MM-Wave Linac and Wiggler Structures

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Abstract

In an international collaboration a new technology is being developed for a 50 MeV millimeter RF-wavelength electron linear accelerator complex for production of coherent tunable synchrotron radiation. The accelerator components and the wiggler are being designed with planar geometries suitable for deep X-ray lithography and subsequent electroplating (LIGA) or for etching and electroplating silicon wafers. The basic design ideas of different components for bunching, pre-acceleration, acceleration, focussing and the wiggler are presented.

1. INTRODUCTION

Micromechanic technology has developed a vast range of fabricational methods for devices in the submillimeter range: high precision stamping, diamond lathes, laser cutting, diffusion bonding, lithography and etching of silicon wafers and deep X-ray lithography with subsequent electroplating (LIGA [1]). So, the technology is available for studying and eventually building high precision accelerator components and structures for very high RF frequencies, let us say above 100 GHz. In this context it is of great importance that the relative dimensional and frequency tolerances increase with the square root of the frequency. This matches the mechanical possibilities which are typically a function of the relative tolerances. Also, there are power sources (gyrotrons) available which are being developed for plasma heating. They are in the range between 100 and 240 GHz and have peak powers of up to 1 MW.

Recently the Advanced Photon Source (APS) at Argonne decided to study a 50 MeV electron linac powering a micro wiggler. The study is in collaboration with the Universities of Illinois at Chicago, of Wisconsin at Madison and of Berlin. The linac consists of an RF-gun operating at 30 GHz or alternatively of a low beta structure at 120 GHz, a pre-acceleration stage and a high energy accelerator both at 120 GHz. The RF structures are planar and based on a double-sided muffin-tin. The accelerating gradient is assumed as 10 MV/m. First beam dynamic calculations indicated a steady state beam current of a few mA's. The wiggler may either be a microwave wiggler or an electrodynamic wiggler with a period lenght in the mm-range. The machine would be about 6 m long and would require 1.7 MW peak power.

Now, pushing the dream one step further we imagine an "Integrated MIllimeter-Wave-RAdiation Source" (IMIRAS), Fig. 1. Here, integrated means that the complete machine, i.e. source, accelerator, focussing system and wiggler, are fabricated in planar technology. And since we are dreaming we make the machine superconducting, where we need only 50 kW RF peak power for 1 mA current. This is a reasonably low power level for designing new sources, for instance little sheet beam klystrinos also in planar technology. Then, the whole device would fit on a standard lab table.

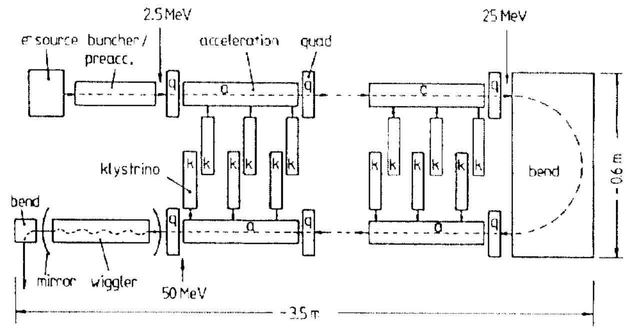

Fig. 1 Conceptual design of an integrated mm-wave radiaton source (IMIRAS)

The paper presents different RF structures for acceleration and pre-acceleration, possible focussing devices and structures for a microwave wiggler. Thereby emphasis is put on planar geometries only which can be fabricated by the LIGA process or by etching silicon wafers and electroplating.

2. THE MUFFIN-TIN STRUCTURE

Above 100 GHz the typical RF structure dimensions are in the millimeter or submillimeter range. At that size one obviously has to choose planar geometries suited for lithography. The double-sided muffin-tin, an iris loaded groove guide, Fig. 2, is such a structure. It fulfills many requirements in an ideal way:

- It is a simple geometry and perfectly suited for lithography.
- It is easy to cool from top and bottom.
- The RF-fields decay exponentially in the side openings thus leaving space for mechanical supports.
- The vertically polarized break-up modes are heavily damped due to the side openings.
- The side openings provide vacuum pumping slots.
- The accelerating mode shows transverse quadrupole fields which may be used for focussing.

The structure was studied in ref. [2]. Its basic RF parameters for a $2\pi/3$ travelling wave mode are given in table 1.

