CERN ATS seminar on 17/11/2022: https://indico.cern.ch/event/1218875/

Using synchrotron radiation to understand and manipulate particle beams
by Sergei Nagaitsev (FNAL)

Number of participants: 15 persons in the Kjell Johnsen Auditorium (30/7-018) + 26 people connected through Webcast

A recording is also available on the indico site

Sergei started his presentation by remembering the basics of

- Schottky noise
- Stochastic cooling
- FNAL's IOTA (Integrable Optics Test Accelerator) => Primary purpose is accelerator science and technology research
  - ✳ First beam: Aug 21, 2018
  - ✳ Circumference: 40 m (133 ns)
  - ✳ Electron energy: 100-150 MeV
- Synchrotron light sources => When the trajectories of high-energy electrons are bent by a magnetic field, they emit a radiation. 2 sources of magnetic fields
  - ✳ Bending magnets => Synchrotron light
  - ✳ Insertion devices => Undulator/wiggler radiation
    - ✦ Undulator => When the undulator strength parameter Ku $\leq$ 1
    - ✦ Wiggler => When the undulator strength parameter Ku >> 1

Sergei mentioned that the necessary cooling bandwidth for the proposed EIC (Electron Ion Collider in RHIC) is ~ 40 THz (due to the rms proton bunch length of ~ 6 cm) => Maxwell's demon goes optical: relativistic particle beams cooled using their own optical radiation. An alternative title of this talk could be "Electron and photon interference in a storage ring" and Sergei discussed 3 experiments:

1) Undulator radiation fluctuations for many electrons

2) Undulator radiation: quantum fluctuations for a single electron

3) Optical Stochastic Cooling (OSC) demonstration

1st experiment: many electrons (~ 10^9)

- They observed super-Poissonian fluctuations in undulator radiation intensity for many electrons, fully consistent with the model of classical and quantum fluctuations
- They proposed and demonstrated a fluctuations-based technique to measure electron beam emittances, which can be particularly useful for state-of-the-art and next-generation x-ray synchrotrons

2nd experiment: a single electron in the ring

- In their experiment with a single electron and a single binary photon detector, they did not observe any statistically significant deviations of the undulator radiation photostatistics from a memoryless Bernoulli process. Their observations directly confirm that at negligible electron recoil, synchrotron radiation produced by a single electron is in a coherent state as predicted by Glauber => See JINST paper "Single electron in a storage ring: a probe into the fundamental properties of synchrotron radiation and a powerful diagnostic tool": https://iopscience.iop.org/article/10.1088/1748-0221/17/02/P02014/pdf.

3rd experiment: OSC

- Their first ever demonstration of stochastic beam cooling at optical frequencies serves as a foundation for more advanced experiments with high-gain optical amplification and advances opportunities for future operational OSC systems with potential benefit to a broad user community in the accelerator-based sciences

- It may offer a feasible method for cooling hadrons at energies below ~ 4 TeV (e.g. at the EIC). It may also enhance the existing synchrotron radiation facilities

Future experiments

- Mach-Zehnder interferometry (interference of the photons in emitted photon pairs with 2 detectors) => In some sense, this is a measurement of the light pulse shape in time domain and this experiment is currently under preparation

- A staged approach for OSC at IOTA

    - Non-amplified OSC (~ 1 microm): simplified optics with strong cooling to enable early exploration of fundamental physics; cooling rates, ranges, phase-space structure of cooling force, single and few-particle OSC

    - Amplified OSC (~ 2 microm): OSC amplifier development, amplified cooling force, QM noise in amplification + effect on cooling, active phase-space control for improved cooling

Summary

- Observed super-Poissonian fluctuations in undulator radiation intensity, fully consistent with the model of classical and quantum fluctuations

- Proposed and demonstrated a fluctuations-based technique to measure electron beam emittances, which can be particularly useful for state-of-the-art and next-generation x-ray synchrotrons

- For the first time, observed 6D OSC, fully consistent with predictions. The OSC demonstration is at an intersection of fundamental beam-physics studies and the development of operational cooling systems

- Established a strong foundation for development of amplified OSC experiment: validated many critical subsystems and concepts; gathered excellent operational experience and learned many valuable lessons

Q&A session

- Following a question from Sergei during his talk, Elias reminded that at CERN, we have undulators (in fact wigglers) in LHC for the Synchrotron Light Profile Monitors. We then had a look again to the very impressive transverse (but also longitudinal) movies of a single electron (see slide 33 for the transverse profile and the longitudinal profile was shown from another set of slides). Some discussion took place about the measurement with some slits.

- A question was raised about the experiment described on slide 39, with the recombination of electron and photon following different paths: Sergei explained that due to the delay introduced by the lens system on the photon path and the recombination with its own electron, we can have at the end of the 2 undulators, one or the other particle arriving before or after the other one.
- Another question was raised about the limitation of the OSC application to beams with E > 4 TeV, as e.g. in the LHC. This subject was already discussed about a decade ago and it was mentioned at that time (in particular by Fritz Caspers) that a possible obstacle would be the significant impedance of the necessary kicker.

Alessandro, Elias, Michele, Thierry (and Sergei)