Thursday 25 July 2019 11:45 [42] (15 minutes) Orals LM 004:
APP - Auditorium G. Testori Low Temperature Detector Applications

High-spatial resolution neutron imaging by using current-biased kinetic inductance detector

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CONTENTS

1. Several superconducting detectors have been very successful to provide competitive performances.
2. Our current-biased kinetic inductance detector (CB-KID) utilizes particularly the local nature of detector physics.
3. We developed a fast readout system (Kalliope-DC) for delay-line timestamps to achieve over-mega pixels imaging.
4. Neutron imaging of test mask absorber (100-μm ^{10}B dot array) showed a *-μm distance resolution using pulsed neutrons without doing center-of-gravity corrections.
5. A delay-line CB-KID can be used for identifying the XY positions of any mesoscopic excitations via 4-ch timestamps of TDC readouts.

Neutron radiography has strong demands and is waiting for LTD

Optical image

Neutron transmission image

http://www.shiei.co.jp/japanese/hou_nrt.shtml

Demands:

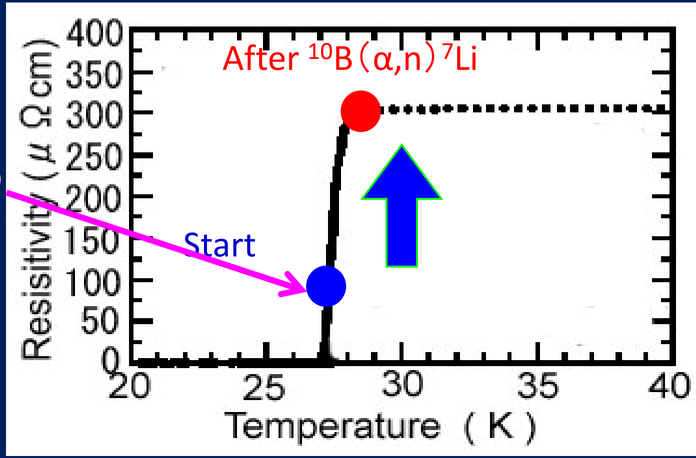
1. Easy observation of light elements (**H**, **C**, **Li**, **O**, etc.) in materials
2. Dynamics of **water** in fuel cells
3. **H** in grain boundary in iron alloys
4. **Carbon**/**water** in plant-soil systems

^{10}B in MgB_2

Our first attempt was MgB_2 because it contains neutron converting ^{10}B in itself.

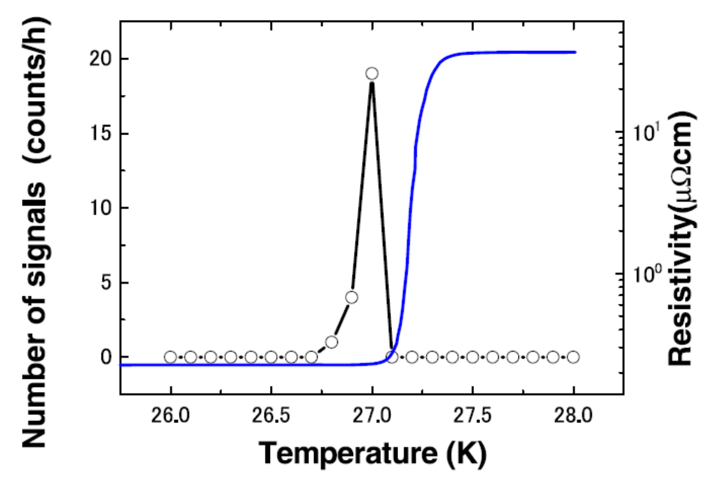
$$^{10}_{5}B + ^{1}_{0}n \rightarrow ^{7}_{3}Li + \alpha$$

0.88MeV 1.47MeV



1. Size 50μm x 50μm
2. Thickness 200nm
3. Line width 3μm
4. **Line length 0.35 mm**
5. Resistance 50Ω (30K)
6. Substrate is sapphires

Difficulties were
● homogeneity, ● multiplexing, ● bias tuning, ● low count rate, and ● sensitive area



T. Ishida *et al.*, J Low Temp. Phys. 151, 1074 (2008).

M. Machida *et al.*, J Low Temp. Phys. 151, 58 (2008).

Recent idea to utilize a superconducting neutron detector

Current-Biased Kinetic Inductance Detector (CB-KID)

Inductance of SC consists of magnetic inductance and kinetic inductance

hot spot

$$L = L_{\mathrm{m}} + L_{\mathrm{k}} + \Delta L_{\mathrm{k}}(t)$$

Local hot spot plays a crucial role.

