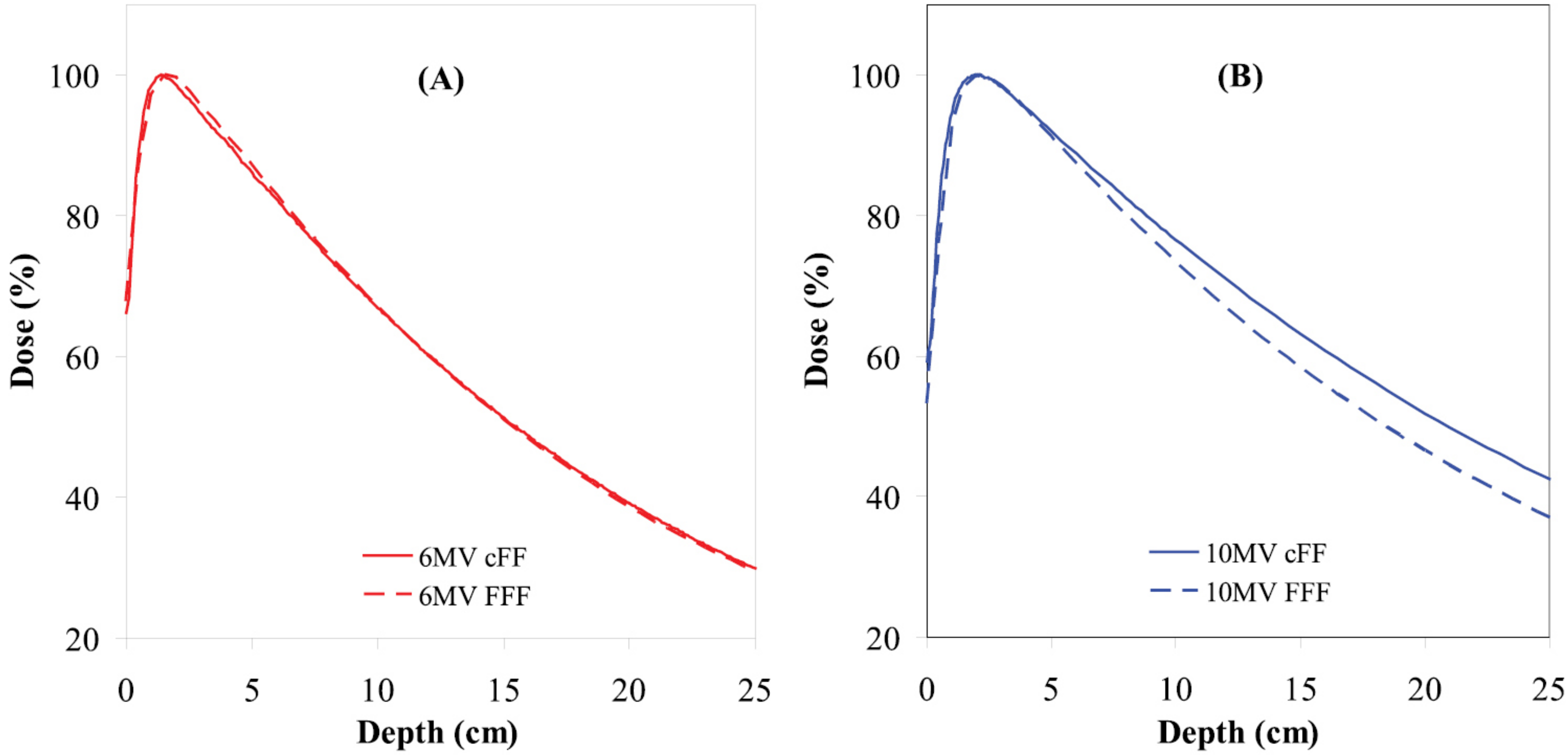

Figure 1. 10 × 10 cm cFF and FFF PDD for (A) 6 MV Elekta and (B) 10 MV Varian.

The measured $TPR_{20/10}$ for an Elekta linac should be close to that of a cFF beam of the same nominal energy, whereas for Varian machines the values of $TPR_{20/10}$ measured for 6 MV FFF and 10 MV FFF will be closer to those of 4 MV and 8 MV cFF beams respectively.

