Transport of Dark Current through the Linac to End Station A Beamline at SLAC

Enabling the search for dark matter via dark current

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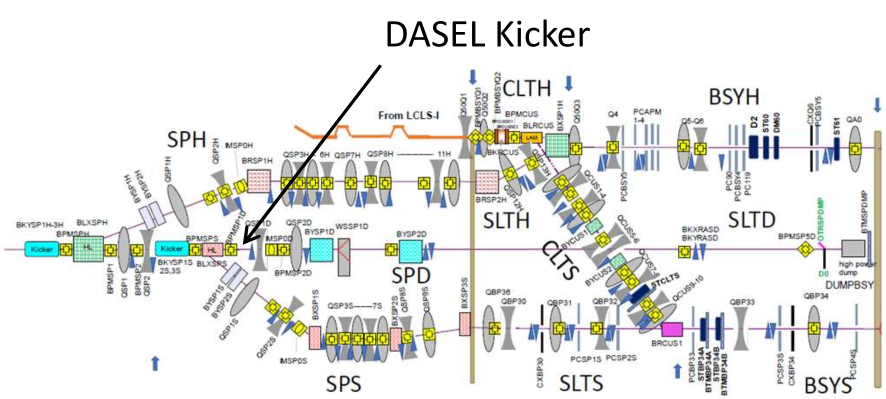
DASEL

What is it?

- The DArk Sector Experiments at LCLS-II (DASEL) project will deliver high-energy (4 – 8 GeV), low-charge electron bunches to End Station A.
- These electrons will be used for experiments such as the Light Dark Matter eXperiment (LDMX).



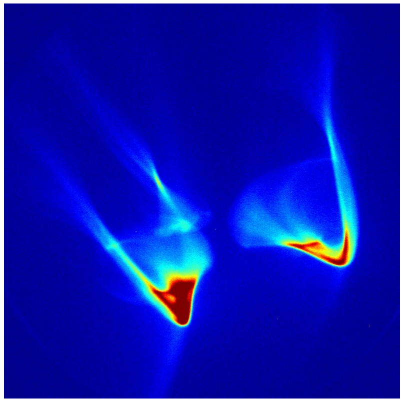
How? S30XL & LESA

- Electrons in the beam switchyard (BSY) are diverted to S30XL by a pulsed kicker between the FEL kickers and the BSY dump.
- S30XL transports dark current to the Linac to End Station A (LESA) beamline.
    - Phased approach allowed us to demonstrate parasitic operation before full LESA construction.
- Two low-charge source options:
    - Dedicated laser to produce a 37 MHz bunch train
    - Dark current at 186 MHz CW RF gun frequency

Dark Current

What is it?

- The beam we want (a.k.a. “photocurrent”) is emitted when a laser hits the photocathode in an RF cavity, the electron gun.
- “Dark current” is emitted even when there is no laser light in the RF cavity – i.e., when it is dark.
  - The strong electric field in the cavity causes field emission.

