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# COMPACT ELECTRON STORAGE RINGS

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## Abstract

There have been many recent developments in the area of compact storage rings. Such rings would have critical wavelengths of typically 10 Å, achieved with beam energies of several hundreds of MeV and superconducting dipole fields of around 5 Tesla. Although the primary motivation for progress in this area is that of commercial x-ray lithography, such sources might be an attractive source for college campuses to operate. They would be useful for many programs in materials science, solid state, x-ray microscopy and other biological areas. We discuss the properties of such sources and review developments around the world, primarily in the USA, Japan and W. Germany.

## 1. Introduction

In recent years increasing attention has been paid, primarily by accelerator physicists, to concepts of synchrotron radiation sources based on very compact storage rings using superconducting magnets. In this paper we will review the characteristics of such rings, which illustrate many of their attractive properties. We will also, however, build perspective around the story of the development of such sources, in particular reviewing the various efforts to construct and commission them with emphasis on the various research and development tasks.

## 2. Compact Synchrotron Source Characteristics

### A. Basic Ring Parameters

We propose that the storage ring have a critical wavelength of 10Å, and that the dipole fields be 5 Tesla. We find that the energy of such a ring is given[1] by:

$$\lambda_c\,(Angstroms) = \frac{18.6}{B\,(Tesla)\,E^2(GeV)} \tag{1}$$

and the bending radius by:

$$\lambda_c\,(Angstroms) = \frac{5.59\rho(m)}{E^3(GeV)} \tag{2}$$

These equations are satisfied if E = 610 MeV and $\rho$ = 41 cm.

## B. Source Brightness 1 : Radiated Flux

If we assume a stored current of 200 mA, the power radiated per mradian is then:

$$p = \frac{2.65E^3IB}{\pi 1000} \tag{3}$$

When the above numbers are inserted we find that p = 1 watt, or similar to the NSLS VUV ring with 800 mA of stored beam. We can calculate the photon flux as a function of wavelength for such a ring using the formula:

$$N(\lambda) = 1.256\,10^{10}\gamma I \frac{\lambda_c}{\lambda}\int_{\frac{\lambda_c}{\lambda}}^{\infty} K_{\frac{5}{3}}(\eta)\,d\eta \tag{4}$$

where $K_{\frac{5}{3}}$ is a modified Bessel function of fractional order. $N(\lambda)$ is the number of photons/sec for a 0.1% bandwidth and per horizontal milliradian. Equation (4) can be solved using methods presented by Williams and Weisenbloom[2], but a useful approximation which we use here has been published by Kostroun[3]. The data are shown in Fig. 1 and Table 1 and are compared with the NSLS VUV ring, Brookhaven.

## C. Source Brightness 2 : Radiation Opening Angles

The vertical angular distribution of the emitted radiation is given by:

$$F(\psi) \approx [1+(\gamma\psi)^2]\left\{K_{\frac{2}{3}}^2(\eta) + \frac{\gamma\psi^2}{[1+(\gamma\psi)^2]} K_{\frac{1}{3}}^2(\eta)\right\} \tag{5}$$

where

$$\eta = \frac{\eta_c}{2}\lambda[1+(\gamma\psi)^2]^{\frac{3}{2}} \tag{6}$$

and the $K_{\frac{2}{3}}$ and $K_{\frac{1}{3}}$ terms represent radiation polarized parallel or perpendicular to the orbit plane, respectively. We also calculate

$$F_{tot}(\psi_1) = \int_0^{\psi_1} F(\psi)\,d\psi \tag{7}$$

for both polarizations as well as their sum. We are then able to derive the percentage of light transmitted by a beam line of a given vertical acceptance. The results of calculations of this type are plotted in Fig.2. The numbers are given in Table 1. where they are compared with the NSLS VUV ring at Brookhaven. As an alternative we could treat the vertical divergence for the parallel component by assuming the angle-intensity function $F(\psi)$ to be Gaussian of the form $e^{-\frac{\psi^2}{2\sigma^2}}$.

