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Northern Illinois Center for Accelerator and Detector Development

NIU

Development of a compact laser-free accelerator-driven X-ray source based on channeling radiation

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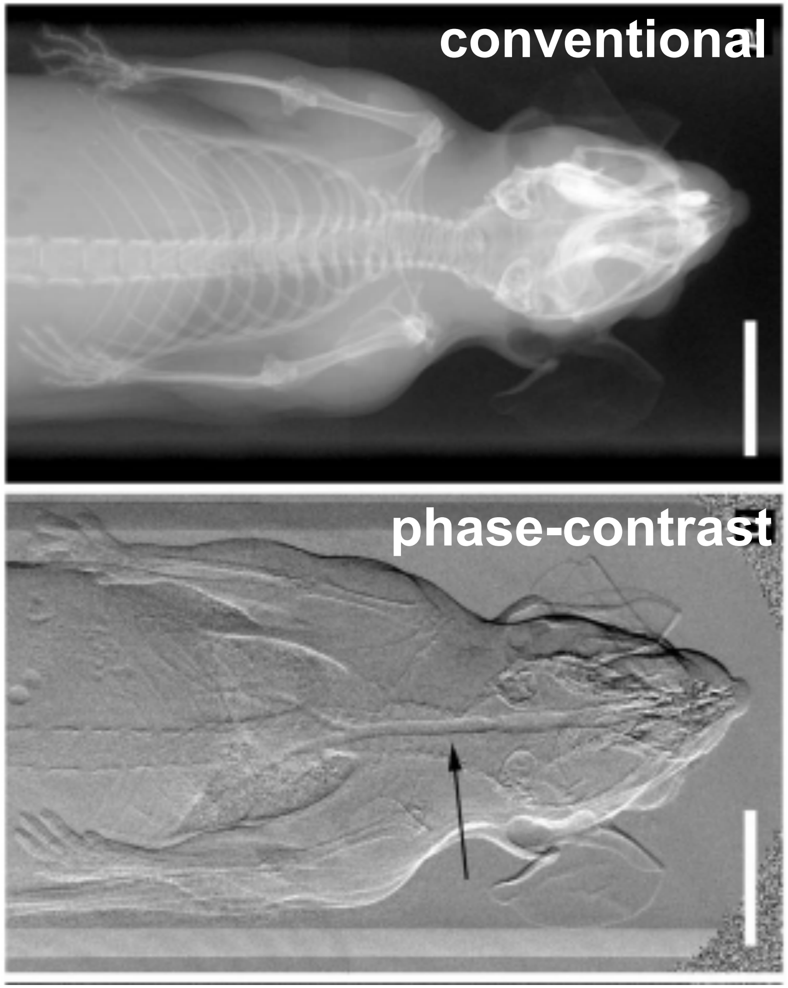
7th International Conference

Charged & Neutral Particles Channeling Phenomena

Motivation: compact & precise X-ray imaging

- Conventional radiography techniques:
  - based on X-ray trans-mission techniques,
  - limited resolution,
  - compact and "cheap" → wide dissemination.
- Phase-contrast imaging
  - based on X-ray refraction
  - High resolution,
  - need a bright source,
  - need to be compact.



*In-vivo X-ray image of a mouse using conventional source w. X-ray grating (**acquisition took 50 sec.**)*

*M.Bech et al., Sci. Rep. **3**, 3209 (2013)*

X-ray sources needed

- Brilliance can finally be related to the electron parameters and yield Υ of the considered X-ray process:

# of electrons per sec.

Brilliance in unit of photon/[sec-(mm-mrad)^2-0.1%BW]

Electron-beam rms divergence

Suppression factor

$$\mathcal{B} \simeq 10^{-3} \times \frac{\gamma^2 N_e \Upsilon \sigma_e'^2}{\varepsilon^2 \Delta E_\gamma / E_\gamma} \mathcal{F}(\sigma_e')$$

