AE122 Status Report & New Proposal 312793: **Remote detection of radioactive materials using long wave infrared laser-driven avalanche breakdown**

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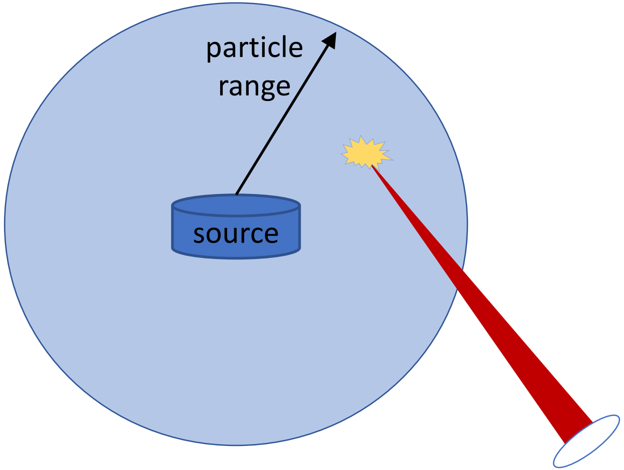
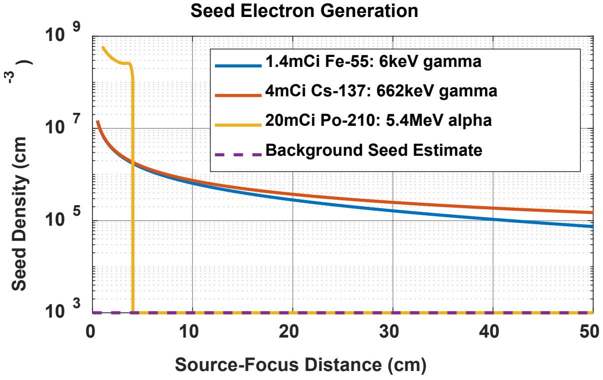
Funding Status: Received

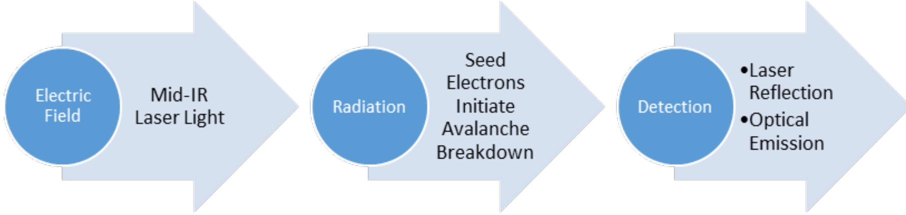
3/1/2023

Background: Long range radiation detection scheme

- Laser-driven avalanche breakdown in a radiation field propagated from outside the range of the decay particles
- Need Mid-IR to Long wave IR laser to suppress Multiphoton ionization of neutrals in air
- Measure reflected laser light characteristics to determine breakdown timing



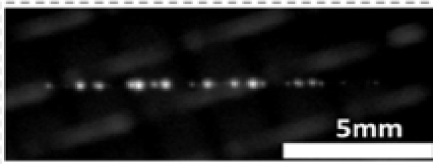




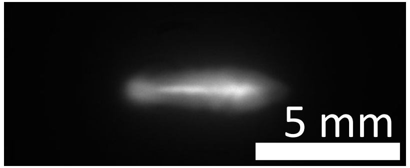
Background: Short Pulse IR Avalanche Breakdowns

- Avalanche breakdowns are local
  - Centered around ***seed electrons***
  - Bounded by ***diffusion*** during pulse
- Discrete plasma sites
  - **Discontinuous** plasma density
  - Each site surrounded by neutrals

Short pulse:
100 ps, λ=4 µm



Long pulse:
100 ns, λ=10.6 µm



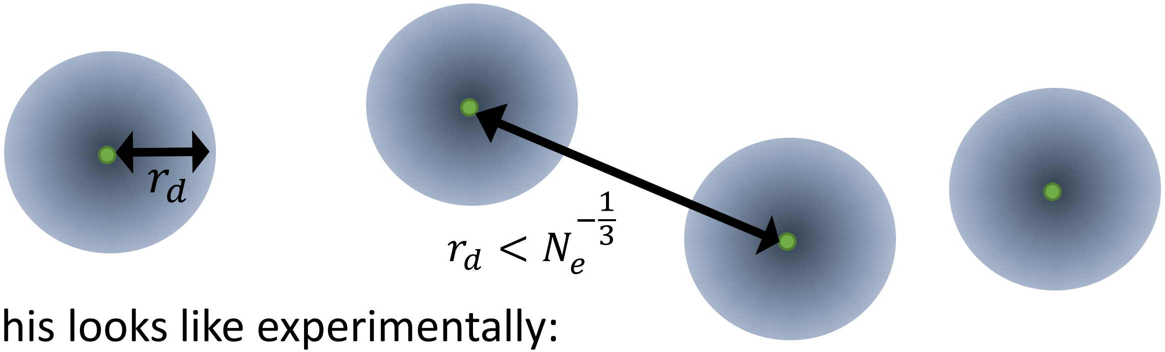
- Short λ
  - Enough unwanted MPI seed electrons that their separation is smaller than the diffusion length
- Long τ_p
  - Enough time that the diffusion length is greater than the seed separation.

