An Investigation of Monoenergetic Electron Beams for High-Energy-Density and Inertial Confinement Fusion Diagnostics

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Summary

- Modern electron-beam–generation techniques provide a broad range of available energies and beam qualities
- These beams have the potential for more-accurate radiography, monoenergetic and tunable x-ray generation, and possibly direct electron diffraction measurements

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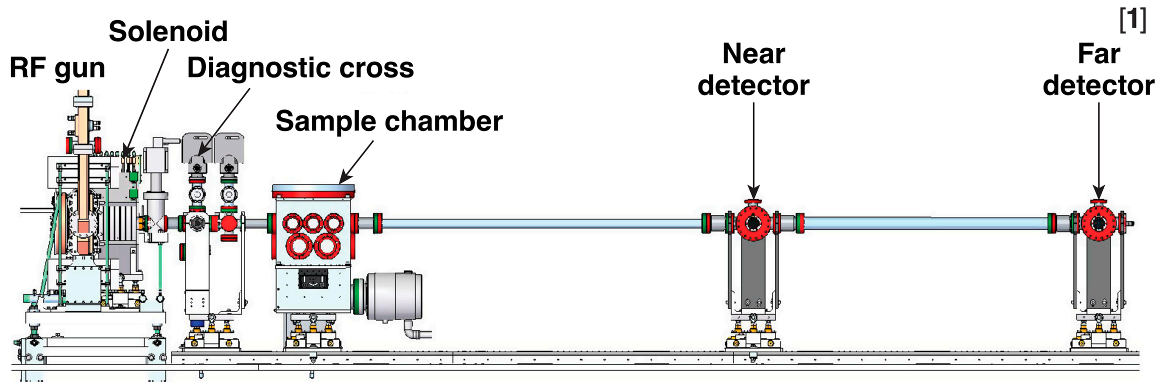
Electron-Beam Sources



- RF accelerators can be purchased from commercial vendors in turn-key packages
  - the large size and costs associated with RF accelerators limit laboratories that can reasonably host one
  - applications needing incredibly precise beams benefit greatly from the small energy spread and emittance
  - the broad tunability of RF accelerators allows for a wide variety of beams to be generated from a single machine [2]

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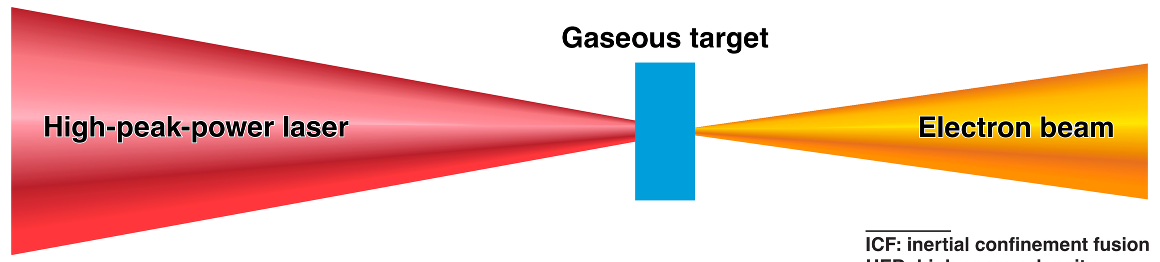
RF: radio-frequency

Accelerator type	Acceleration mechanism	Accelerating gradient	Beam energy spread	Beam emittance
RF accelerator	Conductive resonant cavities powered by an external RF source	~20 MV/m	<1%	Microradians
LWFA	Laser–plasma interactions	>1 GV/m	<10%	Milliradians

- Laser wakefield accelerator (LWFA) technology can often be implemented on existing lasers at ICF/HED research facilities
  - the high emittances and energy spreads limit the use of LWFA beams
  - applications that need hundreds of MeV or greater benefit from the small size afforded by the large gradients
  - the technology is rapidly maturing, with beam quality constantly increasing [3,4]



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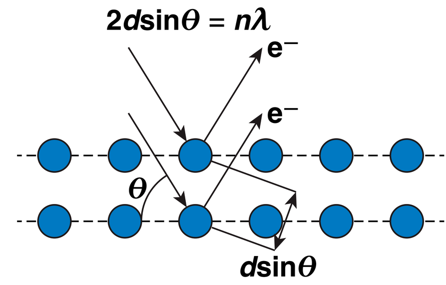
ICF: inertial confinement fusion
HED: high energy density

