FROM WASTE TO INDISPENSABILITY: THE RISE OF SYNCHROTRON LIGHT SOURCES

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MIT

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OUTLINE

- **Many Applications of Accelerators**
- **The Rise of Synchrotron Light Sources**
- **Next Generation Light Sources**
- **Applications of Light Sources**

MANY APPLICATIONS OF ACCELERATORS

Particle and Nuclear Physics

Jefferson Lab (Newport News, VA)

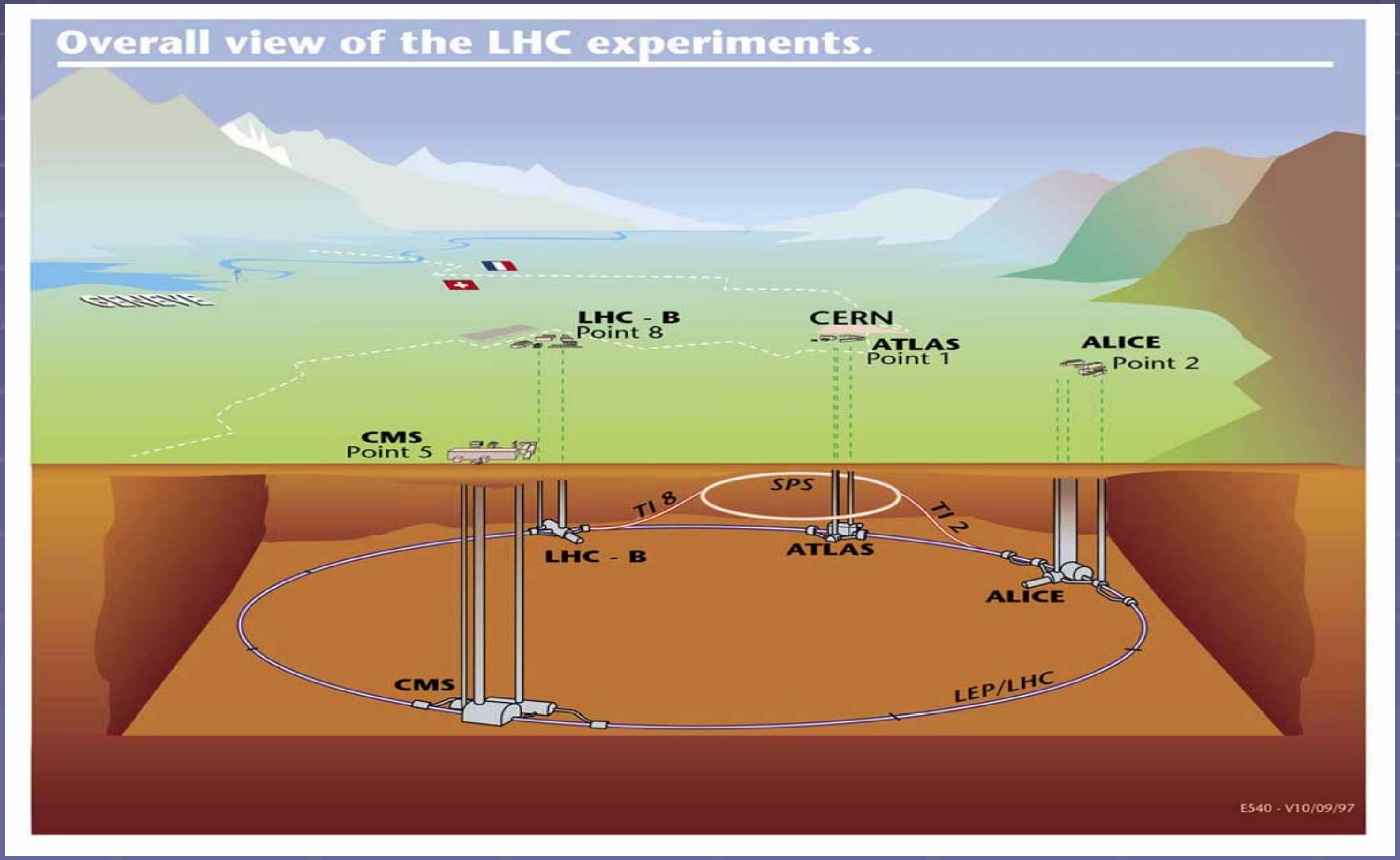
Fermilab (Batavia, IL)

SLAC (Palo Alto, CA)

Large Hadron Collider (Geneva, CH)

LARGE HADRON COLLIDER (LHC) @CERN

SCHEMATIC OF LHC EXPERIMENTS



FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor		Mass GeV/c^2	Electric charge
ν_e	electron neutrino	$<1\times10^{-8}$	0
e	electron	0.000511	−1
ν_μ	muon neutrino	<0.0002	0
μ	muon	0.106	−1
ν_τ	tau neutrino	<0.02	0
τ	tau	1.7771	−1

Quarks spin = 1/2

Flavor		Approx. Mass GeV/c^2	Electric charge
u	up	0.003	2/3
d	down	0.006	−1/3
c	charm	1.3	2/3
s	strange	0.1	−1/3
t	top	175	2/3
b	bottom	4.3	−1/3

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Medical Applications

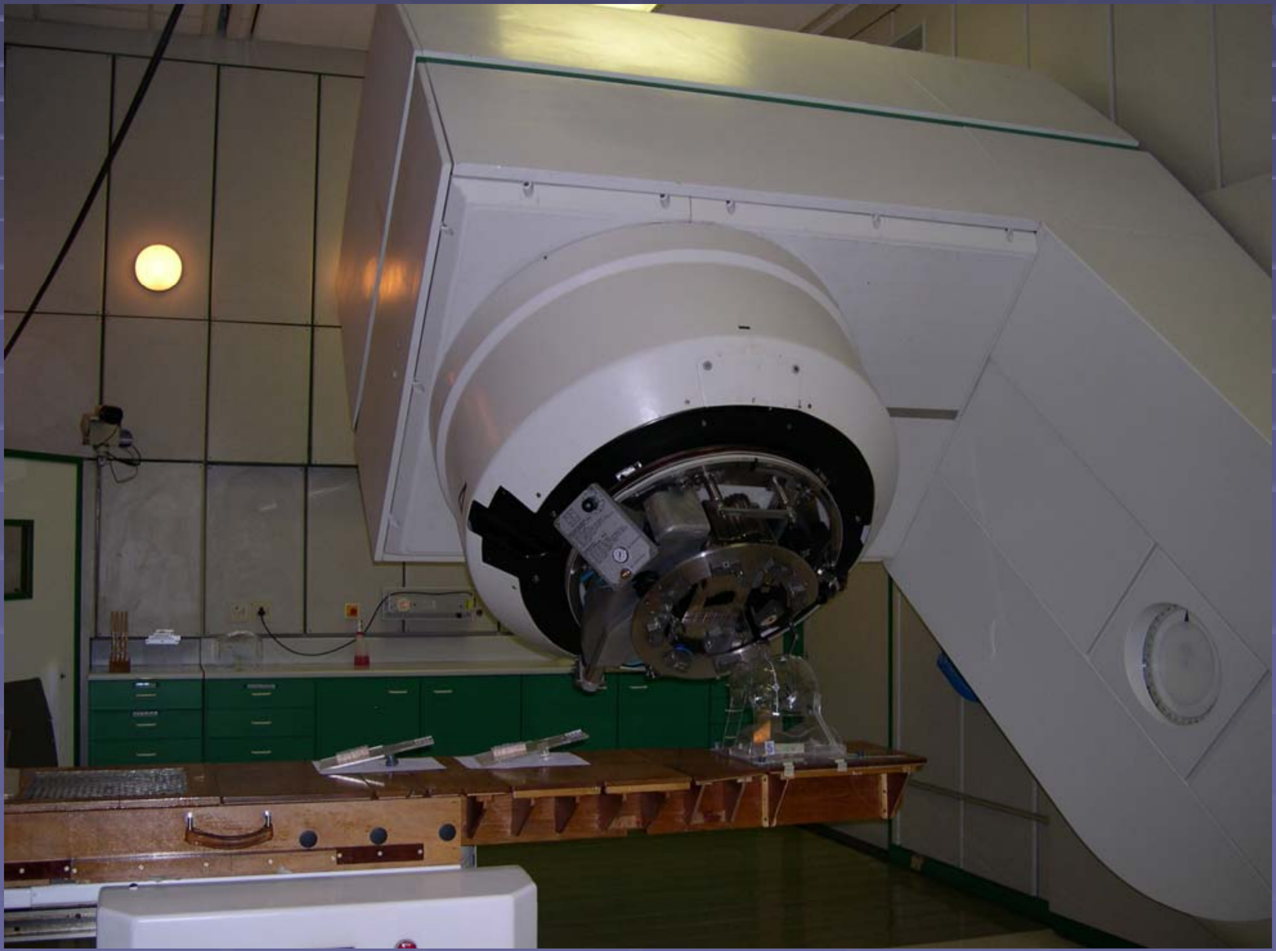
iThemba LABS

(National Accelerator Center)

Outside Cape Town, South Africa

SEGMENTED-SECTOR CYCLOTRON

NEUTRON THERAPY



NEUTRON THERAPY OPERATOR

Neutron Therapy Patients

(6 September 1988 - 30 September 2005)

Diagnosis	Number of Patients
Salivary gland carcinoma	466
Head and neck carcinoma	241
Breast cancers	189
Soft tissue sarcoma	124
Bone sarcoma	109
Uterine sarcoma	91
Malignant melanoma	63
Paranasal sinus carcinoma	52
Mesothelioma	21
Bronchus carcinoma	6
Uterine cervix carcinoma	5
Sundry	65
TOTAL	1432

