CFNS Summer School 2021
Accelerator Physics for EIC

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U.S. DEPARTMENT OF ENERGY | Stanford University

SLAC NATIONAL ACCELERATOR LABORATORY

Content

- **Introduction and accelerator fundamental**
  - Overview of US EIC current design
  - Accelerator physics fundamentals
- **Collider accelerator physics**
  - Luminosity, beam-beam effect
- **Spin dynamics**
  - Spin dynamics in circular accelerators
- **Synchrotron radiation and its applications**

History

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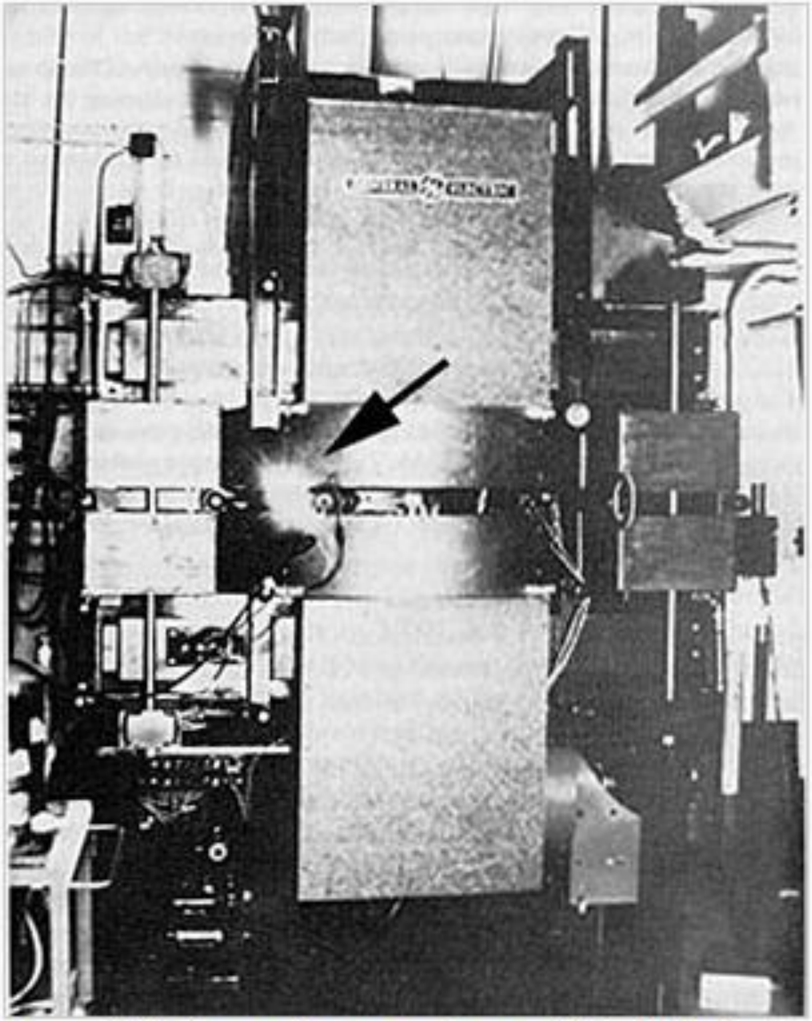
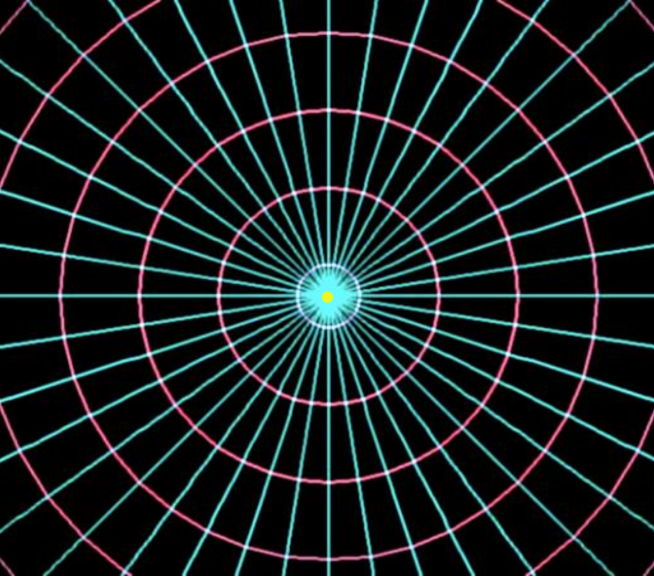
Was first observed in a synchroton in 1947 by Frank Elder, Anatole Gurewitsch, Rober Langmuir and Herb Pollok. The synchrotron belonged to GE and was built in 1946 in New York State.

Initially, this was considered a problem due to the fact this makes the acceleration less efficient

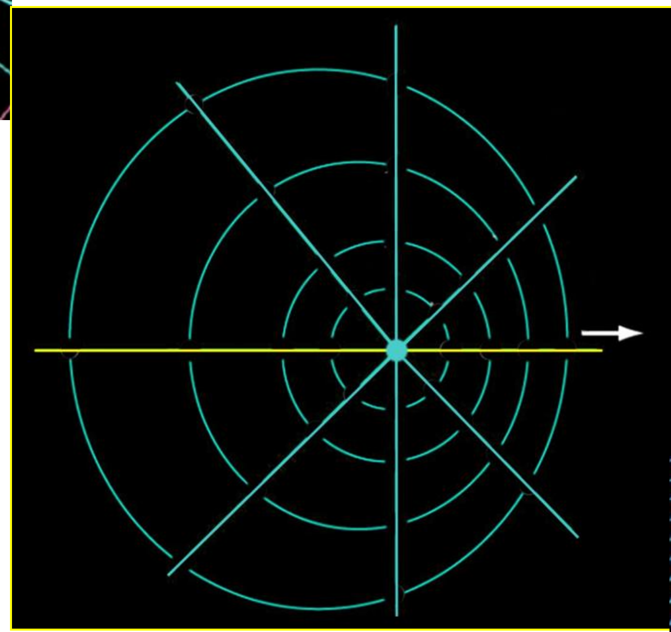


General Electric synchrotron accelerator built in 1946, the origin of the discovery of synchrotron radiation. The arrow indicates the evidence of radiation.

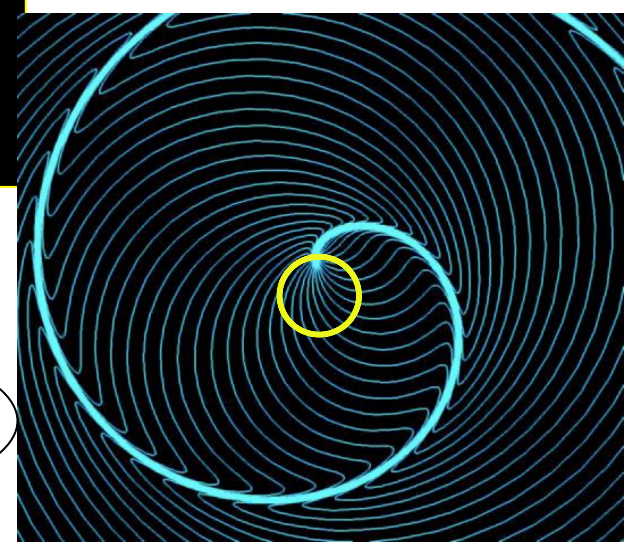


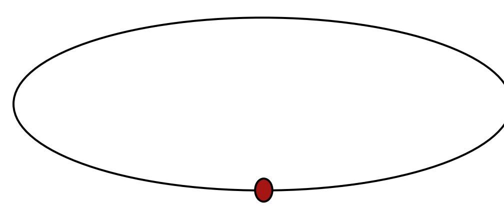
Static charge

Moving charge w constant speed



Moving charge in a
Circular motion





History

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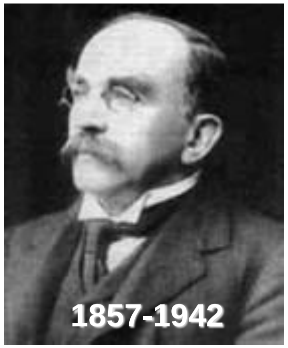


- in **1897 Joseph Larmor** derived the expression for the instantaneous total power radiated by an accelerated charged particle.

$$P = \frac{q^2}{6\pi\varepsilon_0 c^3} a^2$$

Larmor Power

1898 Liénard:

ELECTRIC AND MAGNETIC FIELDS PRODUCED BY A POINT CHARGE MOVING ON AN ARBITRARY PATH

(by means of retarded potentials)


L'Éclairage Électrique

REVUE HEBDOMADAIRE D'ÉLECTRICITÉ

CHAMP ÉLECTRIQUE ET MAGNÉTIQUE

- and in **1898 Alfred Lienard** (before the relativity theory!) extended Larmor's result to the case of a relativistic particle undergoing centripetal acceleration in a circular trajectory