Electron Diffraction

- Electron diffraction utilizes the wave nature of electrons to investigate crystal structure
- Diffraction is induced when the Bragg condition is met [5]

$$2d\sin\theta = n\lambda$$



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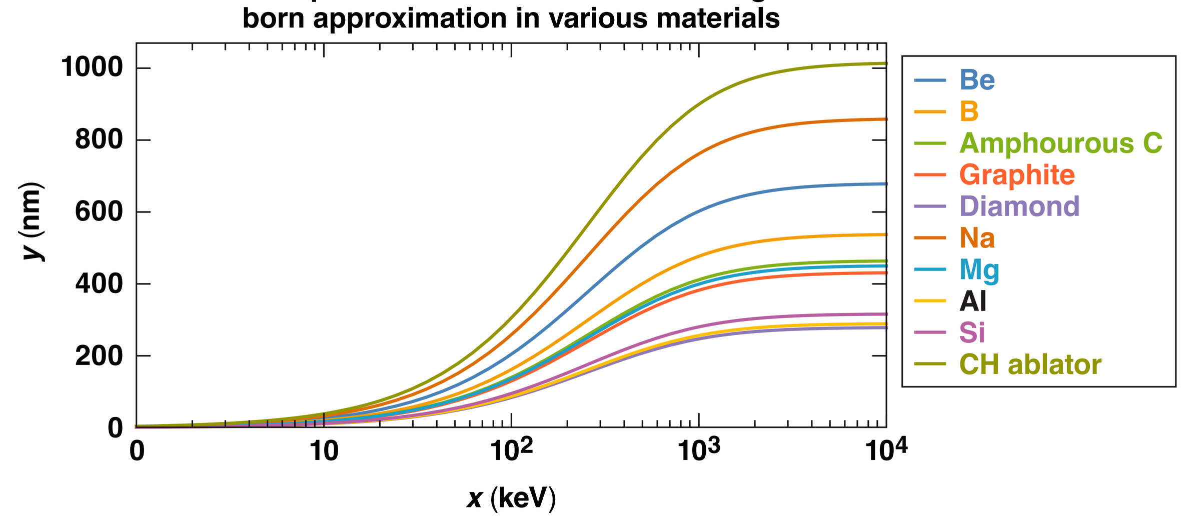
- Modern RF electron accelerators have been used for the successful electron diffraction of dynamic targets [1,5]
  - low-emittance, low-energy spread beams are a must for electron diffraction
- The mean-free path (MFP) of elastic scatter provides strong limits on the targets and useful beam energies
  - typical electron diffraction goes through no more than 4 MFP

Comparison of MFP of electrons using born approximation in various materials



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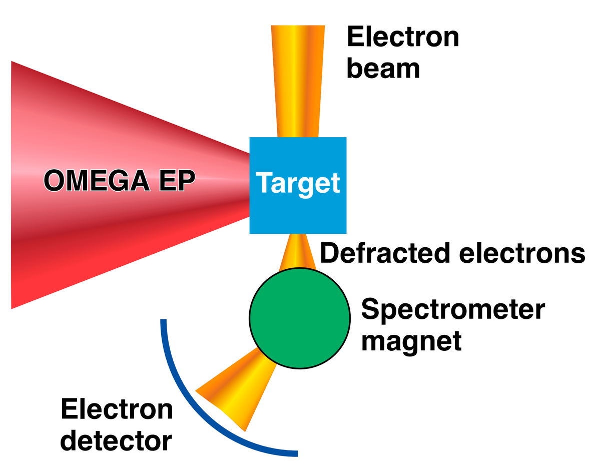
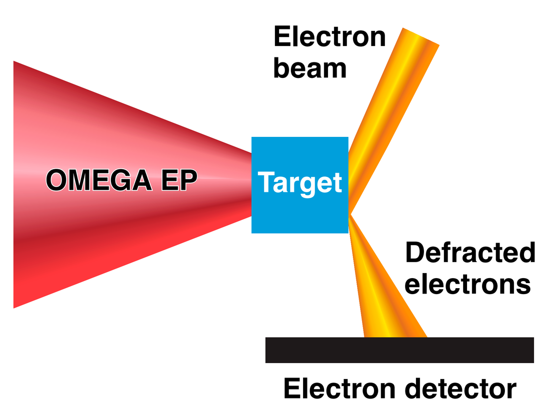
- Reflecting electron diffraction provides one potential solution to the target thickness limits [5]
  - co-timing and target alignment will prove to be challenging
- Thick, uniform, self-tamped targets coupled to a spectrometer provide another solution
  - co-timing and detector construction will provide challenges to this technique