Transverse beam emittance

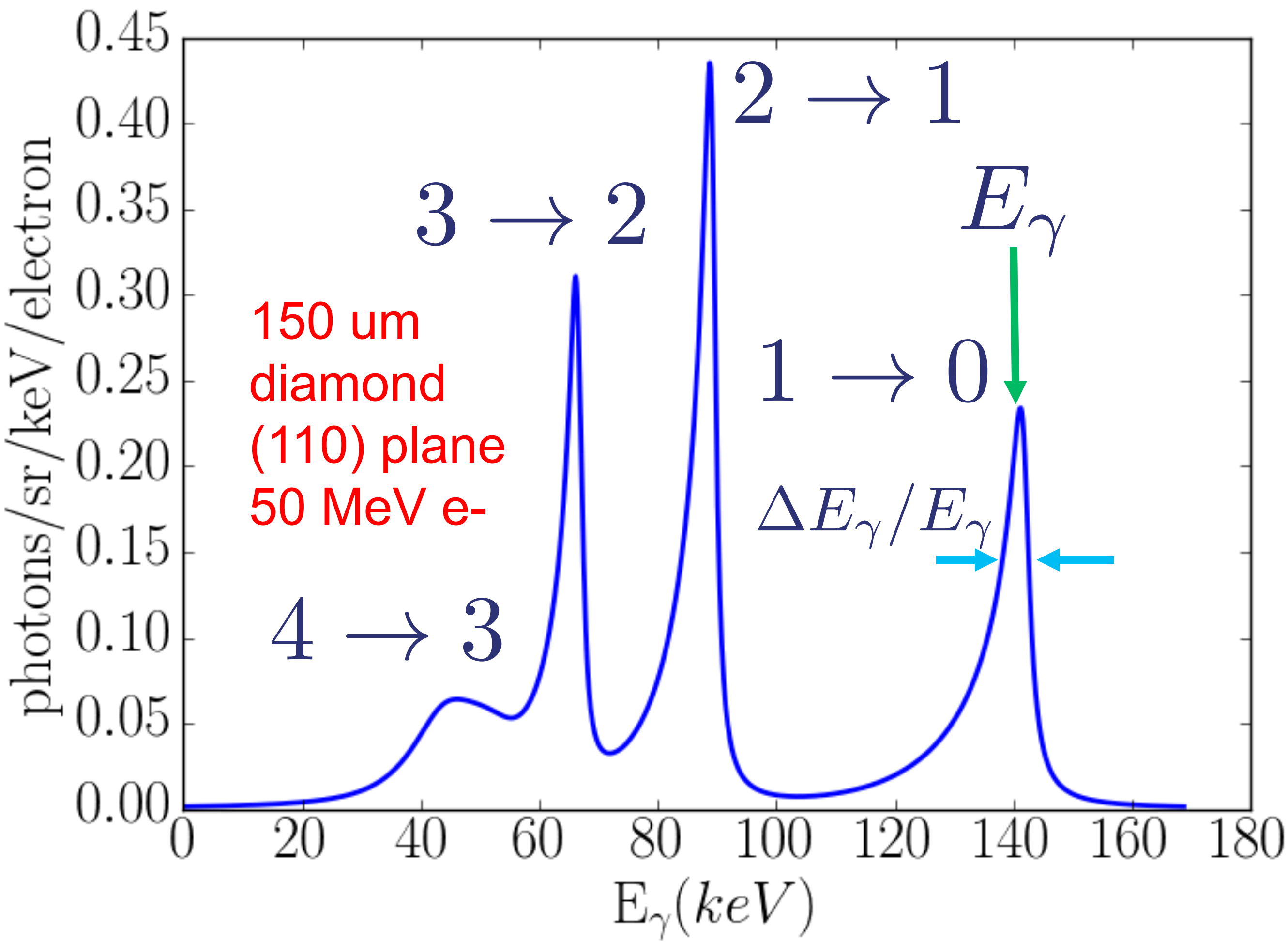
X-ray relative bandwidth

where we take the X-ray divergence $\sigma_\gamma' \sim 1/\gamma$.

Compact High-brilliance X-ray sources

- **Low complexity**
  - No laser (so no inv. Compton scatt.)
  - Based on an electron beam (available compact e sources)
- **High brilliance**
  - High yield
    - channeling
  - Low emittance
  - Small bandwidth
    - Channeling
    - PXR?, ICS?
  - Large N_e
    - High duty cycle?
- **Maximum # photon flux**
  - for reduced acquisition time
- **Compact**
  - High gradient accelerator

Relevant energy for ~100 keV X-ray



- Computed spectrum using Azadegan's mathematica code [B. Azadegan, Comp. Phys. Comm, 184, 1064 (2013)]

A possible concept

[C. Brau et al., Sync. Rad. News **25** (1) (2012)]

- use a ~50 MeV e-beam combined with channeling process,
- Electron beam is formed from a field emission electron source

