A procedure to directly measure the strength of Landau damping

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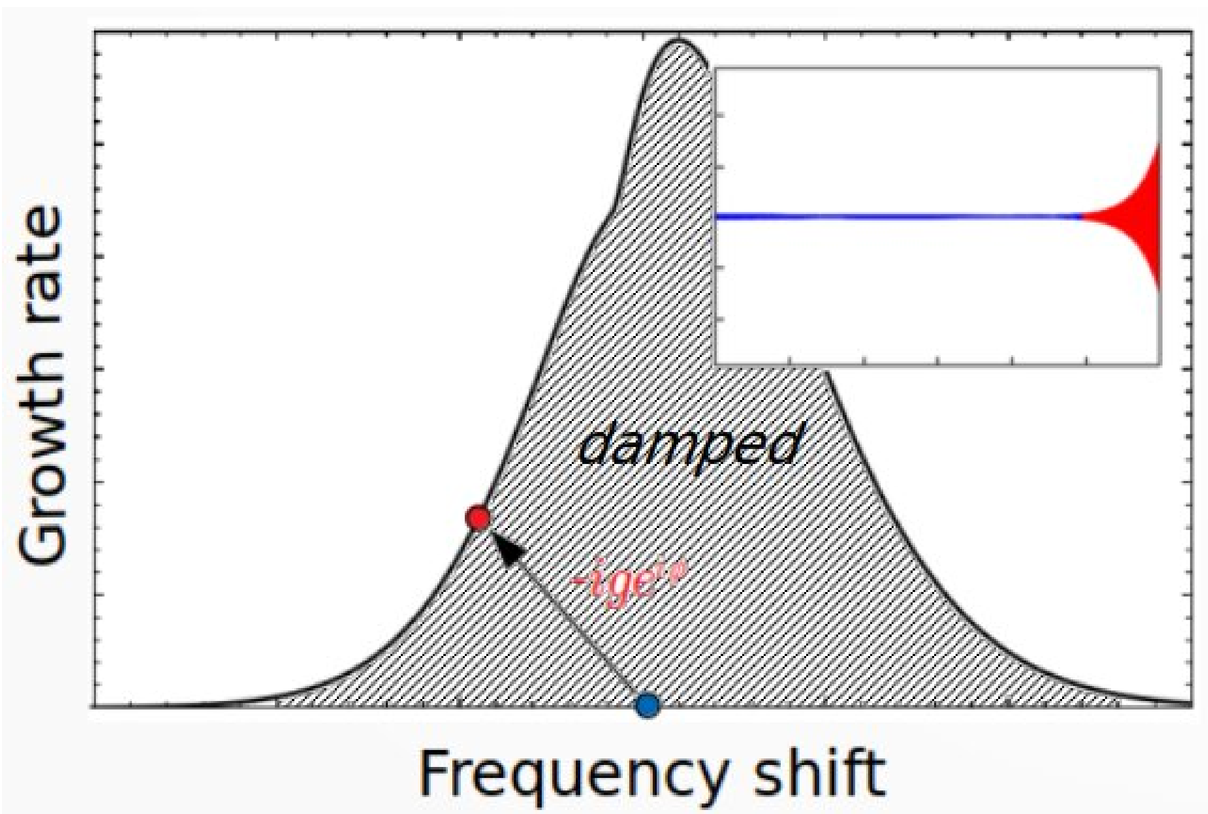

In a particle accelerator, bunches of elementary particles circle around a carefully designed orbit. As they have an electric charge, they interact with each other and with their surroundings, leading to small oscillations around the reference trajectory (much like a pendulum). If the interaction is too strong the amplitude of these oscillations grows over time, pushing the particle away from the orbit. The researchers characterize this motion in terms of its frequency, or tune, and its growth rate. Landau damping helps to make the region of particle motion that would otherwise be unstable stable. In their experiment, the researchers used the feedback to reach the limit of this stable region. Credit: Antipov et al.

Landau damping, a phenomenon originally predicted by Lev Landau in 1946, is essential to ensure the collective beam stability in particle accelerators. By precisely measuring the strength of Landau damping, physicists can predict the stability of beams in high-energy colliders.

Researchers at the European Organization for Nuclear Research (CERN) recently introduced a procedure to measure the strength of Landau damping and the limits of beam stability for high-energy colliders. This procedure, outlined in a paper published in *Physical Review Letters*, is based on the use of an active transverse feedback as a controllable source of beam coupling impedance.

