



LA RADIACIÓN DE SINCROTRÓN. PRINCIPIOS, INSTRUMENTACIÓN

José Manuel Quesada Molina, Sevilla 2010

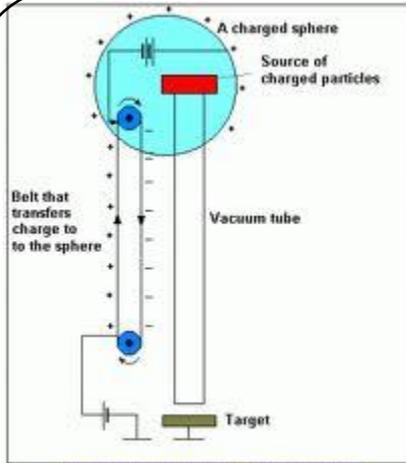
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1. HISTORIA

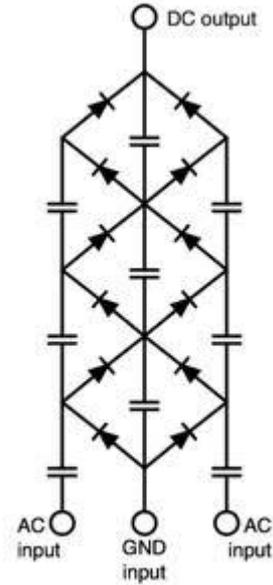
Los aceleradores de partículas

- Los primeros aceleradores fueron construidos por físicos de partículas en los años 30. El objetivo de estos era romper el núcleo del átomos usando la energía de colisión de las partículas. De estos experimentos pretendían obtener información básica sobre las leyes fundamentales de la física que gobiernan el comportamiento del universo.
- Lineales (electrostáticos):
 - **Cockroft-Walton** (Cavendish Laboratory, Cambridge 1932) : protones a 600 keV
 - **Van de Graaff** (MIT, Boston 1931): 1 MV
- Circulares :
 - **Ciclotrón** (Berkeley, California, E. O. Lawrence & M. S. Livingston, 1932): protones a 1.2 MeV
 - **Betatrón** (Illinois, 1940): electrones a 300 MeV
 - **Sincrotrón** (Idea: **McMillan** , Berkeley Radiation Lab, California, 1945): electrones a varias decenas de MeV

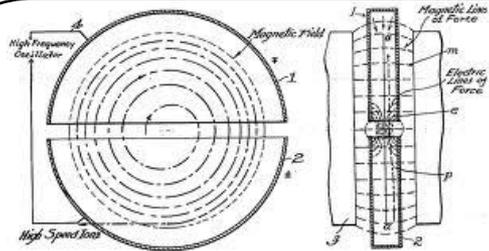


Scanned at the American Institute of Physics

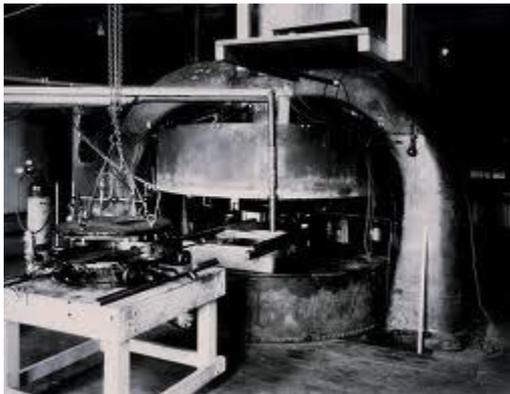
Van de Graaff



Cockcroft-Walton



Ciclotrón



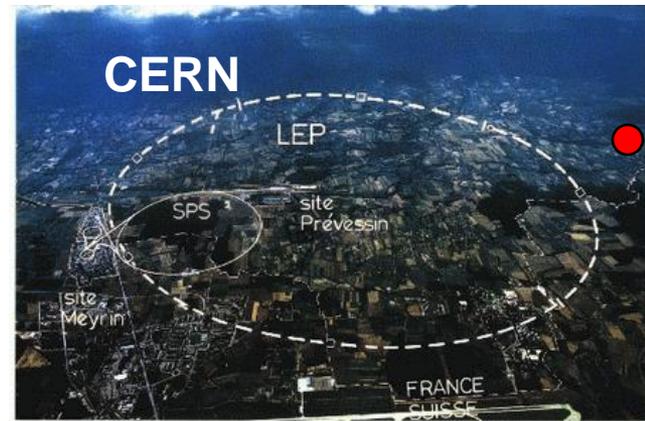
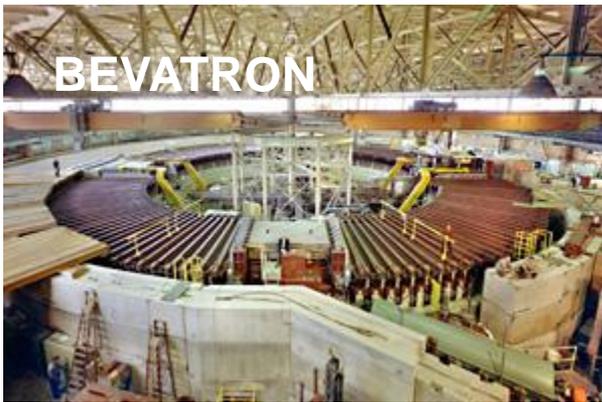
Imágenes

Betrón



1. HISTORIA

- Sincrotrones (focalización débil) :
 - **Bevatrón** (Lawrence Berkeley Lab, California, 1950): protones a 6.3 GeV
 - **Cosmotrón** (Brookhaven National Lab, New York 1953): protones a 3.3 GeV
 - Sincrotrones (focalización fuerte: **gradientes alternos**) :
 - **CERN Proton Sincrotron** (1961, Ginebra, 1959): protones a 28 GeV
 - **SPS, 2x** (CERN, Ginebra, 1976): protones-antiprotones (300-450 GeV) , electrones-positrones (->LEP)
 - **Tevatron, 2x** (Fermilab, Chicago, 1983): protones a ~ 1 TeV
 - **LEP, 2x** (CERN, Ginebra, 1989->2000): electrones-positrones a ~ 45 GeV
 - **LHC, 2x** (CERN, Ginebra, 2008): protones-protones a 7 TeV
- **SPEAR 2x** (SLAC, 1972): electrones –positrones a 4 GeV (dedicada a partir de 1990)
 - **SOR-Ring** (Tokyo, 1974): electrones a 300 MeV (dedicada)
 - **ESRF** (Grenoble, 1994): electrones 6 GeV
 - **APS** (Argonne National Lab, Illinois, 1995) : electrones a 7 GeV
 - **Spring-8** (Hyogo, Japón, 1997):electrones 8 GeV
 - **ALBA** (Barcelona, 2010): electrones 3 GeV



1. HISTORIA

El origen de la luz de sincrotrón

- La radiación sincrotrón se observó por primera vez en los laboratorios de la compañía General Electric en EEUU en 1947 en el recién propuesto (McMillan, 1945) **sincrotrón**.
- Al principio se consideraba un efecto indeseable, pues las partículas perdían energía, pero en los años 60 fue reconocida por como una radiación con excelentes propiedades.
- Se comenzó a utilizar en modo *parásito* a la par que se realizaban experimentos en Física de Partículas (SPEAR) ← 1ª generación de fuentes de RS
- Pronto se desarrollaron las primeras máquinas dedicadas a la producción de RS (SOR-Ring) ← 2ª generación de fuentes de RS

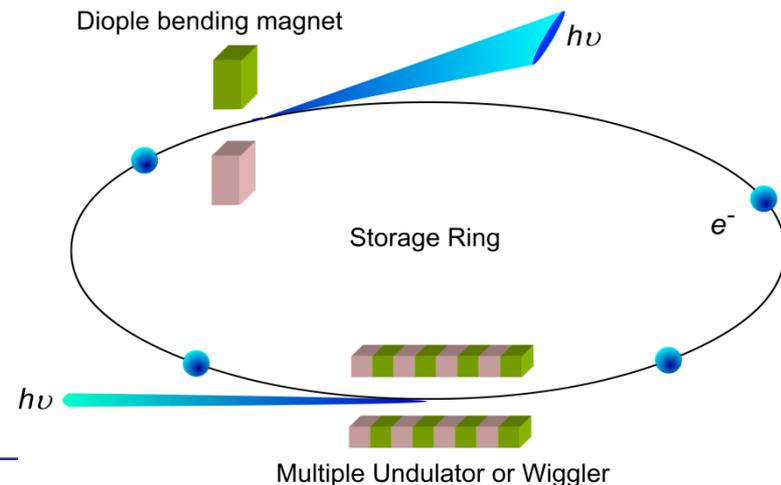
2. CONCEPTOS BASICOS

¿Qué es la radiación sincrotrón?

- Radiación electromagnética emitida cuando partículas cargadas de muy alta energía se desplazan en trayectorias curvas.

¿Dónde se produce?

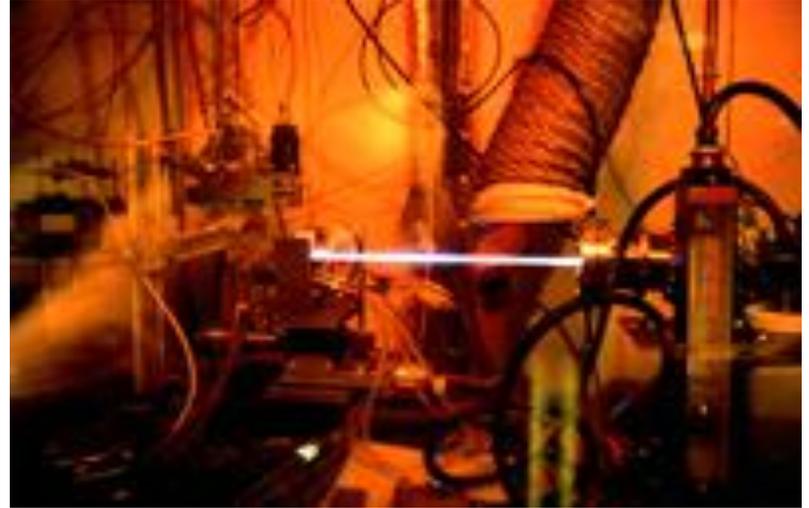
- Tangencialmente a la trayectoria del haz de electrones en los imanes dipolares de los anillos de almacenamiento.



2. CONCEPTOS BASICOS

¿Para qué sirven?

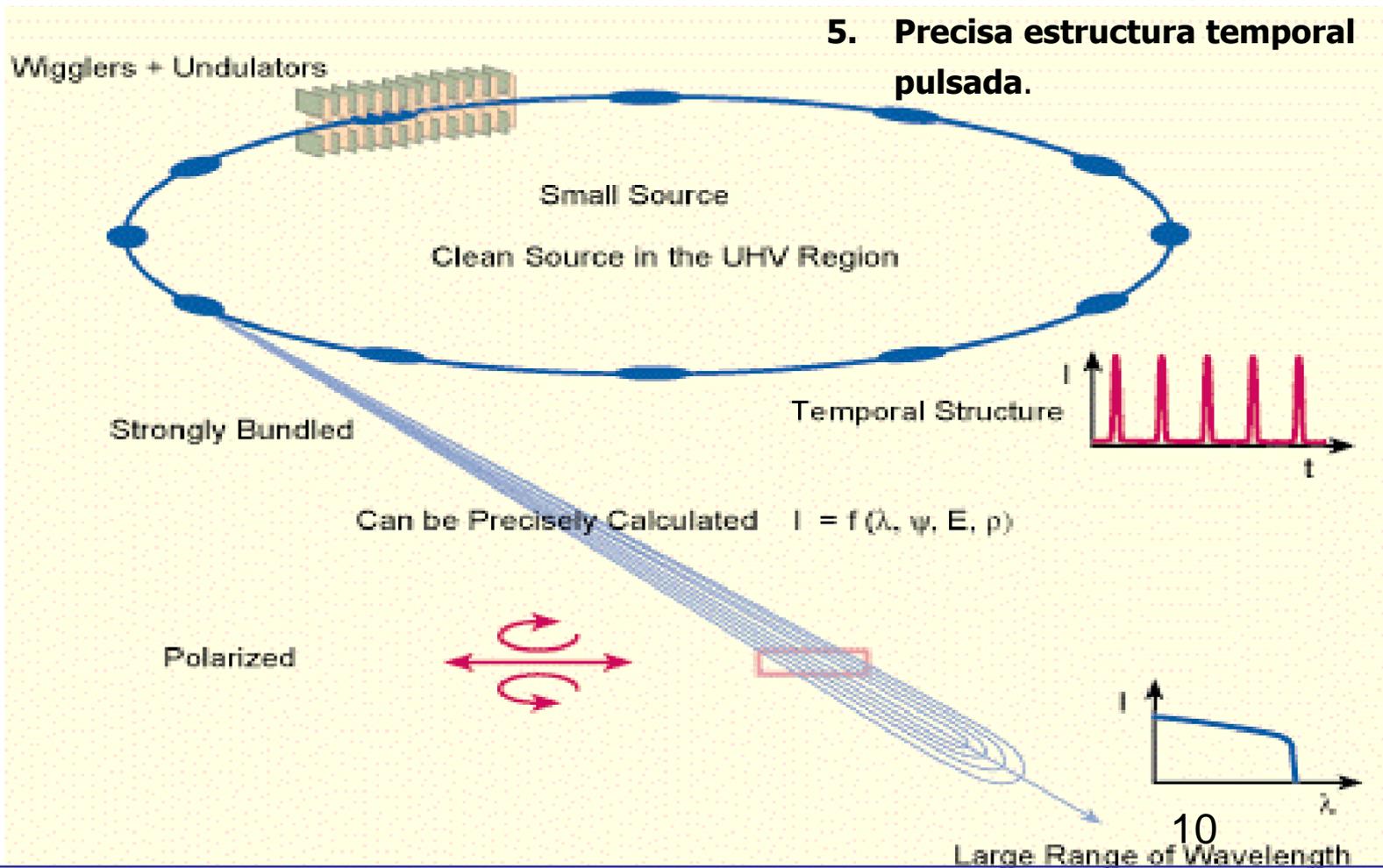
- ¿De qué están hechos los planetas?
- ¿en que procesos se sustenta la vida?
- ¿cómo podemos explicar las propiedades de la materia y desarrollar nuevos materiales?
- ¿será posible un día conquistar los virus, predecir las catástrofes naturales o eliminar la contaminación ambiental?



