Synchrotron Radiation: Generation and Application in Accelerator Physics

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Pisa, Italy

Synchrotron Radiation

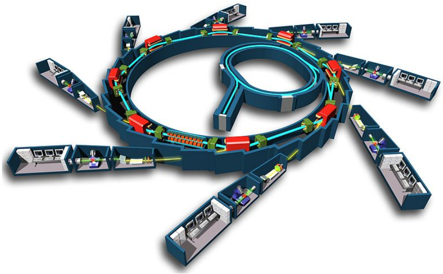
Generation

Application

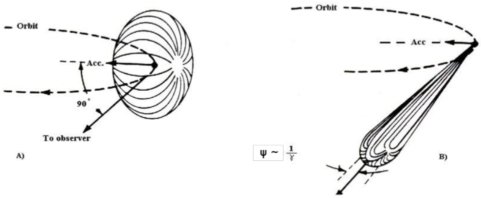
Synchrotron Radiation

The electromagnetic radiation emitted when a high energetic charged particle is accelerated radially is called *Synchrotron Radiation*

- High radiation flux
- High brilliance
- Wide radiation spectrum
- Tunability
- Defined polarization



CHARACTERISTICS



- ψ: Emission angle
- ω: Radiation frequency
- c: Speed of light
- r_0: Classical electron radius
- p_T: Transverse momentum
- γ: Lorentz factor
- ω_c: $\frac{3c\gamma^3}{2\rho} = \frac{\varepsilon_c}{\hbar}$
- F_σ, F_π: Combination of Airy functions

Observed Power Distribution

$$\frac{d^2 P_{ob}(\omega, \psi)}{d\omega d\psi} = \frac{4\pi c r_0 \dot{p}_T^2 \gamma^3}{3\omega_c m c^2} (F_\sigma(\omega, \psi) + F_\pi(\omega, \psi))$$

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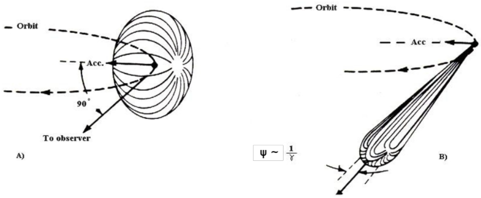

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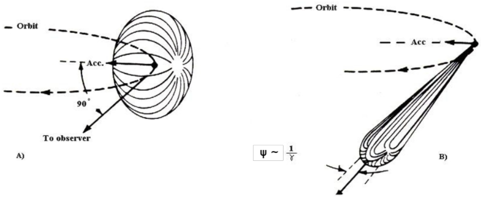

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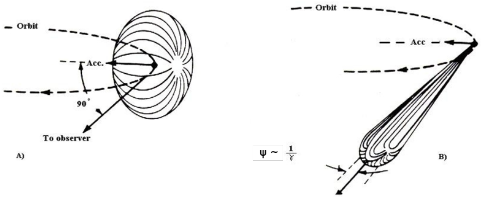

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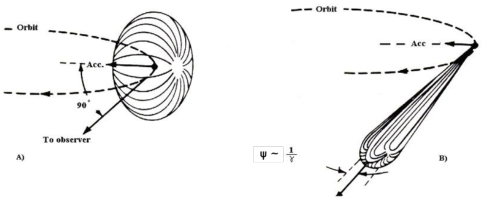

