A focused very high energy electron beam for fractionated stereotactic radiotherapy

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Motivation and conclusion

Electron beams of very high energy (50–250 MeV) can potentially produce a more favorable radiotherapy dose distribution compared to state-of-the-art photon-based radiotherapy techniques. To produce an electron beam of sufficiently high energy to allow for a long penetration depth (several cm), very large accelerating structures are needed when using conventional radio-frequency technology, which might be challenging due to economical or spatial constraints. In this work, we show transport and focusing of laser wakefield accelerated electron beams with a maximum energy of 160 MeV using electromagnetic quadrupole magnets in a point-to-point imaging configuration. Focusing the electron beam enables control of the depth dose distribution and improved dose conformity. It is further shown that irradiation from many different angles allows for the precise dose delivery that is required for stereotactic radiotherapy treatment.

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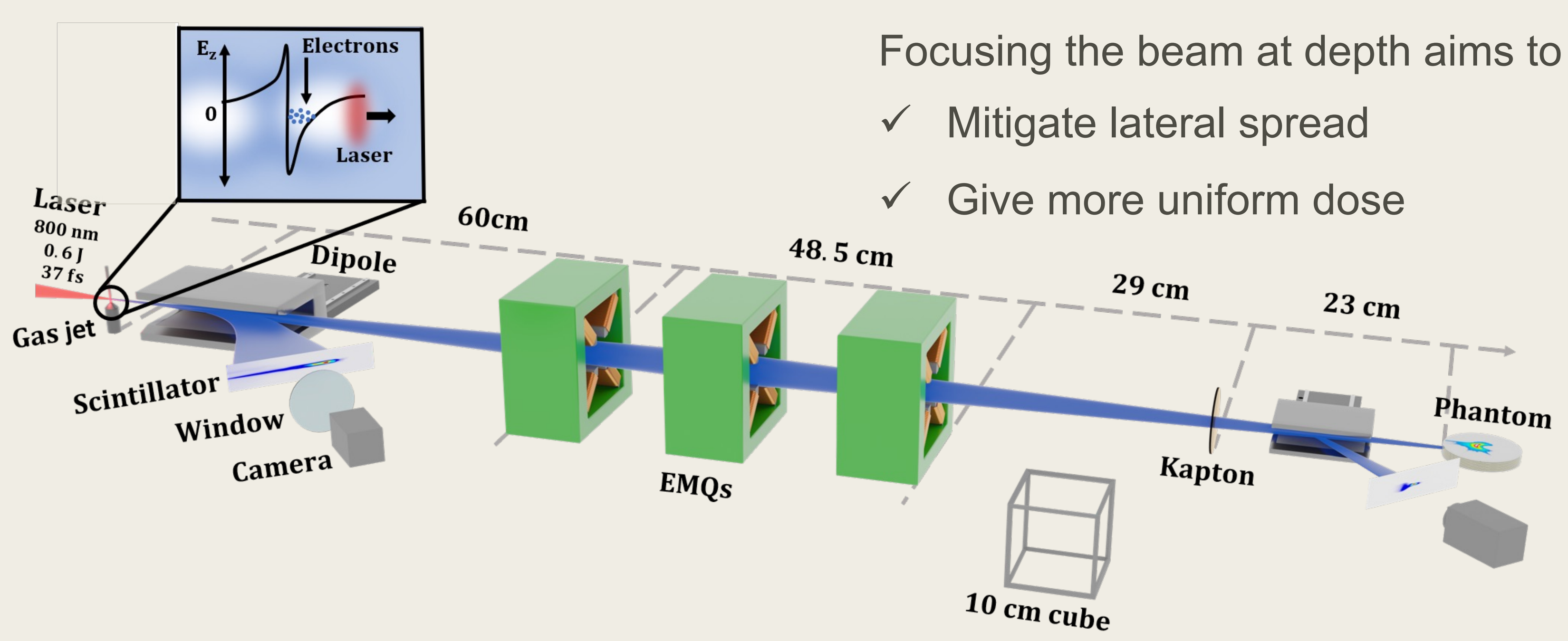
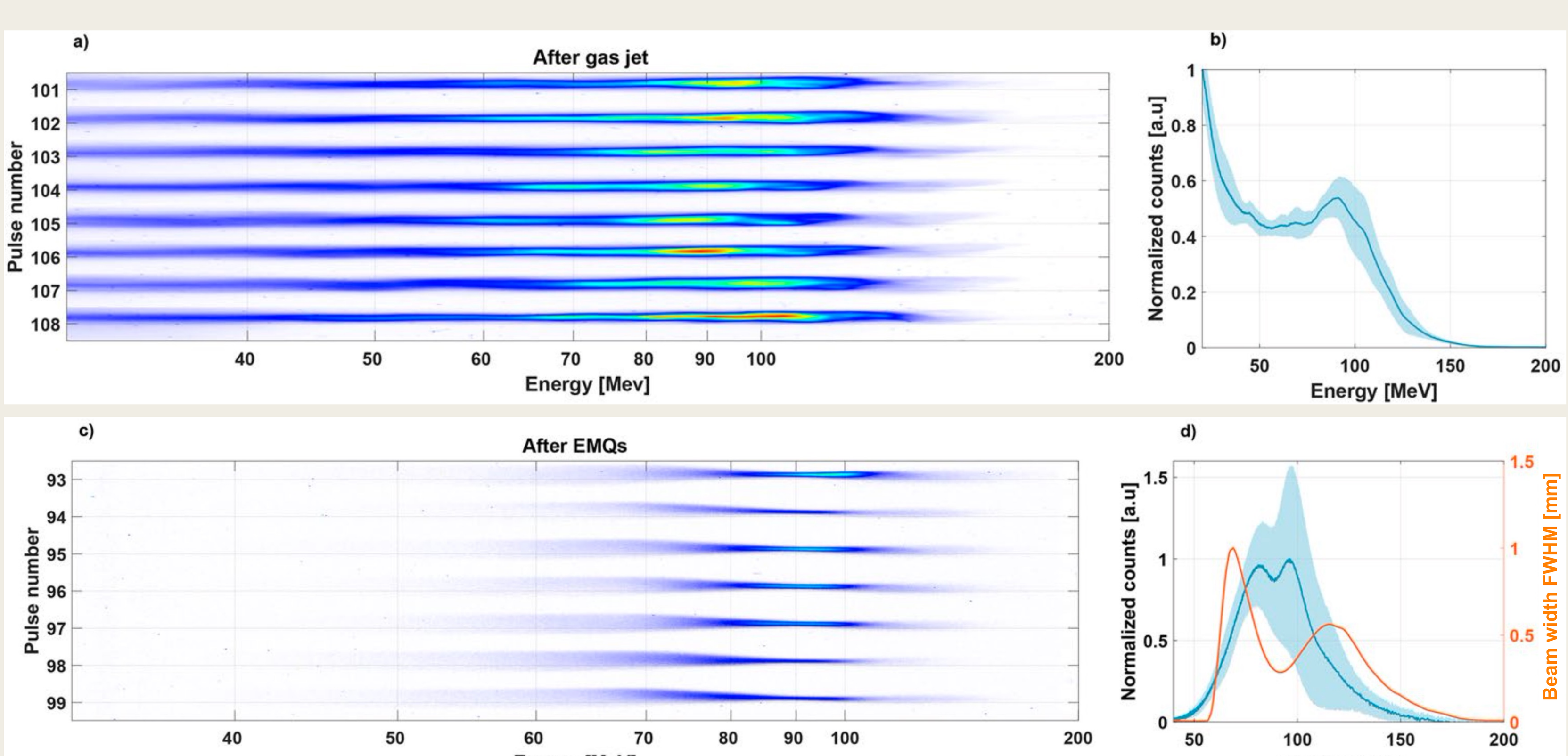
Beam shaping using EMQ magnets

