MEC-Upgrade Project

Physics Technical Note

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Title	Photon Energy Requirement
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Scientific Cases for high photon energy

MEC science often concerns dense, high Z materials of >100 µm spatial extent, and the MEC-U upgrade will give access to more powerful laser drivers, which will be used to extend both the volumes of materials studied and the atomic number. More than any other science area, MEC therefore drives a desire to reach the highest photon energies from LCLS. Higher photon energies allow more plasma background to be shielded, give access to inner shells of higher Z materials, and penetrate such materials more deeply.

A scientific case for high photon energy can be found in the conceptual design work for DMMSC (formerly MaRIE). This case focuses on penetrating dense, thick materials and maximizing the ratio of elastic (Thomson) to total scattering in materials of interest. The point of maximizing this ratio to minimize X-ray heating in the sample for a given required signal level. Minimizing all sources of heating is necessary to stay as close as possible to the isentrope during dynamic (ramp) compression.

The plots in Figure 1 are from Cris Barnes' 2019 Colloquium "The Dynamic Mesoscale Materials Science Capability (DMMSC is the problem) Formerly known as Matter-Radiation Interactions in Extremes Project (MaRIE should be the solution)". Note that the marker of the third harmonic at the K-edge of uranium is the main motivation for the named *first harmonic* photon energy design point (42 keV). Therefore, the precise figure of 42 keV written on the slide will not apply to MEC-U based on the near-term projected capabilities of LCLS (126 keV is arbitrarily several keV above the K-edge anyway).

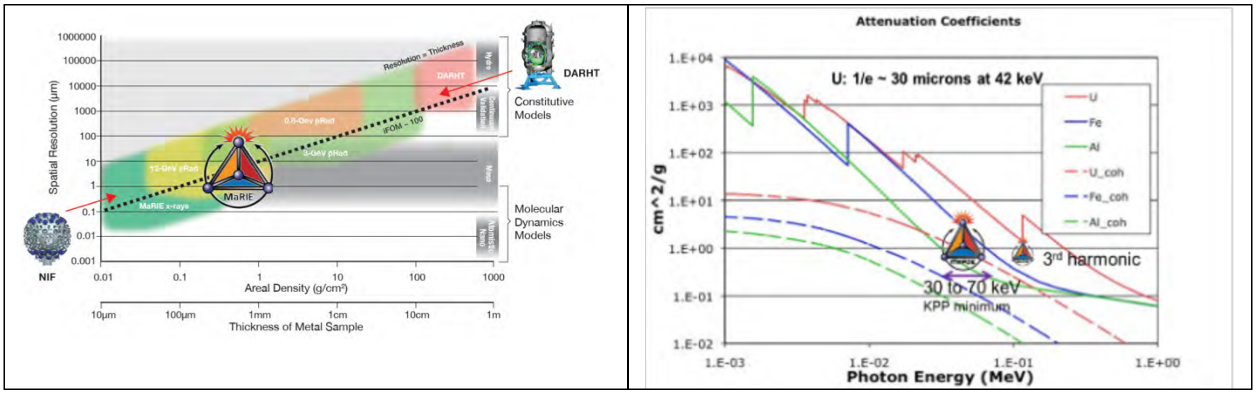


Figure 1: Plots from MaRIE science case illustrating (left) spatial resolution vs aereal density or thickness of sample and (right) scattering cross sections for various materials. Solid lines indicate total absorption and dashed lines are coherent scattering.

Attenuation lengths and coherent vs total scattering cross sections can be quickly obtained using the NIST XCOM web app. **Note:** In the below we also show values for 55 keV because technically the known mirror solution giving access to 45 keV (discussed in the final section) also gives access up to 55 keV. However, the KPP being considered for change is set to 45 keV, so this is the value we should consider for comparison.

