A Novel "Smart Microchip Proppants" Technology for Precision Diagnostics of Hydraulic Fracture Networks

Project Number: DE-FE0031784

Amirmasoud Kalantari Dahaghi (PI)
Assistant Professor
The University of Kansas

U.S. Department of Energy
National Energy Technology Laboratory
2021 Carbon Management and Oil and Gas Research Project Review Meeting
August 2021

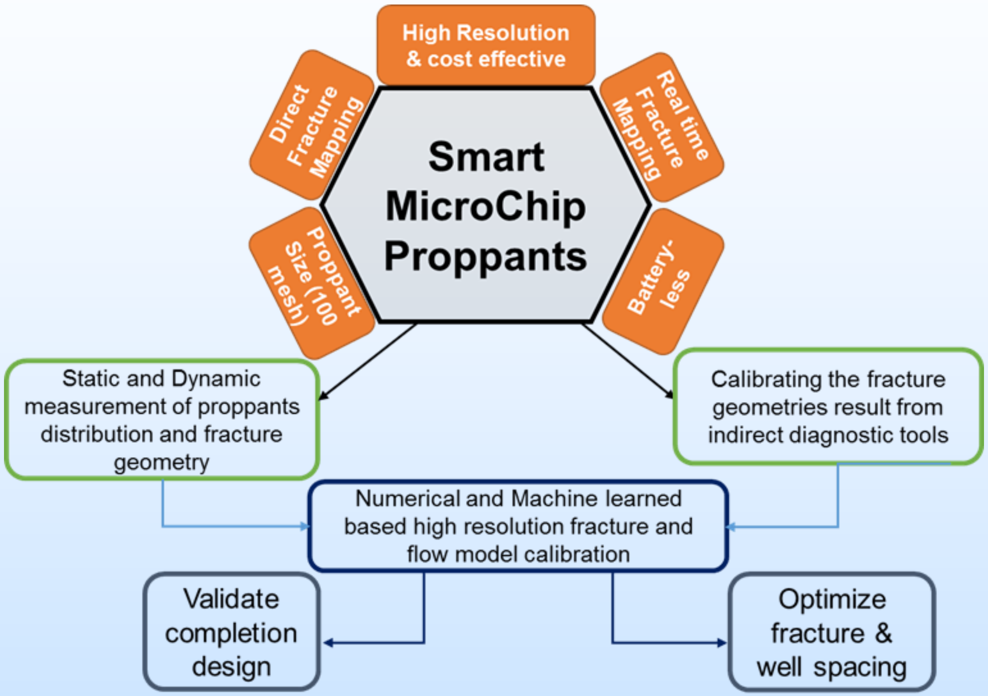
Presentation Outline

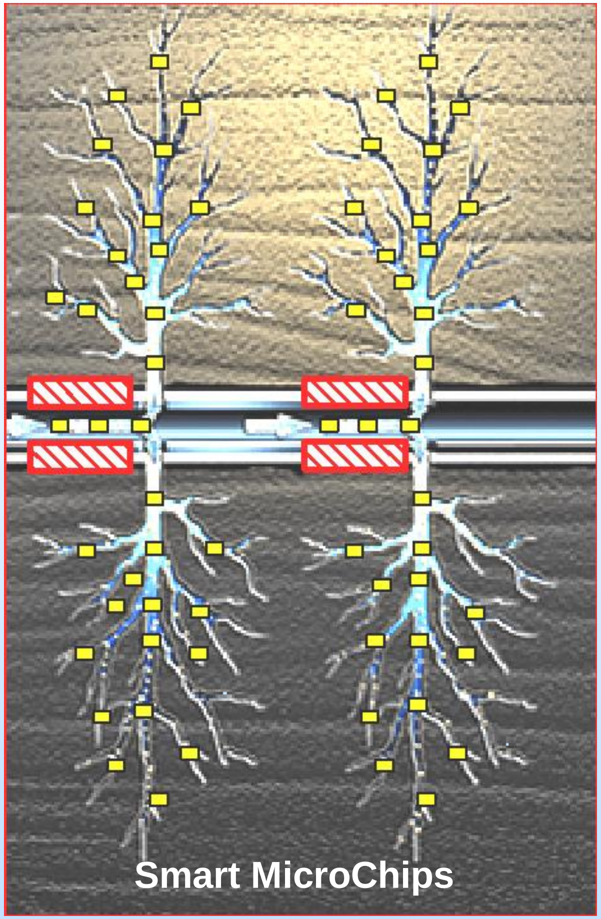
- Technology Background
- Benefit to the Program
- Technical Approach/Project Scope
- Accomplishments to Date
  - Pilot site selection and static data collection
  - Laboratory testing
  - Building Smart Microchip Sensors
  - Building downhole tool to power the chips
  - 3D printed core with complex fracture network
  - Novel iGeoSensing Fracture Diagnostic tool
- Plans for future testing/development/ commercialization
- Organization Chart
- Gantt Chart

Program Overview

- Funding
  - (DOE:$2.49M and Cost Share:$1M)
- Overall Project Performance Dates:
  - October 2019-September 2023
- Project Participants
  - University of Kansas(Lead institution), UCLA, MicroSilicon Inc., NSI Fracturing Inc., Confractus Inc, NITEC Inc and EOG Resources
- Overall Project Objectives
  - to develop and field test fine size and wirelessly powered smart MicroChip Proppants
  - to develop a closed-loop fracture diagnostic and modeling workflow using the collected data from Smart MicroChip Sensor to better characterize propped fracture geometry.

Technology Background





Pilot Location:
Permian Basin, Yeso Field, Paddock Reservoir, NM
Cored interval 2594-2600 (6ft)

Technology Background

- The proposed technology responds to the current limited understanding of the near wellbore fracture properties.
- Smart MicroChip proppants map the geometry of a fracture network with a resolution of less than 1 ft.
- A downhole tool will be built to inject electromagnetic energy through the perforations.
- The sensor harvests energy from these electromagnetic waves activates an on-chip radio to communicate back with the down-hole tool.
- MicroChips change the frequency of the received signal and respond back in a different band.

Technology Background

- Frequency-shift technology enables the down-hole tool to separate the strong reflection caused by the reservoir from the signals generated by the MicroChips.
- Future down-hole tools may communicate with the MicroChips in the frequency range from 3MHz to 100MHz depending on the resistivity of the reservoir with frequencies above 50MHz providing enhanced resolution (in >1000 Ωm formations)
- For initial development, EOG has chosen a series of modestly-high resistivity formation where ~40MHz should give good results without need of geolocation.
- In some future scenarios, separate transmitters can be envisaged to create a background magnetic field that will act as a beacon for the Microchips to geolocate.

Benefit to the Program

Technology Impact:

- Reduces unconventional resources development cost by optimizing well spacing while minimizing the development related environmental footprint.
- Maintain the US leadership in unconventional energy development

Vision

Metric	State of the Art	Proposed
Resolution	50 ft	<1ft
Data streaming	Only during the hydraulic fracturing (HF)	Real time, during , after the HF job and during the production
Manufacturing cost	$10-100 per proppant	Few cents

MEMS (micro electro mechanical systems)

Technical Approach/Project Scope

Experimental design and work plan

- experimental components:
  - ✓ build and calibrate novel Smart MicroChip Sensor in the lab environment
  - ✓ construct synthetic cores with different levels of fracture complexity for testing Microchips.
  - ✓ build a downhole logging tool to power the Smart MicroChip Sensor and assimilate their data
  - ✓ perform basic and comprehensive rock mechanical tests
  - ✓ conduct two fluid sensitivity testing-pH& Potassium Chloride (KCl) tests
  - ✓ determine the reduction of particle size due to mechanical attrition and reaction of shale particles with the reacting fluids
  - ✓ Field Laboratory testing

Technical Approach/Project Scope

Experimental design and work plan:

- computational components:
  - ✓ interpret and map the received data from the “Virtual” Smart MicroChip Sensor by developing a new stochastic algorithm to process discrete points
  - Converting the response of swarm of chips into discrete points
  - Real-time fracture mapping
  - proppant transport modeling
  - Flow back and production history matching by coupling numerical and machine-learned models.

