Focused RF Hyperthermia Using Ultra-High Field MRI

Joshua de Bever, PhD

Department of Radiology

Stanford University

RADIOLOGICAL SCIENCES LABORATORY
STANFORD MEDICINE

SCIT STANFORD CANCER IMAGING TRAINEESHIP

UHF Focused RF (FRF) Hyperthermia

- **GOAL:** Generate localized & controlled tissue hyperthermia (40-43 °C) using *Radio Frequency* (RF) parallel transmit MRI coils.

- **BENEFITS:** Open new treatment options.
  - Non-invasive tissue heating would enable targeted drug delivery and BBB opening.

- MRI could become an All-In-One 'theranostic' modality

Therapy Wish List

Non-Invasive

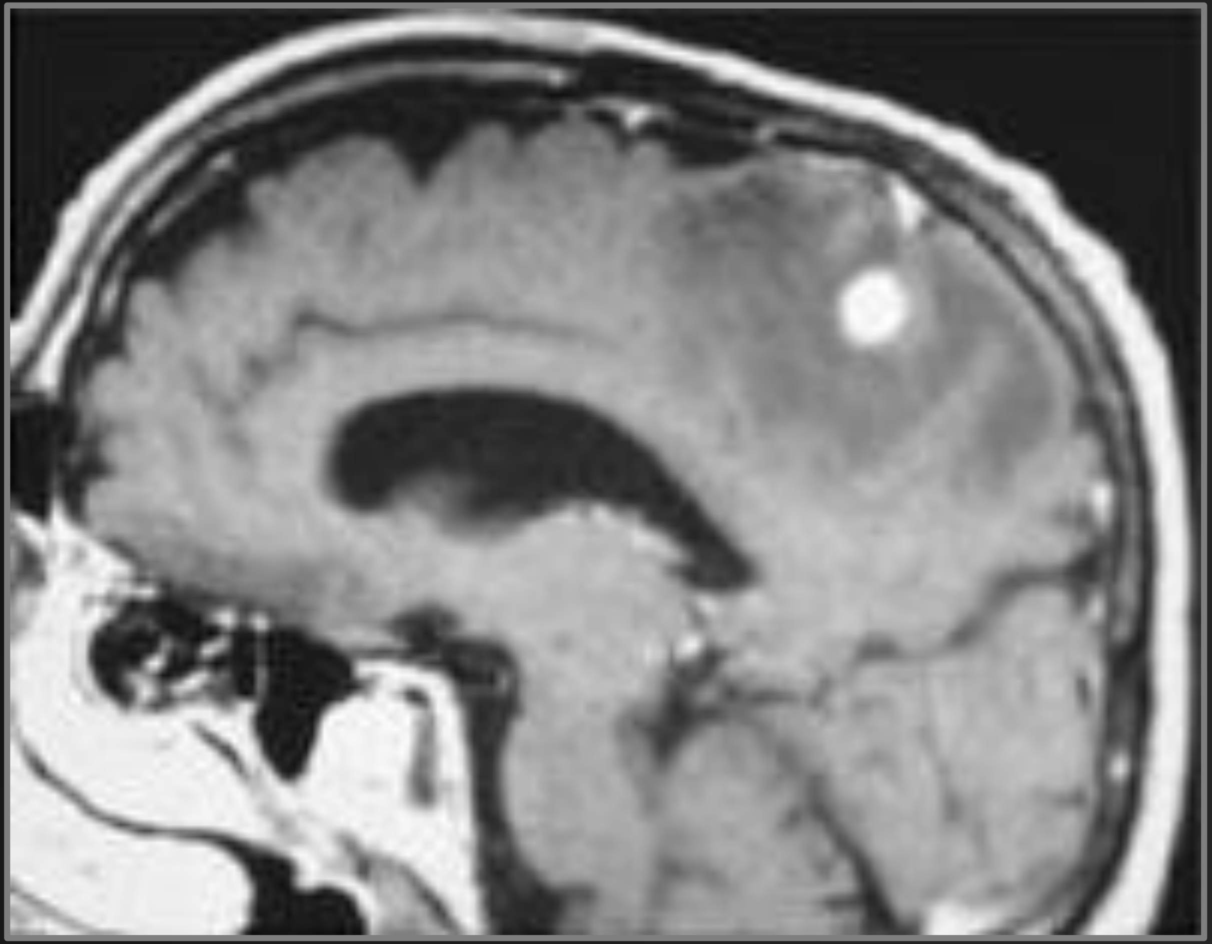
Free of Ionizing Radiation

Free of Toxic Chemicals

Monitor treatment (Feedback)

Brain Metastases: Motivation

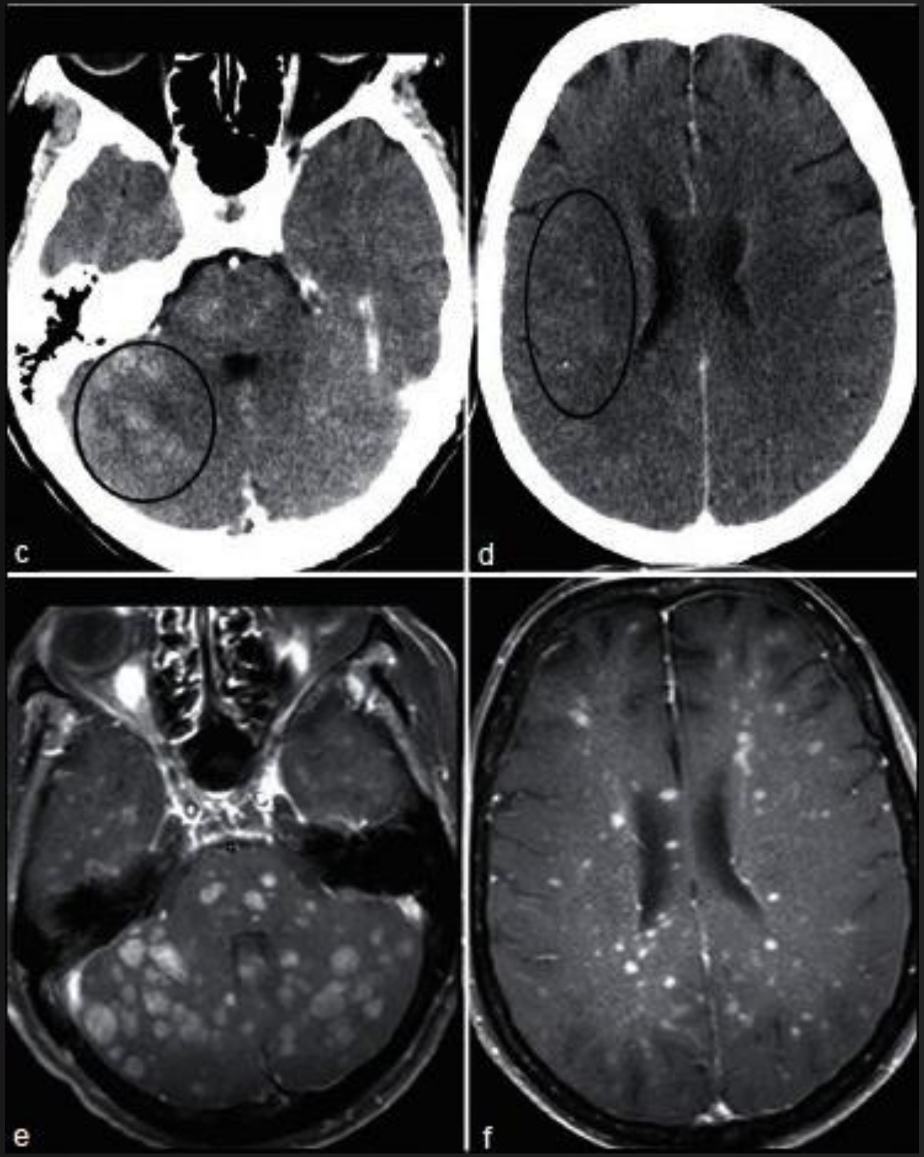
- Most common type of brain tumors
  - ~200,000 cases per year (USA)
  - > all intracranial tumors
  - Primary cancers: Lung, Breast, Melanoma
- Treatment options
  - Surgical resection
  - Whole-brain radiation therapy (WBRT)
  - Corticosteroids
  - Stereotactic Radiosurgery (SRS)
- Median overall survival:
  - Untreated: 1 month
  - With treatment: 3-11 months



T1w - Gd

Ultra-High Field (UHF) MRI

- MRI w Gd leads in BM detection
- 20% of patients who present with a single lesion on CT actually have multiple lesions
- Higher Field = More Signal
- Increase: Resolution, speed, etc



CECT

MRI w Gd

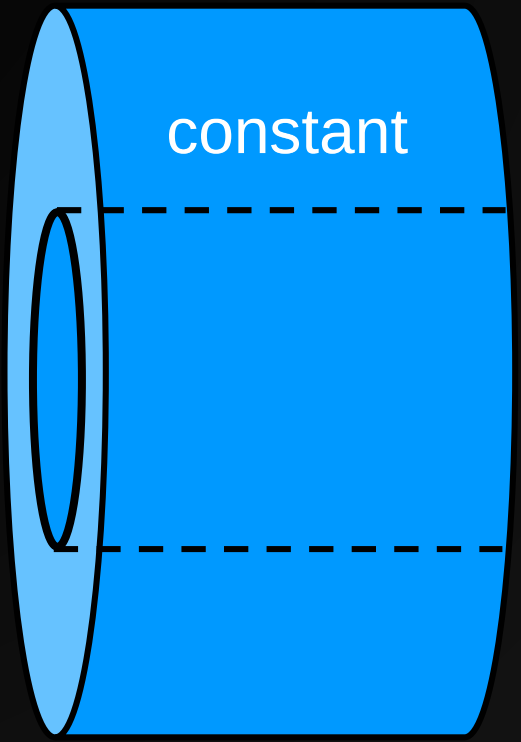
Fink *et al*, *SNI,* 2013

Neuro Degenerative & Developmental Disorders

- The blood-brain barrier (BBB) diminishes effectiveness of therapeutic agents
  - Impedes access to central nervous system (CNS)

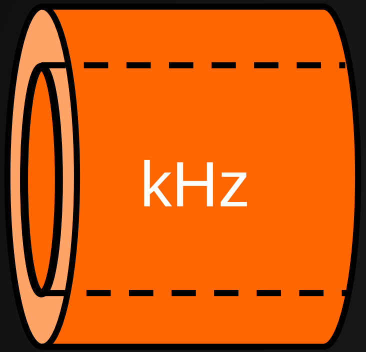
- *Reversible* BBB permeability modulation would greatly improve therapeutic impact