Discrete model necessary for:
- $\lambda > 2\mu m$
- $\tau_p < 1ns$

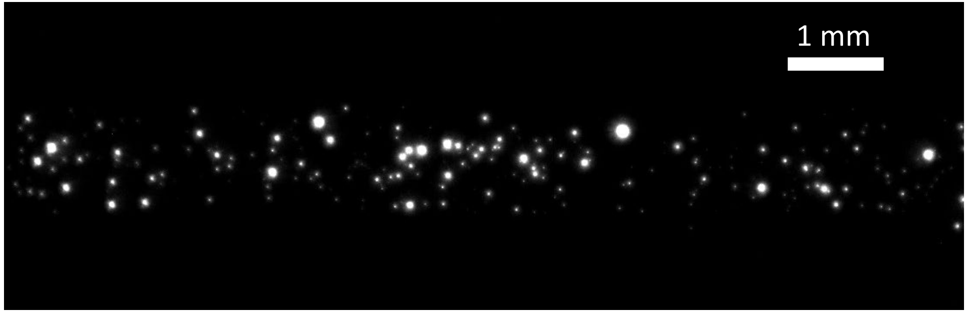
Background: Short Pulse IR Avalanche Breakdowns

Electron motion is limited by diffusion, leading to discrete countable sites

$$r_d \sim \sqrt{2k_B T / m\nu_{en}} = \approx 0.3\sqrt{\tau[\mathrm{ps}]\, T_e\, [\mathrm{eV}])}\ \mu\mathrm{m}$$

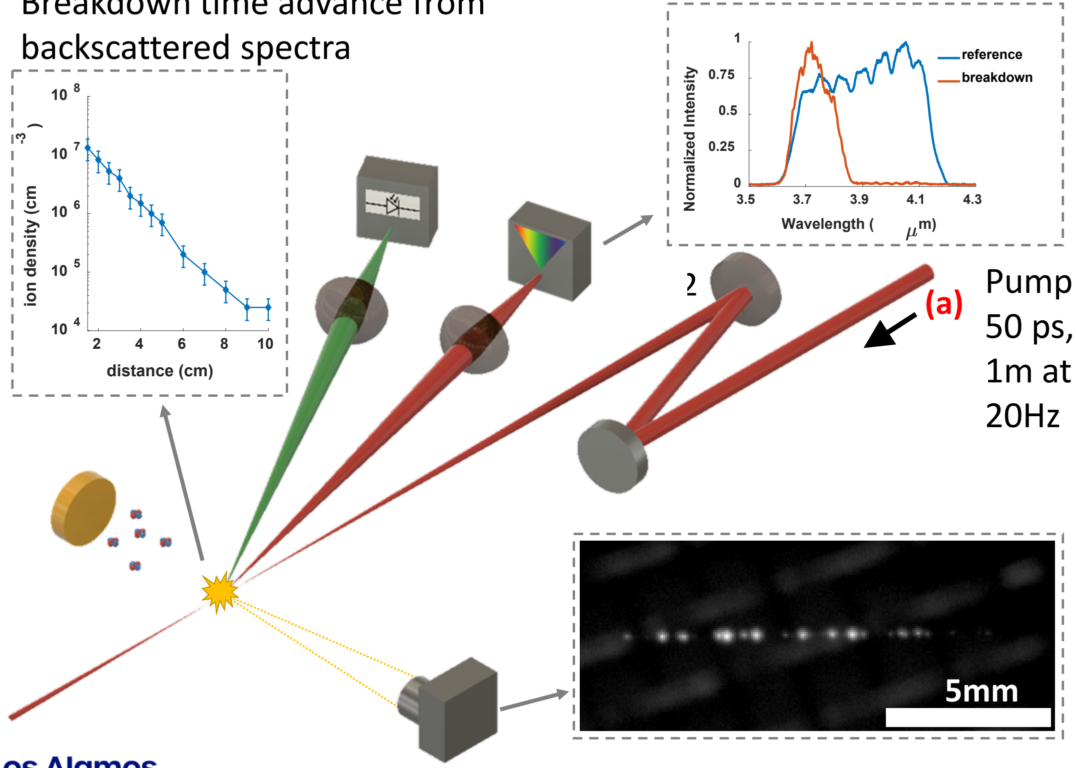


What this looks like experimentally:



Background: Proof-of-Concept Experiments

Breakdown time advance from backscattered spectra



Shot-by-shot spectra of the backscattered pulse

Pump pulse:
50 ps, 3.9 μm 15-35 mJ focused
1m at f/33
20Hz

-R. M. Schwartz, D. Woodbury, J. Isaacs, P. Sprangle, and H. M. Milchberg, Sci. Adv. **5**, eaav6804 (2019)

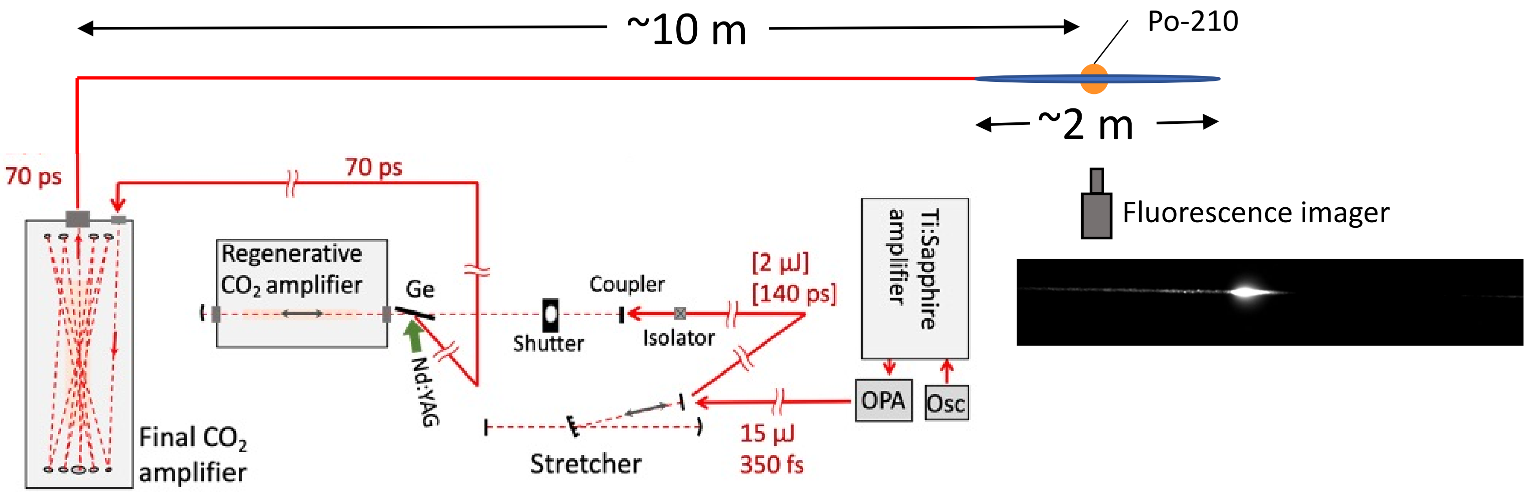
-D. Woodbury R. M. Schwartz, and H. M. Milchberg, Optica **6** (6) (2019)

