Generation and Application of Channeling X-Rays using a Novel, Low-Emittance Electron Beam - Plans and Status

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Vanderbilt University, Nashville, Tennessee, USA

for our collaboration

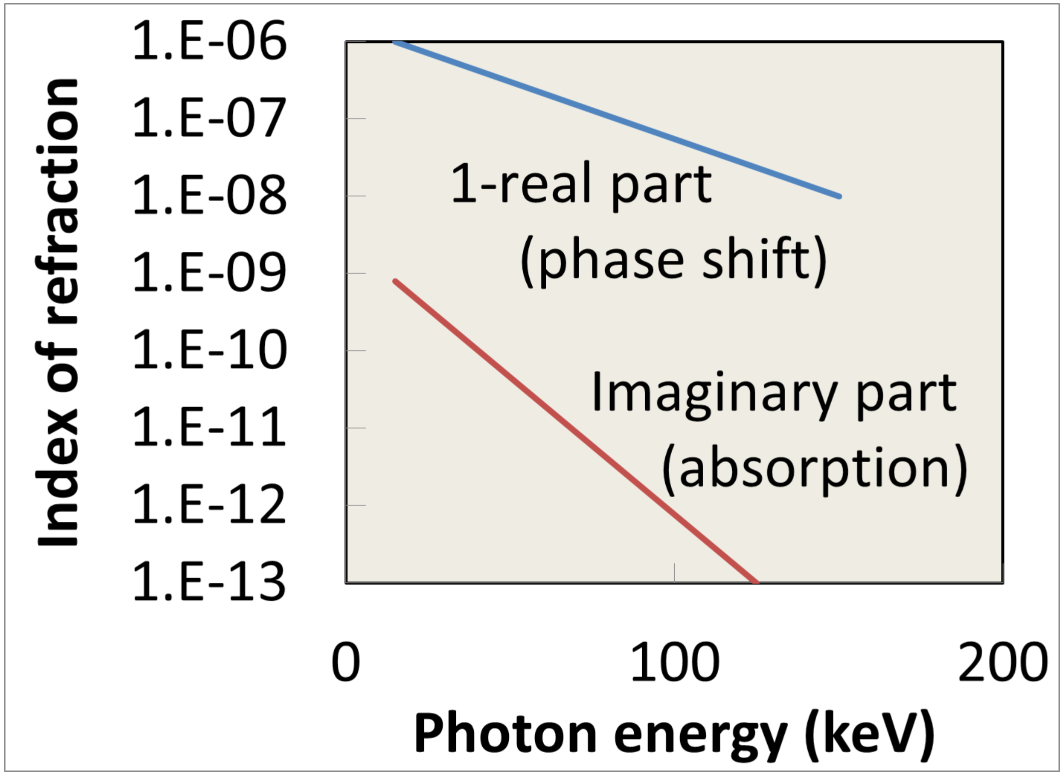
Wednesday 26 September 2012
Channeling 2012, Alghero, Sardinia

The Collaboration

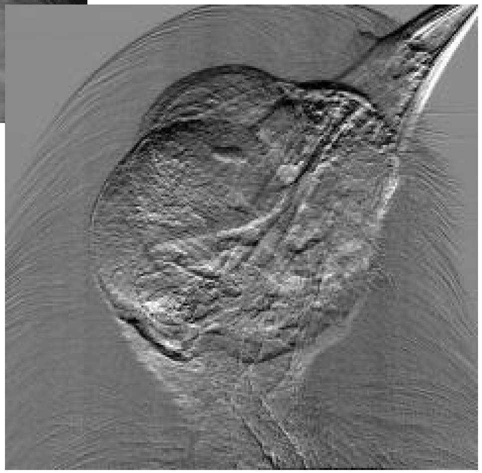
- Charlie Brau, Bo Choi, Jonathan Jarvis, Bill Gabella, Borislav Ivanov, Marcus Mendenhall
  Vanderbilt University, Nashville, Tennesee
- Philippe Piot, Daniel Mihalcea
  Northern Illinois University, Dekalb, Illinois and Fermilab
- Richard Carrigan
  Fermilab, Batavia, Illinois
- Wolfgang Wagner
  Rosendorf/Dresden, Germany
- John Lewellyn
  Naval Postgraduate School, Monterrey, California and Los Alamos National Laboratory, Los Alamos, New Mexico

DARPA AXiS challenge: a portable x-ray source for phase-contrast medical imaging of soft tissue

- X-ray Index of Refraction is dominated by the real part



- Absorption image



- Refraction image

Spectral brilliance of an X-ray source is a useful figure of merit to compare sources

- Spectral brilliance:

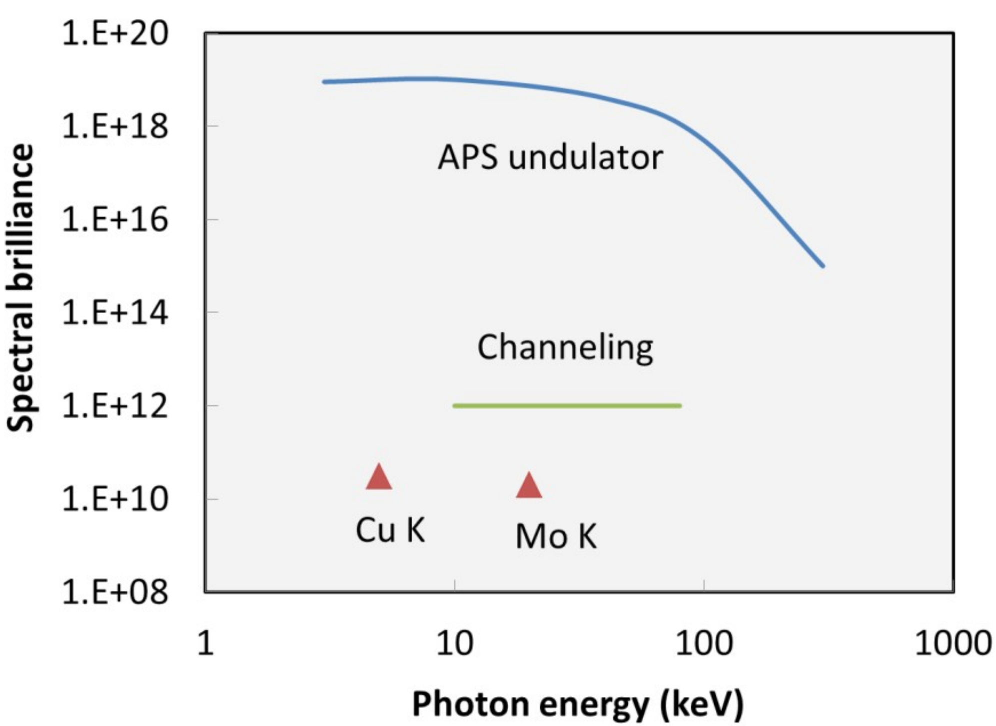
$$B_\nu = \frac{\nu\, d^4 N}{dA\, d\Omega\, d\nu\, dt}$$

$$\propto \text{degeneracy}\ (\ll 1)$$

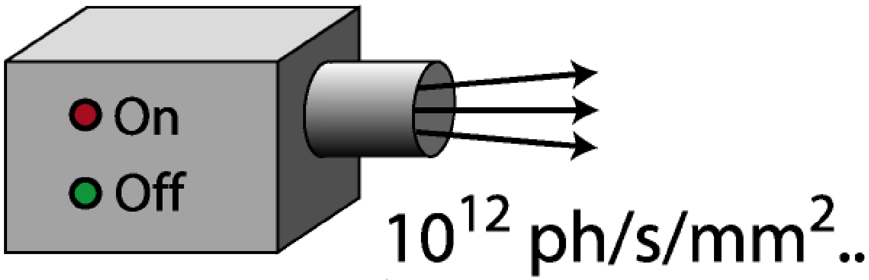
- Other figures of merit:
  - Photons/second
  - Transverse coherence
- A high quality (equals low emittance) beam can give high spectral brilliance
- The area of emission of the x-rays can be made small, that is, a small dA

DARPA AXiS objectives are well beyond the state of the art in conventional x-ray sources

