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AN X-BAND LINEARISER FOR THE CLARA FEL

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Abstract

The CLARA FEL under construction at Daresbury Laboratory will employ four S-band linacs to accelerate electron bunches to 250 MeV/c. In order to compress the bunch sufficiently to achieve peak currents suitable for FEL lasing, one must compensate for curvature imprinted on the longitudinal phase space of the bunch. For CLARA a harmonic RF linearization system has been designed to achieve this requirement. The linearization will be achieved by an X-band travelling wave cavity of the PSI/CERN design, which incorporates wake-field monitoring of the bunch position. A five-axis mover will align the cavity to the beam axis. Pulse compression of a 6 MW klystron pulse will provide the required power to achieve a 30 MV/m operational gradient.

INTRODUCTION

CLARA at Daresbury Laboratory [1] is the UK's National Free-Electron Laser test facility, the results from which will inform the design of a future UK-XFEL user facility.

CLARA will have a maximum beam momentum of 250 MeV and FEL radiation will be produced in the 100-400 nm range. The intention is to test and validate new FEL schemes in areas such as ultra-short pulse generation, temporal coherence and pulse-tailoring.

In order to efficiently drive the FEL interaction, a high peak current, low emittance beam must be delivered to the FEL undulator section.

The S-band CLARA RF system currently consists of an RF photoinjector and a 2 meter linac, and is capable of reaching a beam momentum of 49 MeV/c. This will be augmented by three 4 meter linacs to reach the final momentum of 250 MeV/c. Two diagnostic dipole mode transverse deflecting cavities will allow longitudinal beam characterisation. The focus of this paper is the x-band fourth harmonic cavity (4HC), which will allow linearization of the longitudinal phase space of the electron bunch

LINEARISER REQUIREMENT

Four dipole compression will be used to achieve short bunches down to 200 fs RMS for the CLARA FEL. For this compression method the pulse must have a longitudinal energy chirp, provided by off crest acceleration in the four S-band linacs. However, this leaves a curvature in the longitudinal phase space, which must be corrected by a higher harmonic cavity at decelerating phase. The cavity compensates for the non-linear energy-time correlation imprinted on the bunch.

Figure 1 below shows a typical bunch compression scheme in CLARA. The plots each show the energy deviation along the bunch at three stages. In black we see the bunch at 150 MeV/c before the lineariser, in blue the bunch after the lineariser, and in red the bunch after compression and acceleration to 250 MeV/c. In the upper plot the lineariser is at 30 MV/m, and the lower plot it is off. The bunch is compressed to 0.8 ps with the lineariser on, and to 1.7 ps with a clear nonlinearity without the lineariser.

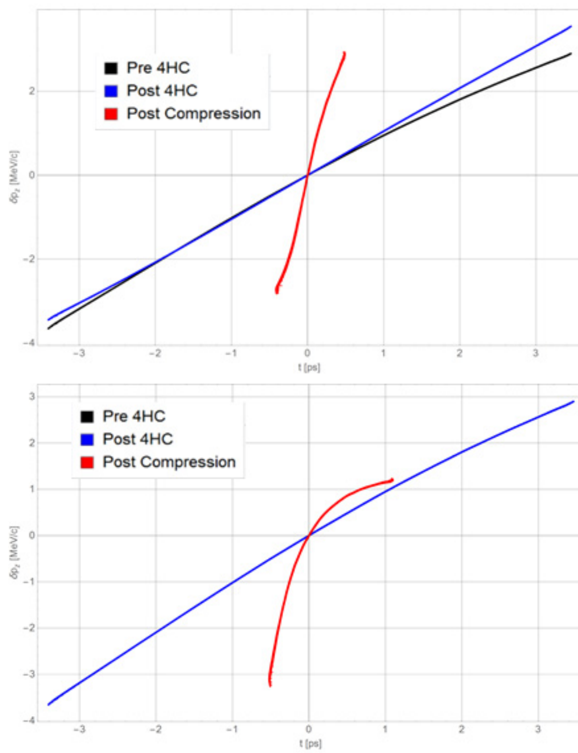

Figure 1: Bunch compression in CLARA with (top) and without (bottom) the linearising cavity.

X-BAND CAVITY

Cavity Choice

An 11994 MHz X-band system operating at the fourth harmonic of the CLARA S-band operating frequency was chosen due to availability of technology at this frequency. A maximum operational voltage of 22.5 MV was required, with a maximum space in the lattice of 1 m. The cavity must operate at 100 Hz, and the RMS amplitude jitter must not exceed 0.1%. The RMS phase jitter tolerance is 0.3°, these values come from the 10 fs arrival time jitter requirement [1].

The PSI-CERN X-band cavity [2] was the baseline for our cavity selection. This constant gradient travelling wave cavity has a minimum aperture size of 8.24 mm, a phase advance of 5π/6, and could achieve a 30 MV/m gradient over the 0.75 m active length with 16.3 MW of input power. The design frequency is 11992 MHz but the cavity has a 10 MHz tuning range.

