Superconducting Tunnel Junction Detectors

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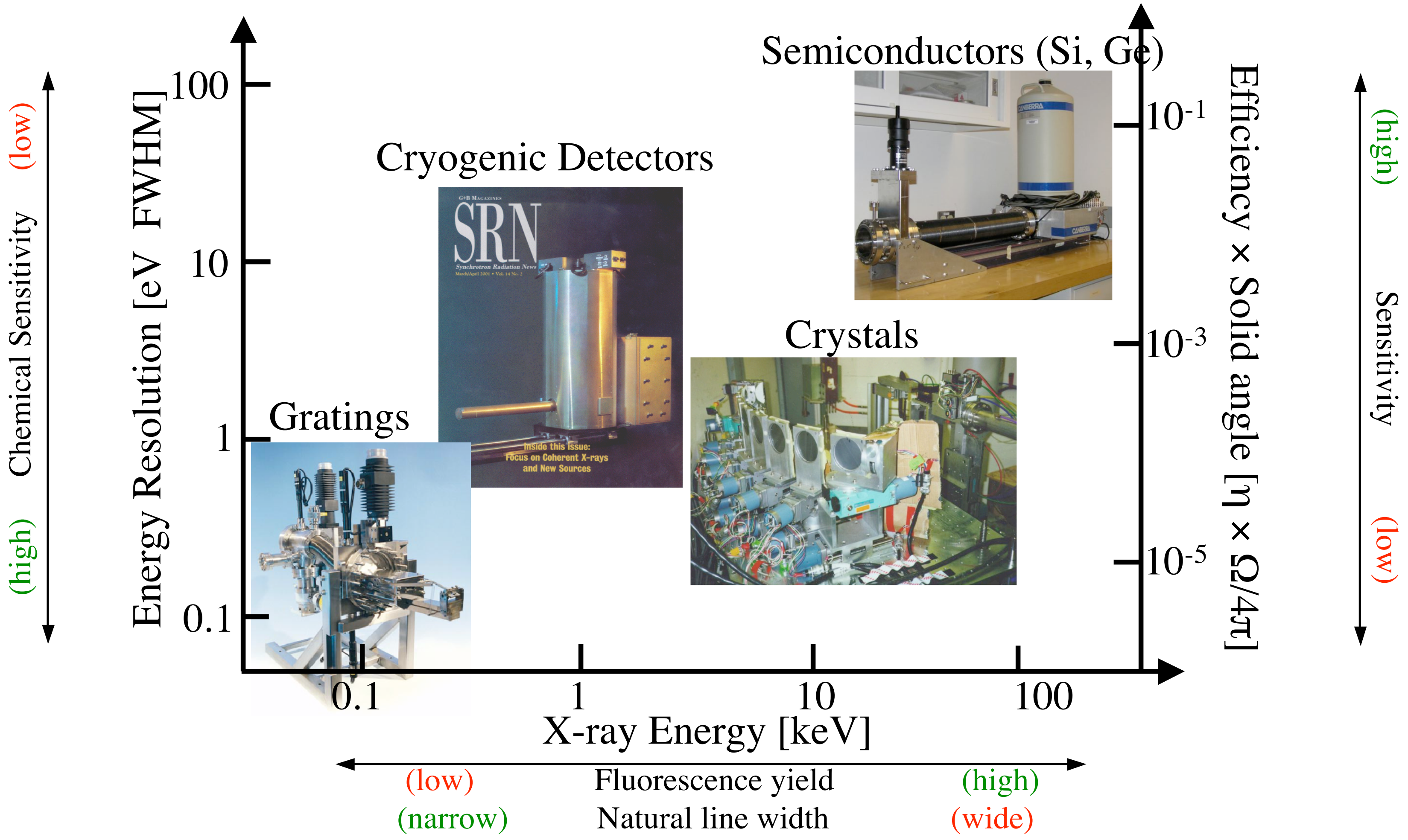
ABEX
Advanced Biological and
Environmental X-Ray Spectroscopy

Advanced Detector Group, LLNL
Advanced Biological and Environmental X-ray Facility, LBNL

Outline:

I. Overview: Why STJ detectors, and for which applications?
II. Science: The chemistry of dilute samples by X-ray absorption spectroscopy (XAS)
III. Detector requirements for XAS
IV. STJ detector development roadmap

I. Overview: Why Cryogenic Spectrometers?



Cryogenic detectors offer advantages when better energy resolution than Ge or Si *and* higher efficiency than grating spectrometers are needed.

And then there are other analytical techniques: EPR, Raman, FTIR, Mössbauer, SIMS...

Cryogenic Detector Technologies

	Tunnel Junctions	Microcalorimeters
Operating principle	$E \Rightarrow \delta Q$ (electrons)	$E \Rightarrow \delta T$ (phonons)
⇒ Max volume	low ($\Rightarrow E_x < 10$ keV)	high ($\Rightarrow E_x <$ MeV)
Energy resolution	$[1.7\Delta_{sc}E_x(F+1+1/\langle n\rangle)]^{1/2}$	$[k_B T^2 C_{abs}(\alpha/n)^{1/2}]^{1/2}$
	~2 - 10 eV FWHM	~1 - 5 eV FWHM
Max. count rate	~30,000 cts/s	~500 cts/s
Device resistance	High, > 1000 Ω	Low, < 0.1 Ω
⇒ Electronic readout	FET at room T	SQUID at 4 K
Max. operating T	~0.5 K	~0.1 K
Dead layer?	no	no

X-ray astrophysics

Nuclear science,
Dark Matter

Microcalorimeters are preferred for highest energy resolution and large volume absorbers.
Tunnel junctions are preferred for high speed applications.

Synchrotron applications

Cryogenic Detector Group

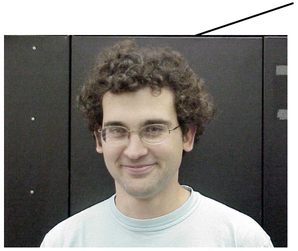
Advanced Detector Group
Bill Craig, Group Leader

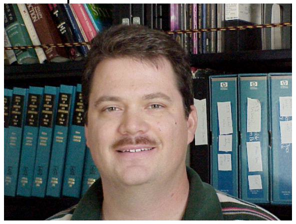
Cryogenic Detector Group
Stephan Friedrich

Radiation Detection Center
Simon Labov, Director

Microcalorimeters (TES)

Tunnel Junctions (STJ)





<u>X-ray Detectors</u>

Stephane Terracol

<u>X-ray Astronomy</u>
(NASA)
<u>Atomic (ion) physics</u>
J.P. Briand, U Paris

<u>Gamma Detectors</u>

Shafinaz Ali

<u>Nucl. Non-proliferation</u>
(DOE NA-22)
D. Donohue, IAEA
J. Halverson, SRTC

<u>Neutron Detectors</u>

Thomas Niedermayr, Dragos Hau

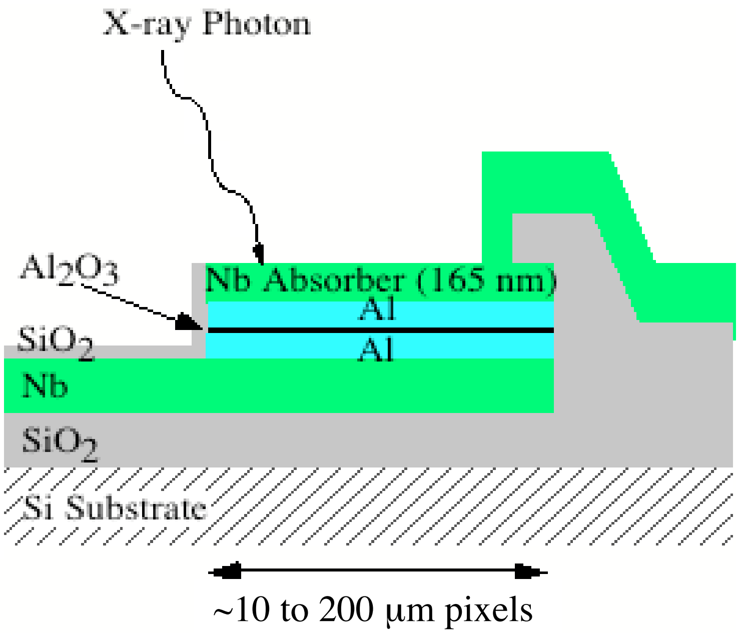
<u>Nuclear Physics</u>
(DOE NA-22)
J. Vujic, S. Prussin, UC Berkeley
Z. Bell, ORNL
A. Burger, Fisk U

