BEAM ENERGY REPLACEMENT IN A COMPACT FEL

M W Poole and P A McIntosh,
CLRC Daresbury Laboratory, Warrington WA4 4AD, UK

G Saxon
Private Consultant, Bramhall, Cheshire, UK

M de Wijs
Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, Netherlands

Abstract

To achieve high energy extraction from a compact FEL requires a method to negate the energy loss from the electron beam. A number of proposals have been made to incorporate an accelerating system within the FEL to overcome this restriction. The present study has examined various RF structures that can be conveniently integrated with an undulator magnet and has assessed the resultant performance limitations of possible infrared FELs. The muffin-tin geometry has been shown to be feasible for longer output wavelengths, whereas a side-coupled structure looks more promising below 50 µm. Magnet design options have also been explored and solutions for practical FELs are proposed that should allow high power output despite relatively low electron energies.

1 BACKGROUND

Free electron lasers (FELs) have now demonstrated that they can provide a unique source of radiation with a combination of very high power and wide tunability [1]. They have been operated from the millimetre wave region all the way down to the present record of 240 nm, but their greatest success so far has been in the infrared (IR) regime where many user facilities have now been established [2]. Despite the lack of a material lasing medium FELs still encounter a saturation phenomenon that is due to a desynchronisation of the energy exchange process as the electrons give up their energy to the laser field. The gain curve has a width $(2N)^{-1}$ for N magnetic periods in the device so that maximun energy transfer is limited to this fraction of the initial electron energy; in practice this limits the power efficiency of an FEL to about 1 % at saturation. Attempts have been made since the early days of FEL development to overcome this limit by employing a so-called tapering of the FEL undulator magnet properties along the interaction region [3,4]. Inspection of the output wavelength equation illustrates the requirement to vary either the magnet period λ_u or the field strength (or both) since:

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left[1+\frac{K^2}{2}\right] \qquad [1]$$

where K is the undulator parameter ($\sim\lambda_u B$). The magnet parameters are therefore scaled to match the changing γ (E/mc^2) along its length, maintaining resonance with the wavelength λ. However there are severe problems with this approach, most notably the fact that the single pass gain is significantly reduced: in fact a dynamic taper not acting before saturation is desirable. The best result so far achieved was a 4-5 % energy extraction in a Los Alamos experiment [5].

2 REACCELERATION SCHEMES

The alternative solution is to replace the lost electron energy and so to preserve the wave-particle synchronism. This was proposed both as a DC field scheme [6] and for use of microwaves [7], but the only active experimental project has been that of the Pantell group at Stanford. Their initial proposal [8] was to copper plate the poles of an undulator magnet to create an integrated accelerating structure. Because this was a permanent magnet structure its field strength was therefore necessarily fixed and the FEL could not be tunable, so the group adopted a novel staggered pole array driven by a variable superconducting solenoidal field. A 10 µm experiment with a predicted efficiency of 20 % (HEFEL - High Efficiency FEL) is underway with a $\pi/2$ mode structure that has been modelled and measured [9] and results are eagerly awaited.

This paper presents two alternative proposals that revert to the use of a conventional planar undulator geometry. The aim of the work is to demonstrate that a relatively simple device can be constructed and that the output power can be enhanced by at least an order of magnitude compared with FELs so far operated with similar electron accelerators. This higher power is the attraction, rather than the actual efficiency increase, since the latter is less important in most FEL applications.

In both versions the electron source is assumed to have comparable quality to the FELIX linac that was highly optimised for FEL use [10]. The shorter output wavelength scheme adopts a novel side-coupled structure.

3 A FAR INFRARED SOLUTION

The FEL arrangement is shown in Figure 1. It is a series of coupled cells reminiscent of a disc-loaded linac waveguide and it differs from the Stanford scheme in that the structure is distinct from the undulator magnet poles, allowing field variation of a pure permanent magnet (PPM) if desired by sliding of the poles. Assuming S-band operation the periodicity is defined by the operating mode, which has been assessed in MAFIA simulations by optimising critical dimensions [11]. The π mode has good shunt impedance and at 3 GHz implies a magnet period of 100 mm; it has been modelled with a (vertical) beam aperture of 40 mm.

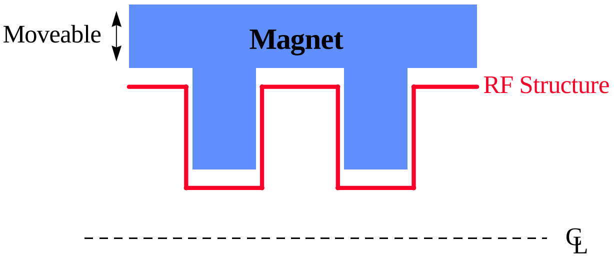

Figure 1: Moving Pole with Fixed Waveguide

It is most advantageous to maintain as low an electron energy as possible, based on cost, radiation shielding, space etc, and a target of about 10 MeV is attractive. Figure 2 plots the FEL output tuning range in this region and it is seen that a notional range of 100-300 μm is achievable at modest K values.

