High-flux x-ray undulator radiation from proposed *B* factory storage rings at Cornell University

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(Presented on 15 July 1991)

Two intersecting storage rings (8 GeV, 1 A and 3.5 GeV, 2 A) have been proposed to be built at Cornell University to enhance both the production of *B* mesons and synchrotron radiation. Exceedingly high x-ray flux from 3-m long undulators will be the new feature of a *B* factory for the CHESS laboratory. The flux produced integrated over the central cone of radiation can be as much as an order of magnitude higher than from the third-generation storage rings (now under construction) operating at 0.1 A.

I. INTRODUCTION

Cornell University is proposing to build two new storage rings which promise to usher in a new era of experimentation for both high-energy physics and synchrotron radiation research. The machine will collide electrons and positrons from two rings, one operating at 8 GeV, 1 A and the other at 3.5 GeV, 2 A of beam current. The rings will dramatically increase the number of *B* mesons produced for physics investigations, hence the term "*B* factory."

The storage rings at Cornell will be capable of producing synchrotron radiation beams of tremendously high flux from undulators and wigglers permanently installed in the rings. We will be able to operate undulators in the storage rings full time and not just during dedicated periods. We plan to increase our present number of beam lines from five to eight, including two hard x-ray and one soft x-ray undulators. To make best use of the new insertion device capabilities, we envision adding 7000 ft^2 (650 m^2) of addition floor space near our current *A* line as well as keeping the present CHESS East and West laboratory space.

The optimization of these rings is different than for the third generation of high brilliance machines such as the APS, ALS, ESRF, Spring-8, etc. The *B* factory rings will be able to store about 10 times the current of these high brilliance storage rings by having 230 bunches of charge stored in bunches of modest beam size. The electron and positron beams will be refilled to their peak currents every 5 min or so with only 5% of this time devoted to filling. Thus radiation will be produced at near peak power during operations.

The *B* factory will possess a vertical emittance comparable to the APS although the horizontal emittance will be about 12 times larger. The 3-m-long *B* factory undulators will be capable of producing one-half the brilliance of a 2.5-m-long APS undulator *A*, but will surpass the APS by a factor of 3 in brightness and 10 in flux. This will give the synchrotron radiation community an opportunity to develop experiments optimized on flux rather than brilliance. These high intensity beams will provide unique opportunities for advances in chemistry, materials research, biology, physics, and medicine in a very cost effective manner with an appealing geographic location well suited to a large East Coast population of scientists in the United States and Canada.

II. LABORATORY DESIGN

The CHESS *B* laboratory floor plan is shown in Fig. 1 and further described in a recent proposal.[1] The proposed facility differs from the present one in several basic ways. The present magnets and shielding wall are all moved from their current positions, necessitating a redeployment of some, but not all, of our existing beam lines. For instance, all the lines in CHESS West (*A*,*B*,*C*) will be relocated. However, the East lines (*D* and *F*) will remain roughly where they are and will be fed from the 3.5-GeV ring. New straight sections will be provided on the 8-GeV ring for operation of two hard x-ray undulators. The number of beam lines will be increased from the present five to a total of eight. (See Table I.)

III. UNDULATOR SOURCES

There are three features of the *B* factory design that are relevant for achieving high-flux production from an undu-

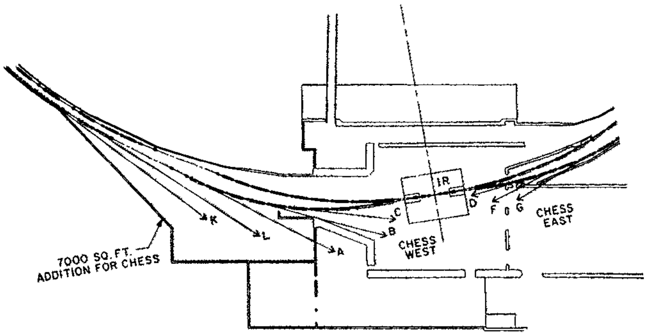

FIG. 1. Schematic layout of eight beam lines attached to both the 8- and 3.5-GeV rings of a *B* factory. The shaded area denotes new space to be added to the existing CHESS West laboratory. The lines marked *B*, *C*, *D*, and *F* are continuations of the present beam lines in the current CHESS laboratory.

