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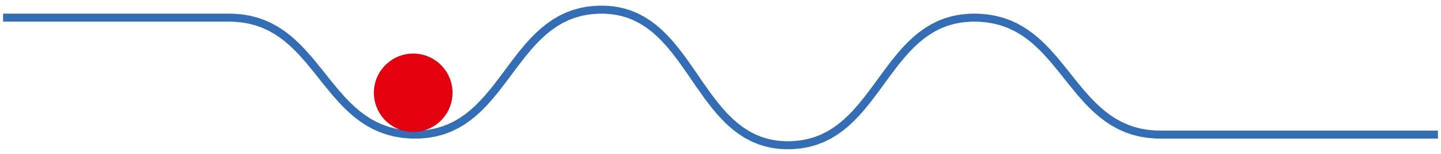


Surfatron: catch the wave of accelerators

Ricardo Torres

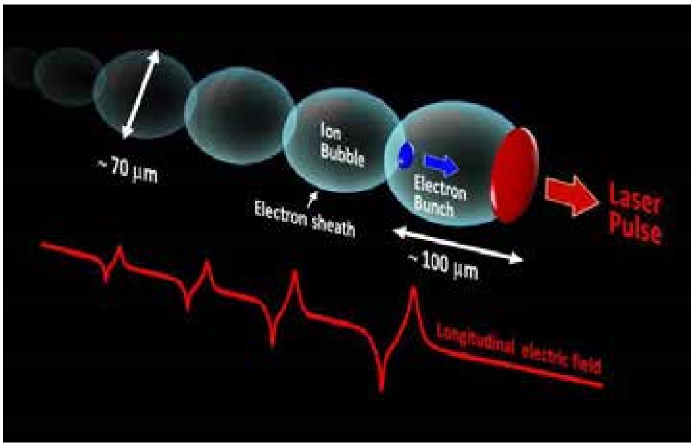
Try your hand at Surfatron, a game that lets students experience the challenges faced by particle accelerator scientists while learning the physics of waves.

Introduction

Accelerator science is a constantly evolving field. New technological advances allow large colliders – like the Large Hadron Collider (LHC) – to reach higher energies and discover new particles. At the same time, particle accelerators that are used in hospitals for cancer treatment may offer a safer, more effective, and more affordable service.

New technology, which could revolutionize the field of accelerators, relies on the ability of scientists to inject a beam of particles with a well-defined energy into a suitable plasma wave to gain energy, much in the same way as a surfer catches a wave at sea to be pushed forward.

Surfatron illustrates the same process, by simulating the motion of a ball on an undulating track. The purpose of the game is to get the ball – the surfer – to gain as much speed as possible by finding the optimum parameters of the wave (amplitude, wavelength, and frequency) and launching the ball at the right time with the appropriate initial speed.



A laser pulse travelling through a gas of ionized atoms creates a wake of plasma waves that can be used to accelerate electrons to a very high energy.

Image courtesy of Ricardo Torres

To play the game, students have to manipulate the amplitude, wavelength, and frequency of a wave, helping them to understand intuitively the properties of waves and the basic working principles of linear particle accelerators, while learning to interpret velocity plots.

Using Surfatron

Surfatron can be found here, and it can be played online without the need to download or install any software. On the same website, there is a downsized version of Surfatron that is better suited to being played on a mobile phone, and a link to a video with a description of the game.

The main screen of Surfatron consists of a control panel with slide controls, buttons, switches, and displays (figure 1). The graph on the left shows a sinusoidal wave, which represents a track, and a red circle, which represents the ball. A switch on the right allows the player to choose between standing and travelling waves for the track, and the slides at the bottom adjust the amplitude, wavelength, and frequency of the wave. Other slides adjust the initial velocity of the ball and the friction of the track.

By clicking on the red square labelled as 'Release', the ball is launched into the track at the speed set by the 'Injection Velocity' slide. Clicking again on the now green 'Reset' button restarts the game.

The graph on the right represents either the speed of the ball over time or its trajectory in phase space. Both modes can be selected by flicking the switch to the bottom left of the graph. In 'V Plot' mode, the graphs shows two curves: the red one is the horizontal speed of the ball, and the blue one is the vertical speed. In 'Phase Space' mode, the graph on the right represents the horizontal speed of the ball as a function of its position of the track.

