Synchrotron-Cherenkov radiation observed in laboratory being predicted in astronomy, which will feasible compact X-ray laser

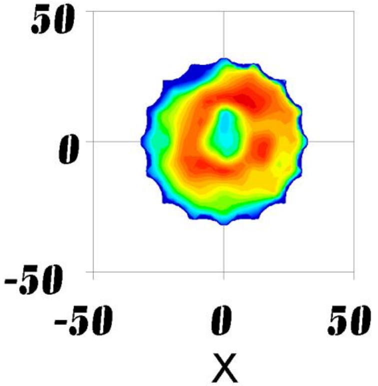
H. Yamada

Ritsumeikan University,
Tabletop Synchrotron Laboratory

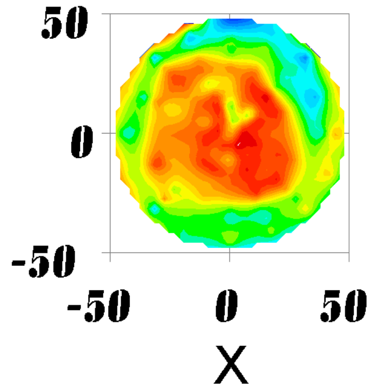
J. Synchrotron Rad. (2011). 18

Measurement of angular distribution of soft X-ray radiation from thin targets in the tabletop storage ring MIRRORCLE-20SX

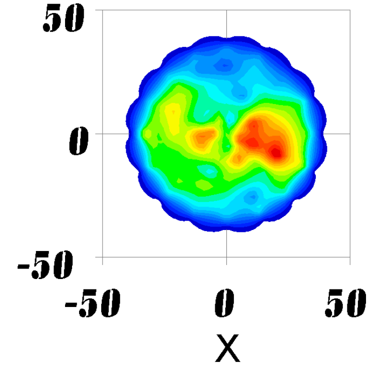
Hironari Yamada et al.



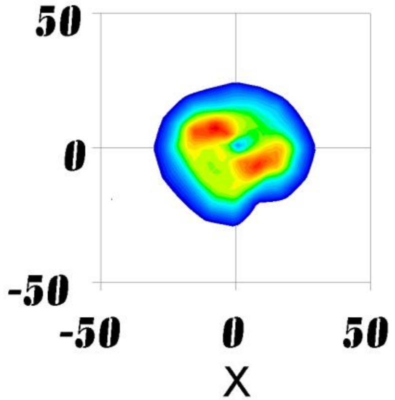
5 μm thick Mo sheet



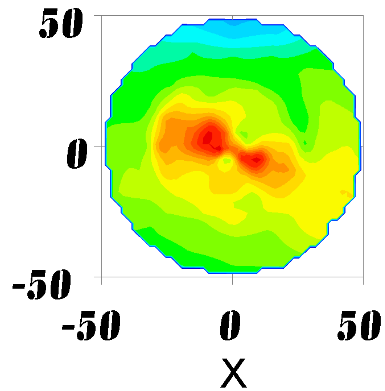
150 μm dia. Sn wire



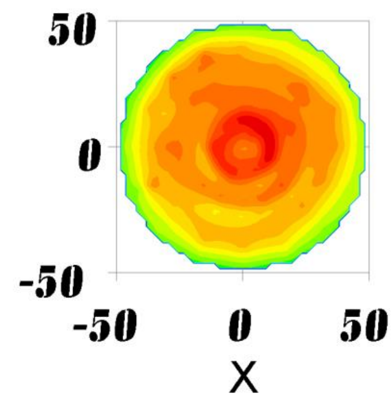
385 nm thick Al strip



15 μm thick CNT yarn



55 nm thick DLC strip



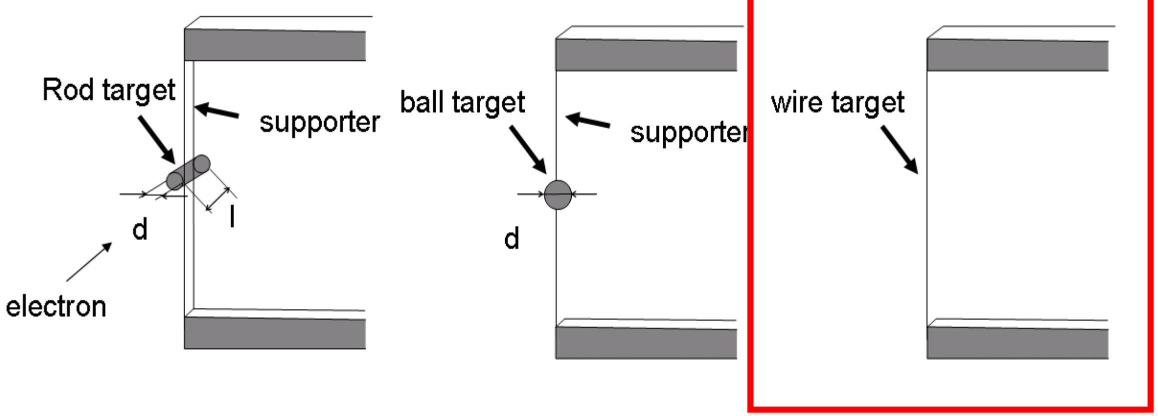
5 nm thick DLC strip with 385 nm thick Al filter

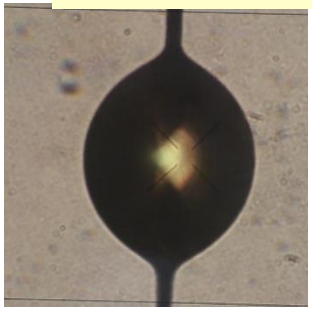
In this talk we are concerned followings

- What are those radiations?
  Transition, Cherenkov, Bremsstrahlung, or Synchrotron?
- What is the effect of magnetic field on these radiations.
- Synchrotron-Cherenkov radiation theory.
- Measured radiation power.
- What sort of applications will be opened.
  X-ray laser, EUV Lithography, research on optical nature at the absorption edge

MIRRORCLE tabletop storage ring enables placing targets in the orbit

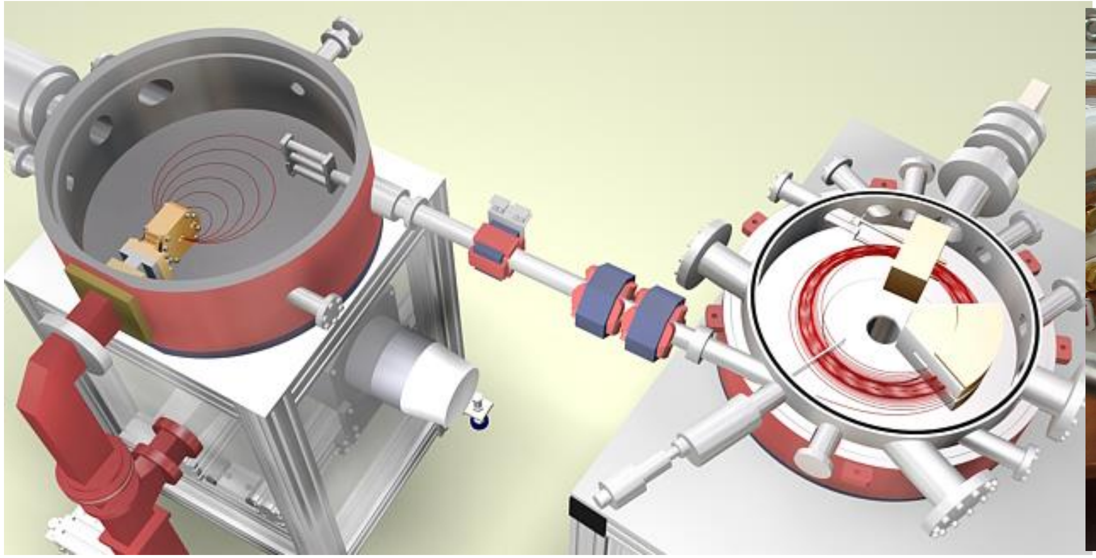
One micron wide line source will be most appropriate for mask inspection!!!





