**List of projects for the Summer School**

1. Project Drift Tube Linac, Alvarez cavity, Wideroe Advisor: Anders K

In this project you analyze the Drift Tube Linac that is a common cavity in Linac structures.

- Describe the Wideroe cavity that was the predecessor to the DTL. Make a simple analysis and determine the lengths of a Wideroe cavity when the energy of the entering particle is known and the voltage is known.

- describe the DTL. Design a simple DTL in Comsol that should accelerate the bunches of ESS. The bunches come with a frequency of 352 MHz. Thus you need to design a DTL with a fundamental frequency of 352 MHz. Let the DTL have 5 cells. Assume that the entering protons have an energy of 400 MeV and that they should gain 50 MeV.

Basic theory:

Comsol instructions:

2. The TM010 mode. Elliptic cavities, traveling wave cavities Advisor: Anders K

In this project you analyze the Elliptic cavities that is a common cavity in Linac structures for acceleration of protons.

The cylindrical cavity is described below. It has an infinite number of resonances. They are denoted TE$\_{mnl}$ and TM$\_{mnl}$. TM stands for transverse magnetic and means that the magnetic field has no component in the $z-$direction, and TE stands for transverse electric. The indices $mnl$ are described below. The most important mode is the TM$\_{010}$ mode and its electric and magnetic fields are described below. It is the TM$\_{010}$ mode that is used in most cavities for particle accelerators. Mostly the cylinder is deformed in order to get better performance. One way to deform it is indicated in the figure. Such a cavity is called an elliptic cavity since the cross section can be constructed by ellipses and straight lines.

In this project you use Comsol to design an elliptic cavity for the ESS. You make a simple version, as suggested in figure B below. The frequency for the pi-mode should 704 MHz. It should fullfil its purpose. Check the frequencies for the higher order modes (HOM) for the axially symmetric modes.

Basic theory:

Comsol instructions:

3. Project Rectangular waveguides

The modern high energy accelerators rely on radio frequency sources and cavities for the acceleration of particles. The microwaves are generated in sources such as klystrons (high power) and solid state amplifiers (low power). The power is transported from the sources to the cavities via waveguides. At frequencies above 300 MHz it is mostly rectangular waveguides that are used for this purpose. At frequencies below 300 MHz coaxial waveguides are more common.

This project concerns different aspects of rectangular waveguides. You will use Comsol multiphysics to find examine the following aspects:

- Basic facts about rectangular waveguides: waveguide modes, fundamental mode, cut-off frequencies, phase speed, group speed

- Use Comsol to determine attenuation, wave propagation in waveguides with bends, circulators

- How is the coupling done from the klystron to the waveguide?

- What is the electric and magnetic fields of the fundamental mode. Check both the analysis below and use Comsol.

- What sizes are needed for waveguides at 3 GHz (MAX IV linac), 704 MHz (SLAC at Cern, ESS), 352 MHz (ESS).

- Use Comsol to determine the difference of attenuation of coaxial waveguides and rectangular waveguides at some different frequencies.

Basic theory:

4 *Project title: Preservation of ultra low emittance in linear colliders Advisor Erik Adli*

*In this project the students will design a small piece of the linac for a linear electron positron collider. In order to generate enough luminosity, the beams in a linear collider must be very small at the collision point. This implies that both the beam focusing (beta function) and the beam quality (emittance) must be very small. Preservation of very small beam emittance all the way to the interaction point is one of the key challenges in linear collider design.*

*The students will first design a periodic lattice for beam transport, given constraints on the beta functions and phase advance as input. Next the students will investigate the deterioration of beam emittance as the lattice elements are misaligned. The students will apply two different steering techniques and investigate how the emittance preservation is improved by applying these techniques. The two steering techniques to be studies are 1-to-1 steering and dispersion-free steering.*

*Requirements: the students must have access to the optics code MADX, and to a numerical calculation program like Matlab, or similar.*

*Recommendations for literature: relevant references to read will be given in the final description of the project.*

5. Magnets for beam lines Advisor: Pauli Heikkinen

## Starting conditions:

An accelerator laboratory is built for 123-I and 18-F production. The cyclotron will be bought from a commercial supplier. The beam will be guided to two different production targets.

