# Laser-induced nuclear physics and applications

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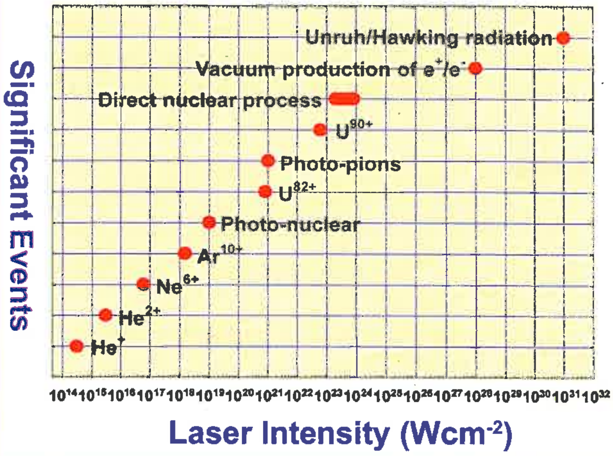
This story started nearly fourteen years ago when two of us KWDL and RPS were discussing with Joe Magill (Karlsruhe) the seminal theoretical paper by Boyer, Luc and Rhodes (1988) on the possibility of using a high intensity focused laser beam ($10^{21}$ $Wcm^{-2}$ and 248 nm) to induce fission in $^{238}U$.

Many probes had been used to induce fission, particularly neutrons both fast and slow. Other nuclear probes had also been used e.g. protons, deuterons, $\alpha$ particles and heavy ions as well as non nuclear beams e.g. $\gamma$-rays, electrons and muons. It is perhaps not surprising for a sufficiently intense light source to induce fission especially since a number of lasers had pulse powers of a terawatt ($10^{12}$ W) or even a petawatt ($10^{15}$W). A terawatt is the total electrical power generated in the USA.

This initiated, for the research team at Glasgow working in collaboration with Imperial College and the plasma physics group at the Rutherford Appleton Laboratory and now many other groups around the world, an exciting new area of physics that we have named "laser-induced nuclear physics".

## Historical Perspective

The mechanism of the interaction of charged particles with intense electromagnetic fields has been considered for more than fifty years. This was one of the first explanations put forward by the early workers to explain the origin and energies of cosmic rays, e.g. Fermi (1949). Simply the idea is as follows: a charged particle in an intense electromagnetic field is accelerated initially along the direction of the electric field. The v×B force causes the particle's path to bend into the direction of travel of the wave. In large fields the particle's velocity rapidly approaches the velocity of light and it tends to travel with the EM wave gaining energy from it. In astrophysical situations the solar corona was thought to be one of the sources of the electromagnetic waves. Such astrophysical phenomena are the counterparts of the machines built on the earth to accelerate particles to high energies.



▲ **Fig. 1:** Some significant atomic and nuclear events as a function of laser intensity. At present the highest laser intensities reach $10^{21}$ $Wcm^{-2}$. Plans are already in place to build lasers 100 times more intense.

In the late seventies, Tajima and Dawson (1979) realised that by focusing laser light into a plasma medium, very high accelerated energies could be generated. They proposed the construction of a laser-electron accelerator which could be created when an intense laser pulse produced a wake of plasma oscillations (volumes of low and high densities of electrons). Similar to a boat creating a bow wave or wake as it moves through water, a bunch of high velocity electrons creates a wake of plasma waves as it passes through a plasma. They demonstrated with computer simulations that existing glass lasers of $10^{18}$ $Wcm^{-2}$ could yield electron acceleration gradients of 100 GeV/m. It is known that conventional accelerators are limited by electrical breakdown at fields of about 20 MV/m; at these fields the electrons are torn from the atoms in the accelerator's support structure. Thus these plasma particle accelerators promise fields more than 1000 times stronger that those of the most powerful conventional accelerators.

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It is instructive to show what experiments can be carried out with very intense laser sources. Figure 1 presents threshold intensities of some of the significant events that can occur. There is no significance to the y co-ordinate apart from spatially separating the events to ease viewing. With a 1 ps pulse laser at 1 µm wavelength, He gas is ionised at about $3\times10^{14}$ $Wcm^{-2}$. As the intensity increases, the inert gases become multiply ionised and between $10^{18-19}$ $Wcm^{-2}$ photon induced nuclear reactions are energetically possibly. Close to $10^{21}$ $Wcm^{-2}$, pion production can take place- the first of the elementary particles. At the very high intensities of $10^{28}$ $Wcm^{-2}$, it can be shown that electron-positron pairs can be created from the vacuum.