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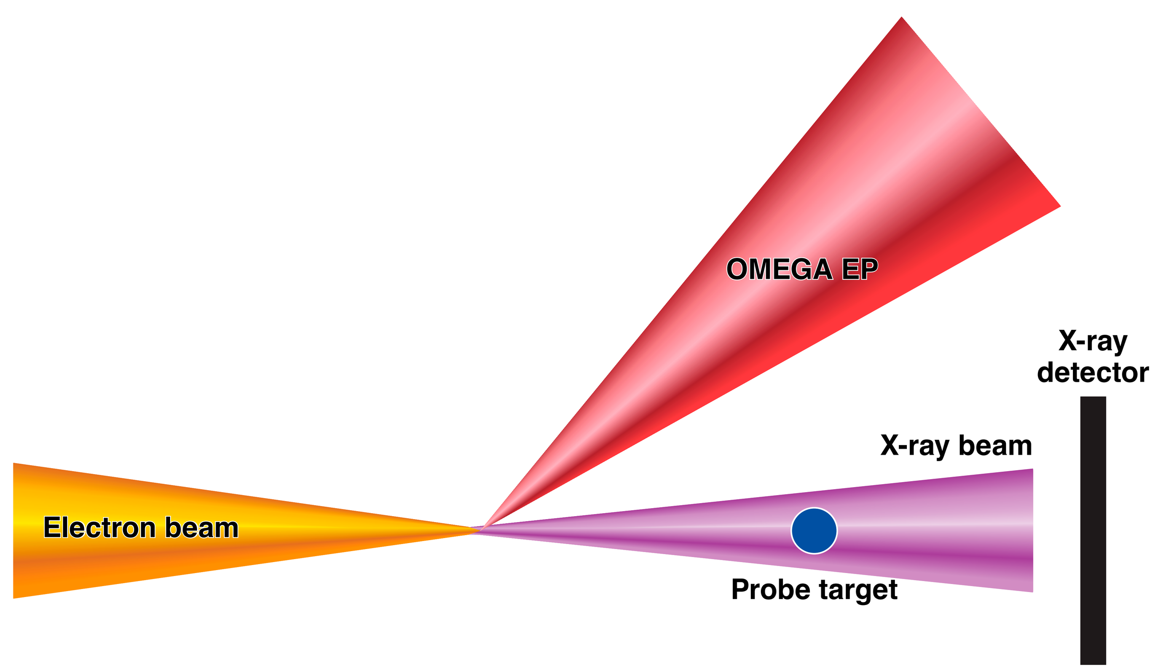
Inverse-Compton Scattering X-Ray Sources

- Electron beams can interact with lasers to form monoenergetic x-ray beams via inverse Compton scattering [6]
- The x-ray beam inherits the beam qualities of the parent beams
- If high-intensity lasers are used, a nonlinear scaling with x-ray yield and x-ray energy begins to occur following these equations [4]

$$E_{\text{x-ray photon}} \cong \frac{4\gamma_e^2 E_{\text{laser-photon}} N_\gamma}{1+(\gamma_e\theta)^2+\frac{a_0^2}{2}+\frac{2N_{\gamma\chi}}{a_0}}$$

$$N_{\text{x rays}} \cong \frac{\sigma_c N_{\text{lesser}} N_e}{\pi w_0^2}$$

- An inverse Compton source can be built using the same accelerator that would be used for electron diffraction experiments
- This x-ray source would be bright, tunable, and monoenergetic
- The x-ray beam could also be increased in bandwidth by adjusting the electron beam parameters



X-ray Source using 5-MeV Electron Beam

Laser	X-ray (KeV)	Bandwidth (eV)	X-ray yield per pC of electron	a_0
MTW OPAL	4.24	9.26	6×10^6	3.47
EP 1000 J	1.041	0.22	1×10^9	1.65
EP 350 J	4.502	0.22	4×10^8	4.52
EP OPAL	61.823	1479	1×10^9	43.95

- A 100-pC system coupled to MTW-OPAL would nearly be equal in brightness to standard foil x-ray backlighters, but would be more tunable
- The same system coupled to OMEGA EP would exceed the standard x-ray backlighter brightness by a factor of 100

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a_0: unitless laser strength parameter
MTW: multi-terawatt
OPAL: optical parametric amplifier line

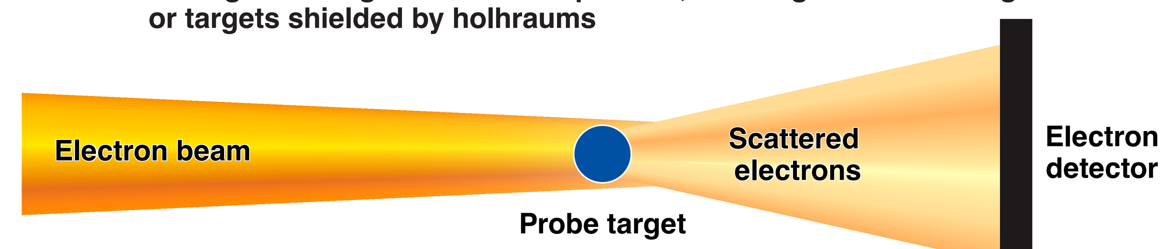
Electron Radiography

- MeV-scale electrons can easily penetrate ICF and HED targets [7] and act as a radiography source [8]
- LWFA-generated electron beams can also be made more resistant to magnetic fields than protons. The resistance of a given charged particle to deflection by a magnetic field is given by [2,8]