### Known parameters:

|  |  |  |
| --- | --- | --- |
| Particles |  | H-, D- |
| Beam energy |  | 30 MeV, 15 MeV |
| Beam intensity |  | 300 A, 150 A |
| Emittance at cyclotron exit | Horizontal, vertical | 5  mm mrad, 10  mm mrad |
| Beam width at cyclotron exit | Horizontal, vertical | 2 mm, 3 mm |
| Orientation of emittance ellipse at cyclotron exit |  | Upright |
| Cooling water temperature |  | 20 oC |
| Max pressure drop of cooling water |  | 6 bar |
| Beam diameter at target |  | < 10 mm |

### Task:

Design the ionoptical elements needed for beam transport

* Geometrical dimensions
	+ Length/bending radius
	+ Apertures
* Coils
	+ Conductor
	+ Dimensions of coils
	+ Cooling
		- Max temperature rise 20 oC
	+ Power supply parameters (current voltage)

10 m

10 m

10 m

Target

Cyclotron

60 o

**Accelerator for proton therapy:**

6. Proton Therapy

One of the new developments in radiation therapy is treatment with high energy protons, which for many treatment sites provides a superior dose distribution in the patient with less dose to healthy tissue. In the present project, you should design a proton cyclotron or synchrotron for proton therapy. The following aspects could be included in the project:

1. Advantages/disadvantages of a cyclotron or synchrotron
2. Design parameters of the accelerator:
	1. Max. proton energy (proton range in the patient)
	2. Beam optics, size of accelerator, and magnetic field strength
	3. RF system and beam acceleration
	4. Beam current, beam extraction, and beam intensity control
	5. Vacuum system
3. Design parameters of the protons delivery system (deposition of the planned dose distribution in the patient):
	1. Energy adjustment
	2. Gantry design
	3. Passive/active scattering of the proton beam
	4. Treatment time and treatment field size
	5. Proton beam size and energy spread

**7) Compare low emittance synchrotron radiation sources.**

Several ultra low emittance storage rings are under commissioning or construction, either as new facilities (MAX IV, Sirius, NSLS-II) or as upgrades (ESRF, APS, PETRA-III). How is the ultra low emittance designed and implemented in these facilities. What are the similarities and differences? How is the technology used? What are the breakthroughs and what are the limitations? What are the main accelerator physics issues with these machines? Describe, compare, analyze!

**8) Errors in storage rings.**

The performance of a storage ring is dependent on errors in the machine. Errors could come from many different sources like magnets, insertion devices, alignment etc. Study how magnet errors (strength, position) influence the operation of the machine. Take a sample machine and introduce errors. Consider tune changes and closed orbit. Try also to look on the dynamic aperture of the machine.

Describe your work by discussing how you model errors, what problems you see and what tolerances you have found.

9) Carlo’s project.