In the range $0.2 < \frac{\lambda}{\lambda_c} < 100$ $\sigma_R$ can be approximated by

$$\sigma_R = \frac{0.57}{\lambda}\left\{\frac{\lambda}{\lambda_c}\right\}^{0.43} \tag{8}$$

### D. Source Brightness 3 : Source Size

It would appear that in principle such a ring could have a source size whose Gaussian $\sigma$ value was 0.1 mm vertical by 1 mm horizontal. Rather more conservative values of 1 mm x 1 mm have been chosen for the prototype machines. however, as these are adequate for lithography purposes[4]. It is X-ray lithography which has driven this compact ring development.

## 3. Historical Perspective

The first small storage ring to be discussed was called "Klein Erna"[5] and was based on a single superconducting magnet with an iron core. Later, at BESSY in Berlin, a modified concept without the heavy ion core was considered[6] and termed COSY for compact synchrotron. The radiofrequency cavity was incorporated between the coils with acceleration planned via the betatron effect.

Further studies, particularly of the engineering of the superconducting magnets led Wilson[7] to suggest replacing the single dipole by two, three or four dipoles with the rf cavity, injection and other elements for focusing, tune and chromaticity correction in straight sections between the dipoles. The magnet gap can thus be reduced which results in considerable economies.

Van Steenbergen and Grobman[8] also considered multi-dipole configurations and several papers appeared in SPIE proceedings Vol. 448 in 1983.

Following this, Mulhaupt and his co-workers at BESSY and the Fraunhofer Institut, Berlin, set out to construct a small superconducting storage ring based on two dipoles, of parameters close to those discussed in Section 2. They planned to use a microtron injector. Using room temperature magnets of the same radius as the future superconducting ones, they obtained a low energy stored beam in early 1986.

In Japan, by late 1986 there were several efforts in place in the compact storage ring area. Three industrial efforts involve (1) SORTEC (a 12 company consortium), (2) NTT - building a 50 meter circumference warm machine and a superconducting maching at Atsugi and (3) the Fujitsu Company. The NTT warm machine will be installed in the fall of 1987, the cold machine 3-4 years later. The ElectroTechnical Laboratory is also working on NIJI, a small machine which will be used as an injector for a superconducting ring. Sumitomo is making the superconducting magnets for the ETL machine and also has a ring project of its own, as has Hitachi[9].

Other international efforts to design and build compact rings have been made by Oxford Instruments of England and Scanditronix of Sweden. Both plans utilize superconducting dipoles, the latter has an incorporated microtron injector.

Starting in the fall of 1985 a group from Brookhaven proposed and subsequently held a series of workshops involving the lithography industry. These defined the source parameters[4] and later presented designs for room temperature rings from Brookhaven and Brobeck Corporation and a superconducting ring using two dipoles from Brookhaven[10,11]. The latter is shown with 10 meter beam lines and end stations, in Fig. 3. Following the development of a program plan[12], funding was obtained midway through Fiscal 87 to begin a program to design these two rings, including injection and a building. The aims of the program are to build and commission a known technology ring at minimal risk as early as possible (2-3 years). This would enable lithography R&D, which in the interim is being conducted at SSRL, Brookhaven and Wisconsin, to proceed. The room temperature ring would be around 30 meters circumference, have a critical energy of 10 Å and be injected by a full energy linac. The beam energy is 1080 MeV, the bending radius 2.25 m. Other parameters are given in Table 2.

In parallel with this, R&D studies have begun on the superconducting ring - the ultimate goal being the production of a commercially viable prototype. Several areas of high risk for such a ring, concern the magnets, the lattice and low energy injection with subsequent ramping. Activities in these areas are proceeding at this time. The parameters for the early ring design are shown in Table 2. For both of the Brookhaven rings the source size is given by the Gaussian parameters $\sigma_{vert} = \sigma_{horiz} = 1 mm$. The intrinsic beam divergence in the vertical is 1 mradian or less.

