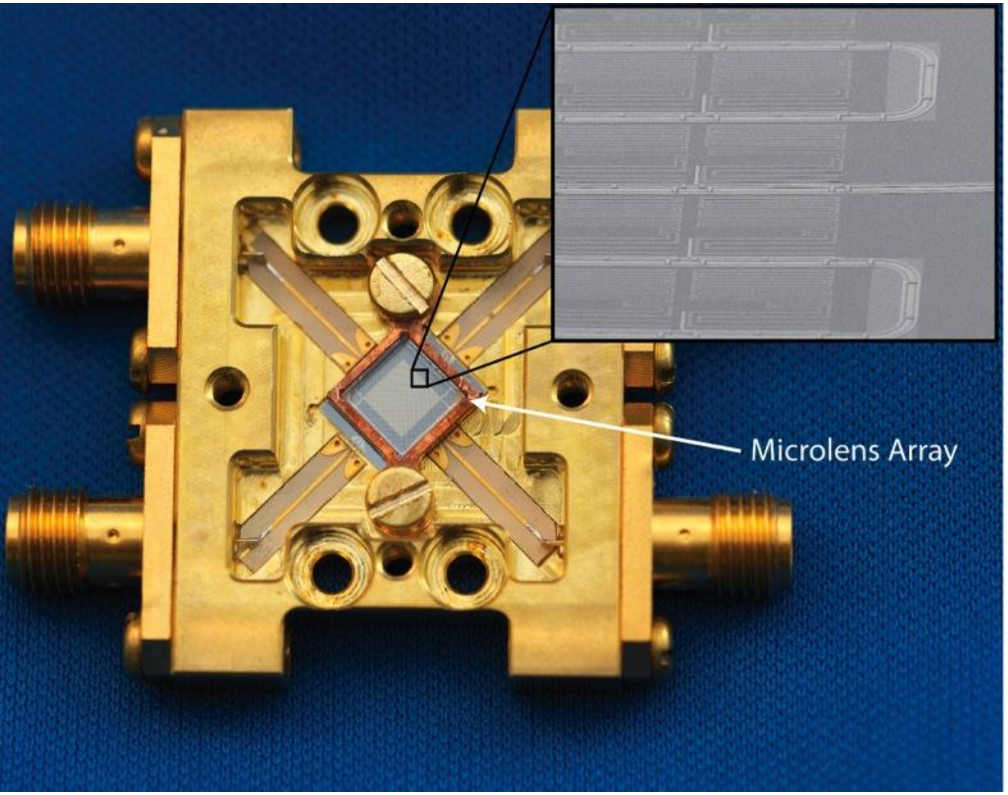
Microwave Kinetic Inductance Detectors and Cosmology workshop at Fermilab, Aug. 2013.