The $2\pi/3$ mode was chosen because it has the highest shunt impedance and a large group velocity. The latter is very important since the sensitivity of the structure against frequency and fabricational errors is a strong function of v_g.

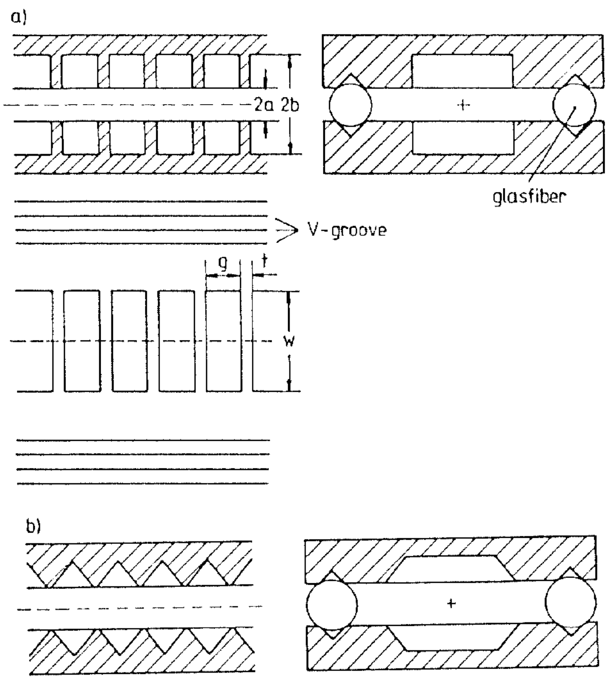

Figure 2. The double-sided muffin-tin structure.
a) rectangular cavities suited for LIGA
b) triangular cavities for etching in silicon

Table 1
Geometrical and RF parameters for a $2\pi/3$ travelling wave mode in a muffin-tin with rectangular cavities.

$a = 0.3$ mm	$b = 0.9$ mm	$w = 1.8$ mm
$g = 0.633$ mm	$t = 0.2$ mm	$d = 0.8$ mm
$Q_0 = 2160$ for Cu	$r_0/Q = 144.6$ kΩ/m	
$r_0 = 312$ MΩ/m	$k = 0.0475$	
$v_g = 0.043\ c_0$	$\alpha = 13.5\ m^{-1}$	

Also, the cell to cell phase error is lowest for modes close to the $\pi/2$ phase shift per cell.

With the attenuation α, the optimum structure length l, i.e. with the highest energy gain for a given input power, is $\alpha l=1.26$ or $l=9.3$ cm. However, there are many reasons to make l shorter and in ref. [2] it was chosen to be 7 cm. This corresponds to N=84 cells. Then, the required input power per structure is 29 kW in order to get 10 MV/m average gradient. Since the fields are attenuated along the structure, the ratio of power dissipation at input and output is 6.6 to 1. As was shown in ref. [3] this may lead to an appreciable temperature rise in the irises. It may also be very difficult to control such a strong gradient in heat deposition with an adequate cooling system.

One way out is a constant gradient (CG) structure. The width w and the depth b of the cavities are varied in such a way that the frequency remains constant but the group velocity, which is proportional to the relative bandwidth k, decreases along the structure. The relations are shown in Figure 4 of ref. [2]. As can be seen, k, and therefore v_g, varies by a factor of 1.6 only. But for a constant power dissipation we would need a variation of 6.6. Therefore, we can only reduce the input to output power ratio from 6.6 to 4.1. If this turns out to be still not tolerable we were forced to decrease also the aperture along the structure.

Although a CG-structure is possible and even desirable (it has a higher beam break-up limit and is less sensitive to frequency deviations) it would enormously complicate the fabrication.

3. Side-Coupled Muffin-Tin

In many respects the TW-CG structure is the ideal structure for electron acceleration. It has a high shunt impedance, a constant power dissipation and is less sensitive to frequency deviations and to beam break-up. But to change cavity depth and aperture is not easy to realize.

