2nd International Accelerator School for Linear Colliders
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Final Examination Problems

NAME: ____

Problem 1 (Introduction)

The general scaling law for a linear collider shows – in general – that the luminosity can be increased by increasing the beam power, i.e.

$$L \propto P_{beam} = \eta_{RF\to beam} P_{RF}$$

The beam power is related to the basic bunch structure and centre-of-mass energy as

$$P_{beam} \propto n_b N f_{rep} E_{CM} \,.$$

At some point in the future, it may be desirable to increase the ILC luminosity by doubling the beam power. Consider the following 4 methods to double the beam power:

1. Double the pulse repetition rate of the machine f_{rep};
2. Double the single-bunch charge N;
3. Double the number of bunches (n_b) in a bunch train, keeping the bunch spacing Δt_b constant (ie, double the bunch train length);
4. Double the number of bunches (n_b) in a bunch train, halving the bunch spacing Δt_b, such that the total train length remains constant.

In principle each of these methods will double the luminosity; in practice, each of these changes will have "side effects" which potentially reduce the luminosity, so that the full factor of 2 may not be achieved without some redesign or re-engineering of the ILC.

(a) In the case in which the pulse repetition frequency f_{rep} is doubled, which areas of the ILC will require modification to achieve a full doubling of the luminosity? Circle all that apply and explain.
   1. Damping rings
   2. Main linac
   3. Final Focus

[3 points]

(b) In the case in which the single bunch charge N is doubled, which areas of the ILC will require modification to achieve a full doubling of the luminosity? Circle all that apply and explain.

a. Damping rings
b. Main linac
c. Final focus

[3 points]

(c) In the case in which the bunch train length is doubled, which areas of the ILC will require modification to achieve a full doubling of the luminosity? Circle all that apply and explain.

a. Damping rings
b. Main linac
c. Final focus

[3 points]

(d) In the case in which the bunch spacing in the train is halved, which areas of the ILC will require modification to achieve a full doubling of the luminosity? Circle all that apply and explain.

a. Damping rings
b. Main Linac
c. Final focus

[3 points]

Problem 2 (Sources & bunch compressors)

Beam sources:

(a) How much is the beam current in ILC macro pulse, i.e. 3.2 nC every 369 ns spacing?

[2 points]

(b) How much laser power do we need to generate ILC electron bunch train? Assume 0.5 % quantum efficiency and 800 nm laser wave length.

[2 points]

We consider ILC Bunch Compressor section at 5 GeV beam energy.

(c) Calculate the expected final bunch length after Bunch Compression section with $\delta_0 = 0.15$ % (initial relative energy spread) and $R_{56} = -0.2$ m.

[2 point]

(d) What is appropriate R_{65} for this Bunch Compression section?

[2 points]

(e) How much voltage (V_{RF}) is required for energy modulation? Assume 1.3 GHz RF.

[3 points]

Problem 3 (Damping ring)

The ILC damping ring has a circumference of 6.6 km, and contains 120 dipole magnets (without quadrupole gradient), each of length 6 meters. The beam energy is 5 GeV. The ring contains a damping wiggler, which can be turned on or off.

(a) Assuming that the wiggler is turned off, calculate:

- i) the bending radius of each dipole; *[1 point]*
- ii) the second and third synchrotron radiation integrals; *[2 points]*
- iii) the synchrotron radiation energy loss of each particle per turn through the ring; *[1 point]*
- iv) the horizontal, vertical and longitudinal damping times; *[1 point]*
- v) the equilibrium rms energy spread. *[1 point]*

(b) Assume that with the wiggler turned on, the maximum energy spread is dominated by the damping wiggler. Given that the maximum allowed rms energy spread in the beam is 0.13%, calculate the maximum allowed peak wiggler field. What is the bending radius corresponding to this field?

[3 points]

(c) Using your answer from (b) for the peak wiggler field, calculate the length of wiggler needed to achieve a horizontal damping time in the ring of 25 ms.

[3 points]

You may find the following constants helpful:

$c = 2.998\times10^{8}$ m/s

$m_e = 511$ keV/c^2

$C_\gamma = 8.846\times10^{-5}$ m/GeV^3

$C_q = 3.832\times10^{-13}$ m

Problem 4 (Linac)

An ILC experimenter proposes to construct a cavity for use in the ILC injectors which has a geometry identical to the standard ILC 9-cell cavity but which operates at room temperature and is made from oxygen-free electronic grade (OFE) copper. The resulting cavity is found to have a wall Q value which is typical of 1.3 GHz copper cavities, $Q_w \approx 22{,}000$.

(a) What is the approximate R/Q of this cavity, given that the superconducting ILC cavity has R/Q = 1036 Ω?