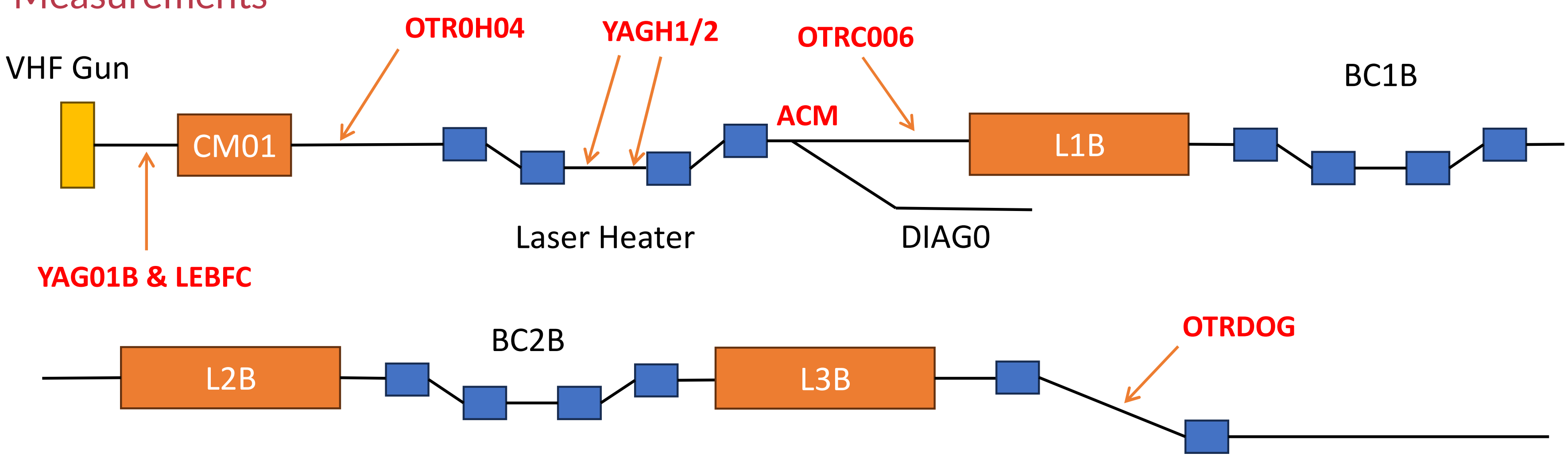


Why is it a challenge for LCLS-II?

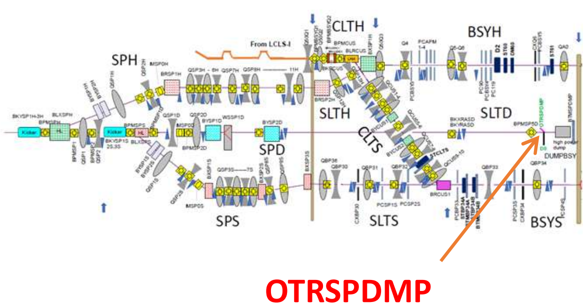
- LCLS-II requires a high-gradient, CW, low-frequency RF gun to produce bunches up to 300 pC at ~1 MHz.
- Dark current is emitted off-axis over a larger range of RF phase.
  - Different initial $(\vec{x}, t) \Longrightarrow$ different path through the accelerator.
  - Orbits are much larger than the design orbit.
- Dark current wreaks havoc throughout the accelerator. It can cause:
  - Excessive collimator heating
  - Premature failure of cameras and other diagnostics
  - Damage to magnets and cryomodules
  - Excessive radiation in the tunnel
  - Vacuum problems

Dark Current Measurements in LCLS-II

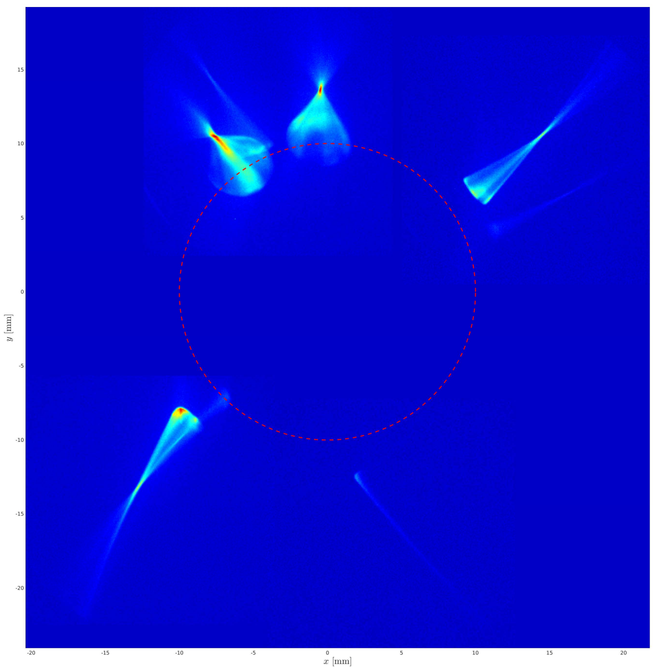
Measurements



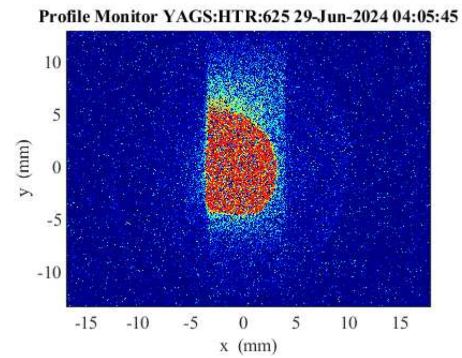
- Magnitude can be directly measured at LEBFC and ACM.
  - Can often be inferred from images and PBLM/collimator measurements.
- Images can be collected throughout the machine.
  - YAG01B, OTR0H04, YAGH1/2, OTRC006, OTRDOG, and OTRSPDMP.



