Assessing Magnetic Particle Content in Algae Using Compact Time Domain Nuclear Magnetic Resonance

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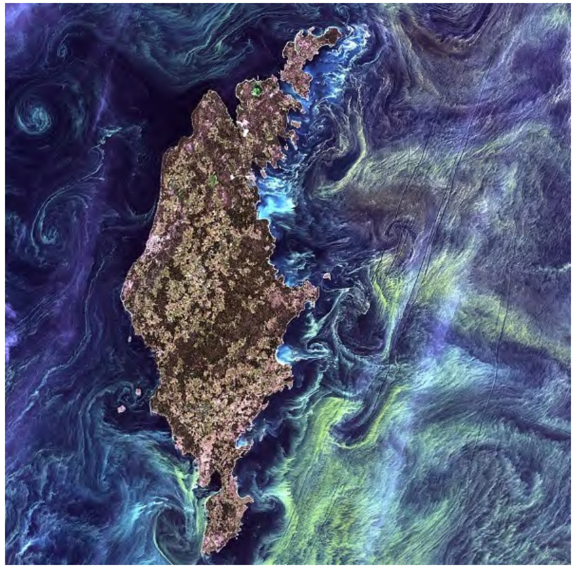


Satellite image of phytoplankton swirling around the Swedish island of Gotland in the Baltic Sea, in 2005

NASA Goddard Space Flight Center
Credit: USGS/NASA/Landsat 7 - Flickr: Van Gogh from Space

UNIVERSITY OF SOUTH CAROLINA

Harmful algal blooms in Harford County, Md
Chesapeake Bay Program

Algae blooms

- Algae plays an important role in ecosystem wellness
  - Form the base of aquatic food webs
- Algae overgrowth, however, can be detrimental to an ecosystem
  - Introduce toxins that affect the availability of safe drinking water
  - Block sunlight needed for aquatic organisms
  - Contribute to the depletion of a habitat's oxygen levels

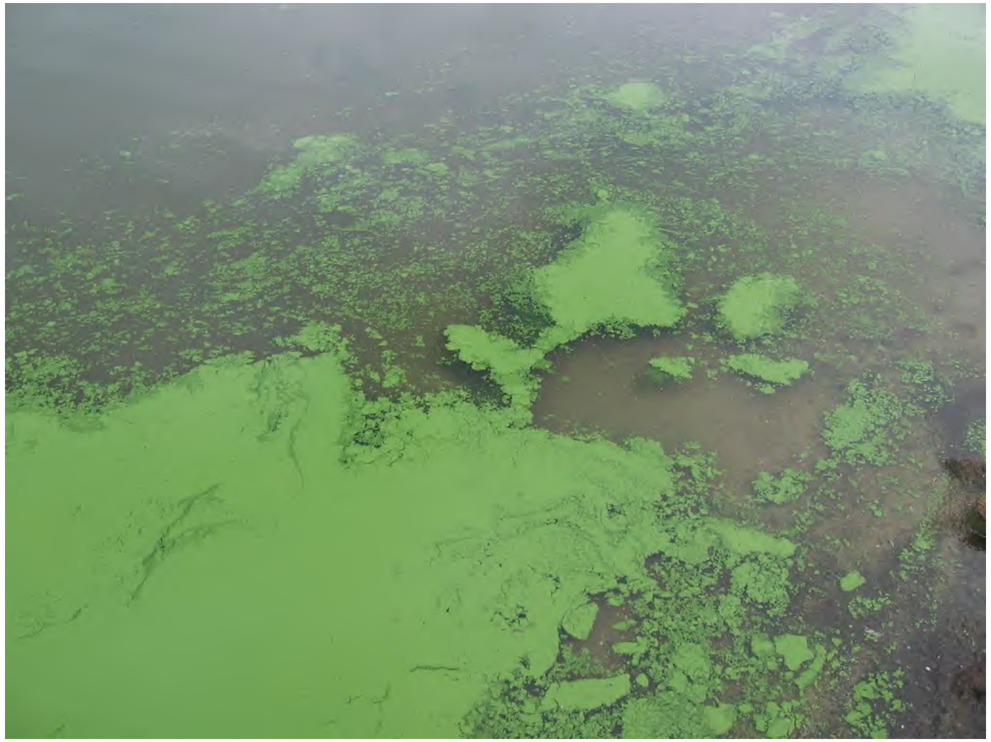


Photo Credit: Dr. Jennifer L. Graham | U.S. Geological Survey

Why assess magnetic particle (MP) content in algae?

