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Let there be lightning

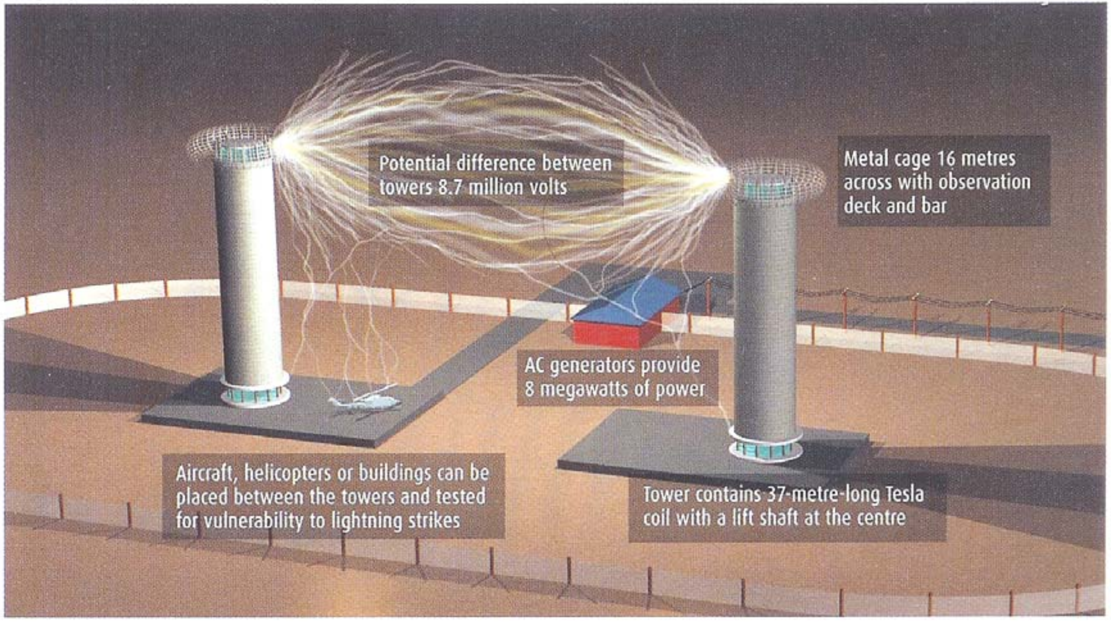
21 June 2006 NewScientist.com news service Hazel Muir

GREG LEYH spends his daylight hours at one of the world's top particle smashers, helping to coax matter and antimatter particles to fly in orderly lines at just a whisker off the speed of light. By night, he likes to generate lightning bolts, the bigger the better. With giant coils charged up to millions of volts, he rips the night air apart with dazzling forks of light - for no other reason, really, than the pure drama of it all.

Watching lightning crackle out from the coils is "a very spinal experience", Leyh says. "Many people describe it as primal," he says. "When it first starts, it's more visually alluring than anything else, then the arcs grow bigger and bigger, reaching out and striking like a snake. And then, somehow, it turns from allure to fear."

Now Leyh is planning the biggest, most dramatic lightning project ever. Using two metal coils 37 metres high, he hopes to launch mammoth lightning bolts across a space the size of a football stadium in the Nevada desert. Assuming a wealthy financier steps up to foot the bill, prepare for the most awesome light show on Earth as Leyh unleashes a staggering 8 million volts - and maybe solves one of lightning's biggest mysteries at the same time.

