Microtron base RF gun for low emittance electron source

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Photon Production Lab. co. Ltd.

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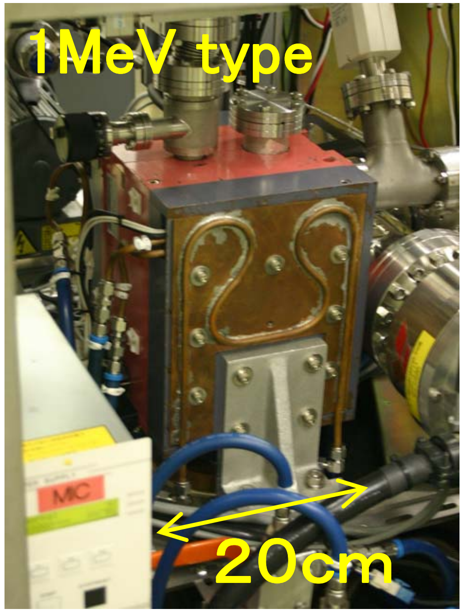
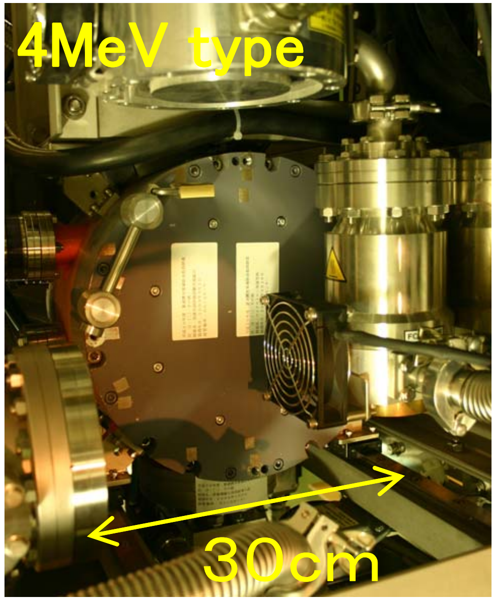
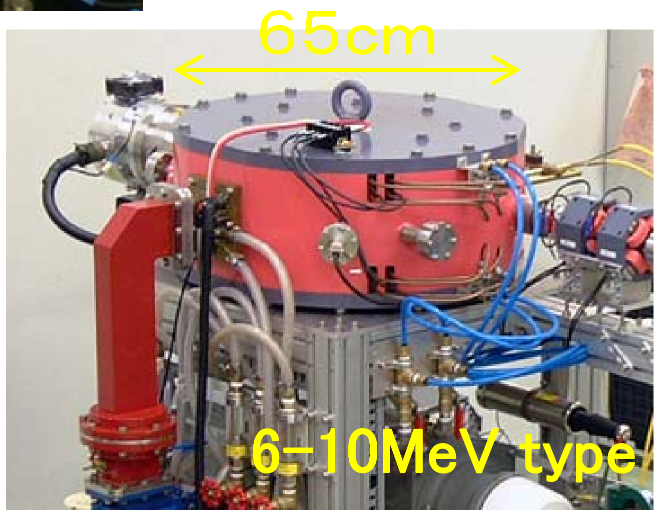
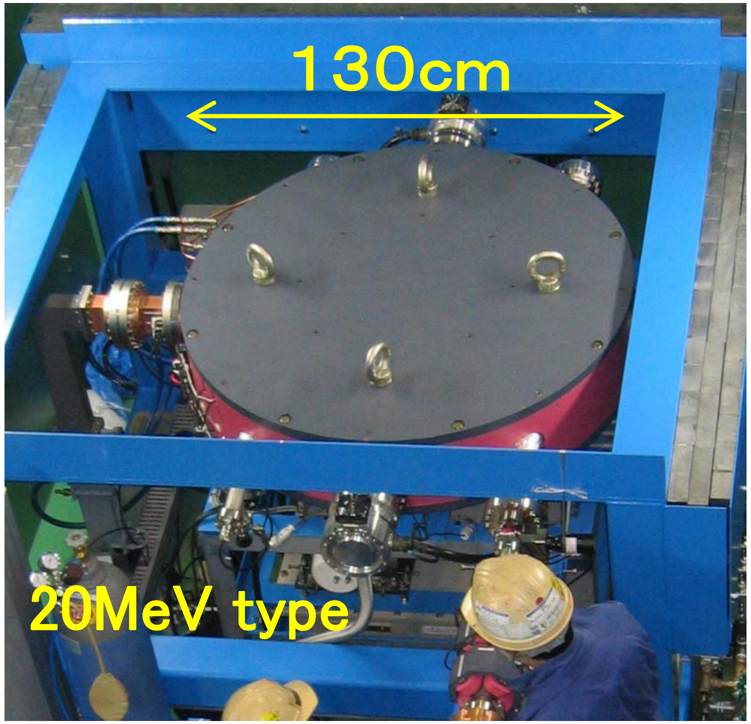
Our experiences on MICROTRON