- Spectral Brilliance
  - Synchrotrons
  - Bremsstrahlung



- DARPA goal

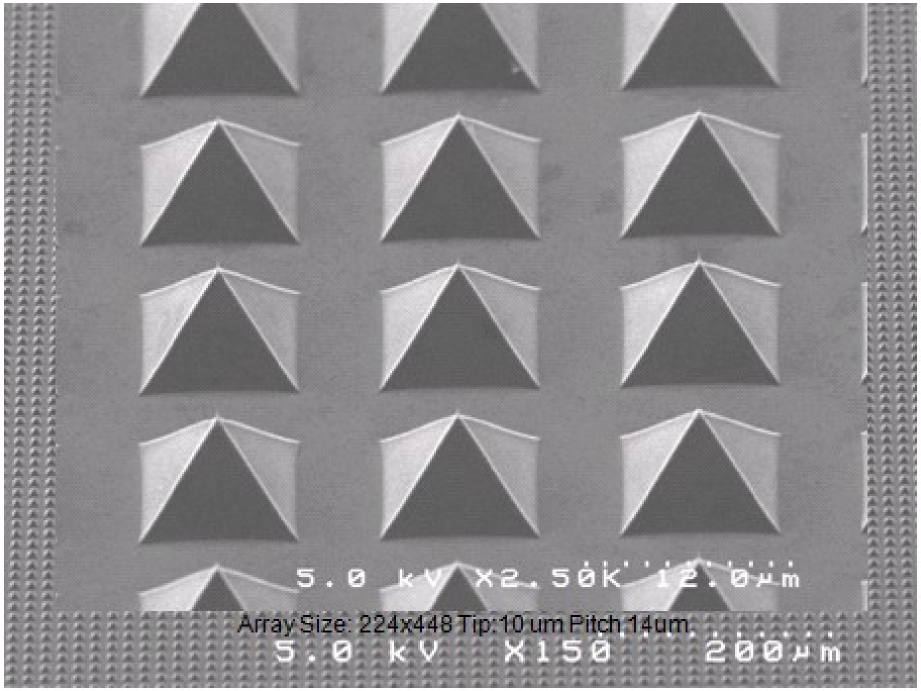


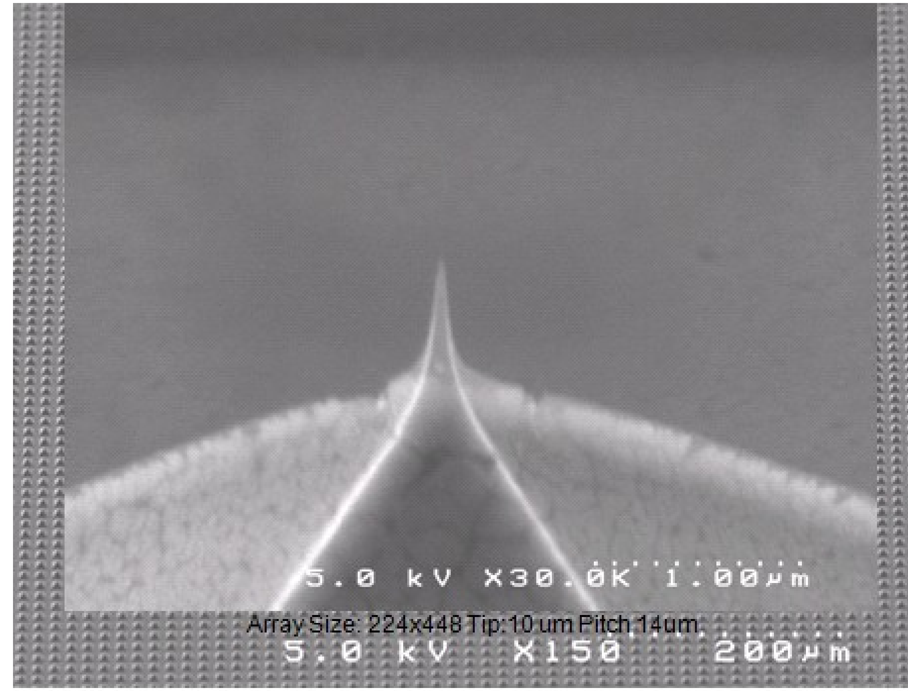
- Bν~10^12 ph/s…0.1%BW
- hν~10-80 keV
- Size~0.01 m^3
- "Revolutionary advances," no "evolutionary improvements"

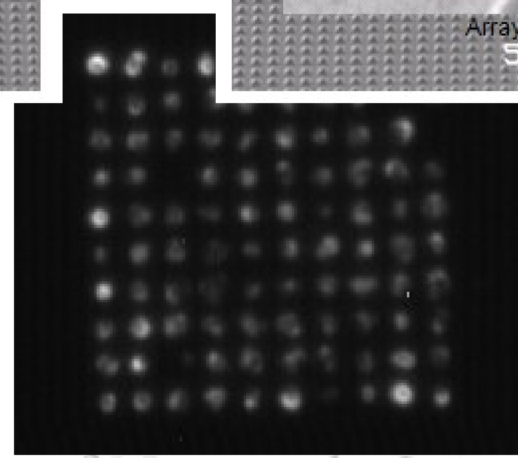
Field Emission Cathodes

- Charlie Brau and personnel in his lab at Vanderbilt have a history of looking at emission from tungsten needles, MWCNT on tungsten needle tips, and most relevant for this report, **diamond tips** and **gated diamond tips.**
- Field emission off of very small radii tips makes use of the strong electric field enhancement
  - diamond tips are approximately 1-10 nm in radius
  - tips sit atop pyramids, either a single pyramid for low current, high brightness applications
  - or an array of pyramids (100x100 = 3mm x 3mm) for high current, modest brightness

Field Emission Cathodes, ungated





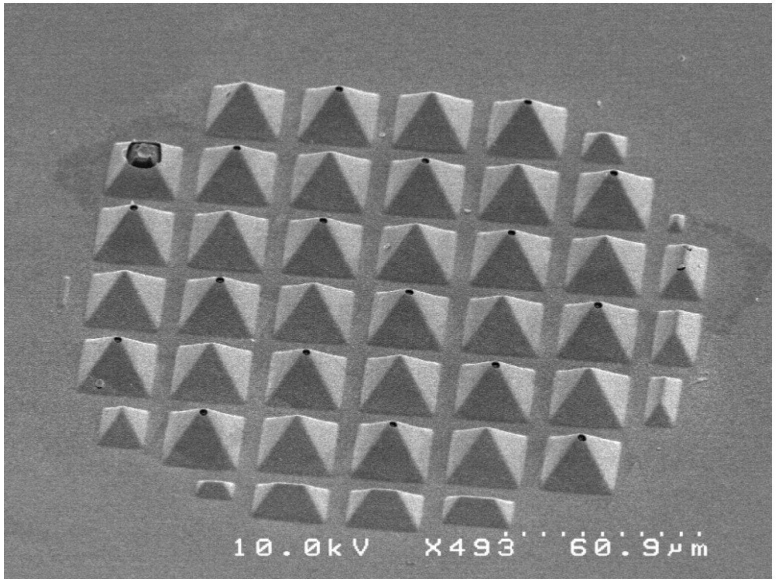


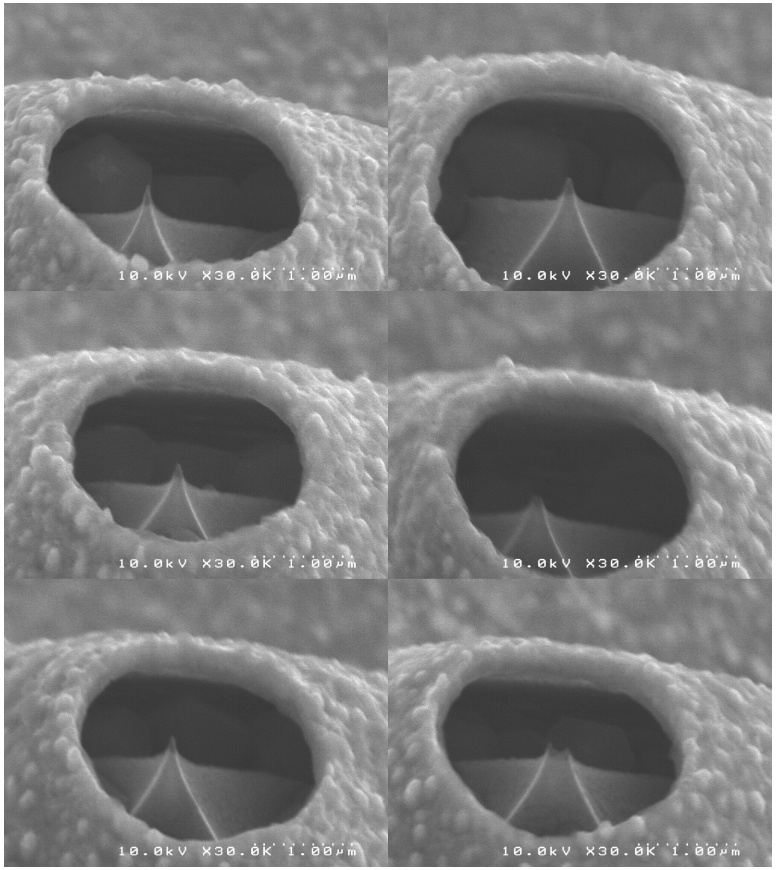
phosphor screen

Bo Choi and team at

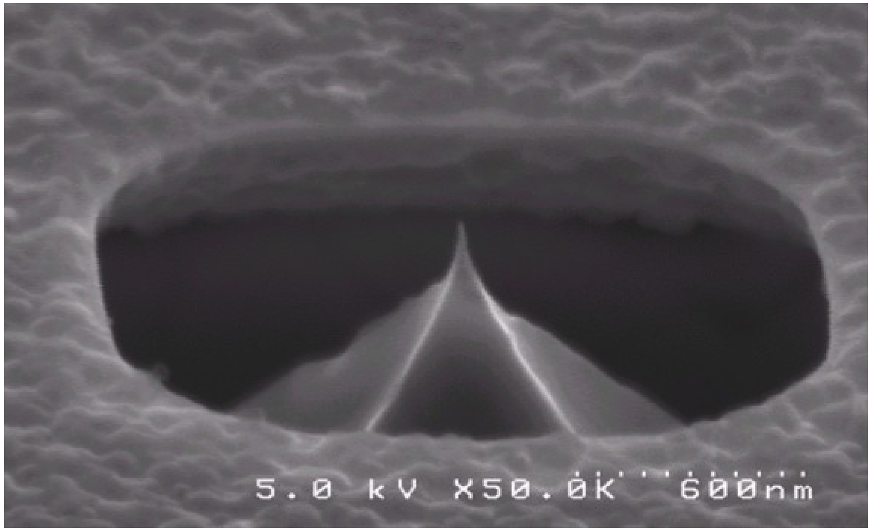
ViNSE Vanderbilt Institute of Nanoscale Science and Engineering