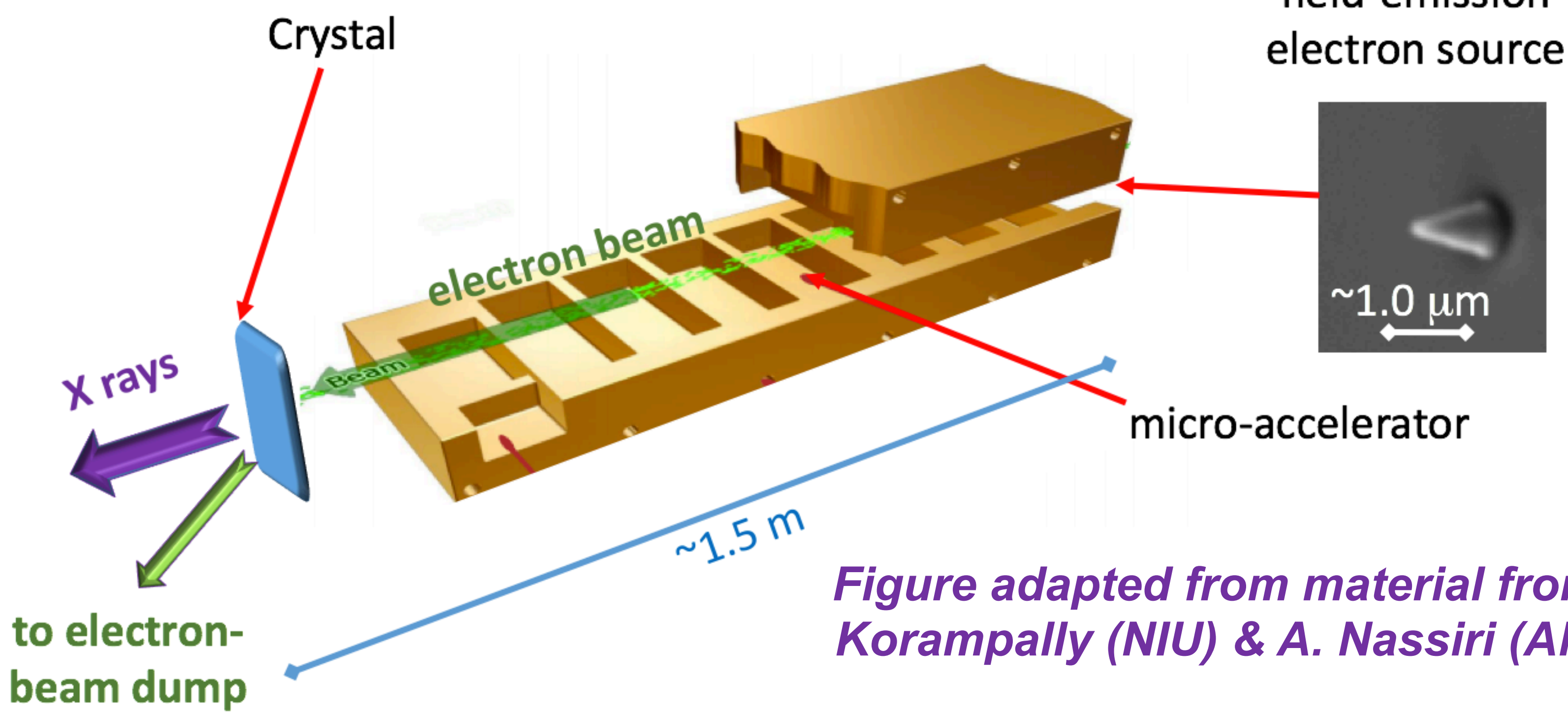


Figure adapted from material from V. Korampally (NIU) & A. Nassiri (ANL).

Requirement on electron source

- Take the following beam parameters:
  - $\sigma'_e = 10^{-4} \ll \psi_c \simeq 10^{-3} \Rightarrow \mathcal{F}(\sigma'_e) \simeq 1$
  - $\gamma = 100$
  - $\Delta E_\gamma / E_\gamma = 0.1$
- So one gets