## 4. Concluding Remarks

Several plans exist to develop compact storage rings. The cost of such rings could be around 10 million dollars including injection, and thus, they could prove attractive for companies to use for manufacturing and research, as well as for Universities. The brightness could be improved by reducing the source size as experience on the early rings develops. Insertion devices in the straight sections of such rings could provide unique research opportunities.

I have attempted to present details of some novel storage rings and their properties. Further, I have described the history of the evolution of the designs of such rings.

## Acknowledgements

I would not have been able to write this without constant discussions and interactions with my colleagues at the National Synchrotron Light Source.

# References

1. G.K. Green, Spectra and Optics of Synchrotron Radiation. Brookhaven National Laboratory Report 50595 (1976).

2. G.P. Williams and J. Weisenbloom. Brookhaven National Laboratory Report 26874 (1979).

3. V.A. Kostroun, Nucl. Instrum. and Methods **172** .(1980) 371.

4. M.L. Knotek, W.Marcuse. F. Salzano and G.P. Williams, Brookhaven National Laboratory Report 52005 (1986).

5. U. Trinks and A. Jahnke, Nucl. Instrum. and Methods **200** , (1982) 475.

6. A. Heuberger, S.P.I.E. **448** , (1983) 8.

7. M. Wilson, private communication.

8. A. van Steenbergen and W. Grobman. S.P.I.E. **448** . (1983) 72.

9. K. Tsumaki. IEEE Proceedings. to be published.

10. M.Q. Barton. B. Craft and G.P. Williams. Brookhaven National Laboratory Report 38789 (1986).

11. G.A. Decker and B.C. Craft. IEEE Proceedings. to be published.

12. J.B. Godel. W. Marcuse and G.P. Williams. Brookhaven National Laboratory Report 52046 (1986).

# Figure Captions.

Figure 1. Calculated output flux from superconducting storage ring of radius 38cm. and beam energy .59GeV for 150mamps. of beam. Flux is per horizontal milliradian into a 0.1% bandpass.

Figure 2. Calculated vertical distribution of synchrotron radiation from superconducting storage ring of radius 38cm. and beam energy

Figure 3. Superconducting compact storage ring shown with 10meter beamlines. The bending radius is 69cm. the field 3.5 Tesla and the beam energy 728MeV.

| $\lambda$ | CR Flux | $\psi$ | NSLS Flux | $\psi$ |
|---|---|---|---|---|
| 3 | $6.3.10^{11}$ | | $1.7.10^{11}$ | |
| 10 | $4.7.10^{12}$ | 1.6 | $3.0.10^{12}$ | 0.7 |
| 30 | $6.7.10^{12}$ | | $3.0.10^{12}$ | |
| 100 | $6.0.10^{12}$ | 4.0 | $6.5.10^{12}$ | 2.3 |
| 300 | $4.7.10^{12}$ | | $6.5.10^{12}$ | |
| 1000 | $3.2.10^{12}$ | 8.8 | $5.0.10^{12}$ | 5.0 |