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TABLE I. General beam line specifications for CHESS *B*.

Line	Source	Ring	Comments
A	Undulator 1	8.0 GeV	5.4-cm period, 111 poles, 3 m fundamental = 1.7 to 7.5 keV for a 2.0 to 3.8-cm gap (5 to 22 keV in third order)
B	Bend magnet	8.0	$E_c = 25$ keV, $r = 45$ m
C	Bend magnet	8.0	$E_c = 25$ keV, $r = 45$ m
D	Wiggler 1	3.5	$E_c = 10$ keV at 1.2 T
F	Wiggler 2	3.5	$E_c = 10$ keV at 1.2 T
G	Undulator 3	3.5	1–2-keV soft x-ray undulator, parameters to be determined
K	Bend magnet	8.0	$E_c = 25$ keV, $r = 45$ m
L	Undulator 2	8.0	5.4-cm period, 111 poles 3 m, fundamental = 1.7 to 7.5 keV for a 2.0- to 3.8-cm gap (5 to 22 keV in third order)

lator operating in the 5- to 20-keV range: the 8-GeV machine energy, a low vertical emittance, and very large beam currents. The CHESS group has had considerable experience in producing and utilizing undulator radiation. The Cornell staff have worked jointly together with Advanced Photon Source and Spectra Technology staff members to design a 123-pole undulator with a 3.3-cm period and to operate[2–4] it in CESR as a prototype test of APS undulator "*A*."

The x-ray energy at the *p*th harmonic of an undulator for on-axis observation points is given by

$$E_p = \frac{0.949pE^2}{\lambda_u(1+K^2/2)},$$

where E_p is the photon energy in keV, λ_u is the undulator period in cm, p is the harmonic numbers, and E is the storage ring energy in GeV. The parameter K is the ratio of the particle deflection angle to the natural opening angle of the radiation and is given in terms of the undulator period λ (cm) and the peak magnetic field B (T) by

$$K = 0.934\lambda_u B.$$

For proper undulator performance this parameter usually is of order 1. For 2- to 4-cm undulator gaps, appropriate undulator periods are from 3 to 6 cm with peak fields of order 0.1 to 0.8 T.

The undulator harmonics may be tuned for a particular application by varying the undulator gap and therefore its peak magnetic field. One example of the utility of this tunability may be found in the excitation of a sample near its resonant x-ray absorption edge, causing atoms of this one particular kind to be "highlighted" with respect to all the other elements in the sample.

In Fig. 2 a family of curves is presented to illustrate how the first harmonic energy varies with gap for various undulator periods. The calculation assumes an 8-GeV energy and an undulator of the magnetic hybrid type built using Nd-Fe-B permanent magnets which is similar to our present design. The results indicate that a final design for a CHESS B undulator and its range of tunability will depend critically on the minimum vertical gap available on CESR *B*. Too small a gap leads to injection and/or beam lifetime problems. Too large a gap means poor tunability and low-flux production. Chambers will be built initially for the *B* factory with a conservative working gap of 3.0 cm with the expectation of replacing them with 2.0-cm chambers at a later date. Assuming a minimum gap of 2.0 cm, a 5.4-cm period undulator will tune from 1.7 to 7.5 keV in first order and from 5 to 22 keV in third order, covering a significant number of *K* and *L* absorption edges of interest.

