Synchrotrons: Physics of Synchrotron Radiation

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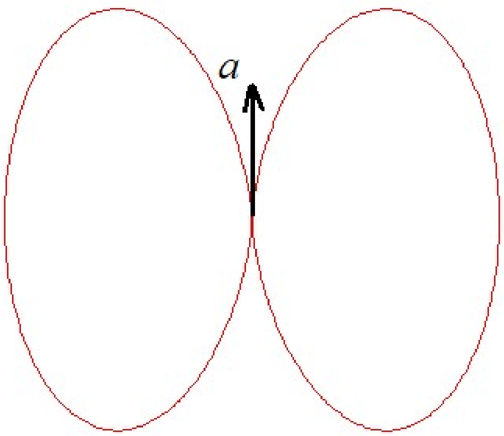
Content

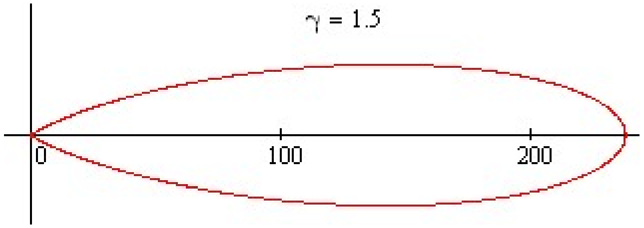
Basics of Synchrotron Radiation

- Radiation in non-relativistic case
  (Landau, v. II, Eq. 67.7)

$$\frac{dI}{d\Omega}=\frac{1}{4\pi c^3}\left[\ddot{\mathbf{d}}\times\mathbf{n}\right]^2 \longrightarrow \frac{dI}{d\Omega}=\frac{e^2a^2}{4\pi c^3}\sin^2\theta$$

$$\longrightarrow \quad I=\frac{2e^2a^2}{3c^3}=\frac{2e^2}{3c^3}\left(\frac{eE}{m}\right)^2=\frac{2e^4E^2}{3m^2c^3}$$

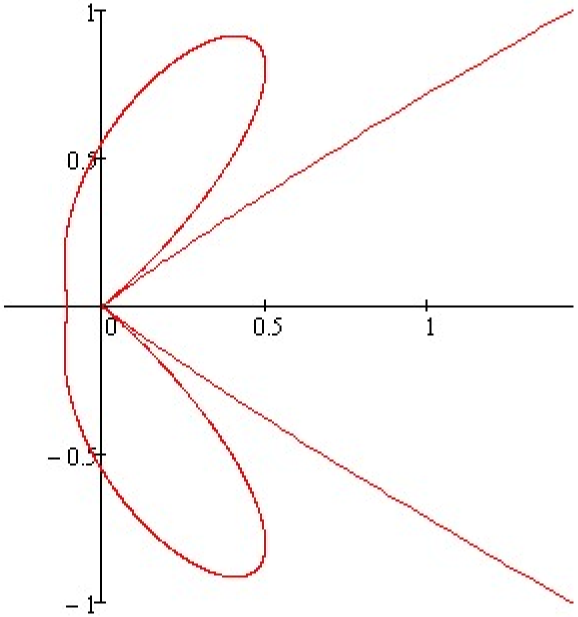




- Total radiation power of in magnetic field (general case)

$$I=\frac{2e^4}{3m^2c^3}\left(\frac{\mathrm{v}}{c}B\right)^2\gamma^2=\frac{2e^4B^2}{3m^2c^3}\beta^2\gamma^2$$

  - One γ comes from shortening of radiation time in the lab frame, another one due to Lorentz transformation of momentum-energy
  - For ultra relativistic case the radiation is mostly directed forward to the cone of 1/γ



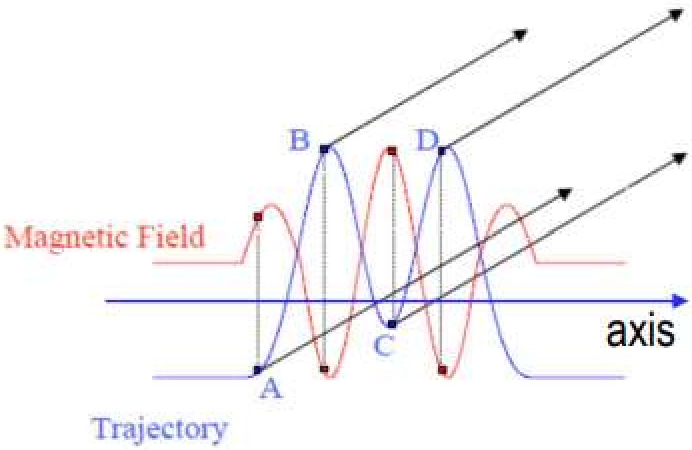
Radiation from Undulators

Undulator Radiation for Small Undulator Parameter

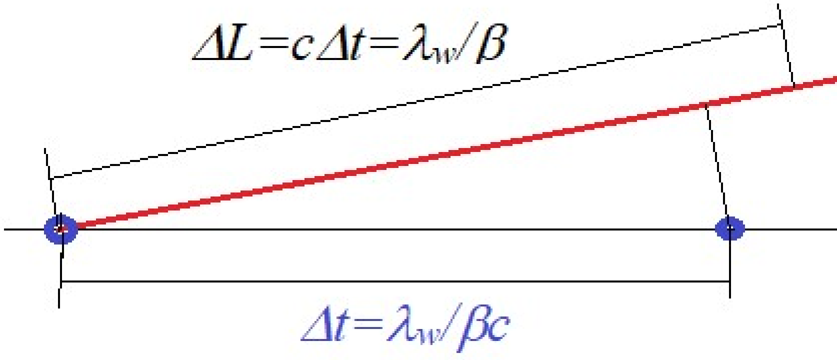
- Maximum angle deflection

$$\frac{dp}{dt}=eB_0\cos\left(2\pi\frac{ct}{\lambda_w}\right)\Rightarrow i\omega p_0\theta_{\max}=eB_0$$

$$\xrightarrow{\omega=2\pi c/\lambda_w}\theta_{\max}=\frac{eB_0\lambda_w}{2\pi c p_0}$$



- Divergence of radiation $\theta_\gamma=1/\gamma$
- Undulator parameter $K=\frac{\theta_{\max}}{\theta_\gamma}=\frac{eB_0\lambda_w}{2\pi mc^2}$
- For K<<1 one can obtain radiation fields making Lorentz transform for the radiation intensity



- There is radiation into a single harmonic. However, the frequency of radiation depends on the angle of observation (angle-dependent Doppler shift)

$$\lambda=\lambda_w\cos\theta-\frac{\lambda_w}{\beta}\simeq\lambda_w\left(1-\frac{\theta^2}{2}-\frac{1}{\beta}\right)\xrightarrow{1-\beta=1/2\gamma^2}\boxed{\lambda=\frac{\lambda_w}{2\gamma^2}\left(1+\gamma^2\left(\theta_x{}^2+\theta_y{}^2\right)\right)}$$

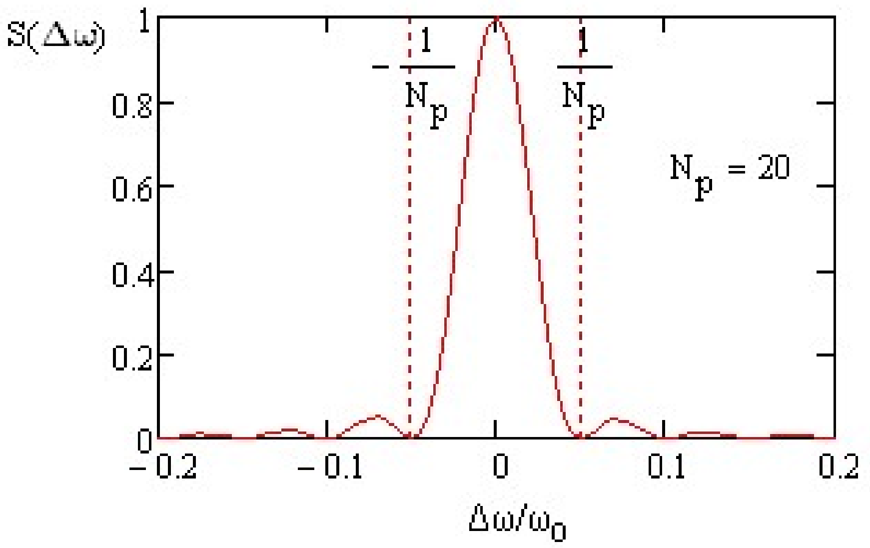
Undulator Radiation for Small Undulator Parameter (2)

