Thermionic cathode-based injector R&D at Argonne National Laboratory

Ryan R. Lindberg

Compact x-ray FELs using high-brightness beams workshop
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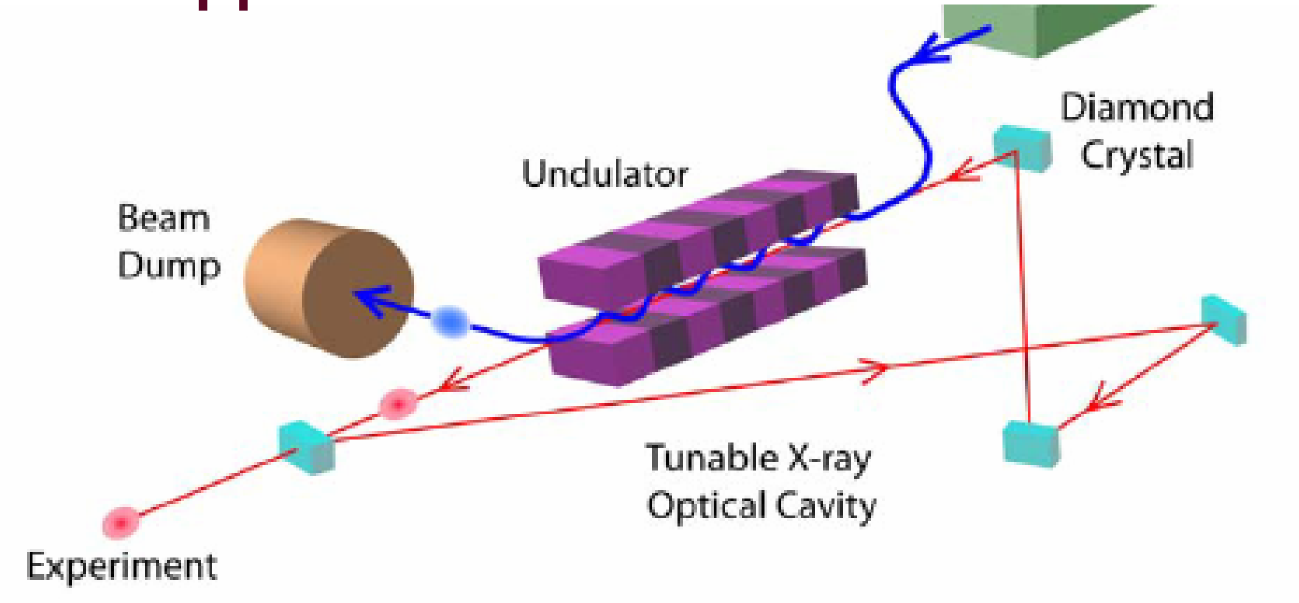
Acknowledgements

- ANL

  M. Borland, X. Dong, K. Harkay, K.-J. Kim, A. Nassiri, P.N. Ostroumov, J. Power, N. Sereno, …

- P. Piot (NIU), T. Shintake (SPring-8), LBNL CBP, …

Motivation: an x-ray FEL oscillator for ultra-low bandwidth applications



An x-ray pulse is stored in a cavity formed by diamond Bragg crystals
➔ low pass gain and spectral cleaning over many passes

Fourier transform limited pulses: $\Delta\omega/\omega \sim 10^{-7}$ ➔ $\hbar\Delta\omega \sim 1$ meV

10^9 photons/pulse with brightness 10^{32} photons/s/mm^2/mrad^2/0.1%BW

1. R. Colella and A. Luccio, Optics Comm. **50**, 41 (1984).
2. K.-J. Kim, Y. Shvyd' ko, and S. Reiche, Phys. Rev. Lett. **100**, 244802 (2008)

Injector requirements for an x-ray FEL oscillator

- High beam quality

  Normalized emittance < 0.2 mm-mrad (rms)

  Energy spread $\Delta E/E < 2 \times 10^{-4}$ (rms)

- "Long" bunch length ~ 0.1 to 1 ps (rms)

  Fourier transform limited electron beam bandwidth < Bragg crystal bandwidth $\Delta\omega/\omega \sim 10^{-6}$ to 10^{-7}

- Low charge < 50 pC: peak current between 10 and 100 A

- Bunch repetition rate 1 MHz (to 10 MHz for multiple XFELOs)