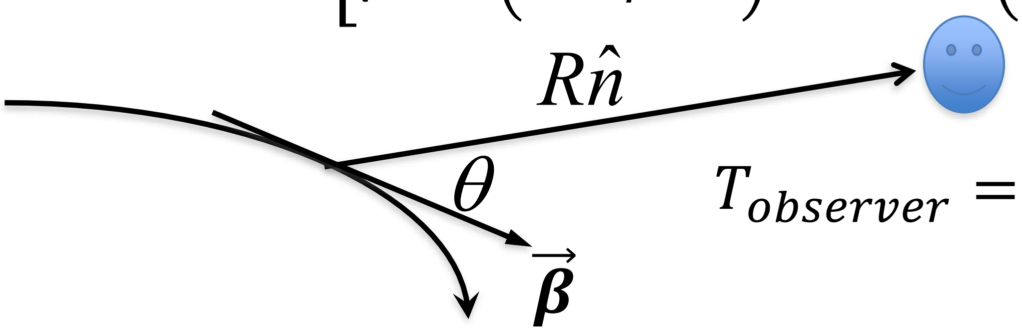
Radiation of a Moving particle

Lienard-Wiechert field

$$\vec{B}(\vec{r},t) = -\frac{\mu_0 q}{4\pi}\left[\frac{c\vec{\beta}\times\hat{n}}{\gamma^2 R^2\left(1-\vec{\beta}\cdot\hat{n}\right)^3} + \frac{\hat{n}\times\left[\hat{n}\times\left[\left(\hat{n}-\vec{\beta}\right)\times\dot{\vec{\beta}}\right]\right]}{R\left(1-\vec{\beta}\cdot\hat{n}\right)^3}\right]$$

$$\vec{E}(\vec{r},t) = \frac{q}{4\pi\epsilon_0}\left[\frac{\hat{n}-\vec{\beta}}{\gamma^2 R^2\left(1-\vec{\beta}\cdot\hat{n}\right)^3} + \frac{\hat{n}\times\left(\left[\hat{n}-\vec{\beta}\right]\times\dot{\vec{\beta}}\right)}{cR\left(1-\vec{\beta}\cdot\hat{n}\right)^3}\right]$$

where



$$T_{observer} = \left(1-\hat{n}\cdot\vec{\beta}\right)T_{source}$$

Radiation of a Moving particle

Poynting's vector of L-W field

$$\vec{s}\cdot\hat{n} = \vec{E}\times\vec{B} = \frac{q^2}{16\pi^2\epsilon_0 c}\left[\frac{1}{R^2}\left|\frac{\hat{n}\times\left(\hat{n}-\vec{\beta}\right)\times\dot{\vec{\beta}}}{\left(1-\vec{\beta}\cdot\hat{n}\right)^3}\right|^2\right]$$

Energy radiated into per solid angle

$$\frac{dP}{d\Omega} = R(t')^2[\vec{s}(t')\cdot\hat{n}(t')]\frac{dt}{dt'} = R(t')^2[\vec{s}(t')\cdot\hat{n}(t')]\left[1-\vec{\beta}(t')\cdot\hat{n}(t')\right]$$

$$= \frac{q^2}{16\pi^2\epsilon_0 c}\left[\frac{\left|\hat{n}(t')\times\left(\hat{n}(t')-\vec{\beta}(t')\right)\times\dot{\vec{\beta}}\right|^2}{\left(1-\vec{\beta}(t')\cdot\hat{n}(t')\right)^5}\right]$$

Energy radiated into per solid angle,

Larmor's formula

Power of the radiation

$$P = \frac{q^2}{6\pi^2 \epsilon_0 c} \gamma^6 \left[\left| \dot{\vec{\beta}} \right|^2 - \left| \vec{\beta} \times \dot{\vec{\beta}} \right|^2 \right]$$

$$\because \dot{\vec{\beta}} = \overrightarrow{\dot{\beta}_\parallel} + \overrightarrow{\dot{\beta}_\perp}$$

$$P_\parallel = \frac{q^2}{6\pi^2 \epsilon_0 c} \gamma^6 \left| \overrightarrow{\dot{\beta}_\parallel} \right|^2, \text{ and } P_\perp = \frac{q^2}{6\pi^2 \epsilon_0 c} \gamma^4 \left| \overrightarrow{\dot{\beta}_\perp} \right|^2$$

For synchrotron, the radiation power is

$$P = \frac{q^2}{6\pi^2 \epsilon_0 c} \gamma^4 \left| \dot{\vec{\beta}} \right|^2 \text{ or } P = \frac{q^2 c}{6\pi \epsilon_0} \frac{(\beta\gamma)^4}{\rho^2}$$

- goes with beam energy to the power of 4th and bending radius of power of 2

Energy Loss due to Synchrotron Radiation

For a dipole

$$U_0 = \frac{4\pi r_e}{3(m_0c^2)^3}\frac{E_0^4}{\rho} = C_\gamma \frac{E_0^4}{\rho}$$

Energy loss per turn

$U_0 = \oint P_{sR} dt$, where $P_{SR} = \frac{2cr_e}{3(mc^2)^3}\frac{E^4}{\rho^4}$ and $r_e = \frac{q^2}{4\pi\epsilon_0 mc^2}$

And the average power is

$\langle P_{SR}\rangle = \frac{U_0}{T_0} = \frac{4\pi c r_e}{3(m_0c^2)^3}\frac{E_0^4}{\rho L}$ where L is the ring circumference

Synchrotron Radiation Spectrum

Radiation is emitted in a cone of angle $\frac{1}{\gamma}$

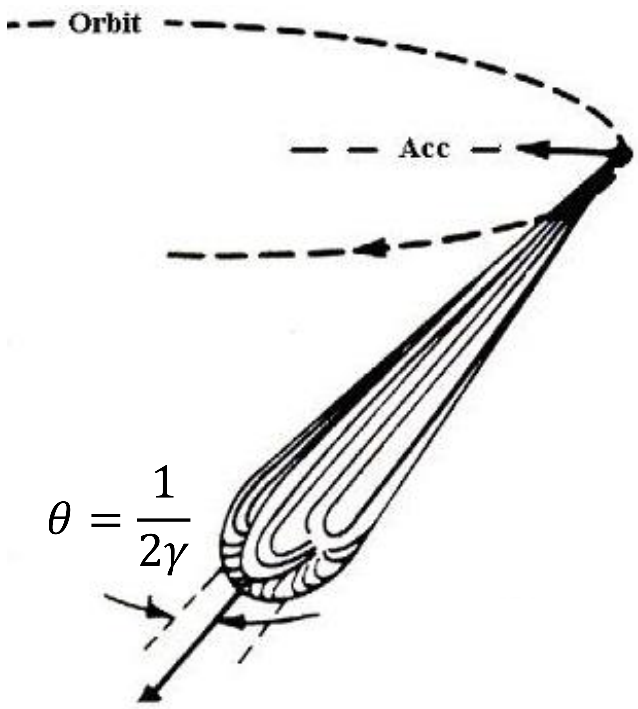
Retarded time period is $\Delta t_{ret} \approx \frac{\rho}{\gamma c}$

Time period by observer is

$$\Delta t_{obs} = \Delta t_{ret} \frac{dt_{obs}}{dt_{ret}} = \frac{1}{\gamma^2} \Delta t_{ret}$$

And the frequency

$$\omega = \frac{1}{\Delta t_{obs}} = \frac{\gamma^3 c}{\rho}$$



Synchrotron Radiation Spectrum

Radiation density is

$$\frac{d^3 I}{d\Omega d\omega} = \frac{e^2}{16\pi^3 \varepsilon_0 c}\left(\frac{2\omega\rho}{3c\gamma^2}\right)^2 \left(1+\gamma^2\theta^2\right)^2 \left[K_{2/3}^2(\xi) + \frac{\gamma^2\theta^2}{1+\gamma^2\theta^2} K_{1/3}^2(\xi)\right]$$