- Radiation has linear polarization in the plane of undulator wiggles
- Electric field amplitudes are:

$$\begin{bmatrix}E_x\\ E_y\end{bmatrix}=\frac{4eB_0\gamma^3}{mc^2R\left(1-\gamma^2\theta^2\right)^3}\begin{bmatrix}1+\gamma^2\theta^2-2\gamma^2\theta^2\cos^2\phi\\ \gamma^2\theta^2\sin(2\phi)\end{bmatrix}$$

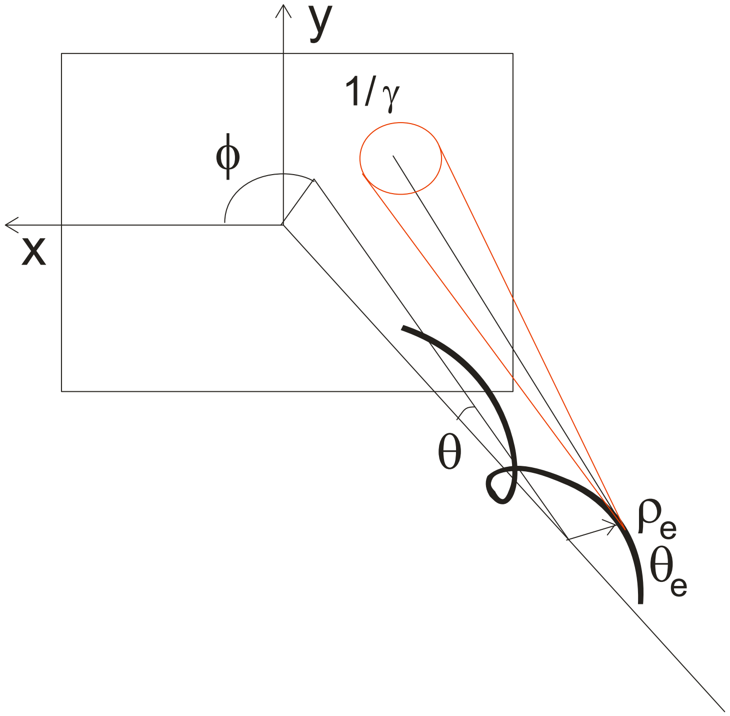
  - ♦ As one can see the radiation is peaked into the angle 1/g
- Bandwidth of Undulator radiation
  - ♦ There are two parameters determining the radiation bandwidth:
    - The number of wiggler periods: $\Delta f/f=1/2N_p$
    - And the angle wrapping the radiation: $\Delta f/f=\gamma^2\theta^2$

      $\Rightarrow$ For $\theta > 1/\gamma$ radiation power decreases fast



Radiation from Wiggler

- Undulator with large K is usually called wiggler



- Radiation of ultra-relativistic particle is concentrated in $1/\gamma$ angle
- Undulator parameter:

$$K \equiv \gamma\theta_e = \frac{\lambda_{wgl}}{2\pi}\frac{eB_0}{mc^2}$$

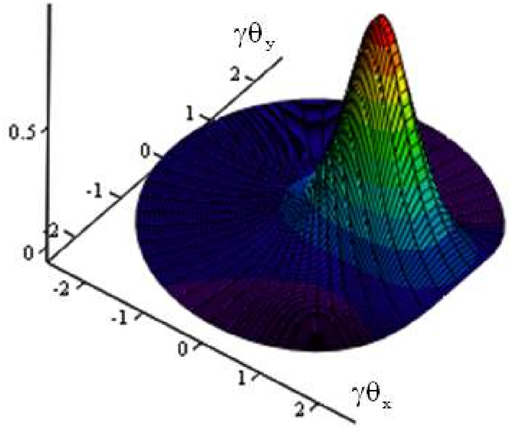
- For K ≥ 1 the radiation is mainly radiated into higher harmonics

- Liénard-Wiechert potentials and E-field of moving charge in wave zone

$$\begin{cases} \varphi(\mathbf{r},t) = \left.\dfrac{e}{(R-\boldsymbol{\beta}\cdot\mathbf{R})}\right|_{t-R/c} \\ \mathbf{A}(\mathbf{r},t) = \left.\dfrac{e\mathbf{v}}{(R-\boldsymbol{\beta}\cdot\mathbf{R})}\right|_{t-R/c} \end{cases} \Rightarrow$$

$$\mathbf{E}(\mathbf{r},t) = \frac{e}{c^2}\left.\frac{(\mathbf{R}-\boldsymbol{\beta}\cdot R)(\mathbf{a}\cdot\mathbf{R}) - \mathbf{a}R(R-\boldsymbol{\beta}\cdot\mathbf{R})}{(R-\boldsymbol{\beta}\cdot\mathbf{R})^3}\right|_{t-R/c}$$

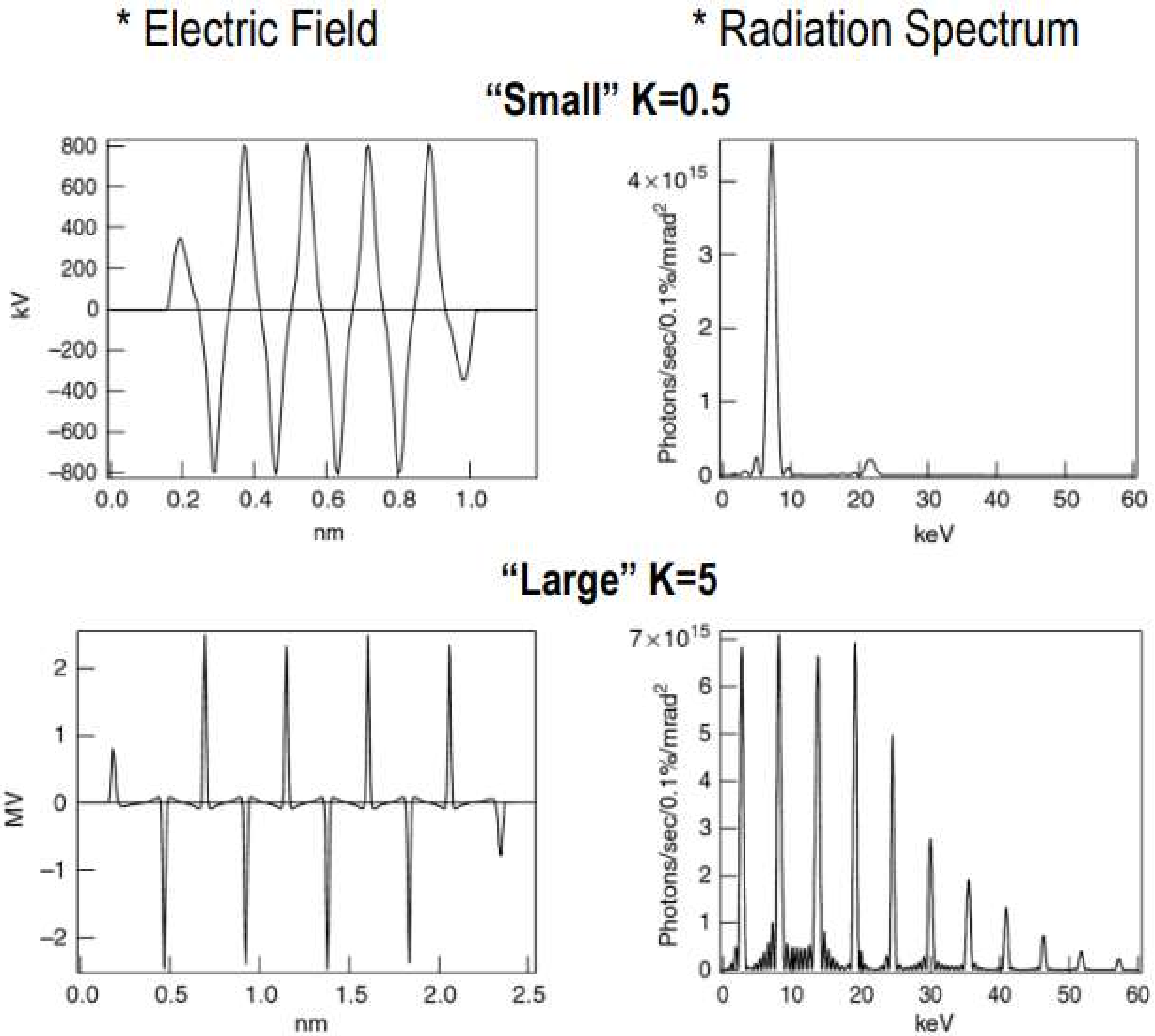
where $\mathbf{a} \equiv \dfrac{d\mathbf{v}}{dt}$