W40 sphe.
(5.5um)wire

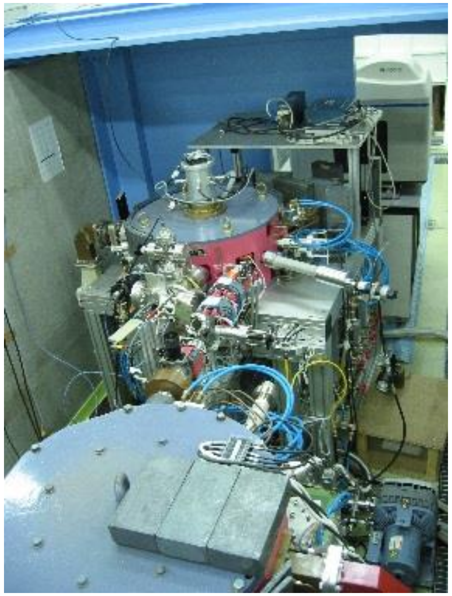
Cu10 sphe.
(4.5um)wire



Choice of MIRRORCLE

20 MeV

6MeV



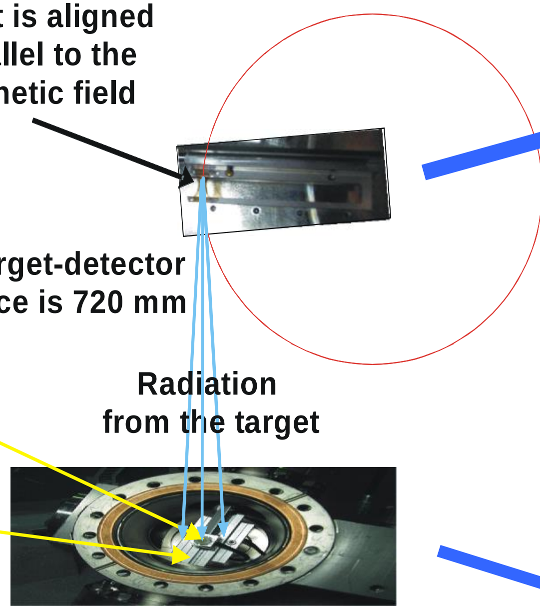
4MeV

Experimental set up

Case of MIRRORCE-20 the magnetic field applied is 3300G

Electron orbit

Target is aligned parallel to the magnetic field



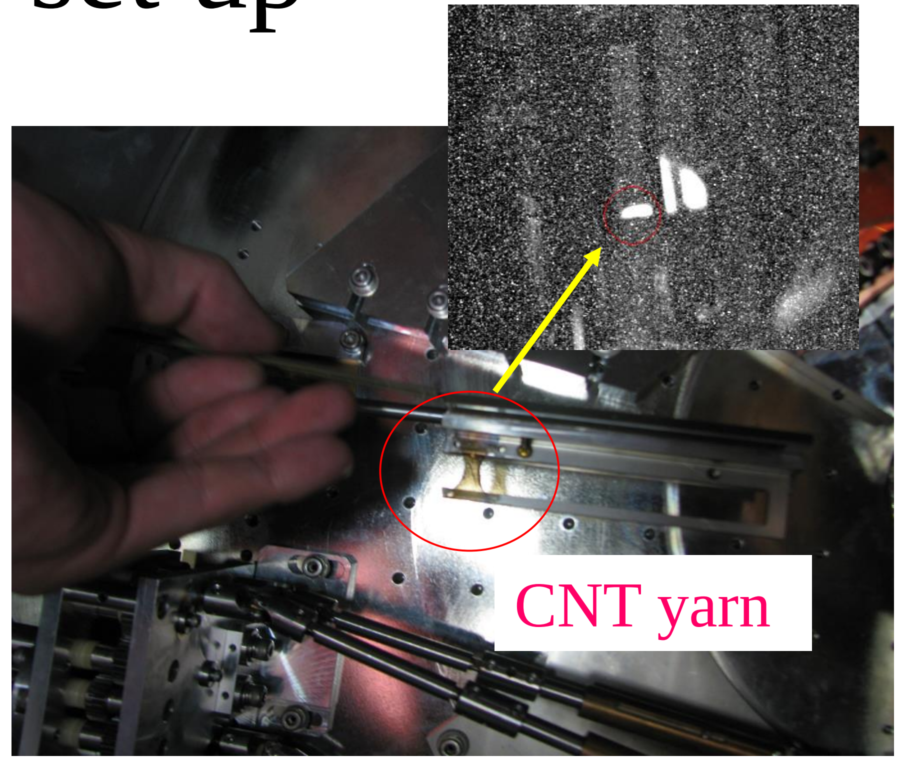
The target-detector distance is 720 mm

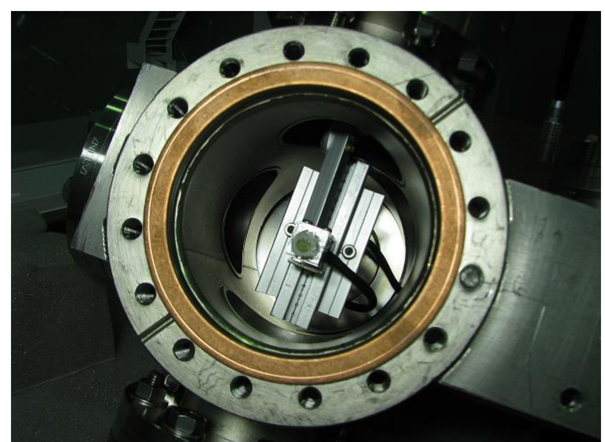
Plastic scintillator

Radiation from the target

Radially positioning system

The scintillator scans in the plane perpendicular to the median plane of the electron orbit

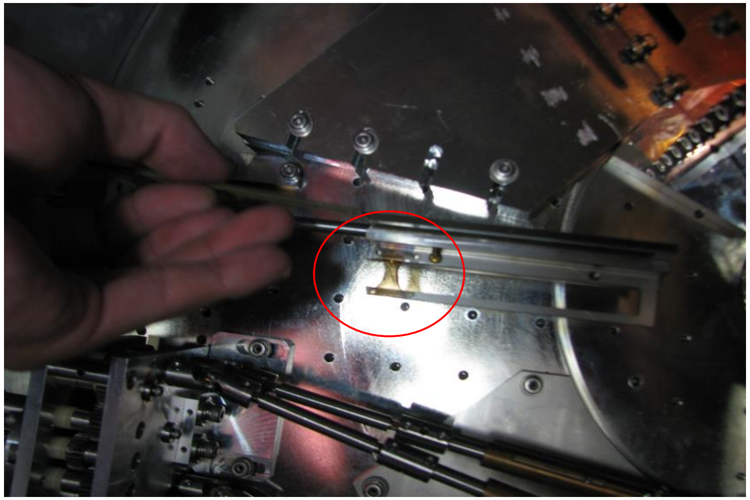


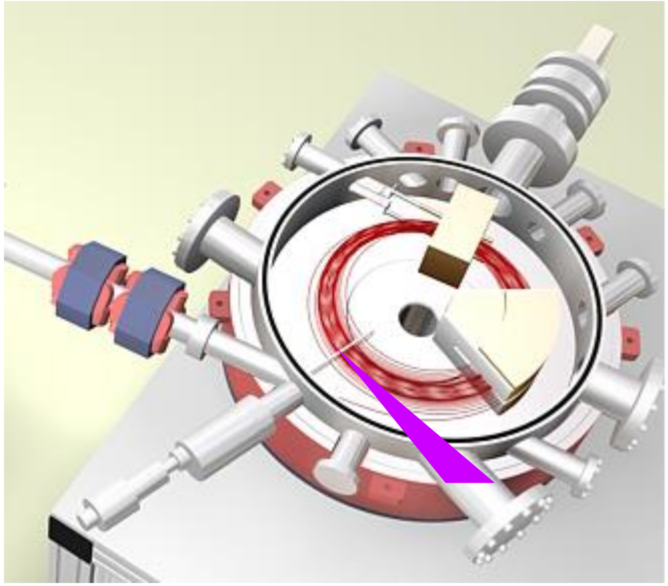


$3 \times 3 mm^2$ 8.5μm thick Scintillator detector

State of art technology 1

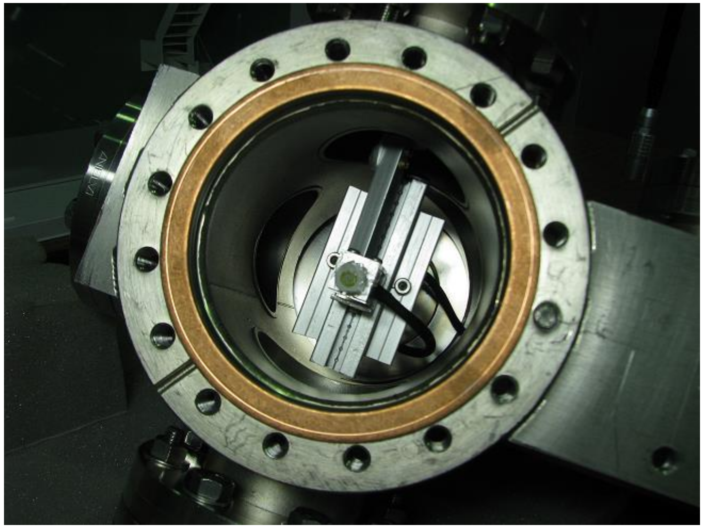
- The EM radiation yield from 100nm thick CNT yarn must be very weak.
- If thick target is used, soft X-ray is captured inside of target.
- Electrons are hitting target every 1.5ns repeatedly in the storage ring.
- Electron penetrate the thin target and re-circulate.
- The beam current is 40A