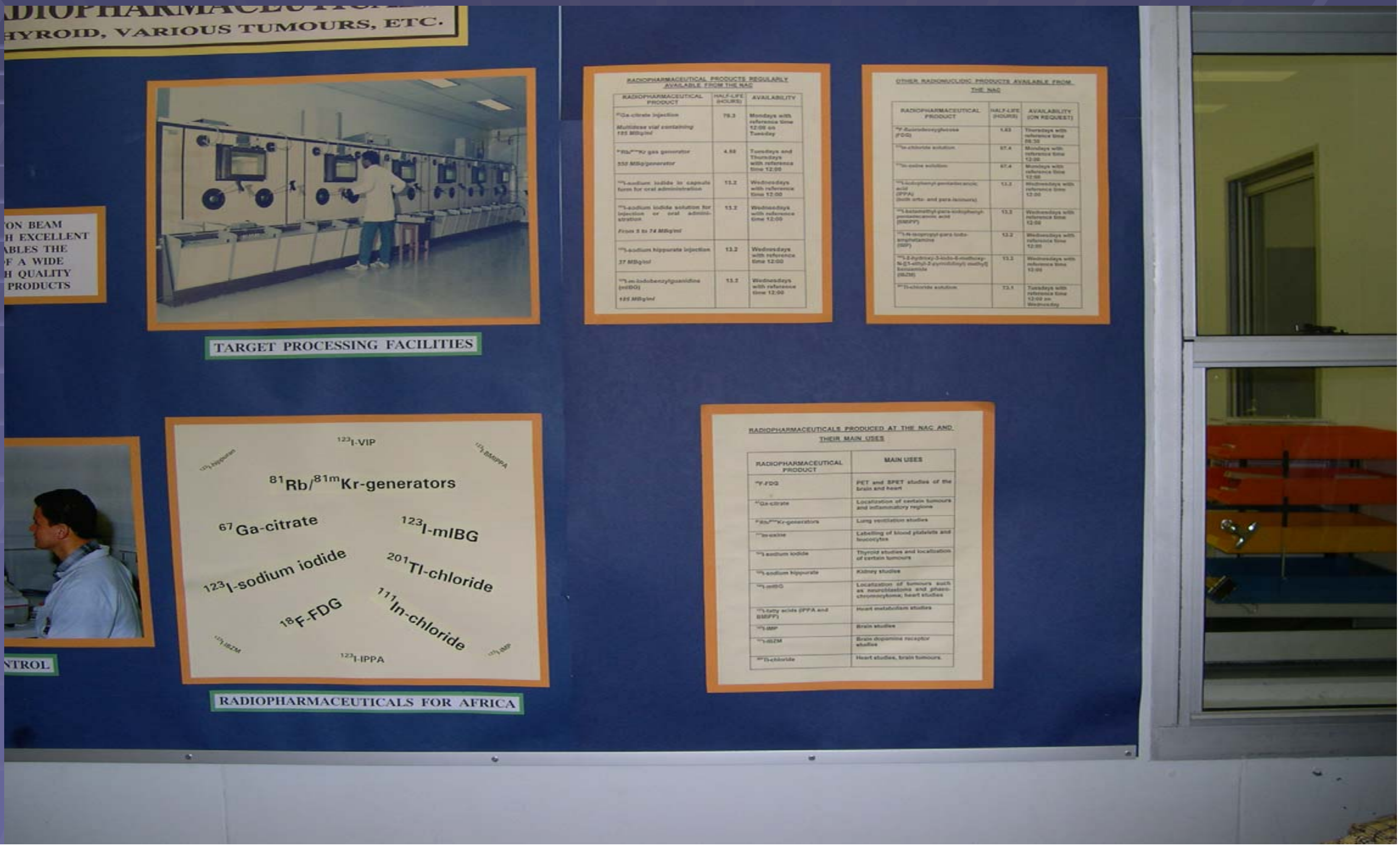
Radioisotope Production

iThemba LABS

TARGETS TO IRRADIATE FOR RADIOISOTOPE PRODUCTION

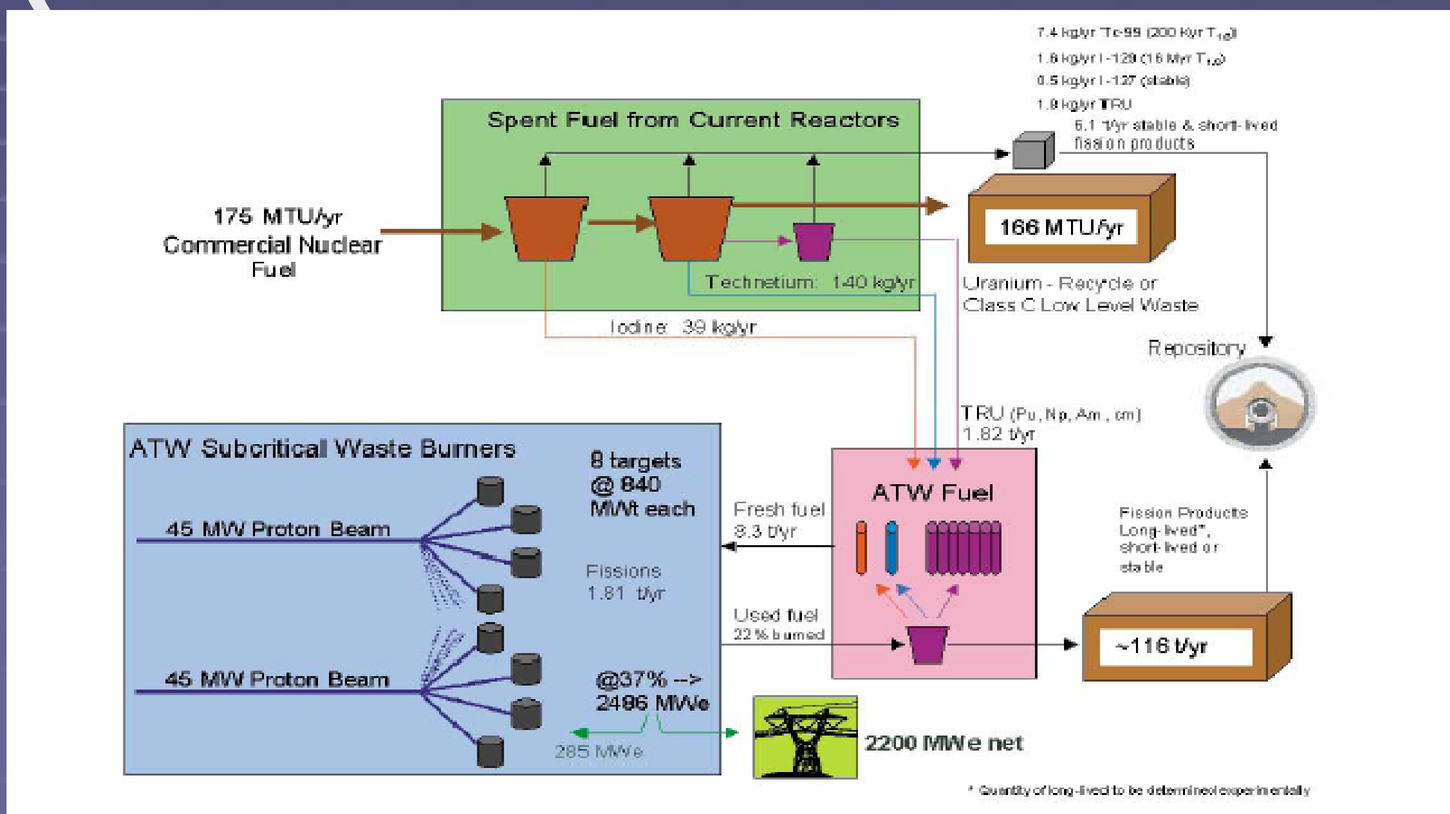
HOT CELLS TO PROCESS IRRADIATED TARGETS

Sample Radioisotopes Produced



Transmutation of Spent Nuclear Reactor Fuel

CONCEPTUAL ACCELERATOR TRANSMUTATION SYSTEM (1999 DOE REPORT TO CONGRESS)

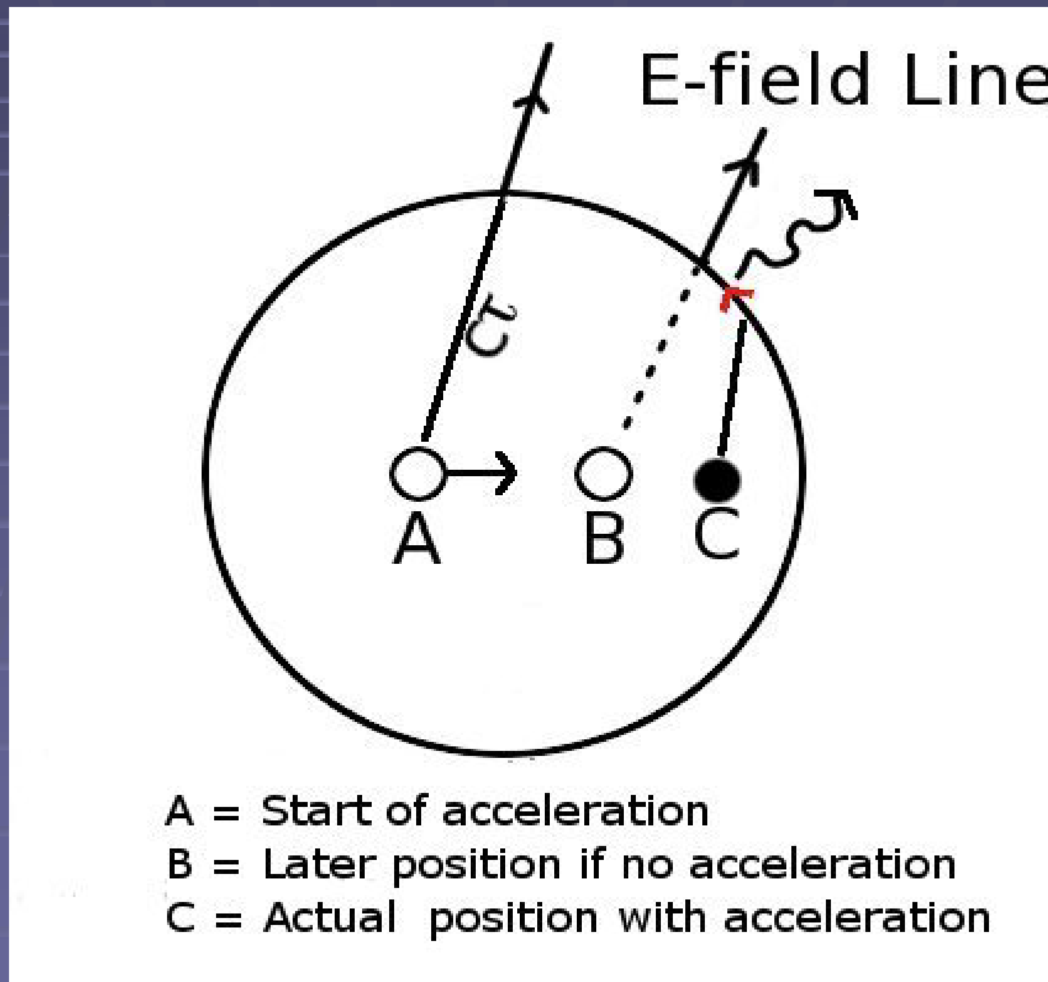


THE RISE OF SYNCHROTRON LIGHT SOURCES

REFERENCES

- Classical Electrodynamics
  - John Jackson
  - John Wiley & Sons Publishers
- Soft X-Rays and Extreme Ultraviolet Radiation: Principles and Applications
  - David Attwood
  - Cambridge University Press
- Particle Accelerator Physics I and II
  - Helmut Wiedemann
  - Springer Publishers
- Handbook of Accelerator Physics
  - Alexander Chao and Maury Tigner
  - World Scientific Publishers

Mechanism for EM Radiation



Maxwell's Equations and the Wave Equation

Maxwell's equations:

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J} \qquad \text{(Ampere's law)} \tag{2.1}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad \text{(Faraday's law)} \tag{2.2}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{2.3}$$

$$\nabla \cdot \mathbf{D} = \rho \qquad \text{(Coulomb's law)} \tag{2.4}$$

$$\mathbf{D} = \epsilon_0 \mathbf{E} \tag{2.5}$$

$$\mathbf{B} = \mu_0 \mathbf{H} \tag{2.6}$$

The wave equation:

$$\left(\frac{\partial^2}{\partial t^2} - c^2\nabla^2\right)\mathbf{E}_{\mathrm{T}}(\mathbf{r}, t) = -\frac{1}{\epsilon_0}\frac{\partial \mathbf{J}_{\mathrm{T}}(\mathbf{r}, t)}{\partial t} \tag{3.1}$$