E_x for K=1

Undulator Radiation for Large K

- Horizontal component of Electric field seen by observer on-axis
- For a small K the field is sinusoidal with the spectrum dominated by a single peak at the fundamental harmonic frequency
- For large K, the field is "spiky", leading to a series of narrow spectral peaks corresponding to higher harmonics



* Electric Field

* Radiation Spectrum

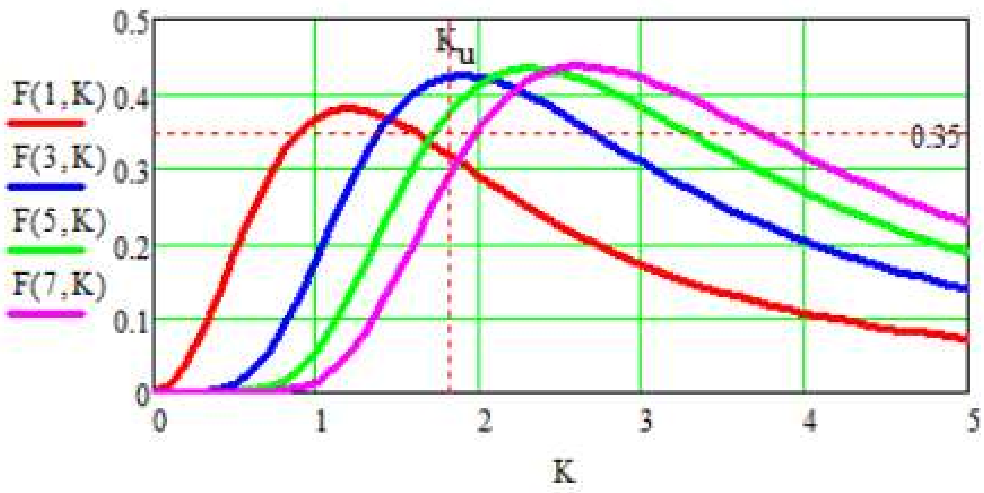
"Small" K=0.5

"Large" K=5

Total Spectral Flux

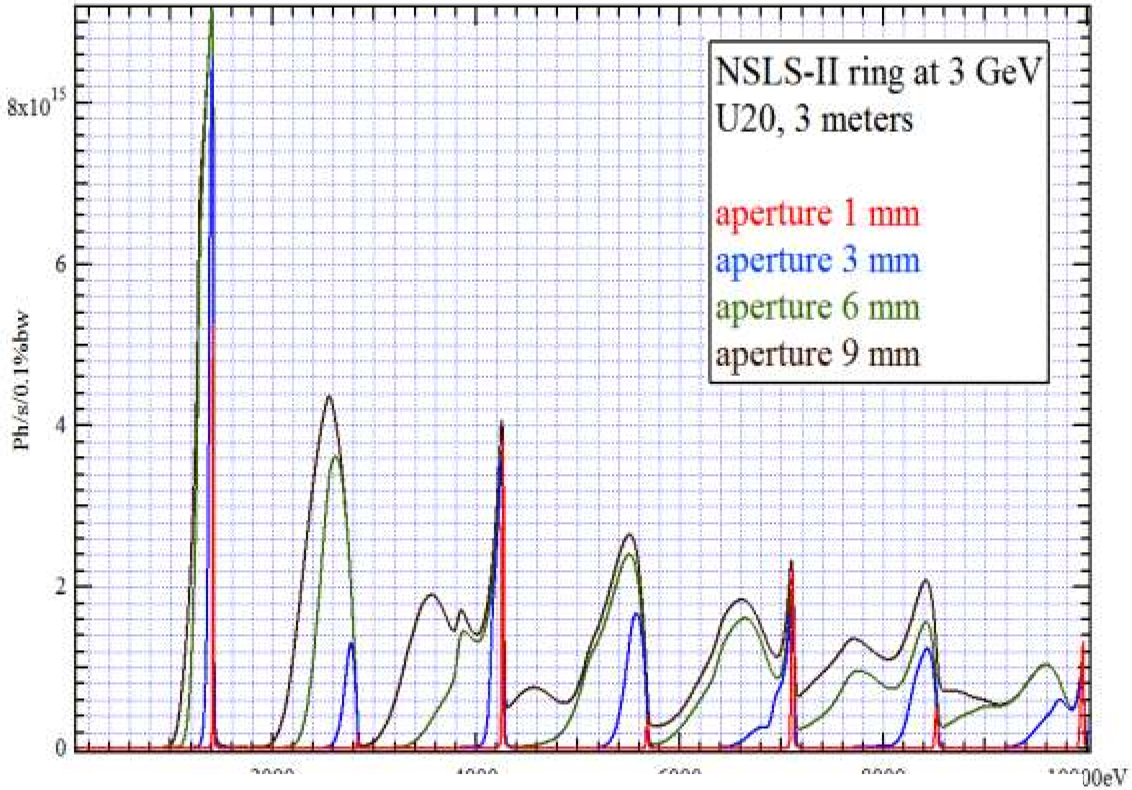
- Motion with wiggles additionally decreases the longitudinal particle velocity so that $\Delta s/s = \theta^2/4$. That results in an increase if the radiation wave length

$$F(n,K) := \frac{n^2 \cdot K^2}{\left(1+\frac{K^2}{2}\right)^2} \cdot \left(\mathrm{Jn}\left(\frac{n-1}{2}, \frac{n \cdot K^2}{4+2 \cdot K^2}\right) - \mathrm{Jn}\left(\frac{n+1}{2}, \frac{n \cdot K^2}{4+2 \cdot K^2}\right)\right)^2$$



$$\boxed{\lambda_n = \frac{1}{n}\frac{\lambda_w}{2\gamma^2}\left(1+\frac{K_x{}^2}{2}+\frac{K_y{}^2}{2}+\gamma^2\left(\theta_x{}^2+\theta_y{}^2\right)\right), \quad \lambda_0 = \frac{\lambda_w}{2\gamma^2}}$$

Spectrum: effect of sampling aperture



Energy – angle distribution of undulator radiation

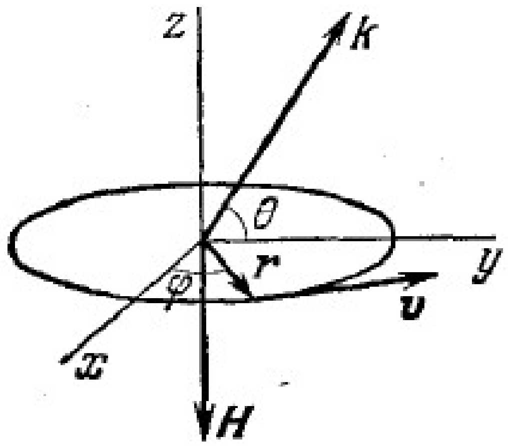
- Opening aperture broadens spectral bandwidth
- Spectrum exhibits only odd harmonics on axis
- Even harmonics show up off-axis
- Monochromators select narrow spectral bandwidth
- Effective emittance of radiation:

$$\varepsilon_\gamma \equiv \Delta\theta\Delta r \approx \left(\frac{1}{\gamma}\right)(\lambda_0\gamma) = \lambda_0$$

- Consequently, to achieve diffraction limited brightness one need to have the beam emittance smaller than λ
- Numerical example (NSLS-II): λ_w=5 cm, B_0=1 T, K=4.67, E=3 GeV λ_0=8.6, ε_x=1 nm, ε_y=0.01 nm

Radiation from Dipoles

Useful Estimates



- For ultra-relativistic particles the energy radiated per turn grows as E^4

$$I=\frac{2e^4B^2}{3m^2c^3}\beta^2\gamma^2\xrightarrow{T=2\pi mc\gamma/eB}\Delta E=IT=\frac{4\pi e^3B}{3mc^2}\beta^2\gamma^3$$

$$\xrightarrow{R=mc^2\beta\gamma/eB}\Delta E=IT=\frac{4\pi e^3}{3mc^2}\frac{mc^2\beta\gamma}{eR}\beta^2\gamma^3=\frac{4\pi e^2}{3R}\beta^3\gamma^4$$