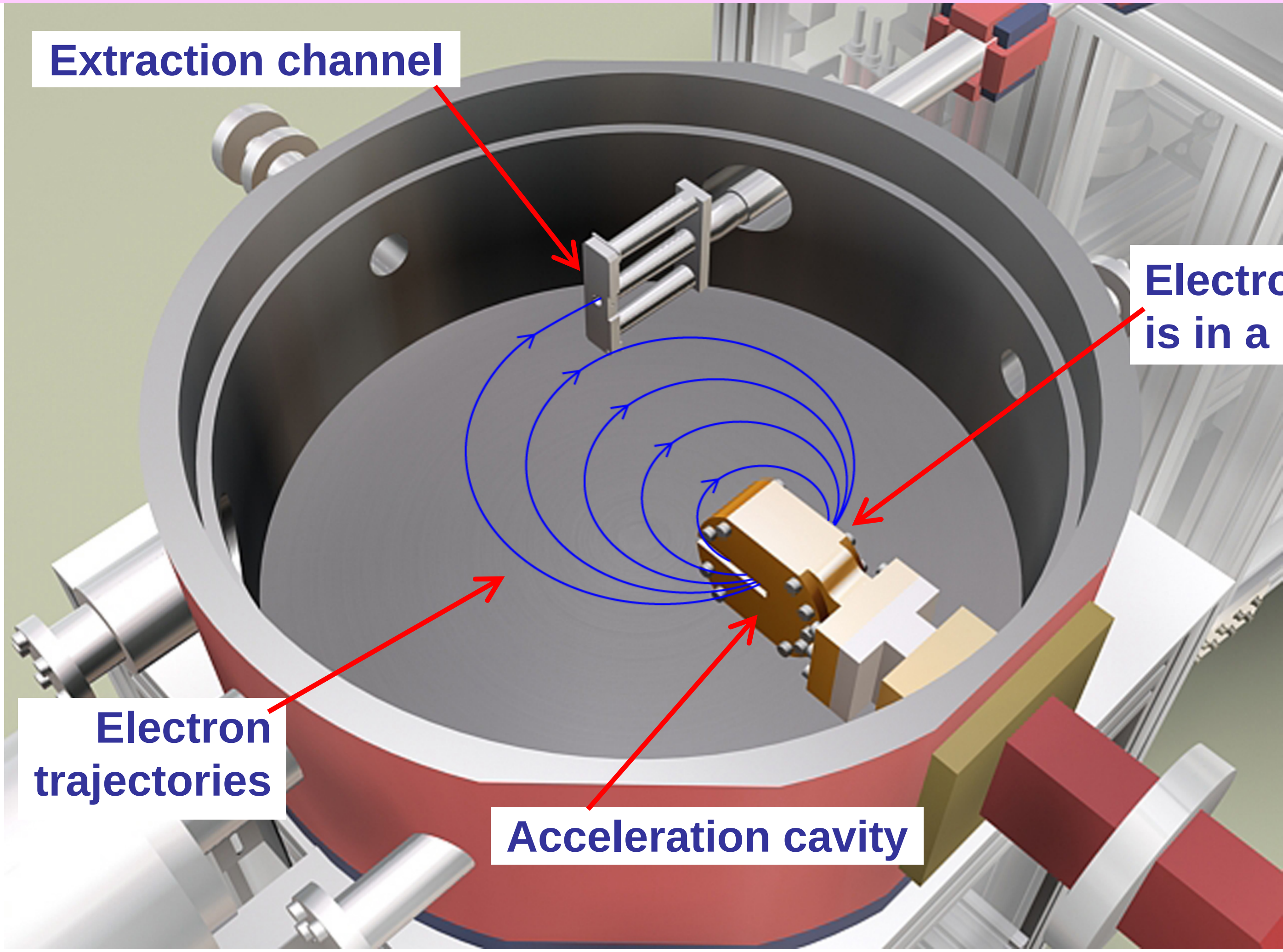








Microtron principle



Electrons are accelerated through the cavity circulating under the uniform magnetic field and extracted to the outside when they reach the designed energy.

Microtron principle

The Circulating period on *n*th turn is set to *n*-times of the RF period.

$$T_n = 2\pi m_n/eB_0\,,\quad T_n = nT_{\mathrm{rf}}$$

$$\boxed{2\pi m_n/eB_0 = nT_{\mathrm{rf}}}$$

where, T_n: circulating period of *n*th turn

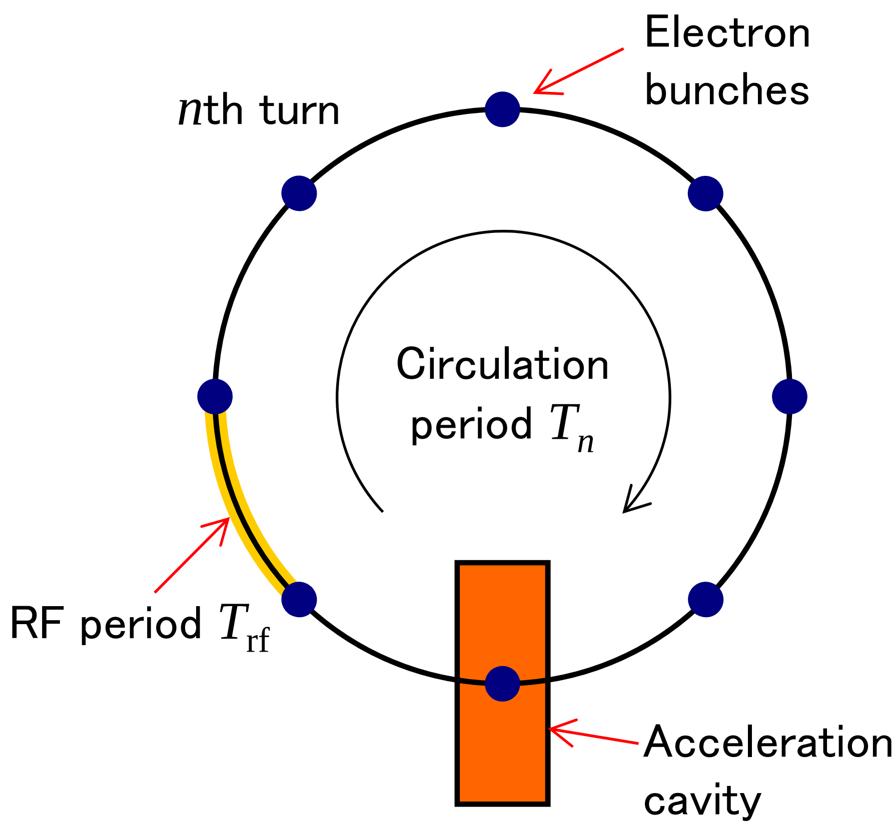
T_{rf}: RF period

m_n: electron mass on the *n*th turn

B_0: uniform magnetic field

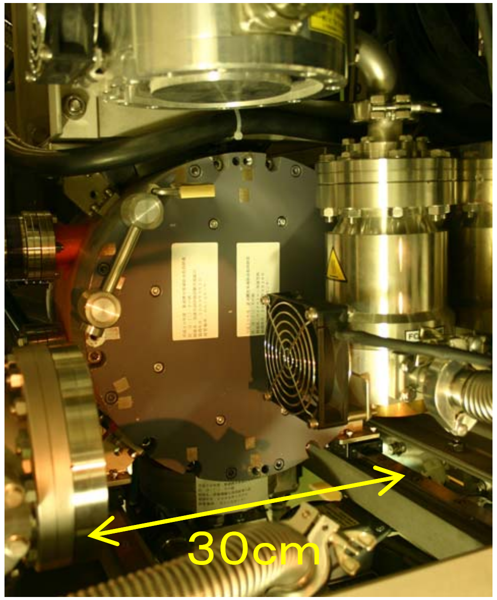
$$m_n = n\Delta m \quad (\Delta m = \Delta E/c^2)$$