## Using lasers to accelerate particles

Since the beginning of laser science in the early 1960s there have been continuous efforts made to increase the power of lasers. Today laser systems are readily available with several Terawatts (1 TW=$10^{12}$ Watts) of power and some of the largest laser systems such as the VULCAN laser (Figure 2), situated at the Rutherford Appleton Laboratory, near Oxford in the UK, will shortly be able to reach Petawatts ($10^{15}$ Watts of power). This laser is currently able to deliver over 100 Joules of energy in a picosecond ($10^{-12}$ s) pulse.

The VULCAN laser uses Nd:glass (optical glass doped with Neodymium) as its amplifying medium. This is an excellent

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◀ **Fig. 2:** The VULCAN laser facility at the RAL near Oxford, UK.
a) Part of the VULCAN laser Nd:glass amplifier chain.
b) The interaction chamber used for nuclear experiments.
c) Installation of the optics for the new Petawatt upgrade.

medium for producing pulses of high energy and short duration, although at these enormous power densities, damage to the amplifying medium can occur. This problem is overcome by the use of an ingenious technique called Chirped Pulse Amplification (CPA) (Perry & Mourou 1994). In CPA, a short, low power laser pulse is first stretched temporally, then amplified at a safe level to reduce the power density in the amplifying medium, before it is finally re-compressed to its original duration. CPA has brought about a revolution in peak laser powers, and all ultra-high power laser systems today employ this technique.

After being stretched, amplified and recompressed, the VULCAN pulses are transported under vacuum to a large interaction chamber, where the experiments take place. Typically one pulse is delivered every 20 minutes. The pulse is focused to an area of a few $\mu m^2$ using a parabolic mirror. In this small area an intensity of $10^{20}$ Watts per square centimetre is achieved. Unique and extreme states of matter are produced in the resulting interaction. Electric fields of the order of $10^{11}$ $Vcm^{-1}$ are generated along with huge alternating magnetic fields close to $10^9$ Gauss, only a factor of 1000 smaller than the magnetic field of a typical black hole. Under these conditions a target is completely ionised creating a plasma of positively and negatively charged particles.

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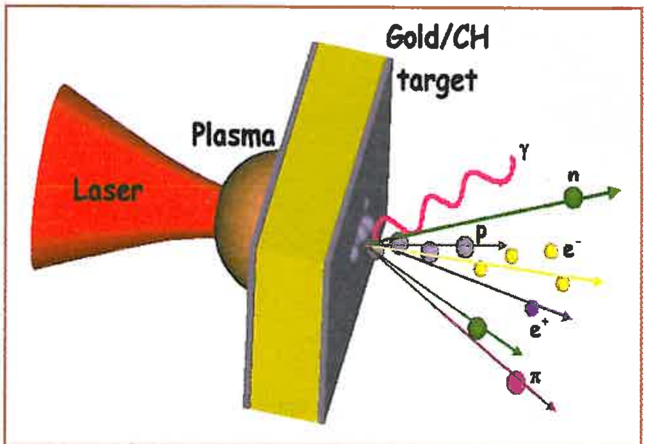

▲ **Fig. 3:** The interaction of a high intensity, short laser pulse with a solid target leads to the production of high energy particles and radiation.

The short powerful laser pulse sets up electrostatic waves within the plasma by displacing the negatively charged electrons with respect to the heavier positively charged ions. This displacement of the charges creates electrostatic acceleration fields. Within the strong laser electric fields the electrons oscillate at close to the speed of light introducing relativistic effects. They can be accelerated over large to very high energies by the induced fields. Electron energies of over 200 MeV have been created in this way.

In a target of sufficiently high atomic number Z (number of protons in the nucleus), the accelerated electrons are slowed down in the target material emitting high energy photons ($\gamma$-radiation) via 'bremsstrahlung' or 'braking radiation'. The energy of these gamma-rays can reach up to the maximum energy of the accelerated electrons. It is these high energy photons which can be used to induce nuclear reactions in materials.