Technical Approach/Project Scope

Project schedule –key milestones

Task/ Subtask	Milestone Title/ Description	Planned Completion Date	% of Completion
1.2	Project Kickoff Meeting Held	10/28/2019	100
4.1	Field Laboratory (Science Well) Site Selection and Static data collection	Q5	100
4.2	Field Laboratory –Dynamic Data collection	Q16	
5	Detailed Rock Mechanics testing, Un-propped Crack Test, Fluid Sensitivity Test, and Embedment Test	Q12	80
6.1 and 6.5	Build and calibrate novel Smart MicroChip Sensor	Q12	50
6.2	Constructing multiple synthetic fracture network models, building synthetic cores using 3D printing technology	Q7	95
6.3	Testing imaging capability of Smart MicroChip Sensor using the 3D printed cores	Q10	0
6.4	Test the Smart MicroChip Sensor in a high pressure and temperature lab environment.	Q12	0
6.6	Build a downhole logging tool to power the Smart MicroChip Sensor and assimilate their data.	Q13	50
6.7	Report the results of injecting the Smart MicroChip Sensor into the formation (small-scale frac job) and validate the survival of the chips.	Q16	0
6.8	Interpret and map the received data from the Smart MicroChip Sensor- iGeoSensing Fracture Diagnostic Software Package Development	Q16	50
7	Integration of near wellbore (Smart MicroChip Sensor) and the other diagnostic tools including Microseismic	Q16	0
8.1 and 8.2	Development of state-of-the-art predictive fracture and flow models	Q16	0
8.3	Develop new diagnostic plots and enhance analytical solutions/ type curves	Q16	0
9.0	Data submitted to NETL-EDX	Q16	

Progress and Current Status of Project

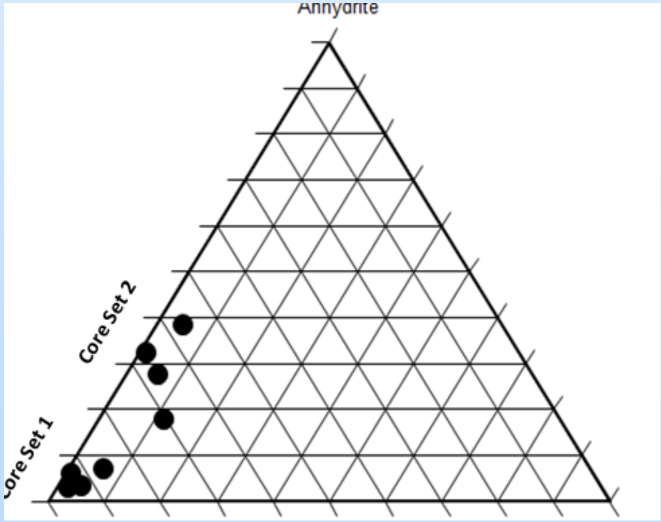
Field Laboratory (Science Well) Site Selection and Static data collection

- We worked with EOG resources to identify multiple locations for the field pilot testing.
  - ✓ Permian Basin, Yeso Field, Paddock Reservoir, NM is selected for field trial (Boyd State #15H Eddy County, New Mexico)
  - ✓ 6ft of core and logs were obtained from the pilot well (Boyd XState)

Progress and Current Status of Project

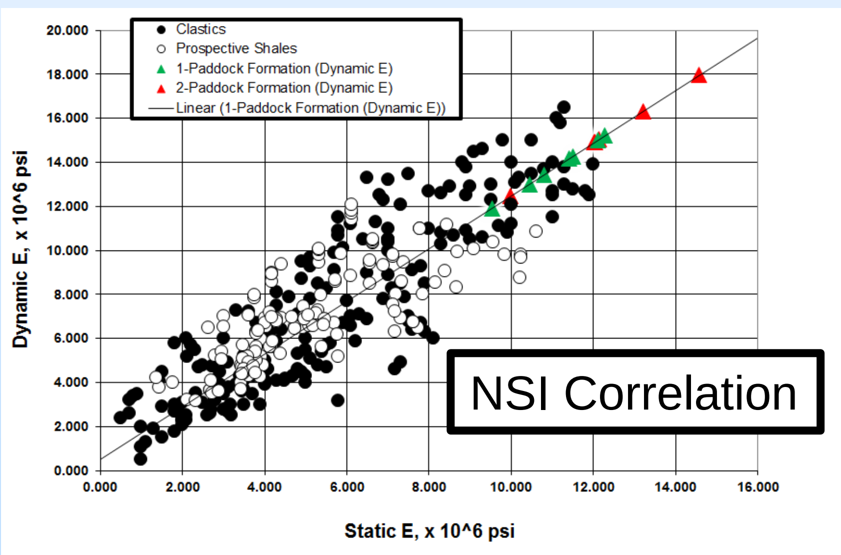
Geomechanical Evaluation, Un-propped Crack Test, Fluid Sensitivity Test, and Embedment Test

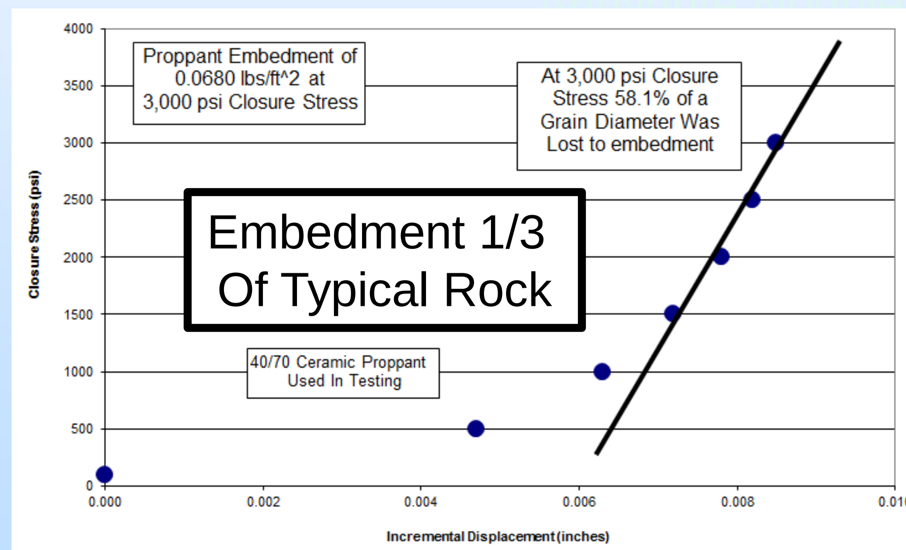
- **Core Analysis (Boyd State) Site Selection**
  - ✓ Permian Basin, Yeso Field, Paddock Reservoir, NM is selected for field trial
  - ✓ 6ft of core and logs were obtained from the pilot well (Boyd XState)
  - ✓ Shows Paddock Reservoir is A Dolomite W/ Anhydrite



Progress and Current Status of Project

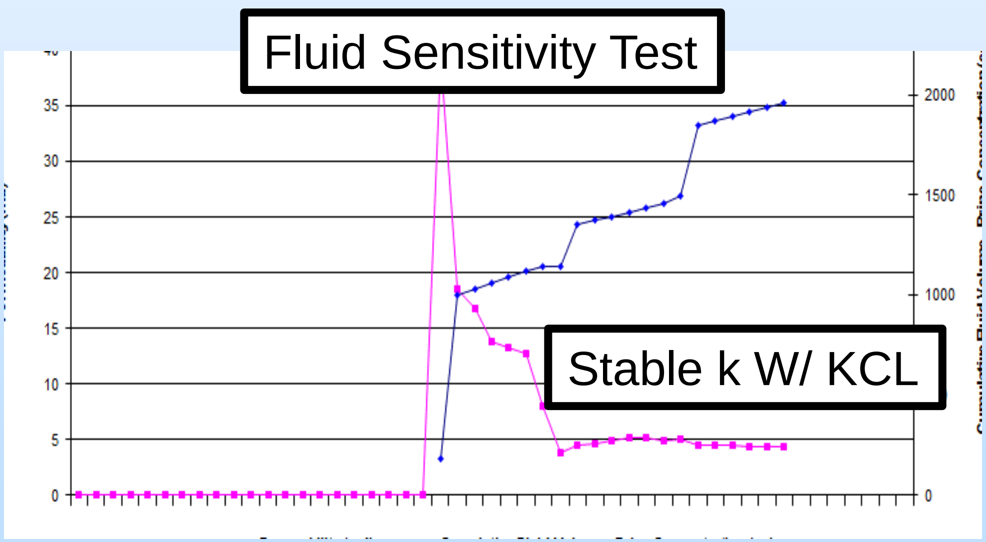
- **Core Analysis (Boyd State) Site Selection**
  - ✓ Conducted Ultrasonic Velocity Tests For Dynamic Young's Modulus
    - Used NSI Correlation To Estimate Static Young's Modulus
    - Average E_{static}= 11.7 x 10^6 psi (Ranged From 9.5-14.6 x 10^6 psi)
    - Little Shear Anisotropy (Averages 4.8 Percent)
    - Paddock Formation Very Brittle W/ Little Proppant Embedment