Publications

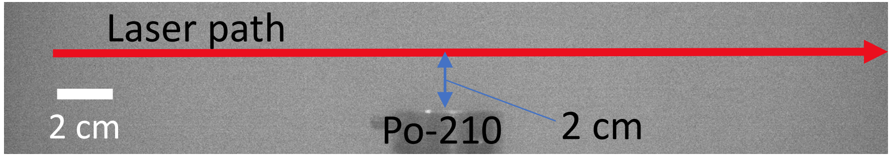
1. R. M. Schwartz, D. Woodbury, J. Isaacs, P. Sprangle, and H. M. Milchberg, “Remote detection of radioactive material using mid-IR laser-driven electron avalanche,” Sci. Adv. 5, eaav6804 (2019).
2. D. Woodbury R. M. Schwartz, and H. M. Milchberg, “Measurement of ultralow radiation-induced charge densities using picosecond mid-IR laser-induced breakdown,” Optica 6 (6) (2019).
3. D. Woodbury R. M. Schwartz, E. Rockafellow, J. K. Wahlstrand, and H. M. Milchberg, “Absolute Measurement of Laser Ionization Yield in Atmospheric Pressure Range Gases over 14 Decades,” Phys. Rev. Lett. 124, 013201 (2019).
4. R. Lakis, J. Sears, A Favalli, T. Stockman “Concept of Operations for Mid-IR Laser Driven Ion Detection,” LA-UR-21-21282.
5. D. Woodbury, A. Goffin, R. M. Schwartz, J. Isaacs, and H. M. Milchberg, “Self-Guiding of Long-Wave Infrared Laser Pulses Mediated by Avalanche Ionization,” Phys. Rev. Lett. 125, 133201 (2020).
6. A. Zingale, S. Waczynski, J. Sears, R. E. Lakis, H. M. Milchberg, “Atmospheric effects on laser driven avalanche-based remote detection of radiation,” Optics Letters (submitted)

AE122 07/2022: Experimental Setup

- λ = 9.2 μm, 70 ps FWHM duration, 50 mJ - 1 J energy range
- Diagnostics: backscatter photodiodes (MCT) ~ns time resolution, images of plasma fluorescence
- ~f/200 geometry: 2.1 mm FWHM beam waist diameter, ~2 m Rayleigh range, 0.21 TW/cm^2 breakdown threshold

