Micropole Undulators in Accelerator and Storage Ring Technology

Roman Tatchyn*
Stanford Synchrotron Radiation Laboratory,
Stanford University, Stanford, CA 94305, USA
and
Department of Physics
University of Oregon, Eugene, OR 97403, USA

Paul Csonka
Institute of Theoretical Science
and
Department of Physics
University of Oregon, Eugene, OR 97403, USA

Arthur Toor
Lawrence Livermore National Laboratory
Livermore, CA 94550, USA

Abstract

In this paper, a general overview of the properties of micropole undulators as insertion devices for both accelerators and synchrotron storage rings is given. Comparisons with long-period devices are drawn on the basis of a **"coherence length/output power"** parameter defined by us for the purpose of this study. It is shown that micropole insertion devices, particularly undulators, have the potential for transforming conventional accelerator and synchrotron radiation technology. Some novel physical experiments, made possible by the availability of such devices, are mentioned.

I. Introduction

A micropole undulator has been defined [1,2] to be an undulator with submillimeter period, with its pole dimensions conveniently expressed in microns. Operation of a micropole undulator has many advantages over long-period devices. For example, the submillimeter period makes it a natural source for soft x-rays on low-to-medium energy linacs. The required small gap also makes it naturally adaptable to linacs, as there are no aperture-dependent lifetime considerations as there are on circular machines. On synchrotron storage rings, on the other hand, micropole undulators promise to produce outputs and energy resolutions far exceeding those of conventional machines at greatly reduced ring energies and costs - provided, of course, that beam lifetime problems and emittances can be suitably solved and upgraded. In this paper we set up the formalism defining a limited set of important operating parameters of accelerators, undulators, and storage rings, and use it to demonstrate some of the potential advantages of micropole insertion devices in a quantitative fashion. A more comprehensive study, including emittance and diffraction effects, is postponed for future treatment, as their omission here will not detract from the main conclusions to be arrived at.

II. Definitions and Formulas

N ≡ number of undulator periods

λ_μ ≡ undulator period in cm

B_0[Tesla] ≡ peak on-axis undulator field

m_ec^2 ≡ rest mass energy of an electron in GeV

$K = .934\, B_0\lambda_\mu$ ≡ undulator "K" parameter; measure of undulation amplitude

E[GeV] ≡ linac or storage ring energy

λ_{OUT} ≡ wavelength of the on-axis component of the first undulator harmonic

P_{TOT} ≡ total output power emitted by an undulator

$P_{\lambda_{OUT}}$ ≡ power emitted into the on-axis spectral component of the first harmonic

$\gamma = E/m_ec^2$

$\theta_{\lambda_{OUT}} = 1/\gamma\sqrt{N}$ ≡ half-power angle of the on-axis spectral component of the first harmonic

$\ell_c = N\lambda_{OUT}$ ≡ coherence length of the on-axis component of the first undulator harmonic

L[meters] ≡ undulator length

I_{RING}[mA] ≡ ring or linac current

In doing an optimization study in insertion device/machine parameter space, we will naturally select those parameters that represent either costs or benefits. Thus, we associate ℓ_c, P_{TOT}, and $P_{\lambda_{OUT}}$ with benefits, and E and L with parameters representing cost. In order to arrive at a convenient graphical representation, we introduce the following formulas [3]:

For low-K devices

$$\lambda_{OUT}[Å] = \frac{13.06\ \lambda_\mu[cm]}{E^2[GeV]} \tag{1}$$

Multiplying both sides by N, we get the **"coherence length/machine energy"** product, expressible as

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$$\ell_c[\text{Å}] = \frac{1306\ L[\text{m}]}{E^2[\text{GeV}]} \qquad (2)$$

The total output power of an undulator in watts is

$$P_{TOT} \cong 633\ E^2[\text{GeV}]B_o^2[\text{Tesla}]L[\text{m}]I[\text{Amp}] \qquad (3)$$

and the output power concentrated in the on-axis component of the first harmonic is

$$P_{\lambda OUT} \cong \frac{1900\ E^2[\text{GeV}]B_o^2[\text{Tesla}]L[\text{m}]I[\text{Amp}]}{N} \qquad (4)$$

Each spectral component in P_{TOT} has an energy resolution of $\sim 1/N$.

If we define $P_{TOT}/I[\text{mA}]$ as a new variable and multiply both sides of (3) by ℓ_c, we get a **"coherence length/output power"** product expressible as

$$\ell_c[\text{Å}] = 829 B_o^2[\text{Tesla}]L^2[\text{m}]\left(\frac{P_{TOT}[\text{Watts}]}{I_{RING}[\text{mA}]}\right)^{-1} \qquad (5)$$

III. Graphical Study

In Fig. 1 we have plotted Eqs. (2) and (5) on a log-log scale with L as a parameter. Using the dotted curves, one can find the ring or linac energy required to produce a coherence length ℓ_c, for an undulator of given length L. For the given ℓ_c, we can also find the total power per unit machine current that will be generated by the same undulator /machine energy combination from the solid curves. An important point of Fig. 1 is the concept of the **"coherent power limit,"** which denotes the fact that moving to higher energy rings and longer period undulators of the same length will increase the power emitted with a coherence length of ℓ_c only linearly with the period ratio. If one then postulates that for undulators with fewer periods than for the one at the **"coherent power limit"** one must use monochromators with low efficiencies, one finds that in most cases one can get more high resolution light with a lower energy ring, a micro-pole undulator, and no monochromator.