Where

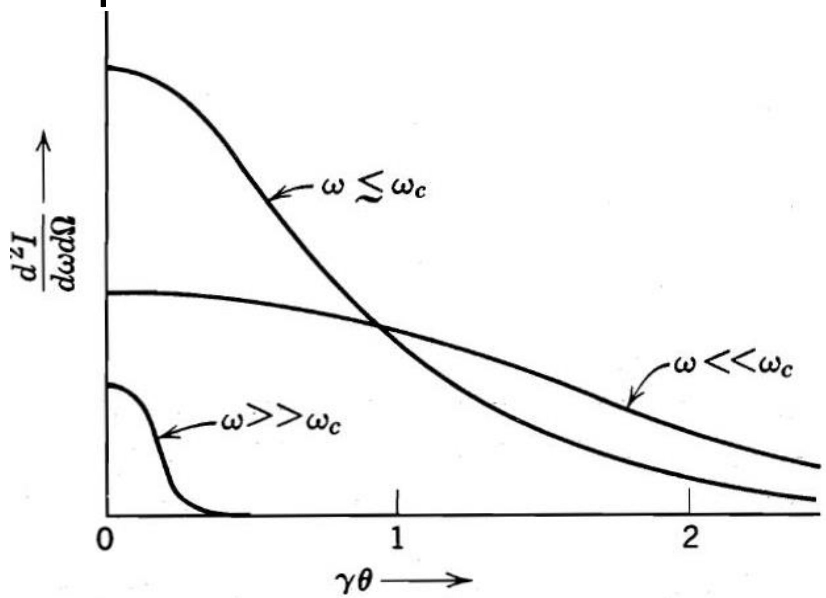
$$\xi = \left(\frac{\omega\rho}{3c\gamma^3}\right)\left(1+\gamma^2\theta^2\right)^{\frac{2}{3}}$$

Critical frequency: when $\xi \geq 1$, radiation power becomes negligible, i.e

$$\omega_c = \frac{3}{2}\frac{c}{\rho}\gamma^3 \approx \omega_{rev}\gamma^3$$

Critical angle

$$\theta_c = \frac{1}{\gamma}\left(\frac{\omega_c}{\omega}\right)^{1/3}$$



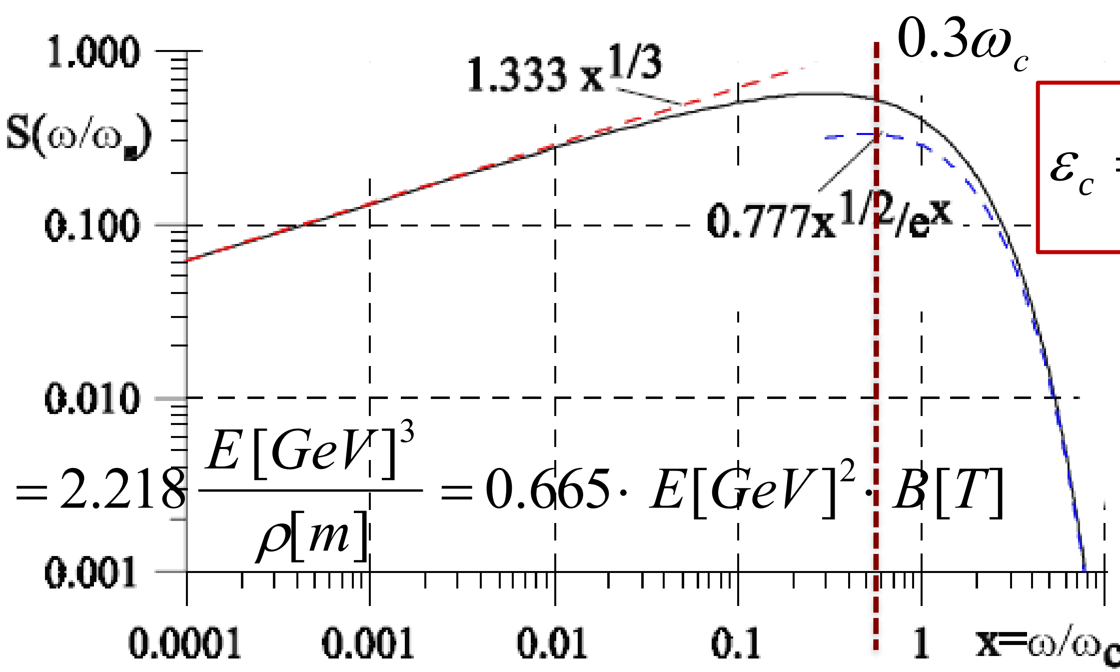
Synchrotron Radiation Spectral Density

Spectral density

$$\frac{dI}{d\omega} = \iint_{4\pi} \frac{d^3 I}{d\omega\, d\Omega} d\Omega = \frac{\sqrt{3} e^2}{4\pi\varepsilon_0 c} \gamma \frac{\omega}{\omega_C} \int_{\omega/\omega_C}^{\infty} K_{5/3}(x) dx$$

$$\frac{dI}{d\omega} \approx \frac{e^2}{4\pi\varepsilon_0 c} \left(\frac{\omega\rho}{c}\right)^{1/3} \qquad \omega \ll \omega_c$$

$$\frac{dI}{d\omega} \approx \sqrt{\frac{3\pi}{2}} \frac{e^2}{4\pi\varepsilon_0 c} \gamma \left(\frac{\omega}{\omega_c}\right)^{1/2} e^{-\omega/\omega_c} \qquad \omega \gg \omega_c$$



$$\varepsilon_c = \hbar\omega_c = \frac{3}{2} \frac{\hbar c}{\rho} \gamma^3$$

$$\varepsilon_{c,electron}[keV] = 2.218 \frac{E[GeV]^3}{\rho[m]} = 0.665 \cdot E[GeV]^2 \cdot B[T]$$

Energy Loss due to Synchrotron Radiation

Energy Loss per turn (per particle)

$$U_{o,electron}(keV) = \frac{e^2\gamma^4}{3\varepsilon_0\rho} = 88.46\frac{E(GeV)^4}{\rho(m)}$$

$$U_{o,proton}(keV) = \frac{e^2\gamma^4}{3\varepsilon_0\rho} = 6.03\frac{E(TeV)^4}{\rho(m)}$$

Power radiated by a beam of average current I_b: to be restored by RF system

$$N_{tot} = \frac{I_b \cdot T_{rev}}{e}$$

$$P_{electron}(kW) = \frac{e\gamma^4}{3\varepsilon_0\rho} I_b = 88.46\frac{E(GeV)^4 I(A)}{\rho(m)}$$

$$P_{proton}(kW) = \frac{e\gamma^4}{3\varepsilon_0\rho} I_b = 6.03\frac{E(TeV)^4 I(A)}{\rho(m)}$$

Power radiated by a beam of average current I_b in a dipole of length L (energy loss per second)

$$P_e(kW) = \frac{e\gamma^4}{6\pi\varepsilon_0\rho^2} L I_b = 14.08\frac{L(m)I(A)E(GeV)^4}{\rho(m)^2}$$

of photons emitted

Since the energy lost per turn is

$$U_0 \sim \frac{e^2\gamma^4}{\rho}$$

And average energy per photon is the

$$\langle \varepsilon_\gamma \rangle \approx \frac{1}{3}\varepsilon_c = \frac{\hbar\omega_c}{3} = \frac{1}{2}\frac{\hbar c}{\rho}\gamma^3$$

The average number of photons emitted per revolution is

$$\langle n_\gamma \rangle \sim \gamma$$

Synchrotron Radiation between facilities

		LEP200	LHC	SSC	HERA	VLHC
Beam particle		e+ e-	p	p	p	p
Circumference	km	26.7	26.7	82.9	6.45	95
Beam energy	TeV	0.1	7	20	0.82	50
Beam current	A	0.006	0.54	0.072	0.05	0.125
Critical energy of SR	eV	$7\ 10^{5}$	44	284	0.34	3000
SR power (total)	kW	$1.7\ 10^{4}$	7.5	8.8	$3\ 10^{-4}$	800
Linear power density	W/m	882	0.22	0.14	$8\ 10^{-5}$	4
Desorbing photons	$s^{-1}\ m^{-1}$	$2.4\ 10^{16}$	$1\ 10^{17}$	$6.6\ 10^{15}$	none	$3\ 10^{16}$

Synchrotron Radiation Effect on Beam Dynamics

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Energy loss due to synchrotron radiation

$$U_o = C_\gamma \frac{E^4}{\rho(m)}; \quad C_\gamma = \frac{4\pi r_0}{3\left(m_0 c^2\right)^3}$$

RF system needs to restore the lost energy per turn

$$\Delta E = U_0 = eV_0 \sin(\varphi_s)$$

Longitudinal radiation damping

$$U = U_0 + w\Delta E \qquad \tau = \alpha_c T_0 \frac{\Delta E}{E} \Rightarrow \frac{d\tau}{dt} = \alpha_c \frac{\Delta E}{E}$$

$$\frac{d\Delta E}{dt} = \frac{eV(\tau) - U}{T_0} = \frac{eV_0 \sin\left(\omega_{rf}\tau + \varphi_s\right) - U}{T_0} = \frac{1}{T_0}\left(eV_0\omega_{rf}\cos\varphi_s - w\Delta E\right)$$

$$\tau'' + \frac{W}{T_0}\tau' - \boxed{\frac{\alpha_c e V_0 \omega_{rf} cos\varphi_s}{T_0 E}}\tau = 0 \Rightarrow \boxed{\tau(t) = Ae^{-\frac{w}{2T_0}t}\cos\left(\omega_s t - \chi\right)}$$

