Low Cost, High-Density Digital Electronics for Nuclear Physics

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SkuTek Instrumentation

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Outline

- The company and its capabilities.
    - Customers.
- Hardware progress.
    - New compact instrument FemtoDAQ+.
- Firmware and software progress.
    - Improved firmware structure.
    - Portable remote Web GUI.
- R&D in support of (Very) Low Energy Physics in Hot Plasma environment.
- Highlights.
- Acknowledgements.

The company and its capabilities

- The team: three physicists, a senior software engineer, a part time engineering associate, and a manager. We regularly work with a local EE consultant.
- We worked with several interns listed on the Acknowledgements page.

Our focus:

Digital data acquisition (DAQ) for nuclear physics, high energy physics, DM search, etc.

Our capabilities: Development of cutting edge instruments.

- Electronic design.
- Firmware development for Field Programmable Gate Arrays (FPGA).
- Software development for embedded processors, especially Embedded Linux.
- Algorithms for pulse processing.
- Algorithm implementation in FPGAs (VHDL, Verilog) and in embedded processors (Pascal, Python, C).
- Processing data from nuclear detectors of any kind.
- Development of simple detector assemblies using scintillators, PMTs, or SiPMs.

Our customers

UNIVERSITY of ROCHESTER

HOUGHTON COLLEGE

THE UNIVERSITY OF TENNESSEE KNOXVILLE

SFU SIMON FRASER UNIVERSITY
ENGAGING THE WORLD

UNIVERSITÉ LAVAL

AUGUSTANA UNIVERSITY

上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

Los Alamos National Laboratory

Fermilab

Brookhaven National Laboratory — Added last week!

NSCL National Superconducting Cyclotron Laboratory

Albert Einstein Center for Fundamental Physics

UNIVERSITÄT BERN

BROWN — Brown University

WIENER Plein & Baus, Corp.

Progress

COVID: Slowed us down quite a bit. Working face to face is hard to substitute.

Hardware progress: 2-channel **FemtoDAQ+** is replacing the former FemtoDAQ.

- More powerful FPGA: Spartan-6 replaced with Artix-7.
- Longer waveforms, faster readout.
- Two analog reconstruction channels can synthesize the signal, possibly after digital filtering, or output an arbitrary analog waveform.
- BeagleBone is replaced with MicroBone Single Board Computer, which is also our product.
- The old FemtoDAQ is still available. It will soon become the “last time buy”.

Firmware progress.

- Unified interface between the FPGA and the Linux MicroBone SBC.

Software progress.

- Web-based GUI for setup and control works with any operating system using the web browser technology.

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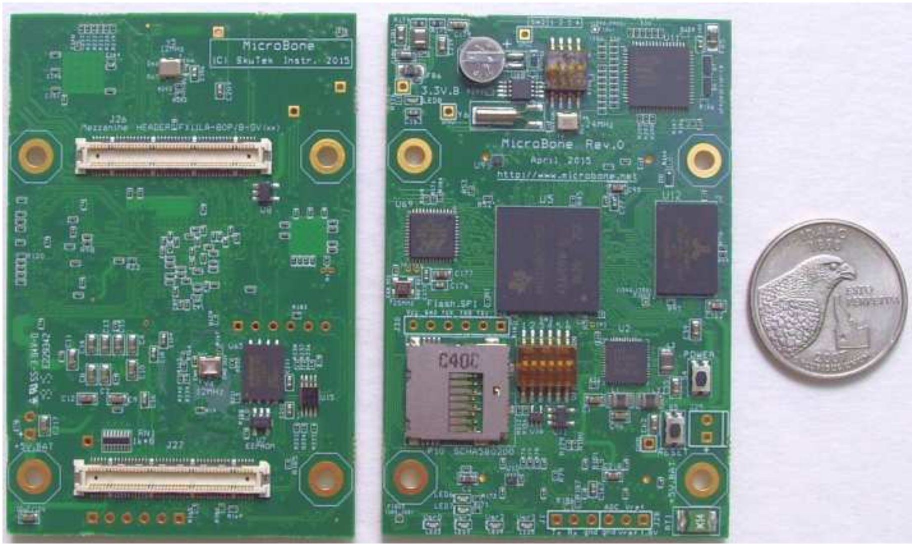
MicroBone: BeagleBone - Compatible SBC

- After introducing FemtoDAQ+, all our products will now use MicroBone SBC.
- ARM Linux System on Module (SOM) with a low-power 1 GHz ARM processor AM3358.
- It provides embedded Linux with laptop-class performance to all our products.
  - Local data logging, remote display for monitoring and diagnostic.
- Hardware:
  - We added an 8-channel ADC/DAC chip with 12 bit resolution and 5 Volts input / output range.
- Software:
  - Adopted Debian-10 for this SBC.
  - Developed both Python and C capabilities: SBC is its own development system.