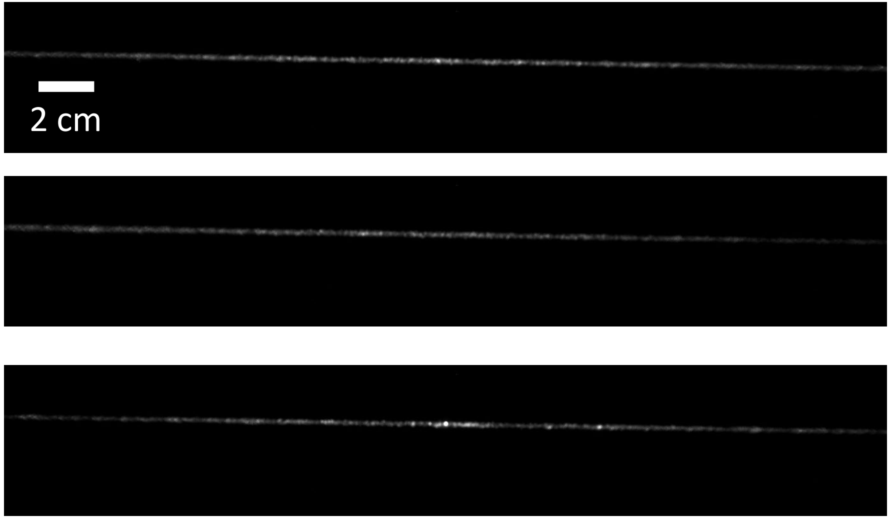


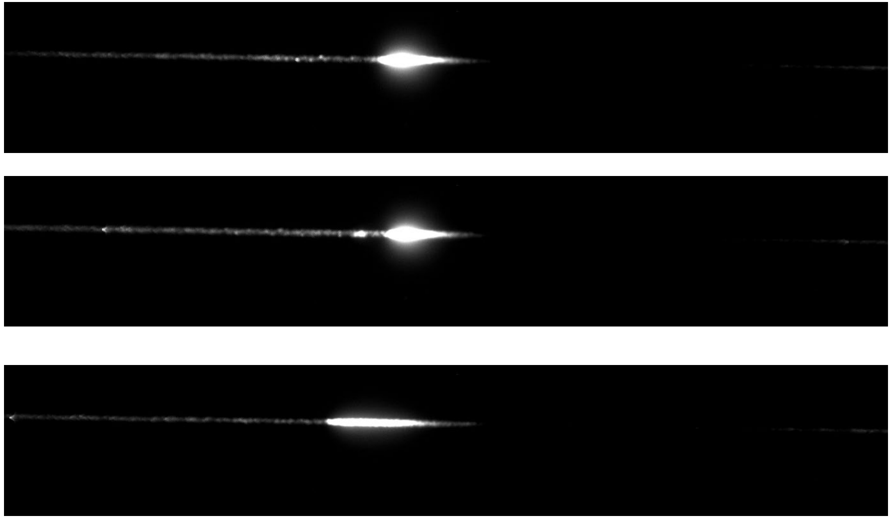
AE122 07/2022: Fluorescence images



Source covered with foil

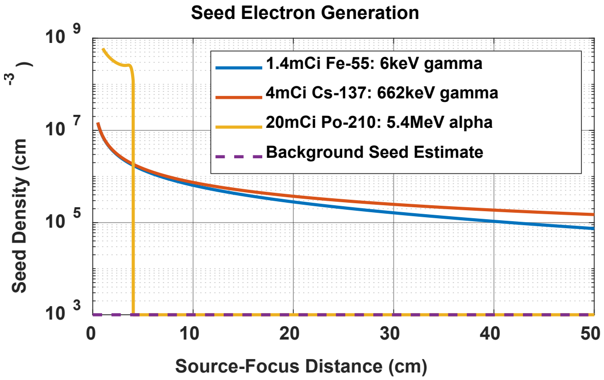
Source uncovered

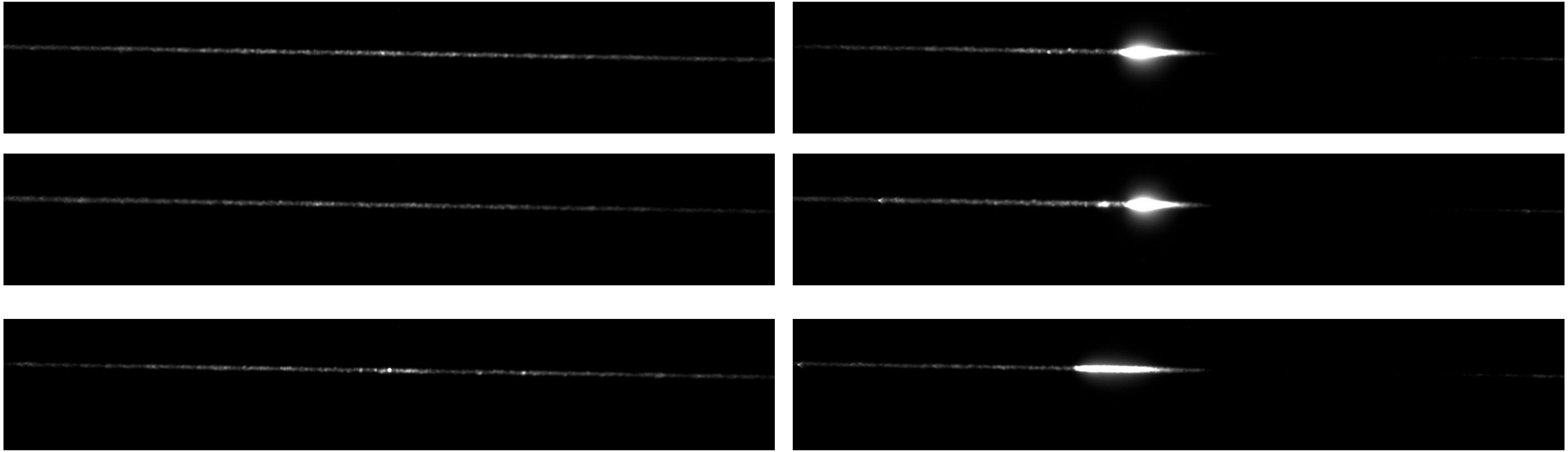




AE122 07/2022: Fluorescence images

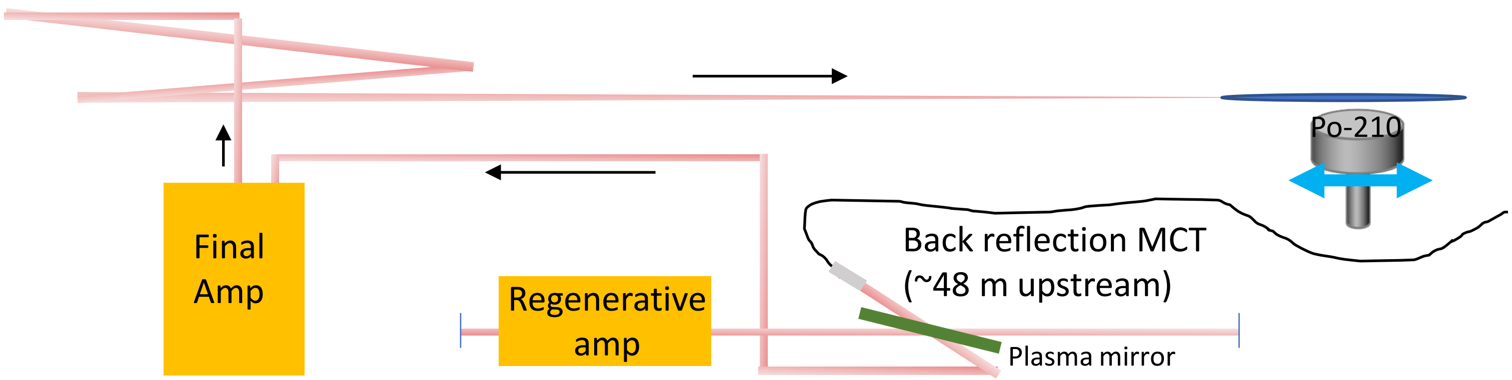
- Image taken at ~40 inches from focus with 1.5” collection lens
- Scaled back to 10 m this would require a ~12” collection optic
- Readily reproduce this image at 10 m standoff distance





