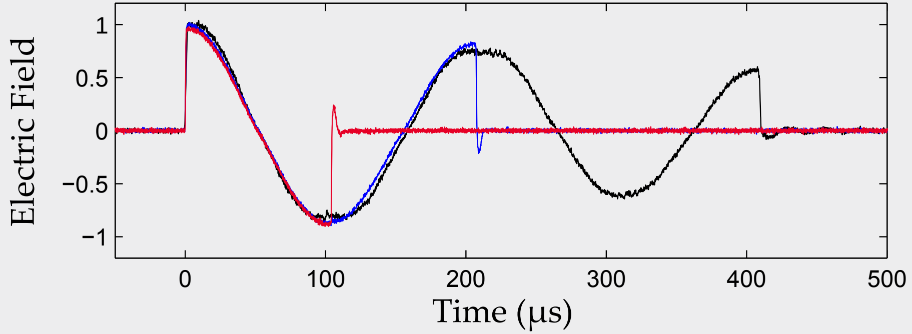
Roberts, *Anatomy of the Ship: The Battleship Dreadnought*, 1992

Conventional stimulators



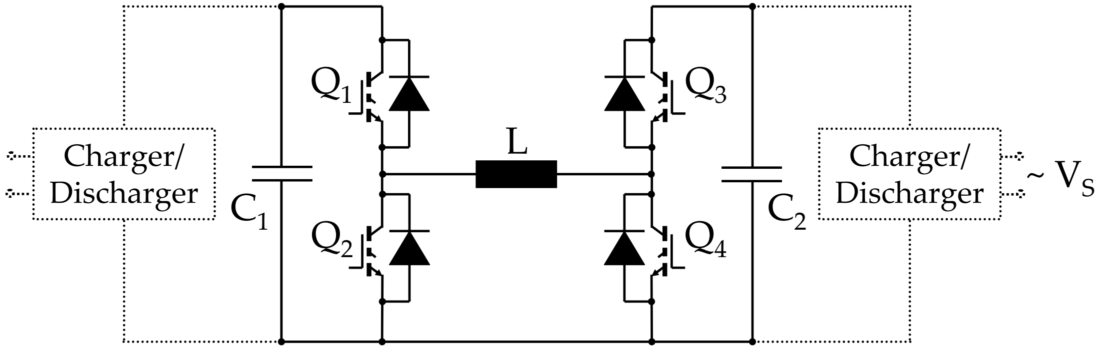


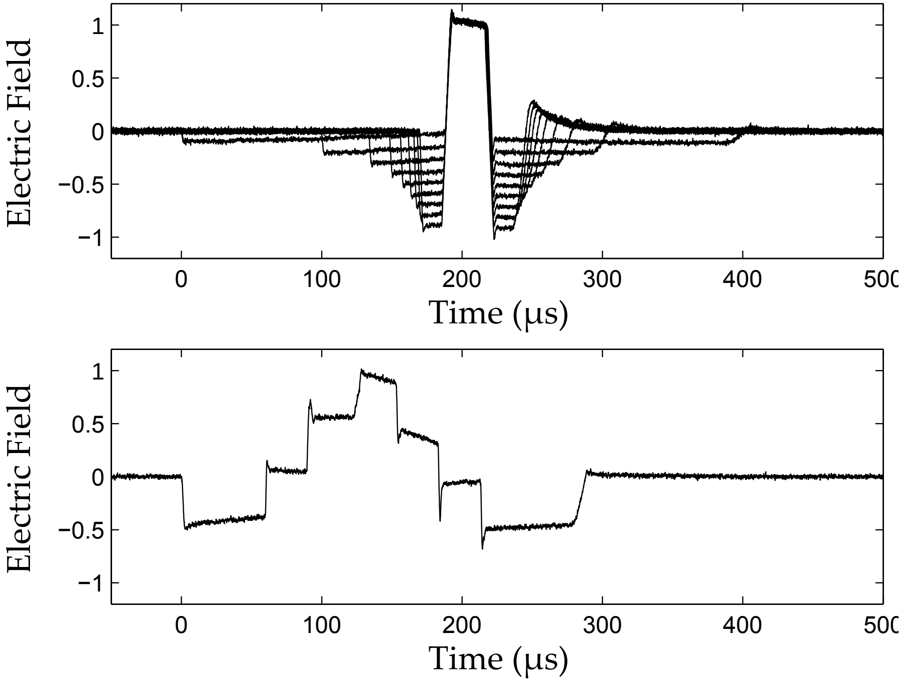




Goetz & Deng, *Int Rev Pscyhiatry*, 2017

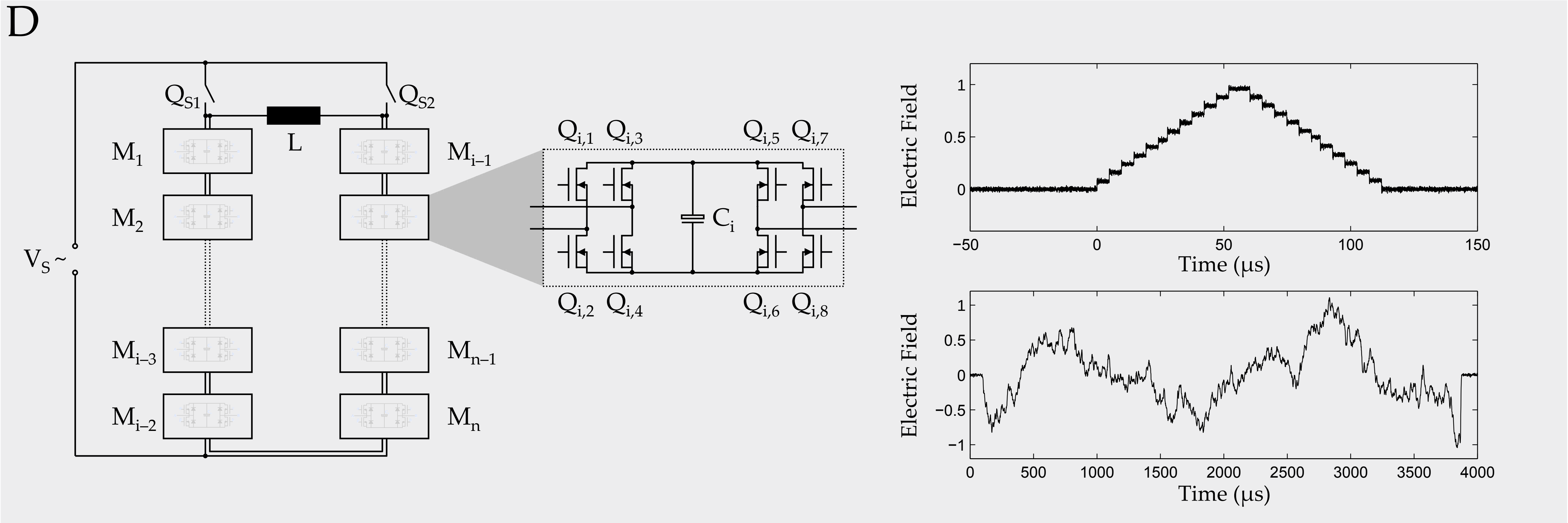
Controllable pulse-width TMS





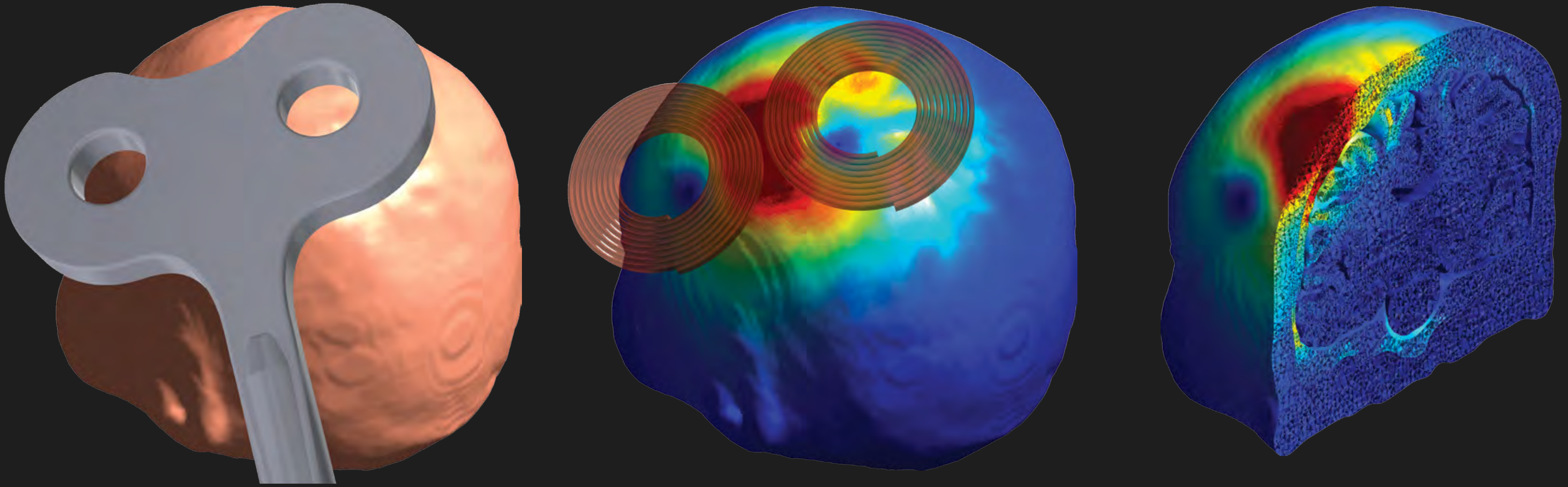
Goetz & Deng, *Int Rev Pscyhiatry*, 2017

Synthesizer

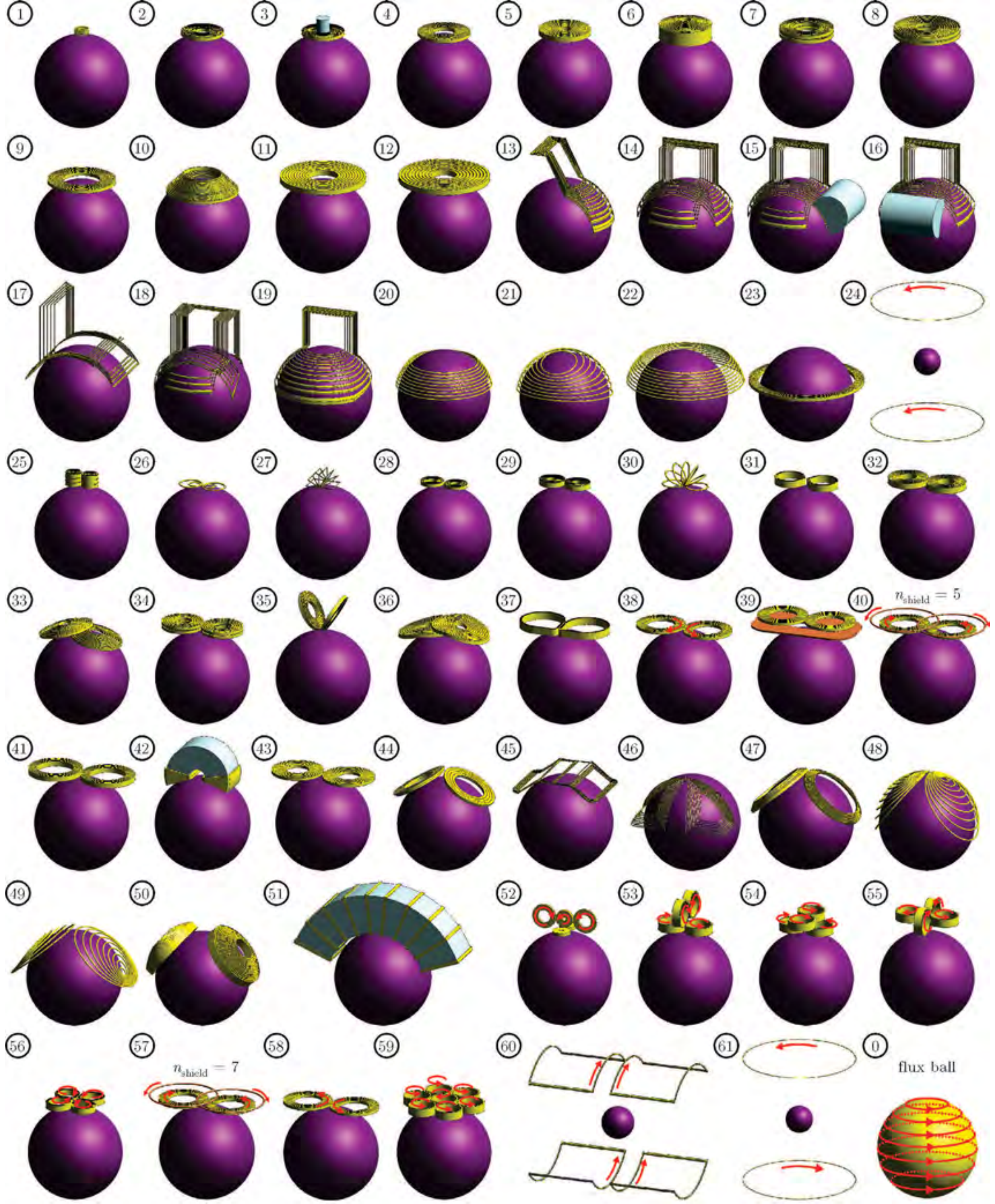


Goetz & Deng, *Int Rev Pscyhiatry*, 2017

Spatial targeting



- § no 3D focusing in depth
- § conventional coils have low electric field penetration ~2–3 cm from head surface