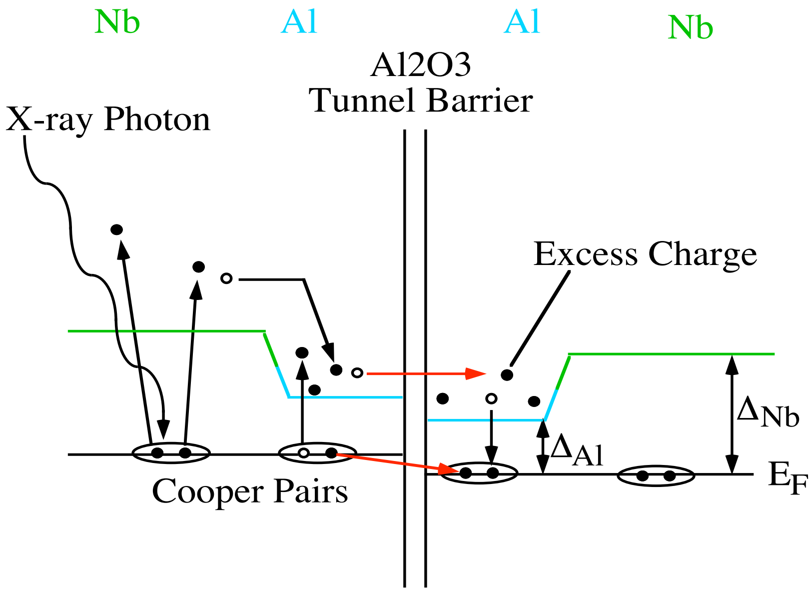
<u>X-ray Detectors</u>

Owen Drury

<u>Biophysics, Env. Science</u>
(DOE-OBER, NIH-GM)
S.P. Cramer, UC Davis
<u>Material Science, Astronomy</u>
(NSF-MRI, UC-CLE, NASA)
J.E. Harris, Stanford
A. Jones, K. Nealson, USC

Superconducting Tunnel Junction Detectors





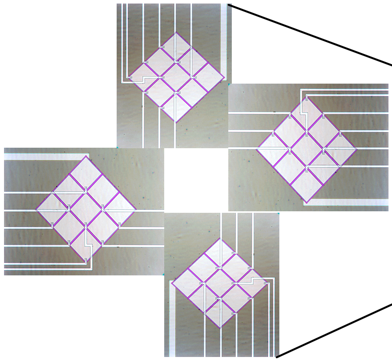
Signal = Current Pulse

$$E_{FWHM} = 2.355\sqrt{(1.7\Delta E(F+1+1/\langle n\rangle)}$$

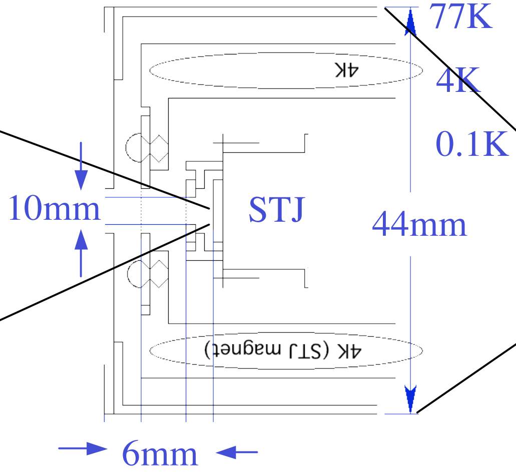
Small energy gap (Δ≈1meV) ⇒High energy resolution (≈10 eV FWHM)
Short excess charge life time (μs) ⇒ (Comparably) high count rate (≈10,000 counts/s)

STJ Spectrometer

200 × 200µm² STJ pixels
36 pixels at ~8 mm



Cold finger schematic



G+B Magazines

SRN

Synchrotron Radiation News

March/April 2001 • Vol. 14 No. 2

Inside this issue:
Focus on Coherent X-rays
and New Sources

10-15 eV FWHM below ~1keV, ~10^6 counts/s total, solid angle coverage $\Omega/4\pi \approx 10^{-3}$
Quantum efficiency set by window transmission (low E) and Nb absorption (at high E).

II. Science: X-ray Absorption Spectroscopy

Synchrotron beam

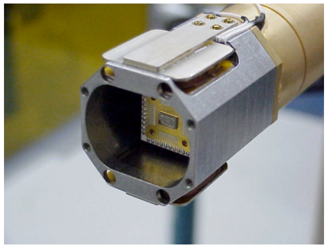
Monochromatic, tunable
$I_0 \approx 10^{12}$ photons/s, $\Delta E = 0.1$ eV

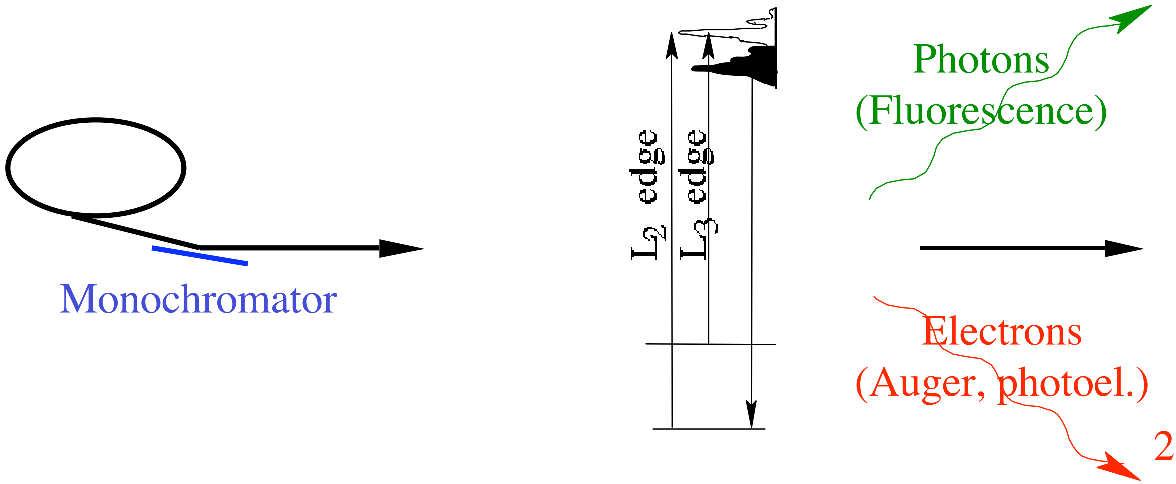
Sample x

Absorption $\mu_x(E)$

Detection

3) Fluorescence: S/N ~ $\mu_x / \sqrt{\mu_x}$





Monochromator

L_2 edge

L_3 edge

Photons
(Fluorescence)

Electrons
(Auger, photoel.)

1) Transmission: S/N ~ $\mu_x / \sqrt{I_0}$
Thin samples, high background

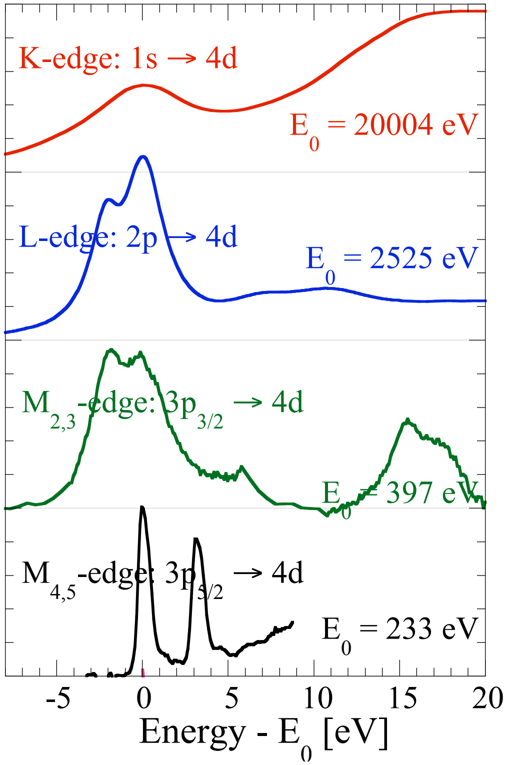
2) Electron signal: S/N ~ $\mu_x / \sqrt{\mu_{total}}$
Surface sensitive, moderate bgnd.