  Rep rate matches round trip time of x-rays in cavity

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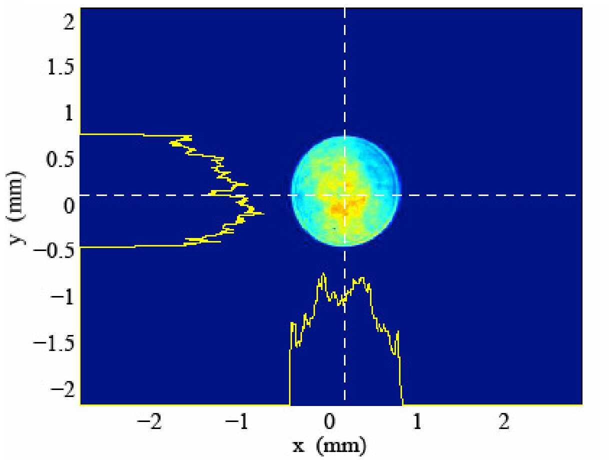
Electron gun technologies in use and under development

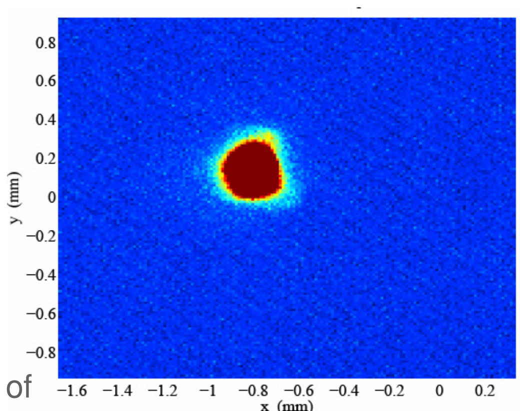
- The LCLS photoinjector produces low-charge beams of sufficient quality ($\varepsilon_{x,n}$ = 0.14 @ 20 pC charge), but the repetition rate ~120 Hz
- The PITZ gun may be suitable for a *pulsed* x-ray FEL oscillator
  - $\varepsilon_{x,n}$ = 0.3-0.4 mm-mrad @ 100 pC charge, f_b = 1 MHz for 800 μs, f_{macro} = 10 Hz
- ERL-type guns may satisfy XFELO requirements
  - Cornell: $\varepsilon_{x,n}$ = 0.2 mm-mrad @ 20 pC charge (but calls for 750 kV DC voltage)
  - KEK-JAEA: : $\varepsilon_{x,n}$ = 0.1 mm-mrad @ 6 pC charge (using 600 kV DC voltage)
- The LBNL 200 MHz gun design (presented earlier) could be configured to satisfy the XFELO requirements
- RIKEN/SPring-8 thermionic pulsed DC
  - 500 kV @ 60 Hz, $\varepsilon_{x,n}$ = 0.6 mm-mrad with a 3mm cathode diameter
- We discuss an alternative approach drawing on these ideas/designs

Photocathode or thermionic cathode?

