Storage Ring in Brief

F. Iazzourene

Elettra Synchrotron Laboratory

Summary

Introduction

- Storage ring *definition*
- Synchrotron light sources based on storage rings

Third Generation Light Sources

- Facilities (short list)
- Complex
- How it works?
- Storage ring: vacuum, RF cavities, timing, magnets, power supplies, diagnostics, control system, personnel safety system
- Synchrotron radiation

Storage ring figures of merit

- Brightness and flux
- Beam stability
- Time structure

Conclusions

Storage rings definition

A storage ring is a circular particle accelerator in which a beam of particles is stored and kept circulating for hours and even days.

A storage ring can accumulate a high beam flux from an injection accelerator that achieves a much lower flux

The commonly stored particles are protons (p), antiprotons (pbar), electrons (e^-) or positrons (e^+).

Schematically, the storage rings can be used :

- for storage only, e.g. the Antiproton Accumulator (AA) at CERN → used then as injector
- as colliders, e.g. LHC, LEP, KEKB, PEP-II, RHIC, Tevatron, HERA → two stored beam particles are brought into collision at discrete locations
- as synchrotron radiation source in the light source facilities → use of the synchrotron radiation emitted by the stored electrons or positrons

Synchrotron light sources using storage rings

Synchrotron light sources based on storage rings are of:

- **1st generation** → synchrotron radiation was used **parasitically** from accelerator facilities of high energy physics.

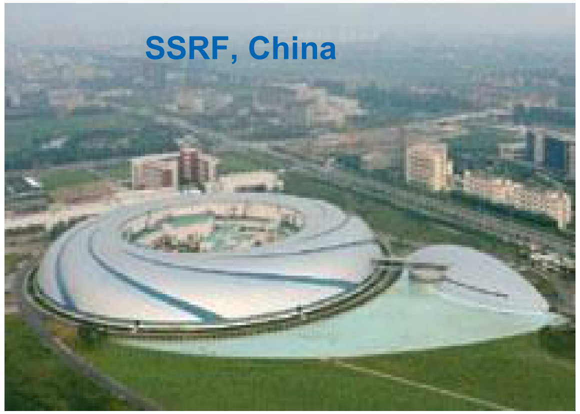
- **2nd generation**, early 1970's, first **dedicated** storage rings were exclusively built to generate synchrotron radiation. The synchrotron radiation is mainly from the beam guiding **dipole magnets** of the storage ring

- **3rd generation**, early 1990's, the synchrotron radiation is mainly from special magnet structures, the so-called "**insertion devices**" (ID). Storage rings are **designed** to incorporate long straight sections in order to accommodate the IDs and particular arrangement of magnets are used and optimized to provide a **light with a higher flux and quality**, from both the dipole magnets and the IDs.

Third generation light sources facilities

In operation

1992	ESRF, France (EU)	6GeV
	ALS, USA	1.5 – 1.9GeV
1993	TLS, Taiwan	1.5GeV
1994	ELETTRA, Italy	2 -2.4GeV
	PLS, Korea	2GeV
	MAX II, Sweden	1.5GeV
1996	APS, USA	7GeV
	LNLS, Brazil	1.35GeV
1997	Spring-8, Japan	8GeV
1998	BESSY II, Germany	1.9GeV
2000	ANKA, Germany	2.5GeV
	SLS, Switzerland	2.4GeV
2004	SPEAR3, USA	3GeV
	CLS, Canada	2.9GeV
2006	SOLEIL, France	2.8GeV
	DIAMOND, UK	3GeV
	ASP, Australia	3GeV
	MAX III, Sweden	0.7GeV
	Indus-II, India	2.5GeV
2008	SSRF, China	3.4GeV
2009	PETRA-III, Germany	6GeV



Third generation light sources facilities

Under construction, operational 2015

NSLS-II, USA	3GeV
SESAME, Jordan	2.5GeV
MAX-IV, Sweden	1.5-3GeV
TPS, Taiwan	3GeV
SOLARIS, Poland	3GeV

Planned

CANDLE, Armenia	3GeV
ILSF, Iran	3GeV
TURKAY, Turkey	3GeV

Third generation light sources complex

1) Accelerator system : a storage ring and its injector → electrons or positrons

2) beam lines & front ends → synchrotron radiation

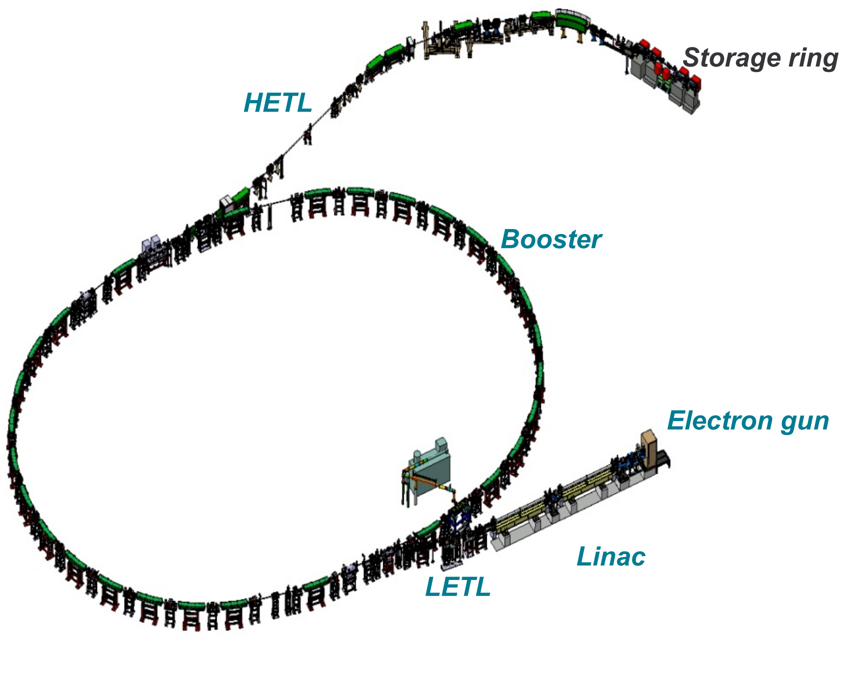
3) Service area : accelerator system equipments

4) Control room : remote control of the accelerator system equipments

5) Experimental hall : the experiments area

Third generation light sources: how it works?