- Iron uptake mechanisms of algae have been the subject of much research
  - Especially pertinent in commercial applications requiring the growth of microalgae
- A quick & reliable method for monitoring MP concentrations in algae has an abundance of applications
  - Water quality monitoring
  - Conservation initiatives
  - Iron harvesting

Iron-oxidizing bacteria in surface water

NH Estuaries Project - taken by New Hampshire Estuaries Project (www.nhep.unh.edu)

Goals (now and future)

1. Quickly assess the MP content of algae & surrounding water
2. Monitor the magnetic iron uptake of algae blooms/mats
3. Develop a system for in situ MP estimations

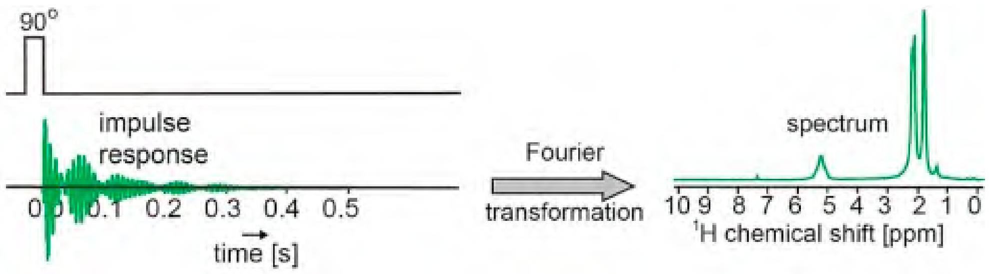
Approach: Time domain nuclear magnetic resonance (TD-NMR) to monitor iron uptake in Lyngbya Wollei (recently renamed Microseira wollei)

Filamentous cyanobacterium of a genus Lyngbya, as collected in Baja California

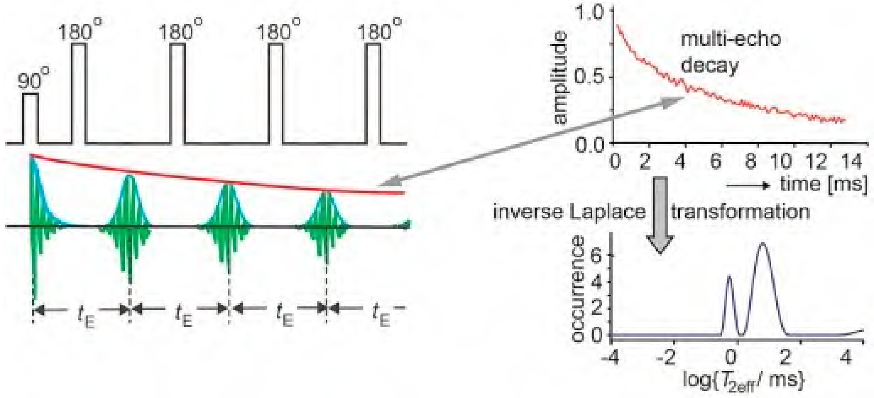
NASA - http://microbes.arc.nasa.gov/images/content/gallery/lightms/publication/lyngbya.jpg

Nuclear magnetic resonance (NMR) techniques

- High-field NMR spectroscopy
  - Frequency domain analysis
  - High resolution
  - Expensive & bulky
- Low-field NMR relaxometry
  - Time domain analysis
  - Low resolution
  - Inexpensive and portable



B. Blümich, "Introduction to compact NMR: A review of methods," TrAC Trends in Analytical Chemistry, vol. 83, pp. 2–11, Oct. 2016.