- Easy to embed 2” by 3” size, fits within DAQ module.
- Two 80-pin expansion connectors.
  - Memory interface, USB, GbE, SPI, I^2C.
- 512 megabytes of RAM.
- 1 GHz ARM AM3358 running Linux.
- Two Programmable Real Time processor cores.
- µSD card acting as Solid State Disk, up to 64 GB.
- Eight analog pins: 12-bit ADC or 12-bit DAC each.
- Optional Real Time Clock with battery backup.



Two Markets: Research DAQ & Small DAQ

Our digitizers are using **MicroBone Linux SBC** and **three different FPGA families** to optimize their cost to performance balance. The left column is for research DAQ. The right column is for small applications.

High density digitizer: **32 channels**
Kintex-7
1G Ethernet at wire speed
Rear Transition Module:
10G demonstrated
Time and Trigger Protocol (TTCL)

Mid density digitizer: **10 channels**
Spartan-6, remote Web interface

Low density digitizer: **2 channels**
Artix-7, remote Web interface

MicroBone

New FemtoDAQ+ With Artix-7 and MicroBone

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- Replaced the BeagleBone with the MicroBone developed by SkuTek.
- Increased the waveform memory from 64 kB to 2 MB. (Waveforms up to 50 ms @ 100 MSPS.)
- Upgraded Spartan-6 to Artix-7 providing more resources and better performance.

Two outputs: arbitrary wave generator

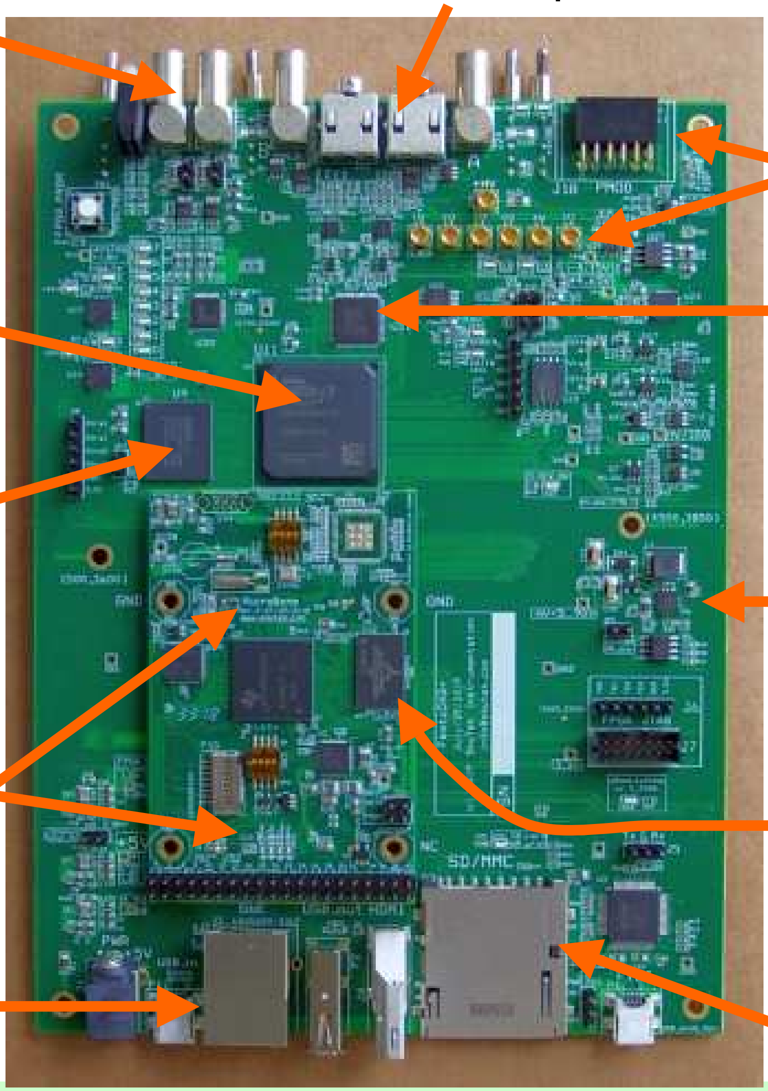
Two inputs with termination: 50Ω, 1kΩ, 10kΩ

Logic I/O, 8 single pins and 6 coaxial MMCX

Artix-7

ADC 14/16 bits
14 or 16 bits @ 100 MHz
14 bits @ 250 MHz

RAM space for 1 million samples
2 ch * 50 ms @ 100 MSPS



SiPM bias generator
+5V to +90V
in 1.4 mV steps

MicroBone Linux
Single Board Computer
Running Debian-10

RAM for ~200 million samples
2 ch * 1 sec, not continuous
(only the burst mode)

GbE and USB-2

SD card

FemtoDAQ+ Status

- The pre-prototypes were extensively tested. We are ready for the production prototypes.
- Remote Web GUI has been developed (next section).