$$\mathcal{B} \simeq 10^{-6} \Upsilon \frac{N_e}{\varepsilon^2}$$

electron-beam averaged brightness

with ultimate electron-beam brightness is given by

$$\frac{N_e}{\varepsilon^2} \sim \frac{f}{\lambda_c^2}$$

Bunch frequency

Compton wavelength

Brightness of current sources

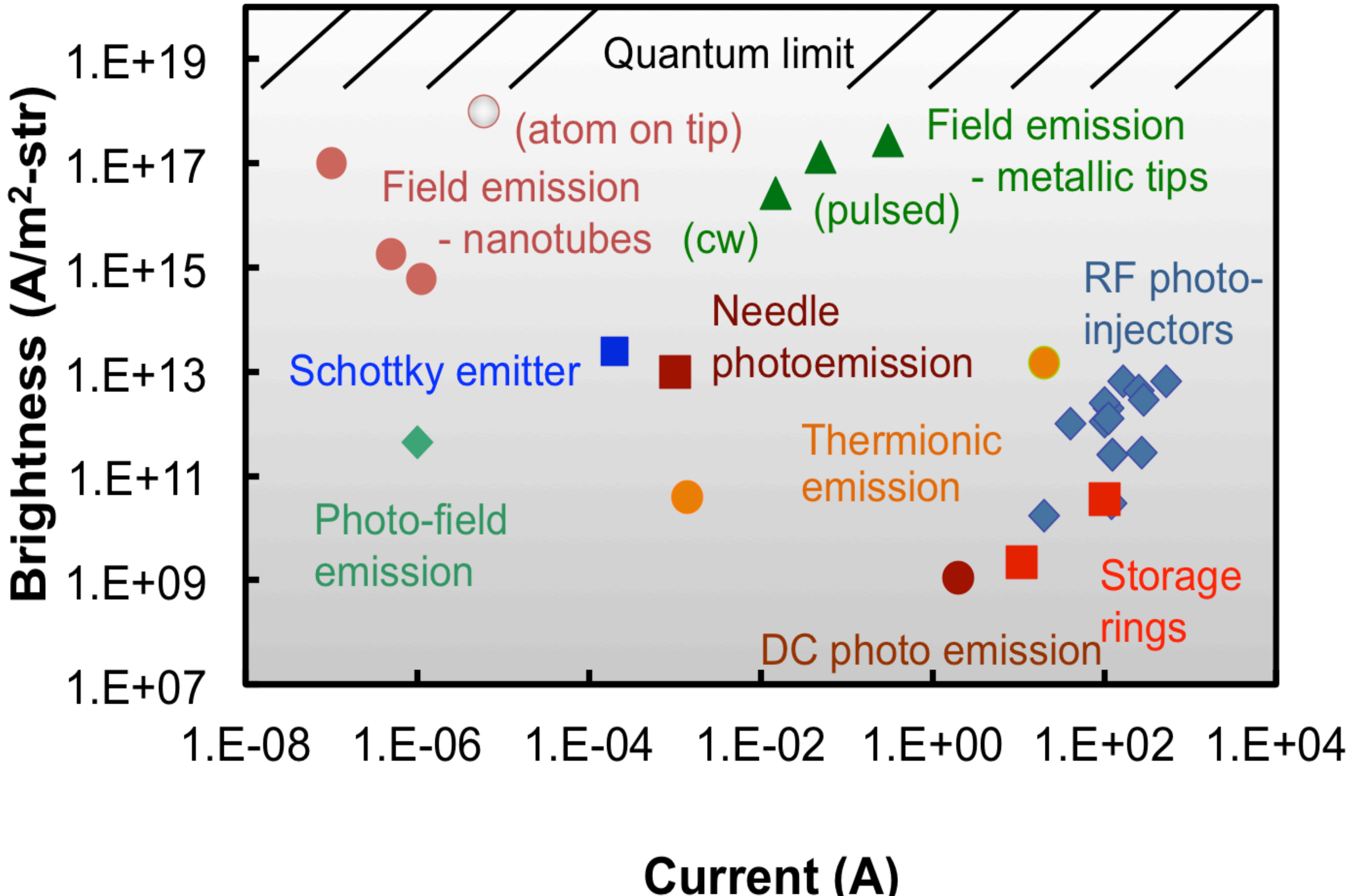


Figure from C. A. Brau (Vanderbilt University)

Electron source R&D

- Field-emission electron sources are the best candidates:
  - Can reach brightness close to the quantum limit,
  - Rugged,
  - emission can be triggered with RF field.
- Field emission is well studied. Current density is given by Fowler-Nordheim:

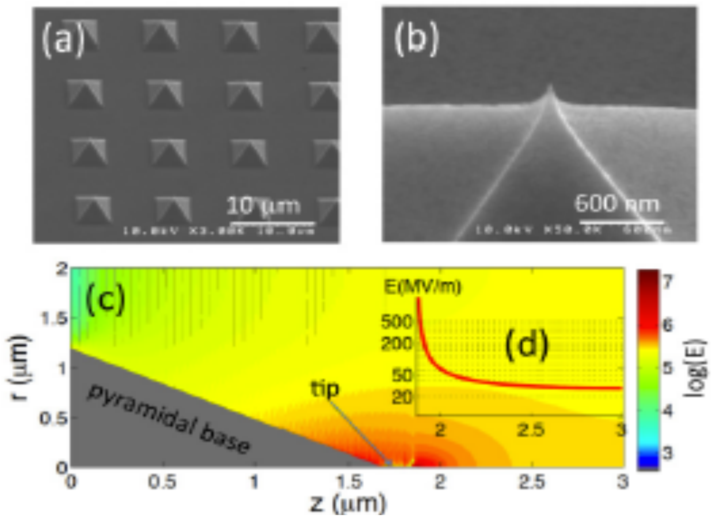
$$\boldsymbol{j}(\boldsymbol{x},t) = A(\Phi)E(\boldsymbol{x},t)^2 \exp\left(-\frac{B(\Phi)}{E(\boldsymbol{x},t)}\right)\hat{\boldsymbol{n}}(\boldsymbol{x})$$