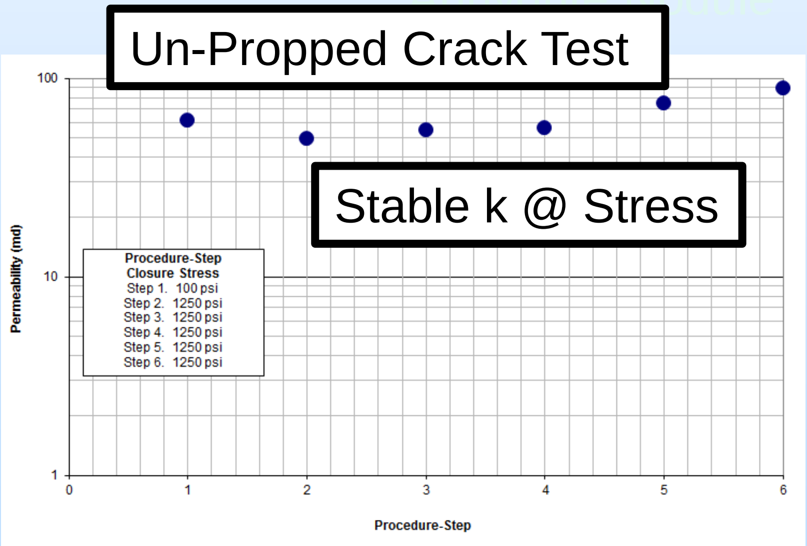




Progress and Current Status of Project

- **Core Analysis (Boyd State) Site Selection**
  - ✓ Conducted Fluid Sensitivity & Un-Propped Crack Tests
    - Little Fluid Sensitivity To KCL Concentration
    - Un-Propped Crack Maintains Conductivity
    - Paddock Formation Is Very Brittle
    - Good Water Frac Candidate Assuming Low Leak-Off





Progress and Current Status of Project

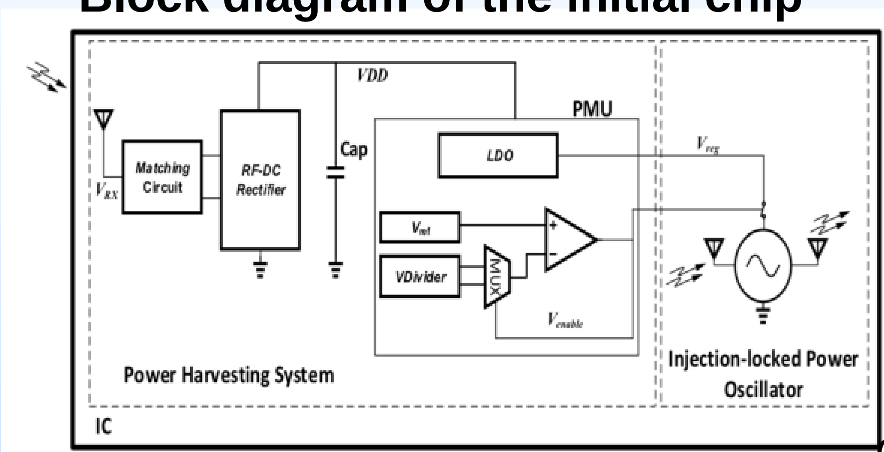
- **Build and calibrate novel Smart MicroChip Sensor**
  - ✓ demonstrated successful Coherent Radiation from a Swarm of Chips operating in GHz range
  - ✓ designed a 40MHz wirelessly powered tag to increase the depth of penetration
  - ✓ measured the electromagnetic properties of the EOG’s pilot well cores

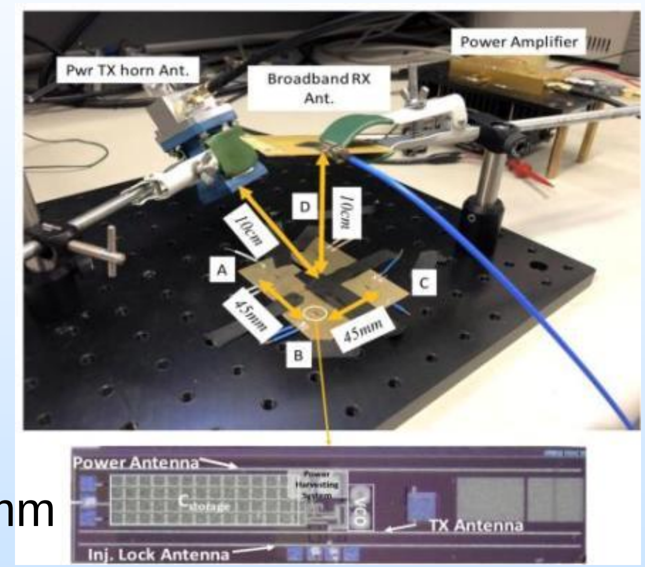
Progress and Current Status of Project

- **Build and calibrate novel Smart MicroChip Sensor**
  - ✓ **Coherent Radiation from a Swarm of Chips**

Benchtop Measurement

Block diagram of the initial chip





0.7mm

Chip Micrograph

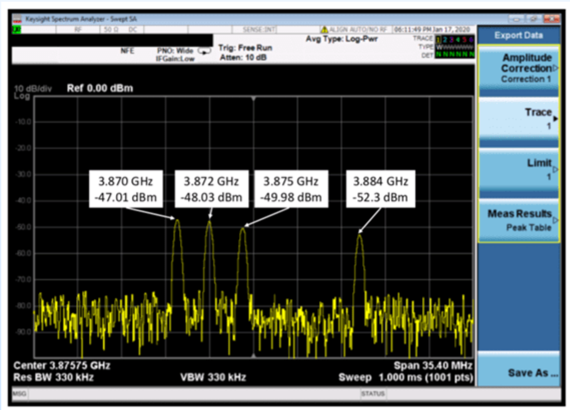
3.9mm

- A new technique is developed to <u>synchronize a swarm of sensor nodes at the RF domain</u> and produce coherent radiation from the sensor nodes to increase the amplitude of the reflected signal. That <u>data swarm is then converted into discrete chip positions.</u>
- A network is formed by an <u>array of microchips that are wirelessly powered</u>, and <u>upon activation, radiate back an RF signal</u>.