80 μs waveforms → 50 ms waveforms

Previous FemtoDAQ with BeagleBone

To be retired

SiPM bias generator
+5V to +90V
in 1.4 mV steps

Logic I/O
coax

Two outputs:
arbitrary wave
generators

Logic I/O, 8 pins

Two inputs: 50Ω, 1kΩ, 10kΩ
14 or 16 bits, 100 MSPS
Design is ready for 250 MSPS

Firmware and Software Progress

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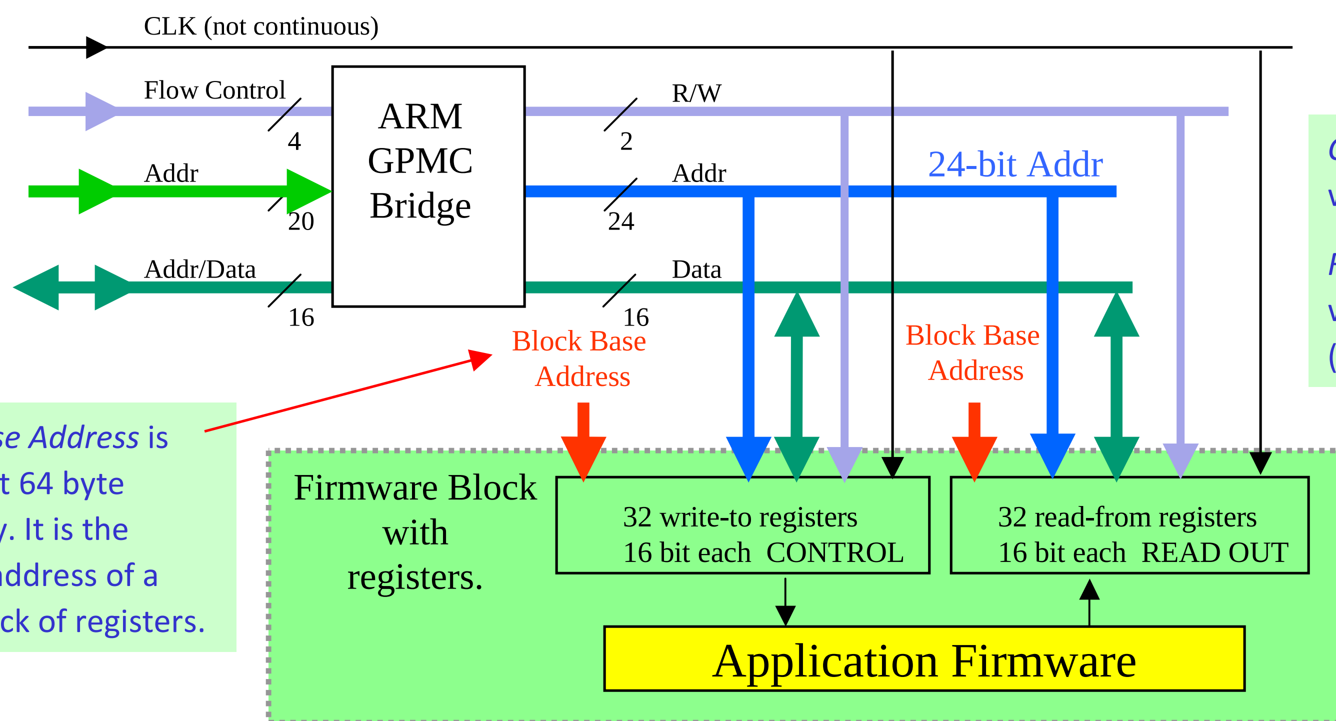
Firmware Interface With the Linux SBC

We organize the FW and SW into *Features* offered by the instrument to the user.

The ***Instrument Feature*** consists of Application Logic, the register interface, SBC software, and remote control.

- Internally in the FPGA, the *Feature* is a Firmware Module with Registers for control and read out.
- Registers have addresses in the Linux memory space.
- The Base Address defines where the registers start in the Linux memory space.
- The *Feature* is interfaced to Linux SBC using the ARM General Purpose Memory Controller (GPMC).
- GPMC is a memory bus between the SBC and the FPGA.