"Landau damping is a fascinating phenomenon happening in plasmas," Sergey Antipov, one of the researchers who carried out the study, told Phys.org. "It is a suppression of external perturbations of the dynamic system through collective incoherent behaviour of its individual elements. Different members react to the excitation slightly differently, interact and share energy with each other and as a result the excitation gets damped, creating a sort of order from chaos."

Landaus first predicted damping while he was analyzing the Vlasov equation, which is essentially the "standard model" of plasma physics. In a paper published in 1946, Landau showed that electromagnetic waves propagating through plasma should decay even if the plasma itself has no friction (i.e., no dissipation energy).

"Back then, this unintuitive conclusion was highly debated, until it was finally observed 20 years after it was hypothesized," Antipov said. "Only in 2009, mathematicians Mouhot and Villani finally solved the equation rigorously, putting a solid mathematical foundation under the existence of Landau damping, for which they earned the Fields award."

The movement of particles inside particle accelerators, such as the Large Hadron Collider (LHC), also follows the rules outlined by the Vlasov equation. As a result, Landau damping also exists in particle beams inside these accelerators.

Physicists rely on Landau damping to suppress undesirable motions that can result from the interaction of a particle beam with its surroundings through induced electromagnetic wakefields. So far, researchers have only been able to estimate the strength of Landau damping in a particle beam using a series of simple models, as there was no way of directly measuring its strength.

"One day, my colleagues and I were sitting at a dinner table after a physics workshop in the French Evian, back in the days when there were still live workshops," Antipov explained. "After a couple of drinks and some good food, the conversation shifted from the operational issues, the topic of the workshop, to more fun things we could do with the LHC collider. That's when I proposed to try and measure Landau damping. It turned out that the LHC feedback system could be capable of doing that, and the person in charge of it, Daniel, was sitting right in front of me."

The general idea behind the procedure devised by Antipov and his colleagues was to use a transverse feedback system to emulate the collective force acting on a particle beam. Typically, this feedback measures the beam's orbit. If the orbit deviates from the desired design, the beam can be then 'moved' in the right direction.

"We set the transverse feedback system up in a way that its gain and its phase delay varied with the amplitude of the beam's motion, in the same way the beam's self-wake force would," Antipov said. "This set-up allowed us to drive a collective instability in the beam, but at the same time, keep it under control. "Then, we just varied the destabilizing force until we saw Landau damping overcoming it and stabilizing the beam—that's when the two effects, the instability and the damping, are equal—and that's how you know the strength of Landau damping in the beam."

Antipov and his colleagues evaluated the procedure they developed in a proof-of-principle test performed at the LHC. Their findings highlight their method's potential, suggesting that it could be used to accurately predict beam stability in state-of-the-art high-energy colliders.

"The LHC is a unique machine to carry out studies in terms of its capabilities, but it comes with a cost," Antipov said. "Because the machine is so expensive and sensitive, everything should work from the first try, without trial and error, and failure is not an option. We thus assembled a small group of experts and started preparing the plan. It took a bit of time to upgrade the feedback, to study different scenarios and find the right parameters where we were most likely to make a clean measurement. Then, one Saturday night, we just went to the control room, sat there all night and did it."

The proof-of-principle test performed by this team of researchers proves that directly measuring the strength of Landau damping is possible. In addition, Antipov and his colleagues identified the conditions necessary to collect such a measurement.

In the future, their work could thus serve as a recipe that other teams can follow to accurately quantify the strength of Landau damping. Meanwhile, the team at the European Organization for Nuclear Research plans to test the procedure on other machines and colliders at CERN in Switzerland and GSI in Germany.

"The most interesting application for our procedure seems to be on lower energy high intensity accelerators, where strong Coulomb forces affect the collective behavior of the particles in a beam drastically," Antipov said. "That's where Landau damping must play a crucial role in stabilizing particle beams, but currently no solid theoretical model exists, so accelerator scientists have to rely on sophisticated numerical simulations. Hopefully, an experimental method will help shed some light on the problem."

More information: Proof-of-principle direct measurement of Landau damping strength at the Large Hadron Collider with an antidamper. *Physical Review Letters*(2021). DOI: 10.1103/PhysRevLett.126.164801.