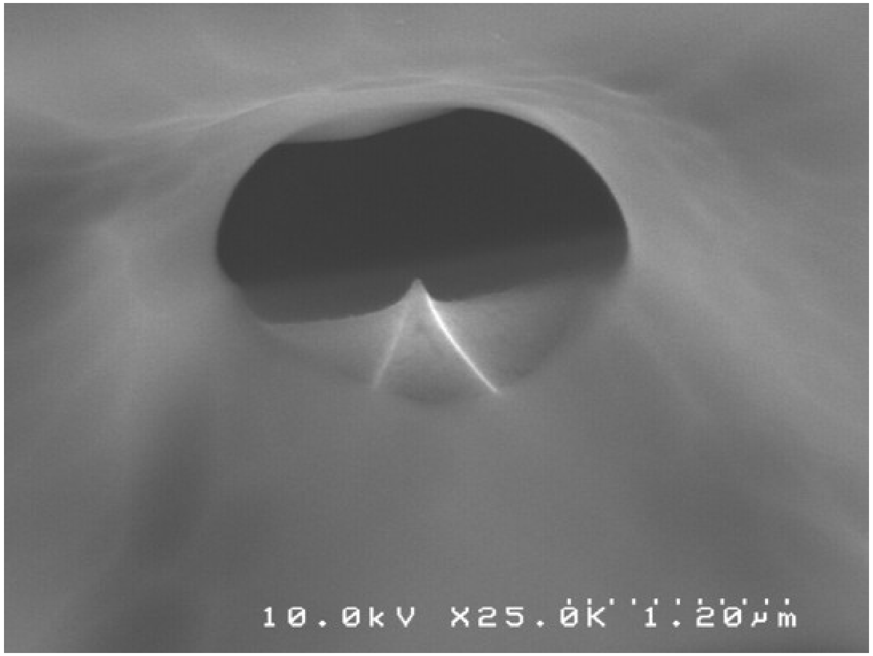
Field Emission Cathodes, gated





- Two types of gated arrays
  - SOI structure
  - “Volcano” structure





- All are fabricated at Vanderbilt by Bo Choi
- DC tests also done at Vanderbilt by Jarvis, Gabella, Brau, and Ivanov

Field-emission cathodes have the potential for exquisitely small emittance

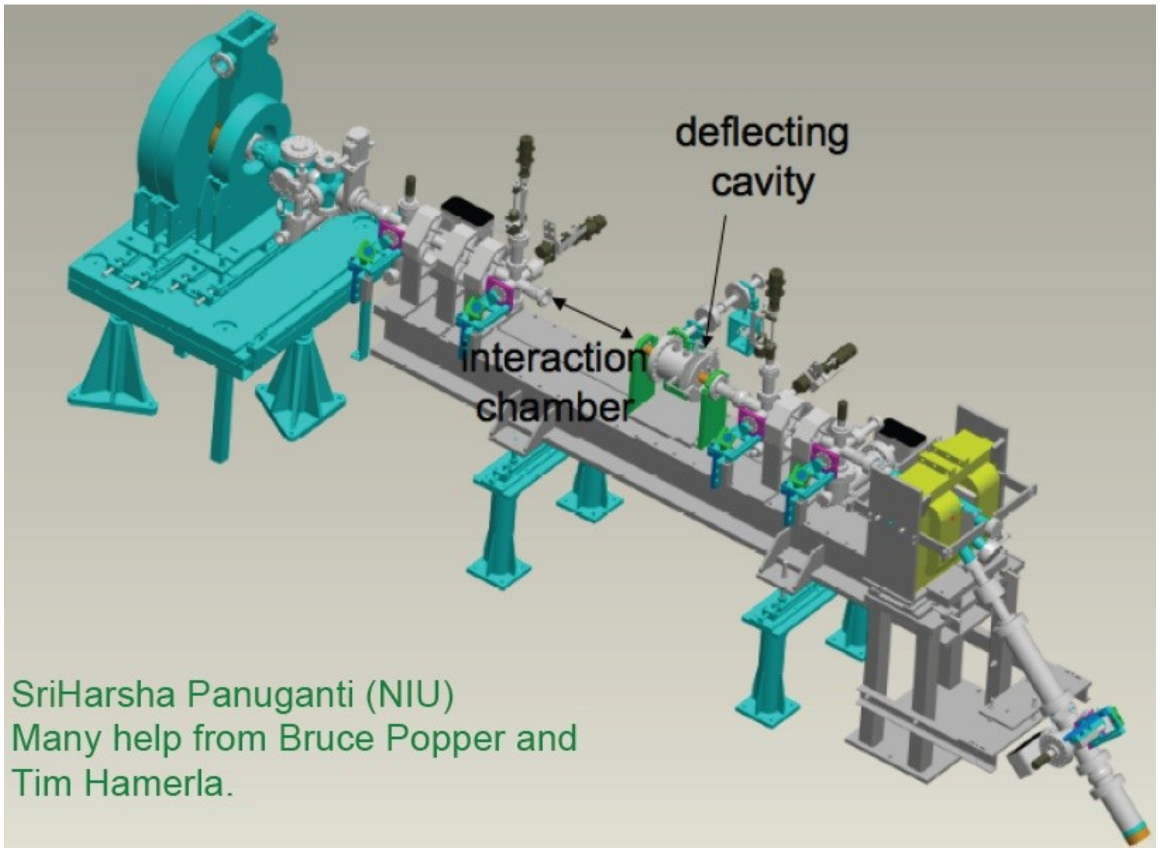
- Ungated arrays are highly developed for FEL applications
  - We have delivered ungated arrays to Niowave and Fermilab for early tests
- Expect normalized emittance of one diamond needle on a pyramid of <1 nm rad
- Simulations of a single cathode in an RF gun find a normalized emittance of <3 nm rad, and that due to the long bunch length and chromatic effects coming from the linac
- P. Mesumeci, ONR Review, 2012, reconstructs a 30 nm emittance

Experiment at Fermilab's High Brightness Electron Source Laboratory (HBESL) facility

- normal conducting 1.5 cell RF gun for testing Vanderbilt cathodes and duplicating channeling x-ray generation both with new cathodes and conventional photocathode
- beam energy 4.5 MeV
- photocathode currents are ~ 200 μA average over a ~ 400-μs macropulse
- beamline has a third harmonic RF deflecting cavity and slits
- use the “Carrigan” goniometer, previously used at A0 (Thank You!)