Another effect produced in the interaction of the high intensity, short laser pulse with a target is the production and acceleration of ions. This occurs when the high energy electrons exit the target setting up strong electrostatic fields. The ions from the plasma are dragged by the energetic electrons as a result of charge separation and are accelerated to energies of tens of MeV. In particular protons are accelerated with great efficiency. These high energy protons and heavier ions are also capable of inducing nuclear reactions.

In its simplest form the interaction of an intense short pulse of laser radiation with a target can be viewed (Figure 3) as an exchange of energy from the laser pulse through a number of successive energy transfers leading to the production of high energy particles and radiation which have applications to nuclear physics.

### Photo-Nuclear Physics With a Light Source

Nuclear fission: Laser-induced fission of $^{238}$U was observed at the VULCAN laser facility at RAL in 1999. Uranium nucleus has a rugby ball shape—the attractive short-range nuclear force balances the repulsive coulomb force due to the 92 protons to give the nucleus its prolate deformation. Because uranium is such a large nucleus, it behaves like a drop of liquid. Supply of energy from the outside (from, e.g., an incident neutron or $\gamma$-ray) causes the nucleus to vibrate and rotate. The vibrations produce increased average distance between the nucleons resulting in a reduction of the binding effects of the short-range nuclear force, while the infinite ranged coulomb force is little affected. At some stage in the vibrations, the attractive forces are no longer able to hold the nucleus together and it flies apart with two main fragments, a few evaporated neutrons and gamma rays. The fragments are more tightly bound than the original uranium nucleus and the excess energy is released as kinetic energy of motion. Fission of uranium produces a double-headed asymmetric yield distribution of fragments with maximum yields at mass numbers about 95 and 140 corresponding to the neutron magic numbers of 50 and 82 (Figure 4).

Evidence for fission events is normally carried out by detecting the characteristic gamma rays from the principal fission fragments.

Three 80 J pulses from the VULCAN laser irradiated a 1.75 mm Ta target backed with a 2 mm thick $^{238}$U sample. The $^{238}$U was shrink wrapped in plastic to contain any gaseous activity and enclosed in an aluminium container. The laser pulses produced a flux of high energy gamma rays which induced fission in uranium nuclei as described above. Unambiguous characteristic gamma rays from the fission fragments $^{134}$I, $^{138}$Cs and $^{92}$Sr were observed. From the measured intensities, it is concluded that about a million fission events are generated by a $10^{19}$ Wcm$^{-2}$ laser shot in a 2 mm thick $^{238}$U target. The predictions of Boyer, Luk and Rhodes (1988) were confirmed and the experimental field of laser-induced nuclear physics was born.

(γ,n) reactions: The relativistic electrons produced by the laser-matter interaction have an exponential energy distribution characterised by the parameter kT, called the electron or plasma temperature. kT is an important parameter in plasma physics but is difficult to measure accurately by current technology. Laser-induced (γ,n) reactions provide a reliable method of measuring kT.

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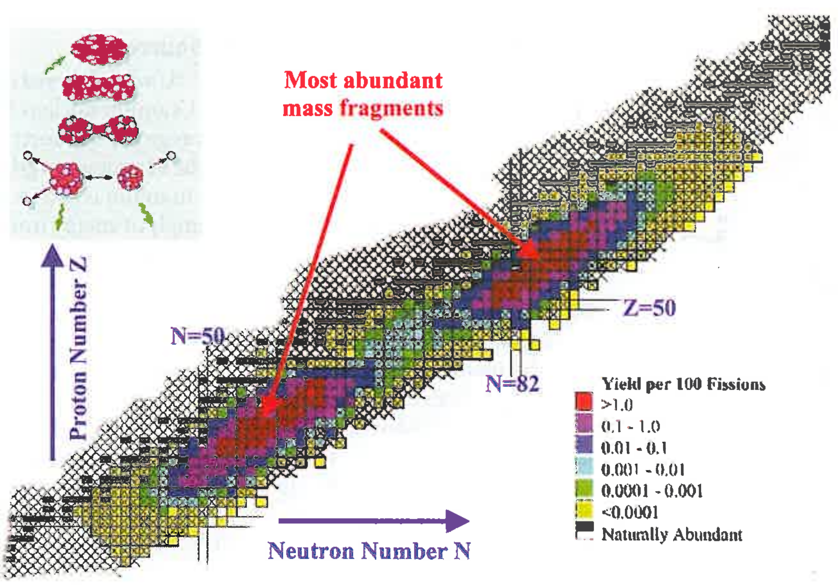
While fission addresses overwhelmingly the collective aspects of nuclear response to excitation, (γ,n) reactions deal with the way individual nuclei decay by the emission of neutrons when excited by gamma rays of energy greater than a threshold value—the Q-value. For most nuclei the Q-value is 8 MeV or larger. Below the Q-value, nuclei remove the excess excitation energy by emitting one or more photons.