- Se necesita un profundo conocimiento de la estructura de la materia para contestar estas cuestiones.
- Las fuentes de radiación sincrotrón pueden compararse con “**supermicroscopios**” capaces de revelar información útil en numerosos campos de investigación.
- Hay en torno a 50 sincrotrones en el mundo que son usados por un número creciente de científicos

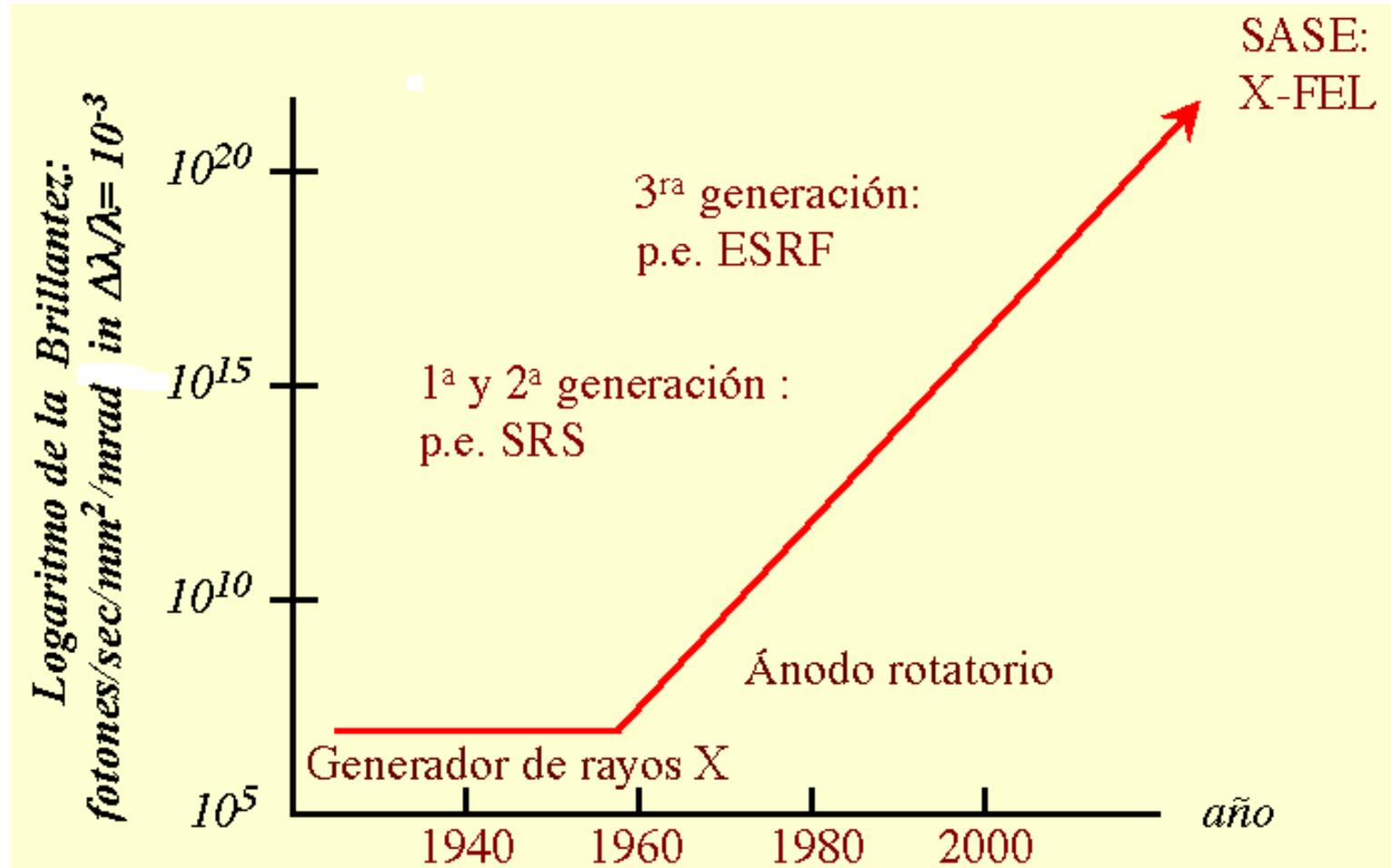
3. PROPIEDADES

1. Alta intensidad, 10^3 - 10^6 superior a la de tubos de Rayos X
2. Amplio rango de longitudes de onda
3. Polarización lineal en el plano de la órbita (elíptica: con inserciones).
4. Alta colimación o pequeña divergencia
5. Precisa estructura temporal pulsada.



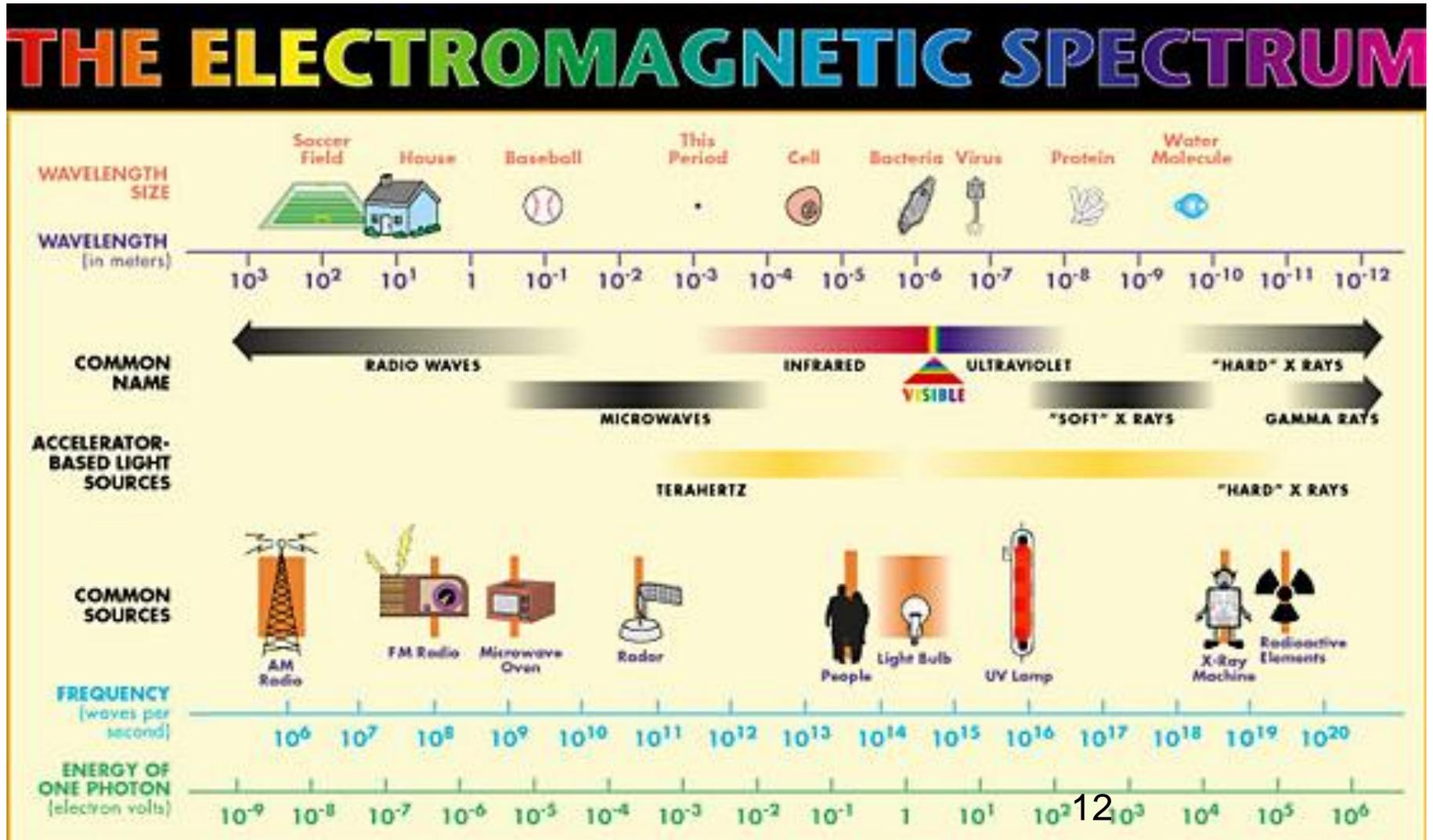
3. PROPIEDADES

1. Alta intensidad, 10^3 - 10^6 superior a la de tubos de Rayos X



3. PROPIEDADES

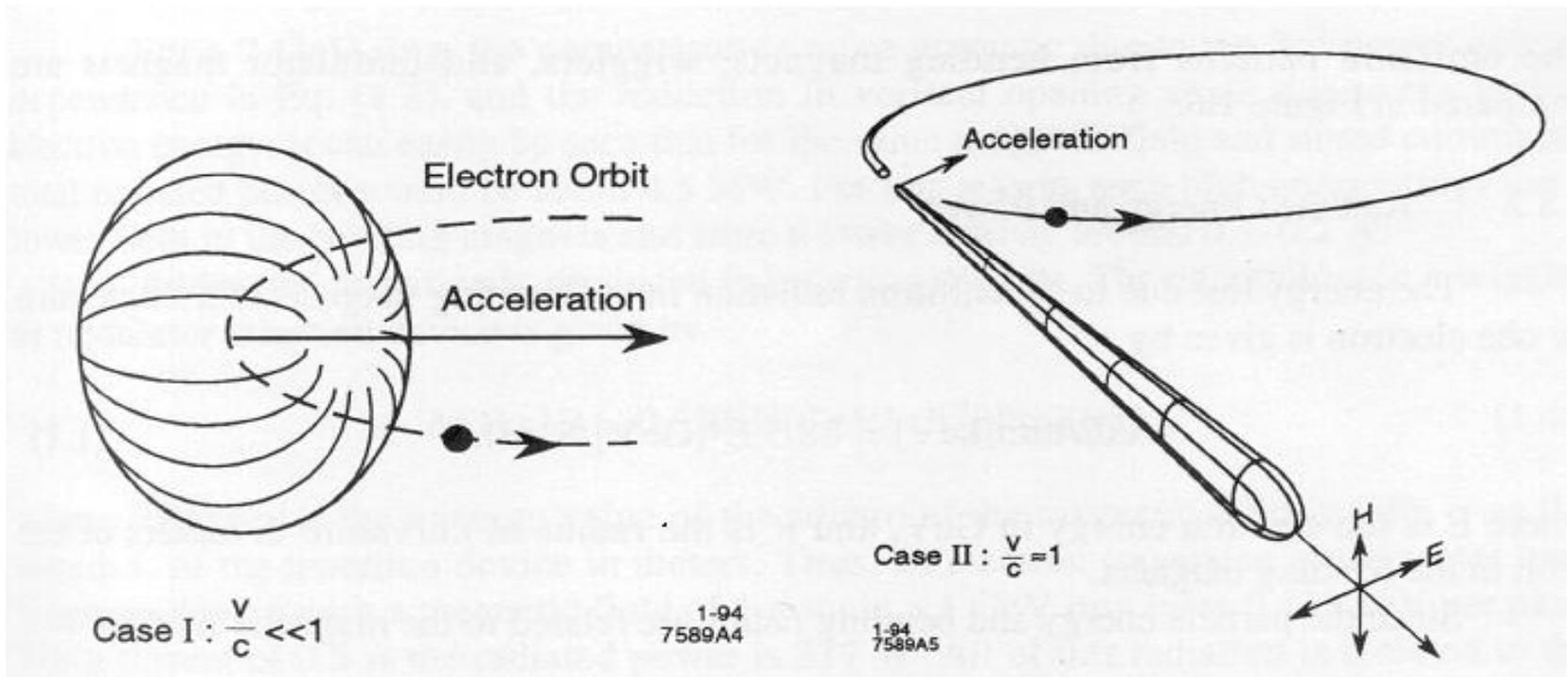
2. Amplio rango de longitudes de onda



3. PROPIEDADES

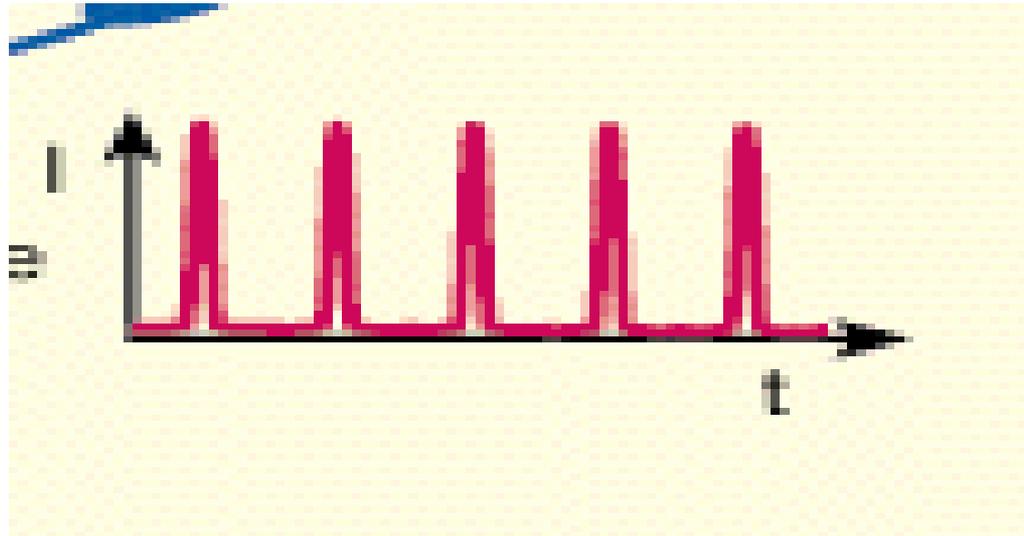
3. Fuerte polarización en el plano de la órbita.