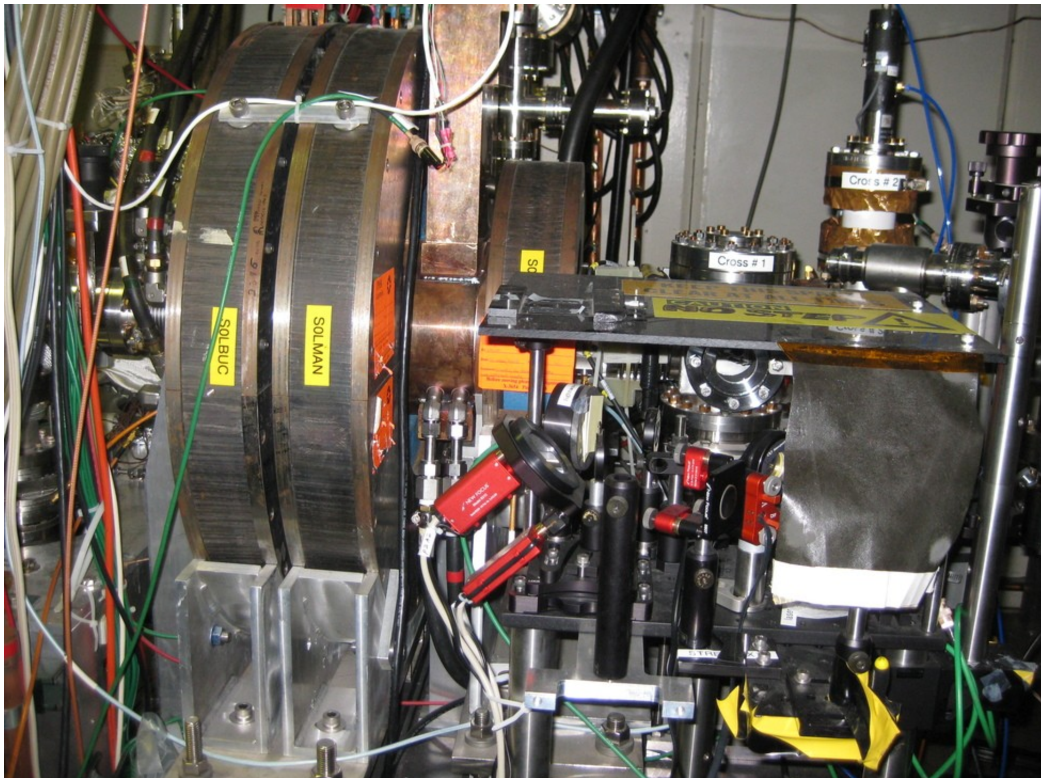
VANDERBILT UNIVERSITY

Fermilab's HBESL at A0

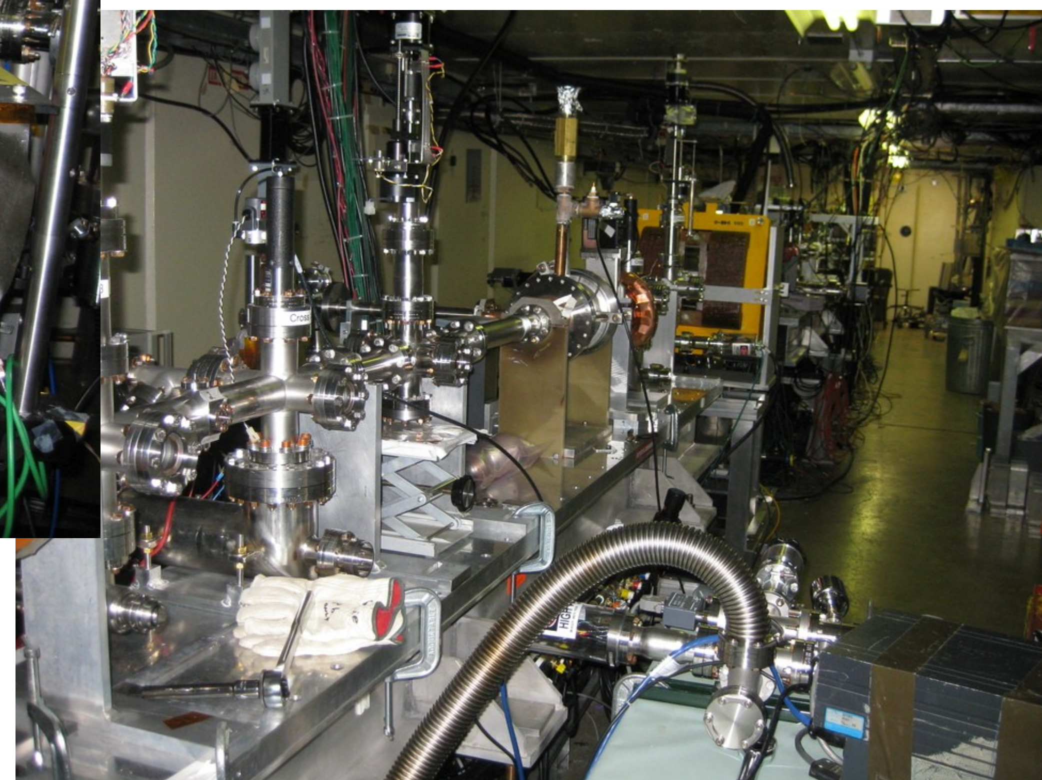


VANDERBILT UNIVERSITY

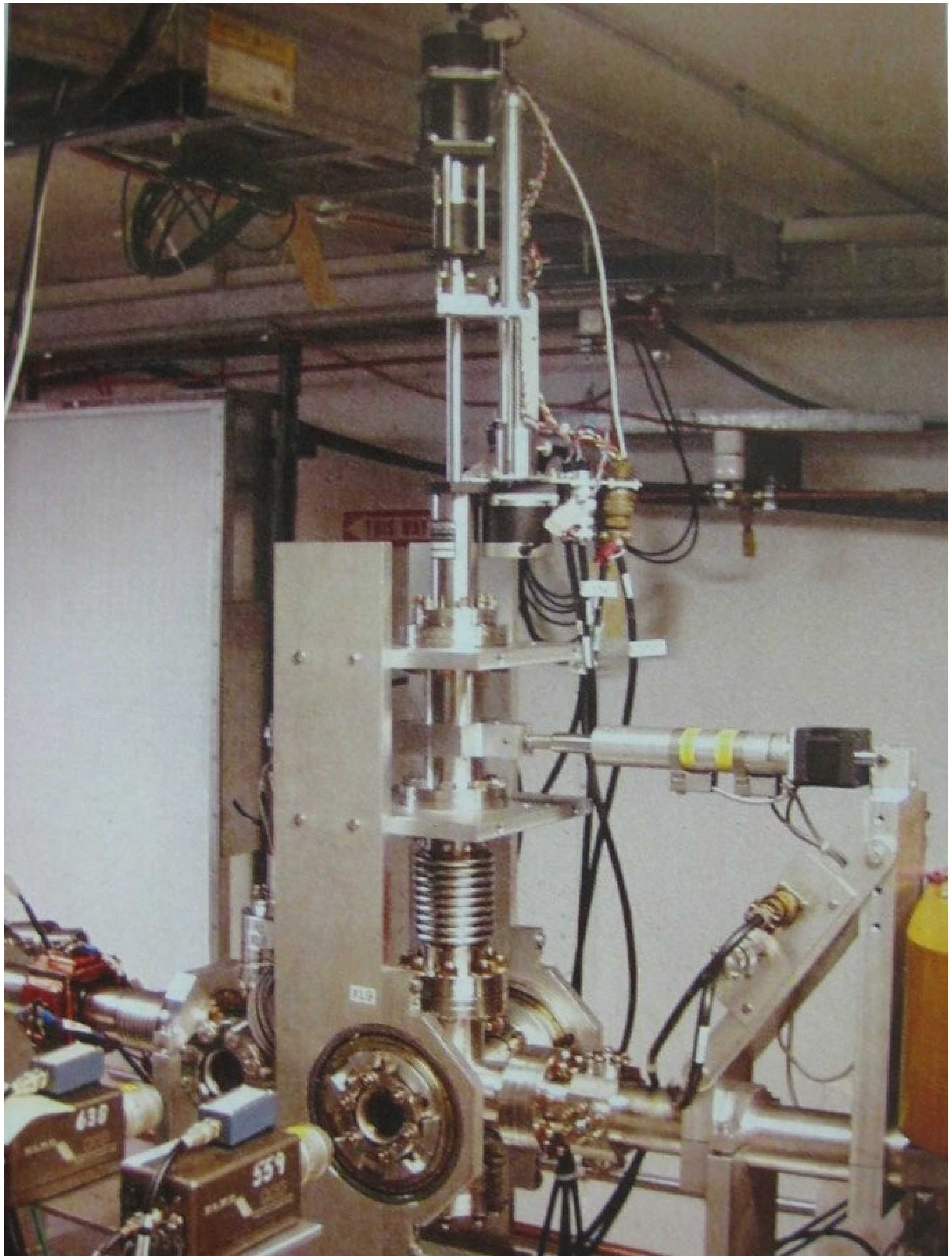
Fermilab's HBESL at A0



RF gun and solenoids



beamline



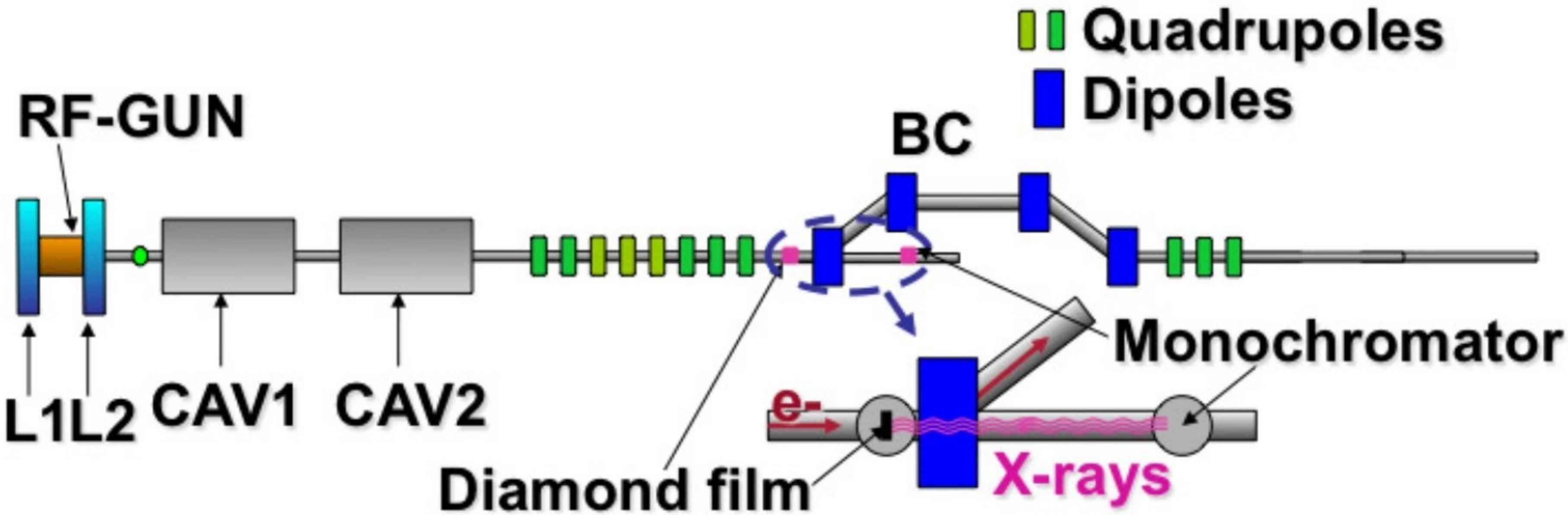
“Carrigan's” goniometer, around 2000

Fermilab's HBESL at A0

Channeling Radiation, what do we expect?