- Introduce the formation length

$$L_f=R\Delta\theta=\frac{R}{\gamma}$$

- The characteristic wave length

$$\lambdabar_c\sim L_f\left(1-\beta\right)\xrightarrow{\beta=1-1/2\gamma^2}\frac{L_f}{2\gamma^2}=\frac{R}{2\gamma^3}$$

Accurate computation introduces the characteristic wave length as

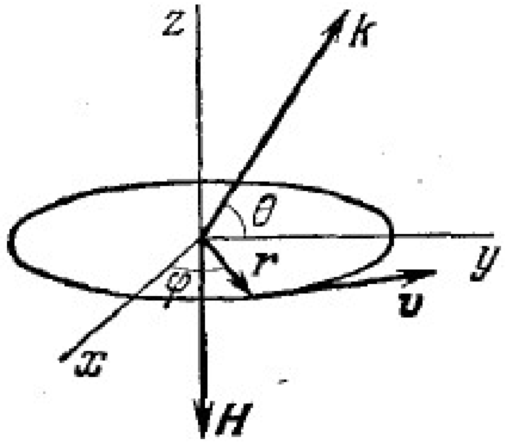
$$\boxed{\lambdabar_c=\frac{2mc^2}{3eB\gamma^2}=\frac{2R}{3\gamma^3}\,,\qquad \lambda_c=2\pi\lambdabar_c}$$

Spectrum of Synchrotron Radiation from Dipoles

- Fourier harmonics of electric field in the far zone
  (Landau, v.II, Eqs.66.3, 74.6, 74.7)

$$\begin{cases} E_{Hn} = ikA_x = ik\dfrac{ie\beta}{R_0}e^{ikR_0}J_n'(n\beta\cos\theta)\,, \\ E_{Vn} = ik_zA_y = ik\dfrac{e}{R_0\cos\theta}e^{ikR_0}\sin(\theta)J_n(n\beta\cos\theta)\,, \end{cases}$$

$$k = \frac{n\omega_0}{c}$$



- Bessel function: $J_n(x) = \dfrac{1}{2\pi}\displaystyle\int_{-\pi}^{\pi} e^{i(x\sin\phi - n\phi)}d\phi$

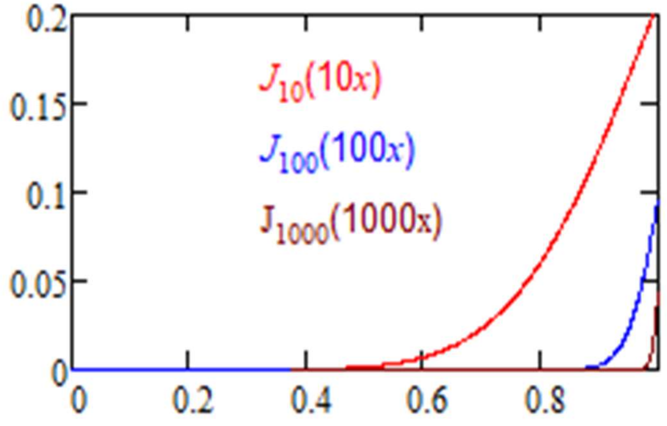
For large n, the range of small ϕ makes the major contribution ($n >> 1, \quad 1-x \ll 1$)

$$J_n(nx) = \frac{1}{2\pi}\int_{-\pi}^{\pi} e^{in(x\sin\phi-\phi)}d\phi \xrightarrow[|x|\le 1]{n\gg 1} \frac{1}{2\pi}\int_{-\infty}^{\infty} e^{in\left(x\left(\phi-\phi^3/6\right)-\phi\right)}d\phi$$

$$= \frac{1}{\pi}\int_0^\infty \cos\left(n\phi(x-1) - nx\phi^3/6\right)d\phi \xrightarrow{y^3 = nx\phi^3/2}$$

$$= \frac{1}{\pi}\int_0^\infty \cos\left(\left[n\frac{\sqrt[3]{2}}{\sqrt[3]{nx}}(x-1)\right]y - y^3/3\right)\sqrt[3]{\frac{2}{nx}}dy$$

$$= \sqrt[3]{\frac{2}{nx}}\sqrt{\pi}\,\Phi\left(\sqrt[3]{\frac{2n^2}{x}}(1-x)\right), \qquad \Phi(x) = \frac{1}{\sqrt{\pi}}\int_0^\infty \cos\left(xy + y^3/3\right)dy$$



where $\Phi(x)$ is the Airy function

Spectrum of Synchrotron Radiation from Dipoles (2)

- For ultra-relativistic beam

$$\beta\cos\theta \approx \left(1-\frac{1}{2\gamma^2}\right)\left(1-\frac{\theta^2}{2}\right) \approx 1-\frac{1}{2\gamma^2}\left(1+\gamma^2\theta^2\right) \approx 1-\frac{1}{2\gamma^2}\left(1+\Theta^2\right), \quad \Theta=\gamma\theta$$

- For numeric computations we express the Airy function through the modified Bessel function. Combining we have

$$\boxed{\begin{bmatrix} E_{Hn} \\ E_{Vn} \end{bmatrix} = \frac{\mathrm{e}k\,e^{ikR_0}}{\sqrt{3}\pi\gamma^2 R_0}\begin{bmatrix} \left(1+\Theta^2\right)K_{2/3}\left(\Omega\left(1+\Theta^2\right)^{3/2}/2\right) \\ i\Theta\sqrt{1+\Theta^2}\,K_{1/3}\left(\Omega\left(1+\Theta^2\right)^{3/2}/2\right) \end{bmatrix}}$$

where $\underline{\Theta=\gamma\theta\,, \quad \Omega=n/n_c\equiv\omega/\omega_c\,, \quad n_c=3\gamma^3/2\,, \quad \omega_c=3\mathrm{e}B_0\gamma^2/(2m_ec)}$

and we accounted that

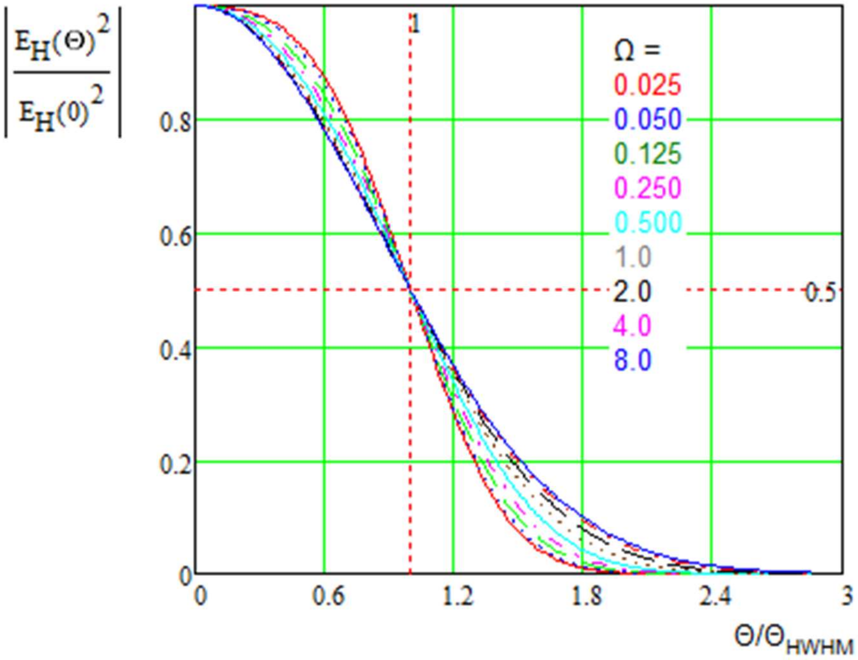
$$J_n(n(1-\varepsilon)) = \frac{\sqrt{2\varepsilon}}{\pi\sqrt{3}}K_{1/3}\left(\frac{2\sqrt{2}}{3}n\varepsilon^{3/2}\right), \qquad xK_{4/3}(x)-\frac{2}{3}K_{1/3}(x)=xK_{2/3}(x)$$