Greg Leyh's proposed Nevada lightning lab facility



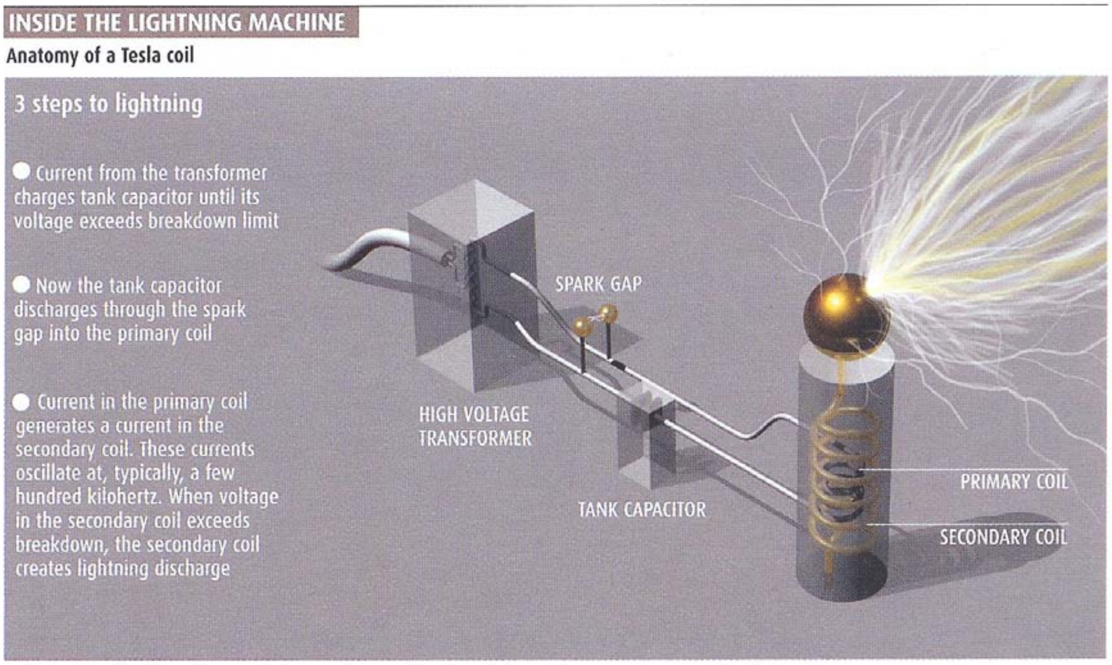
Leyh works as an electrical engineer at the Stanford Linear Accelerator Center (SLAC) in California, where he converts AC power from the national grid into all the flavours of current that the 3-kilometre particle accelerator needs to steer, focus and collide beams of electrons and positrons. By squeezing amazing amounts of energy into a small spot, particle collisions at SLAC recreate the energetic conditions in the universe just moments after the big bang.

His day job is not entirely unrelated to Leyh's passion for generating lightning. "I'm fascinated with systems and devices that concentrate energy as highly and as tightly as possible," he says. He's also captivated by the technologies that were being developed at the beginning of the 20th century, the era of Nikola Tesla, a Serbian visionary who emigrated to the US where, along with countless other inventions, he pioneered the use of AC electricity.

Tesla was mesmerised by resonance, the notion that small forces, if carefully timed, can add up to create huge energies, just as a child on a playground swing goes higher and higher when given a small push at the right time. While testing a vibration machine in his lab one day, he hit the natural frequency of vibration of the four-storey building and convinced the terrified inhabitants they were about to die in a devastating earthquake.

Another of Tesla's achievements was to realise the possibilities of electrical resonance within conducting coils and invent the Tesla coil, in 1891. A Tesla coil is really two coils, one nested inside the other. When an alternating current builds in the primary coil, it generates a magnetic field that induces current in the secondary coil (see Diagram). Tesla found that for this induction to occur efficiently, the current flowing through the primary and secondary coils must oscillate at the same high frequency. By designing both coils to have the same resonant frequency, Tesla discovered he could hike up the voltage on the secondary coil higher and higher.

In effect, the coil pair acts like a transformer, converting the high current and low voltage in the primary into a low current and high voltage in the secondary coil. "The trick is to energise the first coil at a relatively low voltage, say 20,000 volts," says Leyh. "The secondary coil has many more turns, so when the energy is all transferred over, it can build up millions of volts." The larger the secondary coil, the larger the voltage, which can eventually soar so high that it breaks down the air around it into charged ions that allow current to flow, so discharging the pent-up energy in a sizzling arc.



INSIDE THE LIGHTNING MACHINE

Anatomy of a Tesla coil

3 steps to lightning

- Current from the transformer charges tank capacitor until its voltage exceeds breakdown limit
- Now the tank capacitor discharges through the spark gap into the primary coil
- Current in the primary coil generates a current in the secondary coil. These currents oscillate at, typically, a few hundred kilohertz. When voltage in the secondary coil exceeds breakdown, the secondary coil creates lightning discharge

In 1901, Tesla began constructing Wardenclyffe Tower, a giant Tesla coil 57 metres high on the coast of Long Island. He had described the project to financiers as a high-power radio transmitter for communications, but secretly, Tesla had other plans. He hoped to use the tower to distribute power to anywhere around the globe, using the Earth's ionosphere as an electrical circuit. When the chief investor realised this he pulled the plug on the project and the tower was eventually destroyed during the first world war in case German submarines found it useful as a landmark.