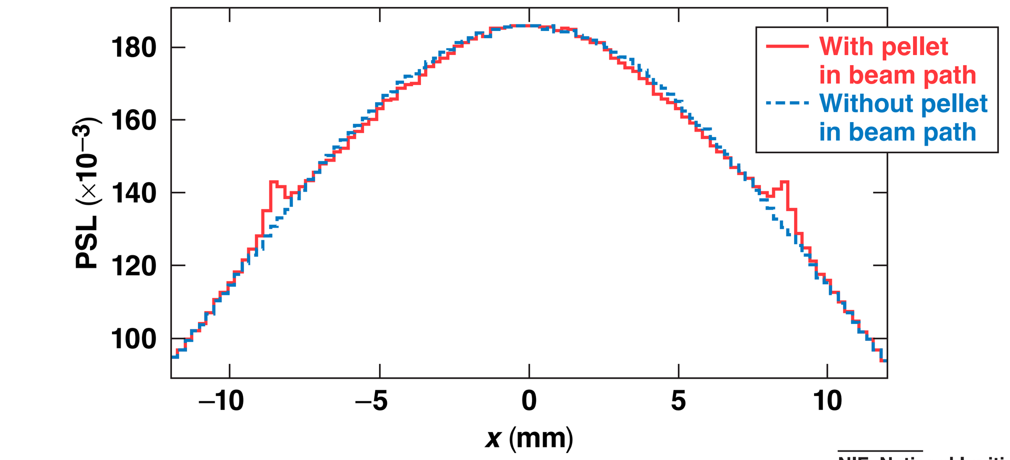
$$B \times r = \frac{p}{q},$$

where B is the magnetic field, r is the deflection length, p is the particle momentum, and q is the particle charge

- D^3He proton radiography has a magnetic rigidity of ~0.6 T-m [9]
- A 300-MeV electron beam has twice the magnetic rigidity of D^3He protons and is well within the range of a typical LWFA source
- The electron beam also has range in materials that is two orders of magnitude higher than D^3He protons, allowing for denser targets or targets shielded by holhraums



300-MeV image-plate electron radiograph of a NIF pellet mid-compression



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NIF: National Ignition Facility

References

[1] S. P. Weathersby *et al.*, Rev. Sci. Instrum. 86, 073702 (2015).
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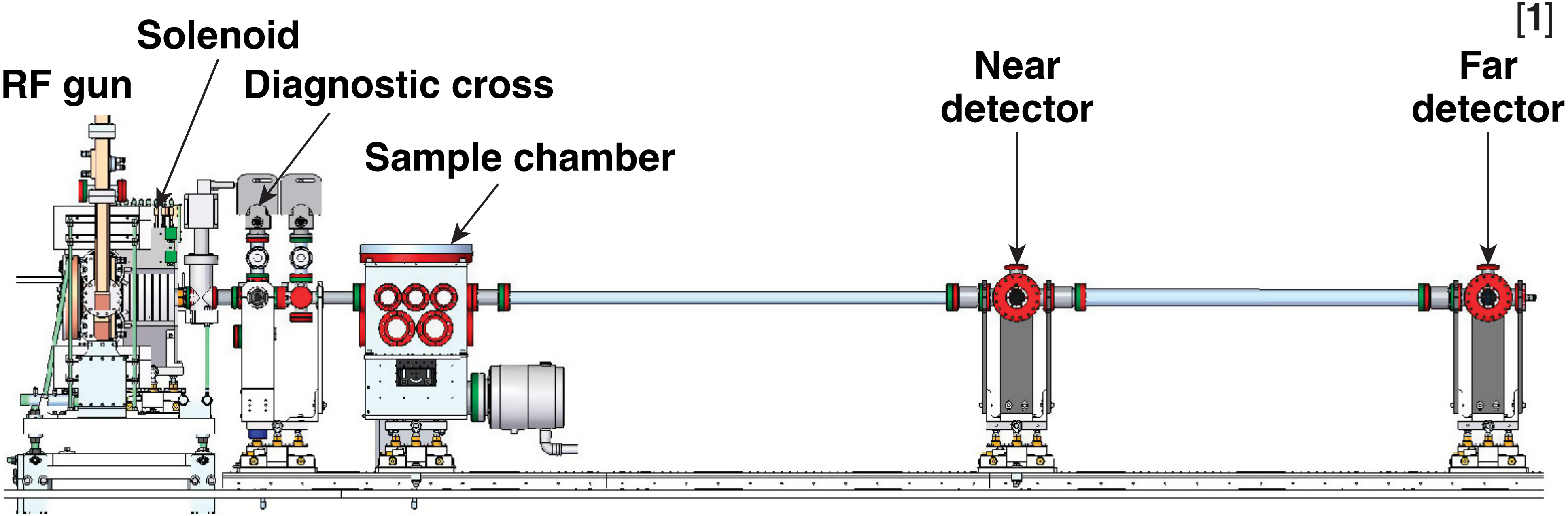