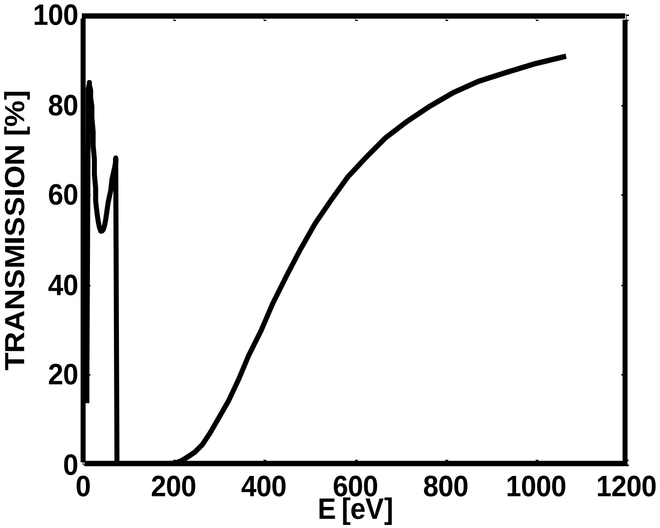




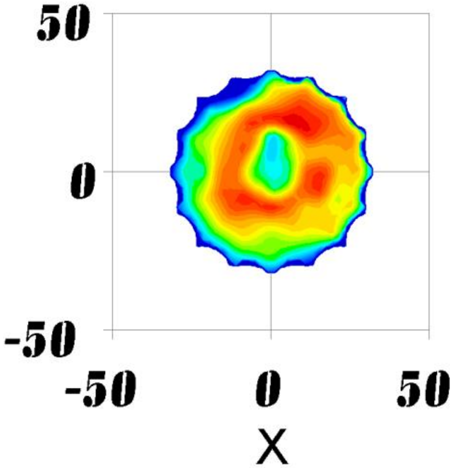
State of art technology 2

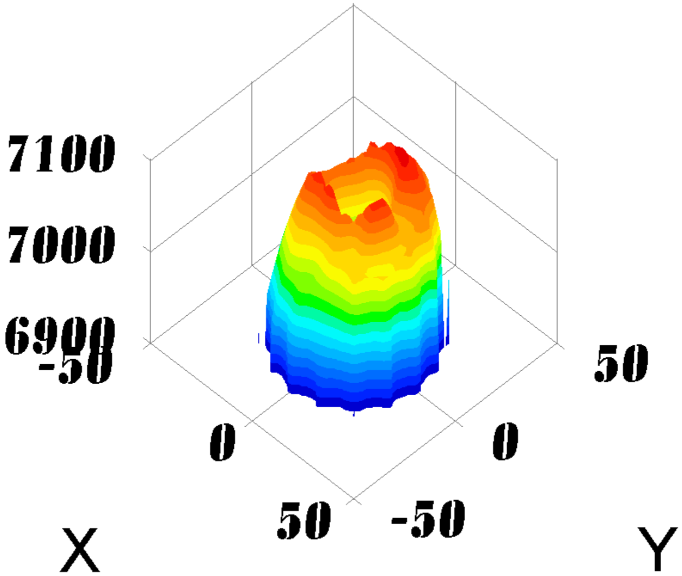
- Plastic scintillator (PS) is connected by plastic fiver to photo multiplier (PM).
- Read current from PM and CF converter is used.
- Mechanism moves the PS radially and rotate around the axis of radiation
- 8.5 μm thick NE102 plastic scintillator only detect EUV and soft X-rays up to 2keV, but no hard X-rays or UV’s are detected.
- Filter made of 385 nm thick Al foil select radiations higher than 400eV





Experimental results on Mo strip

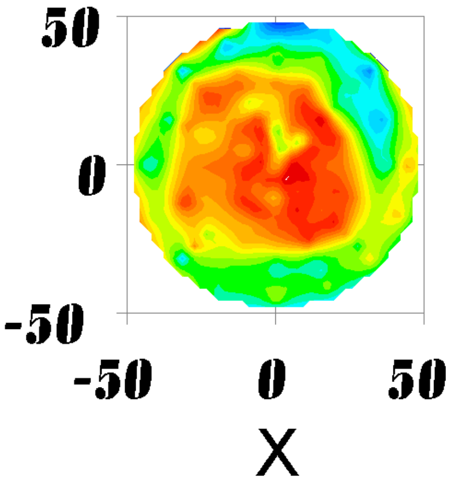


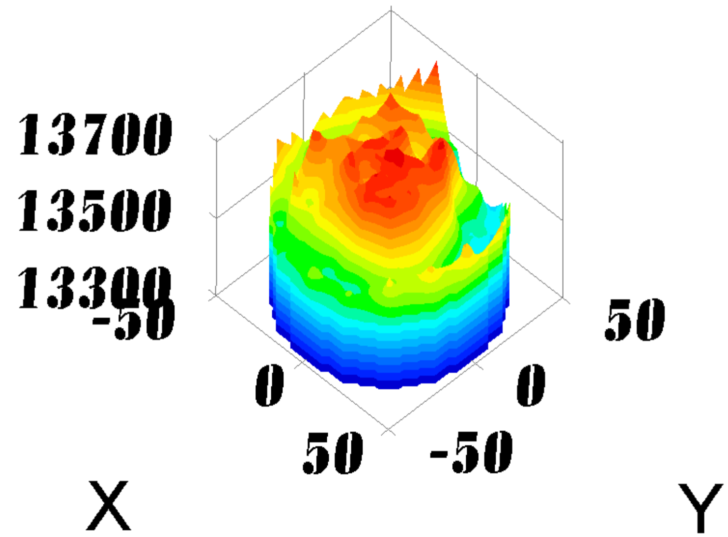


Measured angular distribution of the radiation
from 5 μm thick Mo strip target.

Transition radiation is expected for the metal target,
But ±10 mrad spread is extremely narrow.
$1/\gamma=1/40=25$mrad
Question arises that effect of magnetic field there?