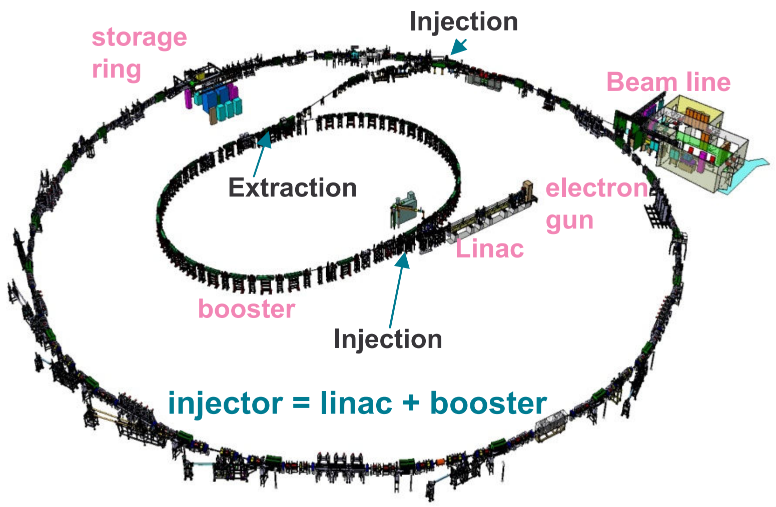
The storage ring has an **injector** which consists of an **electron gun**, and often a linear accelerator (**linac**) and a **booster**, together with two transfer lines, a low energy line (**LETL**) to transport the electron beam from the linac to the booster and a high energy line (**HETL**), to transport the beam from the booster to the storage ring



Some synchrotron light source facilities use a **microtron** instead of a linac, e.g. Indus in India, Anka and Bessy in Germany. Some others use only a linac, e.g. Pohang Light Source (PLS) in Korea, or Elettra before 2008.

The injector can be a **full energy system**, meaning that the energy of the beam at the exit of the injector is the operating energy of the storage ring. If not, the beam will be *ramped* in the storage ring to the operating energy, e.g. Anka (Germany), Indus (India) or Elettra (Italy) before the full energy booster operation in 2008.

Third generation light sources: how it works?



1. Electron gun & Linear accelerator (linac)

A stream of free electrons is produced in an electron gun.

The electrons are fed in the linac where they get

- packed longitudinally in a train (*pulse*) with one or more bunches → time structure
- focused
- maintained under vacuum (10^{-7}mbar)
- accelerated to the foreseen energy e.g. Elettra : 100 millions of eV (100MeV). Here they usually get their maximum speed ~ 99.9996% of speed of light

2) Booster synchrotron

The pulse of electrons is injected in the booster, where the electrons are

- forced on a circular path
- focused
- maintained under high vacuum (10^{-8}mbar)
- accelerated to the foreseen energy, eg. Elettra 2.5 billions of eV (2.5GeV)

3) Storage ring

The pulse of electrons is extracted from the booster and injected in the storage ring. The steps 1 and 2 are repeated up to when the wished beam intensity is reached.

In the storage ring the electrons are

- forced on a circular path
- focused
- maintained under ultra high vacuum (10^{-9}mbar)