Deng et al., *Brain Stimul*, 2013

Circular type

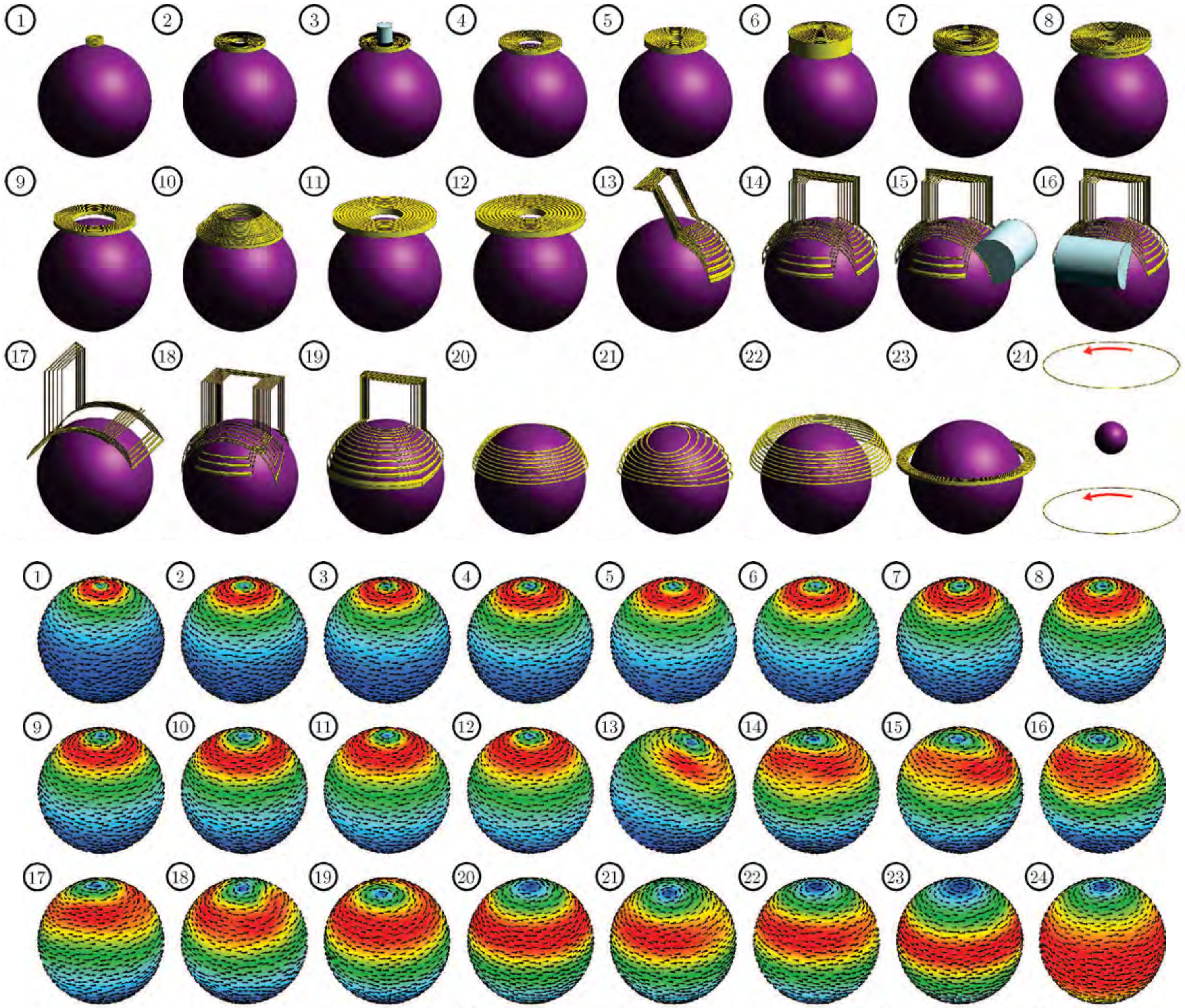
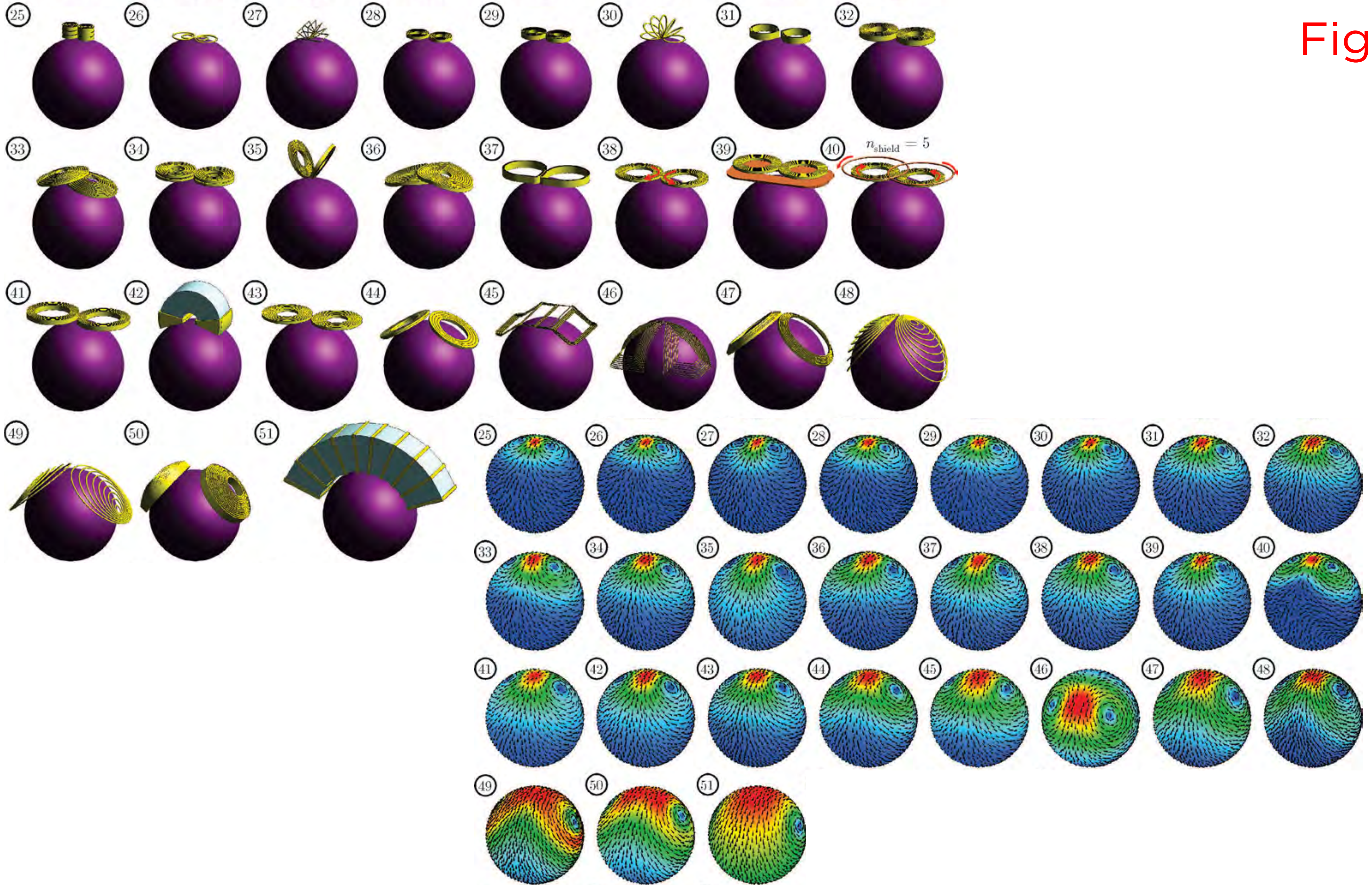
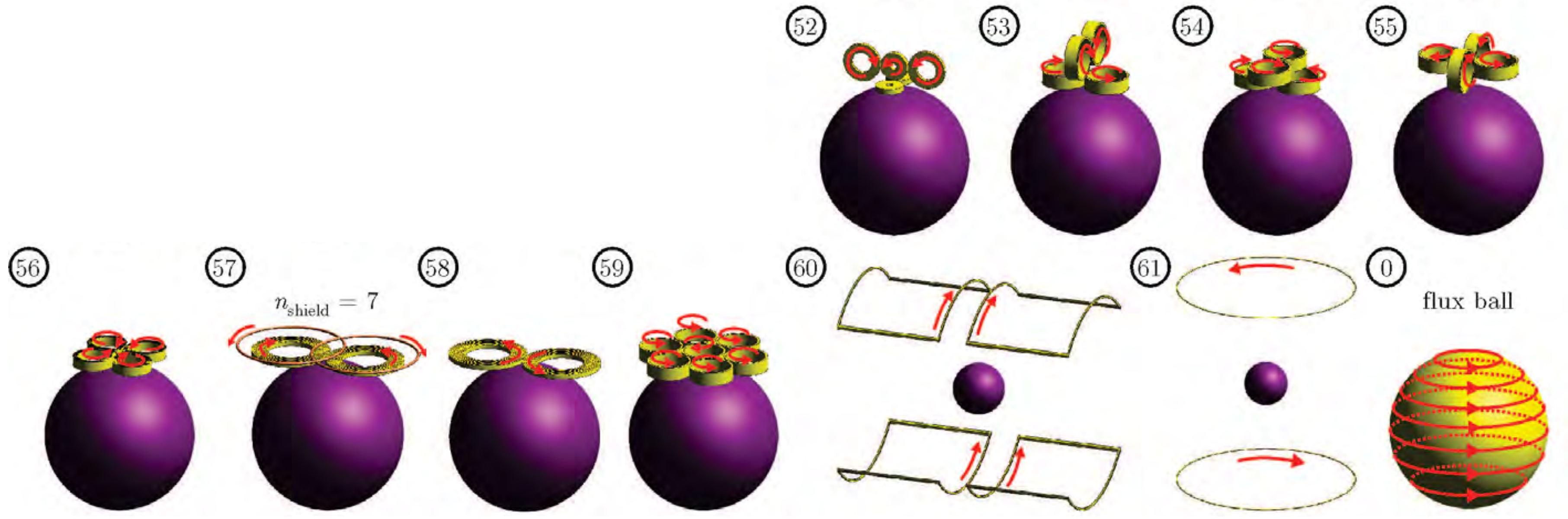
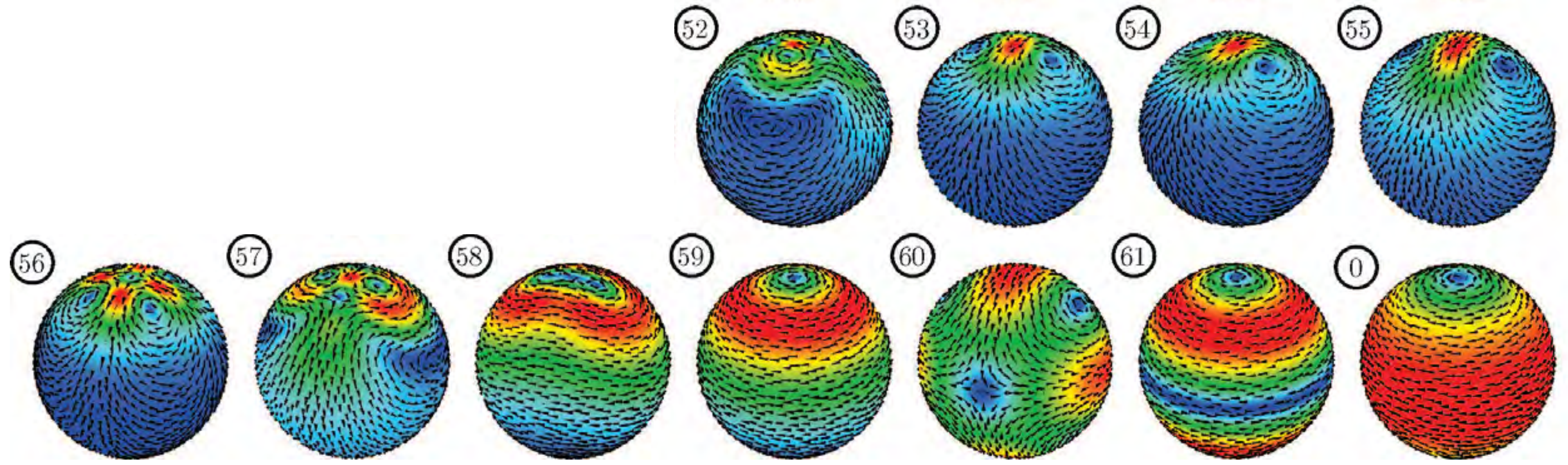