In the excitation process, a high energy photon is absorbed by a nucleus. The excited nucleus may be visualised as one in which the protons are oscillating against the neutrons—the nuclear giant dipole resonance (GDR). The probability of absorbing a photon of energy near the peak of this broad resonance is very high. When excited, GDRs mostly decay by emitting a proton or a neutron—neutron emission being the more probable. After the emission of a neutron, the resulting nucleus has an excess of protons and exhibits positron-decay activity—it is a $\beta^+$ emitter. The positron annihilates with an electron in the material to produce two γ rays travelling in opposite directions. Positron activities may be measured accurately by counting the two 511 keV annihilation γ rays in a coincidence arrangement. A measurement of the activity as a function of time provides the decay curve that may be used to characterise and identify the half life of the daughter nucleus.

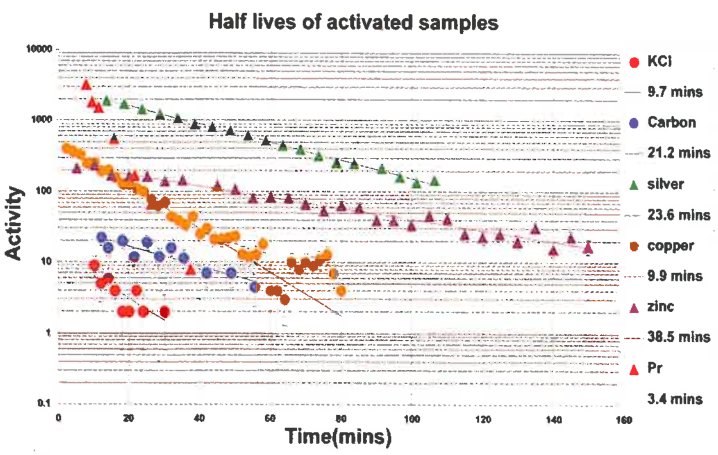
(γ,n) reactions were studied for a range of nuclei by irradiating a 1.8 mm thick Ta target with an 80J VULCAN laser pulse. In Ta, the high energy electrons produced bremsstrahlung γ rays whose energy spectrum is completely determined by that of the electrons. The γ rays induced positron activity in a range of targets (Figure 5). The half-lives determined are in excellent agreement with the accepted values. The absolute value of the activity for a target nucleus is primarily determined by the γ ray energy distribution and the known cross sections for the excitation of the GDR. A comparison of induced activities in nuclei with different Q-values provides a measurement of the γ ray energy spectrum and hence that of the electrons in the plasma. A plasma temperature kT = 1.6 MeV was determined by comparing the (γ,n) data for $^{12}$C (Q = 18.7 MeV) and $^{63}$Cu (Q = 10.9 MeV). This unique plasma diagnostic method has been further developed by using (γ,n) and (γ,3n) data from a $^{181}$Ta target, obviating the need to measure the relative target thicknesses etc and measurements can be made from just one sample.

## Laser Production of Protons and Applications

When an ultra-intense laser is focused on to a solid target, beams of protons are produced both in front of and behind the target. The protons originate from hydrocarbon and water impurity layers on the target surfaces. For laser intensities $>10^{19}$ Wcm$^{-2}$, these protons have energies in the MeV regime. Hence, ultra-intense lasers can generate protons of energy similar to that of a



◀ Fig. 4: Uranium fission mass yields according to proton and neutron number. The most abundant fragments correspond to the neutron "magic numbers" of 50 and 82.