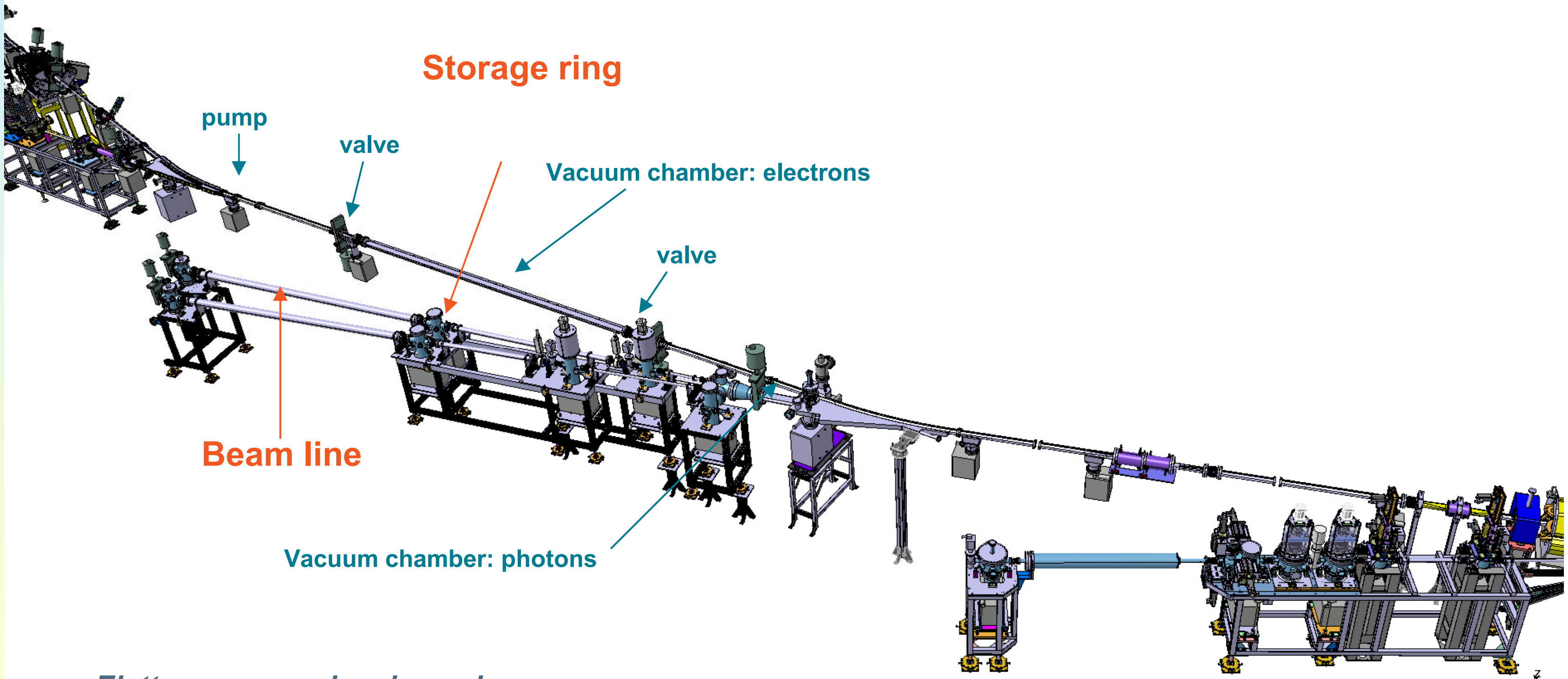
4) Beamlines

The emitted synchrotron radiation is channeled to the photon beam lines to be used by the users

Third generation light sources: storage ring

Vacuum system

- The vacuum system has to ensure an **average pressure of 10^{-9} mbar** with the considered electron beam intensity
- **Smooth transition** from one vacuum chamber cross-section to another is necessary for the electron beam stability. This minimizes the electromagnetic fields generated by the image current circulating in the walls of the vacuum vessels.
- **Valves** separate the ring in sectors. In case of vacuum leak, surrounding valves get closed to protect the rest of the ring

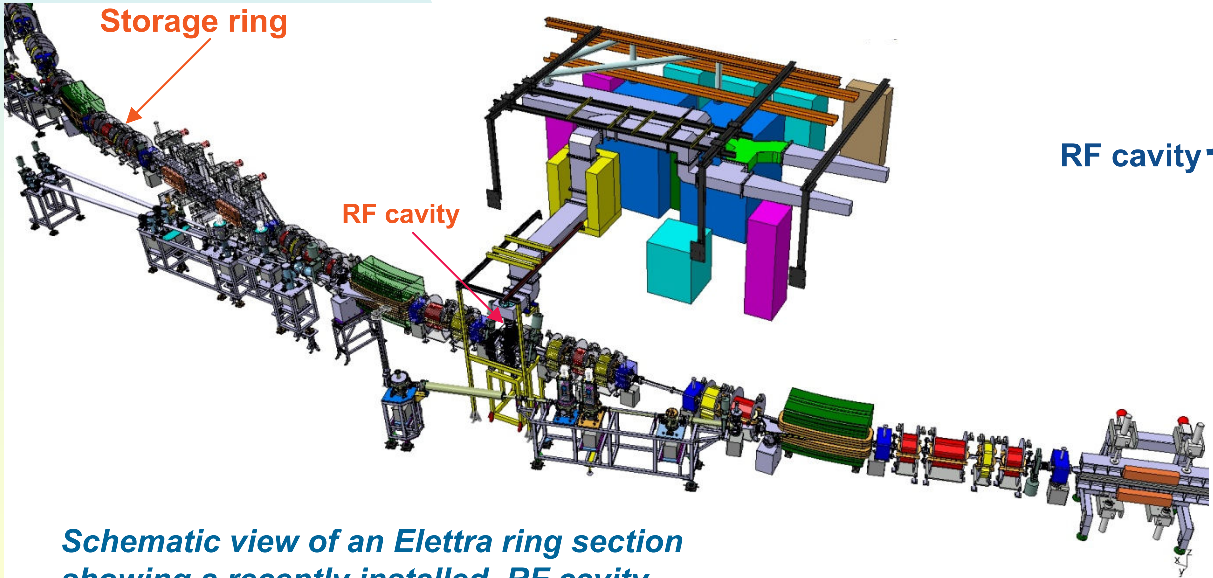


e.g. Elettra vacuum chamber scheme

Third generation light sources: storage ring

RF cavities

- restore the energy lost by the particles when emitting the synchrotron radiation
- provide longitudinal focusing
- provide synchrotron radiation damping



Schematic view of an Elettra ring section showing a recently installed RF cavity

RF cavity in the Elettra storage ring

Third generation light sources: storage ring

RF cavities

Longitudinal focusing → RF energy acceptance → RF bucket

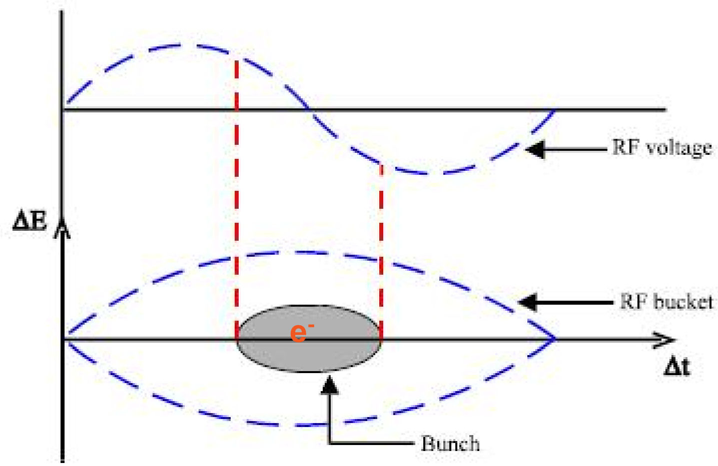
The total number of maximum circulating buckets in the storage ring is the harmonic number h

h = RF cavity_frequency / beam revolution_frequency

revolution_frequency = beam_speed / ring_circumference

Elettra : h = 432

The electrons inside the *pulse* are stored in the *buckets* provided by the RF cavities of the storage ring, one bunch per bucket .