Magnet



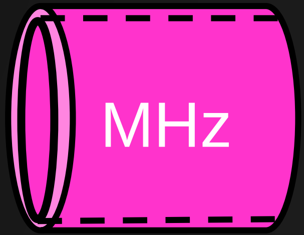
(1) magnetize the object

Gradient Coils

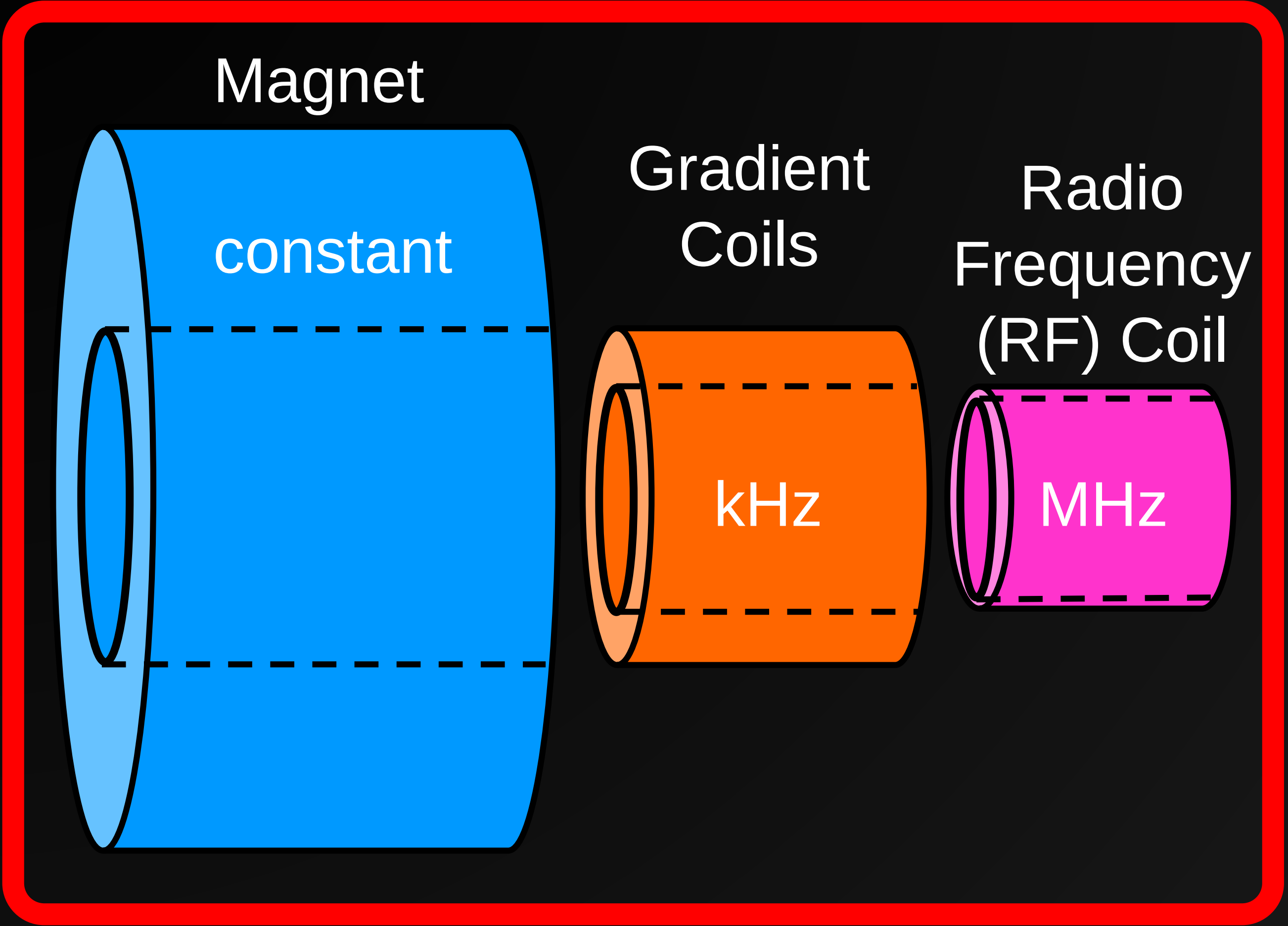


(2) encode frequency as a function of position

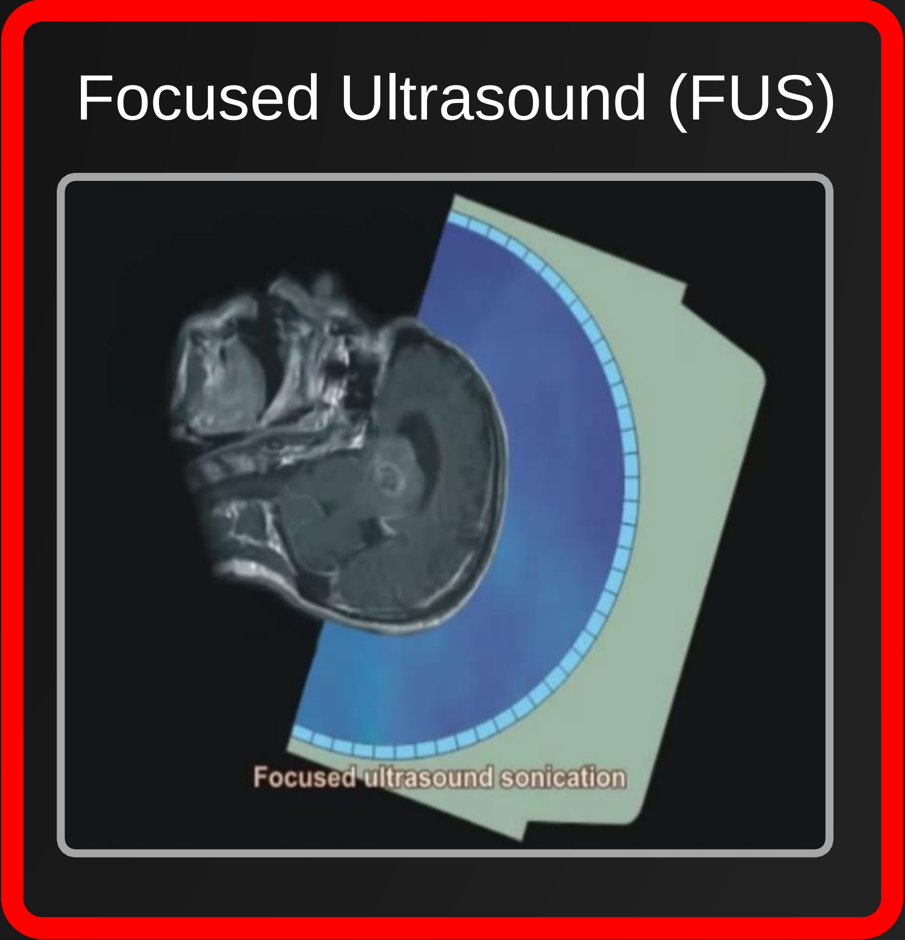
Radio Frequency (RF) coil



(3) Excite sample & detect the signal

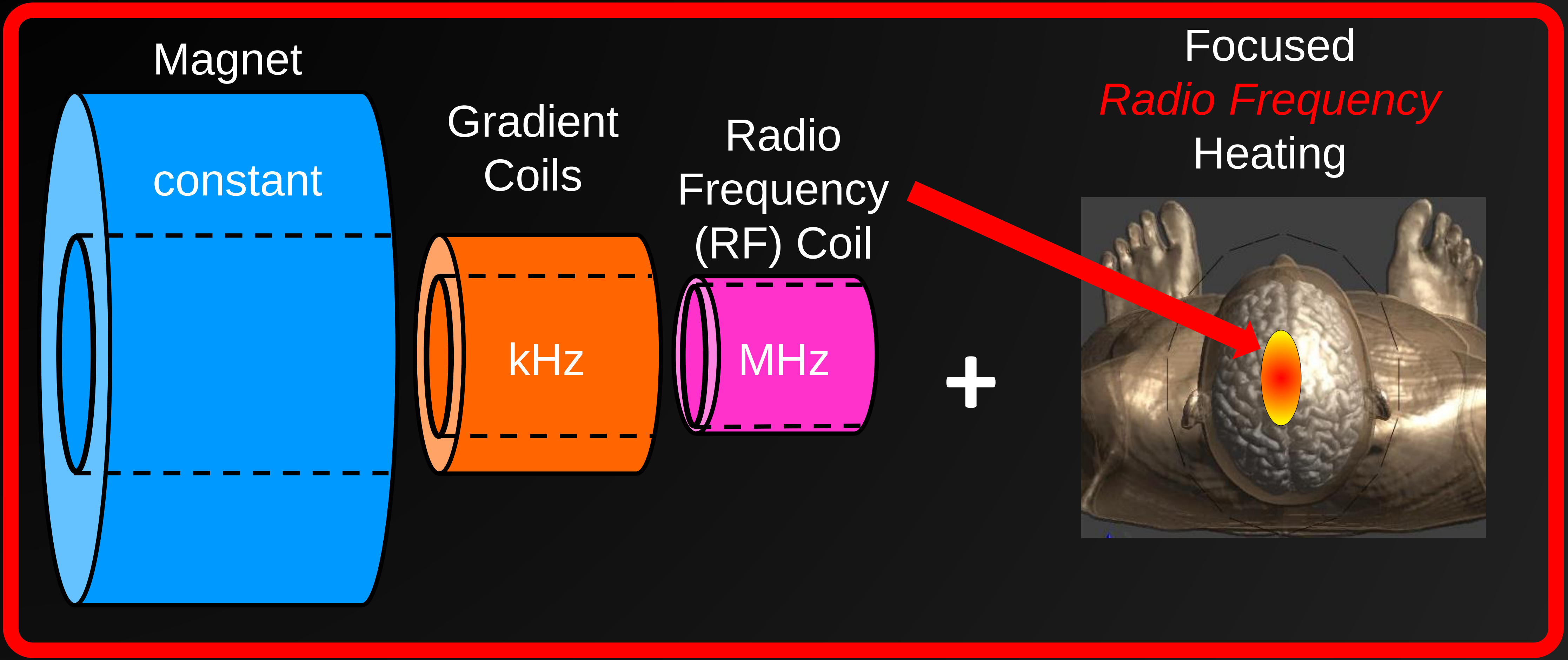


+



- Anatomical imaging
- MR Thermometry

- Non-invasive tissue heating
- Blood-brain barrier opening



- Anatomical imaging
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- Non-invasive tissue heating
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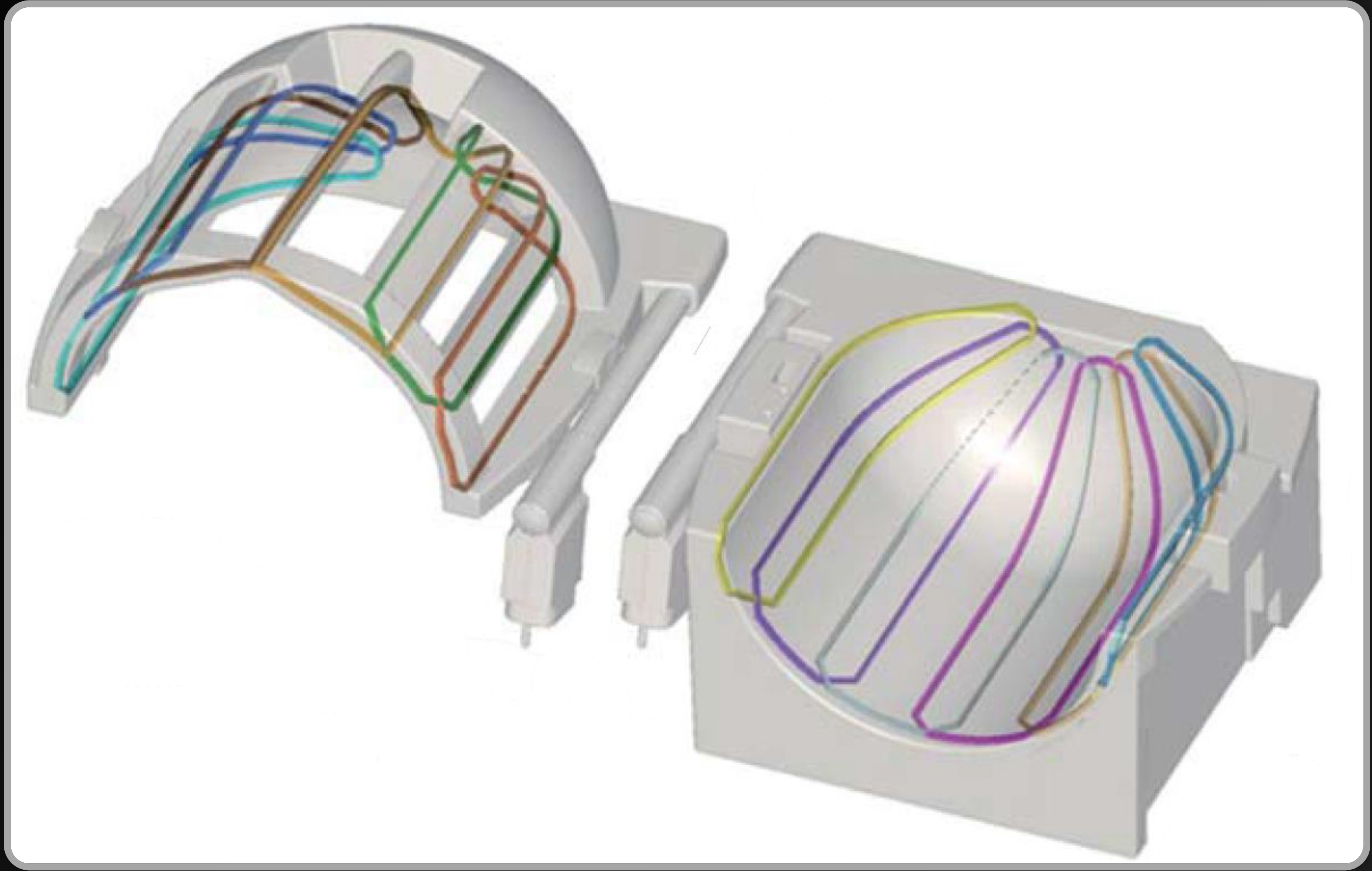
Ultra High-Field MRI: Imaging

