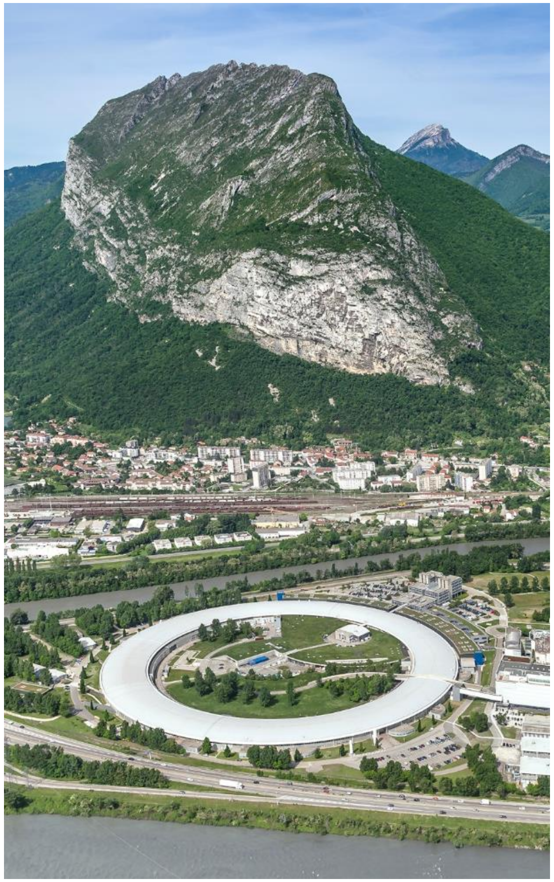
ESRF | The European Synchrotron

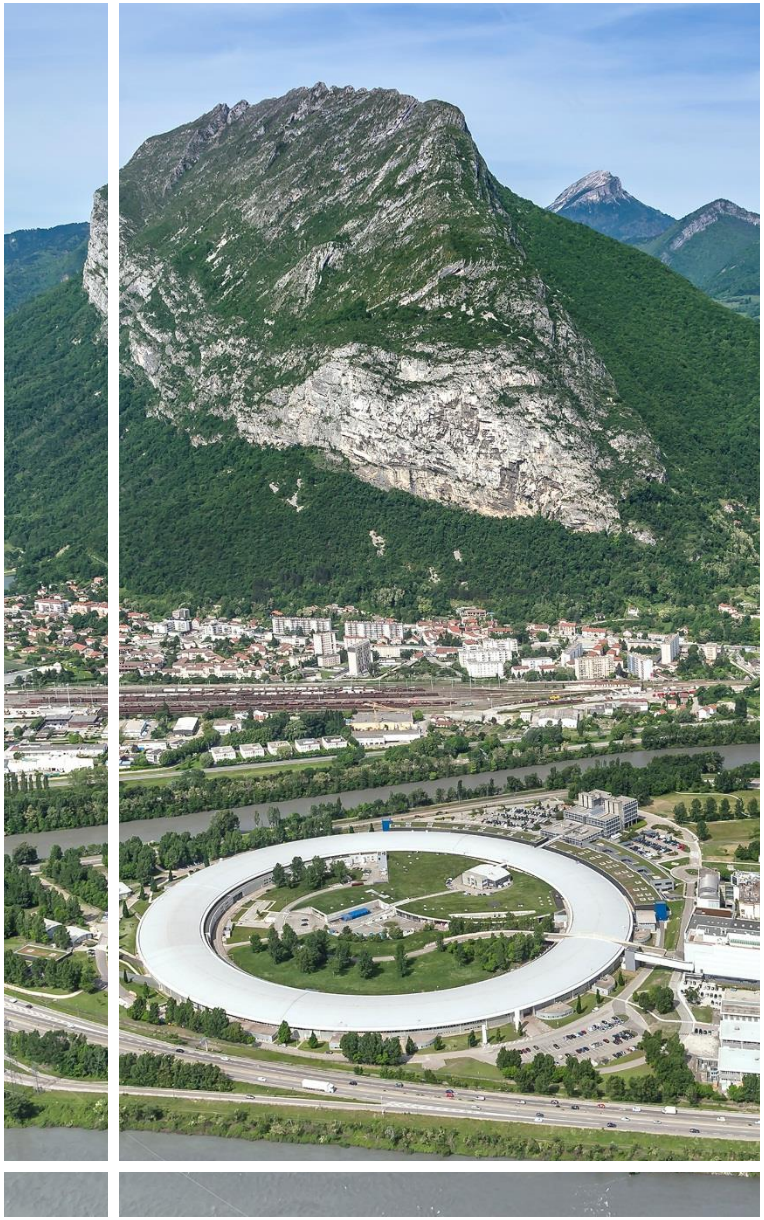


1) General presentation

2) The ESRF today

3) The ESRF Upgrade

Monday 16 January 2017
JUAS 2017 Revol Jean-Luc



ESRF
The European Synchrotron

General presentation

HOW DOES THE ESRF WORK?

The most intense source of synchrotron-generated light

100 billion times brighter than the X-rays used in hospitals

Scientific excellence recognised worldwide

- N°1 in scientific output
- N°2 in number of users
- N°1 in reliability & quality
- 4 Nobel prize-winners among the ESRF users
- 25,166 reference articles during the period 1994-2014
- ~30 articles in *Nature* and *Science* per year
- Nearly 2,000 publications per year: ~5 every day

13 Member states:

France	27,5 %
Germany	24 %
Italy	13,2 %
United Kingdom	10,5 %
Russia	6 %
Benesync (Belgium, The Netherlands)	5,8 %
Nordsync (Denmark, Finland, Norway, Sweden)	5 %
Spain	4 %
Switzerland	4 %

Contribution to the budget in %

8 Associate countries:

Israel	1,5 %
Austria	1,3 %
Centralsync (Czech Republic, Hungary, Slovakia)	1,05%
Poland	1 %
Portugal	1 %
South Africa	0,3 %

21 partner nations
Annual budget: **100 million euros**
Members of staff: **630 of 40 different nationalities**
Legal status: **Private civil company subject to French law**

A UNIQUE SITE FOR RESEARCH AND INNOVATION

european photon & neutron science campus

ESRF The European Synchrotron | NEUTRONS FOR SCIENCE® | EMBL | ibs Institut de Biologie Structurale

AT THE HEART OF THE GLOBAL INNOVATION CAMPUS GIANT

Assembling research, innovation and higher education in one location

GIANT
INNOVATION CAMPUS

EIROforum

European Intergovernmental Research Organisations forum

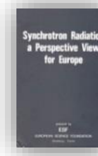
Collaborations on:

- Technology transfer
- Instrumentation
- International affairs
- Information technology
- Education and outreach

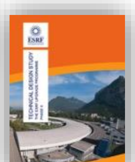
CERN ESO esa EUROfusion European XFEL ESRF NEUTRONS FOR SCIENCE EMBL

Science in School
The European journal for science teachers

ESRF: MORE THAN 20 YEARS OF SUCCESS AND EXCELLENCE



- **1988** 11 member states sign the creation of the ESRF
- **1992** 1st electron beam in the storage ring
- **1994** Inauguration: 15 beamlines
In time and within budget
- **1998** 40 beamlines
In time and within budget
- **2009-2015** Upgrade Programme Phase I
In time and within budget
- **2012** New design for the storage ring
- **2015** Upgrade Programme Phase II: ESRF-EBS

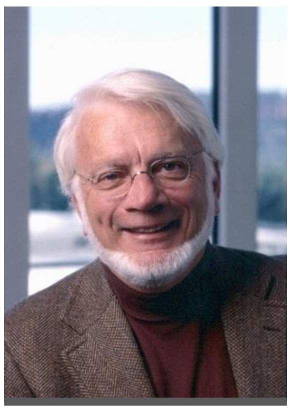


4 NOBEL PRIZE-WINNERS AMONG THE ESRF USERS

Ribosome

Nobel prize in Chemistry 2009

Venkatraman Ramakrishnan
MRC Laboratory of Molecular Biology, Cambridge, UK

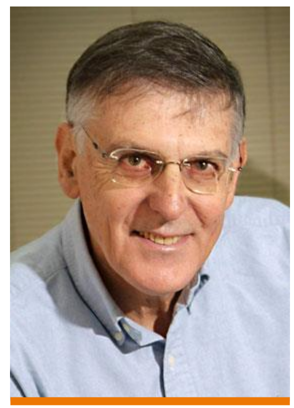


Thomas A. Steitz
Yale University, New Haven, CT, USA

Ada E. Yonath
Weizmann Institute of Science, Rehovot, Israel

Quasicrystals

Nobel prize in Chemistry 2011



Dan Shechtman
Technion – Israel Institute of Technology, Haifa, Israel

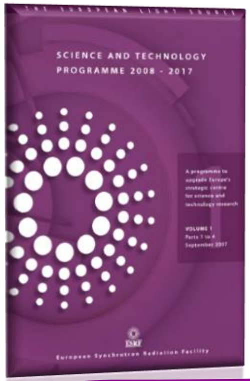
G-protein-coupled receptors

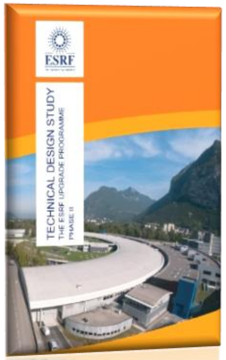
Nobel prize in Chemistry 2012

Robert J. Lefkowitz
Howard Hughes Medical Institute, Durham, NC, USA

Brian K. Kobilka
Stanford University School of Medicine, Stanford, CA, USA

Purple
Book
January
2008





Orange
Book
January
2015

ESRF UPGRADE PHASE I
180 M€ (2009-2015):
ESFRI ROADMAP 2006-2016
IN TIME – WITHIN BUDGET

- 19 new beamlines, many specialised on *nano*-beam science
- Upgrade and renewal of facilities and support laboratories