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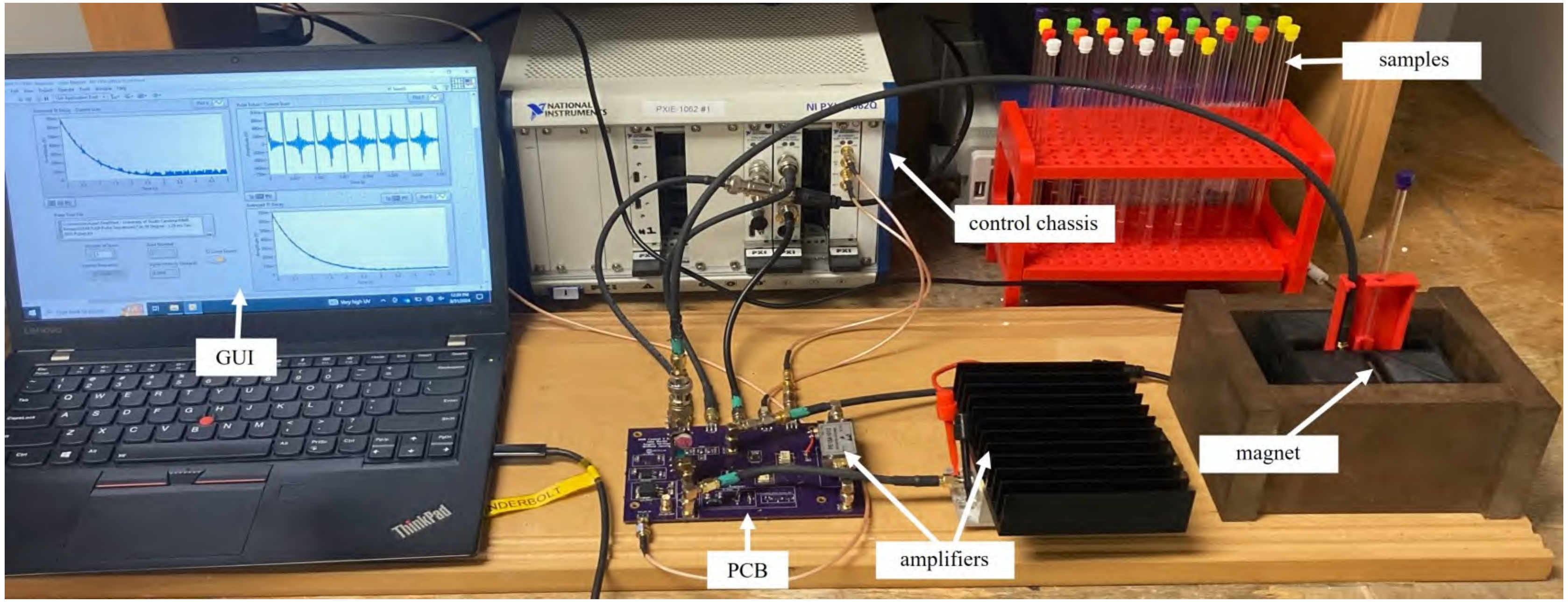
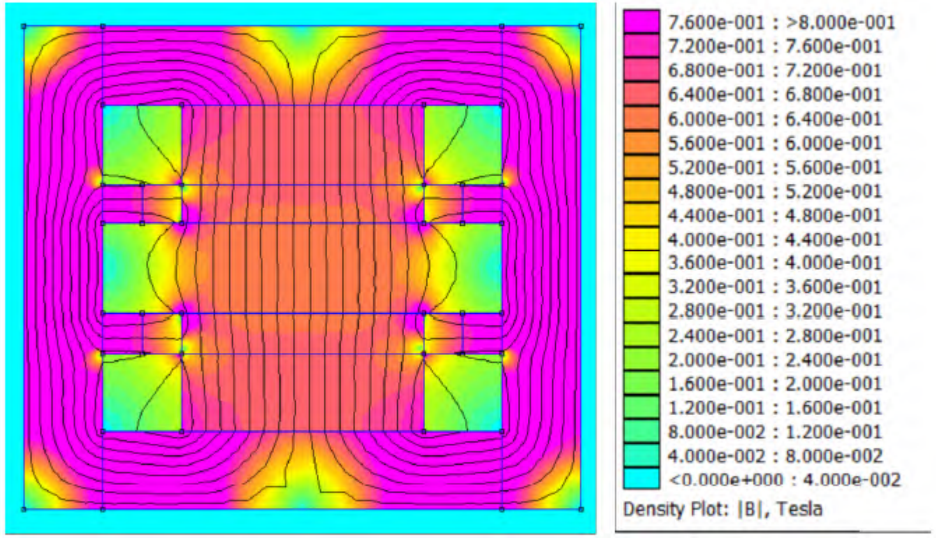
ARTS-Lab desktop NMR system

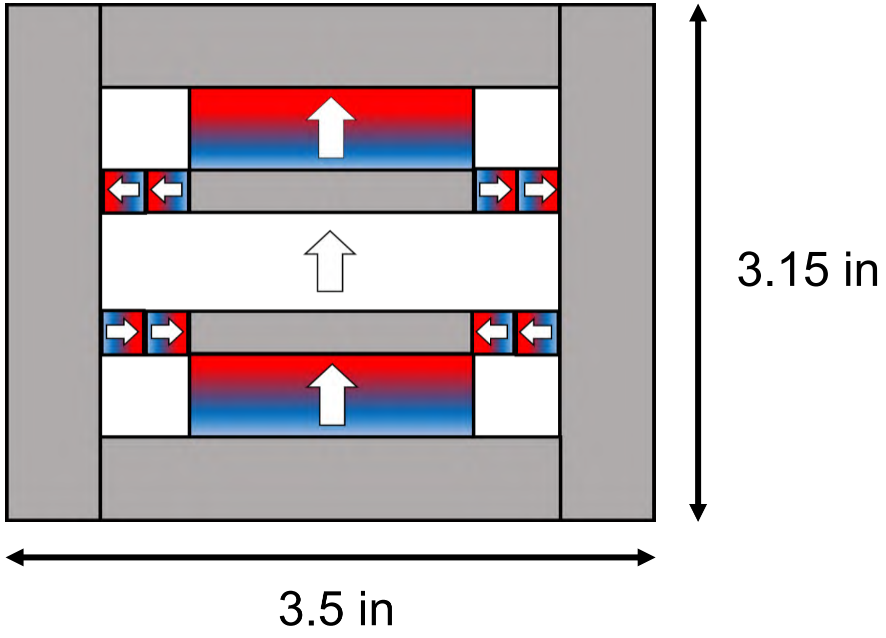
- Control handled by LabVIEW program and NI-PXI chassis
- All electronics (barring two amplifiers) housed on a single PCB
- GUI developed for easy data acquisition and export