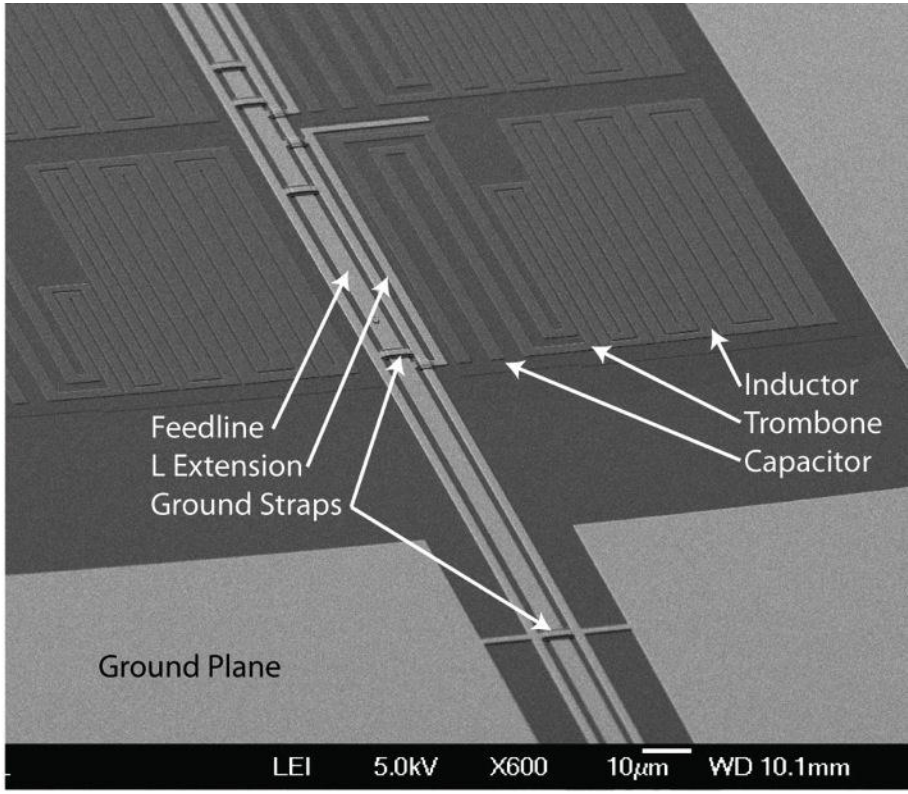
Readout system for large MKID arrays

Gustavo Cancelo

MKIDs (Microwave Kinetic Inductance Devices)

- Pixelated micro-size resonator array.
- Superconducting devices with meV energy gap.
  - **Theoretically, energy resolution of several 100's in the visible+near infrared. Excellent for cosmology, dark energy. (Also X-ray and CMB applications)**
  - **High bandwidth!: Allows for filtering of atmospheric fluctuations at ~100 Hz or faster.**





Ben Mazin, UCSB

MKIDs for cosmology

GIGA-Z: A 100,000 OBJECT SUPERCONDUCTING SPECTROPHOTOMETER FOR LSST FOLLOW-UP

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Draft version July 22, 2013

ABSTRACT

We simulate the performance of a new type of instrument, a Superconducting Multi-Object Spectrograph (SuperMOS), that uses Microwave Kinetic Inductance Detectors (MKIDs). MKIDs, a new detector technology, feature good QE in the UVOIR, can count individual photons with microsecond timing accuracy and, like X-ray calorimeters, determine their energy to several percent. The performance

- **Mid resolution spectrometry of 10^9 galaxies**
- **Already many interesting ideas coming out of today's talks.**
- **They point out to an MKID instrument with ~100Kpixels**

to multiplying the LSST Fisher matrix by a factor of $\alpha = 1.27\,(w_p)$, $1.53\,(w_a)$, or $1.98\,(\Delta\gamma)$. This is equivalent to multiplying both the LSST coverage area and the training sets by α, and reducing all systematics by a factor of $1/\sqrt{\alpha}$, advantages that are robust to even more extreme models of intrinsic alignment.

Subject headings: dark energy – galaxies: surveys – instrumentation: detectors – photometric redshift – weak lensing

MKIDs for cosmology

Well aligned with community interests

1

Instrumentation Frontier Report

Conveners: M. Demarteau, R. Lipton, H. Nicholson, I. Shipsey

J. Alexander, M. Artuso, D. Bortoletto, E. Blucher, C. Chang, J. Estrada, J. Fast, B. Fleming, M. Garcia-Sciveres G. Gilchriese, P. Gorham, G. Haller, C. Hast, U. Heintz, M. Hohlmann, R. Lipton, T. Liu, D. Lissauer, D. MacFarlane, D. Nygren, A. Para, E. Ramberg, R. Rusack, S. Seidel, A. Seiden, W. Smith, D. Su, R. Svoboda, J. Thom, G. Varner, J. Va'vra R. Wagner, M. Wetstein, A. White, J. Yu, R. Zhu

1.4.2.2 Key Issues and Next Steps

One of the key technical needs of all dark energy experiments is to be able to do spectral analysis. DES and LSST use different filters and large CCD cameras to carry out a 5 or 6 point spectral analysis. The ability to carry out spectral analysis with the camera pixels themselves would be a major technological step forward in this research.

There is a current R&D effort underway to develop a larger spectrometer using Microwave Kinetic Inductance Detectors (MKIDs). These are superconducting resonators. When a photon strikes the superconductor, it breaks Cooper pairs which change the inductance of the resonator. This changes the resonant frequency and phase. The phase change is then measured, providing a time and energy measurement for each photon. The theoretical resolution R is ~100 and up to 2000 resonators could be multiplexed to the same readout line.

An MKID spectrometer (Giga-Z) has been proposed that will consist of 100,000 MKIDs. The built-in spectral resolution of the MKIDs allows the use of direct lens-coupled, aperture mask spectroscopy as opposed to the fiber-fed spectroscopy, promising a far more efficient use of telescope time with wavelength coverage extends to the near infrared, important for observations of high redshift galaxies. Outstanding issues are getting R closer to the theoretical limit, improving the packaging and RF electronics, improving the quantum efficiency, and developing a flat, RF cable which works at 100 mK.