	Photon energies (keV)			
Property	25	40	45	55
Attenuation Length				
Al	2 mm	6.5 mm	8.3 mm	12 mm
Ti	265 µm	1 mm	1.38 mm	2.34 mm
Cu	61.3 µm	230 µm	319 µm	554 µm
Xe liquid	225 µm	144 µm	195 µm	331 µm
Au	11 µm	40 µm	54 µm	91 µm
Coherent scattering / total absorption				
Al	.079	0.12	.126	.126
Au	.038	.068	.077	.094
Cu	.024	.044	.05	.062
Ti	.034	.062	.071	.085
Xe liquid	.068	.022	.024	.03
Cold K edge: highest Z target	Pd (Ag)	La (Ce)	Nd	Ho (55.6)
CDI Resolution		No advantages identified		
Nuclear transitions of interest?		None identified		
Dense plasma lines	Baseline	41.3 keV to reach hydrogen-like Xe line	41.3 keV to reach hydrogen-like Xe line	None found

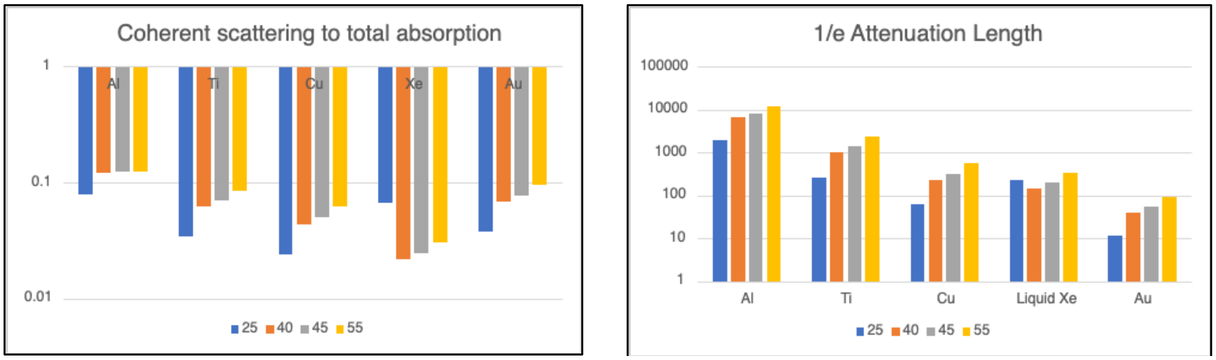
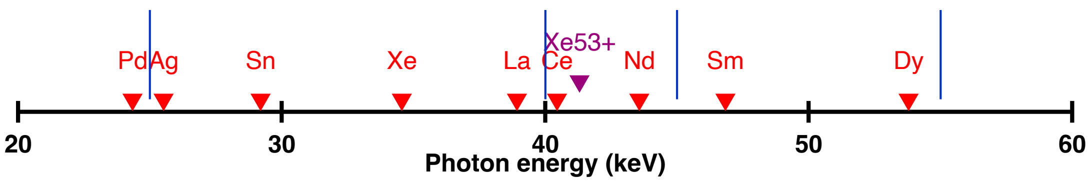


Figure 2 Log plots for representative materials showing (left) ratio of coherent scattering to total absorption and (right) attenuation length. The strongest difference generally comes in the jump from 25 to 40; the difference between 40 and 45 is negligible.

Looking only at room temperature conditions of the K edges, we can see where we pass over these photon energy boundaries. Nd is an example of a material of some interest whose edge falls above 40 keV. Also, Hydrogen and He-like Xe ionize at just over 40 keV (41.3 and 40.2 keV respectively). These examples are of only minor interest. The Au K edge is fully out of range.



Nuclear transitions

The possibility has been raised that certain nuclear transitions of interest may exist within the 40-55 keV range. However, a brief literature review and survey of the UAP did not return any candidates, and for most applications the required intensity is much higher than would be achieved in this energy range for the 3rd harmonic. Known applications don't appear to apply to conditions or timescales relevant to HED plasmas.

1.Bürvenich, T. J., Evers, J. & Keitel, C. H. Nuclear Quantum Optics with X-Ray Laser Pulses. *Phys Rev Lett* **96**, 142501 (2006).