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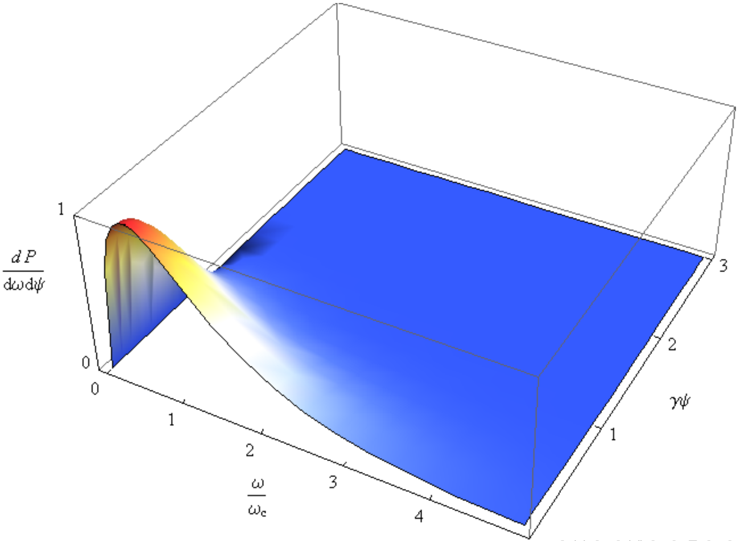
POWER DISTRIBUTION



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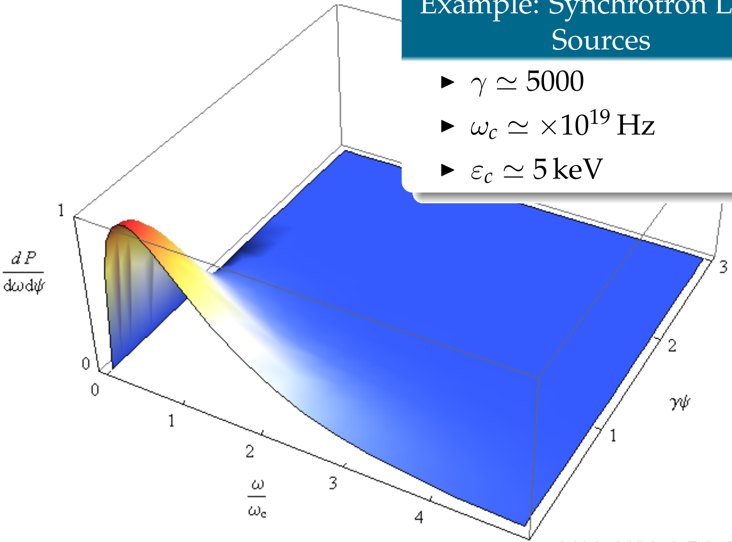


Example: Synchrotron Light Sources

- $\gamma \simeq 5000$
- $\omega_c \simeq \times 10^{19}\,\mathrm{Hz}$
- $\varepsilon_c \simeq 5\,\mathrm{keV}$

Synchrotron Radiation

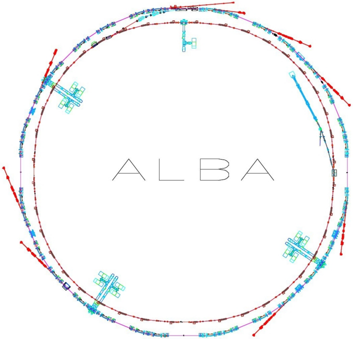
Generation

Application

SYNCHROTRON LIGHT SOURCES

Because of its peculiar characteristics synchrotron radiation used for experiments is produced at dedicated accelerator facilities with specific characteristics

- Electron beam energy ($\simeq$ GeV)
- Low emittance ($\simeq 10\,\text{nm rad}$)
- Full energy injection system
- Compact lattice to insert Insertion Devices
- High reliability



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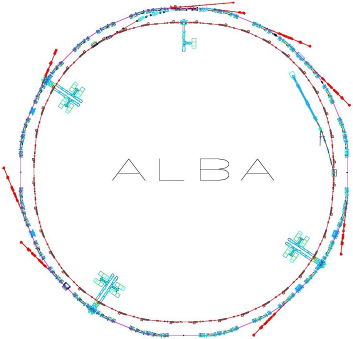
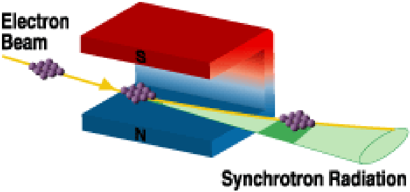