4. Alta colimación o pequeña divergencia



3. PROPIEDADES

5. Precisa estructura temporal pulsada, en la escala de los femto o pico segundos



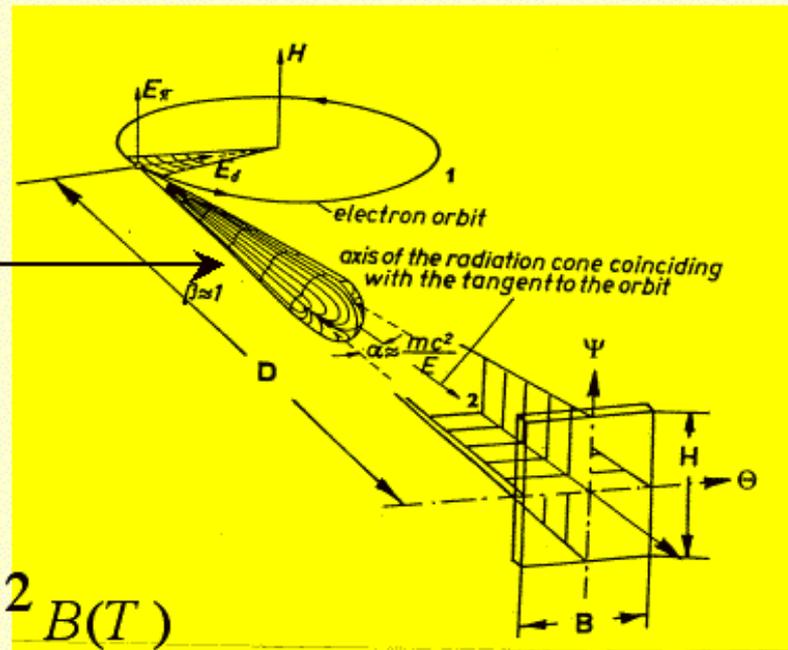
4. PATRONES DE EMISIÓN

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} = \frac{E_e}{m_0 c^2} \quad \beta = \frac{v}{c}$$

Colimación de la LS: $1/\gamma$

Energía Crítica

$$E_c (keV) = 0.665 E_e (GeV)^2 B(T)$$



4. PATRONES DE EMISIÓN

Ángulo de apertura del cono:

$$1/\gamma = Mc^2/E$$

$$Mc^2 = 0.511 \text{ MeV, si } E = 6 \text{ GeV,}$$



$$(1/\gamma) = (0.511 \text{ MeV}) / (6 \text{ GeV}) = 0.08 \text{ mrad} = 0.004^\circ$$

ESTRUCTURA TEMPORAL (RF)

- Haz: paquetes de electrones
- Anchura: *Paquete de $\sim 3 \text{ cm}$ a $v = c$*



pulso de ~ 100 picosegundos

POLARIZACIÓN

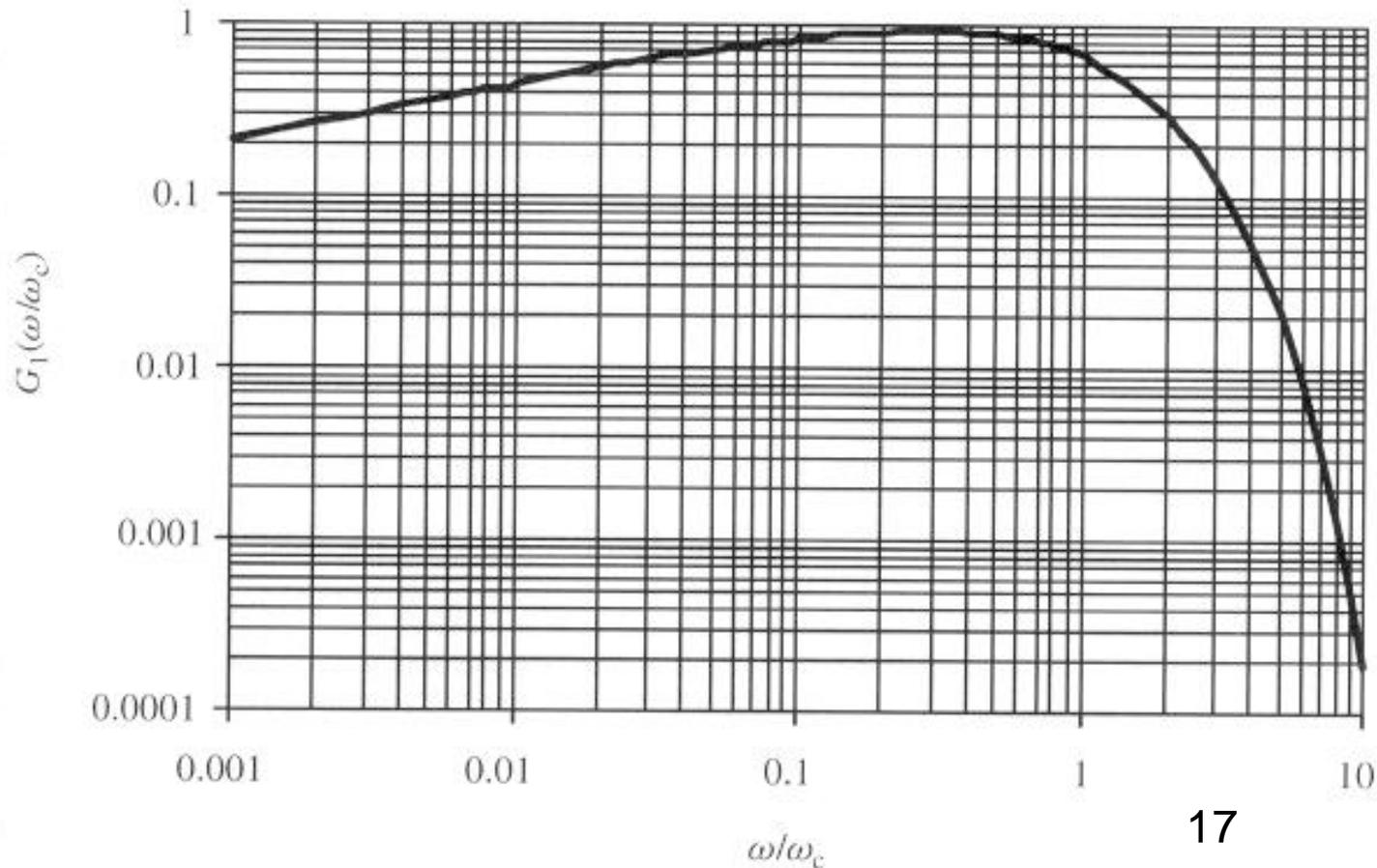
- Electrón dipolo eléctrico oscilante en plano de la orbita
- Radiación polarizada casi al 100%

4. PATRONES DE EMISIÓN

El flujo de fotones, F , emitido por la fuente es función de la energía de las partículas E , de la energía crítica, ϵ_c , y de la intensidad de corriente, I , que circula por el anillo:

$$F[\text{fotones/s/mrad/0.1\%BW}] = 2.457 \cdot 10^{10} E[\text{GeV}] I[\text{mA}] G\left(\frac{\omega}{\omega_c}\right)$$

ω_c = frecuencia crítica



4. PATRONES DE EMISIÓN

La potencia emitida por unidad de intervalo de frecuencia (ω) viene dada por:

$$\frac{dP_\gamma}{d\omega} = \frac{P_\gamma}{\omega_c} S\left(\frac{\omega}{\omega_c}\right)$$

donde la *función universal S* viene dada por:

$$S\left(\frac{\omega}{\omega_c}\right) = \frac{9\sqrt{3}}{8\pi} \left(\frac{\omega}{\omega_c}\right) \int_{\frac{\omega}{\omega_c}}^{\infty} K_{5/3}\left(\frac{\omega}{\omega_c}\right) d\left(\frac{\omega}{\omega_c}\right)$$

y la *frecuencia crítica* ω_c :

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

Obviamente se cumple :

$$\int_0^\infty S\left(\frac{\omega}{\omega_c}\right) d\left(\frac{\omega}{\omega_c}\right) = 1$$

La energía de cada fotón emitido es:

$$\epsilon = \hbar\omega$$

si definimos $n(\epsilon)d\epsilon$ como el número de fotones emitidos por unidad de tiempo con energía entre ϵ y $\epsilon + d\epsilon$, se cumple

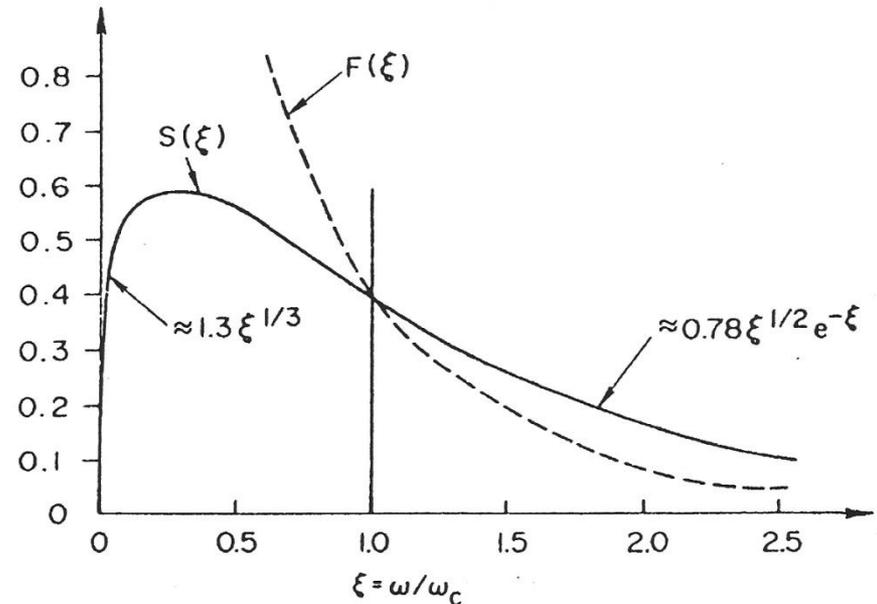
$$\epsilon n(\epsilon)d\epsilon = \frac{dP_\gamma}{d\omega} d\omega$$

con lo que

$$n(\epsilon) = \frac{P_\gamma}{\epsilon_c^2} F\left(\frac{\epsilon}{\epsilon_c}\right)$$

con

$$F\left(\frac{\epsilon}{\epsilon_c}\right) = \left(\frac{\epsilon}{\epsilon_c}\right)^{-1} S\left(\frac{\epsilon}{\epsilon_c}\right)$$



Normalized power spectrum S and photon number spectrum F

4. PARAMETROS FUNDAMENTALES

Por la condición de equilibrio en la órbita se cumple que:

$$R = \frac{p}{eB} = \frac{\sqrt{T(T + 2m_e c^2)}}{ceB}$$

siendo $p = m_e \gamma \beta c$ ($\beta = v/c$).