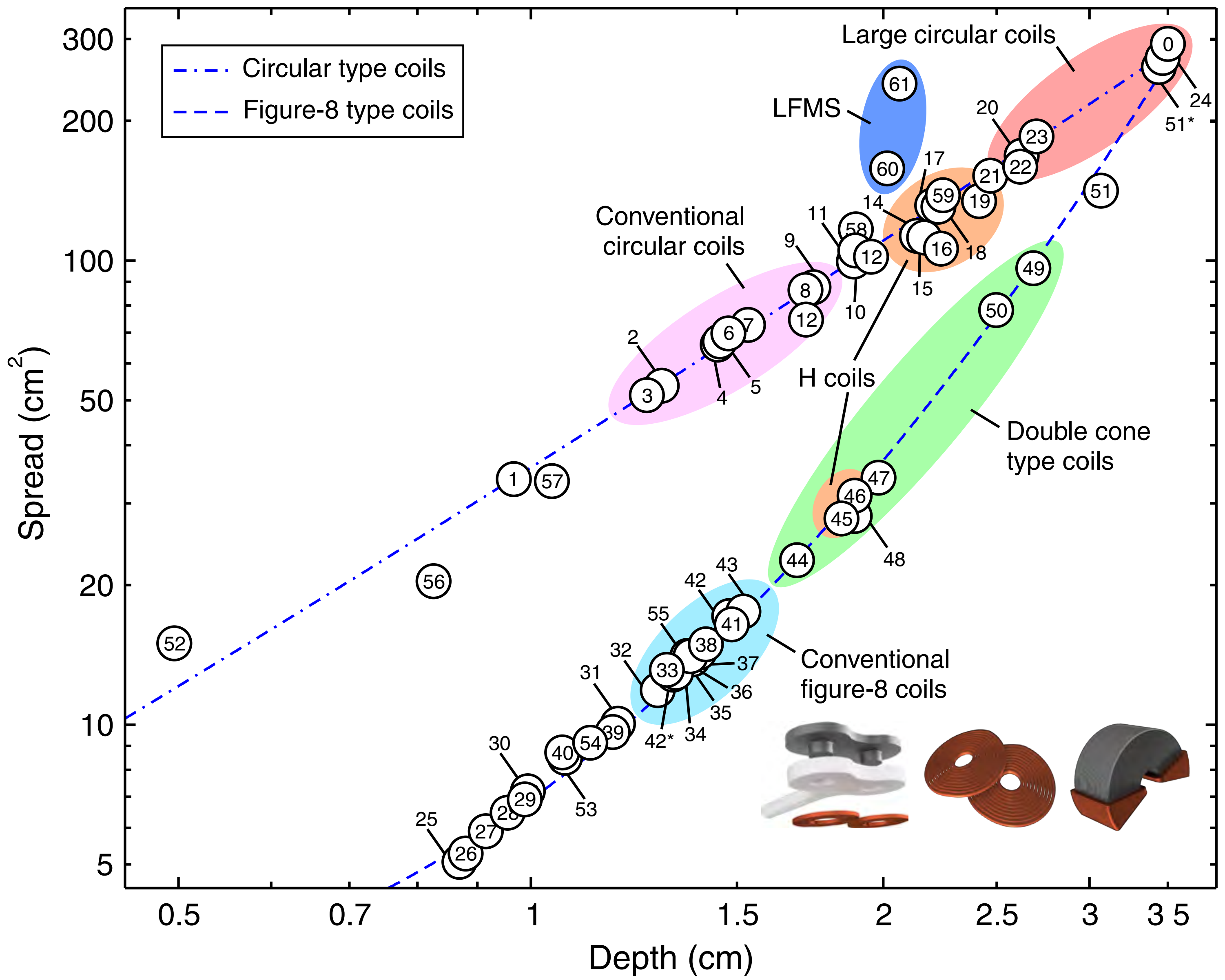
Figure-8 type




52
53
54
55
56
57
$n_{\text{shield}} = 7$
58
59
60
61
0
flux ball

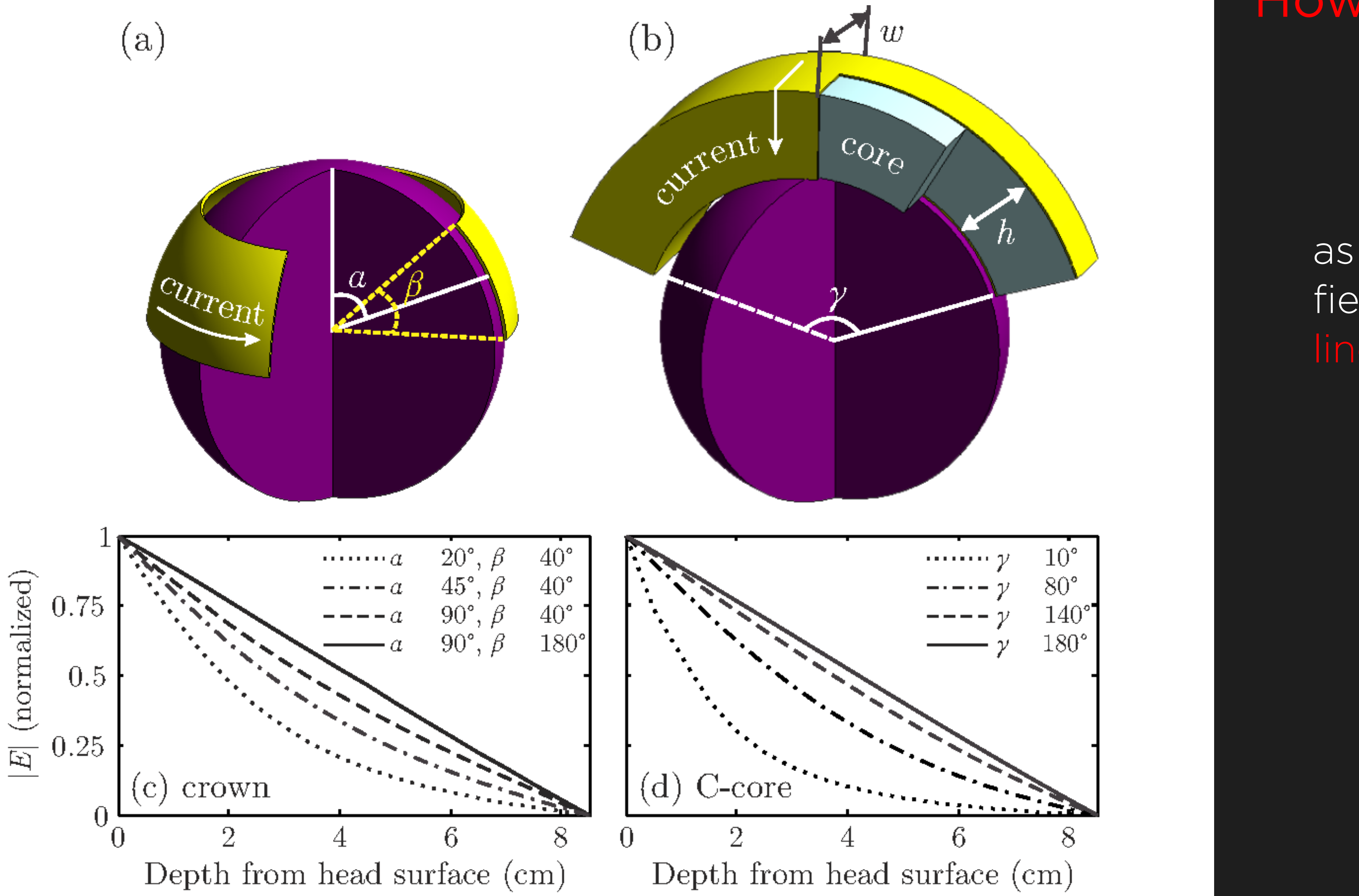

52
53
54
55
56
57
58
59
60
61
0

Depth–focality tradeoff



Deng et al., *Brain Stimul*, 2013

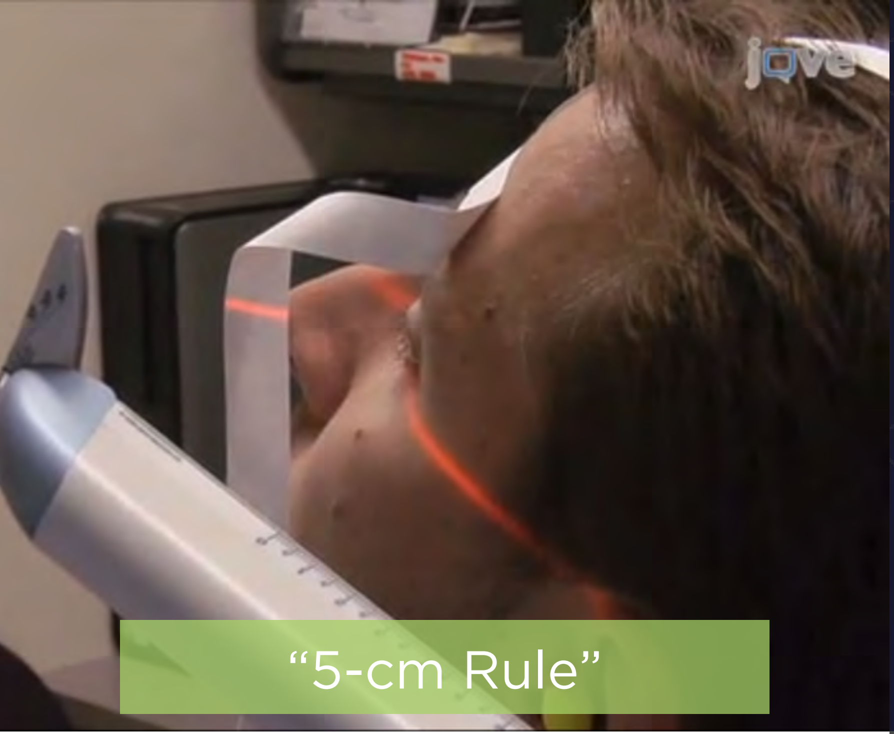
How deep can we get?



