

Transcranial Magnetic Stimulation

Physics, devices, & modeling

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Research Fellow

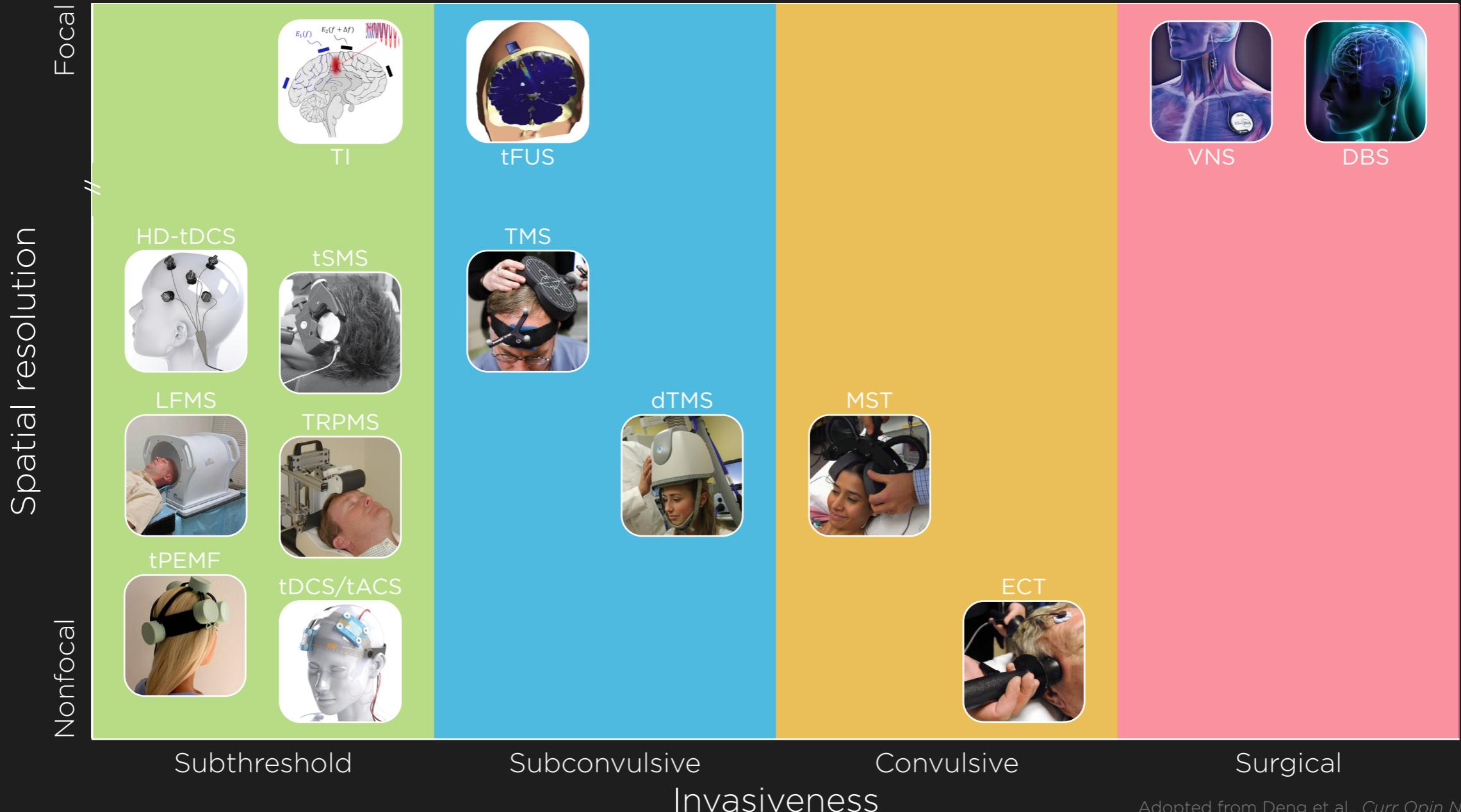
Noninvasive Neuromodulation Unit

Experimental Therapeutics & Pathophysiology Branch

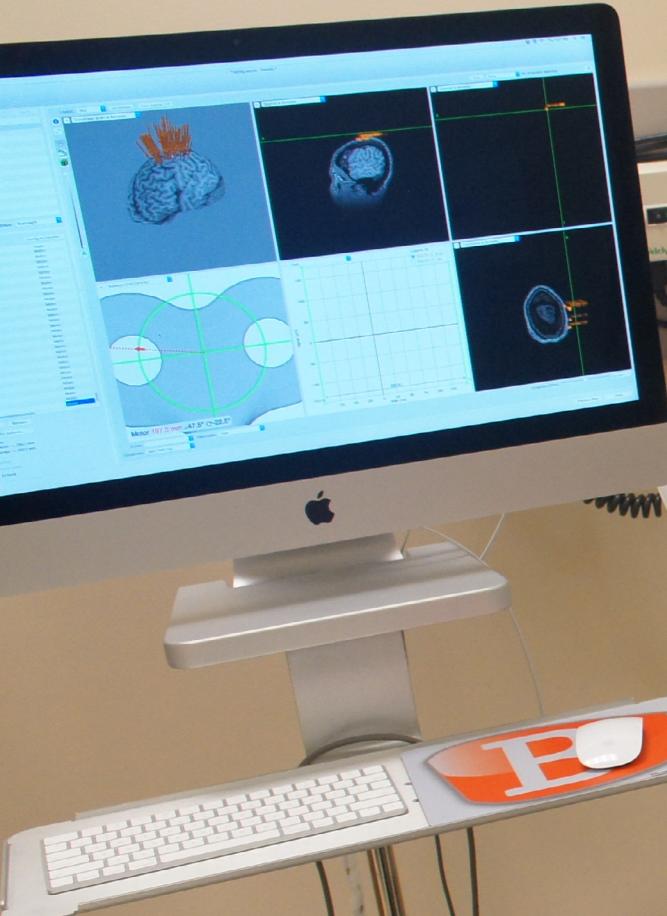
National Institute of Mental Health, NIH

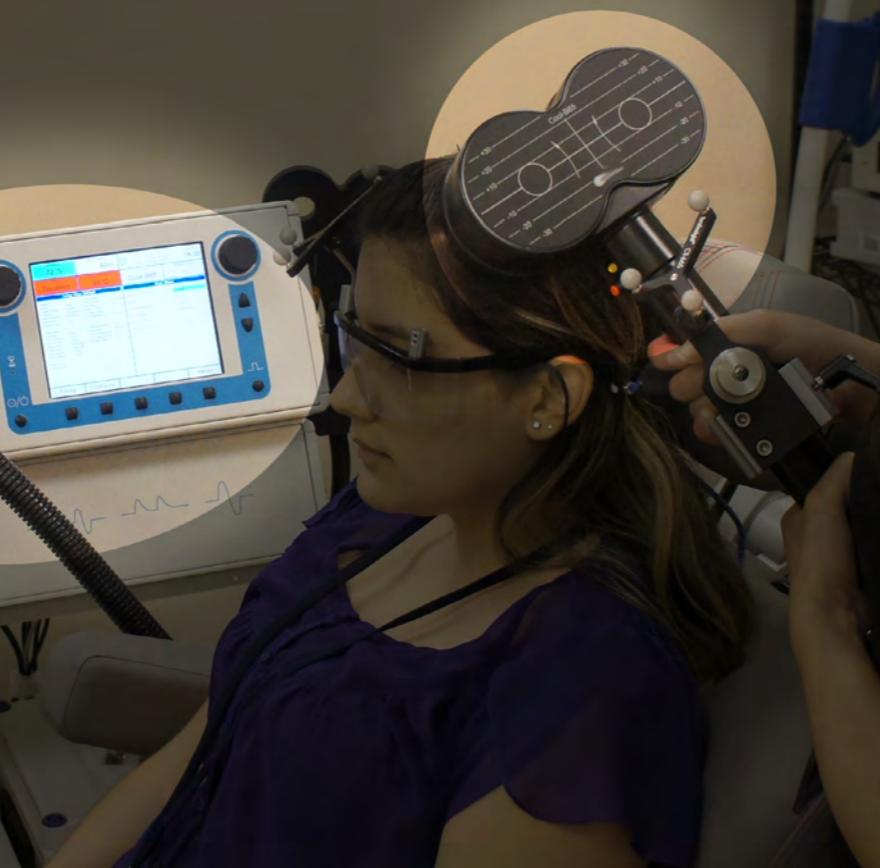
Disclosure

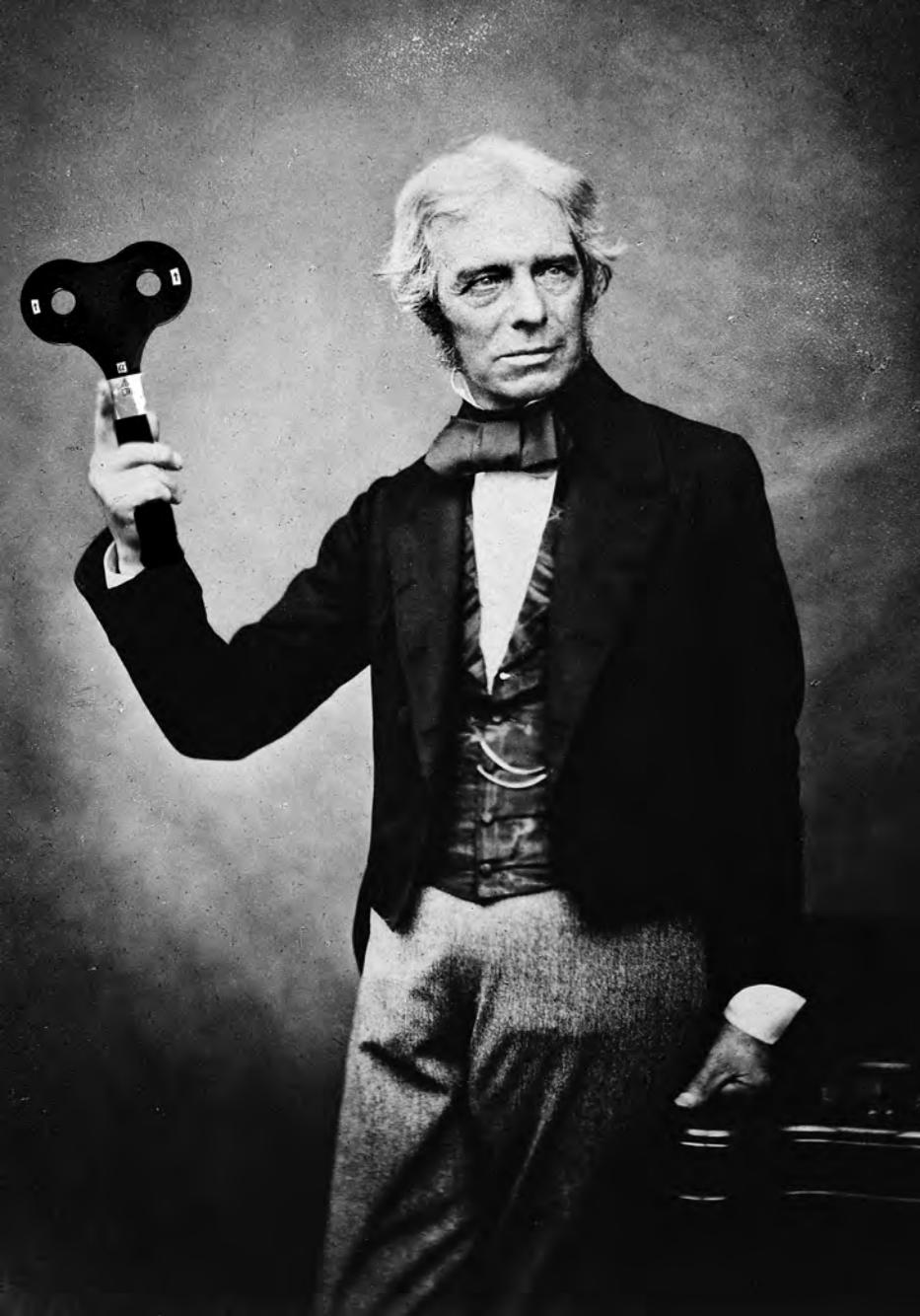
I am inventor on patents/patent applications
held by MIT, Columbia, Duke, NEVA Electromagnetics



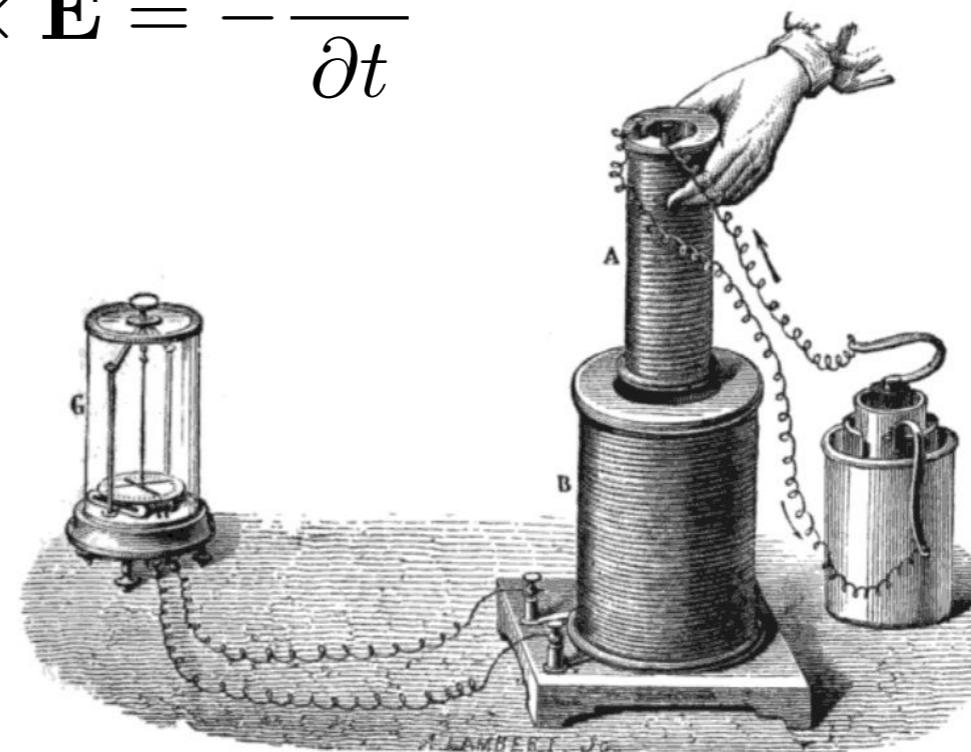
Adopted from Deng et al., *Curr Opin Neurobiol*, 2015



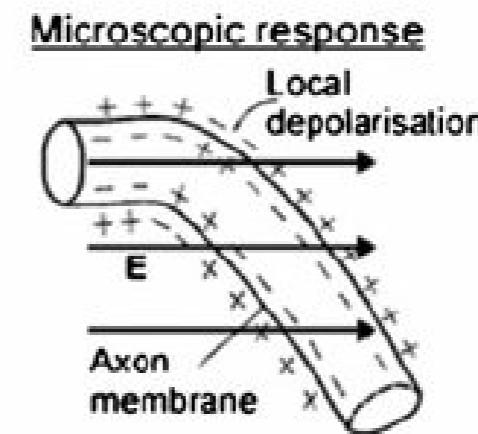
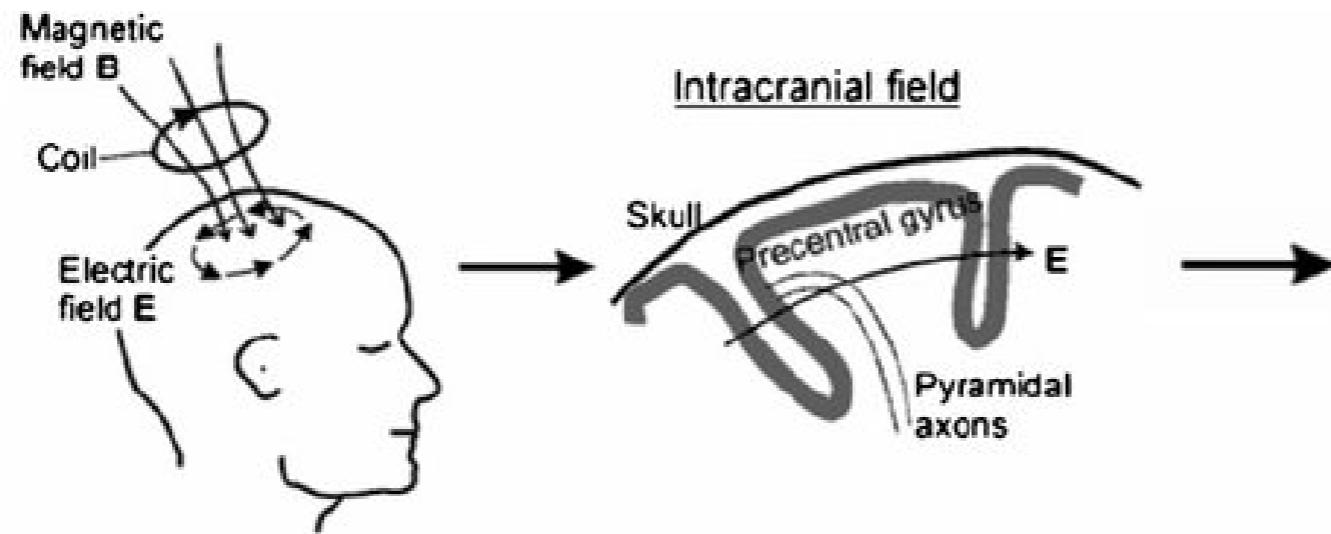




$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$



Faraday's experiment with induction.