(boxed term $= \omega_s^2$)

Synchrotron Radiation Effect on Beam Dynamics

Damping time

$$\tau_s = \frac{2T_0}{w}; \qquad and \qquad w = \frac{dU}{dE}$$

$$U = \oint p_{sr} dt = \oint p_{sr}\left(1+\frac{x}{\rho}\right)ds = \oint p_{sr}\left(1+\frac{D}{\rho}\frac{\Delta E}{E}\right)ds; \qquad p_{sr} = \frac{cC_\gamma}{2\pi}\frac{E^4}{\rho^2}$$

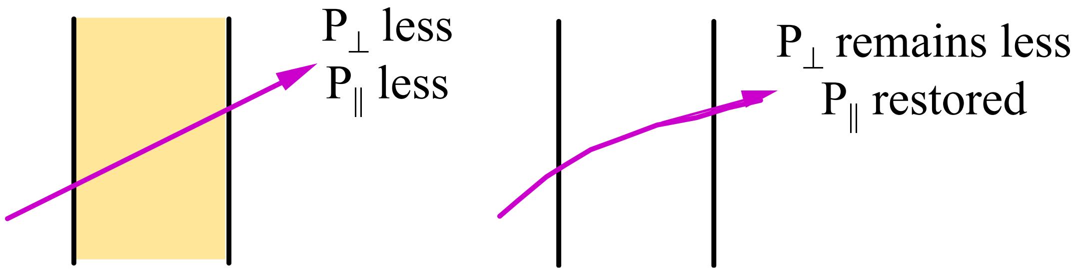
$$\frac{dU}{dE} = \frac{1}{c}\oint\left\{2\frac{p_{sr}}{E} + 2\frac{p_{sr}}{B}\frac{D}{E}\frac{dB}{dx} + \frac{p_{sr}}{E}\frac{D}{\rho}\right\}ds$$

$$= \frac{U_0}{E}\left[2 + \frac{1}{cU_0}\oint\left\{Dp_{sr}\left(\frac{1}{\rho}+\frac{2}{B}\frac{dB}{dx}\right)\right\}ds\right]$$

→ D

$$\tau_s = \frac{2T_0}{w} = \frac{2T_0 E}{U_0(2+\mathrm{D})}$$

Transverse Damping



Passage through dipoles

Acceleration in RF cavity

$$z = A\cos\phi; \quad z' = \frac{p_\perp}{p} = -\frac{A}{\beta}\sin\phi$$

$$z' \rightarrow z'\left(1 - \frac{\Delta E}{E}\right) \qquad \Delta z' = -z'\frac{\Delta E}{E}$$

$$A^2 = z^2 + (\beta z')^2 \qquad A\Delta A = \beta^2 z'\Delta z' = -(\beta z')^2\frac{U}{E}$$

$$\frac{1}{A}\frac{dA}{dt} = -\frac{U}{2ET}$$

Transverse damping time: $\tau_z = \dfrac{2ET}{U} = \dfrac{2E}{p_{sr}}$

Challenges of Electron Storage Rings

Figure of merit of a storage ring synchrotron radiation source

- Photon flux $\dot{N} = \int \dot{n}(\omega) d\omega = \frac{15\sqrt{3}}{8} \frac{P}{\hbar\omega_c}$

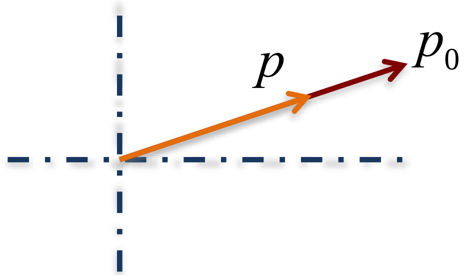
$$\dot{n}(\omega) = \frac{1}{\hbar\omega}\frac{dP}{d\omega} = \frac{P}{\omega\omega_c}\frac{9\sqrt{3}}{8\pi}\frac{\omega}{\omega_c}\int_{\frac{\omega}{\omega_c}}^{\infty} K_{5/3}(x)\,dx$$

- Critical frequency $w_c = \frac{3}{2}\frac{c}{r}g^3$
- Brightness
  - Brightness = Photons per sec per mm^2 per mrad^2 per BandWidth
  - The smaller beam emittance, the brighter the light
- Stability
  - Beam lifetime
  - Orbit stability

Small Emittance

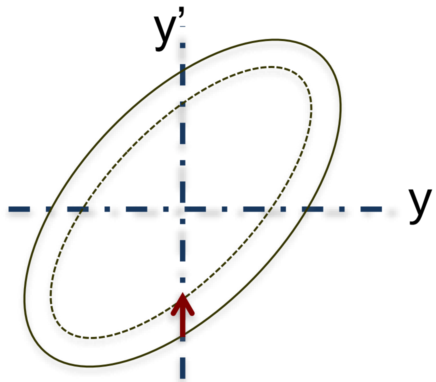
Beam emittance in an electron storage ring is determined by synchrotron radiation induced damping as well as quantum excitation

Synchrotron radiation damping



$$p_y \text{»} p_{y,0}(1 - \frac{dp}{p_0})$$

$$\frac{d\varepsilon_y}{dt} = -\varepsilon_y \oint \frac{dp}{p_0} / T_0 \approx -\frac{U_0}{E_0 T_0}\varepsilon_y$$



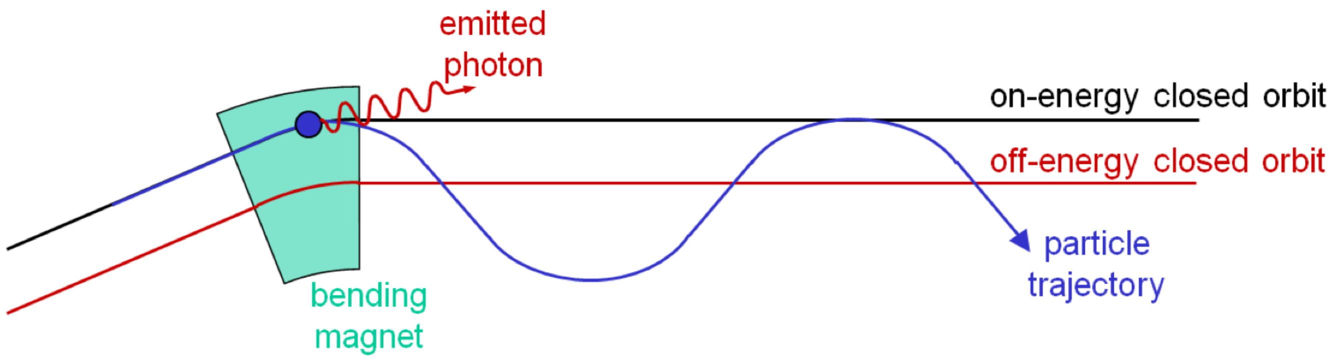
$U_0 = \oint P_\gamma \, dt = \frac{C_\gamma}{2\pi} E_0^4 \oint \frac{1}{\rho^2} ds$ is the energy loss per turn, and

$I_2 = \oint \frac{1}{\rho^2} ds$ is the second synchrotron radiation integral

Andy Wolski, Storage Ring Design

Horizontal Emittance

The energy loss due to the emitted photon excites a horizontal betatron oscillation around the closed orbit corresponding to its new energy, aka quantum excitation



As a combination of damping and quantum excitation

$$\frac{d\epsilon_x}{dt} = -\frac{2\epsilon_x}{\tau_x} + \frac{2}{j_x\tau_x} C_q \gamma^2 \frac{I_5}{I_2},\ C_q = \frac{55}{32\sqrt{3}}\frac{\hbar}{mc} \simeq 3.832x10^{-13}\text{m}$$

and $j_x = 1 - \frac{I_4}{I_2},\ I_4 = \oint \frac{\eta_x}{\rho}\left(\frac{1}{\rho^2} + 2\frac{\frac{\partial B_y}{\partial x}}{B\rho}\right) ds,\ I_5 = \oint \frac{H_x}{|\rho^3|} ds$, where

$$H_x = \gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta_{px} + \beta_x \eta_{px}^2$$

Natural Emittance

$$\frac{d\varepsilon_x}{dt} = -\frac{2\varepsilon_x}{\tau_x} + \frac{2}{j_x \tau_x} C_q \gamma^2 \frac{I_5}{I_2} = 0 \qquad \varepsilon_x = C_q \frac{\gamma^2}{j_x} \frac{I_5}{I_2}$$

$$I_5 = \oint \frac{H_x}{|\rho^3|} ds \qquad H_x = \gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta_{px} + \beta_x \eta_{px}^2$$

Minimize H function to obtain small natural emittance

- Lattice choices: FODO, DBA, TBA, MBA

Theoretical Minimum Emittance by minimizing I_5 w.r.t to dispersions and twiss parameters

$$\varepsilon_{TME} \approx \frac{1}{12\sqrt{15}} C_q \gamma^2 \theta^3$$

- This requires the dispersion reaches its minimum in the middle of the dipole. Not practical for light source