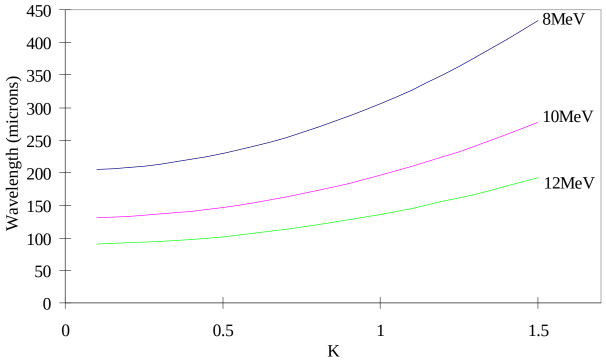

Figure 2: Output Tuning Range for 100mm Period

Selection of a suitable undulator magnet design has involved a comparison of permanent (NdFeB) and electromagnet technology, illustrated in Figure 3. A hybrid undulator arrangement (steel pole plus side magnets) is unattractive with the long pole piece here. Results of PANDIRA simulations confirm that the desired tuning range can be achieved with either solution, a maximum field of about 0.15 T being attainable (less than 10 A/mm^2 in the coils). The minimum magnet gap is 44 mm to provide for the waveguide wall thickness. The electromagnet solution is very promising for its ease of tunability; the illustrated pole taper reduces saturation effects (there is significant pole leakage in this geometry even for an on-axis field of only 0.15 T).

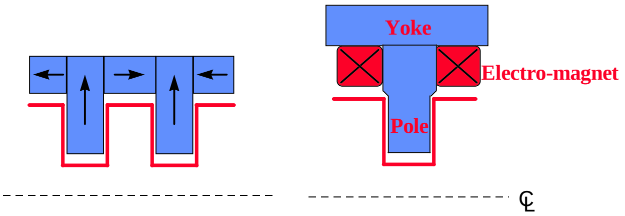

Figure 3: Alternative PPM and EM Schemes

The ideal small signal gain of an FEL based on this scheme with a 1 m undulator has been calculated to be in the range 35-60 % per pass at 100-300 μm in the absence of electron beam energy spread, emittance and short bunch length contributions, assuming the 70 A peak current achieved at FELIX [10]. The real transverse effects will depress this appreciably, by 10-15 % from energy spread and by as much as a factor 5 at the longest wavelength due to pulse lethargy. Nevertheless adequate gain is attainable for FEL operation. The layout of such an FEL is given in Figure 4, showing a common source of input power. Energy extraction occurs in the downstream part of the FEL after bunching has formed so the reacceleration is needed there. Although the input power should be ramped up in compensation as saturation approaches, with consequent need for fast phase and amplitude control, it will also be necessary to supply sufficient input to overcome beam loading losses.

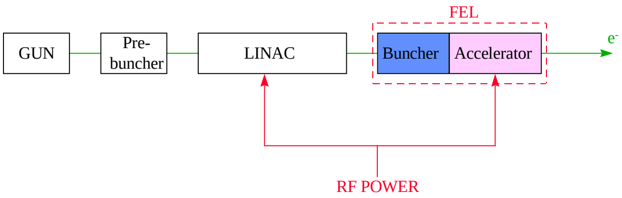

Figure 4: FEL Layout

No detailed calculation of the ultimate FEL output power limit has yet been performed but in principle it is only limited by factors such as input power and structure length. A 1 m waveguide has been estimated easily to replace 5 MeV or about 50 % of the electron energy, so a compact, high power FEL is realisable.

Finally an attempt has been made to see if the output wavelength could be shortened towards 10 μm without the need for much higher electron energies. The π/2 mode allows the magnet period to be decreased to 50 mm but no acceptable undulator magnet solution can be found without a comparable gap reduction. It became clear that the 40 mm aperture was close to the minimum to avoid waveguide cut-off problems in the coupling between cells so this approach was abandoned [11].

4 NEW STRUCTURE FOR SHORT WAVELENGTHS

The problem of inter-cell coupling could be overcome by adoption of a side-coupling philosophy, allowing the vertical aperture between accelerating cells to be closed down and magnet period reduced by use of the $\pi/2$ structure. Extending this idea further, the waveguide can be abandoned and replaced by an array of simple single cells, say the rectangular waveguide, half wavelength resonators as illustrated in Figure 5. It is then convenient to feed input power via slots from a parallel coaxial line that is also shown, as first proposed at Cornell [12]. Short circuiting this line creates a standing wave that can be suitably phased for cavity control. Textbook solutions can be used to study required cavity dimensions, which are very narrow in the beam direction and can also have a smaller height than the waveguide structures, easing the magnet design. Properties of the TE_{101} mode are readily obtained but MAFIA checks have also been done [11].