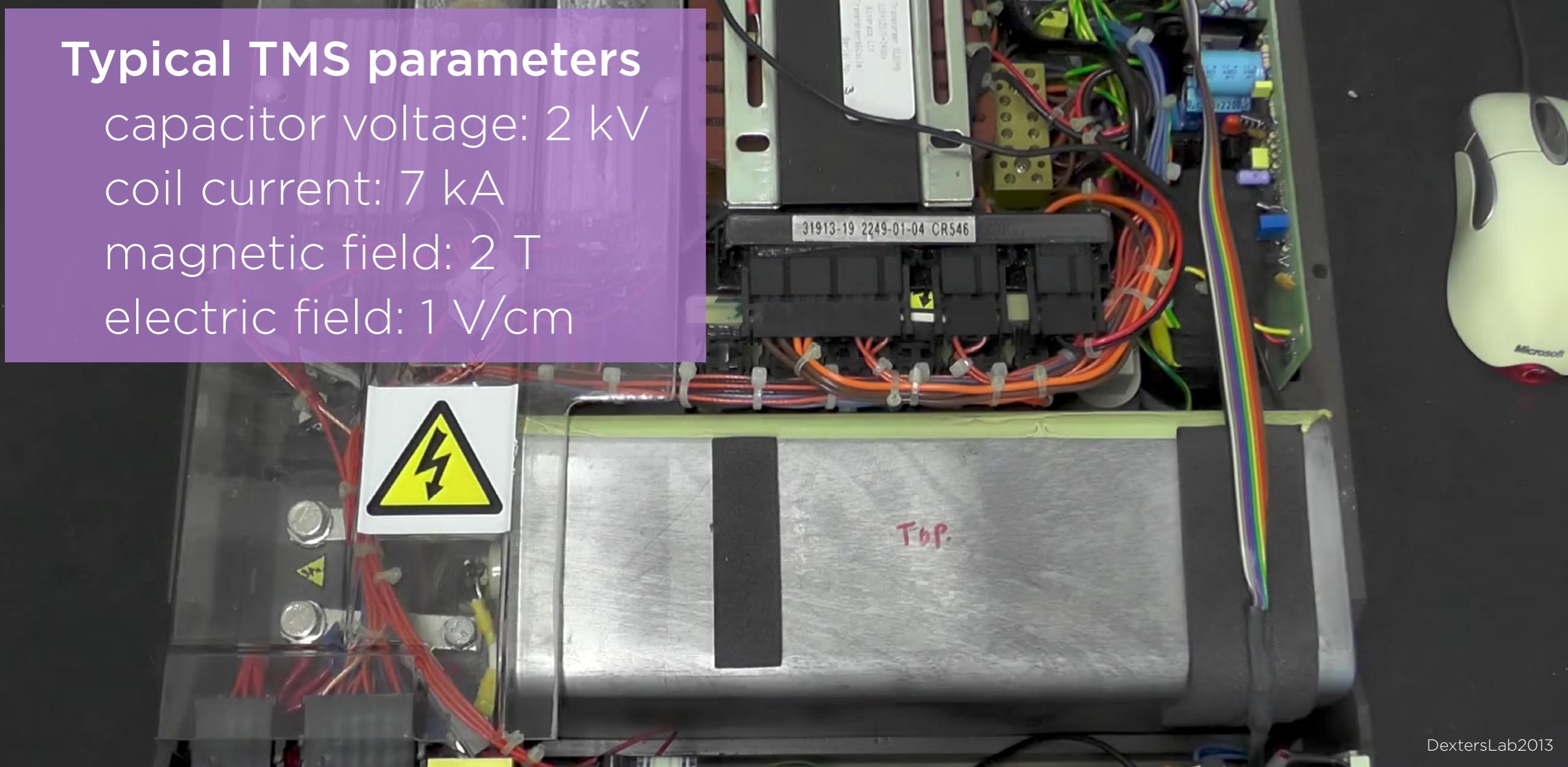
Typical TMS parameters

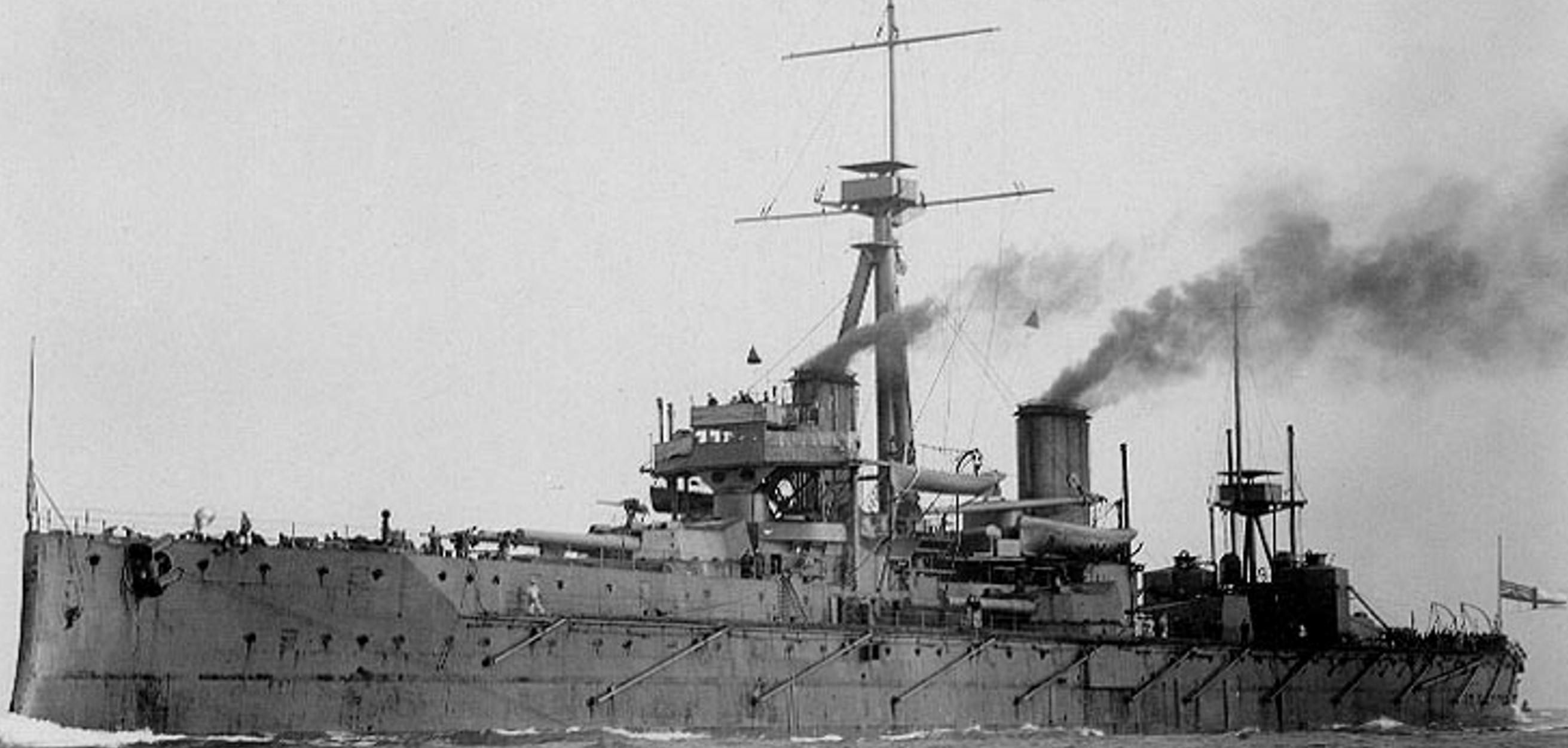
capacitor voltage: 2 kV

coil current: 7 kA

magnetic field: 2 T

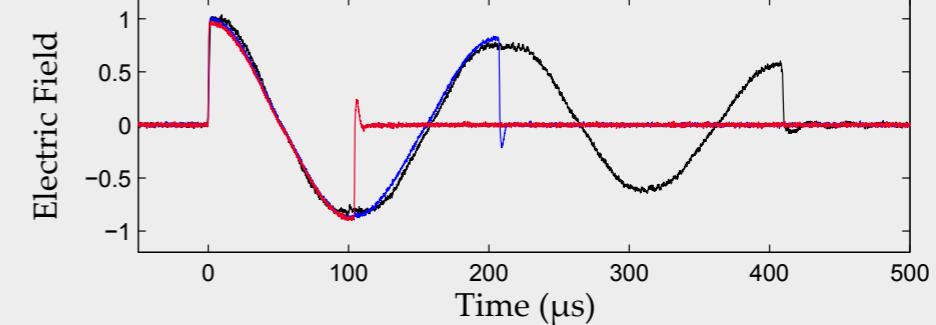
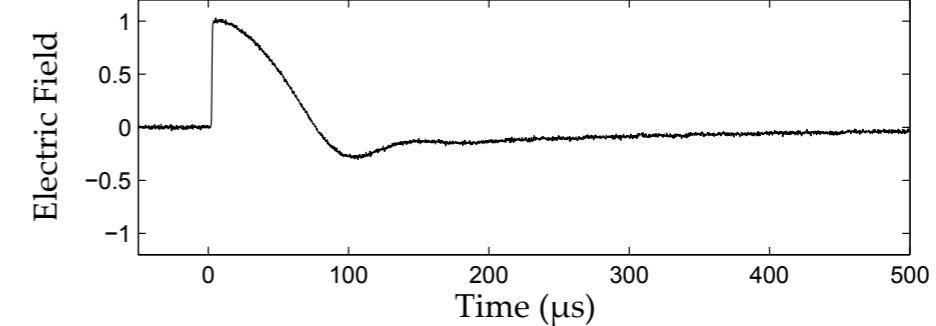
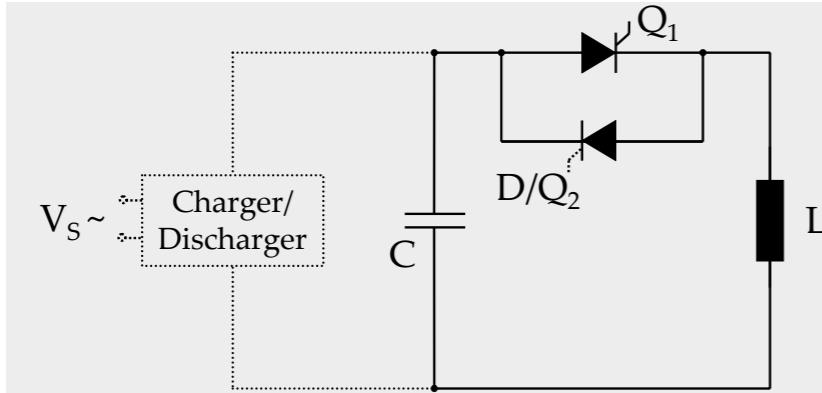
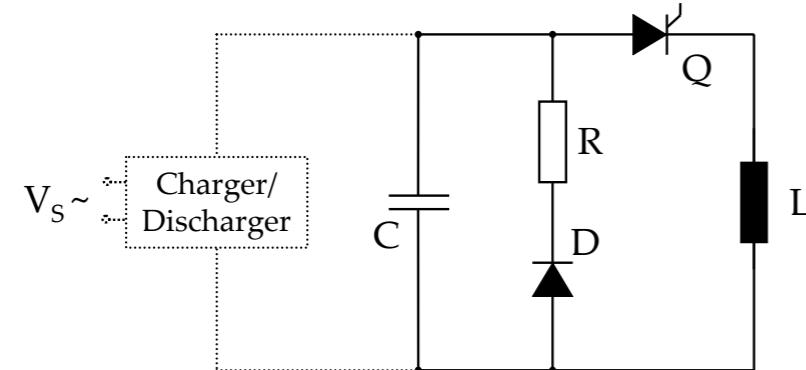
electric field: 1 V/cm



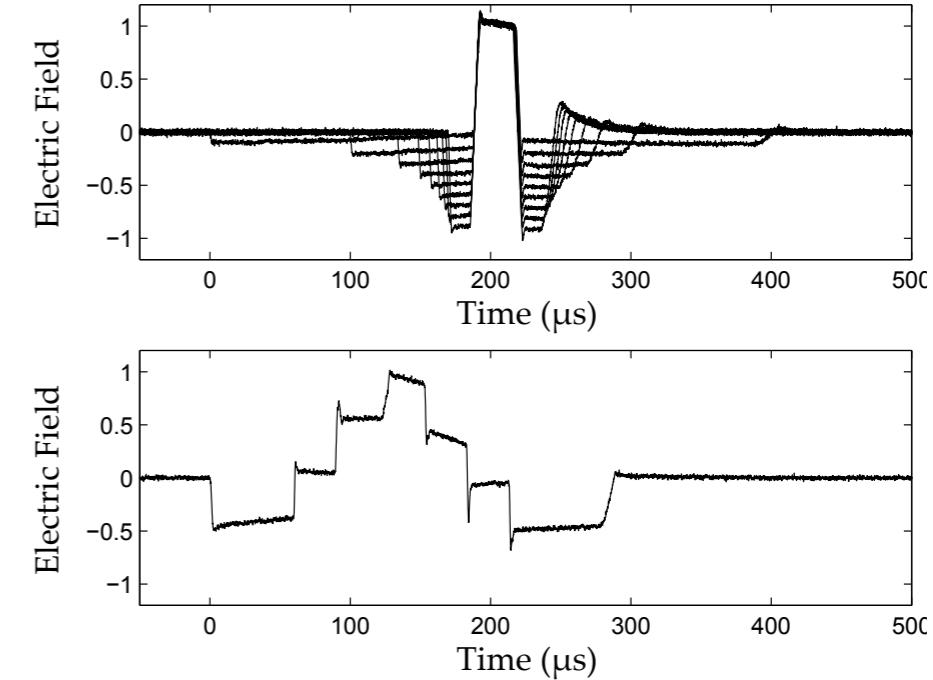
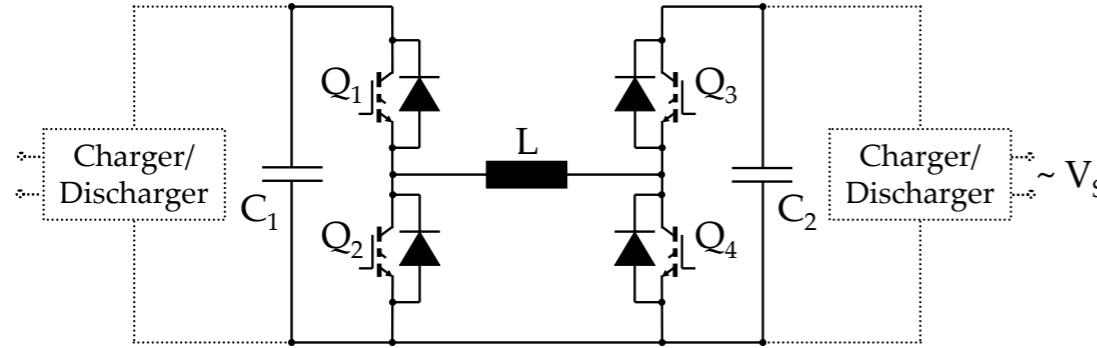