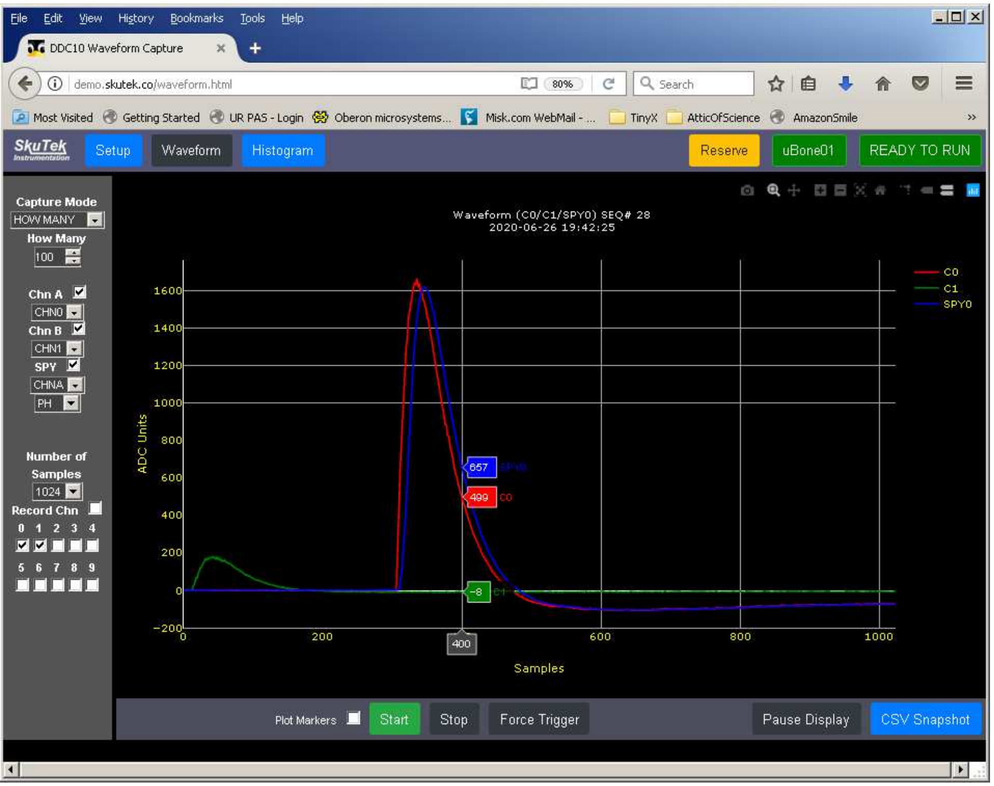
Block Base Address is aligned at 64 byte boundary. It is the starting address of a given block of registers.

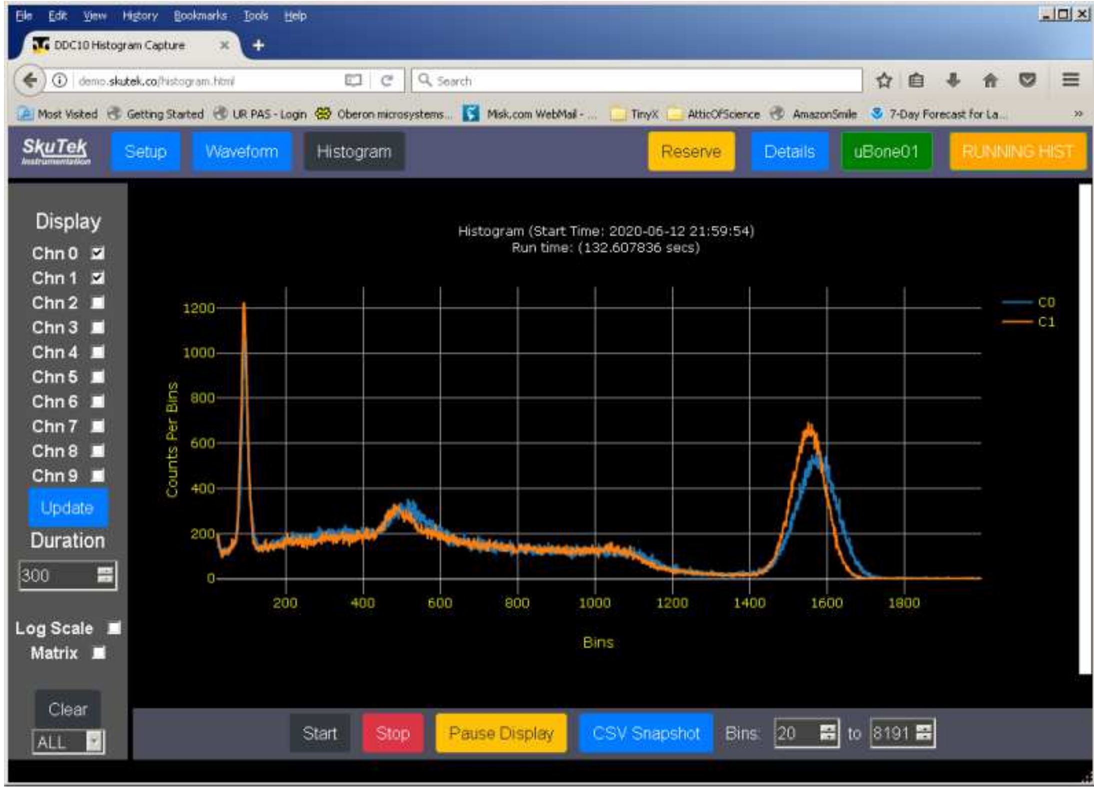
Control: The Write Register which can also be read back.