- **Tissue heating** *is a known problem* for ***imaging*** due to increased Specific Absorption Rate (SAR) at 7T+ (UHF)

- Mitigated by:
  - Multi-element RF coils
  - Intelligent parallel transmit excitation algorithms
    - IMPULSE – minSAR optimizer for a given flip angle homogeneity

UHF RF Solution: Array Coils

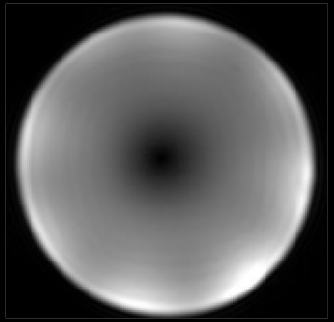


Kaza *et al*, JMRI, 34:1553–62, 2011

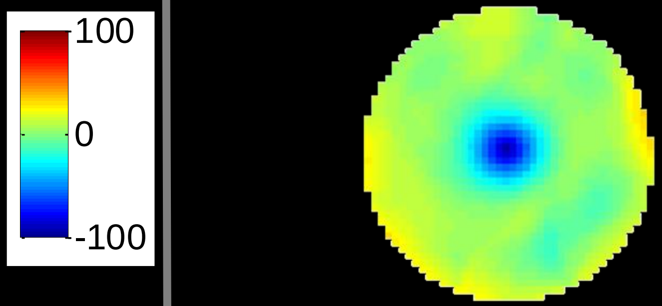
Ultra High-Field MRI: Challenges

BIRDCAGE MODE

SPGR
TR=4000ms
FA = 30°



FA error (%)

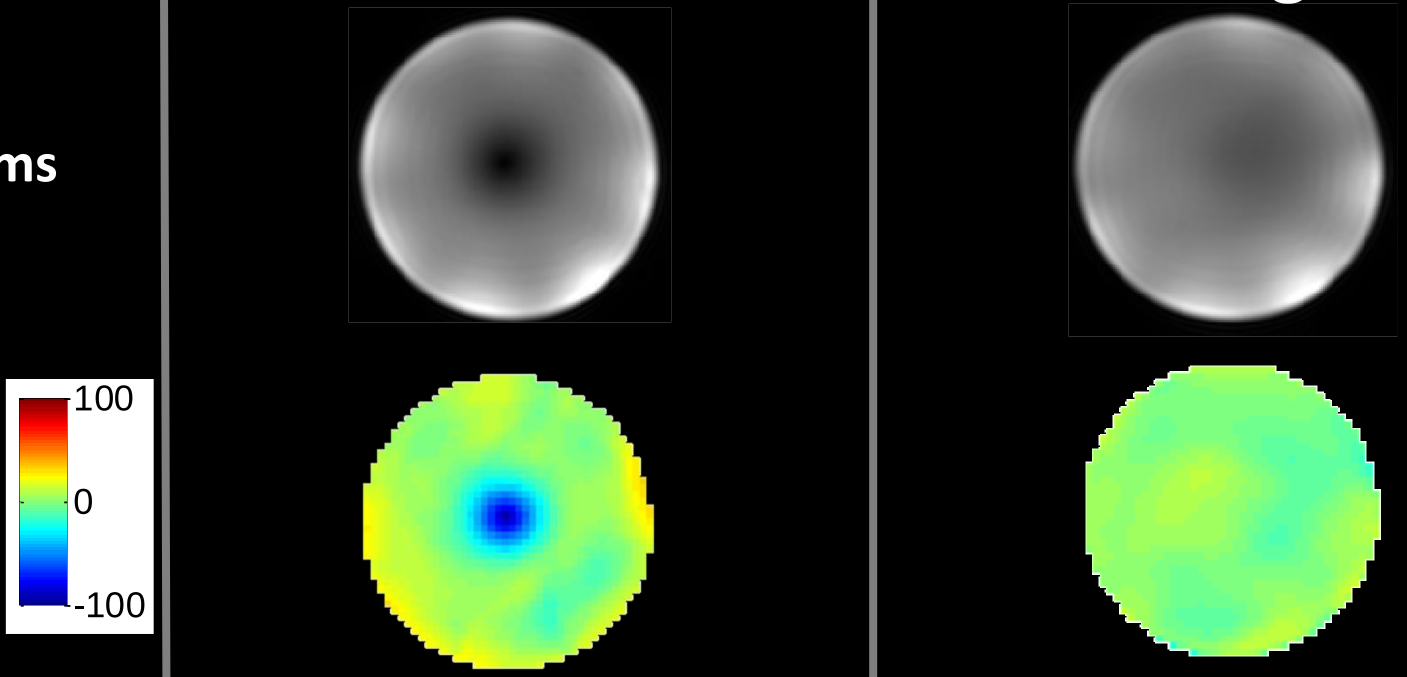


Ultra High-Field MRI: Challenges

BIRDCAGE MODE | **Grissom Algorithm[1]**

SPGR
TR=4000ms
FA = 30°

FA error (%)



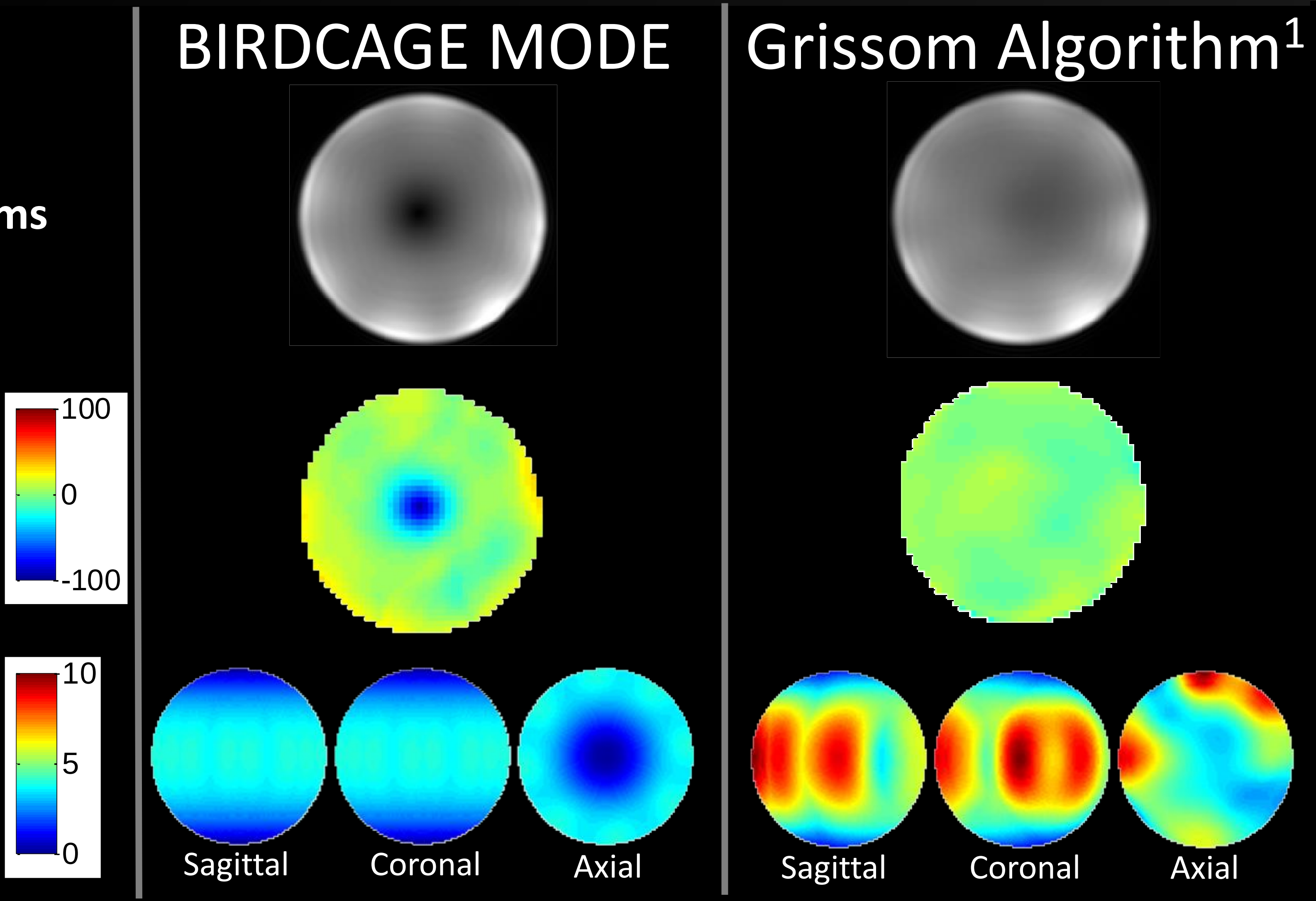
[1]Grissom, MRM 2012;68:1553–1562

Ultra High-Field MRI: Challenges

SPGR
TR=4000ms
FA = 30°

FA error (%)

Local SAR MIP (W/kg)



Courtesy of: Mihir Pendse, ISMRM 2015 #573

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Ultra High-Field MRI: Challenges

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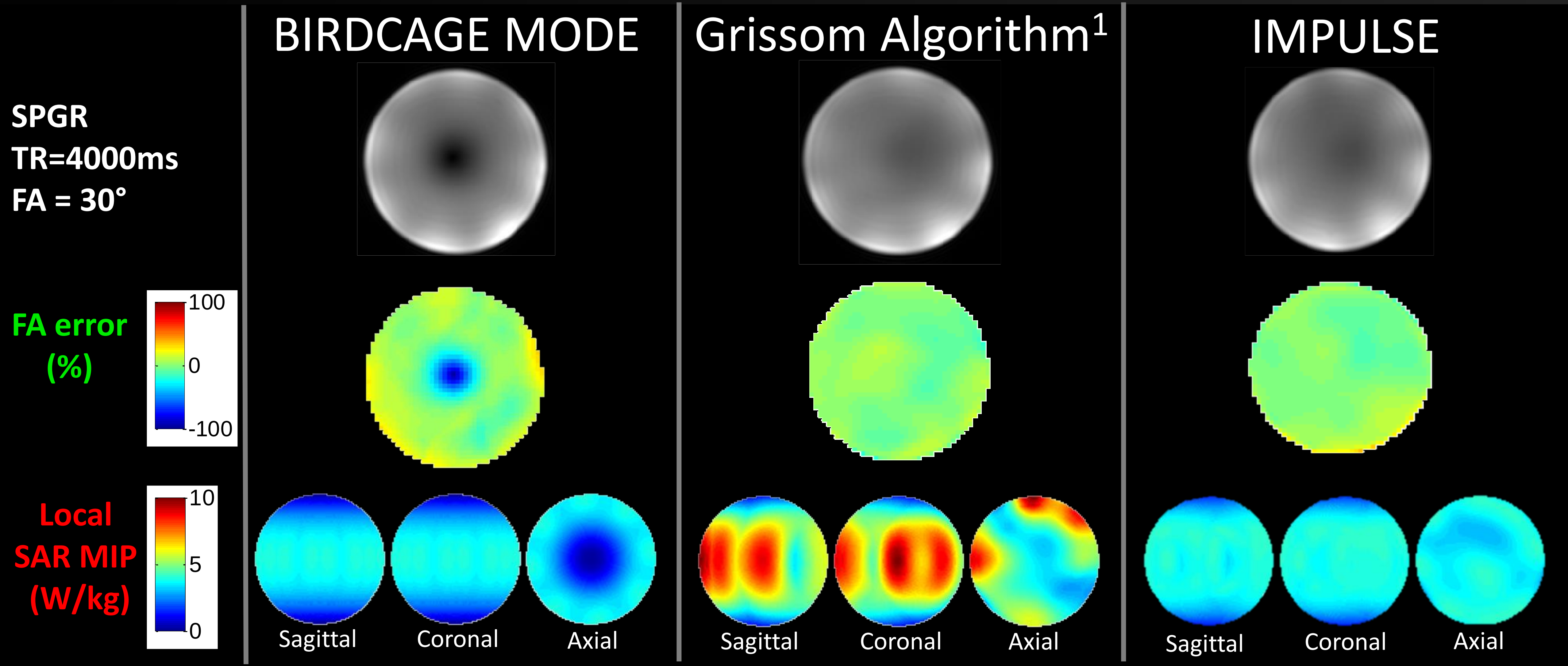
Ultra High-Field MRI: Challenges



