Ultrashort laser pulses on the cathode: blow-out regime and multiphoton photoemission

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Future Light Sources, 2010
Outline

- Ultrashort laser and electron beams in RF photoinjectors
- Ultrafast is a new trend in HEBE
  - Ultrafast defined by photoinjectors evolution path: anything shorter than a few hundred fs.
- Trend away from HEP/traditional 5-10 ps-long 1 nC charge driven by luminosity requirements. Not really needed for light sources.
  - Progress in laser systems. Commercial sub-40 fs Ti:Sa systems available.
  - Applications of high brightness beams.
    - Single spike FEL
    - TV/m plasma wakefields
    - Ultrafast Electron Diffraction.
- Blow out beam characterization at UCLA Pegasus laboratory
- Advantages
  - Longitudinal and transverse phase space linearities.
The RF photoinjector: highest brightness beam source

• RF photoinjectors have been one of the key technological advances to allow the development of high gain FEL amplifiers

• The RF photoinjector has been/is/will be the electron source for all the major past, present and future single pass FEL amplifier projects: LEUTL, VISA, TTF, SDL, FLASH, SPARC, LCLS, etc. (with the notable exception of the Spring 8 FEL.)

• State of the art designs of high brightness electron beam sources involve the use of uniformly filled, temporally flat, cylindrical laser pulses and hence beam distributions.

• “Beer-can” beam suffers from
  – Edge erosion, non-uniform distribution
  – Nonlinear fields at edges
  – Severe practical difficulties with laser
Dynamically optimized beam distributions: a new regime of the RF photoinjector

• Ideal beam distributions.
  – Kapchinskii-Vladimirskii, uniformly filled ellipsoids, waterbags have always helped theorists in accelerator beam physics.
  – Analytical field expressions
  – Linear space charge fields in each direction
  – The problem is how to generate such beams in real systems
  – Blow-out regime of photo-injectors.
  – No particular longitudinal shape needed
  – Existing hardware compatibility

GPT simulation
UCLA Pegasus Laboratory

- Home of the first UCLA SASE FEL experiments (decades ago)
- Advanced photoinjector laboratory student-driven located at UCLA.
  - state-of-the-art Ti:Sapphire ultrafast drive laser system.
- Ideal for blowout regimes studies
  - Availability of sub-100 fsec diagnostics.
  - Electro-optic sampling
  - 9.6 GHz RF deflector.
- Also for ultra-fast electron diffraction
- Bunch train generation
- THz production
Ellipsoidal beam experimental demonstration
At Pegasus

- Charge 20 pC. Laser spot size 400 μm rms (limited by asymmetry due to image charge)

- rms length ~300 fs

- Very sharp ellipsoidal beam boundary due to the ultrashort beam on the cathode.

- What is really new here is:
  - Shorter beams.
  - More linear phase spaces (transverse and longitudinal).
  - Control beam tails.
  - Ease requirements on laser system.

Limits of the Photoinjector Blowout Regime
Head-Tail Asymmetry

- Increasing the charge we observe the development of an asymmetry in the ellipse boundary.

- Reversing the deflecting voltage by going 180 degrees off in phase, we obtain the same picture upside down.

- Simulations predict this effect, which is mainly due to the image charge at the cathode that ‘pulls’ the beam tail.

- When the space charge field at the cathode reaches approximately 10 % of the accelerating field, a strong asymmetry develops in the formation of the ellipsoid quickly degrading the beam quality.

GPT simulation with Pegasus photoinjector parameters
Longitudinal phase space

- Use vertically deflecting cavity in conjunction with horizontally dispersing dipole
- Control the induced energy spread from the cavity as predicted by Panofsky-Wenzel theorem
- Record resolution in time (50 fs) and energy (1 keV).
  - Advantages of measurement on low energy beams.

Very linear phase space

High 6D beam brightness

Ultralow longitudinal emittance (<0.5 um)

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS  12, 070704 (2009)

Longitudinal phase space characterization of the blow-out regime of rf photoinjector operation

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(Received 27 April 2009; published 29 July 2009)
Longitudinal phase space characterization of ellipsoidal beams

Extremely small uncorrelated energy spread and longitudinal emittance. (emittance exchange techniques?)

Chirp is insensitive to changes in RF phase and charge

Head-tail asymmetry. Agreement with simulations.
Beam brightness definition


\[
\frac{B_n}{f} \bigg|_{\text{max}} = \frac{mc^2\epsilon_0E_{\text{cath}}}{2\pi kT}.
\]

- Transverse brightness is not the all story.
- 6D brightness should be a measure of electron beam density in 6D phase space.

\[
B_{6D} = \frac{N}{V_{6D}} \neq \frac{N}{\epsilon_x\epsilon_y\epsilon_z}
\]

- But, even after being able to measure the x,y,z emittances, 6D brightness is still very difficult to quantify as there are lots of correlations between the different planes.
- Blow-out regime is not “higher brightness”. It is just a beam with very different properties (no shaping required, shorter beam, more linear phase spaces, etc.)
- In the end, it depends on the beam application which brightness is relevant.
- Question for the working group. Is a low rep rate RF gun capable of higher brightness (due to the larger field on the cathode...)?
Ultrashort laser pulses for bunch train generation

- Enable direct generation at the cathode of pulse trains with sub-ps spacing.

Increase the average brightness:
- splitting photocathode drive laser
- creating multiple low charge high peak brightness beams

Reference: M. Boscolo, M. Ferrario
NIM A 577 (2007) 409–416
Electro-Optic Sampling.
Non destructive single-shot synchronization

- Novel 90 degrees crossing spatial encoding geometry
- Single-shot non destructive Time-Of-Arrival information
- EOS signal from 10 pC 4 MeV beam!