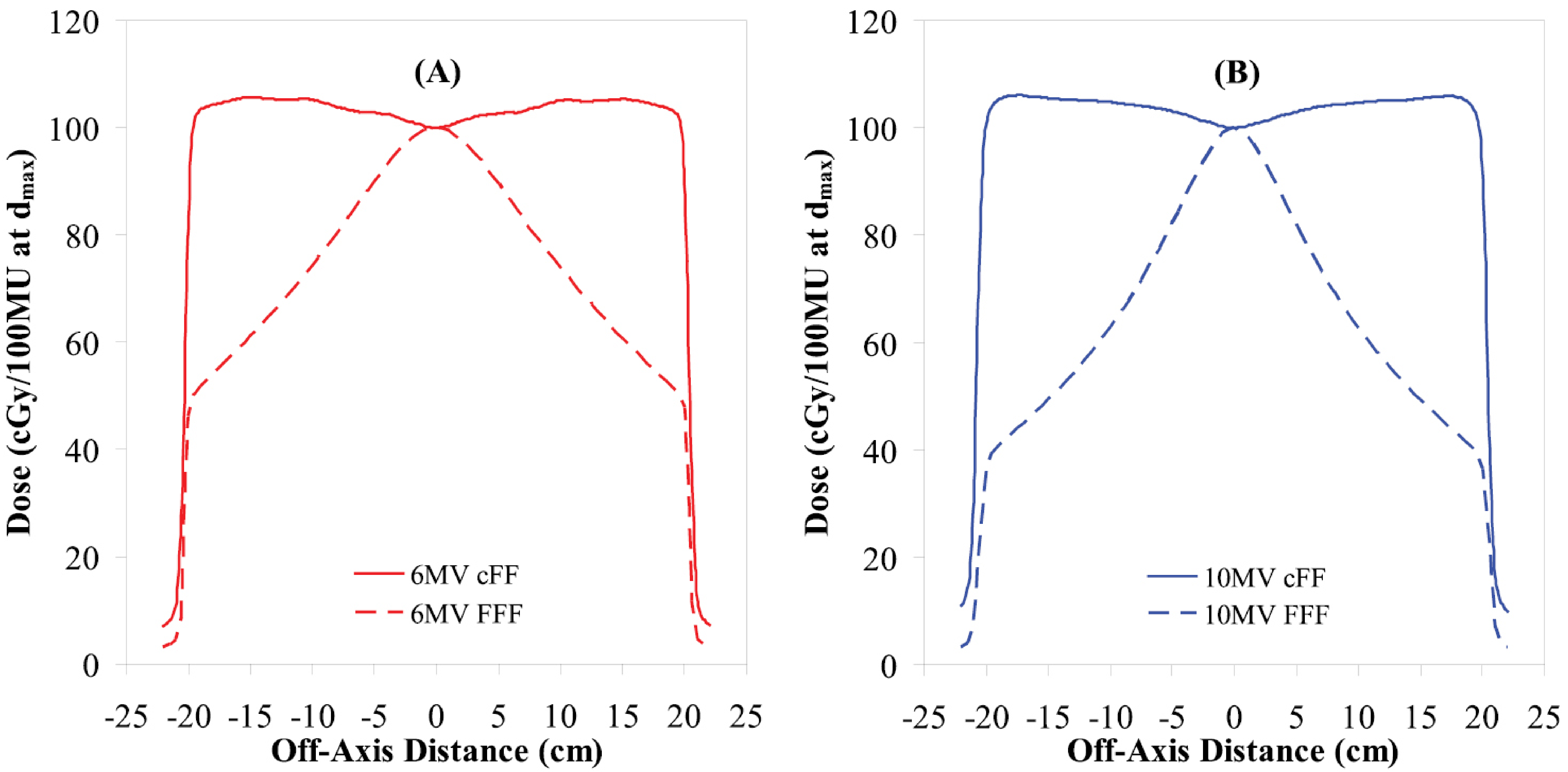

Figure 2. 40 × 40 cm cFF and FFF profiles for (A) 6 MV Elekta and (B) 10 MV Varian at d_{max}.