Fluorescence-detected XAS enables chemical analysis of dilute samples, if…

1) The detector can resolve characteristic X-ray fluorescence of interest,
2) Offers count rate capabilities sufficient for total fluorescence flux,
3) Covers a large solid angle for high sensitivity.

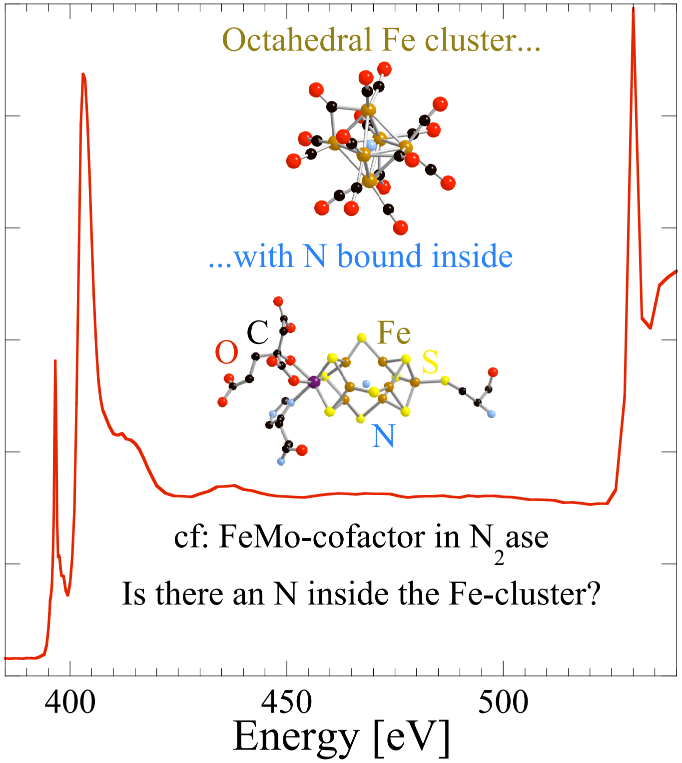
XAS: Chemistry of dilute samples

Mo edges in $NaMoO_4$



For example:
Bio-inorganic
chemistry

$Fe_6(CO)_{15}N$ model compound



cf: FeMo-cofactor in N_2ase

Is there an N inside the Fe-cluster?

courtesy
R. della Pergola
U. of Milan

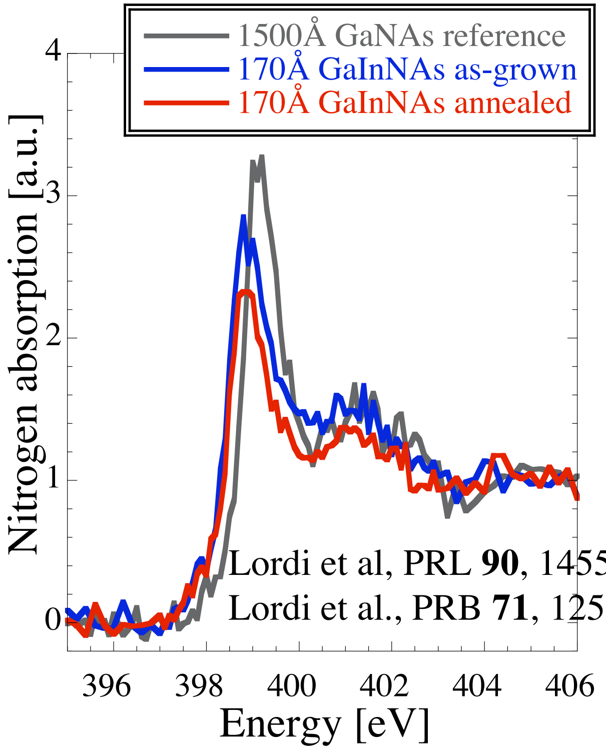
Chemical sensitivity increases for low-energy transitions.

(Longer life times ⇒ Narrower transitions ⇒ Smaller chemical shifts detectable)

Low fluorescence yield so far prevents analysis of higher edges of more dilute heavy metals.

Material Science: Dopants and Impurities

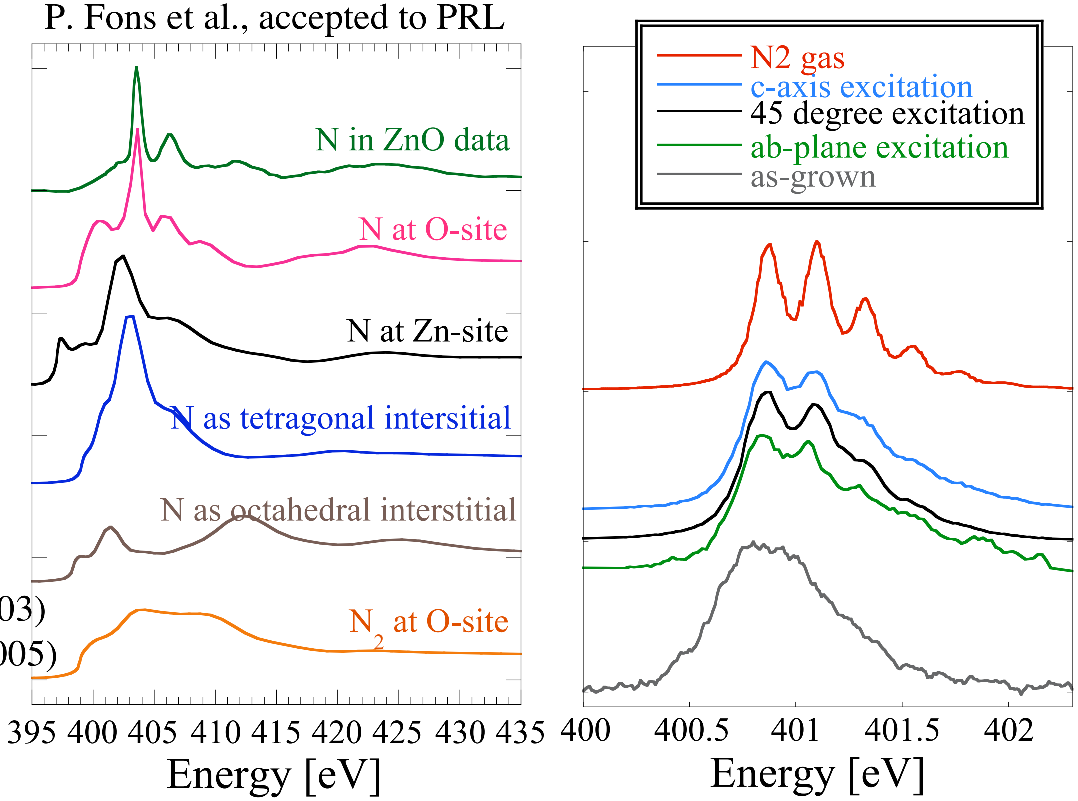
III-V semiconductors
for telecommunications



Lordi et al, PRL **90**, 145505 (2003)
Lordi et al., PRB **71**, 125309 (2005)

N dopants in wide bandgap semiconductor ZnO

P. Fons et al., accepted to PRL

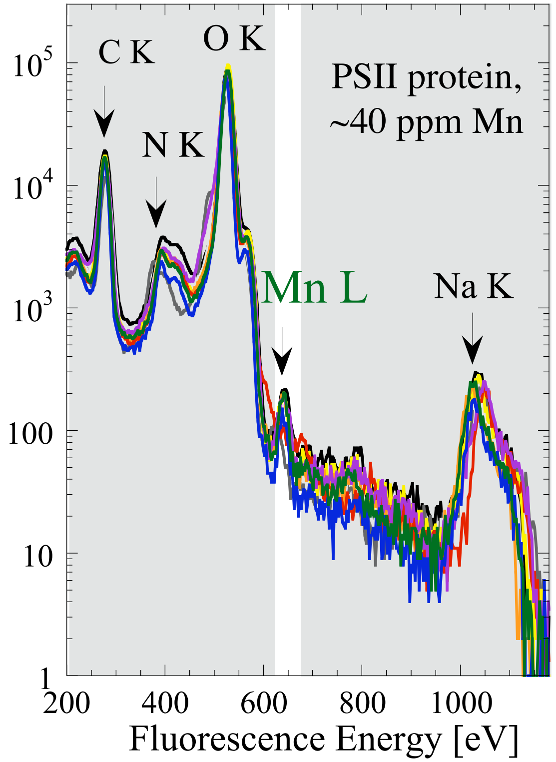


Chemical analysis of ~1% N in a ~100Å buried film is possible in ~1 hour.