![Diagram of Electro-Optic Sampling](image)
FRED: Femtosecond Relativistic Electron Diffraction

- New application of high brightness ultrashort electron beams from RF photoinjector.
- High quality single shot diffraction patterns from thin metal targets. $10^7$ electrons in <100 fs pulse length.
- Probe beam three orders of magnitude more intense than conventional UED sources
- Enable pump and probe studies of irreversible ultrafast phase transitions!

RF gun UCLA/BNL/SLAC
6 MW 2.856 GHz

Probing electron beam
100 fs rms long
5 pC 3.5 MeV

UV laser pulse
1-10 μJ 40 fs rms

Pump pulse
0.5 mJ 800 nm
0.1 mJ 400 nm 40 fs rms

Collaboration with LLNL, and NSTEC (LANL).
12 bit camera + MCP detector screen

Two axes x-y sample-holder movement
Multiphoton photoelectric effect

• “Violating” Einstein photoelectric effect...
  o For a given metal and frequency of incident radiation, the rate at which photoelectrons are ejected is directly proportional to the intensity of the incident light.
  o For a given metal, there exists a certain minimum frequency of incident radiation below which no photoelectrons can be emitted. This frequency is called the threshold frequency

• .....and few years of RF photoinjector common practice spent on “getting ready the UV on the cathode”

• Two or more small photons can do the job of a big one.

• Generalized Fowler-Dubridge theory: photoelectric current can be written as sum of different terms.

\[
J = \sum_n J_n \\
J_n = \alpha_n A \left( \frac{e}{h \nu} \right)^n (1 - R)^n I^n T_e^2 F \left( \frac{n h \nu - e \Phi_0}{k T_e} \right)
\]

Fowler function selects the dominant n-order of the process
Send ultrashort IR pulses on the cathode

**Question:** Why hasn’t this been done before?

- Very early results from Srinivasan-Rao et al. and Muggli et al. (mid 90s)....
- Recent interest in pancake regime. Ultrashort beam at cathode => uniformly filled ellipsoidal beam.
- Very high extraction field in RF photoinjector: away from space charge induced emission cutoff. (Early experiments using low gradient setups.)
- Damage threshold few 100 GW/cm² at sub-100 fs pulse lengths.

Measure yield for different spot sizes.

*BUT conversion efficiency is ~10%*
Multiphoton photoemission scaling laws

- The current density (charge per unit time per unit area) is proportional to the cube of the laser intensity.
- At emission the electron beam is as long the laser pulse.

\[ Q = J_\tau A = C_\tau A I^3 = C \frac{E^3}{\tau^2 A^2} \]
**Prompt multi-photon photoemission**

Is it thermally assisted photoemission? The signature would be a slower response.

Autocorrelation of two IR pulses on the cathode shows promptness of emission.

**Nonequilibrium Electron and Lattice Temperatures in Tungsten**


**Optical PG autocorrelator**

Operating Range:
Al Mirrors: 200–1000+nm @ > 80% Reflection
Polarizers: 200–6000nm @ > 80% Transmission
Waveplate: Wavelength Specific
BeamSplitter: Wavelength Specific

by M.S. Gutierrez
MgF₂ coated Cu cathode

- Off-axis diamond turning gives mirror-like surface; no tool pressure in critical center of emitting surface.
- Hard MgF₂ film on a substrate improves scratch resistance, act as anti-reflective coating.
- QE in UV has been stable 3-4E-5 after many months of operation at ~ 90 MV/m.
- AR coated for 266 nm, also measured reflectivity @ 800 nm 15 % (key to multiphoton photoemission results).
- Next step: AR coating @ 800 nm ?
Surface analysis (SEM)

- IR Reflectivity drops a lot due to coating. (75% -> 15 %) UV (22 % - 4 %)
- For 3-photon process that is a gain of factor of (1-R)³ ~ 40!
- Good vacuum conditions.
- Good RF behavior.
- Thermal emittance and dark current levels very comparable for the UV pulses.
Beam dynamics of IR photoelectrons

- Excess kinetic energy same as in UV case
  \[ E_k = n\hbar \nu - e\Phi_0 \]

- Thermal emittance very similar to UV measurements

- Still about a factor of 2 larger than theory predictions...
Blow-out regime with IR

- Beam has little memory on what process is used for emission.
- Space charged dominated beam dynamics takes over.
- Creation of uniformly filled ellipsoidal beam
- Very sharp boundary due to prompt emission at the cathode.

- Reducing the charge the minimum bunch length is < 200 fs.
Study of transverse uniformity and amplitude jitter

- Charge density emitted depends on $I^3$.
- Beam transverse profile very sensitive to laser uniformity.
- Charge jitter proportional to $E^3$.
- But UV energy after tripling crystals has the same dependency (neglecting saturation effects...).
Conclusions

• Ultrashort laser pulses coupled to RF photoinjectors open new pathways to generate/manipulate/diagnose ultrashort electron beams.

• Blow-out regime is a valid alternative operating mode of traditional scenarios.

• Multiphoton photoemission can be surprisingly useful to generate large amounts of charge from metal cathodes
  – Application for high average power guns? With a 5 MHz 2 uJ oscillator (10 W total power) -> 50 pC/pulse.
  – Multiphoton photoemission from semiconductors?
  – Explore other ways to increase the coupling (surface plasmon...?)

• Collaboration with INFN SPARC team (L. Cultrera, M. Ferrario, D. Filippetto, G. Gatti, C. Vicario) on the studies of IR laser pulses on the cathode.

• Special acknowledgements to graduate students J. T. Moody and C. M. Scoby

• Work funded by JTO-MRI and DOE-HEP.