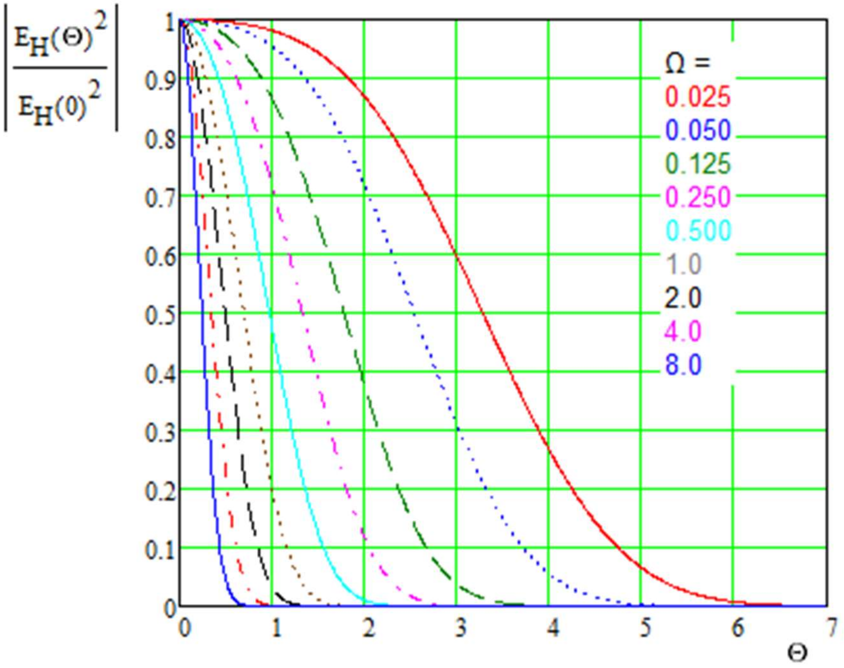
$$J_n'(n(1-\varepsilon)) = \frac{\sqrt{2}}{\pi n\sqrt{3\varepsilon}}\left(\sqrt{2}n\varepsilon^{3/2}K_{4/3}\left(\frac{2\sqrt{2}}{3}n\varepsilon^{3/2}\right)-K_{1/3}\left(\frac{2\sqrt{2}n}{3}n\varepsilon^{3/2}\right)\right),$$

Divergence of Synchrotron Radiation with Horizontal Polarization (σ - mode)

- With reduction of Ω the harmonic power decays faster with the relative angle (Θ/Θ_{HWHM})
  - Exponential – gaussian-like decay with angle
- The width of the power spectral density decays with frequency as:

$$\boxed{\Theta_{HWHM} \approx \frac{0.71}{\sqrt{0.02+\Omega}}, \quad 0.025 \le \Omega \le 8}$$

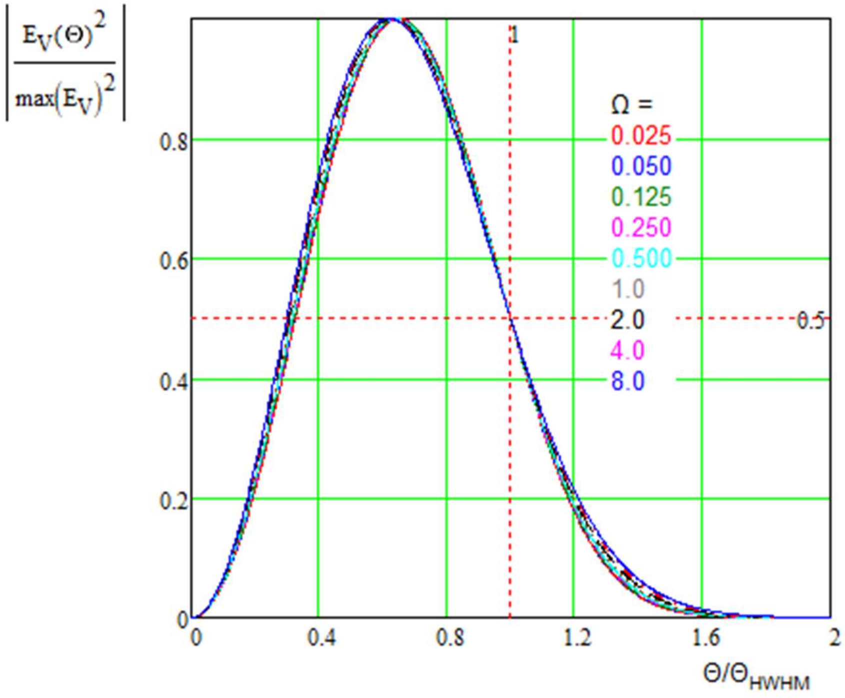


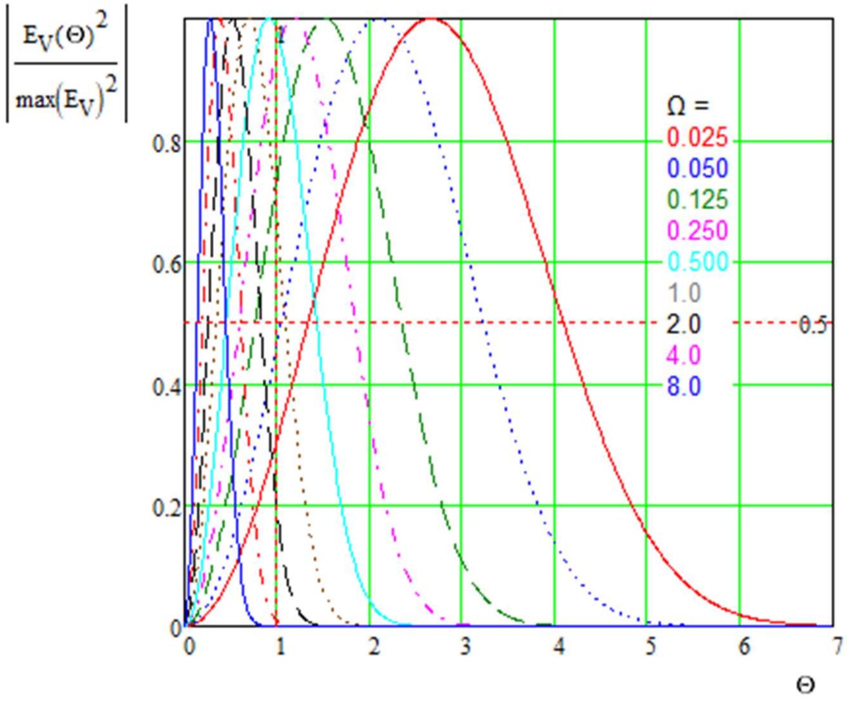


Divergence of Synchrotron Radiation with Vertical Polarization (π - mode)

- Electric field changes sign with sign change of Θ
- Weak dependence of the harmonic power shape on Ω
  - Exponential – gaussian-like decay with angle
- The width of the power spectral density decays with frequency as:

$$\boxed{\Theta_{HWHM} \approx \frac{1.1}{(0.022+\Omega)^{0.43}}, \quad 0.025 \le \Omega \le 8}$$





Resolution of Synchrotron Light Monitor (Σ mode)

- Sync light monitor focuses SR (makes image) into a CCD camera.
- Simple estimate of the resolution

$$\Delta y \approx \frac{\lambda}{\theta} = \frac{\lambda\gamma}{\Theta_{HWHM}(\omega/\omega_c)} \xrightarrow[polarization]{horizontal} \approx \frac{\lambda\gamma}{0.071}\sqrt{0.02+\frac{\lambda_c}{\lambda}}, \quad 0.025 \le \frac{\lambda_c}{\lambda} \le 8$$

- Accurate computation uses Kirchhoff formula which requires integration of electric field over lens surface with correctly accounted phase delay
  - Lens compensates the quadratic terms in the phase.
  - ⇨ Expending phase into Tailor series and leaving terms including cubic one obtains the intensity distribution for horizontal polarization in the image plane (M 1:1)