The 'Velocity Gain' (the difference between final and initial horizontal speeds) is recorded as the player's score.
By clicking on the tabs on the top-left corner of the front panel, the user can find instructions on how to play the game, as well as information about the AWAKE project.

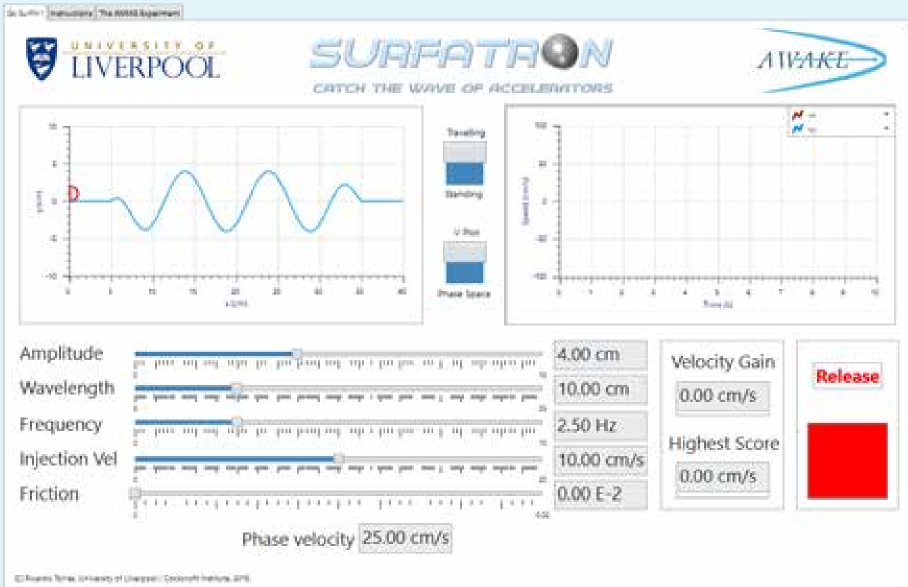


Figure 1: Screenshot of the control panel of Surfatron

Activity 1: Introducing Surfatron science

In this activity, teachers review how particle accelerators work and their limitations, and then introduce the basic principle of wakefield acceleration, which underlies the function of Surfatron. This is an interesting piece of cutting-edge science that can be used as a stand-alone lesson, but it also provides important context for the rest of the activities. It should take about 30 min.

Materials

- Science of Surfatron infosheet
- Any other teaching resources available on particle accelerators to recap and compare techniques

Procedure

1. Review particle accelerators, how they work, and what they are used for. This is probably already on the curriculum, but, otherwise, you can use this page on particle accelerators from CERN.

2. Discuss radiofrequency (RF) cavities, as the working principle of conventional accelerators.
3. Hand out the Science of Surfatron infosheet and go through it with the class. Discuss the differences and potential advantages compared with conventional accelerators.

Discussion

Particle accelerators work by exposing bunches of charged particles to high-intensity electric fields. The amount of energy that the particles gain over a given distance is called the accelerating gradient, which is proportional to the intensity of the electric field.

Conventional accelerators employ oscillating electric fields contained in an evacuated metallic cavity called the RF cavity, which is usually meters long. The accelerating gradient of RF cavities is limited by electrical breakdown, that is, arcing inside the cavity when the field is too intense. Therefore, longer accelerating distances are required to achieve higher energies, leading to the big and expensive machines that are in use today.

On the other hand, plasma accelerators use a cavity filled with plasma. The plasma can sustain much stronger electric fields, providing accelerating gradients that are two-to-three orders of magnitude higher than those of conventional accelerators. Thus, the required acceleration length may be reduced by 100–1000 times, also decreasing the cost of the machine. Moreover, plasma accelerators provide shorter particle bunches than conventional accelerators, opening up exciting new opportunities for research, namely, the observation of ultrafast processes in biomolecules.

Activity 2: Teaching with Surfatron

In this activity, students use Surfatron to learn the properties of waves in an intuitive manner. They are required to interpret simple kinematic graphs, and they have the chance to explore the mechanics of surfing as an analogy to particle acceleration. Teachers may guide students through the following lessons, each one requiring about 30 min. Lessons 1 and 2 are accessible to 14–16 year olds, whereas Lesson 3 is more suitable for students aged 16–19.