Analysis of more dilute dopants or of impurities is not.

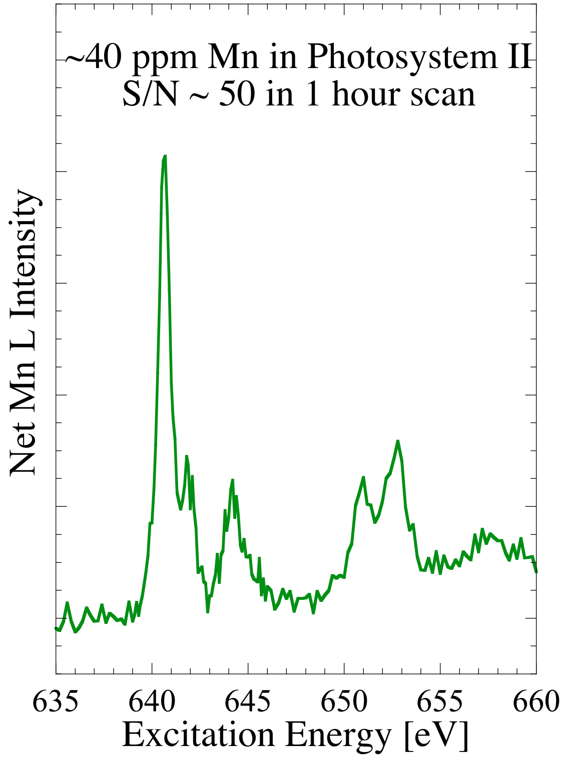
Biophysics: Protein Reaction Mechanisms

STJ detector response



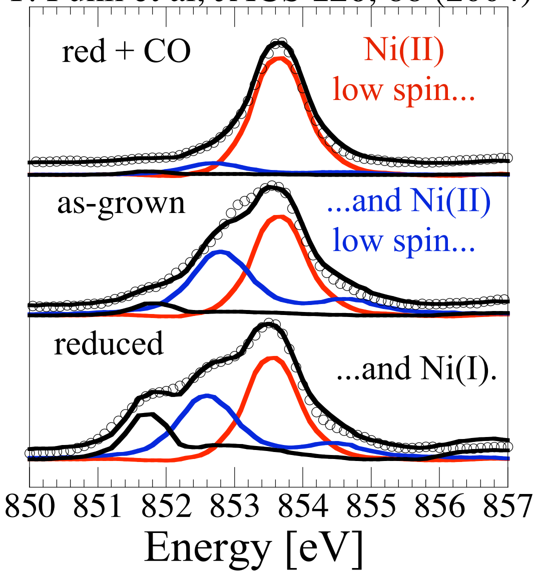
e.g. oxygen evolution

S. Friedrich et al., SRI-8



e.g. carbon binding: ACDS

T. Funk et al, JACS **126**, 88 (2004)



Also:

Nitrogen fixation: N_2ase

Hydrogen production: H_2ase

Analysis of concentrated proteins (~100 ppm, mMolar) is possible in ~1 hour.

Analysis of protein solutions is not, and 1 h at 10^{12} photons/s is too long for many proteins.

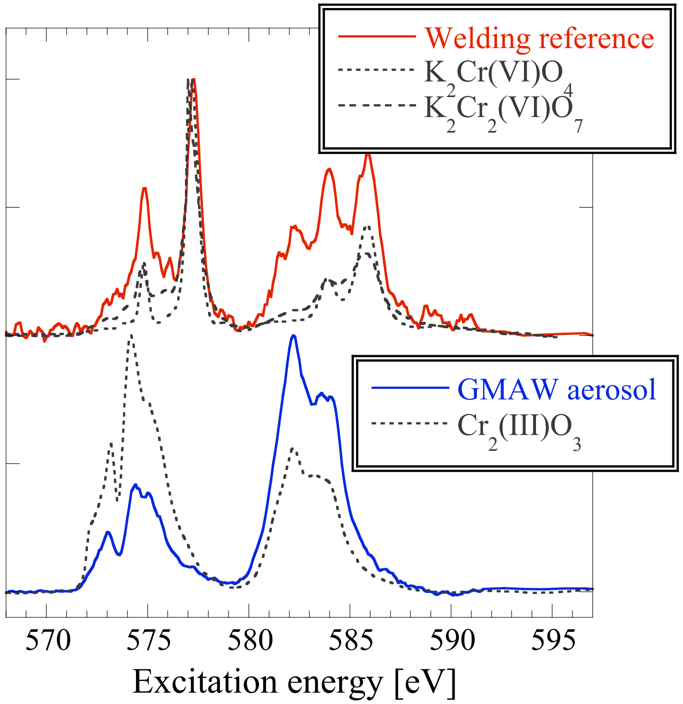
Radiation damage makes low-flux beam lines competitive with higher efficiency detectors.

Environmental Heavy Metal Contaminations

Heavy metal toxicity ⇔ Bio-availability ⇔ Solubility in water ⇔ Oxidation state

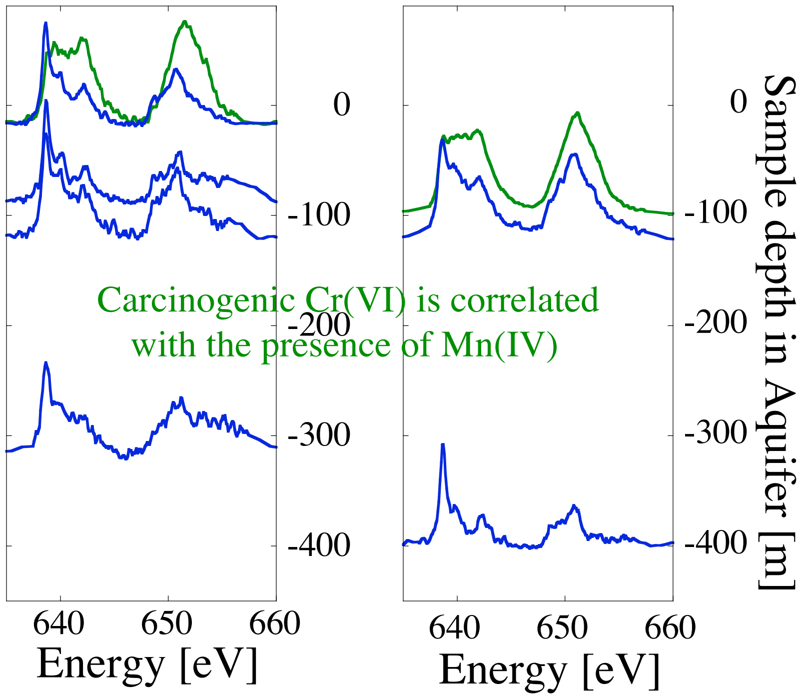
Cr in welding aerosols

S. Friedrich et al., NIMA (2006)



Natural Cr oxidation by biogenic Mn(IV)

S. Friedrich et al., submitted to Nature



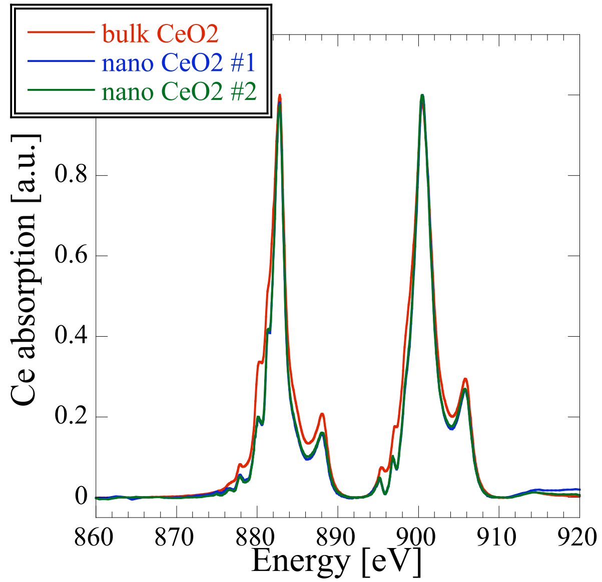
Carcinogenic Cr(VI) is correlated with the presence of Mn(IV)

Again, ~100 ppm samples can be analyzed, but ppb contaminations can still be relevant.