En las fuentes de sincrotrón se cumple que $T(\sim GeV) \gg m_e c^2 (511 keV)$ (siendo $E = T + m_e c^2$ la energía total) por lo cual con muy buena aproximación:

$$E \simeq T = ceBR$$

que conduce a la muy utilizada expresión

$$E[GeV] = 0.3B[T]R[m]$$

El parámetro γ :

$$\gamma = \frac{E}{m_e c^2} = \frac{E[GeV]}{0.511 \times 10^{-3}}$$

Los parámetros críticos:

$$\omega_c[MHz] = \frac{3\gamma^3 c}{2R} = 4.5 \times 10^2 \frac{\gamma^3}{R[m]}$$

$$\epsilon_c[eV] = 665 B[T](E[GeV])^2 = 2218 \frac{(E[GeV])^3}{R[m]}$$

$$\lambda_c[\text{Å}] = 5.6 \frac{R[m]}{(E[GeV])^3} = \frac{18.6}{B[T] (E[GeV])^2}$$

E: Energía de las partículas cargadas que circulan por el anillo

$\epsilon_c \omega_c \lambda_c$: *Energía, frecuencia, longitud de onda críticas* de los fotones emitidos

B : Campo magnético

R: Radio de curvatura

EMITANCIA Y BRILLO

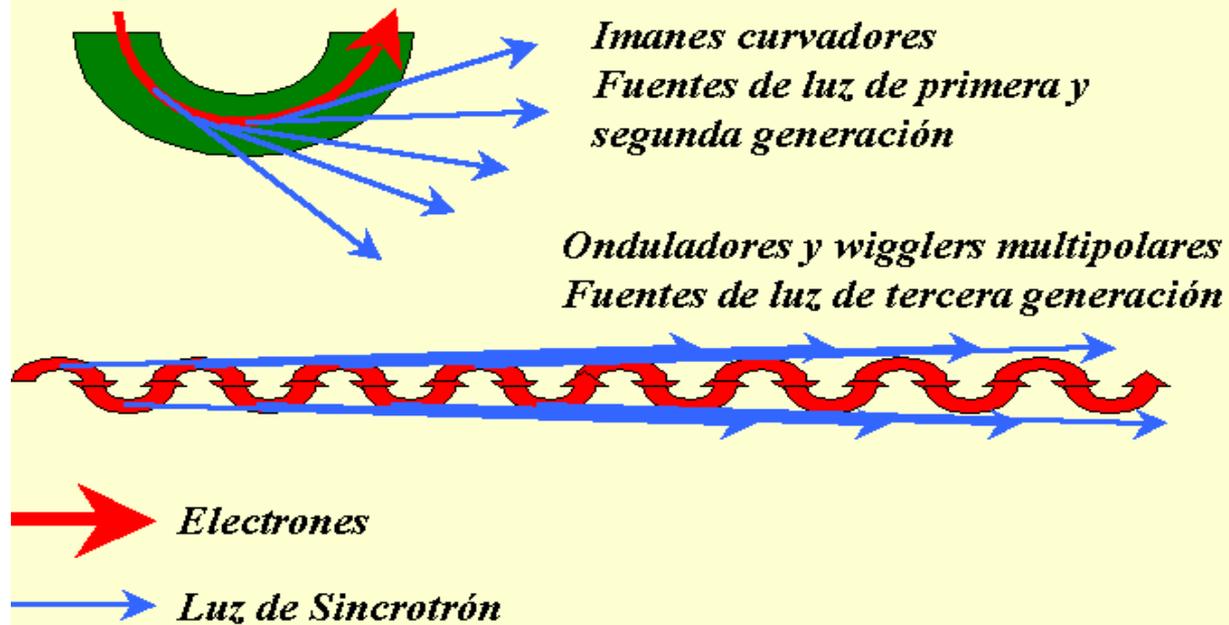
Emitancia: tamaño del haz x divergencia.

Brillo : fot/seg/angulo solido/area sup emisora

Brillo espectral: brillo/0.1 % BW

5. DISPOSITIVOS DE INSERCIÓN

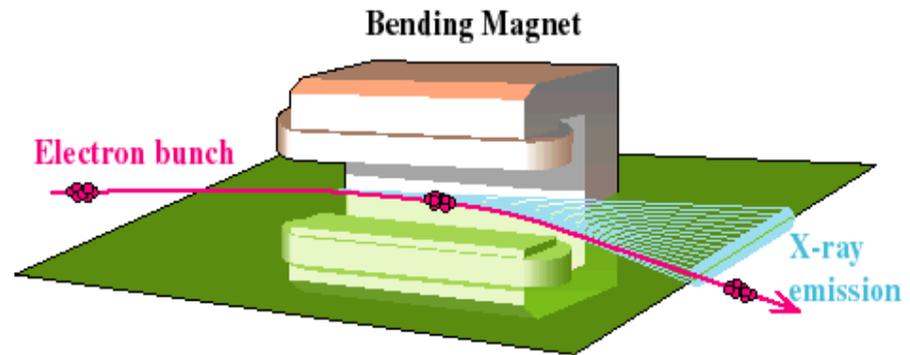
Fuentes de Luz



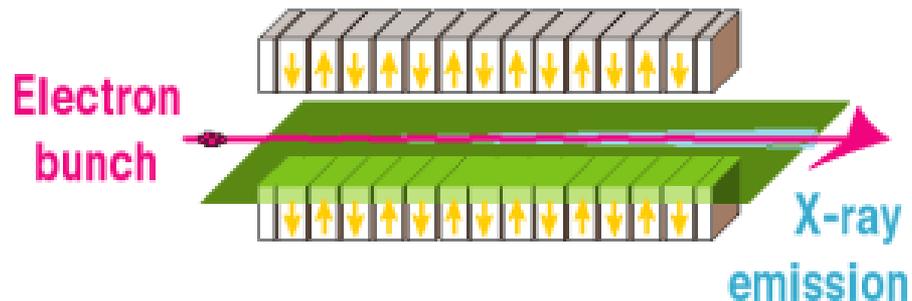
5. DISPOSITIVOS DE INSERCIÓN

1ª generación : Aceleradores de física de altas energías

2ª generación : Radiación emitida "imán de curvatura" (BM)



3ª generación : radiación emitida "dispositivos inserción"
(wiggler, ondulador)

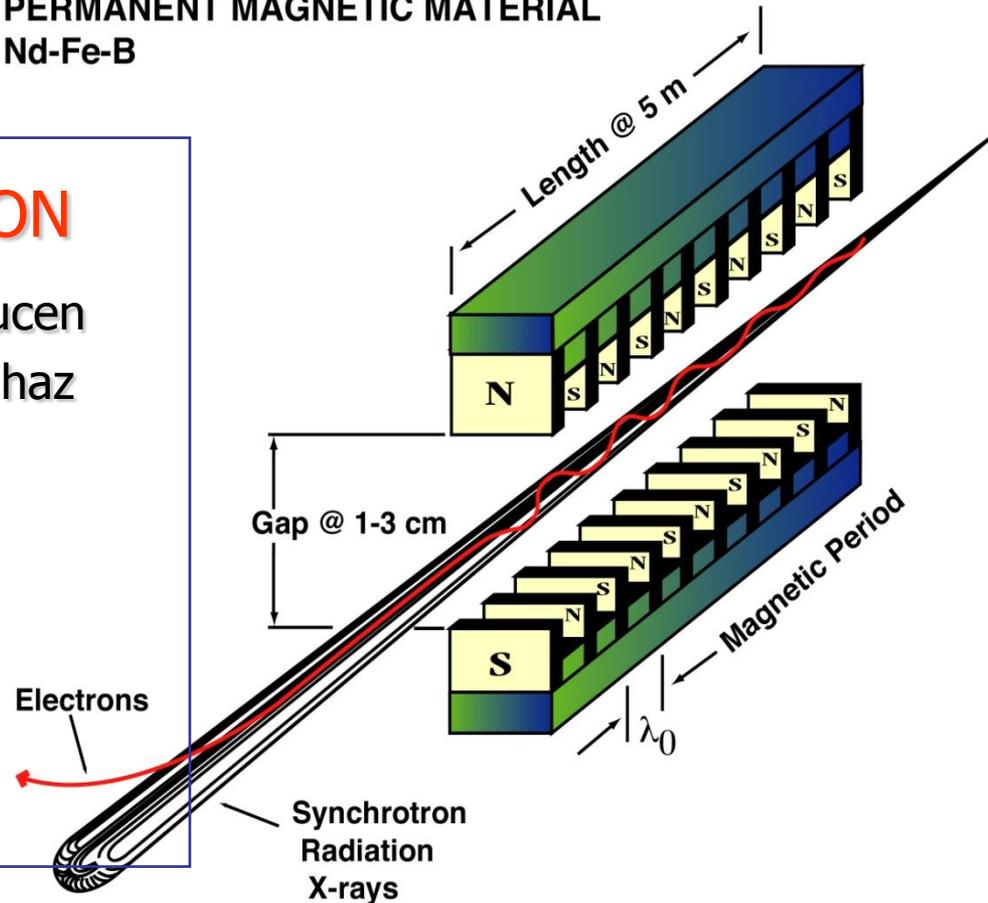


INSERTION DEVICE (WIGGLER OR UNDULATOR)
PERMANENT MAGNETIC MATERIAL
Nd-Fe-B

5. DISPOSITIVOS DE INSERCIÓN

- Dipolos magnéticos alternos que producen campos magnéticos perpendiculares al haz
- Modifican **emitancia** y el **brillo** del haz
- Parámetro de deflexión:

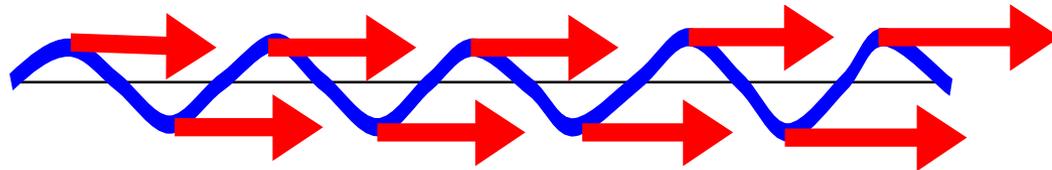
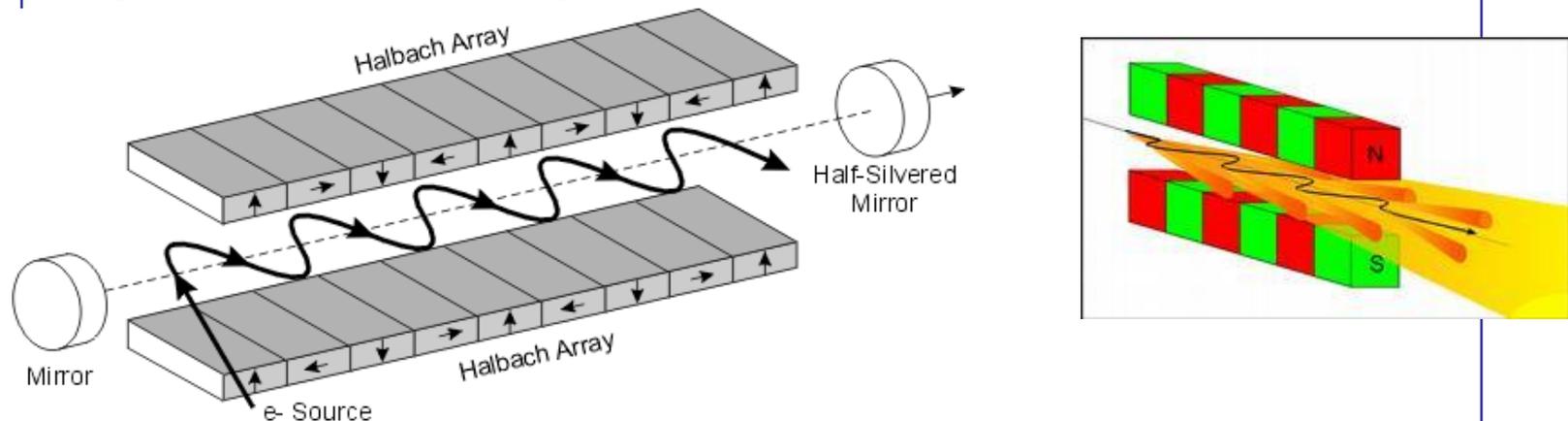
$$K = \frac{eB\lambda_u}{2\pi m_e c}$$



5. DISPOSITIVOS DE INSERCIÓN

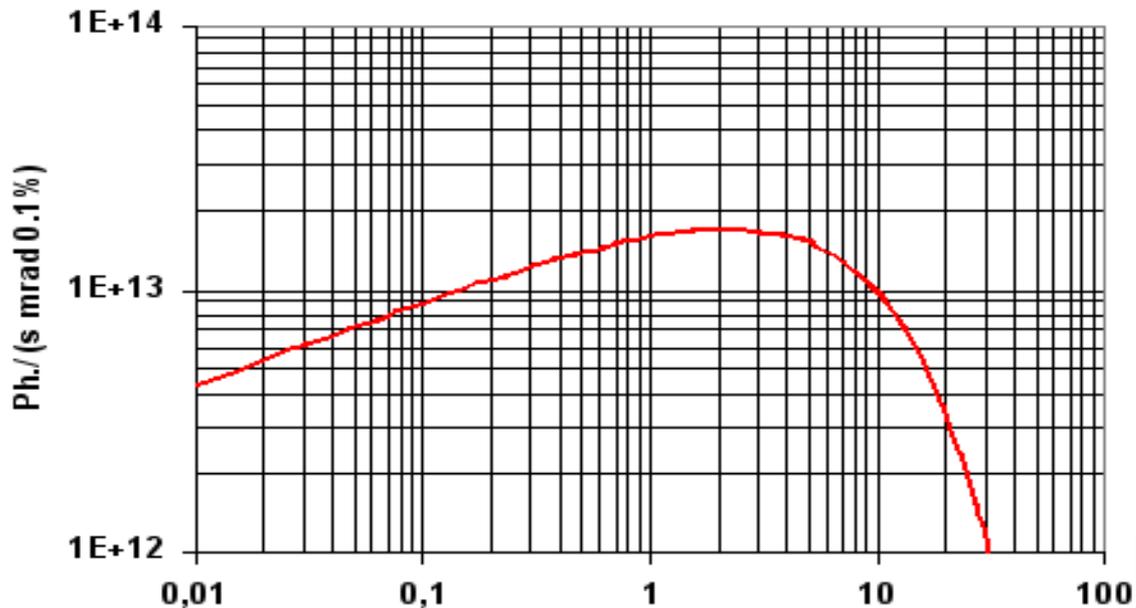
Wiggler

Disposicion de imanes permanentes (verde y amarillos) en un wiggler. La longitud del periodo es "larga". Parámetro de deflexión $K \gg 1$