Read out: The Read Register which cannot be written into. (Writing to it has no effect.)

Remote Web GUI Interface

- The waveform and histogram displays can be shown in any browser, any operating system.
- One can even use a cell phone. Not really encouraged, but it works.
- The GUI does **not** require any software installation on the remote host. It runs in the browser.
- Multiple users can connect to the same instrument.
- We use a “virtual sticky note” to warn against access conflicts.





(Very) Low Energy Nuclear Physics

in Hot Plasma Environment

Development of Digitization at High Count Rates

(Very) Low Energy Nuclear Physics in Hot Plasma Environment

Mark Yuly, Houghton College

Mark was the very first FemtoDAQ user!

Stephen Padalino, SUNY Geneseo

Sean Regan, Craig Sangster, Laboratory for Laser Energetics

Wojtek Skulski, Jeff Maggio, Robert Cross, et al.

- **The goal:** Measure extremely low production cross sections of light, unstable nuclei such as 6He at energies relevant for nuclear nucleosynthesis in stellar environments.
- This experiment, if performed at the accelerator, would require **centuries of beam time**.
- Hot, compressed plasma is produced in OMEGA laser shots. Fuel isotopes (deuterium, tritium, lithium, beryllium) will react to produce unstable nuclei like 6He.
- The products will decay within a phoswich detector. They induce pulses digitized by SkuTek electronics.
- FemtoDAQ was used over the last few years. As the number of the produced nuclei per shot has grown, FemtoDAQ design is showing its limitations.
- **A new, better performing device is needed for the new generation of these experiments.**

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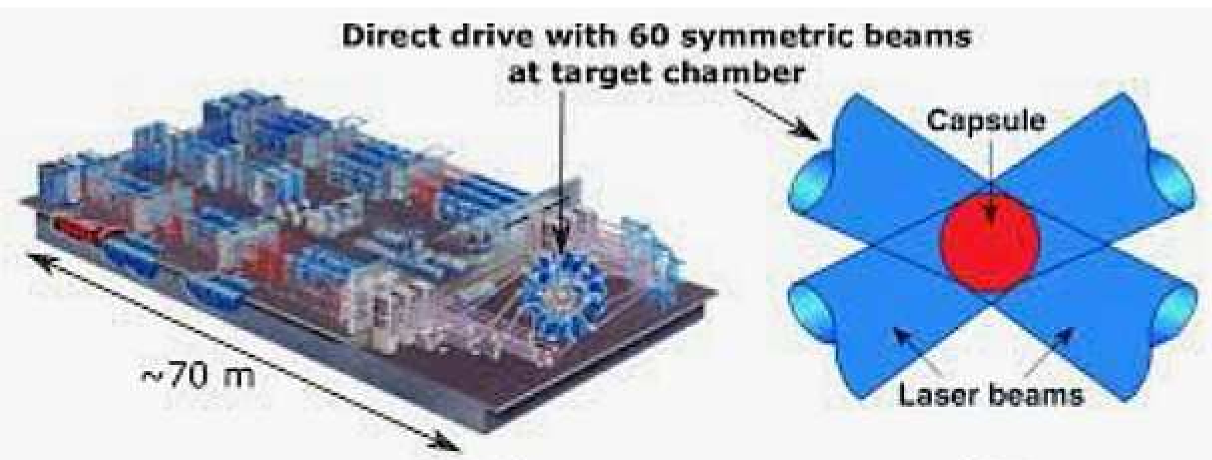
(Very) Low Energy Nuclear Physics

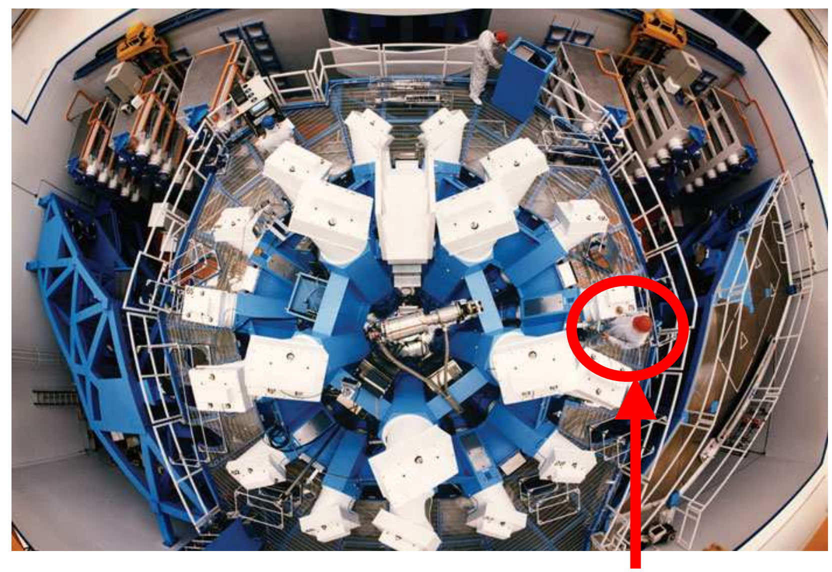
Nuclear Reactions of Interest [1] in Inertial Confinement Fusion (ICF)