2.Pálffy, A. A systematic study of nuclear photoexcitation with X-ray laser fields. *J Mod Optic* **55**, 2603–2615 (2008).

Practical implications for photon energy requirements at LCLS

LCLS mirrors currently yield a cutoff of just over 25 keV, using Ni coatings on three mirrors. The first two mirrors, HOMS mirrors common to all instruments served by the hard X-ray undulator, set the photon energy limit because of their angle of incidence (2.1 mrad). The MEC turning mirror is set to 1.375 mrad, and so is not the limiting factor.

Currently mirrors have two stripes on them: SiC for lower photon energies and Ni for higher photon energies (see Figure 3). It was recently found that higher Z coatings used to reach higher photon energies are more susceptible to damage than previously expected.

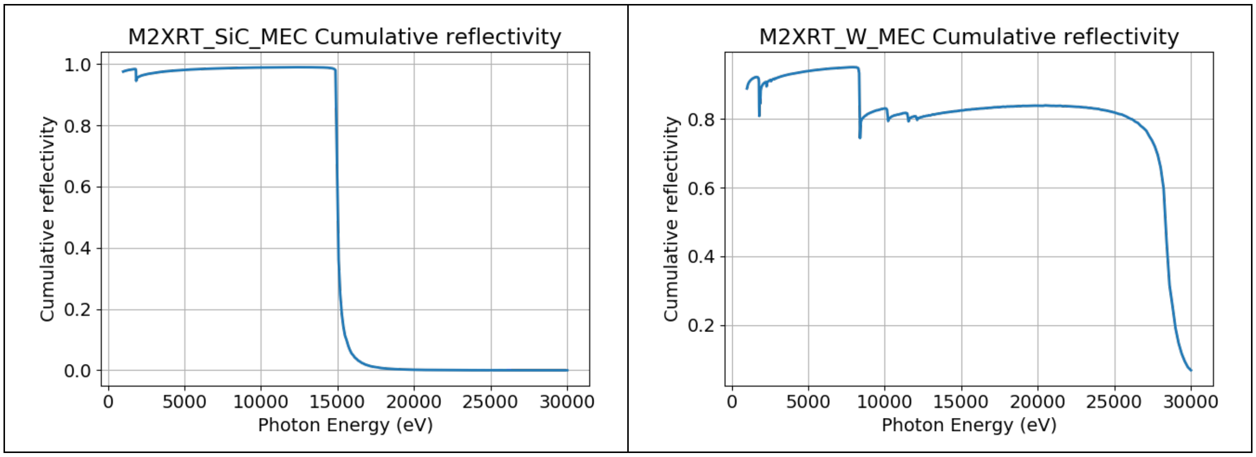


Figure 3: Reflectivity for low photon energies using SiC. *Captured all of first harmonic prior to LCLS-II upgrade*

A relatively straightforward upgrade gives LCLS access to a cutoff energy just over 40 keV, by adding a new mirror chamber and mirror to give the same grazing incidence on the HOMS mirrors as the MEC mirrors (see Figure 4). This could be installed in such a way that the original HOMS configuration could still be used for photon energies < 25 keV (where the beam size at the mirrors is larger, for higher throughput). By adding a stripe with W coating to all three mirrors (first HOMS, new alternate HOMS, and MEC turning mirror), photon energies up to 55 keV can be accessed. However, this would negatively impact the mirrors used by the rest of LCLS, negatively impacting operations because of the higher risk of mirror damage, and complexity of the mirrors. Figure 5 compares the transmission curves of the current situation (black line), and the use of the new mirror chambers with Ni (blue line) or W (red line) coatings in the HOMS.

As pointed out in the March 29 2022 UAP meeting, Figure 5 shows that, while 45 keV is beyond the cutoff, the transmission is still predicted to be at about 10%, so the photons are hardly extinguished, although it is preferable not to deal with sharply changing transmission curves.