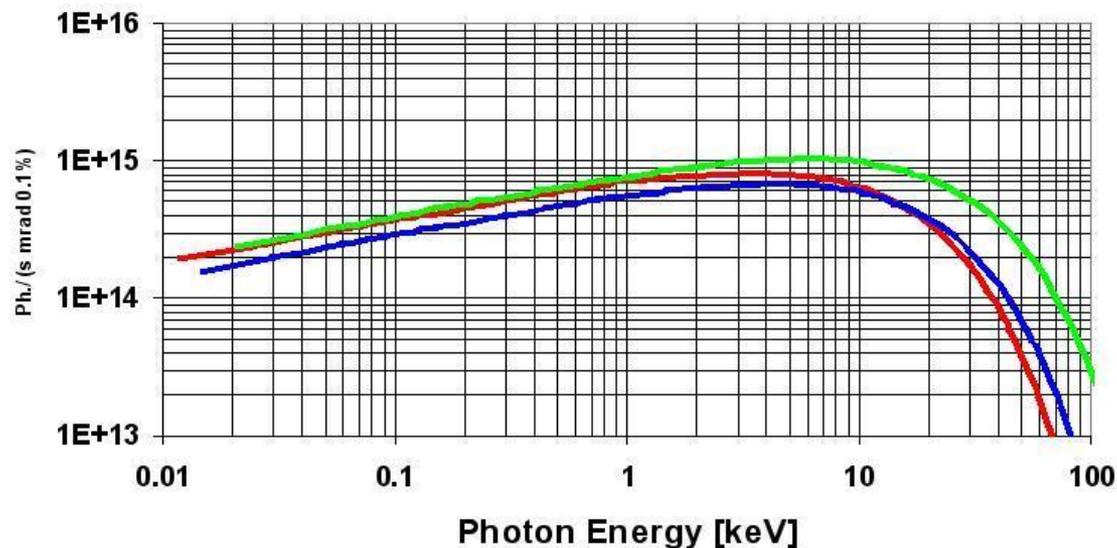
La trayectoria de un haz de electrones en un wiggler (línea azul). Las flechas rojas simbolizan la radiación sincrotrón emitida, la intensidad aumenta por el solapamiento de los conos de radiación.

5. DISPOSITIVOS DE INSERCIÓN



Iman de curvatura

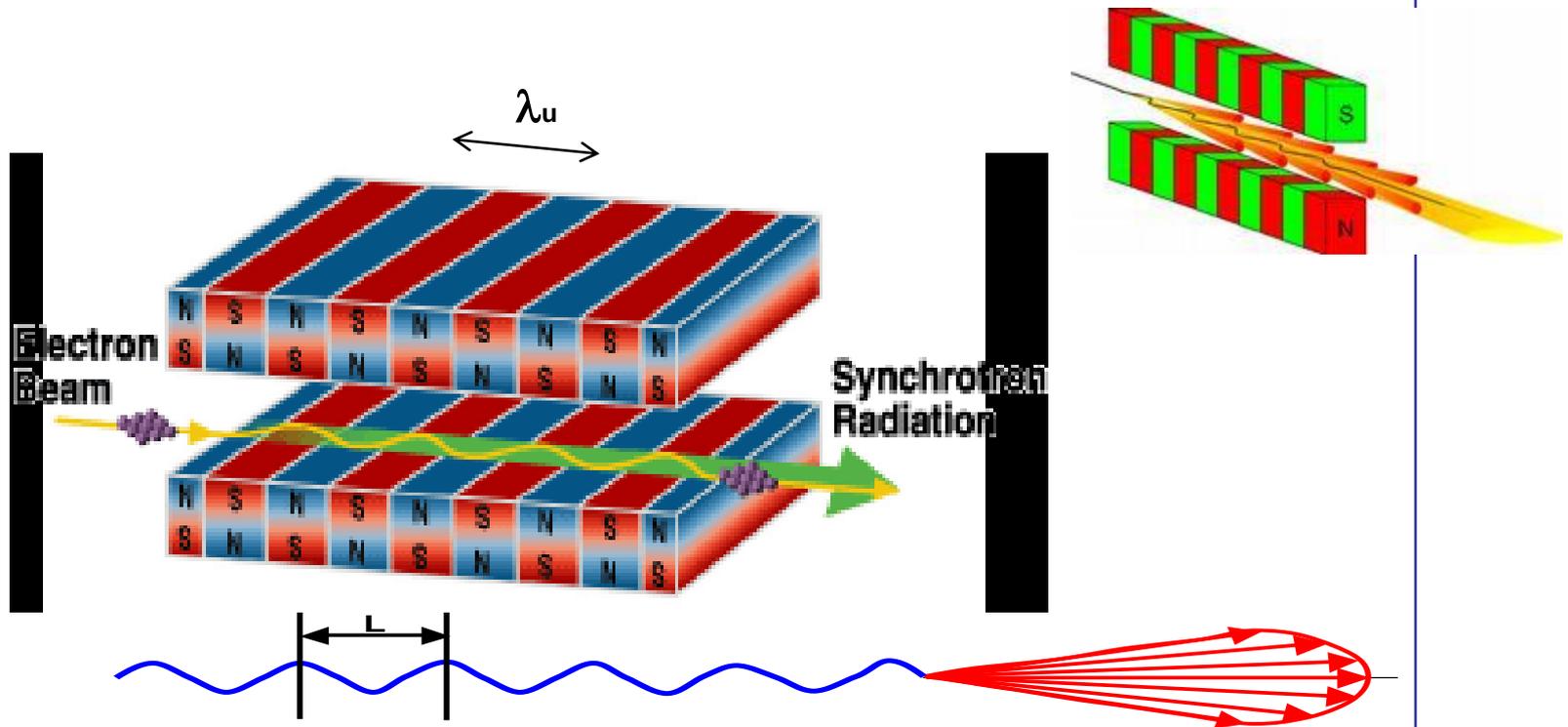
Flujo de fotones emitido por una fuente de 3 GeV y una corriente de 250 mA



Wiggler

5. DISPOSITIVOS DE INSERCIÓN

Ondulador



Trayectoria de un haz de electrones en un ondulator (línea azul). Las flechas rojas simbolizan la radiación sincrotrón emitida. En este caso tiene lugar un fenómeno de interferencia. *Parámetro de deflexión $K \ll 1$*

6. COMPONENTES TÉCNICOS

INYECTOR

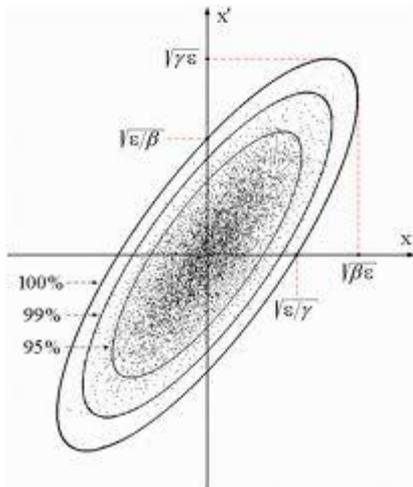
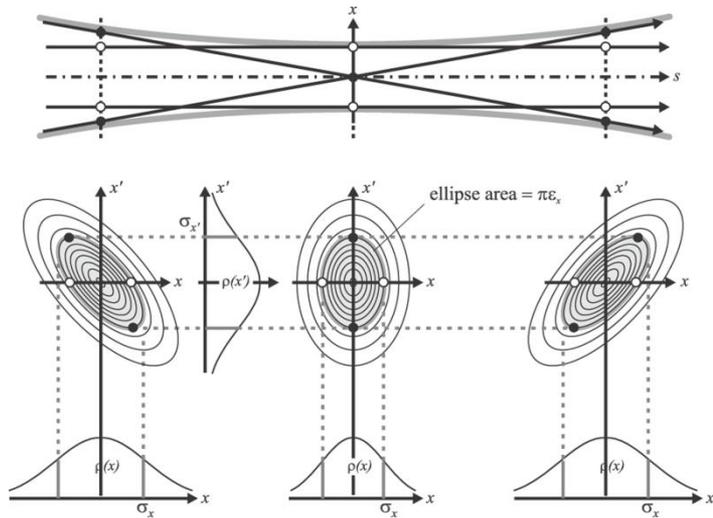
- **Cañón de electrones**
- **Linac**: acelerador lineal

BOOSTER + ANILLO DE ACUMULACIÓN:

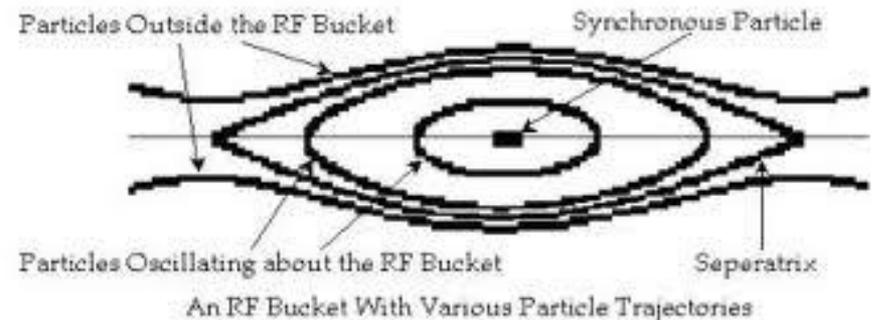
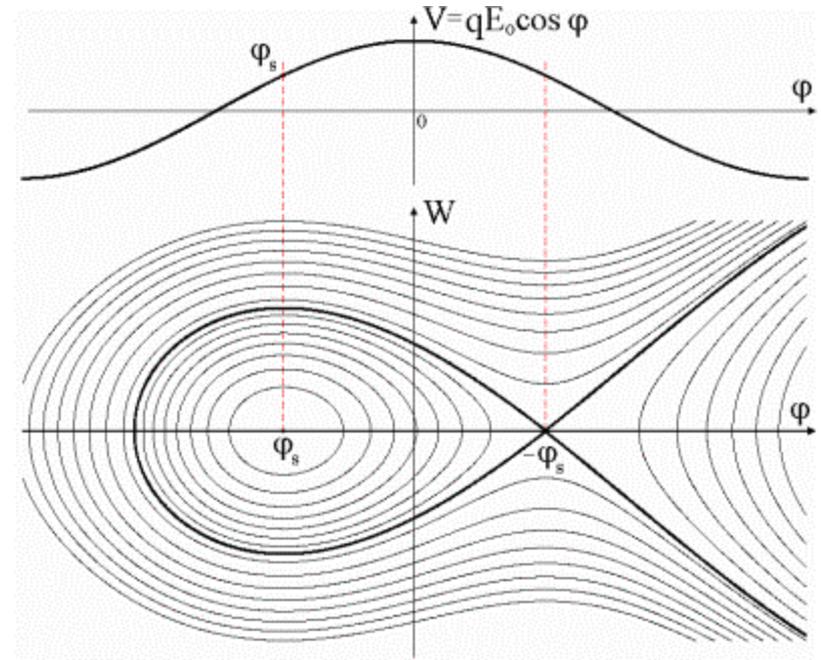
- **Red magnética** (lattice)
 - Conjunto de imanes
 - Dipolos: curvan la trayectoria del haz
 - Cuadrupolos: focalizan
 - Sextupolos: correcciones de las órbitas.
 - Fija propiedades básicas haz: "emitancia", dimensiones (**dinámica transversal**)
- **Sistema de RF**
 - Fuentes de alimentación, guías de ondas
 - Cavidades RF
 - Acelera (Booster) y/o suministra al haz la energía perdida como radiación sincrotrón (anillo de acumulación) (**dinámica longitudinal**)

6. COMPONENTES TÉCNICOS

Dinámica transversal: red magnética



Dinámica longitudinal: sistema RF



6. COMPONENTES TÉCNICOS

BOSTER+ ANILLO DE ACUMULACIÓN (continuación):

- **Sistema de alto (booster)/ultraalto (anillo de acumulación) vacío**
 - El haz de electrones circula en un tubo en ultraltovacío, ($P=10^{-9}$ - 10^{-10} torr) para mantener su intensidad (1/2 de la inicial tras 5-50 horas).