A readout architecture for 100,000 pixel MKID Detector array

- Technical challenges:
- Low system noise covering a frequency spectrum that goes from DC to microwave RF.
- Highly multiplexed RF system.
- Mixed analog and digital electronics.
- High data throughput.
- On board digital signal processing.
- Temporal and spatial synchronization.
- Complex system calibration.
- Data processing pipeline.

A readout architecture for 100,000 pixel MKID Detector array

Draft version June 21, 2013
Preprint typeset using LaTeX style emulateapj v. 5/2/11

ARCONS: A 2024 PIXEL OPTICAL THROUGH NEAR-IR CRYOGENIC IMAGING SPECTROPHOTOMETER

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Draft version June 21, 2013

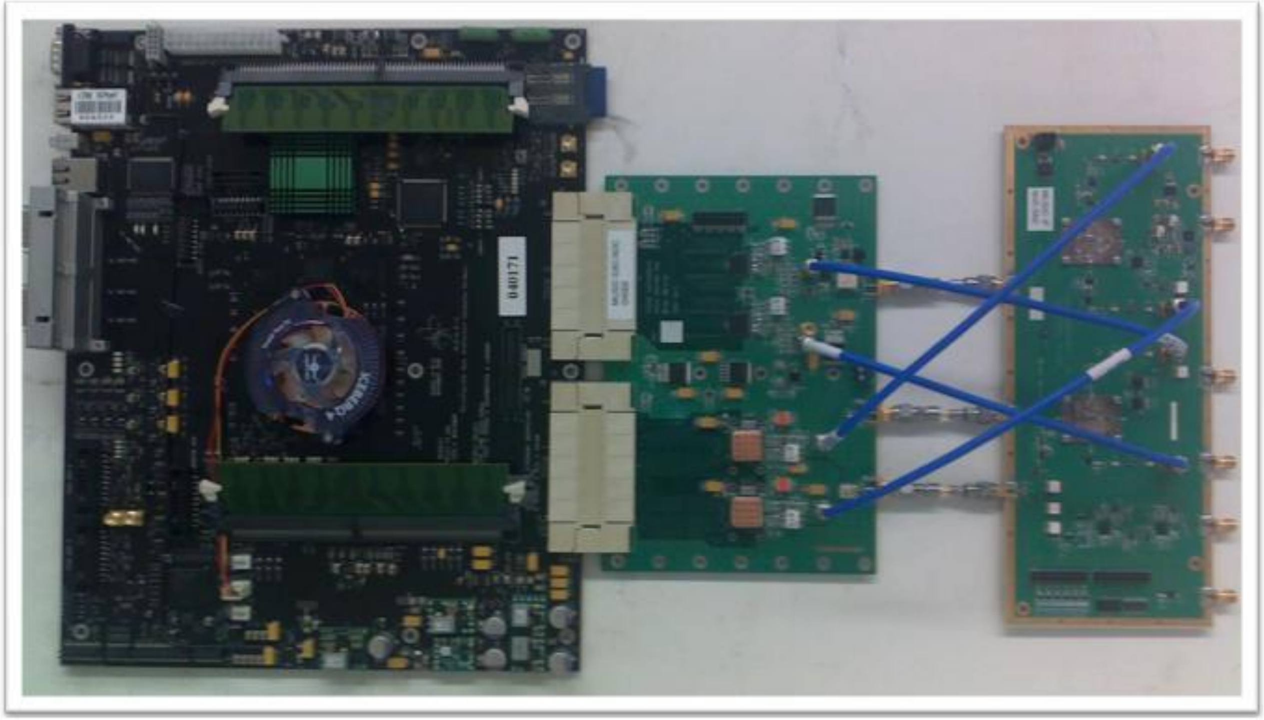
ABSTRACT

We present the design, construction, and commissioning results of ARCONS, the **Ar**ray **C**amera for **O**ptical to **N**ear-IR **S**pectrophotometry. ARCONS is the first ground-based instrument in the optical through near-IR wavelength range based on Microwave Kinetic Inductance Detectors (MKIDs). MKIDs are revolutionary cryogenic detectors, capable of detecting single photons and measuring their