RF bucket and electrons bunch

Third generation light sources: storage ring

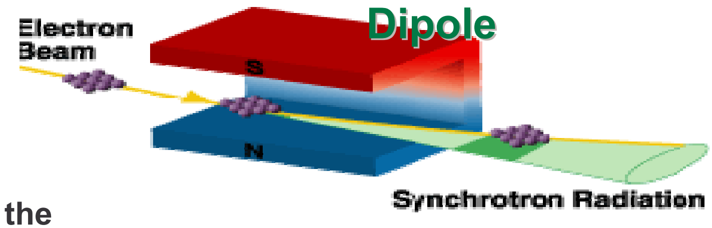
Timing system **handles**

- **start/stop injection, extraction, electron gun, booster ramping, etc**
- **the filling of the selected buckets → filling pattern**

Third generation light sources: storage ring

Magnets

- ***Dipoles*** → (Bending magnets)
  → force the electrons on a closed circular path, sum of the bending angles along the ring = 360º
  → synchrotron radiation emission source



- ***Quadrupoles*** → focus the beam (transverse)

- ***Correctors*** → are small bending magnets used to correct the trajectory deviations from the nominal path. There are

→ horizontal correctors to correct the horizontal trajectory deviations and

→ vertical correctors to correct the vertical trajectory deviations

At Elettra, they are combined in one element for economy of space

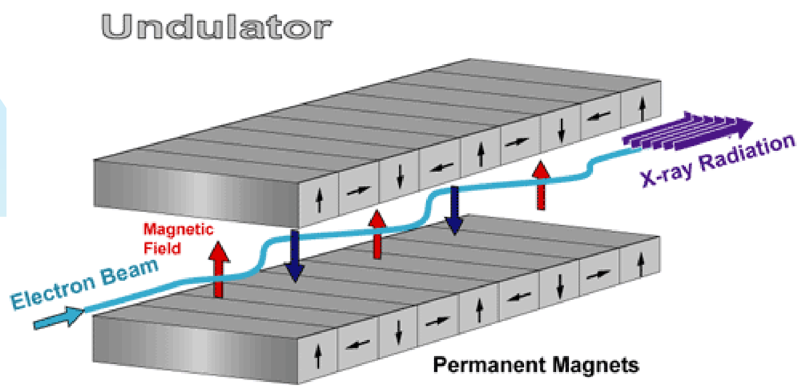
- ***Sextupoles*** (chromatic) → compensate the chromatic effects

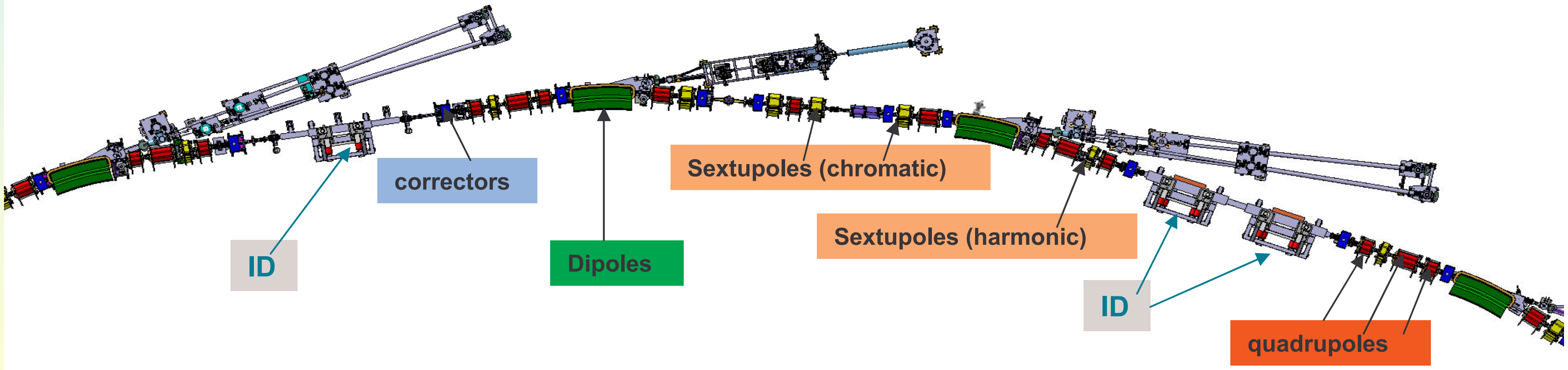
- ***Octupoles*** or/and ***harmonic sextupoles*** →
compensate the nonlinear effects (introduced by chromatic sextupoles + ID)

Third generation light sources: storage ring

Magnets

- *Insertion devices* (ID)→ synchrotron radiation emission source.





e.g. Elettra ring lattice (G. Loda courtesy)

Third generation light sources: storage ring

Power supplies → provide current to

- the electromagnetic magnets and
- electromagnetic insertion devices, e.g. electromagnetic wiggler of Aloisa beam line

Diagnostics → measure the beam position, beam intensity, beam tune, radiation dose, vacuum pressure, etc.

Control system → remote control of the accelerator system equipments

Personnel safety system → to guarantee personnel safety against the harmful effects of ionizing radiation, in accordance with the law in force.

Third generation light sources: storage ring

Synchrotron radiation

The synchrotron radiation is produced through the **bending magnets** and **insertion devices**.