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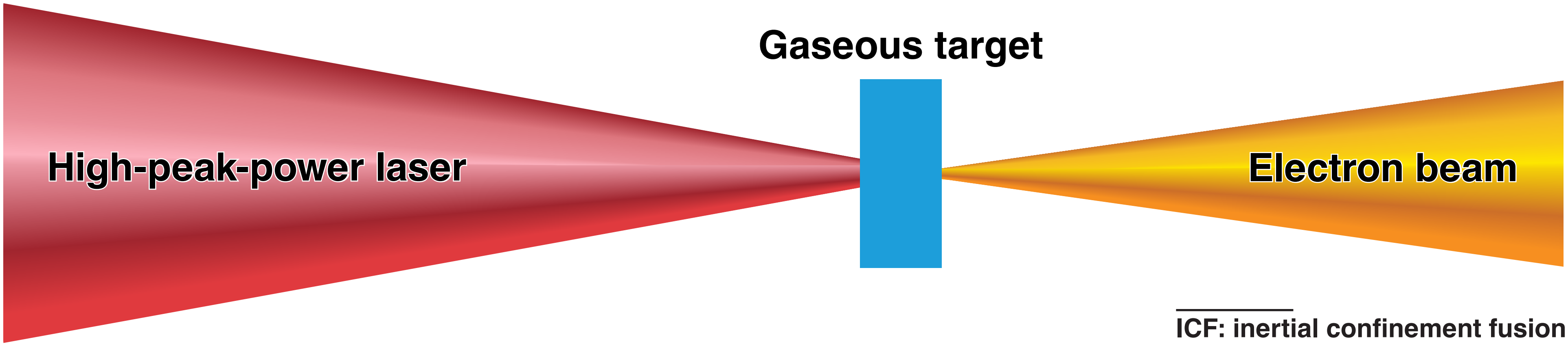

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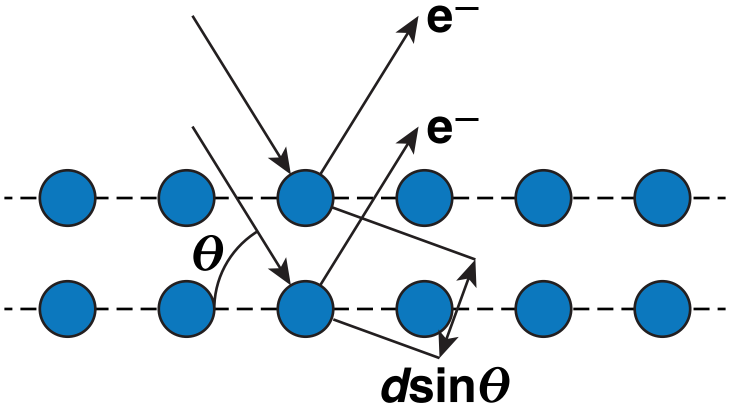

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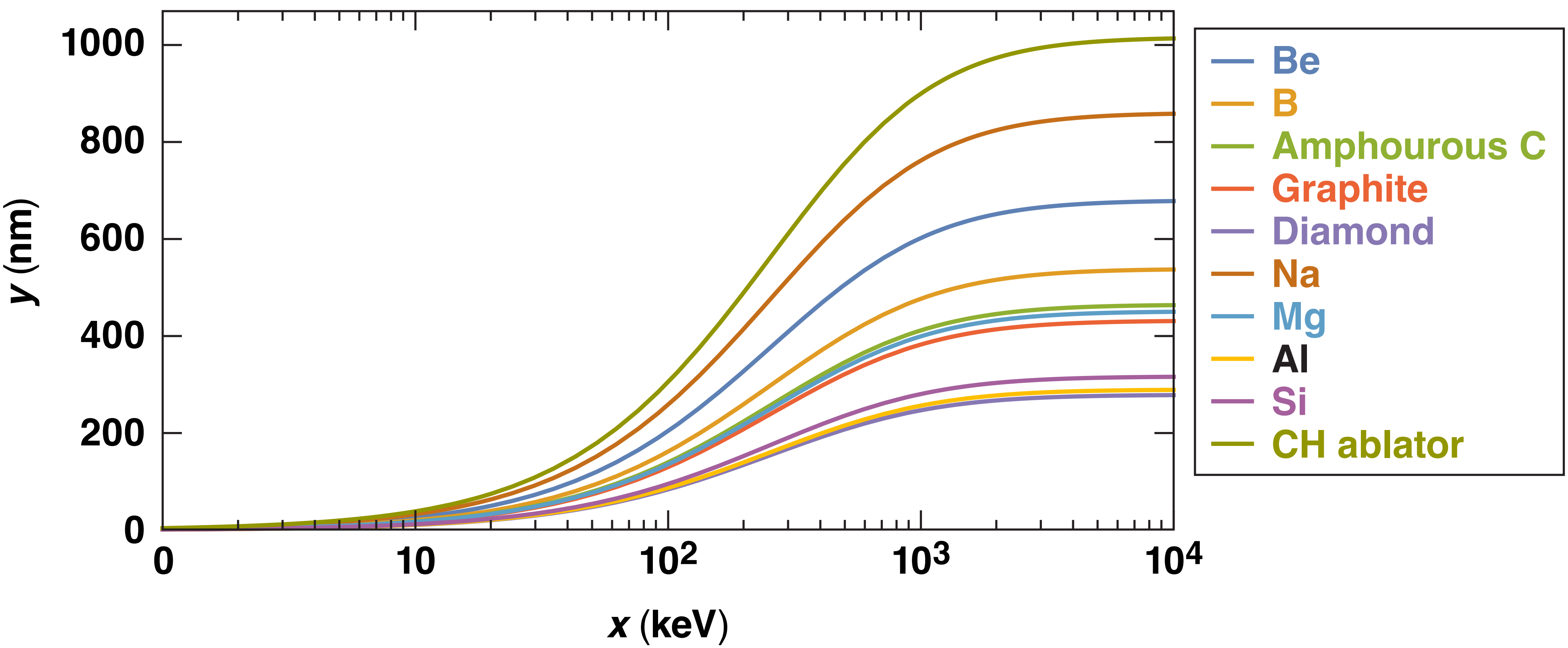

