PULSED UNDULATORS FOR HIGH EFFICIENCY FEL OSCILLATORS USABLE IN THE VISIBLE SPECTRUM

Hubert LEBOUTET
c/o CEA-DAM (Service PTN) BP 12 91680 Bruyeres le Chatel

ABSTRACT The problem for reaching high efficiencies in RF-linac driven FEL's , is to cross the perturbed region between the small signal and the large-signal operation due to large phase shifts variations.

We consider the FEL as a Traveling-Wave-Tube (TWT) or the reverse of a tapered buncher as in an electron accelerator The equivalent transverse gradient is

$$E_{||} = \frac{K}{2\gamma} . E_{\perp}$$

.The difference with a TWT is that the EM beam instead of being guided inside a waveguide , is in free space

A- ASSUMPTIONS :

1-multi-pass operation : the build-up of the oscillation requires 100 to 200 turns (order of 1μs)

2-gain per pass 1.02-1.03 in gradient to compensate losses and useful power : E=Const

3-efficiency : energy transfer - electrons-to-EM - at each pass: For a 20% efficiency , the product $p(1+\frac{K^2}{2})$ has to change about 40-50% in value along the undulator during the steady-state operation .

4-spontaneous emission does not contribute to a substantial amount to the exchange of energy between the electron beam and the EM wave. Harmonics can be considered , eventually as a nuisance for the mirrors ,or as a low power source .

5-Coupling impedance :

Two conditions are necessary for a substantial exchange of energy between beam and RF :

a/ the beam current must carry a large component at the frequency of operation , -means good bunching-

b/ the line must create a coupling impedance Z which ,in the case of a perfect undulator and a transverse wave , in ideal conditions , is simply

$$Z = \frac{K}{\gamma}\sqrt{\frac{\mu_o}{\varepsilon_o}} = \frac{K}{\gamma}\,\eta$$

This is true as well for the fondamental or harmonics if we would like to generate them with an acceptable efficiency.

B-EQUATIONS

p is the period and K (.94 B.p) the conventional undulator factor . They are defined for one full period

Since the period and the magnetic field may vary , we introduce a coefficient proportional to the inverse of phase velocity , versus a reference given by p_o and K_o :

$$\alpha^2 = p_o(1+\frac{K_o^2}{2}) \,/\, p\,(1+\frac{K^2}{2})$$

The abscissa is refered to the period or fraction of period : x is the independant variable

$$dz = p(x)\,dx$$

and we use the two equations for phase and energy along the line :

$$\frac{d\Psi}{dx} = 2\pi\left[(\alpha-1+\alpha u)\frac{\alpha+1+\alpha u}{\alpha^2(1+u)^2}\right]$$

$$\frac{du}{dx} = -\frac{K}{1+\frac{K^2}{2}} \cdot \frac{E\lambda}{m_o c^2} \cdot \frac{1}{\alpha^2(1+u)} \cdot \text{Sin}\,\Psi \qquad u = \frac{\gamma}{\gamma_o} - 1$$

In these equations , the wavelength enters as the scaling parameter $E_o\lambda$.

The "transfer coefficient" a is the sum of the values of u over all phases calculated at each period .

C- UNIFORM UNDULATOR and UNIFORM-TAPERED :

Fig 1 and 2 summarize the results in those two conventional situations . The data come in two sets of curves : evolution of phase and energy along the line for each value of the RF level (Eλ) , and value of the transfer efficiency v Eλ.