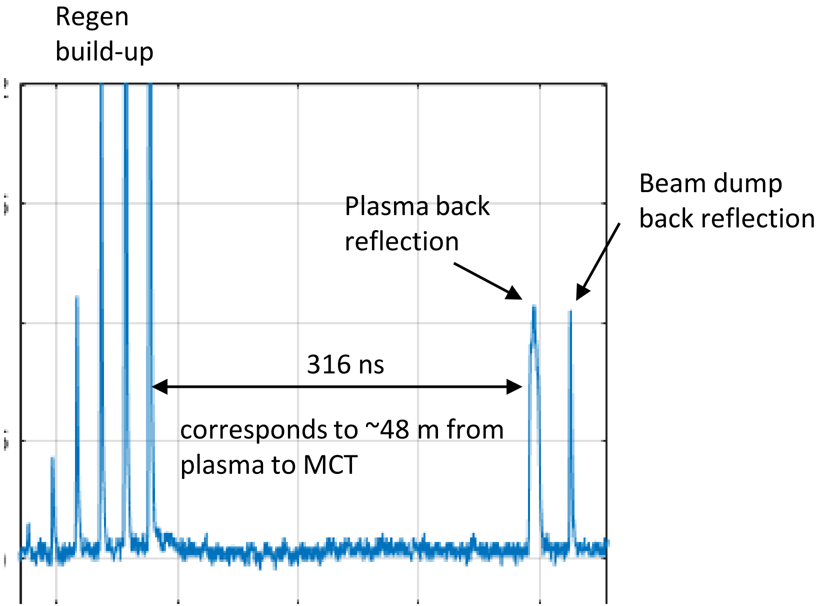
AE122 07/2022: Amplified back-reflection diagnostic

- Laser path shown below
- Gain lifetime of CO_2 is ~1 µs. Back reflected light is amplified by the laser and detected by *in-situ* regenerative amplifier energy monitor (MCT)



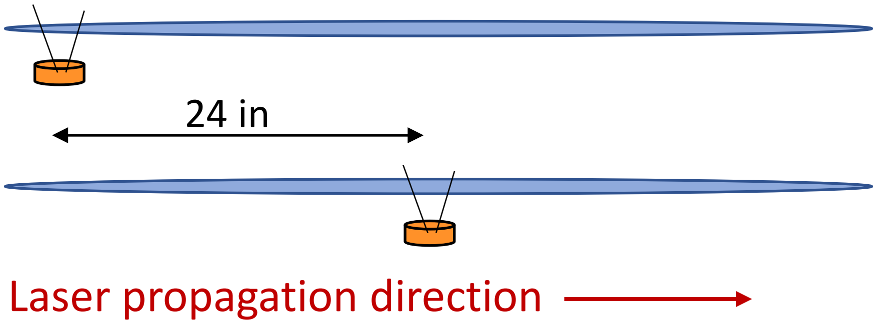
AE122 07/2022: Amplified back-reflection diagnostic

- Gain lifetime of CO_2 is ~1 μs. Back reflected light is amplified by the laser and detected by *in-situ* regenerative amplifier energy monitor (MCT)
- Temporally resolved (~1 ns), not spatially resolved
- Sample trace:

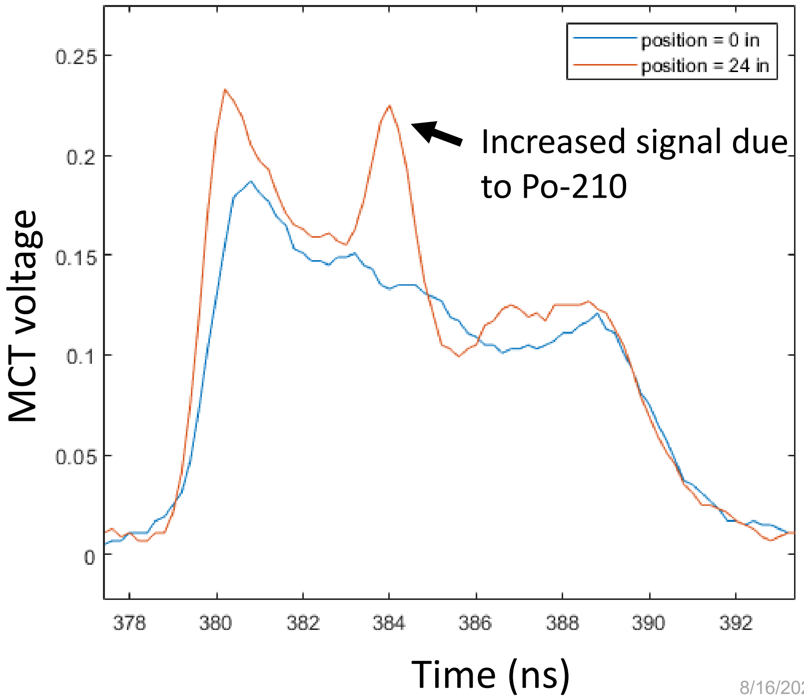


AE122 07/2022: Source longitudinal position scan

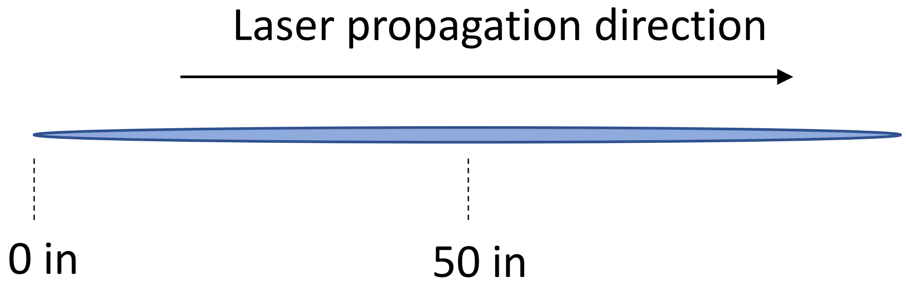
- Move source along laser propagation direction, keeping transverse distance constant