ESRF-EBS
EXTREMELY BRILLIANT SOURCE

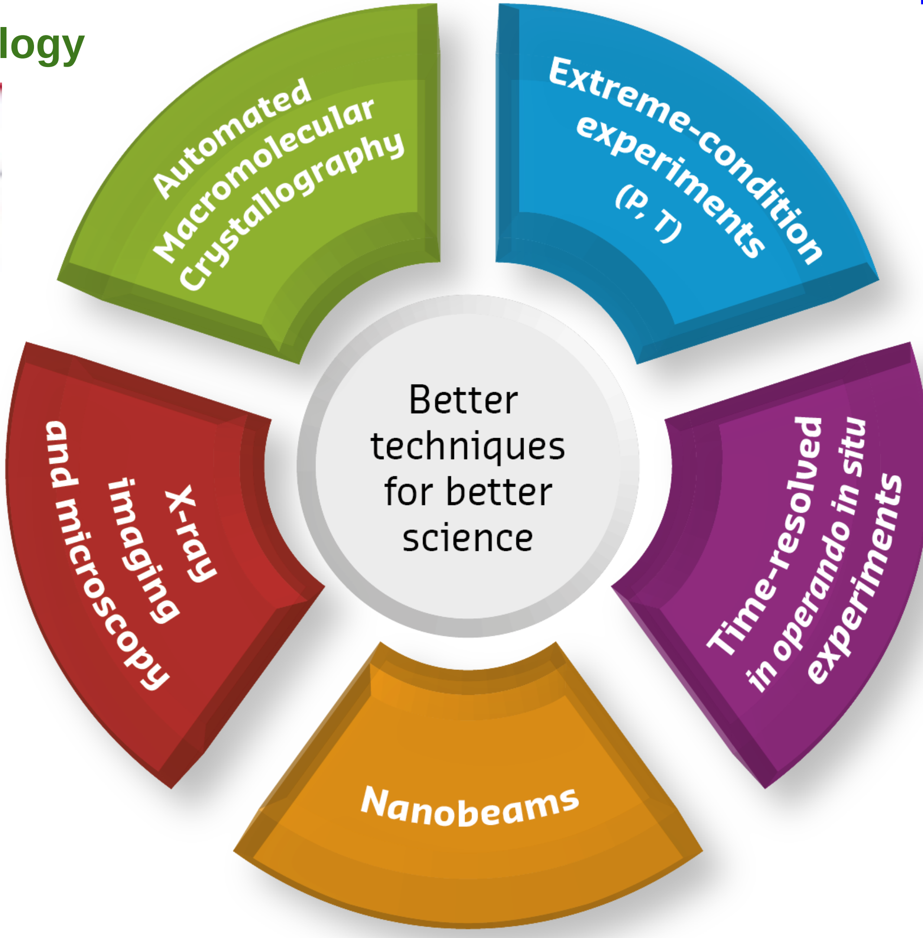
ESFRI

European Commission

ESRF-EBS
Extremely Brilliant Source
150 M€ (2015-2022):
ESFRI LANDMARK (2016)

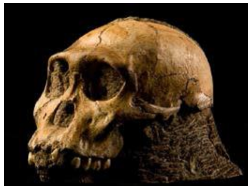
revolutionary design
for a new generation of synchrotron source storage rings

Health,
Structural biology

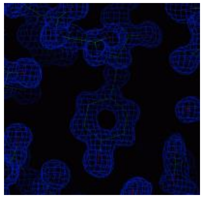


Earth sciences,
New materials

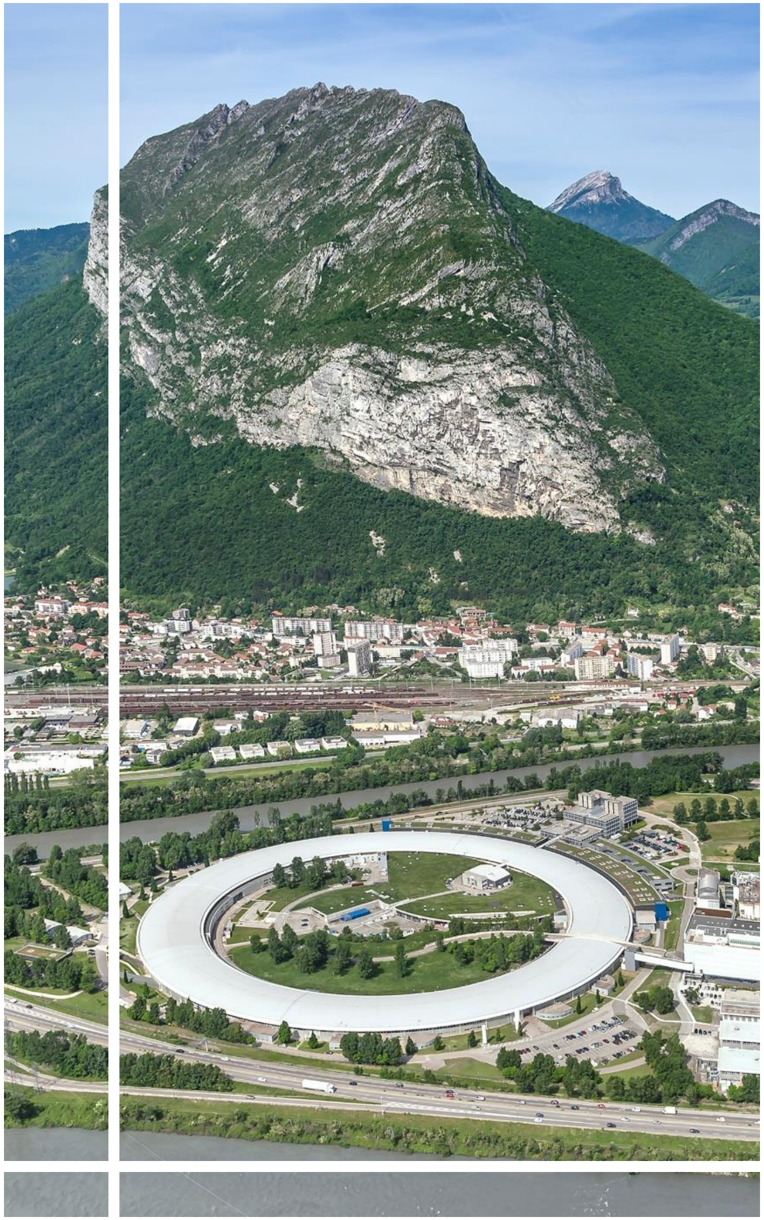
Medicine,
Paleontology,
Cultural heritage