Roberts, *Anatomy of the Ship: The Battleship Dreadnought*, 1992

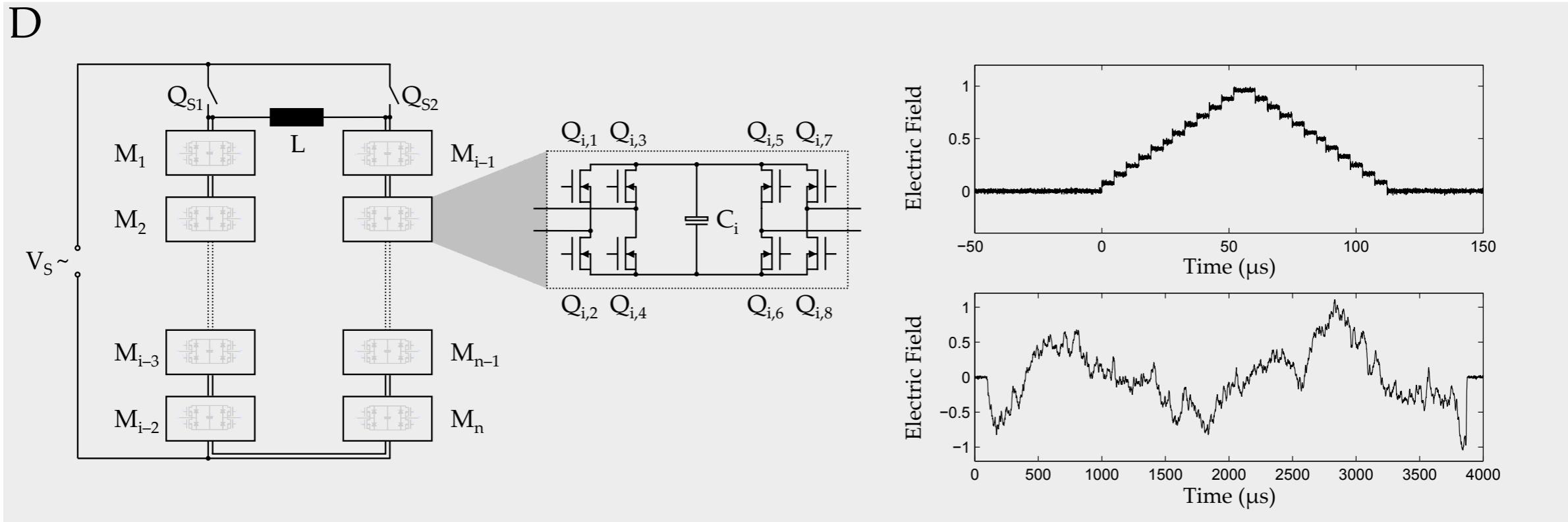
Conventional stimulators



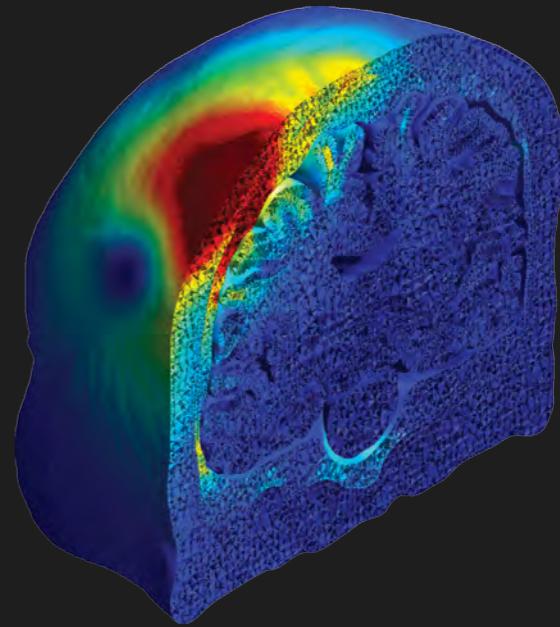
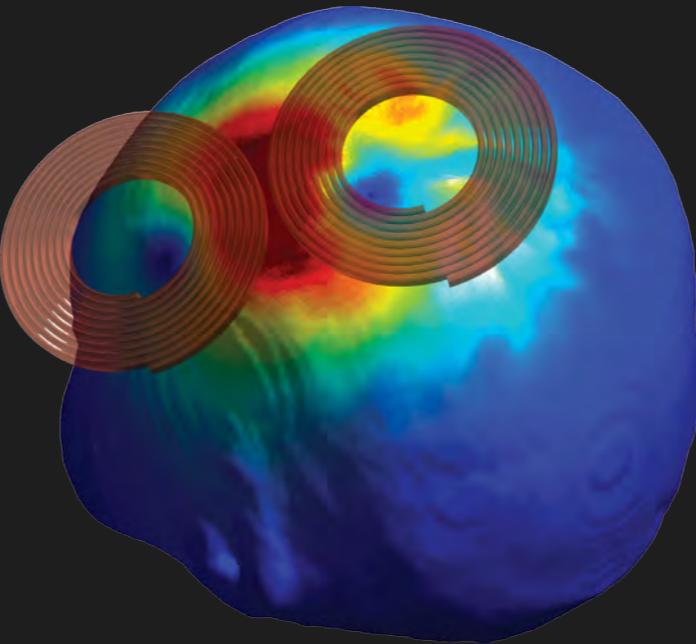
Controllable pulse-width TMS



Synthesizer



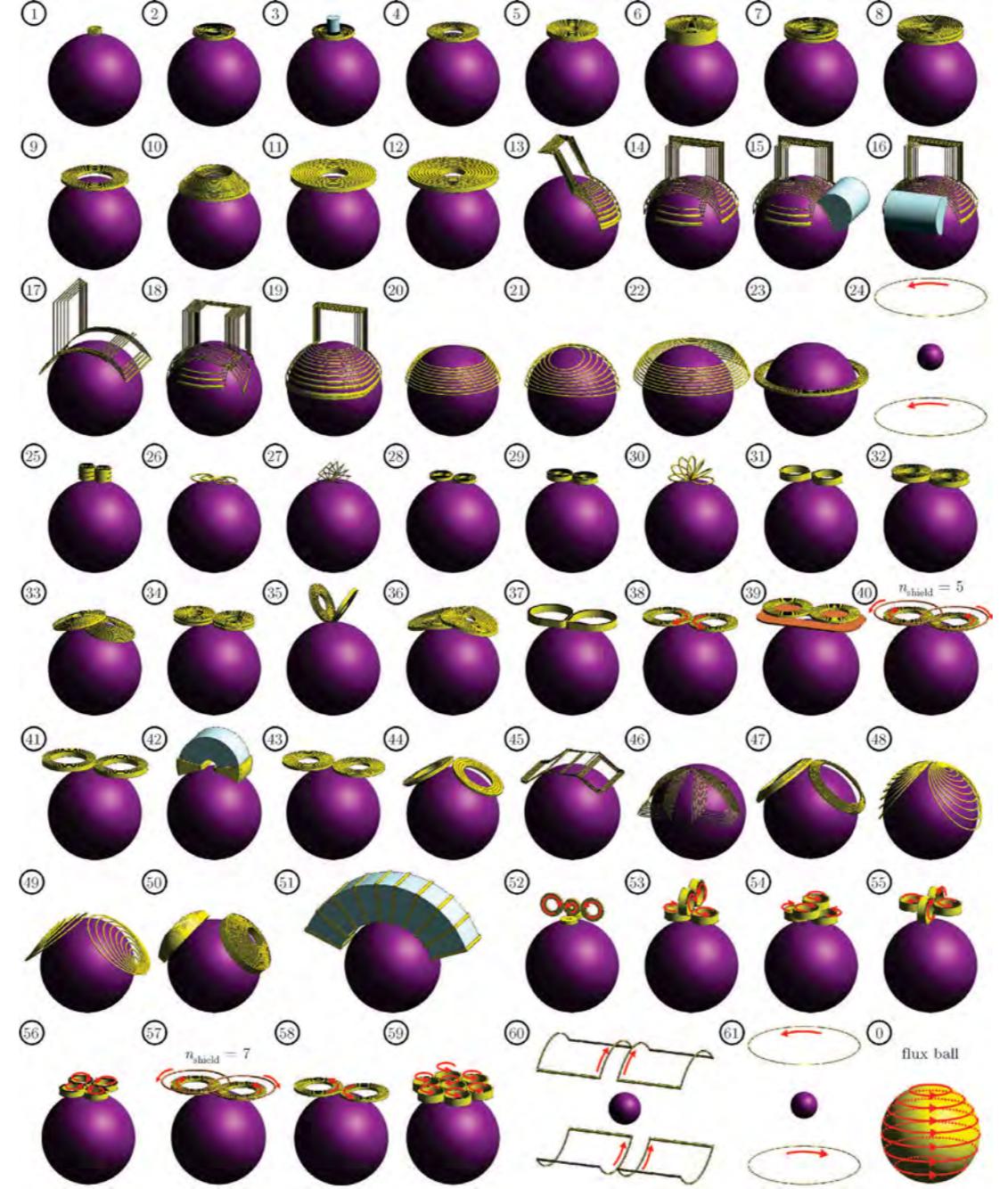
Spatial targeting



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

E-field spatial distribution depends on coil geometry





Circular type

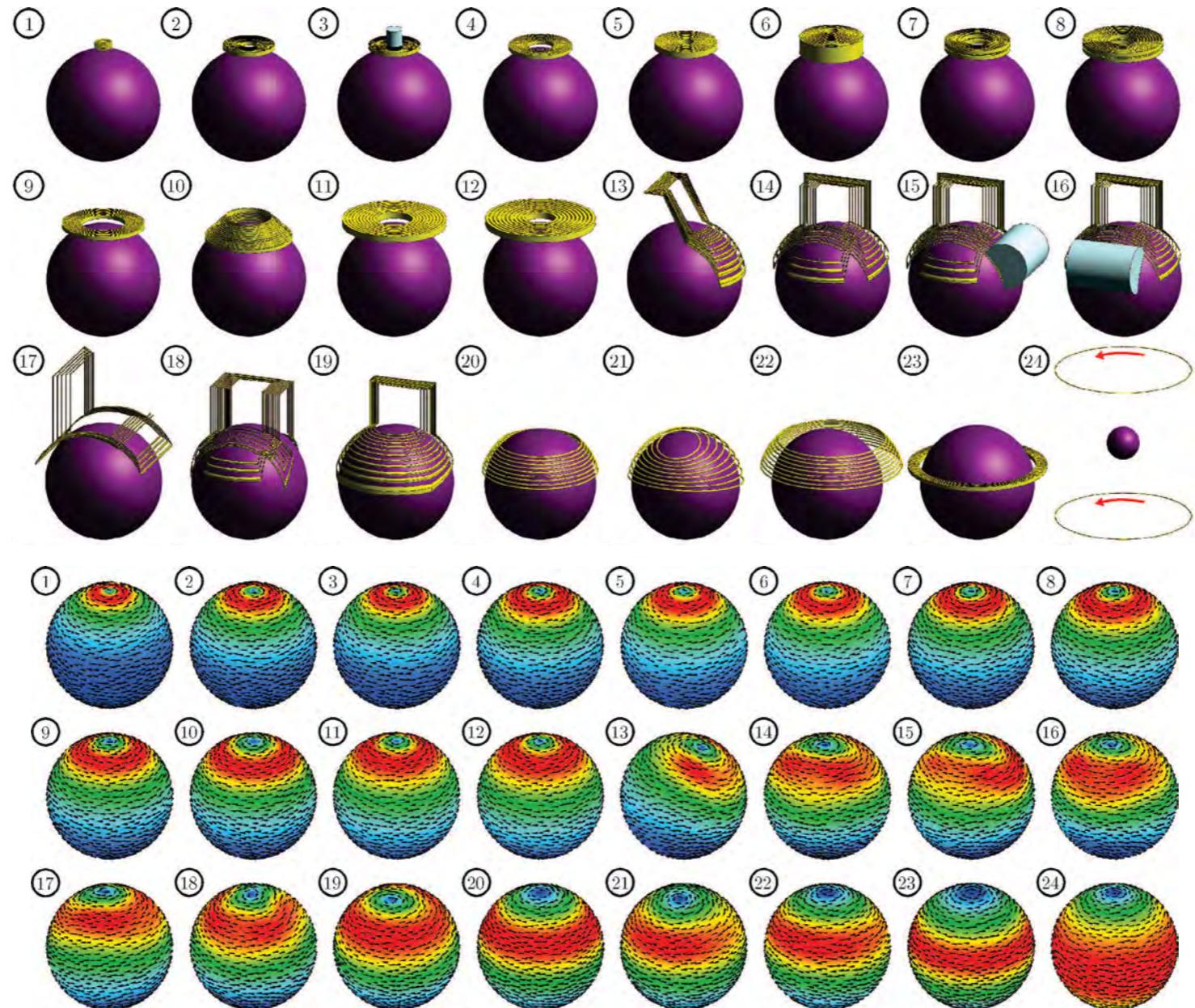
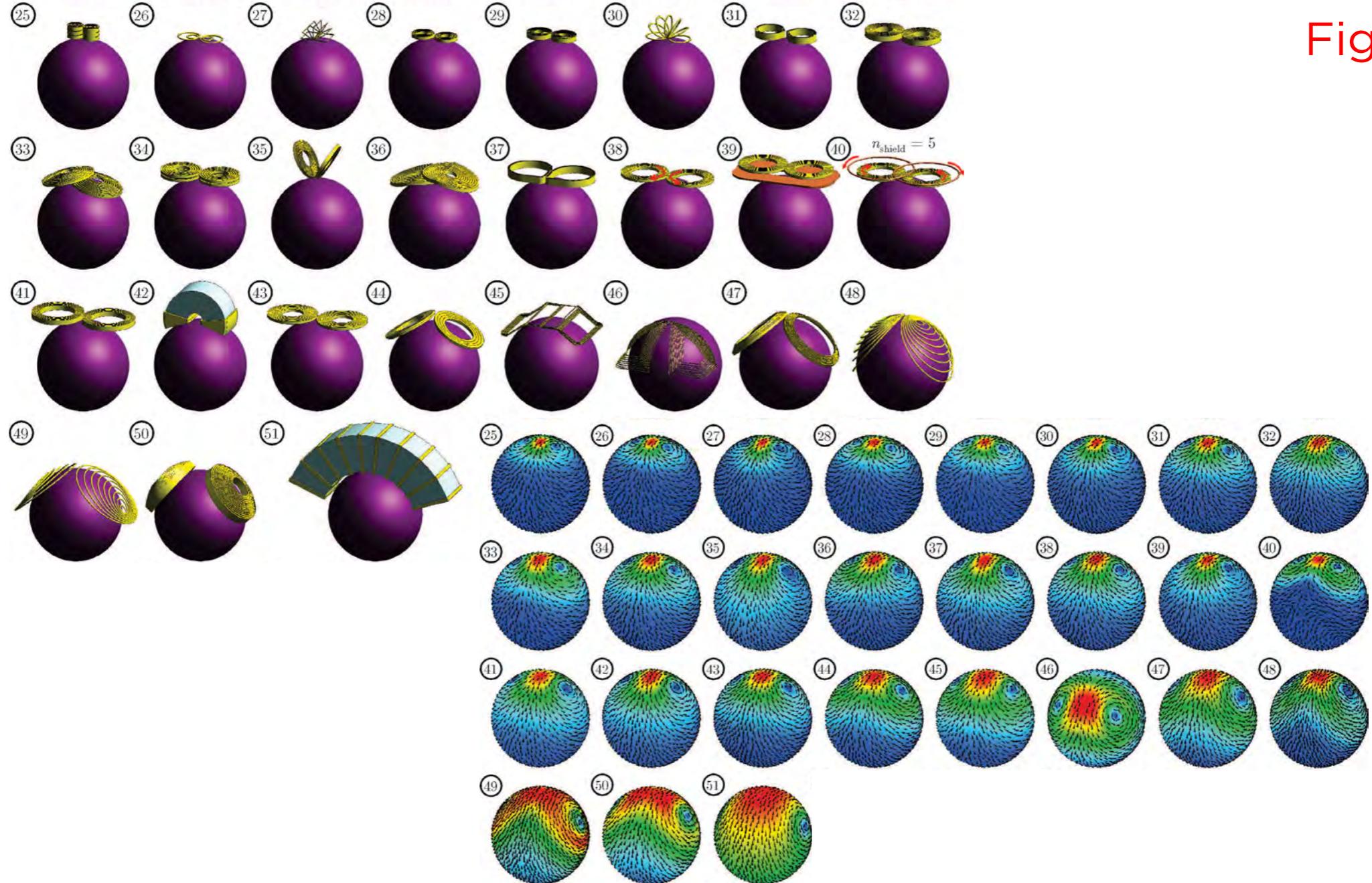
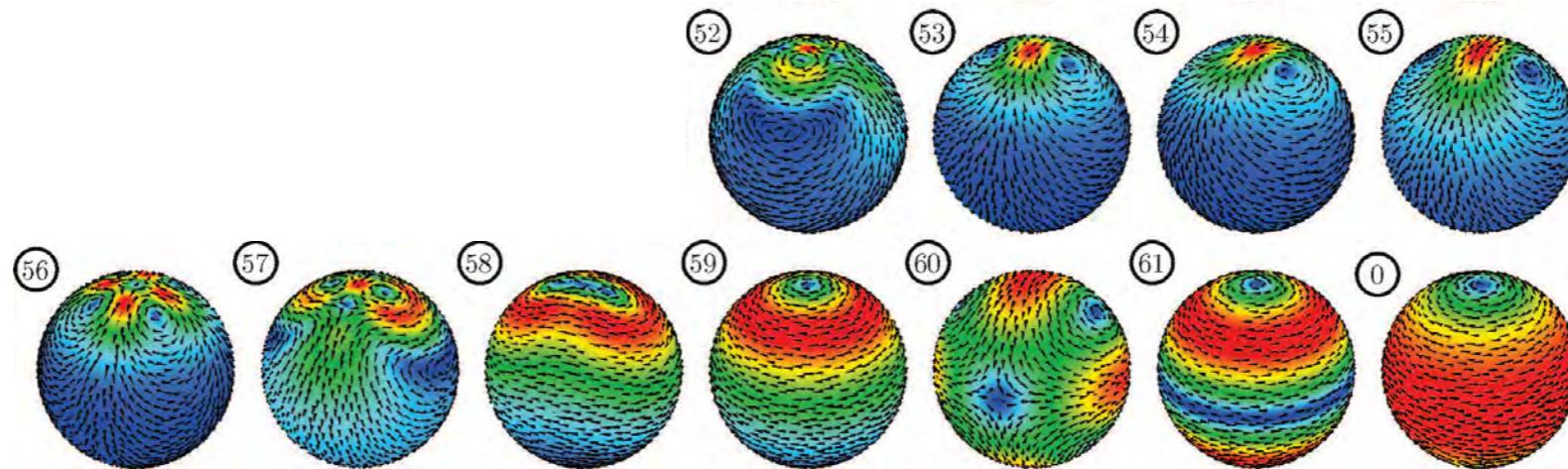
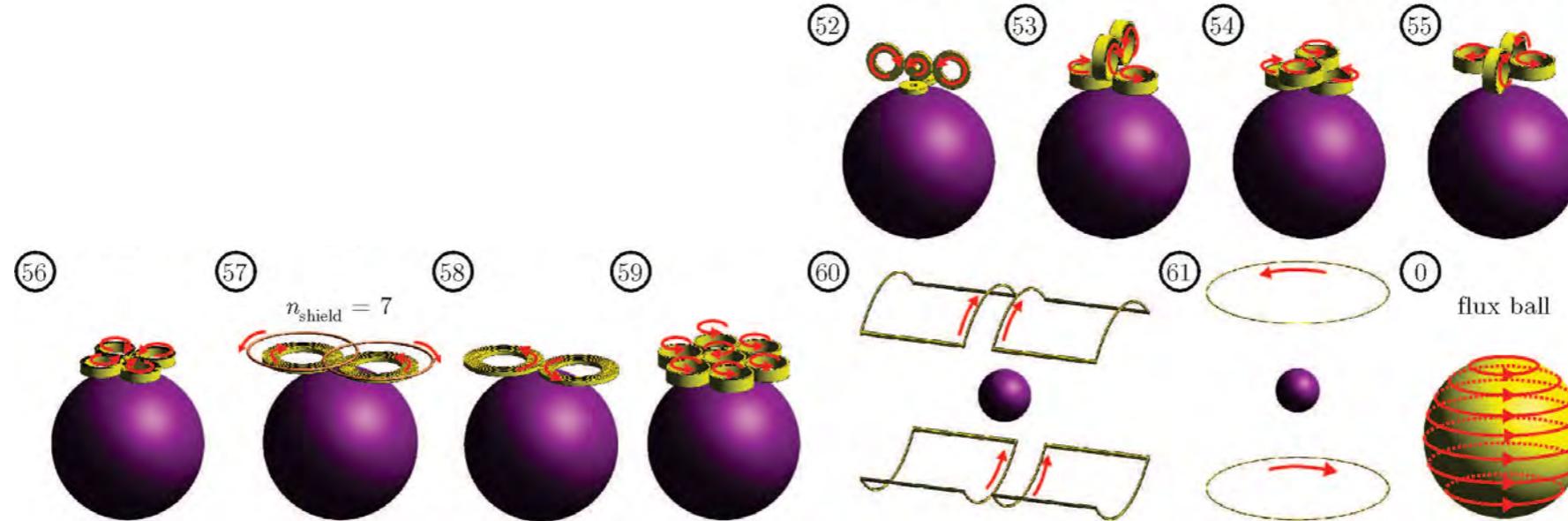
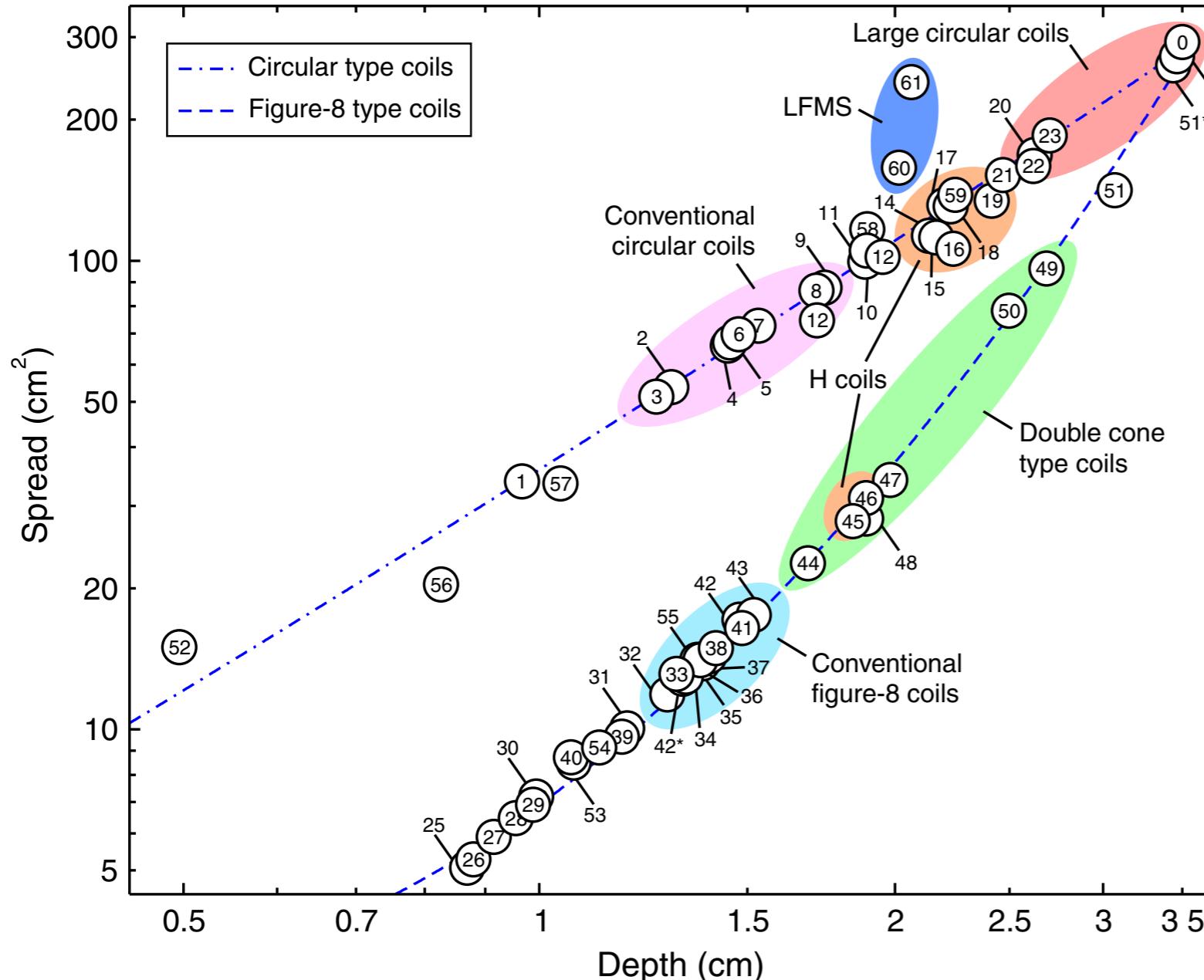