The Wave Equation

From Maxwell's Equations, take the curl of equation 2.2

$$\nabla \times \boxed{\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}} \tag{2.2}$$

and use the vector identity from Appendix D.1, pg. 440,

$$\nabla \times (\nabla \times \mathbf{A}) = \nabla(\nabla \cdot \mathbf{A}) - \nabla^2 \mathbf{A} \tag{D.7}$$

to form the Wave Equation

$$\left(\frac{\partial^2}{\partial t^2} - c^2\nabla^2\right)\mathbf{E}(\mathbf{r}, t) = -\frac{1}{\epsilon_0}\left[\frac{\partial \mathbf{J}(\mathbf{r}, t)}{\partial t} + c^2\nabla\rho(\mathbf{r}, t)\right] \tag{2.7}$$

where $$c \equiv \frac{1}{\sqrt{\epsilon_0\mu_0}} \tag{2.8}$$

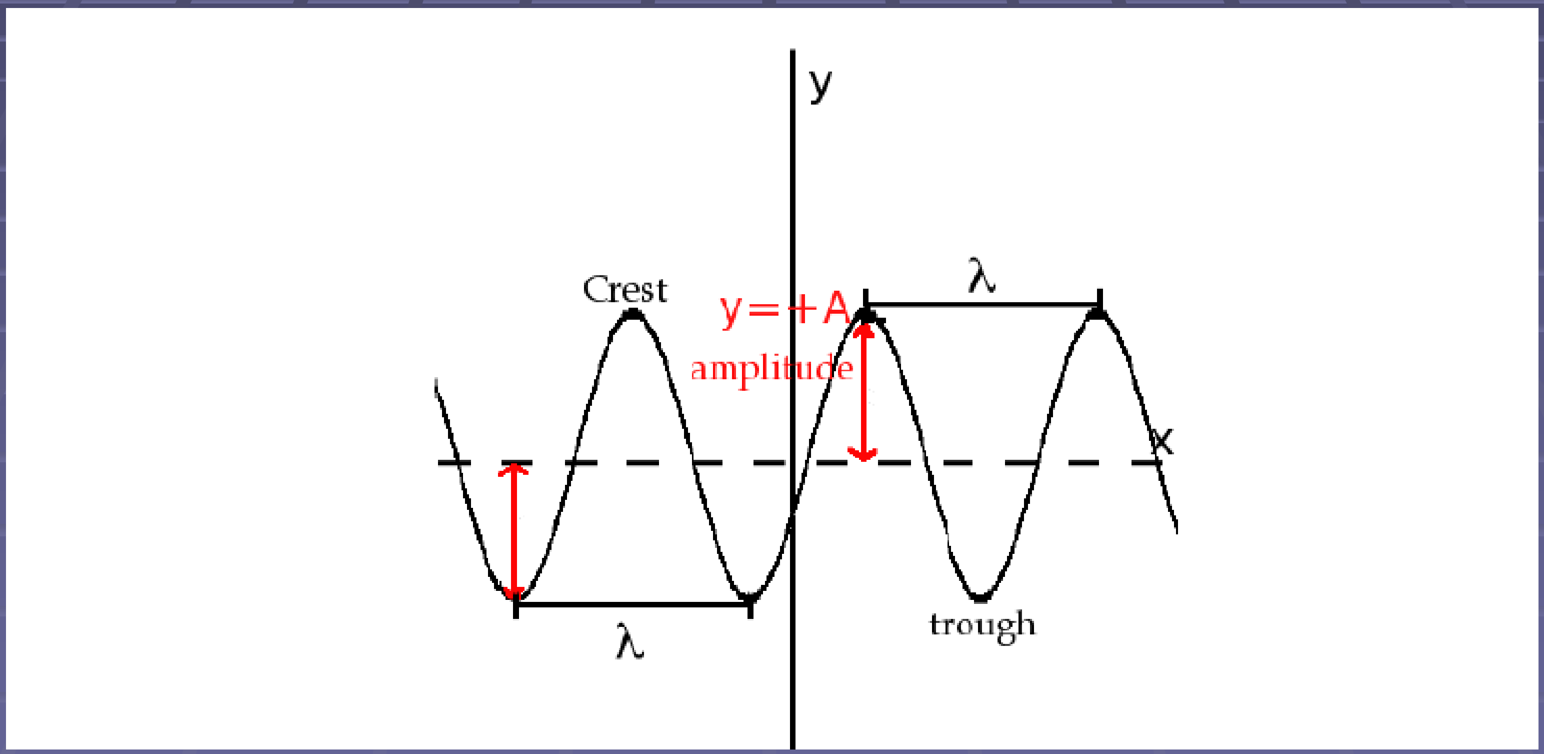
where $\mathbf{J}(\mathbf{r},t)$ is the current density in vacuum and ρ is the charge density:

$$\mathbf{J}(\mathbf{r},t) = qn(\mathbf{r},t)\mathbf{v}(\mathbf{r},t) \tag{2.10}$$

For transverse waves the Wave Equation reduces to

$$\boxed{\left(\frac{\partial^2}{\partial t^2} - c^2\nabla^2\right)\mathbf{E}_T(\mathbf{r}, t) = -\frac{1}{\epsilon_0}\frac{\partial \mathbf{J}_T(\mathbf{r}, t)}{\partial t}} \tag{3.1}$$

1-DIMENSIONAL WAVES ON ROPE



$$y = A\sin(kx - \omega t) \tag{18-8}$$

Then we can take various derivatives of the sinusoidal wave and these derivatives are

$$\frac{\partial y}{\partial x} = Ak\cos(kx - \omega t) \tag{18-9a}$$
$$\frac{\partial^2 y}{\partial x^2} = -Ak^2\sin(kx - \omega t) \tag{18-9b}$$
$$\frac{\partial y}{\partial t} = -\omega A\cos(kx - \omega t) \tag{18-9c}$$
$$\frac{\partial^2 y}{\partial t^2} = -\omega^2 A\sin(kx - \omega t) \tag{18-9d}$$

Putting them all together we arrive at

$$\frac{\partial^2 y}{\partial x^2} = \frac{k}{\omega^2} \cdot \frac{\partial^2 y}{\partial t^2} \tag{18-10}$$

Where $\frac{k^2}{\omega^2}$ is no more than just the velocity $\frac{1}{v^2}$ as shown

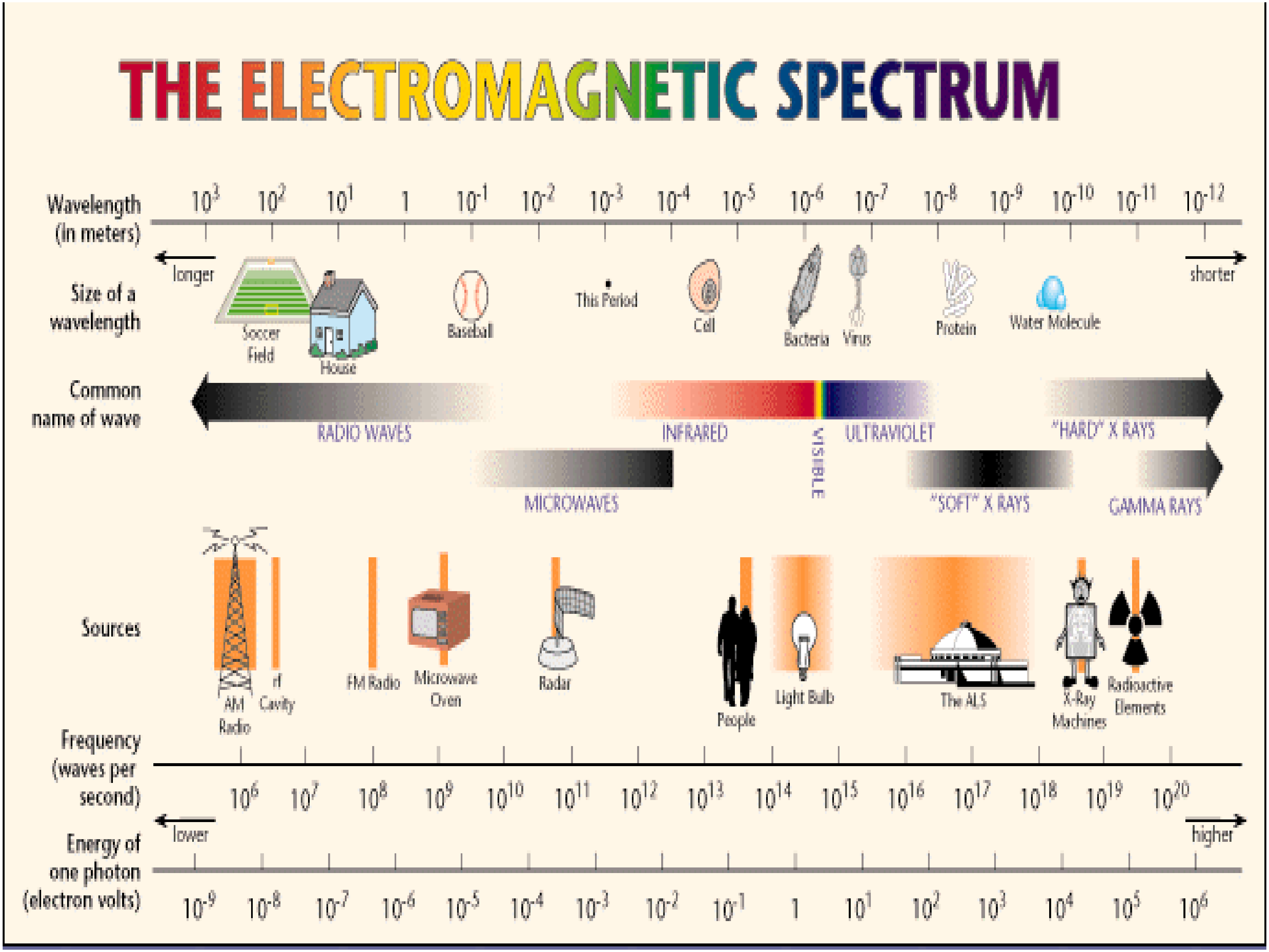
$$\begin{aligned} \frac{k^2}{\omega^2} &= \left(\frac{2\pi}{\lambda}\right)^2 \frac{1}{(2\pi f)^2} \\ &= \frac{1}{v^2} \end{aligned} \tag{18-11}$$

Thus, the 1-dimensional wave equation which governs waves on ropes is

$$\frac{\partial^2 y}{\partial x^2} - \frac{1}{v^2}\frac{\partial^2 y}{\partial t^2} = 0 \tag{18-12}$$

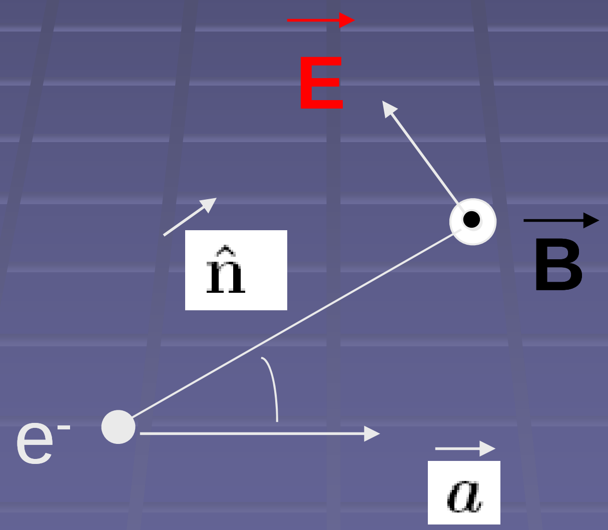
The 1-dimensional wave equation in Eq. (18-12) has a natural extension in three dimension and can be written

$$\nabla^2 y - \frac{1}{v^2}\frac{\partial^2 y}{\partial t^2} = 0 \tag{18-13a}$$


THE ELECTROMAGNETIC SPECTRUM
Wavelength (in meters)
10^3 10^2 10^1 1 10^-1 10^-2 10^-3 10^-4 10^-5 10^-6 10^-7 10^-8 10^-9 10^-10 10^-11 10^-12
longer
shorter
Size of a wavelength
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
Common name of wave
RADIO WAVES
INFRARED
VISIBLE
ULTRAVIOLET
"HARD" X RAYS
MICROWAVES
"SOFT" X RAYS
GAMMA RAYS
Sources
AM Radio
rf Cavity
FM Radio
Microwave Oven
Radar
People
Light Bulb
The ALS
X-Ray Machines
Radioactive Elements
Frequency (waves per second)
10^6 10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14 10^15 10^16 10^17 10^18 10^19 10^20
lower
higher
Energy of one photon (electron volts)
10^-9 10^-8 10^-7 10^-6 10^-5 10^-4 10^-3 10^-2 10^-1 1 10^1 10^2 10^3 10^4 10^5 10^6

Synchrotron Radiation

FIRST, CONSIDER A NONRELATIVISTIC ELECTRON ACCELERATED ALONG A STRAIGHT LINE.