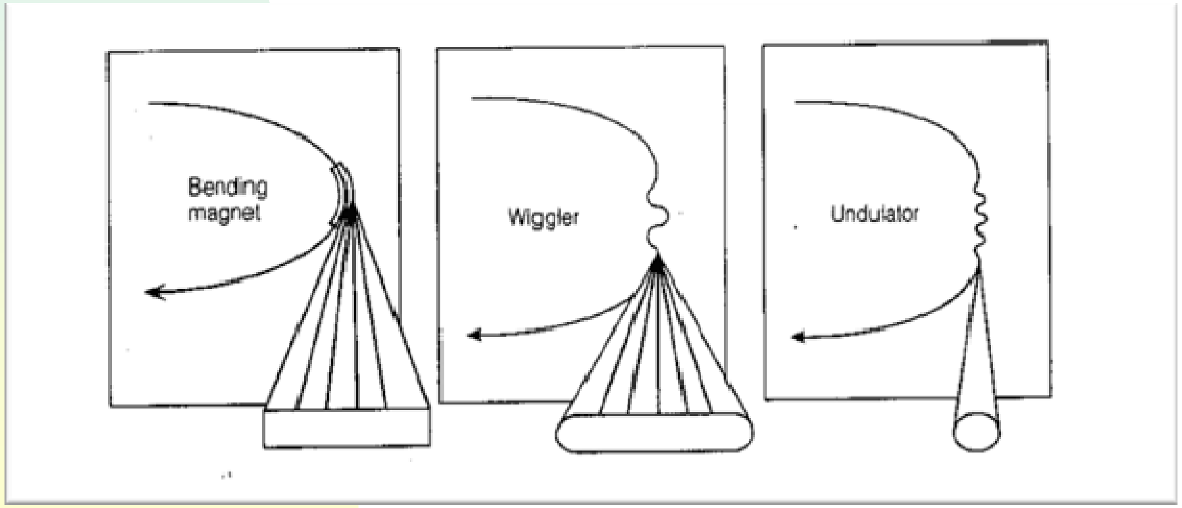
With respect to the bending magnets,

- the flux and the brightness of the emitted radiation by the insertion devices can be thousands times higher
- the emitted light is designed and tunable to fit the specifications required by the experiments, in terms of **wavelength**, **flux**, **brightness**, **polarization**

The insertion devices are called:

→ **wigglers**: when the **magnetic field is high**. These are used to generate *enhanced* flux levels

→ **undulators**: when the **magnetic field is low(er)**. These devices generate radiation at specific harmonics

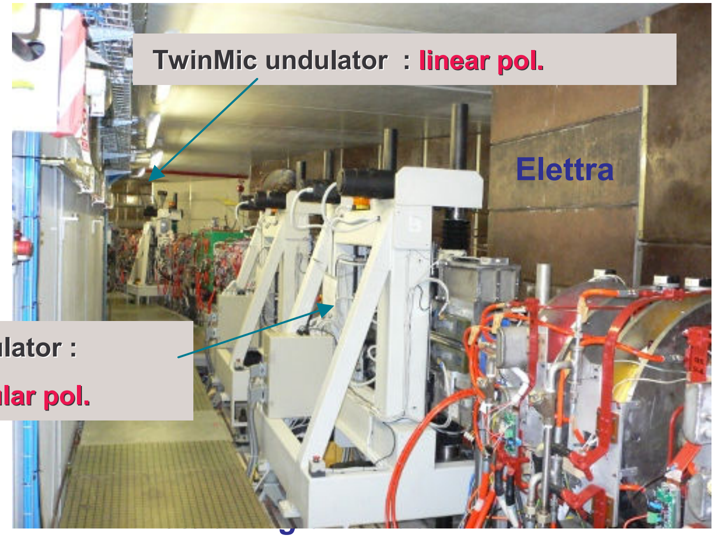


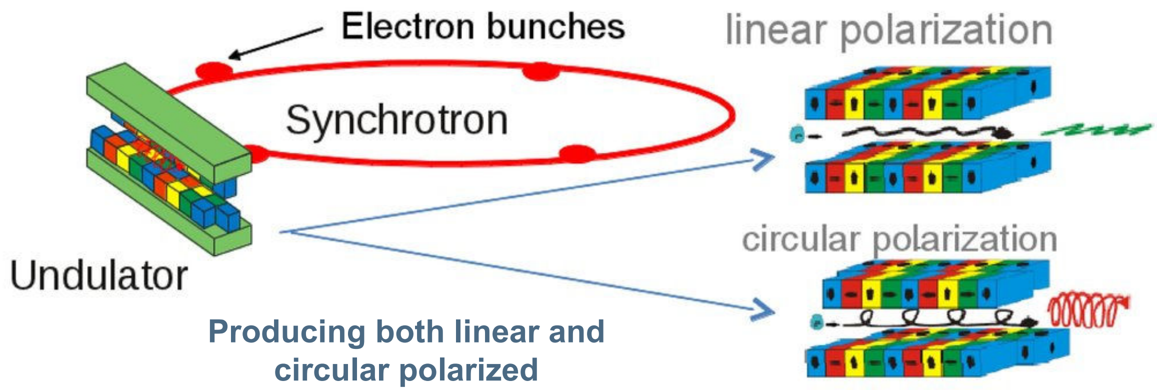
Third generation light sources: storage ring

Synchrotron radiation

There are insertion devices which produce

- only a linear polarization
- or both linear and circular





Producing both linear and circular polarized synchrotron radiation

Third generation light sources: storage ring figures of merit

Users → high flux and brightness, beam stability and time structure

Stored electron beam intensity → photon flux and brightness values

Transverse electron beam emittance → photon brightness value

Electron beam stability → photon flux and brightness stability

Time structure → filling pattern, short bunches

Undulators and wigglers → photon spectrum range, flux, brightness

With time, the above list is about the same, what changed are the requested numbers and tolerances

Stored electron beam intensity

Electron beam current value is limited by:

- **Heat load** on the vacuum chamber → vacuum system
- **RF power** → RF classical cavities or/and superconducting cavities
- **Multibunch & single bunch instabilities**

  → vacuum system (non evaporable getter, NEG, coating tube and vacuum chamber tapering)

  → compensate with transverse and longitudinal fast feedbacks during storage ring operation
- **Beam decay**

  → 3rd harmonic superconducting cavity to increase the beam lifetime

  → top up to keep the beam current constant

Top up operation consists in the frequent injections in the storage ring while the beam lines are open to the users to keep the stored current constant

Transverse electron beam emittance

The electron beam emittance is a key storage ring parameter as we have

brightness $\propto$ 1 / emittance

The oscillations of the electron beam circulating in the storage ring

- are excited by the emission of the photons and
- are damped on average when the electrons travel through the RF cavities