Intensity distribution of a "good" laser spot

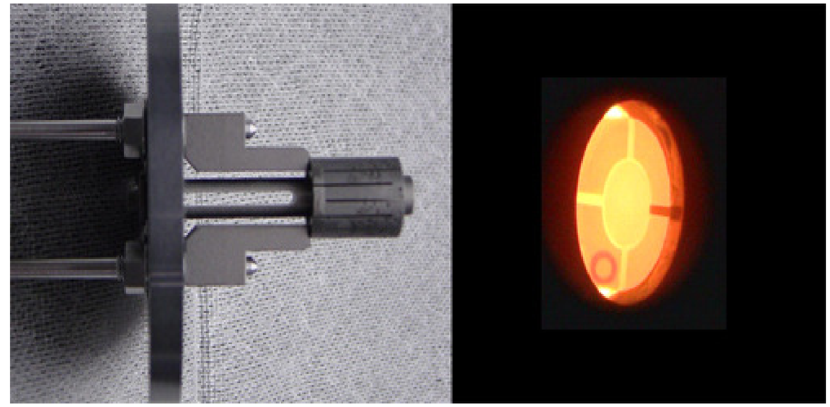


Electron distribution from the photocathode

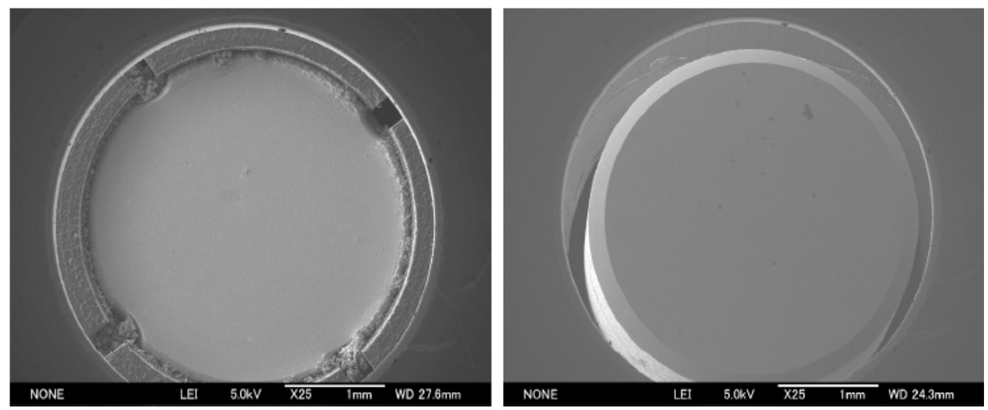


Courtesy of D. Dowell

SCSS CeB_6 thermionic cathode



CeB_6 cathode after 20,000 hrs. of operation (left) and new (right)



Courtesy of T. Shintake

For low intensity and ultra-low emittance, thermionic cathodes are an option capable of long-term, stable operation

A high repetition rate thermionic injector

- Current paradigm of injector design is based on the laser-driven rf photocathode

    Demonstrated success for high-current, low emittance beams

- XFELO requirements are different:

    Low-current, ultra-low emittance beams at a constant MHz repetition rate

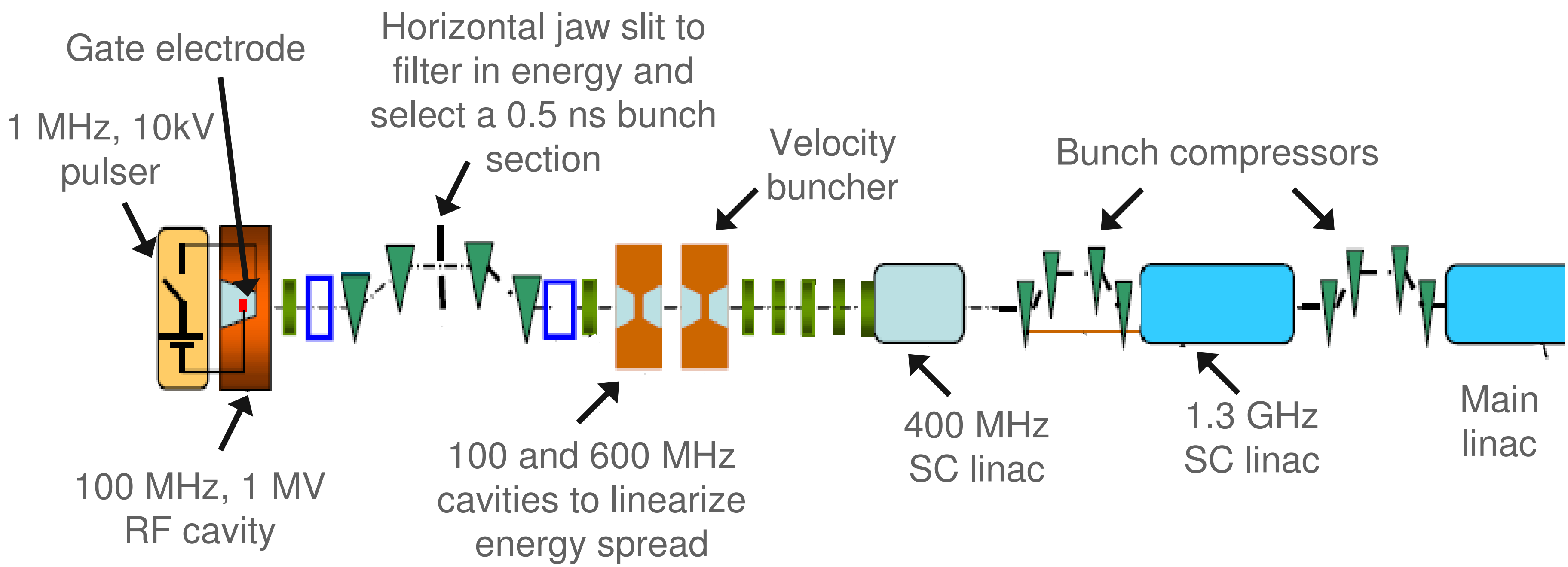
- An alternative approach uses a thermionic cathode inside a low frequency RF cavity