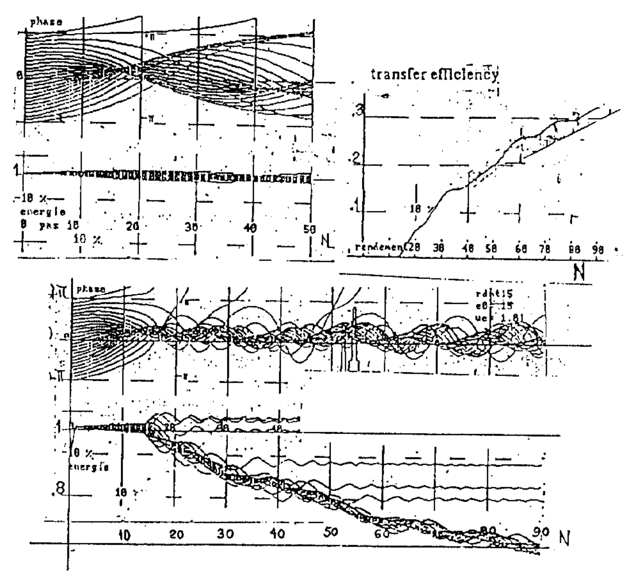

FIG 1 . Phase and energy diagrams .
TOP : uniform undulator Eλ =1kV
BOTTOM : Buncher +tapered undulator Eλ =15kV
the efficiency displayed here is 33% with a 90 periods undulator , including 14 periods for the buncher

For the uniform undulator ,and Eλ < .5 kV ,the transfer coefficient is in $(E\lambda)^2$,(slope 2 on the graphic Fig 2) as in the conventional small-signal theory .

The efficiency levels off at about 1-1.5% and starts to drop if the RF level is made to increase above 1 kV.

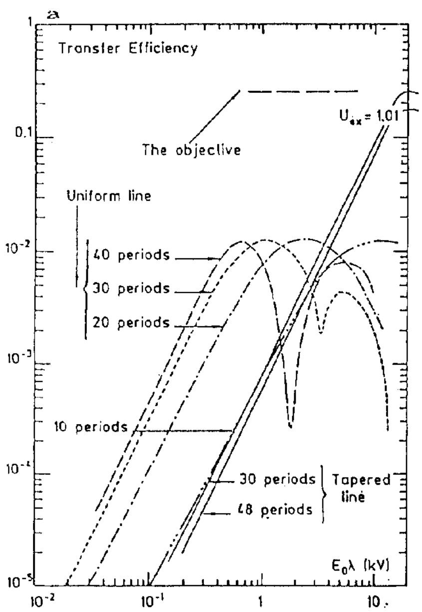

FIG 2 Transfer coefficient vs (Eλ)

With the tapered undulator ,and values of the parameter Eλ above a few kVolts , we are in the "large-signal" conditions . The bunching is nearly complete . The efficiency of transfer is then roughly proportional to Eλ instead of $(E\lambda)^2$ as in the small signal situation .

The beam intensity which can sustain the oscillation is:

$$I_{(Amp)} = \frac{b}{\xi}\cdot\frac{1}{4\pi}\cdot\frac{e}{m_o c^2}\cdot\frac{2}{1+\frac{K^2}{2}}\cdot\gamma\cdot\frac{\pi\varepsilon_n}{\gamma\lambda}\cdot ff \qquad \xi = \frac{a}{N(E\lambda)^2}$$

ff : form factor of the RF beam (order of 1.4)

b : loss coefficient per turn of the RF (3-5%)

It is well known and can be seen on Fig 2 , that such a tapered line has no gain at small signal (slope below .5 kV larger than 2) : oscillation does not start !

D- BUNCHER+STRONG TAPER +UNIFORM+SLIGHT TAPER

A high gain structure must be added , of course not *ahead* of the tapered part (it would behave as above)! , but *after* . And we arrive at a geometry similar to the one already described and tested°.

At small signal , the tapered part acts as a delay line between the buncher and the uniform line . The small signal coming out of the buncher is amplified and must arrive at the correct phase in the line . In the large signal operation , buncher + tapered portion behave as previously.

However there are very strict limitations in this operation : The number of periods of each part is critical , in order to get the optimum phase shift.