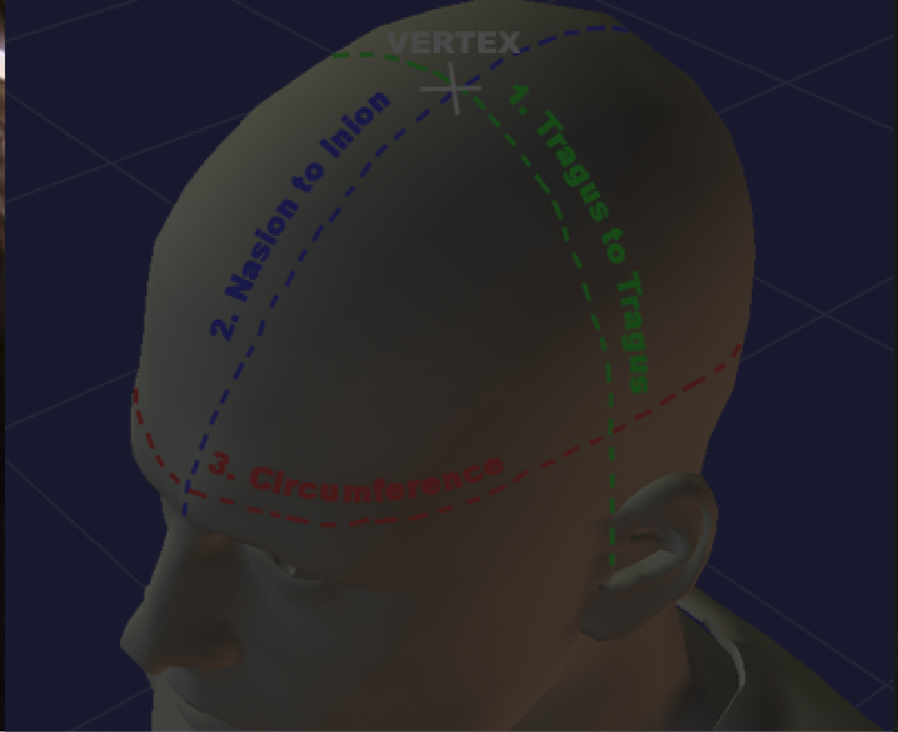
as coil size increases, field decay becomes linear

Deng et al., *Clin Neurophysiol* 2014

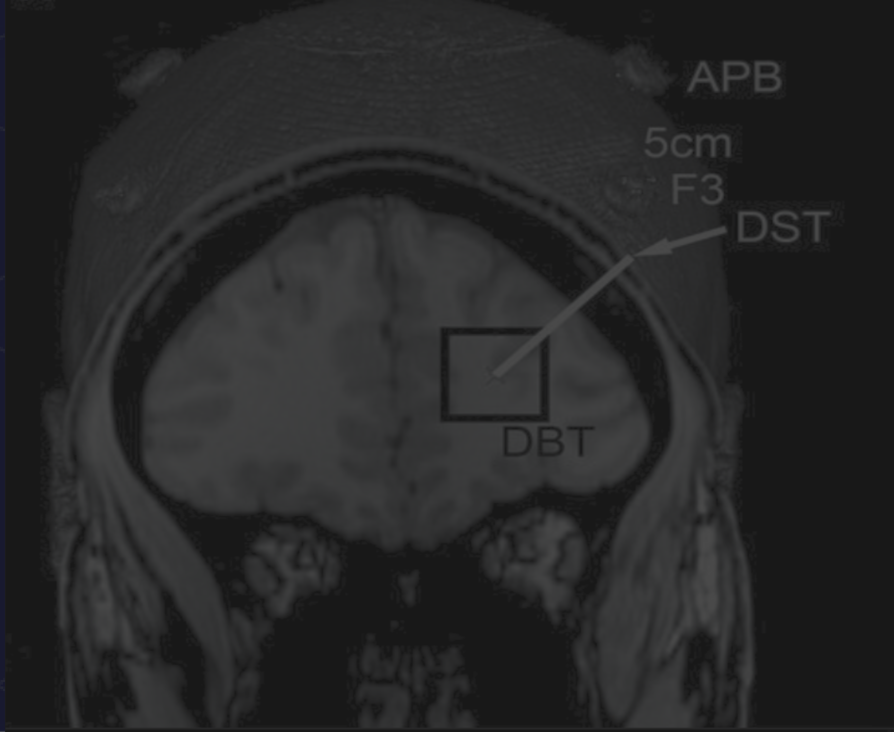
modeling and targeting



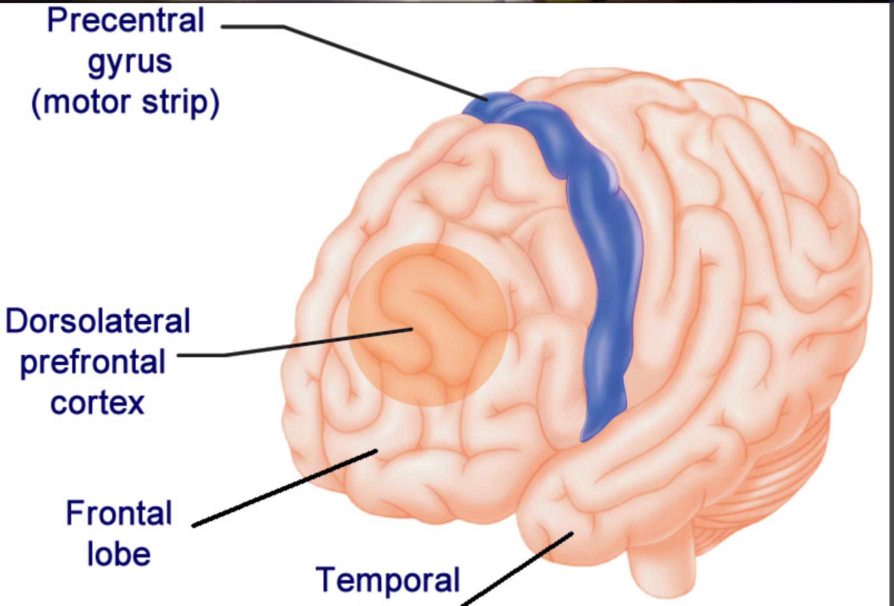
“5-cm Rule”



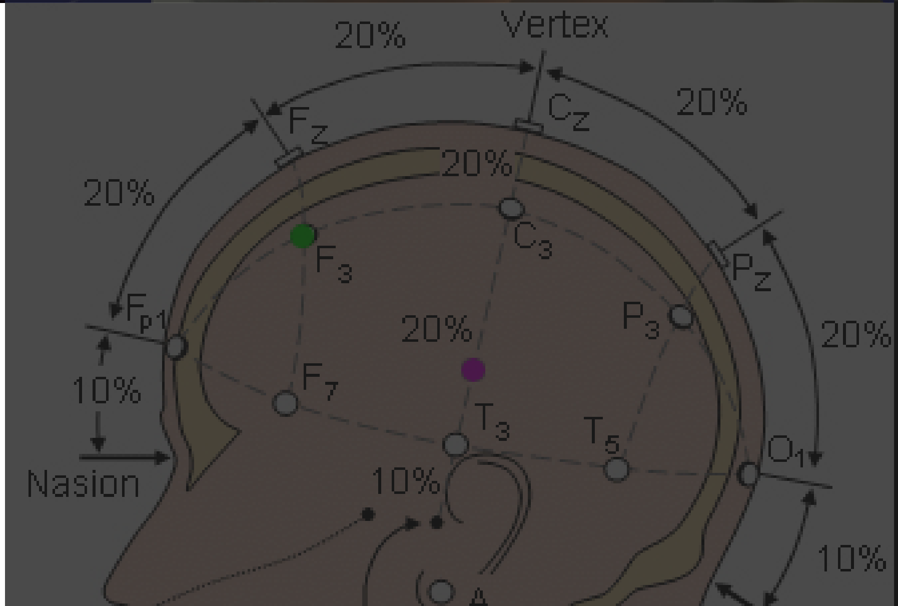
VERTEX
1. Tragus to Tragus
2. Nasion to Inion
3. Circumference



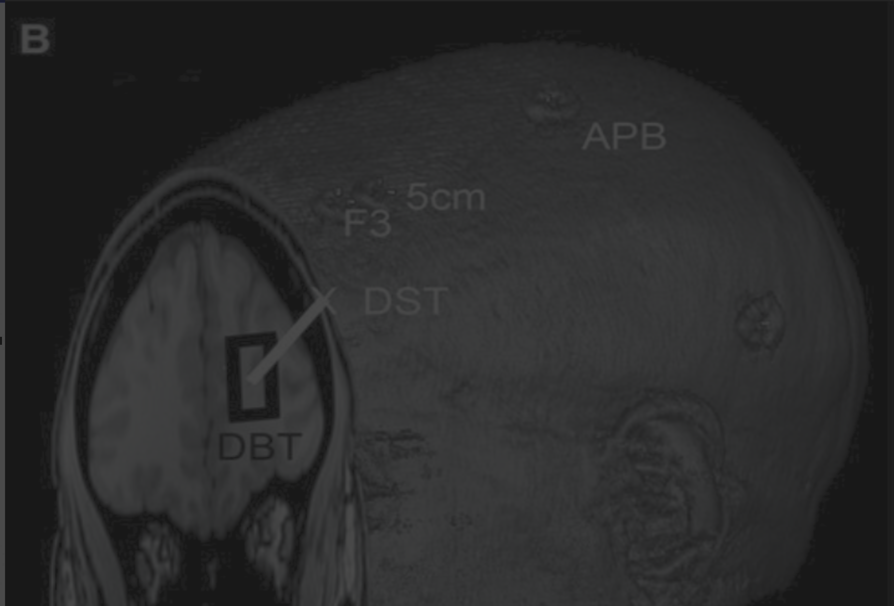
APB
5cm
F3
DST
DBT



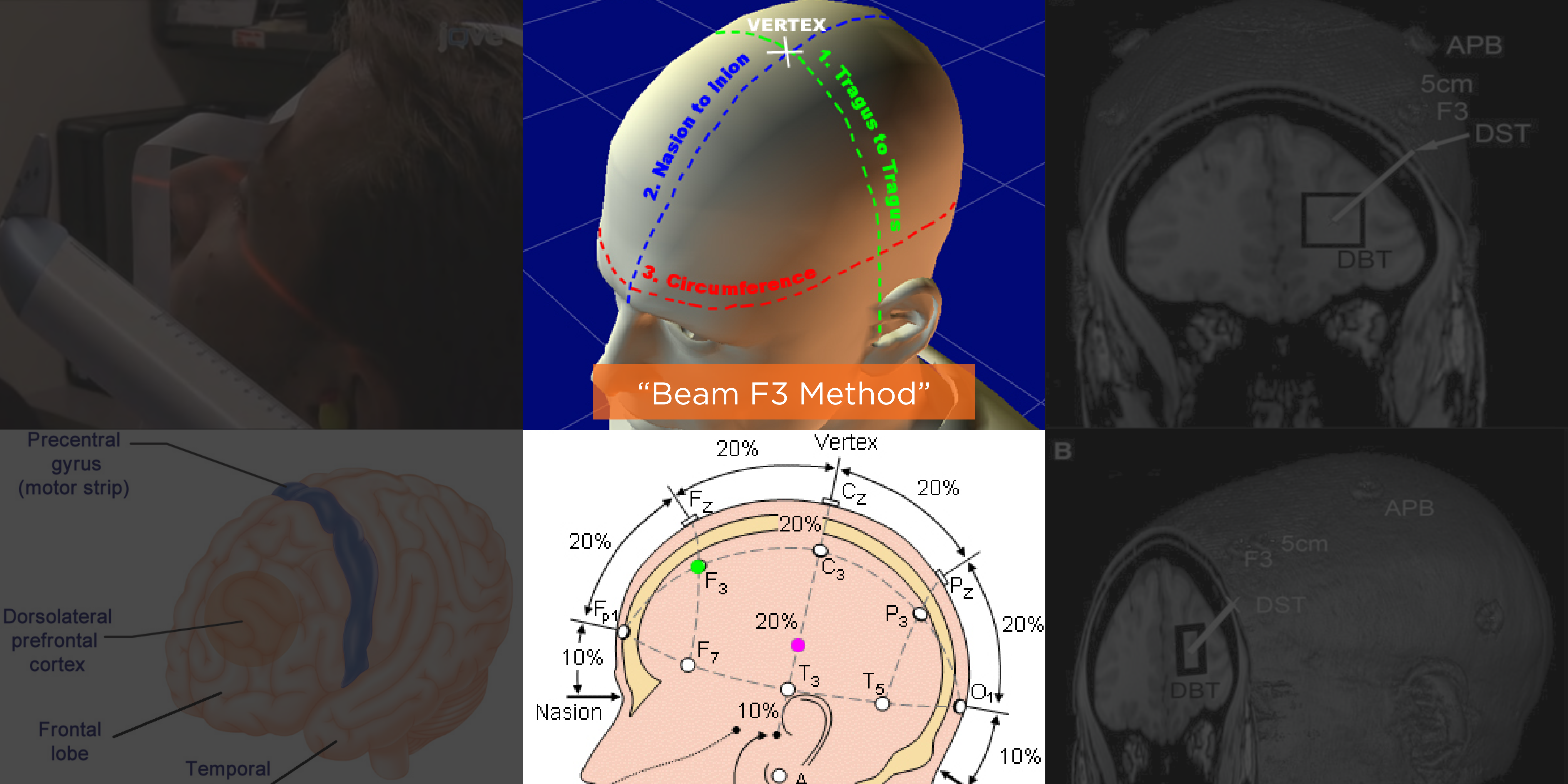
Precentral gyrus (motor strip)
Dorsolateral prefrontal cortex
Frontal lobe
Temporal