[1 point]

(b) What is the shunt impedance of this cavity?

[2 points]

(c) What are the wall losses in this cavity at a voltage of 32.8 MV (ie, the nominal ILC cavity voltage)? Assuming a pulse width of 1 ms and a repetition rate of 5 Hz, what is the average power into the cavity walls?

[2 points]

(d) During steady-state operation with 9 mA beam current, what input power is required to sustain 32.8 MV? Assume that the coupler is properly matched to the current (ie, at 32.8 MV and 9 mA the field emitted from the cavity and the field from reflected energy are equal and opposite, so no net power flows away from the cavity back towards the klystron).

[2 points]

(e) Imagine that someone proposed to build a linac out of cavities of the type described above, operating at 32.8 MV with 1 ms pulse length and 5 Hz repetition rate. What is the total voltage achieved when the average power dissipated in the cavity walls equals the total site power of the ILC (240 MW)?

[3 points]

(f) For a bunch with the nominal ILC charge but 1/3 the rms length (q=3.2 nC, σ_z=100 μm), estimate the mean and rms decelerating voltage from the single-bunch longitudinal wakefield (you may use a 2-particle model for this estimate).

[2 points]

(g) For a bunch as described in (f), estimate the deflecting voltage experienced by the tail of a single bunch due to a cavity offset of 1 mm.

[2 points]

Problem 5 (LLRF & high power RF)

The rf systems of the main linac of the European XFEL must provide rf power for 736 cavities to accelerate the beam from 2.5 GeV to 20 GeV. Each rf station consists of 1 klystron driving 32 cavities. With a linac beam current of 5 mA and for on-crest operation, calculate:

(a) the average gradient of the cavities (cavity length 1.038 m).

[2 points]

(b) the rf klystron power required for each rf station if the complete power is transferred to the beam. It is assumed that the Lorentz force detuning is compensated with the piezo tuners.

[2 points]

(c) the loaded Q required to achieve the matched condition in (b). Matched conditions exist if the beam induced voltage is equal to the accelerating voltage. The normalized shunt impedance (R/Q) of the cavities is 1036 Ω.

[2 points]

(d) the cavity phase fluctuations of a single cavity at the loaded Q from (c) if the microphonics noise level is 10 Hz (rms). The relation of detuning angle Ψ to detuning Δf is given by $\tan(\Psi) = 2 \cdot Q_L \cdot \frac{\Delta f}{f}$.

[2 points]

(e) What feedback gain G is required for the control of a single cavity to suppress the residual phase error to 0.1 deg. (rms) if the phase errors are suppressed by the factor (1+G).

[2 points]

(f) What are the phase fluctuations of the vector-sum of 32 cavities for the conditions in (d) if the errors in the individual cavities are uncorrelated? What is the required feedback gain under these conditions to achieve a vector-sum phase stability of 0.1 deg. (rms) ?

[2 points]

Problem 6 (Superconducting RF)

Here we consider the critical field of SRF cavity made of type-II superconductor like niobium.

(a) Using Abrikosov theory, derive the formulas for λ (field penetration depth) and ξ (coherent length) in terms of Hc (statistical critical magnetic field) and Hc2 (upper critical magnetic field).

[2 points]

(b) The temperature dependences of Hc and λ are given by both the Abrikosov theory and experimental result as follows:

$$\lambda(T) = \frac{\lambda(0)}{\sqrt{1-\left(\frac{T}{T_C}\right)^4}}, \quad H_C(T) = H_C(0)\cdot\left[1-\left(\frac{T}{T_C}\right)^2\right].$$

Stating with these T dependences, derive the formulas for Hc2(T), ξ(T), and κ(T)=λ(T)/ ξ(T).

[2 points]

Here we calculate RF parameters from an output of SUPEFISH, which is often used for SRF cavity designs.

(c) When you have a set of output from SUPERFISH RF as following:

f=1293.77430MHz (RF resonance frequency),
Ploss=1118.1551 W (power loss on the cavity inner surface),
Qo=28257.6 (unload Q-value)
(Rsh/Qo)=109.24 Ω,
Hp=1753.44 A/m (surface maximum magnetic field),
Ep=0.946176 MV/m (surface maximum electric field),
Γ (geometrical factor)=265.171 Ω,

calculate the following cavity RF parameters:

Rsh (shunt impedance)=
V (accelerating voltage)=
Eacc (gradient)= $\frac{V}{L_{eff}}$ = here, use Leff = λ/2
Eacc[V/m]= $Z\cdot\sqrt{P_{loss}\cdot Q_O}$, Z=

[2 points]

(d) The cable correction factors in the vertical cryogenic test are measured as follows:

Cin=685.8 (for input power)
Cr=6127(for reflected power)
Ct=19.45(for pick up power).