Figure-8 type







Depth-focality tradeoff

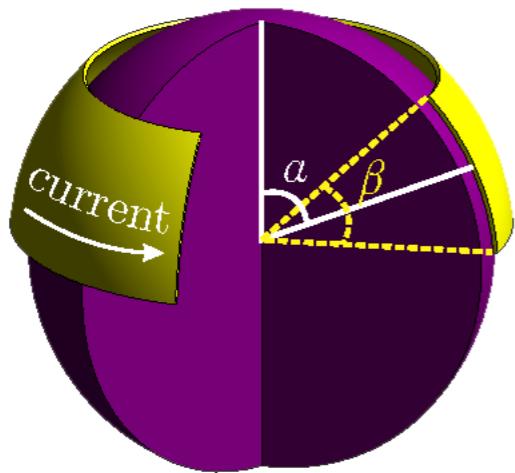
no coil in lower right corner...
cannot be deep and focal

in fact, the deeper one stimulates, the more nonfocal

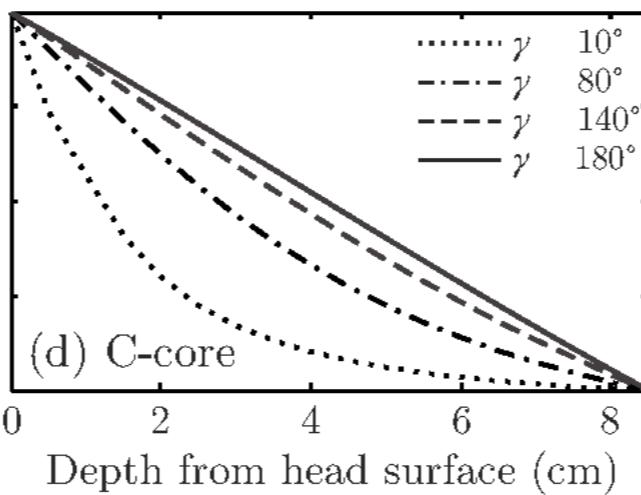
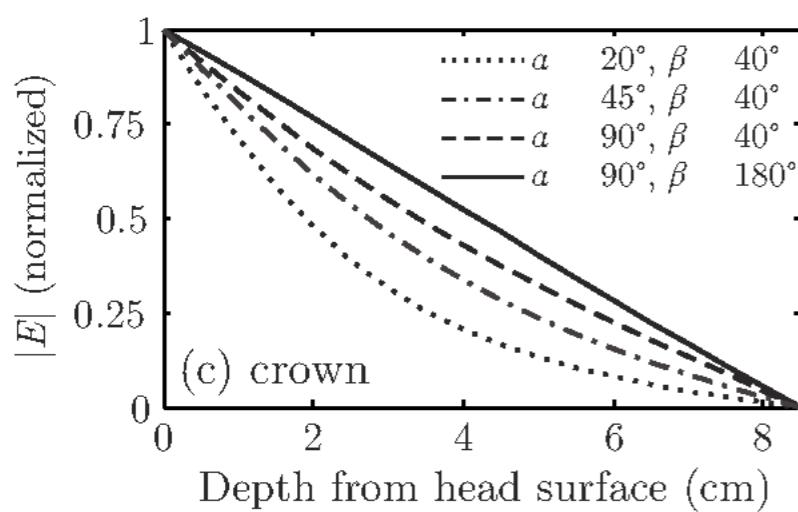
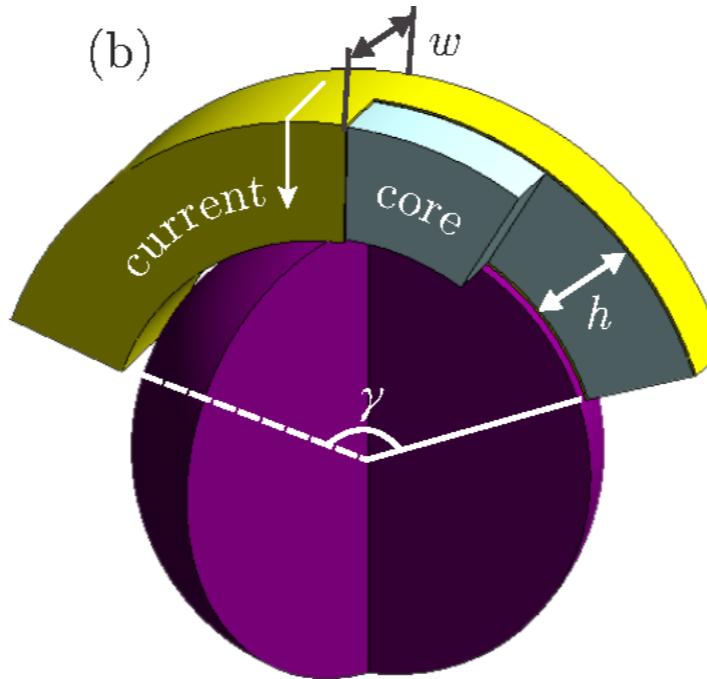
figure-8 coils are fundamentally more focal compared to circular type coils

How deep can we get?

(a)



(b)



as coil size increases,
field decay becomes
linear

Use computational model to...

benchmark existing technology

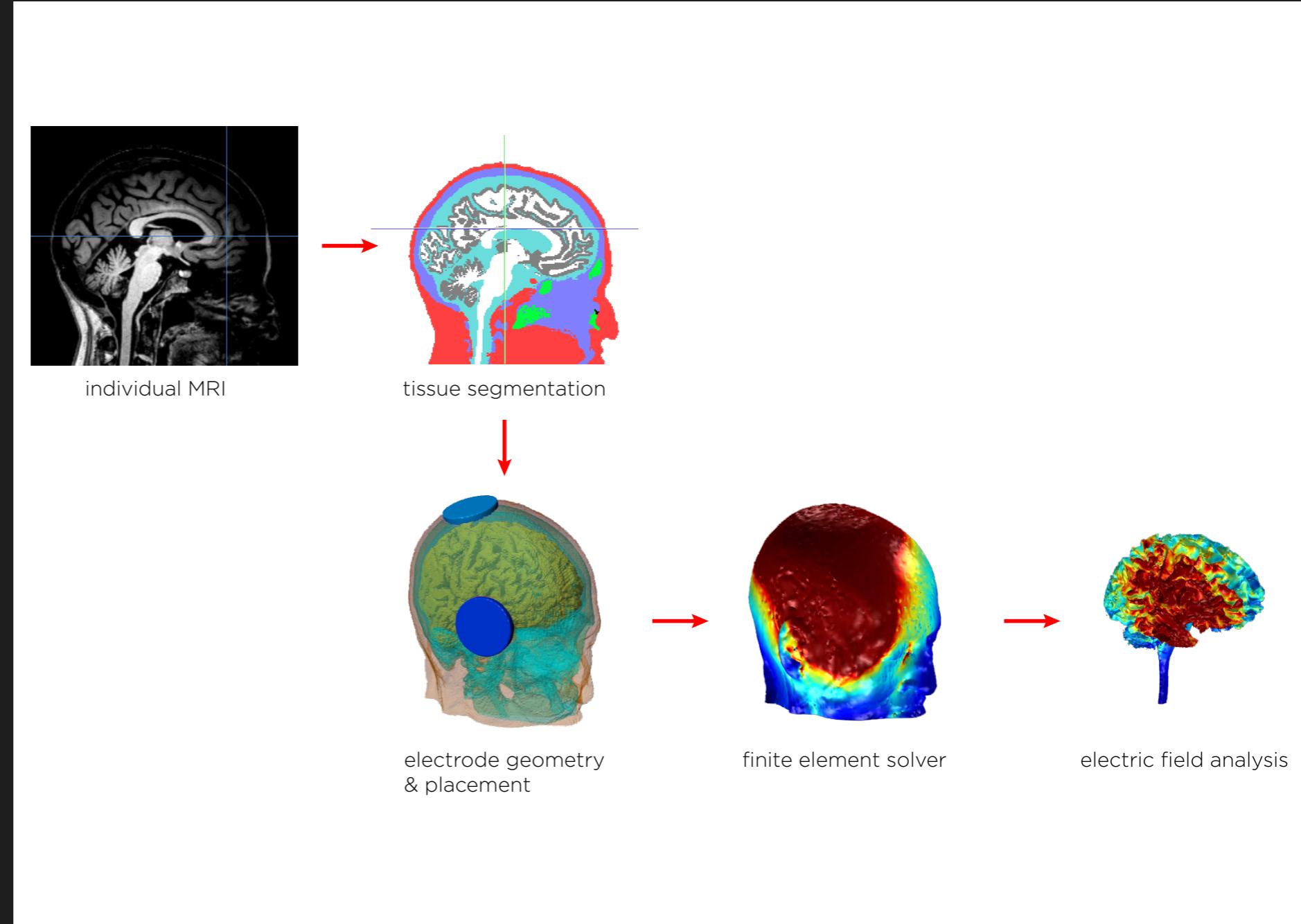
and to evaluate...