$$\boxed{T_{\mathrm{rf}} = 2\pi\Delta m/eB_0}$$

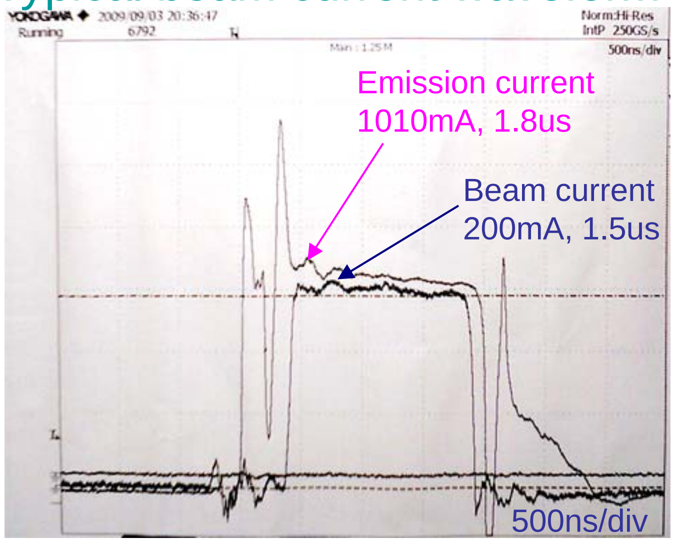


ΔE is set at 0.511 MeV or 1 MeV.

Parameters of the 4MeV MICROTRON



Typical beam current waveform



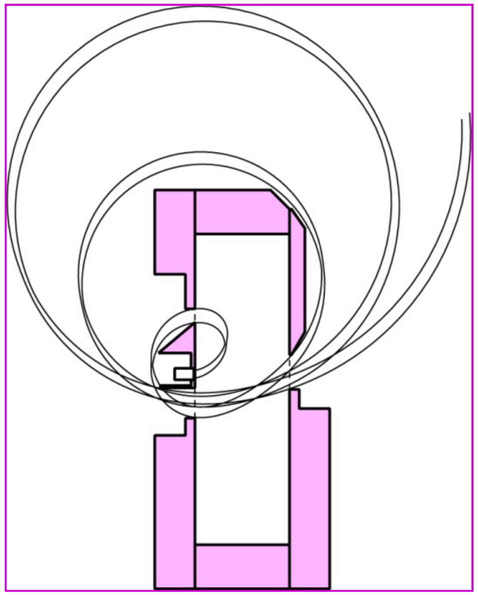
Energy range [MV]	3.0 - 4.0
Peak current [mA]	**300**
Pulse width [us]	2
Repetition rate [pps]	500
Average current [mA]	0.2
Beam output power [kW]	0.8
Multi beam Klystron specification (model, frequency, average output power)	KUI-168 2,856MHz 5kW-ave
Weight (main body) [kg]	400
Body size	W90 x D100 x H80 cm
Electricity [kVA]	30
Cooling water flow [L/min]	40

We use non-uniform magnetic field!!
Beam current is 3-4 times higher than that of LINAC

Advanced features of our microtron

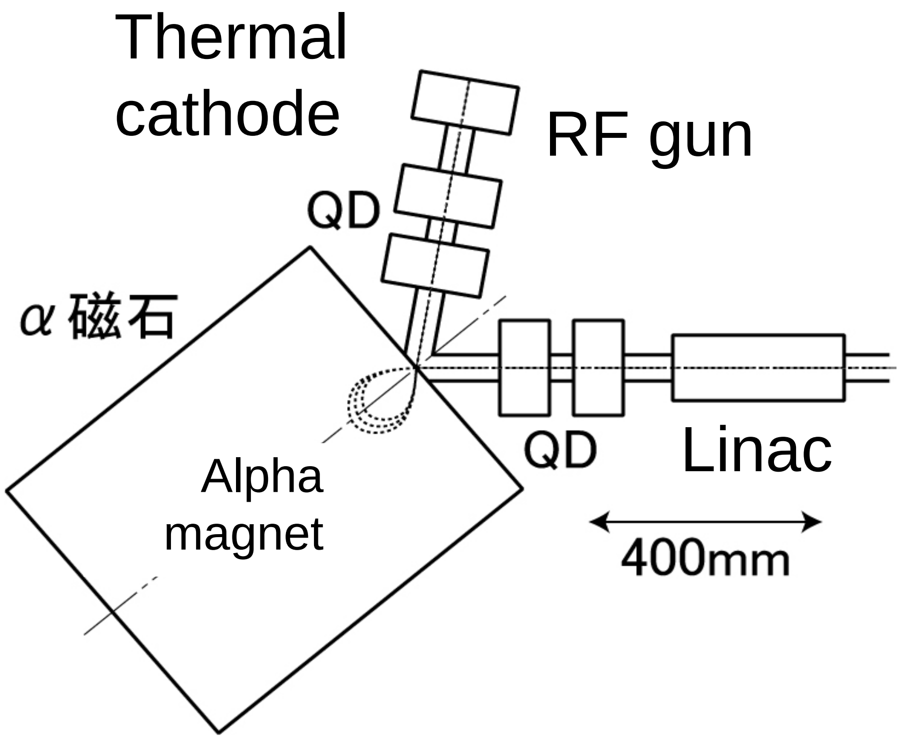
Electron emitter is set in the cavity wall.

>>>>>>   Electric field is as high as 1MV/2.3cm.



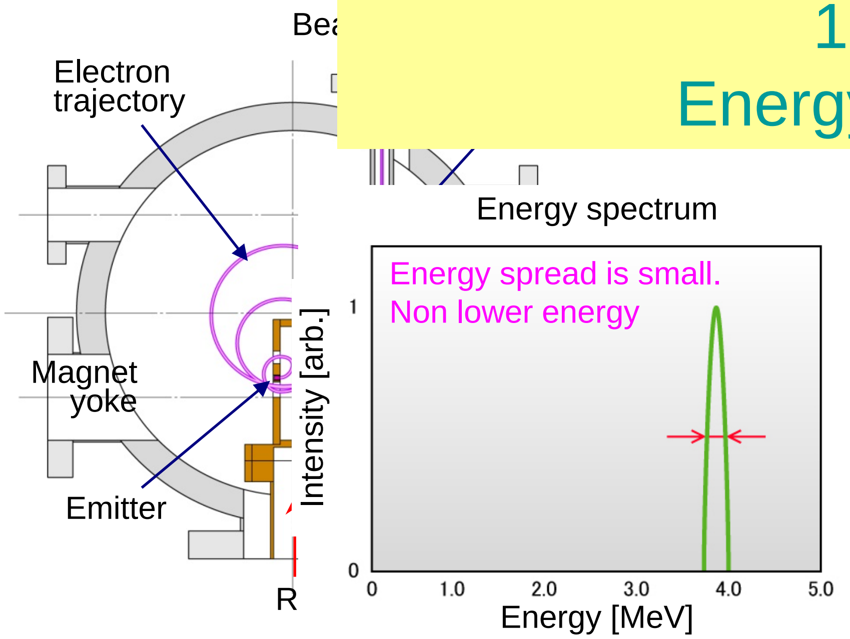
Electrons are accelerated under the magnetic field.