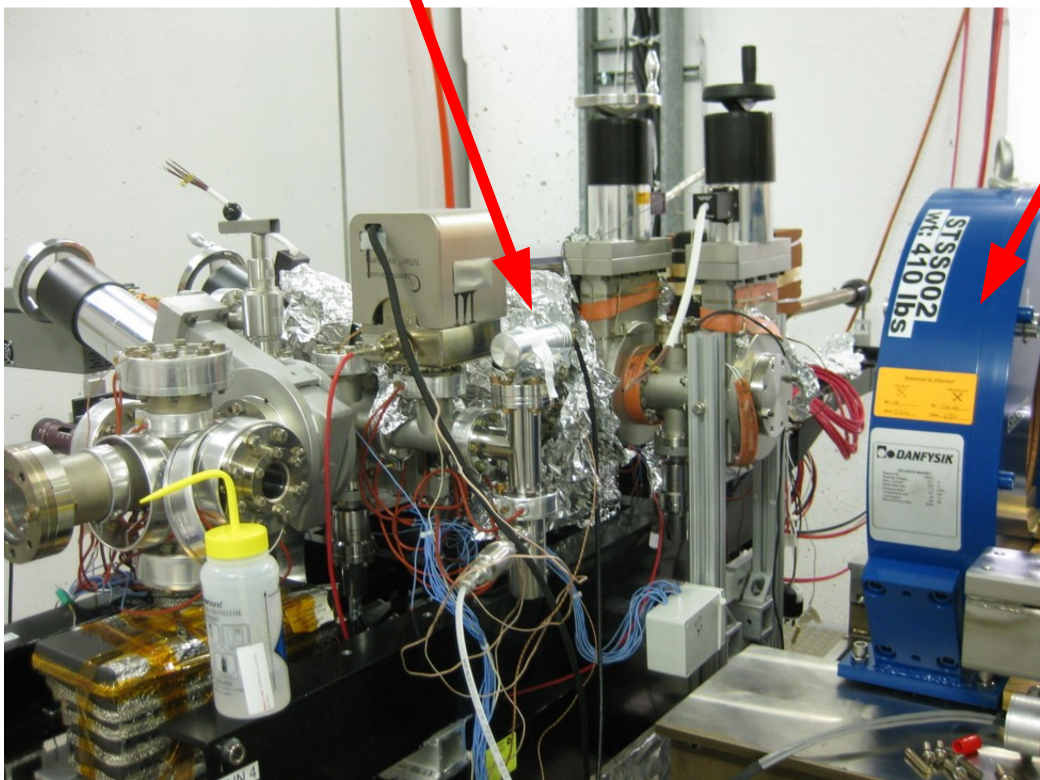
- electron energy 4.5 MeV
- low energy x-rays, 2.5 keV, 7.1 keV, 10.6 keV
- working in vacuum
- as we test new cathodes we have the possibility to see the effect on the x-rays

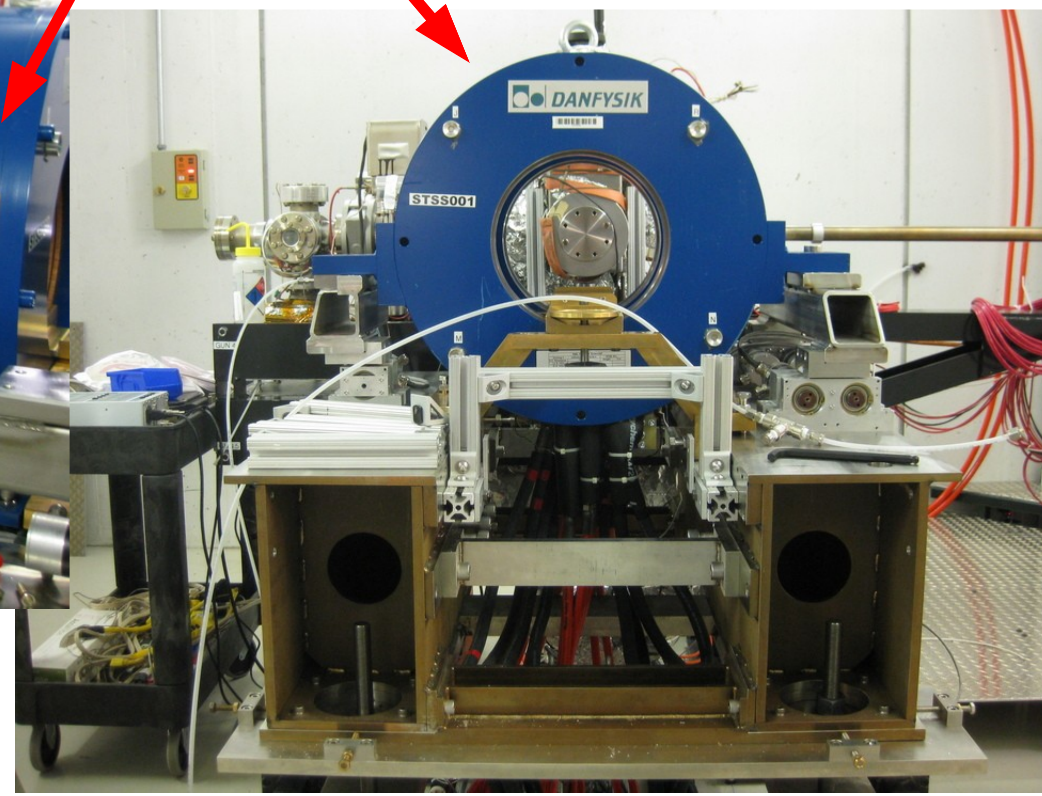
Experiment at Fermilab's Advanced Superconducting Test Accelerator (ASTA)