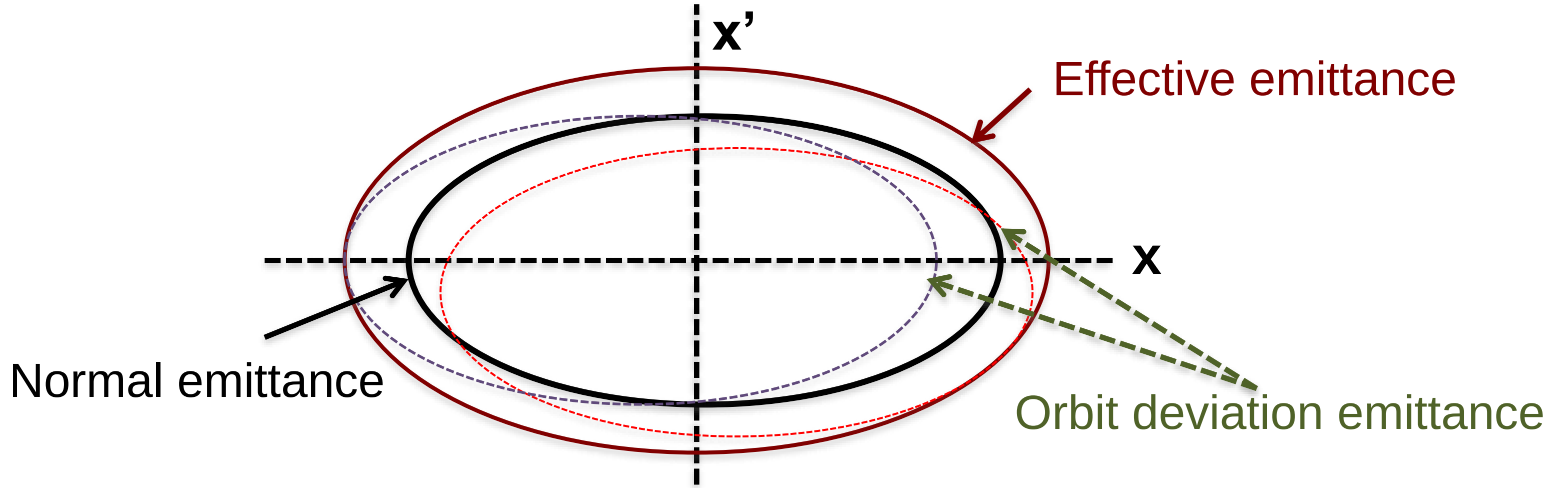
Andy Wolski, Storage Ring Design

Natural Emittance

Lattice	Minimum emittance	conditions
90o FODO	$\approx 2\sqrt{2}C_q\gamma^2\theta^3$	$\frac{f}{L} = \frac{1}{\sqrt{2}}$
137o FODO	$\approx 1.2C_q\gamma^2\theta^3$	Minimum for FODO
DBA	$\approx C_q\gamma^2 \frac{1}{4\sqrt{15}}\theta^3$	at end of dipole $\eta_{x,px} = 0$; $\beta_x \approx \sqrt{12/5}L$; $\alpha_x \approx \sqrt{15}$
TME	$\approx C_q\gamma^2 \frac{1}{12\sqrt{15}}\theta^3$	$\eta_{x,\min} \approx \frac{L\theta}{24}$; $\beta_{x,\min} \approx \frac{L}{2\sqrt{15}}$
MBA	$\approx C_q\gamma^2 \frac{1}{12\sqrt{15}}\left(\frac{M+1}{M-1}\right)\theta^3$	2 < M < infinity

Orbit Stability

Unstable closed orbit results in effective emittance growth

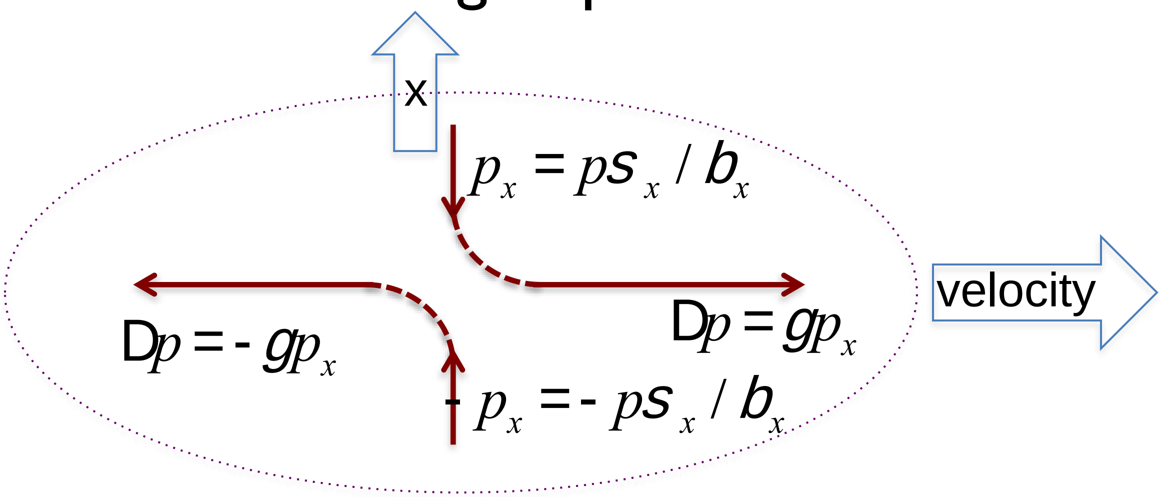


Many sources of orbit disturbance

- Ground motion
- Tidal motion
- power supply of steering magnets
- Etc.

Touschek Effect

large-angle coulomb scattering of particles in a bunch



can result in large longitudinal oscillations that exceed momentum acceptance or dynamic aperture of the machine

most dominant lifetime limitation for low electron storage rings with low emittance

Touschek Lifetime

Is given by

$$\frac{1}{\tau} = -\frac{1}{N}\frac{dN}{dt} = \frac{r_e^2 c N}{8\pi \sigma_x \sigma_y \sigma_z}\frac{1}{\gamma^2 |\delta|_{\max}^3} D(u); \quad u = \left(\frac{|\delta|_{\max} \beta_x}{\gamma \sigma_x}\right)^2$$

and $$D(u) = \sqrt{u}\left[-\frac{3}{2}e^{-u} + \frac{u}{2}\int_u^\infty \frac{\ln x}{x} e^{-x}\,dx + \frac{1}{2}\left(3u - u\ln u + 2\right)\int_u^\infty \frac{e^{-x}}{x}\,dx\right]$$

where $|\delta|_{\max}$ is the momentum acceptance.

Most dominant lifetime limitation for low electron storage rings with low emittance

Increase Touschek Lifetime

Careful choice of working point

Spring-8, M. Takao, et al,

EPAX 2000, 1569

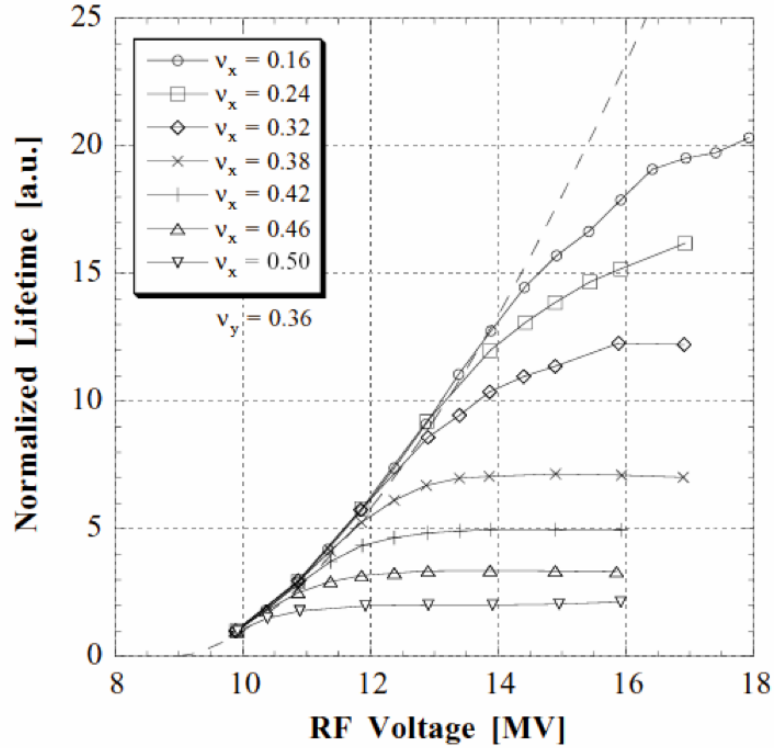


Figure 3: Normalized beam lifetime as a function of rf voltage with different operation points. The dashed line indicates the expected lifetime from the rf bucket height.