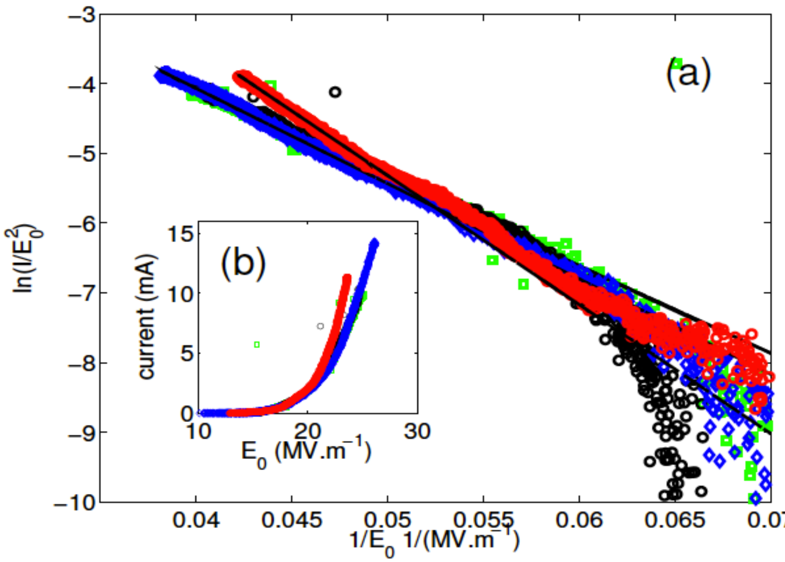
- we need *pulsed* emission (for subsequent acceleration in a linac)

Recent tests of field emission in a L-band RF gun (focused on high current)

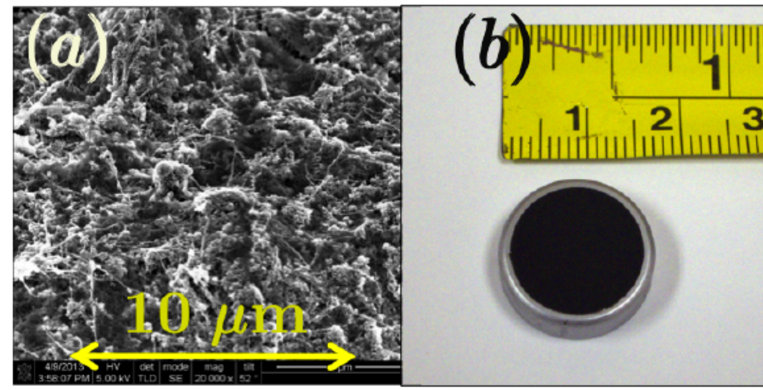
P. Piot, et al., Appl. Phys. Lett. 104, 263504 (2014).

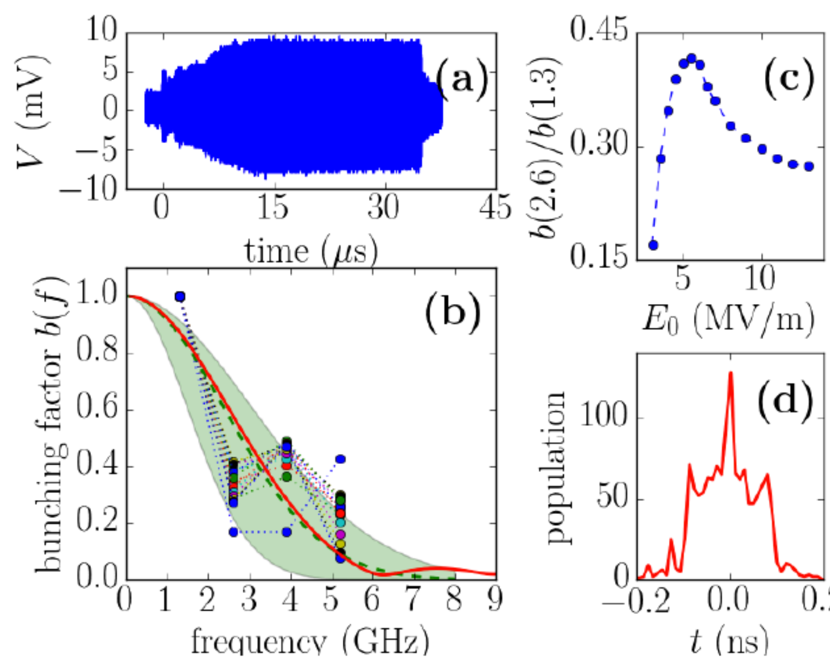
- Diamond field emitter arrays





- Carbon-nanotube "forest"