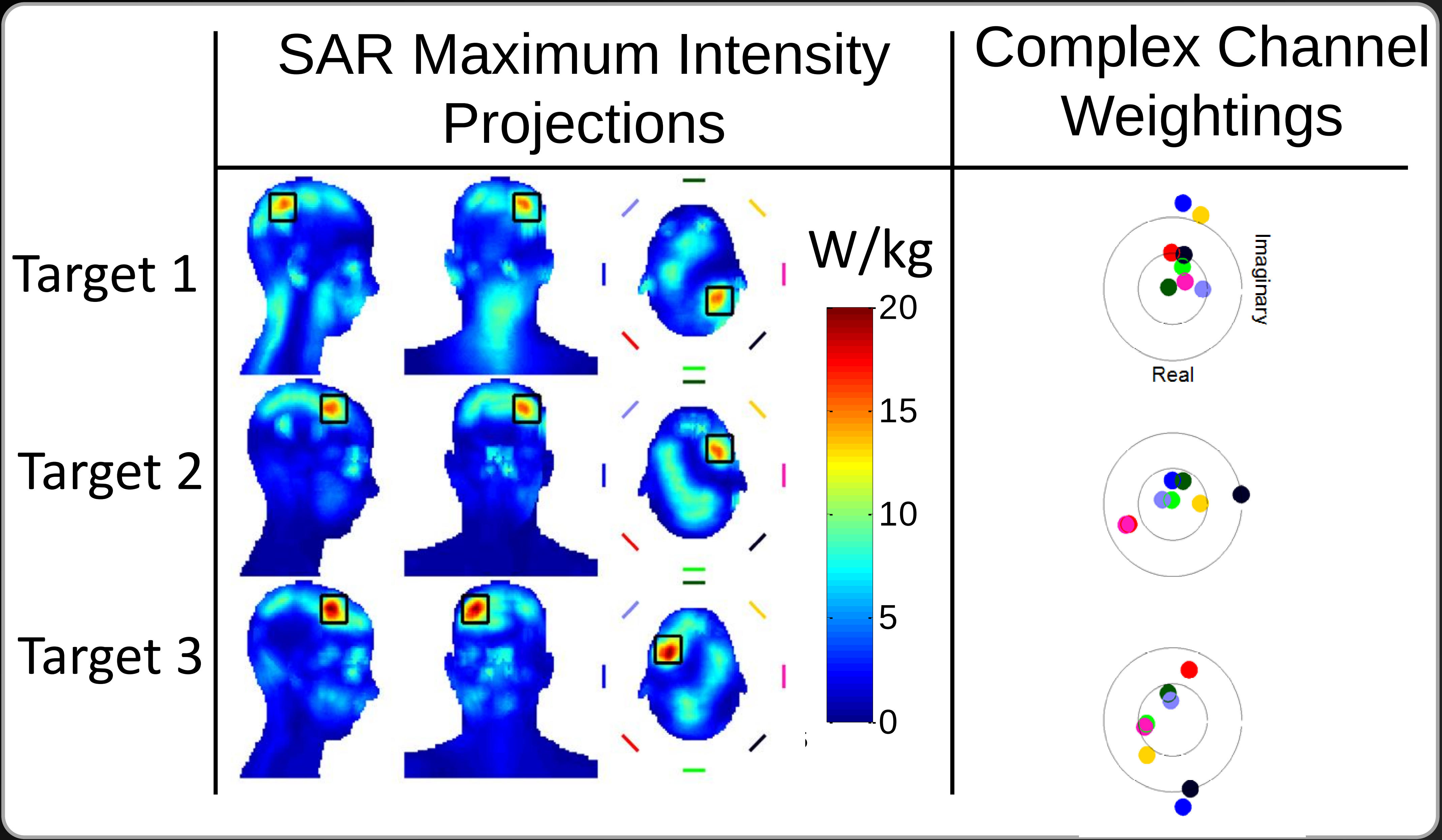
Courtesy of: Mihir Pendse, ISMRM 2015 #573

[1]Grissom, MRM 2012;68:1553–1562

UHF Focused RF Hyperthermia

- Leverages increased SAR at 7T+ for **GOOD**

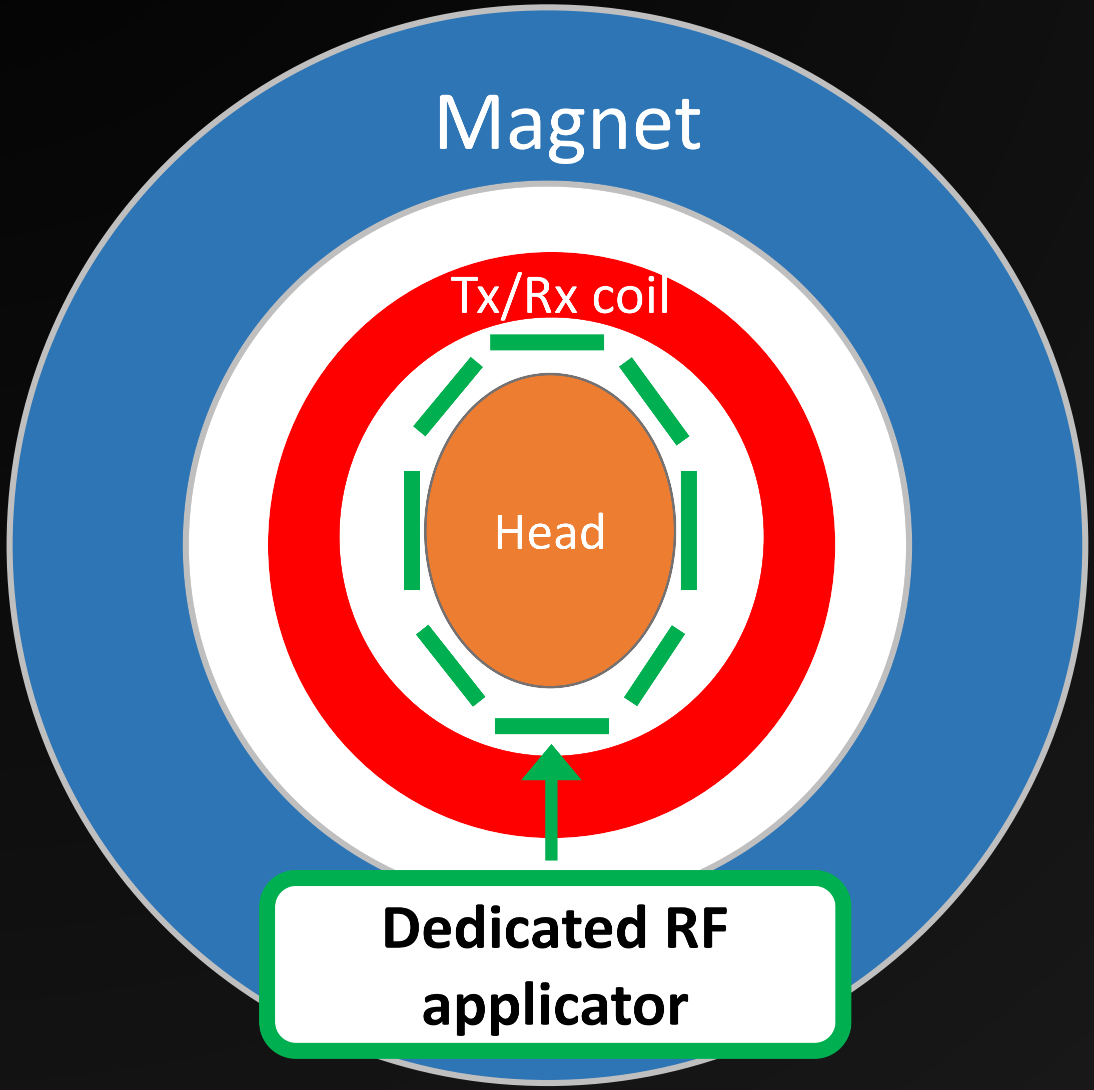
- **MaxSAR** algorithm – optimizes RF energy transmitted to achieve TARGETED and CONTROLLED volumetric heating



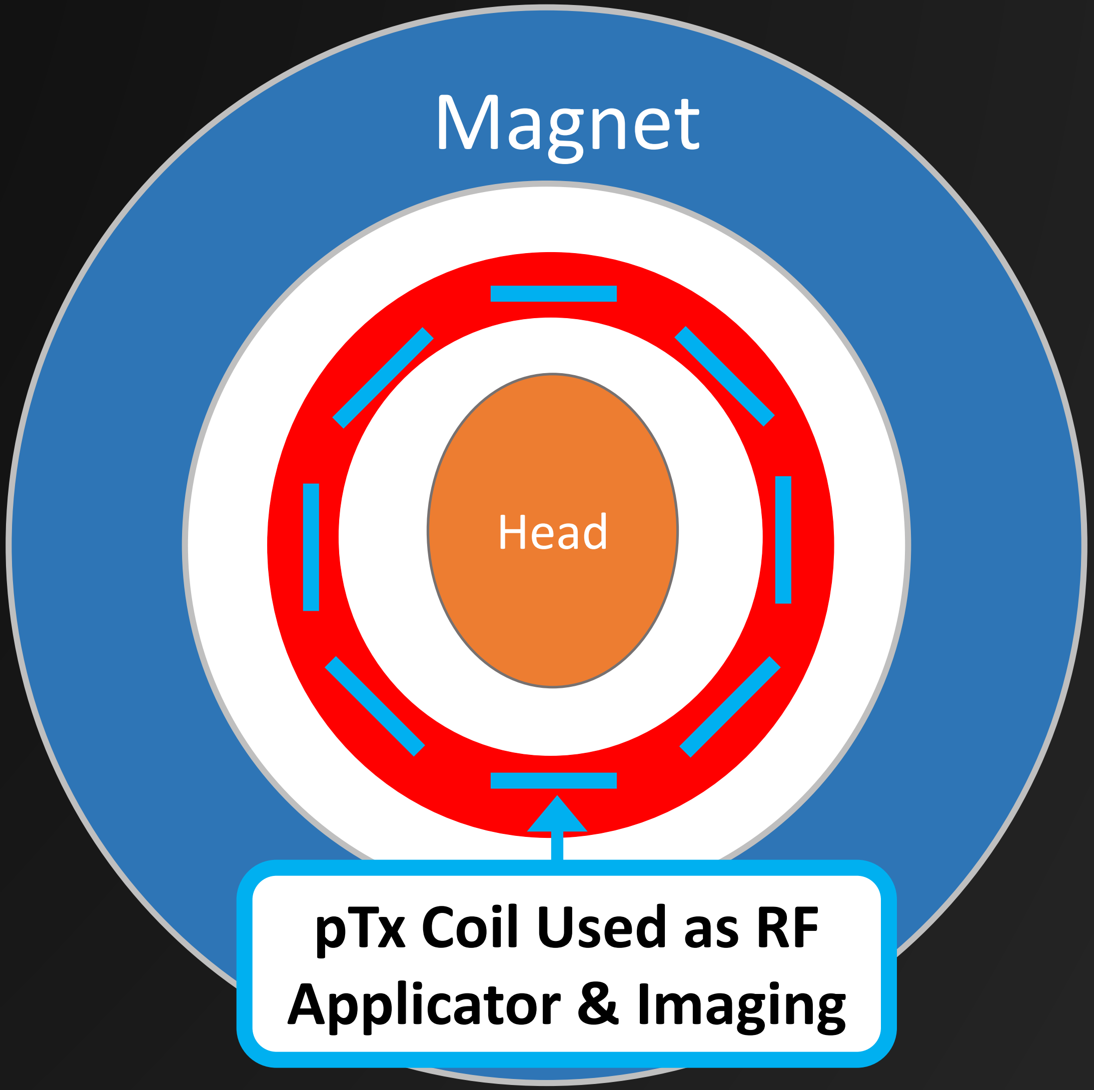
Courtesy of: Mihir Pendse, ISMRM 2015 #573