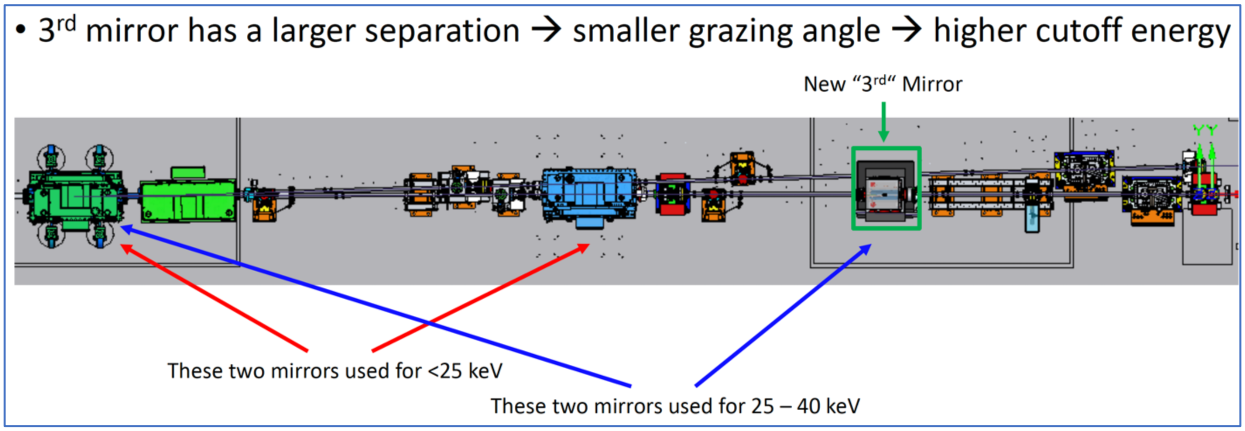


Figure 4: Concept for increasing maximum energies by inserting a new mirror

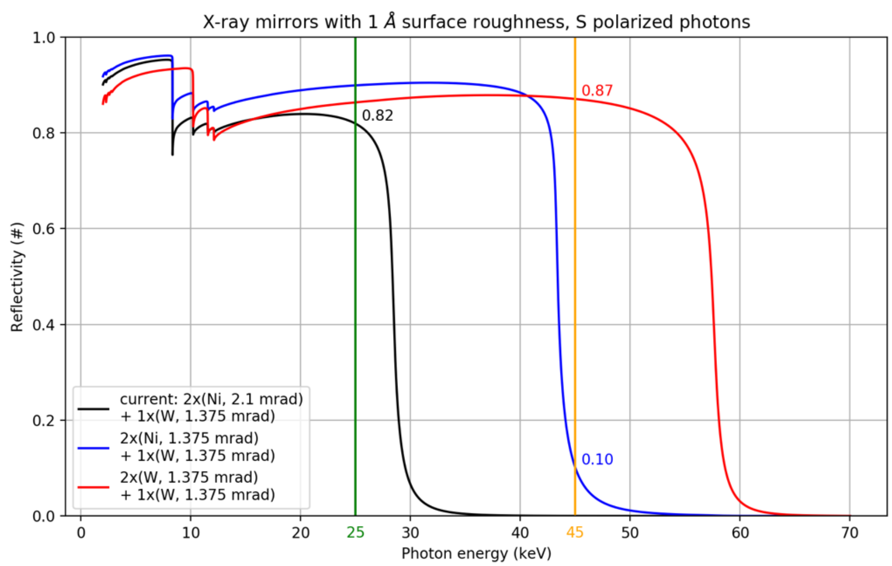


Figure 5: Plot of transmission curves for different scenarios. Black curve: current capability; Yellow curve: future capability with new HOMS mirror position and Nickel coatings (W on MEC / MFX mirror); Red curve: same mirrors with W coating on all.

Conclusion

There is no compelling scientific basis mandating an objective cutoff energy for X-rays of 45 keV rather than 40 keV, as any advantages are marginal. Even considering that the known solution that gives access to 45 keV would raise the cutoff energy to 55 keV, this would not open substantial new scientific opportunities warranting the operational risk to LCLS and MEC-U of adding a tungsten coating strip. Therefore, the preliminary objective KPP should be changed from 45 keV to 40 keV.