This cavity is operational as a linearising cavity at the SwissFEL injector facility [3] and FERMI@ELETTRA [4] it is powered directly (with no pulse compression) in both cases by a 50 MW klystron at 100 Hz. This enables gradients up to 40 MV/m to be reached, higher than our requirements.

New design cavity options considered included a 7π/8 phase advance structure and a 5π/6 phase advance structure with nose cones. Both options have minimum beam apertures larger than 10 mm, which would be beneficial for minimisation of wake-fields and ease of beam steering.

The large aperture allows nose cones to be considered to increase shunt impedance, and keep the group velocity within the required values. The 5π/6 phase advance structure used varying nose cone length to achieve a constant gradient structure. The structure had high peak fields, up to 160 MV/m at 30 MV/m accelerating gradient. This can be seen in Figure 2. The structure also had a higher power requirement than the baseline structure.

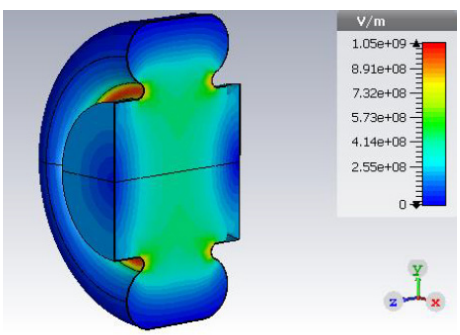

Figure 2: High peak fields in nose-cone region of 5π/6 structure. Divide scale values by 6.6.

Higher phase advances lower a structures group velocity but using very large apertures can compensate for this. The viability of the 7π/8 phase advance structure was studied with respect to error tolerance. Field flatness sensitivity is known to increase with phase advance, but it was found in preliminary studies that this could be compensated for by increasing the structure group velocity slightly, although the studies did not go as far as including the coupler.

Also considered was a scheme of 4 independently powered standing wave cavities, which would allow for approximately 12 mm iris diameters. This would be a simple cavity design and low power requirements for each cavity, but would require 4 in-phase RF feeds as well as klystron protection from reflections. The associated costs of the multiple high power RF inputs as well as the lower tolerances in the cavity fabrication meant this prospect was not viable from an economic perspective.

An aperture gain of less than 2 mm did not merit the risk of an untested structure, which would require significant RF and mechanical design effort. As this effort was not available it was decided to adopt the proven solution of the PSI-CERN cavity. The cavity will be fabricated at CERN.

Alignment Monitors

The PSI-CERN cavity structure has integrated wakefield alignment monitors. These will be used on CLARA, along with a 5-axis actuator platform to provide beam-based alignment of the cavity. The wake field monitors can be seen in Figure 3 [5].

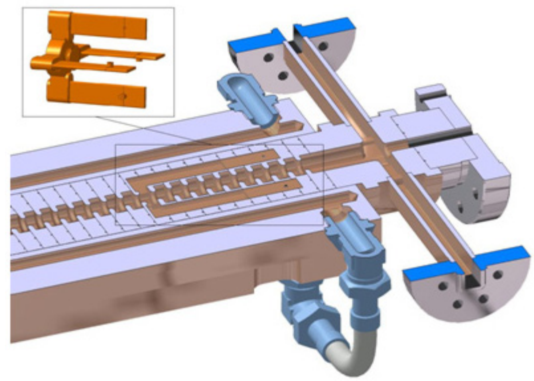

Figure 3: Model of PSI-CERN cavity showing integrated alignment monitors.

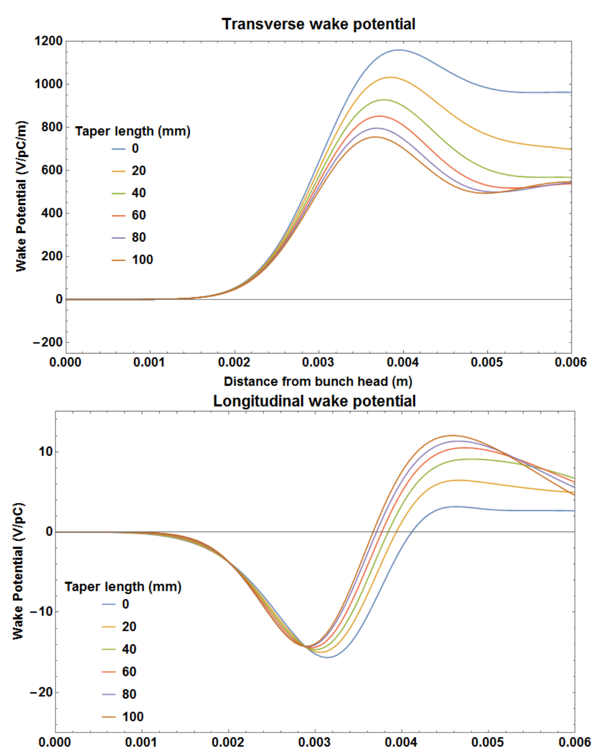

Figure 4: Transverse and longitudinal wake potentials with varying taper lengths.