    Inspired by the success of the pulsed DC thermionic gun at SPring-8

- The injector can also be configured to produce beams suitable for ultrafast SASE (i.e., few fs pulses), although this is not our focus

3. P.N.. Ostroumov, K.-J. Kim, and P. Piot, Proceedings of the LINAC-08, pp 666
4. P.N. Ostroumov, D. Capatina, K.-J. Kim, S.A. Kondrashev, B. Mustapha, and A. Nassiri, Proceedings of the 2009 Particle Accelerator Conference

Injector concept applicable to XFELO



- 100 MHz RF scaled from the Berkeley design[5]
- Thermionic cathode inspired by SPring-8 success[6]
- High voltage, 1 MHz pulsed electrode to gate emission, eliminating need for high power beam dump and mitigating back-bombardment on the cathode

5. K. Baptiste, J. Corlett, S. Kwiatkowski, S. Lidia, J. Quiang, F. Sannibale, K. Sonnad, J. Stapes, S. Virostek, and R. Wells, Nucl. Instrum. Methods Res. A **599**, 9 (2009).
6. K. Togawa, T. Shintake, T. Inagake, K. Onoe, T. Tanaka, H. Baba, and H. Matsumoto, Phys. Rev. ST-Accel. Beams **10**, 020703 (2007).

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Taming the electron beam power

- To achieve emittance goals, the effective cathode area should be ~ 10 times smaller than the cathode used at SPring-8.
- Very small cathodes may suffer in performance
  - ➔ Dominated by the etched/damaged cathode periphery
- So, we'd like to select some small transverse portion of the beam
- If we do this after accelerating by the ~1 MV in the gun, the beam power on the slits/aperture would be several kWs
- To deal with this beam power, we might use

Pulsed gate electrode?

Extreme beam dump?

Laser-assisted flash heating?

???

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- So, we'd like to select some small transverse portion of the beam
- If we do this after accelerating by the ~1 MV in the gun, the beam power on the slits/aperture would be tens of kW
- To deal with this beam power, we might use

Pulsed gate electrode — Our base-line design choice

Extreme beam dump?

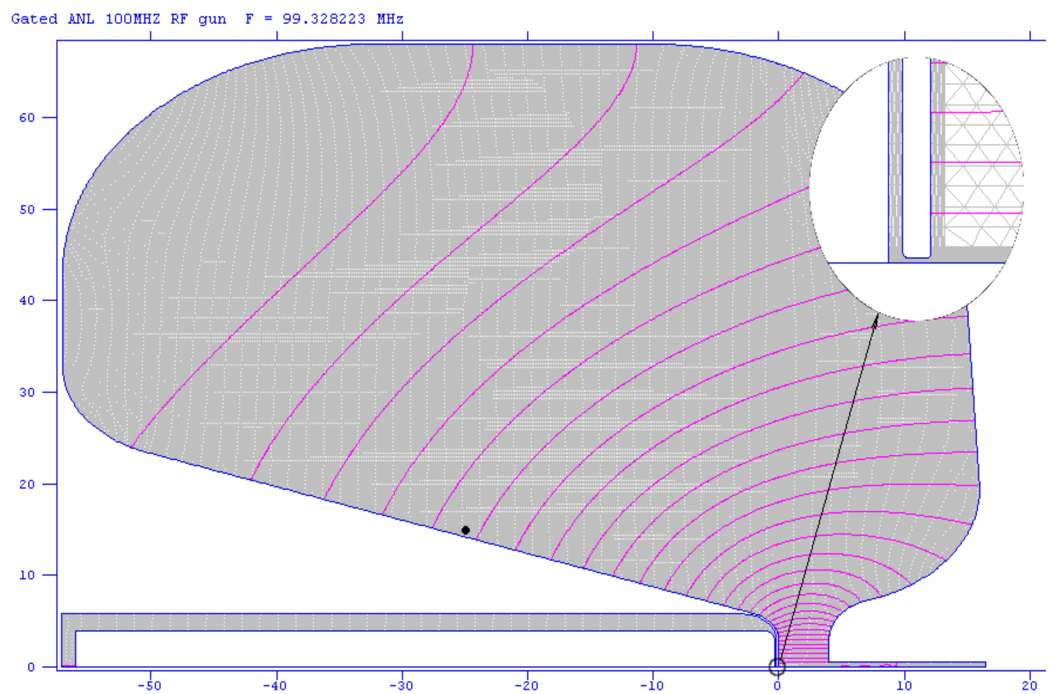
Laser-assisted flash heating?