SYNCHROTRON RADIATION GENERATION

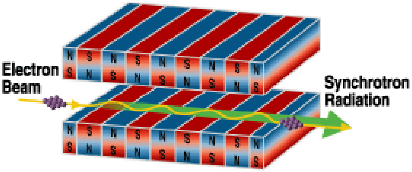
To provide synchrotron radiation to experiments three different devices are used:

Bending Magnet



Part of the machine

Wiggler/Undulator



Inserted in straight sections

Wigglers Vs Undulators

High photon flux

$\Downarrow$

Increase the number of magnetic poles

$$K = \frac{eB\lambda_0}{2\pi\beta mc} \simeq 0.0934 B[\mathrm{T}]\lambda_0[\mathrm{mm}]$$

Wigglers $K >> 1$

Increase the photon energy

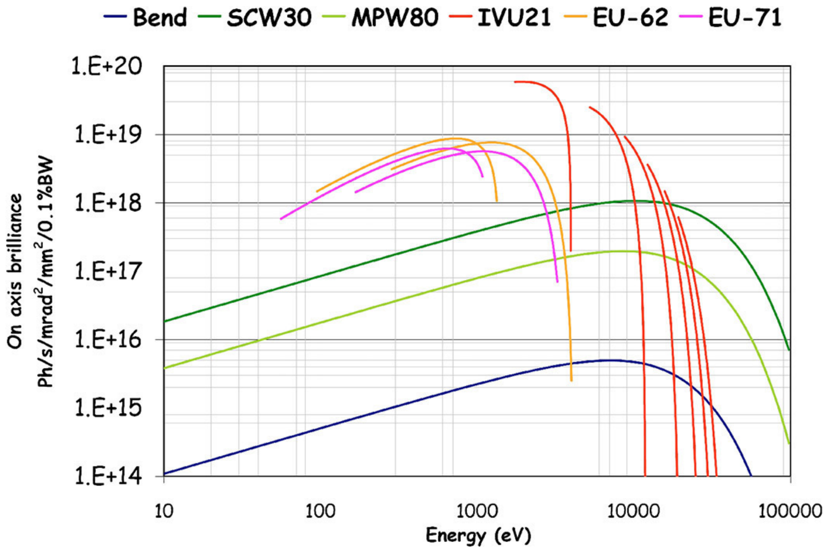
- $\varepsilon_c[\mathrm{keV}] = 0.665 B[\mathrm{T}] E^2[\mathrm{GeV}^2]$
- High magnetic field are used

Undulators $K \simeq 1$

Quasi-monochromatic radiation

- $\lambda_0 = \left(\frac{1}{\beta} - 1\right) L$
- Interference between the light produced by the same electron at each wiggle

Generated Radiation



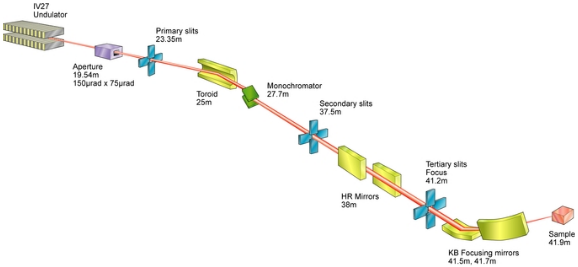
BEAMLINES

Once produced the radiation is guided to the beamlines

Bending/Insertion device

Photon energy

Nature of the experiment



- Physics
- Chemistry
- Industrial applications
- Cultural heritage
- ...