Hardware Configurations

#1: Dedicated RF Applicator



#2: All-In-One



Hardware Configurations

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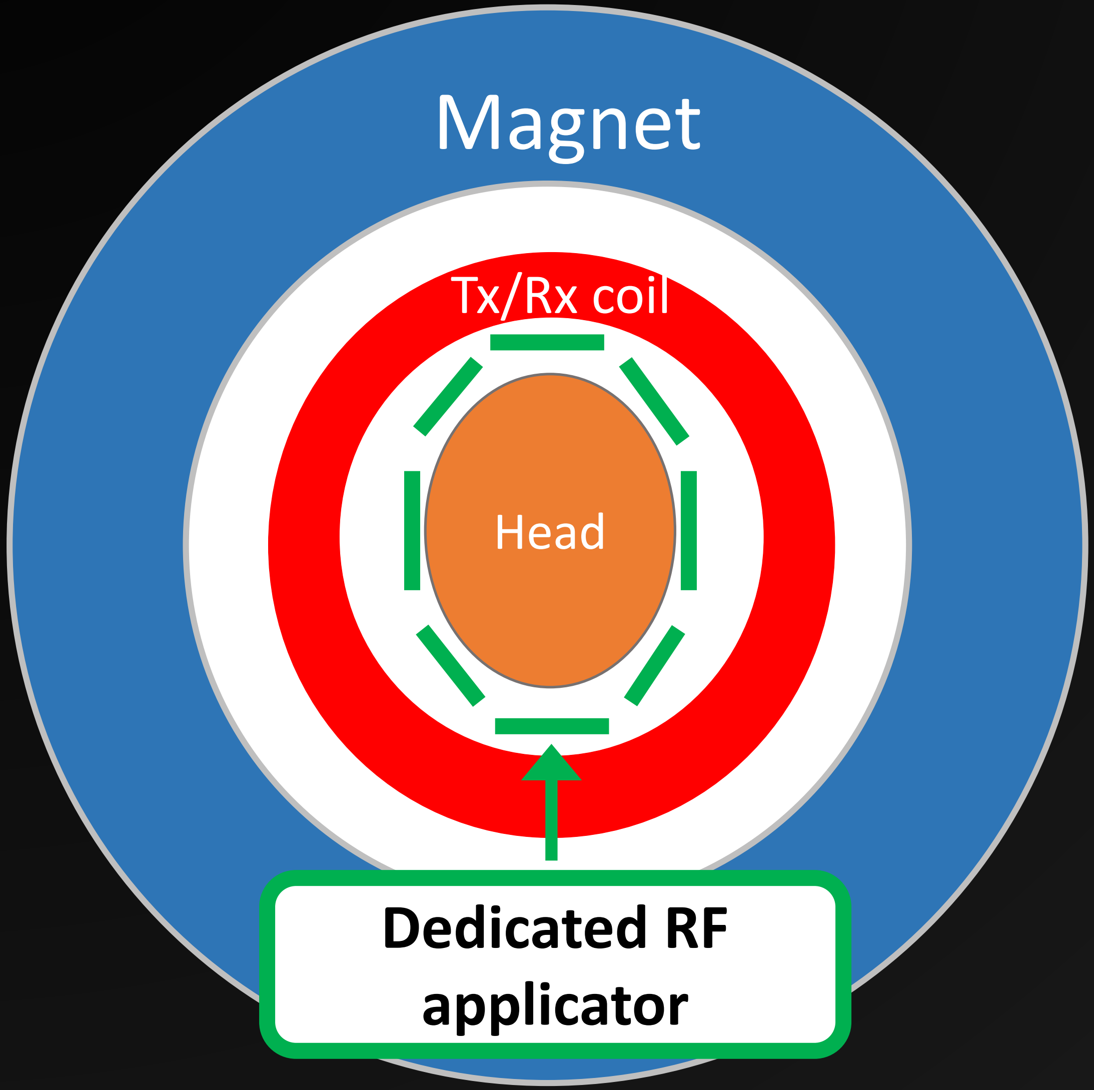


Advantages

- Better spatial control (proximity)
- Thermometry and hyperthermia can occur simultaneously
- Frequency of applicator can be different from imaging frequency

Disadvantages

- More hardware, cables
- Coupling between two transmitters is possible

Hardware Configurations

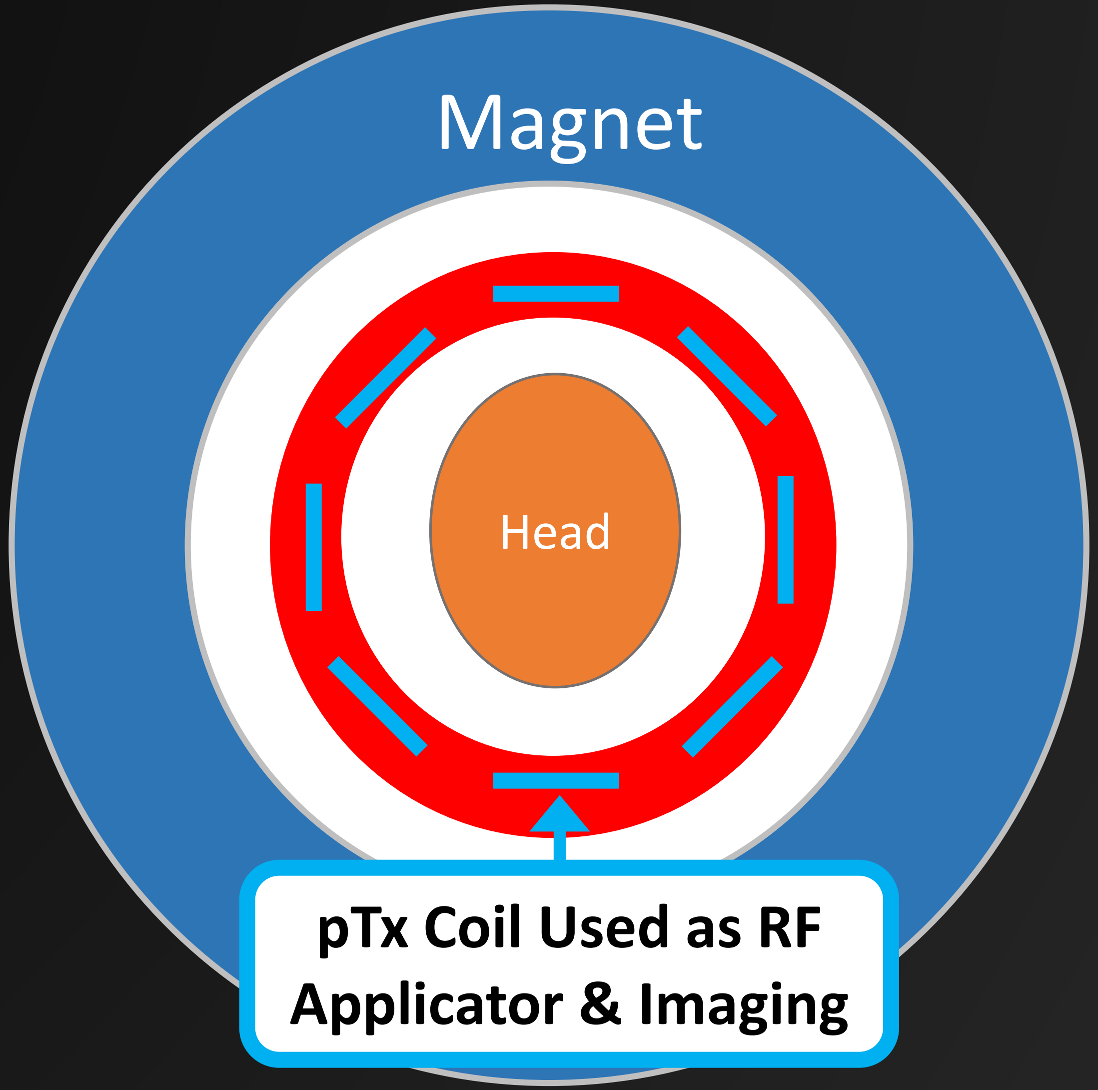
Advantages

- Single piece of hardware
- Fewer cables, coupling, etc

Disadvantages

- Only possible at ultra-high fields (7T+)
    - Need high Larmour frequency to achieve focal heating
- Must interleave hyperthermia & imaging
- Spatial control is limited by size and frequency of pTx coil

#2: All-In-One

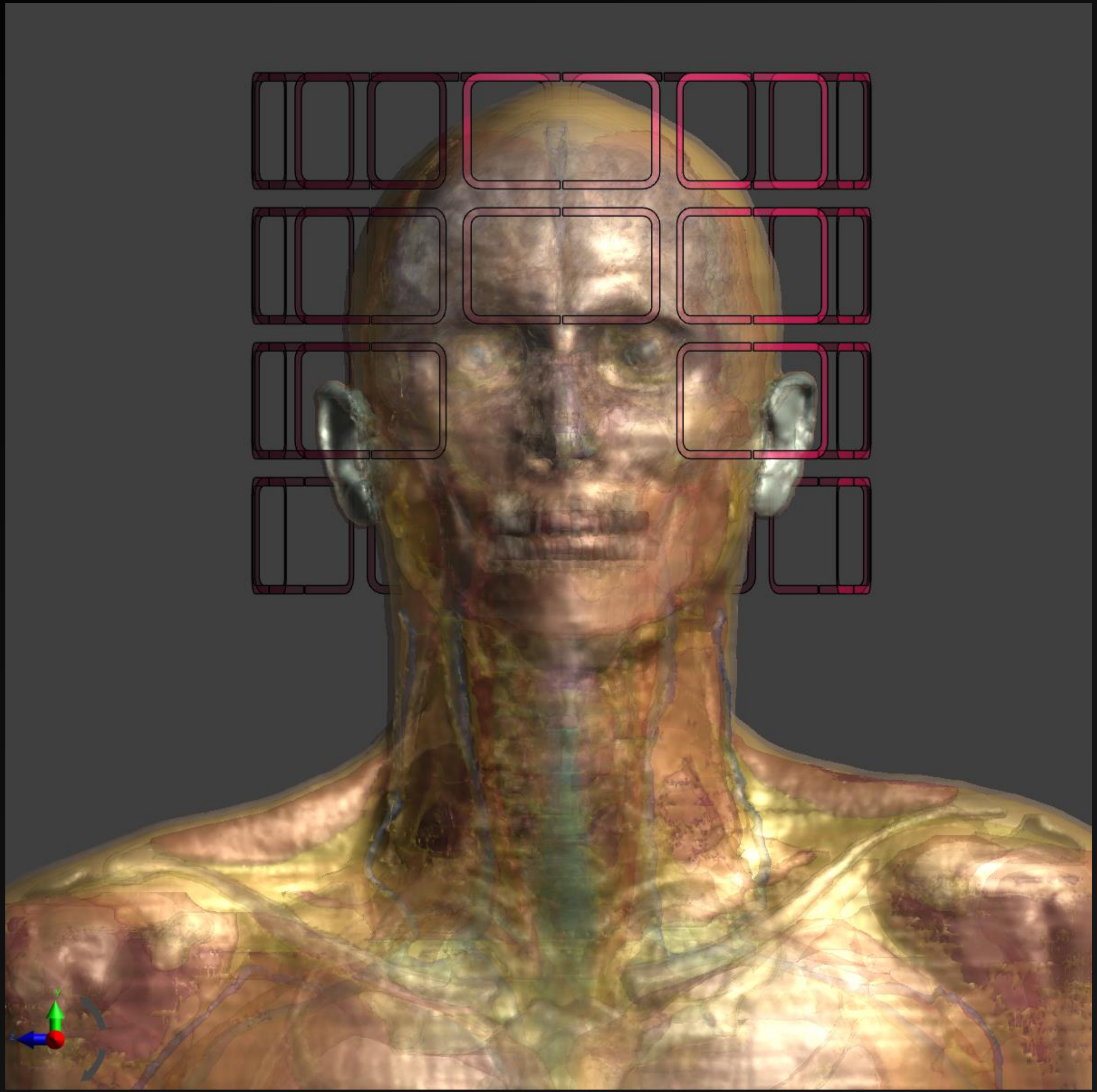


Goal #1: Optimize RF Coil Design

- Large parameter space to explore
  - Hardware configuration
  - # of elements
  - Element geometry
  - Element placement
  - Effect of field strength (Frequency)
  - Reachable target locations