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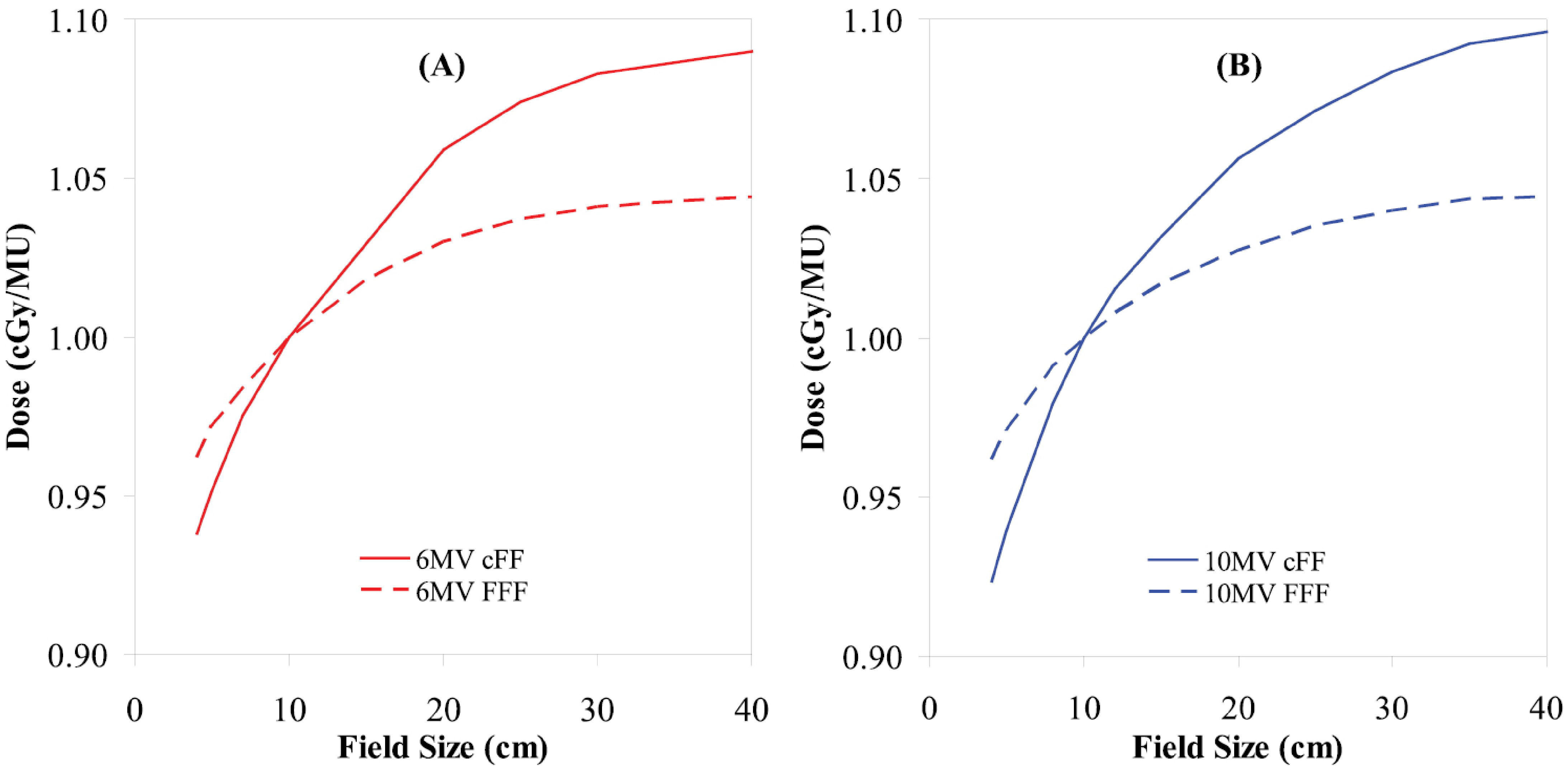

Figure 3. cFF and FFF relative output factors for (A) 6 MV Elekta and (B) 10 MV Varian at d_{max}.

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- The key difference between the manufacturers is how they approach this issue of beam energy.
- In simple terms the Varian implementation utilises the same electron beam to create both cFF and FFF beams, resulting in a less penetrating beam for FFF compared to a cFF beam of the same nominal energy.
- In the Elekta system the FFF beams are independent of the cFF beams and energy-matching is undertaken to maintain central axis depth dose under nominal conditions (90 cm source to surface distance (SSD), 10 cm deep, 10 × 10 cm^2).
- A 6 MV FFF beam on a Varian linac therefore has depth dose characteristics similar to a 4 MV cFF beam (Vassiliev *et al* 2006b), whereas an Elekta 6 MV FFF beam PDD remains similar to an Elekta 6 MV cFF PDD.
- These differences in beam energy between accelerator manufacturers must be kept in mind when comparing not just beam properties, but also room shielding and treatment plans.

Table 1. Beam characteristics for 6 and 10 MV FFF and cFF beams from Varian and Elekta. See Xiao *et al* (2015) for Siemens data.