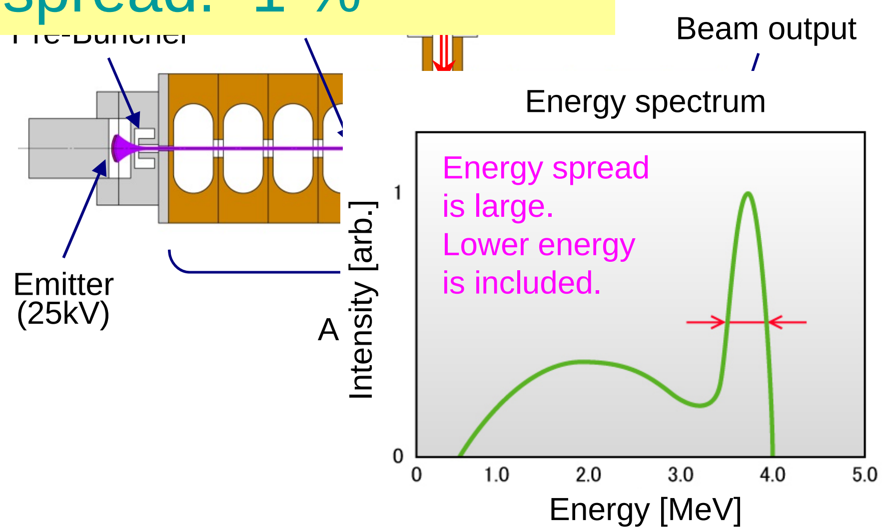
>>>>>> our microtron is comparable to the system combining a pre-buncher, LINAC, and alpha-magnet.



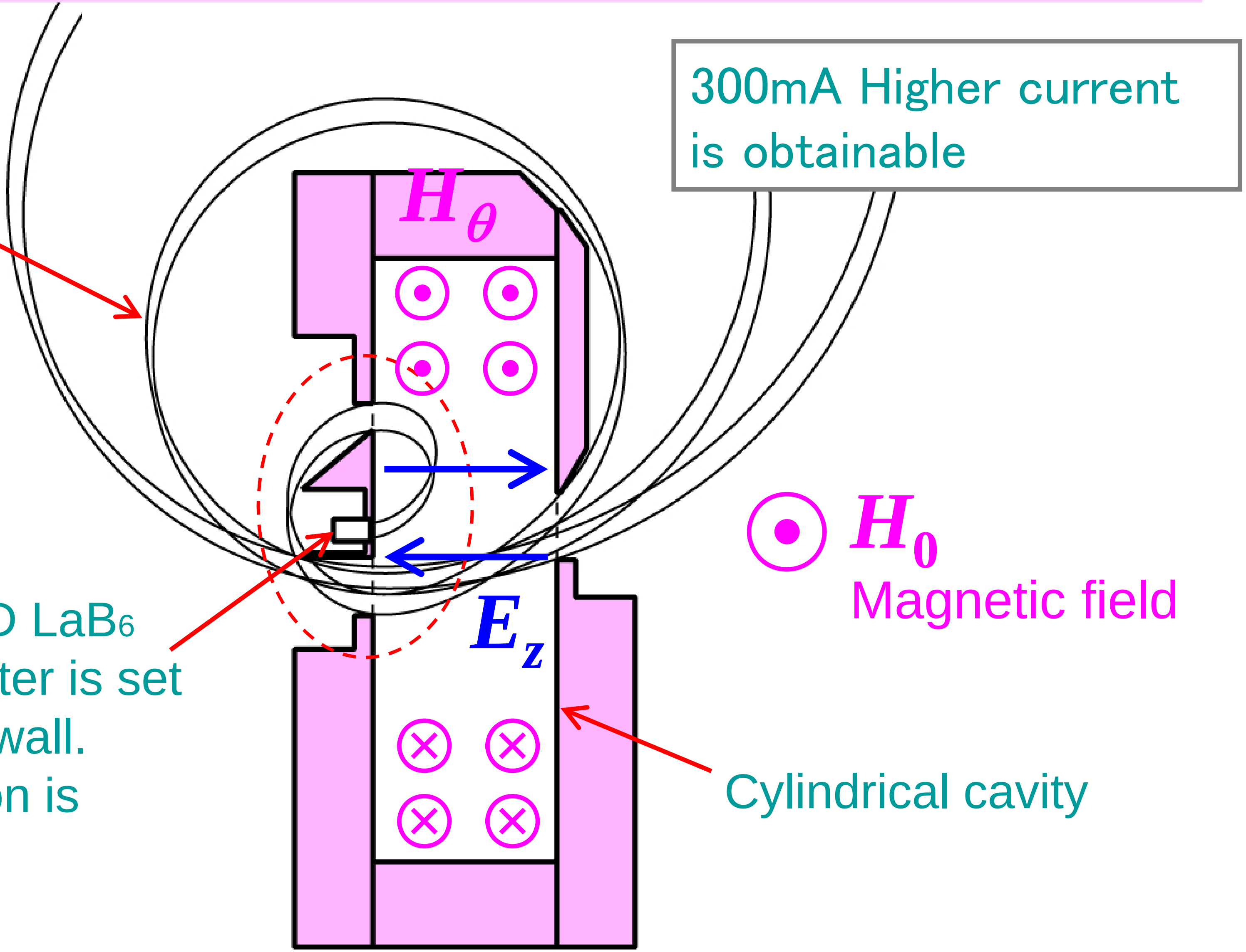
The small energy spread, low emittance and high beam current e-gun should provides the highly efficient acceleration in the successive acceleration

1MeV type: current 400 mA
4MeV type: 300 mA, 20 MeV type: 150 mA
Energy spread: 1 %