$\Delta\ell \ll \ell$ $\quad$ $\Delta L_k \ll L_k$

Two-fluid model

$$\boldsymbol{n_s(T)} = n_s(0)\sqrt{1-\left(\frac{T}{T_c}\right)^4}$$

1 Magnetic inductance

$$L_{\mathrm{m}} = \frac{\mu l}{4\pi}$$

2 Kinetic inductance

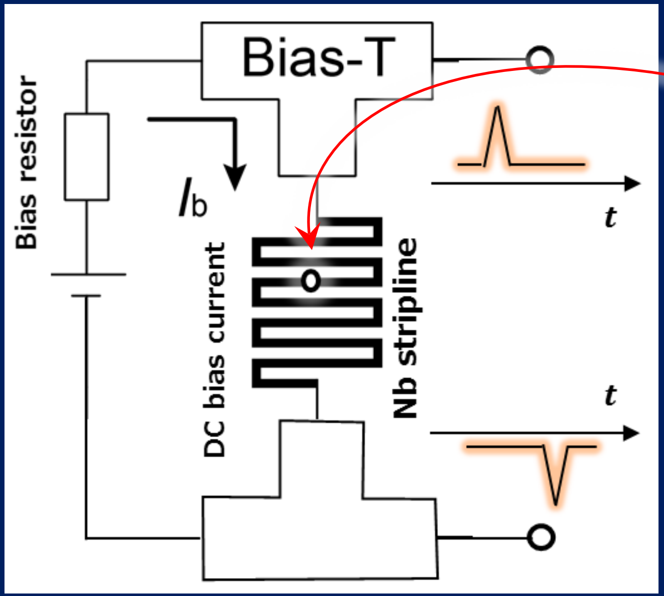
$$L_k = \frac{m}{n_s q^2}\frac{\ell}{S}$$

3

$$\Delta L_k = \frac{m}{n_s q^2}\frac{\Delta\ell}{S}$$

- m : Mass of Cooper pairs
- q : Charge of Cooper pairs
- n_s : Superfluid density
- S : Cross section
- $\Delta\ell$: Nanowire length of a possible hot spot

Of our interest is a very small kinetic inductance ΔL_k from a tiny hot spot $\Delta\ell$.



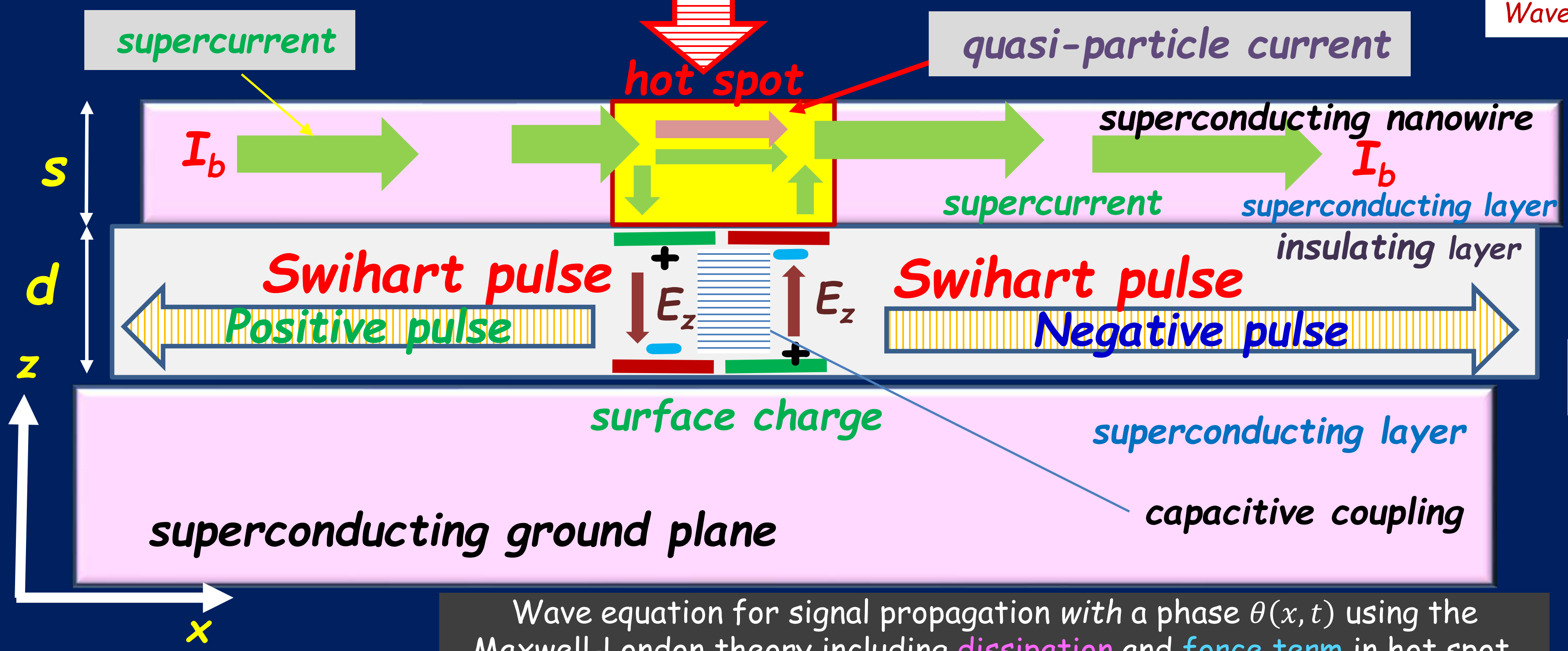
$$V(t) = \frac{d(LI_{\mathrm{b}})}{dt} = L\frac{dI_{\mathrm{b}}}{dt} + I_{\mathrm{b}}\frac{dL}{dt} \approx I_{\mathrm{b}}\frac{d(\Delta L_{\mathrm{k}}(t))}{dt}$$