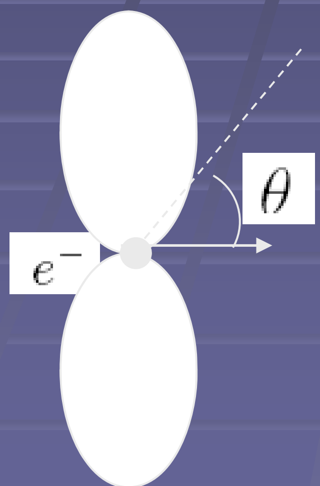


DIPOLE RADIATION PATTERN NON-RELATIVISTIC

ENERGY FLUX IS GIVEN BY THE

POYNTING VECTOR

$$\overrightarrow{\mathbf{S}} = \frac{c}{4\pi}\overrightarrow{\mathbf{E}} \times \overrightarrow{\mathbf{B}} \quad \textbf{in cgs units}$$

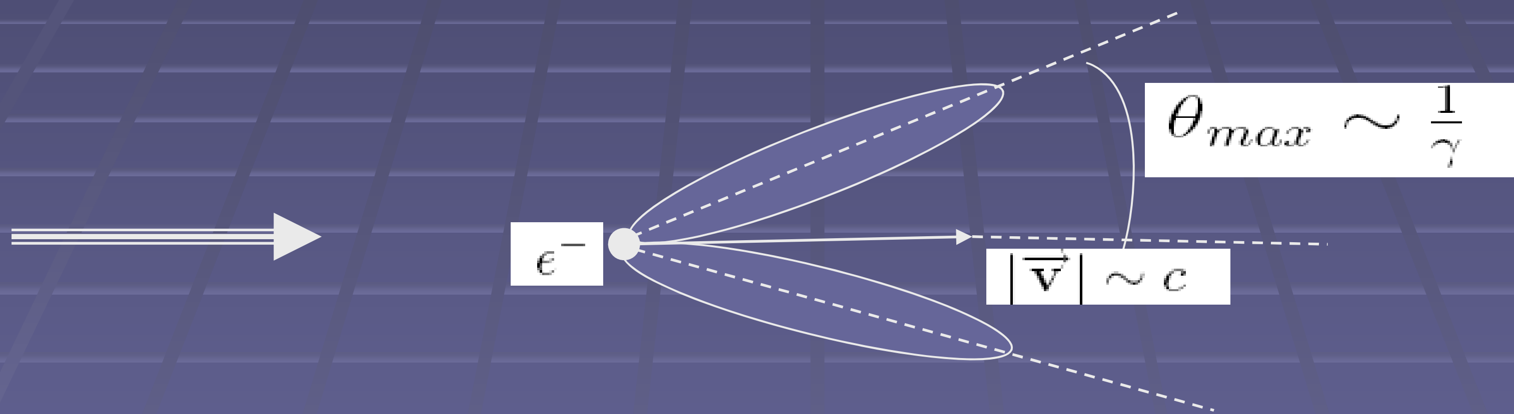


Power spectrum

$$\frac{dP}{d\Omega} = \frac{e^2}{4\pi c^3}\, \boldsymbol{a}^2 \sin^2\theta$$

RADIATION PATTERN FOR RELATIVISTIC PARTICLE

For acceleration of relativistic particle,



where from Einstein's theory of Special Relativity

$$E = \gamma m_0 c^2$$

EXAMPLE: 1 GeV ELECTRON

TYPICAL OF SYNCHROTRON LIGHT SOURCES

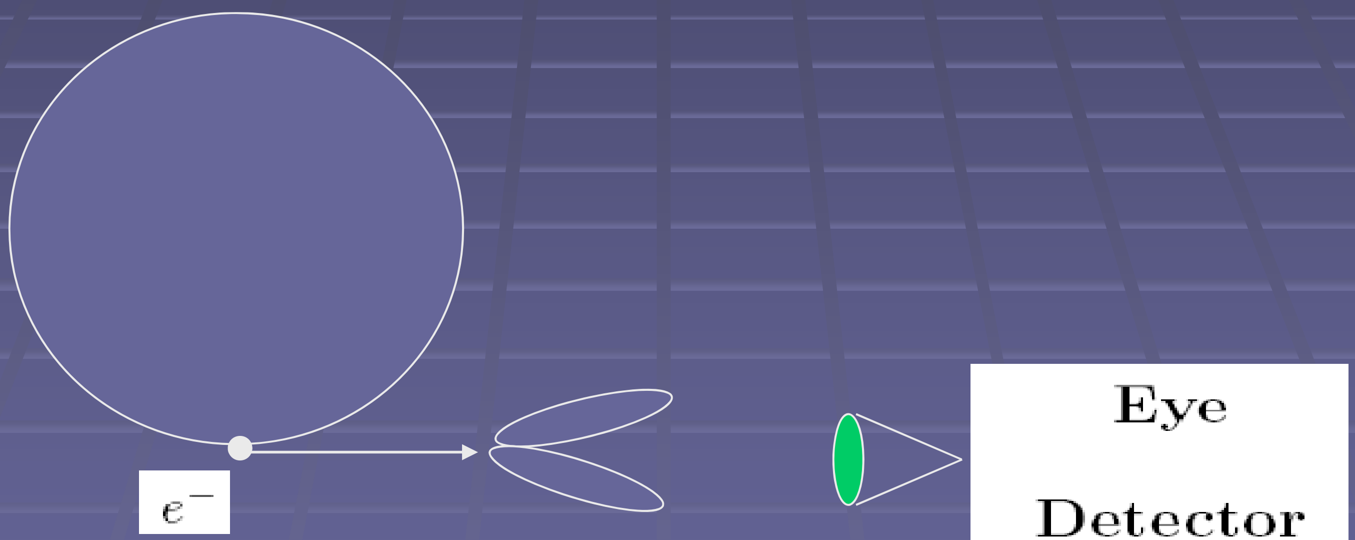
$$\gamma \sim \frac{1000MeV}{0.5MeV} \sim 2000$$

$$\theta_{max} \sim 0.0005 \text{ radians} \sim .03 \text{ degrees}$$

Radiation is essentially in forward direction!

CONSIDER ACCELERATION ALONG CIRCULAR PATH

Peaking of radiation along $\vec{v}$ is still observed.



Seems like e^- has a flashlight fixed to its head!

FOR e$^-$'s, LINEAR IS BETTER!

- Synchrotron radiation power due to linear acceleration

$$P_{\|} = \frac{2}{3}\frac{q^2}{m^2c^3}\left(\frac{d\mathbf{p}_{\|}}{dt}\right)^2$$

(Independent of particle's energy)

- Synchrotron radiation power due to circular (transverse) acceleration

$$P_{\perp} = \frac{2}{3}\frac{q^2}{m^2c^3}\gamma^2\left(\frac{d\mathbf{p}_{\perp}}{dt}\right)^2$$

WHAT ABOUT PROTON CIRCULAR ACCELERATORS?

Synchrotron radiation power $\sim \frac{1}{m^2}$

$$\mathbf{m}_e \sim \tfrac{1}{2}\ \mathbf{MeV}$$

while

$$\mathbf{m}_p \sim 1000\ \mathbf{MeV}$$

Thus,

$$P^e \sim 2 \times 10^6\ P^p.$$

Big problem for circular e^- accelerators!

$\Longrightarrow$ SLAC, a two-mile straight shot.

But not a problem for circular proton accelerators

$\Longrightarrow$ Fermilab's Tevatron.

BUT WAIT!

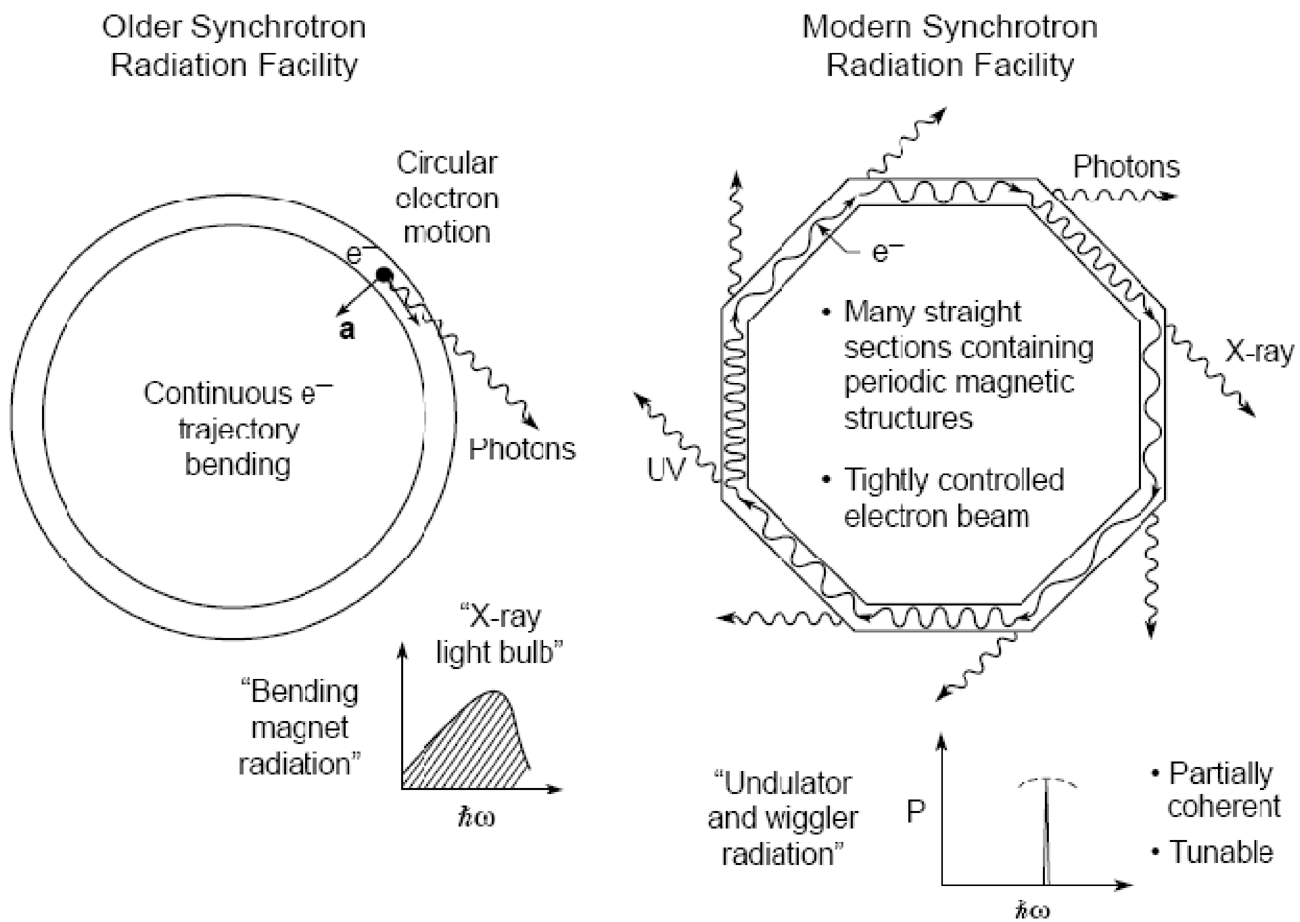
- Someone recognized that the photons being discarded by electron beam could be useful for irradiating targets.

- High energy and nuclear physicists started performing their usual experiments while others parasitically used the X-Rays produced at the bending magnets.
  (1st generation synchrotron light sources)

- Then physicists and engineers began building accelerators dedicated entirely for X-Rays from the bending magnets. (2nd generation)

- To increase the number and variety of X-Ray beams, scientists started installing insertion devices (3rd gen.)

Modern Synchrotron Radiation Facility



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GOOD NEWS!

Radiation in synchrotrons spans the region of the electromagnetic spectrum from the infrared to hard X-ray regimes.

Precisely what is needed to pursue a variety of studies, including materials, protein structure, chemistry, and even industrial applications.