◄ **Fig. 5:** Decay plots of the products of (γ,n) reactions. The half-lives measured agree well with the accepted values.

cyclotron or van de Graaf, although the equipment used and acceleration physics are vastly different.

Conventional accelerators are used in nuclear medicine to generate beams of MeV protons to induce nuclear reactions in materials, e.g. the reaction $^{18}$O(p,n)$^{18}$F. The product isotope is a short-lived positron emitter. These sources are used in the medical imaging technique Positron Emission Tomography (PET). The patient receives by injection a pharmaceutical labelled with a short-lived positron emitting isotope. The radio-pharmaceutical is metabolised at specific sites in the body. Positrons annihilate with background electrons to produce two back-to-back gamma rays. By detecting these gamma rays using a ring of gamma cameras, specific sites of high pharmaceutical uptake in the body can be imaged. PET has proven to be extremely useful in imaging e.g. blood flow, amino acid transport and brain tumours. Figure 6 shows the equipment involved in PET.

The main positron emitting nuclei used in PET are $^{11}$C, $^{13}$N, $^{15}$O and $^{18}$F. The proton-induced nuclear reactions commonly employed to produce these isotopes are shown in Figure 6. The reason that protons are the preferred projectile rather than e.g. gamma rays is that the radio-isotope produced has a different atomic number from the original isotope, and the positron emitter can be separated from the carrier using fast chemistry.

Ultra-intense lasers offer an alternative source of MeV protons and hence PET sources. While the large-scale VULCAN laser was used in the proof-of-principle experimentation described below, it is envisaged that practical applications of laser-produced protons will be found through the use of "table-top", high-repetition rate lasers operating at similar intensities. A laser proton source will be more compact, less expensive and require less shielding and maintenance than conventional accelerator technology.

Proton and PET isotope production was studied using the VULCAN laser operating at $10^{20}$ Wcm$^{-2}$ and incident on a thin aluminium target. Protons originate from hydrogen impurities on the target surfaces, since a proton is an ionised hydrogen atom.

The numbers and energies of protons produced both in the direction of the incoming laser (in front of the target) and behind the target were measured (Figure 7). Behind the target, protons of energies up to 37 MeV were produced whereas in front of the target, the maximum energy was 25 MeV. Both proton beams obtained may be used to produce PET isotopes.

To demonstrate laser PET isotope production, a boron sample was placed in front of the Al target and the laser was focused onto target. The boron sample was then removed from the target chamber and placed in a coincidence system which counts positron annihilation events. The activity of the sample was measured as a function of time as shown in Figure 7. A half-life of 20.3±0.4 minutes was measured. This showed that the PET isotope $^{11}$C was produced (accepted half-life 20.34 min), via the reaction $^{11}$B(p,n)$^{11}$C. At the time of laser irradiation, around 200 kBq of $^{11}$C was produced.

Although $^{11}$C is a useful isotope for PET, the favoured isotope at the moment is $^{18}$F. The reaction usually employed to produce $^{18}$F is $^{18}$O(p,n)$^{18}$F. The integrated cross section for this reaction is about half that of the reaction $^{11}$B(p,n)$^{11}$C, hence it is feasible that a laser pulse of $10^{20}$ Wcm$^{-2}$ could produce $10^5$ Bq of $^{18}$F.

A typical patient dose for PET is $2\times10^8$ Bq although $8\times10^8$ Bq sources are necessary to allow time for fast chemistry to be performed for isotope separation. Assuming that a VULCAN type laser could deliver 10 Hz, then the integrated activity after 500 s is about $10^9$ Bq. At the time of writing, an immense amount of work is being conducted on high repetition rate table-top lasers worldwide, to test the feasibility of proton production on such systems.

## Amazing Physics at Laser Intensities > $10^{22}$Wcm$^{-2}$

Exciting new phenomena are expected at these intensities. We shall mention a few dealing specifically with nuclear and particle physics.