Reaction	Product Half-life	Reactant Abundance	Predicted Yield
$^{3}H(t,\gamma)^{6}He$	807 ms	10^{-7} branching	8×10^{4}
$^{6}Li(t,p)^{8}Li$	840 ms	7.6%	$0.2\text{-}1\times10^{7}$
$^{7}Li(t,\alpha)^{6}He$	807 ms	92.4%	$0.7\text{-}2\times10^{6}$
$^{9}Be(t,\alpha)^{8}Li$	840 ms	100%	5×10^{5}

[1] Mark Yuly, Stephen Padalino, Adam Brown, Micah Christensen, Micah Condie, private communication.

ICF is induced in the chamber by sixty high power laser beams





A person

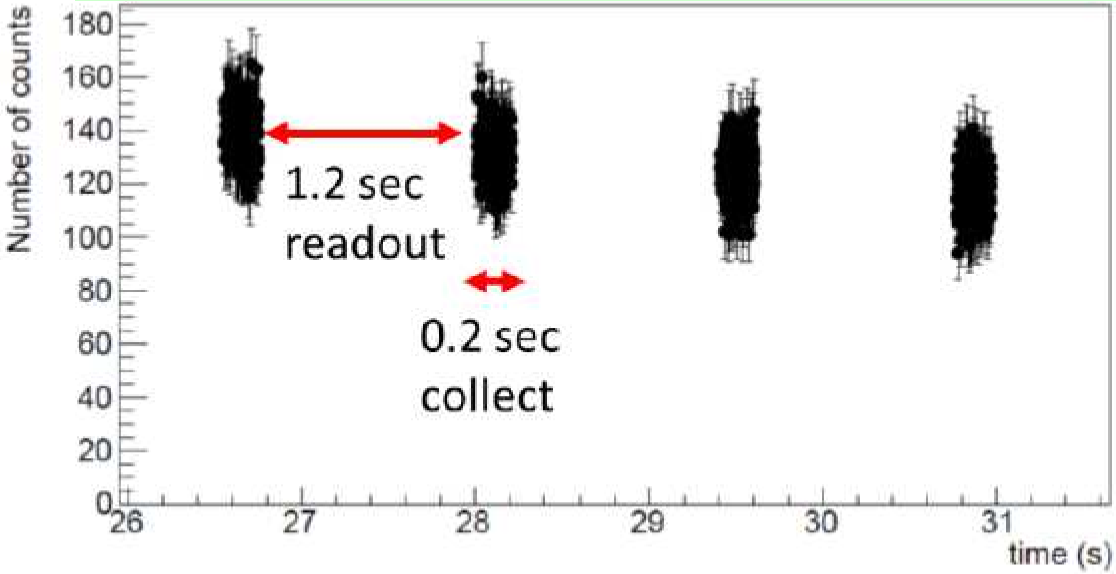
(Very) Low Energy Nuclear Physics

ICF products are collected inside a hollow phoswich detector constructed at Houghton College.

Not wrapped yet

Wrapped

Example of FemtoDAQ digitization and readout



The original FemtoDAQ was struggling to keep up with high pulse rate from the phoswich detector. It took only 0.2 sec to fill the internal memory buffer, which was then transferred to a host computer every 1.2 sec. Low transfer speed was due to using the Serial Peripheral Interface (SPI) for data transfer. Using SPI was an unfortunate limitation of the BeagleBone design, which was not meant for high performance instruments.

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(Very) Low Energy Nuclear Physics