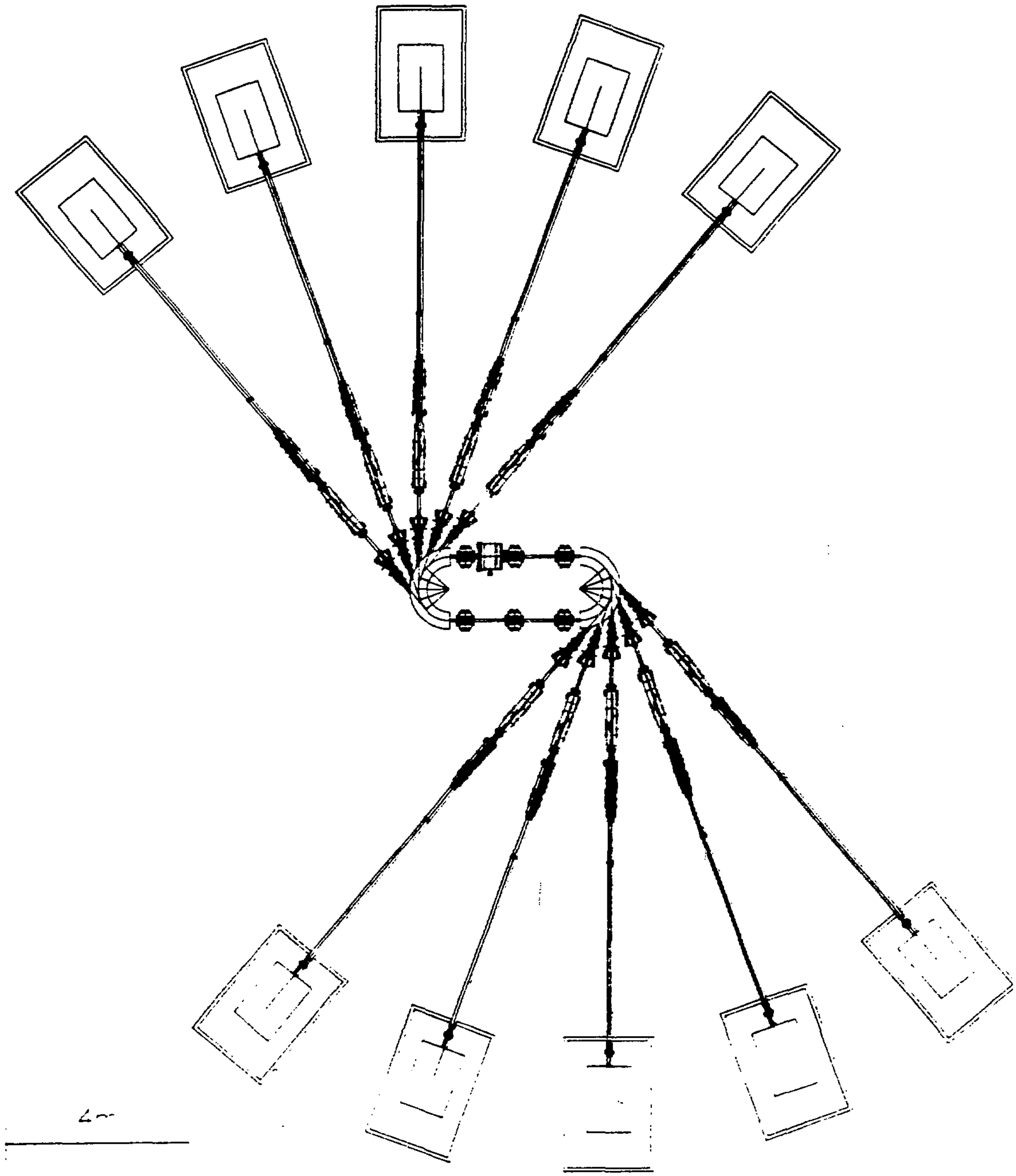
Table 1.

