COMPACT STORAGE RING NIJI-II AS AN UNDULATOR RADIATION SOURCE

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Abstract

A compact storage ring NIJI-II with an undulator has been developed for free electron laser experiment and photon-induced chemical process. Four 90 ° bending magnets produce synchrotron radiation with critical wavelength 36.2A. A 1.36m long undulator is installed in a long straight section produces quasimonochromatic radiation with high intensity and peak wavelength shorter than 1000A near the ionization edge of methane. It is shown that these synchrotron radiation and tunable undulator radiation are promising photon sources for photon-induced chemical vapor deposition processes.

Introduction

Synchrotron radiation (SR) and undulator radiation (UR) are expected as new sources of vuv and soft X-rays for photon-induced chemical vapor deposition. The expectant characteristics of this process are low temperature, high purity, and good controllability. This matches the requisites for microdevice production. In order to experiment on this process, we have constructed a compact storage ring NIJI-II installing an undulator under technical guidance of Electrotechnical Laboratory. A straight section of NIJI-II is prepared for an undulator. The construction of NIJI-II was started in April 1989. The first beam storage was obtained in August 1989. This paper describes the outline of NIJI-II with a 1.36m undulator for synchrotron radiation induced chemical vapor deposition (SR-CVD) and properties of these radiations.

General Design Consideration

The size of the medium energy experimental room where NIJI-II is installed instead of NIJI-I is 8m x 10m. Considering the configuration of NIJI-II and electron beam transport from the ETL electron linac, the ring size must be less than 7m x 4m. A Long straight section is needed to install an undulator. Furthermore, an utility space and radiation shieldings must be secured.

For example, for testing deposition of carbon film by SR-CVD, requirements for the storage ring and the undulator are as follows:

(a) Peak wavelength of the first harmonic of UR be shorter than 1000A.
(b) Critical wavelength of SR from the bending magnet must be shorter than 42.6A to cause carbon k-shell (Ck-shell) ionization.
(c) Stored beam should have long life time.

We have already made primary SR-CVD experiments of preparing carbon film with methane using SR from NIJI-I. Although NIJI-I has provided valuable data needed for the development of industrial compact ring[1-4], quasimonochromatic radiation with high photon density could not be utilized, since it has no long straight section installing an undulator. Quasimonochromatic radiation is more effective to study detailed relations between film properties and the peak wavelength. For these studies, the peak wavelength of undulator radiation must be shorter than 1000A, because methane can be excited by the radiation shorter than 1000A.

It also possible to control hydrogen content of carbon film by SR-CVD. Ck-shell ionization is effective to decrease hydrogen content, because the doubly charged CH_4^{2+} is produced by Ck-ionization followed by Auger processes, and it is known the doubly charged CH_4^{2+} can dissociate into several fragments. Therefore a number of hydrogen combined carbon of the dissociation CH_4^{2+} is less than one of the dissociation of singly charged or neutral molecules. The wavelength corresponding to Ck-edge of ionization is 42.6A.

Long lifetime of stored beam is necessary to shorten experiment time. The Touscheck lifetime is inversely proportional to the density of electron. According to the Touscheck effect, high density beams and very small beam size cause extremely short lifetime. Peak photon density of UR decreases as the beam size becomes large. Therefore it is important to choose a beam size taking into account of both of the Touscheck effect and UR spectra.

Lattice Layout

Fig.1 shows a layout of NIJI-II. This ring employs four normal conductive bending magnets with field index 0. The maximum magnetic field is 1.43T, the bending radius is 1.4m, and maximum beam energy is 600MeV. The critical wavelength at 600MeV is 36.2A which can cause Ck-shell ionization.

In four straight sections, quadrupole magnets, a rf cavity, an inflector, and a kicker magnet are located. The 1.36m Undulator can be installed in the long straight section. Maximum total length of an undulator which can be installed is 1.5m. The lattice order is O/2 Q_F B Q_F' B Q_F O/2 and circumference of the ring is approximately 17m. Frequency of an rf cavity is 158.2MHz as the ninth harmonics of the revolution frequency. Table.1 shows the designed ring parameters.