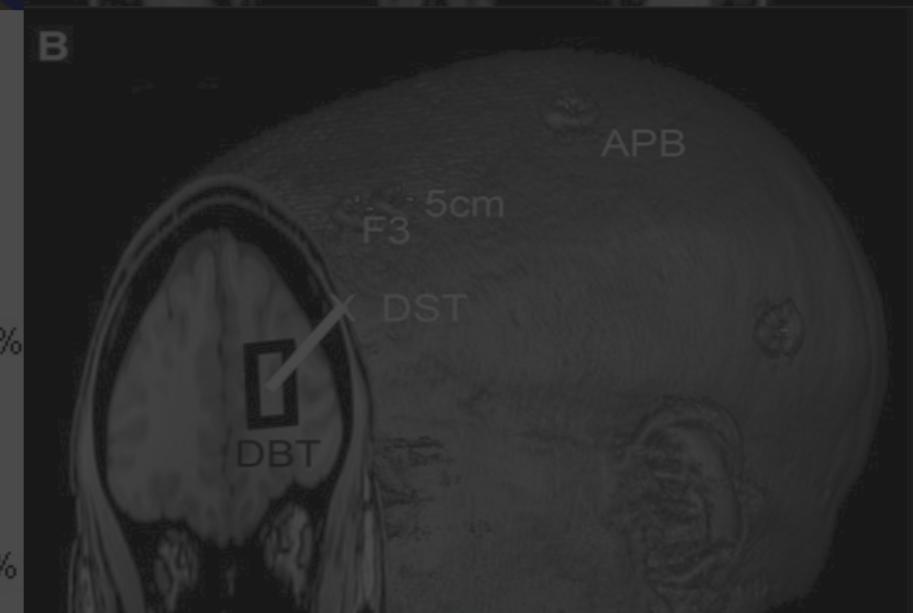
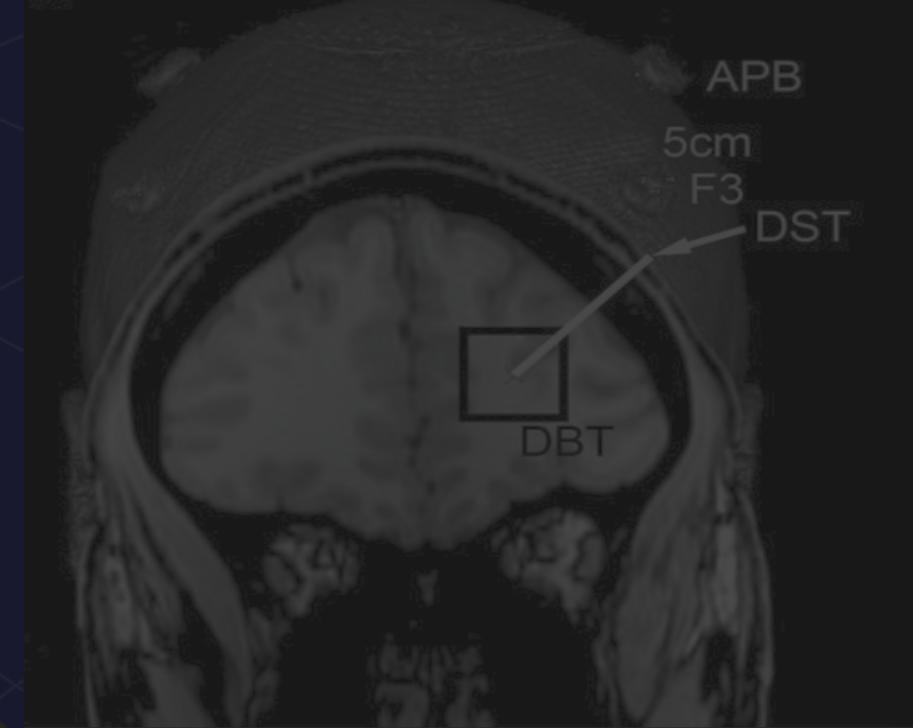
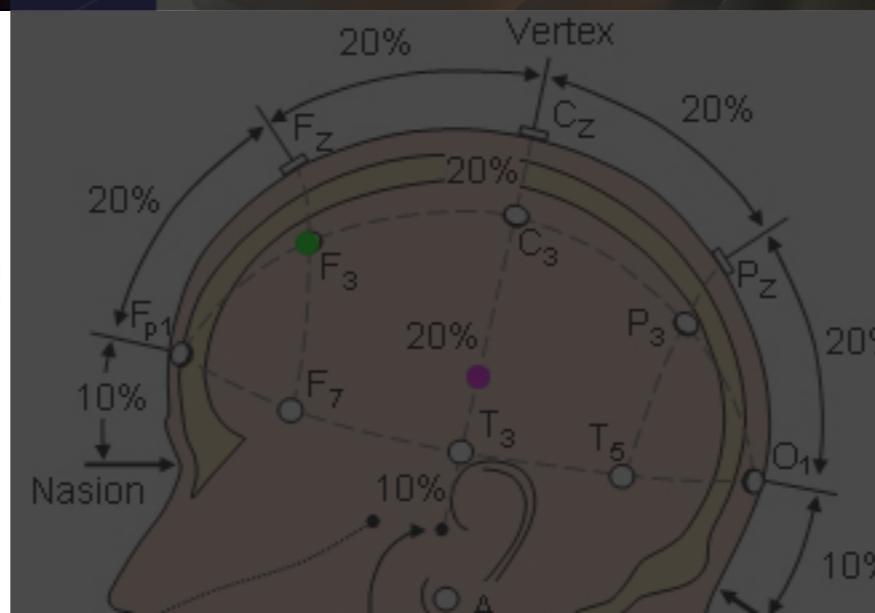
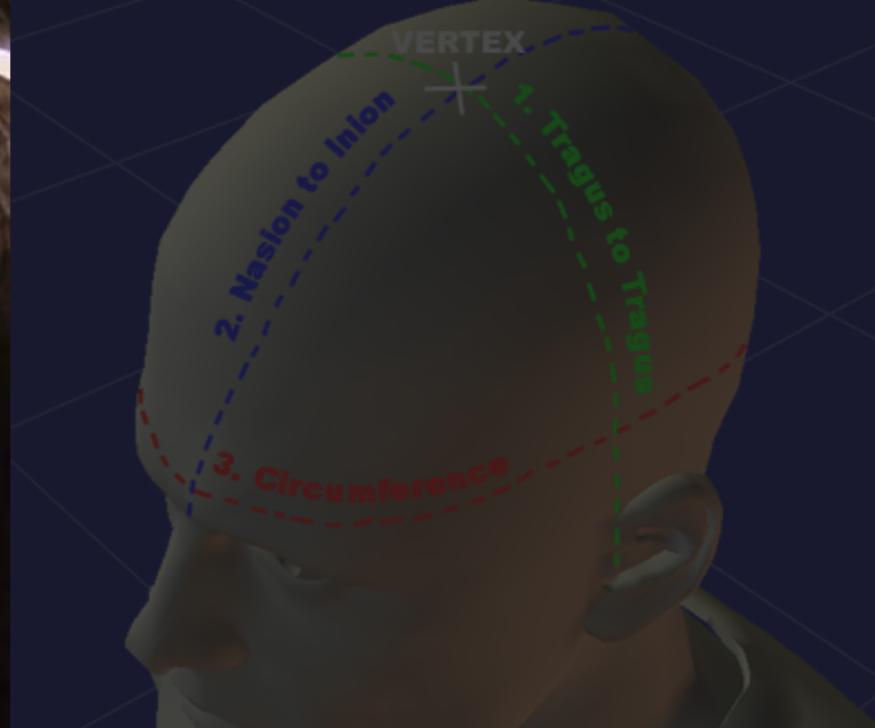
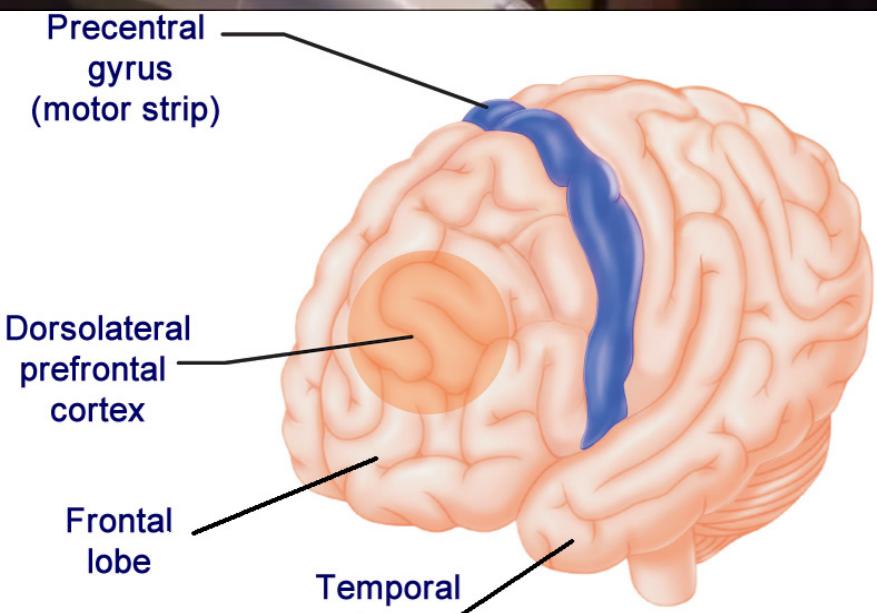
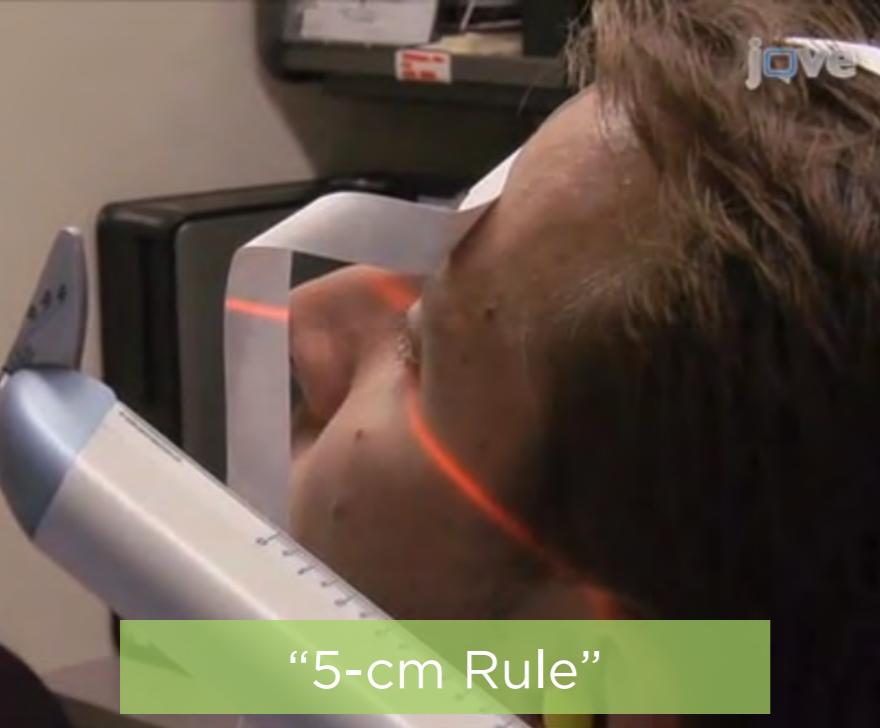
targeting strategies

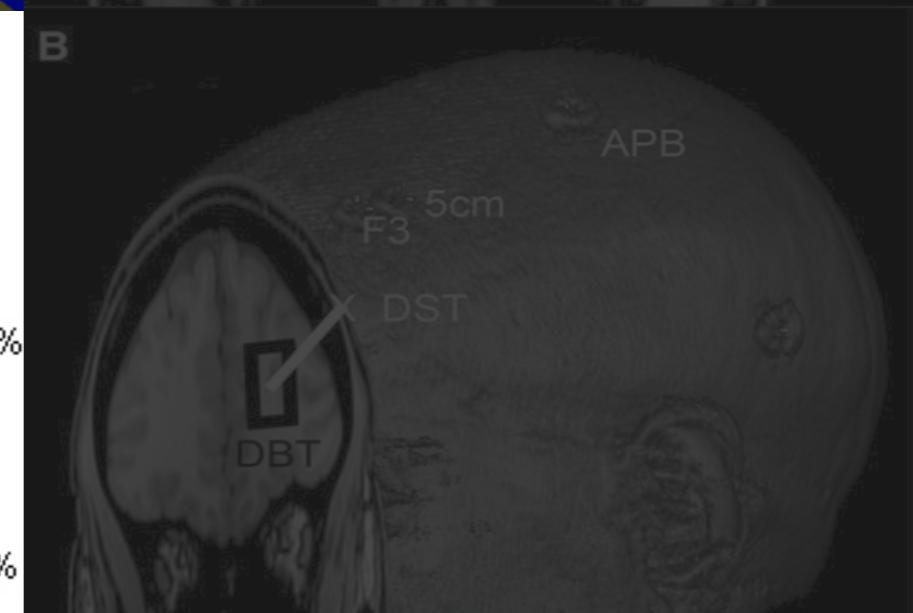
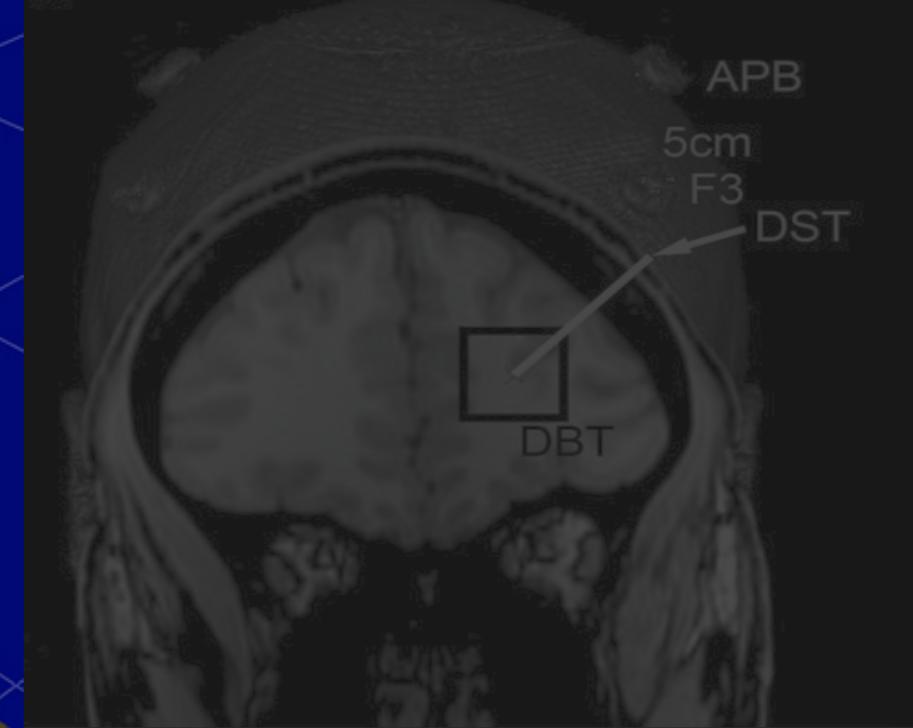
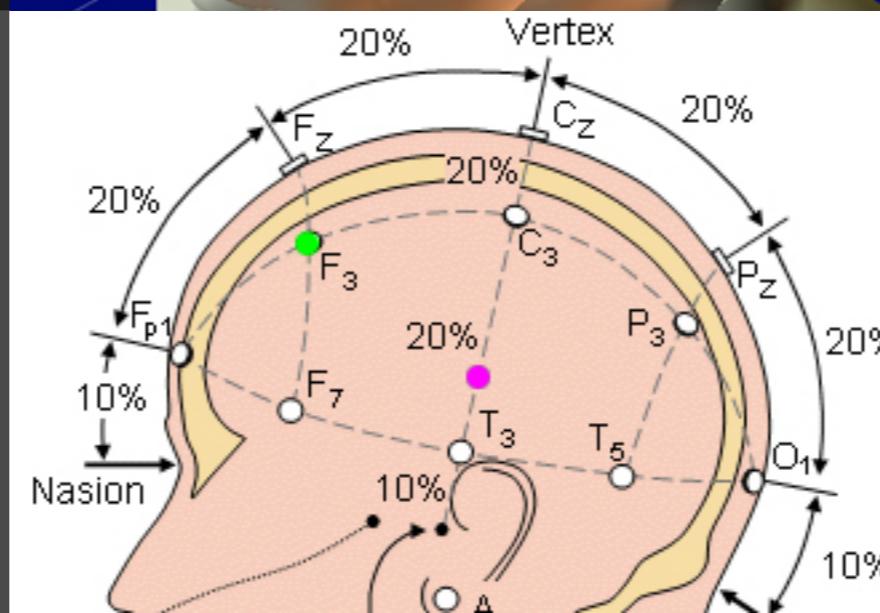
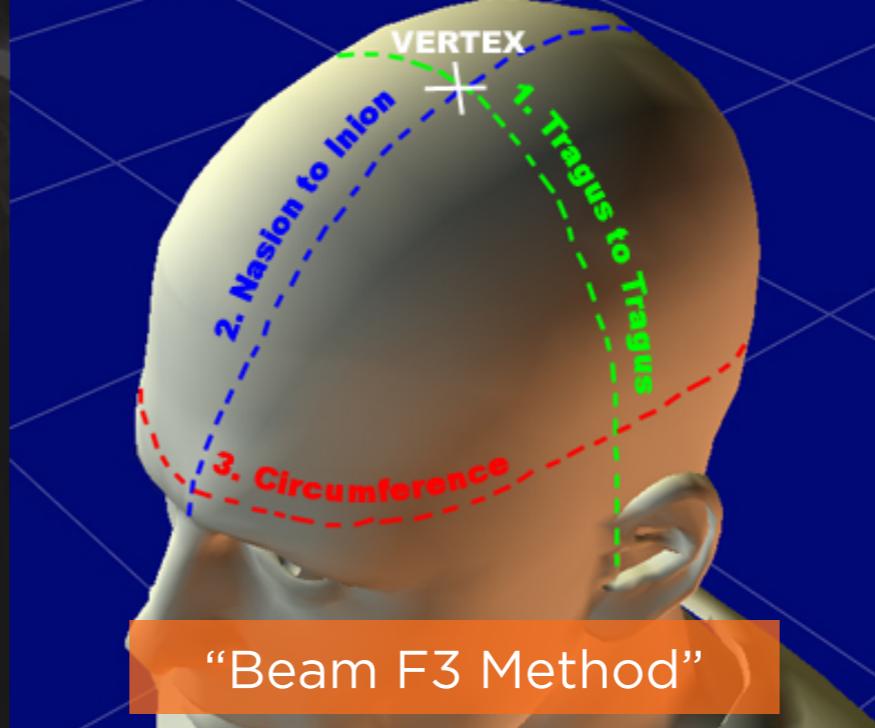
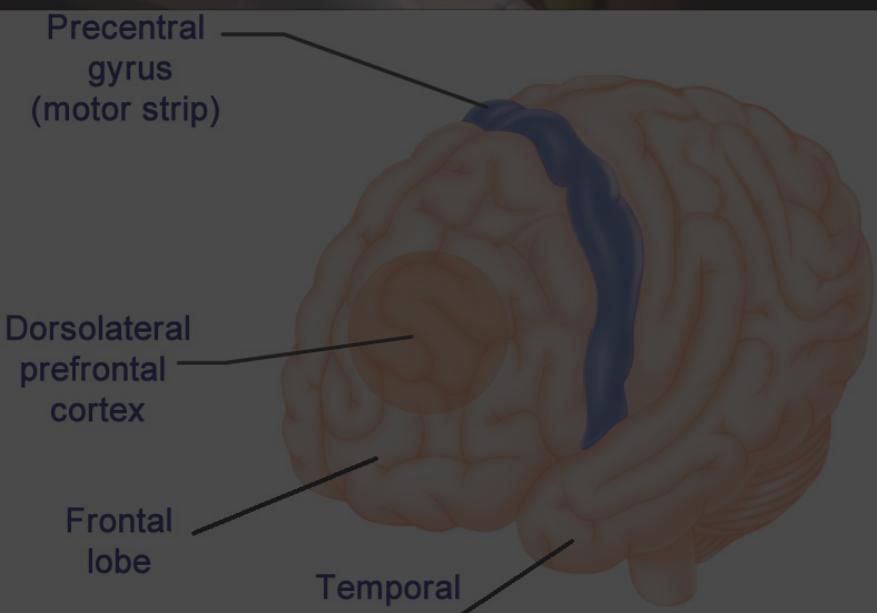
variability