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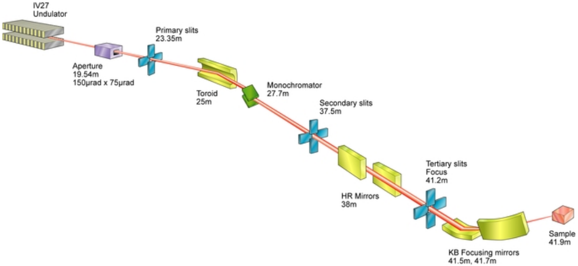

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- Beam diagnostic

Synchrotron Radiation

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Beam Diagnostic using SR

SR characteristics
$\Updownarrow$
Beam characteristics

Advantages

- Produced "for free"
- Wide spectrum
- Real-time
- Non-invasive

Disadvantages

- Need of a source
- Radiation exposure
- "Only" for light particle
- Machine design

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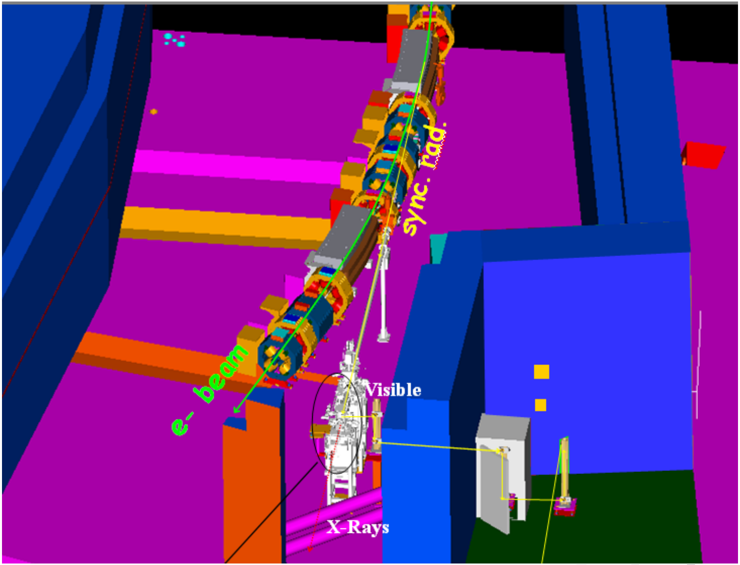
Visible radiation coming from a bending and extracted through a mirror chicane

DIAGNOSTIC BEAMLINE



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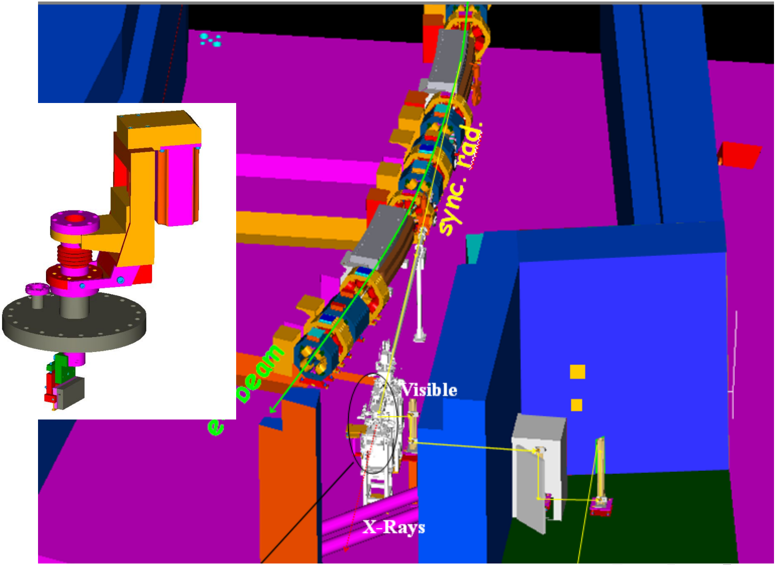


DIAGNOSTIC USING SR

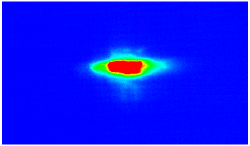
Transverse beam measurements

- Beam size (X-Rays)
- Beam size (Visible)