At the operating point, the beam size and divergence are indicated in Table.1. Emittance is large at 600MeV. Therefore, intensity of the UR is not very

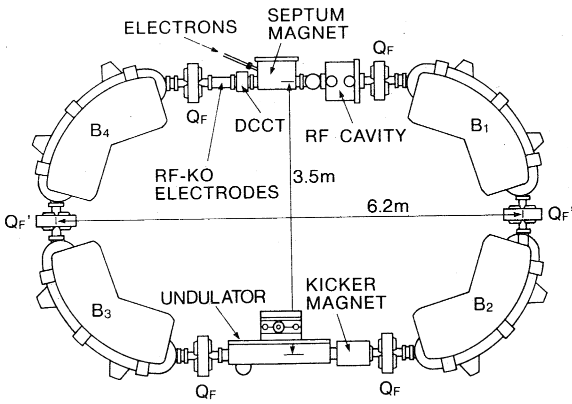

Fig.1. Layout of NIJI-II with an undulator

strong, but the Touscheck lifetime is long (about 1.3h at E=600MeV, I=100mA). Changes of the UR spectral distribution caused by beam size and divergence is discussed in the next section.

Table.1 Design parameters of NIJI-II

	(designed)
Final energy	600MeV
Injection energy	150MeV
Critical wavelength	36.2A
Circumference	17.06m
Periodicity	2
Bending magnet	
Radius	1.4m
Field(Max)	1.43T
Field index	0
Radio frequency	158.2MHz
Harmonic number	9
RF power	2kW
Nominal tune	
ν_x	1.36
ν_y	0.65
Beam size and beam divergence (at the center of undulator, 600Mev)	
σ_x	1.74mm
σ_y	0.81mm
σ'_x	0.79mrad
σ'_y	0.22mrad
Emittance	
ε	1.35×10^{-6} m·rad

Experimental Program and Radiation Source Properties

1.4T Bending Magnet

Fig.2 shows the calculated photon density of radiation from the bending magnet. Beam energy is variable from 150MeV to 600MeV. Fig.3 shows spectral dependence on absorption cross section σ_{abs} of CH_4[6]. CH_4 is one of the material gases of carbon film. The absorption region longer than 43A is valence electron excitation region, and the absorption region shorter than 42.6A is Ck-shell ionization region. At the beam energy higher than 500MeV, the radiation can cause both Ck-shell ionization and valence electron excitation. The sorts and quantity of ion and neutral products at Ck-shell ionization are very different from the one at valence electron excitation. This difference affect characteristics of deposition film. To investigate this difference is very interesting to control the film properties.

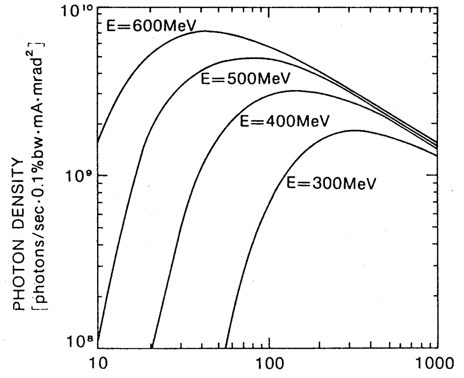

Fig.2. Spectral distributions of SR from NIJI-II bending magnets

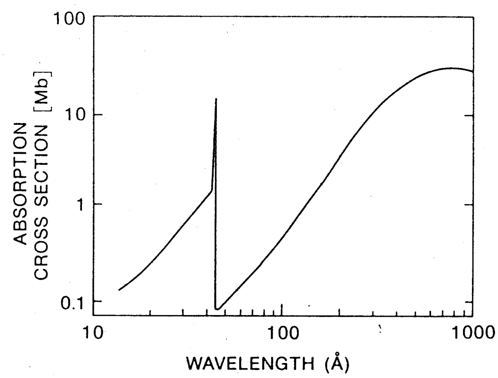

Fig.3. Spectral dependence of the adsorption cross section σ abs of CH_4[6]