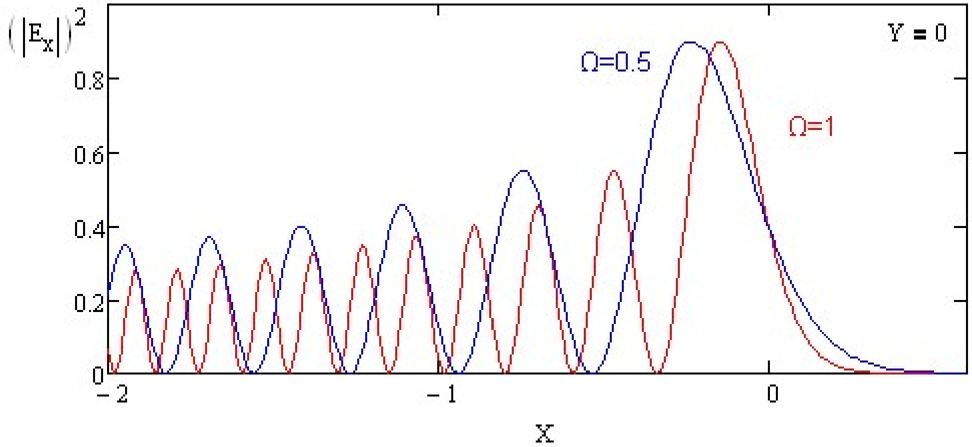
$$E_{Hn}(X,Y) \propto E_{x1}(X)E_{x2}(Y), \quad X = x/r_c\,, \quad Y = y/r_c\,, \quad r_c = \lambda_c\gamma = 4\pi R/(3\gamma^2)$$

$$E_{x1}(X) = \int \exp\left(-i\Omega\left(\frac{\Theta_x^{\ 3}}{4} + 2\pi\Theta_x X\right)\right) d\Theta_x$$

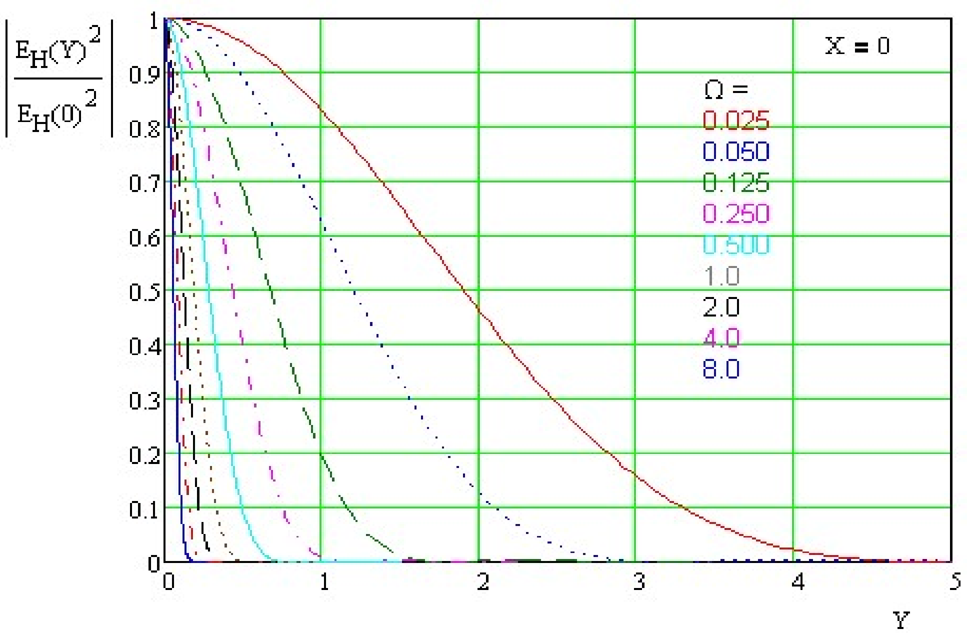
$$E_{x2}(Y) = \int \left(1+\Theta_y^{\ 2}\right) K_{2/3}\left(\Omega\left(1+\Theta_y^{\ 2}\right)^{3/2}/2\right) \exp\left(-2\pi i\Omega\Theta_y Y\right) d\Theta_y$$

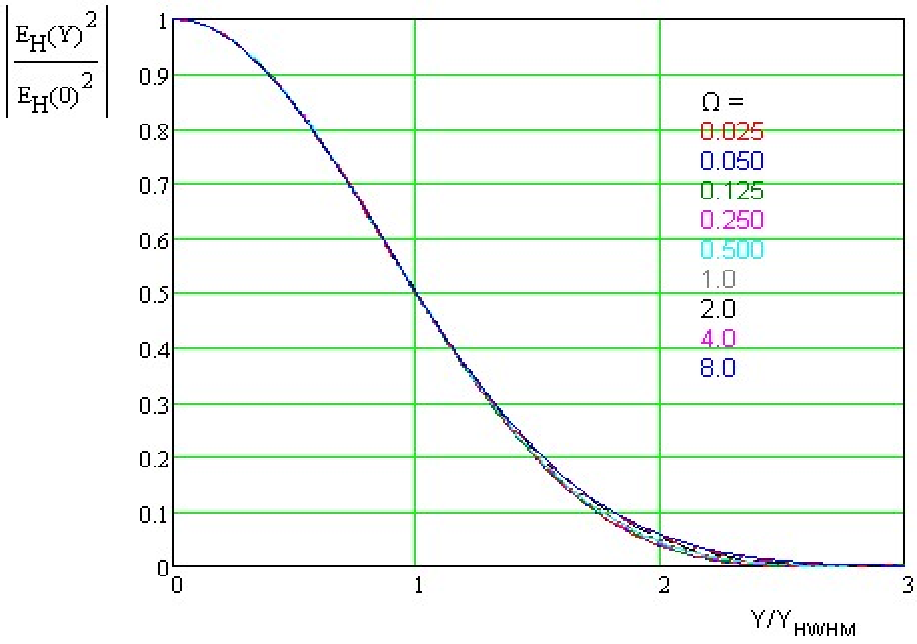
Remind that $\lambda_c = 4\pi R/(3\gamma^3)$ is the critical wavelength

Semi-analytical computation of SR Monitor Resolution



$$Y_{HWHM} \approx 0.19/\Omega^{0.6}\ , \quad \Omega \in [0.025, 8]$$



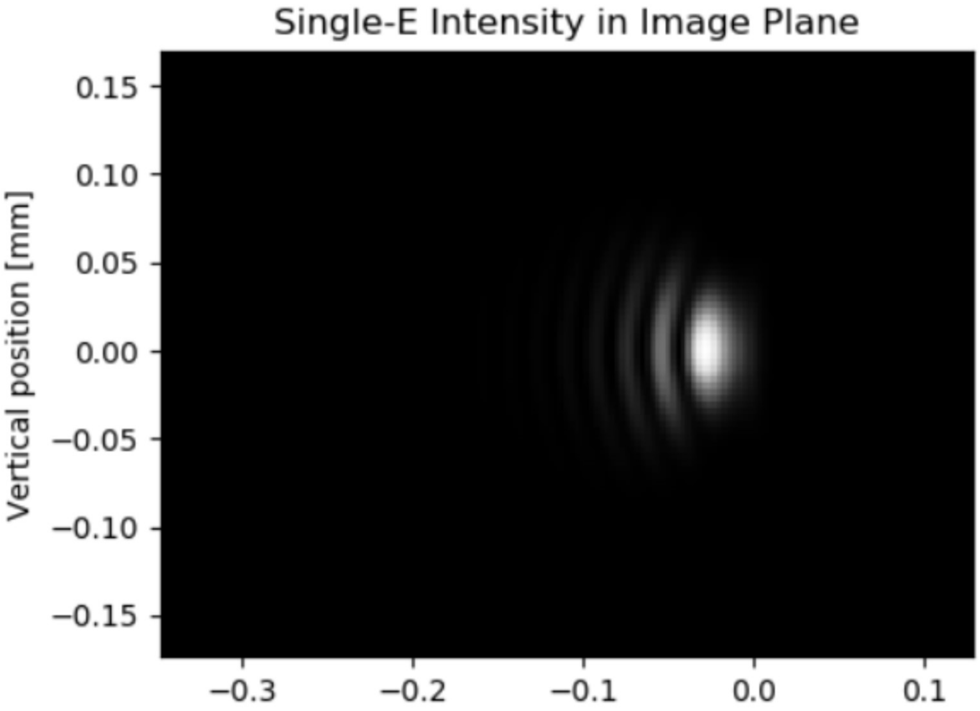


- To obtain horizontal intensity distribution one need to integrate over spectral sensitivity of the photo-receiver

Numeric Computation of SR Monitor Resolution

- To obtain accurate intensity distribution one need to use numerical simulations
  - Code SRW is suppterted by BNL

- In the picture one can see
  - The horizontal resolution is better than the vertical one – effect of larger spot size on the lens (equal to lens aperture)
  - Extra ring related to narrow bend of photo-receiver
  - Ring has radius because no Tailor expansion is used in computation of phase
    - Wider band would create tail