Permanent magnet array

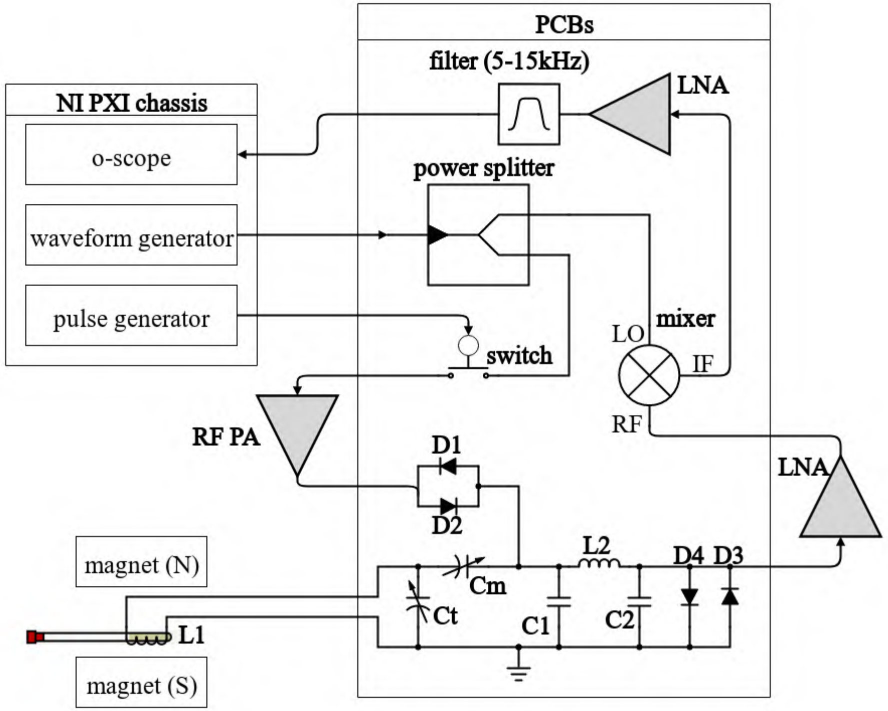
- N42 cylindrical dipole magnets enclosed by a steel yolk
- 1018 carbon steel caps affixed to magnet surfaces
- Peak flux density of 0.645 T → Larmor frequency of 27.5 MHz
- Temperature shift gradient of -800 ppm/K





RF electronics

- A single 24 V DC power supply required
- Impedance of all cables and PCB traces matched to 50 Ω
- Waveform generator → sine wave at Larmor frequency
- Pulse generator → CPMG pulse train
- Duplexer (crossed diodes) isolates probe and LNA