Focusing the beam at depth aims to
- ✓ Mitigate lateral spread
- ✓ Give more uniform dose



The laser pulse is focused to 12 µm (FWHM) on a supersonic gas jet from a 1.5 mm orifice ejecting a mixture of He and 1% of N_2 at a backing pressure of 4 bar, corresponding to a fully ionized plasma density of $4{\cdot}10^{18}$ cm^{-3}. The electron beam passes through three electro-magnetic quadrupoles (EMQs) and exits the vacuum chamber through a 50 µm Kapton window. Two movable dipole magnets are used to measure the electron spectrum before and after the EMQs. Finally, cylindrical and planar dosimetry phantoms are placed in the electron focus.

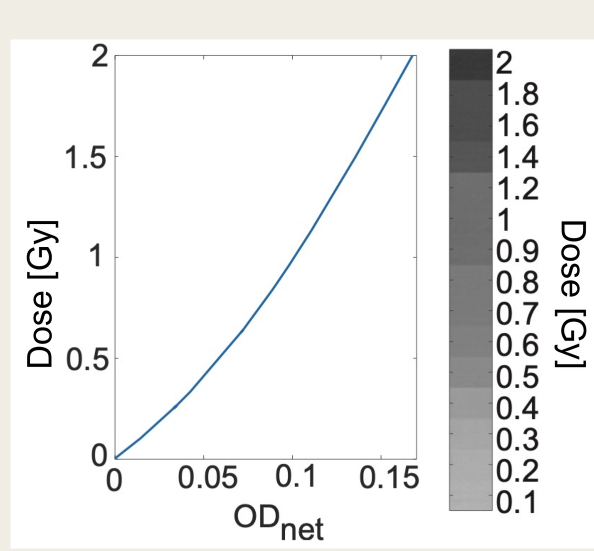
Focused electron beams



(a) shows 8 electron spectrometer scintillating screen images of the electron beam before focusing, with an average charge of 94 pC, **(b)** shows the average and standard deviation of the electron beam energy spectra. **(c)** Shows 7 electron spectrometer scintillating screen images of the electron beam after focusing and **(d)** shows the corresponding average electron beam energy spectra, along with the vertical FWHM of the electron beam size for pulse 97, shown in orange.

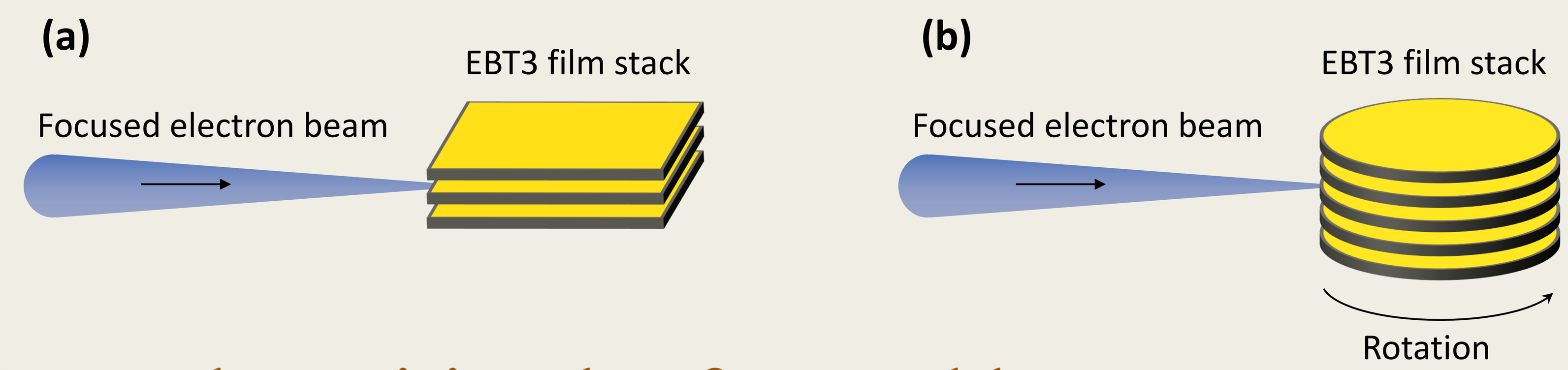
Dose calibration

Gafchromic EBT3 films were irradiated using an ELEKTA Precise linear accelerator, calibrated with an ion chamber according to the IAEA standard. The change in optical density (OD) was measured with an Epson V800 photo-scanner. For each dose value, the red channel of 3 irradiated EBT3 films were averaged (montage to the right). This calibrated scanner was used to obtain the absolute dose deposited by the laser wakefield accelerator.