From Nanoscience to Medical Imaging

Subtle spectral changes in nano-size samples

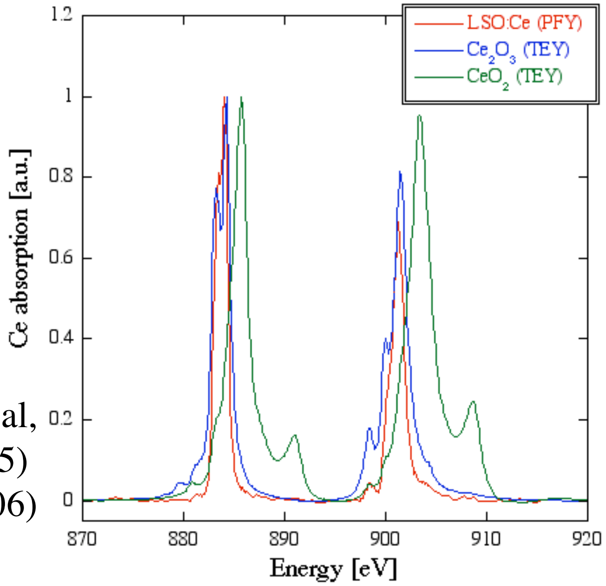
Are spectral changes related to different chemical behavior of nanoparticles (e.g. in catalysis)?



Ce activators in LSO scintillators for PET

Ce is a widely-used activator in scintillators, and only Ce(III) is optically active.

Melcher et al, TNS (2005) NIMA (2006)



Chemical analysis of dilute samples by soft X-ray spectroscopy has a vast range of applications.

Higher sensitvity for more dilute samples would be very desirable.

BL 4.0.2 is the most desirable beam line at the ALS (8-times oversubscribed).

III. Detector requirements

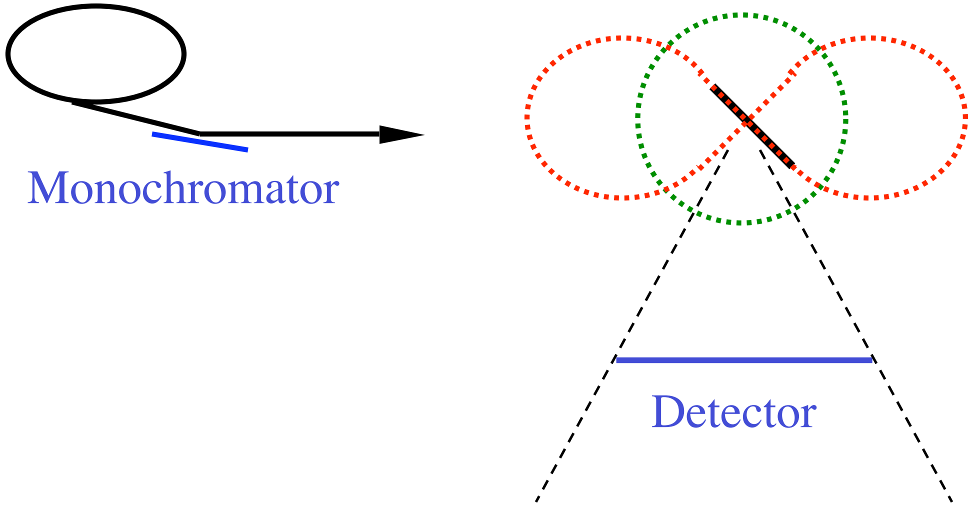
Synchrotron beam

$I_0 \approx 10^{12}$ photons/s

Sample x

Concentration c_x

Fluorescence yield ε_x



Isotropic Signal:

$$I_x(E_F) \approx I_0 \frac{\mu_x(E_0)\varepsilon_x}{\mu_{tot}(E_0)+\mu_{tot}(E_F)} \frac{\Omega}{4\pi} \eta_{\mathrm{det}}$$

Anisotropic Scatter:

$$I_{scatter} \propto Z^2 (1+\cos^2 \Theta)$$

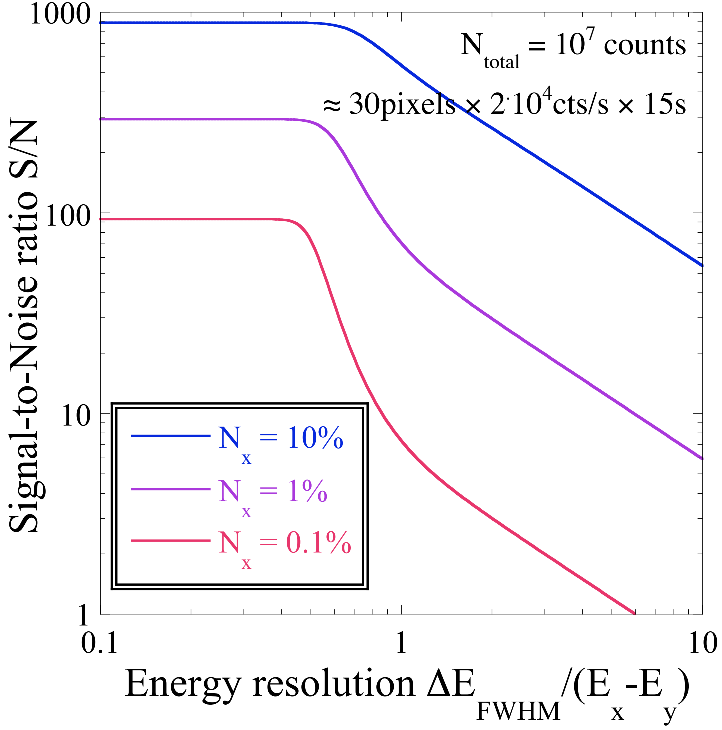
1) Energy resolution: Sufficient to resolve weak characteristic X-ray fluorescence
2) Count rate: Sufficient for total flux at minimum detector distance of ~8 mm
3) Solid angle: Covering entire area where scatter does not dominate
4) Peak-to-background ratio: As high as possible

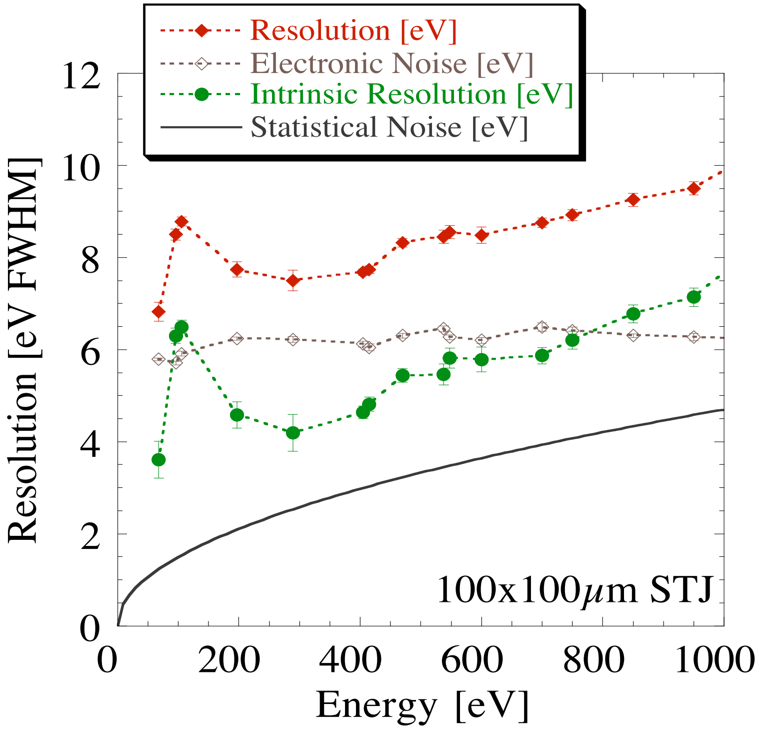
Which Energy Resolution do we need?