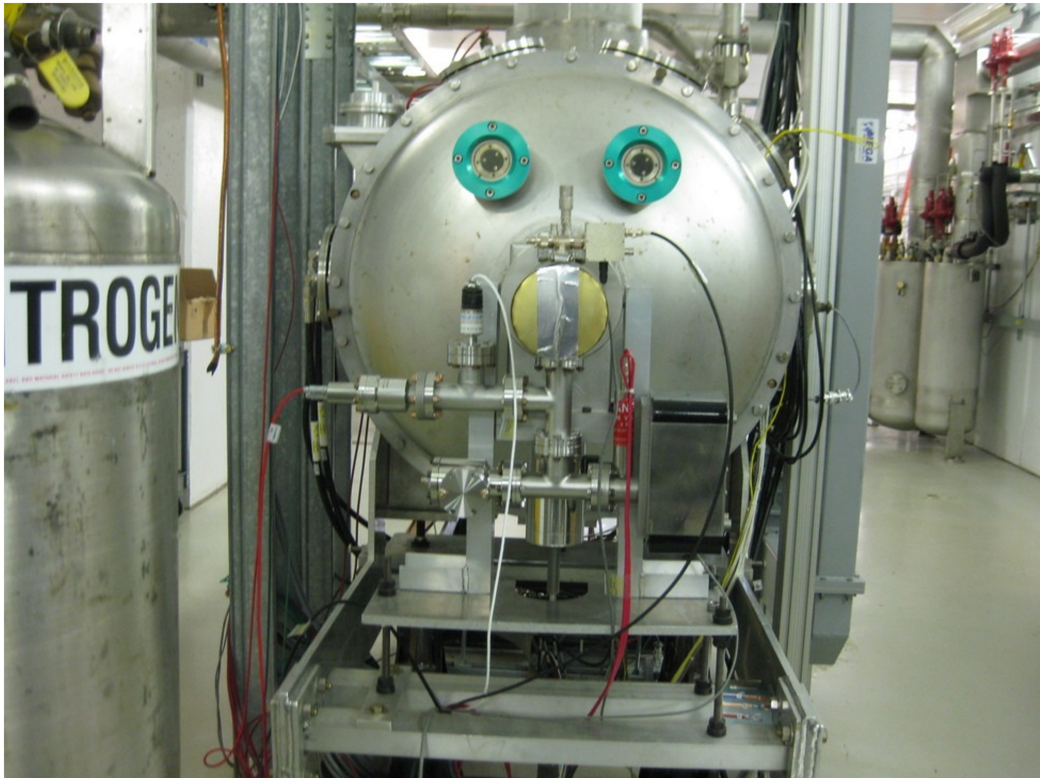


RF gun

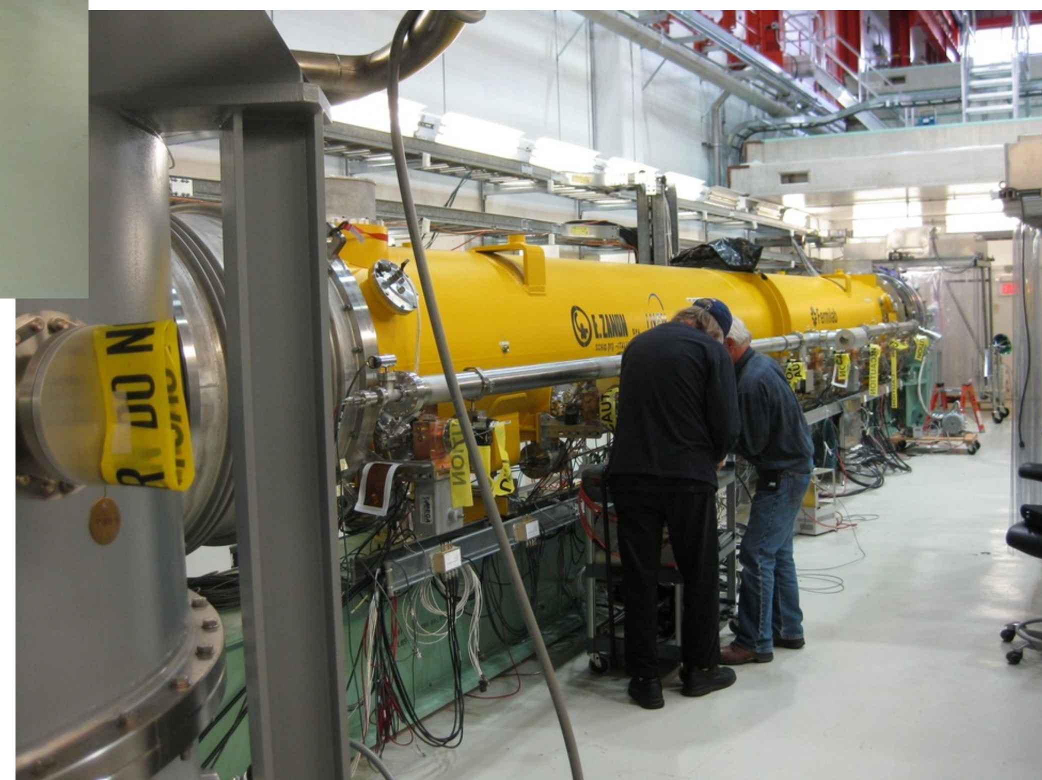
solenoid magnets





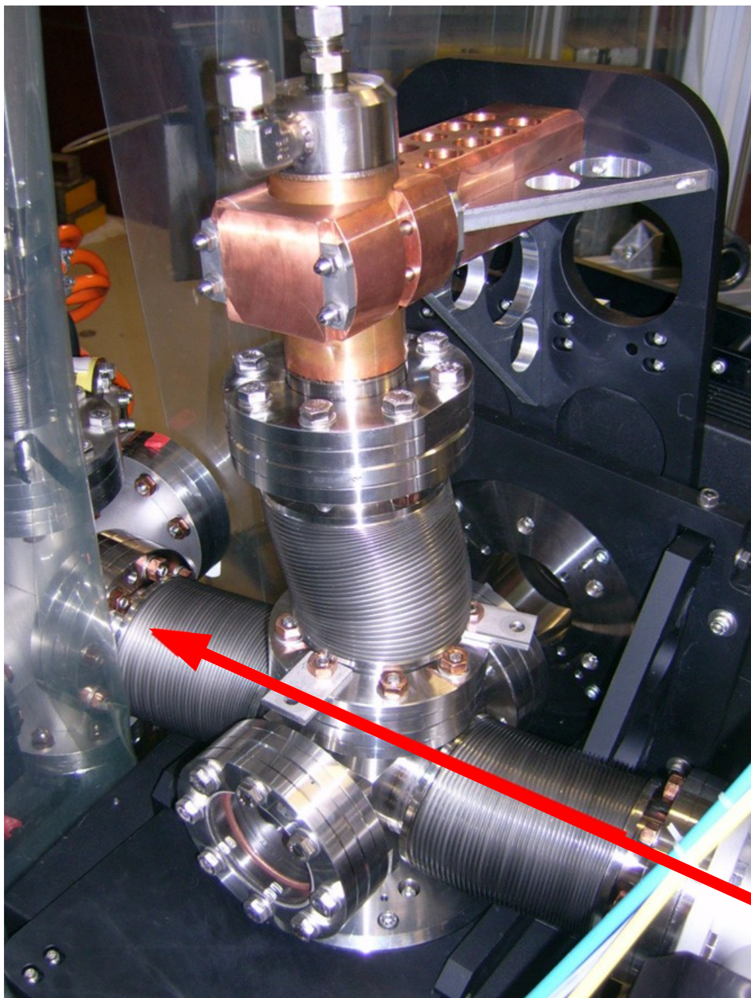


looking at cryo containing two RF cavities

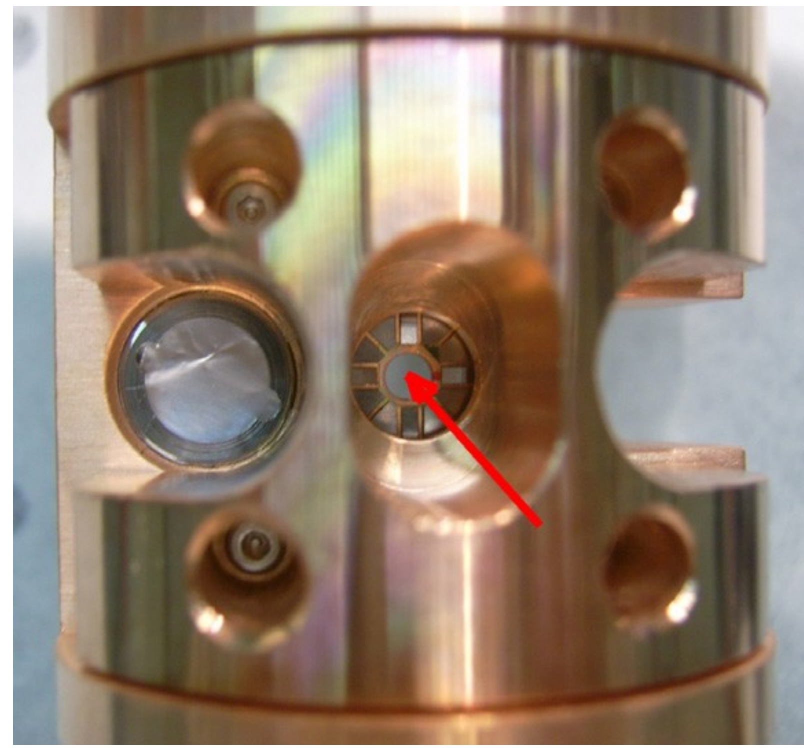


looking at cryo containing new RF cavities; this is after our crystal

Rosendorf/Dresden/ELBE Goniometer



shows diamond



beam direction

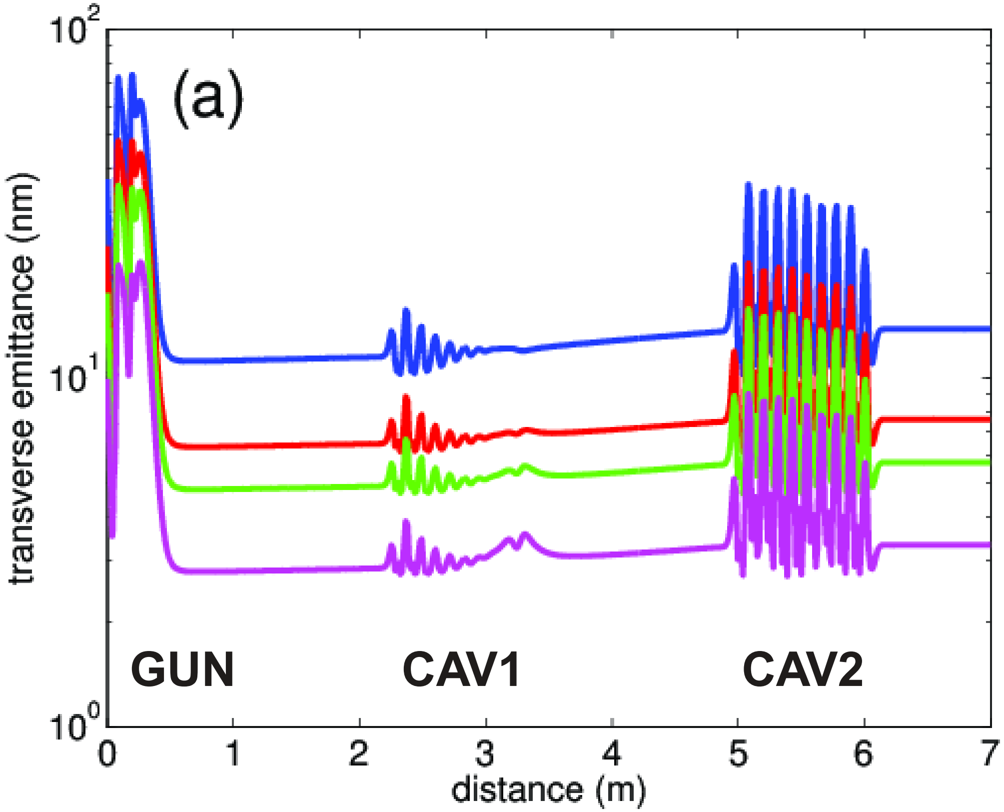
Rosendorf/Dresden/ELBE Goniometer

- hope to have the goniometer at Vanderbilt soon and will add motor controls and take to Fermilab
- has three “slots,” empty, foil, and diamond

Experiment at Fermilab's ASTA accelerator

- superconducting system, with 40 MeV electrons available at the crystal
- RF pulse structure, 1 ms macropulse with 1.3e6 micropulses every 10 Hz
    - 1.3e7 micropulses every second
- photocathode at the start, Cs2Te, Q<10nC per pulse
    - drive lasers either 1 MHz (Nd:YLF) or 1 Hz (Ti:Sapph)
    - later as they become “qualified” the Vanderbilt field emission cathode gives 1000 electrons every RF pulse
- use the Rossendorf/Dresden goniometer (Thank You!)
- crystals anyone?
- what thickness?