Synchrotron Light Sources of the World

Advanced Light Source (ALS), Berkeley, California
Advanced Photon Source (APS), Argonne, Illinois
ALBA Synchrotron Light Facilty (formerly Laboratorio de Luz Sincrotrón), Vallés, Spain
ANKA Synchrotron Strahlungsquelle, Karlsruhe, Germany
Australian Synchrotron, Melbourne, Victoria
Beijing Synchrotron Radiation Facility (BSRF), Beijing
Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung (BESSY), Berlin
Canadian Light Source (CLS), Saskatoon, Saskatchewan
Center for Advanced Microstructures and Devices (CAMD), Baton Rouge, Louisiana
Center for Advanced Technology (INDUS-1 and INDUS-2), Indore, India
Cornell High Energy Synchrotron Source (CHESS), Ithaca, New York
diamond, Rutherford Appleton Laboratory, Didcot, England
Dortmund Electron Test Accelerator (DELTA), Dortmund, Germany
Electron Stretcher Accelerator (ELSA), Bonn, Germany
Elettra Synchrotron Light Source, Trieste, Italy
European Synchrotron Radiation Facility (ESRF), Grenoble, France
Hamburger Synchrotronstrahlungslabor (HASYLAB) at DESY, Hamburg, Germany
Institute for Storage Ring Facilities (ISA, ASTRID), Aarhus, Denmark
Laboratoire pour l'Utilisation du Rayonnement Electromagnétique (LURE), Orsay, France
Laboratório Nacional de Luz Síncrotron (LNLS) Sao Paolo, Brazil
MAX-lab, Lund, Sweden
National Synchrotron Light Source (NSLS), Brookhaven, New York
National Synchrotron Radiation Laboratory (NSRL), Hefei, China
National Synchrotron Radiation Research Center (NSRRC), Hsinchu, Taiwan, R.O.C
National Synchrotron Research Center (NSRC), Nakhon Ratchasima, Thailand
Photonics Research Institute, National Institute of Advanced Industrial Science and Technology (AIST)
Photon Factory (PF) at KEK, Tsukuba, Japan
Pohang Accelerator Laboratory, Pohang, Korea
Shanghai Synchrotron Radiation Facility, (SSRF)
Siberian Synchrotron Radiation Centre (SSRC), Novosibirsk, Russia
Singapore Synchrotron Light Source (SSLS), Singapore
SOLEIL Synchrotron, Saint-Aubin, France
Stanford Synchrotron Radiation Laboratory (SSRL), Menlo Park, California
Super Photon Ring - 8 GeV (SPring8), Nishi-Harima, Japan
Swiss Light Source (SLS), Villigen, Switzerland
Synchrotron Radiation Center (SRC), Madison, Wisconsin
Synchrotron Radiation Source (SRS), Daresbury, U.K.
Synchrotron Ultraviolet Radiation Facilty (SURF III) at the National Institute of Standards and Technology (NIST)
UVSOR Facility, Okazaki, Japan   and VSX Light Source, Kashiwa, Japan

The ALS with San Francisco in the Background

1.9 GeV, $\gamma = 3720$, 197 m circumference

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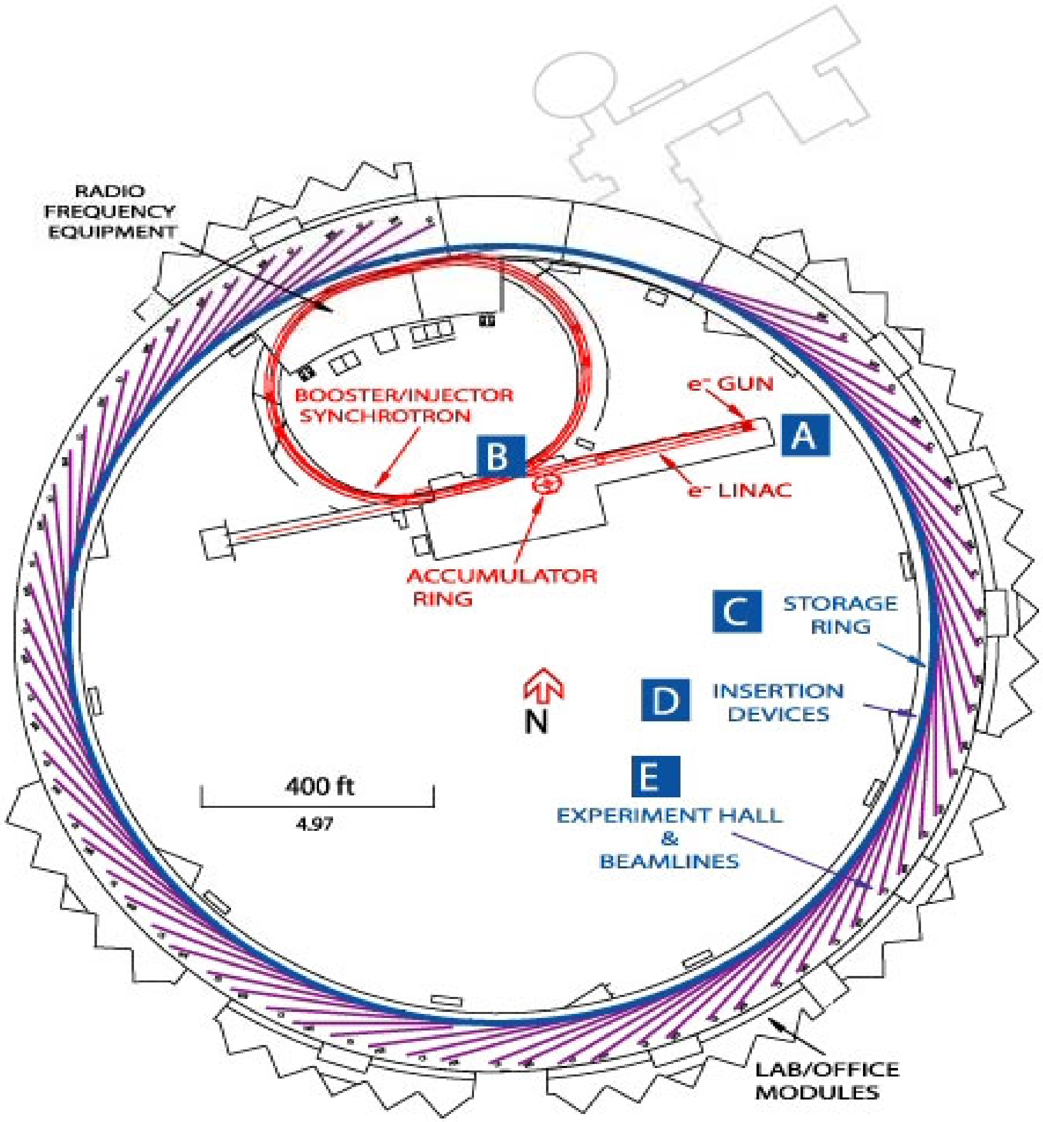
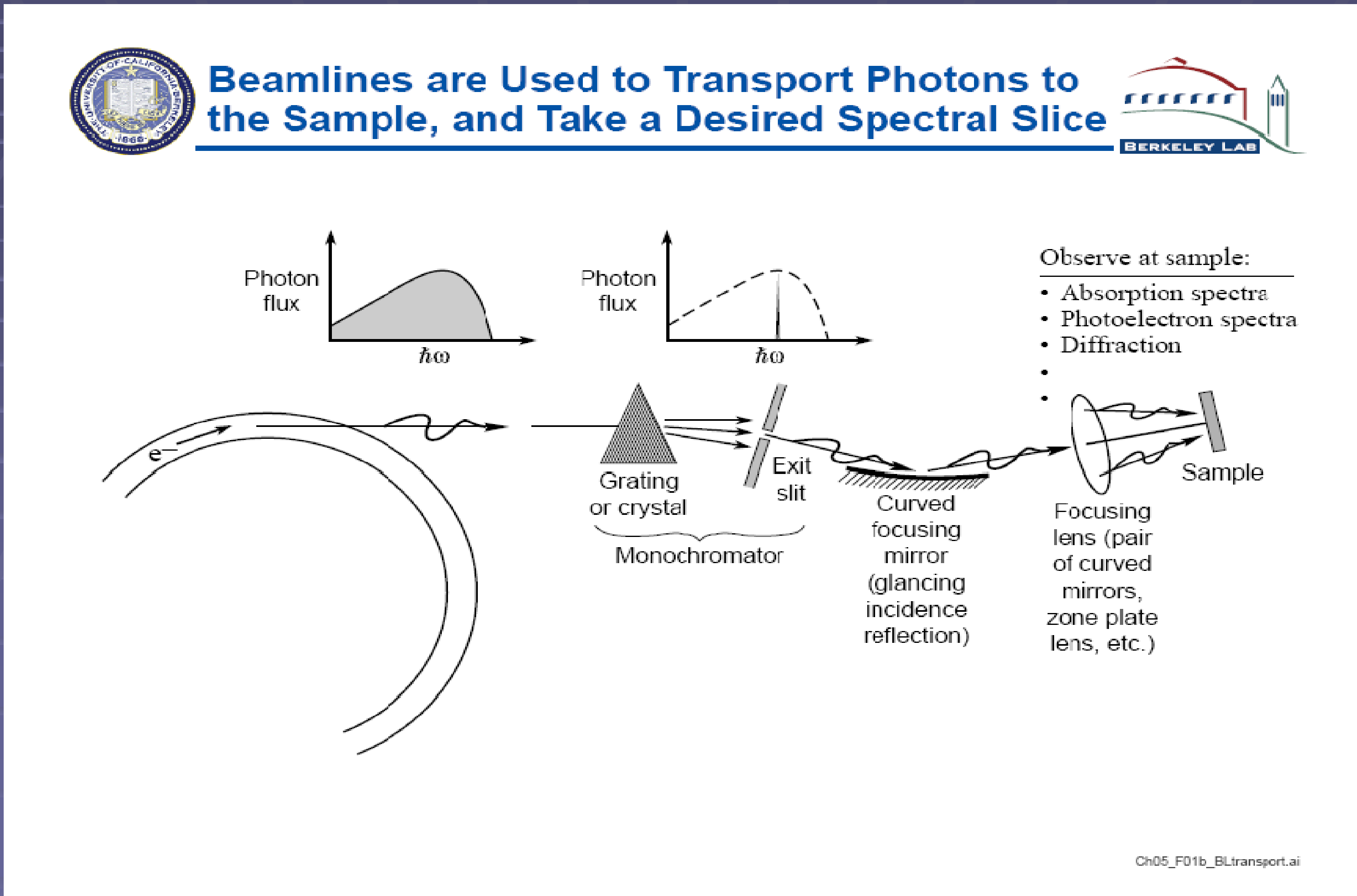
ADVANCED PHOTON SOURCE (APS)

ARGONNE NATIONAL LABORATORY

APS BEAMLINES



(See Attwood Reference)



(See Attwood Reference)