For monoenergetic electrons , there always remains a "hole" in the efficiency curve ,between .5 to 1 kV, and the system would stop building up . Fortunately , this hole is not exactly at the same place for different electron energies ,within 0.4% . So, if the available current in the beam were sufficient , this critical transition could be passed

E- PROGRAMMING THE PROFILE DURING BUILD UP OF OSCILLATION

This will be the correct solution : change the line profile , so that the profile is continuously adjusted to the level of RF power . In a TWT , this , of course , is impossible . But here , the build up covers 100 turns or more , which represents a duration of one , or a few , microseconds which is enough to program the currents which create the magnetic field in the undulator .

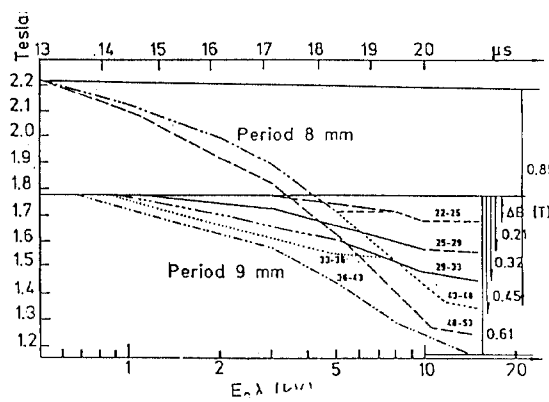

FIG 3 Variation of the magnetic field *vs* (Eλ) and N.
For (Eλ)< .5 kV , there is no taper
above .5 kV, the diagram is swept during the few microseconds of rise time .
Tapering starts just one or two periods after the buncher .

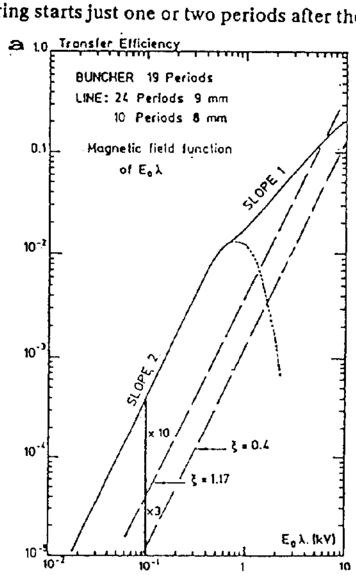

FIG 4 Transfer coefficient vs (Eλ) .The transition between small and large signal is smooth , and efficiencies larger than 20% can theoretically be obtained with 35 - 40 periods (not including the buncher).

Of course , this implies that the undulator has no magnetic material , and is short enough so that the reactances are kept small .

Fig 3 gives the slopes of the taper *vs* the RF level .

In the large signal region , (Eλ) increases of an equal amount per turn , and since each turn has the same duration , dE/dt is a constant .
Fig 4 is a typical plot of the transfer coefficient , for a 34 period-line preceeded by a 19 period-buncher , which shows a 20% efficiency at a value of (Eλ) not too high for the mirrors .
It can be seen that the bunching is of the order of 80% , so that side-bands excitation has a very low efficiency °° and the bunches are 30-40 degrees in phase so that the space-charge fields stay below a few percent of the main RF field °°°. The "transfer coefficient" can be of the order of .4-.5 % per period

F- TECHNOLOGY

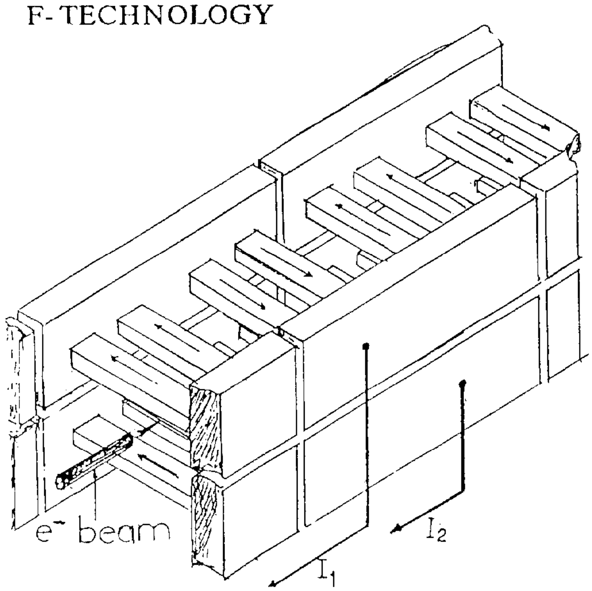

FIG 5 Schematic vue of an undulator
I_1 and I_2 : Derivation currents to control B(z) *vs* time.