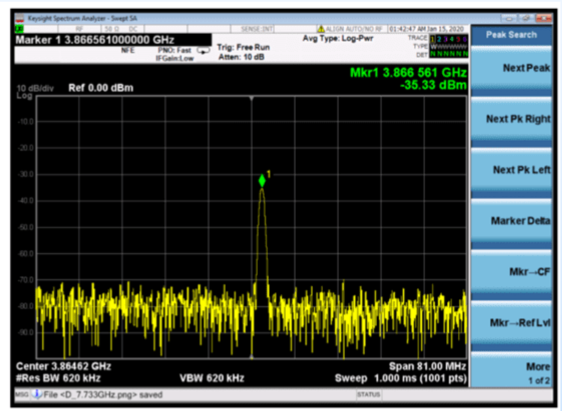
Progress and Current Status of Project

- **Build and calibrate novel Smart MicroChip Sensor**
  - ✓ **Experimental Results on Coherent Radiation**

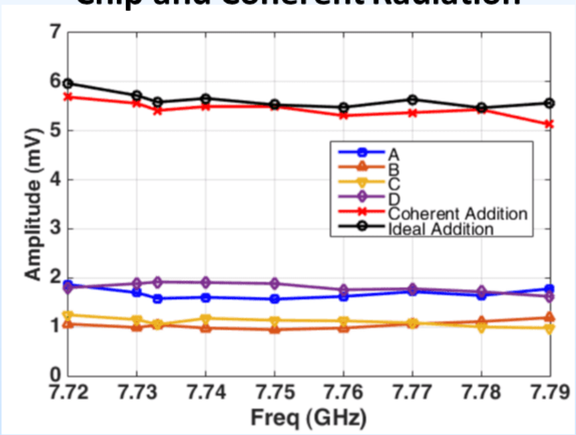
Four Chips Radiate Incoherently



Coherent Radiation Boosts the Signal Radiated by Microchips



Comparison between Individual Chip and Coherent Radiation



- When all chips are synchronized and radiated coherently, the signal radiated by the swarm of chips become strong. In theory, N chips increase the radiated signal by N^2.
- More details provided in this reference:

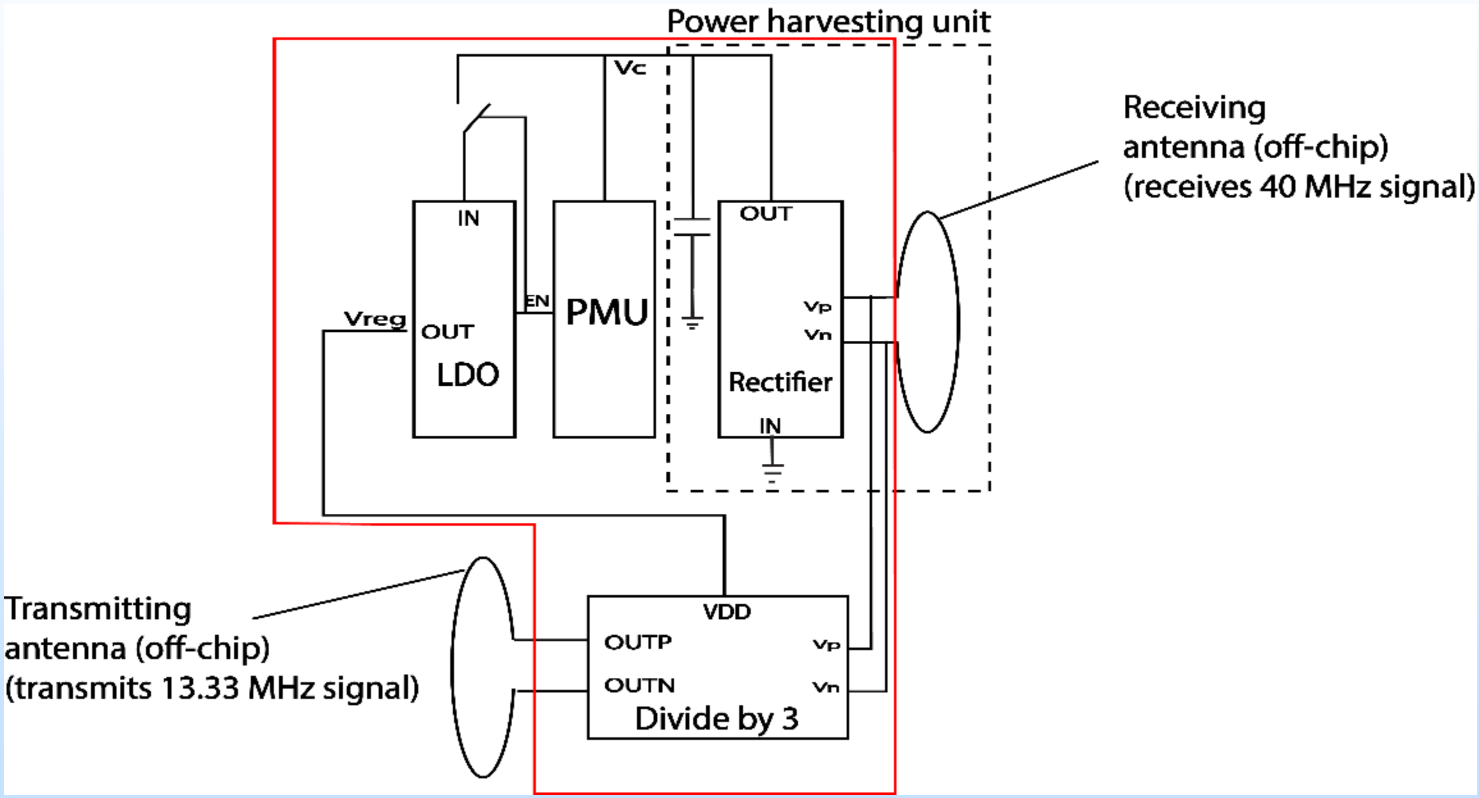
H. Rahmani, Y. Sun, M. Kherwa, S. Pal and A. Babakhani, "Coherent Radiation From a Swarm of Wirelessly Powered and Synchronized Sensor Nodes," in *IEEE Sensors Journal*, vol. 20, no. 19, pp. 11608-11616, 1 Oct.1, 2020, doi: 10.1109/JSEN.2020.2996571.

Progress and Current Status of Project

- **Build and calibrate novel Smart MicroChip Sensor**
  - ✓ **Status of 40MHz Wirelessly-Powered Chips**
    - o We are designing a new RFID chip that harvests energy around 40MHz and radiate back at 13MHz.
    - o This unique frequency separations allows the downhole tool to send a large power at 40MHz while listening to a weak signal radiated from the chips at 13MHz.
    - o The design of this chip is finalized and being sent for fabrication.
    - o We already tested RFID chips that successfully harvest energy at 40MHz but they don’t yet have a 13MHz transmitter to radiate back. The 13MHz transmitter will be included in the next version of the chip.
    - o Picture of a proof-of-concept RFID operating at 40MHz is shown below. The current dimensions of the PCB is 3mm by 17mm. We are reducing the dimensions to around 3mm x 3mm.

