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Case Studies

CERN Accelerator School – FELs and ERLs

Case Studies – General Remarks

- Goal is to learn more on the topics of ERL and FELs with a assigned case as orientation.
- The primary activity to inform yourselves by publication and papers on that specific topic. Most of the problems and solutions have been discussed in these papers.
- Mentors (e.g. myself) will be present during the school to help with the case studies.
- For calculation it is recommended to use web application or apps for android (seen next slide)

The Ming Xie Model

- A very useful tool is the Ming Xie Model. It is prediction of the FEL performance based on the 1D model with a correction for different input parameters. There parameters are:
  - The electron beam size
  - The electron emittance
  - The electron energy spread
- Note that the Model does not work well if space charge is playing a role, which is mostly the case for long wavelength FELs

- The original article can be found here:

  https://accelconf.web.cern.ch/accelconf/p95/ARTICLES/TPG/TPG10.PDF

- The Ming Xie model has been implemented in various ways:
  - As app for android smart phones: TAPAS by Michael Borland, ANL

    https://play.google.com/store/apps/details?id=borland.TAPAs&hl=en
  - Web-based calculator by Bart Faatz, DESY

    http://adweb.desy.de/home/faatz/www/parms/parms.html

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Case 1 – High Average Power UV FEL

- Goal: ***Design a high repetition FEL at a wavelength of 13.5 nm with an average power of more than 2 kW***
- Background: To generate the fine structures in micro chips with lithorgraphy it requires a coherent light source and a mask for the fabrication of waivers. More average power results in faster fabrication. It should be at least above 1 kW because otherwise alternative solution exists.
- Approach: A high FEL power requires also a high average electron beam power. Due to the limited efficiency of FELs (less than 1% extracted energy) a lot of power would be wasted. Therefore an ERL might be a solution to reduce the dumped beam energy to an acceptable level.

Case 1 – Tasks

- Define the undulator parameters. Allow for a large undulator gap to allow for a save beam transport of a high average beam current, reducing potential beam losses
- Define beam parameters at the undulator. Discuss whether higher rep rate with less charge per bunch is better or worse for stability of the FEL beam.
- Make a layout of the machine and estimate its size. Define a suitable compression scheme for best FEL performance
- Make suggestions for non-invasive beam diagnostics.

Case 2 – High Peak Power X-Ray FEL

- Goal: ***Design an FEL, operating at 1 Angstrom, with a saturation power of more than 20 GW with a possible enhancement by tapering to up to 1 TW.***

- Background: The holy grail of FEL application is the single molecule imaging by coherent diffraction. Large angle scattering of photons have a low probability and therefore must be compensated by a high photon flux. They are needed to allow for the determination of the orientation of the molecule, which changes from shot to shot of proteins in liquid solutions. Also the FEL pulse has to be shorter than 10 fs, otherwise the molecule is damaged and a significant rearrangement of the atoms can occur

- Approach: Saturation power scales with the FEL parameter and the beam energy. It is beneficial to improve both quantities till other effects degrades the performance (e.g. quantum fluctuation). The remaining power can be extracted by tapering – keeping the bunching phase constant with respect to the radiation phase

Case 2 - Tasks

- Which parameters of the electron beam and/or undulator needs to be increased to increase the saturation power while keeping the wavelength the same?

- A practical limit is quantum fluctuation in the undulator, which increases the relative energy spread more than the FEL requirement of $\sigma_E/E < \rho$. Give an estimate on this limit

- Beyond saturation radiation power is increased by tapering following a similar approach as deceleration in a storage ring. Estimate the rate and length required to reach 1 TW. What is a limitation on the tapering.

