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Working Group Summary: New Technologies*

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There was agreement that the main subject of discussion in this Group was "undulator magnets". Participants were C. Bazin, T. Dickinson, K. Halbach, K. Kim, J. Ortega, R. Pantell.

In a broad sense, undulators can be regarded as the free electron laser "media". Thus, also crystals, gratings and pump lasers are undulators.

Undulators are characterized by a dimensionless parameter, or undulator strength

$$K = \frac{e}{2\pi mc} \lambda_o B$$

where λ_o is the undulator period and B the magnetic field. Some Authors use peak field and some r.m.s. field; accordingly there is a $\sqrt{2}$ difference for a transverse undulator, no difference for a helical undulator.

The fundamental wavelength on axis produced by an undulator is given by

$$\lambda = \frac{\lambda_o}{2 \gamma^2} (1 + K^2)$$

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where γ is the energy of the electron in units of mc^2 and K is the r.m.s. value.

1. Undulator structure

1.1. Conventional static undulators (magnetic field at rest in the laboratory frame).

They can be electromagnets, either normal or superconducting.

Electromagnetic undulators are suitable for the production of long wavelength radiation, since their period cannot be made shorter than, say, 10 cm. Advantages are:

Field is easily controllable (normal electromagnet);

They may reach very high K values (superconducting);

Their geometry is changed easily, by changing electrical connections.

This latter feature allows one to move from the ordinary undulator to the optical klystron structure (e.g. Frascati).

Disadvantages are:

Electromagnets are space inefficient;

They may have high operating costs (superconducting).

The first point can be important for undulators to be inserted in a straight section of an electron storage ring.

Undulators can be built with permanent magnets, typically Rare Earth-Cobalt or Nd-Fe. The most common trend for the generation of short

wavelengths is to use this kind of undulators. They can be built with very short period, of a few cm (conceivably down to 1 cm) and with a strength K of 0.5 to 2.

Advantages are that they are very space efficient and are particularly suited for long multi-period undulators; their operation cost is nil and their construction cost comparable with normal electromagnetic undulators.

Main disadvantage is that they are mechanically complex, in their variable field varieties, obtained by mechanically changing the magnetic gap.

Permanent magnet undulators of the transverse type have been built in considerable number, and permanent magnet helical undulators have been proposed (K.Halbach).

Magnetic field and strength of a typical pure Sm-Co undulator are shown in Fig. 1 (Brookhaven FEL undulator). This has the basic arrangement proposed early by K.Halbach.

Higher magnetic strengths are obtained with the hybrid structure of mild steel or permendur pole pieces and permanent magnet blocks discussed by K.Halbach in his invited paper to this Meeting.

Vacuum chambers for undulators are an important subject of discussion. Three basic structural varieties have been implemented: stationary chambers, squeezable and movable chambers.

Fixed chambers are suited for transverse undulators with large

magnetic gaps (3 cm and up). These chambers are inserted in the gap and must therefore have very thin walls to allow for maximum inside clearance.

Variable-gap undulators can be accommodated inside a fixed chamber, if the gap has to be reduced to very small values (Brookhaven). By enclosing the magnet pieces in vacuum-tight boxes evacuated to a differential pressure, we may ease the problem of keeping a permanent magnet undulator in a very high vacuum environment.

Variable chambers can be built either by making them squeezable (shoebox) or movable sideways on- and off the beam.

The shoebox offers a good challenge to the mechanical engineer (Fig. 2a). It allows to accommodate a variable-gap transverse undulator set in air, where it is easy to intervene on it. This version is particularly useful with storage rings where large chamber openings may be required at injection.

Similar advantages are offered by the movable "keyhole" chamber of the ACO and VEPP storage rings (Fig. 2b).

1.2. Gratings as undulators

The stationary "evanescent" wave existing in the proximity of a grating on which a laser wave is being diffracted has the alternate field structure of a very short period ($\lambda_0 \sim 1 \mu\text{m}$) undulator. Undulator radiation (Smith-Purcell effect) is seen if an electron beam is made to propagate at a distance from the grating compared to λ_0 and parallel to the grating surface.

Limits are set by the amount of electron beam current that can be brought so close to a material surface (this was discussed, inter alia, in the 1982 Los Alamos Workshop on Laser Acceleration) and by the damage threshold of a grating exposed to high power laser radiation.

Use of gratings as undulators can be interesting in cases of very intense and concentrated electron pulses, as in the SLAC collider.

1.3. Crystals as undulators (R.Pantell)

They are Nature's undulators, with very short periods ($\lambda_0 \sim 0.1 \text{ } \mu\text{m}$ and down) and with reasonable strength ($K \sim 0.1$).

In crystals such as Si, Ge, Diamond, BeO, LiF, W, NaCl, electrons propagate along natural channels (Fig. 3a) and emit radiation that is 1-2 orders of magnitude more intense than bremsstrahlung.

A typical example (Kephart, Klein, Pantell, Park) is shown in Fig. 3b: for $\gamma = 1000$, $\lambda_0 = 2000 \text{ A.u.}$, radiation is emitted at $\sim 0.1 \text{ A.u}$ or $\sim 100 \text{ KeV}$, with 0.1 % bandwidth.

1.4. Pump Wave

A laser wave of wavelength λ_L directed counter the electron beam acts as an undulator of period relativistic contracted, in the rest frame of the electron, by 2γ . (Conversely, a conventional undulator is seen by the electron as a quasi-wave).

The radiation produced by the electron in this undulator is also described as Thomson or Compton backscattered (Fig. 4) and its frequency

in the laboratory is $4\gamma^2$ the frequency of the pump laser.