???

Gating electrode

- Thin (~ 1 mm) plate with small (~ 1 mm) hole shields rf field
- The current is gated by a pulse of ~ 10 kV over ~ 5 ns
- The hole selects a small portion of the beam at low energy and a 1 MHz repetition rate, yielding low emittance at low beam power.

Calculation of the cavity fields including the gating electrode using Superfish/Poisson



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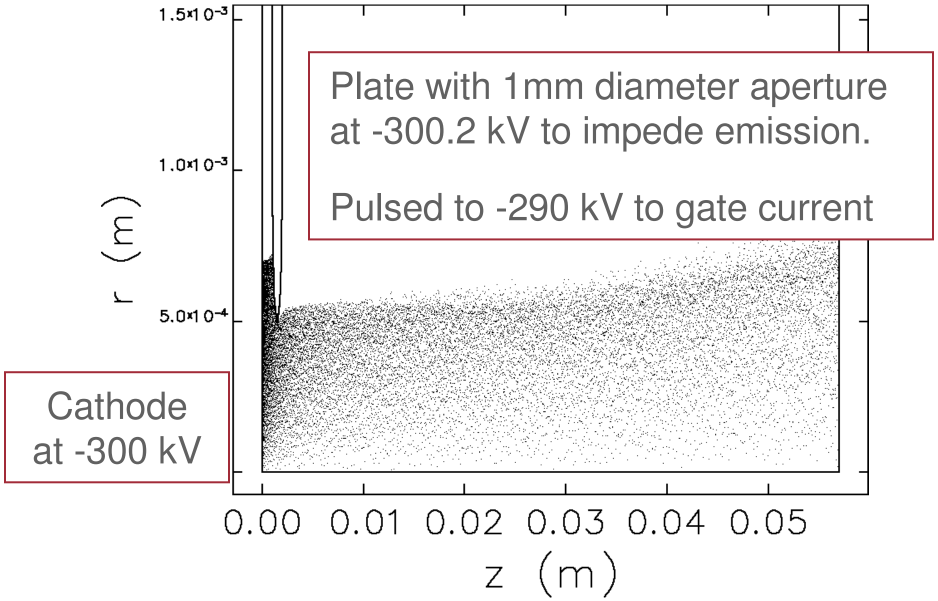
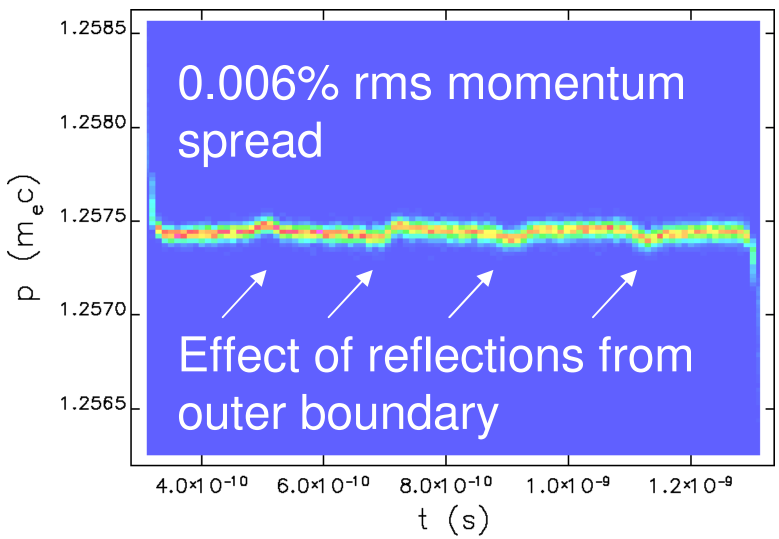
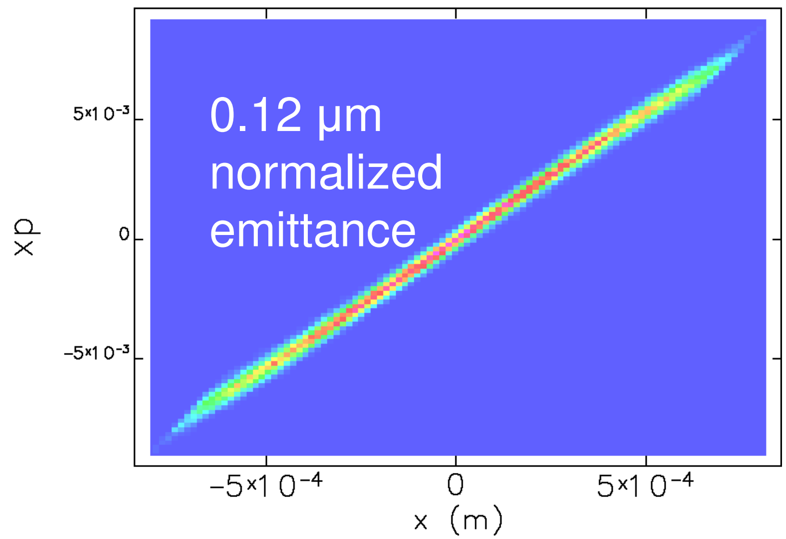
First look at a 1 MHz, 300 kV DC gated gun

