DEVELOPMENTS TOWARDS A FULL ENERGY RECOVERY LINAC

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Abstract

Energy Recovery Linacs (ERLs) are high potential drivers for light sources based on laser Compton scattering with high brilliance photon beams and sub pico second time structure [1]. We report on developments for an advanced ERL design, which allows the recovery of nearly full electron beam energy up to the limits set by the energy width of the beam. This "Full" Energy Recovery Linac (FERL) allows a substantial reduction of the complexity of the accelerator systems resulting into a very compact light source design suitable for industrial and medical applications.

INTRODUCTION

Beam energy recovery allows the acceleration of high beam currents with low rf power consumption. This statement is valid only for the recirculating part of the accelerator. The injector however accelerates the full beam current at high rf power levels up to the funnelling energy in the range of 5 to 15 MeV. This results in two parallel developments for ERL accelerator structures and sub systems. The first kind of structures handles low rf power at high accelerating gradients in the recirculating part of the accelerator. The other kind of structures has to handle with high rf power levels at small gradients. Besides that one has to provide also both high and low power rf amplifiers and couplers.

The FERL design [2] integrates the injector into the re-circulating beam path (s. Fig. 3). Coaxial injection avoids the problem of beam funnelling at multi MeV energy level for emittance preservation. Since initial and recirculating beam run parallel from the starting point, there is no need for dedicated high power rf structures at the injector level.

Due to the low injection energy the extraction energy can be reduced also. The energy limit is the energy width of the beam determined by longitudinal beam dynamics and the energy loss by Compton scattering. Simulations show the feasibility to reduce the energy at the beam dump to less than 0.5 MeV. This apparently reduces the radiation power and energy at the beam dump by more than a factor of 10.

SRF GUN INJECTOR

The beam is injected into the FERL by a superconducting rf gun (SRF gun) with a tubular cathode. The special cathode geometry allows a coaxial injection of the initial beam to the recirculating beam. The srf gun design is based on a 1.3 GHz 3 ½ cell cavity with TESLA geometry with a thermally isolated photocathode plug [3, 4] (s. Fig. 1). The thermal insulation compared to the surrounding cavity allows the extension of the cathode diameter sufficiently for parallel guidance of the injected and the re-circulated beam without compromising the cryogenic losses of the SRF gun.

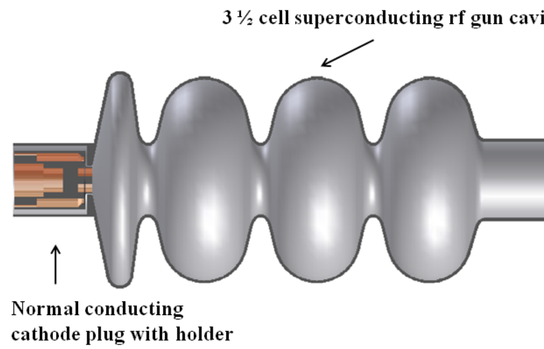

Figure 1: Cross section of the SRF gun cavity.

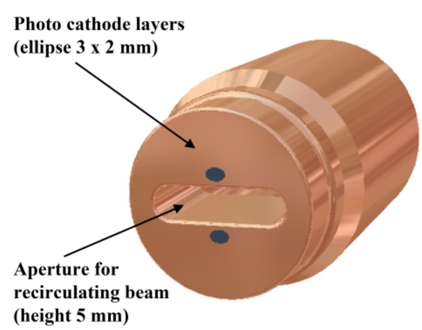

Figure 2: Copper cathode plug.

The cathode plug is made of OFHC copper hold by a liquid nitrogen cooled support structure. The rf surface of the cavity and the plug are separated by a 1 mm vacuum gap. A rf choke filter avoids rf power propagation through the gap towards the direction of the backward beam tube. A special choke design using liquid nitrogen (LN_2) as dielectric and coolant is integrated into the cathode support structure. The cathode has two elliptical photocathode layers on its cavity facing surface, placed symmetrically on both sides of the median aperture of the cathode plug (s. Fig. 2). The recirculating beam is directed through the central aperture from the back side of the gun.