Using Fig. 1 we can study the specific case of generation of high-resolution soft x-rays. This case study is depicted in Fig. 2. Using an assumed relative resoluton of 10^{-4} over the 500 eV-3000 eV range, a figure which is a factor of 3-8 better than that of any existing undulator/monochromator system [4], we see that the corresponding coherence lengths can be generated with micropole undulators of 1-4 meters in length and storage rings (or linacs) in the 50-600 MeV range. The vertical lines denote existing or planned storage rings, and the points where they intersect the curves denote existing or planned undulators. If we compare the output of a hypothetical 200 μ period, 2 m long, undulator operating in a 150 MeV ring (or linac) to the output of the upcoming Beam Line V undulator/ monochromator system at SSRL [4], which will operate at 3 GeV, we find that the micropole undulator's output will be about 100 times greater at 1000 eV (± .1 eV). This is due to the fact that no

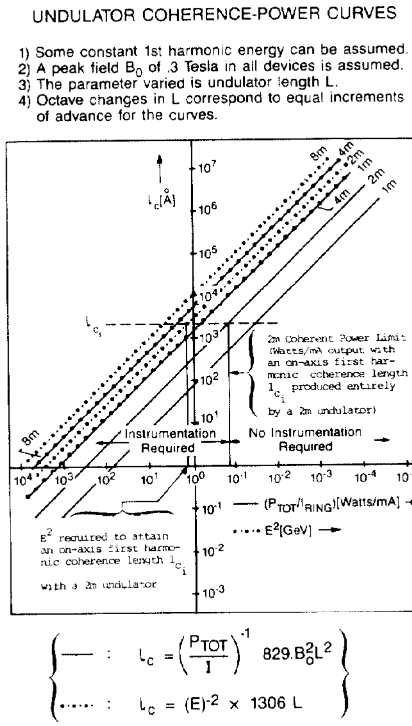

Fig. 1. Coherence/power and coherence/machine energy are plotted with undulator length L as the parameter. At the coherent power limit, the on-axis component of the first harmonic has coherence length ℓ_c, thus no monochromatization is required for that wavelength.

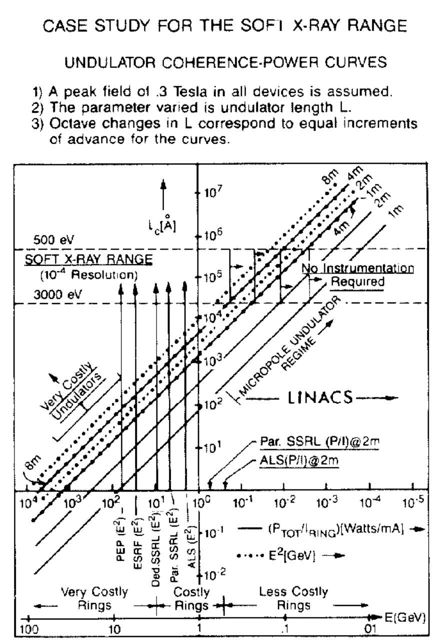

Fig.2. Case study assumes a relative energy resolution of 10^{-4}. The axis on the bottom plots the square root of the higher axis in units of ring energy E.

monochromatization of the micropole device's output would be required.

It is true that in order to attain a 10^{-4} resolution with the micropole device in the above case, one has to center an angular aperture of 10^{-5} rad on its axis, but this can be easily done with two 10 μ apertures spaced 2 meters apart.

IV. Technological Difficulties

The ultimate widespread utilization of micropole undulators in storage rings will require the resolution of several technological problems. The first problem is the minimization of beam emittance. The vertical size of the beam must be made small enough to pass through the $\lesssim 500\ \mu$ apertures that will be required. Secondly, the beam divergence must be small enough so that the beam will stay small for significant distances. Thus, for a 150 μ gap and a 1 meter long micropole undulator, the required vertical emittance would be $\varepsilon_v \lesssim 6 \cdot 10^{-10}$ rad-meter, assuming a 20 μ high beam.

For efficient utilization of micropole undulators as sources of monochromatic light, the requirements are even more stringent. For example, for a resolution of 10^{-4} and a γ of 600, both the vertical and horizontal divergence angles must be

$$\lesssim 10^{-5}, \text{ which implies, } \varepsilon_V, \varepsilon_H \lesssim 10^{-10} \text{ rad-meter.}$$

The second problem, that of adequate vacuum, is related to the first in that beam scattering off the vacuum molecules and ions greatly reduces beam lifetimes for small apertures of a given size. In order to be able to run beams of adequate lifetime ($\gtrsim$ 30 min.) in storage rings with $\gamma \simeq 300$ MeV, vacuums in the vicinity of a micropole undulator gap of $\lesssim 10^{-11}$ Torr will be required.