Intensity distribution computed by SRW for IOTA sync. light upgrade

SR Damping

SR Damping for Longitudinal Motion

- Dependence of energy loss on energy for ultra relativistic beam for the beam moving in constant magnetic field

$$I=\frac{2e^4B^2}{3m^2c^3}\beta^2\gamma^2 \quad \Rightarrow \quad \frac{dI}{dE}=2\frac{I}{E}$$

- Equations of longitudinal motion

$$\begin{cases}\dfrac{d\varphi}{dt}=q\omega_0\eta\dfrac{\Delta p}{p}\\ \dfrac{d}{dt}\left(\dfrac{\Delta p}{p}\right)=\dfrac{1}{\beta^2}\dfrac{d}{dt}\left(\dfrac{\Delta E}{E}\right)=\dfrac{1}{\beta^2 E}\left(-eV_0\dfrac{\omega_0}{2\pi}\varphi-\dfrac{dI}{dE}\Delta E\right)\end{cases}\xrightarrow[\beta=1]{cp=E}\frac{d^2}{dt^2}\frac{\Delta p}{p}=-\Omega_s{}^2\frac{\Delta p}{p}-\frac{dI}{dE}\frac{d}{dt}\left(\frac{\Delta p}{p}\right)$$

- Solution

$$-\omega^2=-\Omega_s{}^2-\frac{dI}{dE}i\omega\xrightarrow{dI/dE\ll\Omega_s}\omega=\sqrt{\Omega_s{}^2+\frac{dI}{dE}i\Omega_s}=\Omega_s+\frac{i}{2}\frac{dI}{dE}$$

- Damping rate for longitudinal motion

$$\lambda_s=\frac{1}{2}\frac{dI}{dE}=\frac{1}{2}\left(2\frac{I}{E}\right)$$

SR Damping for Transverse Motion

- RF system compensates longitudinal energy. Then SR effect on vertical motion is:

$$p\frac{d\theta_y}{dt}=\frac{dp_y}{dt}=\theta_y\frac{dp_{\|}}{dt}=-\theta_y I \quad\Rightarrow\quad \frac{d\theta_y}{dt}=-\frac{I}{E}\theta_y \quad\Rightarrow\quad \lambda_y=\frac{I}{E}$$

  Accounting of betatron motion yields factor ½ :

$$\lambda_y=\frac{I}{2E}$$

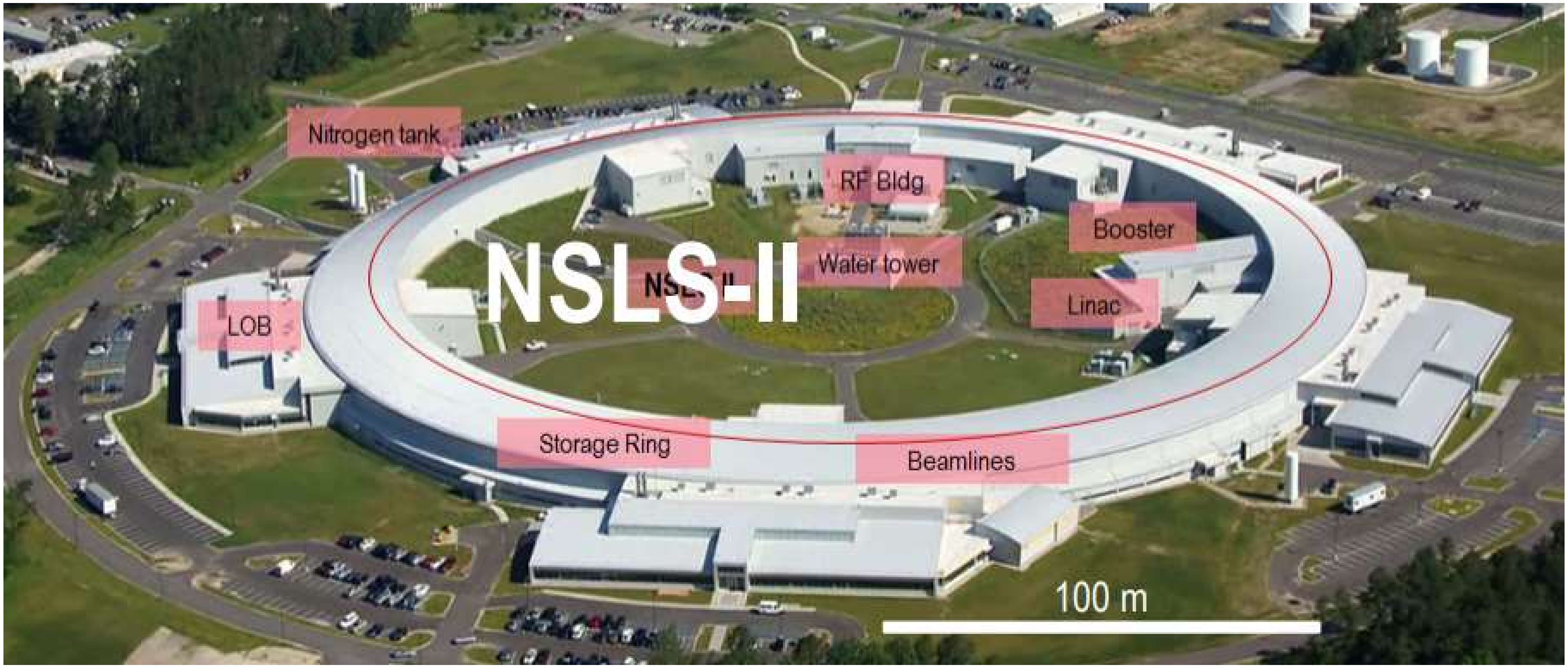
- The same effect would be on the horizontal motion if the beam moves in uniform bending field.
- In real machine we can write:

$$\begin{bmatrix}\lambda_x\\ \lambda_y\\ \lambda_s\end{bmatrix}=\frac{I}{2E}\begin{bmatrix}g_x\\ g_y\\ g_s\end{bmatrix}$$

- In the above consideration we saw that: $g_x+g_y+g_s=4$
  - The theorem on the sum of decrements states that this equation stays correct in all cases

Modern Synchrotron Light Source (BNL)

- Major fraction of synchrotrons are SR sources
- In Russia: BINP, Khurchatov institute
- New ones planned/constructed: Novosibirsk, Serpukhov, Vladivostok



NSLS-II (BNL)

Facility name	Location	Country	Energy (GeV)	Circumference (m)	Commissioned for synchrotron radiation studies	Decommissioned
National Synchrotron Light Source (NSLS-II)	Brookhaven National Laboratory	US	3	792	2015	
Synchrotron Ultraviolet Radiation Facility (SURF)	National Institute of Standards and Technology, Gaithersburg, Maryland	US	0.18		1961	
SURF II storage ring, Synchrotron Ultraviolet Radiation Facility	National Institute of Standards and Technology, Gaithersburg, Maryland	US	0.25		1974	
SURF III Synchrotron Ultraviolet Radiation Facility	National Institute of Standards and Technology, Gaithersburg, Maryland	US	0.416	5.27	2000	
Frascati Synchrotron Radiation Collaboration	1 GeV electronsynchrotron (built in 1958) at Laboratori Nazionali di Frascati	Italy	1	12	1963	1970
Institute for Nuclear Studies-Synchrotron Orbital Radiation (INS-SOR)	Tokyo	Japan	0.75		1965	
Storage ring of INS-SOR (Institute for Nuclear Studies-Synchrotron Orbital Radiation)	Tokyo	Japan	0.3		1974	

Facility name	Location	Country	Energy (GeV)	Circumference (m)	Commissioned for synchrotron radiation studies	Decommissioned
DESY (Deutsches Elektronen Synchrotron)	DESY	Germany	7.4		1967	1987
DORIS (Doppel-Ring-Speicher)	DESY	Germany	3.5 (5 in 1978)	289	1974	1993
DORIS III	DESY	Germany	5	289	1993	2012
PETRA II	DESY	Germany	12	2304	1995	2007
PETRA III	DESY	Germany	6.0	2304	2009	
Tantalus at the Synchrotron Radiation Center	University of Wisconsin	US	0.24	9.38	1968	1987
Synchrotron Radiation Center(SRC)	University of Wisconsin	US	1	121	1987	2014
Solidi Roma Synchrotron Radiation Facility	Recycled 1GeV electronsynchrotron at Laboratori Nazionali di Frascati	Italy	1	12	1972	1975
Stanford Synchrotron Radiation Lightsource (SSRL)	SPEAR storage ring at SLAC National Accelerator Laboratory	US	3	234	1973	
Linac Coherent Light Source (LCLS)	SLAC National Accelerator Laboratory	US	8	3000	2007	
Anneau de Collisions d'Orsay (ACO)	Orsay	France	0.54		1973	1988
Cornell High Energy Synchrotron Source (CHESS)	Cornell University, Ithaca, NY	US	6.0	768	1979	
Progetto Utilizzazione Luce di Sincrotrone (PULS)	recycled Adone storage ring with wiggler (built in 1968) at Laboratori Nazionali di Frascati	Italy	1.5	33.5	1980	1993
Synchrotron Radiation Source	Daresbury Laboratory	UK	2	96	1981	2008