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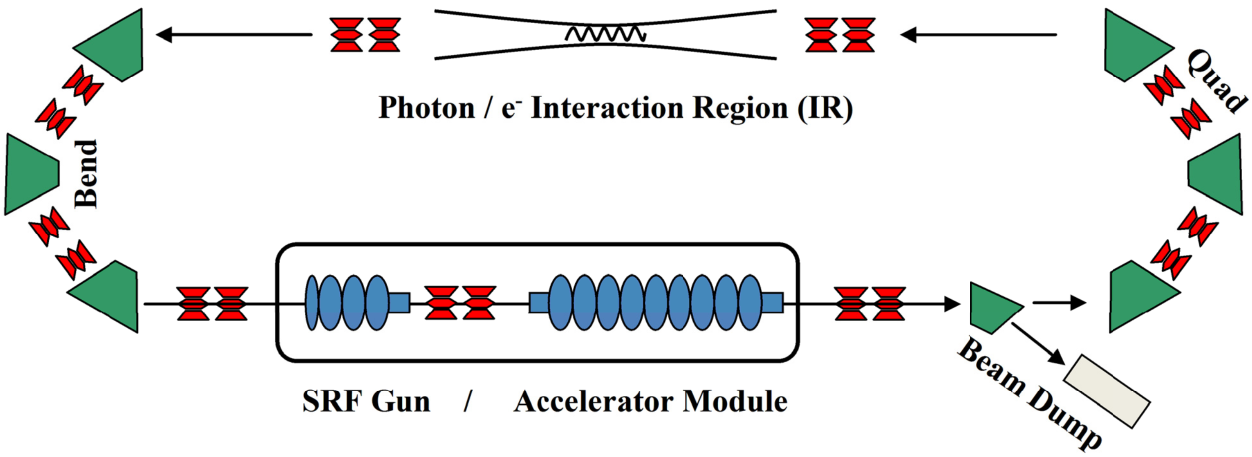

Figure 3: Layout of the FERL.

BEAM DYNAMICS SIMULATION

Numerous simulation runs have been conducted to get a first optimisation level for the FERL's new design features. These refer mainly to the coaxial beam path of initial and recirculating beam and different cathode geometries to maximize the beam brilliance at the interaction region. In order to simplify the simulations in the early design stage the FERL setup was simplified to a sequential setup of two identical linacs. The first one generates the initial acceleration phase and the second one the following deceleration/energy recovery phase. From the afore mentioned follows, that emittance deteriorating effects like coherent synchrotron radiation etc. from bends were neglected.

Table 1: Simulation Setup and Results

Accelerator Configuration	
module 1	srf gun + 1 nine cell cavity
module 2	2 nine cell cavities
f_{op}	1.3 GHz
E_{acc}:	15 MV/M
Beam Parameters	
bunch charge	50 pC
final energy@IR	53 MeV
norm. emittance ε_x @IR	beamlet: 1 mm mrad total: 16 mm mrad
norm. emittance ε_y @IR	total: 1 mm mrad
energy @ beam dump	0.5 MeV

The standard accelerator lattice was built from 1.3 GHz nine cell structures (TESLA type cavity) bundled in pairs into one accelerator module. Intermediate doublets and triplets were employed for matching the beam between the modules and to the interaction region. The simulations were performed with the PARMELA/SUPERFISH software package [5] from Los Alamos National Laboratories. Table 1 lists the accelerator configuration and results for a typical simulation run.

Interaction Region

Figure 4 shows the transverse phase space of the beam at the interaction region. Due to the two photocathode layers the beam consist of two beamlets, each with an emittance around 1 mm mrad for a moderate beam charge of 50 pC.

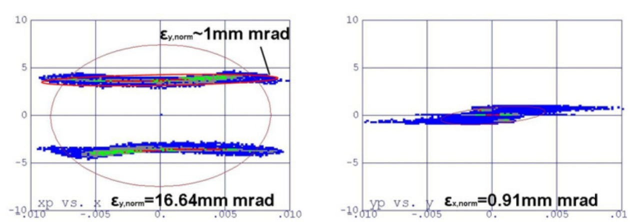

Figure 4: Transverse phase space at interaction region.

This leads to a relatively large transverse emittance of 16 mm mrad in the symmetry plane intersecting both photocathode spots. For Compton scattering applications this fact will be of secondary concern, since the incident laser beam will be matched to the trajectory of the individual beamlet at the interaction point.

Beam Dump

The coaxial injection allows the deceleration of the spent beam to an energy level nearly ten times lower than conventional ERL designs. The minimum energy of the dumped beam is mainly limited by two effects. The first one is the beam loss due to space charge blow up for high bunch charges (>50 pC) and the second one is the beam loss due to rf defocusing for low charge bunches.

A very effective way to cure these two effects is a geometry modification of the last accelerating cavity in front of the beam dump. We used a nine cell cavity with a low beta ($\beta \approx 0.5$) end cell, which is basically a reversed multi cell rf gun cavity (s. Fig. 5). The rf focussing of the last low beta cell cures the beam blow up when the spent beam is decelerated to low energies and directs the beam safely out off the superconducting accelerator module, where any beam loss is critical. For bunch charges with nearly negligible space charge forces a deceleration to 250 keV showed to be feasible for our simplified simulation setup.