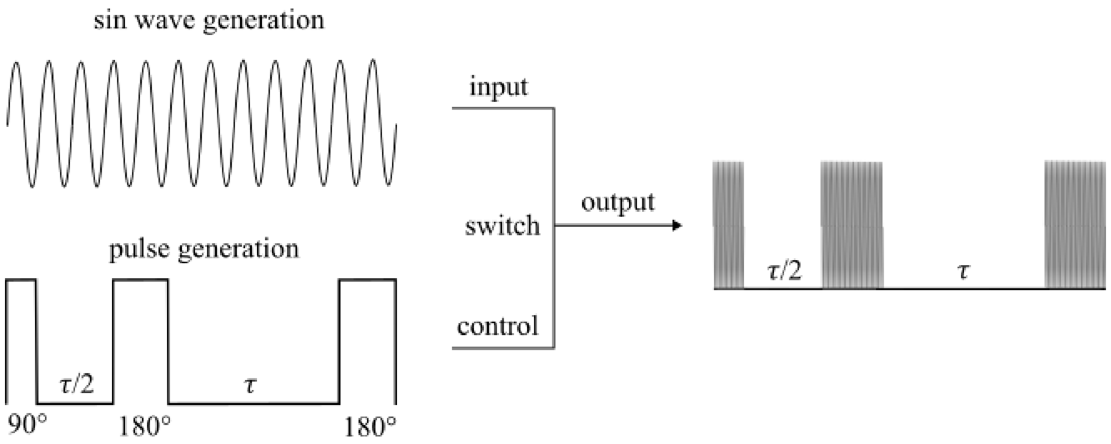


General flow

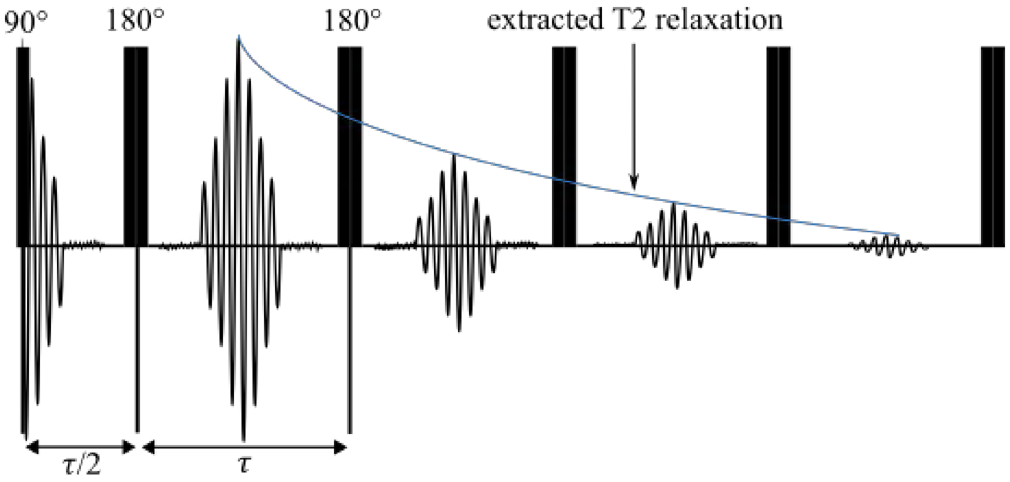
excitation → NMR response → amplification → mixing → filtering

Signal generation and control

- NI PXI chassis
  - Arbitrary waveform generator
  - Pulse train generator
  - 16-bit digitizer

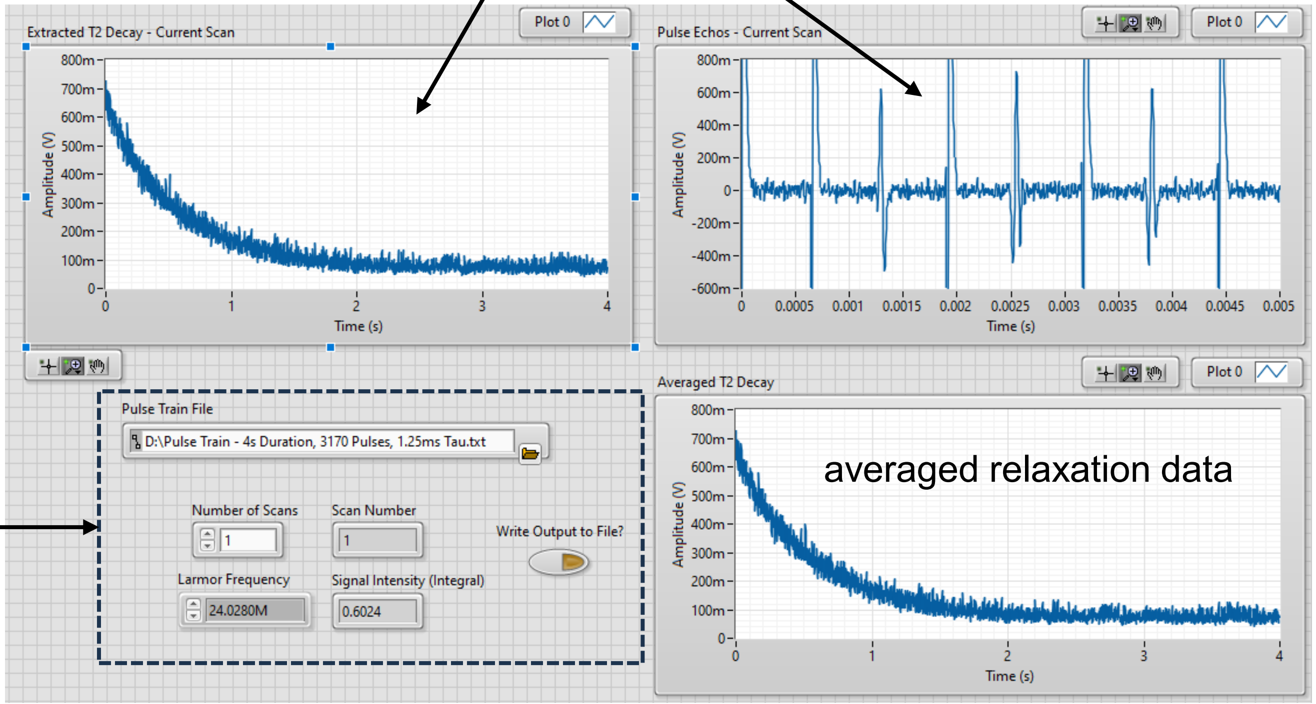


- CPMG pulse train
  - 3955 total pulses
  - 90° pulse duration is 6 μs
  - $\tau = 0.625$ ms