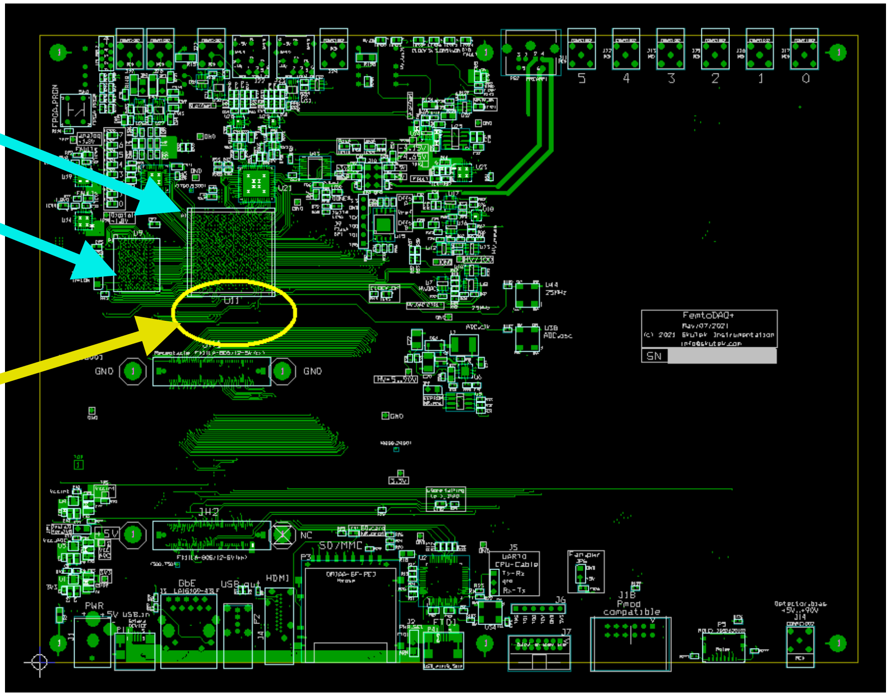
The old FemtoDAQ has reached its limits. What can we do?

1. Stop using Serial Peripheral Interface (SPI). Start using Programmable Real Time Units (PRU) provided by the ARM Sitara architecture. It would require substantial changes to both FW and SW. This solution can improve the readout speed, but it will not address other limitations of this aging instrument.
2. Replace the FemtoDAQ with the new FemtoDAQ+. We can expect at least 10 times improvement of the readout speed thanks to using General Purpose Memory Controller (GPMC). However, the limited amount of RAM may still impose a bottleneck. To be determined.
3. We can use the largest Artix-7 200T, and we can add more RAM in the location indicated below.

FPGA

2 MB

Space for even more RAM



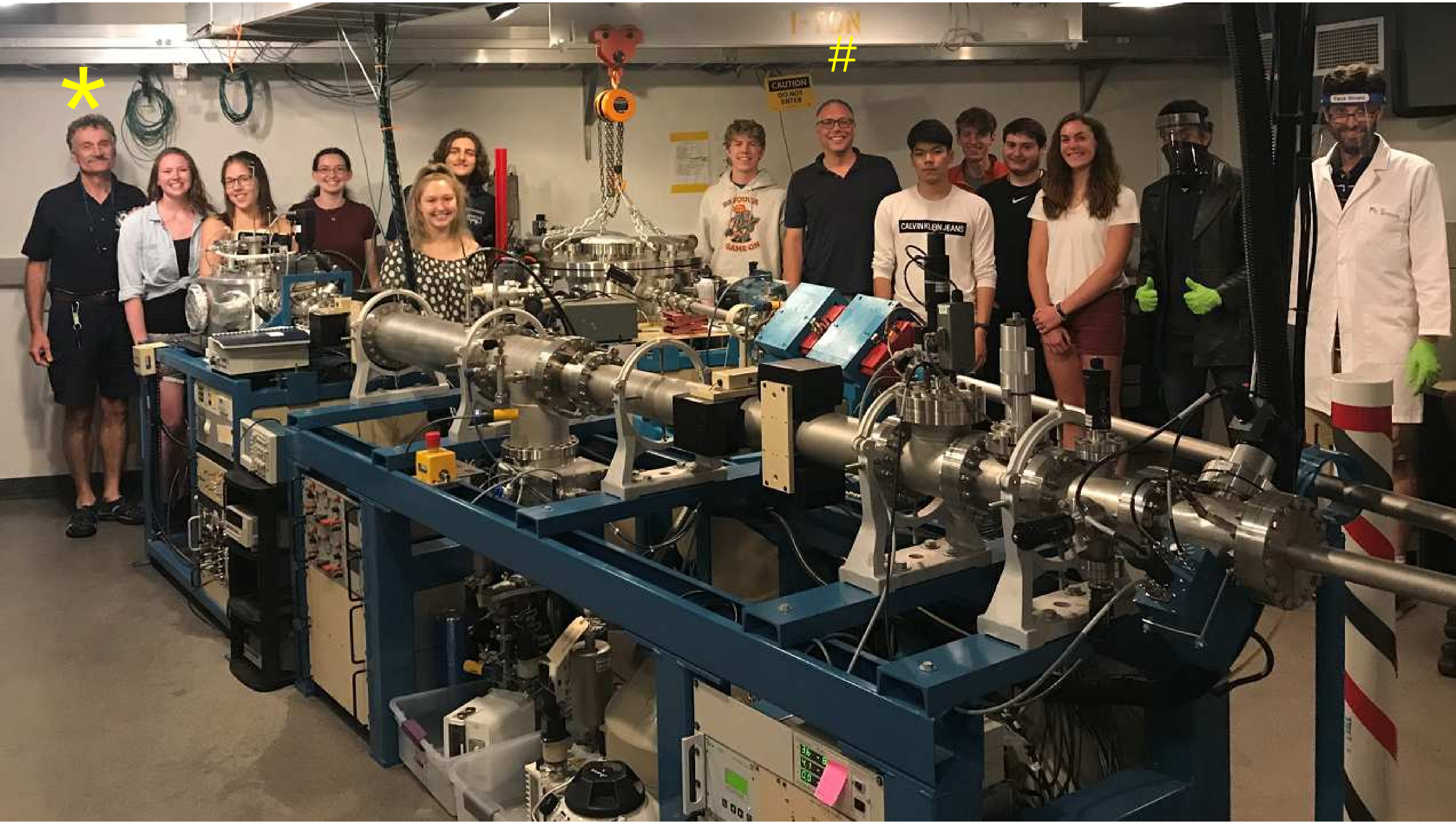
A modified FD+ layout will provide more space for adding extra RAM needed for buffering the events during high count rate digitization.