Materials

- Computer with internet connection.
- The Surfatron simulator: http://www.awake-uk.org/surfatron

Lesson 1: Properties of waves

Learning outcomes

- Understand the notions of wave amplitude, frequency, wavelength, time period, and wave speed (phase velocity).
- Understand the difference between travelling and standing waves.

Procedure

1. Have students open the Surfatron simulator and introduce the display and controls.
2. Use the slide controls to change the amplitude, wavelength, and frequency of the wave and observe their effects on the wave graph.
3. Switch between standing and travelling waves and observe the differences.
4. Measure the speed at which the peaks move in a travelling wave and demonstrate it is equal to the wavelength times the frequency.

Discussion

The waveform (travelling wave) represented in Surfatron is expressed mathematically as a sine function – whose rgument depends on time and position – multiplied by an envelope function $g(x)$, which vanishes at the extremes to make both ends of the track flat:

$$f(x,t) = A\,g(x)\sin(2\pi\nu t - \frac{2\pi}{\lambda}x) \qquad (1)$$

A is the wave amplitude, ν is the frequency, and λ is the wavelength. The minus sign in the argument of the sine function in equation (1) ensures that the wave travels towards the right with velocity phase $c = \lambda\,\nu$.

The standing wave is obtained by adding two waves like equation (1) with the same amplitude, frequency, and wavelength, but opposite signs in the argument of the sine function, that is, travelling in opposite directions.

Lesson 2: Kinematics and interpreting graphs

Learning outcomes

- Interpret graphs and obtain data from them.
- Understand the differences between instantaneous and average speed, and instantaneous and average acceleration.
- Understand the concept of phase space. Interpret the shape of the trajectory of a particle in phase space and relate it to the motion of the particle.

Procedure

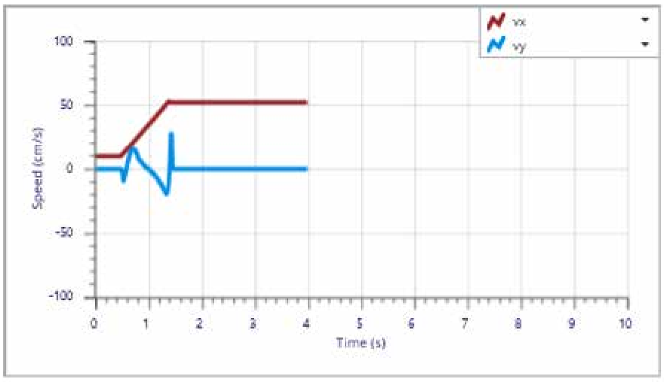
1. Launch the ball into the wave and observe the velocity plot.
2. From a given plot, obtain the initial and final speeds, as well as the instantaneous and average accelerations.
3. Introduce some friction in the track with the corresponding slide, observe and interpret its effect on the velocity plot.
4. Switch the graph to phase-space mode (click on the 'Clear' button to clear the graph). Observe and interpret the trajectories of the ball in phase space.

Discussion

The maximum velocity gain will be obtained when the ball is constantly accelerated from the beginning to the end of the track. In this scenario, the horizontal velocity plot will appear as a straight line (figure 2a).

With a stationary wave, it is not possible to exert a constant acceleration on the ball; therefore, the maximum velocity gain achievable will be lower than that possible with travelling waves (figure 2b).

(a)



(b)

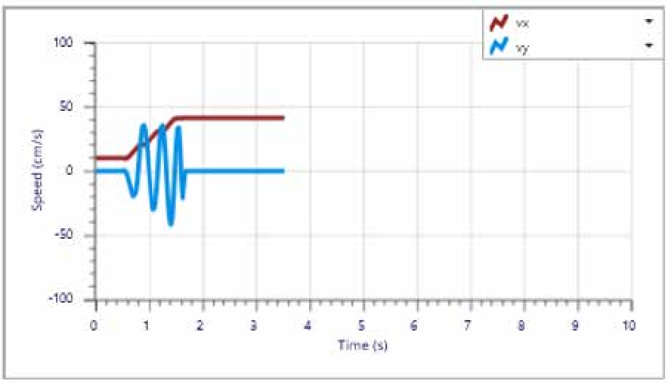


Figure 2: Velocity plots for optimum acceleration conditions in Surfatron with a travelling wave (a) and a stationary wave (b)

Lesson 3: Surfing the waves

Learning outcomes

- Understand the mechanics of surfing and its analogy to linear accelerators.
- Understand the importance of synchronisation and matching speeds, as well as the detrimental effect of dephasing.