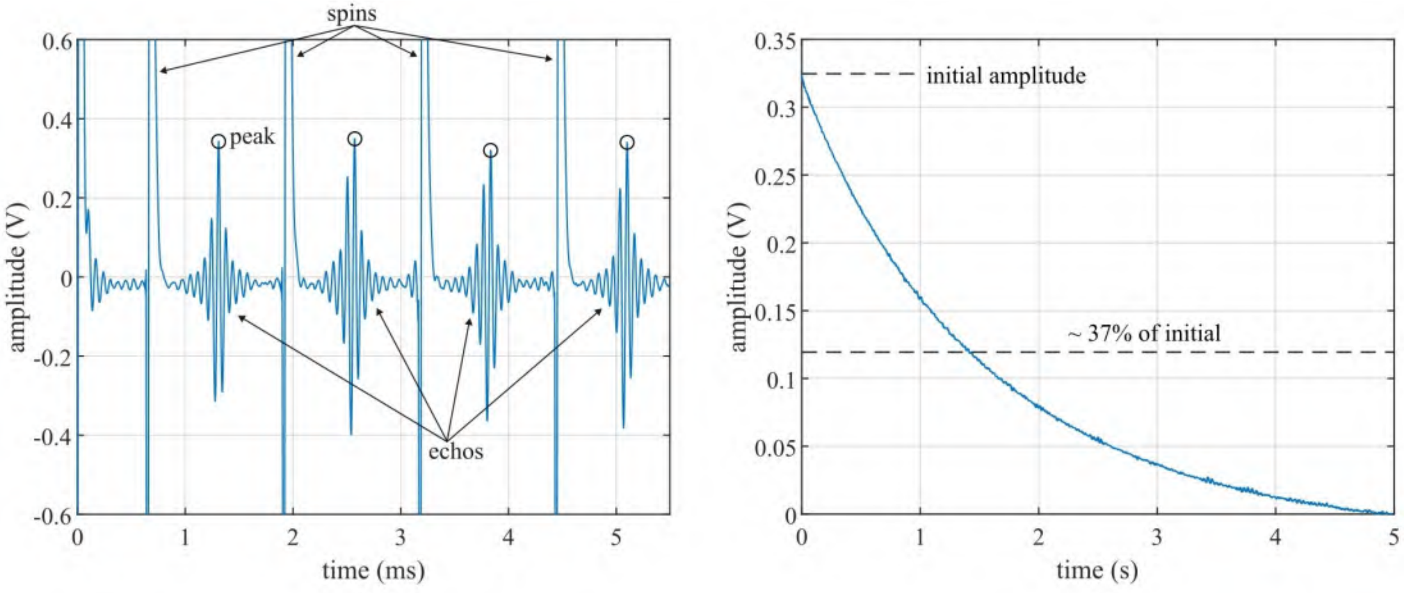
Data acquisition

- LabVIEW GUI serves as front end
- Each test comprises 5 scans (averages)
- Time for T_2 curve acquisition < 1 min
- Thermocouple used for frequency calibration



TD-NMR signals and MP content

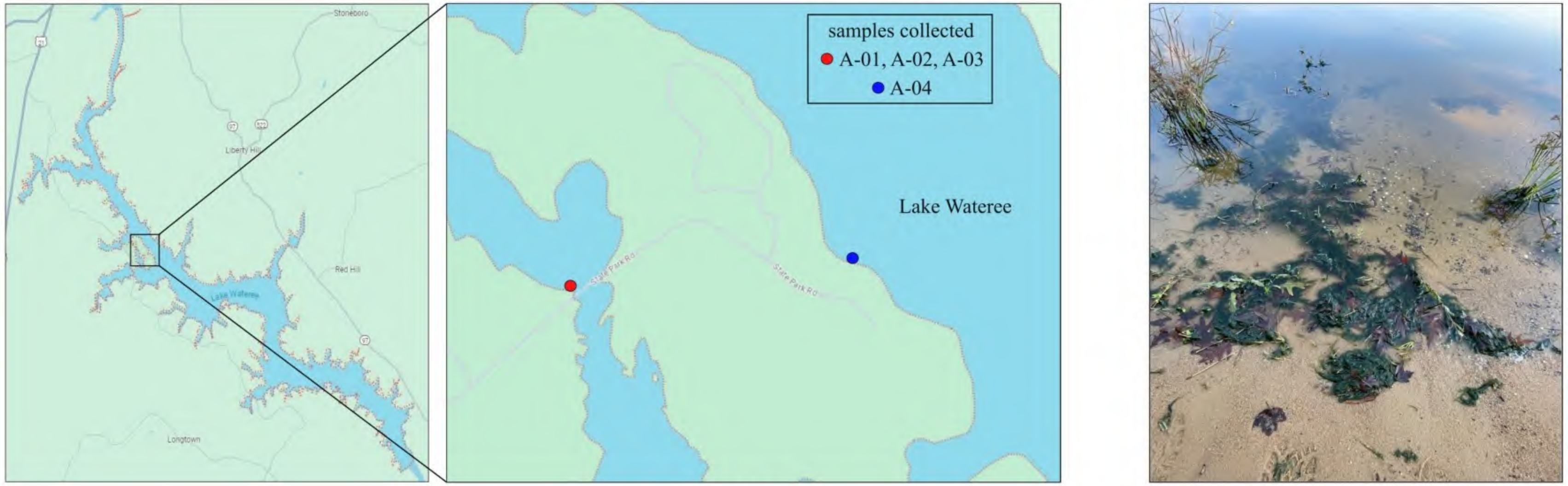
- T_2 relaxation modeled as $M_{\mathrm{xy}}(t) = M_0 \exp(-t/T_2)$
- Relaxation rate is the reciprocal of relaxation time (i.e., $R_2 = 1/T_2$)
- Linear relationship between R_2 and MP concentration well established