The reached equilibrium leads to the so called equilibrium emittance & energy spread

The shorter the damping times the higher the beam stability and beam lifetime

Third generation light sources: storage ring figures of merit

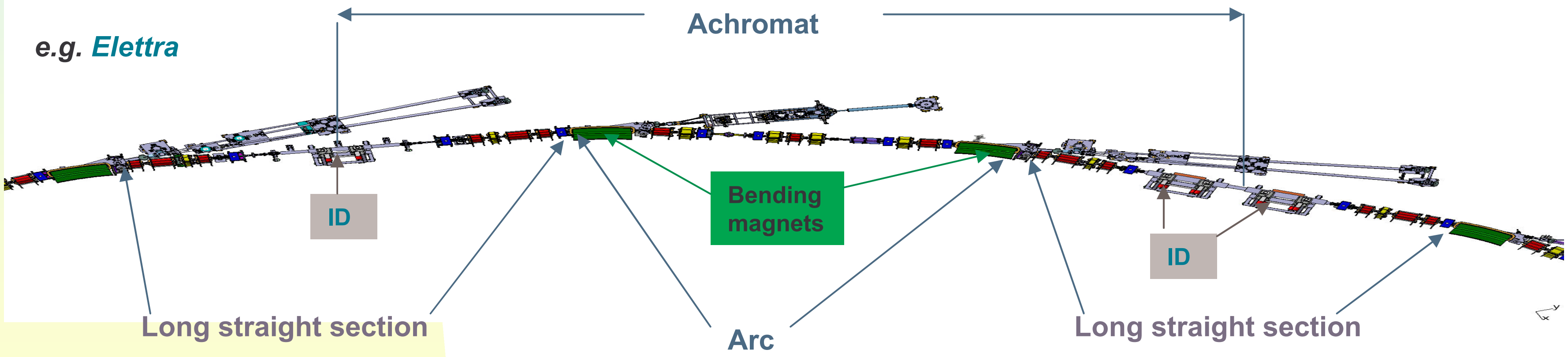
Transverse electron beam emittance

Low **horizontal emittance** and suitable straight sections to accommodate insertion devices are obtained in the so called DBA (Double Bend Achromat) and TBA (Triple Bend Achromat) magnet lattices

- Achromat = half long straight section + arc + half long straight section
- Achromat → dispersion is zero (or very small) outside the arc
- storage ring = sequence of n *identical* achromats. At Elettra, n = 12

DBA lattice : arc with two bending magnets → Elettra and most light sources facilities
TBA lattice : arc with three bending magnets → Soleil

e.g. Elettra



Third generation light sources: storage ring figures of merit

Transverse electron beam emittance

The horizontal emittance is determined by the dispersion generated by the bending magnets

$$\varepsilon_h \propto \langle \gamma D^2 + 2 \alpha D D' + \beta D'^2 \rangle$$

D and D' are the horizontal amplitude and angle of the dispersion

γ, α and β are the so called Twiss parameters in the horizontal plane

<> means the average around the storage ring

Lowering the dispersion lowers the horizontal emittance

against: need strong chromatic sextupole strengths

Leads to

→ large non linear magnetic fields

→ small dynamic aperture (small stable amplitude area)

Third generation light sources: storage ring figures of merit

Transverse electron beam emittance

The horizontal emittance is also determined by the number N_b of bending magnets in the storage ring

$$\varepsilon_h \propto 1/N_b^3$$

Increasing the number of bending magnets lowers the horizontal emittance

Trend for new projects/upgrades of light source facilities →

Use MBA (Multi Bend Achromat) magnet lattice (BessyII : 7 bending magnets/arc)

against:

→ larger storage ring → larger occupied space → higher cost

Transverse electron beam emittance

The **horizontal emittance** depends also on a so called partition number J_h

$$\varepsilon_h \propto 1 / J_h$$

With bending magnets without gradient, J_h is approximately equal to 1

It can be made larger by introducing a **vertical focusing** in the bending magnets → **combined function magnet with positive index n**

Example : **Elettra and Trend for new projects/upgrades of light source facilities**

In practice, $J_h \leq 2$ → emittance reduction factor at most 2

Third generation light sources: storage ring figures of merit

Transverse electron beam emittance

The horizontal emittance can also be reduced installing the so called "damping wigglers" in the storage ring

These solutions/methods to lower the horizontal emittance are the main trend used in the so called ultimate synchrotron light source facilities

Transverse electron beam emittance

The vertical emittance is ideally zero as there is no vertical dispersion.

It is only determined by the coupling between the horizontal and vertical planes due to the magnets imperfections and misalignments.

Typically the coupling is in the order of few percents …

to lower it

- lower horizontal emittance
- better magnets alignment
- beam based alignment
- orbit correction
- vertical dispersion correction
- skew quadrupoles for fine tuning of the remaining coupling

Third generation light sources: storage ring figures of merit

Transverse electron beam emittance

Low transverse electron beam emittance

Against :

→ Lower beam lifetime, but less important thanks to top up

→ more stress on the electron beam dynamics → intense studies and optimizations

Pro :

→ higher brightness

→ smaller ID gaps → higher flux and brightness

Third generation light sources: storage ring figures of merit

Electron beam stability

Position stability

Beam position stability should be better than 10% of the beam size and divergence

→ Position and angle variation should be in the micron level meters and radians

Closed orbit deviations can be slow or fast

→ slow orbit deviations : tidal motion, ground settling, day/night and seasons thermal variations, thermal drifts of the electronics, power supplies, cooling water flow, insertion device gap/phase variation, re-injection

→ fast orbit deviations: ground vibrations, air compressors, refrigerators , multi bunch instabilities, single bunch instabilities

***Cures* :**

Control vibrations

Slow and fast orbit correction feedbacks

Fast transverse multi bunch feedback

Top up → constant thermal load on components

Third generation light sources: storage ring figures of merit

Electron beam stability

Beam dimension stability

Variations:

Insertion device gap/phase variation

Transverse multi bunch instabilities

Single bunch instabilities

Beam current intensity decay (mostly) in single bunch mode operation

Cures :

Tune feedback → beam dimensions

Transverse multi bunch feedback

Top up → instabilities and beam decay

Third generation light sources: storage ring figures of merit

Electron beam stability

Beam flux stability

Variations:

- Insertion device gap/phase variation
- Transverse and longitudinal multi bunch instabilities
- Single bunch instabilities
- Beam current decay
- Orbit variation
- Optics variation ..