- Modeled using SPIFFE[7] with static potentials (not pulsed)
- 0.07 A measured current
- Beam quality includes thermal velocity spread (1500 K cathode)



7. M. Borland, Users guide to SPIFFE, www.aps.anl.gov





Fast switch technology

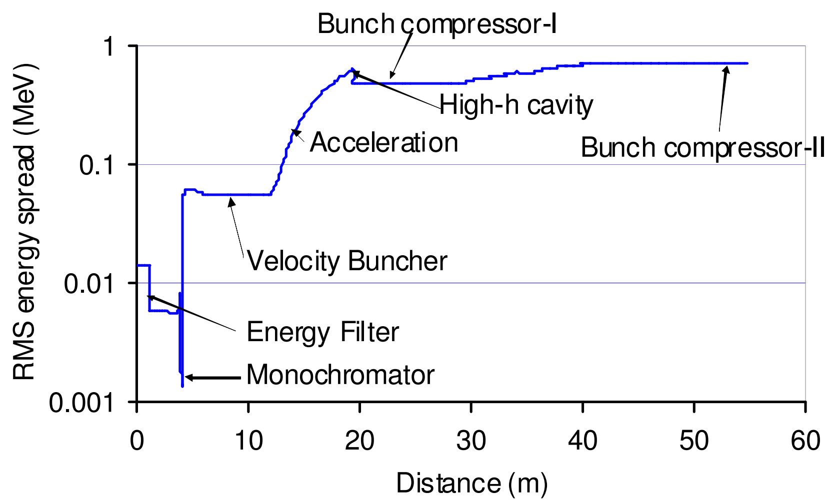
- Main commercial supplier is FID
- < 1kV, 1 MHz fast switch suitable for constant operation exists today
- A 10 kV, 3 MHz fast switch is being presently used at the Accelerator Test Facility (KEK)

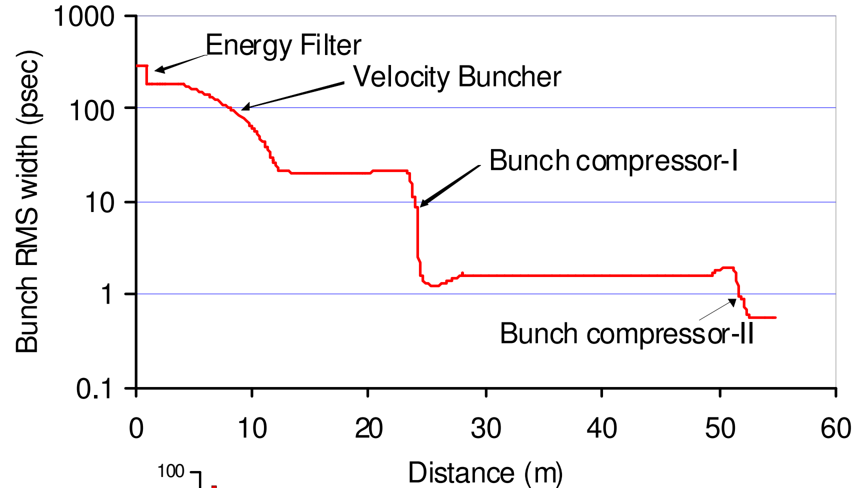
  Pulsed operation for a ~ millisecond every 5 Hz
- A 10 kV, 1 MHz fast switch for constant operation is a technological challenge