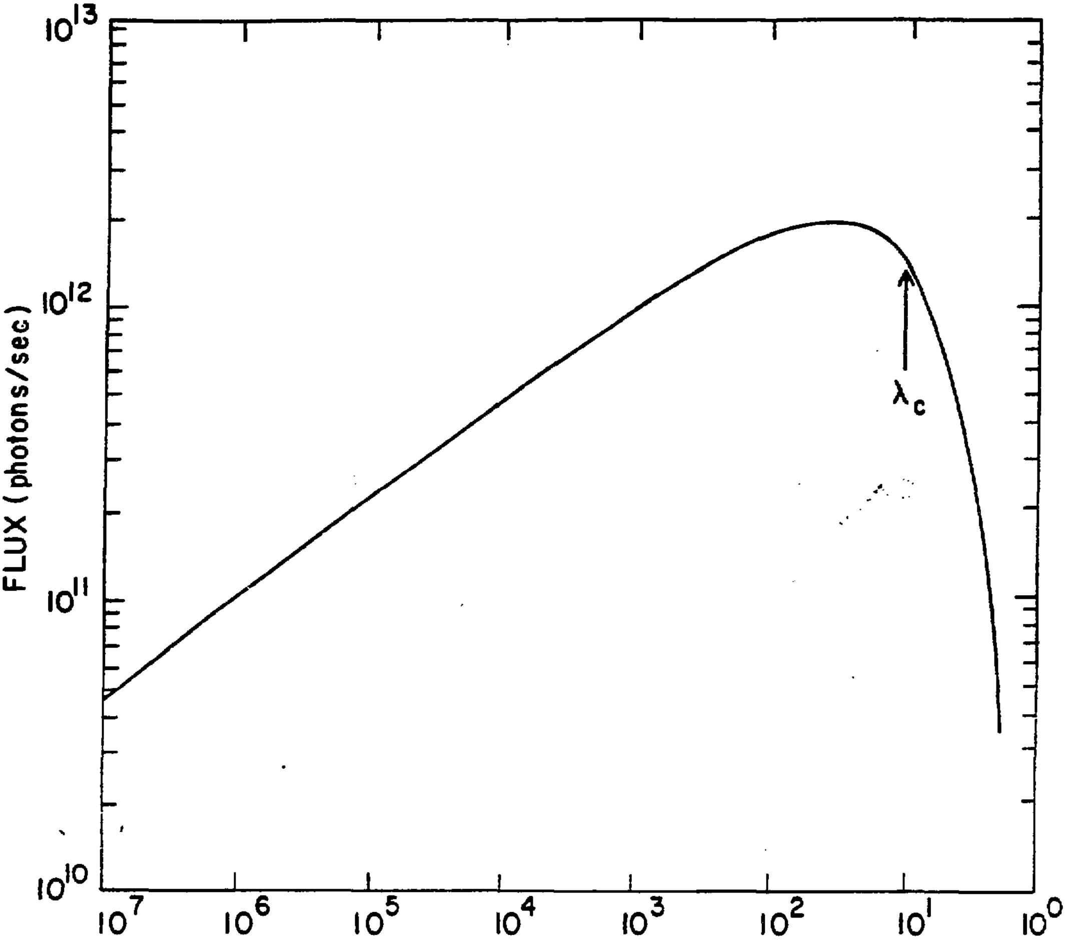
Comparison of flux from Compact Ring (CR) and the NSLS VUV ring. In both cases a stored beam of 500mamps was assumed. The vertical angles ($\psi$) are those required to pass 90% of the total radiation emitted. The units are photons/sec into a 0.1% bandwidth for the flux, and milliradians for $\psi$.

| | | |
|---|---|---|
| Energy | 1080MeV | 728MeV |
| Circumference | 29.74m | 10.2m |
| Critical Wavelength | 10A | 10A |
| Dipole Magnets | 4 | 2 |
| Field Strength | 1.6T | 3.5T |
| Bending Radius | 2.25m | .694m |
| Horizontal Betatron Tune | 3.14 | 1.56 |
| Vertical Betatron Tune | 1.18 | 1.60 |
| Maximum Dispersion | .73m | 1.44m |
| Momentum Compaction | .068 | .23 |
| Damped Emittance | $4.79.10^{-8}$m-rad | $4.25.10^{-7}$ m-rad |