Once the lines are fully resolved, i.e. $E_{FWHM}<E_{separation}/3$, S/N does no longer depends on resolution for high P/B

The energy resolution of STJ detectors is <10 eV FWHM for energies below 1 keV

O. Drury et al., TAS **15**, 613 (2005)



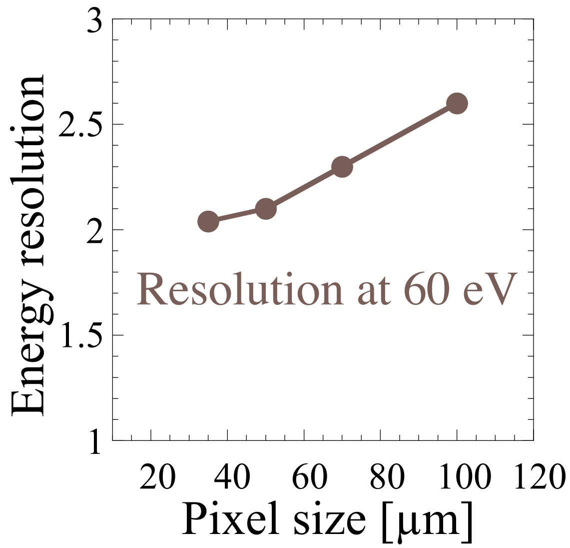


Line separations for soft X-rays are typically no less than ~50eV ⇒

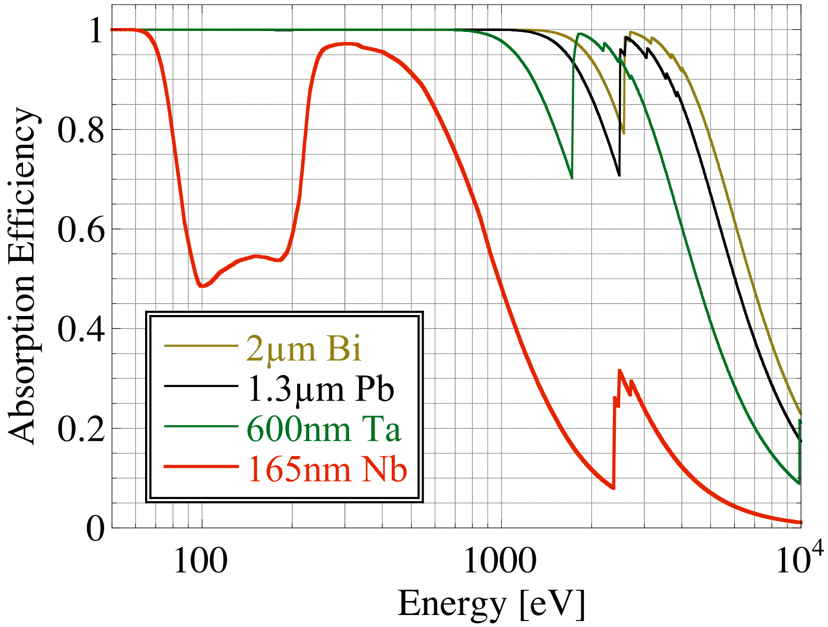
The current STJ energy resolution of 10-15 eV below 1 keV is sufficient.

How big and efficient can we make an STJ pixel?

Resolution degrades for large pixels, which are limited in size to ~200×200μm^2



QE close to 1 is achievable for Ta and Pb-based STJs



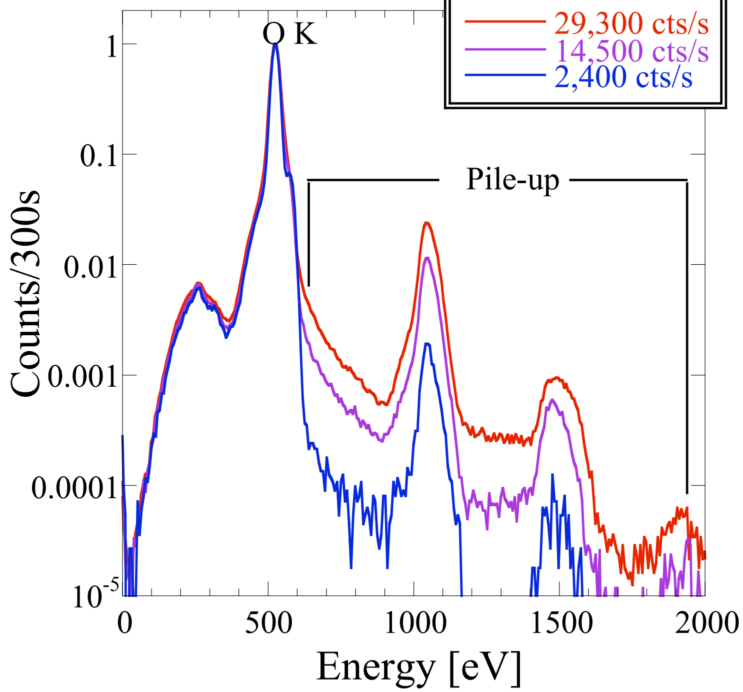
Three IR windows limit QE for very low E < 200eV
They also limit distance of STJ to sample to ~8 mm.

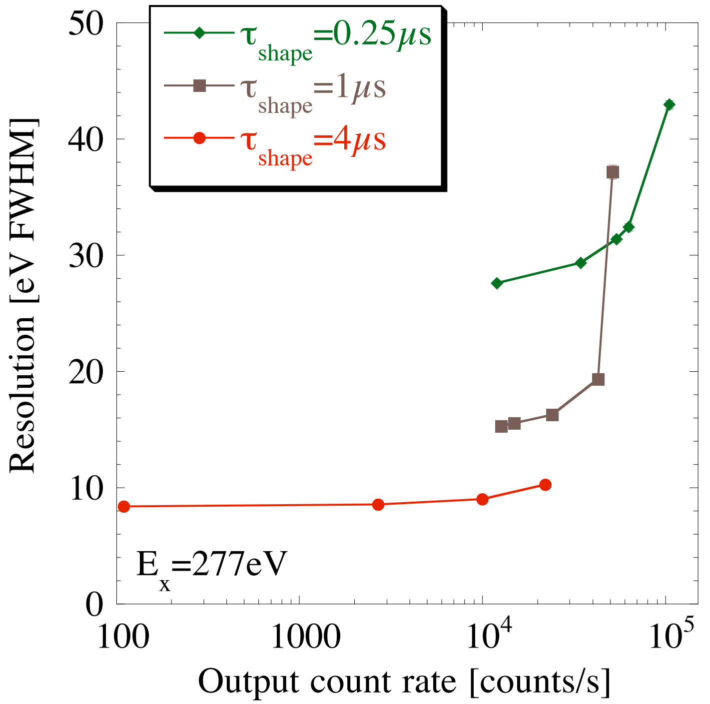
A 200×200μm^2 pixel at a distance of ~8 mm can cover $\Omega/4\pi \approx 3\times10^{-5}$ with a QE ≈ 1.

Which Count Rate do we need?

$$\text{Total flux } I_{F,total} \approx I_0 \varepsilon_{avg} \frac{\Omega}{4\pi} \eta_{\det} \approx 10^{12} \cdot 10^{-3} \cdot 3 \cdot 10^{-5} \cdot 1 \approx 30{,}000 \text{ cts/s max}$$

XIA DSP readout



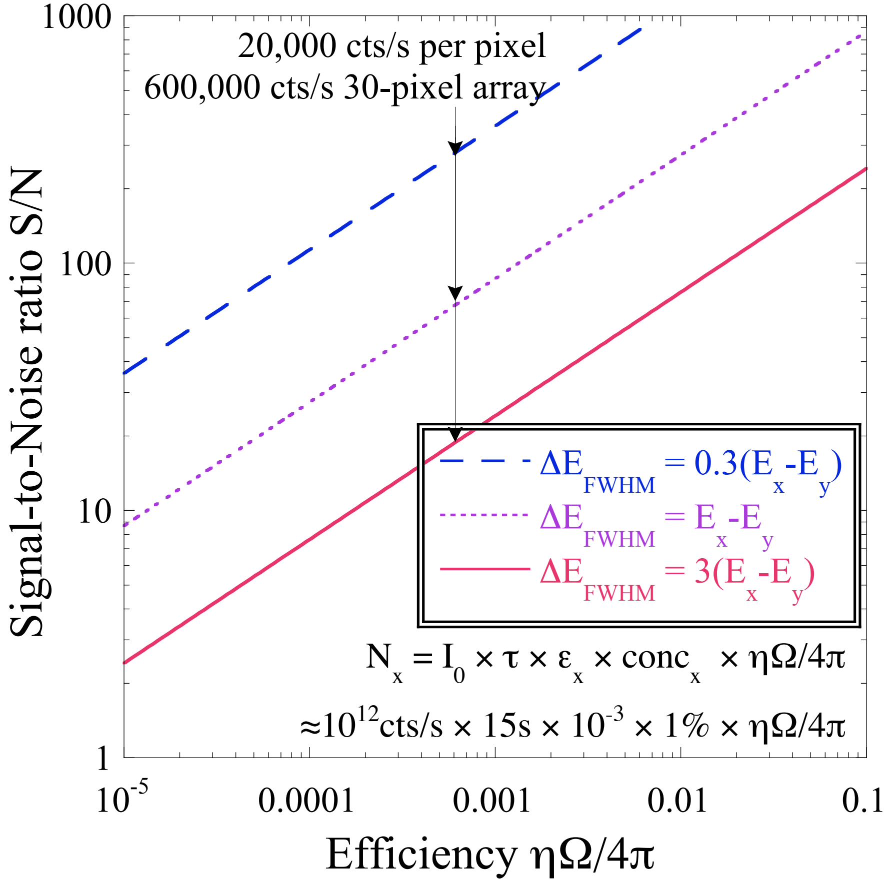


~30,000 counts/s is sufficient for a 200×200μm^2 detector at 8 mm.