Experimental results on Sn wire

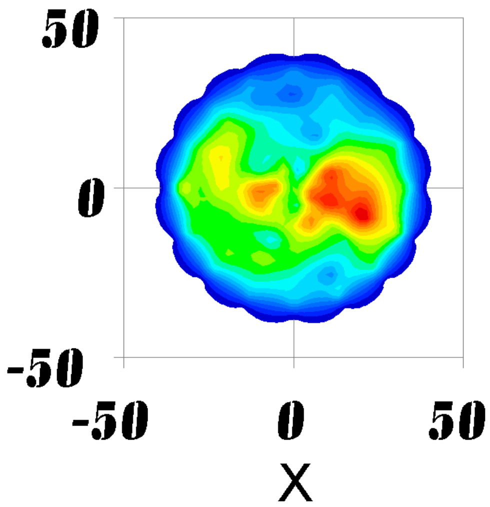


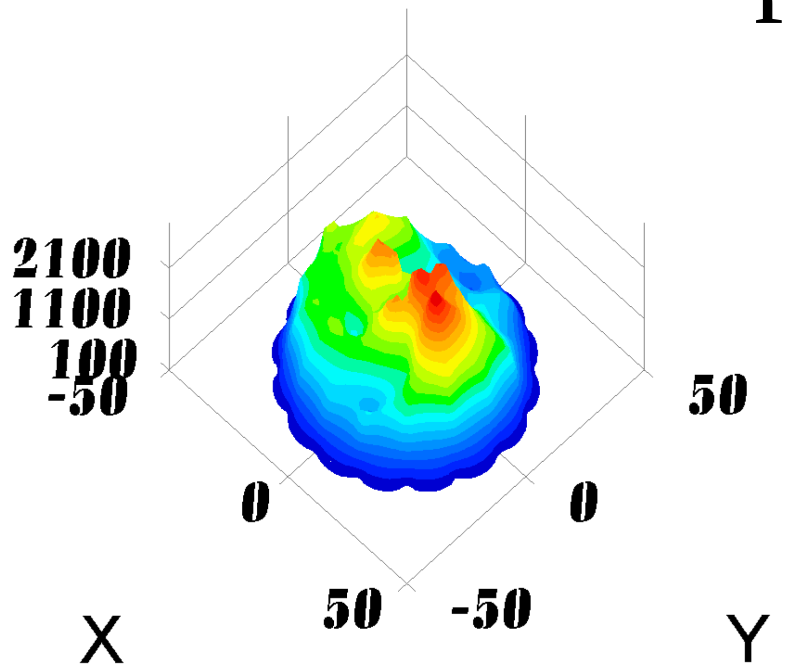


Angular distribution for Sn wire of thickness 150 µm.

Not only the hollow distribution, but some peaks appear.
Energy higher than 1000 eV is detected.
Radiation spread is about 25 mrad

Experimental results on Al strip

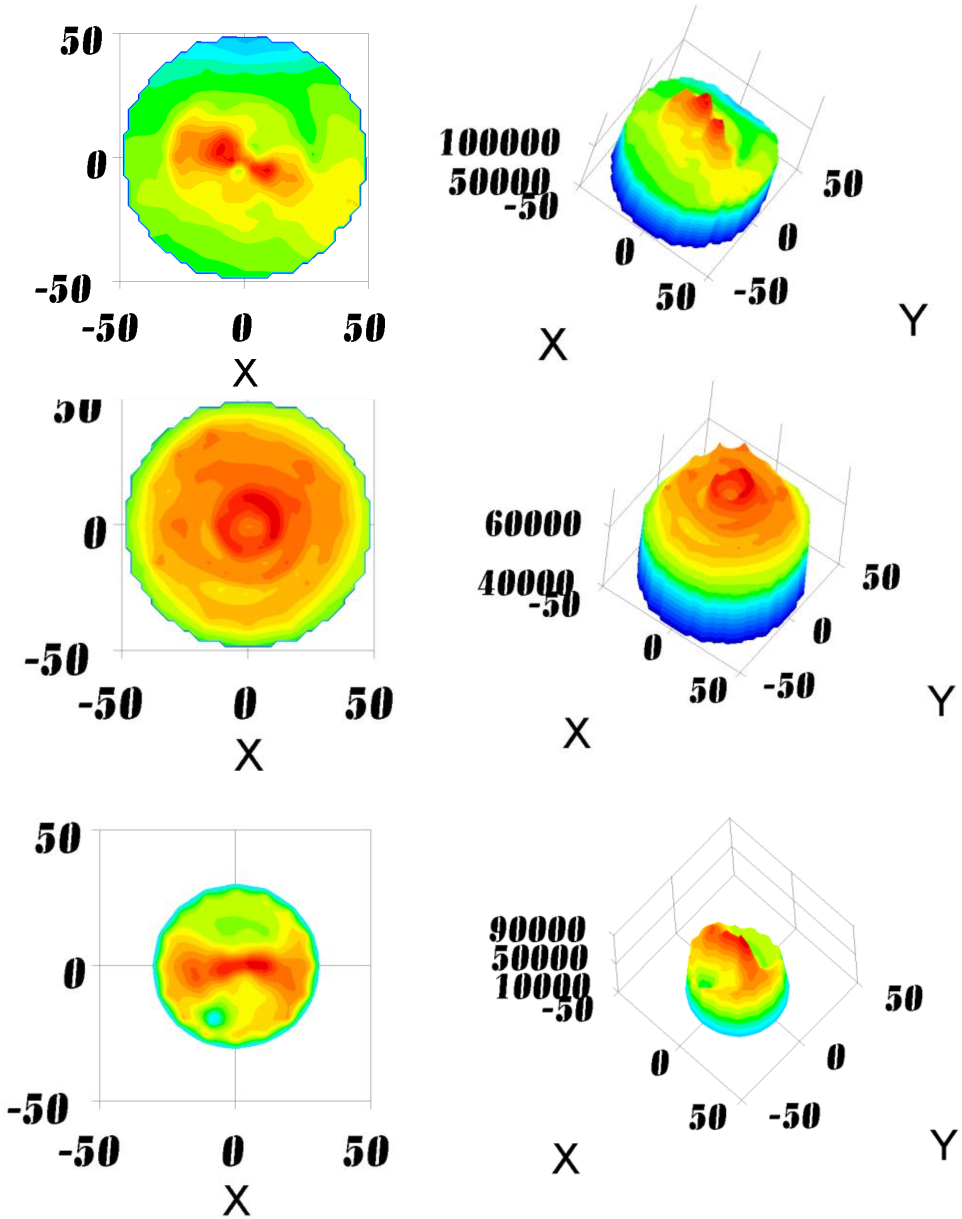




Angular distribution for 385 nm thick Al strip target.

Energy higher than 400 eV is detected.
Several spots appears, but no hollow radiation.
Peak position is asymmetry

Experimental results on 55nm thick DLC



(a)Without Al filter

Photon energy higher than 73eV is detected
2 peaks appears

(b) With Al filter

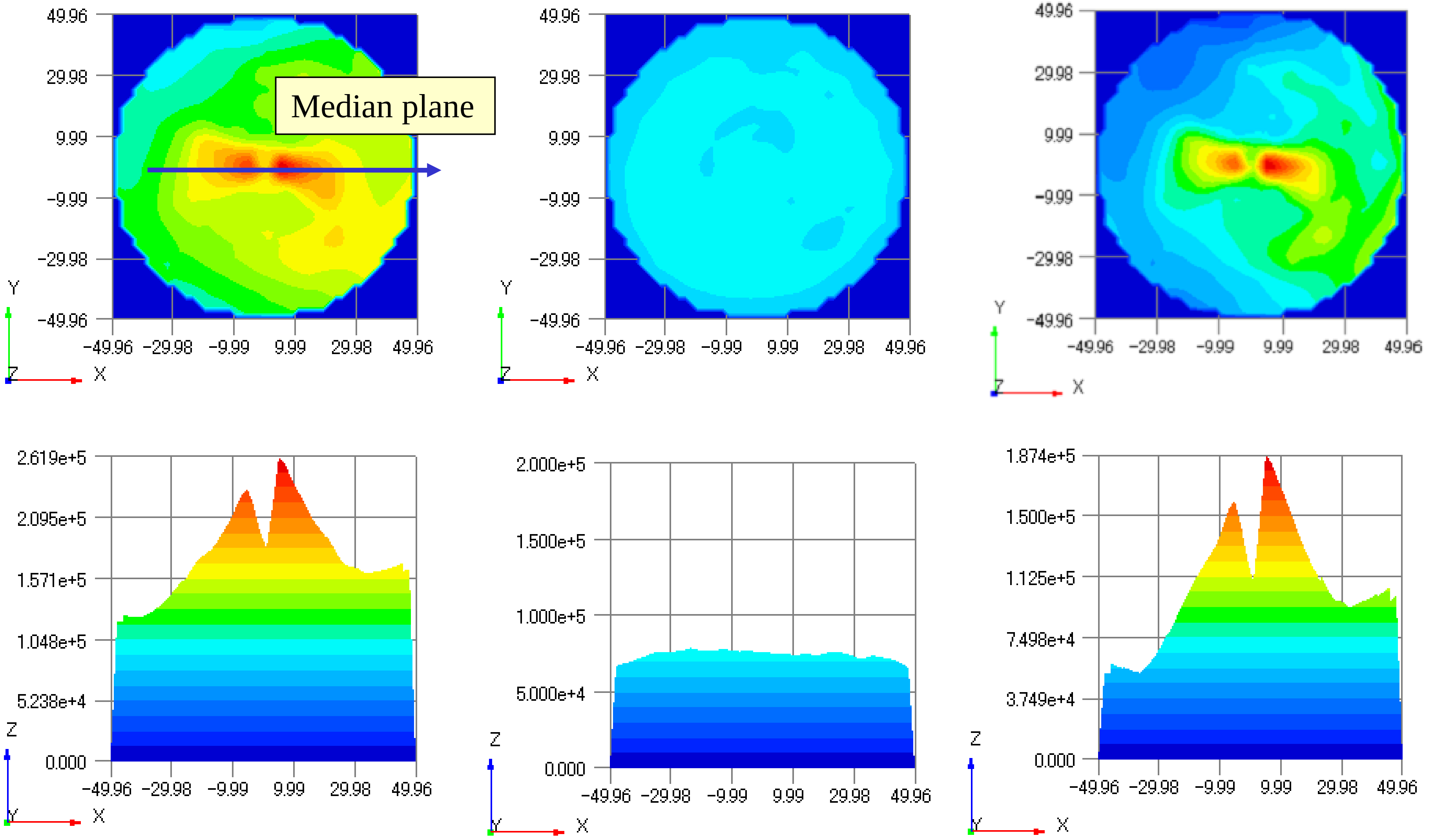
Photon energy higher than 400eV is detected
Hollow radiation having 3 ridges appears