***Cures* :**

- Slow and fast orbit correction feedbacks
- Fast transverse multi bunch feedback
- Fast longitudinal multi bunch feedback
- Tune feedback
- Top up → constant stored electron beam current

Third generation light sources: storage ring figures of merit

Electron beam stability

Uptime

- percentage of the users time → high > 95%
- duration : high, ideally days

Downtime

- percentage of the users time → low
- Duration → low
- Frequency → low

Top up

- constant photon flux
- constant thermal load on components

Third generation light sources: storage ring figures of merit

Time structure

Filling pattern :

- **Single bunch mode** : only one bucket gets filled
- **Few bunch mode** : 2 or more equidistant buckets on the ring are filled
- **Uniform filling mode** : all the buckets get filled
- **Multi bunch mode** : empty buckets (gap) + filled remaining buckets

→ Widely used in synchrotron light sources facilities

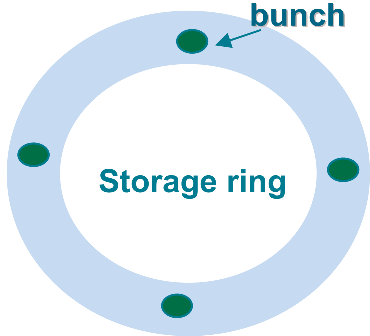
- **Hybrid (camshaft) mode** : continuous chain of bunches on one side and a single bunch on the centre of the other side (gap)

→ Used for Time Resolved Experiments

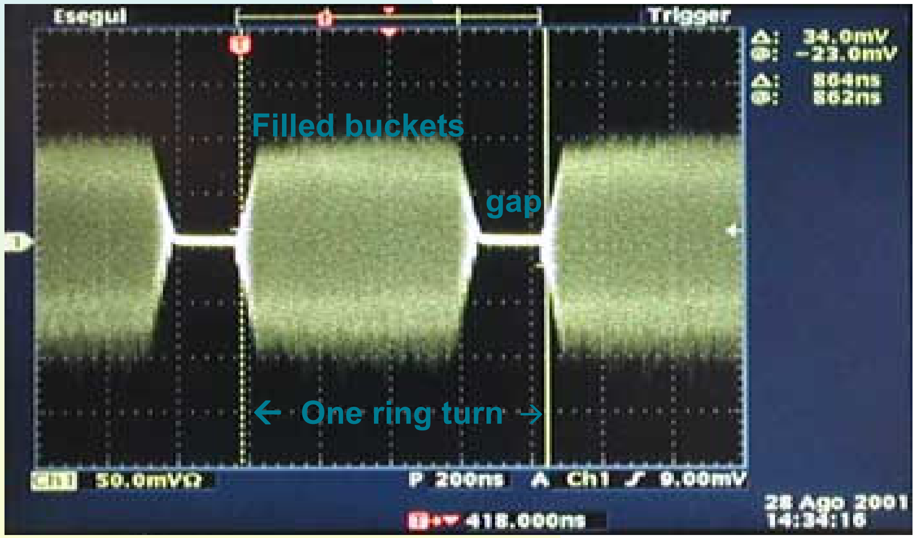
Third generation light sources: storage ring figures of merit

Time structure

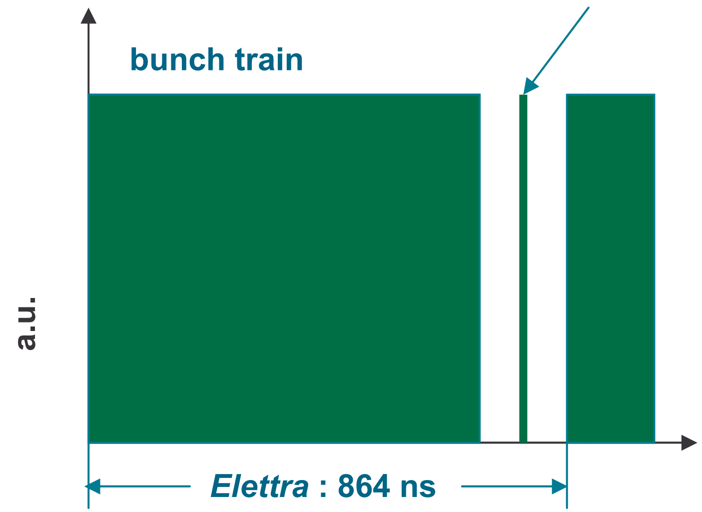
Filling patterns at Elettra



4 equidistant buckets filled (Elettra storage ring FEL experiments)



Multi bunch mode: Beam train seen on an oscilloscope at Elettra



Hybrid (camshaft) mode: scheme

Third generation light sources: storage ring figures of merit

Time structure

Bunch length

- Natural bunch length defined by the equilibrium energy spread
- Longer bunch length → 3rd harmonic cavity to increase the beam lifetime
- Shorter bunch length

