Generation of high-brightness electron beams from a needle cathode and their application to make channeling x-rays

Bill Gabella, Department of Physics and Astronomy, Vanderbilt University, Nashville, Tennessee, USA

for our collaboration

Thursday 28 March 2013
HBEB 2013, San Juan, Puerto Rico
We have three Theses:

- Field emission from single, diamond, needle cathodes gives an electron source with small emittance.
- That emittance can be preserved through acceleration to 30-40 MeV, in the sense, that “enough” electrons in the beam have small emittance.
- A small emittance electron beam can be used as a source of channeling radiation making x-rays of small source size.
Field Emission Cathodes are enhanced with small tips

- Charlie Brau's lab at Vanderbilt has 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 for spacing,
    - either a single pyramid for low current, high brightness applications
    - or an array of pyramids (300x300 ~ 3mm x 3mm) for high current, modest brightness
Field Emission Cathodes can be ungated

Bo Choi and team at Vanderbilt Institute of Nanoscale Science and Engineering
or Field Emission Cathodes can gated

Gated 41st (2.4um opening)

Single and Double tips are possible.
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, Ivanov, and students
Single pyramid for DARPA AXiS program for the Channeling Radiation experiment

Gated 48-2 Single Pyramid & Needle, Cr gate
Field-emission cathodes have the potential for exquisitely small emittance

- Ungated arrays are highly developed for FEL applications
  - We have early tests of ungated arrays at Niowave and Fermilab HBESL RF guns.

- 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
HBESL has seen electrons from a Vanderbilt diamond field emitter array

Fowler-Nordheim I vs V

20.5 MV/m

23.6 MV/m

Ugly beam, but a beam

from Piot and Mihalcea
Channeling means the electron is confined by the charges in a plane or along an axis.
Classically, for relativistic electrons the 110 plane presents a confining potential.

\[ \theta_0 = \sqrt{\frac{2U_0}{E_z}} \]
Classically, in the other view there are betatron oscillations.
Quantum mechanically, for relativistic electrons the 110 plane presents a confining potential with a few states.
Quantum mechanically, see transitions between various states.

\[ 2 \rightarrow 1 \quad 1 \rightarrow 0 \quad 2 \rightarrow 0 \]

diamond 110
168um thick xtal
30 MeV ebeam

Azadegan, Wagner, Pawelke PRB74 (2006)
Channeling Radiation

- Proposed AXiS design is based on experimental measurements at ELBE (Wagner and Azadegan)

- 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, expected
  ~ 10^{13} photons/s/mm^2/\text{mr}^2/0.1\%BW
# Channeling Radiation - Parameters

Table 1: Electron and Channeling Radiation Parameters

<table>
<thead>
<tr>
<th></th>
<th>HBESL (photocathode)</th>
<th>HBESL (field emitter)</th>
<th>ASTA (field emitter)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cathode</strong></td>
<td>CsTe</td>
<td>Diamond tip</td>
<td>Diamond tip</td>
</tr>
<tr>
<td><strong>RF frequency</strong></td>
<td>1.3 GHz</td>
<td>1.3 GHz</td>
<td>1.3 GHz</td>
</tr>
<tr>
<td><strong>Macropulse duration (ms)</strong></td>
<td>0.4</td>
<td>0.4</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Macropulse current (nA)</strong></td>
<td>20000</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td><strong>Beam Energy (MeV)</strong></td>
<td>4.5</td>
<td>4.5</td>
<td>38</td>
</tr>
<tr>
<td><strong>Emittance, norm. (nm)</strong></td>
<td>4000</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td><strong>Spot size (nm)</strong></td>
<td>4500000</td>
<td>300</td>
<td>40</td>
</tr>
<tr>
<td><strong>Photon energy (keV)</strong></td>
<td>2.7</td>
<td>2.7</td>
<td>87</td>
</tr>
<tr>
<td><strong>Macropulse brilliance (1/sr-s)</strong></td>
<td>$1 \times 10^4$</td>
<td>$2 \times 10^8$</td>
<td>$7 \times 10^{11}$</td>
</tr>
<tr>
<td><strong>Macropulse flux (1/sr-s)</strong></td>
<td>$4 \times 10^{11}$</td>
<td>$4 \times 10^9$</td>
<td>$7 \times 10^{11}$</td>
</tr>
<tr>
<td><strong>Crystal thickness (µm)</strong></td>
<td>20</td>
<td>20</td>
<td>43</td>
</tr>
<tr>
<td><strong>Diamond cons. (mm²/hr)</strong></td>
<td>$8 \times 10^{-4}$</td>
<td>$8 \times 10^{-6}$</td>
<td>$1 \times 10^{-5}$</td>
</tr>
<tr>
<td><strong>Critical channeling angle, (110) plane (mrad)</strong></td>
<td>4.05</td>
<td>4.05</td>
<td>1.39</td>
</tr>
<tr>
<td><strong>Detector</strong></td>
<td>Amptek 123SDD</td>
<td>Amptek 123SDD</td>
<td>Amptek 123CdTe</td>
</tr>
</tbody>
</table>
Experiment at Fermilab's High Brightness Electron Source Laboratory (HBESL) facility