Local detector

- CB-KID utilizes not a tiny fraction ΔL_k but a visible change $d\Delta L_k/dt$ to generate a very fast signal.
- Kinetic inductance is involved in a very restricted regime $\Delta\ell$.

Physics scenario for generating a pair of signals in CB-KID by stimuli

heat pulse by mesoscopic stimuli



J. C. Swihart, J. Appl. Phys. **32**, 461 (1961).

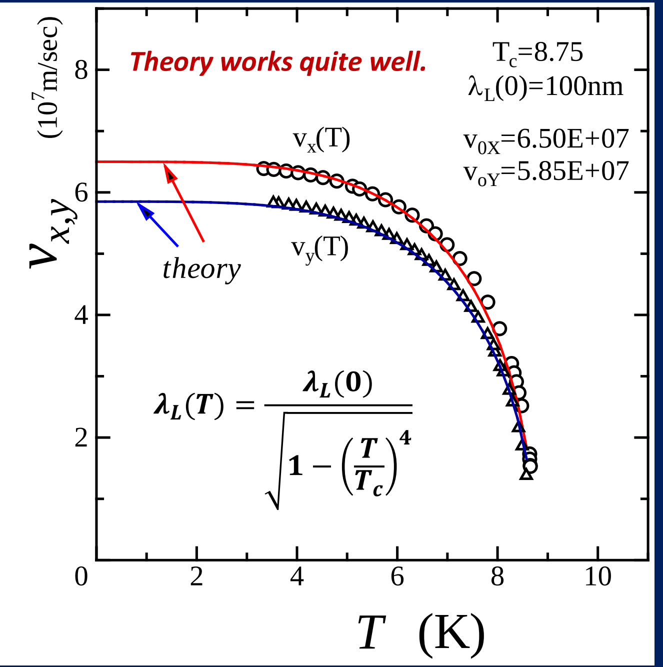
Wave-propagation equation outside of hot spot

$$\frac{1}{v^2}\partial_t^2\theta(x,t) - \partial_x^2\theta(x,t) = 0$$

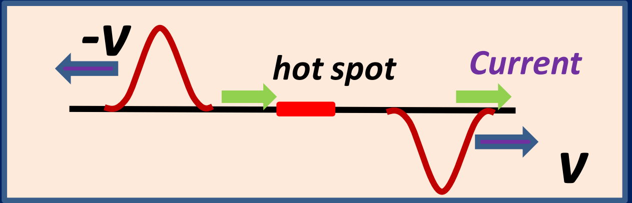
at a T-dependent velocity

$$v = \frac{c}{\sqrt{\epsilon}}\sqrt{\frac{d}{\left\{d + \lambda_L\left(1 + \coth\left(\frac{s}{\lambda_L}\right)\right)\right\}}}$$

where s=40 nm and d=250 nm and λ_L of two fluid model



Wave equation for signal propagation *with* a phase $\theta(x,t)$ using the Maxwell-London theory including dissipation and force term in hot spot.



$$\frac{1}{v^2}\partial_t^2\theta(x,t) - \partial_x^2\theta(x,t) - \frac{\gamma}{c}\partial_t\partial_x^2\theta(x,t) = F(x,t)$$