6. COMPONENTES TÉCNICOS

IMANES

SR Dipolo



SR Cuadrupolo

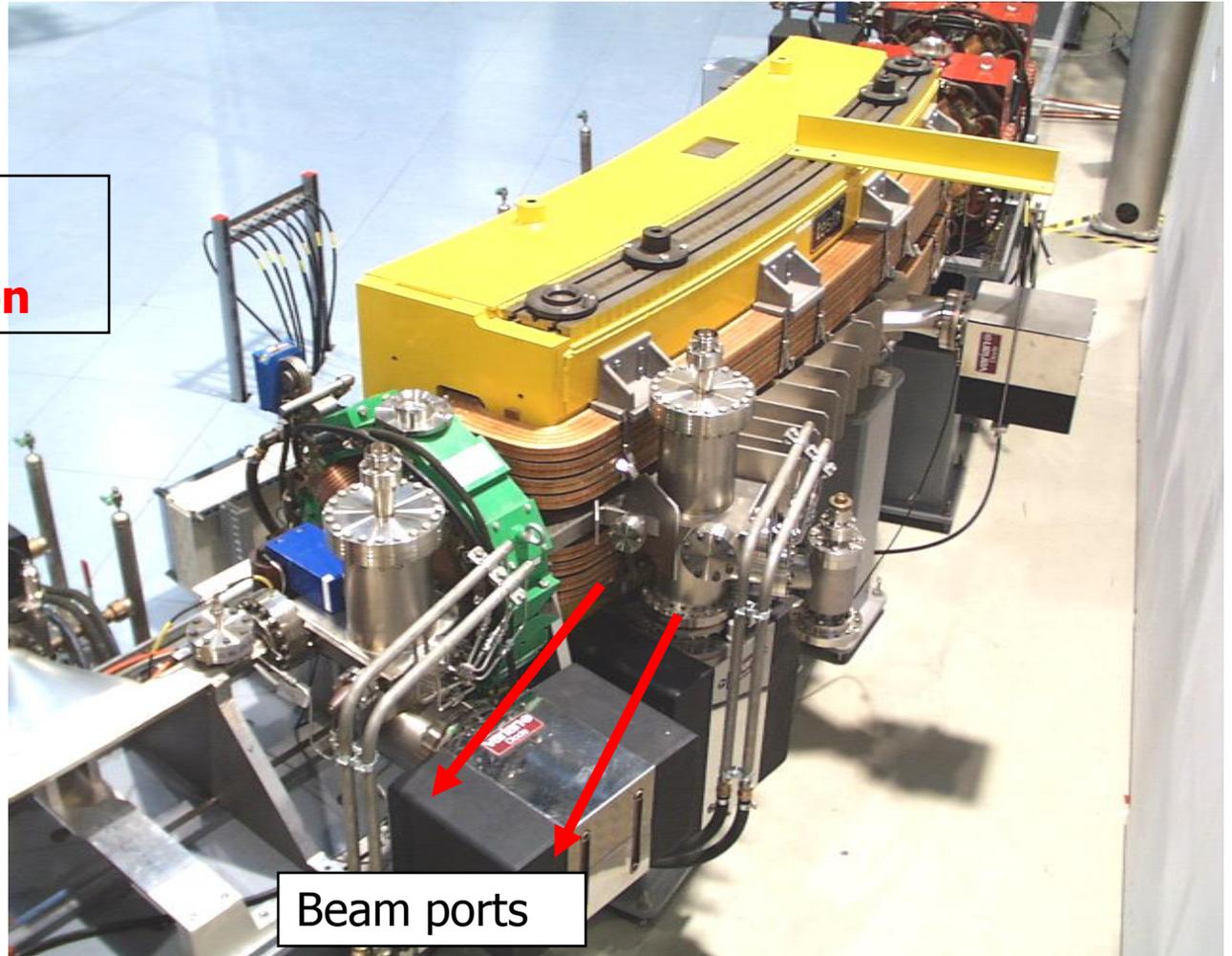


SR Sextupolo



6. COMPONENTES TÉCNICOS

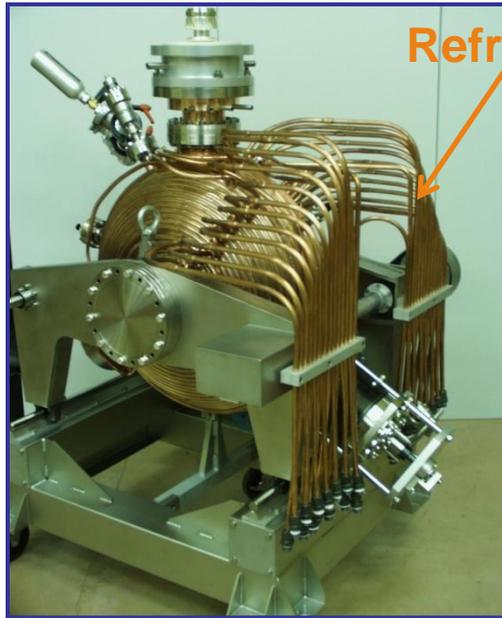
**Imán de curvatura
y línea de extracción**



Courtesy: E.Huttel, ANKA

6. COMPONENTES TÉCNICOS

Sistemas de Radio Frecuencia



Refrigeración

Alimentación:
guías de ondas



Convencional



Superconductor



Vista general

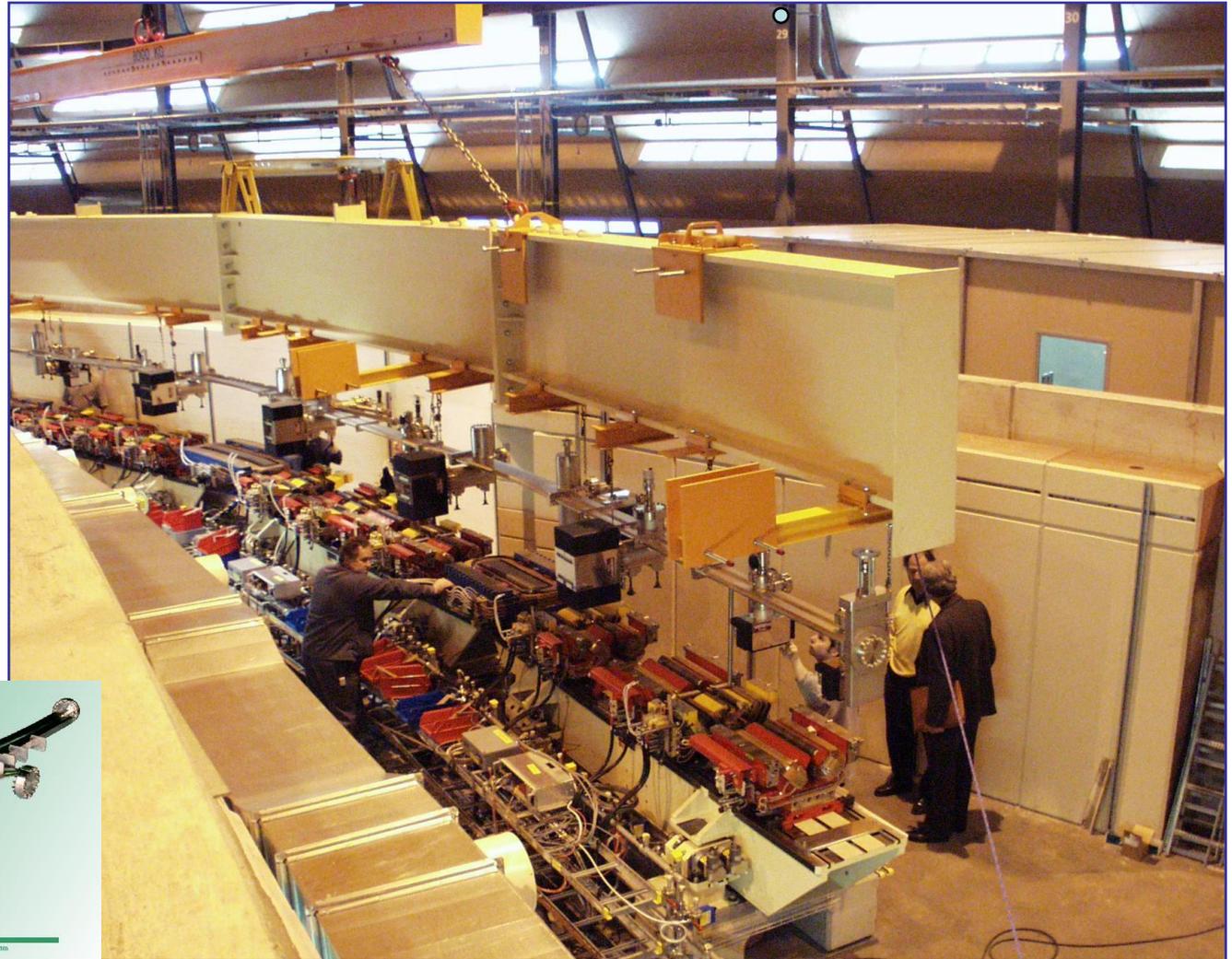


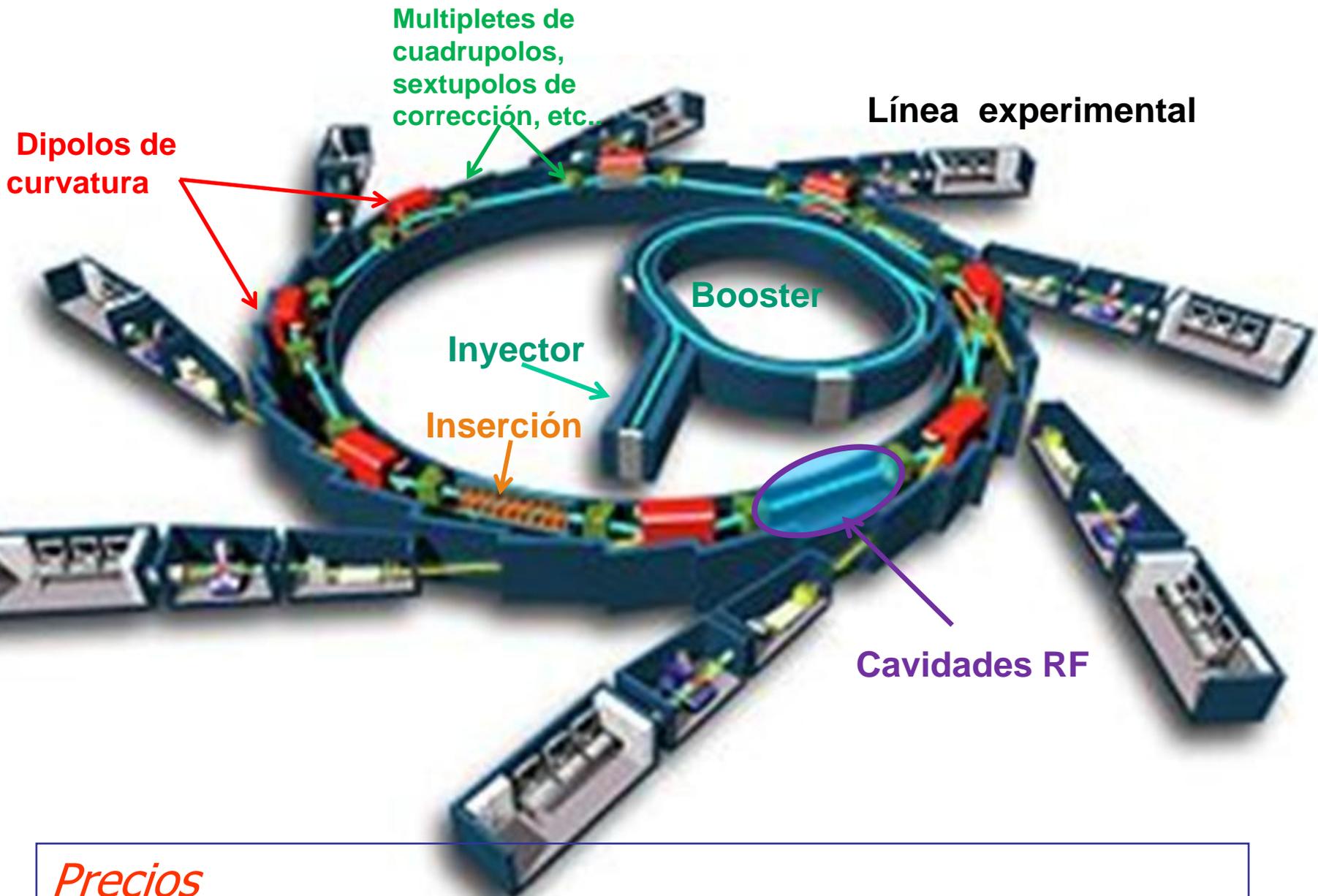
6. COMPONENTES TÉCNICOS

Montaje de un sector de vacío en el Swiss Light Source

Vacio

Cortesía de L.Rivkin,
SLS



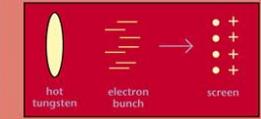


Precios

- *Anillo 3^a generación, 90 m y 3 GeV de energía: 160 millones de euros (más otros tantos para la construcción de "beam-lines")*

Electron Gun: Where do the electrons come from?

Bunches of electrons blast out of an electron gun. The electron source is a button-sized piece of treated tungsten (the same material as in light bulb filaments) that releases electrons (e⁻) when it is heated to about 1000C. A screen near the electron source is given a strong, short-lived positive charge 125 million times each second, and this positive charge pulls negatively charged electrons away from the electron source (opposites attract) in bunches of billions of electrons each.



AT THE END OF ELECTRON GUN			
Time 400 billionths of a second	Distance 1 meter	Speed 59.5% of speed of light (178,484,000 meters per second)	Energy 120,000 electron volts

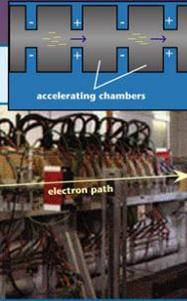
Linac: How do you make the electrons go faster?

A long series of accelerating chambers drives electrons nearly to the speed of light.