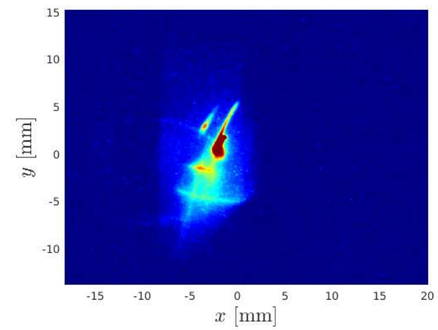
Measurements throughout LCLS-II



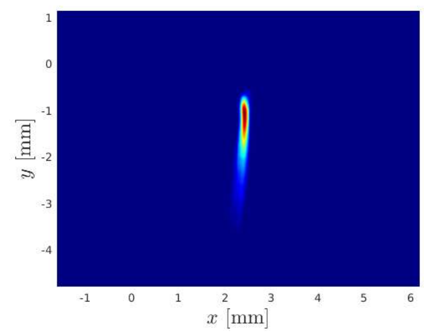
Images of dark current on YAG01B, shifted to the positions they would be in at corrector settings used during normal injector operation.



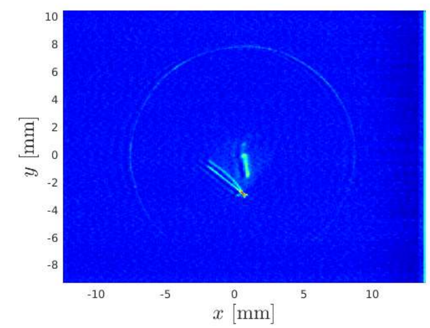
YAGH1



OTRC006

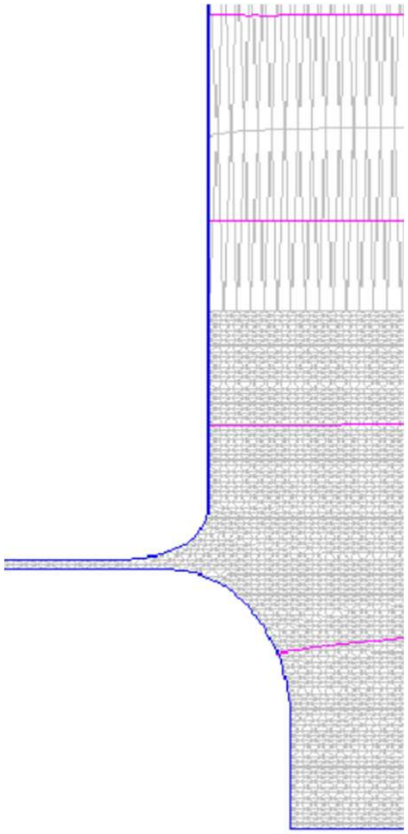


OTRDOG

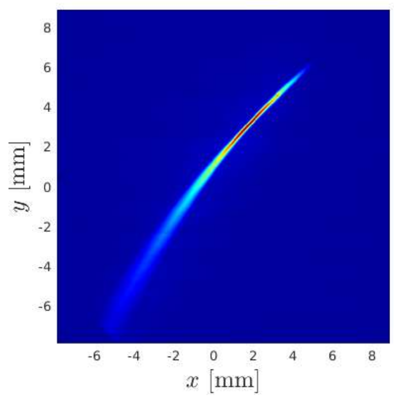


OTRSPDMP

Reduced Dark Current with 1 mm Cathode Plug Extension



- Protruding cathode plug partially shields cavity wall surrounding plug from strong electric field.
  - Recall exponential dependence of emission on field strength.
- **Dark current at LEBFC was reduced from ~3-4 μA to 3 nA!**
  - As measured after cathode plug change on February 25, 2025.
  - Measured ~10 nA on March 10, 2025.
- Protruding cathode plug produces defocusing field near cathode surface.