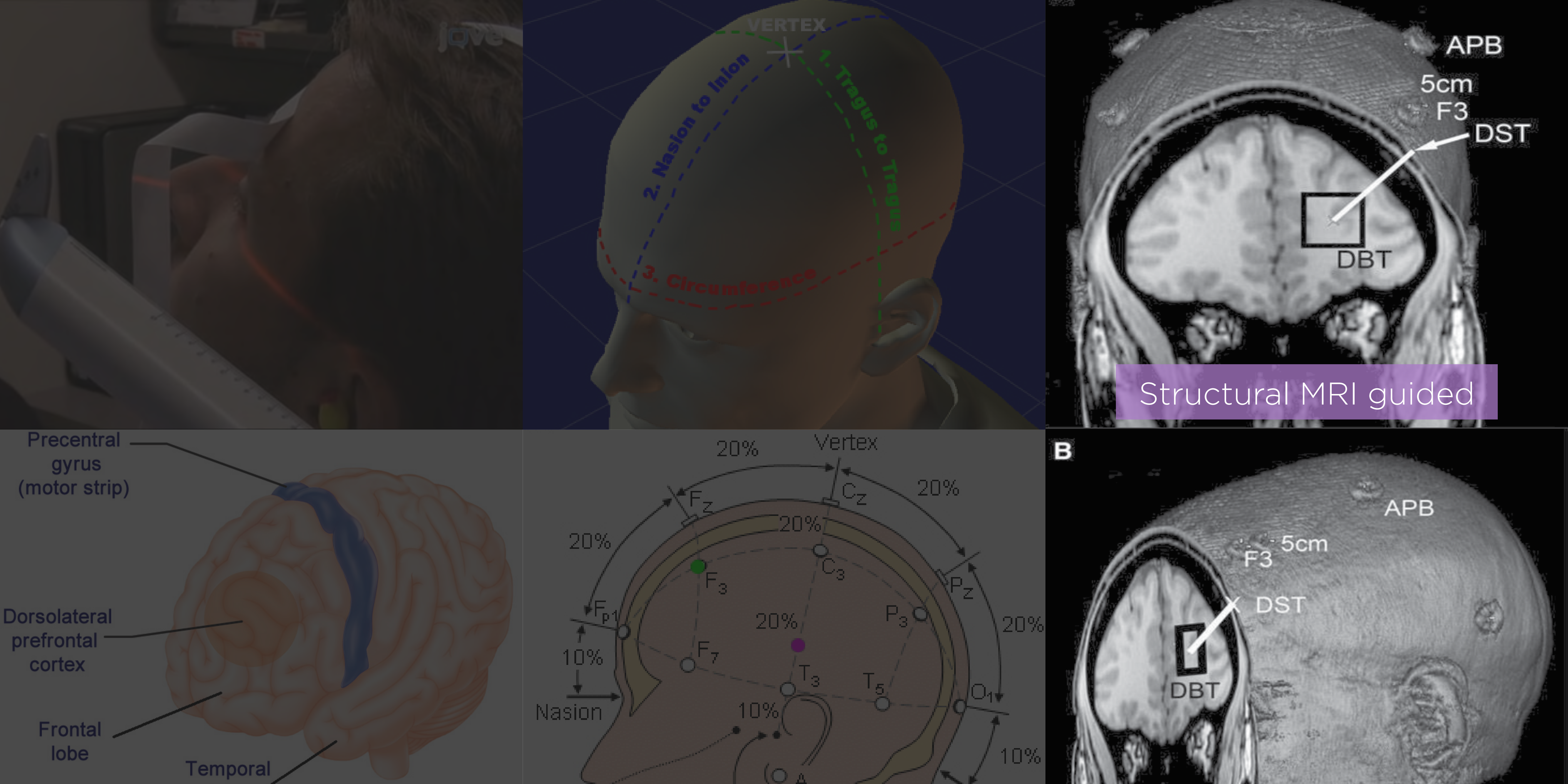


Vertex
20%
20%
20%
20%
20%
20%
10%
10%
10%
Nasion
F_z
C_z
P_z
F_3
C_3
P_3
F_{p1}
F_7
T_3
T_5
O_1

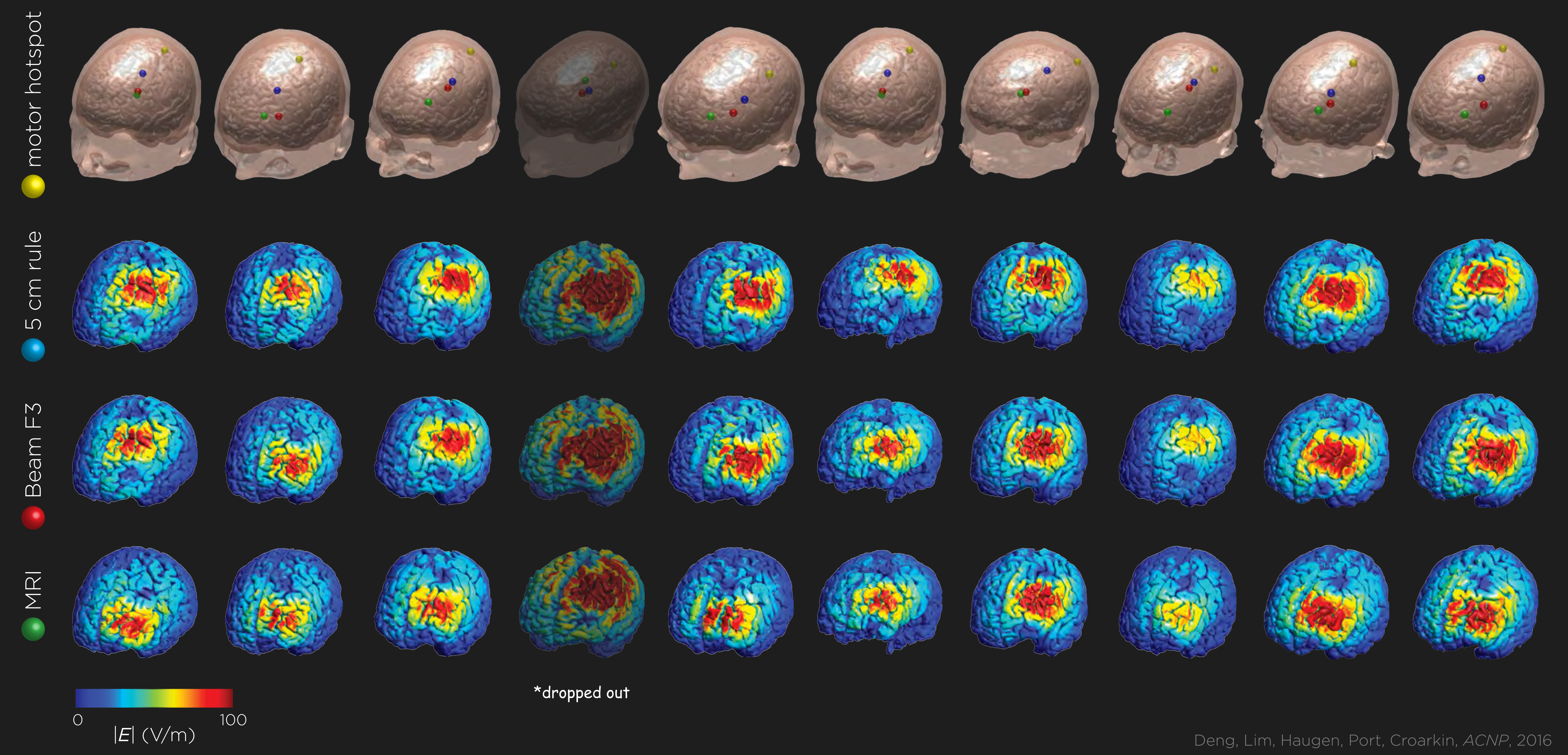


B
APB
5cm
F3
DST
DBT


VERTEX
2. Nasion to Inion
1. Tragus to Tragus
3. Circumference
“Beam F3 Method”
APB
5cm
F3
DST
DBT
Precentral gyrus (motor strip)
Dorsolateral prefrontal cortex
Frontal lobe
Temporal
Vertex
20%
Fz
Cz
20%
20%
20%
Fp1
F3
C3
Pz
P3
20%
20%
10%
F7
T3
T5
O1
Nasion
10%
10%
B
APB
5cm
F3
DST
DBT

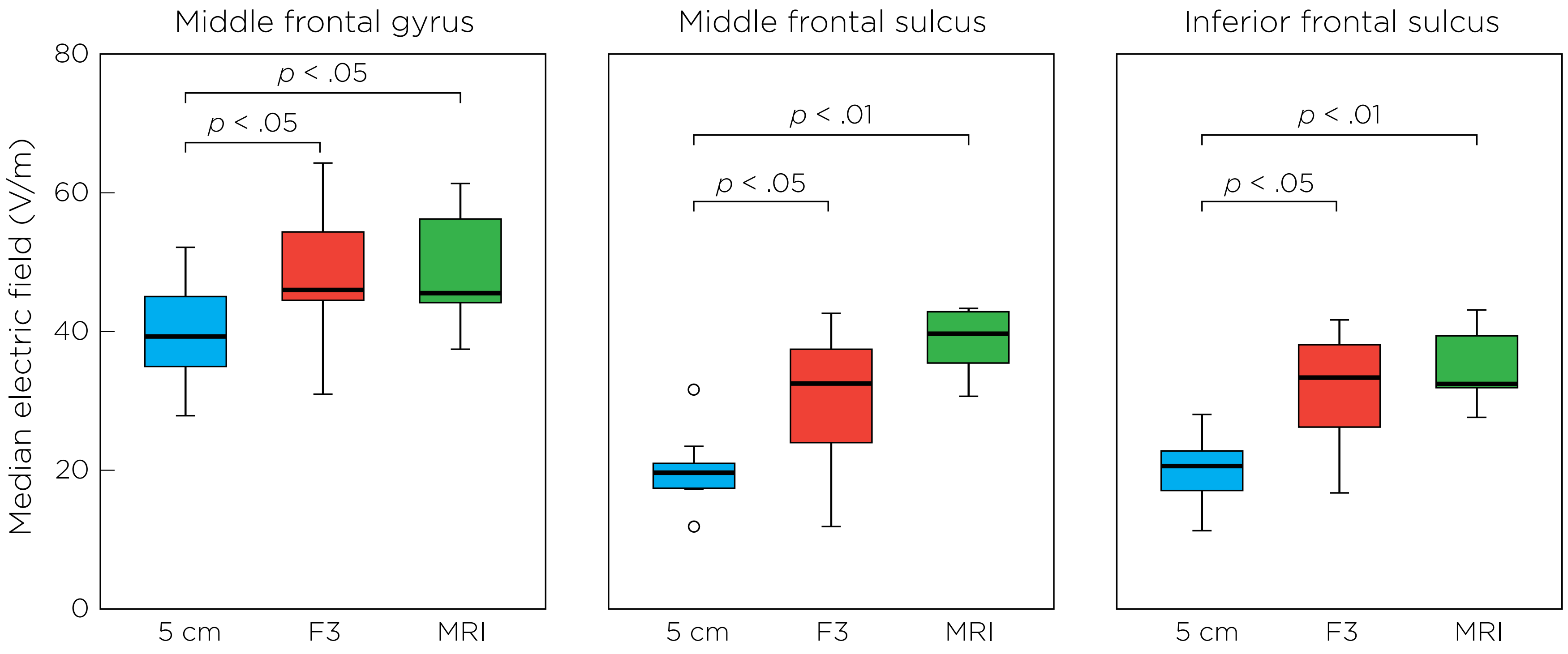


VERTEX
1. Tragus to Tragus
2. Nasion to Inion
3. Circumference
APB
5cm
F3
DST
DBT
Structural MRI guided
Precentral gyrus (motor strip)
Dorsolateral prefrontal cortex
Frontal lobe
Temporal
Vertex
20%
Fz
Cz
20%
20%
20%
F3
C3
Pz
Fp1
20%
P3
20%
F7
10%
T3
T5
O1
Nasion
10%
10%
B
APB
5cm
F3
DST
DBT


motor hotspot
5 cm rule
Beam F3
MRI
*dropped out
0
100
|E| (V/m)
Deng, Lim, Haugen, Port, Croarkin, ACNP, 2016

5-cm rule consistently underdoses DLPFC

The clinical standard is suboptimal



Deng, Lim, Haugen, Port, Croarkin, *ACNP*, 2016

Cornell study

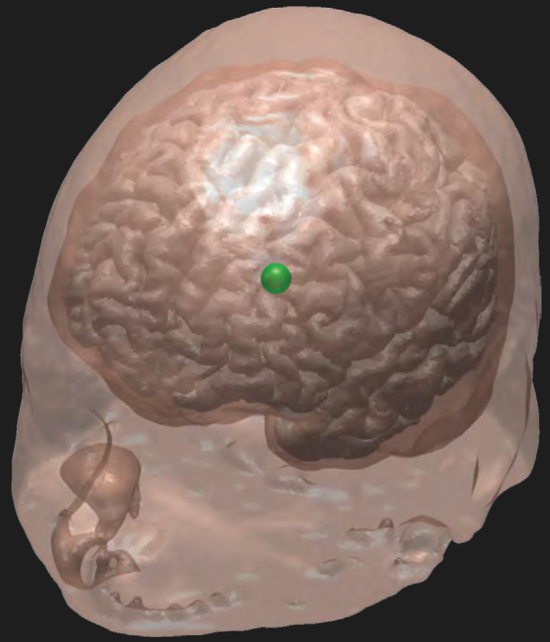
26 depressed patients (age 21–68)