You measured following values:

Cavity frequency=1303.590529 MHz
$\tau_{1/2}$ (decay time) =23.6 ms
Coupling is $\beta>1$ (over)

RF powers in your control room are:

Pin=3.11mW (input power)
Pr=192 nW (reflected power)
Pt=0.142 mW (pick up power).

Using the cavity RF parameters in (d), calculate the following quantities:

Pin (at the cavity)
Pr(at the cavity)
Pt(at the cavity)
Ploss
Q_L
Qo
Qt
Rs (surface resistance)
Eacc
Ep

[5 points]

Problem 7 (Beam delivery & beam-beam)

There are five multiple choice questions. Circle the correct answer. Attach separate pages showing your calculations/explanations. Points are given according to both your answer and your calculation/explanation.

(a) Beam of 150 GeV electrons with non-normalized rms vertical emittance ε_y=1.2e-13 m, has the following vertical rms size in front of the final focusing quadrupole: σ_y=60 μm. The final quadrupole length is L_Q=1 m and its gradient is G=20 kGs/cm. What is the vertical beam size at the IP, assuming that the energy spread in the beam is zero:

a. 5 nm
b. 10 nm
c. 20 nm

[2 points]

(b) The above mentioned final quadrupole, as well as the vertex detector at the IP, have radius of their aperture equal to a=1 cm. What is the approximate vertical collimation depth needed to prevent synchrotron radiation photons produced by beam halo in the final quadrupole to touch any IP apertures:

a. 50
b. 150
c. 167 nm

[3 points]

(c) Survivability of spoilers in the collimation system depends on the following parameters (circle the one which is NOT relevant):

a. Vertical beam size in the final quadrupole
b. Vertical collimation depth
c. Horizontal beam size in the location of spoiler
d. Fractional population of the beam halo
e. Number of electrons in the bunch
f. Material properties of the spoiler

[2 points]

(d) In the final focus with local chromaticity correction, the two sextupoles embedded in the final doublet compensate:

a. Vertical and horizontal chromaticity produced by final quadrupoles;
b. Horizontal and twice of vertical chromaticity produced by final quadrupoles;
c. Vertical and twice the horizontal chromaticity produced by final quadrupoles

[3 points]

(e) ILC-like trains of bunches with IP sizes σ_y^*=10 nm and σ_x^*=500 nm are collided with assistance of intra-train feedback. What initial offsets between trains could be reliably corrected by the feedback (capture range):

a. approximately 5 nm;
b. approximately 250 nm

[2 points]

Problem 8 (Instrumentation & control, Operations)

(a) The ILC 'RTML' has ~ 2% energy spread, max dispersion = 100 mm, beta function = 50 m, with a 5 GeV beam. Use

$$\sigma = \sqrt{\beta\varepsilon + \eta^2\delta^2}$$

to estimate the beam aspect ratio. Why is it hard to measure the vertical beam size accurately? (also include 3:1 β_x/β_y variation expected in a reasonable lattice)

[3 points]

(b) From the energy loss per turn, estimate the watts/cm dissipated on the damping ring vacuum chamber surface. (hint – the entire beam energy is radiated away each damping time)

[3 points]

(c) Given the beam delivery dipole bending radius (100 km), estimate the electron beam energy above which the critical synchrotron radiation will liberate neutrons from the surrounding material.

[3 points]

(d) Explain what happens to power flow in the ILC linac when the beam goes away.

[3 points]

Problem 9 (CLIC)

(a) What are the main advantages of the 'Drive Beam' compared to the direct use of klystrons for the acceleration of the main beam?

[2 points]

Assume you want to generate a 120 A drive beam for a CLIC type collider with a frequency of 18 GHz. Further assume that the initial beam pulse must have a beam current below 5 A (not included!), the initial bunch repetition frequency can be in the range of 0.5 – 1 GHz.

(b) What configurations of Delay Loop (DL) and Combiner Ring(s) (CR) can you use? Remember you need one Delay Loop, and keep the multiplication factor in each CR ≤ 5. Choose your preferred solution among the possibilities, keeping the number of CRs minimal.

[3 points]

(c) What is your initial beam current?

[1 point]

(d) What is your initial bunch repetition frequency?

[1 point]

The final RF pulses (= bunch train pulse length) are to have a length of t_p = 100 ns. (Hint: this determines the length of the DL. If you have more than one CR, keep the highest multiplication factor for the last combination stage.)

(e) What is the length of the DL and the CR(s)?

[2 points]

(f) What are the frequencies of the RF deflectors?

[2 points]

(g) Sketch the time structure (pulse length and pulse distance) of the pulses after the DL and each CR.

[2 points]