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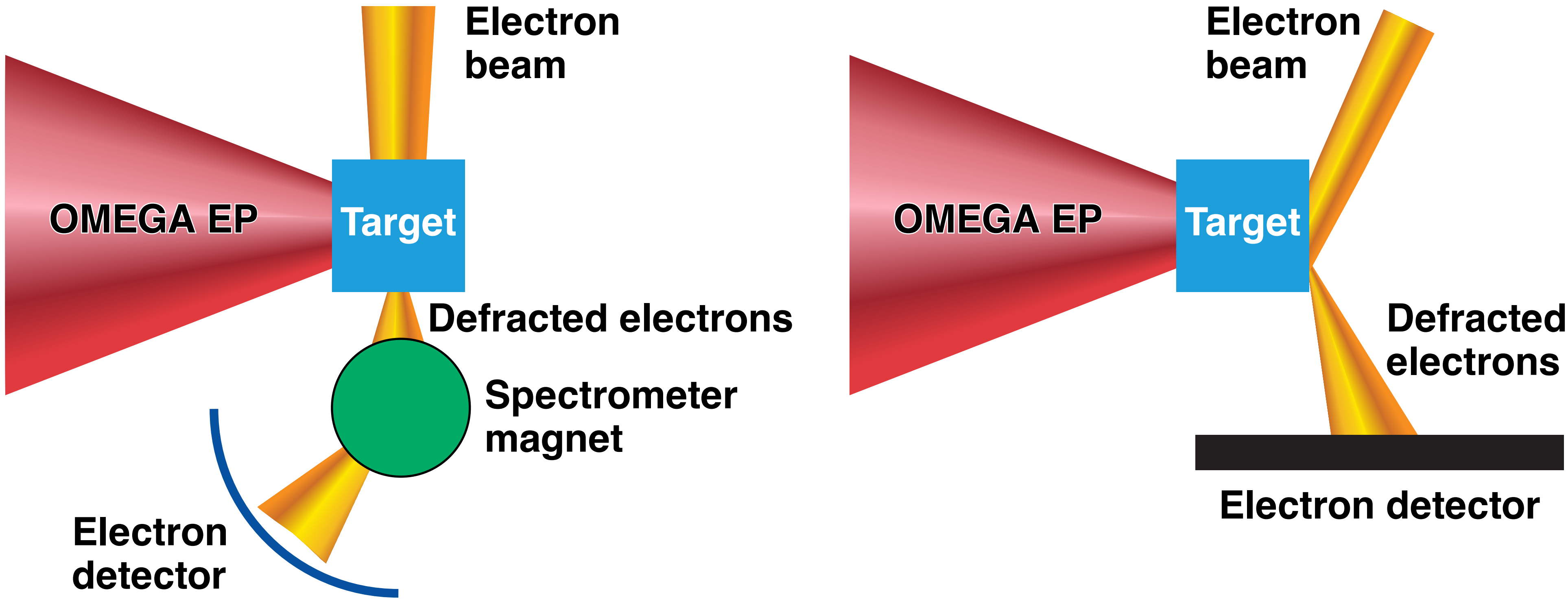