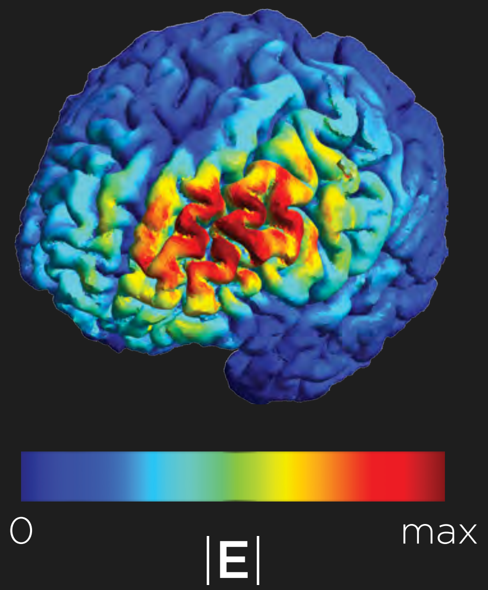
Standard 10 Hz rTMS protocol at the **F3 target**

T1-weighted MRI & DTI acquired when 7 days prior to treatment course

Motor threshold determined by visualization of movement at baseline

FEM head models constructed using SimNIBS 2.0.1



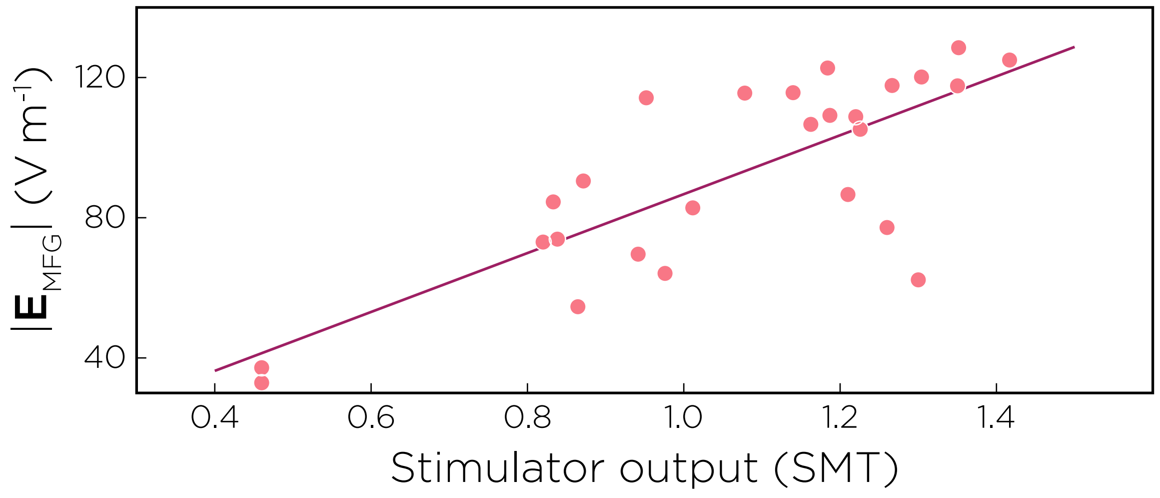


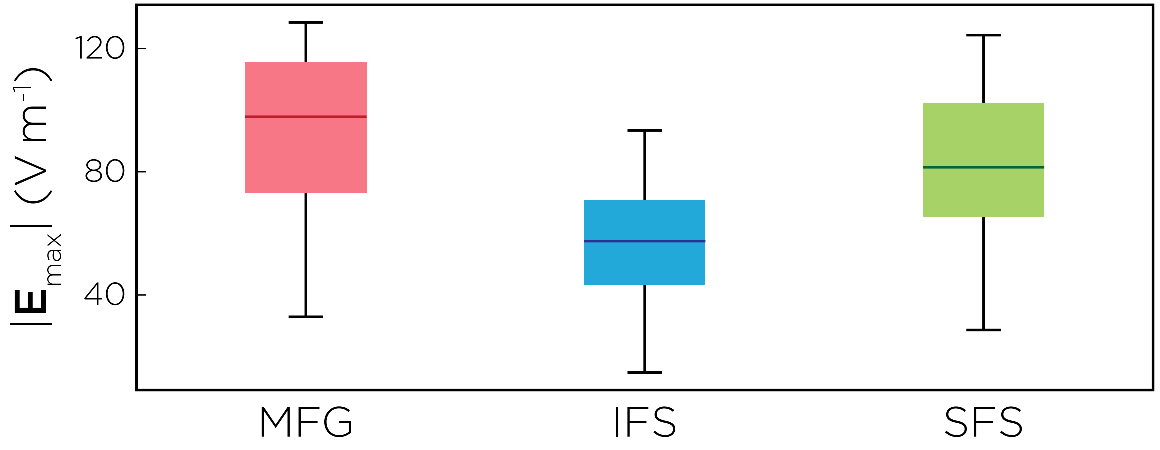
Deng, Liston, Gunning, Dubin, *IEEE EMBC*, 2018

Considerable variability in E-field
IQR E_{MFG}: ~40–120 V/m

... although, not everyone was administered the full dose of 120%MT

E-field strengths at MFG, IFG, and SFG were **not correlated** with change in HAMD-24



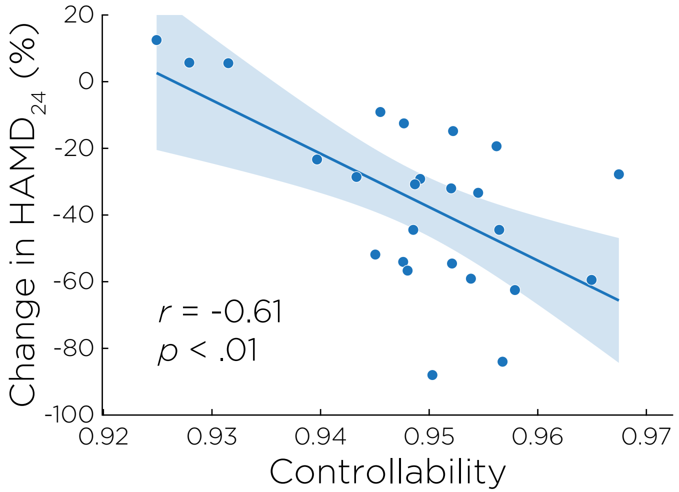


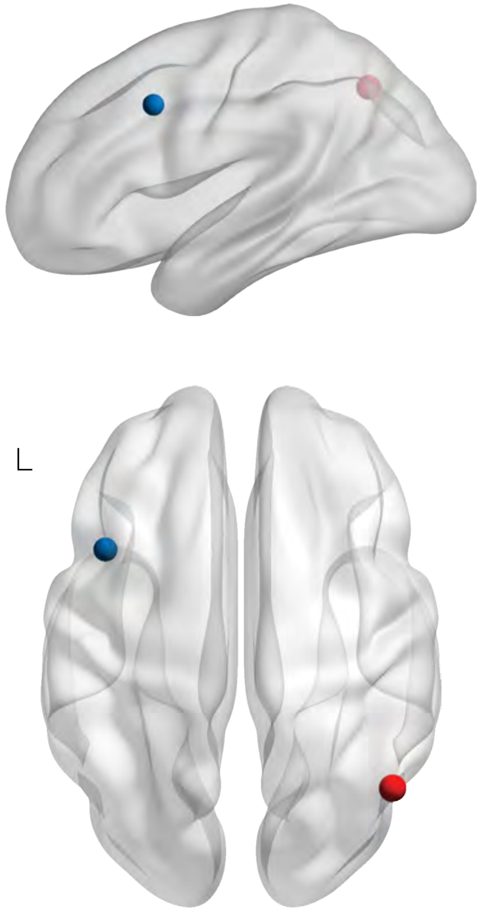
Controllability correlates with TMS treatment response