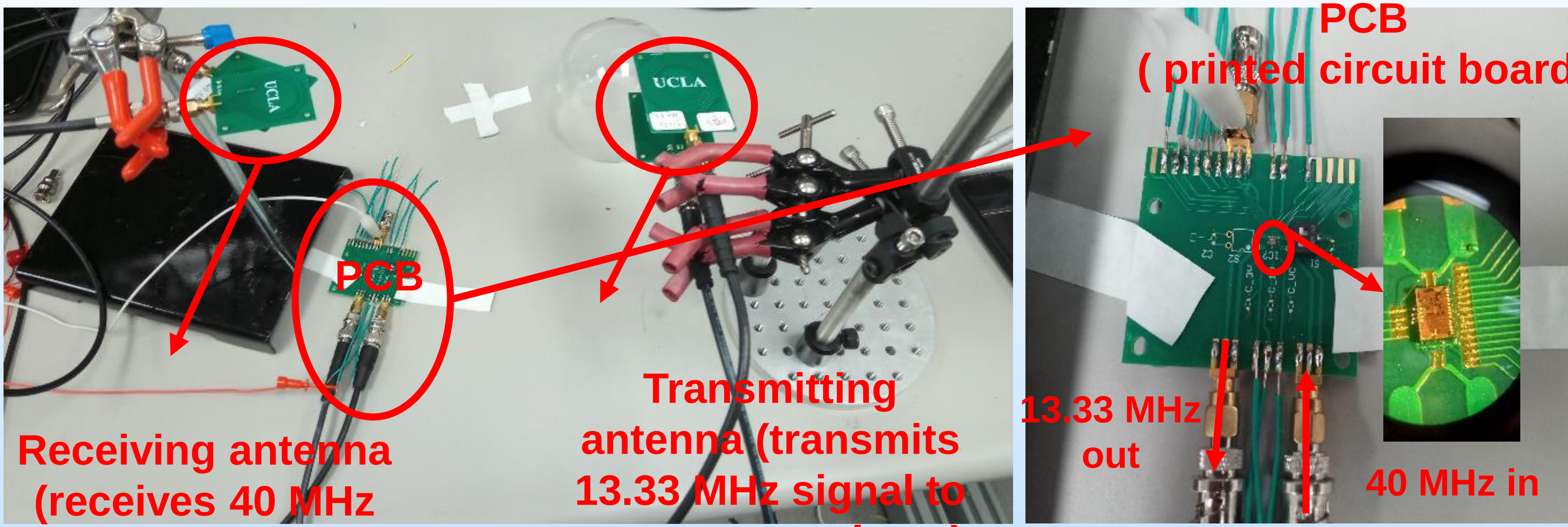
Progress and Current Status of Project

Block diagram of chip for localization



Progress and Current Status of Project

Measurement setup



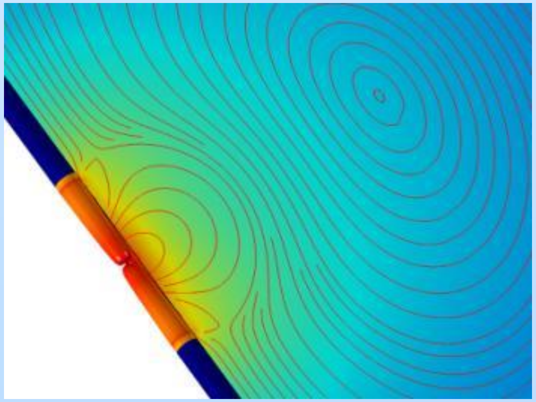
Progress and Current Status of Project

Procedure for localization

- The 40 MHz RF signal from the arbitrary waveform generator is wirelessly sensed by the chip using the receiving antenna
- Using the rectifier, PMU and LDO, a DC voltage (nominally 1.1 V) is generated from the RF signal for wirelessly powering the chip
- The divide-by-3 circuit generates a phase-coherent 13.33 MHz signal
- The 13.33 MHz signal is radiated wirelessly using the transmitting antenna and the received power is measured by the spectrum analyzer

Progress and Current Status of Project

- **Build a downhole logging tool to power the Smart MicroChip Sensor**
  - Specifications of the downhole tool have been completed. It will use a “horn” shaped antenna that approximates a resonant dipole and has optimized mechanical configuration for borehole geometry.
  - All deployed chips will be charged at the same frequency (~40MHz) and they will all respond at the same frequency (~13MHz).
  - A mockup of the antenna has been constructed for lab use
  - We tested the chips with a downhole tool and and confirmed that it can activate the chips with an antenna.

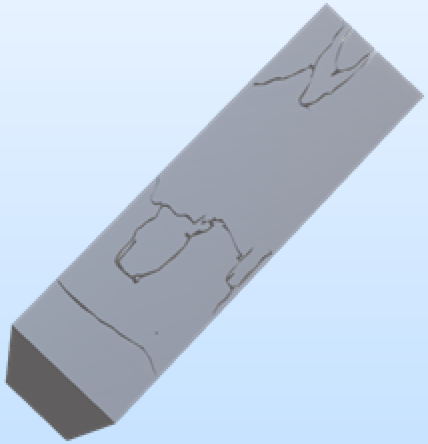
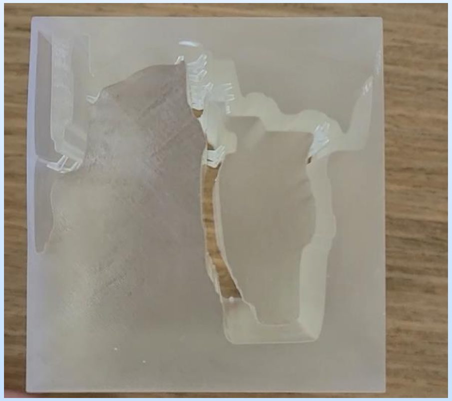


Progress and Current Status of Project

- **Build a downhole logging tool to power the Smart MicroChip Sensor**

Progress and Current Status of Project

- **3D Printing of Synthetic Cores with Complex Fracture Geometry for Testing of Smart Microchips in the Lab**


Progress and Current Status of Project

Interpret and map the received data from the Smart MicroChip Sensor. iGeoSensing Fracture Diagnostic Software Package Development

- developed initial architecture of the i-Geo Sensing Fracture Diagnostic and Interpretation for the geo-sensor data from the “Virtual” SMPs
- challenges in developing i-GSFD from highly- complexed fracture networks are addressed and being resolved.

Progress and Current Status of Project

iGeoSensing Fracture Diagnostic Software Package:

- **Interpret and map the received data from the Smart MicroChip Sensor**

✓ Input data to i-GSFD: Number of transmissible SMPs (N) and their coordinate data (x, y, z)

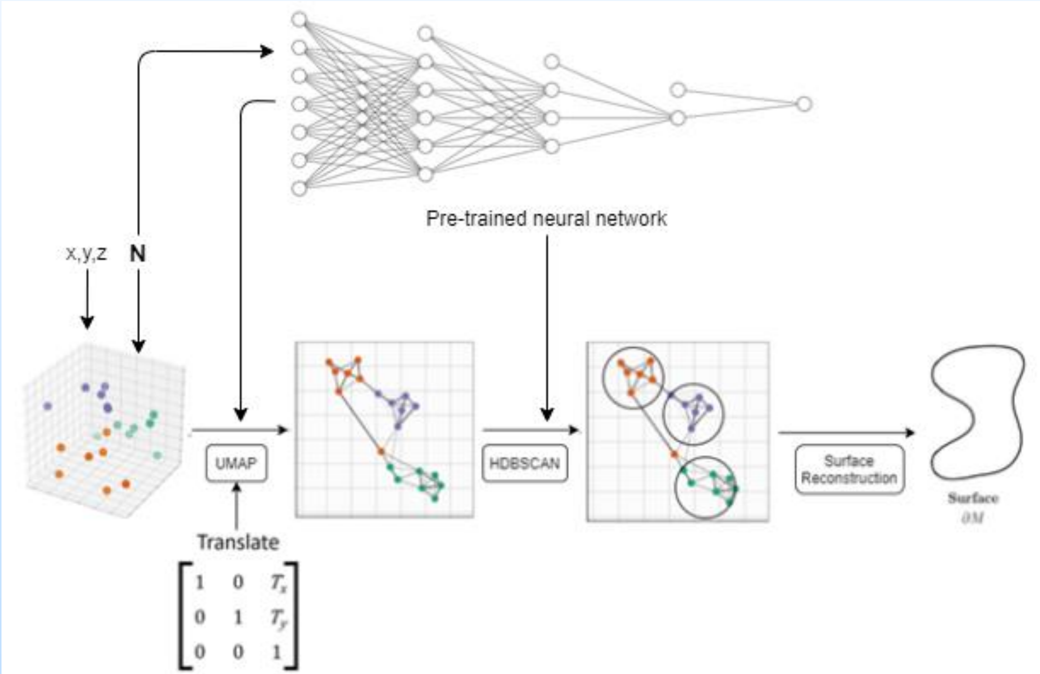
✓ Determination of the optimal parameters for the algorithms in i-GSFD by a pre-trained ANN

✓ UMAP: dimensionality reduction (from 3D x-y-z to 2D x-y)

✓ HDBSCAN: unsupervised clustering (diagnose the fracture network's characteristics)

✓ Surface Reconstruction

$$s_N = f(N, [d_1, d_2, d_3], k, C_{sm}, S_m)$$



Progress and Current Status of Project

iGeoSensing Fracture Diagnostic Software Package:

- **Interpret and map the received data from the Smart MicroChip Sensor**

- From left to right:
  - ✓ Fig.1: 2D x-y projection of the raw geo-sensor data from Virtual SMPs
  - ✓ Fig.2: Processed through i-GSFD to recognize the fractures in the network
  - ✓ Fig.3: 2D x-y projection of the processed data prior to final reconstruction in i-GSFD
  - ✓ Fig.4: 2D x-y projection of the proposed fracture network (after final reconstruction)