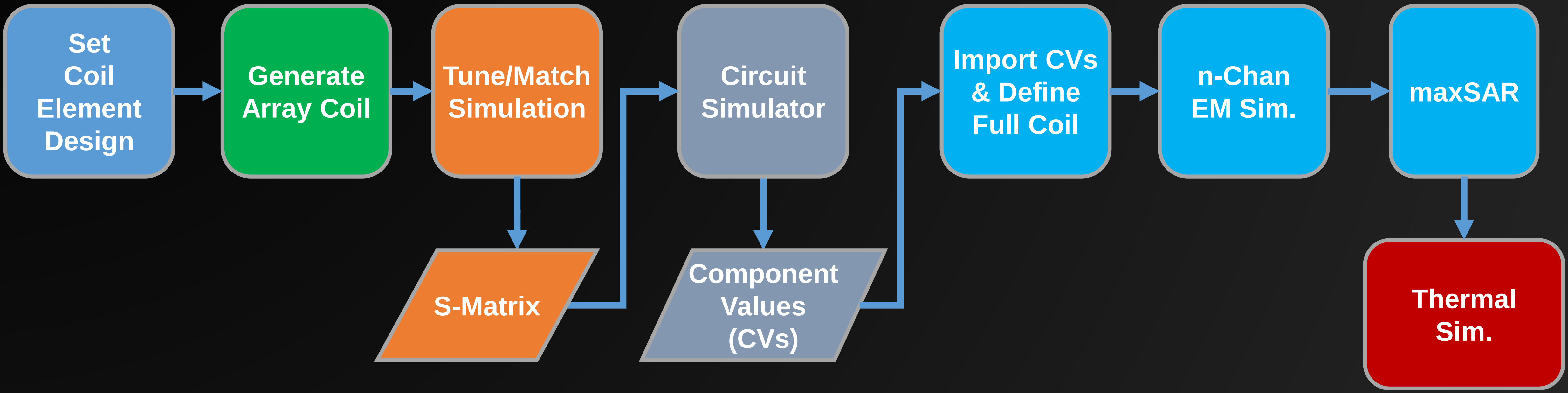
Simulation of High Channel Count RF Coils

SPEAG Sim4Life



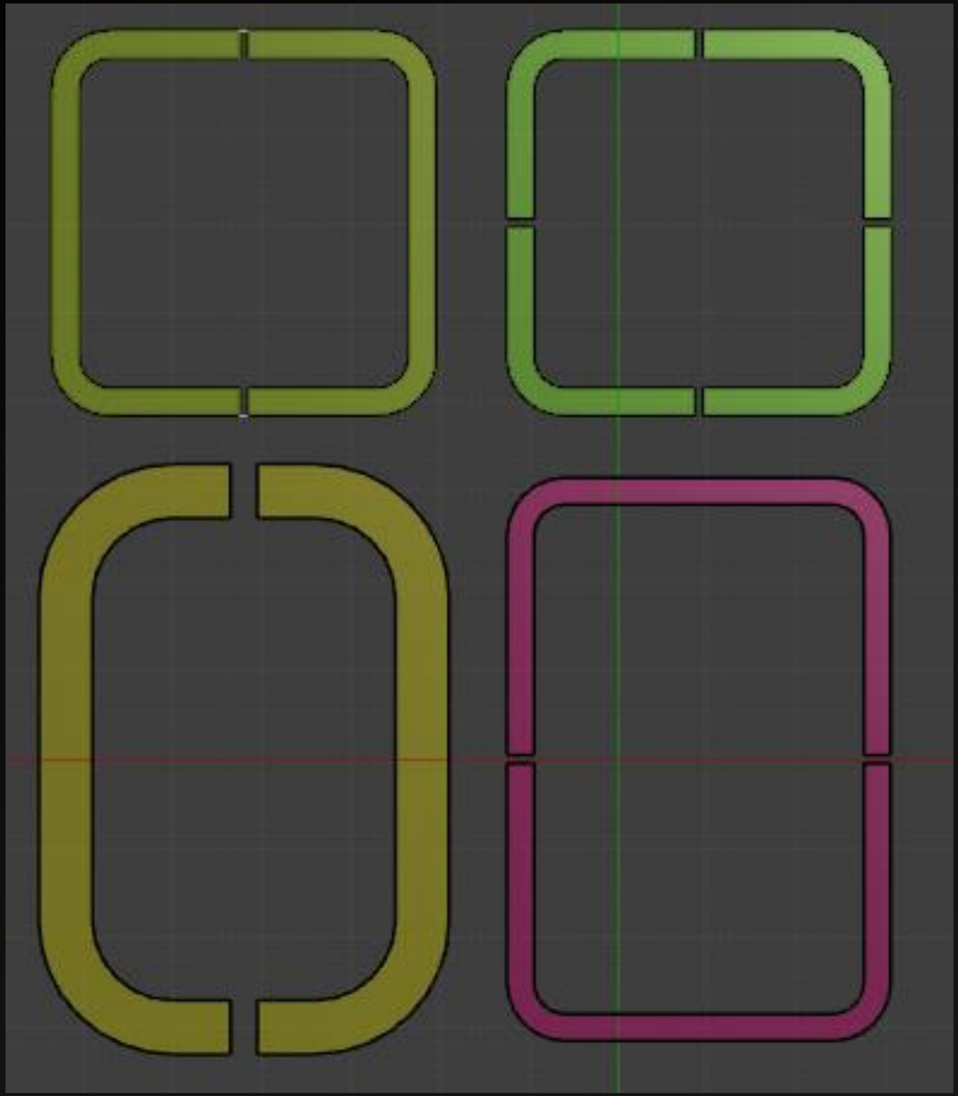
- FDTD Electromagnetic simulations
- Virtual Family – Realistic body models
- Working to accelerate simulations

Coil Design Study Pipeline



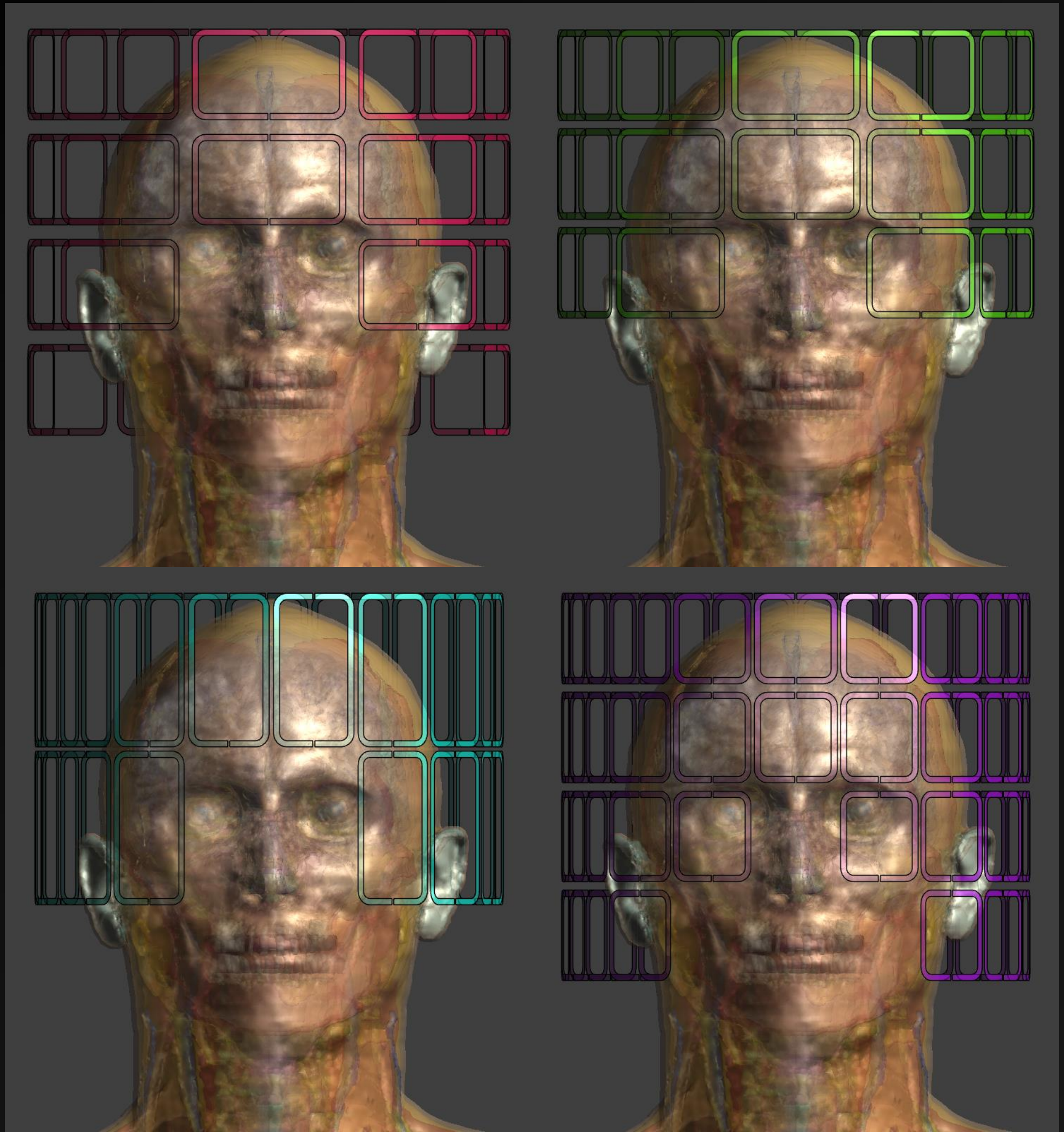
- Have written S4L python code to automate many of these steps
- Working toward full automation

① : Coil Element Design Tool



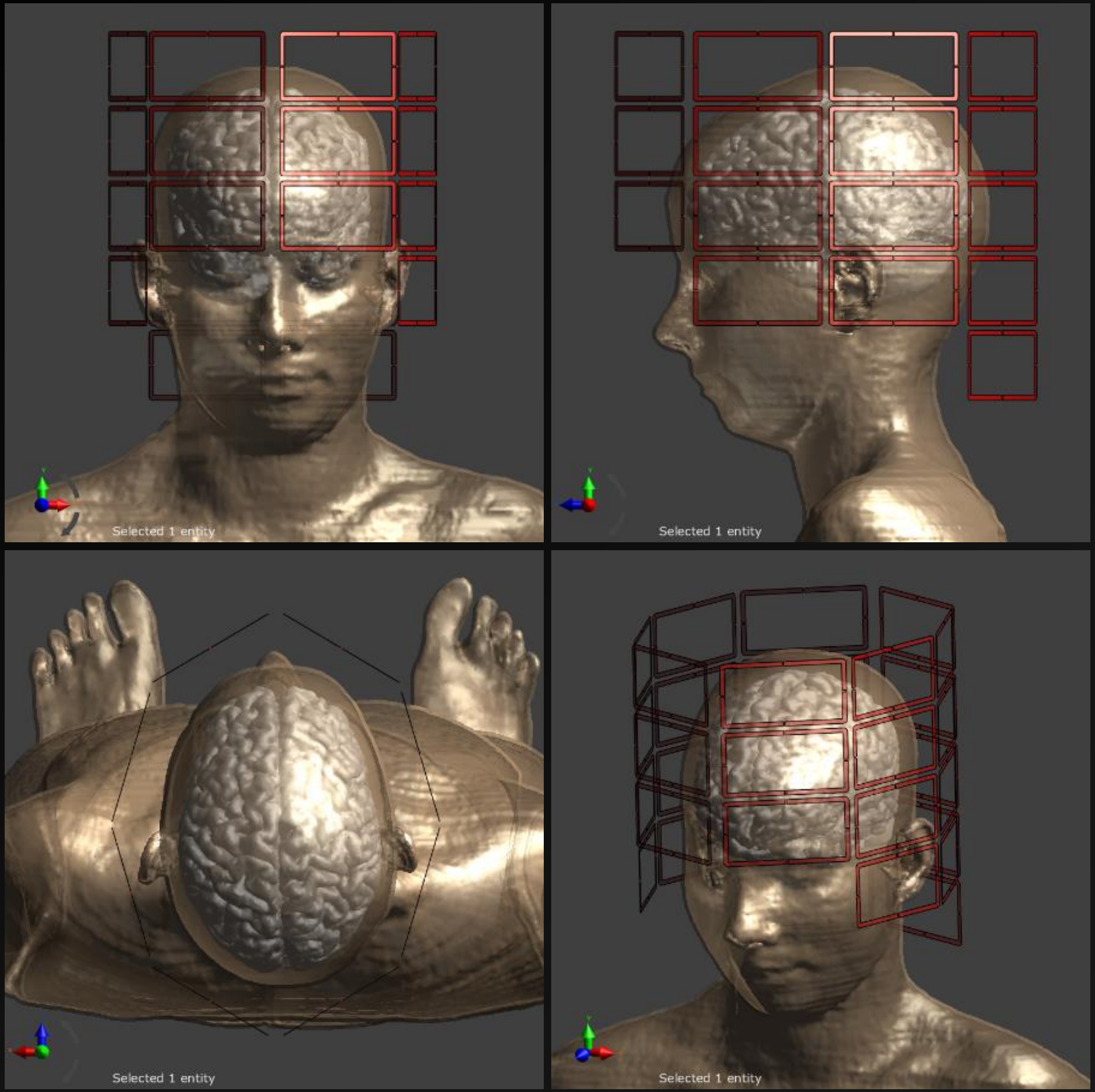
- Can vary multiple parameters:
  - Width
  - Height
  - Conductor width
  - Radius of corner curvature
  - Cuts on horizontal rungs
  - Cuts on vertical rungs
  - Cut width