Expression of pulsed signal and kinetic inductance is given by

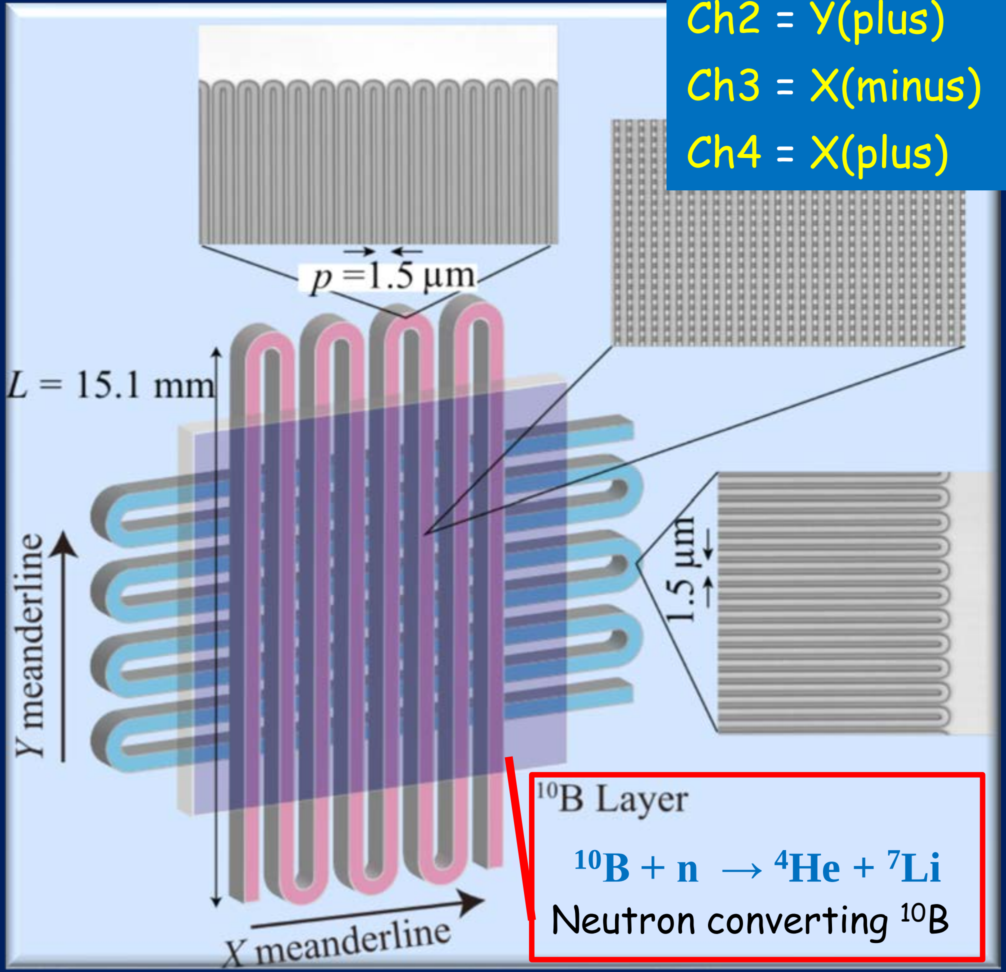
$$V(x,t) = \frac{\partial}{\partial t}L(x,t)\cdot I$$

$$L(x,t) = -\frac{4\pi\lambda_L^2}{s\,c^2}\int_{-\infty}^{\infty}dx'\int_0^{\infty}dt' G(x-x',t-t')\frac{\partial_x\zeta(x',t')}{\zeta(x',t')}$$

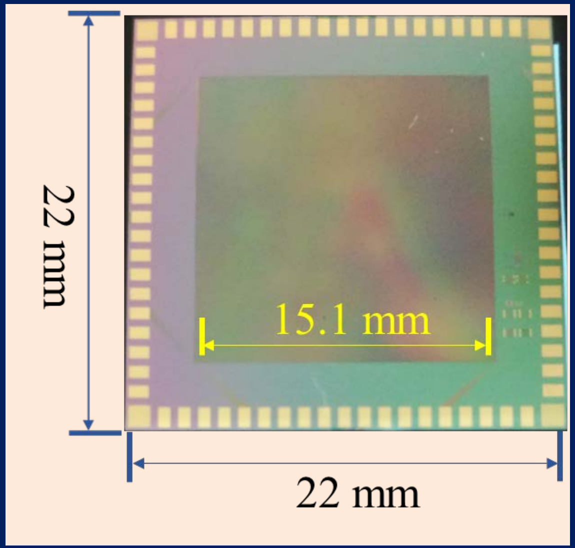
T Koyama, T Ishida, *J. Phys. Conf. Ser.* **1054** 012055 (2018) & in press (2019).