The third problem relates to the fact that a micropole undulator gap represents a greatly constricted channel when compared to the rest of the ring. This can impart electromagnetic shocks that can cause beam instabilities leading to greatly shortened lifetimes.

Finally, for attaining spectral components with resolutions of 1/N, the errors in period placements and dimensions in a micropole device have to be on the order of 1/N as well. For N = 10,000 and a period of 500 μ, this represents accuracy and precision marginally attainable with state of the art technology. Nevertheless, for low K devices such difficulties are much less than for longer-period undulators.

Some of the above problems are not of serious concern in linac operation. On the other hand, it is still important to pass as much of the entire beam as possible through the undulator gap. Thus, emittance characterizations and upgrades into unprecedented regimes will be required for efficient micropole utilization on linacs as well.

Although some of the above problems represent formidable challenges in storage ring (and linac) physics and engineering, their resolution may be viewed as part of the benefits and progress associated with the incorporation of micropole undulators into storage ring and accelerator technology.

V. Ongoing Research

An experiment is presently in progress at the LLNL linac to test a 35 period, 1" long micropole undulator [5]. The experimental layout is schematized in Fig. 3. Under typical operating conditions, outputs of several picowatts are expected. Once the operation of the device is demonstrated, plans are under way to test it on a higher-power linac [6]. Plans are also under way to install short micropole devices on either PEP or SPEAR at Stanford in the near future. In this fashion, we anticipate embarking on a long term program concerned with researching and resolving several of the important problems mentioned above.

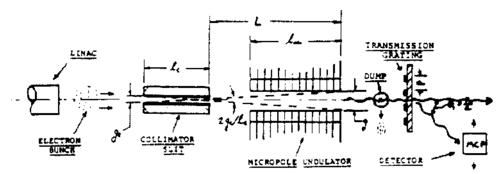

Fig. 3. Schematic layout of experiment to measure the radiation from the micropole undulator on a linac. MCP denotes a "micro-channel plate" detector. Although a transmission grating is shown, any other energy dispersive element could be employed.

VI. Discussion

It should be apparent that once some of the major technological obstacles to the incorporation of micropole insertion devices on storage rings (and linacs) are surmounted, the vast economical advantages accruing from the use of such devices could possibly lead to significant transformations of synchrotron radiation technology. This would be true in the area of conventional applications, as well as in novel experimental possibilities in different areas of physics [7]. We briefly mention some of the ones pertaining exclusively to micropole undulators here.

In conventional applications:

(a) Micropole undulators could replace conventional undulator/monochromator systems on fixed energy rings with simple aperture/scanning mechanisms.

(b) Micropole undulators are ideally suited for use in angiography systems. Due to economic advantages, one can visualize low cost, low energy rings dedicated to such facilities.

(c) Micropole undulators could replace conventional instrumentation in ultra-high resolution photoemission spectroscopy in the soft x-ray range.

(d) Micropole undulators could be used as good broad-band soources for x-ray lithography, both on linacs and storage rings.

(e) Micropole undulators could become the definitive sources for x-ray holography and other coherence experiments.

In novel research applications:

(a) On high energy rings (and linacs) micropole undulators could be used as sources of intense and highly collimated hard x-rays and gamma rays.

(b) Micropole undulators could be used to probe the crystal structures of various phases in high pressure cells, particularly that of metallic hydrogen [8].

(c) Micropole undulators could be used for probing nuclear energy levels and for other areas of nuclear spectroscopy (e.g., Mössbauer).

(d) Micropole undulators could be used in a broad range of high energy particle physics experiments (stochastic particle beam cooling, photon physics, etc.) [7].

Although this represents only a partial listing of the possible applications of micropole undulators, we believe it adequately underscores our claims regarding their potential, and hope that it will help stimulate widespread research efforts and broad-based support for further work in this area.

VII. Acknowledgements

This research was supported primarily by grant DE-AC03-82-ER1300 and additionally by grants DE-FG06-85-ER13309 and AFOSR-85-0326. Portions of the work reported herein were done at SSRL, which is supported by the Department of Energy, Office of Basic Energy Sciences.

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*Affiliate member, Center for X-Ray Optics, LBL, Berkeley, CA 94720, USA.

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[5] The collaborators are John Hunter, Robert Hornady, Dave Whelan, Glenn Westenskow, and E. Källne.

[6] The first linac facility considered for this experiment was the NRL linac in Washington, D.C., offered kindly by David Nagel. Use of the HEPL linac at Stanford has been discussed with John Madey. The Bates linac at MIT is also under consideration. The decision to use the LLNL linac initially was made in order to avoid problems with high level bremstrahlung and neutron noise that would be generated with the particular experimental configuration used (see Fig. 3).

[7] P.L. Csonka, "Insertion Devices, Future Developments, Limitations," SPIE Proceedings No. 582, pp. 298-317, 1986.

[8] These possibilities have been discussed with S. Qadri and Dave Nagel at NRL.