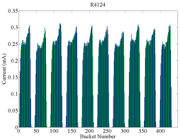
Longitudinal beam measurements

- Filling pattern
- Bunch size

Imaging



Timing



Beam Size-PinHole

Problem

Electron machines $\Rightarrow$ Beam size $\simeq$ tens of μm or smaller

$$\Updownarrow$$

Diffraction limited using visible radiation

$$\Downarrow$$

$$d = \frac{\lambda}{2n\sin\theta} \simeq 100\mu\text{m}$$

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Solution

Use X-Rays

$\Downarrow$

Need a different frontend

&

Need a device set-up suitable for X-Rays

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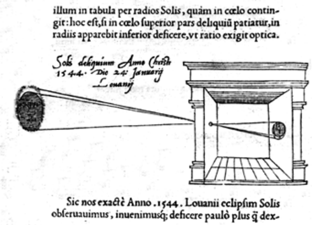
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Beam Size-PinHole

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Electron machines ⇒ Beam size ≃ tens of μm or smaller

⇕

Diffraction limited using visible radiation

⇓

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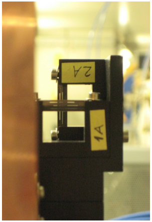


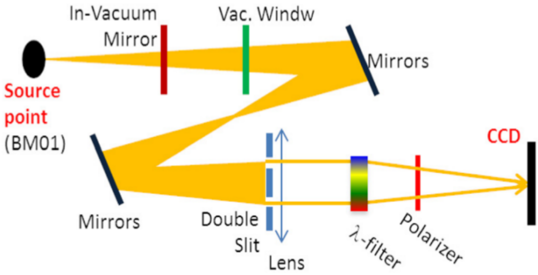
- X-Rays ≃ 40 keV
- Enlarge Factor ≃ 2:5
- Hole ≃ 10 μm
- YAG screen + CCD camera

BEAM SIZE-INTERFEROMETRY

Measurement of the first order of spatial coherence of the synchrotron radiation using a double slit interferometer

$$\sigma = \frac{\lambda d_0}{\pi D}\sqrt{\frac{1}{2}\ln\frac{1}{V}}$$

$$V = \frac{I_{Max} - I_{Min}}{I_{Max} + I_{Min}}$$



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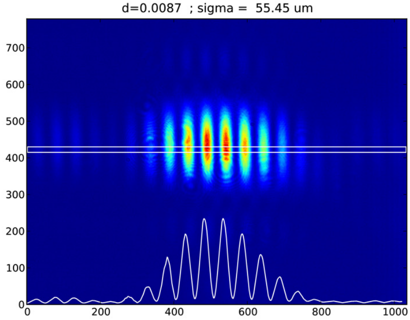
Using good quality optical components

$\Downarrow$

Beam size $< 10\ \mu$m can be achieved



Longitudinal Measurements

The longitudinal structure of a circular accelerator is defined by the beam revolution period and the accelerating RF-frequency

$$h = T \times f_{RF}$$

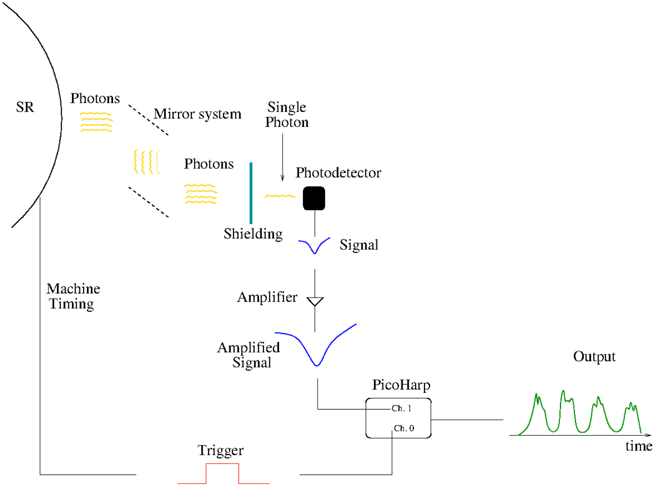
The machine is divided into h ***Buckets***.
Each bucket can be filled with a bunch