(c) = (a)-(b)

Photon energy range
73eV<E<420eV

Experimental results on 10μm thick wire made of CNT strings

A) Measured by plastic Scint. B) With 0.385um Al filter C) A-B 73eV<E<420eV)



Suggesting a new radiation mechanism under magnetic field

Acceleration by Coulomb force Brem. spread $\theta \leq \pm 1/\gamma$

Brems-
strahlung

Synchrotron radiation
Acceleration by
magnetic force

SR spread $\theta \leq 1/\gamma = mc^2/Ee$

Cherenkov radiation by
bound electrons $n=1+\Delta n>1$

$1/\gamma <$ Cherenkov $\sim 2\Delta n$

Transition radiation by free
electrons

TR spread $\theta \leq 1/\gamma$

Under magnetic
field

Synchrotron
Cherenkov (SC)

Synchrotron
Transition (ST)

$2\Delta n <$ SC,ST $< 1/\gamma$

Synchrotron Cherenkov theory

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RADIATION SPECTRA OF CHARGED PARTICLES MOVING IN MAGNETIC FIELDS

A. V. KONSTANTINOVICH, S. V. MELNYCHUK, I. A. KONSTANTINOVICH

Chernivtsi National University, 2, Kotsyubynsky Str., Chernivtsi-12, Ukraine, UA-58012,
e-mail: theormyk@chnu.cv.ua

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The angular distribution of synchrotron-Cerenkov radiation

T. M. Rynne, G. B. Baumgartner, and T. Erber

J. Appl. Phys. 49(4), April 1978, p. 2233

Given formalism is same for SR except the refraction index n≠1

$$I(\omega,\theta)=\left(\frac{e\omega}{c}\right)^2 \lambda_c \frac{E}{mc^2}\frac{H_{cr}}{H}\left[[\beta J_\nu'(\nu\beta n_r \sin\theta)]^2 + \left(\frac{\cot\theta}{n_r} J_\nu(\nu\beta n_r \sin\theta)\right)^2\right];$$

for Δn << 1

$$\frac{d^2N}{d(\hbar\omega)\,d\psi}=\frac{2\alpha}{mc^2}\frac{L}{\lambda_c}\left(\frac{2}{\nu}\right)^{1/3}\left\{[\mathrm{Ai}'(\xi)]^2 + \left[\psi\left(\frac{\nu}{2}\right)^{1/3}\mathrm{Ai}(\xi)\right]^2\right\},$$

SR formalism is given for $(mc^2/E)^2 - 2\Delta n + \psi^2 > 0$

$$\frac{d^2N^s}{d(\hbar\omega)\,d\psi}=\frac{\alpha}{3\pi^2}\frac{L}{\lambda_c}\hbar\omega\frac{mc^2}{E^3}\frac{H_{cr}}{H}\left[1+\left(\frac{E}{mc^2}\psi\right)^2\right]^2 \times\left(K_{2/3}^2(\zeta^s)+\frac{(E\psi/mc^2)^2}{1+(E\psi/mc^2)^2}K_{1/3}^2(\zeta^s)\right)$$

SC formalism is given for $(mc^2/E)^2 - 2\Delta n + \psi^2 < 0.$

SC spectrum (1.13a) then exhibit an oscillatory behavior. It is convenient to introduce a new variable analogous to Eq. (2.1b),

$$\zeta=\tfrac{2}{3}(-\xi)^{3/2}; \tag{2.7}$$

since the limit $H\to 0$ is linked with the limit $\zeta\to\infty$, the spectral form (1.13a) can be replaced by the asymptotic estimate

$$\frac{d^2N}{d(\hbar\omega)\,d\psi}\approx\frac{2\alpha}{\pi mc^2}\frac{L}{\lambda_c}\left\{\left[2\Delta n-\left(\frac{mc^2}{E}\right)^2-\psi^2\right]^{1/2} - \frac{2\Delta n-(mc^2/E)^2-2\psi^2}{[2\Delta n-(mc^2/E)^2-\psi^2]^{1/2}}\sin^2\left(\zeta+\frac{\pi}{4}\right)\right\},$$

$$\zeta\gg 1. \tag{2.8}$$

Oscillatory behavior appears beyond the SR regime $\psi > 1/\gamma$

The basic SC spectrum assumes a particularly simple form in case $\xi \gg 1$ [cf. Eqs. (1.13b), (2.4), and (2.14)]:

$$\frac{d^2N}{d(\hbar\omega)\,d\psi} \approx \frac{\alpha}{2\pi mc^2}\frac{L}{\lambda\!\!\!^{-}_c}\frac{(mc^2/E)^2 - 2\Delta n + 2\psi^2}{[(mc^2/E)^2 - 2\Delta n + \psi^2]^{1/2}} \times \exp\left\{-\frac{2\nu}{3}\left[\left(\frac{mc^2}{E}\right)^2 - 2\,\Delta n + \psi^2\right]^{3/2}\right\}. \qquad (2.18)$$

For appropriate choices of the index, such as $\Delta n \sim -\omega^{-2}$ [cf. Eq. (3.1a)], Eq. (2.18) displays the low-frequency damping which is characteristic of SC radiation.[3] Clearly, the intensity decreases for larger opening angles: In particular, the angle at which the intensity has diminished to one half the peak value is approximately given by

$$\psi^2_{1/2} \sim \frac{0.7(mc^2/\hbar\omega)(H/H_{cr})}{[1 - 2\,\Delta n(E/mc^2)^2]^{1/2}}. \qquad (2.19)$$

In the index-dominated regime (2.15), this estimate can be sharpened to

$$\psi^2_{1/2} \sim \frac{0.5}{(-\,\Delta n)^{1/2}}\frac{(mc^2)^2}{E\hbar\omega}\frac{H}{H_{cr}}, \qquad (2.20)$$

which shows that *increasing* values of the index tend to *reduce* the angular dispersal of the radiation. Since index variations of this kind can be engendered by vacuum polarization, it is possible that novel focusing effects might be associated with pulsar emission.[3]

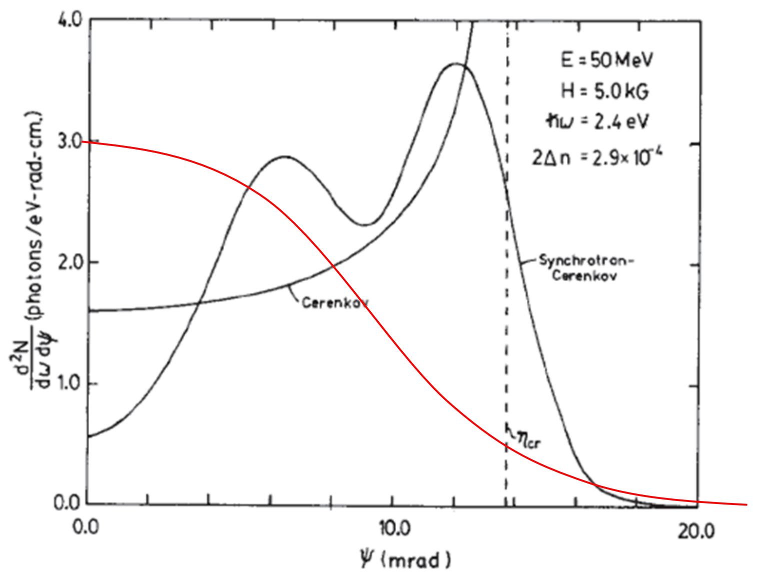
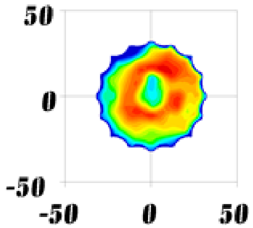


FIG. 9. Striations on the Čerenkov branch.