$$\mathbf{x}[k+1] = \mathbf{A}\mathbf{x}[k] + \mathbf{B}\mathbf{u}[k]$$

$$y[k] = \mathbf{C}^{\mathrm{T}}\mathbf{x}[k]$$

$$\phi_i = \sum_{j=1}^{N} \left(1 - \lambda_j^2(A)\right) v_{ij}^2$$





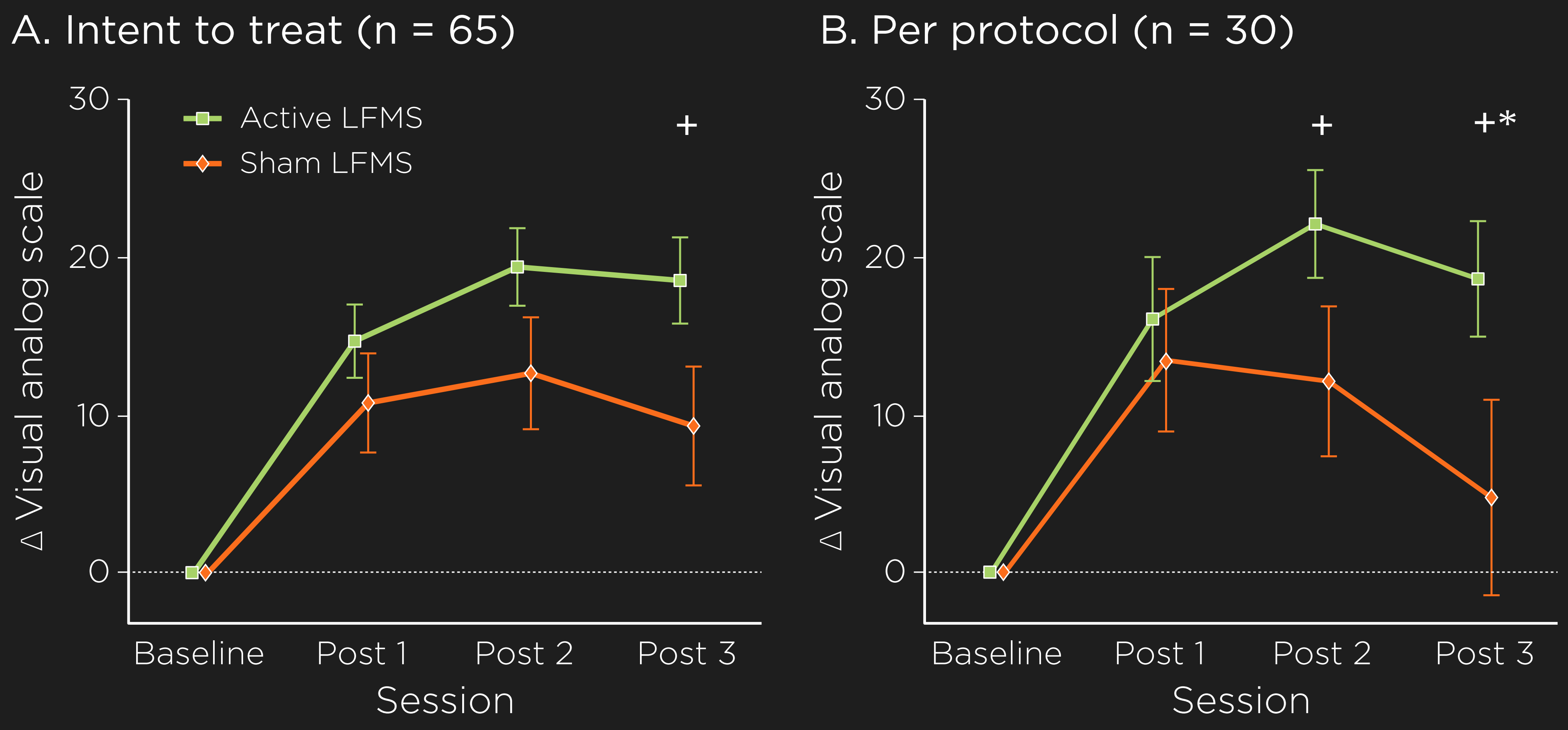
Deng et al, *SOBP*, 2018

other things

Low field magnetic stimulation

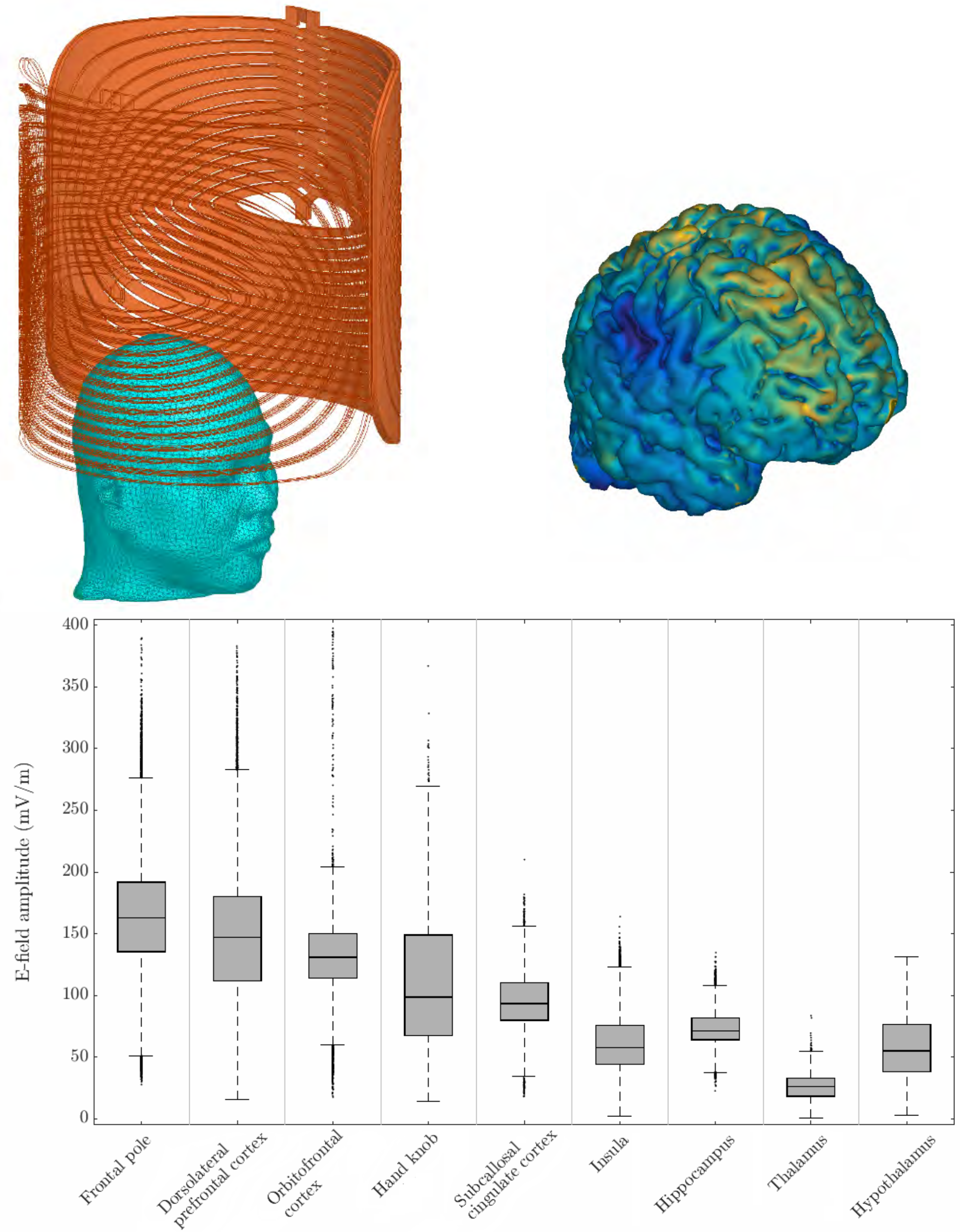
Rohan et al, *Biol Psychiatry*, 2014

LFMS: clinical results



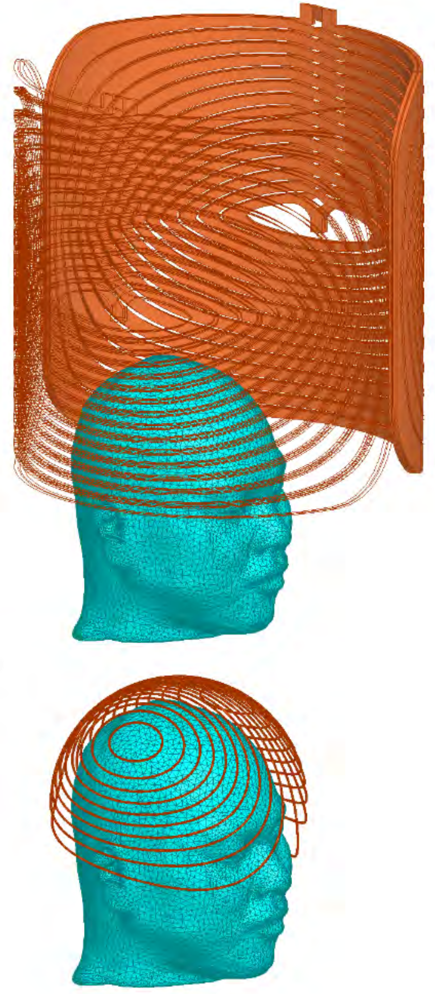
Dubin et al., *Not Yet Rejected*

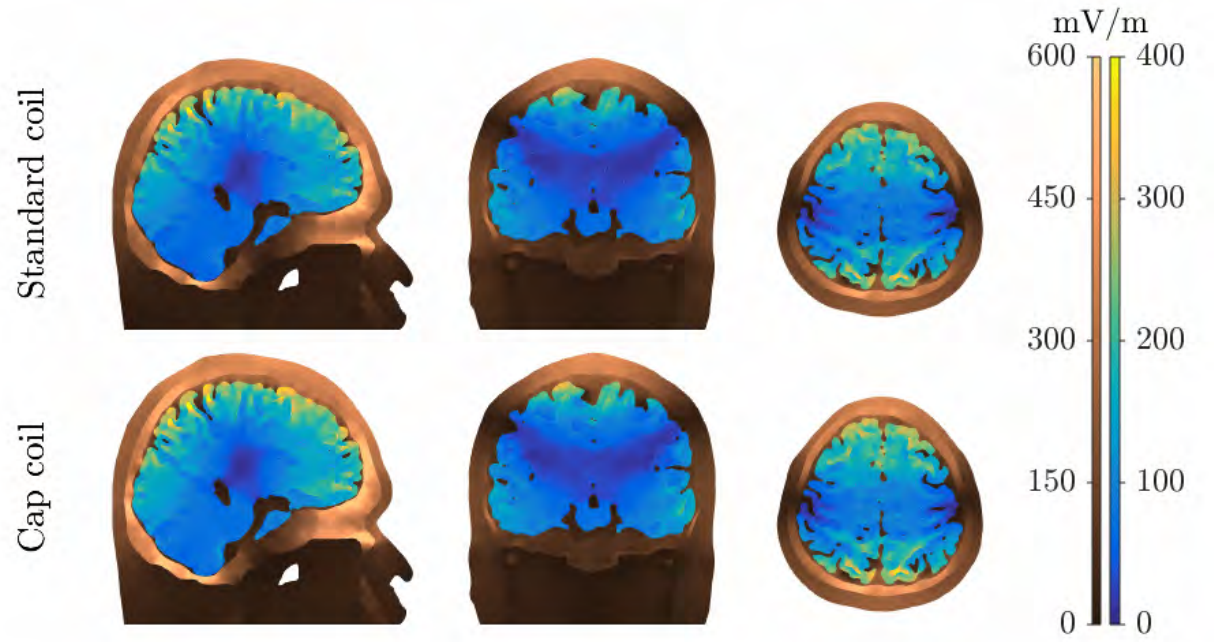
LFMS: electric field



Coil current amplitude = 28.5 A

Wang et al., *J Neural Eng*, 2018

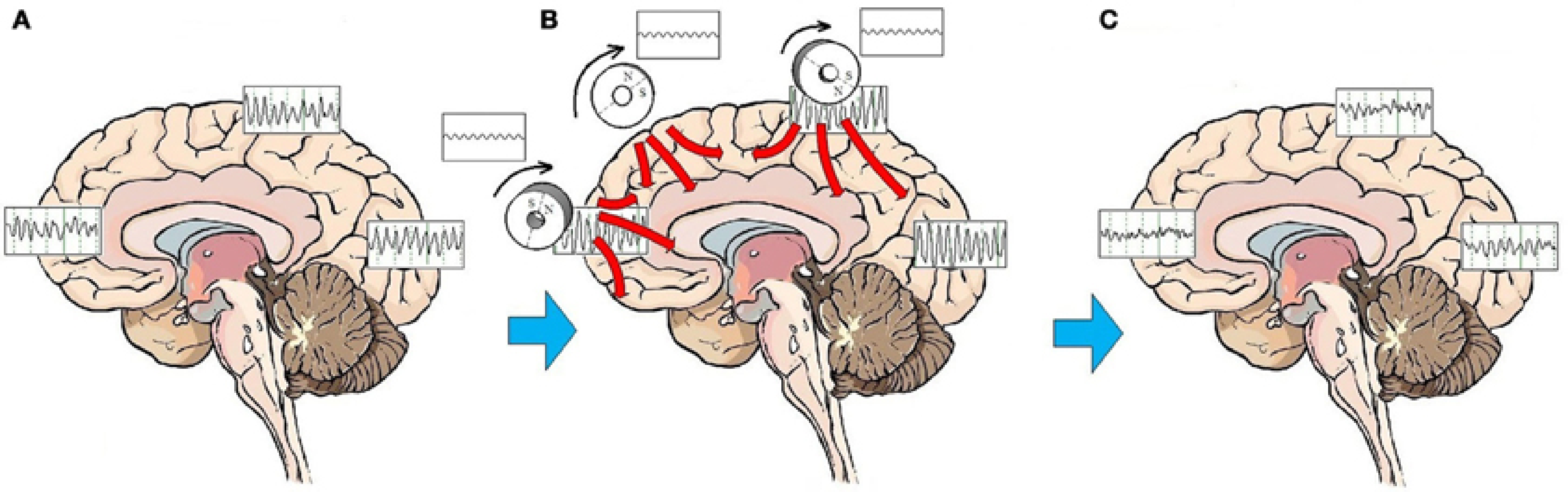




LFMS: equivalent coil

Wang et al., *J Neural Eng*, 2018

Synchronized transcranial magnetic stimulation (sTMS)



- Synchronized stimulation to individual alpha frequency (IAF)
- Entrainment alpha oscillations in frontal polar, frontal, parietal brain regions
- Resetting of cortical oscillators

Leuchter et al., *Front Hum Neurosci*, 2013

sTMS model setup

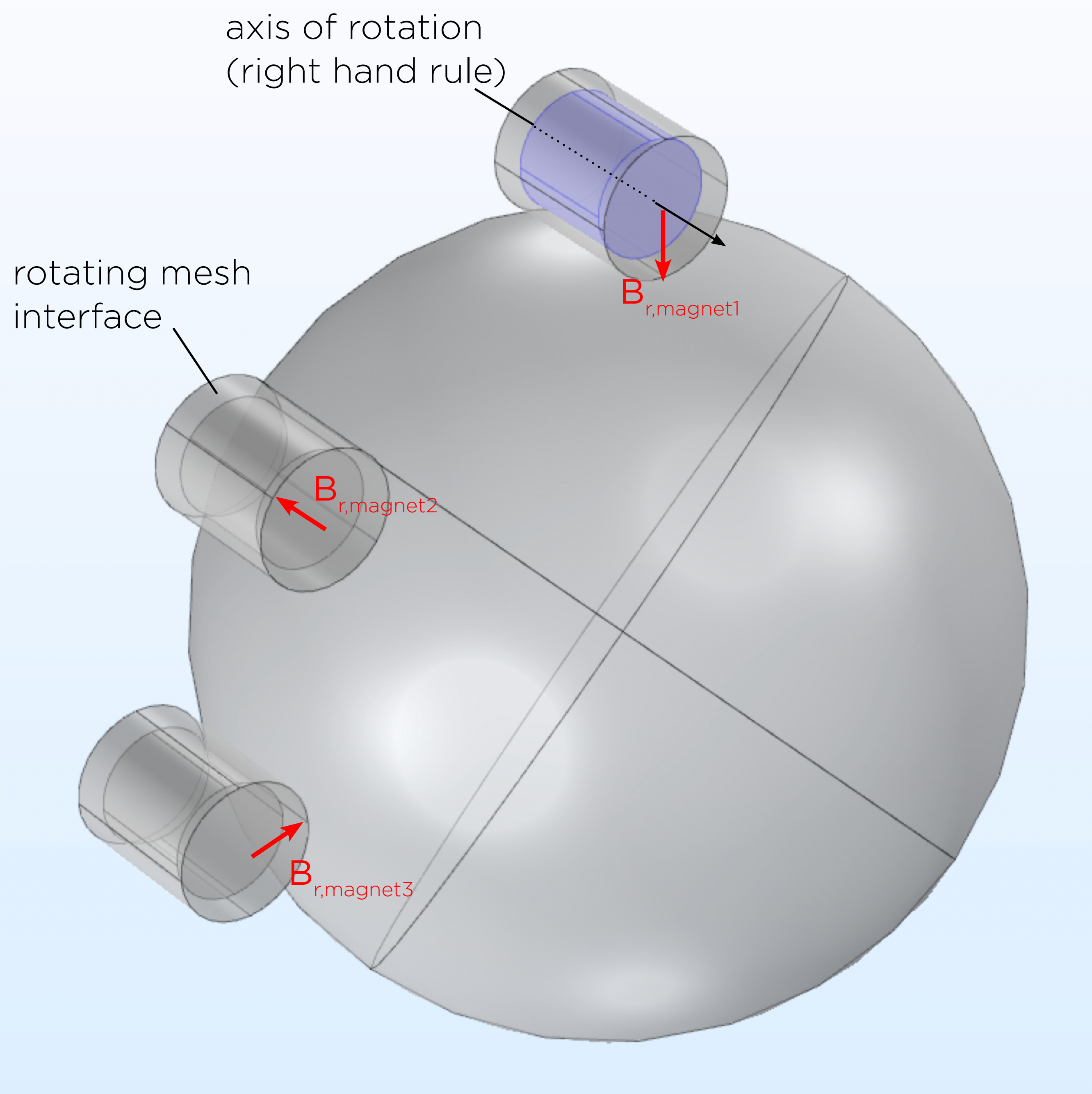
Time-dependent 3D problem

Conductive part of the rotor is modeling using Ampère's law:

$$\sigma\frac{\partial \mathbf{A}}{\partial t} + \nabla \times \left(\frac{1}{\mu}\nabla \times \mathbf{A}\right) = 0$$