Actually, STJ arrays have very high count rate capabilities per unit area.

There is no dead layer that limits the P/B ratio, but pile-up matters at high rates.

Which Solid Angle Coverage do we need?

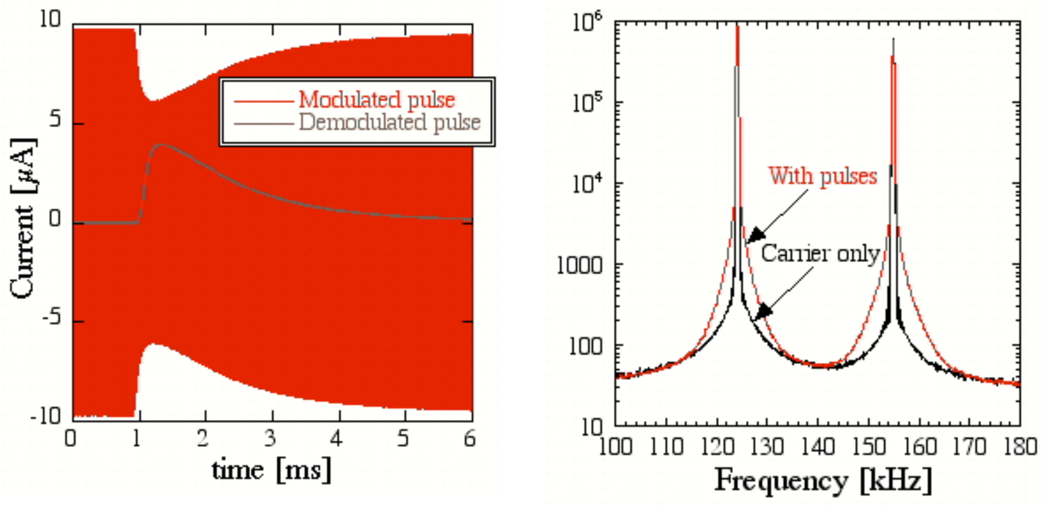


Pixels	$\Omega/4\pi$	Sensitivity
36	0.1%	~100 ppm
100	0.3%	~3 ppm
360	1%	~1 ppm
1000	3%	~0.3 ppm
3600	10%	~0.1 ppm

For more than a few 1000 pixels, elastic scatter is likely to set S/N.

Multiplexing or Parallel Readout?

That depends on the application:
Multiplexing is complicated, and even more so for fast pulses.
Multiplexing is crucial for space-based astrophysics with TES calorimeters.
Multiplexing is not necessary for high-impedance STJ detectors.

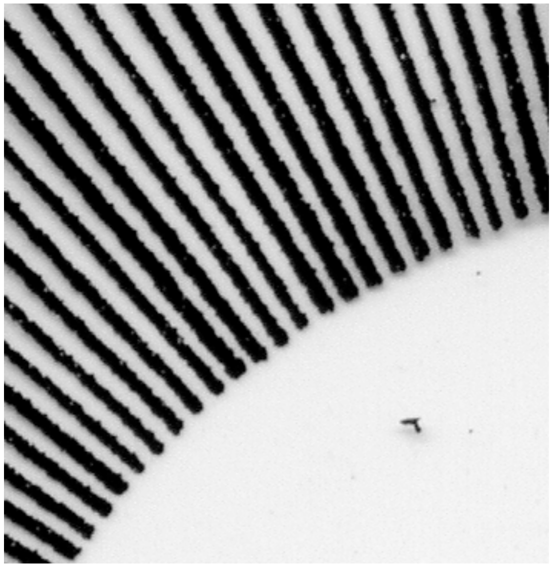


LLNL is developing frequency-domain multiplexing for (slow) Gamma and neutron calorimeter signal readout (M. Cunningham et al., APL (2003))

We are *not* proposing to adapt our frequency multiplexing technology to STJ readout.

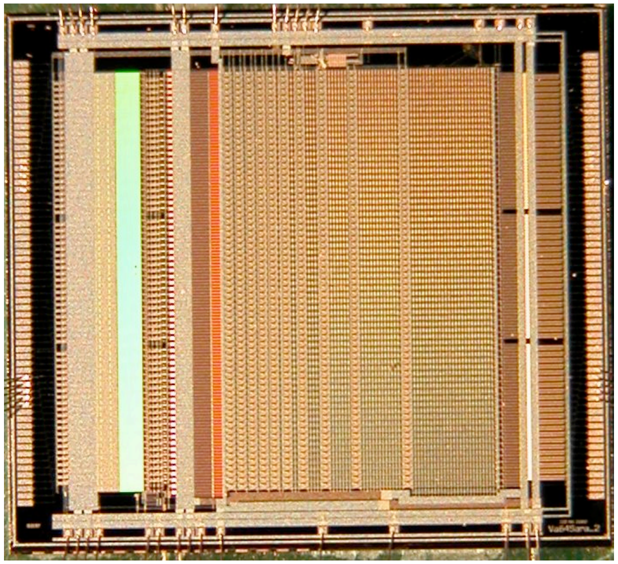
Parallel Wiring and ASIC readout

100×1 μm Fe-Ni-Cr wires on polypropylene
12” length from 300K to base T, Au bonding pads
~200 Ω wire, 1.6 μW heat load/ 1000 wires



Under development at UCSB for CMB
studies with NIS and NTD (courtesy P. Lubin)

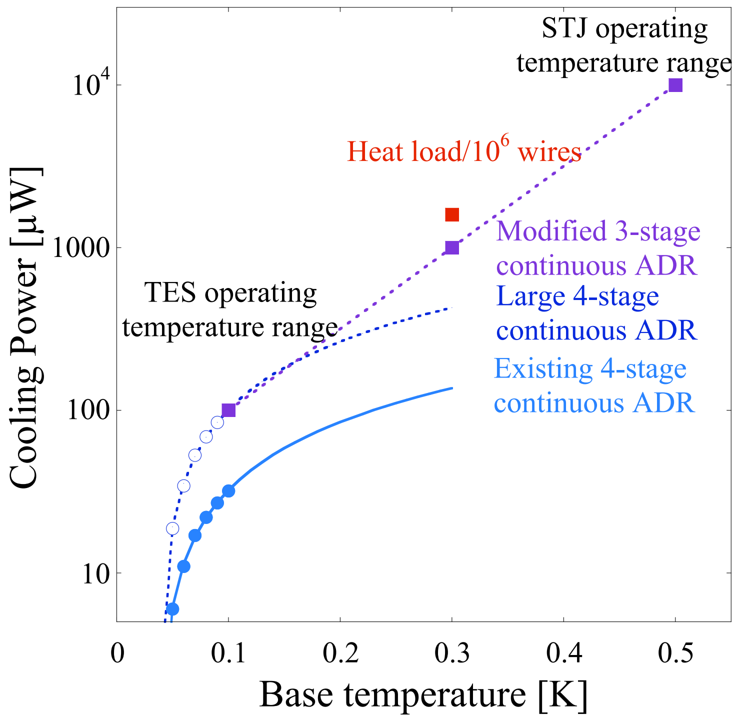
64-channel STJ ASIC (V64SARA)
Low-noise, automated bias, dc V bias

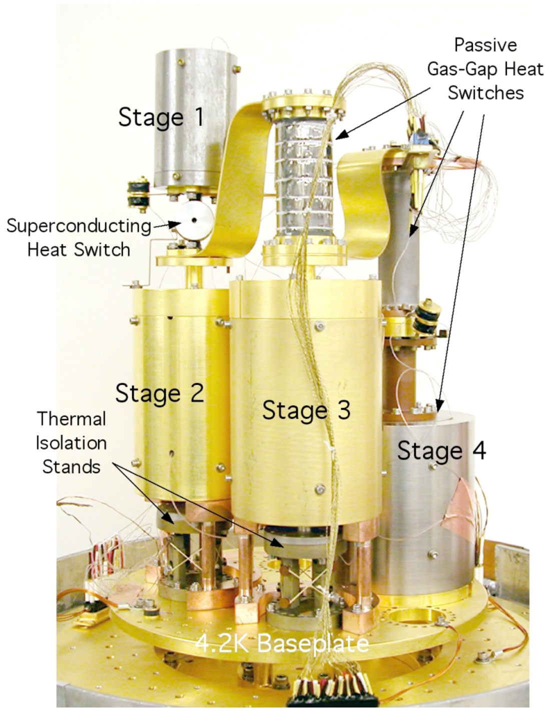


Developed at IDEAS ASA and ESA
for optical astronomy (courtesy D. Martin)

Parallel readout of high-impedance STJs with ASICs is possible.