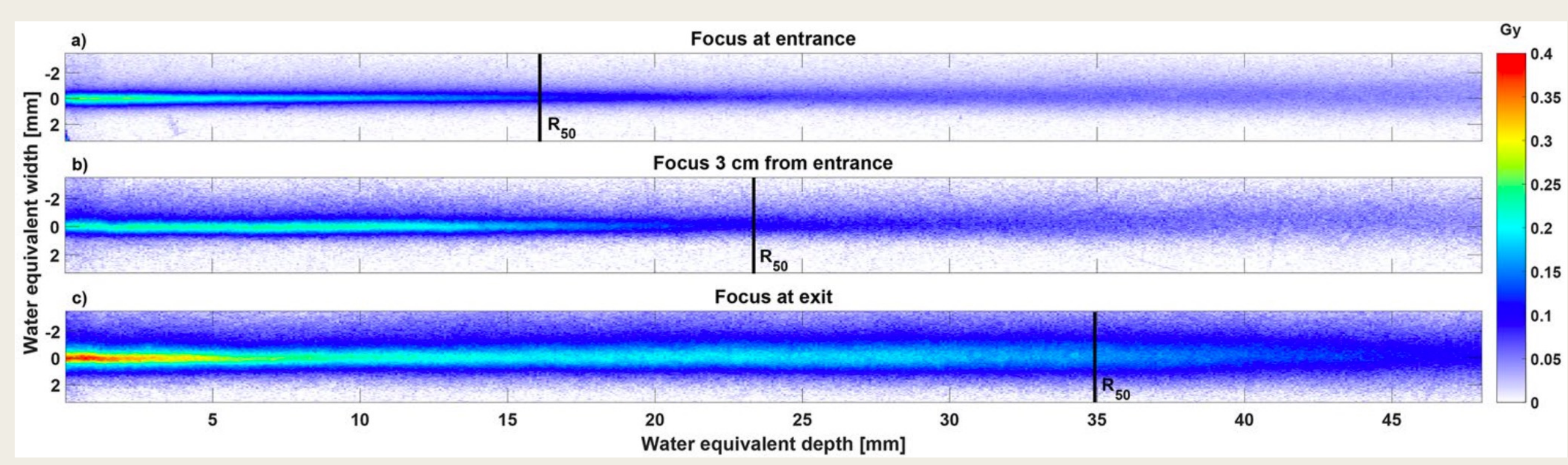


Side-irradiated film stacks

Gafchromic EBT3 films are carefully cut to minimize splitting of the film-edges as the films are irradiated from the side. Two geometries are used: **(a)** rectangular 50 mm EBT3 strip, clamped between 2 mm thick cast acrylic (Perspex) slabs. **(b)** Circular 8 cm diameter films, positioned between a pair of 2 mm thick cast acrylic slabs in a stacked cylindrical phantom. The stacks are clamped to remove any air gaps which could lead to an over-response. The water equivalence of cast acrylic is 1.045, i.e. 1 mm of acrylic is dosimetrically equivalent to 1.045 mm of water for an electron beam.