Since then, no one has attempted to build such an enormous Tesla coil. However, inspired by Tesla's ideas, a band of enthusiasts across the world continue to construct small coils, sharing designs - and tales of triumph and disaster - via the internet (see "The cult of the coil").

Leyh began building large Tesla coils in the 1980s while working with Survival Research Laboratories, a team of robot enthusiasts who get together occasionally to stage a public display of barely scripted technological mayhem (*New Scientist*, 28 July 2001, p 50). "The robots first start off smashing helpless props, then when they run out of props they go after each other," says Leyh.

The first opportunity to build a large coil came when Leyh saw a research laboratory throwing out almost enough material for a 5-metre Tesla coil. He salvaged the cast-offs and built one. The 5-metre coil can shoot out impressive 8-metre arcs, although that pales by comparison with his largest Tesla coil to date, at 11.8 metres tall. With artist Eric Orr, Leyh built the record-breaking coil for an art collector in New Zealand who was after a lightning sculpture. The sculpture, called the Electrum Project, has a spherical cage at the top that can charge up to 3 million volts.

In public demonstrations with the Electrum coil, Leyh has sent 15-metre lightning bolts crackling into the night sky. He has also enjoyed shocking his audience by climbing inside the spherical cage so that lightning bolts launch just inches from his face. It's not as hairy as it sounds. Faraday's law dictates that the electric field inside the cage, or any closed conductor, is zero.

"Ironically, that's the safest place to be," Leyh says. "It's the only place within 500 feet of the coil where the electric field is zero." Leyh installed the Electrum coil on the art collector's farm near Auckland in 1998. Rumour has it that at least one Kiwi couple has since joined the "2 million volt club".

Later, Leyh started thinking about pushing the limits further. How big could a Tesla coil really be? "At that point, the common knowledge was that you could get lightning from a coil a mile high," he says. He discovered otherwise when he came across some clever new software that solves problems about electromagnetism in conductors. To test its wits, he asked it to figure out the behaviour of his 5-metre coil. "I was surprised at how accurate the results were - they were accurate to within a few per cent."

In Tesla's footsteps

So then he asked the trusty software to predict the powers of a giant Tesla coil as high as the Eiffel Tower. "I entered a 300-metre high coil, and the performance was dismal," he says. The problem, he realised, is that as the length of a Tesla coil increases, its resonant frequency drops, just as the frequency of sound from an organ pipe drops as the pipe gets larger.

This has serious consequences if you want to generate lightning bolts. To create a discharge in air, the coil must create an ionised, conducting channel through which a discharge can pass. This channel is short-lived; molecules in the air remain ionised for only a few milliseconds before recombining. It turns out that beyond 40 metres in length, a coil's resonant frequency drops to the point at which the ionised channel disappears before the coil has time to recharge itself, so it simply can't maintain the breakdown of air. By Leyh's calculations, that puts a limit of just under 40 metres on the largest practical coil.

So that's what he dreams of building. His plan is to build twin 37-metre towers, with opposite polarity, about 80 or 90 metres apart. This design allows him to effectively double the peak potential difference he can create. Four 2-megawatt AC generators will charge up a potential difference between the towers of about 8.7 megavolts. Then lightning bolts will arc between doughnut-shaped electrodes about 16 metres wide at the top of each tower. Adventurous visitors will be able to take a lift up inside one of the electrodes, which will be roomy enough for an observation deck with a bar.

Scared off California by bureaucratic regulations, Leyh hopes to build the lightning lab on an Indian reservation in Nevada where the dry climate will help keep the equipment in good condition. He reckons the construction will take about two and a half years, but first he has to raise the $8.9 million that the project will cost.

Meanwhile, he has nearly completed a twelfth-scale model of his towers, each just over 3 metres high, in his garage at his home near San Francisco. He is using the model to experiment with the design. Hopefully it will also impress some dot-com billionaire or wealthy art lover enough to make them commit to funding the project.