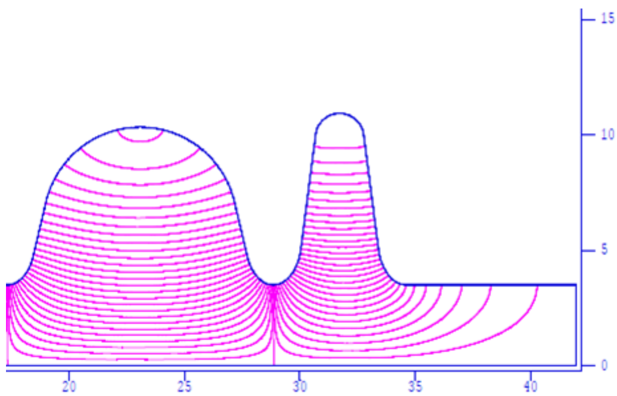

Figure 5: RF field of reduced beta end cell (π-mode).

HOM DAMPING

An efficient damping of higher order modes (HOMs) is essential to shift the beam break-up limit of ERLs as for FERLs to high average beam currents in the range of several 100 mA. Current HOM damper designs contribute significantly to the complexity of the accelerator structure's rf design and resulting costs. A new design approach combining the function of a coaxial fundamental mode power coupler with HOM extraction (s. Fig. 6) is analyzed. Similar designs were already tested either for fundamental mode coupling or for HOM extraction (s. e.g. [6]) without combining both functions. The basic problem is to realise a sufficiently low external Q for the HOMs (10^3 to 10^5) and to provide a high external Q for the fundamental mode ($>10^7$) the same time. The basic solution is to place a fundamental mode rejection filter near the tip of coaxial coupling antenna. The HOMs are extracted through the coaxial line to a rf load outside the cryostat, which is isolated from the fundamental mode frequency by a high pass rf filter.

The choke filter uses liquid nitrogen as coolant and dielectric. LN_2 is an excellent dielectric with a dielectric constant ε_r=1.54 and a very low tan $\delta=5.2*10^{-5}$ in the high frequency range [7, 8]. The choke resonator volume is separated from the beam line vacuum by a cylindrical Alumina ceramic. Using LN_2 as dielectric has two main advantages. Firstly it is an efficient coolant removing the rf losses from the copper choke resonator and cooling it to a temperature level, which can be maintained easily in the vicinity of the superconducting cavity surface without causing excessive thermal radiation. Secondly LN_2 as liquid dielectric suppresses multipacting inside the choke resonator, which limits the rf performance of vacuum filled choke designs. A third benefit is the in situ tunabilty of the choke filter by changing the cooling from LN_2 to gaseous nitrogen. The dielectric constant changes from ε_r=1.54 to approx. 1, which detunes the choke resonator more than 10 times its -20 dB bandwidth. This results into a strong over coupling of the accelerator cavity usable for rf processing.

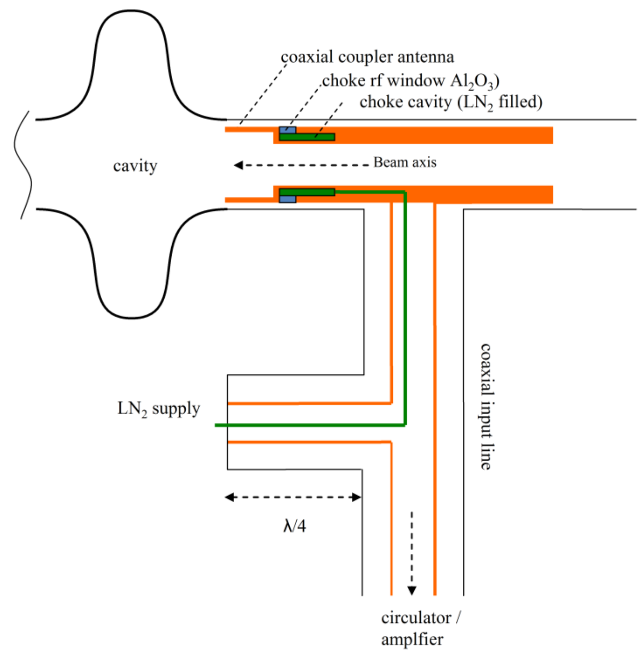

Figure 6: Layout of LN_2 choke HOM damper.

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