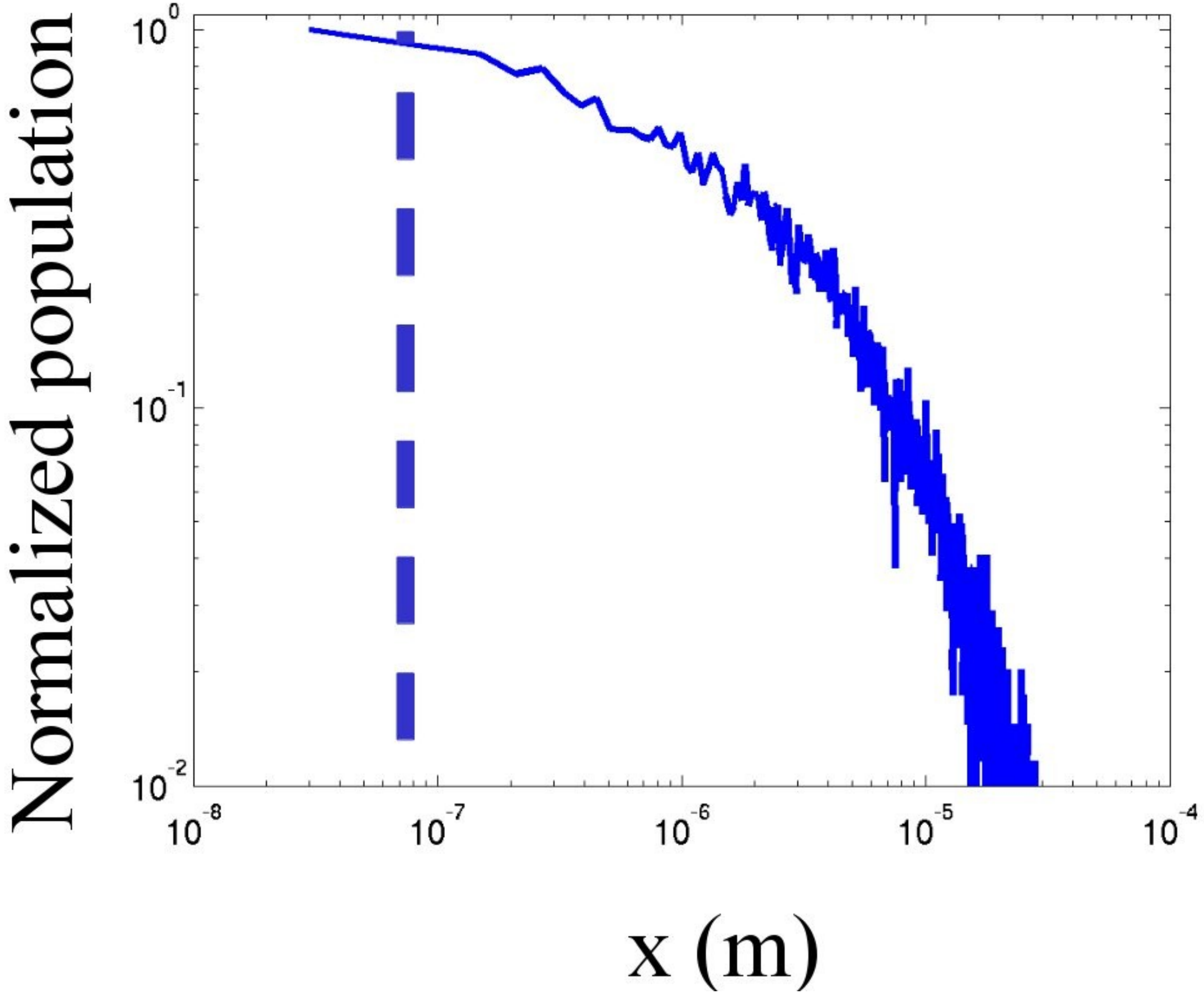
Preserving the emittance from cathode to crystal at ASTA



100%, 95%, 90%, 80% of 25 fC
(we need 100 aC)

Mihalcea and Piot modeling

How to get a 50nm spot



Channeling Radiation

- Proposed AXiS design is based on experimental measurements at ELBE (Dresden)
- Diamond is best crystal
  - x-ray yield
  - thermal properties
  - damage resistance
- Photon yield in x-ray region
  ~ 10-4 photons /electron
- Line width
  ~ 10% (coherence length)
- Spectral yield
  ~ 10-9 photons/mr^2/0.1%BW /electron

Summary

- Fall 2012, attempt channeling radiation at Fermilab A0 facility with low-energy electrons from a photo-cathode
  - Using Carrigan's goniometer
  - Also testing the Vanderbilt diamond cathodes
- Fall/Winter 2012, test at Niowave (Lansing, Michigan USA) of gated diamond cathode in a normal conducting RF gun
- 2013, attempt channeling radiation at Fermilab's ASTA facility using the Dresden/Rossendorf goniometer
  - start with regular photocathode
  - next with Vanderbilt needle cathodes as they "qualify"
- Testing needle cathodes, gated, ungated, diamond tip and carbon nanotube at several facilities

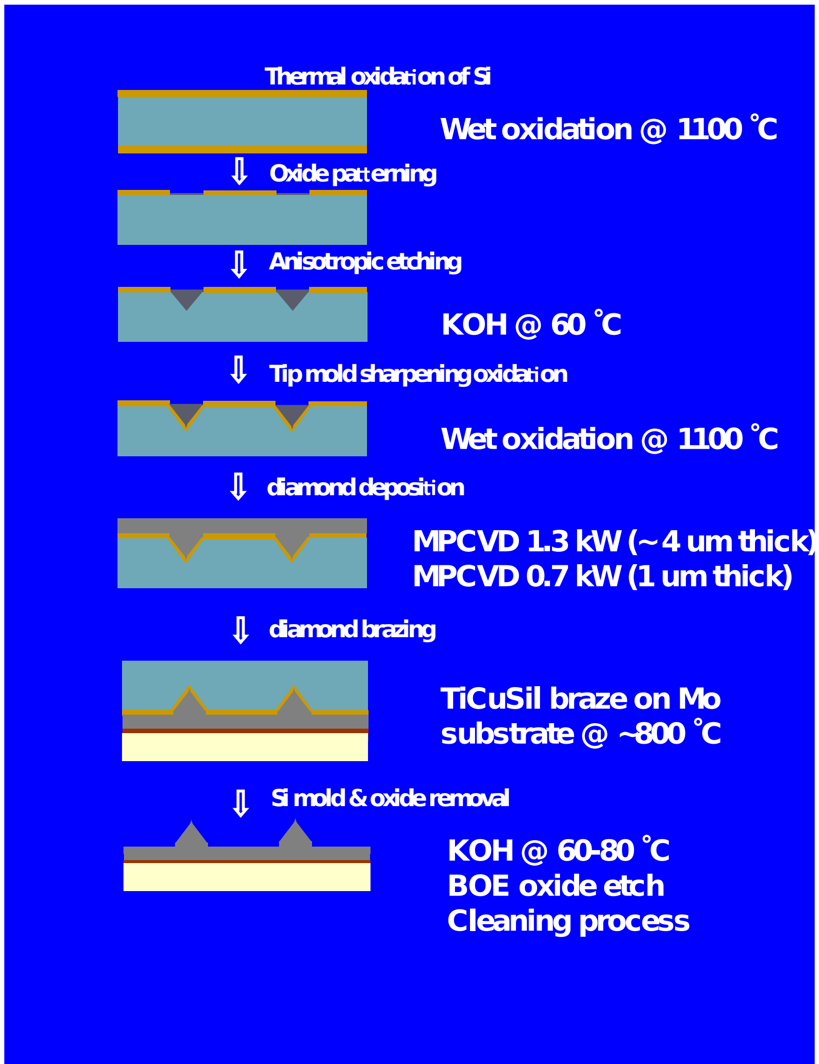
...the end...

...and thank you for your attention...