When an electron bunch enters an accelerating chamber, it speeds toward a positive charge on the far wall (opposites attract). While the electrons race through a hole into the next chamber, the charges are reversed, so the now-negative charge repels the electrons and the now-positive charge ahead attracts them.

The linear accelerator (linac) has 120 small accelerating chambers. Large magnetic focusing coils around the chambers keep the electrons in tight bunches. When the electrons leave the linac, they are traveling fast enough to go around the world 7 1/2 times in one second, but they need more energy to generate x rays.

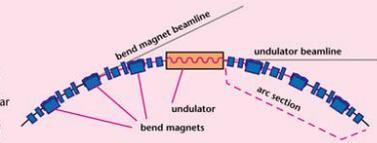
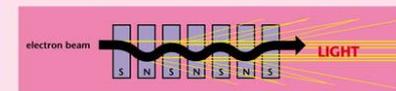
AT THE END OF LINAC			
Time 800 billionths of a second	Distance 5 meters	Speed 99.9948% of speed of light (299,777,000 meters per second)	Energy 50 million electron volts



Storage Ring: How do electrons generate light?

Electrons zip around the storage ring 1.5 million times per second, producing bright light at every turn.

Once the electrons reach their target energy, an injection system transfers them from the booster to the storage ring, where they circulate for hours. At every curve in their path, the electrons emit light (photons) forward like a car headlight. Electrons curving through the bend magnets (e⁻) in the ring's 12 arc sections emit fanlike beams of photons, like cars rounding a bend at night. Between these curves are straight sections where multi-magnet devices called

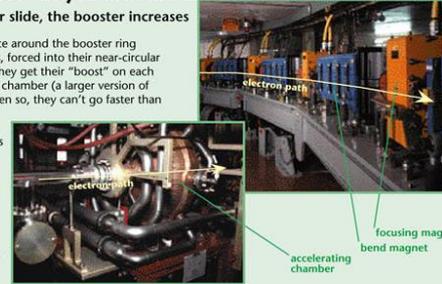


undulators wiggle the electrons back and forth, so the light from each wiggle overlaps and forms a narrow beam 100 million times brighter than conventional x-ray sources.

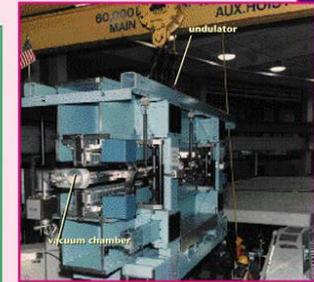
Booster Ring: How do you increase the energy of the electrons?

Like a circular slide, the booster increases

The electrons race around the booster ring more than 1 million times, forced into their near-circular path by bend magnets. They get their "boost" on each turn from an accelerating chamber (a larger version of those in the linac), but even so, they can't go faster than the speed of light. Pushing closer to light speed makes the electrons gain mass, though, and this increases their energy. So the booster's "accelerating chamber," which boosts the electrons' energy by 30 times, does it mostly by increasing their mass, not their speed.



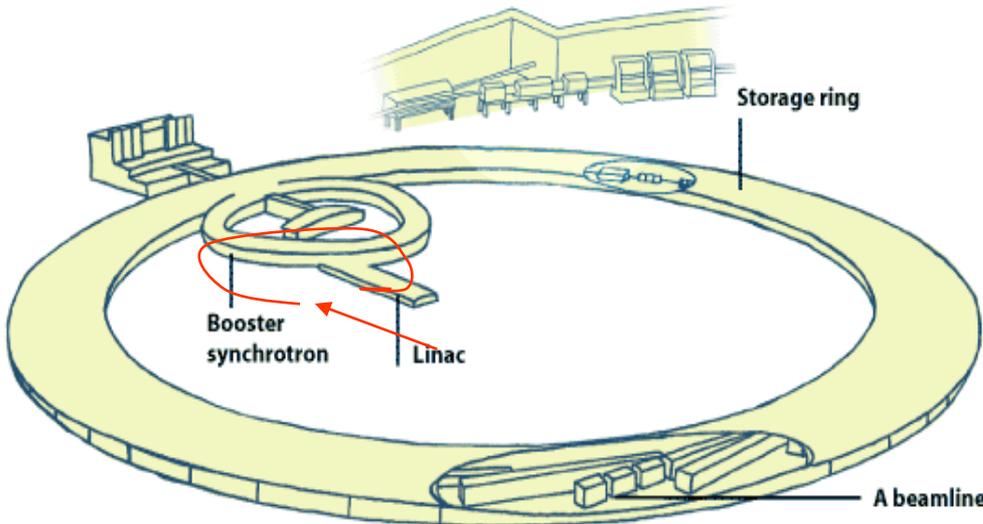
AT THE END OF BOOSTER CYCLE			
Time 0.33 seconds	Distance 98,000 kilometers	Speed 99.999994% of speed of light (299,792,000 meters per second)	Energy 1.5 billion electron volts



The electrons travel in a vacuum chamber with fewer atoms per unit volume than outer space, so there are almost no collisions to slow them down. However, each photon they emit carries off a bit of the electrons' energy (e⁻), which is replenished in two accelerating chambers (like the one in the booster).

AFTER FOUR HOURS IN STORAGE RING			
Time 4 hours	Distance 432 billion kilometers	Speed 99.999994% of speed of light (299,792,000 meters per second)	Energy 1.5 billion electron volts

Viaje de los electrones desde el cañón, al linac, booster y anillo

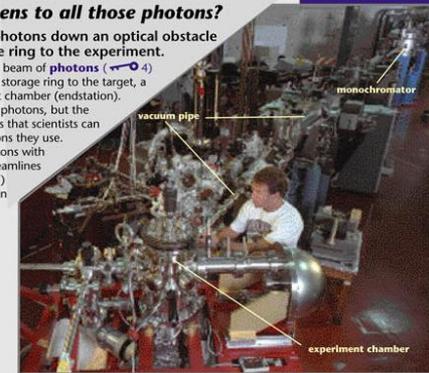


Beamlines: What happens to all those photons?

Beamlines deliver the photons down an optical obstacle course from the storage ring to the experiment.

Beamline mirrors steer and focus a thin beam of photons (e⁻) down meters of vacuum pipe from the storage ring to the target, a sample of interest inside an experiment chamber (endstation). Some experiments use all the available photons, but the storage ring produces so many photons that scientists can afford to be choosy about which photons they use. Scientists who want to select only photons with certain wavelengths (e⁻) use beamlines with monochromators ("one-color-ers") which act like prisms, spreading the thin photon beam into a spectrum of different wavelengths so only the desired ones go through an exit slit.

Researchers make observations by using the photons to produce small changes in their samples, and a variety of instruments record the results. Computers help convert the instruments' readings into images, graphs, or even 3-D models, making new information available for advancing science and technology.



7. Los tres mayores sincrotrones del mundo



ESRF, Europa-France

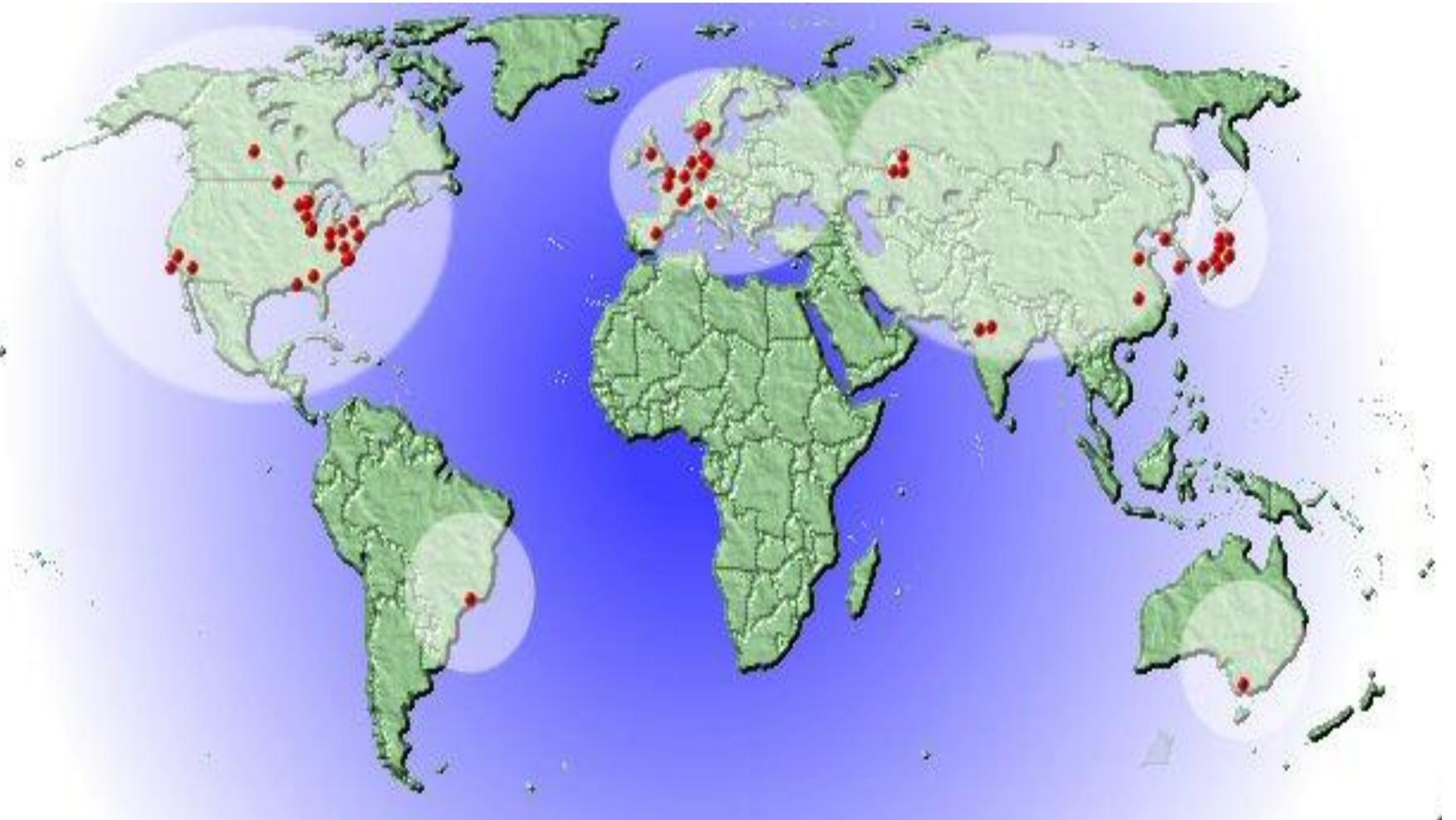
APS, USA



Spring-8, Japón



7. Los sincrotrones del mundo



7. Los sincrotrones del mundo

- TSRF - Laboratory of Nuclear Science - Tohoku University
- SuperSOR Light Source - Institute for Solid State Physics - University of Tokyo
- National Institute of Radiological Sciences (NIRS)
- Nano-Hana
- NSSR - Nagoya University
- UVSOR - Institute for Molecular Research
- Rits SR - MIRRORCLE-20 - MIRRORCLE-6X - Synchrotron Light Life Science Center - Ritsumeikan University
- KSR - Institute for Chemical Research - Kyoto University
- SAGA Synchrotron Light Research Center
- HISOR - Hiroshima University
- Spring8 - NewSUBARU - NIJI-III
- PF - PF-AR - NIJI-II - NIJI-IV - TERAS
- National Institute of Advanced Industrial Science and Technology



JAPÓN

7. Los sincrotrones del mundo

Asia

[BSRF - Beijing Synchrotron Radiation Facility](#), P.R

[CANDLE](#), Armenia

[HSRC - Hiroshima Synchrotron Radiation Center](#), Japan

[iFEL - Institute of Free Electron Laser](#), Japan

[INDUS 1/INDUS 2](#), India

[IR FEL Research Center - FEL-SUT](#), Japan

[Medical Synchrotron Radiation Facility](#), Japan

Nano-Hana, Japan

[NSRL - National Synchrotron Radiation Laboratory](#), P.R. China

[NSRRC - National Synchrotron Radiation Research Center](#), Taiwan

[NSSR - Nagoya University Small Synchrotron Radiation Facility](#), Japan

[KSR - Nuclear Science Research Facility](#), Japan

[PAL - Pohang Accelerator Laboratory](#), Korea

[PF - Photon Factory](#), KEK, Japan

[Ritsumeikan University \(Rits\) Synchrotron Radiation Center](#), Japan

[SAGA-LS - Saga Light Source](#), Japan

[SESAME](#), Jordan

[SPL - Siam Photon Laboratory](#), Thailand

[SPring-8](#), Japan

[SSLS - Singapore Synchrotron Light Source](#), Singapore

[SSRC - Siberian Synchrotron Research Center](#), Russian Federation

[SSRF - Shanghai Synchrotron Radiation Facility](#), P.R. China

[SuperSOR - SuperSOR Synchrotron Radiation Facility](#), Japan

[TSRF - Tohoku Synchrotron Radiation Facility](#), Japan

[UVSOR - Ultraviolet Synchrotron Orbital Radiation Facility](#), Japan

Europe

[ALBA - Synchrotron Light Facility](#), Spain
[ANKA - Angstromquelle Karlsruhe](#), Germany
[BESSY - Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung](#), Germany
[CESLAB - Central European Synchrotron Laboratory](#), Czech Republic (external link)
[CLIO - Centre Laser Infrarouge d'Orsay](#), France
[DAFNE Light](#), Italy
[DELSY - Dubna ELection SYnchrotron](#), Russian Federation
[DELTA - Dortmund Electron Test Accelerator](#), Germany
[Diamond Light Source](#), UK
[ELETTRA - Synchrotron Light Laboratory](#), Italy
[ELSA - Electron Stretcher Accelerator](#), Germany
[ESRF - European Synchrotron Radiation Facility](#), France
[FELBE - Free-Electron Lasers at the ELBE radiation source at the FZD](#), Germany
[FELIX - Free Electron Laser for Infrared eXperiments](#), The Netherlands
[HASYLAB - Hamburger Synchrotronstrahlungslabor at DESY](#), Germany
[ISA - Institute for Storage Ring Facilities](#), Denmark
[ISI-800 - Institute of Metal Physics](#), Ukraine
[Kharkov Institute of Physics and Technology](#), Ukraine
[KSRS - Kurchatov Synchrotron Radiation Source](#), Russian Federation
[MAX-lab](#), Sweden
[MLS - Metrology Light Source](#), Germany
[PSSL - Polish Synchrotron Light Source](#), Poland (external link)
[SLS - Swiss Light Source](#), Switzerland
[SOLEIL](#), France
[TNK - F.V Lukin Institute](#), Russian Federation