Chemistry,
Energy, Materials,
Ultra fast biology

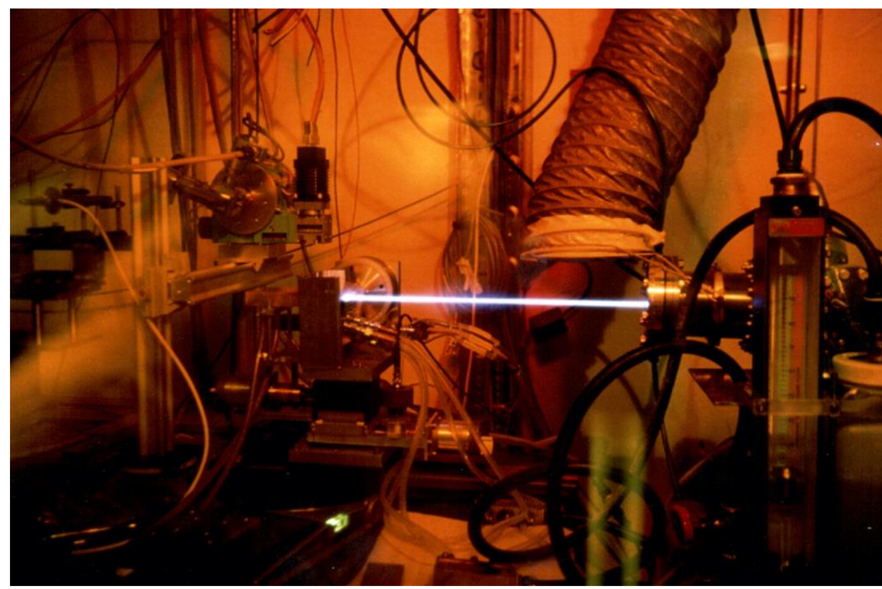


Nanosciences
Information technology

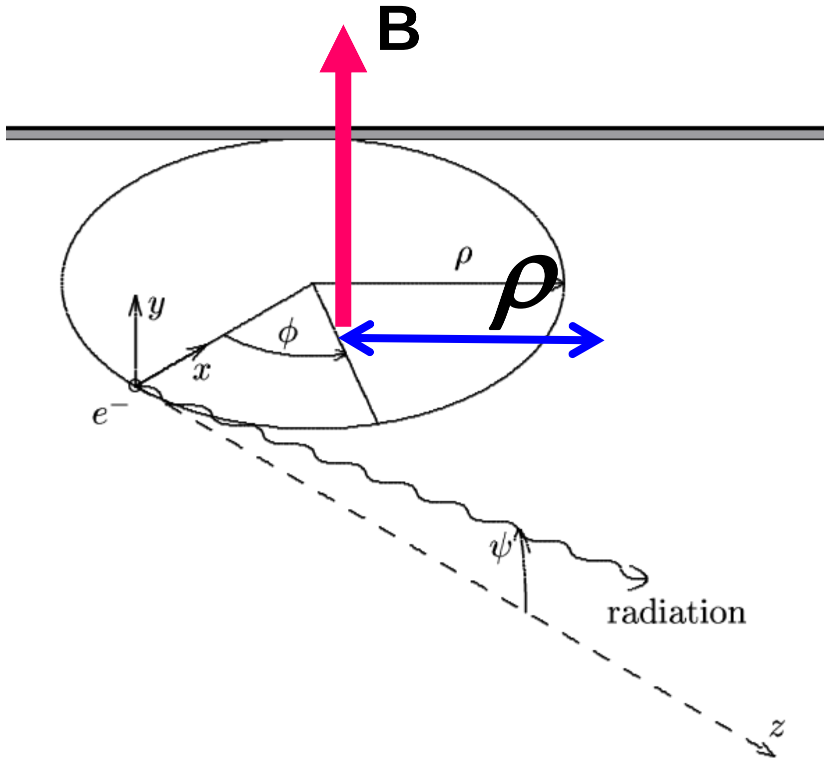


ESRF
The European Synchrotron

The ESRF today



- When a charged particle is deviated in a magnetic field,
  it loose energy by emitting electromagnetic radiation (photons),call synchrotron radiation, tangent to the trajectory.

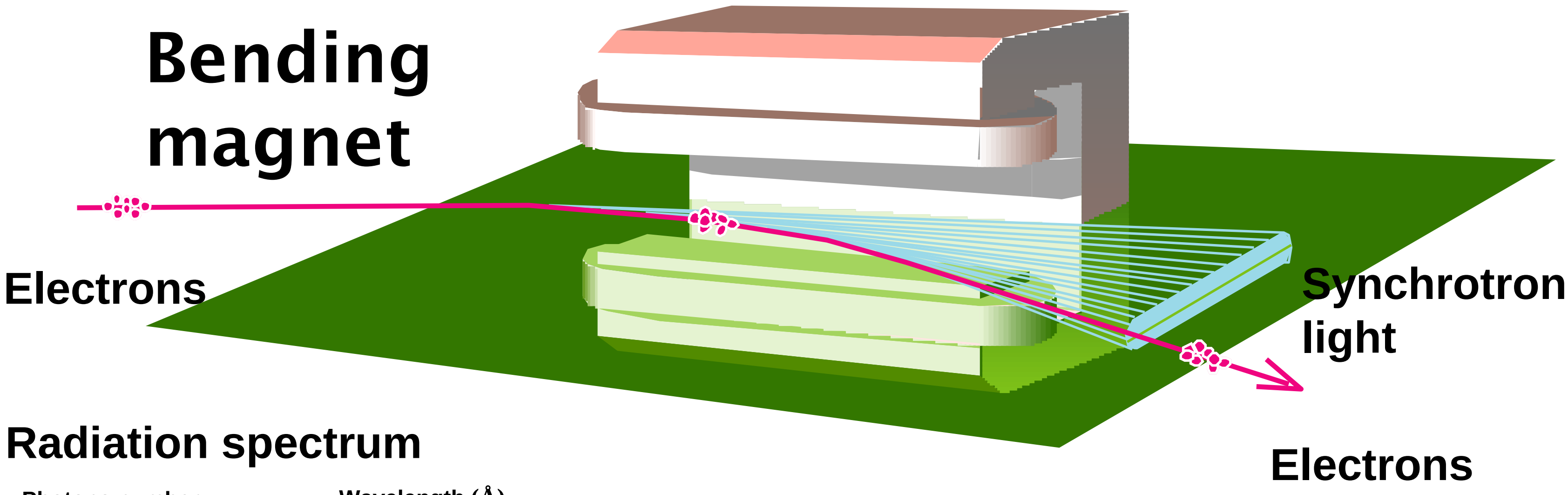


$$P \propto \left(\frac{E}{mc^2}\right)^4 \frac{I}{\rho}$$

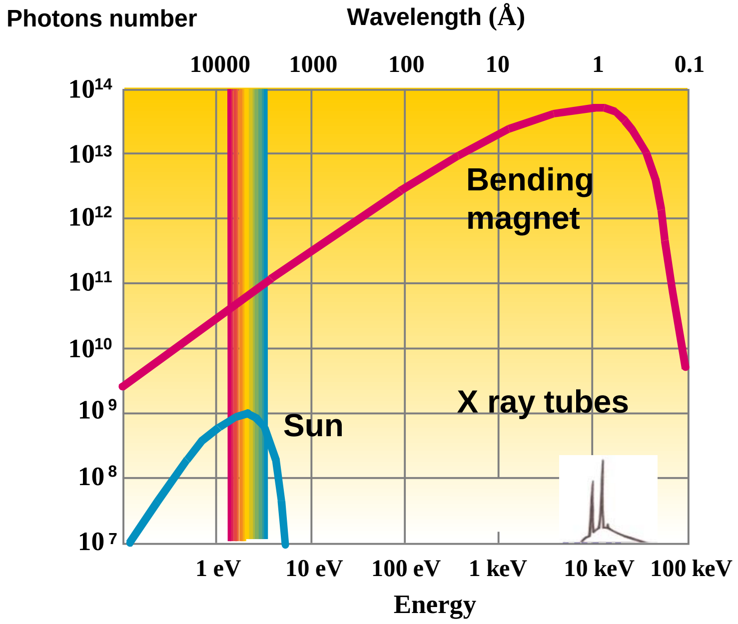
Large difference between electrons and protons !

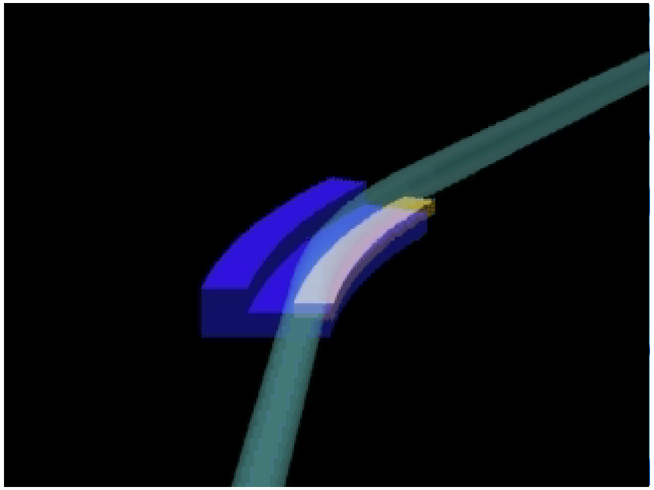
Scale with the square of the energy!

EMISSION OF SYNCHROTRON RADIATION IN CIRCULAR MACHINE



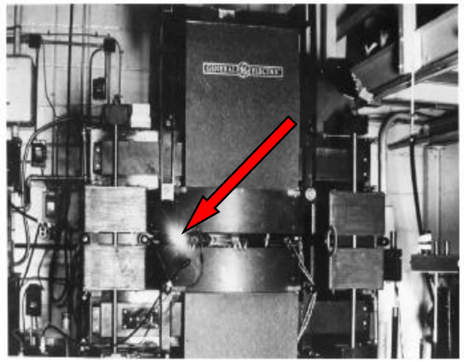
Radiation spectrum



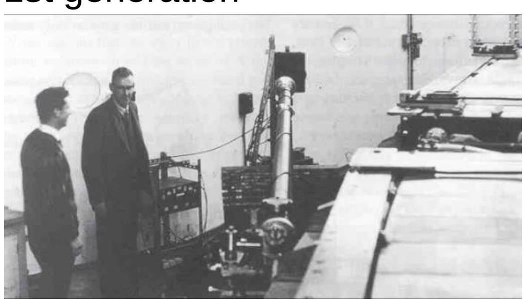


FROM PARASITIC USE TO DEDICATED USER FACILITY

1947: First observation of synchrotron radiation



« Nina », first beamline at Daresburry in1966 (synchrotron 6 GeV électron). 1st generation