Procedure

1. Select a standing wave and a random set of wave parameters and injection velocity; keep friction at zero.
2. Press the release button. The ball will either get caught in the wave or bounce back, depending on the injection velocity, wave parameters, and the time the 'Release' button is pressed. A higher injection velocity will make it easier for the ball to get caught.
3. Try to maximise the score by playing with the wave parameters, injection velocity, and release time, firstly, for a standing wave and then for a travelling wave.

Discussion

The initial speed of the ball must approach that of the wave to get caught in its downward slope, just as surfers do by paddling in the direction of the wave before standing up on the board. Synchronisation is also essential.

Once the ball is caught in the wave, it will accelerate for as long as it stays on a downward portion of the wave, whereas it will slow down if it slips into the upward side. Therefore, to achieve maximum acceleration, one has to aim to get the ball on a downward slope for the whole duration of the trip. In a travelling wave, there are two limiting scenarios. In one, the ball becomes faster than the wave; in the other, the wave overtakes the ball. In both cases, the ball is slowed down as it slips into the upward slope; this phenomenon is called dephasing. The key parameter is then the phase velocity of the wave, which must match the average speed of the ball.

In the stationary wave, the phase velocity is not defined; however, the maximum score is obtained again by adjusting the frequency and wavelength so that their product matches the average speed of the ball.

Optional extension activity

It is also possible to build a mechanical model of Surfatron. The virtual Surfatron can be used alongside its mechanical counterpart to gain insights into the motion of the ball inside the pipe (with the caveat that the virtual Surfatron treats the ball as a point-like particle, ignoring its moment of inertia.) Similarly, scientists use computer simulations to better understand the outcome of their experiments and even anticipate new results by varying parameters that may be difficult to manipulate in practice, like the wave amplitude in the mechanical Surfatron.

Summary

Linear particle accelerators work in much the same way as Surfatron, using standing or travelling electromagnetic waves to accelerate charged particles (see the supporting material). Surfatron lets students experience some of the challenges faced by scientists developing and operating particle accelerators, that is, controlling the electromagnetic field structure, synchronising the particle beam with the field oscillations, and avoiding dephasing to extract the maximum energy from the apparatus. «

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Resources

- Play the Surfatron game.
- Watch a demonstration video on how to use Surfatron.
- Learn more about conventional accelerators and how they work on the CERN website.
- Read an introduction to accelerator science: Welsch CP (2021) The physics of Star Wars: introducing accelerator science. *Science in School* **54**.
- Explore accelerator science with a virtual accelerator: Welsch CP (2021) Build your own virtual accelerator. *Science in School* **54**.
- Create a particle accelerator in your salad bowl: Torres R (2017) A particle accelerator in your salad bowl. *Science in School* **41**: 49–55.
- Build a particle accelerator in your classroom: Brown A, Merkert J, Wilson R (2014) Build your own particle accelerator. *Science in School* **30**: 21–26.
- Learn about antimatter: Kwon D (2017) Ten things you might not know about antimatter. *Science in School* **42**: 14–17.
- Read about the use of proton beams for radiation therapy: Welsch CP (2021) Death Star or cancer tumour: proton torpedoes reach the target. *Science in School* **55**.
- Find out more about the Higgs boson: Chatzidaki et al. (2022) Ten things we've learned about the Higgs boson in the past ten years. *Science in School* **59**.

AUTHOR BIOGRAPHY

Ricardo Torres is a project manager at the Department of Physics of the University of Liverpool, based at the Cockcroft Institute. He has worked for more than 15 years as a researcher in the field of laser science, using short-pulse lasers to take snapshots of the electronic structure of molecules and ultrahigh-intensity lasers to accelerate ions in plasmas. He is currently in charge of communication for several large European accelerator projects and regularly organises science outreach activities for schools.