The major difficulty is obviously to provide sufficient cooling capacity . The undulator presents itself as two layers of " bars " (1 or 2 mm cross-section ,and 10 to 20 mm long) . Copper bars can be cooled at the two ends if 100-150 degrees C can be tolerated between the middle and the ends . The cooling pipes are four- titanium or stainless steel -spirals , cooling the four ends of the successive bars . The period of the spirals is the same as for the undulator . Pipes are available down to 2 mm in diameter , so that the mechanical limit of this type of technology is around 2.5 mm period for the undulator.

The maximum current which can be passed through such a "bar" is

$$I_{(Amp)} \cong 433 \cdot \frac{S}{l} \cdot \sqrt{\frac{\Delta T}{f\tau}}$$

where : s and l are the cross-section and length of the bar (mm)
$f\tau$. is the duty factor
ΔT is the maximum temperature difference.

for a temperature difference of 100 °C and a duty factor of 1/100 ,the period is limited down to 7 mm for K=1.4 and 3mm with 200 °C and 1/300 duty factor
In the end , the major difficulty will be in the mirrors

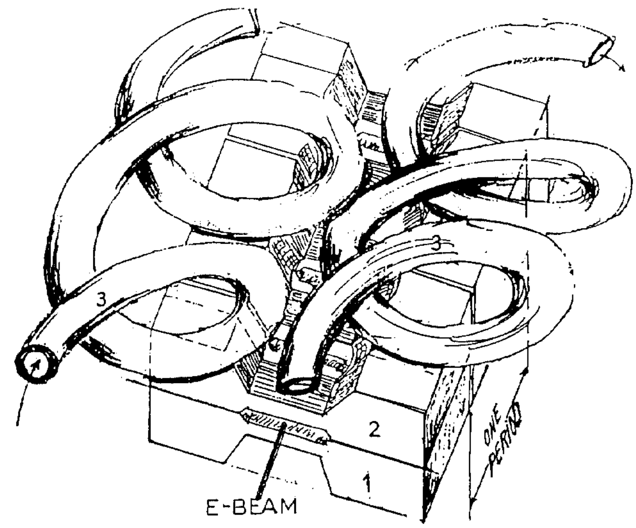

FIG 6 Arrangement of the cooling pipes

G- HARMONICS ENHANCEMENT

If the "bars" corresponding to each half period are divided into two or more "sub-bars" in parallel , as in Fig 5 , it is possible , by changing the relative distances , to have a Kn value of the coupling parameter even larger for the harmonics than for the fondamental as it is shown in Fig 7 .

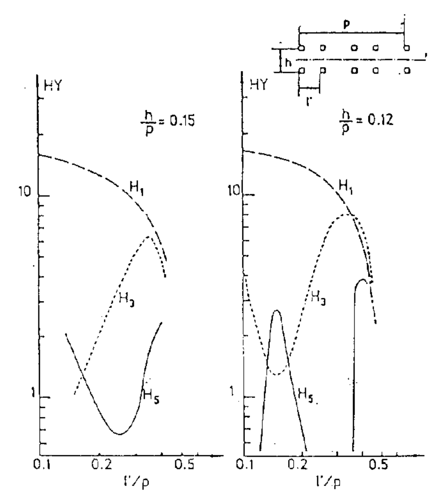

FIG 7 Coupling factor K for the fundamental and harmonics 3 and 5 , for the structure represented on Fig 5 : Two bars in parallel for each half period .

* Variable-Wiggler FEL oscillator
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