7. Los sincrotrones del mundo

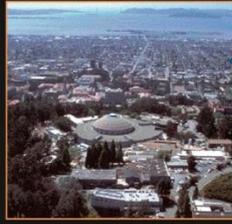
America

[ALS - Advanced Light Source](#), USA
[APS - Advanced Photon Source](#), USA
[CAMD - Center for Advanced Microstructures & Devices](#), USA
[CFN - Center for Functional Nanomaterials](#), USA
[CHESS - Cornell High Energy Synchrotron Source](#), USA
[CLS - Canadian Light Source](#), Canada
[CNM - Center for Nanoscale Materials](#), USA
[CTST - UCSB Center for Terahertz Science and Technology](#), USA
[DFELL - Duke Free Electron Laser Laboratory](#), USA
[FOUNDRY - The Molecular Foundry](#), USA
[Jlab - Jefferson Lab](#), USA
[LCLS - Linac Coherent Light Source](#), USA
[LNLS - Laboratorio Nacional de Luz Sincrotron](#), Brazil
[NSLS - National Synchrotron Light Source](#), USA
[SRC - Synchrotron Radiation Center](#), USA
[SSRL - Stanford Synchrotron Radiation Laboratory](#), USA
[SURF - Synchrotron Ultraviolet Radiation Facility](#), USA
[VU FEL - W. M. Keck Vanderbilt Free-electron Laser Center](#), USA
Australia
[AS - Australian Synchrotron](#)

<http://www.lightsources.org>

The brightest source in America for light from ultraviolet through soft x rays is not a laser, a medical x-ray machine, or even the sun. It is a beam of electrons, accelerated nearly to the speed of light by a large particle accelerator called a synchrotron—the **Advanced Light Source**.

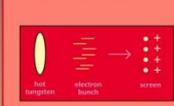
Inside the ALS tells how the electrons start out, speed up, gain energy, and produce exceptionally bright light. This light, often focused into beams thinner than a human hair, fuels scientific experiments from physics to forensics.



Scientists from around the world can do experiments at the ALS, a research facility funded by the Department of Energy and located at Lawrence Berkeley National Laboratory, University of California.

Electron Gun: Where do the electrons come from?

The electron source is a button-sized piece of treated tungsten (the same material as in light bulb filaments) that releases electrons (e^-) when it is heated to about 1000K. A screen near the electron source is given a strong, short-lived positive charge 12.2 million times each second, and this positive charge pulls negatively charged electrons away from the electron source (opposites attract e^-) in bunches of billions of electrons each.



Time	Distance	Speed	Energy
100 femtoseconds (1/10,000,000,000,000 second)	100 micrometers (1/100,000 meter per second)	100,000,000 meters per second	100 eV (electron volts)

Linac: How do you make the electrons go faster?

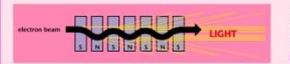
A long series of accelerating chambers drives electrons nearly to the speed of light. When an electron bunch enters an accelerating chamber, it speeds through a positive charge on the far wall (opposite attracts e^-). When the electrons race through a hole into the next chamber, the charges are reversed; so the now-negative charge repels the electrons and the now-positive charge ahead attracts them. The linear accelerator (linac) has 120 small accelerating chambers. Large magnetic focusing (e^-) coils around the chambers keep the electrons in tight bunches. When the electrons leave the linac, they are traveling fast enough to go around the world 7 1/2 times in one second, but they need more energy to generate x rays.

Time	Distance	Speed	Energy
100 femtoseconds (1/10,000,000,000,000 second)	100 micrometers (1/100,000 meter per second)	100,000,000 meters per second	100 eV (electron volts)



Storage Ring: How do electrons generate light?

Electrons zip around the storage ring 1.5 million times per second, producing bright light at every turn. Once the electrons reach their target energy, an injection system transfers them from the booster to the storage ring, where they circulate for hours. At every curve in their path, the electrons emit light (photons e^-) forward like a car headlight. Electrons curving through the bend magnets (e^-) in the ring's 1.3 arc sections emit fanlike beams of photons, like car rounding a bend at the right. Between these curves are straight sections where multi-magnet devices called



undulators wiggle the electrons back and forth, so the light from each wiggle overlaps and forms a narrow beam 100 million times brighter than conventional x-ray (e^-) sources.

Booster Ring: How do you increase the energy of the electrons?

Like a circular slide, the booster increases the electrons' energy. The electrons race around the booster ring more than 1 million times, forced into their near-circular path by bend magnets. They get their "boost" on each turn from an accelerating chamber (a larger version of those in the linac), but even so, they can't go faster than the speed of light. Pushing closer to light speed makes the electrons gain mass, though, and this increases their energy. So the booster's "accelerating chamber," which boosts the electrons' energy by 30 times, does it mostly by increasing their mass, not their speed.

Time	Distance	Speed	Energy
100 femtoseconds (1/10,000,000,000,000 second)	100 micrometers (1/100,000 meter per second)	100,000,000 meters per second	100 eV (electron volts)

Time	Distance	Speed	Energy
4 hours	400 kilometers (1/250,000 meter per second)	100,000,000 meters per second	1.5 MeV (electron volts)

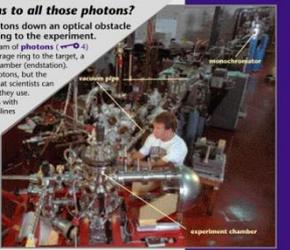
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The electrons travel in a vacuum chamber with fewer atoms per unit volume than outer space, so there are almost no collisions to slow them down. However, each photon they emit carries off a bit of the electron's energy (e^-) which is replenished in two accelerating chambers (like the one in the booster).

Beamlines: What happens to all those photons?

Beamlines deliver the photons down an optical obstacle course from the storage ring to the experiment. Beamline mirrors steer and focus a thin beam of photons (e^-) down meters of vacuum pipe from the storage ring to the target, a sample of interest inside an experiment chamber (endstation). Some experiments use the available photons, but the storage ring produces so many photons that scientists can afford to be choosy about which photons they use. Scientists who want to select only photons with certain wavelengths (e^-) use beamlines with monochromators ("one-color-ers") which act like prisms, spreading the thin photon beam into a spectrum of different wavelengths so only the desired ones go through an exit slit. Researchers make observations by using the photons to produce small changes in their samples, and a variety of instruments record the results. Computers help convert the instrument's readings into images, graphs, or even 3-D models, making new information available for advancing science and technology.

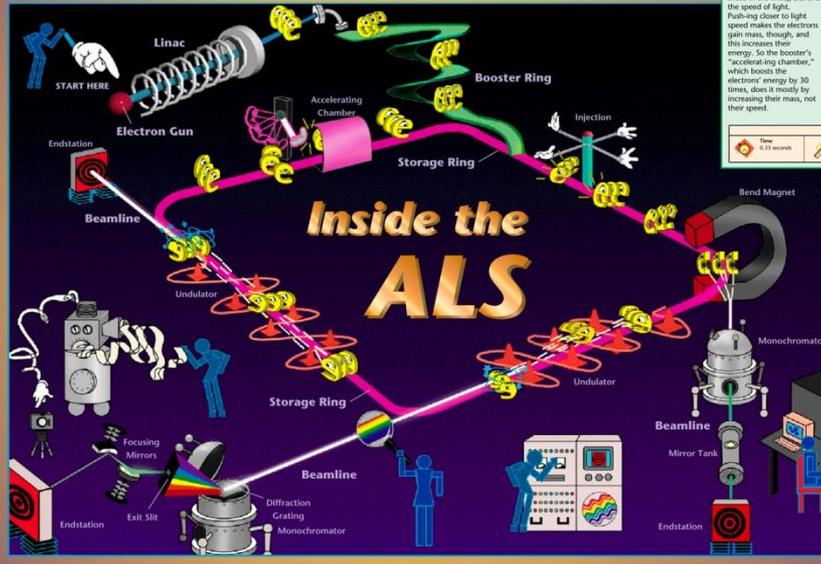


These spectra represent energies of electrons ejected from silicon tetrafluoride by incoming x-rays. The ALS spectrum has higher resolution than previous spectra, so its distinct peaks provide a better test for theoretical models of molecular structure.

A Bird's-Eye View of the ALS



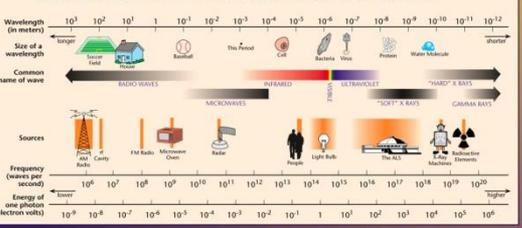
An electron at the Advanced Light Source travels a long but speedy journey on its way to generating light—the yellow electrons at right give an idea of what it might be like! The text and pictures around the edge of the poster will help you follow the action inside the ALS, beginning with the electron gun. Whenever you see the key symbol e^- , you can find more explanation in the Key Concepts section below.



Key Concepts

- What is an electron?**
An electron is a negatively charged particle that orbits outside the positively charged center (nucleus) of an atom. Electrons can be pulled away from atoms to flow as an electric current. In power lines and lamp cords, for example, electrons flow through wires, but in the ALS they circulate inside a vacuum chamber.
- How do you make an electron in the ALS do things?**
If you want the electron to speed up, put positive and/or negative charges nearby. The positive charges will attract the negatively charged electron (opposites attract), and the negative charges will repel it.
- What is an x-ray?**
X rays are light with photon energies of about 100 electron volts or more. They are commonly divided into "soft" and "hard" x rays, with higher energies, penetrate farther through most materials. The ALS mostly produces ultraviolet light and soft x rays, which have just the right energies to explore many of the atomic-level properties of matter.
- Frequency is the number of waves that pass one place each second.**
- Energy refers to the amount of energy carried by one photon. An electron volt (eV) is a very small unit of energy, useful for measuring the tiny amounts of energy that individual photons carry. High-energy, high-frequency photons have the shortest wavelengths.**
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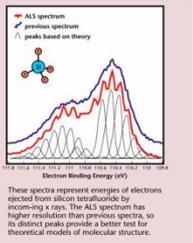
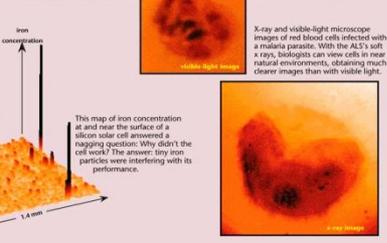
THE ELECTROMAGNETIC SPECTRUM



Target on Science

The bright beams of the ALS illuminate the mysteries of our world, enhancing our ability to see as well as to draw conclusions about what we can't see. The special features of ALS light make it a very useful tool for science. Just a few of the research possibilities include detecting minute traces of substances on surfaces to find out what's there, taking high-resolution images of malaria-infected blood cells to find out how the disease affects them, and providing finely detailed spectra of molecules to reveal the behavior of their electrons—a kind of "chemical fingerprinting."

The most prized characteristic of ALS light is high brightness, meaning the rays of light are very intense and are focused to a small spot. The ALS delivers America's brightest light in the ultraviolet and soft x-ray regions of the electromagnetic spectrum (e^-), making possible a host of different experiments that were once only dreamed of.



Concept and Content: Jane Cross, Deborah J. Dixon, Annette Greiner, Elizabeth Moxon, Jeff Sennsbaugh • Art Direction: Crystal Stevenson • Illustrations: the TEID staff • © 1995, Regents, University of California
For more information, contact Jane Cross, Lawrence Berkeley National Laboratory, MS 2-400, Berkeley, CA 94720; email: jcross@lbl.gov • ALS Web page: <http://hsa.lbl.gov/8001/als/>

Can You Find Them Inside the ALS? Aluminum foil • Red and green water hoses • The words light bulb (2 places) • The words car headlight • A skeleton • North and south poles • A camera • A U.S. flag • A traffic cone • A definition of monochromator • A really big book • A yellow ribbon • A construction barrier • A microwave oven • A hard hat • A parking lot
Prepared for the U.S. Department of Energy under Contract DE-AC02-78SF0086