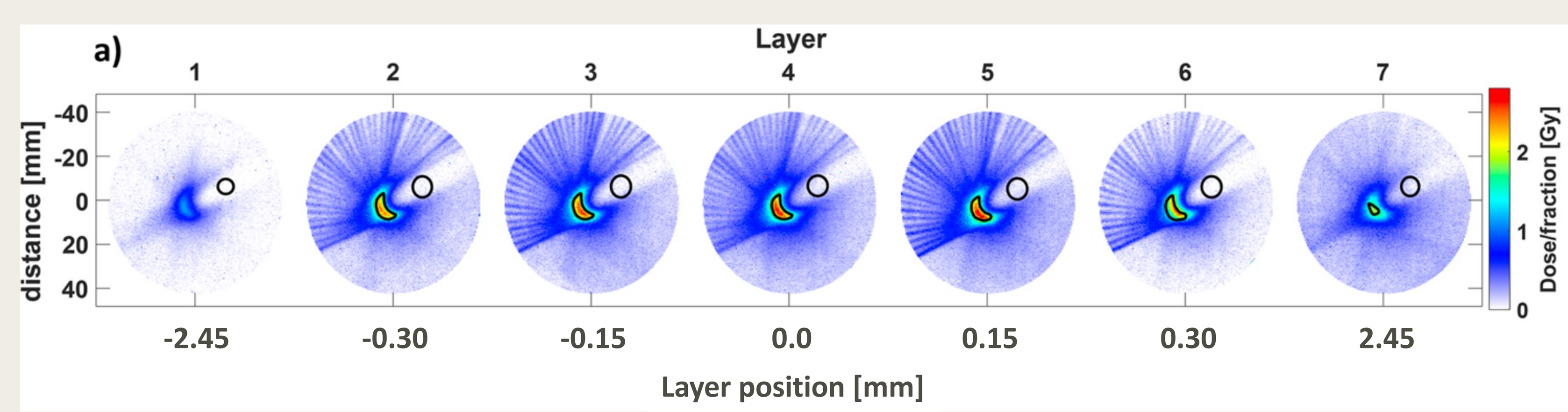


Dose deposition by focused beams



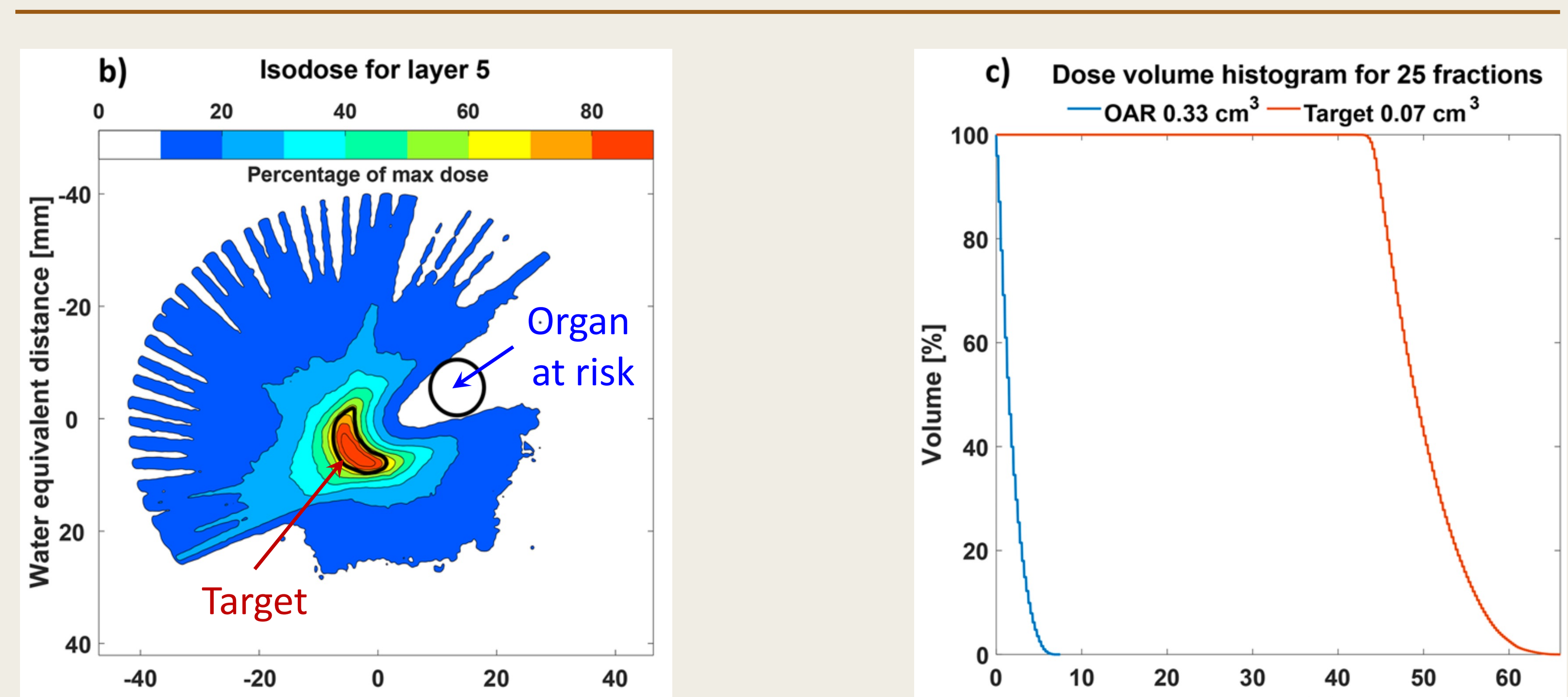
Measured dose profile in a rectangular phantom where the EBT3 film is irradiated from the side. By varying the focal position, the depth dose profile can be tuned. By focusing on the exit of the phantom, a higher dose may be reached in the central region. The position where 50% of the max dose is delivered, R_{50}, is moved 19 mm deeper by shifting the focal plane by 50 mm to the back of the phantom.

Multiple irradiation angles



Measured dose in a cylindrical phantom consisting of Perspex with 7 layers of EBT3 disks, irradiated from 36 entrance angles in 5° increments. Using three pulses per angle, the peak dose reaches 2.7 Gy, corresponding to a dose required for a single fraction. The EMQ point-to-point imaging minimizes pointing fluctuations and allows dose delivery in a precisely defined mm-sized volume in the center of the phantom.

Towards stereotactic radiotherapy



Stereotactic radiotherapy is a precise and focused form of radiation therapy that delivers high-dose radiation to small and well-defined target areas within the body. To imitate a stereotactical case, a bean-shaped target volume and an organ at risk (OAR) volume were assumed. The size of the phantom was chosen as a mean of relevant anatomical sites, comparable in depth and size for a head and neck case. By performing 25 fractions, a total dose to the target area would reach 65 Gy, while keeping the peak dose to the organ at risk below 8 Gy.