    low momentum compaction factor obtained with suitable optics

    crab cavities

    slicing

Third generation light sources: storage ring figures of merit

Undulators and wigglers

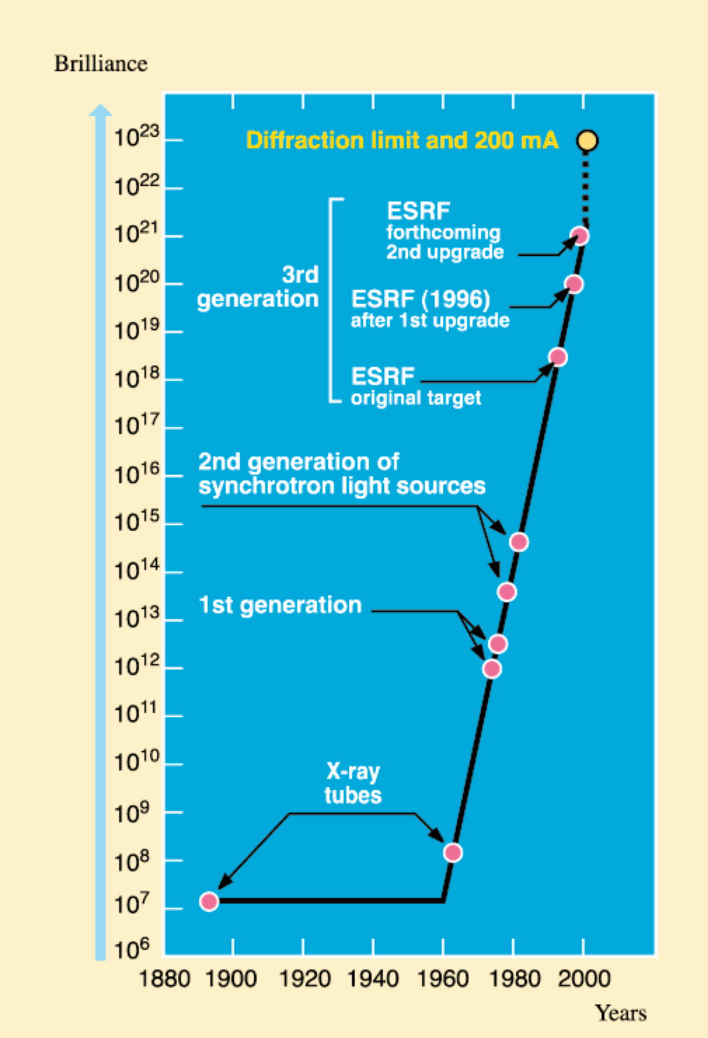
- Number of insertion devices → number of beam lines
- Insertion devices types
- Flux
- Brightness
- Spectrum range
- Polarization: linear, circular, elliptical

Conclusions (I)

The third generation light sources of the 1990's (ESRF, ALS, Elettra) have been commissioned with success and some of their targets have been even exceeded

This gave confidence to push the targets to higher levels

Since the 1990's, the brightness and beam quality are rapidly growing



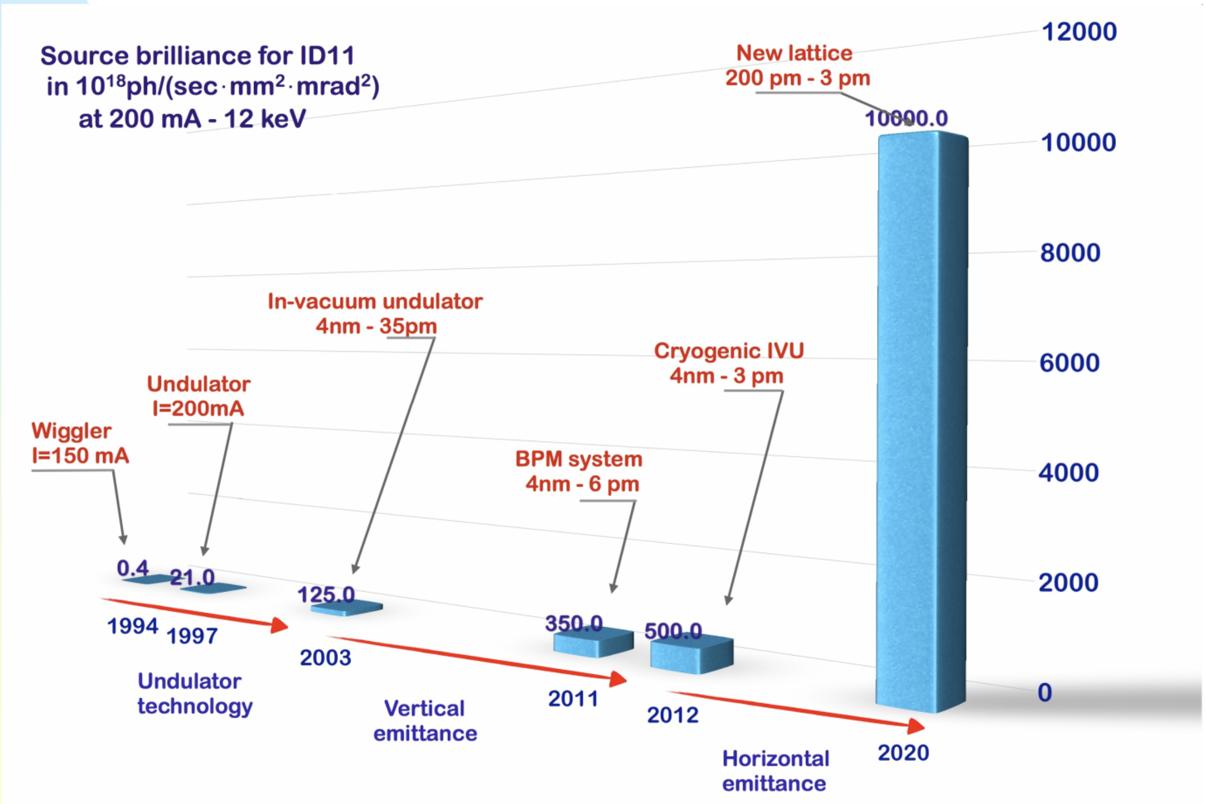
ESRF example

Conclusions (II)

The demands from the users are also more and more challenging

Thanks to beam dynamics techniques development, top up, together with the technological progress of the insertion devices, the beam position monitors, … higher performances are more and more feasible

→ ULTIMATE third generation light source facilities



ESRF example

Limits:

Space, cost,

Thank you for your attention