A standing wave (SW) structure has also a constant power dissipation. Its main disadvantage, however, is a shunt impedance which is only half that of a TW-structure, except for the π-mode. On the other hand, the mode spacing is

$$\Delta\omega = \frac{1}{4} k \omega_r \left(\frac{\pi}{N}\right)^2 \qquad (1)$$

around the π-mode, a factor $\pi/2N$ smaller than for the $\pi/2$-mode. This is the reason for a series of disadvantages. The structure is very sensitive against fabricational and frequency errors, it shows phase errors from cell to cell and it is only possible to couple a small number of cells together. Since the band width has to be smaller than twice the mode spacing

$$2\frac{\omega_r}{Q_0} < \frac{k}{4}\omega_r \left(\frac{\pi}{N}\right)^2 \qquad (2)$$

we could couple at most 11 cells.

A nice trick to overcome these problems is often used in proton machines. The accelerating cells are not coupled directly but via off-axis coupling cells, in such a way that the structure is operated in the $\pi/2$-mode but the effective phase advance from main-to-main cell is π. Such an arrangement is expensive for standard accelerating structures but comes for free in planar structures. In ref. [4] three such structures have been analysed, see Figure 3.

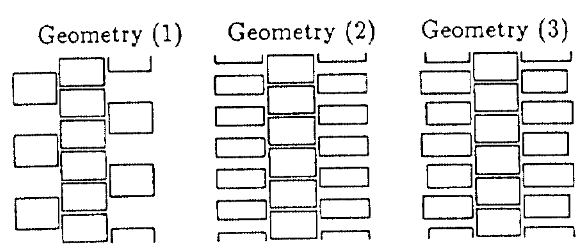

Figure 3. Side-coupled muffin-tin structures with (1) alternating, (2) symmetrically arranged off-axis cells and (3) with broken symmetry.

Geometry (1) corresponds to a standard arrangement with alternating off-axis cells. Two pass-bands coalesce at a 2π phase shift per period, Fig. 4 in ref. [4], and generate a large slope, i.e. a large group velocity. The main-to-main cell phase shift is π. In our case the situation is a little more complicated than usual due to the fact that we also have coupling from main-to-main cell. Nevertheless, the behaviour is what we want: A strongly coupled structure with a high group velocity and the high shunt impedance of the π-mode. The only disadvantage is that because of the large off-axis cells, the electric field on the axis is no longer parallel to the z-axis but slightly wiggling around it. Therefore, we analysed the geometry (2) next. This geometry has the largest bandwidth and is certainly the less sensitive against errors due to the multiple coupling. Unfortunately, it carries a horizontally polarized dipole mode which is synchronous with the beam and has a phase advance of π also. This would have been very dangerous if the shunt impedance were not very low due to the low fields near the axis.

In the third geometry of Fig. 3 the symmetry with respect to the z-axis is broken. This shifts the dipole mode lower in frequency while keeping the accelerating field parallel to the z-axis as in geometry (2). The price we have to pay for it is a somewhat reduced group velocity and a slight increase in error sensibility. Table 2 shows the main RF parameters of the side-coupled structures as compared to the single periodic structure in Table 1.

Table 2
RF parameters of the structures in Fig. 3.

Geometry	(1)	(2)	(3)
Q_0	2820	2590	2720
r_0/Q [kΩ/m]	92	95	98
r_0 [MΩ/m]	260	246	266
v_g/c_0 [%]	5.5	5.8	4.0
α [m^{-1}]	8.1	8.4	11.5

All three geometries are confluent at a π phase shift from main-to-main cell. As a result we find high group velocities with only a slight reduction in shunt impedance. The structures should be operated in SW conditions with the advantage of a constant power dissipation (under TW conditions the off-axis cells are also excited in average thus adding to the losses and reducing the shunt impedance). Since the mode spacing is similar to the one of the single periodic structure at $\pi/2$-mode, i.e. $2N/\pi$ times larger than in equ. (2), one would couple about 100 cells. For reasons of fabrication, good mode separation and good operational stability we choose 54 cells yielding a structure length of 7 cm, the same as for the single-periodic structure.

4. RF FIELD FOCUSSING

Whereas the muffin-tin represents, at least on paper, a good solution for accelerating relativistic electrons, we still have to find a solution for the low and medium velocity regime. Surely, we could use the muffin-tin structure and focus brutally with an external field. But there is a more intelligent solution based on the intrinsic properties of the RF fields.