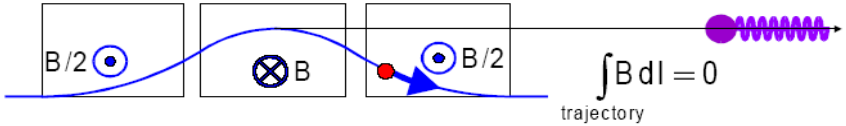


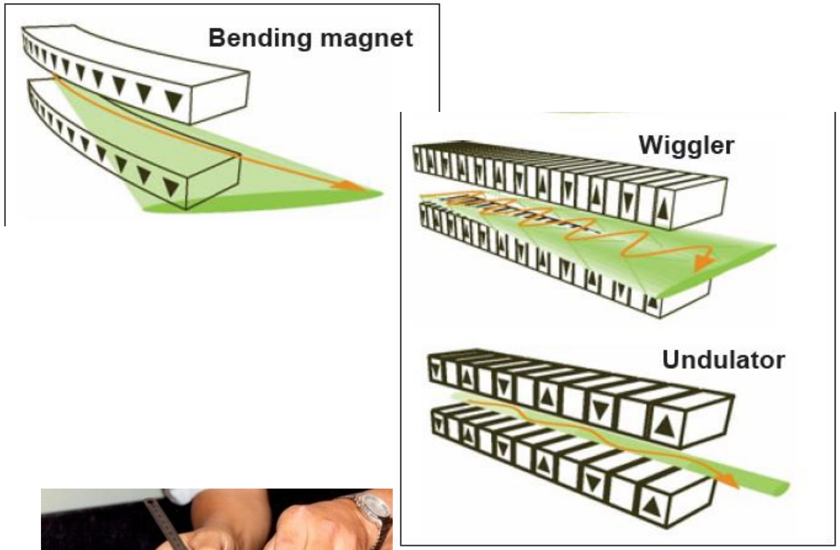
1981: SRS (UK) 1st dedicated X ray light source
2nd generation

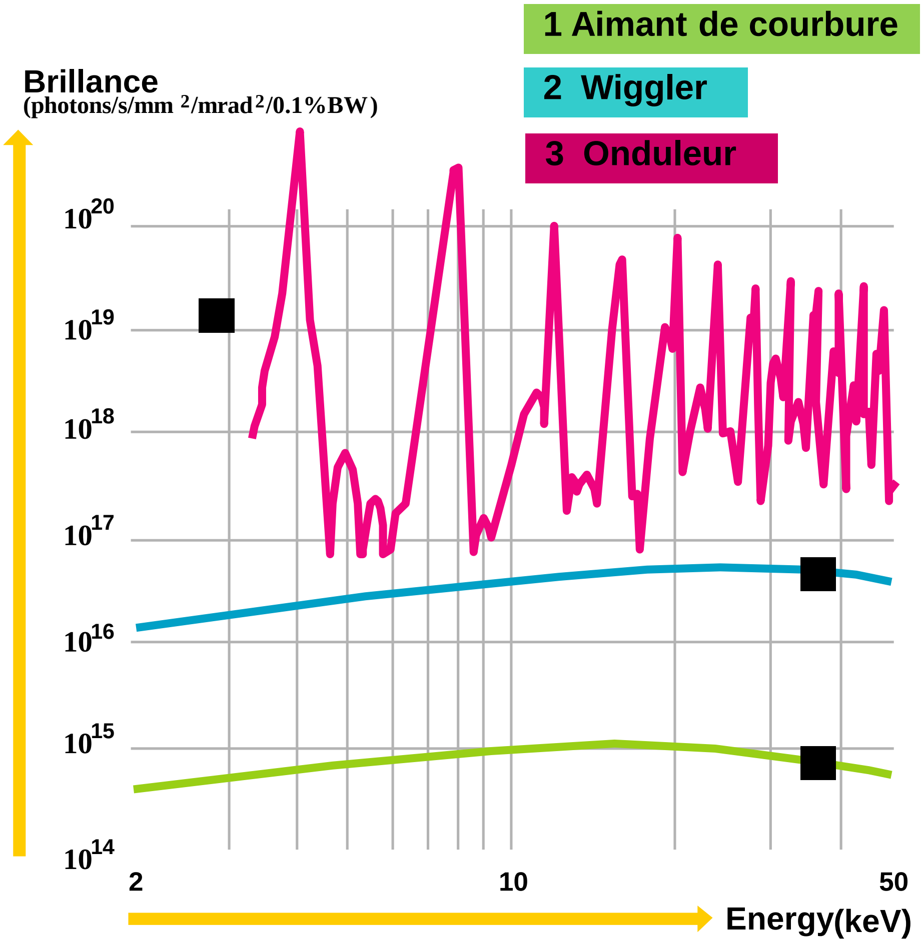
1994: Inauguration of the l'ESRF, The first X ray light source of the 3rd generation

PRINCIPLE OF INSERTION DEVICES

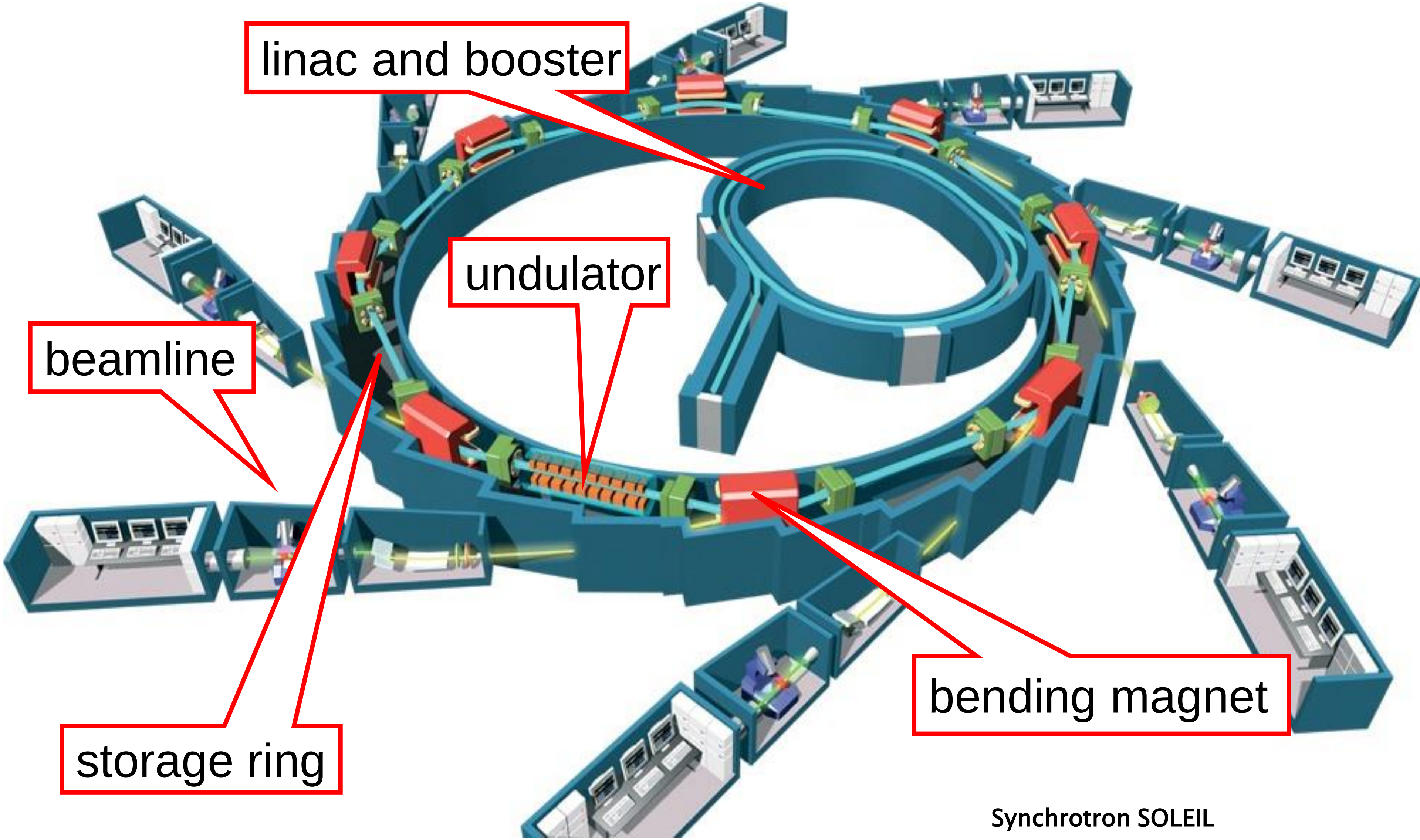
Insert permanent magnets to provide an alternative magnetic field to bend the trajectory.