Filling Pattern

The scheme of distribution of bunches among the machine buckets

FILLING PATTERN-TCSPC

Time Correlated Single Photon Counting



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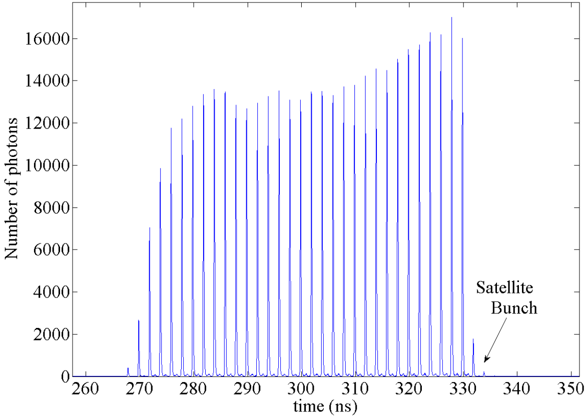

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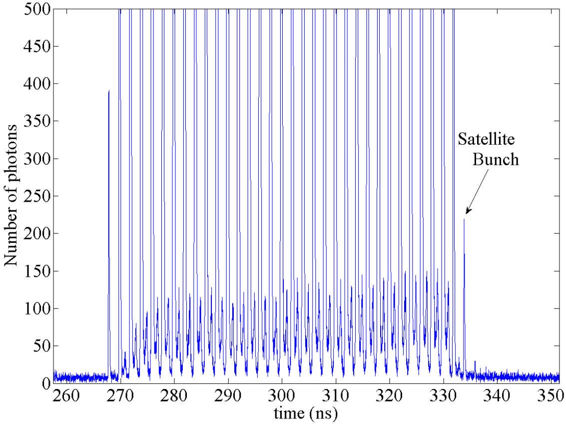
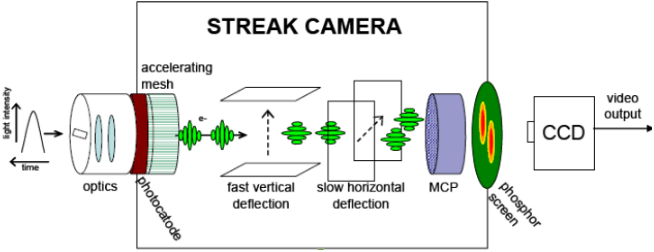
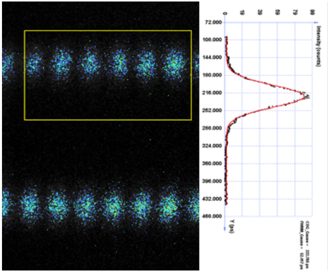


Dynamic Range better than 10^3 $\Rightarrow$ Also bunch purity experiments

Bunch Length-Streak Camera

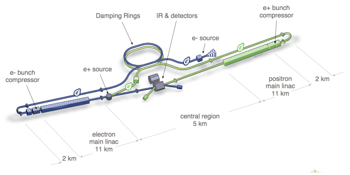




Single bunch Length
$\simeq$ ps

Not Only SLS!

Electron Machines/Linear Collider



LHC

- Bunch Purity with TCSPC
- Imaging
- Interferometry

Possibility of using undulators to increase the photon flux

Muon Storage Rings

Need to know the muon energy ⇒ Measure the μ g-2 using SR emitted by muon decay electrons

$$\omega_a = a_\mu \gamma \omega_{cic}$$

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This project is funded by the European Union under contract PITN-GA-2011-289485