Delay-line CB-KID using crossing Nb-nanowire meanderlines with ^{10}B converter layer

Ch1 = Y(minus)
Ch2 = Y(plus)
Ch3 = X(minus)
Ch4 = X(plus)



CB-KID (22mmNW05B)



Delay-line method

- The differences in the timestamps Δt_x and Δt_y of pulsed signals arrived at anode and cathode.
- The position of nuclear event (x, y) is given by

$$\begin{cases} x = \left(\dfrac{\Delta t_x v_x}{2h_x}\right) p_x \\ y = \left(\dfrac{\Delta t_y v_y}{2h_y}\right) p_y \end{cases}$$

p_x, p_y : pitch
v_x, v_y : velocity
h_x, h_y : segment length

Nb meanderline

- # of lines = 10000
- Length of segment = 15.1 mm
- Line width = 0.9 μm
- Line separation = 0.6 μm
- Nb thickness = 40 nm
- Sensor area =15 mm × 15 mm

- **Total length = 151 m**

Spatial resolution

v_x=6x10^{7}m/s
h_x=15.1mm
p_x=1.5μm

$$\Delta x_p = \left(\frac{1ns \times v_x}{2h_x}\right) p_x$$

Δx_p=3μm *can be expected as the best resolution !*

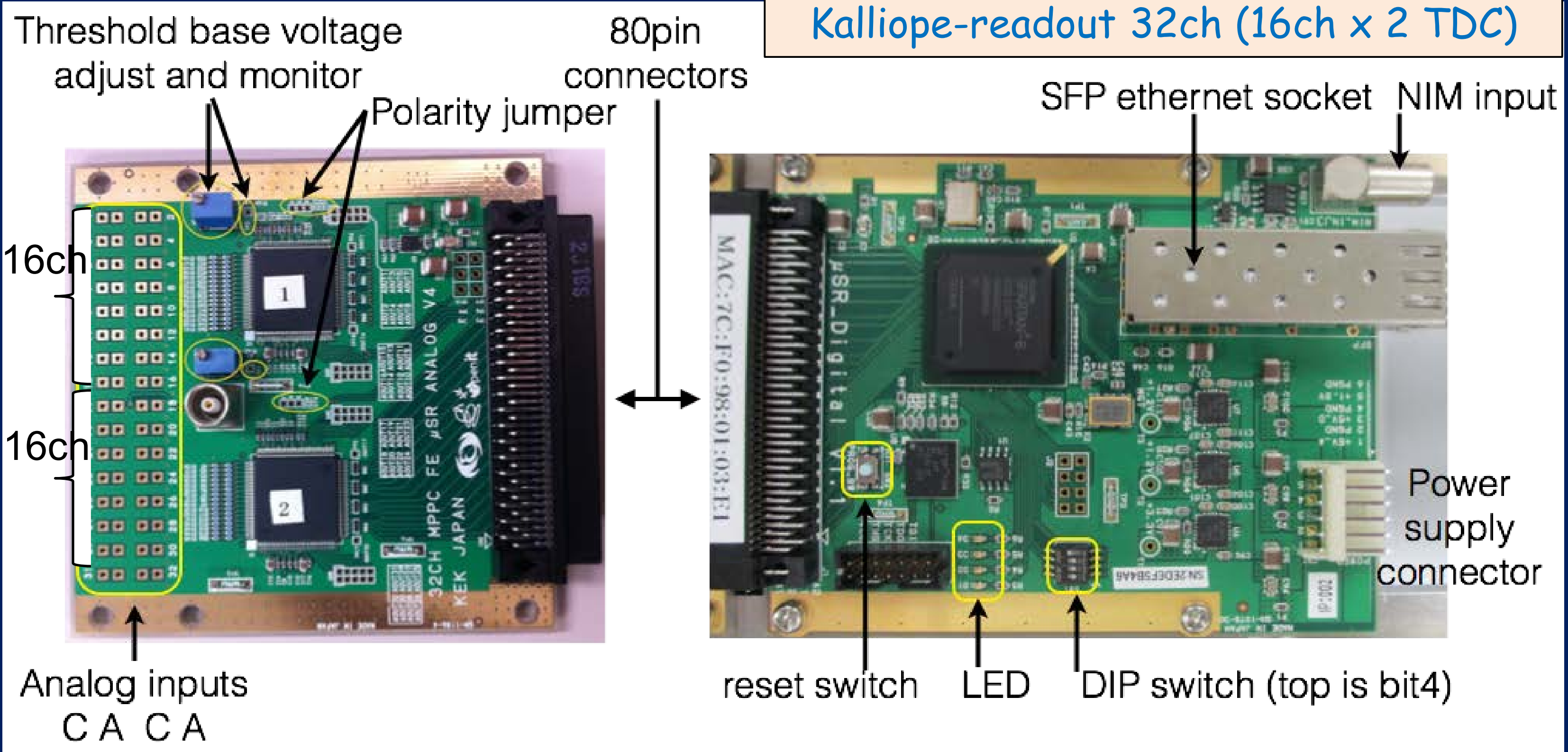
Preceding publication on smaller CB-KID (10mmx10mm):
H. Shishido et al., Phys. Rev. Appl., **10**, 0440440 (2018)

Transmission image of ladybird, nuts, bolts, and ^{10}B dot array via KALLIOPE readout