- For short, intense radiation pulse in a long electron bunch there is a secondary methods of amplification, called superradiance. What is a practical limitation of this method

Case 3 – Soft X-ray HGHG FEL

- Goal: ***Design a 3 stage HGHG FEL, starting with a seed wavelength of 200 nm, reaching 1 nm.***

- Background: To overcome the limitation of limited coherence in SASE FELs a coherent signal at 200 nm is used as a seed for an FEL. By means of harmonic conversions and fresh bunch techniques the final wavelength can be shifted into the 1 nm range. In addition the FEL signal is locked to the laser signal, which reduces the relative jitter of the two signals for possible pump-probe experiments

- Approach: To allow for strong signals the methods of fresh bunches is preferred, which allows to drive each stage deep into radiation and then shifting to a fresh part of the bunch. The shortest FEL pulse length is defined by the slippage at the longest wavelength and thus an estimate for the minimum bunch length, which has to provide at least three fresh bunch sections within the bunch

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Case 3 - Tasks

- Design a possible three stage cascade to reach 200^{th} harmonics. What are the harmonics which can be reached, if none of the single stage has a higher harmonic conversion of 9. To fill the gave the seed laser can be slightly tuned (e.g. 199^{th} harmonic is the same if 200^{th} harmonic is chosen with a 0.5% longer wavelength of seed laser). What is the required tuning range to have a continuous tuning range from 1 to 10 nm.

- Estimate the required length pf the undulator stages, bunch length to allow for two fresh bunch sections in the electron bunch. If the maximum bunch charge is 1 nC, what is the corresponding current and thus the maximum power at 1 nm.

- Consider state-of-the-art synchronization of the seed laser with the electron bunch and allow for a safety margin to overlap electron bunch and seed signal. What is the bunch length with this margin?

- Discuss the amplification of shot noise in a multi stage cascade, which can potentially counteract the HGHG scheme

Case 4 – Compact ERL for THz Radiation

- Goal: ***Design a facility to provide high-rep THz radiation in the range of 1 to 20 THz with either single cycle emission or a bandwidth below 2%***

- Background: THz radiation has become a invaluable tool for non-destructive measurements of organic and non-organic materials. Because the radiation cannot be generated easily in the given frequency range by classical means the coherent emission from a relativistic beam is the most promising way to generate high intense THz radiation, either by means of synchrotron radiation in a bend or the periodic emission in an undulator.

- Approach: THz studies are mostly non-distructive but require a high average power, which makes an ERL an ideal candidate to provide this radiation. While an FEL can be driven only once with a single bunch, coherent emission in bends can provide multiple user stations similar to a 2nd generation light source.

Case 4 -Tasks

- What is the most promising methods to extract a single cycle THz pulse from an electron bunch. Estimate the pulse energy.
- What is the most compact methods to generate a narrow bandwidth signal from an electron bunch in the range from 1 to 20 THz. Estimate the pulse energy.
- Design a facility to allow for both radiation methods. Consider the tuning range of 20 in the central frequency. Consider that both should be extracted from the same bunch at different user station. Discuss whether tuning by undulator or by beam energy is preferable for the narrow band signal.
- What is the average power if included in a high performance ERL layout.
- Consider the advantage and disadvantages to go to a very compact facility.

Case 5 –FEL driven by Plasma Injector

- Goal: ***Use the output from a plasma injector to drive an FEL in the UV range.***
- Background: The non-linear regime of a laser driven plasma channel can generate a relativistic electron beam with small emittance but rather large energy spread. They can potentially shorten the classical RF injector and accelerator of FEL facilities down to a few meters.
- Approach: Experiments have shown promising beam parameters with a current of hundreds of Amperes, small emittances of about 100 to 200 nm but an relative energy spread of 1% at a beam energy of several hundreds of MeV. The practical limit to apply the beam to an FEL is its large energy spread.

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Case 5 - Tasks

- With an expected energy spread of about 1% discuss the methods to over come this limitation by
  1. Stretching the bunch longitudinally, where the energy spread decreases linearly with the decompression but the FEL parameter only with its cubic root
  2. Stretching transversely with dispersion and apply a transverse gradient to the undulator field.

- Propose possible configuration of the machine layout for both methods. Discuss possible limitation in the wavelengths with any of the methods.

- An alternative approach is to generate much higher peak current to overcome the impact of 1% energy spread. What is the minimum current to allow lasing at 300 MeV and a wavelength of 50 nm. Discuss the impact on longitudinal space charge.