The synchronous space harmonic of the E_z component can be written as

$$E_z = E_0 \cos k_x x \, \cos k_y y \cdot e^{j\varphi}, \; \varphi = wt - k_z z \qquad (3)$$

where

$$k_x \approx \pi / w, \; k_z = k / \beta, \; k_y^2 = k_x^2 + (k / \beta\gamma)^2 .$$

Assuming $E_x=0$ which is very well fulfilled, we can easily derive the Lorentz forces from Maxwells equations together with (3)

$$F_z = -eE_0 \cos\varphi$$

$$F_x = -eE_0 \frac{k_x^2}{k} \beta \sin\varphi \cdot x, \quad F_y = eE_0 \frac{k_y^2}{k} \beta \sin\varphi \cdot y. \qquad (4)$$

As can be seen, the transverse forces are of quadrupole character if the particles are not on the crest of the RF ($\varphi=0$). For relativistic particles follows from (3) that $k_y \approx k_x$ and the transverse forces have equal magnitude. The peak value at $\varphi=\pi/2$ corresponds to an equivalent magnetic gradient of 42 T/m for E_0=10 MV/m. For non-relativistic particles the vertical force is larger than the horizontal force by a factor $1+(2/\beta\gamma)^2$, since $k_x \approx k/\sqrt{2}$.

This particular property of the RF fields is a consequence of the non-axissymmetric structure. We can make use of it by choosing different focussing strategies:

a) We rely completely on external focussing.
b) We focus externally in one plane and use RF-focussing in the other plane.
c) We use alternating gradient (AG) RF-focussing by rotating every other structure 90° around its axis.
d) We apply alternating phase focussing (APF) by operating different sections with an RF phase changig periodically between plus and minus φ_0.

Case b) is easy to realize. With a negative phase angle $-\varphi_0$ in (4) we have focussing in logitudinal and x-direction. The defocussing in y-direction can be controlled by a one-dimensional magnetic focussing as for instance proposed in [2].

Strategy c), although straightforward on paper, is not very handy in reality. The alignment of rotated structures with micrometer precision may be difficult. Very promising looks the last option d). Since additional structure elements are free of charge when using lithography, we may easily incorporate delay lines as in Fig. 4a or we may modify the cavities itself such that the lengths change periodically.

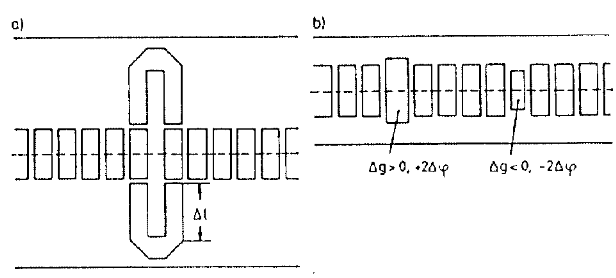

Figure 4. Muffin-tin with a) delay lines, b) periodically changing cavity length.

We correct the detuning due to a change in length by varying the width w. APF has been analyzed in Ref. [5] and indeed it looks very attractive. At energies around 100 keV the focussing cell length can be about 6 mm, and will grow to several centimetres at higher energies.

5. ALTERNATIVE LOW BETA STRUCTURES

A big problem is certainly the bunching of the beam at 120 GHz. One approach, pursued in Argonne, is an RF gun operated at 30 GHz. Thus, every fourth bucket is populated only and the charge per bunch increased correspondingly for a fixed current. Also, if we do not want to compress bunches, we have to generate them at a length of typically 50 μm, a difficult task. Therefore, we were looking for planar high frequency structures which could be used for bunching and accelerating at low velocities around β=0.5. Four different structures have been analysed in [6]. Two are shown in Fig. 5.

Originally, we hoped to simulate an RF quadrupole (RFQ) with geometry a). But it turned out that the interplay between electric and magnetic fields does not generate an AG behaviour with an overall focussing. On the other hand, the geometry b) may be very useful since it provides for simultaneous focussing or defocussing in both transverse planes. Adding some external solenoidal field of about 1 T it is appropriate for accelerating and bunching a continuous low β beam.