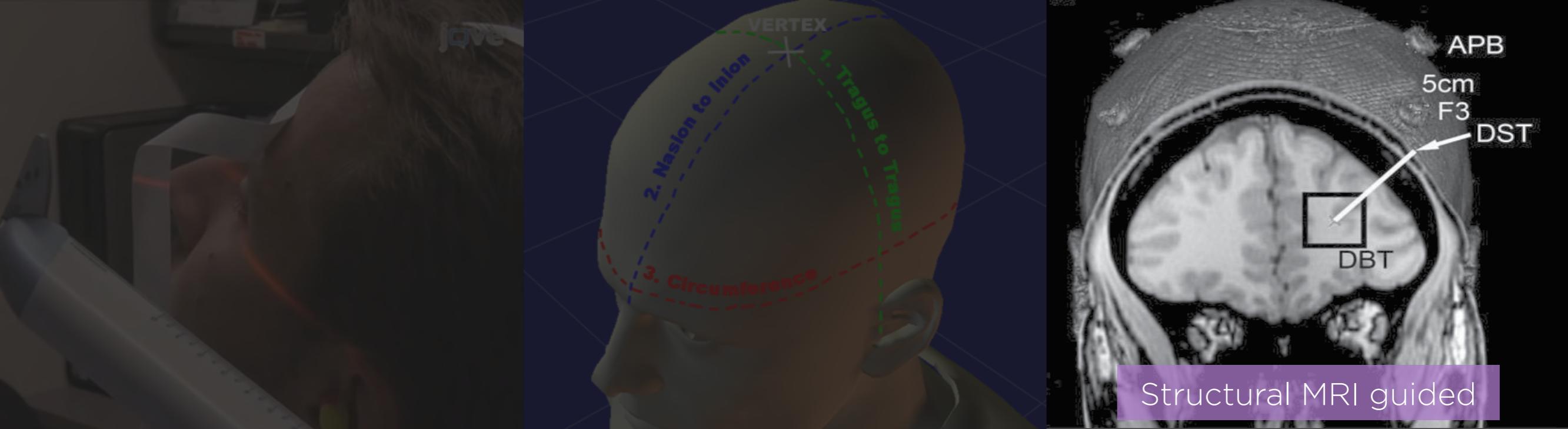
new stimulation modalities

Computational electric field modeling

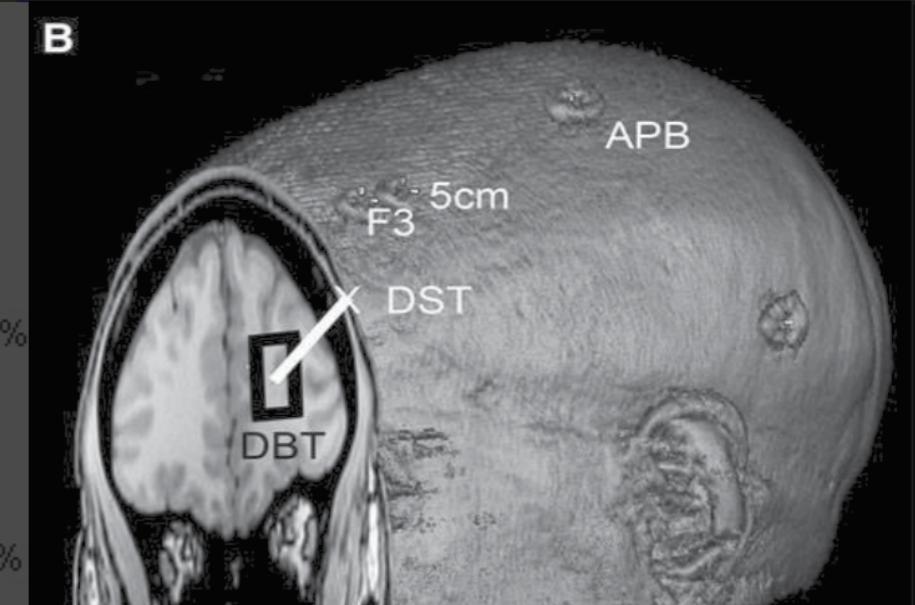
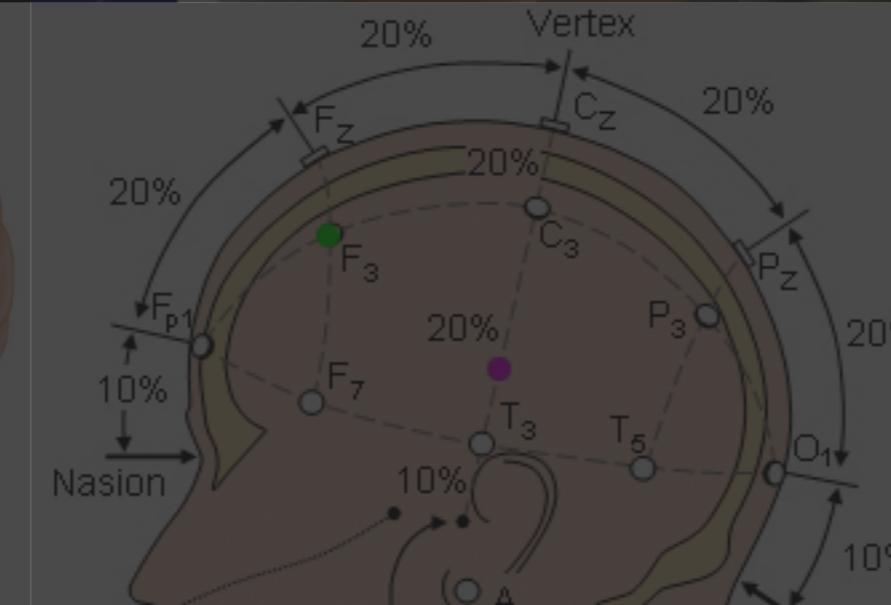
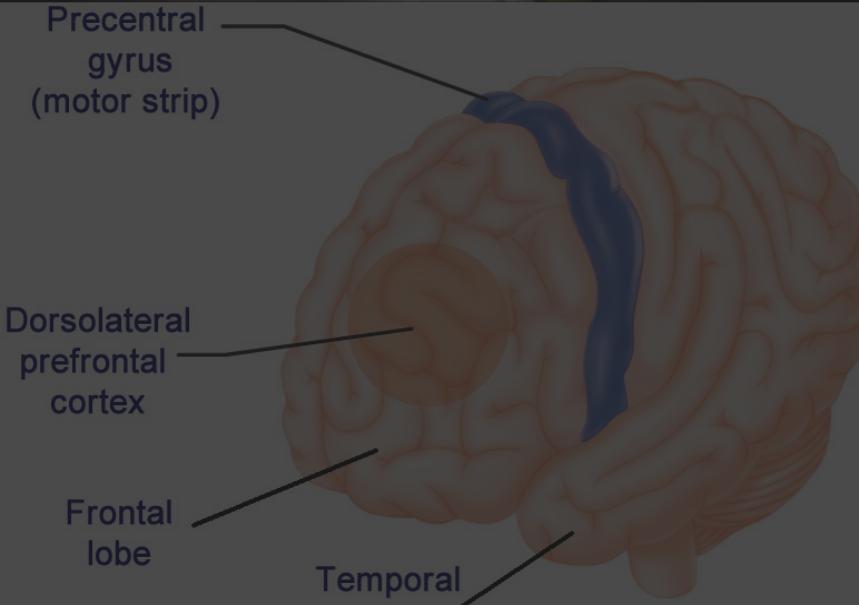




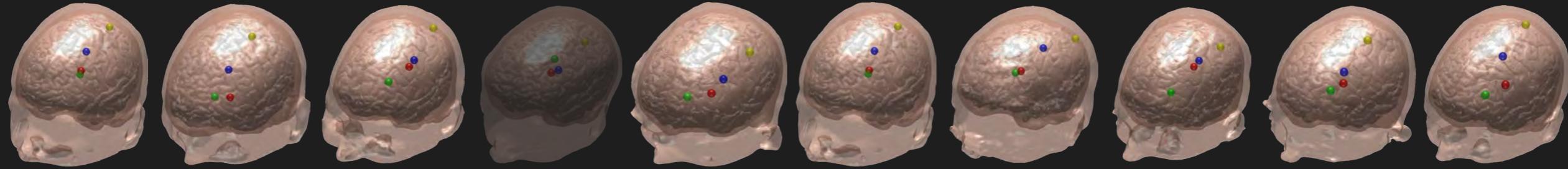




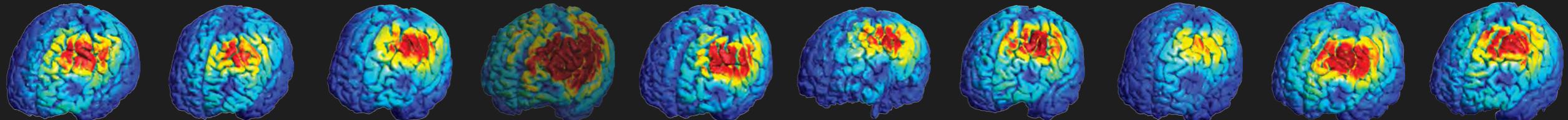
Structural MRI guided



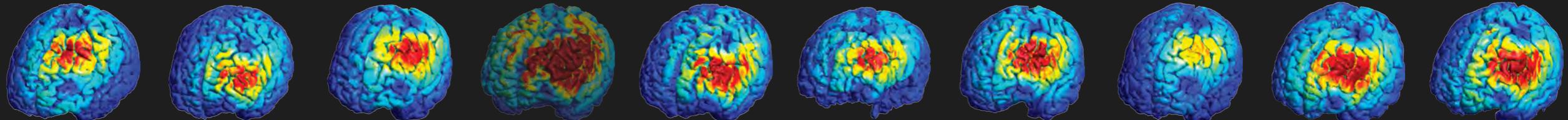
● motor hotspot



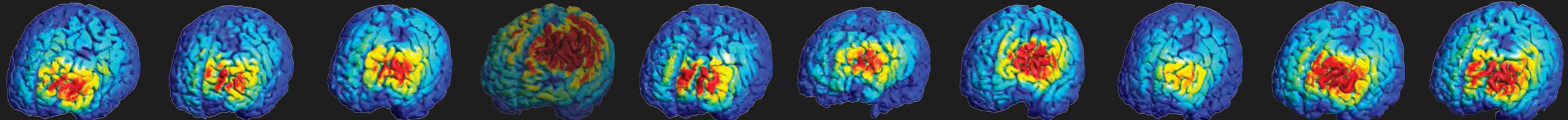
● 5 cm rule



● Beam F3



● MRI

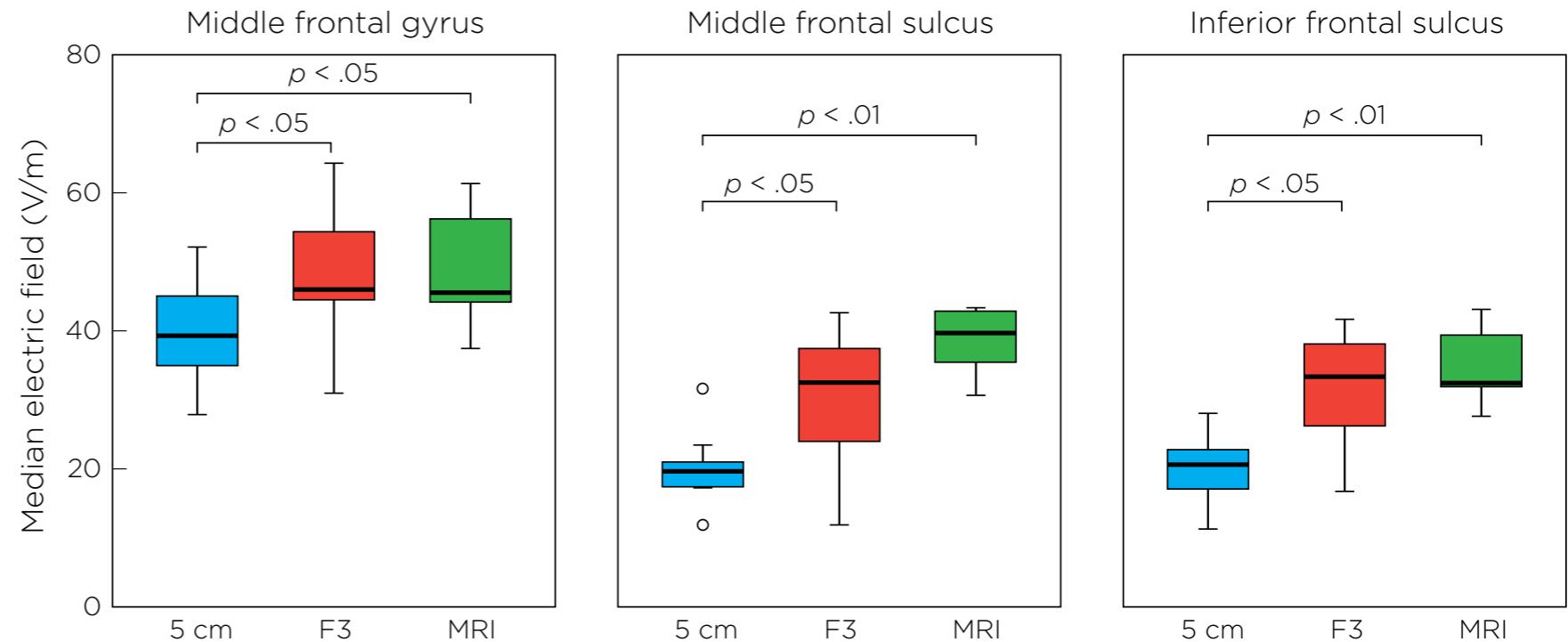


*dropped out



5-cm rule consistently
underdoses DLPFC

The clinical standard
is suboptimal



Cornell study

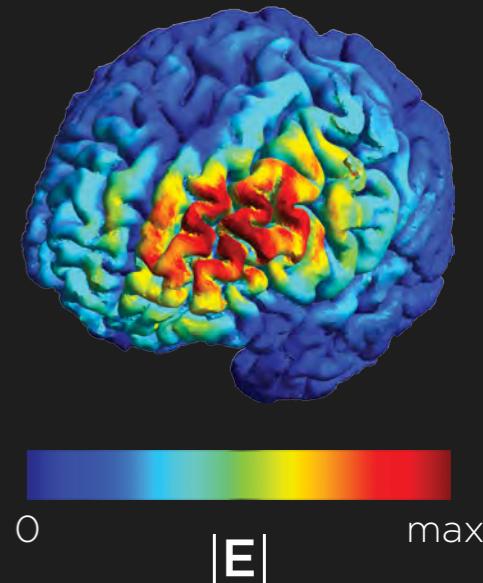
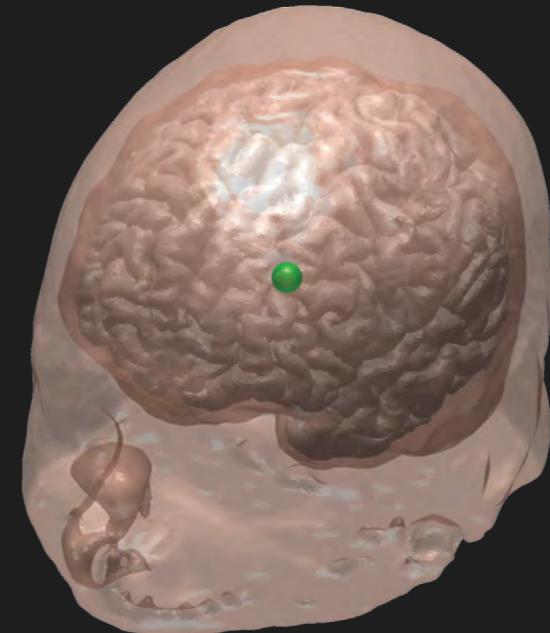
26 depressed patients (age 21-68)