Increase Touschek Lifetime

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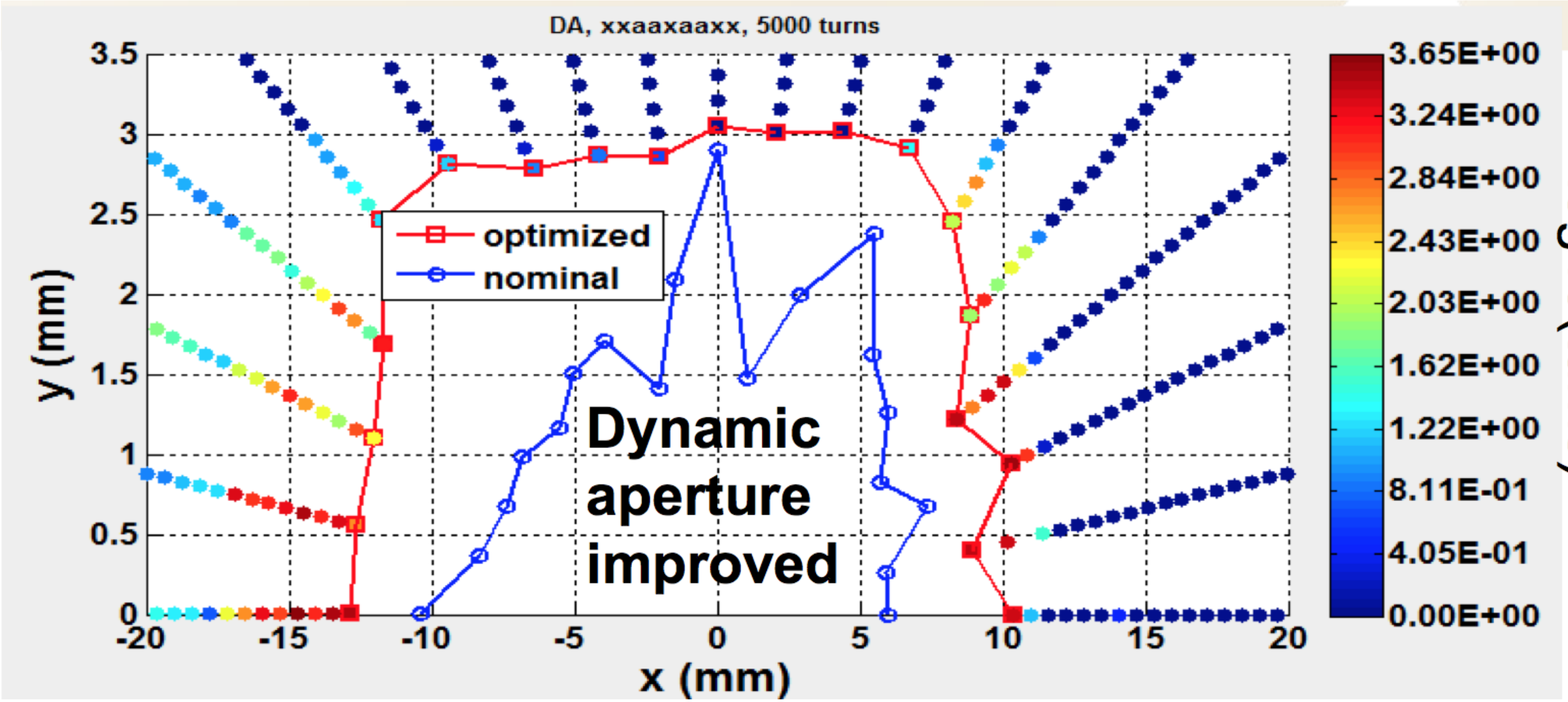
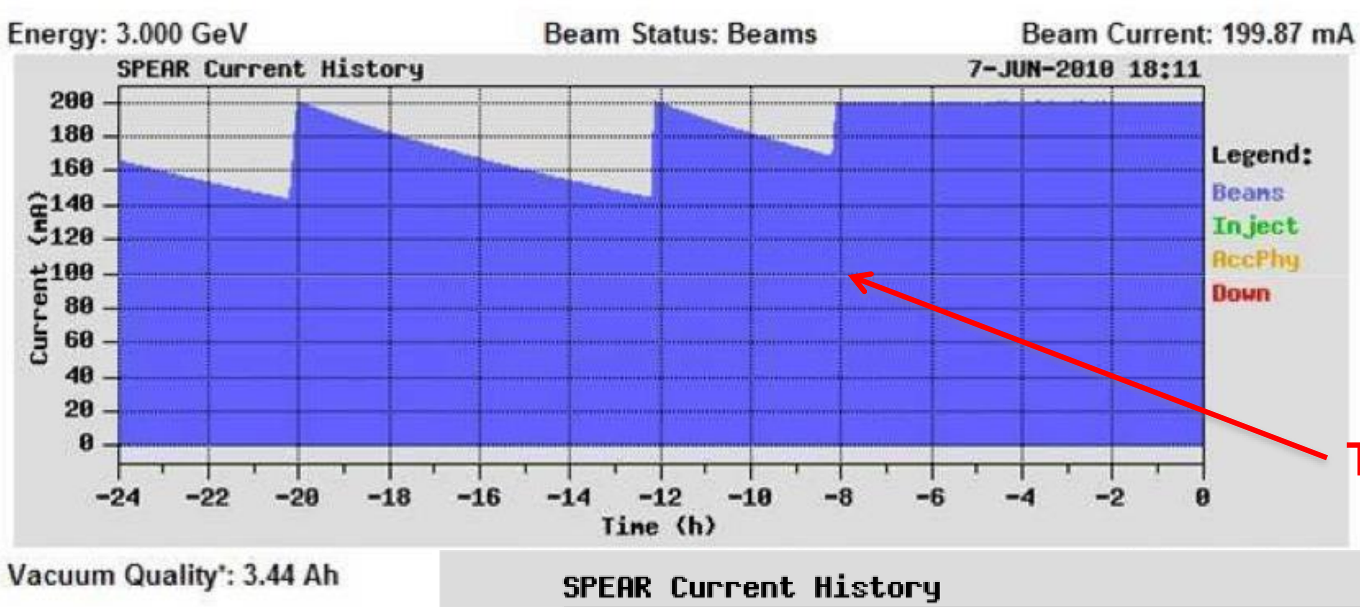
Improve dynamic aperture

- minimize non-linear driving terms of the lattice



Courtesy of J. Safranek

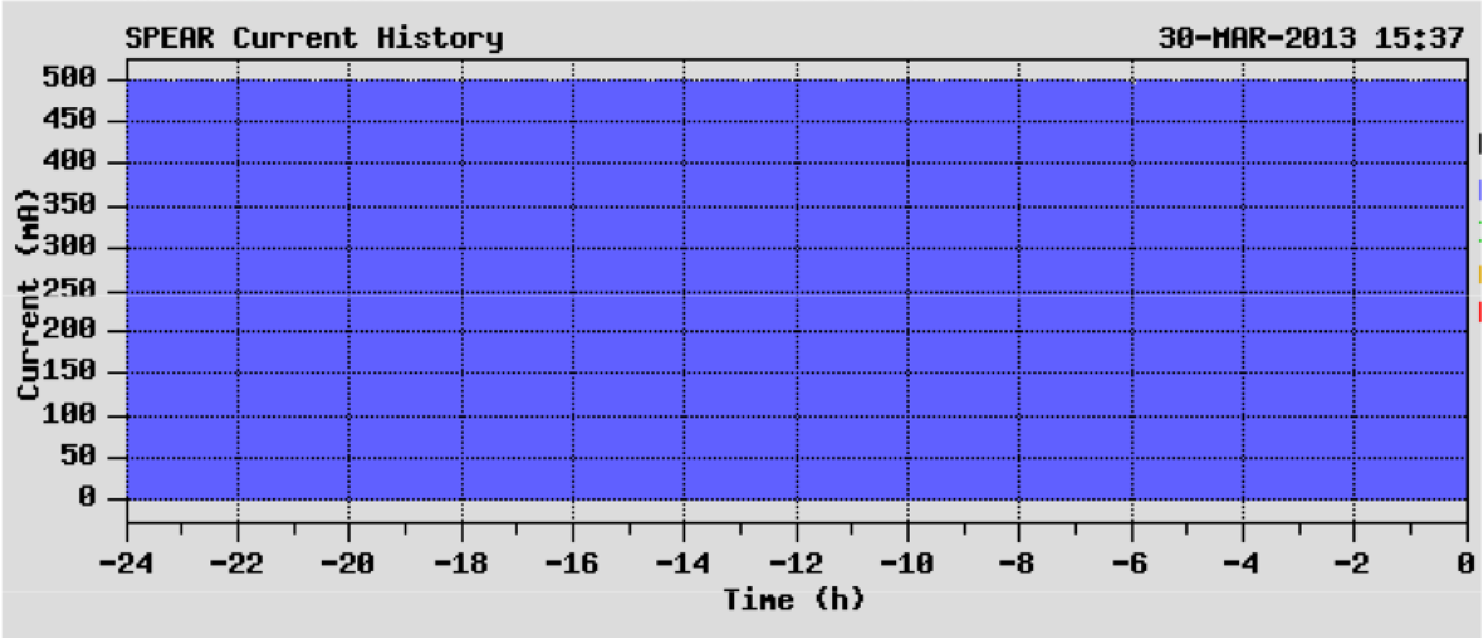
Mitigate Touschek Lifetime: Top-off Injection