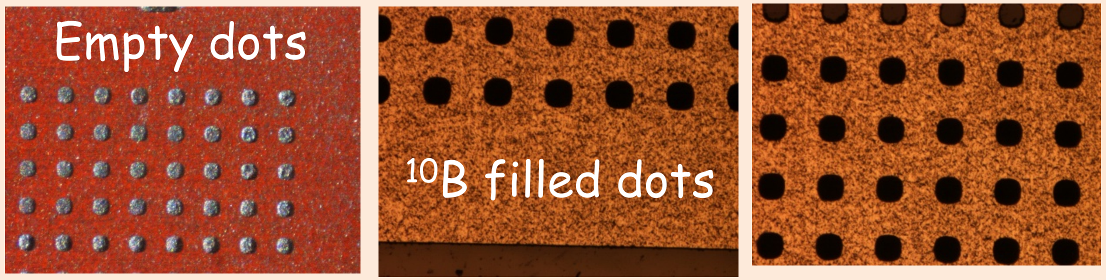
The Dang Vu et al., in preparation

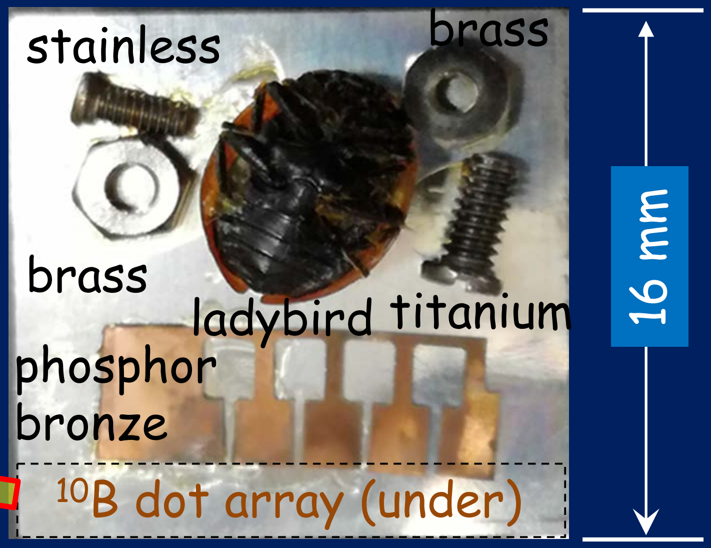
- Oscilloscope data are time consuming and not efficient for pulsed neutrons.
- Timestamps are needed and more essential to be acquired for imaging.

Kalliope-readout 32ch (16ch x 2 TDC)



Pitch 250 µm (CAD)
Dot size was 106µm
in square lattice holes
by wet etching of
SUS304-HTA 50µm†

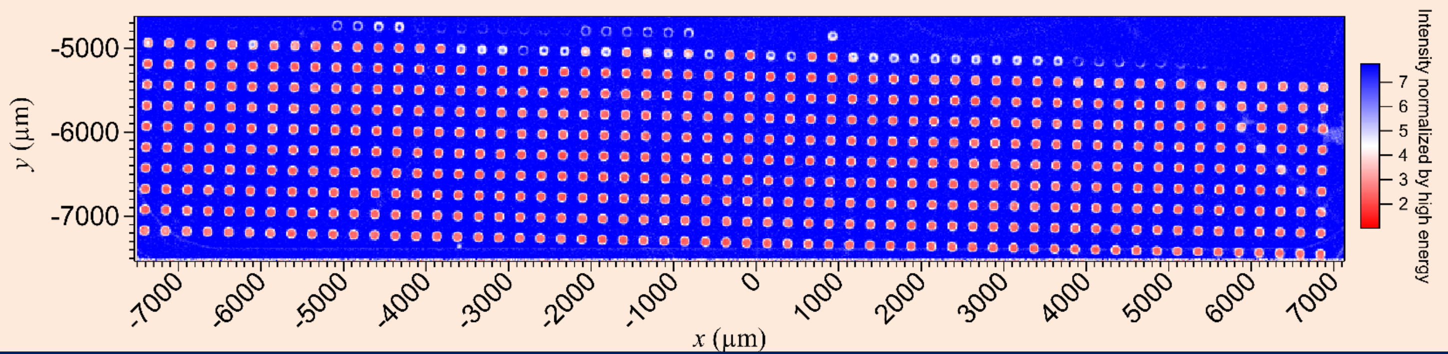




Spatial resolution by measuring distance resolution

The Dang Vu et al., in preparation

- Preceding work demonstrated a resolution of 22 μm on the basis of the sharpness of ^{10}B dot boundaries.
- However, the test sample had some rounding effect of the edge caused by wet etching in producing holes.
- A pitch of ^{10}B dots is of much higher precision because the test mold of stainless steel was fabricated by CAD.



