TUTORIAL

Laser Acceleration of Proton Beams

A technique using high-intensity light pulses could advance research on cancer therapies.

For decades, oncologists have used direct irradiation by X-rays, electrons or proton beams to zap tumors in cancer patients. But conventional radiotherapy can harm surrounding, healthy tissue as well. And, while research has lately suggested that very fast, pulsed delivery of radiation doses could excel at killing tumors while sparing healthy tissues, limited research infrastructure has held back progress.

That's particularly true for proton radiotherapy—long seen as a promising approach, but one for which few accelerator facilities exist that can create sufficiently intense, energetic proton bunches. In a recent study (Nat. Phys., doi: 10.1038/s41567-022-01520-3), scientists based at Germany's Helmholtz-Zentrum Dresden-Rossendorf (HZDR) and Oncoray Dresden demonstrated tumor irradiation in mice via a novel proton acceleration scheme, which relies on intense laser pulses to boost protons to the required energies and enable ultrafast dose delivery. To learn more, OPN talked with Florian Kroll, a member of the HZDR research team.

A compact setup to make the fast proton beams needed for cancer research.

1. Creating fast protons

The proton beam is born when 30-fs laser pulses from the HZDR Draco PW laser are focused onto a 220-nm-thick plastic foil to a spot size of few microns, creating intensities in excess of 10^{21} W/cm^2. That intense field ionizes the foil into a plasma, stripping electrons off atoms in the target and accelerating the electrons to relativistic energies.

Then, in a process called target-normal sheath acceleration (TNSA), the stripped-off electrons—prevented from escape by electrostatic attraction from the positive target ions left behind—form a "sheath" at the rear of the target. The resulting electric field pulls on the ions and shoots them out into a wide-angle beam. The process is most efficient for the hydrogen cores (protons) in the target material.

Optimizing the temporal pulse shape, Kroll notes, "can lead to a significant increase in proton energy, and also in stability." And whereas conventional facilities require large synchrotrons or cyclotrons to achieve the needed proton acceleration, laser-driven TNSA takes care of it across a span of micrometers.

2. Shaping the proton beam

A wide-aperture, pulsed, high-field magnetic solenoid, timed to synchronize with the laser pulses, next gathers in a large part of the divergent proton beam fired from the laser target and sends it further along in the beamline. The energy spectrum of the protons varies across the beam, so an energy-selecting aperture (ESA)—essentially an opening in an aluminum plate—shapes the spectrum for better control of the radiation dose. A second solenoid captures the resulting collimated proton beam and focuses it toward the tumor, and a series of scatterers helps to iron out aberrations and homogenize the beam laterally.

