Accelerator Physics Exercises

- Work to be handed in before tutorial on - 19 January 2017

The aim of the work is to prepare a Student Design Project of a compact ring-based Synchrotron Radiation source with Laser-Plasma Injection (LPI-SR).

An introduction to the conceptual design of the LPI-SR is available at:

https://arxiv.org/abs/1610.05699

and additional information is provided in the Further References section at the end of this paper.

Three versions of the SR source are being considered, with electron beam energies of 1 GeV and 3 GeV and a magnetic lattice design based on normal-conducting magnets (for the 1 GeV electron beam energy version) and superconducting magnets (for both the 1 GeV and 3 GeV electron energy versions). The electron beam recirculates in the storage ring, thus increasing the effective SR flux.

The Student Design Project will concentrate on developing the existing conceptual design, including plasma simulations to improve the electron beam parameters, investigations of the gas-jet design, study of the storage ring lattice optics and particle tracking to optimise the size of the electron beam, and a detailed description of the storage ring magnet design and RF system required for re-acceleration.

Question 5.1 (Introduction)

Imagine you are writing the introductory section of the Student Design Report. Describe clearly and in detail the following:

(a) The physics and applications that can be addressed by the LPI-SR.

(b) The motivation and uniqueness of the LPI-SR compared to third generation and Free Electron Laser (FEL) SR sources.

(c) The LPI-SR overall configuration and performance objectives.

(d) The particle beam requirements for both the 1 GeV and 3 GeV electron beam energy versions. Compare the two particle beam options and elaborate the pros and cons of each.

Question 5.2 (Laser-Plasma Acceleration)

a) A parallel electron beam of E = 200 MeV enters a beamline. It is necessary to focus this beam onto a point at a distance 3 m from the entrance. Estimate the necessary parameters of a quadrupole system (gradients, lengths) that can perform this task.

b) Assuming a plasma density of 1.75×10^{17} cm^{-3}, calculate the wavelength of the laser light that could still penetrate such a plasma. Calculate the corresponding plasma frequency, group velocity of a laser pulse from a Ti:Sapphire (800nm) CPA system, and the wavelength of a plasma wave propagating behind the laser pulse.

c) What laser intensity (in W/cm^2) correspond to a normalized vector potential of $a_0 = 10$, and what are the maximum values of the electric and magnetic fields in the laser wave for both a ruby laser and for a CO_2 laser? **If a Ti:Sapphire CPA laser system delivers this a_0=10 Gaussian pulse of length 50 fs and is focused to a Gaussian focal spot-size of 40 µm, what is the pulse energy?**

d) Assume that we obtain an electron bunch with 1 GeV energy from a laser plasma accelerator and would like to create an undulator from the plasma using the focusing force of the plasma's ions. Suggest the plasma parameters and the amplitude of the beam oscillation that would correspond to the radiation at the boundary of the undulator regime, *i.e.* with the undulator parameter K = 1. Compare the parameters for a Ti:Sapphire laser to a CO_2 laser.

e) In laser plasma acceleration, the final energy of an accelerated electron beam is 1 GeV. The wavelength of the laser used for plasma acceleration is 800 nm. Part of the same laser pulse is redirected with mirrors to collide head-on with the accelerated electron beam. Estimate the energy of the photons created in such a Compton source together with the angular spread of the photons. Also, estimate these parameters if the laser is doubled in frequency before colliding with the electron beam.

For clarification do not hesitate to contact Aakash Sahai - a.sahai@imperial.ac.uk

Question 5.3 (The Lattice)

This question develops the basic structure of the lattice optics for the LPI-SR.

a) Taking your estimated parameters from Question 5.2 (a), create a MAD-X input file that shows a system of quadrupoles to achieve this task.

b) Discuss some of the issues that may arise when an electron beam is re-circulating in a compact ring. What impact will these effects have on the beam itself, or on the machine?

c) The basic ring created in the LPI-SR design report is made from only sector bending magnets with weak and edge focusing. Taking the basic parameters of a ring for 1 GeV electrons with superconducting magnets up to 10T, create a ring in MAD-X similar to that in the report, but with only the main bending magnets (not including the quadrupoles from part (a)). If it does not work, manipulate it until it does! Plot the optics functions including the dispersion. What options might be available to reduce the dispersion in the ring further?

For clarification do not hesitate to contact Suzie Sheehy - suzie.sheehy@physics.ox.ac.uk

Question 5.4 (The RF Cavities)

It has been suggested that an RF system could be adopted for beam re-acceleration in the storage ring.

a) Revisit the lectures on RF cavity design and modeling and look in particular at the slides showing the pillbox, DTL and elliptical-type cavities. Considering an RF frequency of 200 MHz, estimate analytically the diameter of a pillbox cavity at this frequency (mode TM_{010}). Assuming an electron beam energy of 1 GeV, model the cavity in SuperFish. Assume it is made of copper, it operates at room temperature and it has an average axial electric field of 1 MV/m and a length of $\lambda/2$, where λ is the RF wavelength. Plot the field distribution inside the cavity, the electric field on axis and present the dissipated power in the cavity walls, the transit time factor, the effective shunt impedance per unit length (ZTT), the Kilpatrick factor, the accelerating voltage and the quality factor Q. What would be the energy gain of an electron passing through the cavity for a synchronous phase ϕ=0?

b) Making the same assumptions, consider a single DTL-type cavity operating at 400 MHz with an average axial electric field of 3 MV/m. Use SuperFish to find the geometry and model such a cavity. Present the same cavity parameters as in Question 5.4a above.
c) Similarly, model a single-cell superconducting elliptical cavity at 800 MHz, with an average axial electric field of 10 MV/m. Keep the SuperFish default settings for superconducting materials. What is the Q of this cavity, the ratio of peak fields (B_{max}/E_{max}) and the peak-to-average electric field ratio (E_{max}/E_0)? Plot the field distribution inside the cavity, the electric field on axis, and present the accelerating voltage.

Comment on the pros and cons of each cavity type for this project? Start from the examples given in the tutorial.

For clarification do not hesitate to contact Ciprian Plostinar - ciprian.plostinar@stfc.ac.uk

Further References

A. Romanov, AAC-2016 – describes basic requirements for the electron beam in the 70 MeV Integrable Optics Test Accelerator (IOTA) at Fermilab. It considers three methods of injection – a) an on- orbit and on-energy; b) a slightly off-orbit injection corrected with a single kicker; and

c) a stand-alone injection outside of the ring. Only methods a) and b) are relevant to the Student Design Project.

J. Kim *et al.*, FEL-2015 - TUP079 – describes an interesting method to produce a plasma target that appears and disappears very fast – the target is created by another laser which shines on to an aluminium flat plate. This approach to plasma target design may be interesting for our applications.

Ya. Getmanov *et al.*, IPAC-2010, TUPEA078 – describes scattering on a plasma target in the case of a magnesium vapour target and LP injection into the ring is slightly off-orbit, with a single kicker (case (b) above).

S. H. Park *et al.,* IPAC-2015, WEPWA033 – describes standard laser plasma acceleration, and at the end shows an interesting concept of a compact ring and magnet design for a100 MeV electron ring.

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