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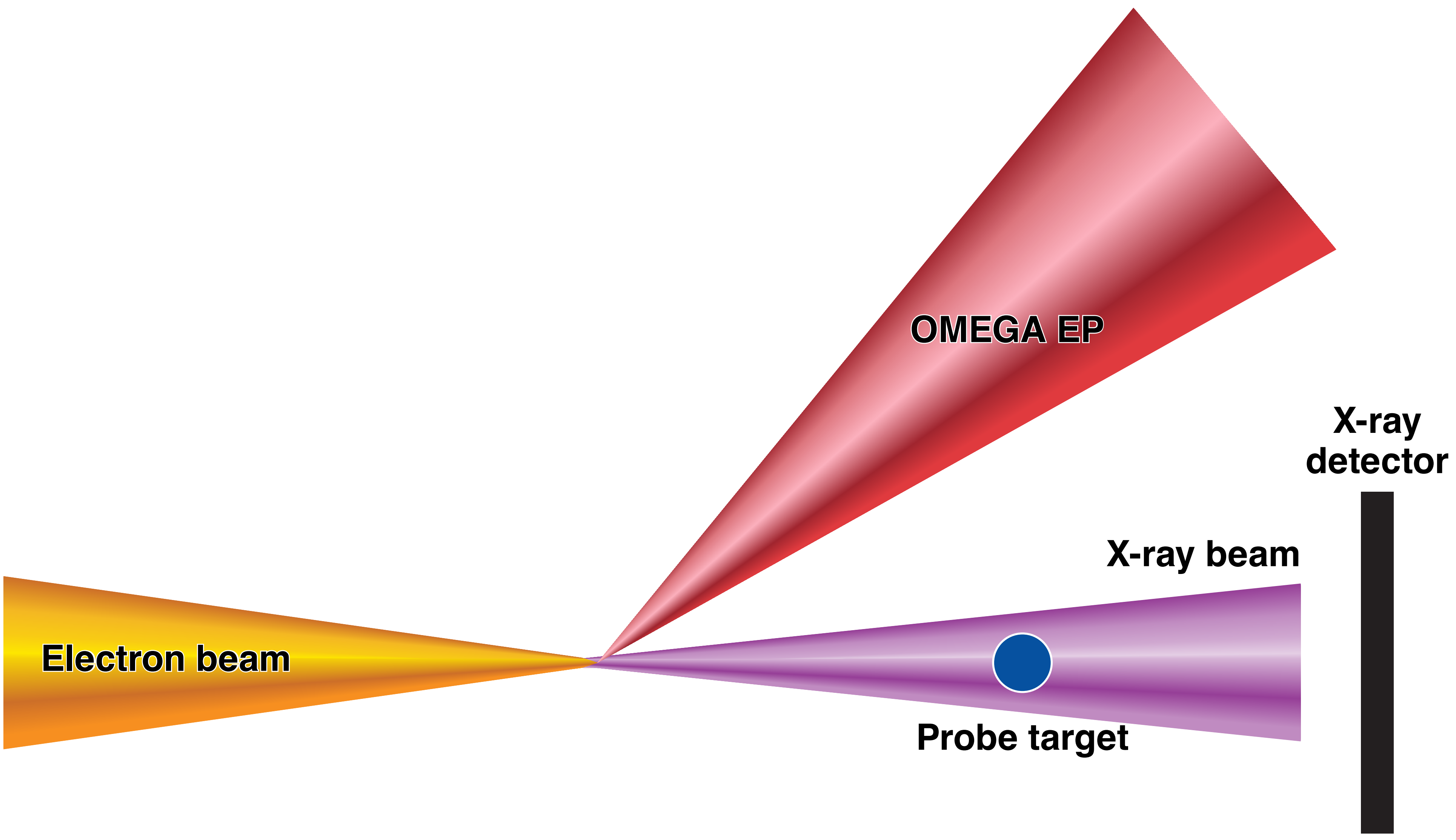

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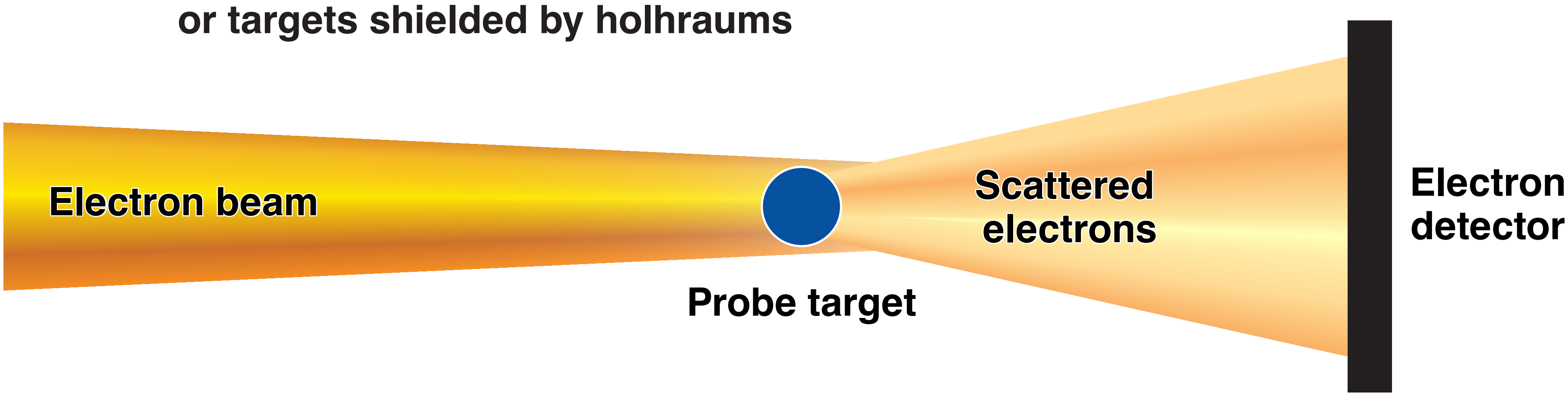