SPEAR 3, SSRL

Top-off injection 10 mins

Top-off injection 5 mins, 500 mA beam current



History of Light Sources

- 1^{st} generation synchrotron radiation source
  - Between early 1960s and mid 1970s
  - Parasitic operation. Most machines were built for other applications including particle physics
  - Beam energy ranges from 180 MeV to 6 GeV
  - Radiation ranges from UV to x-rays
  - Brightness was compromised due to large beam emittance

1st Generation Synchrotron Radiation Sources

Year	Facility	Beam energy[GeV]	Radiation	Country
~1961	SURF (NBS)	0.18-0.25	UV	US
	Frascati Synchrotron	1.1	UV	Italy
1962	CEA (Saclay)	2-3	X-rays	France
~1965	SOR	0.75		Tokyo
	DESY	6	100 keV x-rays	Germany
1967	Tantalus (Wisconsin)	0.24		US
1971	ACO	0.54		Orsay
1974	SURF II (NBS)	0.24		US
	SOR	0.3(design for SR)		Japan
	SPEAR (SLAC)	2.5	1st X-ray beamline	US
1975s	VEPP-3 (INP)	2		Russia
	DCI (Orsay)	1.9		France
	DORIS (DESY)	4.5		Germany
	SPEAR (SLAC)	4.5		US
	CESR (CHESS)	6		US

History of Light Sources

SLAC

-2nd generation synchrotron radiation source

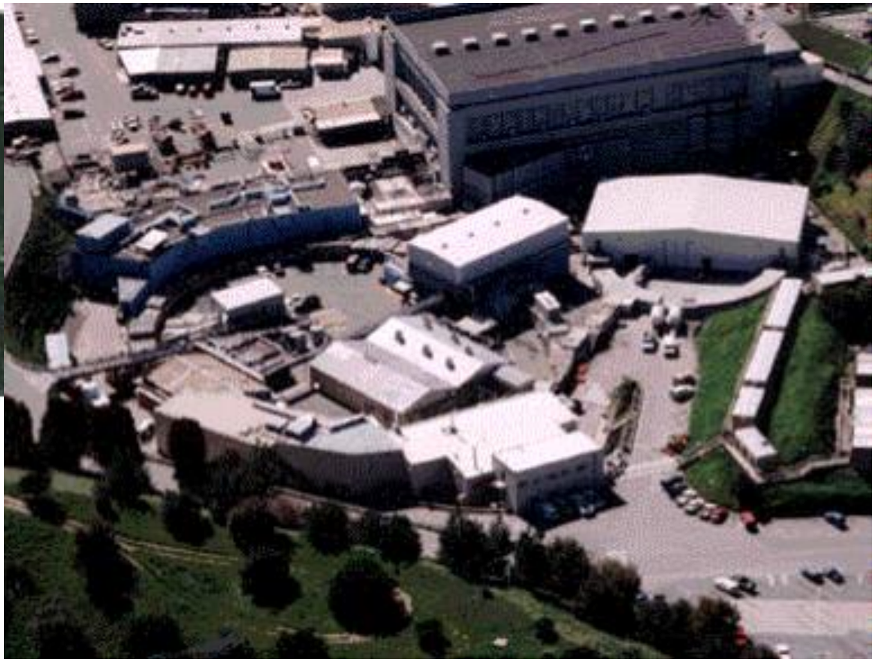
- Dedicated operation for synchrotron radiation

Year	Facility	Beam energy[GeV]	Radiation	Country
~1981	SRS	2		US
1982	VUV (NSLS)	0.7	UV	Italy
	BESSY (Berlin)	0.8	X-rays	France
	NSRL (Hefei)	0.8		Tokyo
1983	Photon Factory	2.5	100 keV x-rays	Japan
1984	NSLS x-ray	2.5		US
	SuperACO(LURE)	0.8		Orsay
1985	MAX-lab (Lund)	0.55		Sweden
	Aladdin (Wisconsin)	1		US
1990	SPEAR 2 (SSRL)	4.5	dedicated	US

2nd Generation Synchrotron Radiation Source

NSLS

SSRL (SPEAR 2)



BESSY, Berlin

NSRL (Hefei)

History of Light Sources

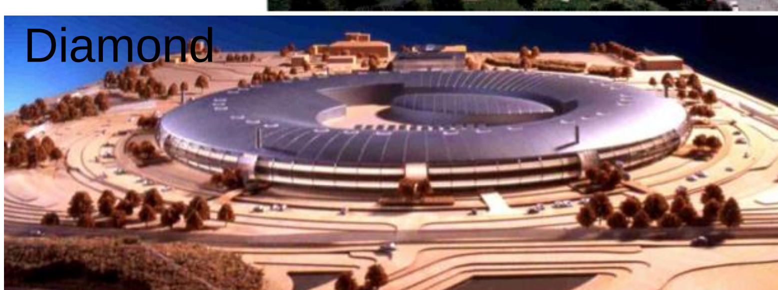
- 3^{rd} generation synchrotron radiation source
  - Dedicated operation
  - High brightness 10^{19} vs. 10^{16} for 2^{nd} generation
  - Low emittance 1-20 nm-rad
  - Insertion devices in addition to bending magnet radiations

ESRF

APS

SPEAR 3
at SSRL

Spring 8



Diamond

History of Undulators

1947: Ginzburg

1953: 1st mm-visible undulator built by Motz

1970s: started to be used in storage rings

1981: 1st permanent magnet undulator built by Halbach for SSRL

1987: ellipitical polarized undulator built at HASYLAB

1990: 6mm-gap undulator built at NSLS

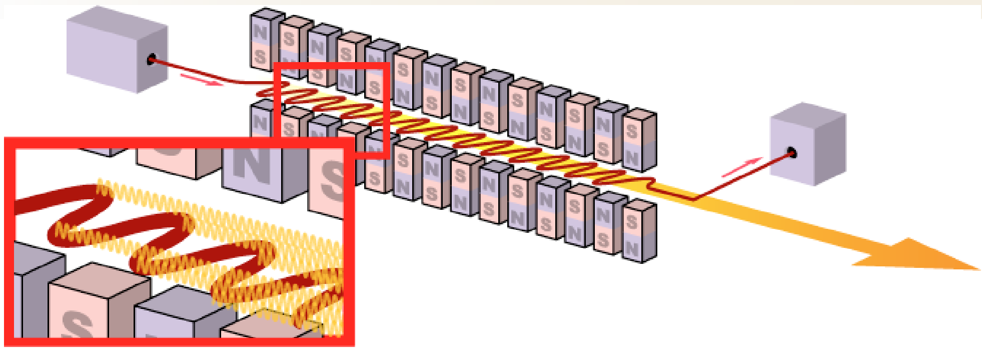
1991: in-vacuum undulator used in Photon Factory