Beamline 7.0 at Berkeley's Advanced Light Source

BERKELEY LAB

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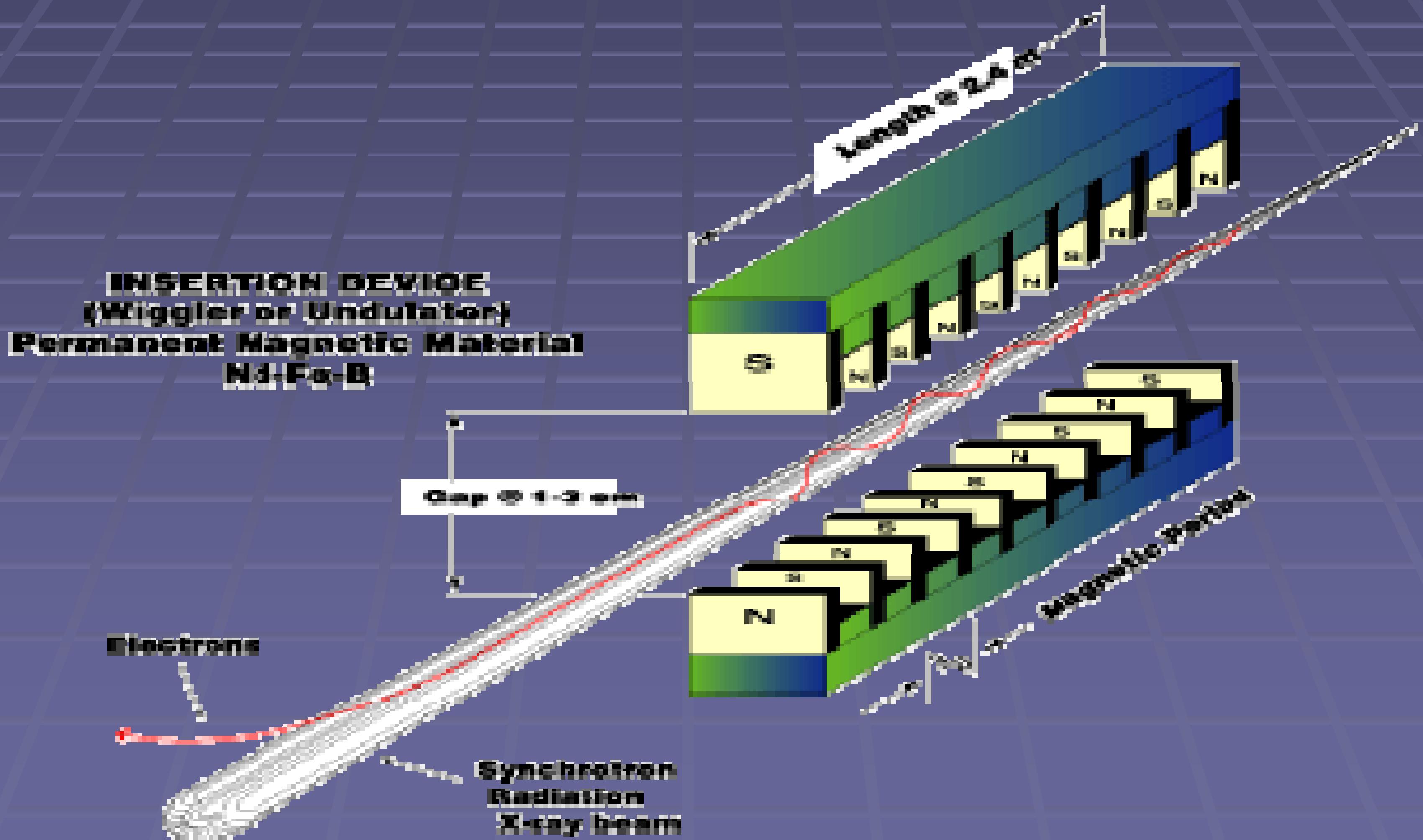
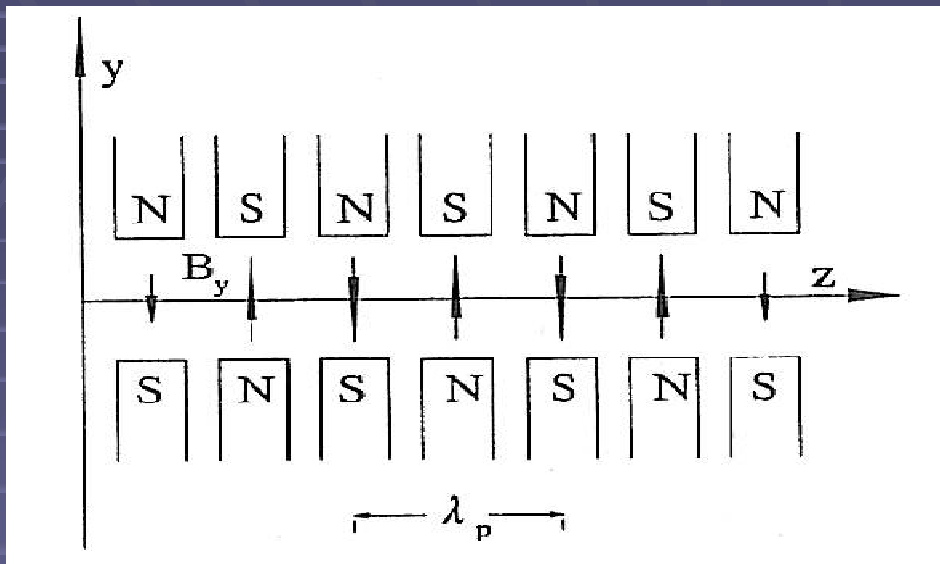
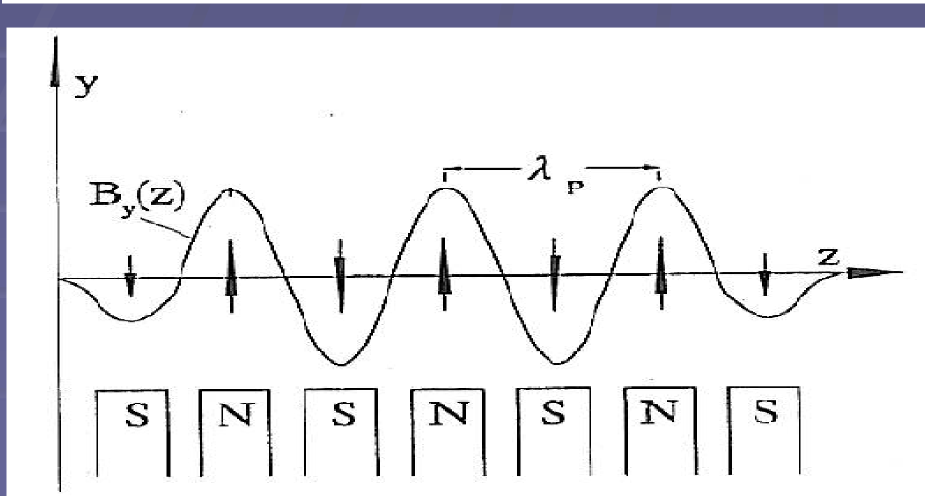
SCHEMATIC OF INSERTION DEVICE



FIELD IN WIGGLER/UNDULATOR





$$B(z) = B_o \cos \frac{2\pi z}{\lambda_p}$$

The Equation of Motion in an Undulator (cont.)

$$m\gamma\, d\mathbf{v}_x = e\, dz\, B_0 \cos\left(\frac{2\pi z}{\lambda_u}\right)$$

integrating both sides

$$m\gamma \mathbf{v}_x = eB_0 \frac{\lambda_u}{2\pi} \int \cos\left(\frac{2\pi z}{\lambda_u}\right) \cdot d\left(\frac{2\pi z}{\lambda_u}\right)$$

$$m\gamma \mathbf{v}_x = \frac{eB_0\lambda_u}{2\pi} \sin\left(\frac{2\pi z}{\lambda_u}\right) \qquad (5.17)$$

$$\boxed{\mathbf{v}_x = \frac{Kc}{\gamma} \sin\left(\frac{2\pi z}{\lambda_u}\right)} \qquad (5.19)$$

$$\boxed{K \equiv \frac{eB_0\lambda_u}{2\pi mc} = 0.9337 B_0(\mathrm{T})\lambda_u(\mathrm{cm})} \qquad (5.18)$$

is the non-dimensional "magnetic deflection parameter."
The "deflection angle", θ, is

$$\theta = \frac{v_x}{v_z} \simeq \frac{v_x}{c} = \frac{K}{\gamma} \sin k_u z$$

tives to magnets. Rf undulators, which have been considered in the past for synchrotron light sources [5-6], are defined by the regime where $\lambda_u B_0 < 0.01$ T-m, where λ_u is the undulator period and B_0 is the peak magnetic field. Braun *et al.* found that rf wigglers performed better

EM WAVELENGTH vs. UNDULATOR PERIOD

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right)\left(1+\frac{\gamma^2}{1+K^2/2}\theta^2\right)$$

$$\boxed{\lambda = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}+\gamma^2\theta^2\right)} \qquad (5.28)$$

where $K \equiv e B_0 \lambda_u / 2\pi mc$. This is the *undulator equation*, which describes the generation of short (x-ray) wavelength radiation by relativistic electrons traversing a periodic magnet structure, accounting for magnetic tuning (K) and off-axis ($\gamma\theta$) radiation. In practical units

$$\lambda(\mathrm{nm}) = \frac{1.306\lambda_u(\mathrm{cm})\left(1+\frac{K^2}{2}+\gamma^2\theta^2\right)}{E_e^2(\mathrm{GeV})} \qquad (5.29a)$$

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Undulator Insertion Device at Advanced Photon Source (ANL)

PROPERTIES OF RADIATION

- Undulator radiation is principally the fundamental line k=1, where k is harmonic number.

- The spectral width of undulators decreases with the number of periods N
$$\Delta\omega_{1/2} \approx \frac{\omega_1}{N}$$

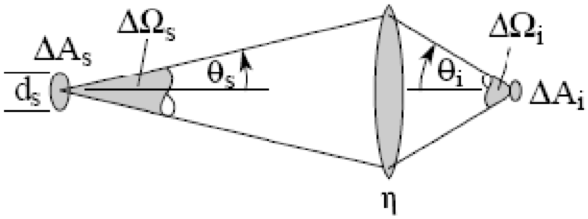
- rms opening angle for undulator with many periods is
$$\frac{1}{\gamma}\sqrt{\frac{1 + {}^1\!/_2 K^2}{2Nk}}$$

- Thus, increasing N both narrows the radiation cone and spectral width.

Brightness and Spectral Brightness

Brightness is defined as radiated power per unit area and per unit solid angle at the source:

$$\boxed{B = \frac{\Delta P}{\Delta A \cdot \Delta\Omega}} \qquad (5.57)$$

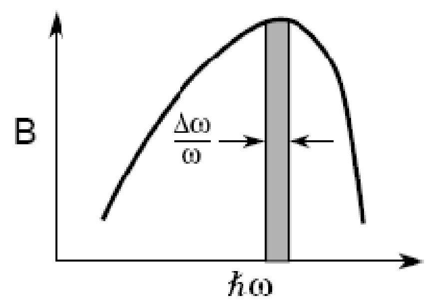


Brightness is a conserved quantity in perfect optical systems, and thus is useful in designing beamlines and synchrotron radiation experiments which involve focusing to small areas.

Perfect optical system:
$\Delta A_s \cdot \Delta\Omega_s = \Delta A_i \cdot \Delta\Omega_i$; $\eta = 100\%$

Spectral brightness is that portion of the brightness lying within a relative spectral bandwidth $\Delta\omega/\omega$:

$$\boxed{B_{\Delta\omega/\omega} = \frac{\Delta P}{\Delta A \cdot \Delta\Omega \cdot \Delta\omega/\omega}} \qquad (5.58)$$



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Spectral Brightness of Undulator Radiation

The Synchrotron radiation community prefers to express spectral brightness in units of photons/sec, rather than power, and has standardized on a relative spectral bandwidth of $\Delta\omega/\omega = 10^{-3}$, or 0.1% BW. To obtain a relationship for spectral brightness of undulator radiation we can use our expression for $\bar{P}_{cen}$, radiated into a solid angle $\Delta\Omega = \pi\theta_{cen}^2 = \pi\theta_{Tx}\theta_{Ty}$, from an elliptically shaped source area of $\Delta A = \pi\sigma_x\sigma_y$, and within a relative spectral bandwidth $\Delta\omega/\omega = 1/N$. Defining the photon flux in the central radiation cone as

$$\bar{F}_{cen} = \frac{\bar{P}_{cen}}{\hbar\omega/\text{photon}} \tag{5.59}$$

$$\bar{B}_{\Delta\omega/\omega} = \frac{\bar{F}_{cen}}{\Delta A \cdot \Delta\Omega \cdot N^{-1}} = \frac{\bar{F}_{cen} \cdot (N/1000)}{\Delta A \cdot \Delta\Omega \cdot (0.1\%\text{BW})} \tag{5.60}$$

on-axis

$$\bar{B}_{\Delta\omega/\omega}(0) = \frac{\bar{F}_{cen} \cdot (N/1000)}{2\pi^2 \sigma_x \sigma_y \theta_{Tx} \theta_{Ty} (0.1\%\text{BW})} \tag{5.64}$$