Cooling Power Requirements





Courtesy P. Shirron, NASA GSFC

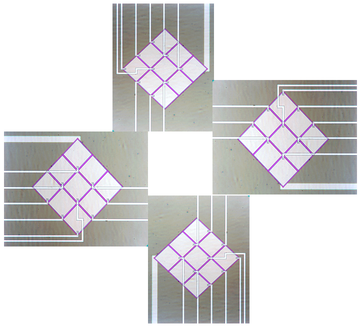
Multi-stage ADRs can provide continuous cooling power for up to ~10^6 wires!

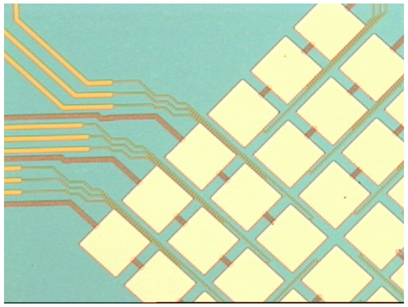
Connecting these wires to the detector and the ASIC readout is daunting.

IV. Roadmap: STJ Detector Development

In operation

36 pixel Nb-Al STJs

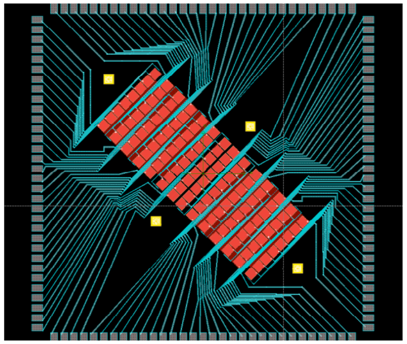


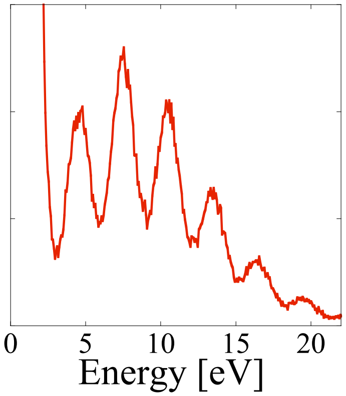


courtesy IPHT Jena

Being Built

112 pixel Ta-Al STJs





courtesy P. Lerch, SLS/ PSI

Next

256 pixels
1000 pixels
3600 pixels
10000 pixels
....

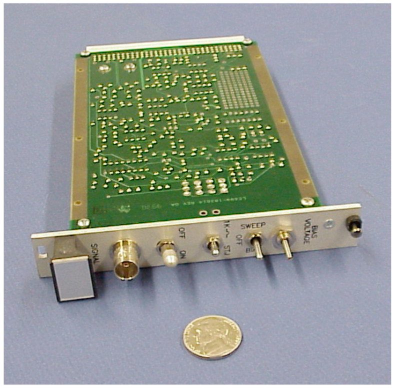
(Fabricating larger arrays will not be the limiting factor.)

Development: ~$1M

Roadmap: Readout Development

In operation

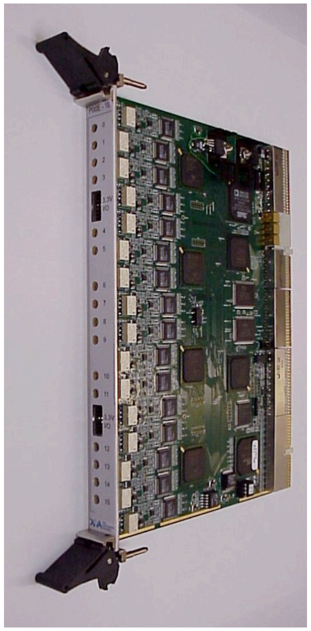
36 individual custom preamps
Manual bias
36 individual ADCs



Being built/ developed

112 custom preamps
Automated bias
Seven 16-channel DSPs

112-chn DSP cost: ~$110k

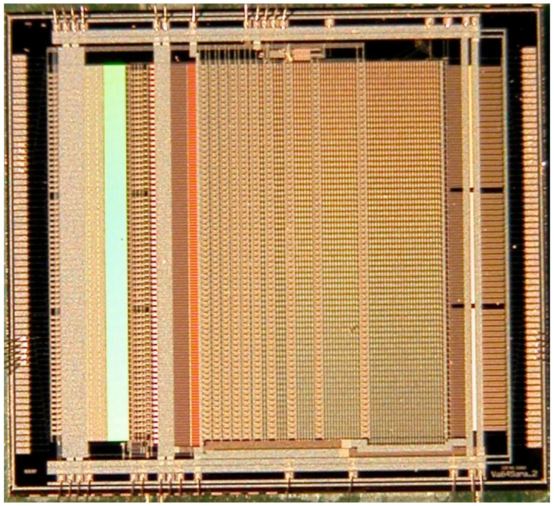


Courtesy W. Warburton, XIA LLC

Next

128 (256?) channel ASICs
Automated bias

Development: ~$1M



Courtesy IDEAS ASA

Wiring development: ~$500k

Roadmap: System Design

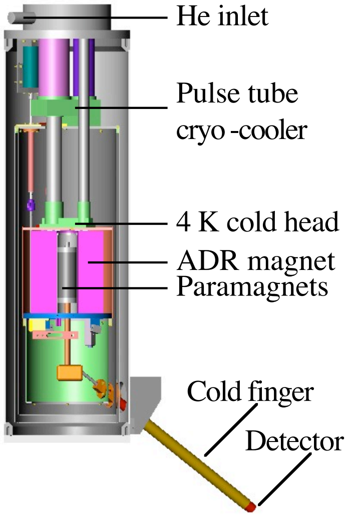
In operation

Liquid N_2, He precooling to 4K, plus 2-stage ADR to 0.1K

Being built

Pulse tube mechanical precooling to 4K, plus 2-stage ADR to 0.1K

Refrigerator cost: ~$200k

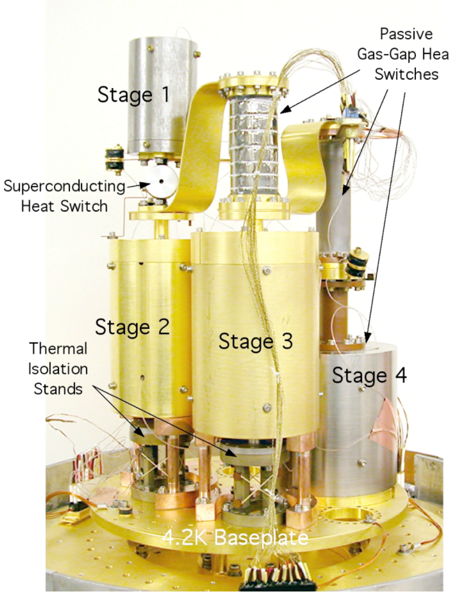


Courtesy J. Höhne, Vericold Inc.

Next

Pulse tube mechanical precooling, plus 3-stage continuous ADR

Development: ~$1M



Courtesy P. Shirron, NASA GSFC

Summary

- Fluorescence-detected soft X-ray absorption spectroscopy has wide applications for sensitive chemical analysis of dilute samples.

- The performance of superconducting tunnel junction X-ray detectors is well-matched to the XAS requirements at third generation synchrotrons:
    - Energy resolution ~10 eV FWHM for energies below 1 keV
    - Count rates >30,000 counts/s per pixel, 10^6 counts/36 pixel array.

- Higher sensitivity (~ppb) requires ~kilopixel arrays with ~10% solid angle:
    - Larger arrays, Ta or Pb-based absorbers
    - Parallel processing with photolithgraphic wiring and ASIC readout
    - User-friendliness: cryogen-free continuous operation, automation