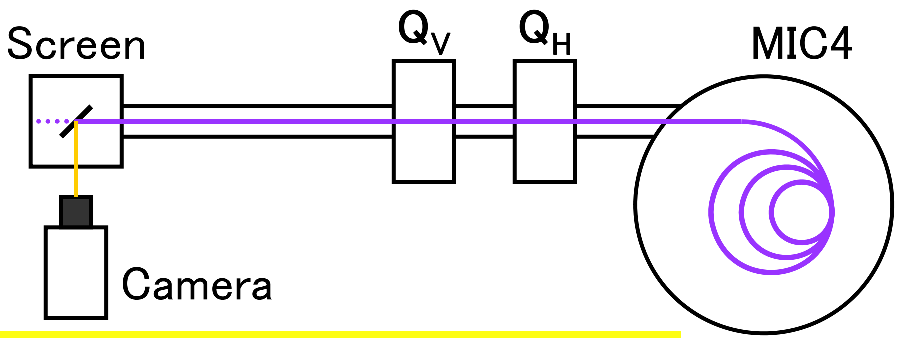


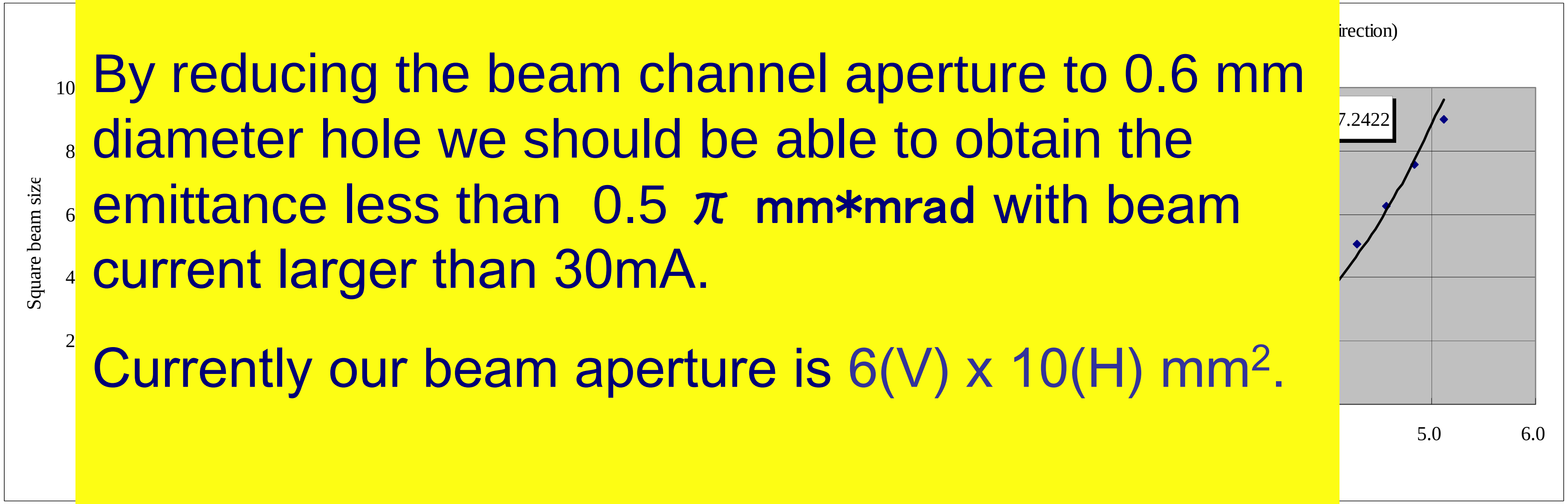
Emission is extracted at the phase of 1MV and gain 0.5MeV leading to a small emittance



- A 3 mm OD LaB_6 electron emitter is set in the cavity wall.
- 2A emission is obtained

Emittance measurement at 300 mA peak current





By reducing the beam channel aperture to 0.6 mm diameter hole we should be able to obtain the emittance less than 0.5 π **mm*mrad** with beam current larger than 30mA.

Currently our beam aperture is 6(V) x 10(H) mm^2.

a = 35.749　　a' = 35.749
b = -227.24　　b' = 3.178
c = 363.28　　c' = 2.165

a = 0.804　　a' = 0.804
b = -4.59　　b' = 2.852
c = 7.24　　c' = 0.702

ε_x = 39.8 π mm·mrad π

ε_y = 5.2 π mm·mrad

Emittance and space charge limit

Elec

temp

As a conclusion,

26 A peak emission current, 1.5 MeV microtron will be suitable for ERL source.

Thre

Average current:

26x10[usec pulse]x10[kHzrepetition]=2.6 A

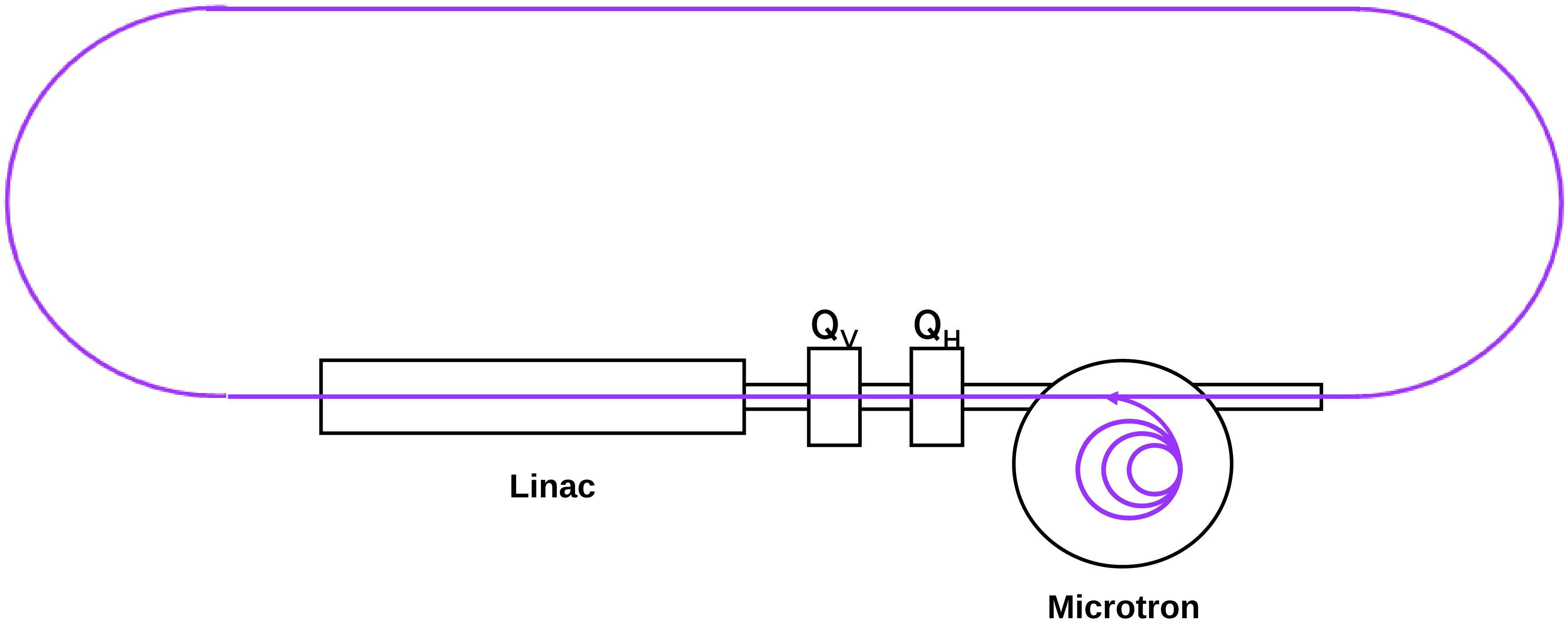
1A emission lead to 100 mA peak current with emittance 0.5 π mm mrad

The ... q.