Our results are consistent with Rinne theory

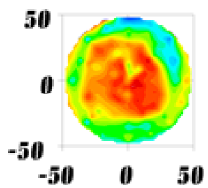
Photon energy range detected by NE102: 70 eV-1.5 keV
with Al filter: 400 eV-1.5 keV

Mo



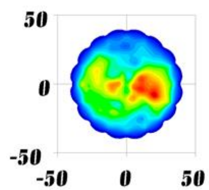
Absorption edge: 2.3keV(L), 17.5 keV(K)
no SCR is expected, so this is TR

Sn



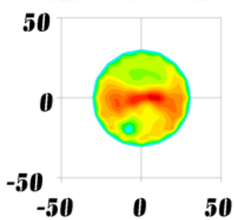
Absorption edge: 3.4keV(L), 25 keV(K)
no SCR but TR

Al

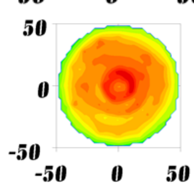


Absorption edge: 1.5keV(K)
SCR is within the detection range

C

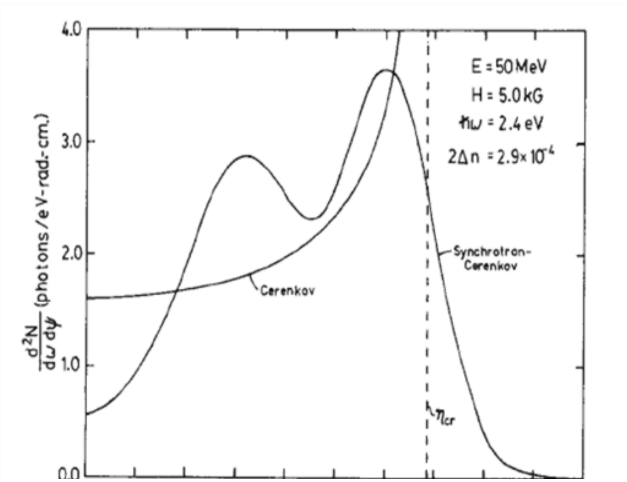


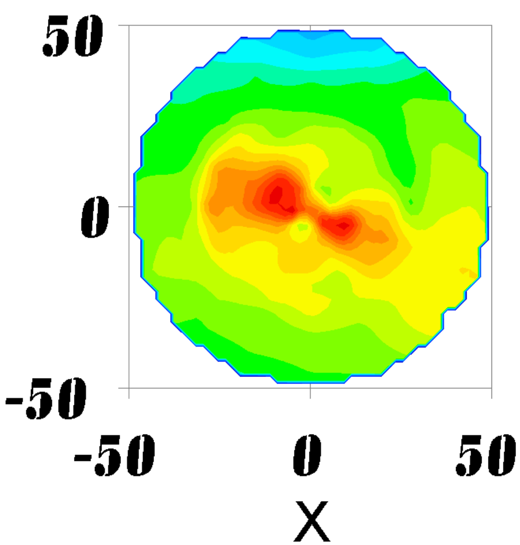
Absorption edge: 277eV(K)
Must be definitely SCR



Photon energy higher than 400 eV
Must be Transition

Obtained △n is reasonable

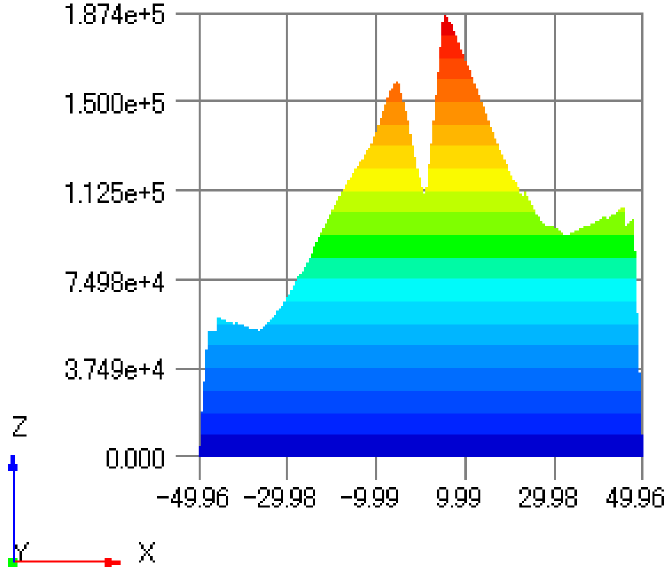




	Our case	theory
E	20	50 MeV
magnetic field	3.3kG	5 kG
photon energy	277 eV	2.4 eV
Obs. or Cal. ψ	5mrad	12 mrad
$\frac{H/E}{h\omega}$	5.9E-4	0.04
$\psi^2 \propto A\frac{H/E}{h\omega}/\sqrt{\Delta n}$		A=4500
Δn	0.0011	$1.56\text{x}10^{-4}$

Higher electron energy, lower magnetic field, higher photon energy, higher Δn reduces the radiation spread

Measured EUV power from CNT



Radiated power from the CNT target is 19μA at repetition 70Hz.

Detector efficiency is 0.236[W/A] at the C k-edge energy 277eV.

Transmission rate by filter is 0.925.

Beam current 100mA,

The radiation power/pixel at 1000Hz repetition,

$P_{max} = 19/0.236/0.925 \cdot 1000/70 =$ 3897μW/pixel

Pixel solid angle Ω_{PS} = (3x3)/(720x720)=1.74x10-5 sr.

(detector is 720mm from the source)

Photon density at the peak P_{max}/Ω_{PS} =235W/sr

= 1.29 x 10^{13} photons/s, mrad^2, 0.1%bw

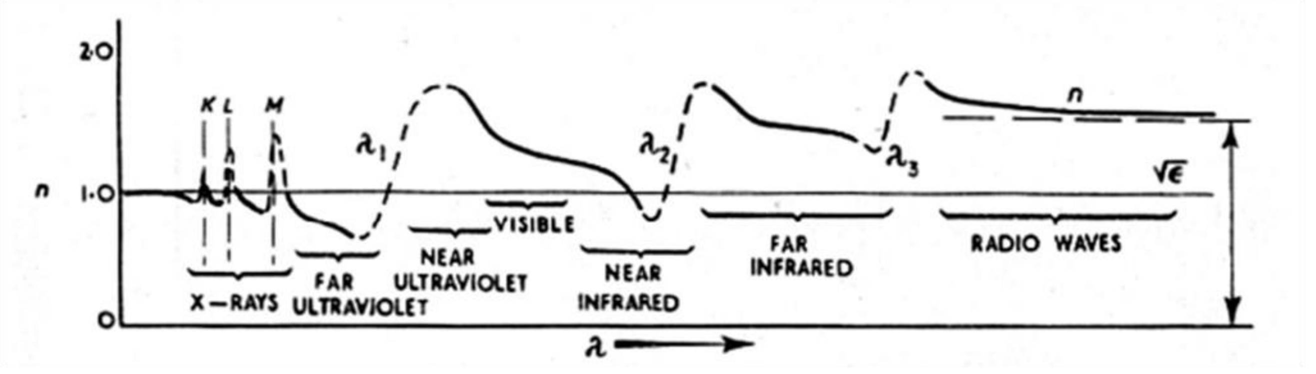
Focus size 3x0.01mm^2 presents the Brilliance

= 4.28 x 10^{14} photons/s, mm^2, mrad^2, 0.1%bw

Average power over the radiation field is 98 mW

Summary of SC radiation

- SC radiation appears at the absorption edge of materials in X-ray region.



- Photon energy is 277eV for C, 1.5keV for Al, 108 eV for Be targets.
- Radiation spread ψ is <1/γ. Higher photon energy presents narrower angular spread.
- 20MeV present 5mrad.
- Radiation is highly coherent.