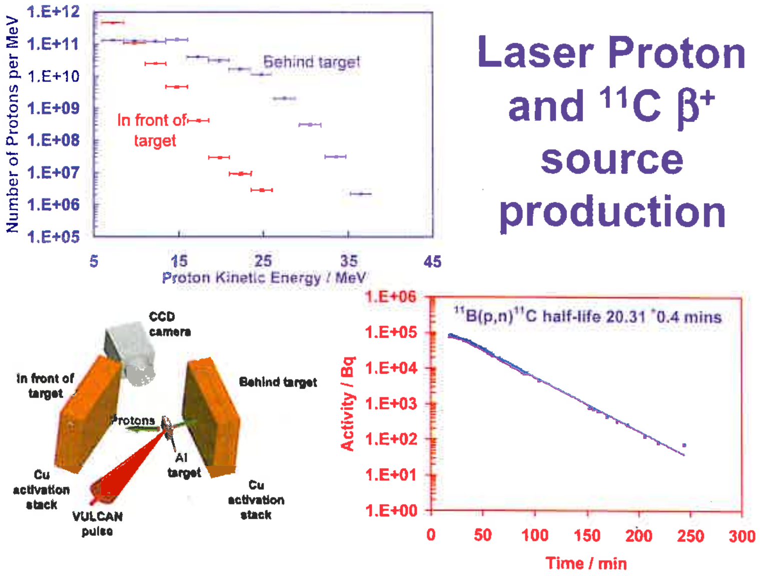
### Direct interaction with the nucleus

As the laser intensity is increased above $10^{22}$ Wcm$^{-2}$, the oscillating electric field can affect the protons in the nucleus in exactly the same way as the electrons in the plasma. At $10^{24}$ Wcm$^{-2}$ this energy

## Positron Emission Tomography

| | | |
|---|---|---|
| $^{14}$N + p ⇒ $^{11}$C + $^{4}$He | $^{11}$C | 20 min |
| $^{13}$C + p ⇒ $^{13}$N + n | $^{13}$N | 10 min |
| $^{15}$N + p ⇒ $^{15}$O + n | $^{15}$O | 2 min |
| $^{18}$O + p ⇒ $^{18}$F + n | $^{18}$F | 110 min |

▲ **Fig. 6:** A PET medical imaging scanner and the nuclear reactions commonly employed to produce PET isotopes.



◀ **Fig. 7:** (Bottom left) experimental set-up defining "in front of" and "behind" target directions, (top left) proton energy spectra measured in front of and behind target, (bottom right) decay plot of the PET isotope $^{11}$C produced via laser generated proton beams.

is 2.5 keV and at $10^{28}$ Wcm$^{-2}$ shifts of the order of 250 keV occur. Thus lasers could radically alter nuclear energy levels and decay half-lives making it possible to shorten the lifetimes of nuclear waste.

### Fusion by direct laser acceleration of ions

Ions oscillating in the field of a laser beam can gain sufficient energy from the field to cause fusion to take place in a D, T target. At $10^{21}$ Wcm$^{-2}$ the collision energy is on average about 8 keV with a corresponding fusion cross section of ~ $10^{-4}$ barn. At $10^{22}$ Wcm$^{-2}$ the collision energy is about 80 keV. The peak of the DT fusion cross section (5 barns) occurs at about 100 keV. Most fusion reactions take place in very large scale facilities but now it will be possible to study fusion reactions in this novel way for the first time for a range of low Z nuclei with small laser systems.

### Particle Physics

At $10^{22}$ Wcm$^{-2}$ the radiation pressure on electrons in a thin target can reach values greater than $10^{12}$ bar and for very thin targets, resulting in low plasma densities, electron energies in excess of 100 GeV are possible. Electron energies as high as $10^{14}$ eV may be generated at laser intensities of $10^{26}$ Wcm$^{-2}$ and $10^{16}$ eV at $10^{28}$ Wcm$^{-2}$.

The production of azimuthal magnetic fields in excess of $10^9$ G close to the fields which exist at the surfaces of black holes is another exciting possibility. At $10^{28}$ Wcm$^{-2}$ electron positron pairs can be produced from the vacuum and at $10^{30}$Wcm$^{-2}$ Hawking/Unruh radiation using counter propogating laser beams can be generated. A γ-γ collider using counter propogation laser-induced photon beams has also been the subject of recent study.

## Epilogue

Since we embarked on this exciting journey of laser-induced nuclear physics and its applications some four years ago, we have never ceased to be amazed at the world-wide interest it has generated. However as with many scientific endeavours, the most important results that come from the study of a new technology may be totally unexpected...

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