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

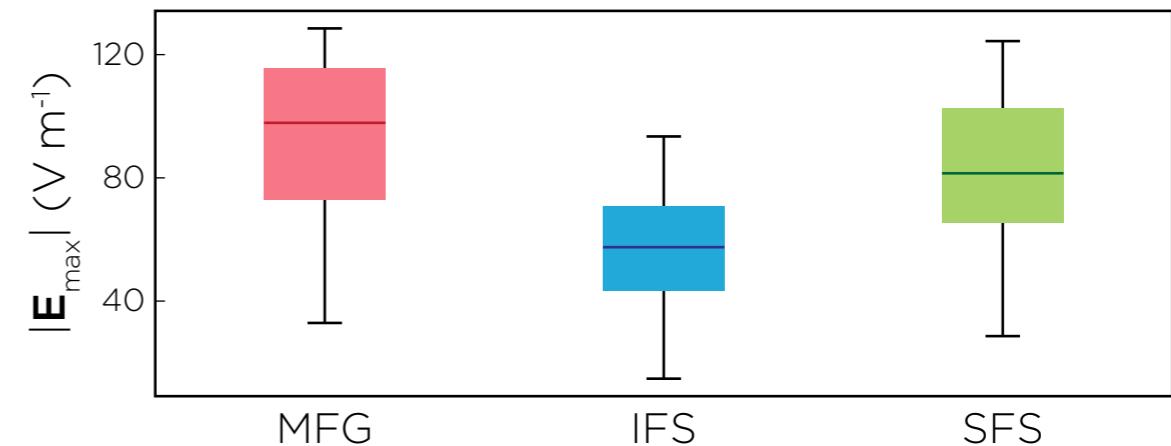
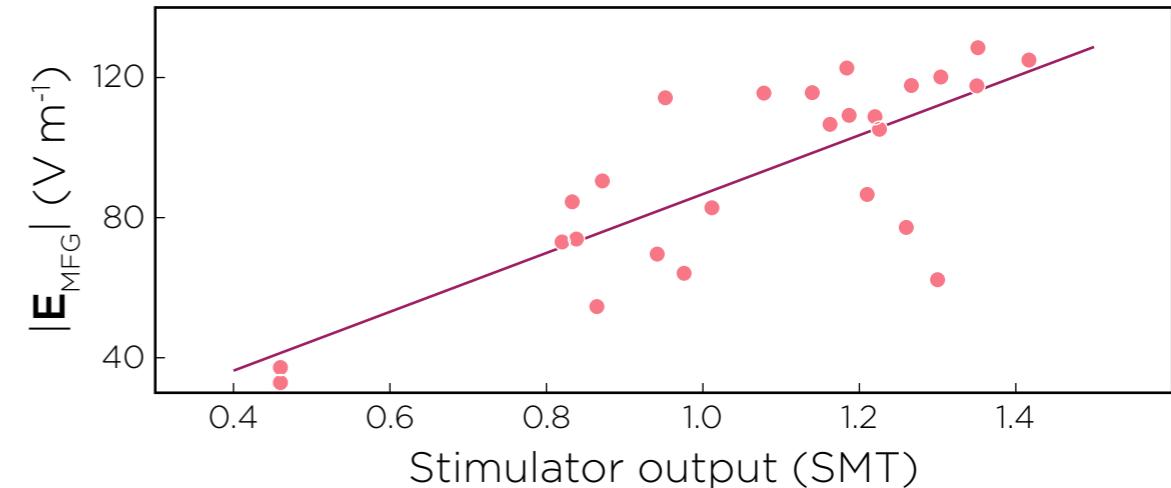
FEM head models constructed using SimNIBS
2.0.1



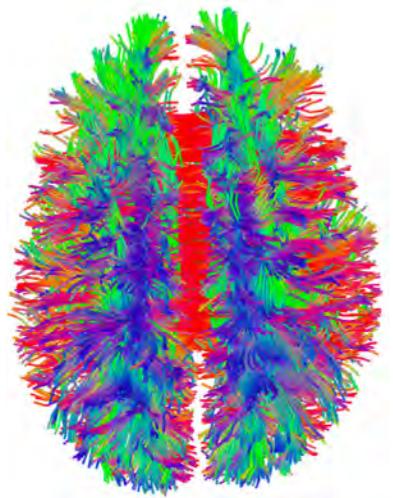
Considerable variability in E-field
IQR E_{MFG} : ~40–120 V/m

... 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



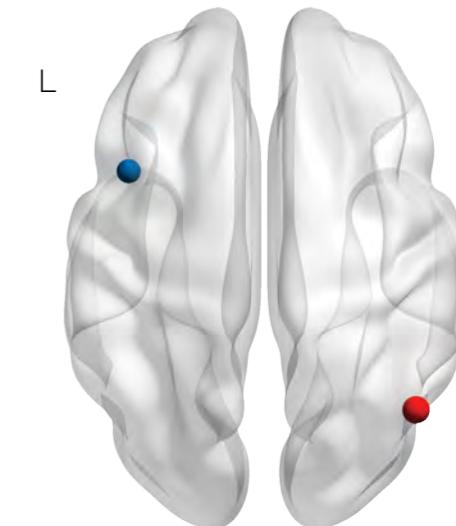
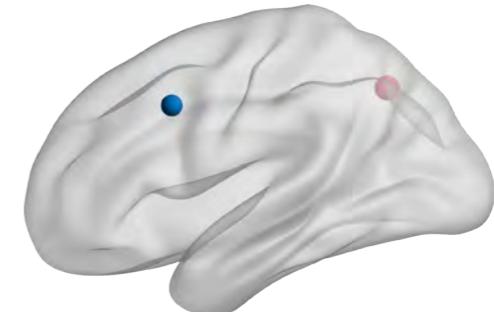
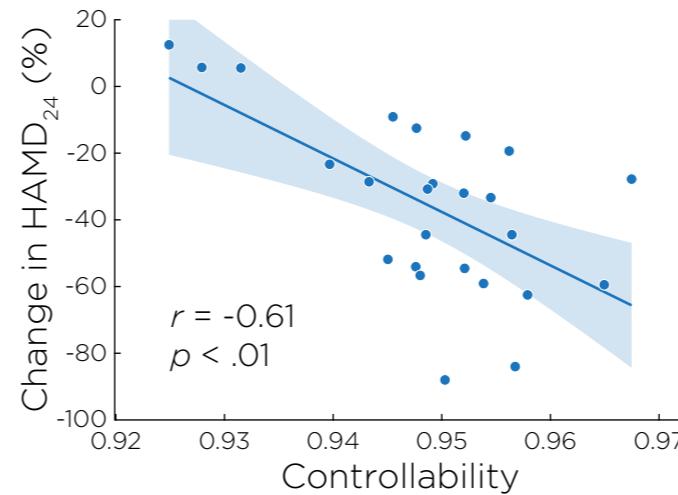
Controllability correlates with TMS treatment response



$$\mathbf{x}[k+1] = \mathbf{Ax}[k] + \mathbf{Bu}[k]$$

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

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

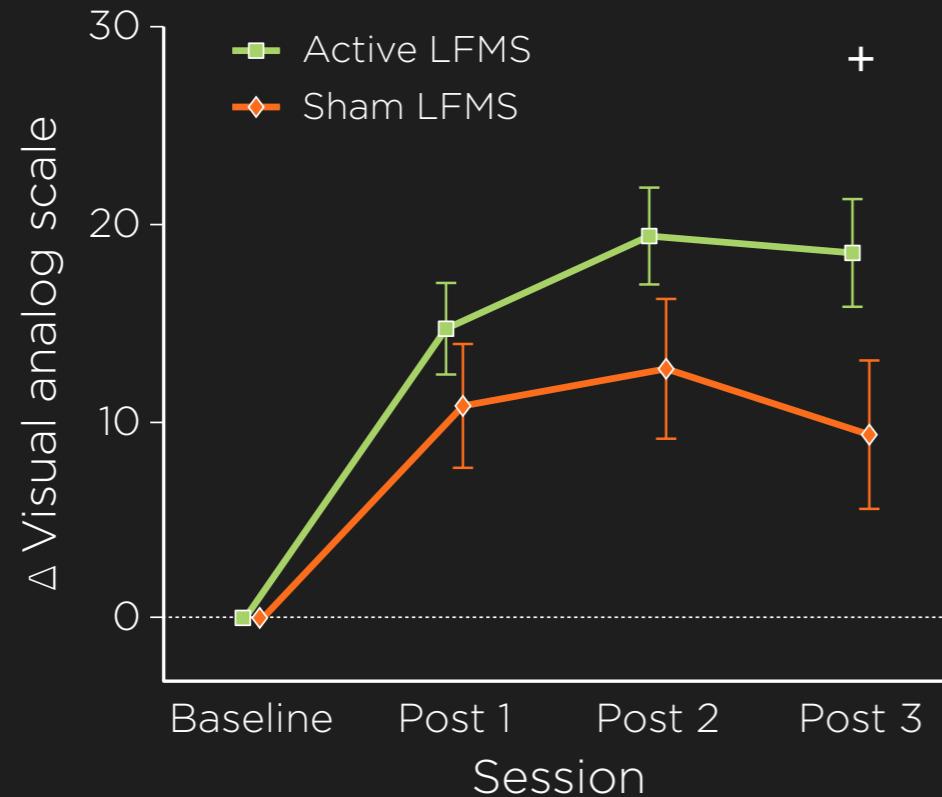


Low field magnetic stimulation

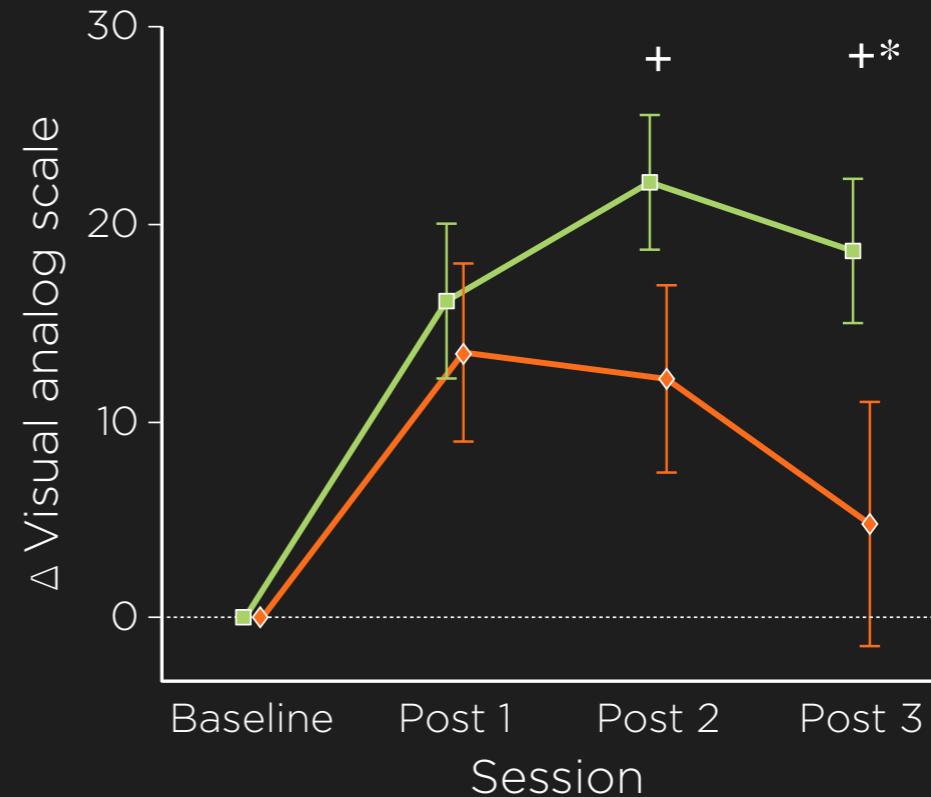


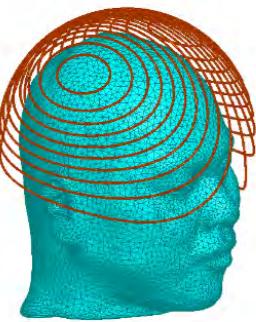
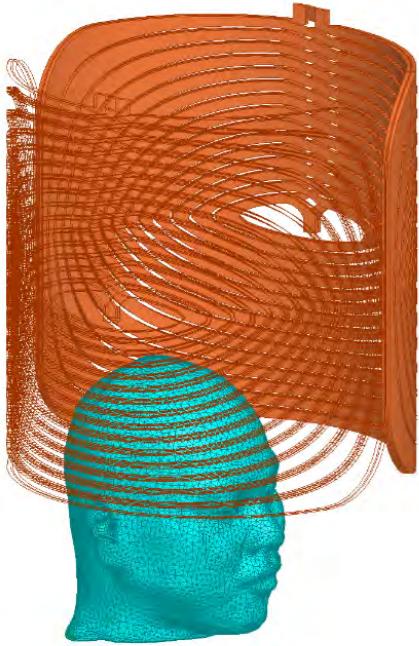
LFMS: clinical results

A. Intent to treat (n = 65)

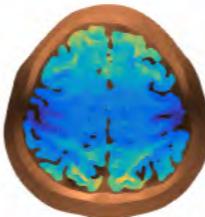
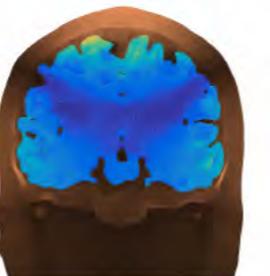
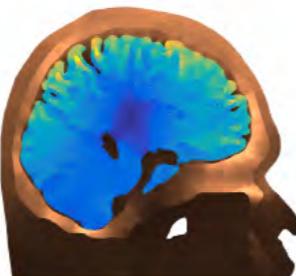


B. Per protocol (n = 30)

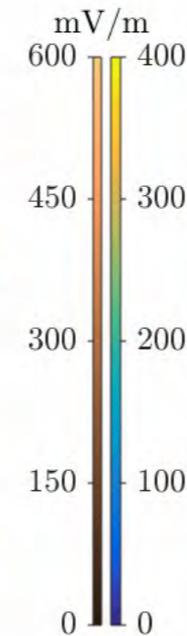
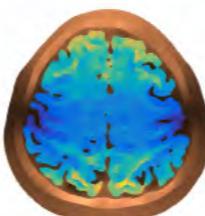
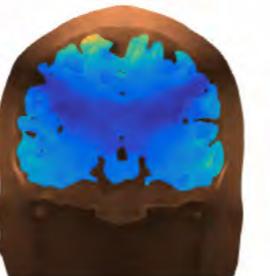
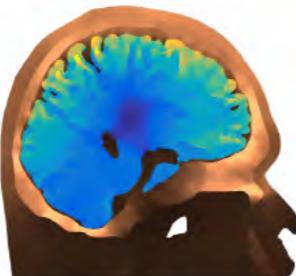