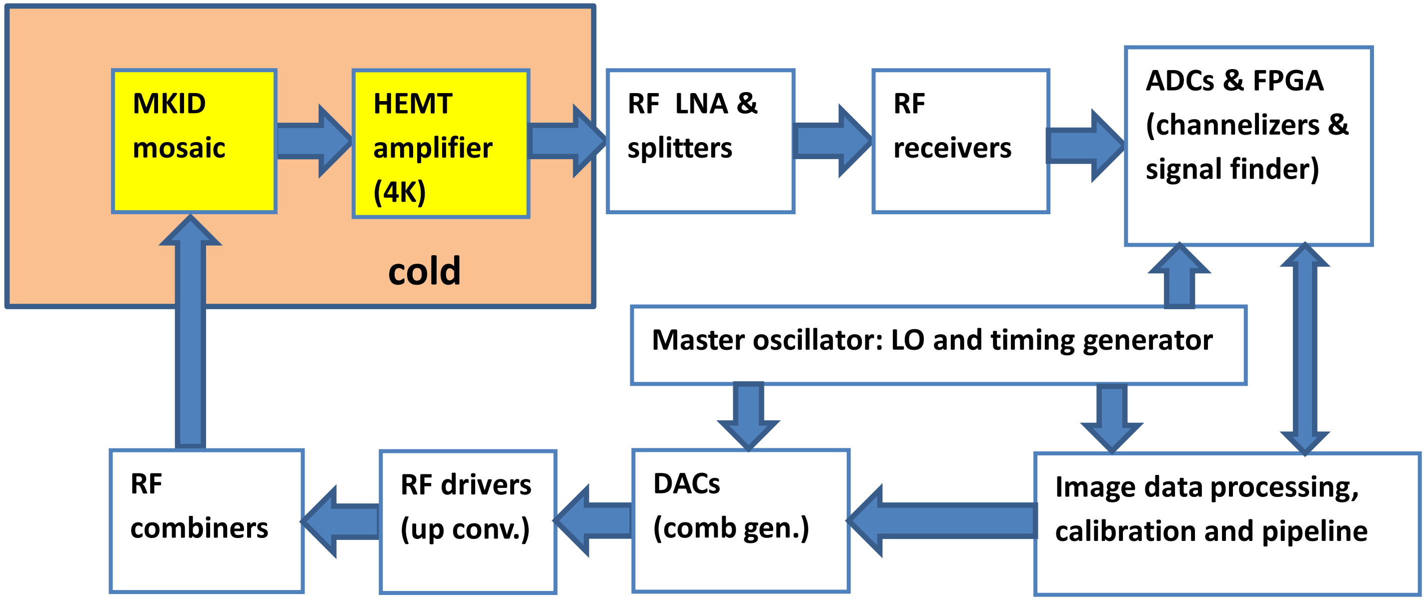
- A factor of 50 over today's largest system.
- The readout system used for ARCONS is the ROACH that can read out up to 256 resonators per feed line in 512 MHz of bandwidth, with 2 MHz spacing between tone frequencies.
- 8 ROACH required for ARCONS

CASPER-ROACH

- **C**ollaboration for **A**stronomy **S**ignal **P**rocessing and **E**lectronics **R**esearch
  - **R**econfigurable **O**pen **A**rchitecture **C**omputing **H**ardware (ROACH)



A readout architecture for 100,000 pixel MKID Detector array



- Typical architecture
- Many technical challenges.
- GOAL: 2000 channels per RF feed line. 2 to 4 GHz per feed line.
- A total of 50 feed lines for a 100K channel system.

- The input and out mapping is done with RF power combiners and splitters.

Data throughput

- At 3.6 Gs/s, 1.5 B/sample each feed line generates 5.4 GB/s and a total of A 270 GB/s for a system of 50 feed lines.
- The output data bandwidth is considerably smaller. Each image of 100 Kpixels at 2 to 3 B/pixel and a rate of 100 images/sec totals 30 MB/s. The stored data can be furthered reduced in size, but there will be ~1000 images/second!!
- That calculation implies that there is considerable signal processing with a data reduction of 1000 in the data acquisition system.
- The channelizing and filtering is typically done by an FPGA because the algorithms are based of FFT and polyfilter bank techniques that require a high degree of parallelism.
- The next processing step must fit the data to obtain pixel signal information. The fit of the complex signal S_{21} requires calibration, rotation and scaling and is done by an FPGA, a GPU or a general processor.