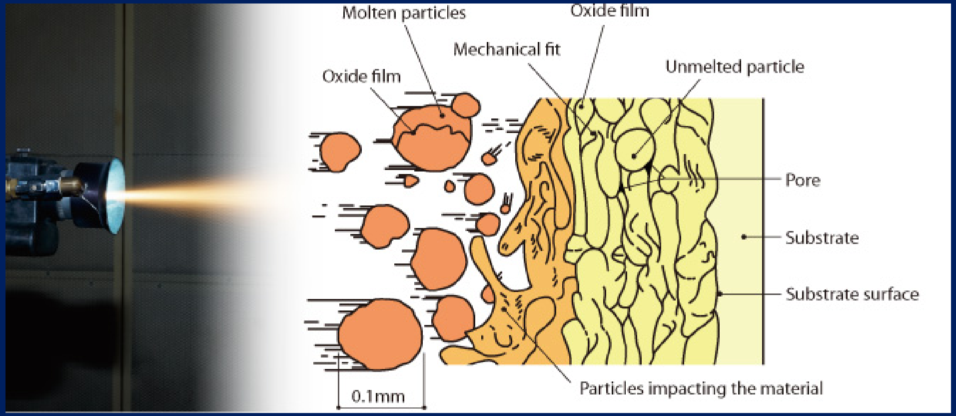
Best possible resolution by 1ns TDC

$$\Delta x_p = \left(\frac{1\text{ns} \times v_x}{2h_x}\right) p_x = 3.24\ \mu\text{m}$$

$$\Delta y_p = \left(\frac{1\text{ns} \times v_y}{2h_y}\right) p_x = 2.86\ \mu\text{m}$$

Realistic neutron transmission imaging of distributed Gd islands

The Dang Vu et al., in preparation



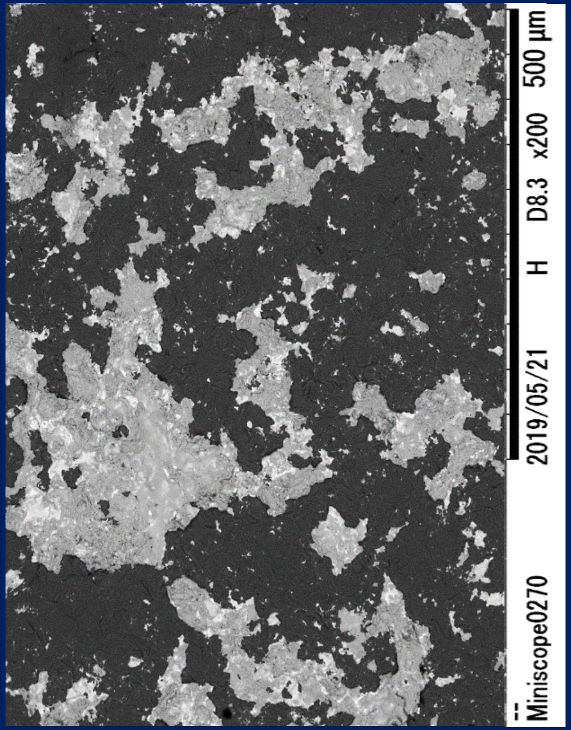
Gd is a good neutron absorber

- Gd islands smaller than 20-μm tick marks can clearly be seen.
- We consider that CB-KID imager will be used in analyzing realistic interesting systems.

Thermal spray deposition technique was used to prepare a realistic test sample of Gd metal.

SEM observation

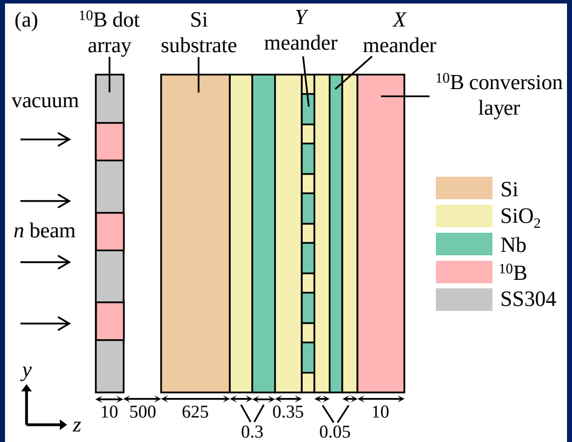
- Gd sample was prepared as islands with random sizes and thicknesses
- There are many small regimes of Gd islands