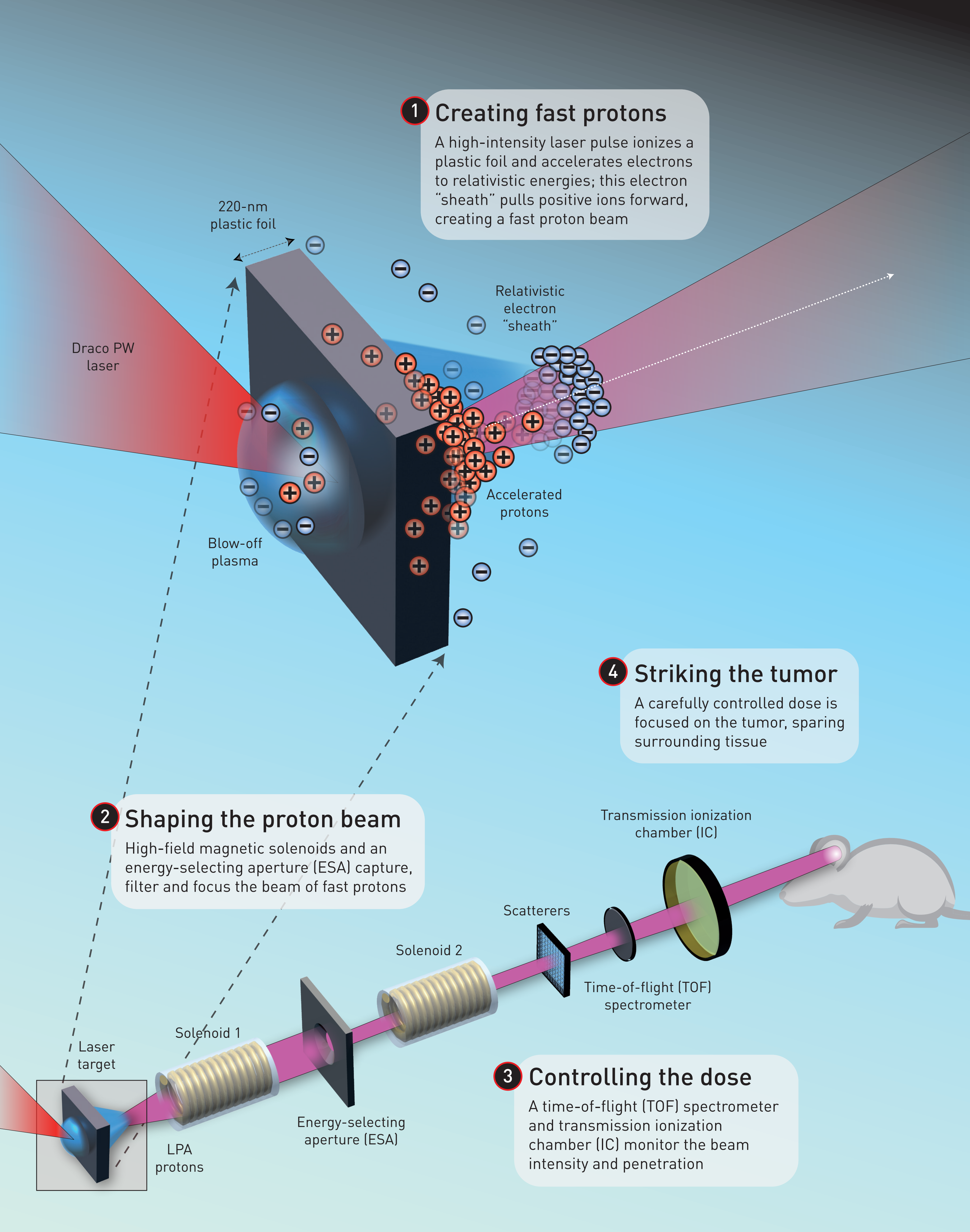
3. Controlling the dose

Because laser-driven proton sources can fluctuate in intensity, keeping tabs on the radiation dose in real time is essential. "We need to monitor our beams, to know when to stop the irradiation," says Kroll. This is accomplished through two instruments in the proton beamline: a time-of-flight spectrometer, to read the beam kinetic energy and predict the depth of penetration for a given dose; and a transmission ionization chamber, to both monitor the single-shot dose and shut off irradiation when the full prescribed dose is reached.

4. Striking the tumor

Using this setup, the HZDR team was able to deliver, in a series of carefully calibrated shots, the prescribed proton radiation dose (4 Gy) precisely to a tumor in a live mouse—the first successful use of laser-accelerated proton irradiation in a live animal. The team believes that the setup could provide a powerful new platform for translational research, to better flesh out the potential and parameters for new approaches to proton and other radiotherapy at ultrahigh dose rates. And, Kroll adds, the setup shows that "we have reached a whole new level of stability in these sources." That, he maintains, could also prove "interesting for other applications—not just radiobiology." OPN

OPN thanks Florian Kroll at HZDR for assistance with this tutorial. For references and resources, go online: **optica-opn.org/tutorials/proton-beam**.



1 Creating fast protons

A high-intensity laser pulse ionizes a plastic foil and accelerates electrons to relativistic energies; this electron "sheath" pulls positive ions forward, creating a fast proton beam

2 Shaping the proton beam

High-field magnetic solenoids and an energy-selecting aperture (ESA) capture, filter and focus the beam of fast protons

3 Controlling the dose

A time-of-flight (TOF) spectrometer and transmission ionization chamber (IC) monitor the beam intensity and penetration

4 Striking the tumor

A carefully controlled dose is focused on the tumor, sparing surrounding tissue

Source: Adapted from F. Kroll et al., Nat. Phys. **18**, 316 (2022) / Art by Phil Saunders