(a) (b)

Sample collection

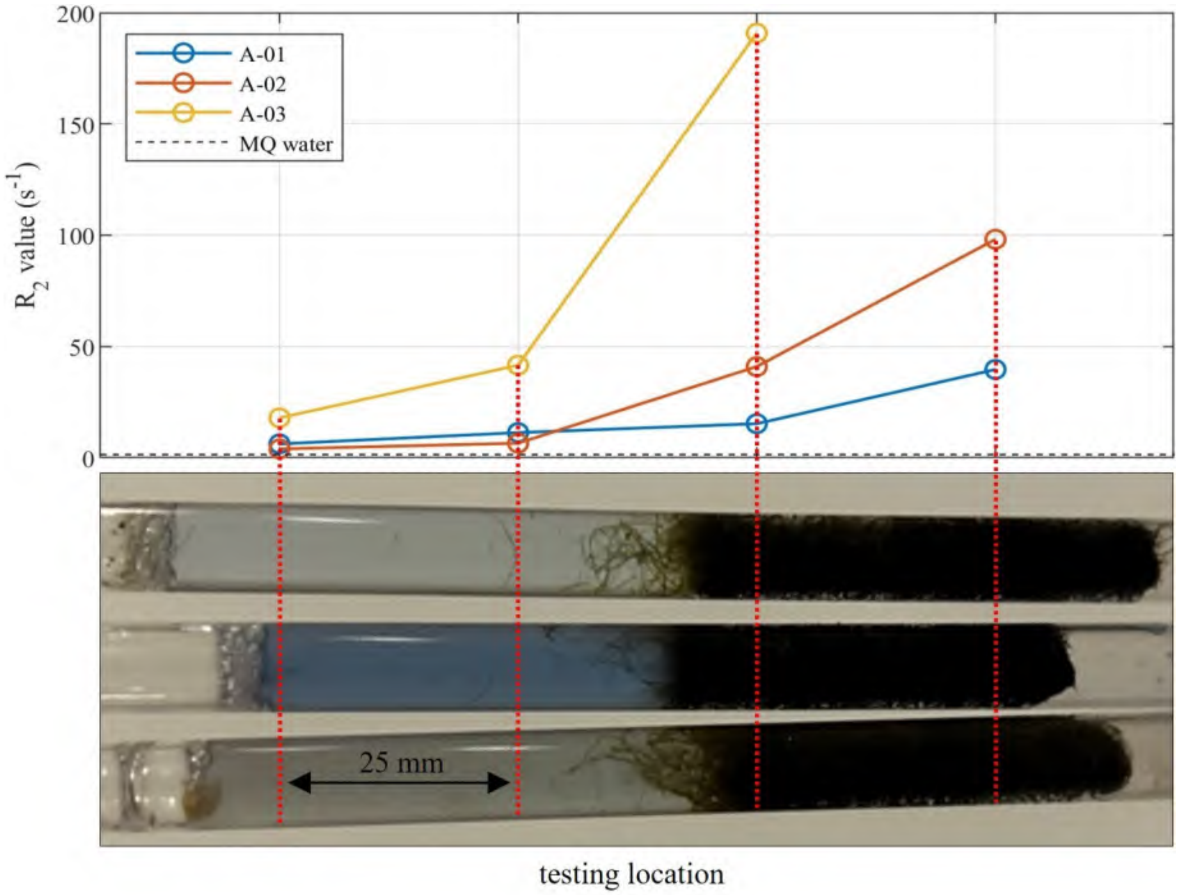
- Four algae samples were sourced from Lake Wateree (South Carolina)
- Samples collected on different dates
- Three samples (A-01, A-02, A-03) frozen with liquid nitrogen and submerged in MQ water
- Fourth sample (A-04) mixed directly with MQ water and sonicated



(a) (b)

Relaxation rates

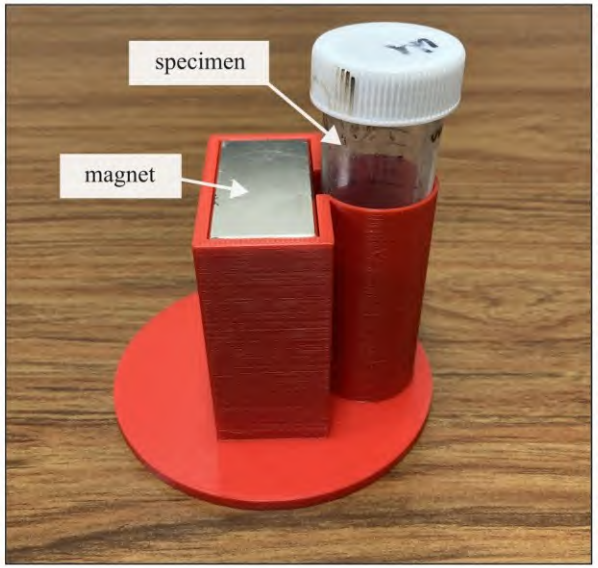
- Various locations along NMR tubes housing algae samples were tested
- Large relaxation rates observed (comparable to those of magnetite samples)
- Decay rates maximized in algae-dense regions