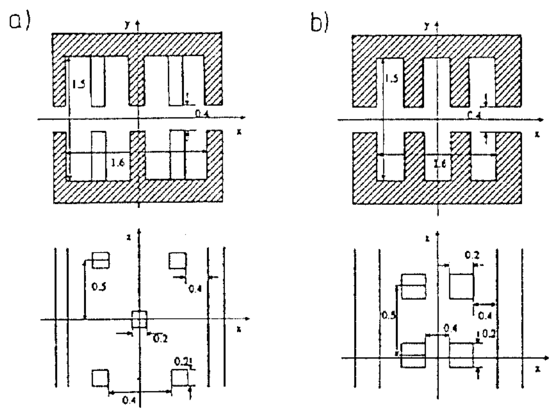

Figure 5. Cross sections and top views of two different low beta structures.

Fig. 6 shows a MAFIA time domain simulation with a structure which has not been matched to the electron velocity. Nevertheless, bunching and acceleration from β=0.4 to β=0.9 is demonstrated.

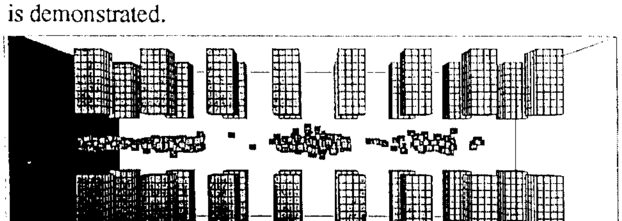

Figure 6. MAFIA simulation of acceleration and bunching of a low β beam.

6. ELECTROMAGNETIC WIGGLER STRUCTURES

Although magnetic wigglers with period lenghts in the mm-range have not been built, it seems perfectly possible to fabricate them with the LIGA technology. Electroplating of iron nickel is well known as well as the deposition of insulators and conductors. This development has been started in the University of Wisconsin.

In parallel, we are studying microwave structures which, again, are planar and which could be used as an electromagnetic wiggler. Closer inspection of different possibilites prooved that we could use geometries very similar to those of the sections 2 and 3. The groove guide, Fig. 7a, is thereby the simplest solution. All we have to do is to slightly increase the dimensions in order to be well above the cut-off of the quasi TE_{01}-mode. If we want a low-loss guide or a high Q resonator it is better to use a heavily overmoded and corrugated structure. The muffin-tin is exactly that. Fig. 7b shows a field plot of the hybrid HE_{11}-mode. For the chosen dimensions, a trade-off between low losses and mode density, the quality factor and the transverse shunt impedance are given in Table 3.

Following the derivation in ref. [7] we conclude that in such a guide the forward travelling wave exerts a very weak deflecting force with a long wiggling period, since the guide wavelength and impedance are close to those of free space.

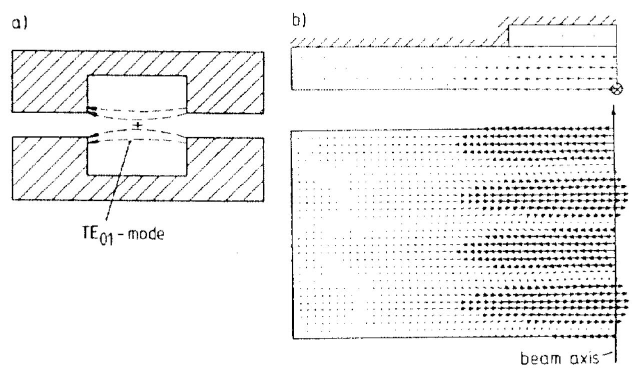

Figure 7. a) Groove waveguide and
b) hybrid HE_{11}- mode in an overmoded muffin-tin

Table 3
Dimension and basic RF parameter for a muffin-tin operated in a $2\pi/3$ standing wave (120 GHz)

a = 1.0 mm	b = 1.6 mm	w = 5.0 mm
g = 0.633 mm	t = 0.2 mm	
λ = 2.9 mm	Q_0 = 26680	r = 6.9 GΩ/m

The backward travelling wave can be replaced by an equivalent wiggler with field strength and period lenght of

$$B_u \approx E_0 / c_0, \qquad \lambda_u \approx \lambda / 2 \qquad (5)$$

where E_0 is the peak deflecting field on the axis. Thus, at 120 GHz the wiggler period would be 1.45 mm. With a 5.3 kW RF power fed into an undulator with 60 periods the deflecting electric field would be 20 MV/m and the equivalent field strength 660 Gauss, using the values of Table 3. The K-parameter would be very small about 0.01 and the resulting radiation wavelength therefore

$$\lambda_{rad} \approx \lambda / 2\gamma^2 \approx 62nm \quad \text{at 50 MeV.} \qquad (6)$$

7. INTEGRATED FOCUSSING MAGNETS

Again, what has been said about the wiggler magnets is valid for the focussing magnets. There seems to be no basic limit that quadrupoles cannot be built in microtechnology. In effect, their development is under way.