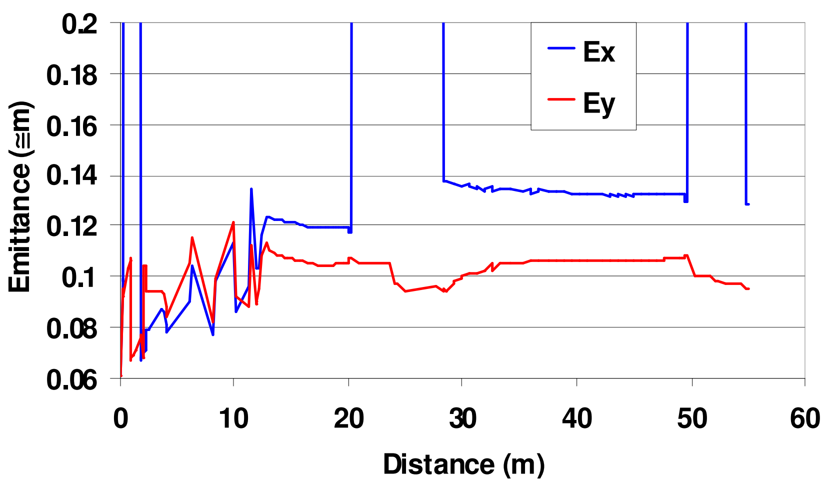
  FID has said it can make a suitable high voltage switch

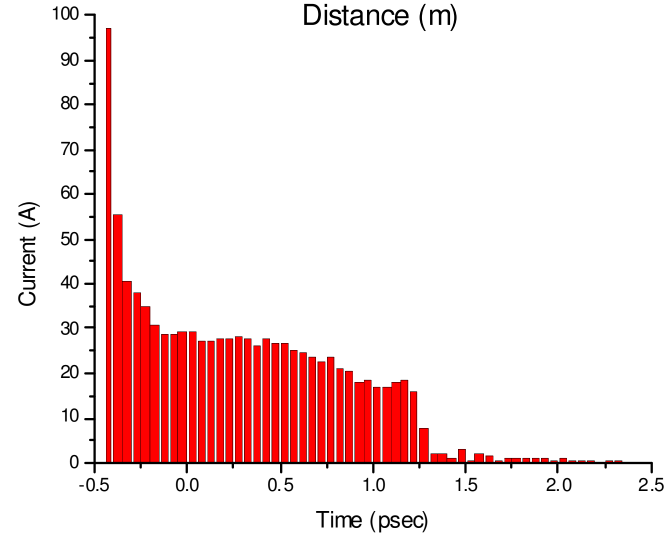
  Advances in semiconductor technology may solve this problem for us…
- These high voltage fast switches may have other applications in, e.g, beam switchyards for high repetition rate FEL facilities

3D TRACK simulation of injector performance, optimized with a genetic algorithm









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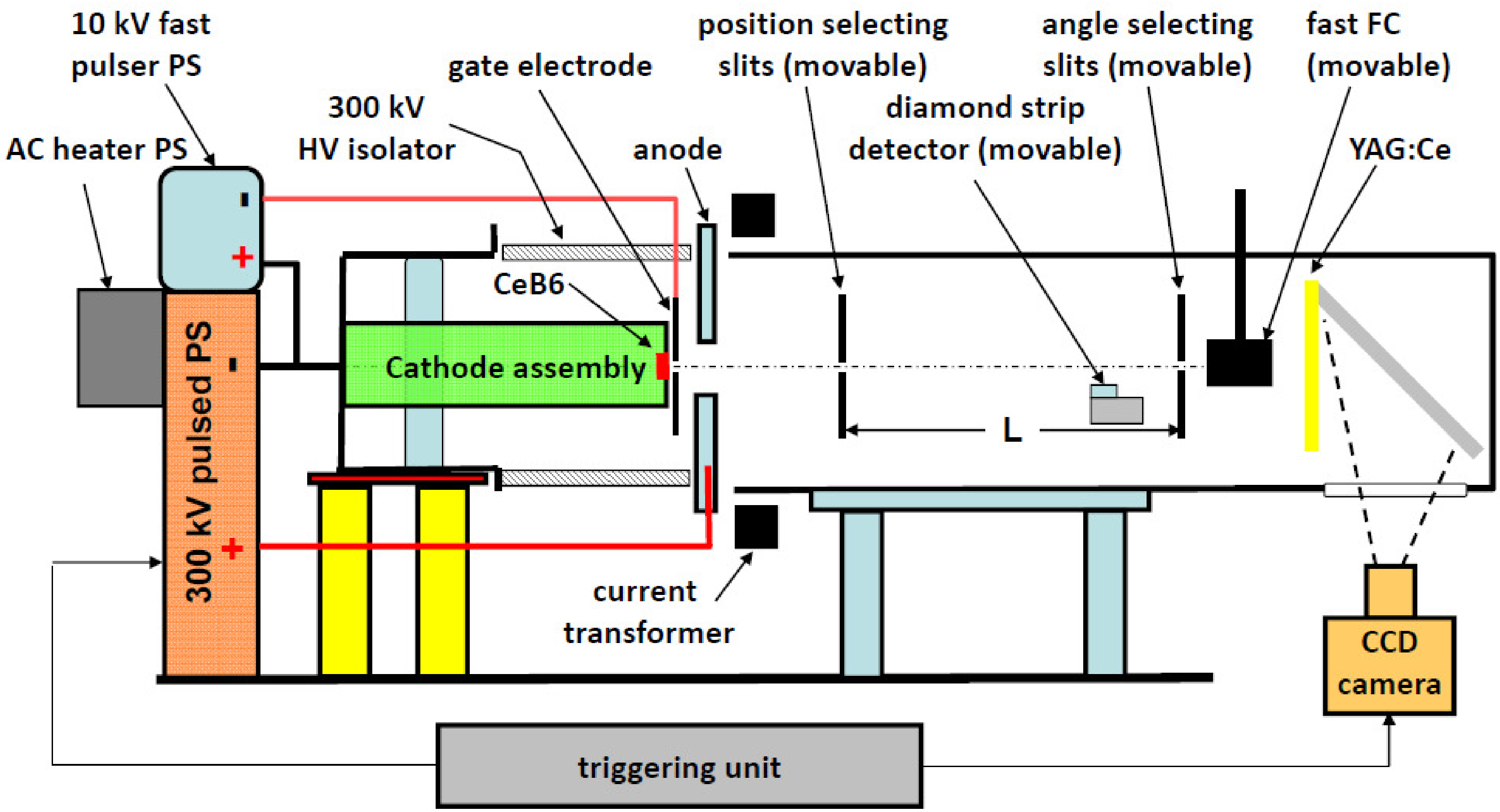
A pulsed DC gun test stand