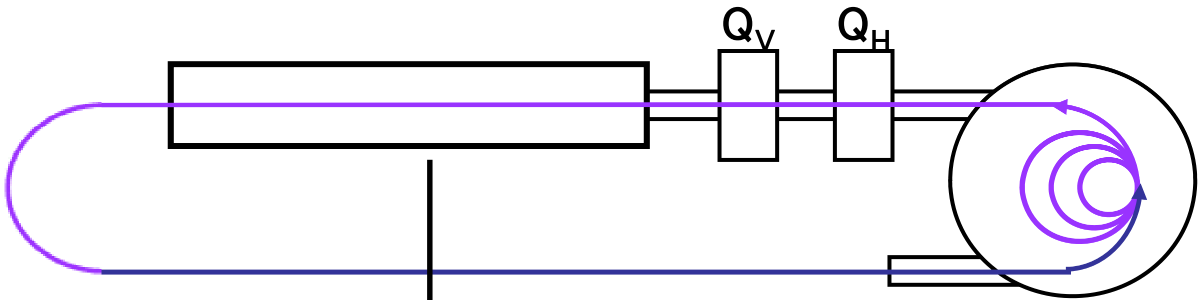
\> 200 mA average 1.5 MeV source is possible.

We could generate 2 A emission by the 1 MeV electric field without losing the low emittance.

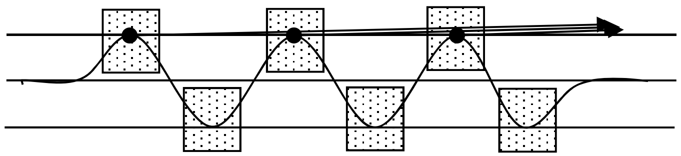
The 1-4 MeV microtron for ERL electron source

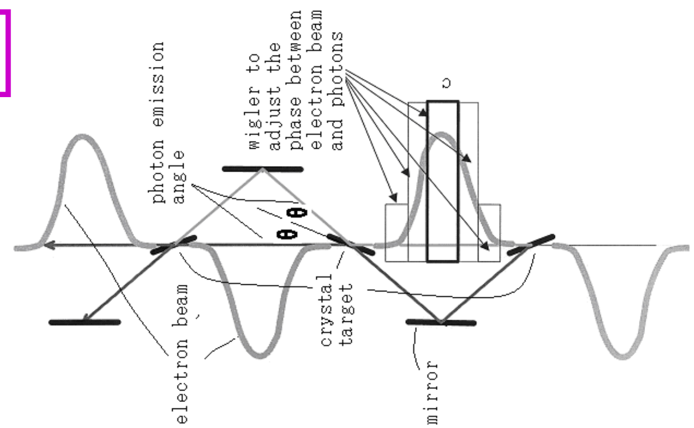


20 MeV ERL machine is enough to generate hard X-ray laser

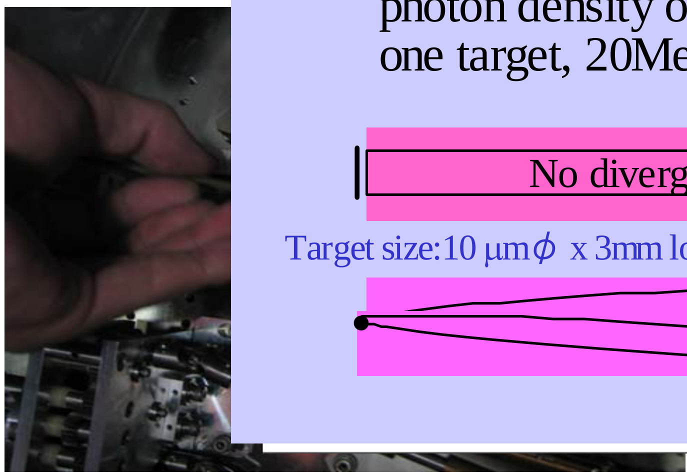


using the Cherenkov radiation



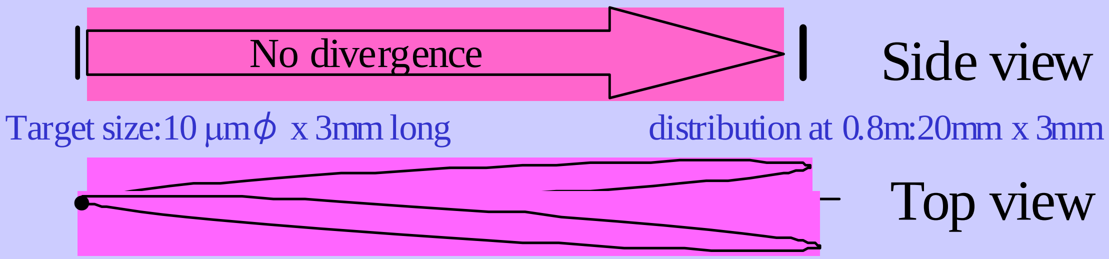


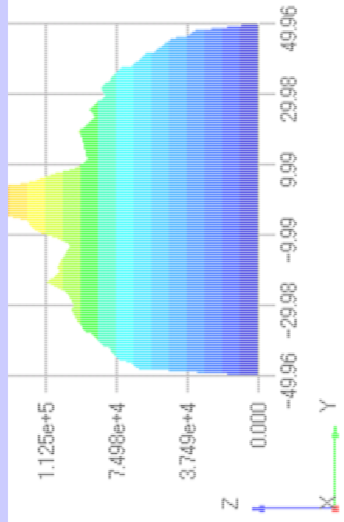
Discovery of novel radiation scheme laser like emission(5mrad V, 20mrad H)



Radiation is extremely parallel in vertical direction

- Beam spread is 0.1x40 mrad^2=4x10^{-6}SR Target size (focal point shape)=6 μmx3mm=1.8x10^{-2}mm^2
- 0.91mW total power in 2% band width is generated from a single target which corresponds to the photon density of about 230KW/mm^2/SR/2%bw by one target, 20MeV machine.