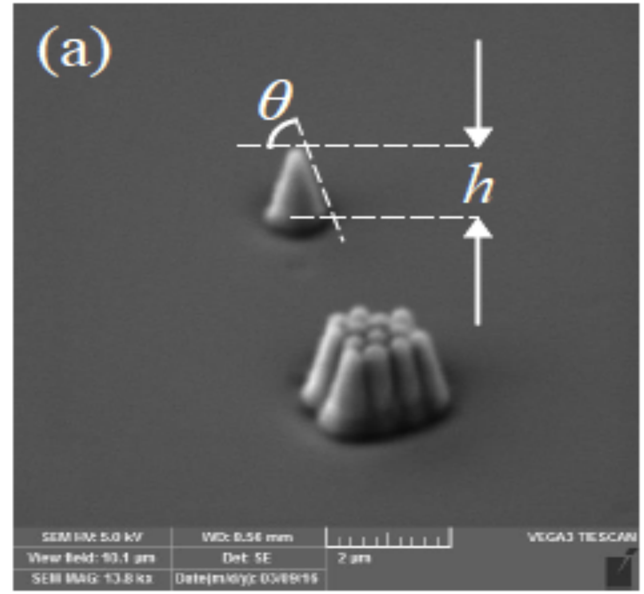


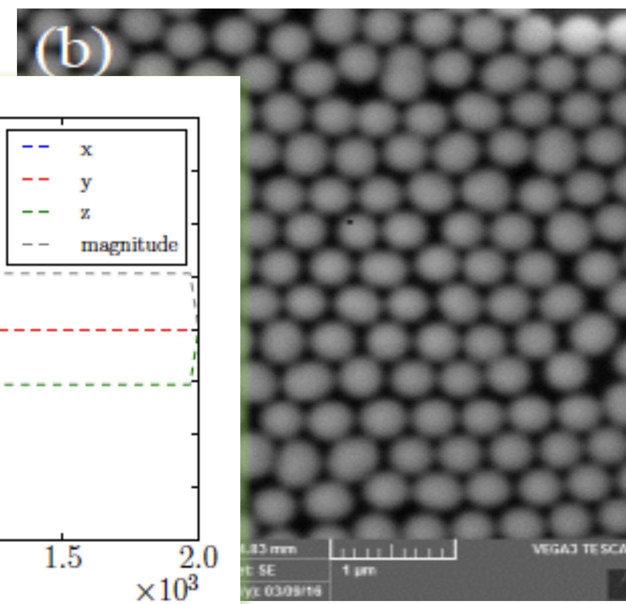


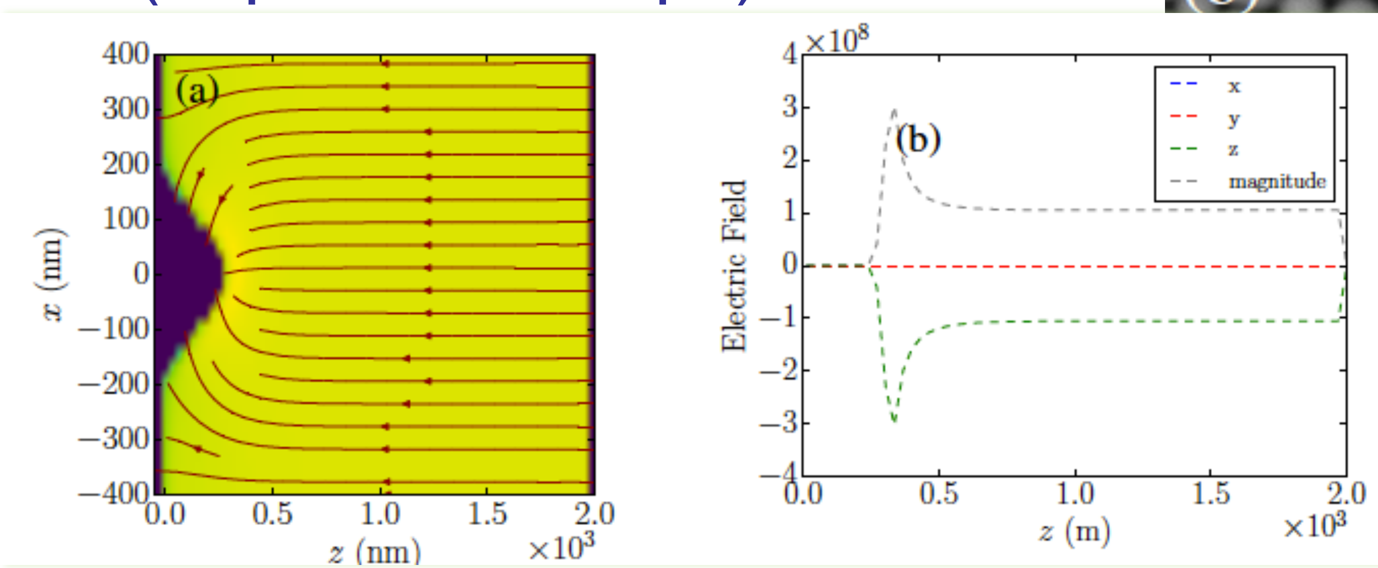
D. Mihalcea et al., Appl. Phys. Lett. 107, 033502 (2015).