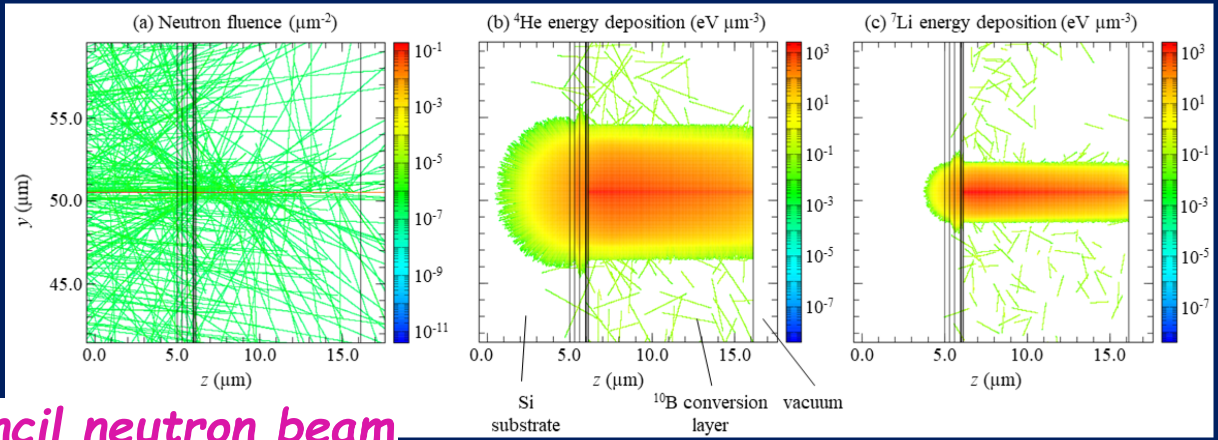
PHITS Simulations of CB-KID for Imaging and Efficiency

Monte Carlo code: Particle and Heavy Ion Transport code System (PHITS) Alex Malins et al., submitted to.

PHITS simulates neutron, ^{4}He, ^{7}Li, photon, electron, ^{10}B(n,alpha)^{7}Li, energy deposition



CB-KID model

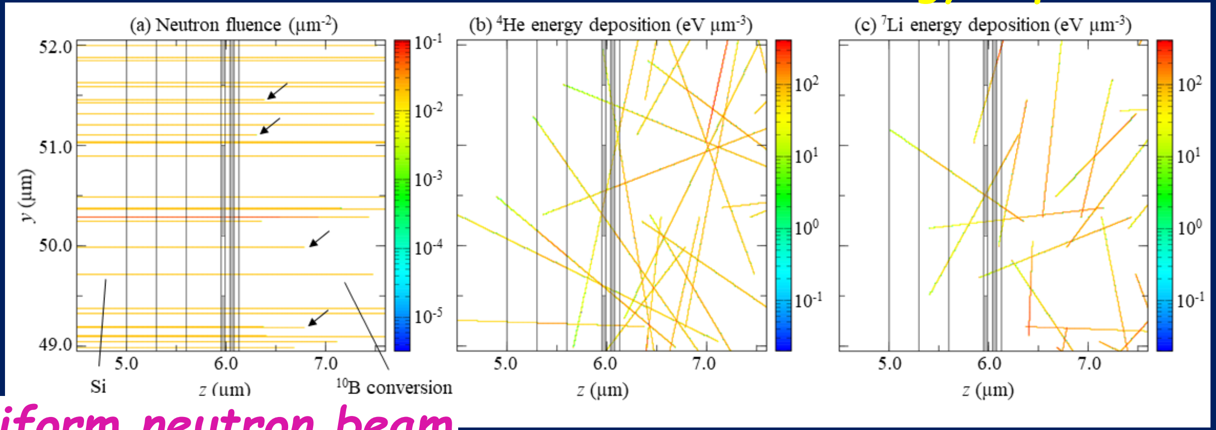


Pencil neutron beam

Neutron fluence

^{4}He energy deposition

^{7}Li energy deposition



Uniform neutron beam

- *PHITS is a powerful tool to assist in designing a superconducting detector !*
- *Detection efficiency of 10% could be achieved for neutrons using a single CB-KID.*

Summary

1. We proposed a delay-line Current-Biased Kinetic Inductance Detector (CB-KIDs) to image location of mesoscopic hot-spots.
2. The CB-KID has several merits of four readouts, small bias currents, zero-resistance operation, and local response.
3. Local breaking of the Cooper pairs creates electromagnetic pulses with opposite polarities, propagating towards the ends.
4. Our system demonstrated a spatial resolution of * μm and *-mega-pixel imaging with TDC of 1-ns resolution.
5. Our system has a good multi-hit tolerance in contrast with other techniques.
6. PHITS simulations are powerful in optimizing a structure of CB-KID as a superconducting neutron detector.

Future works

1. Development of high-speed TDC readout circuit for improving spatial resolution
2. Fabrication technique and optimized design of CB-KID for reliable reproduction with the aid of PHITS simulations.
3. On-line monitoring of transmission image of neutrons.
4. A two-facing CB-KID detector to achieve a higher resolution by compensating randomness of projectile-ion directions.
5. Compact refrigerator to cool down a four-lead CB-KID detector of small heat load.
6. Applications of CB-KID technique to image other sorts of mesoscopic excitations.

Thank you for your kind attention !