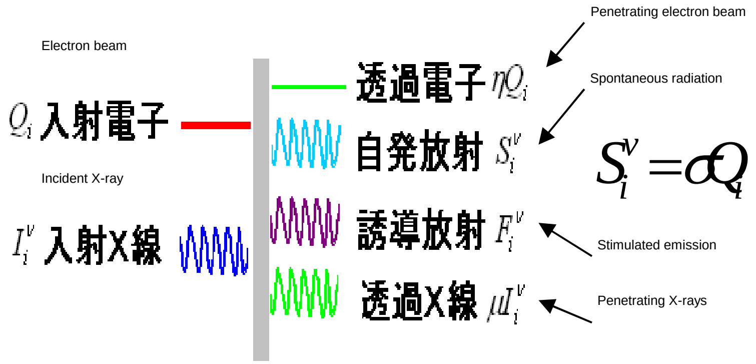


Lasing mechanism is the Einstein’s forced radiation self amplification

Stimulated emission via the state excited by TR, Brems or Cherenkov radiations.

Einstein’s low given to an atomic state is applicable

Electron beam excite the inverse population



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

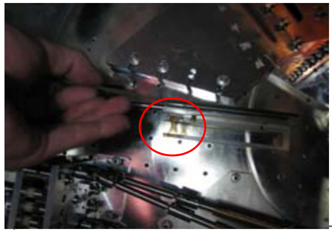
$$I_i^\nu = S_{i-1}^\nu + F_{i-1}^\nu + \mu I_{i-1}^\nu \qquad \kappa = c^2 / 32\pi^2 h\nu^3$$

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

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

Directional EUV radiation from MIRRORCLE-20SX

Directional EUV radiation is observed by hitting CNT thin film with 20 MeV electron beam in a synchrotron orbit.
The observed power is the order of 100mW, but since the radiation is directional, and emitter size is micron order the etendue is 100KW/SR, mm^2.



Cherenkov radiation

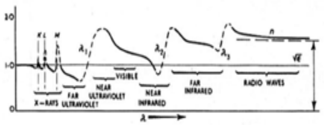
The angular distribution of CR is given by the Cherenkov relation, .

$$\cos\theta = 1/n(\omega)\gamma^2 = 1/\sqrt{\varepsilon_r}\gamma^2$$

When relativistic electron passes through a material radiating CR in the soft X-ray/EUV region, the radiation is directed forward, at a small angle

$$\theta = \sqrt{\chi' - 1/\gamma^2}$$

, along a symmetrical hollow cone. Therefore, CR is appreciable only when χ' is larger than $1/\gamma^2$



Radiation is extremely parallel in vertical direction

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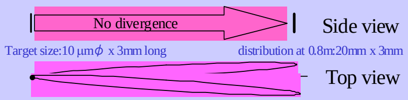
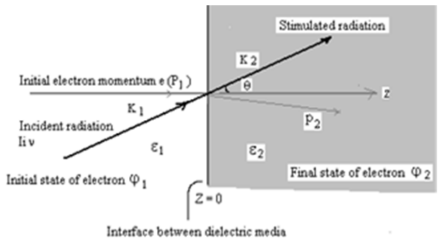


IEEE Journal of Quantum Electronics

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, laser, gain, stimulated emission , transition radiation.**



Stimulated transition radiation at the interface of two media: the refractive index changes from ε1 to ε2 at the interface

Calculation of spontaneous emission rate of transition radiation from relativistic electrons based on phenomenological quantum electrodynamics has been done many years ago by Garibyan [11]. The differential spectral yield is

$$\frac{dN_o}{d\Omega d\omega} = \frac{e2\omega}{16x^3}\frac{E_2E_1 - P_1P_{2z}\cos^2\theta - M^2}{E_1P_{2z}} \left[\frac{1}{P_{1z} - P_{2z} - K_{1z}} - \frac{1}{P_{1Z} - P_{2Z} - K_{2z}}\right]^2 \quad (1)$$

where N_o is the photon number, E_1 is the incident energy of the electron, E_2 is the energy of the electron after emission of a photon, P_1 is the incident electron momentum, P_2 is the electron momentum after emission of a photon, K is the momentum of the photon, M is the electron mass, and θ is the angle of emission as shown in Fig 2.

$$M_{fi} = \langle F|S|I\rangle$$

$$S = e\int d^4x\, N(\bar{\varphi}(x)\gamma^\mu A_\mu(X)\varphi(x))$$

The stimulated emission rate F_{iv} from a current density J when the interface is illuminated by the photon flux, I_{iv}, is thus given by

$$F_{iv} = I_{iv}\frac{1}{e}\frac{e^2}{2\omega}\frac{E_2E_1 - P_1P_{2Z}\cos^2\theta - M^2}{E_1P_{2z}} \times \left(\frac{1}{\sqrt{\varepsilon_1}(P_{1z} - P_{2z}} - \sqrt{\varepsilon_1}\omega\cos\theta) - \frac{1}{\sqrt{\varepsilon_2}(P_{1z} - P_{2z} - \sqrt{\varepsilon_2}\omega\cos\theta)}\right)^2. \quad (8)$$

Thus, coefficient A is calculated by integrating the spontaneous part of (6) over all possible P_2 and averaging over initial electron spin states and summing over final electron spin states and multiplying by the number of radiation modes within the solid angle $\Delta\Omega$ and frequency band width $\Delta\omega$.

Noting that $\Delta^3K = \omega^2\Delta\Omega\Delta\omega$ we have

$$\frac{1}{\tau} = A = \frac{e^2\omega}{16\pi^3L}\frac{E_2E_1 - P_1P_{2z}\cos^2\theta - M^2}{E_1P_{2z}} \times \left(\frac{1}{\sqrt{\varepsilon_1}(P_{1z} - P_{2z} - \sqrt{\varepsilon_1}\omega\cos\theta)} - \frac{1}{\sqrt{\varepsilon_2}(P_{1z} - P_{2z} - \sqrt{\varepsilon_2}\omega\cos\theta)}\right)^2 \Delta\Omega\Delta\omega. \quad (14)$$

Equation (14) gives an analog of Einstein coefficient A for the transition radiation process.