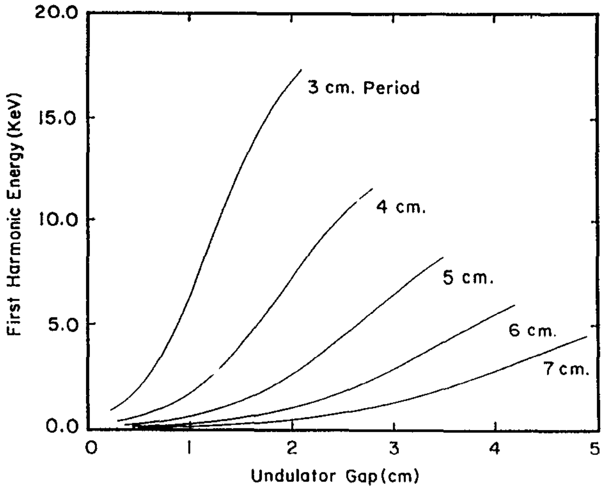

FIG. 2. X-ray energy of the first harmonic of a *B* factory undulator vs gap size, for an 8-GeV beam and 3- to 7-cm undulator periods.

In order to make radiation from successive poles of the undulator add constructively, the emittance of the machine must be significantly lower than the present CESR emittance. The design emittance for the *B* factory is, in fact, quite similar to that obtained for the dedicated undulator runs of 1988 and 1991. Ideally both the horizontal and vertical emittances of the 8-GeV ring would be < 10 and 1.0 nm rad, respectively, the general design range chosen by the developers of the third-generation rings. As it stands, the vertical emittance of the *B* factory will be comparable with these designs and is sufficient to produce "undulator"-like peaks in the energy spectrum. Our anticipated horizontal emittance is of order ten times larger than for these machines, giving rise to a larger horizontal beam size (which can be further reduced with focusing x-ray optics). Since many experiments in the 10-keV regime require the most flux/mm^2 with only modest requirements on divergence, we believe that for a good number of standard experiments the CESR *B* facility will outperform these machines.

Spectral calculations have been performed with the program "SHADOW" to compute the flux, brightness, and brilliance of an undulator as a function of magnet period, gap size, etc. We have assumed a 3-m length for the undulator. This is a compromise that saves considerable cost over longer devices of say 5 to 6 m without greatly com-

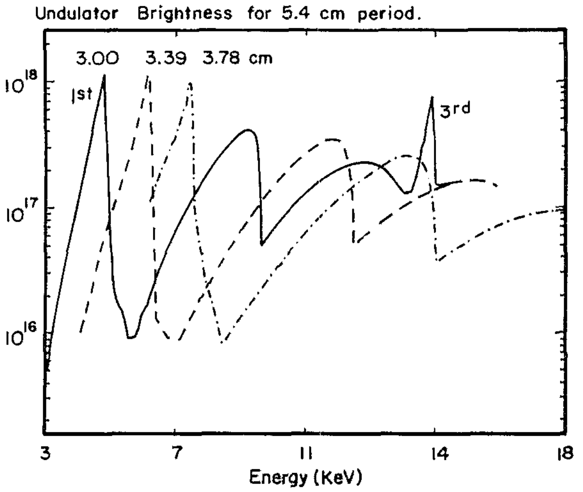

FIG. 3. The brightness (P/S/0.1% bw/mrad^2 of a 5.4-cm period permanent magnet undulator of 3-m length in a B factory of 8 GeV and 1 A. The first and third orders of the radiation are labeled for the curve with a 3-cm gap. Further opening of the gap shifts all the harmonics to higher energy.

promising the main features in the undulator spectrum. The shorter length reduces the peak brilliance by only a factor of 2 or 3.

The calculated brightness of a 5.4-cm period undulator is shown in Fig.3. The undulator radiation from the first and third orders of the spectrum are in the hard x-ray domain and can be tuned in energy by varying the gap. A complete set of parameters used in the calculation of Fig. 3 is given in Table II. Table III presents a numerical comparison of the flux, brightness, and brilliance (brightness/source size) for the first-order spectral peak for this CHESS B undulator with respect to a type A APS undulator of 3.3-cm period and a 2.5-m length. The conclusion from Table III is that CHESS B undulator will produce 10 times the flux, 3 times the brightness, and about 0.5 the brilliance of the APS. Thus the frontier experiments that demand the highest brilliance might best be done at the APS and those mostly driven by brightness or flux would best be done at CHESS B.