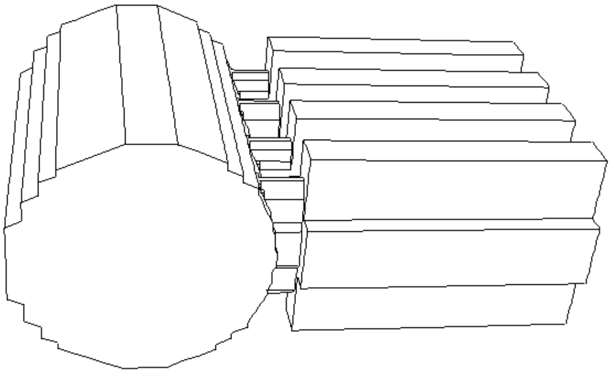

Figure 5: Side-coupled Rectangular Cell Array

As an example take a beam energy of 25 MeV and a target energy extraction of 20 %, suggesting a reaccelerating gradient of 10 MV/m across cells of about 10mm width (ie 100 kV) that fill around 50 % of the space. A calculated cell shunt impedance of about 0.5 MΩ implies about 30 kW per cell to achieve this but the demand will be doubled by beam power for a 0.3 A electron current. A total RF input of 3-4 MW into about 60 cells will be sufficient.

This solution has a length of 1.5 m and therefore a required undulator with 30 periods of 50 mm. The magnet gap can be quite small since RF considerations no longer limit it, nor are IR radiation diffraction effects critical in a short device. However the electromagnet is no longer feasible in such a compact design so a PPM has to be used. With a 20 mm aperture a maximum K of 1.3 is reached and the tuning curve is shown in Figure 6; for a 15 mm gap a K of 1.7 is attainable.

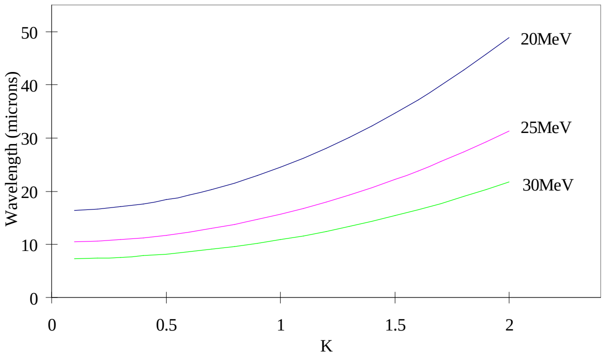

Figure 6: Output Tuning Range for 50mm Period

As an example, the calculated gain of such an FEL, again assuming a FELIX-type electron beam, would then be more than 20 % per pass at 20 µm.

5 CONCLUSIONS

Two promising schemes to integrate accelerating structure with an FEL undulator have been identified. The first is a π mode waveguide that can be used with a far infrared FEL (beyond 100 µm) and the second is a novel solution achieving much shorter wavelength output by use of a series of short single cells with side coupling to allow undulator magnets with small gaps to be inserted between them. In each case adequate gain can be obtained and the prospect of at least 20 % energy transfer from the electron beam achieved in a compact device.

It is intended to carry out a full simulation of anticipated FEL behaviour, including evolution of electron beam properties during operation. This will determine the optimum energy replacement profile, both in space and time. Measurements on model structures of all types will be compared with these theoretical results.

REFERENCES

[1] M W Poole, Rev Sci Instr 63 (1992) 1528
[2] P W van Amersfoort, Proc EPAC-94, London, p 83
[3] C A Brau, IEEE J Quant Electron QE-16 (1980) 335
[4] N M Kroll et al, IEEE J Quant Electron QE-17 (1981) 1436
[5] D W Feldman et al, Nucl Inst Meth A285 (1989) 11
[6] A Gover at al, J Appl Phys 53 (1982) 124
[7] T Taguchi et al, Phys Quant Electron 9 (1982) 849
[8] A H Ho et al, IEEE J Quant Electron QE-23 (1987) 1545
[9] J F Schmerge et al, Nucl Instr Meth A341 (1994) 335
[10] C A J van der Geer et al, Nucl Instr Meth A334 (1993) 607
[11] P A McIntosh and M W Poole, these Proceedings
[12] R Sundelin et al, IEEE Trans Nucl Sci NS-24 (1977)