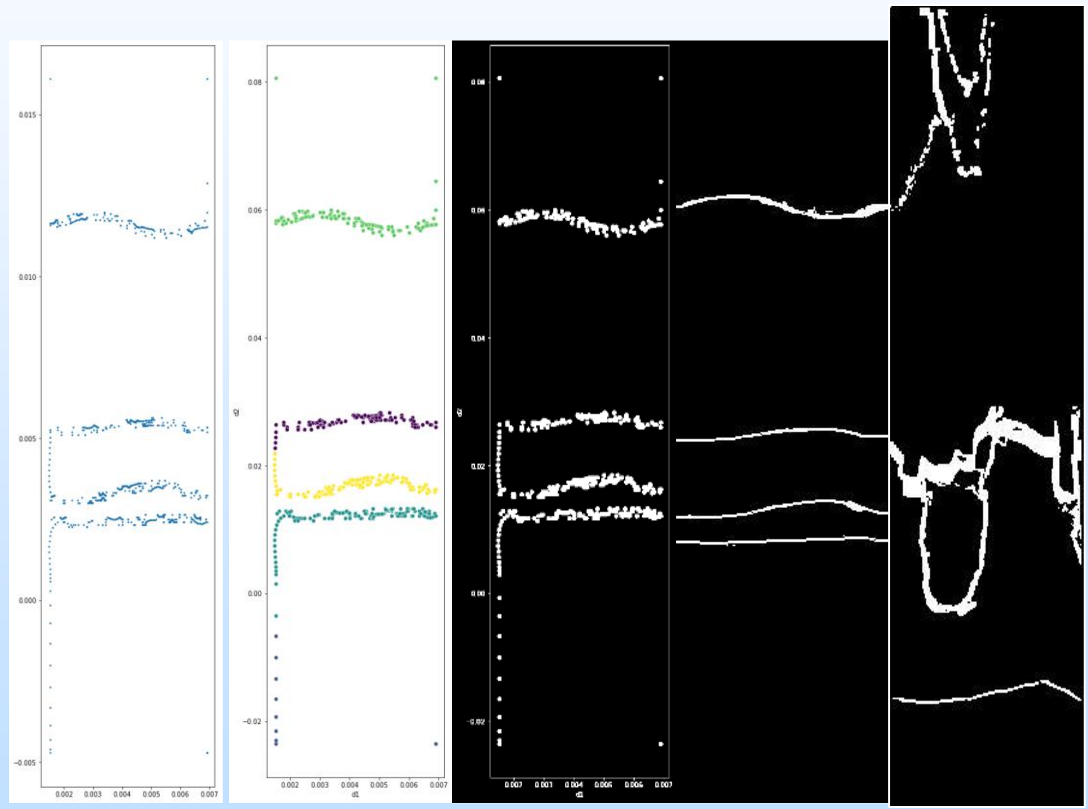
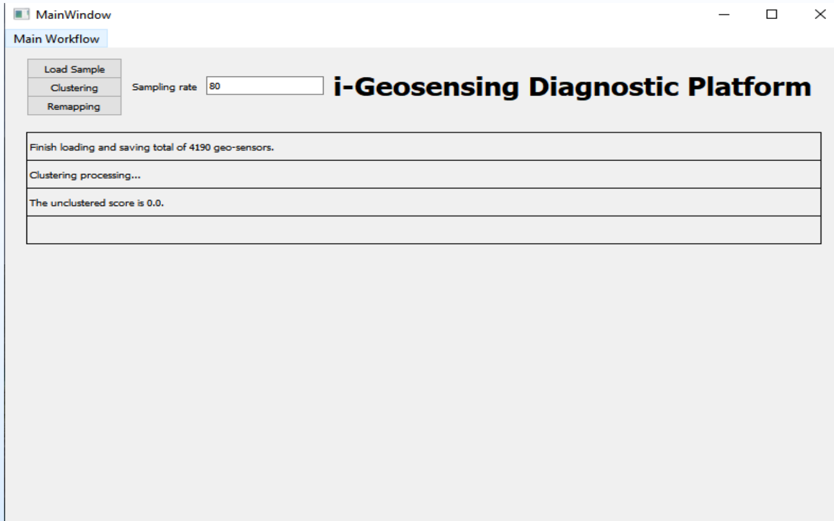


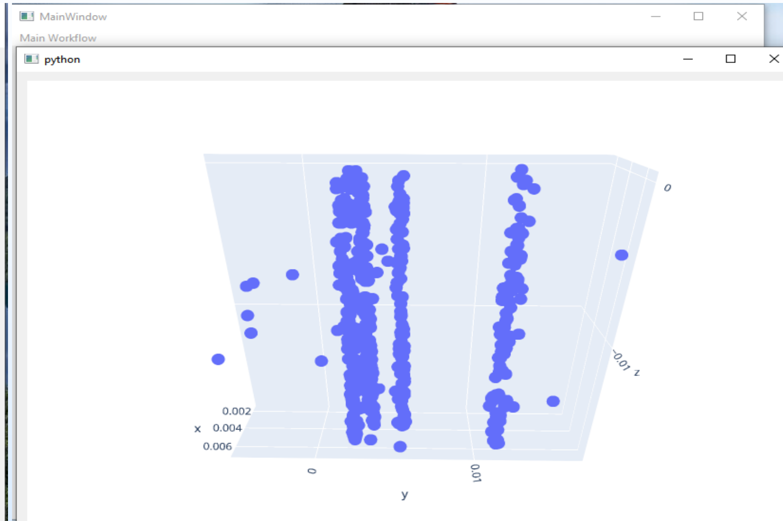
Fig.1 Fig.2 Fig.3 Fig.4

Progress and Current Status of Project

- **Software trial: demo of capability**



Main screen



Geo-sensor data preview

Diagnostic clustering preview

Final remapping preview

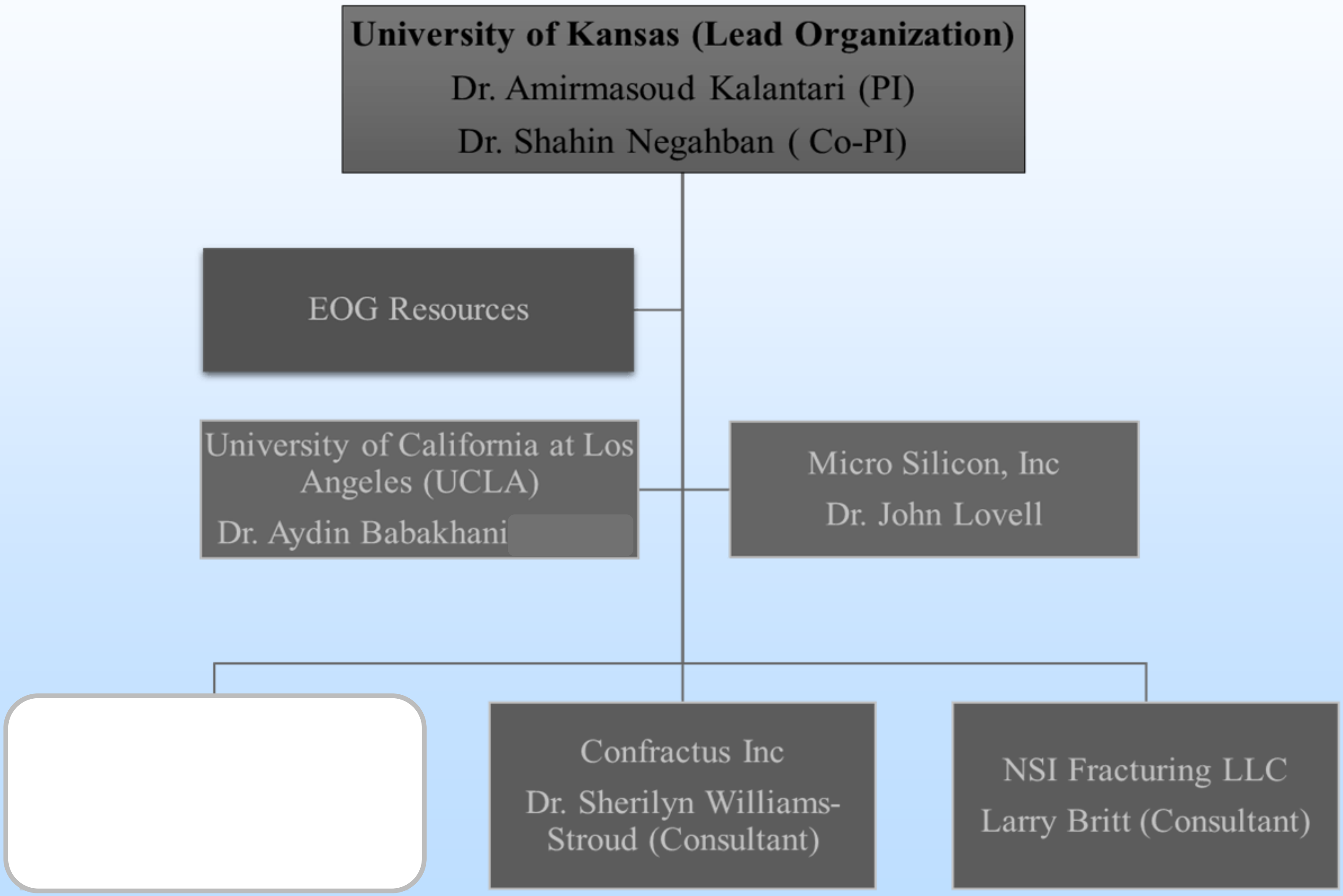
Plans for future testing/development/ commercialization