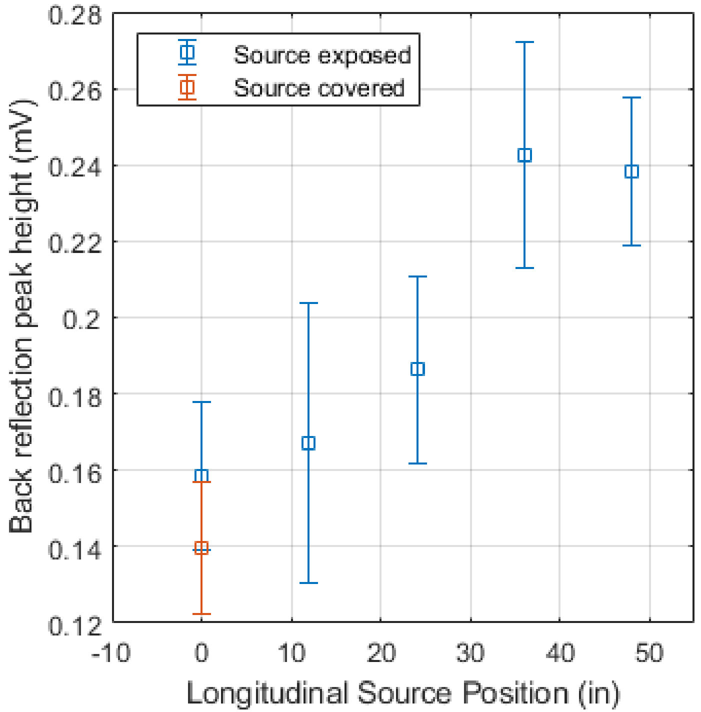
- Temporal profile of back reflection indicated position of source
  - i.e. source moved 2 ft, spike in back reflection shifted 4 ns.



AE122 07/2022: Results



- Mean of peak voltage on MCT
- Increase as the source gets closer to the peak intensity
- Appears to distinguish presence of Po-210 at 50 m path
- Near background level when source is placed at 0 in, near the edge of the focal volume
- Downstream of best focus was inaccessible in the experimental configuration



AE122 07/2022: Conclusions

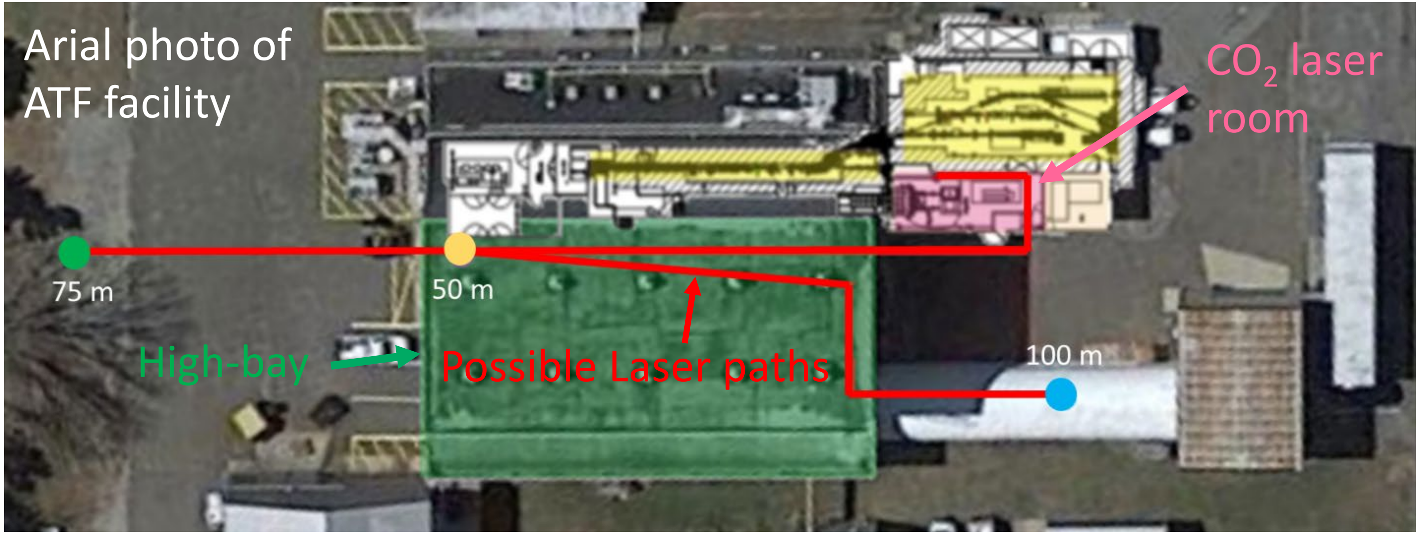
- Successfully distinguished presence of Po-210 with time resolved MCT detectors at >10 m using direct back reflection.