Recent cathode development: emphasis toward ultracold beams

- Collaboration between NIU and Argonne Center for Nanoscale Material
- Developing techniques to produce single-emitter (doped silicon tips)



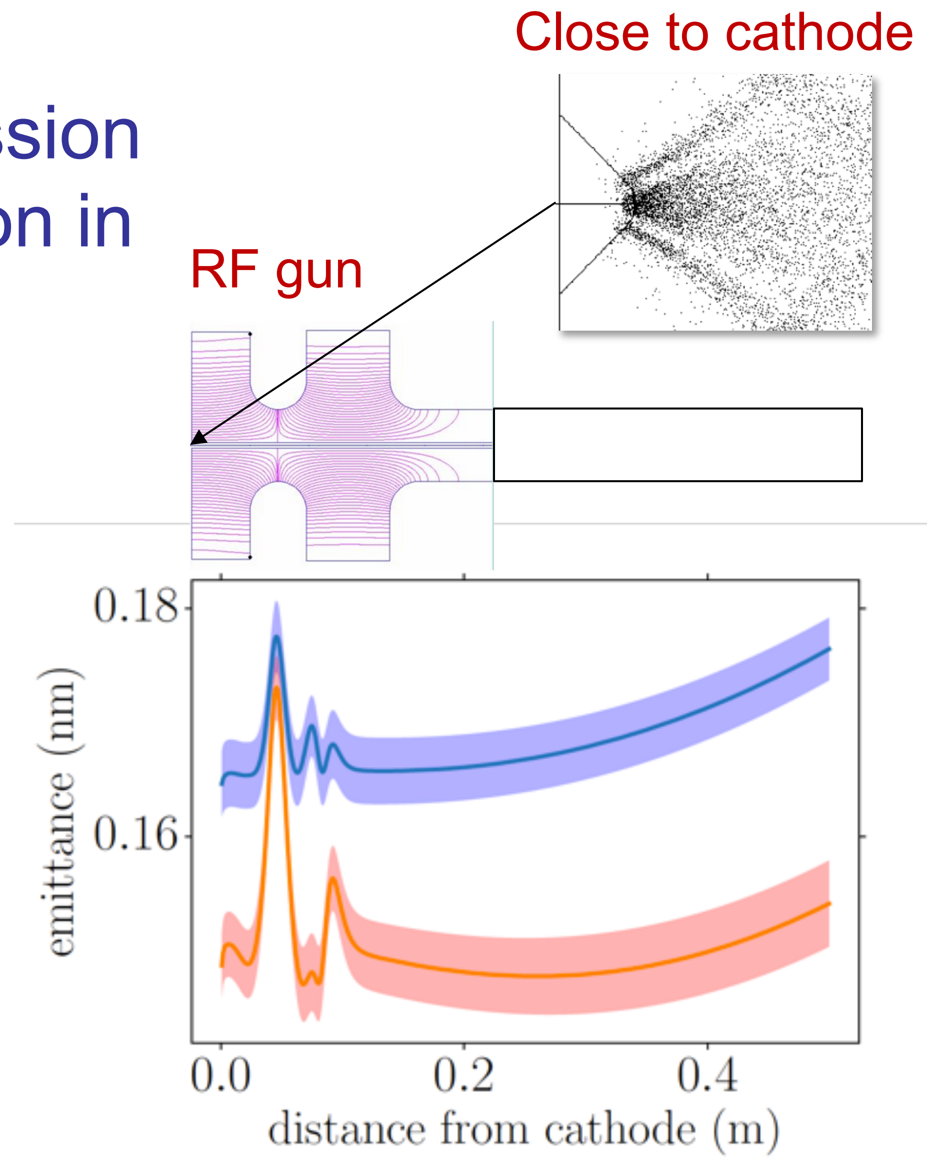




Acceleration to relativistic energies

- PIC simulations of emission process and acceleration in an S-band RF gun
  - Final energy 5.3 MeV
  - sub nm emittances for 100 e-bunch