- In this project, once the Smart MicroChips proppant tested in the lab, we go for the field trial.
- The developed smart Microchips are expected to interface with existing indirect hydraulic fracturing diagnostics to improve understanding of hydraulic fracture geometry.
- It helps the operators to maximize the return from their unconventional reservoir operation.
- It also helps to reduce the environmental footprints and will help in better designing the EOR system for unconventional reservoirs.
- Additionally, regulation agencies can benefit from using this technology to monitor and consequently minimize HF operation issues.
- A low-cost approach and partnership with EOG will aid in transitioning technology to commercial deployment if successful.
- The technology can be further tested in other DOE-sponsored Science wells as well as oil and gas operators' core assets.
- This technology can be further developed to measure pressure and detect phases

Bibliography

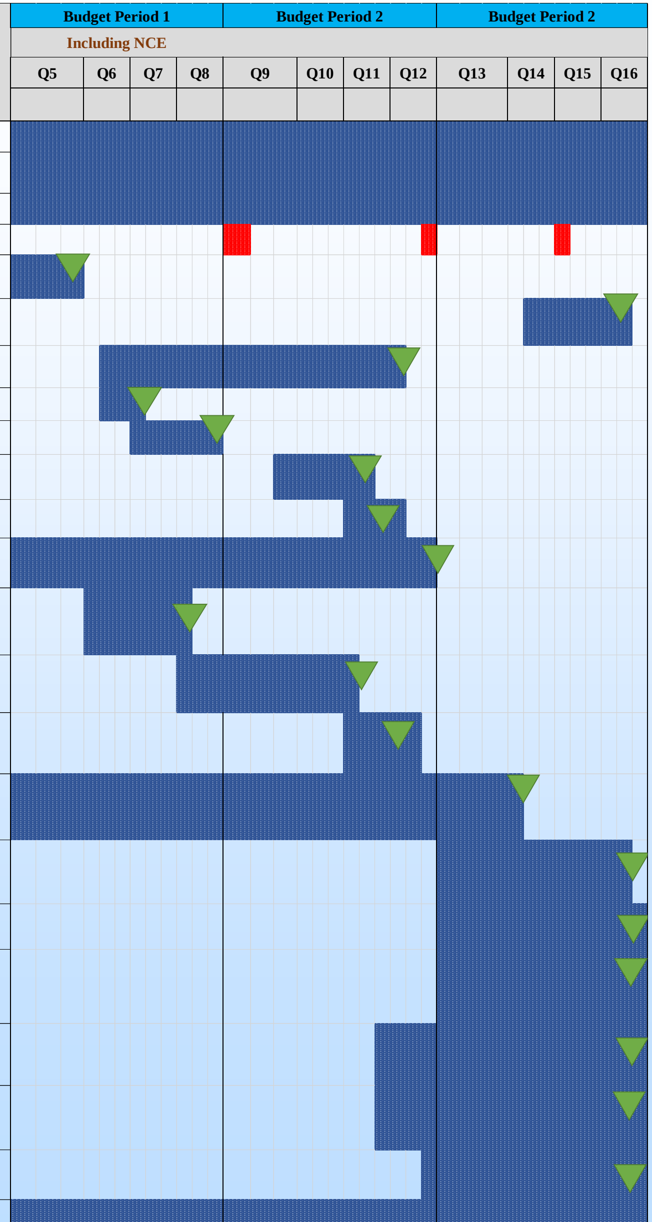
- Pham V, Kalantari-Dahaghi, A, Negahban, S. Babakhani,A, Fincham W, “Intelligent approach in smart microchip proppants data processing for complex hydraulic fractures diagnostic" Submitted to the *2021 IEEE International Conference on INnovations in Intelligent SysTems and Applications (INISTA)*- Accepted for Presentation, August 25-27, 2021
- Pham V, Kalantari-Dahaghi, A, Negahban, S. Babakhani,A, Fincham W, “Machine learning-enabled fracture network imaging using wirelessly-powered smart microchips proppants data" Submitted to the *2021 IEEE International Conference on Imaging Systems and Techniques*- Accepted for Presentation, August 24-26 2021, NewYork
- Pham V, Kalantari-Dahaghi, A, Negahban, S. Babakhani,A, Fincham W, “iGeoSensing Fracture Diagnostic (i-GSFD) For Fast Processing Of The Smart Microchip Proppants Data” 21ATCE-P-1163-SPE. *2021 SPE Annual Technical Conference (ATCE),* September 21-23, 2021.(Accepted for Presentation)
- Pham V, Kalantari-Dahaghi, A, Negahban, S. Babakhani,A, Fincham W, “Intelligent Fracture Diagnostic Procedure Using Smart Microchip Proppants Data" 21ADIP-P-6902-SPE, 2021 *SPE ADIPEC*, November 2021 (Accepted for Presentation)

Organization Chart



Gantt Chart

Task Title	Start Date	End Date
Task 1: Project Management and Planning	Q1	Q16
Task 2.0: Workforce Readiness for Technology Deployment	Q1	Q16
Task 3.0: Data Management Plan	Q1	Q16
Go/No-Go Evaluation		
Task 4.1: Field Laboratory (Science Well) Site Selection and Static data collection	Q1	Q5
Task 4.2: Field Laboratory –Dynamic Data collection	Q14	Q16
Subtask 5.1 to 5.4 Detailed Micro Scale Rock/Fluid experiments	Q6	Q12
Subtask 5.5 Preliminary & basic core work	Q5	Q7
Subtask 5.6 Rock Mechanics Testing	Q5	Q8
Subtask 5.7 Additional project testing (Fluid sensitivity and Un-propped crack tests)	Q9	Q11
Subtask 5.8 Smart Proppant Transport tests in Lab	Q10	Q11
Subtask 6.1: Build and calibrate novel smart MicroChip proppant sensors	Q1	Q12
Subtask 6.2. Constructing multiple synthetic fracture network models and building synthetic cores using 3D printing technology	Q2	Q8
Subtask 6.3: Test the imaging capability of MicroChip proppants with 3D printed synthetic cores	Q7	Q9
Subtask 6.4: Test the MicroChip proppants in a high pressure and temperature lab environment.	Q10	Q11
Subtask 6.6: Build downhole logging tool to power the Microchips and assimilate their data.	Q1	Q14
Subtask 6.7: Inject the MicroChip proppants into the formation (small-scale frac job) and validate survival of the chips.	Q13	Q16
Subtask 6.8: Interpret and map the received data from the MicroChips	Q13	Q16
Task 7.0: Integration of near wellbore (microchip) and the other diagnostic tools through machine learning techniques	Q13	Q16
Task 8.0: Development of state-of-the-art integrated machine earning, analytical and numerical predictive fracture and flow models	Q12	Q16
Subtask 8.2: Develop extremely fine resolution fracture and flow simulation and machine learning model	Q12	Q16
Subtask 8.3: Develop new diagnostic plots and enhance analytical solutions/ type curves	Q12	Q16
Report and presentation	Q1	Q16