		Nominal energy (MV)	Filtration	Effective energy (MV)[a]	d_{max} (cm)	D_{10} (%)	$TPR_{20/10}$	Max dose rate (MU min^{-1})	Dose (mGy) per pulse[b]
Varian	FFF	6	0.8 mm Brass plate	4	1.3	64.2	0.630	1400	0.8
		10		8	2.2	71.7	0.705	2400	1.3
	cFF	6	6/10 MV flattening filter	6	1.4	66.4	0.666	600	0.3
		10		10	2.3	73.6	0.738	600	0.3
Elekta	FFF	6	2.0 mm stainless steel plate	6	1.7	67.5	0.684	1400	0.6
		10		10	2.4	73.0	0.734	2200	0.9
	cFF	6	6/10 MV flattening filter	6	1.5	67.5	0.678	600	0.2
		10		10	2.1	73.0	0.721	600	0.4

[a]Clinical effective energy, based on $TPR_{20/10}$ and percentage depth dose falloff. [b]Measured at d_{max} on beam central axis for standard reference conditions. *Note*: D_{max} refers to depth of maximum dose. MU are monitor units.

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Shielding / Radiation Protection

- FFF beams are delivered at a higher dose rate (currently 1200 MU min^{-1}–2400 MU min^{-1}) compared with cFF beams (typically up to 600 MU min^{-1}). Introduction of FFF beams in an existing linac bunker will therefore increase the maximum dose rates (measured with the beam on) substantially. Annual doses however may be largely unaffected and are likely to be more dependent upon the clinical use of the linac than the higher dose rates specifically.
- Due to the beam profile, IMRT is generally considered essential for larger FFF fields, bringing the potential for increased use of IMRT, or the possibility of increased modulation compared to IMRT with flattened beams, and with it an increase in MU Gy^{-1}required for treatment. This will primarily affect secondary barrier and maze entrance dose rates.
- The total dose over the course of acceptance testing and commissioning is likely to be substantially higher than for commissioning of flattened beams, therefore a detailed radiation risk assessment for individual commissioning periods should be carried out.

Patient scatter

- The change in energy spectrum affects patient scatter considerations. Whilst one would expect patient scatter to be increased due to a decrease in average energy, Kry et al (2009) report that the reduction in beam energy of their Varian FFF beams led to greater patient attenuation and reduction in collimator scatter, which affected the scatter dose to a greater degree, hence reducing patient scattered dose. In addition, if smaller fields are used for FFF in IMRT and VMAT this will result in a lower patient and wall scatter contribution per MU to the maze entrance dose than with cFF

Leakage

- Due to the removal of the flattening filter from the beam, the current required per MU has been reported to decrease by 57% at 6 MV FFF (Vassiliev et al 2006b) and therefore significant reductions in leakage have been reported (50% Kry et al 2009, 58% Cashmore 2008).
- It is also likely that there is a reduction in head scatter due to there being less material in the beam.
- The increased use of IMRT for large FFF beams is however likely to increase, negating some of the reduction in leakage. In clinical use, secondary barriers and mazes are likely to be adequate for FFF beams of the same nominal energy as the bunker was designed for.
- As outlined by Jank *et al* (2014), the IEC guidelines (IEC 2007) state a maximum leakage of 0.1% of isocentre dose. If in the future a linac produces FFF only, it may be that a linac manufacturer will reduce head shielding; this should be specified by the manufacturer.

Neutron production

- Neutrons are not considered to be generated in significant fluences below 10 MV hence will not be an issue for 6 MV FFF beams.
- Consideration should be given to neutron production for FFF beams matched to 10 MV flattened beams, as the maximum energy will be capable of neutron production.
- Kry *et al* (2008) found that removal of the flattening filter for a non-corrected 18 MV beam reduced the number of neutrons produced per MU by a factor of 3.7. However, these high energies are not commercially available for FFF.

Shielding summary:

- If the only expected change from an FFF beam is an increase in instantaneous dose rate, not an increase in patient dose or throughput, and if the shielding is sufficient for the energy of the machine being installed, then no further increase in primary shielding is likely to be needed for FFF.
- Due to the reduction in required current per MU, the secondary shielding present is also likely to be sufficient provided there is no large change in the IMRT factor.
- However use of FFF for high dose per fraction treatments may lead to a higher annual dose rate.
- Special measures may be required for acceptance and commissioning periods. Radiation surveys should usually be carried out soon after installation and environmental monitoring with passive detectors carried out once FFF is in clinical use, to validate both assumptions and calculations.