Insights:

- Direct back-reflection into the laser amplifier can serve as a self-aligned, high sensitivity diagnostic
  - Po-210 only irradiated ~1% of focal volume, γ-source should significantly improve signal level by irradiating larger fraction of focal volume
  - Possibly install a spectrometer instead of a single MCT detector
  - Need to understand integrated back reflection signal as a function of seed density from a 2 m long focal volume, which will include multiple scattering
- Long focusing geometry (f/200) could readily be extended to 100 m scale

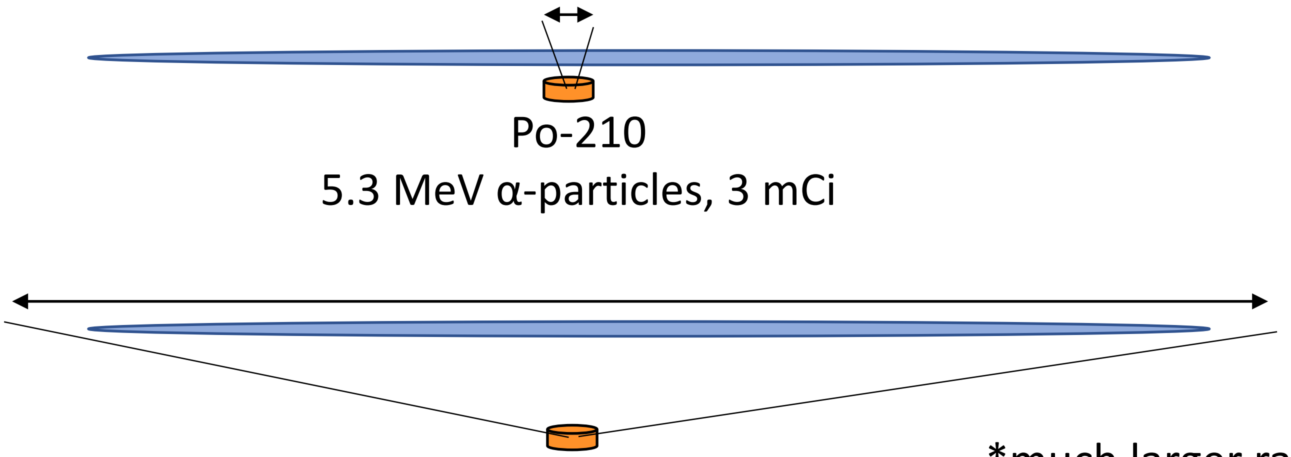
Proposal 312793: Propagation range

- Extend propagation length to 50 - 100 meters
- Use 0.5 m diameter focusing optic for f/200 geometry (same as AE122 experiment)



Proposal 312793: Radioactive source

- Irradiate ~2.5 m long focal volume (70 mCi Cs-137 source available at BNL)



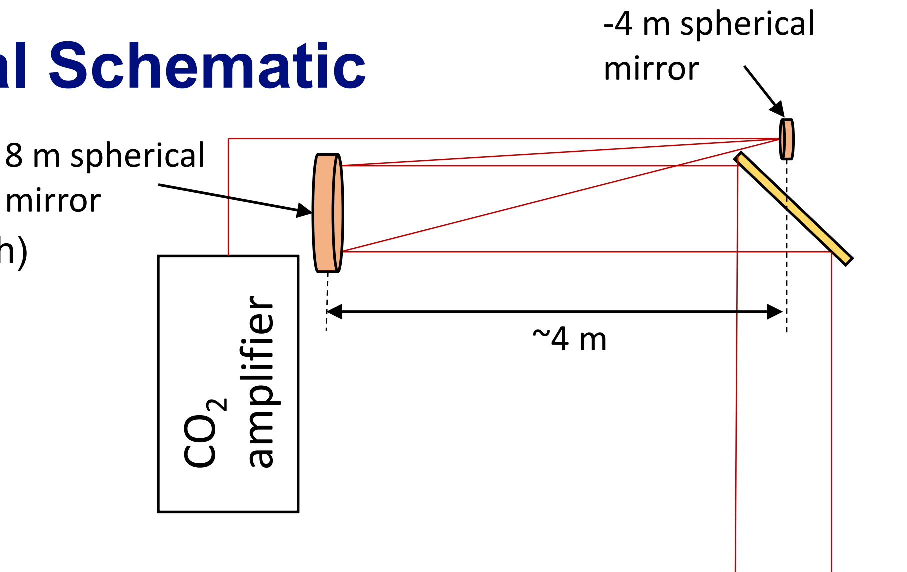
*much larger range of γ-rays allows the source to generate seed ions over the full focal volume

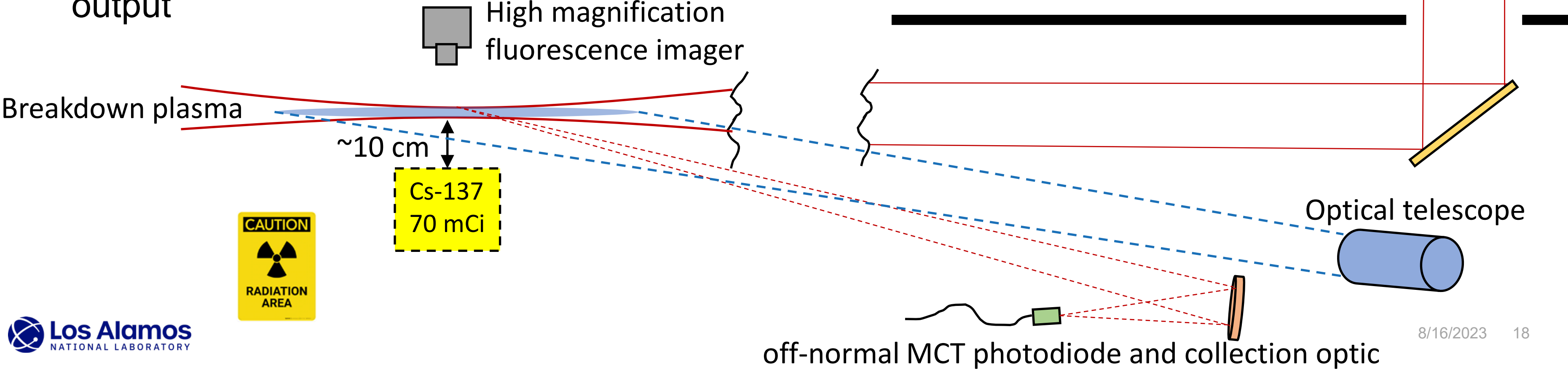
Proposal 312793: Diagnostics

- Amplified back-reflection MCT photodiode
  - Propagation and back-reflection total "time-of-flight" ~668 ns for 100 m propagation
  - May require focusing onto 1 mm^2 MCT photodiode to increase signal, If signal strength falls as r^{-2}, then collection area will need to increase by 100x going from 10 m to 100 m propagation. >100 mm^2 collection lens will be required to maintain signal level
- Non-normal back-reflection MCT that will be placed at various stand-off distances
- Optical telescope to measure the plasma fluorescence at various stand-off distances
  - Brightness of plasma fluorescence goes with the number of individual breakdown sites. Cs-137 will produce $10^3 – 10^4$ times the number of seeds over the entire focal volume