MKID signal detection and noise

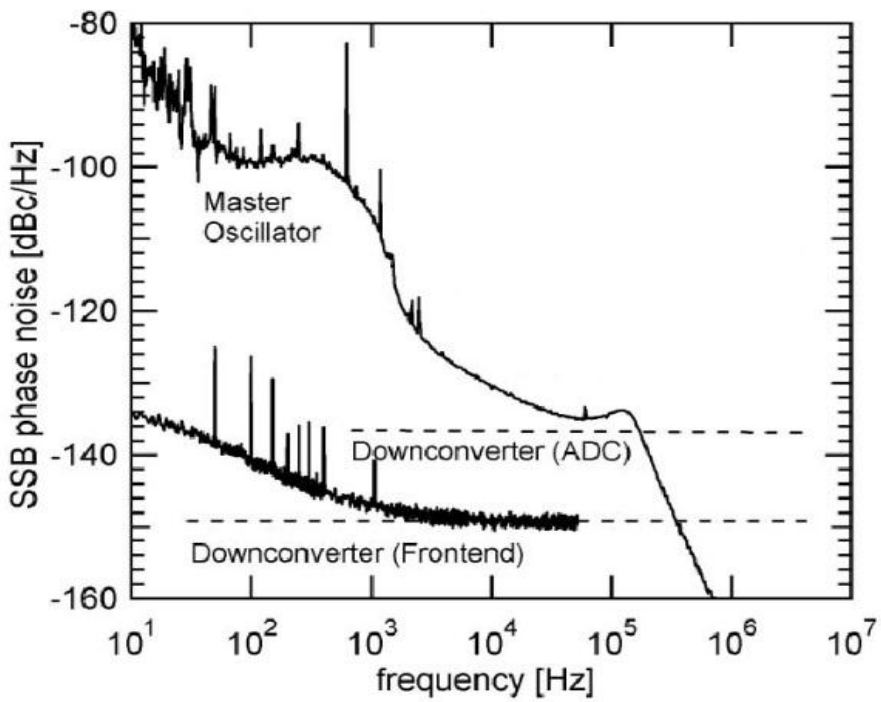
- MKIDs work on the principle that incident photons change the surface impedance of a superconductor through the kinetic inductance effect.
- One of the most attractive characteristics of MKIDs is single photon energy discrimination.
- An MKID pixel operates at a typical power between -85 to -100 dBm. The HEMT noise temperature is about 5 to 6 kelvin for the 2 to 8 GHz spectrum.
- The warm electronics should be able to excite and readout 2000 pixels in an RF feed line without introducing extra noise to the MKID-HEMT system. The warm electronic noise should be below -150 dB/Hz.

Highly multiplexed RF system

- A highly multiplexed and compact system requires a compact design.
- Low noise microwave RF analog and fast sampling ADC and DAC conversion. Special care must be taken to minimize noise at all levels at the same time we maximize the number of channels per board and minimize the total number of boards.
- RF systems are highly sensitive to signal degradation and crosstalk at interfaces and connectors, LO leakage, and high frequency noise from the digital electronics.
- RF systems require calibration due to temperature variations and drifts.

Highly multiplexed RF system

- The analog down converter phase noise is typically dominated by the phase noise in the master oscillator (MO). The MO noise couples through the local oscillator generating sidebands in the IF spectrum.



Temporal and spatial synchronization

- The system synchronization is provided by the master oscillator which is phase locked. The MO can be locked to a GPS which provides a 1pps synchronization signal. The DACs and channelizers must start at same time to provide a consistent phase for all the carrier bins. Absolute time of day is also required.
- DAC, ADC and FPGA synchronization is achieved using a phase locked loop clock distribution device with less than 200 femto second jitter. Data packets will contain a time stamp and a header indicating the spatial pixel location and the complex data.

System calibration

- As part of the data taking procedure each pixel's raw phase response must be mapped to photon energy. For instance the ARCONS camera has developed a system to uniformly illuminate the focal plane with three lasers at the same time before and after science observations, thereby providing a reference to calibrate each detector's response.
- The response for a single detector is given by a histogram using the number of counts for typically a minute of integration. The data is fit and processed to find the location of the laser wavelength providing the conversion to photon energy.