1.36m Undulator

Fig.4 shows a photograph of an undulator will be installed. The full length is 1.36m, λ_0 is 8cm, the peak field strengths are 0.35T for a gap of 4cm and 0.064T for a gap of 8cm, and the gap is variable from 4cm to 40cm. The material of the permanent magnet chosen in the NEOMAX-35 grade with a standard range of remanent field of 1.23T. 134 blocks of size 20 x 20 x 100mm³ are used for the main part of undulator and 4 half-blocks are used for both edges.

This undulator allows wide exposure of high intensity and quasimonochromatic radiations with wavelength from 2850A to 1280A for the gap of 4cm (K=2.6) and from 728A to 324A for the gap of 8cm (K=0.48) by changing the energy of an undulating electron beam from 400 to 600MeV.[5]

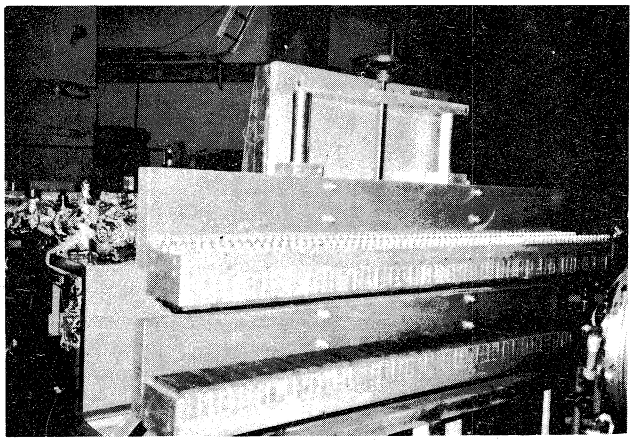

Fig.4. Photograph of 1.36m undulator

The characteristics of UR are well known through a number of theoretical works[8][9]. We calculate NIJI-II undulator spectrum by simple approximation using Monte Carlo method in consideration of beam size σ and beam divergence σ' as follows.

(a) Selecting electrons' situation and injection angle at the center of undulator from binormal distribution using a random number.
(b) Calculating UR spectrum using Eq.(1) at the observation point (z,θ,ϕ) for each electron[10].

$$d^2P_k/d\omega\, d\Omega = (e^2\gamma^2\xi^2/c\pi^2)\cdot[\sin^2(n\pi\,\omega/\omega_1)/(\omega/\omega_1-k)^2] * [\{2S_0\gamma\theta\cos\phi - K(S_1+S_{-1})\}^2 + (2S_0\gamma\theta\sin\phi)^2] \quad (1)$$

$$\omega=2\pi c/\lambda \qquad K=0.934Bu(T)\lambda_0(cm)$$

$$\xi=k/\{1+(\gamma\theta)^2+K^2/2\} \qquad \omega_1=2\gamma^2\omega_0/\{1+(\gamma\theta)^2+K^2/2\}$$

$$\omega_0 = 2\pi c\beta(1-K^2/4\gamma^2)/\lambda_0 \qquad \beta = 1-(1/\gamma^2)$$

$$S_a = \sum_{p=-\infty}^{\infty} J_{k+2p+a}(X) J_p(Y)$$

$$X = 2\xi\gamma\theta K\cos\phi \qquad Y = \xi K^2/4$$

where Ω is solid angle, γ is Lorentz factor, λ is wavelength of undulator radiation, c is the velocity of light, λ_0 is undulator period, N is a number of periods, K is undulator parameter, k is harmonics, Bu is magnetic field of undulator, Jn is nth Bessel function, and z-axis is the direction of the electron orbit in an undulator.

(c) Adding sum of these spectrum.

Fig.5b shows the spectra near the third harmonics of UR calculated with above mentioned approximation (E=500MeV and Bu=0.23T). For reference, Fig.5a shows the UR spectra taking no account of electron beam size σ and beam divergence σ'. Fig.5b indicates decrease of peak photon density, and red shift of peak wavelength. But the photon density from the undulator is about ten times as large as the one from the bending magnet at 345A.