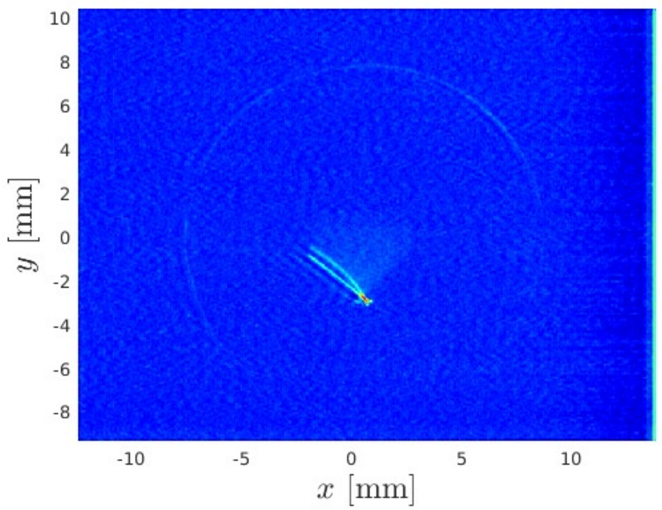


Dark current from only one emitter was found on YAG01B (shifted to screen using X/YC03).

Utilization: DASEL & LDMX

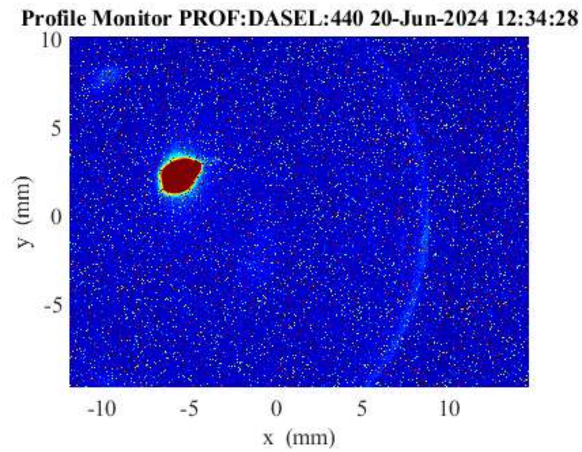
Using residual dark current to search for dark matter

- Although we can reduce dark current to negligible levels, a few electrons still make it all the way to the BSY.
  - Measured dark current at BSYD ranges from ~160 pA to 7 nA.
- Orbit is close to photocurrent beam, but inconsistent in both location and intensity.
  - Low current presents tuning challenges, since limited diagnostics are available to monitor its orbit.



S30XL & LESA Commissioning: Photocurrent & Dark Current

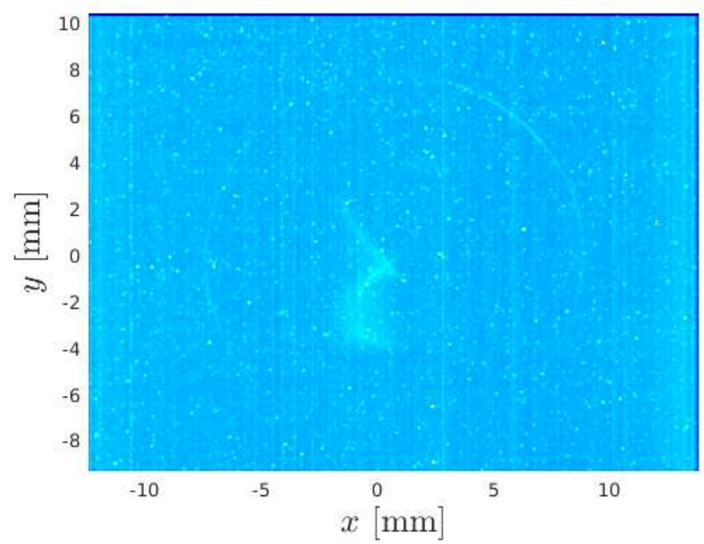
- Photocurrent beam was first delivered to S30XL on June 20, 2024.
  - Measured dark current at BSYD ranges from ~160 pA to 7 nA.
- Dark current was delivered to End Station A and detected by scintillators in December 2025.



- Parasitic mode of operation has been tested and validated.
  - Does not interfere with hard or soft x-ray FEL lines.

Challenges: Accelerator Tuning Changes, Diagnostic Blindness

- The dark current is free, but an unreliable source.
  - Vulnerable to routine accelerator tuning.
- Orbit correction is difficult when the beam is invisible to BPMs!
  - Low current presents tuning challenges, since limited diagnostics are available to monitor its orbit.
- Long integration times are required to resolve with screens, if the dark current is visible at all!
- Scintillators are sensitive to single electrons, but provide low spatial resolution.