Any financier can rest assured that the Nevada lightning lab would create the most awesome made-to-order lightning shows on the planet. Leyh envisages a helicopter flying through the lightning bolts, the sparks dancing from its rotating blades. He'll assemble full-scale models of buildings between the towers and zap them with lightning to set them on fire. He might also set up a glove-box on one electrode's surface, so that premium ticket holders can put their arm inside the chain-mail glove to launch sizzling lightning bolts from their fingertips.

Extra income could be raised by leasing the lightning lab facilities to aircraft engineers to test how vulnerable their new designs are to lightning. Engineers could sit their planes between the towers and see what happens when Leyh zaps them with a 20,000-amp discharge. "The arcs will seek out the sweet spots, the sharp parts of the tail," he says.

Leyh also wants to do some serious research into the nature of lightning, which remains surprisingly mysterious. Traditional theories suggest lightning is simply the sudden release of charge from thunderclouds, which get charged up as a result of collisions between ice particles. The bulk of the charge is negative, so a positive charge is induced in the ground. Eventually, the electric fields get large enough to ionise the air, and a giant current flows as a lightning bolt, either from cloud to cloud or from cloud to ground.

What's strange, however, is that the electric fields in thunderclouds never seem to be powerful enough to trigger lightning at all. Experiments using kites, balloons and aircraft have shown that the fields rarely top 200 kilovolts per metre. To recreate lightning in the lab, you need much higher fields. "One of the age-old riddles of lightning is how it can arc when the voltage is so low," Leyh says. "If you set up two electrodes a metre apart, you need a megavolt to jump that. Natural lightning somehow cheats by a factor of five."

It is possible that thundercloud measurements have simply missed the hotspots in storm clouds where electric fields reach their peak, but as time goes on, researchers are conceding that the fields really do seem too puny to trigger lightning in the classical sense. They suspect some kind of extraterrestrial interference is at work.

The idea suggested in 1992 by Russian physicist Alex Gurevich of the Lebedev Physical Institute in Moscow and his colleagues is that cosmic rays lend a hand in forcing the air to break down. High-energy particles that have been accelerated in shock waves around exploded stars are hitting Earth's atmosphere all the time. One of these particles could ionise a molecule, knocking out an extremely energetic electron, which in the electric fields near a storm cloud could soon reach almost the speed of light. That electron would then hit and ionise other air molecules, producing more and more electrons in a chain reaction.

The cascade of electrons would cause "runaway breakdown", triggering a lightning strike even in the modest electric fields typical of storm clouds (*New Scientist*, 7 May 2005, p 30). There are a few kinks in the theory that still need to be ironed out, though. For instance, there are arguments about how energetic your cosmic ray needs to be. If the necessary energy is too great, then cosmic rays would not pack enough punch to account for the myriad thunderstorms on Earth - some 2000 around the world at any one time.

Researchers are trying to resolve this debate with complex computer models and huge detector arrays, patiently awaiting natural lightning strikes to find out how often they coincide with cosmic ray showers. The Nevada lightning lab could test the theory in an old-fashioned, hands-on way that Nikola Tesla himself would have approved of.

If the lightning lab is built, Leyh hopes to install a compact particle accelerator in one of his towers that can accelerate electrons to about 99.5 per cent of the speed of light. Then he'll find out whether he can trigger lightning bolts in more modest electric fields simply by seeding the air with whizzing electrons.

Not only would that lay a longstanding puzzle to rest, it could also blow the 40-metre height limit out of the water, says Leyh. If electron seeding works, there's no limit to how dramatic future lightning labs could be. With the help of a particle accelerator, you could trigger humongous lightning bolts from Tesla coils 5 kilometres high.

The cult of the coil

Greg Leyh is not alone. Thousands of enthusiasts around the world build Tesla coils in their garages, aided by advice and tip-swapping on the internet.

Mike Tucknott, a train driver from Oxfordshire, UK, has been building Tesla coils since the early 1990s. His best so far, a unit 1.8 metres high, launched lightning bolts nearly 3 metres long - before it burst into flames.

The appeal of building coils is the old-fashioned, hands-on approach in an age when no one has a clue how electrical appliances work, he says. "And the arcs are a fantastic thing to see - it gets you deep down on an emotional level."