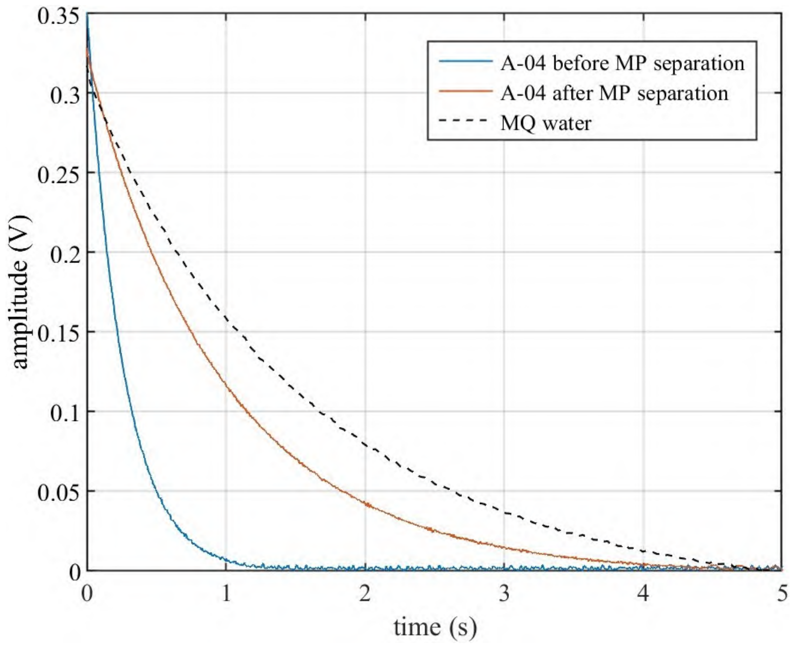
MP separation

- Fourth algae sample tested before & after undergoing MP separation
- MP separator comprises N52 permanent magnet and 3D printed housing
- Large decrease in decay rate observed following MP separation

(a)

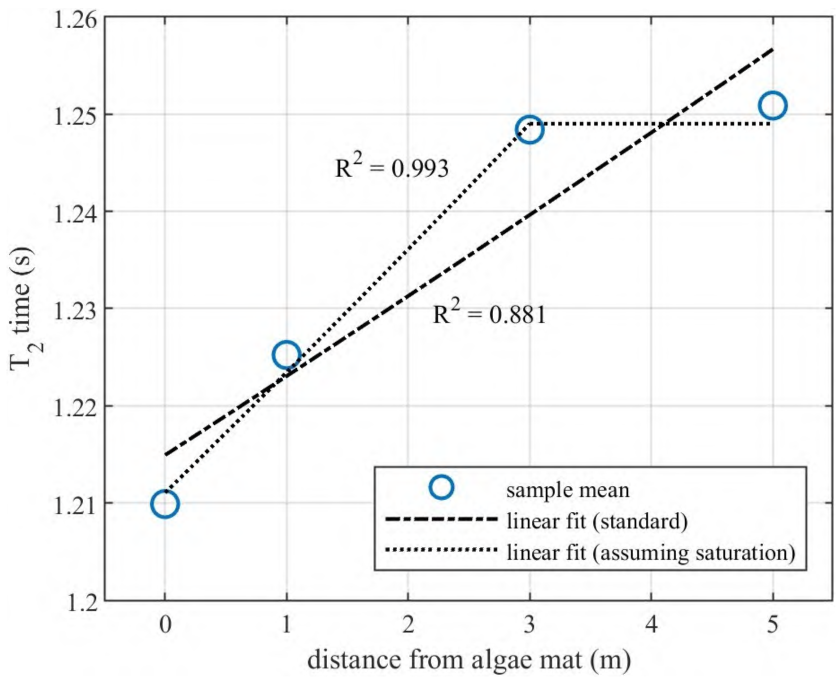


(b)



Preliminary water data

- Four water samples (algae free) gathered at increasing distances from an algae mat
- Samples tested 5 times with each test comprising 5 individual scans
- T_2 time increases with distance from the algae mat



Algae and MPs

- Compact NMR shows promise for MP-based estimations concerning algae
- Clear relationship between R_2 and MPs observed
- Proposed scheme can rapidly assess the relative MP concentration of samples

Future work

- Flow-through system for accelerated probing
- Electromagnet for MP separation
- Deployable NMR for in situ water quality monitoring

Compact-NMR

University of South Carolina

ARTS-Lab
Adaptive Real-Time Systems Laboratory

THANKS!

National Science Foundation

Compact-NMR (cNMR)

Our design is open source and available on GitHub!

https://github.com/ARTS-Laboratory/Compact-NMR

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