A TYPICAL USER FACILITY



Synchrotron SOLEIL

BRILLIANCE OF LIGHT SOURCES

Progress of X ray light sources are summarized in the evolution of the brilliance

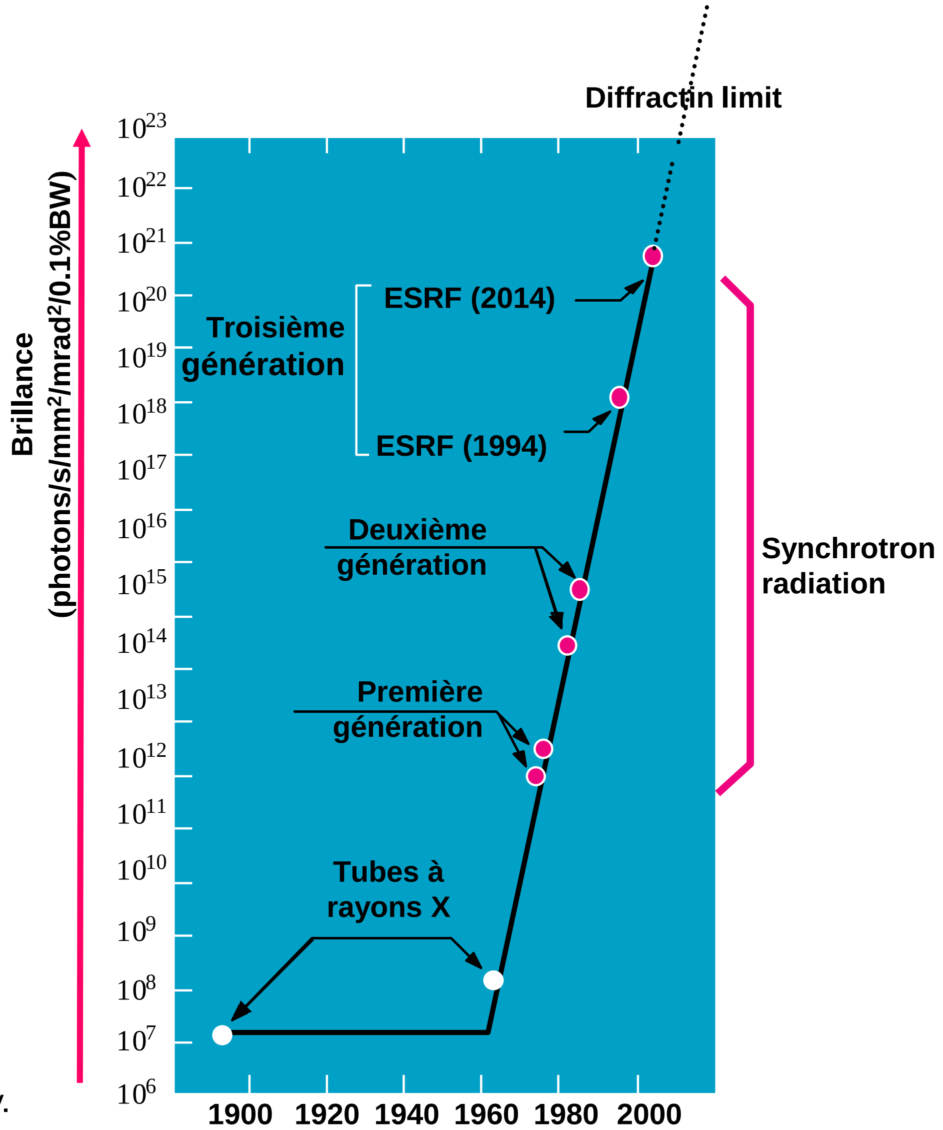
Brilliance =
photons /s / mm² /mrad² /0.1% bandepassante

Number of photons per second

Size horizontale*vertical

Divergence horizontal *vertical

In a bandwith of 0.1 % around the considered energy.



MORE THAN 50 SYNCHROTRON LIGHT SOURCES AROUND THE WORLD

DIFFERENT TYPE OF SOURCES

Many Medium energy rings :2.7-3.5 GeV

SOLEIL, DIAMOND, CLS, ALBA, SSRF, TPS ,Australian Synchrotron, NSLS II …

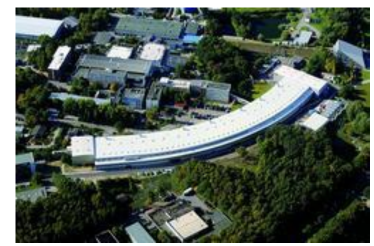
High energy rings (≥ 6.GeV)

SPRING 8

ESRF Upgrade

APS Upgrade

Petra III



X FELs (4th ~~generation light sources~~)

- LCLS   (Stanford)
- SACLA (SPRING8)
- Flash, European XFEL (Hamburg)
- Fermi@ elettra
- …..

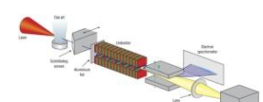
LCLS

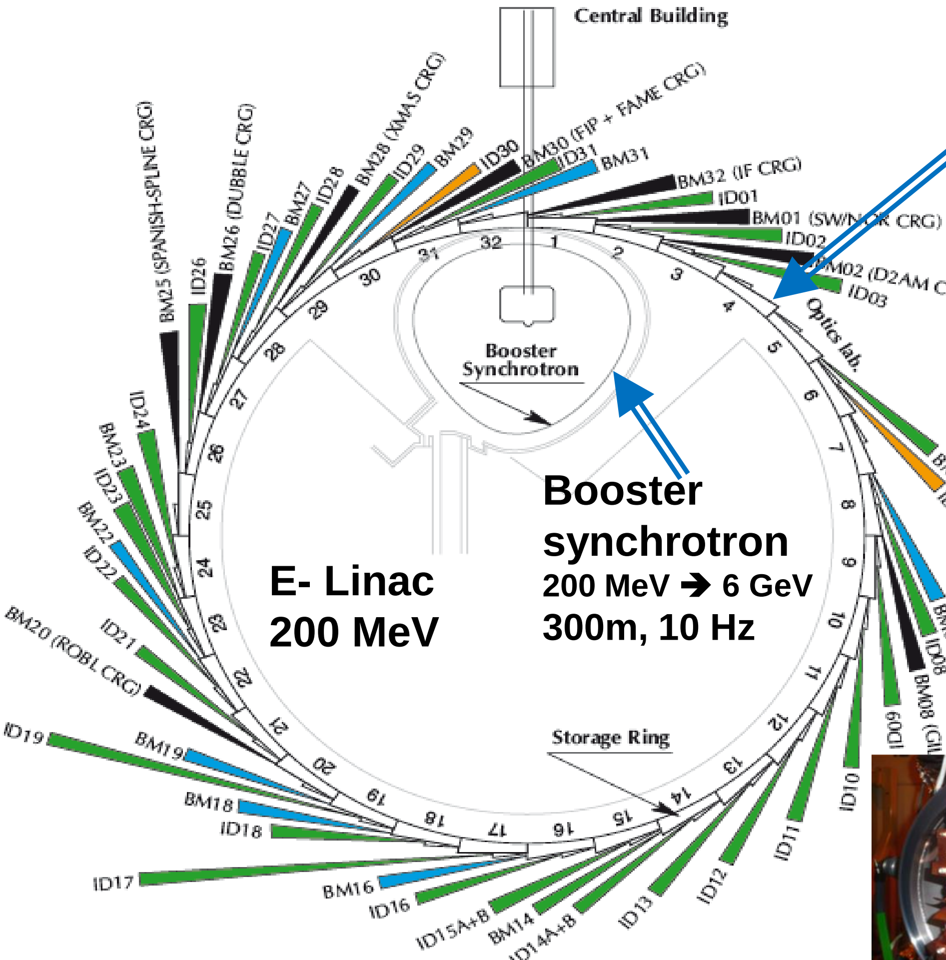
SACLA

European XFEL

Fermi

Laser plasma acceleration: 5th generation light sources





Storage ring
6GeV, 844 m

Booster synchrotron
200 MeV ➔ 6 GeV
300m, 10 Hz

E- Linac
200 MeV

Energy	GeV	6.04
Multibunch Current	mA	200
Horizontal emittance	nm	4
Vertical emittance	pm	4