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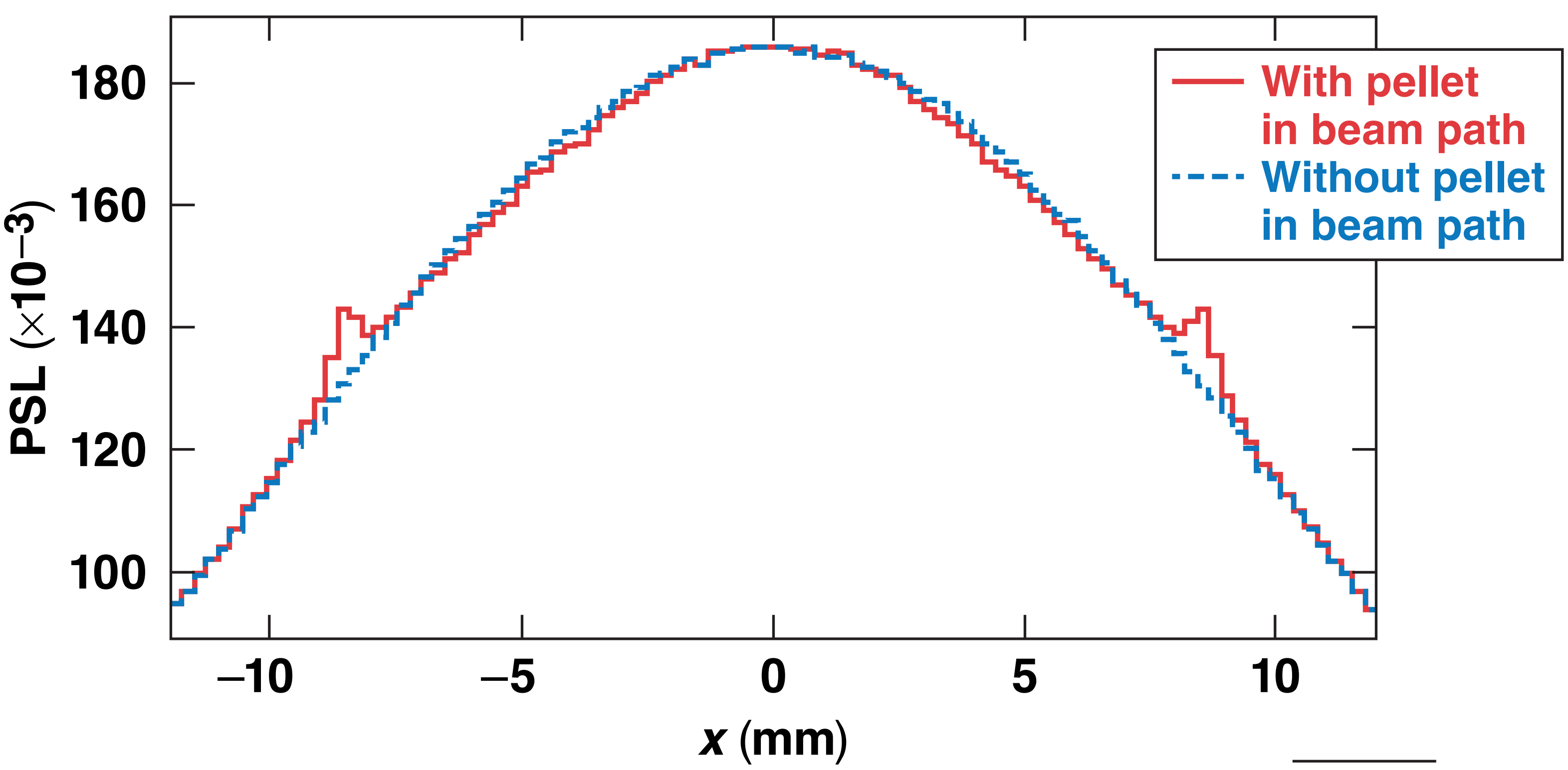

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