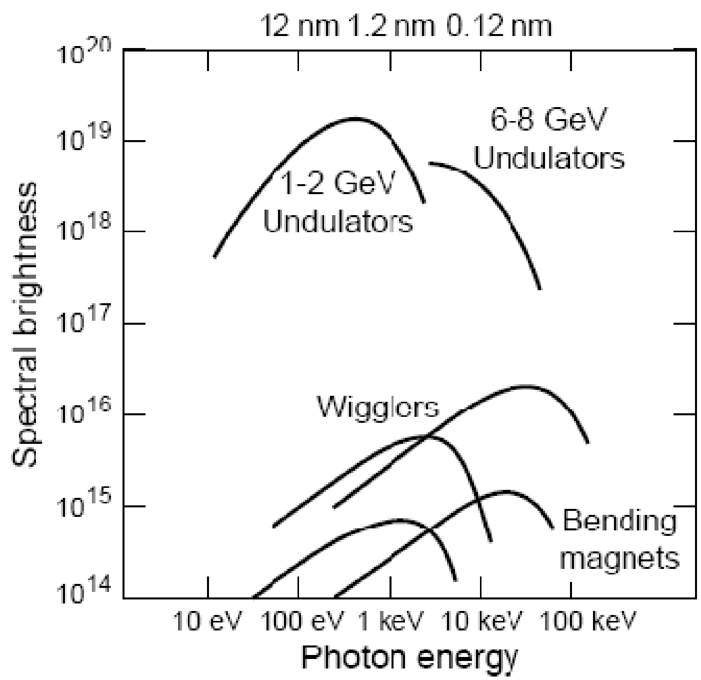
or

$$\bar{B}_{\Delta\omega/\omega}(0) = \frac{7.25 \times 10^6 \gamma^2 N^2 I(\text{A})}{\sigma_x(\text{mm})\sigma_y(\text{mm})\left(1 + \frac{\sigma_x'^2}{\theta_{cen}^2}\right)^{1/2}\left(1 + \frac{\sigma_y'^2}{\theta_{cen}^2}\right)^{1/2}} \cdot \frac{K^2 f(K)}{\left(1 + K^2/2\right)^2} \, \frac{\text{photons/s}}{\text{mm}^2\text{mrad}^2(0.1\%\text{BW})} \tag{5.65}$$

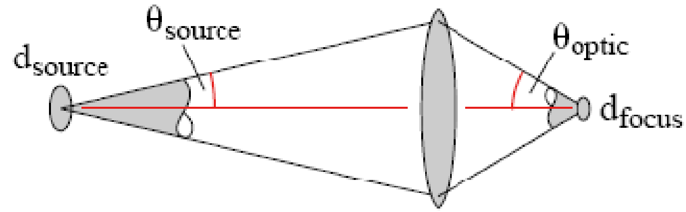
Assumes $\sigma'^2 \ll \theta_{cen}^2$. Note the N^2 factor.

SPECTRAL BRIGHTNESS OF VARIOUS DEVICES

(See Attwood Reference)



- Brightness is conserved (in lossless optical systems)



$$d_{source} \cdot \theta_{source} = d_{focus} \cdot \theta_{optic}$$

Smaller after focus

Large in a focusing optic

- Starting with many photons in a small source area and solid angle, permits high photon flux in an even smaller area

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(See Attwood Reference)

What are the Relative Merits?

Bending magnet radiation	Wiggler radiation	Undulator radiation
• Broad spectrum	• Higher photon energies	• Brighter radiation
• Good photon flux	• More photon flux	• Smaller spot size
• No heat load	• Expensive magnet structure	• Partial coherence
• Less expensive	• Expensive cooled optics	• Expensive
• Easier access	• Less access	• Less access

RelativeMerits.ai

(See Attwood Reference)

Facility	ALS	MAX II	BESSY II	APS	ESRF
Electron energy	1.90 GeV	1.50 GeV	1.70 GeV	7.00 GeV	6.04 GeV
γ	3720	2940	3330	13,700	11,800
Current (mA)	400	250	200	100	200
Circumference (m)	197	90	240	1100	884
RF frequency (MHz)	500	500	500	352	352
Pulse duration (FWHM) (ps)	35-70	200	20-50	100	70
Bending Magnet Radiation:					
Bending magnet field (T)	1.27	1.48	1.30	0.599	0.806
Critical photon energy (keV)	3.05	2.21	2.50	19.5	19.6
Critical photon wavelength	0.407 nm	0.560 nm	0.50 nm	0.636 Å	0.634 Å
Bending magnet sources	24	20	32	35	32
Undulator Radiation:					
Number of straight sections	12	10	16	40	32
Undulator period (typical) (cm)	5.00	5.20	4.90	3.30	4.20
Number of periods	89	49	84	72	38
Photon energy ($K = 1$, $n = 1$)	457 eV	274 eV	373 eV	9.40 keV	5.50 keV
Photon wavelength ($K = 1$, $n = 1$)	2.71 nm	4.53 nm	3.32 nm	1.32 Å	0.225 nm
Tuning range ($n = 1$)	230-620 eV	130-410 eV	140-500 eV	3.5-12 keV	2.6-7.3 keV
Tuning range ($n = 3$)	690-1800 eV	400-1200 eV	410-1100 eV	10-38 keV	7.7-22 keV
Central cone half-angle ($K = 1$)	35 μrad	59 μrad	33 μrad	11 μrad	17 μrad
Power in central cone ($K = 1$, $n = 1$) (W)	2.3	0.88	0.95	12	14
Flux in central cone (photons/s)	3.1×10^{16}	2.0×10^{16}	1.6×10^{16}	7.9×10^{15}	1.6×10^{16}
σ_x, σ_y (μm)	260, 16	300, 45	314, 24	320, 50	395, 9.9
σ'_x, σ'_y (μrad)	23, 3.9	26, 20	18, 12	23, 7	11, 3.9
Brightness ($K - 1$, $n - 1$)^a [(photons/s)/mm^2 · mrad^2 · (0.1%BW)]	2.3×10^{19}	7.8×10^{17}	4.6×10^{18}	5.9×10^{18}	5.1×10^{18}
Total power ($K = 1$, all n, all Θ) (W)	83	17	32	350	480
Other undulator periods (cm)	3.65, 8.00, 10.0	5.88, 6.60	4.1, 5.6, 12.5	2.70, 5.50, 12.8	2.3, 3.2, 5.2, 8.5
Wiggler Radiation:					
Wiggler period (typical) (cm)	16.0	17.4	12.5	8.5	8.0
Number of periods	19	13	32	28	20
Magnetic field (maximum) (T)	2.1	1.80	1.15	1.0	0.81
K (maximum)	32	29.3	12.8	7.9	6.0
Critical photon energy (keV)	5.1	2.69	2.11	33	20
Critical photon wavelength	0.24 nm	0.46 nm	0.59 nm	0.38 Å	0.62 Å
Total power (max. K) (kW)	13	5.9	1.8	7.4	4.8

NEXT GENERATION LIGHT SOURCES

Self-Amplified Spontaneous Emission (SASE-FEL, *from BESSY Website*)

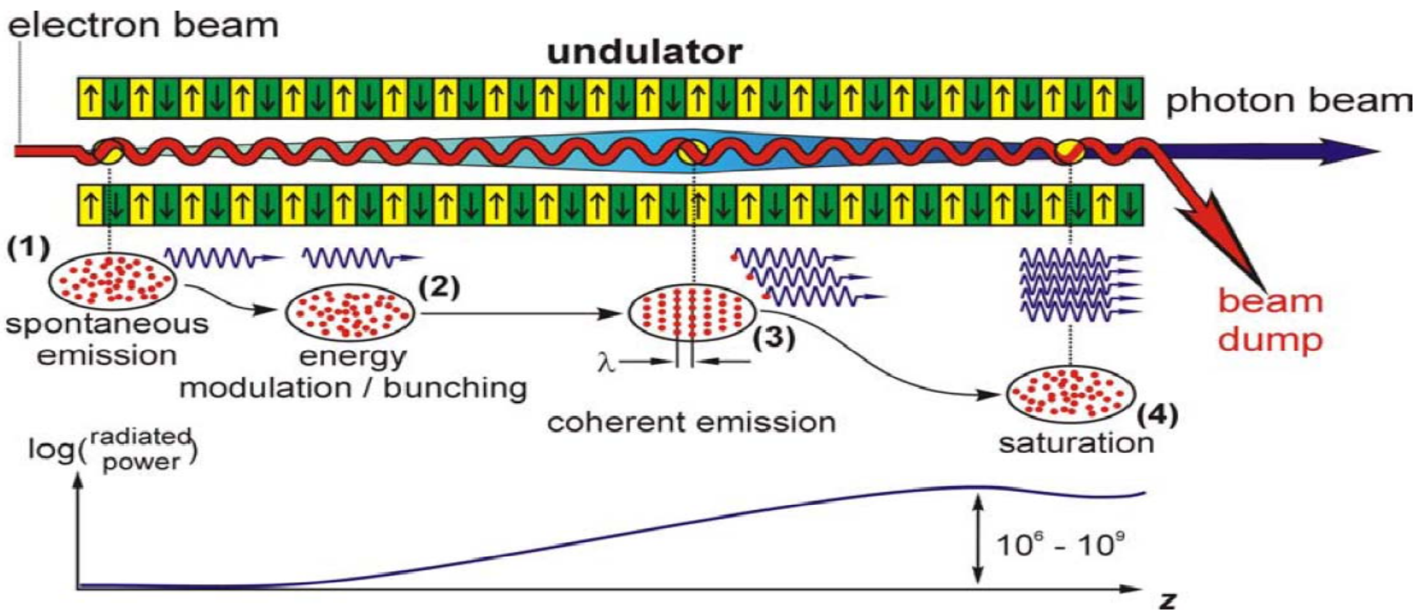
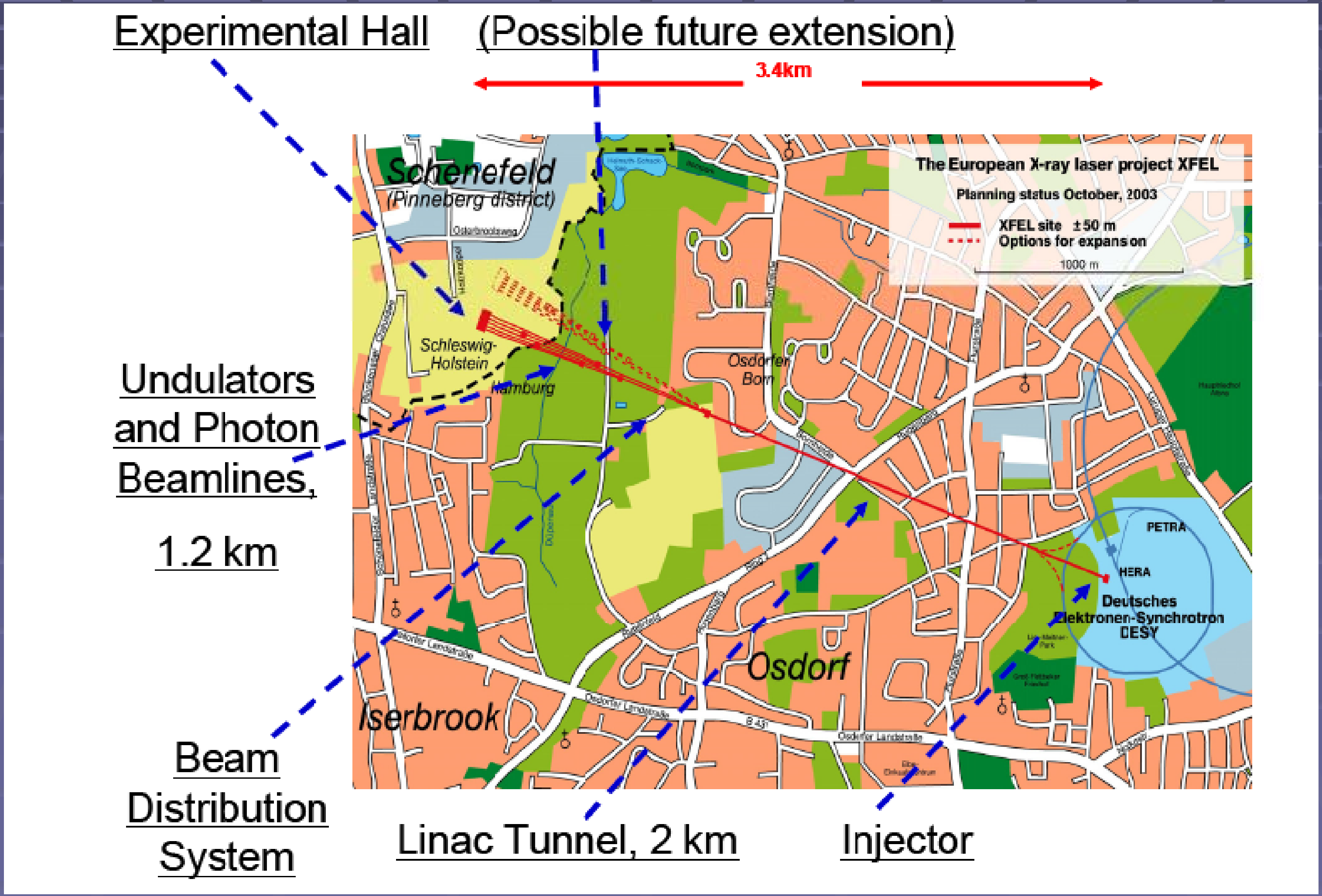


Fig. 2. Schematic summary of the SASE process. On the scale of the radiated wavelength, a uniformly distributed electron beam enters an undulator and produces spontaneous emission (1). Interaction of the electron bunch with its self-generated radiation causes an energy modulation of the electron beam (2) which is transformed into a spatial modulation on the scale of the radiated wavelength (3). This modulation enables the electrons to radiate coherently which results in an exponential growth of the optical power. Saturation occurs when the optical power growth and the corresponding energy loss of the electrons cause the loss of the previously induced bunching (4).