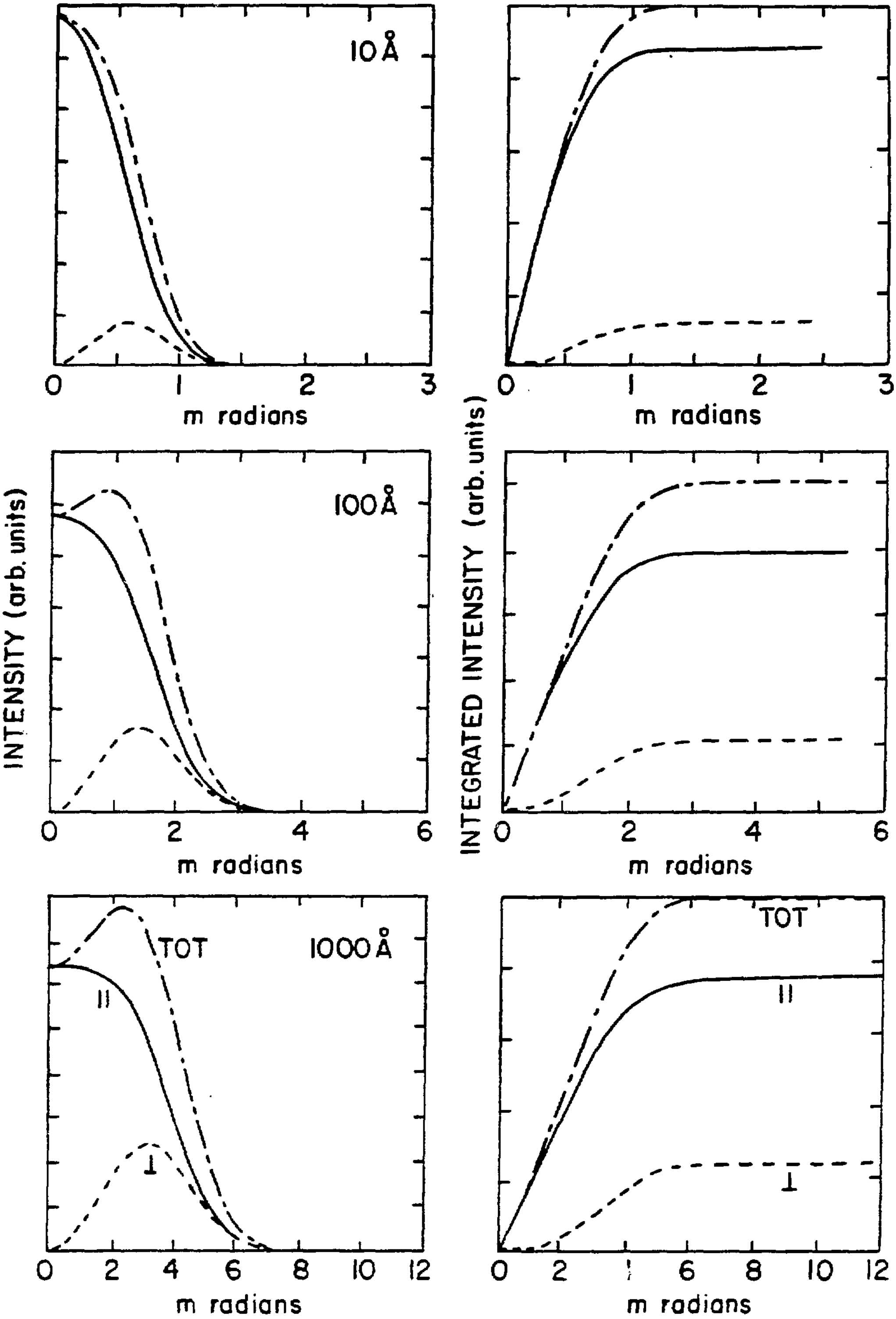
Table 2.

Parameters for the two rings presented by the NSLS at the Brookhaven Workshops in 1986.


4m



FLUX (photons/sec)
$10^{13}$
$10^{12}$
$10^{11}$
$10^{10}$
$\lambda_c$
$10^7$
$10^6$
$10^5$
$10^4$
$10^3$
$10^2$
$10^1$
$10^0$
WAVELENGTH (Å)


10Å
100Å
1000Å
TOT
II
⊥
INTENSITY (arb. units)
INTEGRATED INTENSITY (arb. units)
m radians
0
1
2
3
0
2
4
6
0
2
4
6
8
10
12