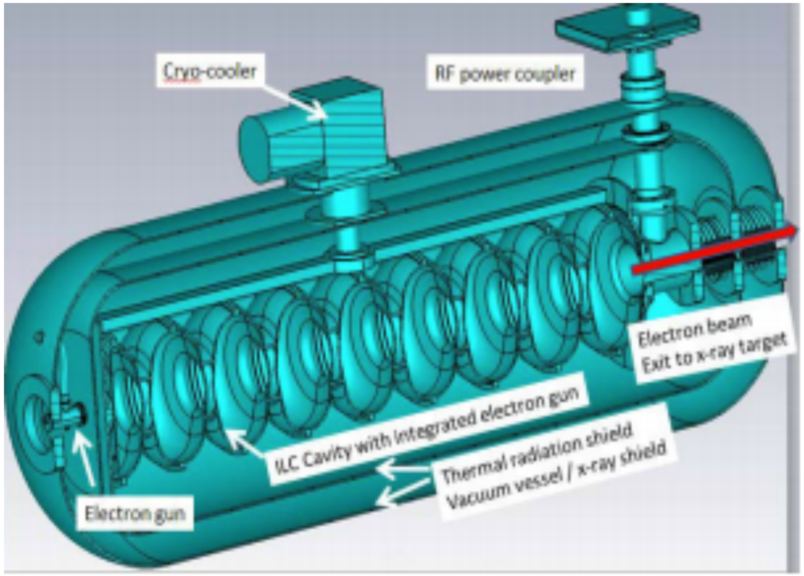
- These results could yield brightness $\mathcal{B} \sim 10^{13}$ in standard units!

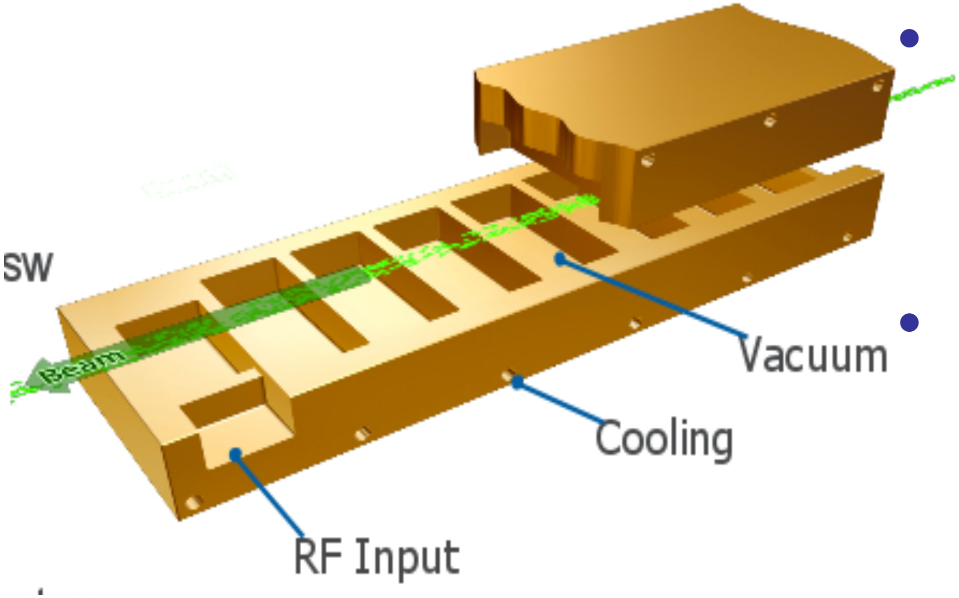


Accelerator options

J. Song et al. Microsystem Tech. **4**, 193 (1998)

- Superconducting high-gradient accelerator on-going at Fermilab using conduction cooling





- High frequency high-gradient accelerator are not ready
- Argonne had a significant R&D effort which is halted

B. Kephart et al., FRBA03, in Proc. SRF15

Summary

- Channeling radiation combined with a compact accelerator including recent advances in electron source is poised to support the development of compact X-ray sources
- An effort was started at Fermilab/NIU/Vanderbilt but eventually stopped
- Currently only e-source R&D is being pursued

- We hope to renew such effort with a wider collaboration…

Credits

- The following individuals contributed this work: C. Brau, C. Buzzart*, B.K. Choi, W. Gabella, V. Korampally, A. Lueangaramwong*, D. Mihalcea, H. Panuganti*, and T. Sen.
  * current or past graduate student at NIU
- Thanks to A. Nassiri (ANL) for discussions

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