AERIAL VIEW OF EUROPEAN XFEL (*taken from TDR*)



SCHEMATIC OF EUROPEAN XFEL (*taken from TDR*)

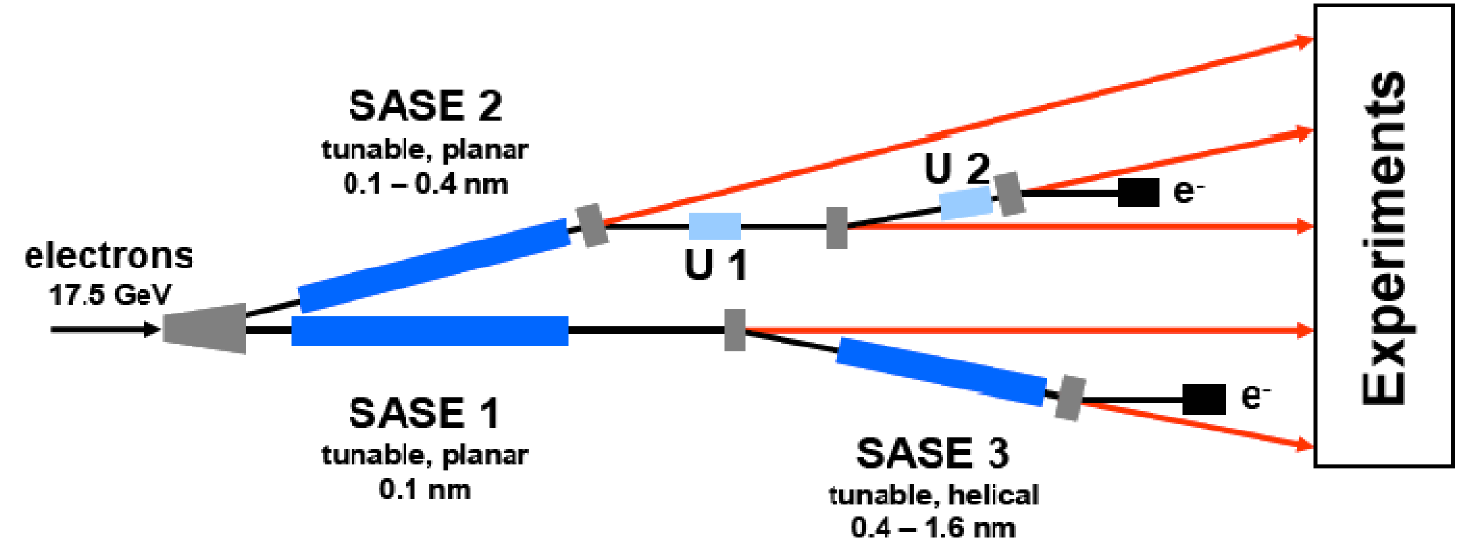
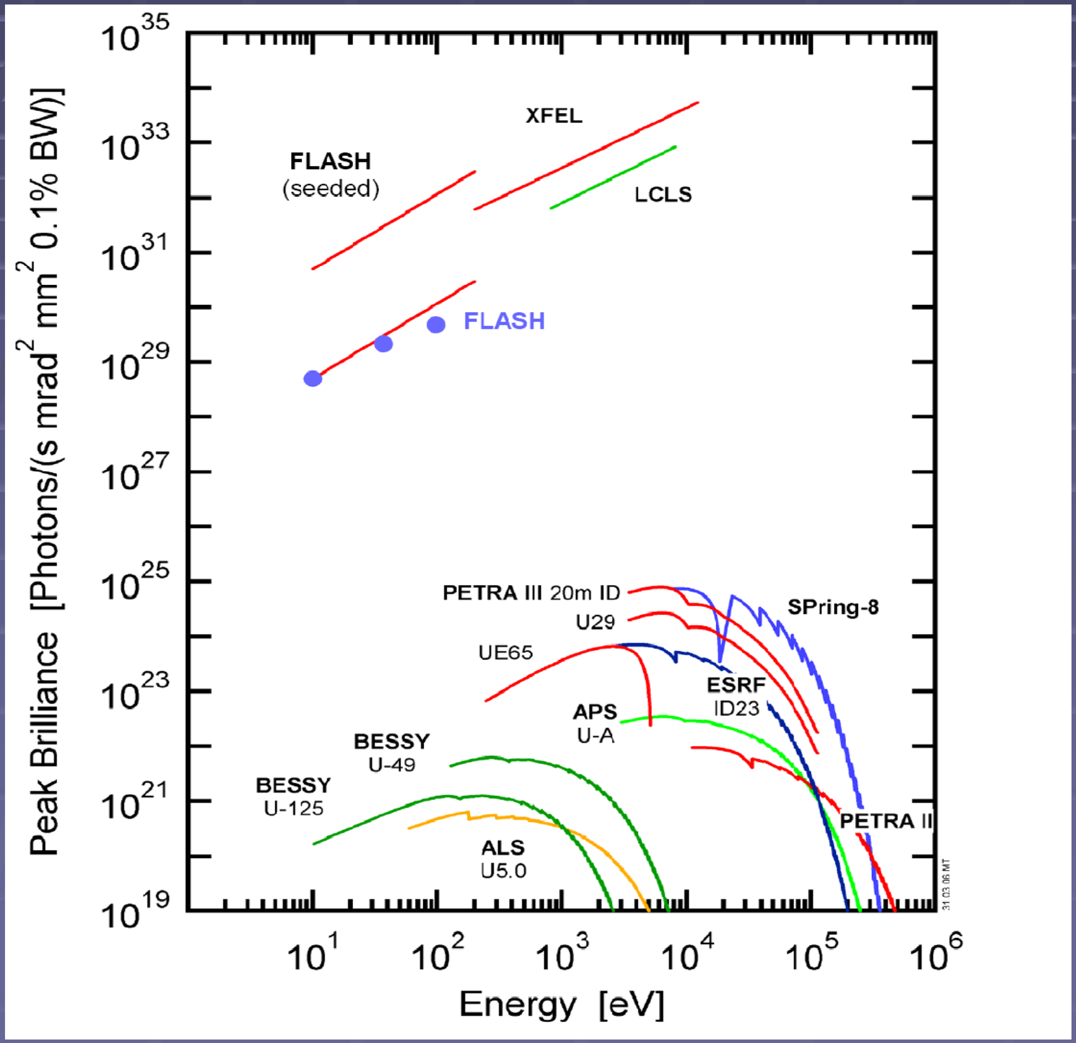


Figure 4.2: *Schematic view of the branching of electron (black) and photon (red) beamlines through the different SASE and spontaneous emission undulators. Electron beamlines terminate into the two beam dumps, photon beamlines into the Experimental Hall.*

In U1 and U2, very hard x-ray photons (wavelengths down to 0.014 and 0.06 nm, respectively)

COMPARISON OF VARIOUS LIGHT SOURCES (*from XFEL TDR*)



APPLICATIONS OF LIGHT SOURCES

FUTURE LIGHT SOURCES (*from LCLS Website*)

- <u>Femtosecond Chemistry</u>
  - Chemical reactions between small molecules are by nature ultra-fast, but the time sequence of these reactions can be captured with the ultra-fast pulses of SASE-FELs.
  - Photosynthesis involves such ultra-fast reactions. A better understanding of photosynthesis has implications for future energy sources and for agriculture, which will be important for Africa.
  - Possibility to intercede during chemical reactions to produce novel compounds.

APPLICATIONS OF FUTURE LIGHT SOURCES (*from LCLS Website*)

- <u>Nanoscience/nanotechnology</u>
  - Modern technology (electronic devices, computer chips, and liquid crystal displays on watches) uses nanoscale materials.
  - Those materials consist of simple constituents arranged in complex, man-made ways, all on a very tiny scale.
  - Often, what is interesting about these molecules is that they change with time in a useful way. (For example, the molecules in an LCD display change their alignment, dictating which numerals appear on the face.)
  - How those states change and how the change is induced can be better studied with the ultra-fast X-Ray pulses from SASE-FELs.
  - As technological devices continue to get smaller and faster, better understanding such nanoscale processes will help to build better technology.

APPLICATIONS OF FUTURE LIGHT SOURCES (*from LCLS Website*)

- <u>Biological systems</u>
  - Using x-rays to study the atomic structures of biological molecules such as proteins has turned out to be invaluable for understanding their roles in life processes.
  - Often, the atomic structure of a molecule is crucial to its biological activity.
  - Nowadays, drug molecules can be created to fit the shape of certain human biological molecules and thereby deliver their effect in a very specific way.
  - This is only possible with the knowledge of the structures of the molecules, most often obtained from synchrotron radiation studies.
  - But the X-Ray diffraction process used to study molecular structure has its limitations; the radiation quickly destroys the molecule being studied.
  - Researchers have found a way to work around this destruction: molecules like proteins are formed into crystals (containing millions of neatly ordered, identical copies of the molecule) so that many molecules are simultaneously examined, thus spreading the radiation damage around.
  - Though this technique has been extremely useful, the crystals are often very difficult to create, and with many molecules, it may be impossible.
  - But SASE-FELs offer another way to work around the radiation damage problem: the extremely bright and ultra-short x-ray pulse can give a picture of just several hundred molecules nearly instantly, before they are destroyed, so that the molecules can be studied in their normal wet environments and no crystallization is necessary.

APPLICATIONS OF FUTURE LIGHT SOURCES (*from LCLS Website*)

- **Matter under extreme conditions**
  - Conditions inside a proto-star (brown dwarf) or a super planet such as Jupiter involve extremely high pressure and extremely high temperatures.
  - These conditions are beyond anything we can create on Earth now.
  - Much of the matter in the universe is locked in these cosmological bodies.
  - SASE-FELS should offer a way to create similar conditions on a minute scale, allowing us to study these conditions and thus learning more about these important astronomical bodies.

APPLICATIONS OF FUTURE LIGHT SOURCES (*from LCLS Website*)

- **Atomic physics**
  - It will be possible for the first time to observe the behavior of atoms that have absorbed many x-rays in rapid succession or atoms that have been struck simultaneously by two x-rays.
  - SASE-FELs will have sufficient intensity to eject ALL the inner-shell electrons from an atom, producing "hollow" atoms.
  - Will study radiation and possibly lasing from XFEL-excited matter.
  - Atomic physics experiments will lay the foundation for subsequent materials science experiments at SASE-FELs.
  - Concepts for producing 1 femtosecond X-Ray pulses with SASE-FELs are currently under development.
  - With 1 fs pulses, it will be possible to catch a glimpse of how electrons move within an atom as it transits from one state to another.

FINAL COMMENTS

- For future synchrotron light sources, to reduce undulator line widths even more and achieve even brighter X-ray beams, small emittance electron beams will be needed, but they are limited by intrabeam scattering, which must be accounted for.

- The current revolution in light sources is the construction of SASE-FELS with orders of magnitude greater spectral brightness than current synchrotron light sources.