Nonconductive parts of both the rotor and stator are modeled using a magnetic flux conservation equation for the scalar magnetic potential:

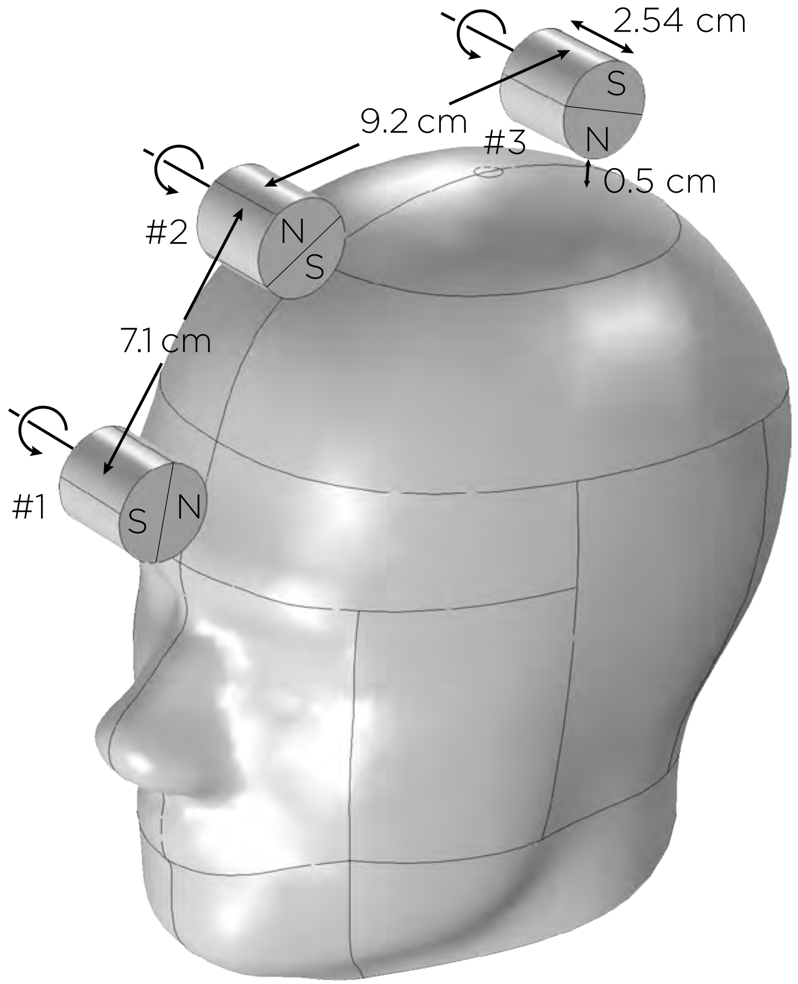
$$-\nabla \cdot (\mu \nabla V_{\mathrm{m}} - \mathbf{B}_{\mathrm{r}}) = 0$$



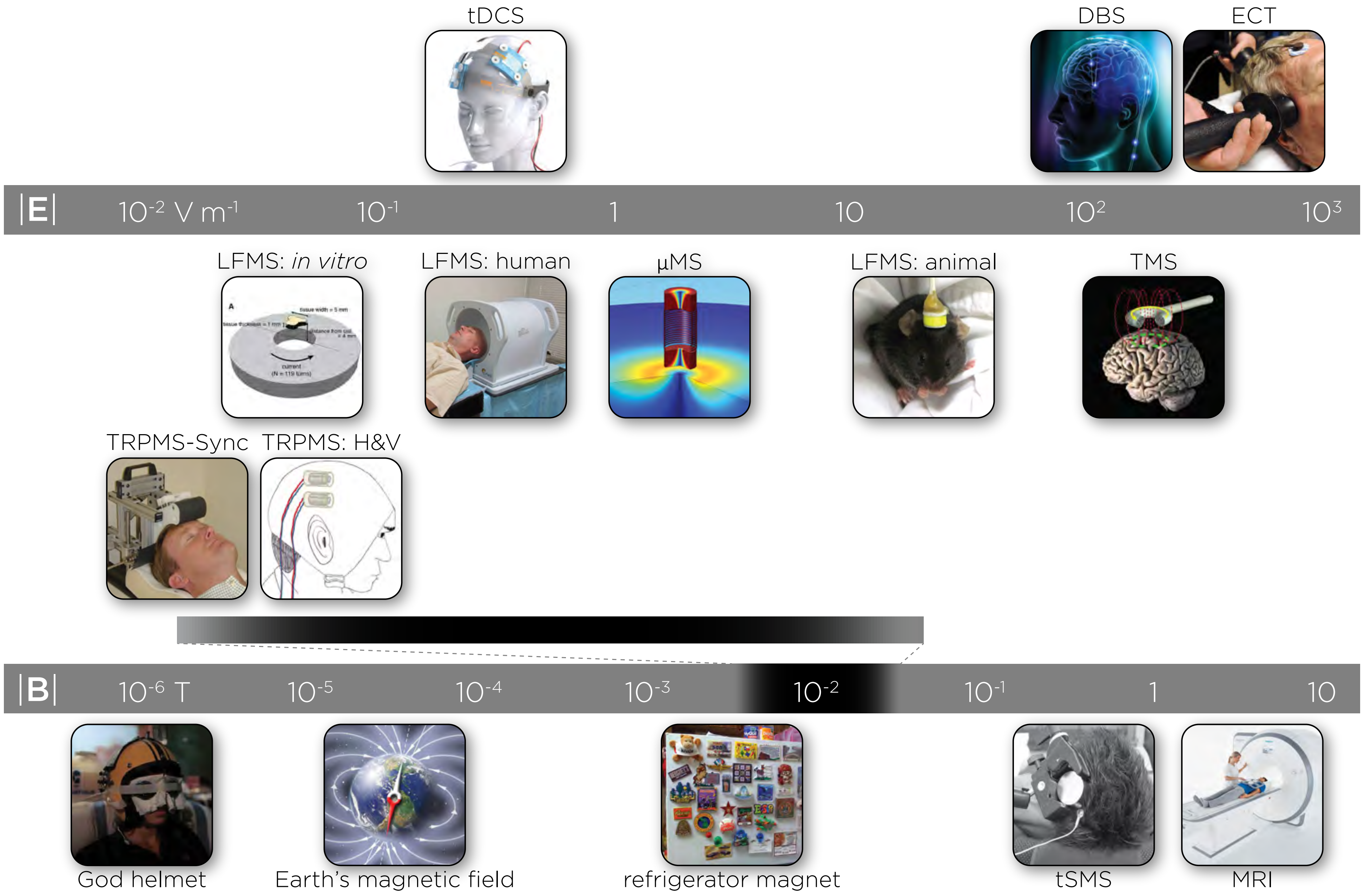
sTMS: SAM head model

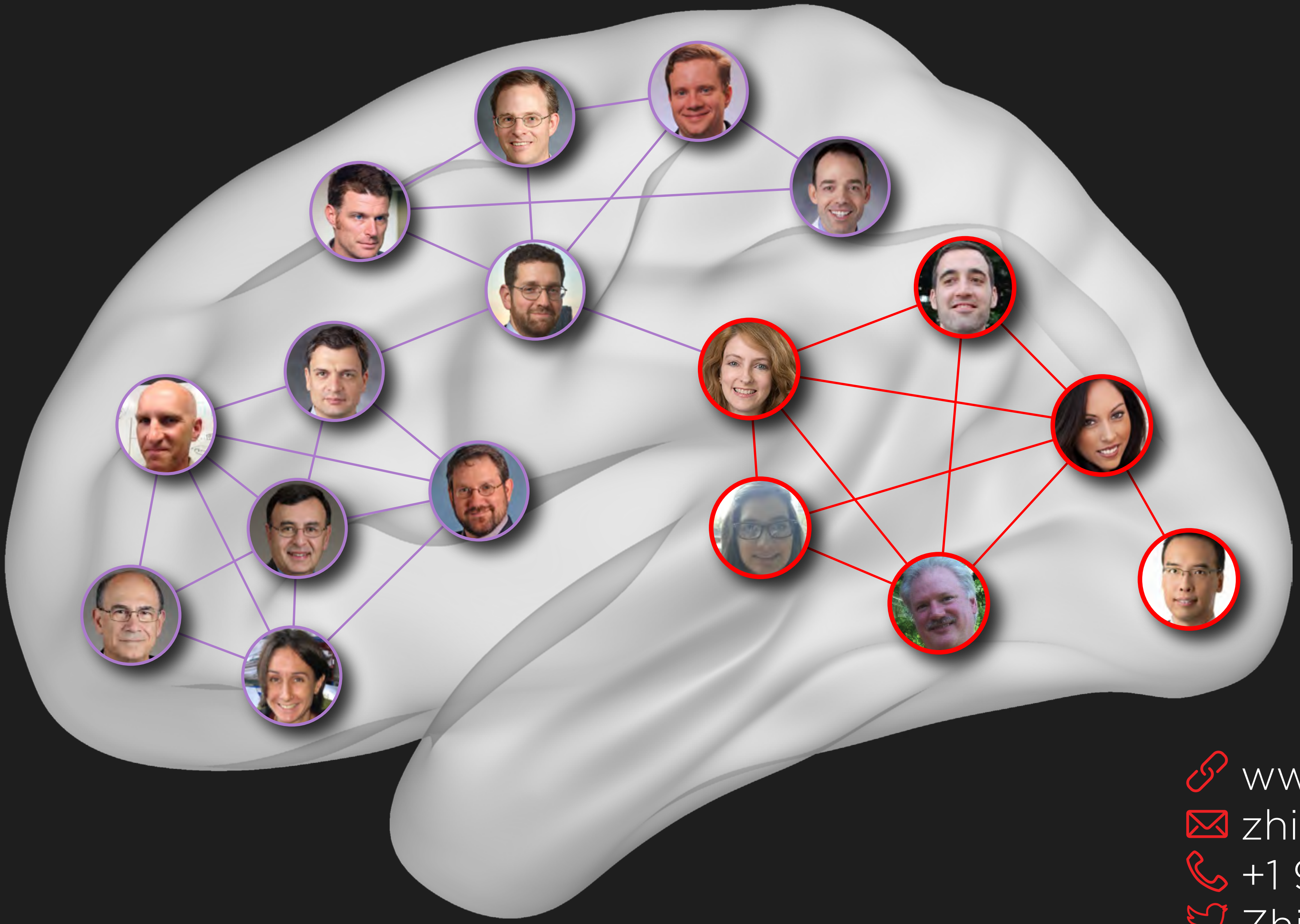
- Three cylindrical, neodymium magnets, 1 inch diameter and height
- $B_r = 0.64$ T
- Diametrically magnetized
- FEM implemented in COMSOL using IEEE SAM phantom (uniform 0.33 S m^{-1})

- Ampère's law applied to all domains
- Magnetic flux conservation for scalar magnetic potential applied to current-free domains
- Continuity in scalar magnetic potential enforced at rotor–statator interface
- Stationary solution first obtained using MUMPS direct solver, then time-dependent problem was solved



sTMS: full model


tDCS
DBS
ECT
|E|
10^{-2} V m^{-1}
10^{-1}
1
10
10^{2}
10^{3}
LFMS: *in vitro*
LFMS: human
μMS
LFMS: animal
TMS
TRPMS-Sync
TRPMS: H&V
|B|
10^{-6} T
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
God helmet
Earth's magnetic field
refrigerator magnet
tSMS
MRI



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