Appendix

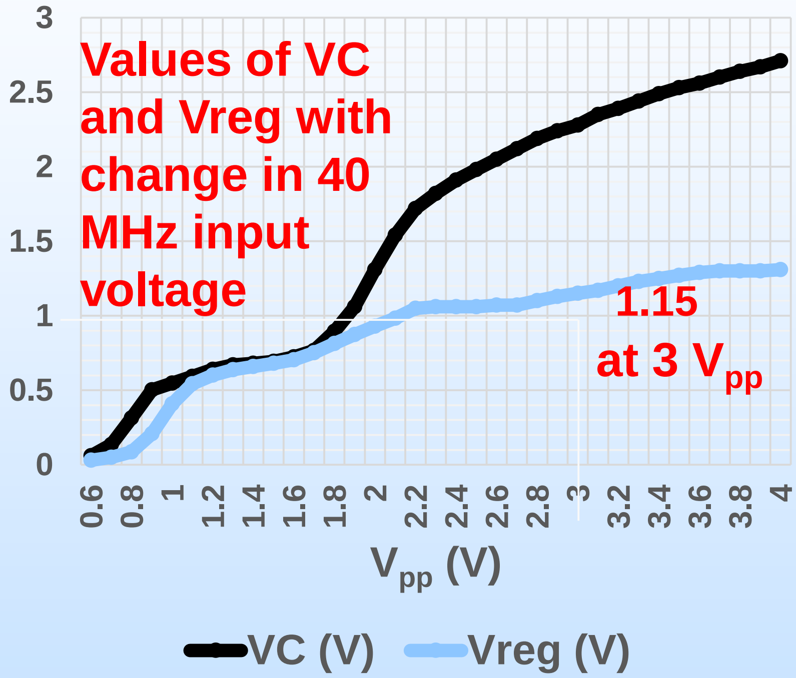
Technology Background

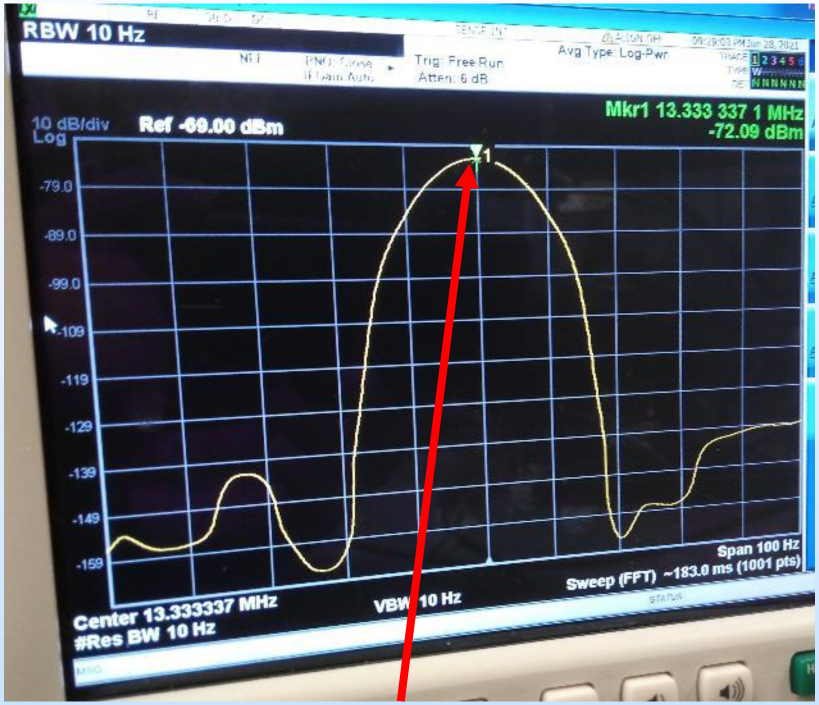
Technical Challenges:

- to miniaturize the smart microchip proppants to 100 mesh.
  - risk mitigation strategy:
    - ✓ use 180 nm CMOS technology to build the smart proppants. If we can't fit the entire electronic components in 100 mesh using 180 nm CMOS process, we will use smaller CMOS nodes such as 22 nm or 16 nm to reduce the size of the active components (transistors) by a factor of larger than 10.
- Antenna size (or on-chip inductor) used to harvest electromagnetic energy.
  - risk mitigation strategy:
    - ✓ ultrathin and flexible antennas such as nanowires. In this case, the core of the active circuitry will be integrated and fit within 100 mesh

Progress and Current Status of Project

Measurement results

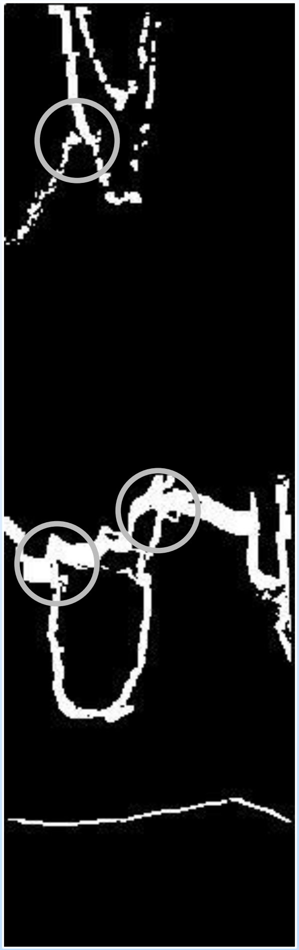




Measured 13.33 MHz output tone of -72.09 dBm for a 40 MHz input of 3 V_{pp}

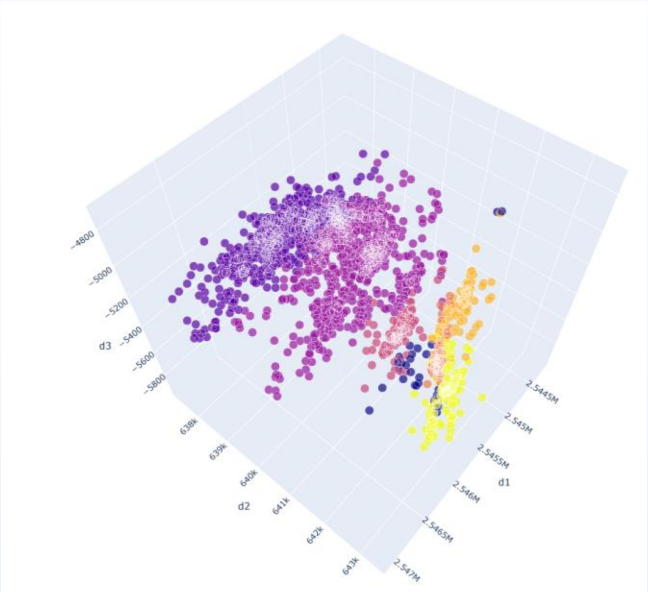
Progress and Current Status of Project

- **Challenges from “joint” locations for the current i-GSFD**
  - 2D projection of the 3rd synthetic fracture network, highest complexity level
  - Critical locations are circled: “joints” of different child fractures in a child fracture network, extreme proximity
  - These “joint” locations makes the i-GSFD performance challenging
  - Low-dimensional projection algorithms (t-SNE, or UMAP used in i-GSFD) are designed to separate the data using the proximity information in the data & preserve the data’s local and/or global structure



Progress and Current Status of Project

- **Software trial: Fracture network clustering, DAS-based synthetic case**



- **Ongoing work:**
  - ✓ Tentative modification of i-GSFD to scope with highly–complexed fracture networks
  - ✓ Automatic coupling between i-GSFD and a numerical simulator engine (as CMG)
  - ✓ Solve the "joints" in complexed fracture networks using Trajectory Clustering (as TRACLUS)
  - ✓ Dynamic use of i-GSFD (i.e. real-time fracture mapping)
  - ✓ Compare between the "ground-truth" (i.e. synthetic) fracture networks and the predicted networks dynamically using statistical analysis.
  - ✓ Construct ML-based modelling proxy for uncertainty analysis using the capability of controlling commercial simulator engine in i-GSFD