The Benefits for the Community and for the Company

1. We can **add a significant value** to the astrophysical research in the ICF environment.
2. We can **help the DOE mission** in two areas at the same time: Nuclear Physics and Fusion.
3. We can **contribute** to an exciting and very valuable research project.
4. The R&D will be **cost effective**. We need to slightly modify the FD+ design anyway to address minor issues. We can add more RAM on this occasion.
5. We can demonstrate our technology and products to the Laser Fusion community.
6. We can contribute to the **student education** at three institutions: Houghton College, SUNY Geneseo, and University of Rochester. See the next slide!
7. We can train our own employees while working on this project.
8. We can bike rather than fly to the site, since LLE is within a biking distance from SkuTek.
9. Our **plan** is to manufacture the modified FD+ and offer it to the experimenters.

Nuclear Physics Education

Professors Stephen Padalino (* left) and Mark Yuly (# right) with their students.



Summary

Summary of Technical Achievements

- Hardware:
  - We added a new FemtoDAQ+ to our digitizer family.
  - FemtoDAQ+ will offer significantly better performance than the previous FemtoDAQ.
    - We will improve FD+, guided by the needs of the fusion experiment at LLE.
  - All our products will uniformly use the same MicroBone SBC for setup and control.
- Firmware**:**
  - We will organize the firmware around Application Firmware, Register Interface, Software Driver, and UI.
  - The Register Interface will use the General Purpose Memory Controller of the AM3358 chip.
    - GPMC was one of the main motivations to develop the FemtoDAQ+.
- Software:
  - We adopted a unified web-based JavaScript technology for instrument setup and control.
  - Running the GUI does not require installing any software on the target host.
  - The GUI is using JavaScript which can run in any browser, even on a cell phone.
  - GUI can setup the instrument and save the configuration.
  - Regular event files can be written to the SD card or to an NFS mounted disk.

Future Plans

- Continue development of firmware and software for our digitizers.
- Adopt the web-based control technology in all our products.
- Develop high performance event streaming for the Laser Fusion experiment.
- Contribute to the exciting research at the nearby institutions.
- Contribute to Nuclear Physics and Laser Fusion student education.
- Train our own employees, using the Laser Fusion experiment.
- Gain recognition in the Laser Fusion community through contributing to their exciting projects.
- Help support the DOE mission in a way which we did not even imagine till recently.
- Have fun doing all the above.

Acknowledgements

Joanna Klima, Gregory Kick, David Miller, James Vitkus

Recently hired: Jeffrey Maggio, Robert Cross

Past employee: David Hunter

Consultant: Eryk Druszkiewicz

Interns:

Mandy Nevins, Jeffrey Sylor, Dinesh Anand Bashkaran,
Brian Kroetz, Vedant Karia.

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Special thanks to Michelle Shinn and Manouchehr Farkhondeh

Highlights of The SkuTek Products

- A **family of digitizers**, from 2 up to 40 channels per unit, 14 or 16 bits @ 100 MSPS.
  - The versions with 250 MSPS are under development. The boards are assembled.
  - The digitizers with more than 16 channels will stay at 100 MSPS because of power.
- The 32-channel digitizer will be compatible with the GRETA / GRETINA / DGS environment.
  - This project will be presented tomorrow.
- Small digitizers are targeting small labs, education, and T&M markets.
- Very low noise: RMS about 160 microvolts, that is ~ 1.3 LSB @ 14 bits.
- Setup, monitoring, and diagnostic with on-board **Linux** Single Board Computer (SBC).
  - SBC can also perform **readout** at the rate ~ a few megabytes per second.
  - SBC can write **formatted event files** directly to NFS mounted disks.
  - SBC can monitor the detector signals with **low latency** in near **real time**.
  - SBC can show an **interactive display** of waveforms and histograms **in any browser**.
- A **variety of options** for the control software and GUI to be executed by the Linux SBC.
  - SSH, command line, Python, Jupyter, and Remote Python Call (RPyC).
  - JavaScript GUI compatible with any browser, any host platform (even a cell phone).