Applications of SC radiation

1. Hard and soft X-ray laser
2. EUV or soft X-ray Lithography source
3. Science on optical nature of absorption Edge in soft and X-ray regions

J. Micro/Nanolith. MEMS MOEMS 11(2), XXXXXX (Apr–Jun 2012)

Tabletop storage ring MIRRORCLE extreme ultraviolet lithography source

Hironari Yamada
Dorian Minkov
Taichi Hayashi
Daisuke Hasegawa
Photon Production Co. Ltd.
1-1-1 Nojihigashi, Kusatsu,
Shiga 525-8577, Japan
E-mail: hironari@poton-production.co.jp

Abstract. Advances of tabletop electron storage rings for generating a brilliant extreme ultraviolet (EUV) or soft X-ray beam are discussed. An electron storage ring called MIRRORCLE-20SX currently provides a stored beam current with an average of 3 A, a 1-minute lifetime, 15 ms radiation damping time, and a beam size of about $3 \times 3\ \mathrm{mm}^2$. We generate EUV by a thin-film target placed in the electron orbit. Photons in the wavelength around 13.9 nm is generated by an Si thin film, and 4.3 nm by a diamond-like carbon (DLC) film placed in the circulating electron beam. It is known from previous experimental studies that the mechanism of EUV emission is a synchrotron Cherenkov radiation (SCR). The observed photon power is 14 W/sr by the DLC film. We report that SCR is suitable for EUV lithography (EUVL) because the spectrum is monochromatic, the radiation angular spread is as narrow as $20 \times 5\ \mathrm{mrad}^2$, and the emitter size can be $0.01 \times 3\ \mathrm{mm}^2$. An optimized EUV source for lithography based on the tabletop synchrotron is proposed. [DOI: 10.1117/1.JMM.11.2.XXXXXX]

Subject terms: EUVL source; soft X-rays; electron storage ring; MIRRORCLE; target.

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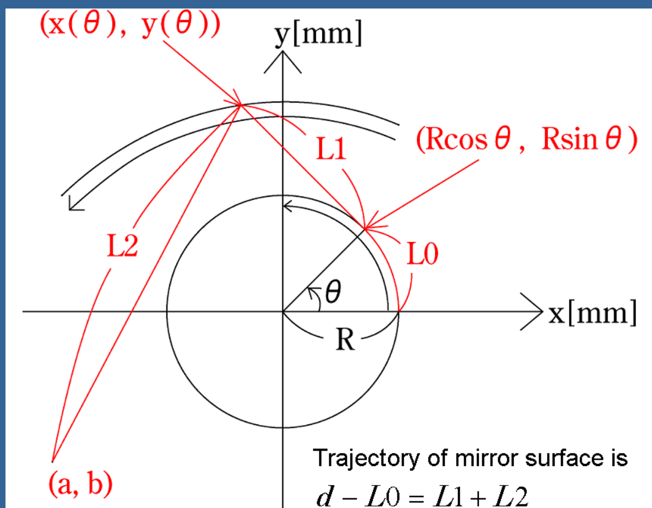
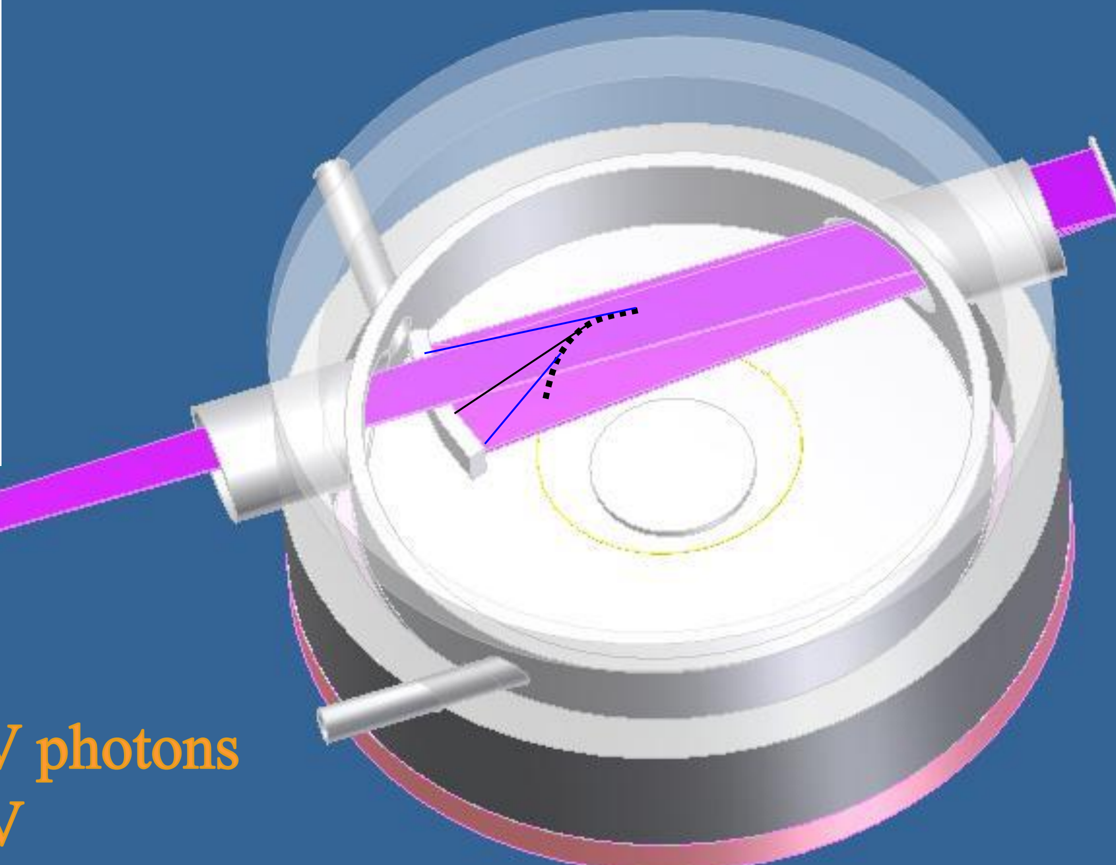
1 kW/sr coherent EUV source is feasible

By setting 1000 of CNT target along the beam orbit
By using a magic mirror (quasi ellipsoidal mirror)





Be generates 108 eV photons
C 277 eV

10KW EUV laser is feasible

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Transition Radiation X-Ray Laser Based on Stimulated Processes at the Boundary Between Two Dielectric Media

Kenneth E. Okoye and Hironari Yamada

***Abstract*—This paper analyzes a model of a transition radiation laser based on stimulated emission induced by relativistic electrons crossing the boundary between two media of different dielectric properties. Interaction between the incident radiation and the electrons in this boundary region is taken into account. Phenomenological quantum electrodynamics is applied to derive analytical expressions for stimulated emission and absorption probabilities. Analogs of Einstein's coefficients for the transition processes have also been derived and discussed. It is shown that stimulated emission is greater than absorption. The gain is then calculated.**