Backup

Ungated diamond field emitters are fabricated by inverse mold process

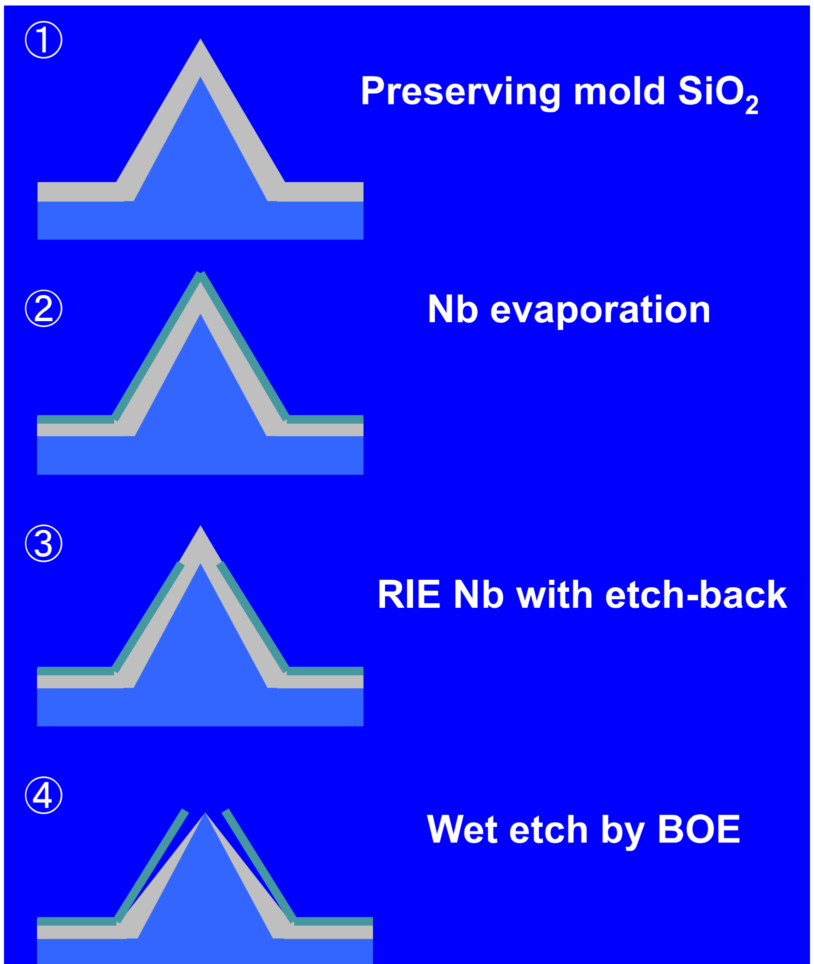
Diamond FEA Fabrication Program



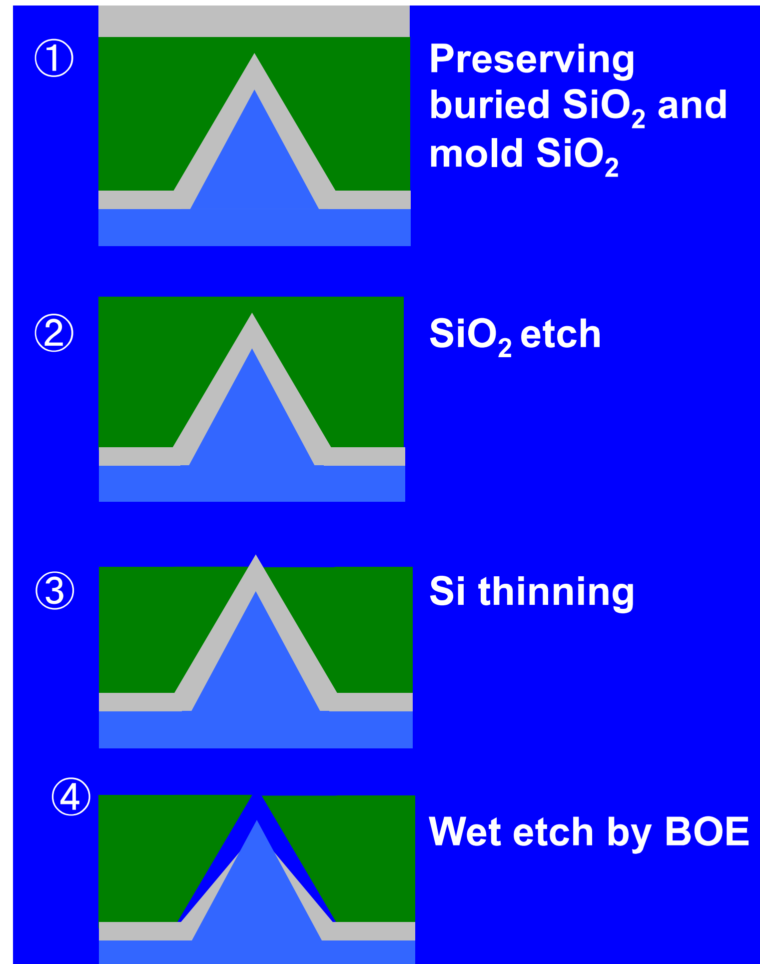
- All fabrication done at Vanderbilt
- DC tests also done at Vanderbilt

Two gated diamond FEA fabrication procedures are under development

- Volcano process

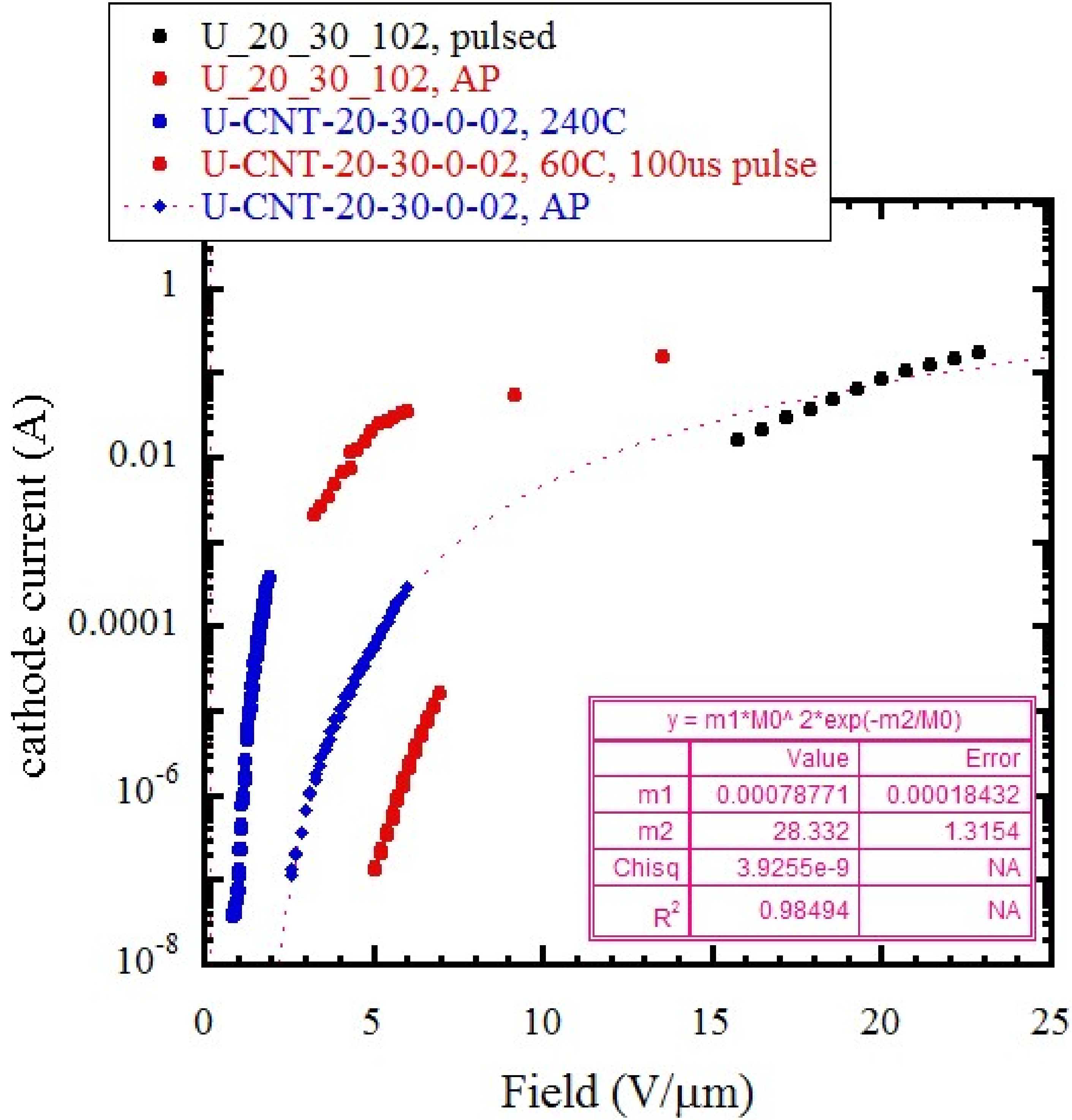


- SOI process



Vanderbilt's Inverse Compton X-Ray Source

- Designed by Marcus Mendenhall with Charlie Brau and Frank Carroll
- Operated 1999 to 2008, now decommissioned
- Experiments with Ed Donnelly on phase contrast using the distance method
- 20-80 keV x-rays in 5 ps pulse once per 5 minutes
  - a single pulse could make an image on a Mar345


U_20_30_102, pulsed
U_20_30_102, AP
U-CNT-20-30-0-02, 240C
U-CNT-20-30-0-02, 60C, 100us pulse
U-CNT-20-30-0-02, AP
cathode current (A)
1
0.01
0.0001
10-6
10-8
0
5
10
15
20
25
Field (V/µm)
y = m1*M0^2*exp(-m2/M0)
Value
Error
m1
0.00078771
0.00018432
m2
28.332
1.3154
Chisq
3.9255e-9
NA
R2
0.98494
NA

other notes

- how to measure the emittance that is so small?
- diamond best crystal?
- any way to limit the number of accessible “channels,” including axial and other planes?
- any way to inject into a state in the channel?
- dechanneling length?
- length of source compared to 50nm transverse size?

The Collaboration, and more...

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Philippe Piot and Daniel Mihalcea Northern Illinois University, Dekalb, Illinois USA and Fermilab

John Lewellyn Naval Postgraduate School, Monterey, California USA and Los Alamos National Lab, Los Alamos, New Mexico USA