Data processing pipeline

- The data pipeline will be based on the ARCONS pipeline. Currently the following blocks have been developed or are under development:
  - Barycenter Photon Arrival Times
  - Cosmic Ray Cleaning
  - Wavelength Calibration
  - Flat field Calibration
  - Spectral Shape Calibration
  - Exposure Time Masking
  - RA/Dec Determination
  - Tip/Tilt Correction

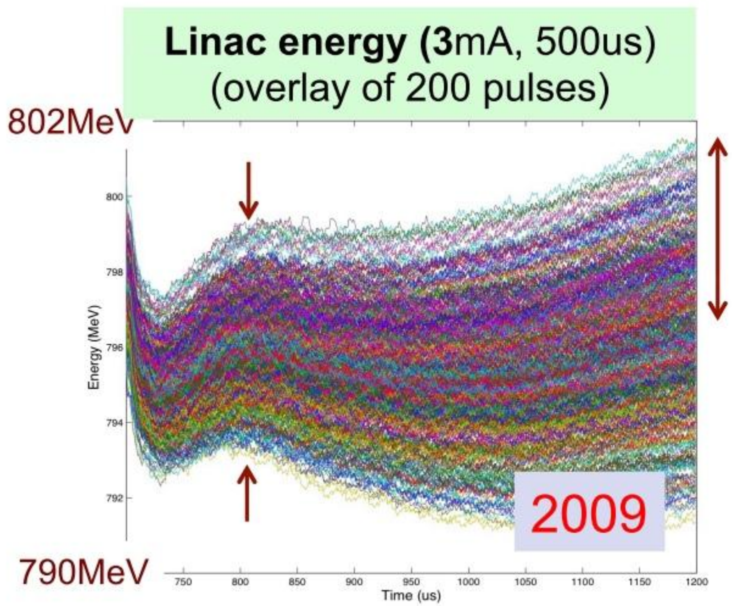
Timetable

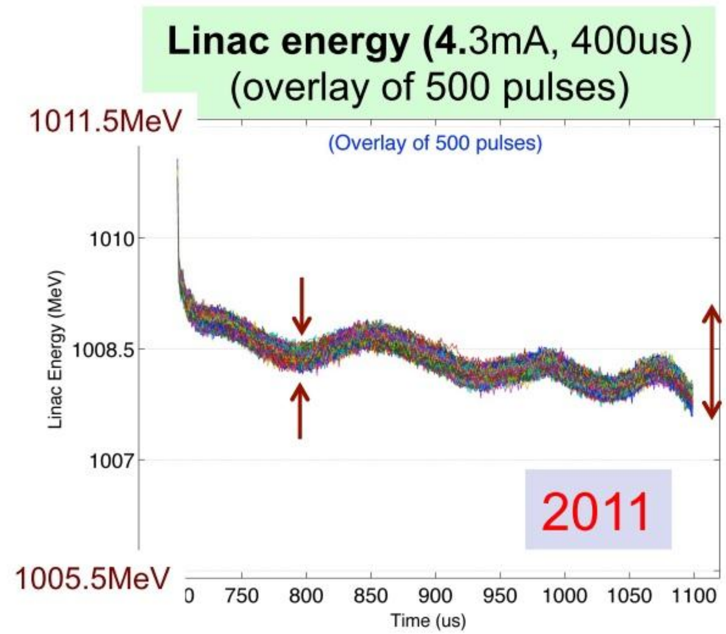
- FY 2014:
- Low noise amplifier (HEMT) characterization.
- Implementation of 2000 ch/RF line using ultra-fast DACs and ADCs.
- Design of a superconducting cable for 50 RF feed lines.
- MKID system testing and characterization.
- Firmware and software development.
-
- FY 2015:
- Multi transistor HEMT packaging.
- High BW data signal processing.
- Design of final RF up/down converters.
-
- FY 2016:
- Build part of the 100Kpixel readout system
- Finalize firmware and software development.

The ESE department at Fermilab

- 14 people and expanding:
  - 3 scientists, 7 engineers, 4 technicians, students.
- We have designed detector electronics and DAQ for large experiments during 30 years.
  - SVX tracker for CDF and D0,
  - Large triggers.
  - NOVA DAQ
  - Mu2e DAQ
- ~7 years of experience in RF electronics
  - ILC and SCRF LLRF.
  - Multi-channel RF. (32 channel)
- Detectors: too many to mention (Si strips, pixels, etc)
  - CCDs for Dark Matter (DAMIC).
  - Sub electron noise readout in CCDs.