Proposal 312793: Experimental Schematic

- Beam focused using telescope
  - 0.15 m diameter expansion optic (-4 m focal length)
  - 0.5 m diameter focusing optic (+8 m focal length)
  - Spacing tuned to generate focus at 50 – 100 m
- Not shown: Amplified back-reflection MCT photodiode is in the laser chain and used to monitor pass-by-pass regenerative amplifier output





Proposal 312793: Experimental Schedule

Experiment	Goals/milestones
Demonstrate detection of radioactive material at 50 - 100 m range (3 weeks, 25% dedicated to setup)	• Optics setup for 50 - 100 m range experiments • Calibrate and optimize the backscatter spectrum diagnostic • Calibrate fluorescence telescope and noise level in outdoor and indoor conditions. • Measure seed density as a function of source distance and validate models for γ-ray sources. • Demonstrate detection of radioactive material at 100 m

Electron Beam Requirements

Parameter	Units	Typical Values	Comments	Requested Values
Beam Energy	MeV	50-65	*Full range is ~15-75 MeV with highest beam quality at nominal values*	**N/A**
Bunch Charge	nC	0.1-2.0	*Bunch length & emittance vary with charge*	**N/A**
Compression	fs	Down to 100 fs (up to 1 kA peak current)	*A magnetic bunch compressor available to compress bunch down to ~100 fs. Beam quality is variable depending on charge and amount of compression required.* *NOTE: Further compression options are being developed to provide bunch lengths down to the ~10 fs level*	**N/A**
Transverse size at IP (σ)	μm	30 – 100 (dependent on IP position)	*It is possible to achieve transverse sizes below 10 um with special permanent magnet optics.*	**N/A**
Normalized Emittance	μm	1 (at 0.3 nC)	*Variable with bunch charge*	**N/A**
Rep. Rate (Hz)	Hz	1.5	*3 Hz also available if needed*	**N/A**
Trains mode	---	Single bunch	*Multi-bunch mode available. Trains of 24 or 48 ns spaced bunches.*	**N/A**

CO_2 Laser Requirements

Configuration	Parameter	Units	Typical Values	Comments	Requested Values
CO_2 Regenerative Amplifier Beam	Wavelength	μm	9.2		
	Peak Power	GW	~3		
	Pulse Mode	---	Single		
	Pulse Length	ps	2		
	Pulse Energy	mJ	6		
	M^2	---	~1.5		
	Repetition Rate	Hz	1.5		
	Polarization	---	Linear		
CO_2 CPA Beam	Wavelength	μm	9.2		**9.2**
Note that delivery of full power pulses to the Experimental Hall is presently limited to Beamline #1 only.	Peak Power	TW	5		**~10 GW**
	Pulse Mode	---	Single		**Single**
	Pulse Length	ps	2	*Uncompressed pulse duration desired*	**~70 ps**
	Pulse Energy	J	~5		**<5 J**
	M^2	---	~2		**~2**
	Repetition Rate	Hz	0.05		**0.05 Hz**
	Polarization		Linear	*Adjustable linear polarization along with circular polarization can be provided upon request*	**Linear**

Other Experimental Laser Requirements

Ti:Sapphire Laser System	**Units**	**Stage I Values**	**Stage II Values**	**Comments**	**Requested Values**
Central Wavelength	nm	800	800		**N/A**
FWHM Bandwidth	nm	20	13		**N/A**
Compressed FWHM Pulse Width	fs	<50	<75		**N/A**
Chirped FWHM Pulse Width	ps	≥50	≥50		**N/A**
Chirped Energy	mJ	10	200		**N/A**
Compressed Energy	mJ	7	~20		**N/A**
Energy to Experiments	mJ	>4.9	>80		**N/A**
Power to Experiments	GW	>98	>1067		

Nd:YAG Laser System	**Units**	**Typical Values**	**Comments**	**Requested Values**
Wavelength	nm	1064		**N/A**
Energy	mJ	5		**N/A**
Pulse Width	ps	14		**N/A**
Wavelength	nm	532		**N/A**
Energy	mJ	0.5		**N/A**
Pulse Width	ps	10		**N/A**

Special Equipment Requirements and Hazards

- Electron Beam
  - N/A
- CO_2 Laser
  - Access to uncompressed 70 ps pulse with <5J energy
  - Extended propagation range (outside laser/accelerator rooms), along with necessary beam enclosure according to BNL safety regulations.
- Ti:Sapphire and Nd:YAG Lasers
  - N/A
- Hazards & Special Installation Requirements
  - 50 - 100 meter propagation range, indoor or outdoor interaction site
  - Equipment: Routing and focusing optics
  - Hazards: BNL owned 70 mCi Cs-137 source

Experimental Time Request

CY2023 Time Request

Capability	Setup Hours	Running Hours
Electron Beam Only		
Laser* Only (in Laser Areas)	**40**	**120**
Laser* + Electron Beam		

Total Time Request for the 3-year Experiment (including CY2023-25)

Capability	Setup Hours	Running Hours
Electron Beam Only		
Laser* Only (in Laser Areas)	**120**	**360**
Laser* + Electron Beam		

* Laser = Near-IR or LWIR (CO_2) Laser