② : S4L Array Generator

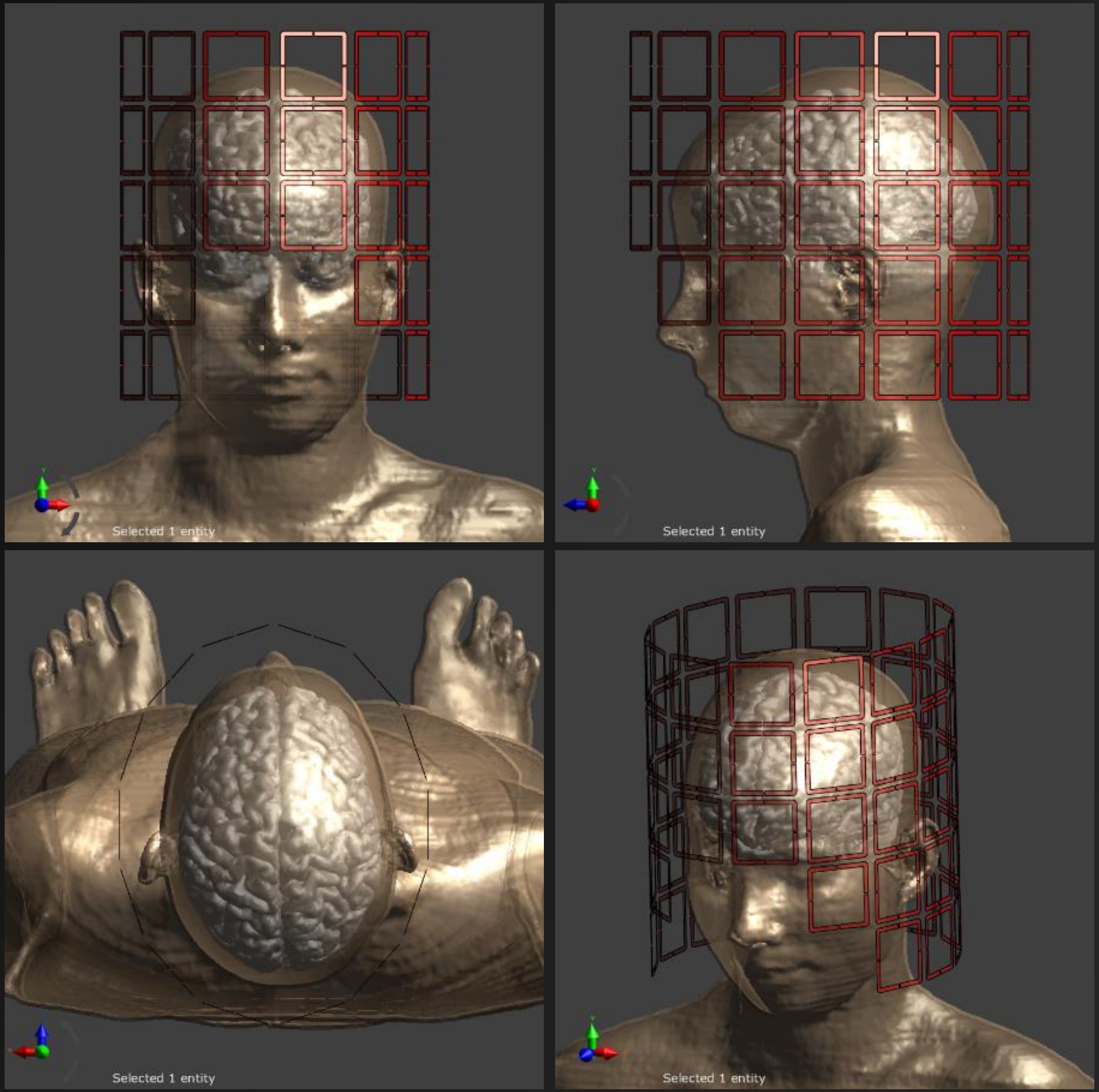


- Automatically places coil elements
- Can vary multiple parameters:
  - # Coil Rows
  - Coils per row
  - Rotation offset

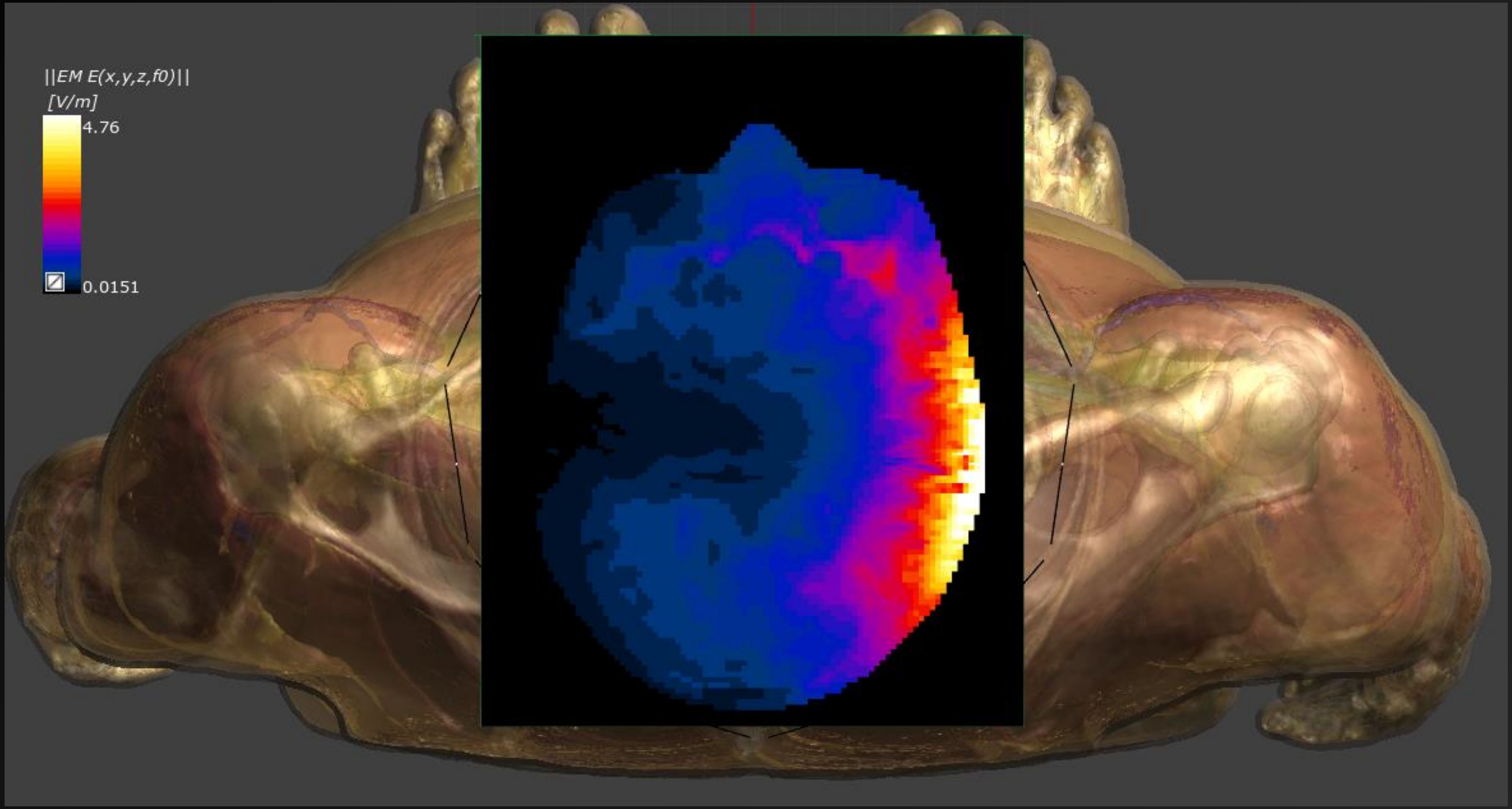
32 Ch Head Coil w. Ella



64 Ch Head Coil w. Ella



③: Tune/Match Element Simulation



Goal #2: Apply maxSAR Clinically

- maxSAR algorithm is FAST
- Need:
  - Electric/magnetic field maps to run IMPULSE
    - Field computation is slow....
    - Not easily applied in clinic today
  - FAST (enough) computation
    - 20-30 minutes
  - Detailed, accurate, models of the patient

In the Clinic

E/B Field Simulation Time

Hardware	1 Chan [Hours]	8 Chan [Hours (Days)]	32 Chan [Hours (Days)]	84 Chan [Hours (Days)]
CPU	55.8	446.7 (18.6)	1786.8 (74.4)	4690.3 (195.4)

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1x GTX 670	8.58	68.7 (2.9)	274.6 (11.4)	720.9 (30.0)

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2x Titan Black (Sherlock)	2.57	20.6 (0.9)	82.4 (3.4)	216.3 (9.01)