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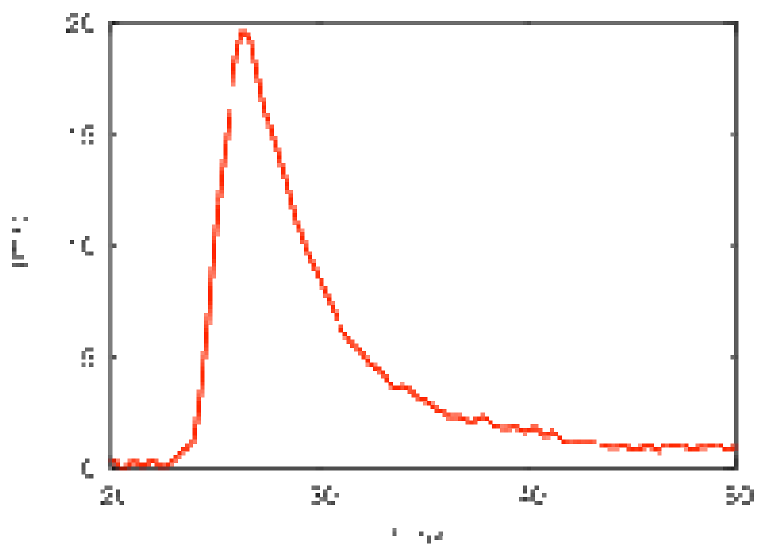
Other possible gating schemes

- High power electron beam dump
  - One could simply remove most of the beam with an rf cosine chopper and a high-power electron beam collector (EBIS-type parameters)
  - Electron back-bombardment ameliorated with 3-pole wiggler
- Laser-assisted thermionic emission
  - Cathode is kept at a temperature below the emission threshold
  - Laser used to flash-heat the cathode over a short time for emission



Experiment at ITS facility at APS showed short pulse emission is possible with reasonable agreement to 1D theory[8]

8. N.S. Sereno, M. Borland, K. Harkay, Y. Li, and R.R. Lindberg, APS technical note in preparation (2010).

Conclusions

- XFELO requires an ultra-low emittance, low charge beam at a high repetition rate
- Thermionic cathodes provide stable, high quality beams that appear to be well-suited for XFELO
- Primary problems to surmount include
  - Back-bombardment on the cathode
  - Beam power to be dumped from the gun

Both problems can be ameliorated by gating the emission at the cathode

- High voltage electrode for gating is theoretically quite attractive
  - Realizing one is challenging but probably feasible
- Other gating mechanisms are also being investigated