- normal conducting 1.5 cell RF gun (1.3 GHz) for testing Vanderbilt cathodes and channeling x-ray generation both with new cathodes and conventional photocathode
- beam energy 4.5 MeV
- photocathode currents are ~ 200 micro-A average over a ~ 400 micro-s macropulse
- beamline has a third harmonic RF deflecting cavity and slits
- use the “Carrigan” goniometer, previously used at A0 (Thank You!)
Fermilab's HBESL at A0 being (re)commissioned.

SriHarsha Panuganti (NIU)
Many help from Bruce Popper and Tim Hamerla.
Fermilab's HBESL at A0

RF gun and solenoids
“Carrigan's” goniometer, around 2000
Channeling Radiation at HBESL/A0, what do we expect?

- electron energy 4.5 MeV
- low energy x-rays, 2.5 keV, 7.1 keV, 10.6 keV
- x-ray detector in vacuum, measure spectrum
- start with photoinjector, as we test new diamond cathodes we have the possibility to see the effect on the x-rays
- not likely very useful
Experiment at Fermilab's Advanced Superconducting Test Accelerator (ASTA)

new position, after chicane, before first beam dump
RF gun

solenoid magnets
looking at cryo containing new RF cavities; this is after our crystal
Rosendorf/Dresden/ELBE Goniometer now at Fermilab after checkout at Vanderbilt.
Experiment at Fermilab's ASTA accelerator

- superconducting system, with 40 MeV electrons available at the crystal
- RF pulse structure, 1 ms macropulse with $1.3 \times 10^6$ micropulses every 10 Hz
  - $1.3 \times 10^7$ micropulses every second
- photocathode at the start, Cs$_2$Te, $Q<10$ nC 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 $\sim 1000$ electrons every RF pulse
- use the Rossendorf/Dresden goniometer and crystals (Thank You!)
At ASTA, simulations suggest that 80% of the beam has 3nm rad emittance at the crystal.

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

Mihalcea and Piot modeling
How to get a 50nm spot
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
  \[ n = 1 - \delta + i \beta \]

- Absorption image

- Refraction image

Can be 1000x greater
Phase-Imaging (Reconstruction)

Edges independently imaged.

Phase information if incr. D's.

From P. Cloetens ESRF, Grenoble, tutorial http://www.esrf.eu/events/announcements/Tutorials

28 March 2013

Gabella-HBE 2013
Summary

- Spring 2013, attempt channeling radiation at Fermilab HBESL/A0 facility with low-energy electrons from a photo-cathode:
  - Using Carrigan's goniometer;
  - Also testing the Vanderbilt diamond cathodes.

- In 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;”
  - goniometer motors and control checked out at Vanderbilt and delivered to the ASTA group for vacuum checkout.

- Testing needle cathodes, gated, ungated, diamond tip and carbon nanotube at RF guns at Niowave (Chase Boulware) and at HBESL (Philippe Piot).
The Collaboration

- Charlie Brau, Bo Choi, Jonathan Jarvis, Bill Gabella, Borislav Ivanov, Marcus Mendenhall
  Vanderbilt University, Nashville, Tennessee
- Philippe Piot, Daniel Mihalcea, Ben Blomberg
  Northern Illinois University, Dekalb, Illinois and Fermilab
- Richard Carrigan
  Fermilab, Batavia, Illinois
- Wolfgang Wagner
  Rosendorf/Dresden, Germany
- John Lewellyn
  Los Alamos National Laboratory, Los Alamos, New Mexico
...thank you...

and

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

- **Spectral Brilliance**
  - Synchrotrons
  - Bremsstrahlung

- **DARPA goal**
  - $B \nu \sim 10^{12}$ ph/s...0.1%BW
  - $h \nu \sim 10^{-80}$ keV
  - Size~0.01 m$^3$
  - “Revolutionary advances,” no “evolutionary improvements”
Spectral brilliance of an X-ray source is a useful figure of merit to compare sources

- Spectral brilliance:

\[ B_\nu = \frac{\nu d^4 N}{dA d\Omega d\nu dt} \propto \text{degeneracy (} \ll 1 \text{)} \]

- Other figures of merit:
  - Photons/second
  - Transverse coherence

- A high quality (equals low emittance) electron beam can give high spectral brilliance.

- The area of emission of the x-rays can be made small, that is, a small \( dA \).