By choosing γ and λ_L in a wide range, this method produces undulators with a wide range of periods, say 1 μm to 1 cm. High frequency radiation can be generated also by low energy electrons.

The limits of pump wave undulators are that their strength is not much. If P is the power of the laser, and Z_0 the impedance of free space, undulator magnetic field is given by

$$B_0 = \frac{1}{c} \sqrt{2Z_0 P}$$

and it can be seen that even with powerful lasers (such CO_2) K remains in the $10^{-6} - 10^{-4}$ range.

2. Problems with conventional undulators

Apart from mechanical engineering, other problems with undulators include: magnetic measurements, calculation of magnetic fields and of trajectories through undulators, calculation of undulator spectra.

2.1. Magnetic measurements

We limited to the discussion of measurements on permanent magnet undulators. They are performed in three steps: measurement of individual magnetic blocks, arrangement of magnets in the undulator, measurements on the entire undulator.

Measurement of individual blocks is done by placing them in a Helmholtz coil pair plus a current integrator or by running a magnetic probe along the surface of the block (absolute meas.). Or else, by pairing each block in turn with a block taken as a reference and measure their

sum- of difference field (relative meas. e.g. done as shown in Fig. 5). It is important to recognize that errors in individual blocks are due to errors in the absolute value of the magnetic moment, in the non uniformity of the magnetization throughout the material and in the lack of coincidence of the magnetic center of mass with the geometrical center of the block. All these errors contribute to errors in the field, resulting in multipole field components and in defects of compensation of field integrals.

Arrangement of permanent magnets along the structure is important, since the field in each point is due to contributions from many magnet pieces (see next).

2.2. Calculation of magnetic field, trajectories and spectra

With reference to permanent magnets, fields are calculated by means of two-dimensional (e.g. Poisson-type) or three dimensional codes (e.g. GFUN-type). In both cases, provisions exist for incorporation of permanent magnet properties in the codes, originally designed for electromagnets.

It is observed however that a simple amperian current model proved adequate for calculation: i.e. each block can be simulated by a double layer of magnetizing currents in a computer calculation with a code incorporating variable permeability materials (This is particularly important in permanent magnet undulators of the hybrid type).

Trajectories are best calculated by integration of the relativ-

stic equations of motion in the measured field. Precision of calculation is of great importance for very long structures, where non exact compensation of field integrals may take place.

A calculated trajectory through a well-ordered permanent magnet undulator is shown in Fig. 6 (Brookhaven. Similar results shown by Daresbury). This figure represents a trajectory through a 38 periods undulator with average magnet errors of 1%. Fig. 7 shows trajectories calculated in an undulator with hypothetical bad magnets (20% error); the effect of ordering dramatically appears.

Good trajectories in very long undulators can be obtained by interrupting the magnet in a few spots to add there focusing elements (they can be also added, however less effectively, from outside the undulator, since the magnetic pieces respond quite linearly to superposition of fields). The effect of interruptions can be described as producing an effective reduction of the total radiation power in each harmonic line (K.J.Kim) by a factor

$$\left(\frac{\sin x/2m}{x} \frac{\sin \frac{x-\rho}{2}}{\sin \frac{x-\rho}{2m}} \right)^2$$

where

$$x = 4\pi N_0 \frac{\gamma - \gamma_R}{\gamma_R}$$

$$\rho = 2\pi \frac{D}{\lambda_0 (1 + K^2)}$$

with m number of sections of the undulator (supposed identical), D the spacing between sections and γ_R the "resonant" energy.

Many effects modify the theoretical shape of the spectral lines from undulators. One obvious is errors in the field (study of the radiation is the most powerful tool to analyze these errors). Another is due to the finite ~~emittance and energy~~ spread of the electron beam. This leads us to distinguish between computer codes that give exact results for theoretically perfect structures (with sums over series of Bessel functions) and codes that calculate the radiation directly by integration of the Lienard-Wiechert retarded potentials for real structures. Both are necessary; the direct approach is more powerful but also expensive in computer time.

Fig. 8 shows an example of an undulator line when the finite emittance of the electron beam is taken into account.

2.3. Matching an undulator with a storage ring

Undulators are insertions in the lattice of the machine and must be matched. Two main possibilities are: action on the magnetic lenses (quadrupoles) in the same straight section in order to maintain the rest of the ring unchanged (this will have the general effect of increasing the local vertical beta function). Or else modify the total optical structure in order to find a more satisfactory overall solution for a ring that, because of the insertion, has lost its original many-fold symmetry. There are examples of both solutions.

Another kind of matching is the optimization of the undulator spectrum, when it is folded with the intrinsic emittance of the electron beam. It can be found that a very long undulator does not produce a

better spectrum than a much shorter one if the electron beam qualities are not adequate.

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Fig. 1. Peak field and strength of the Brookhaven fel undulator, as a function of the magnetic gap.

Fig. 2. Undulator variable vacuum chambers. a) Keyhole, b) Shoebbox.

Fig. 3. Crystals as undulators. a) Channeling of electrons. b) Typical spectrum of channeling radiation.

Fig. 4. Pump wave as undulator. Electron-laser scattering.

Fig. 5. Relative magnetic measurements on a permanent magnet block.

Fig. 6. Calculated trajectory through a well-ordered permanent magnet undulator with 1% errors.

Fig. 7. Calculated trajectory through a bad undulator. a) Magnets at random. b) Magnets ordered.

Fig. 8. Fundamental spectral line of an undulator. — zero emittance;
 - - - finite emittance (beam angles $\sim 1/\gamma$).