Facility name	Location	Country	Energy (GeV)	Circumference (m)	Commissioned for synchrotron radiation studies	Decommissioned
DCI storage ring – LURE (Laboratoire pour l'Utilisation du Rayonnement Electromagnétique)	Orsay	France	1		1981	2006
National Synchrotron Light Source (NSLS)	Brookhaven National Laboratory	US	2.8	170	1982	2014
Photon Factory (PF) at KEK	Tsukuba	Japan	2.5	187	1982	
Super ACO-Laboratoire pour l'Utilisation du Rayonnement Electromagnétique (LURE)	Orsay	France	0.8		1987	2006
ASTRID	Aarhus University	Denmark	0.58	40	1991	2012
ASTRID 2	Aarhus University	Denmark	0.58	45.7	2013	
National Synchrotron Radiation Laboratory (NSRL)	University of Science and Technology China, Hefei	China	0.8	66.13	1991	
Beijing Synchrotron Radiation Facility (BSRF)	Institute of High Energy Physics, Chinese Academy of Sciences, Beijing	China	2.5		1991	
European Synchrotron Radiation Facility (ESRF)	Grenoble	France	6	844	1992	2019
European Synchrotron Radiation Facility – Extremely Brilliant Source (ESRF-EBS)	Grenoble	France	6	844	2020	
Advanced Light Source (ALS)	Lawrence Berkeley Laboratory	US	1.9	196.8	1993	
ELETTRA	Trieste	Italy	2-2.4	260	1993	

Facility name	Location	Country	Energy (GeV)	Circumference (m)	Commissioned for synchrotron radiation studies	Decommissioned
Advanced Photon Source (APS)	Argonne National Laboratory, Argonne, IL	US	7.0	1104	1995	
Kurchatov Synchrotron Radiation Source (SIBIR-1, SIBIR-2)	Kurchatov Institute, Moscow	Russia	2.5	124	1999	
LNLS	CNPEM in Campinas, São Paulo	Brazil	1.37	93.2	1997	
SPring-8	RIKEN	Japan	8	1436	1997	
MAX-I	MAX-lab	Sweden	0.55	30	1986	2015
MAX-II	MAX-lab	Sweden	1.5	90	1997	2015
MAX-III	MAX-lab	Sweden	0.7	36	2008	2015
MAX IV 1.5 GeV Storage Ring	MAX IV	Sweden	1.5	96	2016	
MAX IV 3 GeV Storage Ring	MAX IV	Sweden	3	528	2016	
BESSY II	Helmholtz-Zentrum Berlin in Berlin	Germany	1.7	240	1998	
Indus 1	Raja Ramanna Centre for Advanced Technology, Indore	India	0.45	18.96	1999	
DAFNE light	Istituto Nazionale di Fisica Nucleare, Frascati	Italy	0.51	32	1999	
Karlsruhe Research Accelerator (KARA)	Karlsruhe Institute of Technology	Germany	2.5	110.4	2000	
Swiss Light Source	Paul Scherrer Institute	Switzerland	2.4	288	2001	
SwissFEL	Paul Scherrer Institute	Switzerland			2018	
Canadian Light Source	University of Saskatchewan	Canada	2.9	171	2004	
Synchrotron Light Research Institute [th] (SLRI)	Nakhon Ratchasima	Thailand	1.2	81.4	2004	

Facility name	Location	Country	Energy (GeV)	Circumference (m)	Commissioned for synchrotron radiation studies	Decommissioned
Indus 2	Raja Ramanna Centre for Advanced Technology, Indore	India	2.5	173	2005	
Australian Synchrotron	Melbourne	Australia	3	216	2006	
SOLEIL	Saint-Aubin, Essonne	France	2.75	354	2006	
Diamond Light Source	Rutherford Appleton Laboratory	UK	3	561.6	2006	
Shanghai Synchrotron Radiation Facility (SSRF)	Shanghai	China	3.5	432	2007	
Taiwan Light Source	National Synchrotron Radiation Research Center, Hsinchu Science Park	R.O.C. (Taiwan)	1.5	120	1993	
Taiwan Photon Source	National Synchrotron Radiation Research Center, Hsinchu Science Park	R.O.C (Taiwan)	3	518.4	2015	
Metrology Light Source [de] (MLS)	Berlin	Germany[1]	0.6	48	2008	
Beijing Electron–Positron Collider II (BEPC II)	Institute of High Energy Physics, Chinese Academy of Sciences, Beijing	China	3.7	240	2008	
ALBA	Barcelona Synchrotron Park, Cerdanyola del Vallès near Barcelona	Spain	3	270	2010	
Sirius	CNPEM in Campinas, São Paulo	Brazil	3	518.2	2018	
Synchrotron-Light for Experimental Science and Applications in the Middle East (SESAME)	Al Balqa	Jordan	2.5	133	2016	
Iranian Light Source Facility (ILSF)	Qazvin	Iran	3	489.6	Under Design	

Facility name	Location	Country	Energy (GeV)	Circumference (m)	Commissioned for synchrotron radiation studies	Decommissioned
Center for Advanced Microstructures and Devices (CAMD)	LSU, Louisiana	US	1.5			
Pohang Light Source II [ko]	Pohang University of Science and Technology	South Korea	3.0	281.82	2011	
CANDLE	Yerevan	Armenia			proposed	
Centre Laser Infrarouge d'Orsay (CLIO)	Laboratoire de Chimie Physique (LCP), Orsay	France	0.04		1991	
DELTA	Dortmund University of Technology	Germany	1.5	115.2	1999	
Hiroshima Synchrotron Radiation Center (HSRC)	Hiroshima University, Hiroshima	Japan	0.7	22	1997	
Institute of Free Electron Laser (iFEL)	Osaka University, Osaka	Japan				
IR FEL Research Center (FELSUT)	Tokyo University of Science	Japan				
Medical Synchrotron Radiation Facility	National Institute of Radiological Sciences, Inage-ku, Chiba	Japan				
Nagoya University Small Synchrotron Radiation Facility (NSSR)	Nagoya University	Japan				
Photonics Research Institute	Tsukuba Science City	Japan				
Saga Light Source (SAGA-LS)	Tosu, Saga	Japan				
Ultraviolet Synchrotron Orbital Radiation Facility (UVSOR)	National Institutes of Natural Sciences, Okazaki	Japan				
VSX Light Source	University of Tokyo	Japan				

Facility name	Location	Country	Energy (GeV)	Circumference (m)	Commissioned for synchrotron radiation studies	Decommissioned
Free Electron Laser for Infrared eXperiments (FELIX)	Radboud University, Nijmegen	Netherlands	0.015–0.060		1991	
Dubna Electron Synchrotron (DELSY)	JINR, Dubna	Russia				
Siberian Synchrotron Radiation Centre (SSRC)	Budker Institute of Nuclear Physics, Novosibirsk	Russia	2 - 6[2]	366[3]	1973[2]	
Technical Storage Ring Complex (TNK)	F.V Lukin Institute, Zelenograd, Moscow[4]	Russia	0.45 - 2.2[4]			
Singapore Synchrotron Light Source (SSLS)	National University of Singapore	Singapore	0.7	10.8	2000	
Solaris (synchrotron)	Kraków	Poland	1.5	96	2016	
UCSB Center for Terahertz Science and Technology (CTST)	University of California, Santa Barbara, Santa Barbara, California	US				
Duke Free Electron Laser Laboratory (DFELL)	Duke University, Durham, North Carolina	US	0.2 - 1.2	107.46	1994	
Jefferson Laboratory Free Electron Laser (Jlab)	Thomas Jefferson National Accelerator Facility, Newport News, Virginia	US				
W. M. Keck Vanderbilt Free-electron Laser Center	Vanderbilt University, Nashville, Tennessee	US				
The African Light Source (AfLS)					Conceptual stage	