TABLE II. Comparison between the parameters of the CHESS B undulator and the APS undulator A.

Element	CHESS B	APS
Magnetic period	5.4 cm	3.3 cm
Undulator length	3 m	2.5 m
Gap	3.0 cm	1.39 cm
Fundamental energy	5.3 keV	6.0 keV
Peak magnetic field	0.33 T	0.53 T
K, deflection parameter	1.5	1.64
Number of periods	55	75
Machine energy	8 GeV	7 GeV
Beam current	1 A	0.1 A
Vertical emittance	10^{-9}mrad	0.73×10^{-9} mrad
Horizontal emittance	10^{-7} mrad	8.3×10^{-9} mrad
Horizontal beta, β_x	14 m	13 m
Vertical beta, β_y	21 m	10 m
Horizontal source size, σ_x	1.2 mm	0.308 mm
Vertical source size, σ_y	0.145 mm	0.085 mm
Horizontal divergence, σ_x'	85 mrad	24 mrad
Vertical divergence σ_y'	7 mrad	9 mrad

TABLE III. Comparison between the first harmonic flux, brightness, and brilliance between similar undulators proposed for the 8-GeV ring of CHESS B and the 7-GeV APS ring under construction at Argonne. The flux values are integrated over the central cone of radiation.

	CHESS B	APS Undulator A	Ratio CHESS B/APS
Flux (photons/s/0.1% b.w.)	3.7×10^{15}	3.8×10^{14}	9.7
Brightness (photons/s/0.1% b.w./mrad^2)	1.0×10^{18}	2.9×10^{17}	3.4
Brilliance (photons/s/0.1% b.w./mrad^2)	9.0×10^{17}	1.7×10^{18}	0.53

The 8-GeV ring design beam current is 10 times the 100-mA design for the ESRF and the APS. The high current by itself will make for exceptionally high-flux production and will be unique to a B factory design for some time to come.

IV. BEND MAGNET AND WIGGLER SOURCES

The proposed facility will offer the most powerful sources of hard (and soft) synchrotron bending magnet x-ray radiation available anywhere. The combination of 8-GeV machine energy and 1-A beam current implies that the bend magnets at CHESS B will produce a photon flux comparable to the largest wiggler sources to be built for current third generation of machines. With a critical energy of 25 keV, these magnets will rival the spectral characteristics of our present F line (25-pole wiggler, $E_{\text{critical}} = 22$ keV at 5.3 GeV). Another important spectral property of these bend magnet sources is their polarization characteristics, in particular the circularly polarized component of the radiation emitted off the orbital plane. The brightness and degree of circular polarization of this radiation will equal or exceed that produced by the asymmetric wigglers recently tested in Germany and Japan.[5] The CHESS B bending magnets will be well suited for magnetic Compton scattering up to approximately three times the critical energy or about 75 keV.

Wiggler magnets provide an intense broadband source of synchrotron radiation and also produce copious quantities of x-ray power, a factor which must be included in the design of any beam line that will make use of this kind of radiation. The total power from a synchrotron source can be calculated from

$$P(\text{kW}) = 0.633{*}E(\text{GeV})^2{*}B(\text{T})^2{*}L(\text{m}){*}I(\text{A}),$$

where E is the machine energy, B is the peak magnetic field, L is the effective length of the wiggler, and I is the particle beam current. At 8 GeV and 1 A, a 2-m-long, 1-T device would produce 81 kW of power. This is more than 6 times the heat load we presently accommodate from the current CHESS 25-pole wiggler and is beyond the capabilities of what we will likely be able to handle in the near future. Thus we have no present motivation to install a multiple wiggler on the 8-GeV ring. One remaining possibility is to install a single pole wiggler or wavelength shifter to boost the critical energy to 100 keV if so desired.