9 mA experiment at DESY-FLASH





Delta-E over bunch-train: ~5MeV
Pulse-to-pulse jitter (p-p): ~4MeV

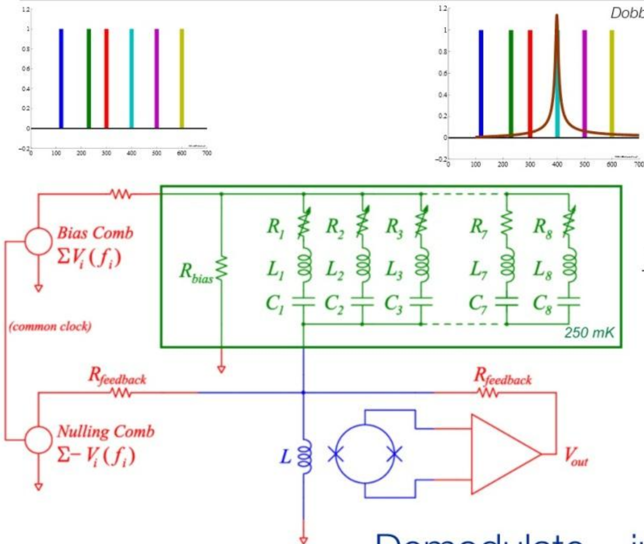
Delta-E over bunch-train: ~1.5MeV
Pulse-to-pulse jitter (p-p): ~0.4MeV

- Amplitude controlled better than 10^{-4}.
- Phase controlled better than 0.02 degrees.

Synergy with TES for CMB

Mar 12, 2013	Hornet's Nest, 10:30	Clarence Chang	Superconducting Technology and Measuring the Cosmic Neutrino Background

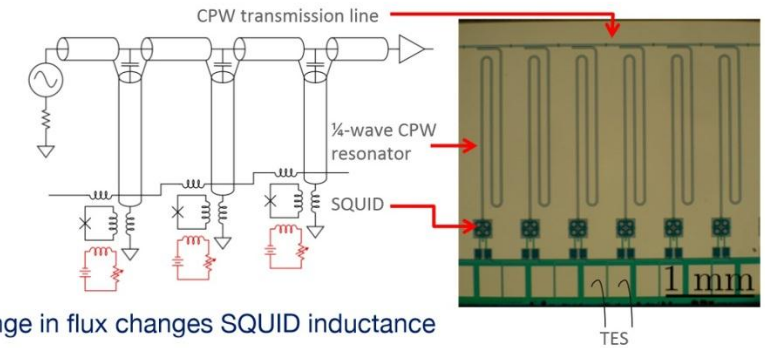
Dobbs et al., Rev. Sci. Instrum. 83, 073113 (2012)



$$I_i = \frac{1}{R_i(t)} V \cos(f_i t)$$

Demodulate... just like AM radio

Microwave-readout Massive SQUID Multiplexer



- Change in flux changes SQUID inductance
- at 1-10 GHz, can support ~1 MHz of bandwidth with ~1000 channels per line
- Originally developed for CMB measurements, recently demonstrated successful operation with X-ray u-cals

- The warm electronics for 100Kpixel MKIDs is very similar to what the TES-SQUID detector for CMB needs.

Thank you

Spare slides

Multichannel Receiver frontend + fast ADC board for prototype testing :
(DWC2.0, BAM1.0)

- Shielded subsections
- Strong AGND to RF GND connections
- Frontend mixer and ADC easily changeable

(Applications:
Bunch-arrival-monitors,
Beam-position-monitors,
Beam-based feedback,
LLRF passive-active)

LO distribution

VME

ADC:
(LT2207,16Bit, 105Msps)

Analog frontend:
(based on High IP3 Mixer HMC483)

IQ detection + fiber interface board :
(ACB 2.0)

- 1GBit/s Optolink,
- 1GBit/s Ethernet
(Rocket IO Interface approx. 350ns latency)

Fiber interface to SIMCON DSP (approx 400ns delay)

Clock shifting Unit:
(based on AD9510)

-FPGA pre-processing
(board 130ns latency)

- Macrobunch Buffer
(approx. 64MB)

Mu2e DAQ

SCD/FPE departments (ESE and ADSS) are developing the DAQ system and Tracker Readout Controllers. The DAQ is based on commercial components, with custom firmware and software. The software framework is ARTDAQ.

This is a “triggerless” architecture. Data throughput is 30 GBytes/sec. after zero-suppression. Filtering is done in 48 online processors (~40 TFLOPS).