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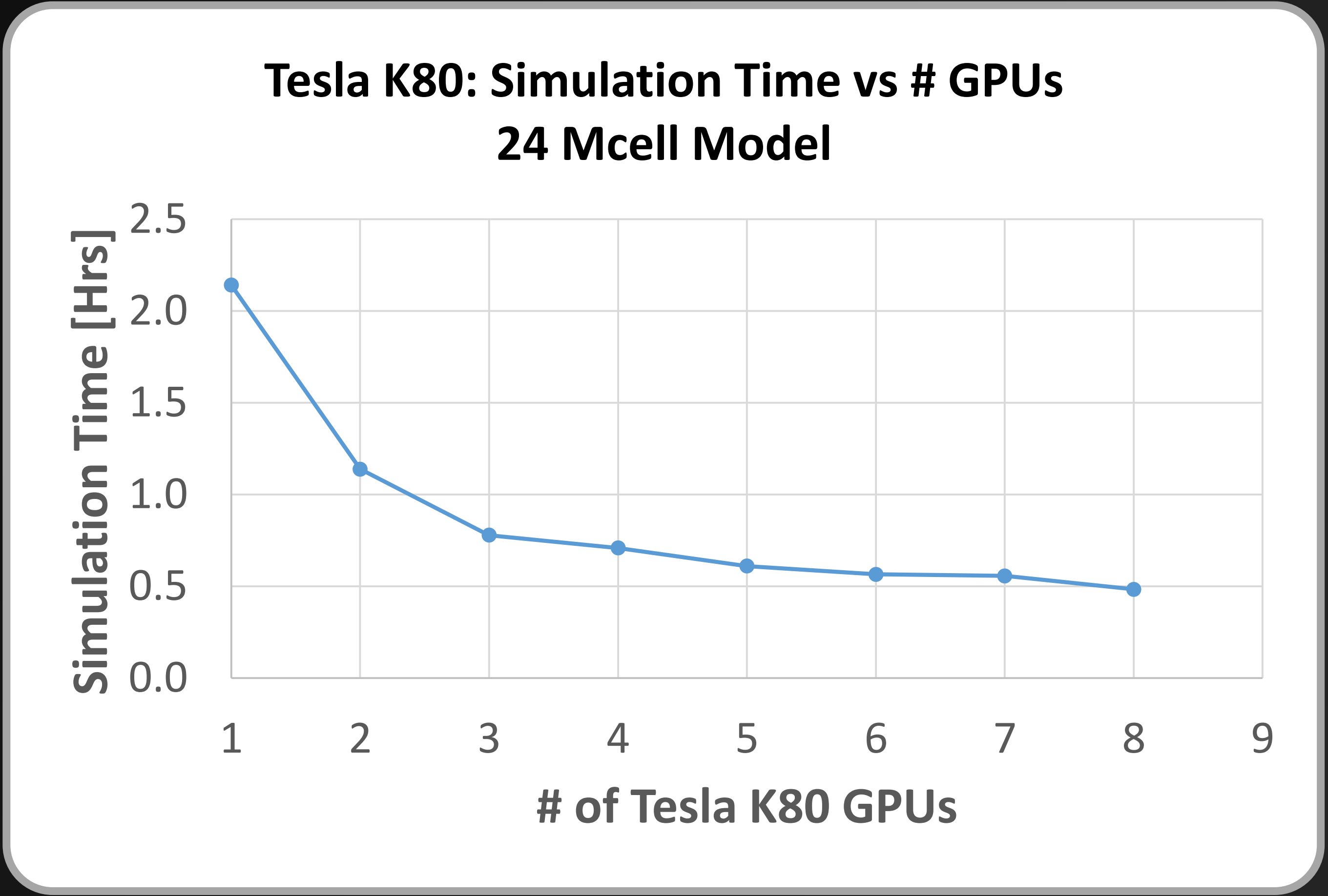
2x Titan Black (Sherlock)	2.57	20.6 (0.9)	82.4 (3.4)	216.3 (9.01)
2x 1080 Ti	1.725	13.8 (0.6)	55.2 (2.3)	144.9 (6.04)

Sherlock Computing Cluster

- For 16 chans in 30 min:
  Need ***128*** GPUs

- For 32 chans in 30 min:
  Need ***256*** GPUs

- For 64 chans in 30 min:
  Need ***512*** GPUs



Stanford XStream GPU Cluster

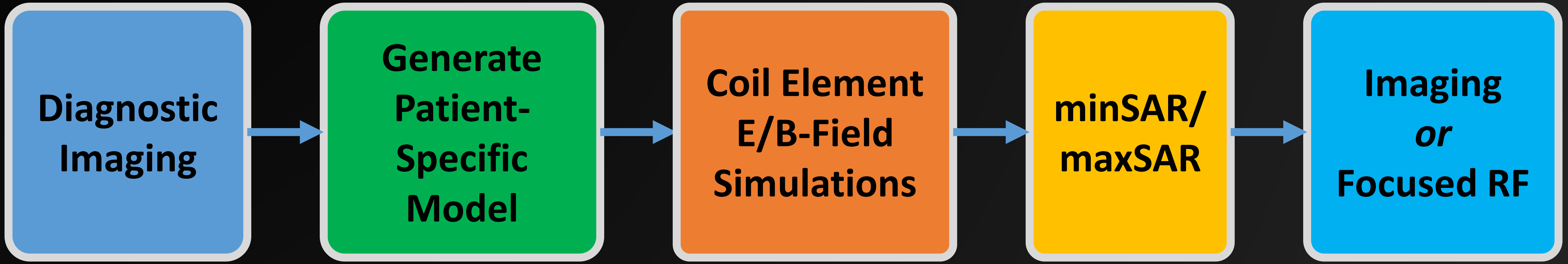
65 compute nodes *EACH* with:

- 8x K80's (16 GPUs) w. 24 GB RAM
- 2x Xeon E5-2680 v2, 10 Cores @ 2.8 GHz
- 256 GB DDR3 RAM
- 520 NVIDIA Tesla K80 cards (2xGPU ea)

Total GPUs: 1040

- Experience gained w. Sherlock will generalize to XStream
    - Uses same OS and SLURM job manager
- Ranked #87 in June 2015 Top500 and #5 in the Nov. 2015 Green 500 supercomputer list

Anticipated Workflow



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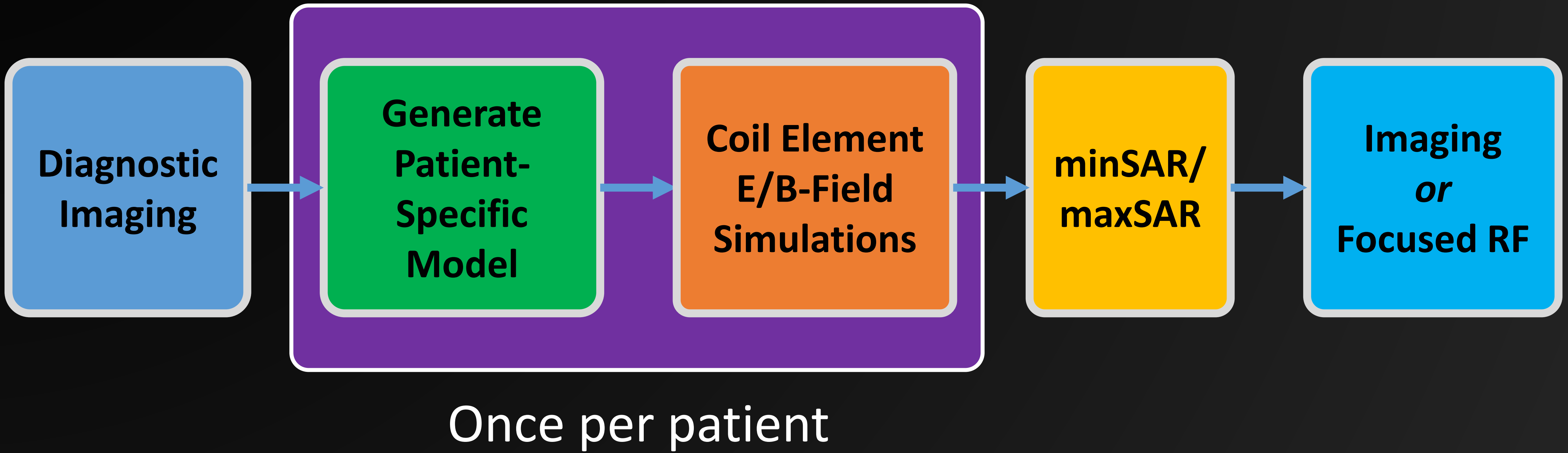

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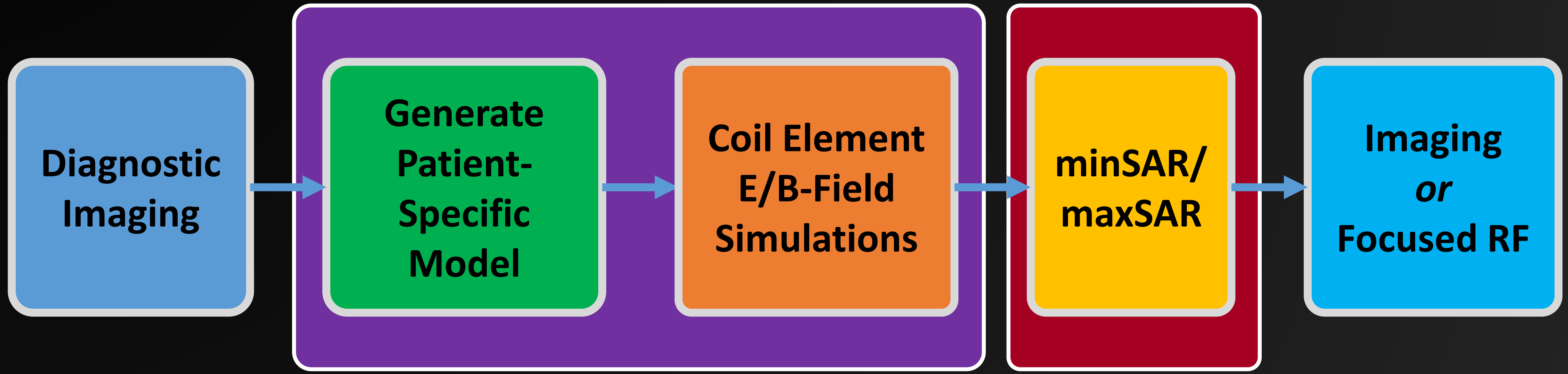
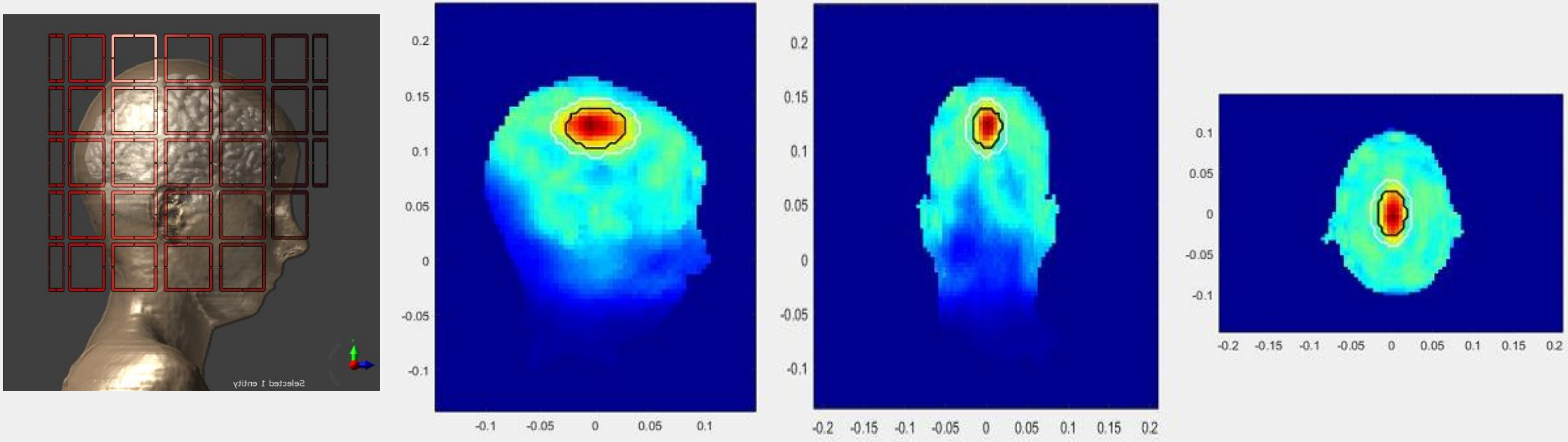


Once per patient

Once per:
imaging protocol
or
focal spot

Preliminary Results: 64 Chan Coil



UHF Focused RF Potential

- Turn MRI into an “Theranostic” All-in-One modality
  - High quality anatomical imaging
  - Therapy + Temperature monitoring

- Hyperthermia (probably not ablation)
  - Treat brain metastases
  - Targeted drug delivery via nanoconstructs and temperature sensitive liposomes
  - BBB modulation can improve treatment of NDDs

Future Work

- ***FUNDED! -*** 4 year Marie Curie MINDED fellowship in collaboration with Italian Institute of Technology

- Simulation studies:
  - Investigate effects of coil design, frequency, etc on heating ability

- Experimentally verify simulations in tissue mimicking phantom

- Demonstrate clinical viability of maxSAR:
  - User interfaces for implementation at scanner
  - Seamless integration with Large-Scale GPU resources

Acknowledgements

- **Stanford SCIT (NCI)**
  - Prof. Brian Rutt
  - Prof. Sam Gambhir
  - Dr. Riccardo Stara
  - Mihir Pendse

SPEAG sim4life

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MINDED

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Stanford Research Computing Center

Sherlock Computing Cluster

THANK YOU!