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Wake-field Simulations

The standard beam pipe on CLARA has a diameter of 35 mm, and the cavity beam pipe diameter is 10 mm. The space for tapers between the two is very short, less than 100 mm each side. A preliminary simulation performed in ABCI found that short tapers had little effect on either transverse or longitudinal wake potentials. The transverse and longitudinal wake potentials for varying taper lengths can be seen in Figure 4.

This simulation coupled with more rigorous simulation of short tapers for cavity beam position monitors on CLARA lead to the conclusion that short tapers offer little to no mitigation of negative wake-field effects, and in fact can increase deleterious wake field potentials. Tapers will therefore not be used.

RF SYSTEM

An overview of the high power RF system for the linearising cavity can be seen in Figure 5. The RF amplification system will consist of a modulator, one 6 MW klystron, and a SLED I type pulse compressor. This was chosen to be the most economical choice from the available technology.

The pulse compressor will be of the CLIC design [6]. The waveguide system will be under vacuum, and directional couplers with ceramic windows will allow measurement of the forward and reflected RF.

The cavity vacuum will be separated from the waveguide vacuum for machine safety and operational reasons. This function will be performed by a ceramic window.

It is currently planned to use a 3D printed spiral load, designed at CLIC [7]. These have been tested on the CERN X band test facilities up to 35 MW peak power.

The power losses along the beam line have been calculated and 19.8 MW at the cavity is expected.

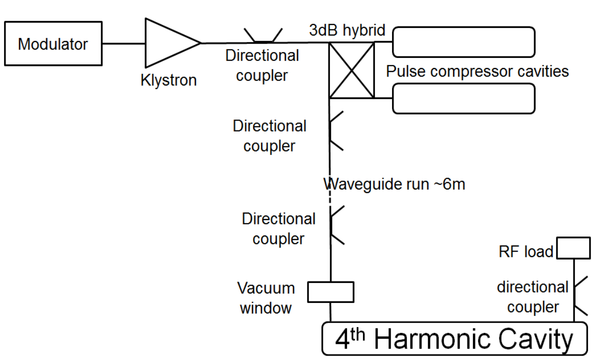

Figure 5: Overview of high power RF system.

Low-level RF

The low level RF will be provided by an I-Tech Libera system the same as that currently operating on the S-band RF systems of CLARA. This will combined with a frequency converter to perform the up- and down- conversion of the forward and measured signals. This system is capable of amplitude and phase adjustment of the output signal in 8 ns steps, allowing the phase flip for operation of the pulse compressor to be optimised as required.

Pulse Compression

To produce a transmitted pulse from the pulse compressor with a region of constant phase and amplitude comparable in length to the fill time of the structure it is necessary to modulate the input.

Optimised phase and amplitude ramps have been generated in simulation to accomplish this. For a 120ns flat top pulse with constant phase a power multiplication factor of 3.8 is expected. Figure 6 shows an example of the compressed pulse.

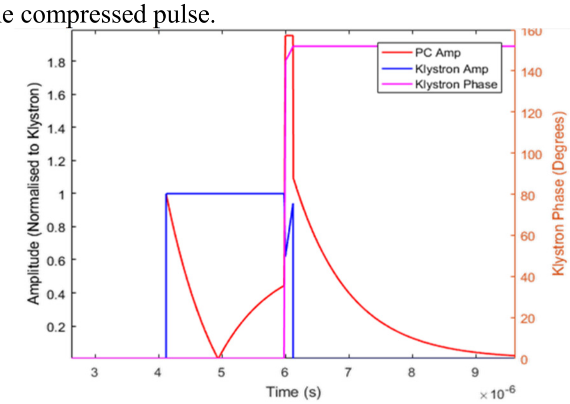

Figure 6: Simulated pulse compressor output, showing klystron amplitude (blue), klystron phase (pink) and compress pulse envelope (red).

Alternatively, for applications where transmitted phase is unimportant i.e. structure conditioning, it is possible to achieve a higher gain with steady amplitude by modulating only the input phase. Simulations predict a power gain of 4.33 is possible by varying the phase while keeping the amplitude at its maximum.

Pulse Compressor Tuning

In practice, the pulse compressor cavities are susceptible to detuning due to temperature deviation during operation. The consequences of this have been investigated in simulation.

If the cavities are not tuned correctly a drop in gain and degradation of the flat top occur. These effects are most significant when both cavity frequencies are increased by 100 kHz.

When the cavities are detuned the transmitted phase changes, notably all combinations still maintain an approximately constant phase during the flat top. Increasing one or both resonant frequencies results in an increase in the transmitted phase while conversely, decreasing one or both decreases the transmitted phase relative to the klystron signal. If the cavities are detuned in opposite directions by an equal amount, the net effect on the transmitted phase is negligible.

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