The net change of flux through the interface ΔI_{iv} is

$$\Delta I_{iv} = F_{iv} - \mu I_{iv}.$$

The gain coefficient g per interface is given by

$$g = \frac{\Delta I_{iv}}{I_{iv}}.$$

From (8), (11), and (12), the gain g simplifies to

$$g - \frac{1}{e}\frac{e^2}{2\omega}\frac{E_2E_1 - P_1P_{2z}\cos^2\theta - M^2}{E_1P_{2z}} \times \left(\frac{1}{\sqrt{\varepsilon_1}(P_{1z} - P_{2z} - \sqrt{\varepsilon_1}\omega\cos\theta)} - \frac{1}{\sqrt{\varepsilon_2}(P_{1z} - P_{2z} - \sqrt{\varepsilon_2}\omega\cos\theta)}\right)^2 \times \left(\frac{1}{P_{2z}} - \frac{1}{P_{2zv}}\right).$$

We see that the gain for a single foil depends on the phase $\frac{(P_{1z} - P_{2z} - \sqrt{\varepsilon_2}\omega\cos\theta)L}{2}$. The maximum gain per foil, G_{fmax} is thus

$$G_{f\max} = 4g. \quad (26)$$

Einstein's coefficient B for stimulated emission is derived from stimulated emission probability rate. The B coefficient is defined by

$$W_e = B \times U(\omega) \quad (15)$$

where $U(\omega)$ represents the energy density of the radiation modes. $U(\omega)$ is given by [14]

$$U(\omega) = \omega N\rho(\omega) \quad (16)$$

$$\rho(\omega) = \frac{\omega^2}{\pi^2}. \quad (17)$$

In view of stimulated emission into a continuum of radiation modes, we multiply stimulated emission part of (6) by the number of radiation modes within the solid angle $\Delta\Omega$ and frequency band width $U(\omega)$ and integrate over all possible P_2 and averaging over initial electron spin states and summing over final electron spin states. We have

$$W_e = N\frac{e^2\omega}{16\pi^3L}\frac{E_2E_1 - p_1p_{2z}cos^2\theta - M^2}{E_1p_{2z}} \times \left(\frac{1}{\sqrt{\varepsilon_1}(p_{1z} - p_{2z} - \sqrt{\varepsilon_1}\omega\cos\theta)} - \frac{1}{\sqrt{\varepsilon_2}(p_{1z} - p_{2z} - \sqrt{\varepsilon_2}\omega\cos\theta)}\right)^2 \Delta\Omega\Delta\omega. \quad (18)$$

From (15), (16), and (17), we have

$$B = \frac{\pi^2}{\omega^2}\frac{e^2\omega}{16\pi^3L}\frac{E_2E_1 - P_1P_{2z}\cos^2\theta - M^2}{E_1P_{2z}} \times \left(\frac{1}{\sqrt{\varepsilon_1}(P_{1z} - P_{2z} - \sqrt{\varepsilon_1}\omega\cos\theta)} - \frac{1}{\sqrt{\varepsilon_2}(P_{1z} - P_{2z} - \sqrt{\varepsilon_2}\omega\cos\theta)}\right)^2 \Delta\Omega\Delta\omega. \quad (19)$$

In the same way, after foil N the intensity is

$$I_N = I_0(1 + G_f)^N. \quad (35)$$

The total gain G after N foils is given as

$$G = (1 + G_f)^N - 1. \quad (36)$$

As an example, the laser gain assuming coherence using 15 beryllium foils of thickness 4.1 μm for $\hbar\omega = 2$ keV, with ϵ_2= 0.999844, $\epsilon_1 = 1$, the peak current density, $J = 10^4$ A/mm^2, $E = 5$ GeV, Ne = 10^6, $[F\lambda) = 0.9$ (by (26) and (38)]

Extremely bright soft X-ray beam observed by the tabletop electron storage ring in the collision with a carbon nano tube yarn target

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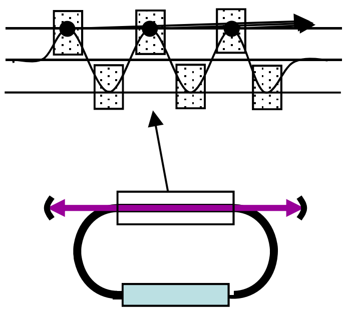
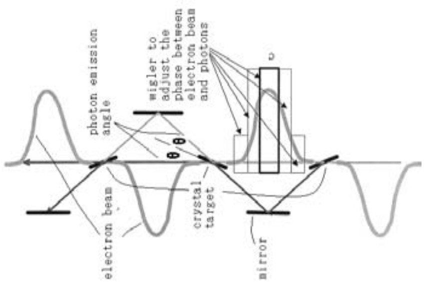
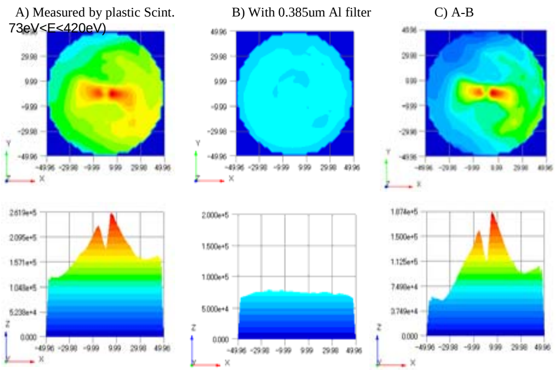
Abstract

A 20 MeV ERL is enough to generate EUV – soft X-ray laser because,





■ Extremely Bright directional radiation is observed by the tabletop synchrotron MIRRORCLE-20SX



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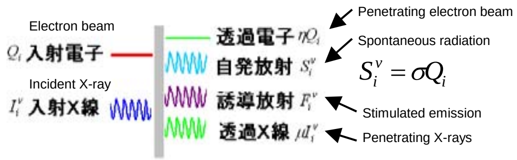
Stimulated emission via the state excited by TR, Brems or Cherenkov radiations.

Einstein's low given to an atomic state is applicable



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

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

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

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

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

References

1) H. Yamada, Ritsumeikan University (Kusatsu, Japan) Synchrotron Light Life Science Centre Annual Rep., pp 31 – 44 , 2005: H. Yamada, "Linear X-ray laser generator", PCT/JP2005/018345(US-2008-0219297-A1)
2) H. Yamada et.al., "Measurement of angular distribution of soft X-ray radiation from thin targets in the tabletop storage ring MIRRORCLE-20SX", J. Synchrotron Rad. (2011). 18.
3) Kenneth E. Okoye and Hironari Yamada, "Transition Radiation X-Ray Laser Based on Stimulated Processes at the Boundary between Two Dielectric Media", IEEE, J Quantum Elect., 46(9) pp.1342-1349 (2010).
4) H. Yamada, Nucl. Instrum. Methods in Phys. Res. A, 1991, pp700-702.