On the 3.5-GeV ring, our present 25-pole device would produce about 35 kW spread out over a much larger area than for a 8-GeV machine. This is about the same total power currently produced by the NSLS superconducting wiggler and this amount of power can be handled with current beam stop technologies. We propose to install this 1.2-T wiggler on the low-energy ring to allow us to reach a 10-keV critical energy and to continue to operate our newly created stations in CHESS East on *D* and *F* lines.

V. SCIENCE EXPERIMENTS

B factory affords us an unparalleled opportunity to develop the next generation of synchrotron radiation source and to address those experiments that are of an x-ray flux limited nature. These areas include nuclear Bragg scattering, x-ray standing waves, magnetic x-ray scattering, inelastic x-ray scattering, angiography, lithography, and many real-time experiments (e.g., real-time studies on buried interfaces, thin films, semiconductor crystal growth, small- and wide-angle scattering on polymers and lipids, Laue diffraction, etc.).

Even protein crystallography experiments are generally flux and not brilliance limited experiments. For instance, our present *F*1 line provides 2×10**12 monochromatic photons/s through a 0.3-mm collimator from a 25-pole CHESS wiggler. Using the entire cone of undulator radiation with a focusing Si(111) monochromator and focusing mirror, an APS undulator *A* (2.5 m) will produce 10 times this *F*1 flux. A 3-m-long *B* factory undulator, however, will produce 100 times this *F*1 flux. (The gain of a factor of 10 over the APS arises mainly from having 10× the beam current. The divergence after focusing will remain low enough to permit spectacular photography of virus single crystals.)

The experimental categories listed above are just a sample of some areas where a large number of experiments can make use of high-flux, low divergence undulator radiation with natural beam sizes that are a few times larger than will be available at third generation sources.

VI. HEAT LOADING OF BEAM LINE COMPONENTS

A real challenge for the laboratory will be its ability to handle high heat loads on exit crotches, beam stops, beryllium windows, and first optical components such as a monochromator crystal.

Under design is a new all beryllium crotch which will need to withstand 2100 W/mm^2 at 8 GeV, 1 A, a factor of 3 times our current design.[6] A beam stop located 20 m away from a 3-m-long, 5.4-cm period undulator with a 3-cm period gap will be exposed to a power density of 1200 W/mm^2 and intercept 13 kW of power. This is only a factor of 2.4 above our current *F*-line design[7] in power density (500 W/mm^2, 17 kW of total power during 5.5-GeV, 200-mA operation from a 1.2-T, 25-pole wiggler). These are straightforward engineering changes that can be accomplished by further inclining the absorbers with respect to the incoming beam.

The vacuum windows just beyond the 20-m point will absorb 80 W/mm^2 of power from a *B* factory undulator in a 500-μ-thick window. Current experience at CHESS has shown that 21 W/mm^2 has already been handled successfully.[8] Thus a four times improvement will be needed. Cryogenic cooling of beryllium (or even of diamond-coated beryllium) is feasible and can easily handle this increase. (At cryogenic temperatures, the beryllium is stronger and conducts heat better than at room temperature.)

The first optical component such as a monochromator crystal will have to be better cooled than is presently the case. Many synchrotron optics groups are at work on this problem[9] and there are ideas that still remain to be further optimized. The present methods are to attempt cooling with microgrooves in silicon just underneath the diffracting surface, use thin crystals, try jet-cooled optics, rotate the monochromator crystal like the spinning anode of an x-ray generator, use inclined or asymmetrically cut crystals, and finally, employ additional optical components such as foil, mirrors, multilayers, etc. One or a combination of these approaches will satisfactorily handle the heat loads at these awesome power densities.

ACKNOWLEDGMENTS

We thank our colleagues of the Laboratory of Nuclear Studies at Cornell University for the opportunity to jointly develop the concept of a laboratory based on high-flux x-ray undulators. This work is based on work conducted at CHESS and supported by the National Science Foundation under Award No. DMR 90-21700.

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