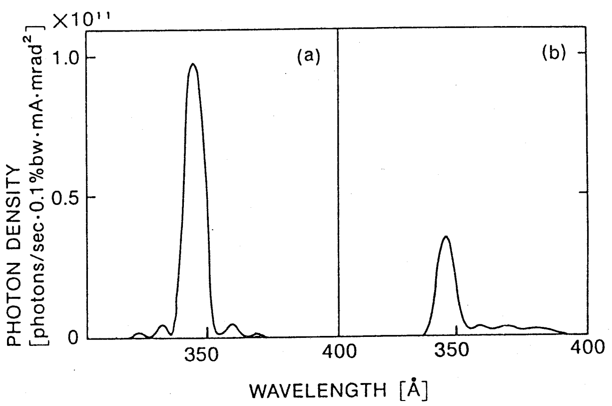

Fig.5. Spectrum near the third harmonics
(a) taking no account of beam size $\sigma_{x,y}$ and divergence $\sigma'_{x,y}$.
(b) taking into account of $\sigma_{x,y}$ and $\sigma'_{x,y}$ (E=500Mev, σ_x=1.48mm, σ_y=0.44mm, σ'_x=0.66mrad, σ'_y=0.20mrad, Bu=0.23T)

Fig.6 shows the photoabsorption cross section σ_{abs} and photoionization cross section σ_i of CH_4[7]. σ_{abs} and σ_i of CH_4 have peak values in the region shorter than 950A and 800A, respectively. Fig.7 shows near the first harmonic of undulator radiation at 463MeV and 407MeV (Bu=0.14T). In case of 463MeV, most of the UR are absorbed in σ_i region for CH_4, so most of the dissociation products are ion species. In case of 407MeV, the UR hardly absorbed σ_i region, so most of dissociation products are neutral species. The difference of products affects characteristics of carbon film. Moreover, the peak photon density is about a hundred times as large as the one from the bending magnet.

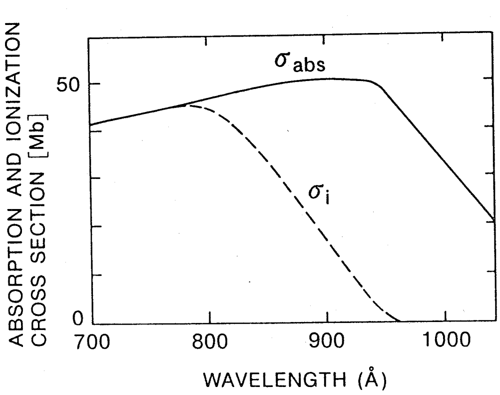

Fig.6. Photoabsorption cross section σ_{abs} and photoionization σ_i of CH_4[7]

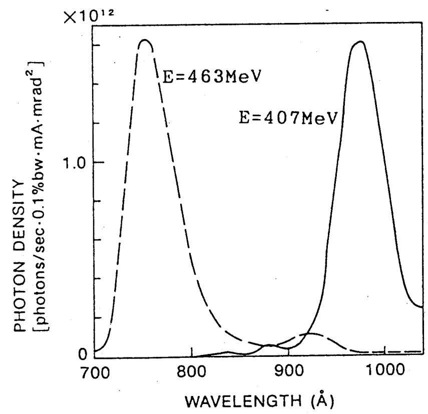

Fig.7. Spectrum near the first harmonic at 463Mev and 407MeV (Bu=0.14T)

Conclusion

It has been shown that radiations from the bending magnet and the undulator can be utilized to experiment on SR-CVD. By using radiations from the bending magnet, carbon film can be prepared with Ck-shell ionization. By using radiations from the undulator, dissociation products between ion and neutral species can be selected for preparing carbon film. In order to study SR-CVD, NIJI-II will be gradually improved so as to storage high current and low emittance beam.

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