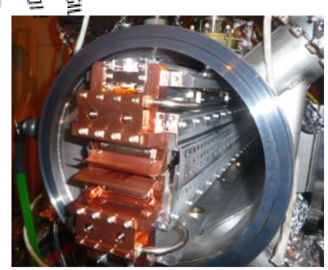
32 straight sections

DBA lattice

42 Beamlines

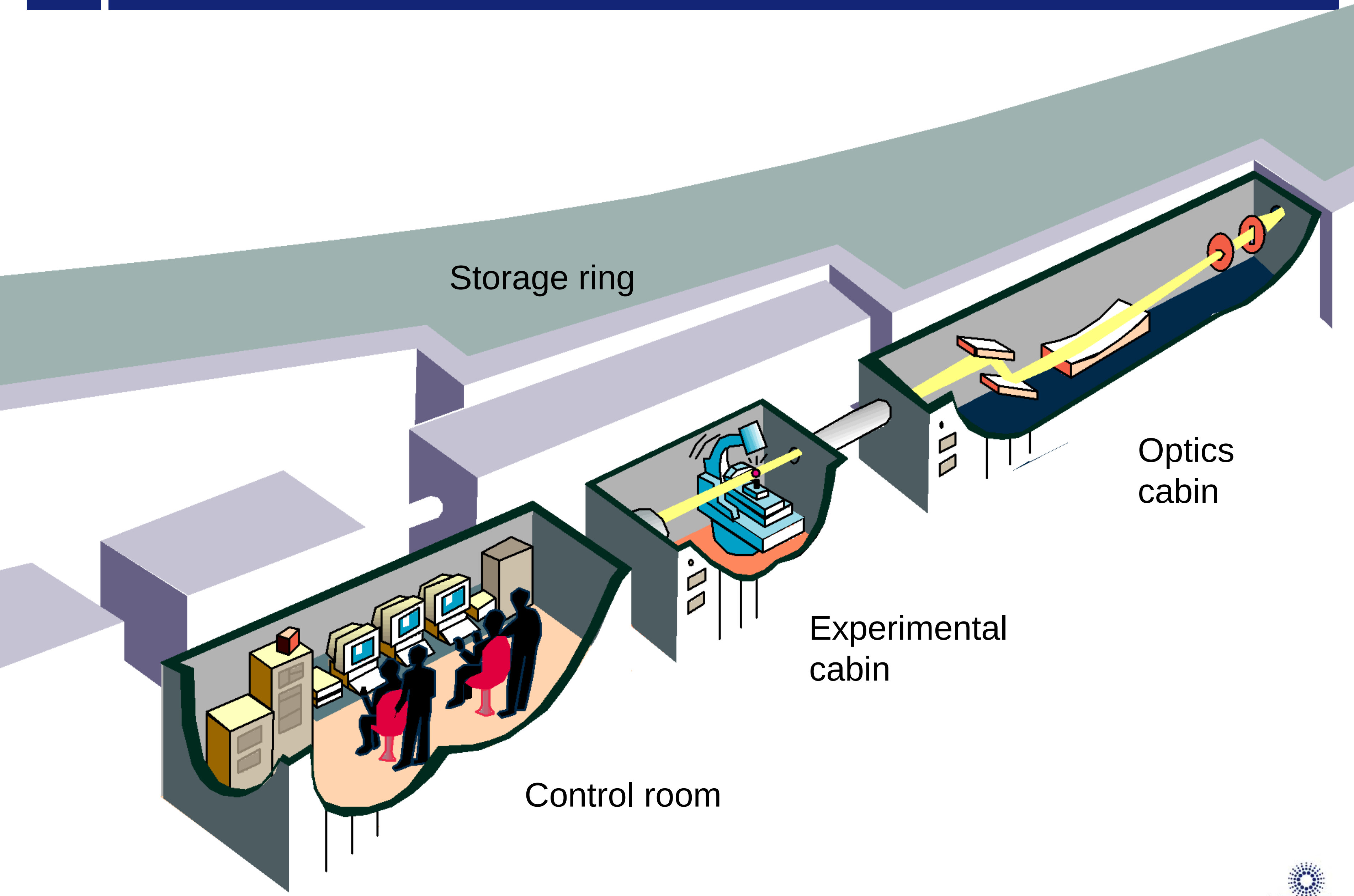
12 on dipoles

30 on insertion devices



72 insertion devices:
55 in-air undulators, 6 wigglers,
10 in-vacuum undulators,
including 3 cryogenic

A TYPICAL BEAMLINE



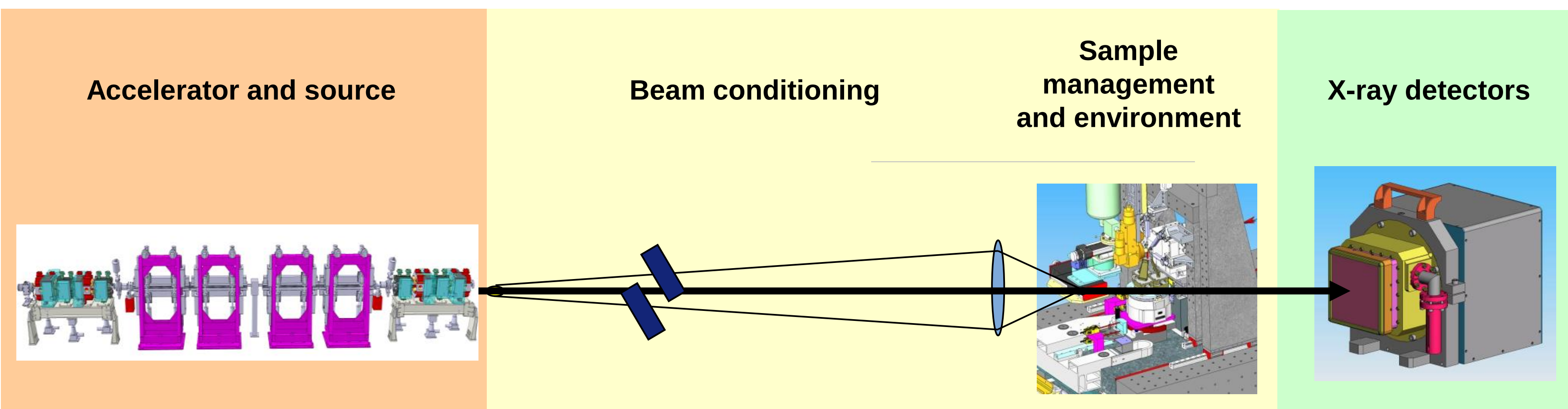
SCIENTIFIC REQUIREMENTS

Scientific requirements for the beam:

- Tunable wavelength
- Flux
- Low emittance
- Position stability
- Temporal structure
- Reliability and reproductibility

A good experiment also requires a performing experimental environment:

- X ray optics
- Sample preparation
- Dedicated detectors
- Data analysis and computing capacity



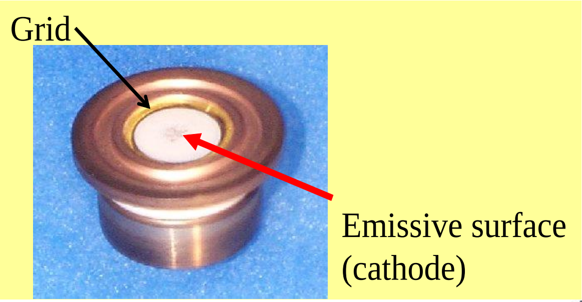
THE ACCELERATOR COMPLEX

THE LINEAR ACCELERATOR

The Linac consists in one **TRIODE** (cathod – anod – grid) powered with 100 KV. Electrons produced have then an energy of 100 keV.

The electrons are then accelerated in 2 sections (each section = 6 meters), accelerating the beam by 100 MeV, i.e., a total of 200 MeV.

Operation mode	Long pulses	Short pulses
Peak current	25 mA	250 mA
Pulse length	1µs	2ns
Energy spread	+/- 1%	+/- 0.5%



THE TRANSFER LINE FROM THE LINAC TO THE BOOSTER: TL1

- Length: 16 metres
- Main components: 2 bending magnets, 7 quadrupoles, 2 pairs of steerers
- Diagnostics: insertable screens + synchrotron radiation screens

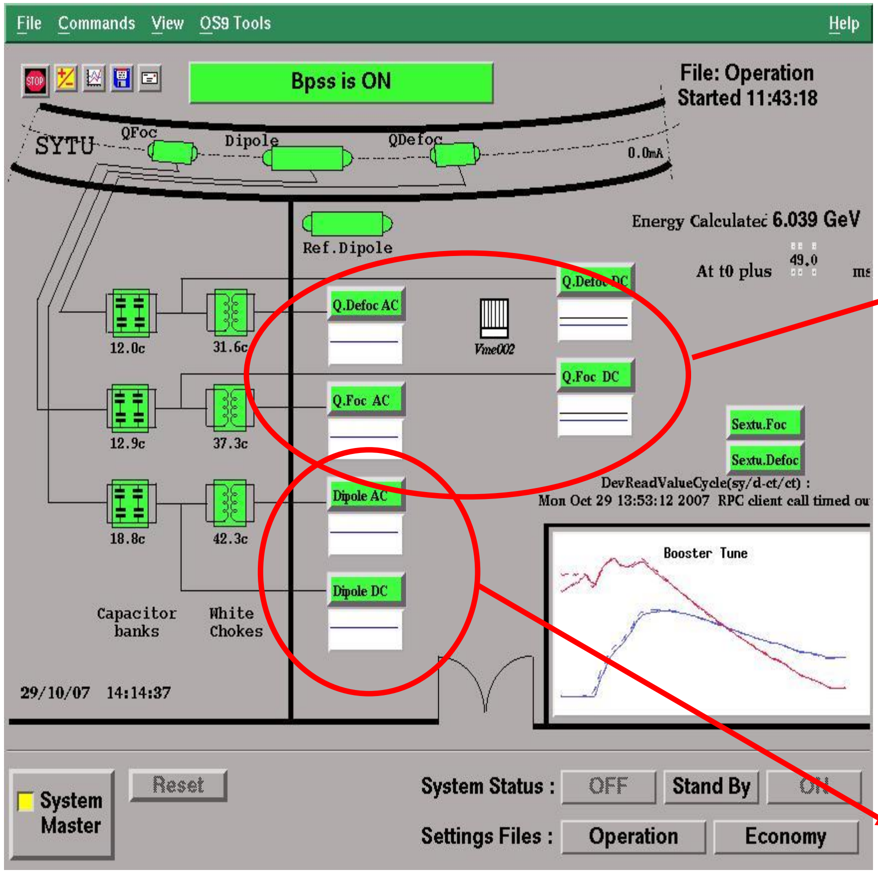
THE SYNCHROTRON (OR BOOSTER)

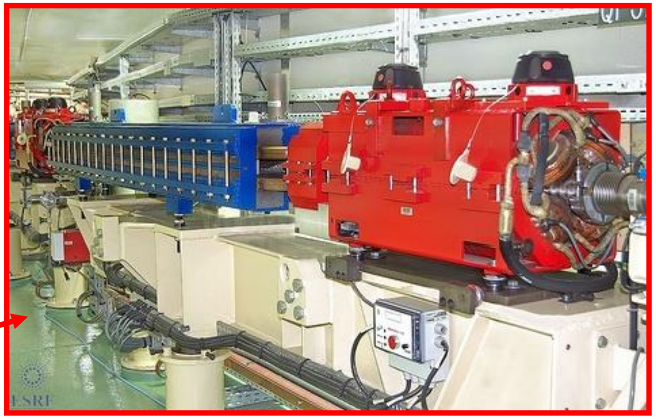
Goal: Accelerate the electrons from 200 MeV to 6 GeV