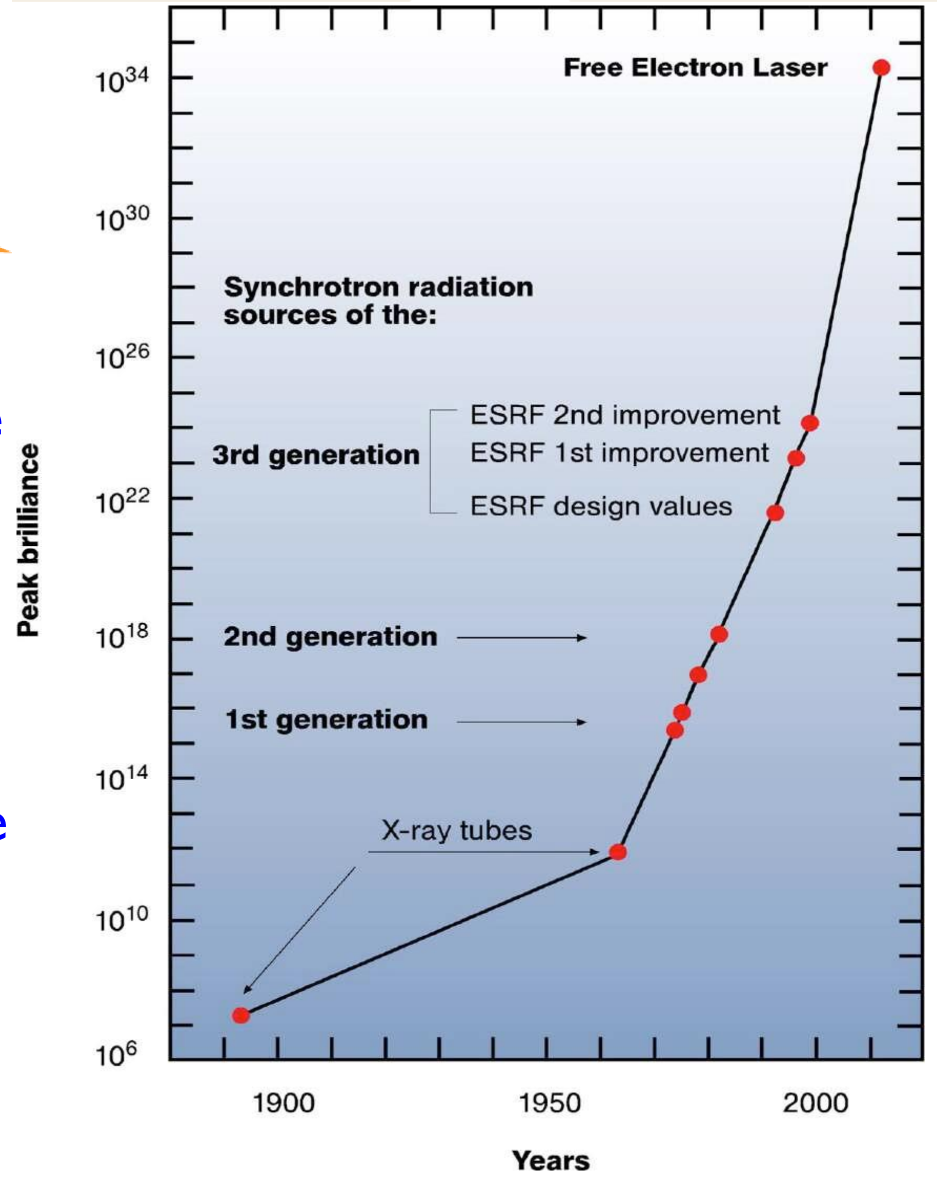
1993: adjustable phase undulator used in Stanford Synchrotron Radiation Lab

Klaus Halbach shown in 1986 with Kwang-Je Kim discussing a model of an undulator that Halbach designed

4th Generation: Free Electron Laser

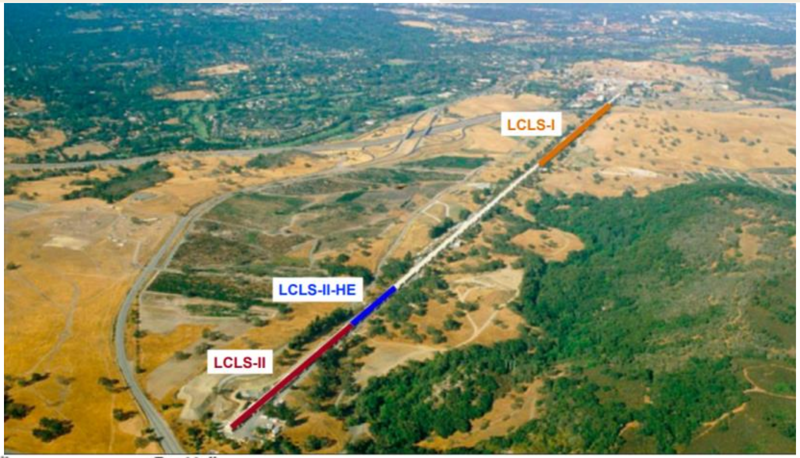
SLAC

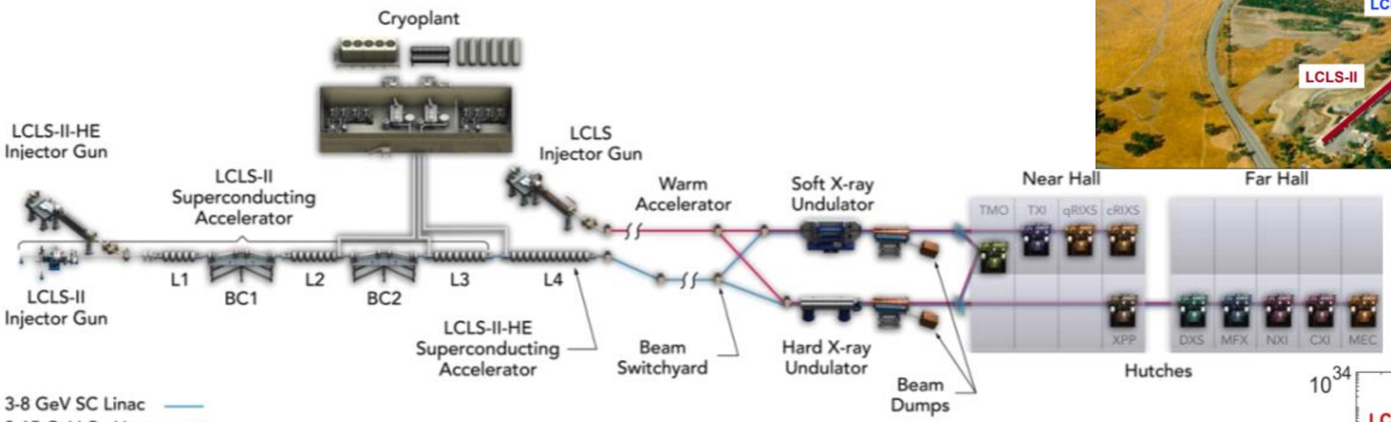


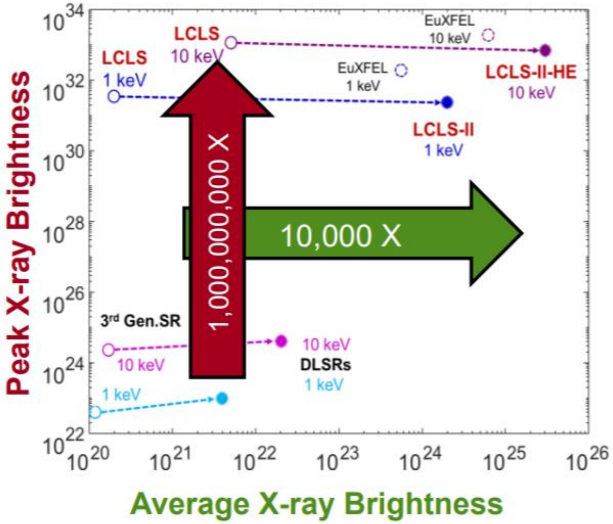


- Extremely bright light sources from the very-high-speed electrons free in an undulator
- Highly tunable from visible spectrum, UV up to x ray
- Extreme short pulse of light can also be obtained
- Example of facilities
  - FLASH, Hamburg, Germany
  - LCLS at SLAC, California, USA

LCLS, LCLS II and beyond







World-wide XFEL

	European XFEL	LCLS	LCLS-II, SCRF	SACLA	SwissFEL	PAL-XFEL	SHINE
Abbreviation for	European X-Ray Free-Electron Laser	Linac Coherent Light Source	Linac Coherent Light Source II	SPRing-8 Compact Free-Electron Laser	Swiss Free-Electron Laser	Pohang Accelerator Laboratory X-Ray Free-Electron Laser	Shanghai High Repetition Rate XFEL and Extreme Light Facility
Location	Germany	USA	USA	Japan	Switzerland	South Korea	China
Start of commissioning	2016	2009	2021	2011	2016	2016	2025
Accelerator technology	Super-conducting	Normal-conducting	Super-conducting	Normal-conducting	Normal-conducting	Normal-conducting	Super-conducting
Number of light flashes per second	27 000	120	1 000 000	60	100	60	1 000 000
Minimum wavelength of the laser	0.05 nm	0.15 nm	0.25 nm	0.08 nm	0.1 nm	0.06 nm	0.05 nm
Maximum electron energy	17.5 GeV	14.3 GeV	4 GeV	8.5 GeV	5.8 GeV	10 GeV	8 GeV
Length of the facility	3.4 km	3 km	3 km	0.75 km	0.74 km	1.1 km	3.1 km
Number of undulators	3	1		3	1	2	
Number of experment stations	6	5		4	3	3	
Peak brilliance	5×10^{33}	2×10^{33} ($2{,}75 \times 10^{34}$ with seeding)	1×10^{32}	1×10^{33}	1×10^{33}	1.3×10^{33}	1×10^{33}