***Index Terms*—Absorption, gain, laser, stimulated emission, transition radiation.**

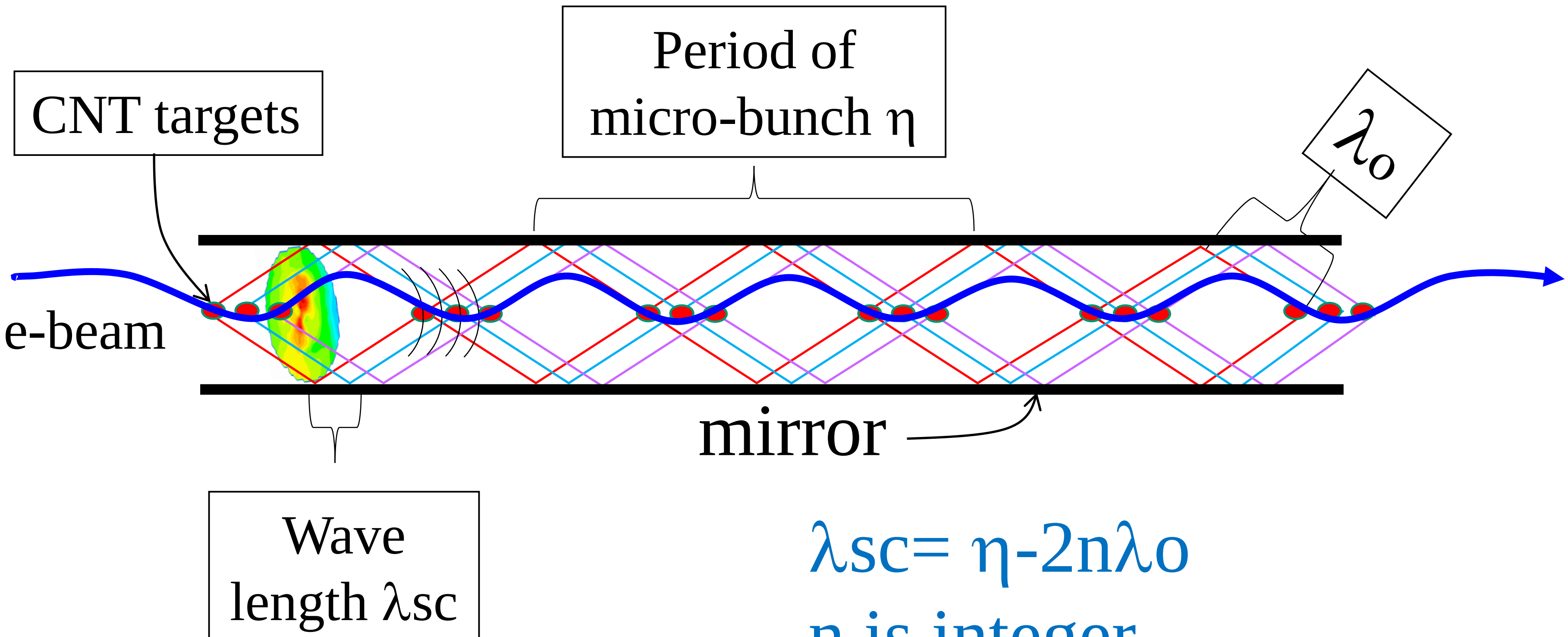
I. Introduction

THE OPERATION of classical laser (CL) is based on the occurrence of population inversion achieved by pumping

[3], which is emitted when an electron crosses the boundary between two media of different dielectric constants. Resonance transition radiation (RTR) using a periodic multilayer foil or stack foils has been reported by many groups [4]. Use of micro bunched beam is also proposed to generate coherent interaction [5]–[8], but any gain is yet to be reported.

A novel laser scheme proposed by Yamada [9] combines FEL mechanism, Einstein's forced radiation mechanism, and one out of the following: Bremsstrahlung, parametric radiation, or transition radiation. The mechanism which selects the wavelength is introduced in this novel scheme similar to SASE-FEL. One of the periodic interactions of the radiation scheme is shown in Fig. 1. Spontaneous radiation is generated at the first stage by thin targets (not shown). This radiation is then monochromatized by a crystal. When the target itself is made of a thin crystal, monochromatic

Synchrotron-Cherenkov Laser



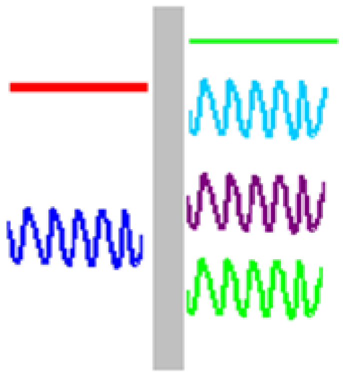
λsc= η-2nλo
n is integer

Photon power: $P = P_o^{number\ of\ targets}$

Synchrotron-Cherenkov Laser is a classical laser but start with coherent radiation

Q_i Primary electron

I_i^ν Primary photon



Trans. elec. ηQ_i

Spontaneous S_i^ν

Induced F_i^ν

Trans. photon μI_i^ν

$$S_i^\nu = \sigma Q_i$$

$$F_i^\nu = N\frac{I_i^\nu}{4\pi c}B_{10} = N\frac{I_i^\nu}{4\pi c}\frac{c^3}{8\pi h\nu^3}A_{10} = S_i^\nu\frac{I_i^\nu c^2}{32\pi^2 h\nu^3}$$

$$I_i^\nu = S_{i-1}^\nu + F_{i-1}^\nu + \mu I_{i-1}^\nu \qquad \kappa = c^2 \big/ 32\pi^2 h\nu^3$$

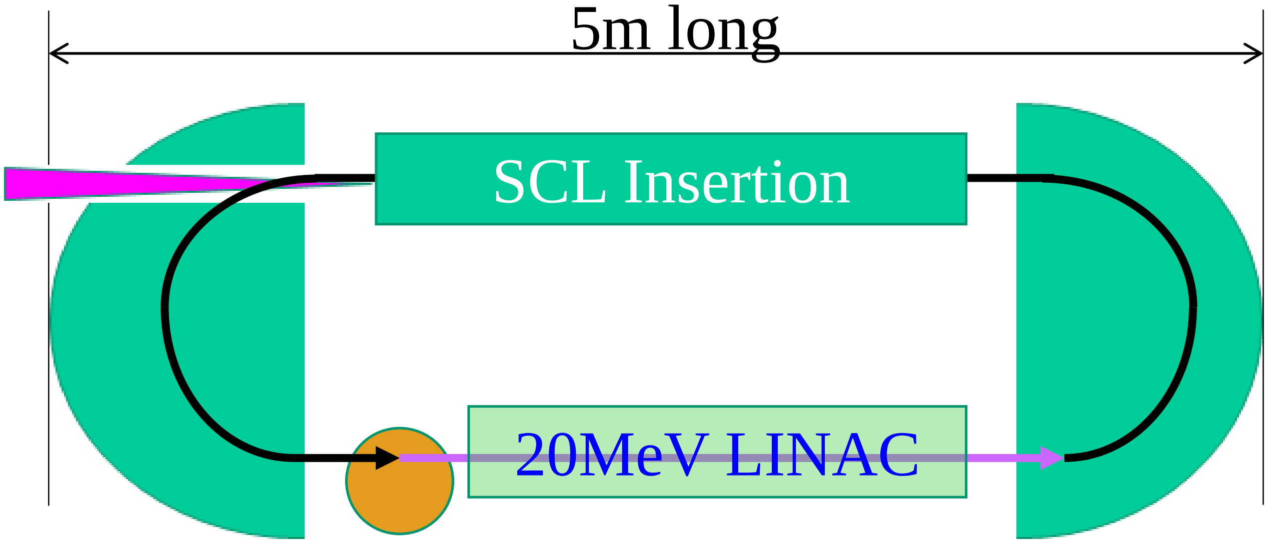
$$I_i = \sigma\eta^{i-1}Q_0 + \sigma\eta^{i-1}Q_0\kappa\mu I_{i-1}^2$$

$$\sigma\eta^{i-1}Q_0\kappa\mu I_{i-1}^2 > I_{i-1}$$

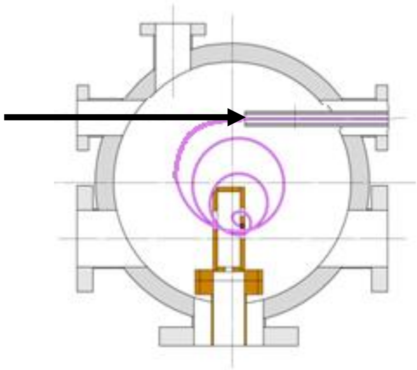
A_{10}, B_{10} : A,B coefficient

σ: radiation yield

Accelerator for SCL can be either ERL or Racetrack Microtron



1MeV MIC
type e-gun



Note: Recovery of electron energy is not essential for only 20 MeV 10KW beam.

Summary

Radiation mechanism	Accele-rator	Ee	Spectrum/coherence	**Focal point**	Power		Cost (MUS$)	Present statue
					Ave.	Ettendue/mrad^2		
undulator	storage ring insertion	>1 GeV	Wide/partially	20μmϕ	10 mW	25W	**30**	Existing
SASE FEL for X-ray	Linac	>1 GeV	Mono /Yes	10μmϕ	1J/pulse	10KJ/pulse	**300**	Existing
FEL for EUV but not for soft X	Linac	>300 MeV	Mono /Yes	1mmϕ	1J/pulse	1J/pulse	**100**	Existing
	ERL with SuC cavity			1mmϕ	10 KW	10 KW	**500**	Feasible
Synchrotron Cherenkov for EUV or soft X	Storage ring	<20 MeV	Mono /Yes	Tunable 10μm x 1mm	0.1 KW	10 KW	**5**	Existing
	ERL with SuC cavity				10 kW	1000 KW	**109**	Feasible

SuC: Superconducting