But it is not at all sure that we need the standard magnet structure with iron core. Pulsed wires integrated on the substrate would provide field gradients sufficient for focussing. Typical conductor cross-sections of 40 times 20 µm carrying 10 A currents at a duty cycle of 1:20 dissipate 1.25 W/cm in average, a perfectly reasonable amout to cool.

A very simple arrangement for focussing in the vertical plane only was first proposed in ref. [2] (see Fig. 8 a also). This could be combined with an RF-field focussing in the horizontal plane corresponding to the strategy b) in section 4. Two simple wires parallel to the z-axis with 0.6 mm spacing and 10 A currents create a field gradient of 36 T/m on the beam axis.

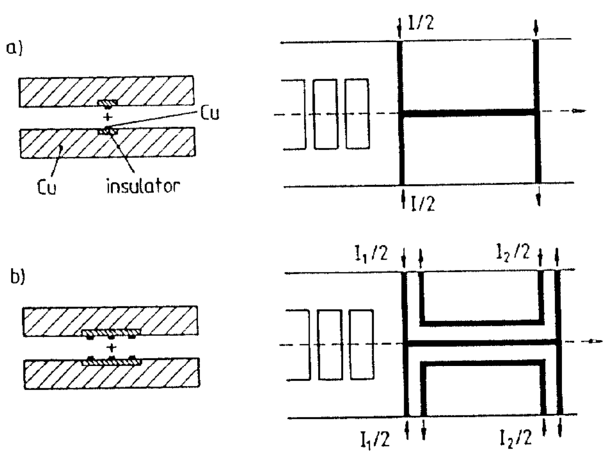

Figure 8. Integrated pulsed wire magnets for focussing in a) the vertical plane and b) in both planes.

Quadrupole fields can easily be achieved with six wires, Fig. 8b. For small displacements form the z-axis we obtain

$$B_x \approx -\frac{\mu_0 I}{\pi a^2}\left[2\left(1-2\left(\frac{a}{\rho}\right)^2\right)\left(\frac{a}{\rho}\right)^2+1\right]y$$

$$B_y \approx \frac{\mu_0 I}{\pi a^2}\left[2\left(1-2\left(\frac{d}{\rho}\right)^2\right)\left(\frac{a}{\rho}\right)^2-1\right]x, \qquad (7)$$

$$\rho^2 = a^2 + d^2.$$

Depending on the ratio d/a the maximum gradient $|B_x|/y$ occurs at $d/a=\sqrt{3}$ yielding

$$|B_x|/y = \frac{5}{4}\frac{\mu_0 I}{\pi a^2} = 28T/m; |B_y|/x = \frac{3}{4}\frac{\mu_0 I}{\pi a^2} = 17T/m \quad (8)$$

if I = 20 A and a = 0.6 mm.

Surely, no exact field calculations have yet be done and it may turn out that the linearity is quite poor. But with the precise fabricational methods which are available there is good hope that we can correct the fields by chosing cross-sections and dimensions properly and eventually even adding additional wires.

8. CONCLUSIONS

The LIGA process and the todays silicon technology, combined eventually with other high-precision micro-mechanic methods, are perfectly suited to build accelerating, focussing and wiggler structures for very high frequency electron linacs. If one chooses only planar structures it seems that a complete machine may be realized in an integrated way. A variety of possible planar geometries are presented in this paper. Plenty of other solutions may be found since our imagination is not limited by cost arguments as usual. Adding more and more complexity to the structures is rather limited by the designers skill but does not increase the fabricational costs when using lithography. As examples stand side-coupled structures, multi-periodic structures or structures with inherent AP focussing. Another example, not mentioned in the above sections, may be integrated resonant rings. If we reduce the losses of the proposed TW-structures by going to lower temperatures it eventually becomes attractive to recirculate the left over RF-power. This, again, can be realized on the same substrate free of costs.

9. ACKNOWLEDGEMENT

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10. REFERENCES

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