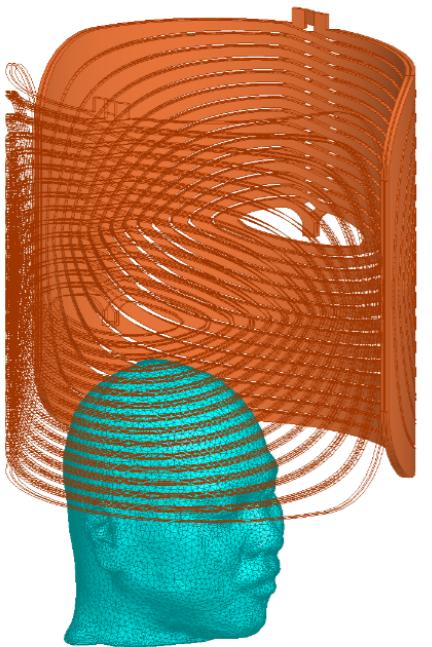
Standard coil



Cap coil



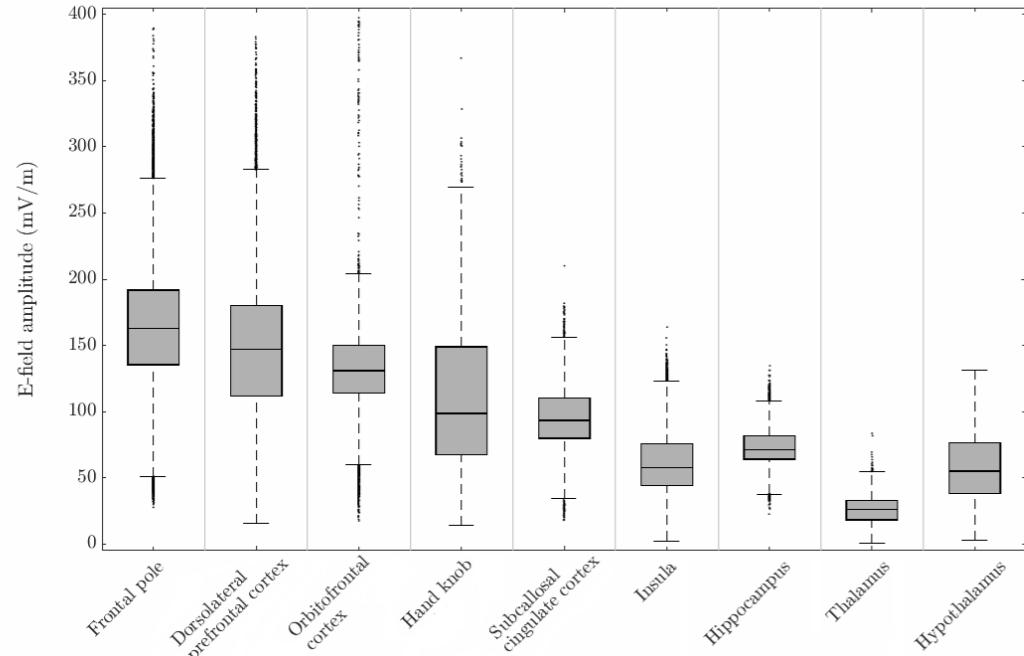
LFMS:
equivalent coil



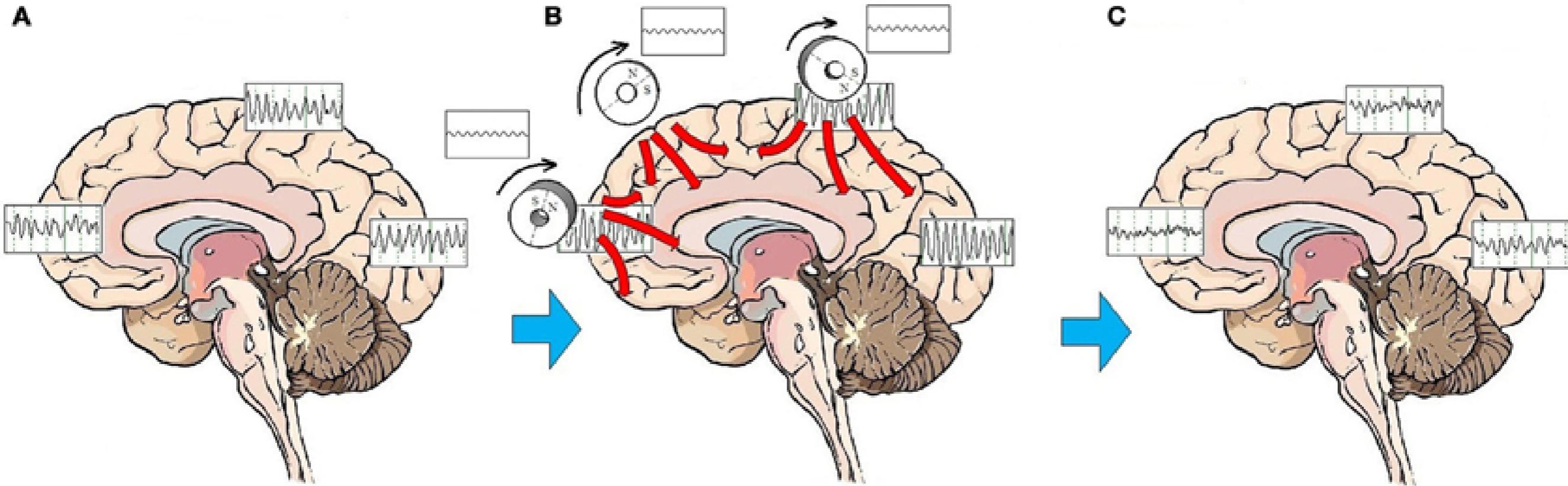
LFMS: electric field

Coil current amplitude = 28.5 A

induced median electric field on the order of
0.1 V/m



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

sTMS model setup

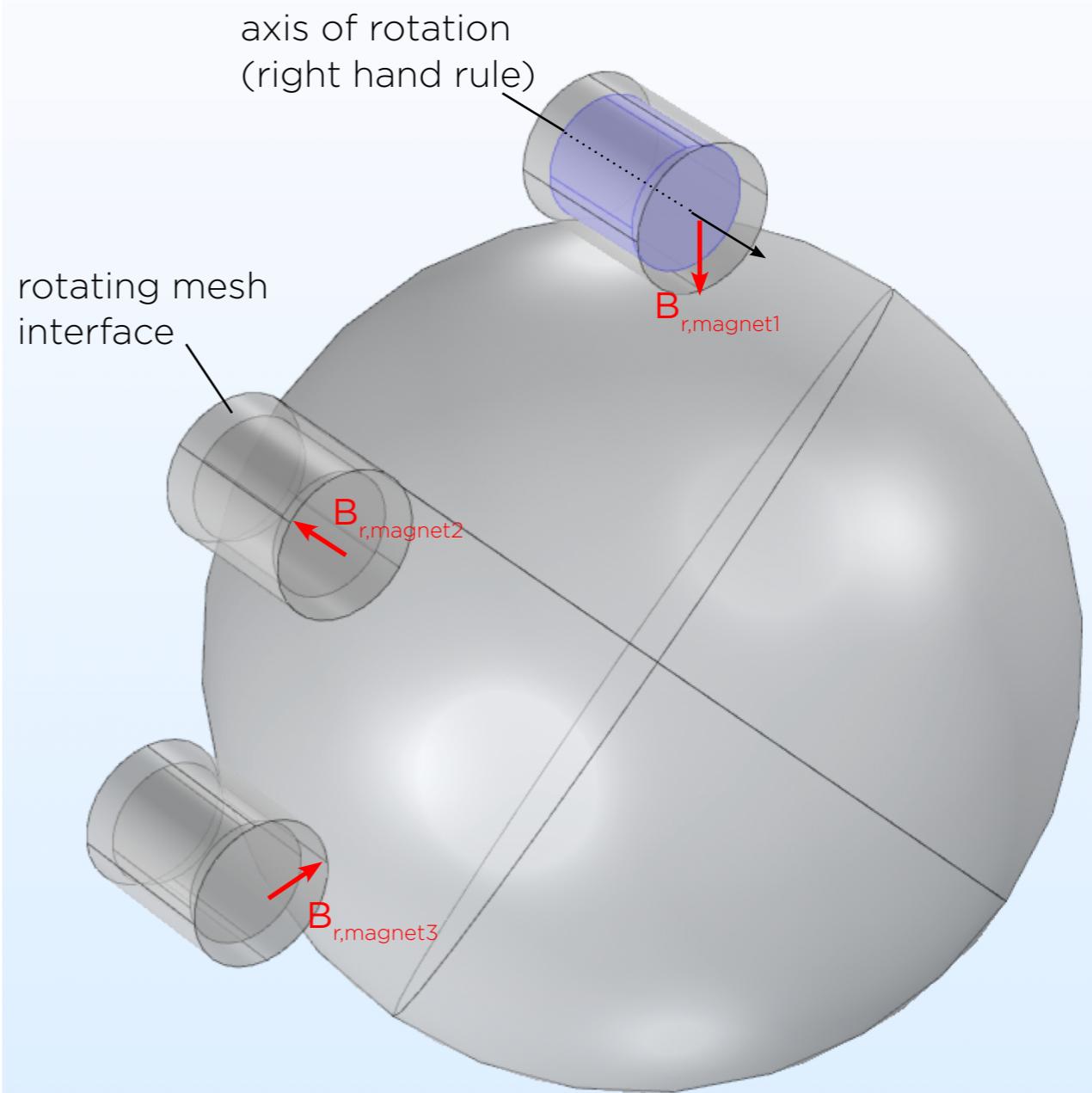
Time-dependent 3D problem

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

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

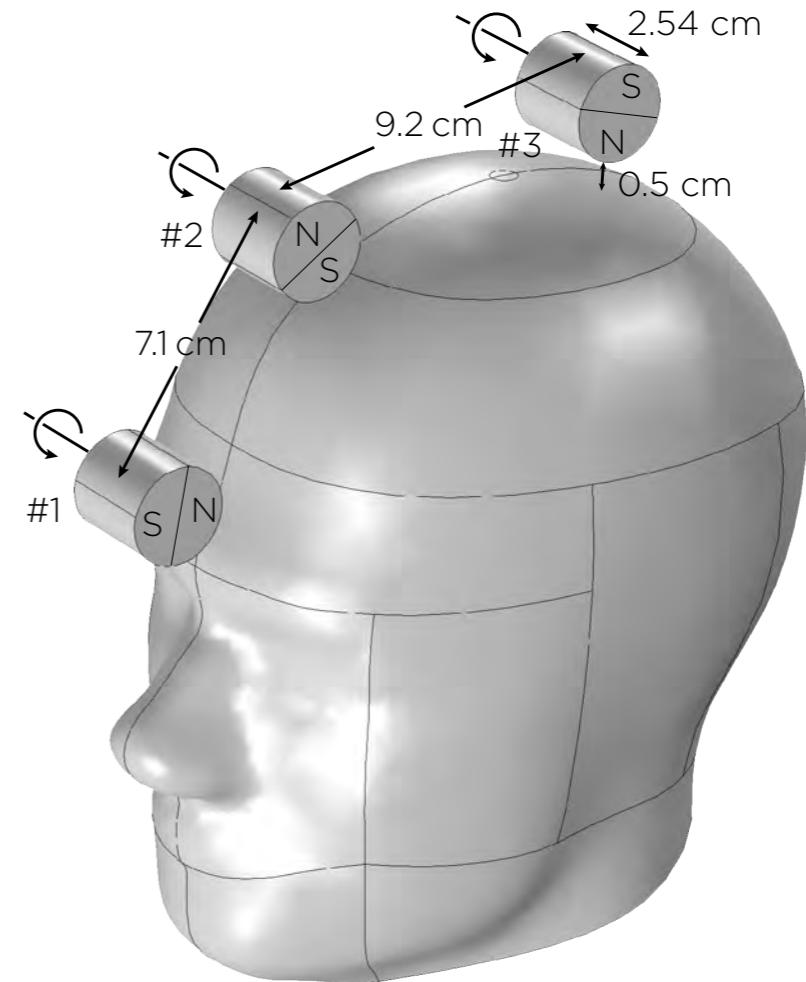
Nonconductive parts of both the rotor and stator are modeled using a magnetic flux conservation equation for the scalar magnetic potential:

$$-\nabla \cdot (\mu \nabla V_m - \mathbf{B}_r) = 0$$



sTMS: SAM head model

- § Three cylindrical, neodymium magnets, 1 inch diameter and height
- § $B_r = 0.64 \text{ T}$
- § Diametrically magnetized
- § FEM implemented in COMSOL using IEEE SAM phantom (uniform 0.33 Sm^{-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-statotor interface
- § Stationary solution first obtained using MUMPS direct solver, then time-dependent problem was solved



sTMS: full model



tDCS



DBS



ECT

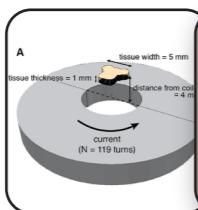


|E|

 10^{-2} V m^{-1} 10^{-1}

1

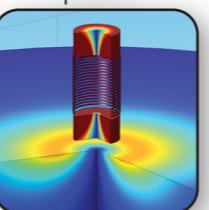
10

 10^2 10^3 LFMS: *in vitro*

tPEMF



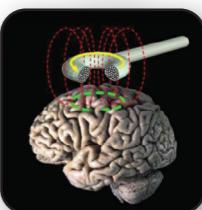
LFMS

 μMS 

LFMS: animal



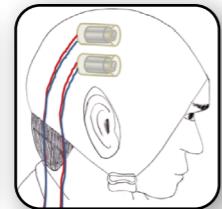
TMS



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



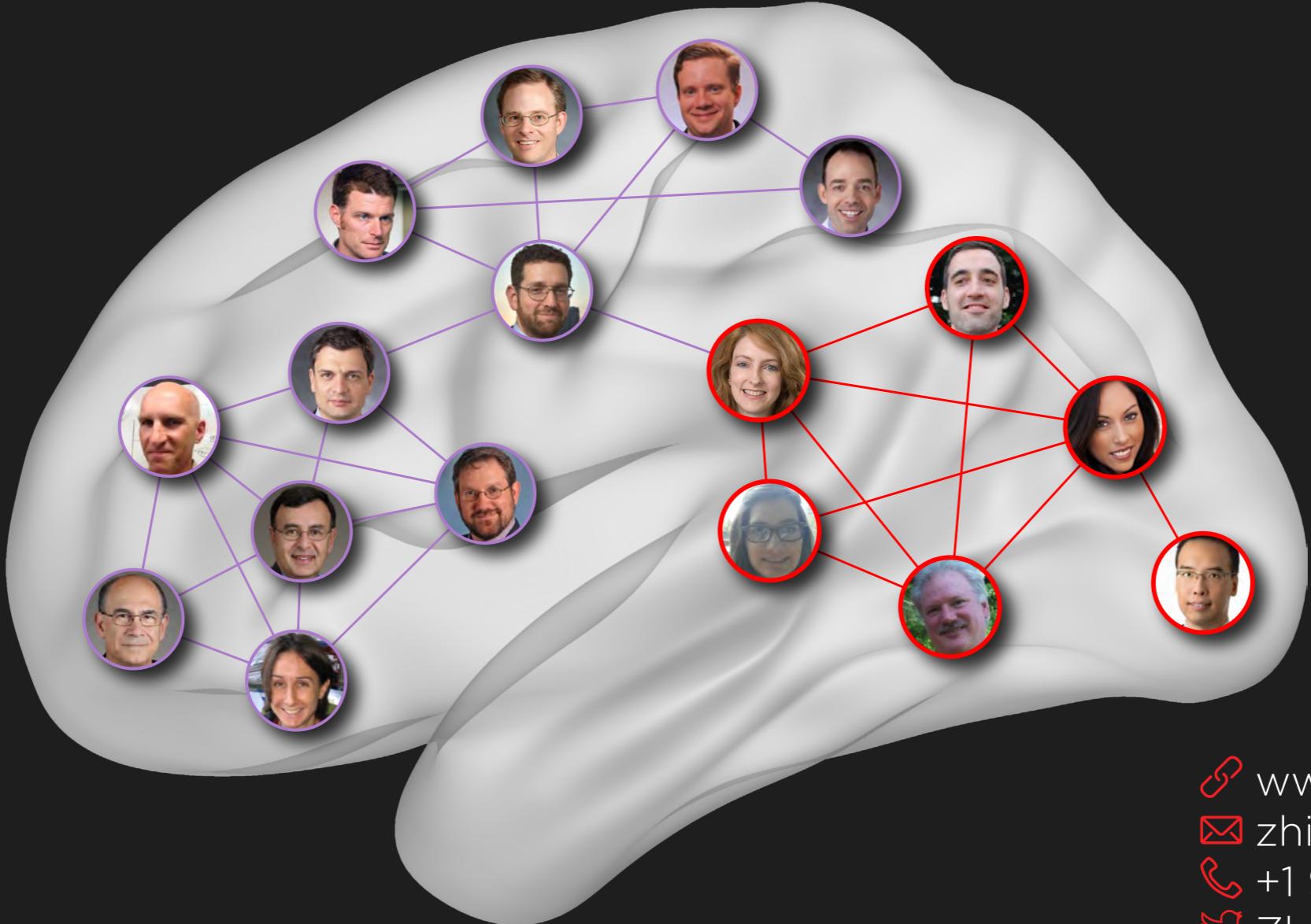
refrigerator magnet



tSMS



MRI



- [🔗 www.zzzdeng.net](http://www.zzzdeng.net)
- [✉ zhi-de.deng@nih.gov](mailto:zhi-de.deng@nih.gov)
- [📞 +1 919 564 5282](tel:+19195645282)
- [🐦 ZhiDeDeng](https://twitter.com/ZhiDeDeng)