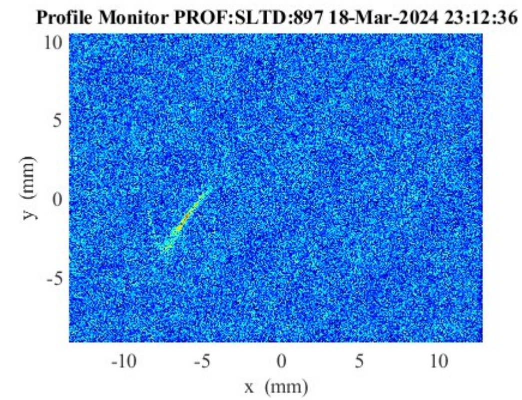


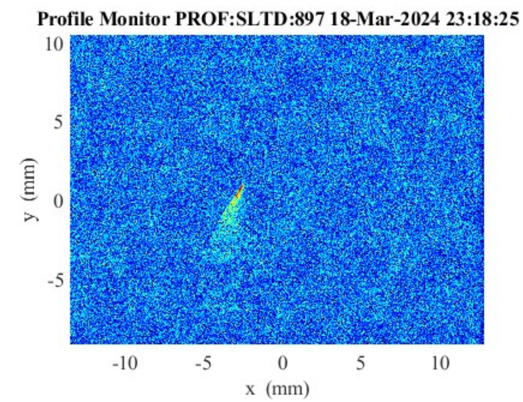
Solutions: Screen/quad-pair orbit measurement & scintillators

- Measure peak position at 2 quadrupole settings
  - Varies transfer matrix M
- Solve for initial (x_i, x_i') and (y_i, y_i')

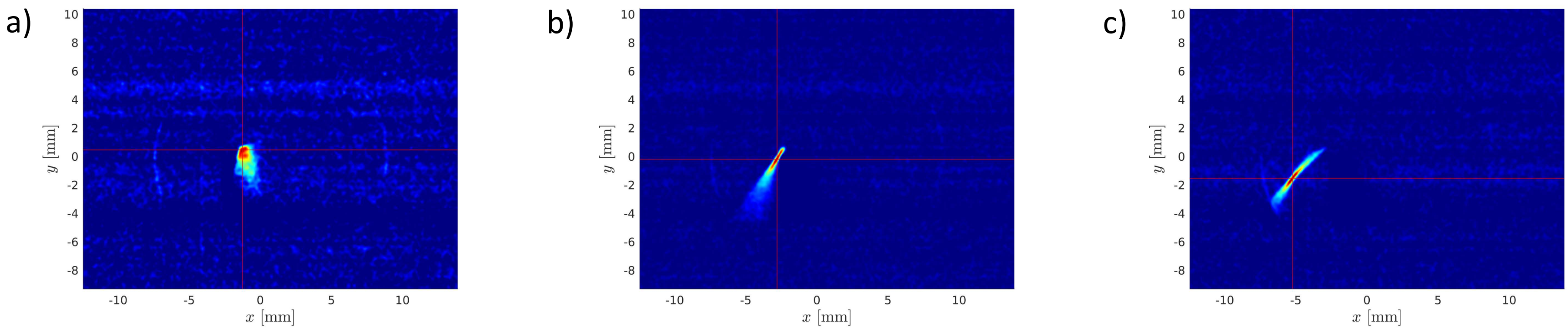
$$\begin{bmatrix} x_i \\ x_i' \end{bmatrix} = \frac{1}{M_{11}^a M_{12}^b - M_{11}^b M_{12}^a} \begin{bmatrix} M_{12}^b & -M_{12}^a \\ -M_{11}^b & M_{11}^a \end{bmatrix} \begin{bmatrix} x_f^a - \delta x_C \\ x_f^b - \delta x_C \end{bmatrix}$$

- Map back to kicker location
- Map forward through LESA & adjust correctors as necessary.
  - Low current presents tuning challenges, since limited diagnostics are available to monitor its orbit. Scintillators can provide validation.





Demonstration on dark current measurements



- Final quadrupole before BSY dump was varied.
- Noise was removed via averaging, background subtraction, Gaussian & median filtering.

	a & b	a & c
x_i	0.662 mm	0.941 mm
x_i'	1.42 mrad	1.45 mrad
y_i	-0.282 mm	-0.475 mm
y_i'	-0.699 mrad	-0.680 mrad

Conclusions

- Dark current provides a convenient, if fickle, source of high-energy electrons to search for dark matter at DASEL.
- We can use otherwise-unwanted dark current to try to answer fundamental questions about dark matter.
- Limited diagnostics for sub-nA current present challenges, but we have sufficient insight for orbit correction.
- Full demonstration will need to wait for LCLS-II-HE!