10)Injection into a storage ring Advisor: Pedro Tavares

* 1. When transferring particle beams from one accelerator to another, e.g., from an injector linac into a storage ring, one is confronted with a fundamental dilemma: the incoming (or injected) beam is initially outside the storage ring chamber and its trajectory needs therefore to be bent in such a way as to bring it into the chamber. However, it is not enough to steer the injected beam into the physical space delimited by the storage ring chamber at the injection point (IP) – in fact, the angle of the injected beam trajectory with respect to the nominal orbit in the storage ring must also be brought within certain limits – otherwise the incoming beam will simply hit the walls of the storage ring vacuum chamber at some point downstream from the IP and be lost. This requirement on steering the incoming beam can be expressed as a requirement for *bringing the injected beam into the storage ring acceptance*.
	2. Consider an electron storage ring with 528 m circumference, injected from a linear accelerator. Electrons are brought from the linac and conducted through a transport line up to the storage ring where the transfer of electrons (the injection process) happens on the horizontal plane, i.e. we assume that (at the IP) the incoming beam from the linac lies at the same vertical coordinate as the storage ring nominal orbit, with zero vertical angle. The incoming beam horizontal position at the IP is -13.5 mm[[1]](#footnote--1) away from the nominal storage ring orbit and the incoming beam’s horizontal trajectory angle with respect to the nominal storage ring orbit is zero. Assume that the storage ring vacuum chamber has inner dimensions of $b=\pm 11$ mm, that the maximum horizontal betatron function over the whole ring is $β\_{x}^{max}=9.8 $m and that horizontal betatron function at the IP is $β\_{x}^{IP}=9.4 $ m. Finally, assume that the injection point is a dispersion-free, symmetry point in the storage ring lattice, so that $α\_{x}^{IP}=0$ and $η\_{x}^{IP}=0$. **Calculate the horizontal acceptance (in mm\*mrad) defined by the storage ring vacuum chamber aperture**. **Draw a phase space diagram at the IP indicating the ring acceptance as well as the incoming beam coordinates**.
	3. In order to bring the incoming beam into the storage ring acceptance, one may add a magnet that deflects the incoming beam horizontally[[2]](#footnote-0) at some point downstream of the IP – let us call this the “kick point” or KP[[3]](#footnote-1). Assume that the betatron phase advance between the IP and the KP is $\frac{π}{2}$ and that the betatron function at the KP is $β\_{x}^{KP}=1.2$ m. **Calculate the required bending angle at the KP to bring the incoming beam all the way to the center of the storage ring acceptance. Calculate the minimum required bend angle at the KP to just bring the incoming beam into the storage ring acceptance (i.e. barely touching the border of the acceptance).**
	4. If we were to implement the bending of the incoming beam by means of a DC magnet, i.e., by a magnetic field that is constant in time, then after one revolution around the ring, the incoming beam would once again suffer the same bend. **Draw a sketch that shows that the incoming beam would be lost (i.e. would again be outside the storage ring acceptance) after one turn in case it is brought to the center of the acceptance in the first pass through the kicker**.
	5. A solution to the problem above is to use a fast pulsed magnet (also called a *kicker*) instead of a DC magnet, so that the incoming beam sees no field at all when it passes by the KP after one turn around the storage ring. **How fast does our pulsed magnet need to be ?**
	6. Once injected and captured in the storage ring, the incoming beam circulates and emits synchrotron radiation – the emission process leads to damping (i.e. acts as “friction” ) of the betatron oscillations and, after a number of damping times (few tens of ms), the injected beam cools down to follow the storage ring nominal closed orbit. The beam will no longer have any memory of the injection process but its dimensions will instead be determined by the equilibrium between damping mechanisms (emission of light) and excitation mechanisms (due to the quantum nature of the light emission process). This leads to the so called equilibrium emittance – Assume that the storage ring equilibrium horizontal emittance is 300 pmrad and indicate the stored beam at the IP in your phase space diagram. **What is the ratio between the amplitude of the incoming beam oscillations and the stored beam size ?**
	7. An additional problem arises when one wants to fire a succession of pulses from the injector linac into the storage ring so that one can *accumulate* the charge from many linac shots in the storage ring. In that case, one needs to remember that a stored beam already exists in the storage ring when a new incoming beam pulse is fired. In the scheme described above, the kicker magnet deflects both the incoming beam **and** the stored beam. **How should we choose the kicker deflection angle to make sure that the incoming beam is captured and that, at the same time, the stored beam is not thrown away from the storage ring acceptance ?**
	8. The discussion above assumes that the kicker magnet produces a homogeneous field, i.e., that the bending angle the kicker imparts to the beam is independent of the transverse position at which the beam crosses the kicker, meaning that both the incoming and stored beams are deflected by then same angle. The kick given to the stored beam produces a transient perturbation on the position of the light source points seen by the storage ring users – even though this perturbation disappears after only a few damping times, it is of interest to make the injection process fully transparent by devising a way to kick the injected beam without perturbing the stored beam. **Put together a conceptual design for a kicker magnet based on four current-carrying wires arranged along the direction of propagation of the stored beam and with current polarities chosen in such a way that the vertical component of the magnetic field at the horizontal center of the magnet is zero whereas the vertical component of the magnet field at the periphery (say at -6 mm from the center) is large enough to kick a 3 GeV beam by 3 mrad. Assume that the longitudinal space available for the kicker is 30 cm and that the minimum vertical full aperture of the magnet is 8 mm and calculate the required current in the four wires. What happens if the stored beam crosses the kicker slightly off-center ? Can we use this kicker with the same phase advance from the IP to the KP and same initial conditions for the incoming beam as in item c above** ?
	9. **Can you propose other ways of generating adequate spatial distributions of the kicker fields that lead to transparent injection ?**
1. The negative sign is meant to indicate the incoming beam is located on the inner side of the ring circumference. [↑](#footnote-ref--1)
2. The deflecting magnet needs therefore to generate a vertical magnet field component. [↑](#footnote-ref-0)
3. Note that the storage ring vacuum chamber needs to be made a little wider in this particular region between the IP and KP to make sure the incoming beam is not lost! [↑](#footnote-ref-1)