Cycle: period of 100 msec (50 msec for the acceleration cycle)

Length: 300 metres

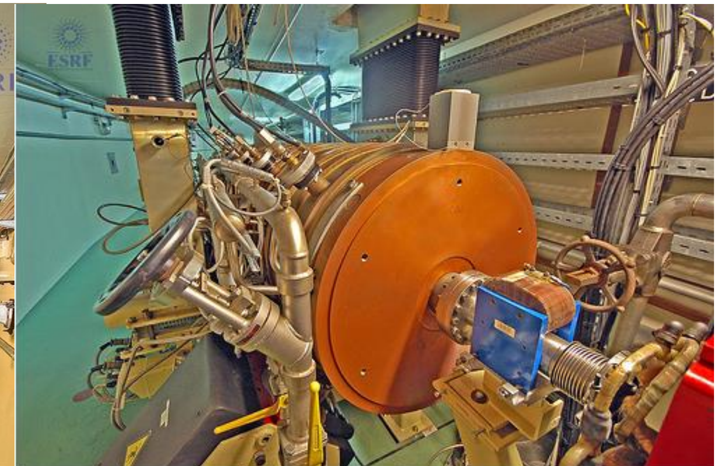
THE BOOSTER MAGNETS

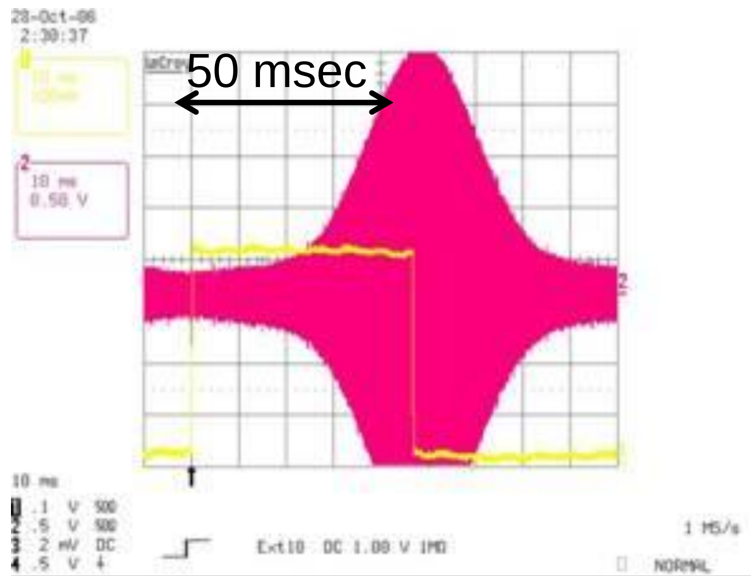




When the field is minimum in the dipoles, it defines the « T0 »: the first trigger of the timing system which manages all the injection/extraction chain.

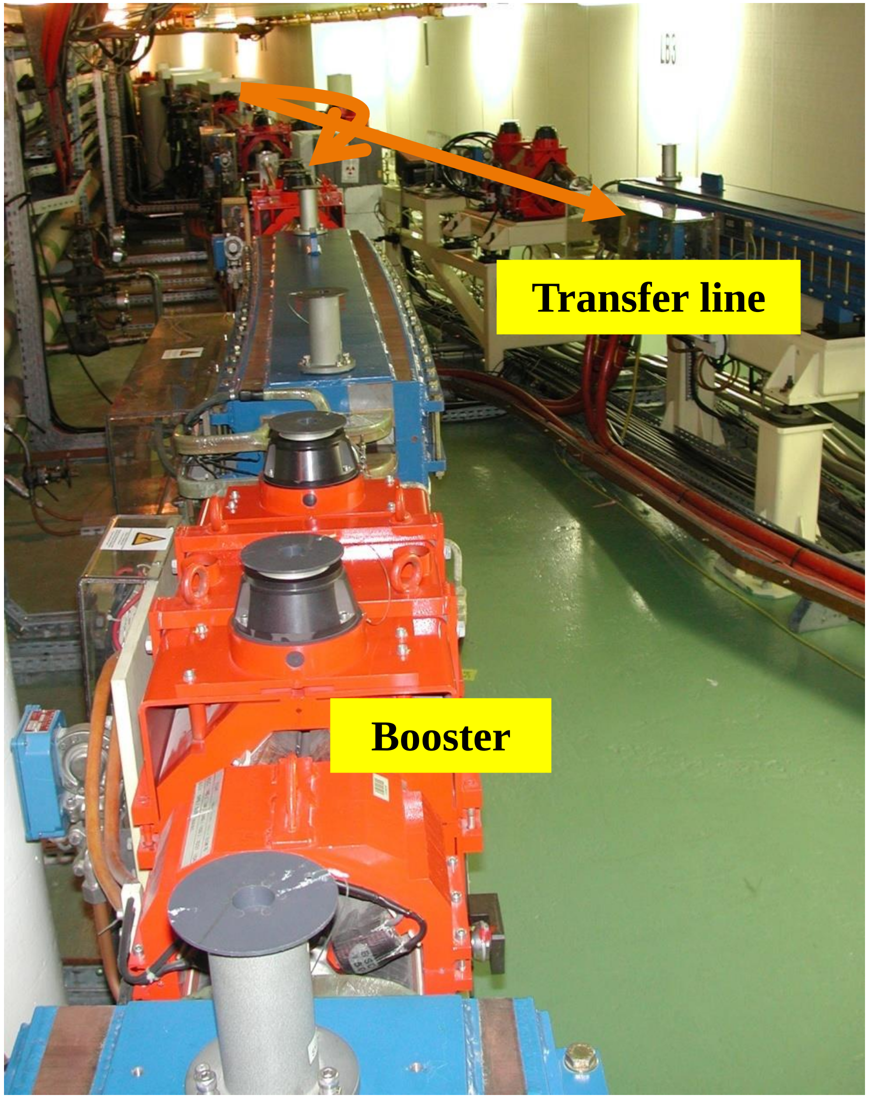
THE BOOSTER RADIOFREQUENCY SYSTEM





- 4 cavities with 5 cells (LEP-type)
- 2 windows / cavity
- Solid State Amplifier Transmitter : 1 MW – 352.2 MHz

THE TRANSFER LINE FROM THE BOOSTER TO THE STORAGE RING: TL2

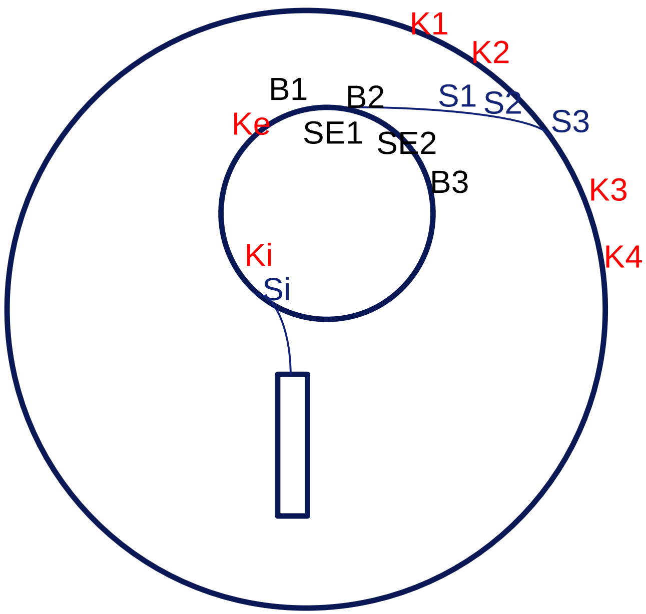


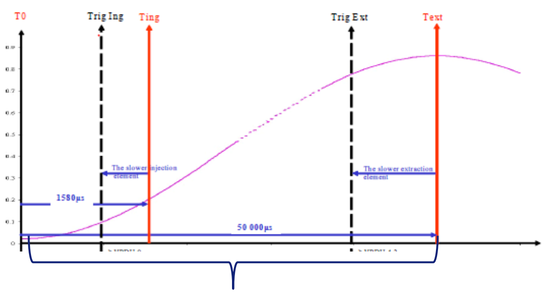
Goal:

Transfer the 6 GeV electrons from the Synchrotron to the storage ring:

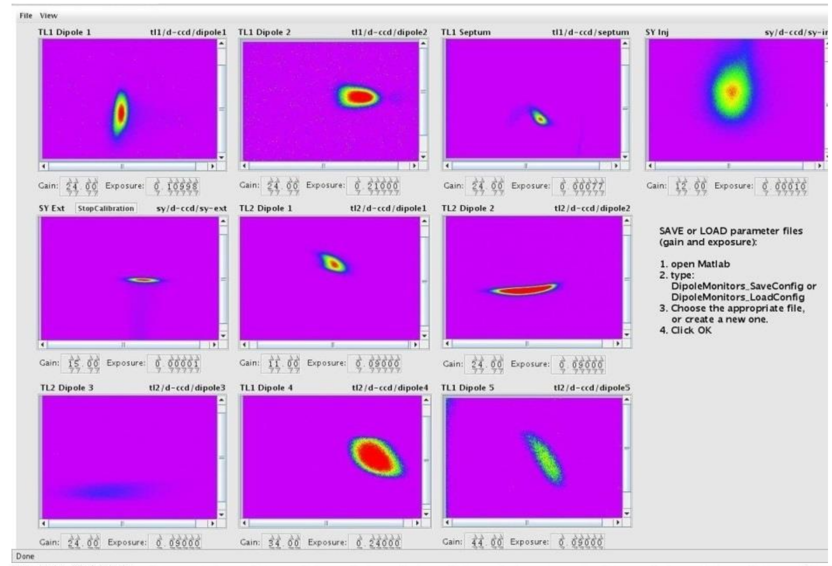
- 5 bending magnets (powered in serie with Booster dipoles)
- 14 quadrupoles
- 9 insertable screens
- Beam Position Monitors
- Synchrotron radiation screens (1 screen / dipole)
- Length: 65 metres

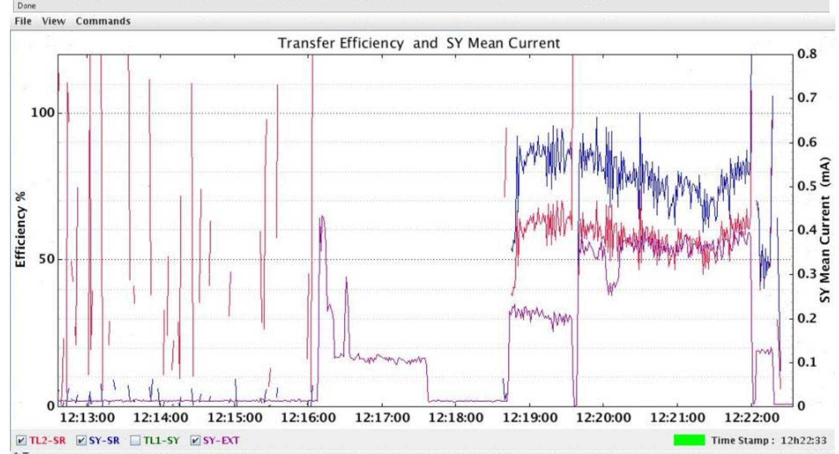
THE INJECTION/EXTRACTION SYSTEM



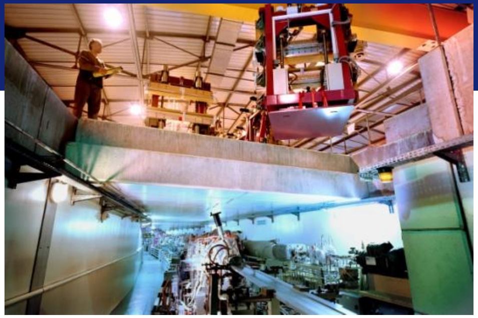


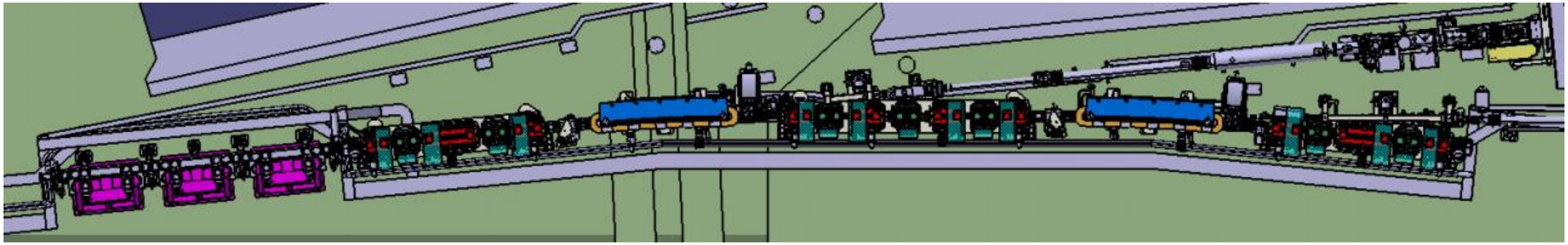
Injection cycle = 50 ms



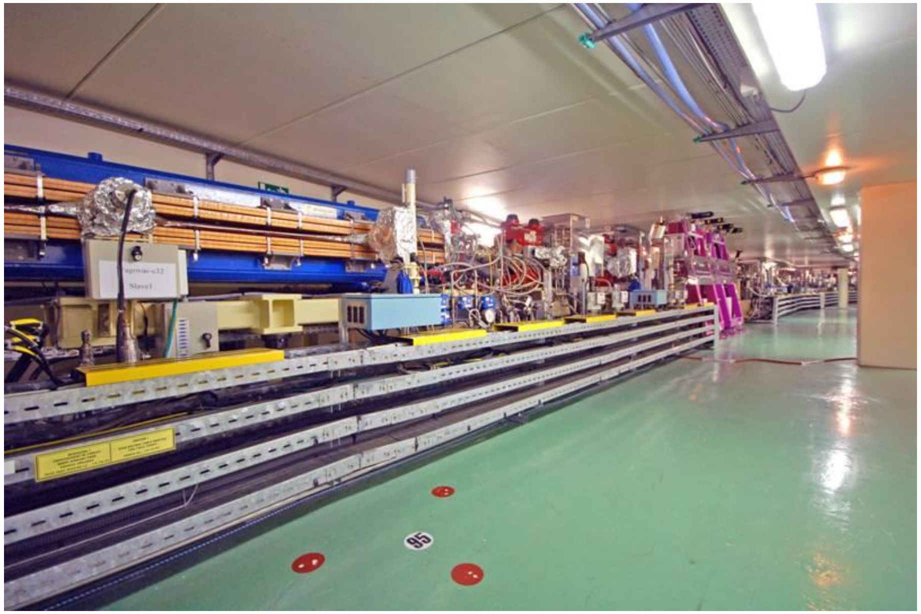


THE STORAGE RING



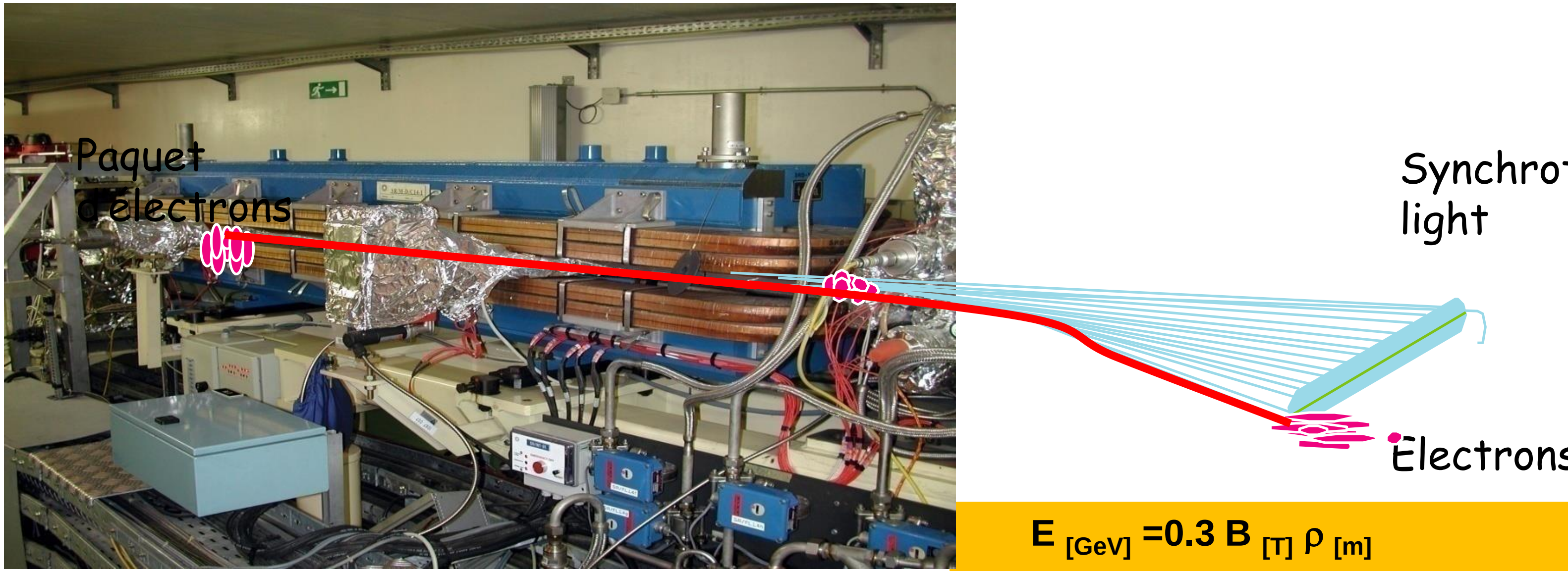


- Circumference: 844 metres
- 16 super-periods of 2 mirror cells➔ 32 cells
- Energy: 6 GeV
- Nominal intensity: 200 mA
- Highest intensity: 300 mA
- Emittance: 4nm rad
- Usual coupling : 0.1 %



THE STORAGE RING BENDING MAGNETS

64 bending magnets (dipoles)



$E_{[GeV]} = 0.3\, B_{[T]}\, \rho_{[m]}$

B=0.8 T $\rho = 25$ *m*

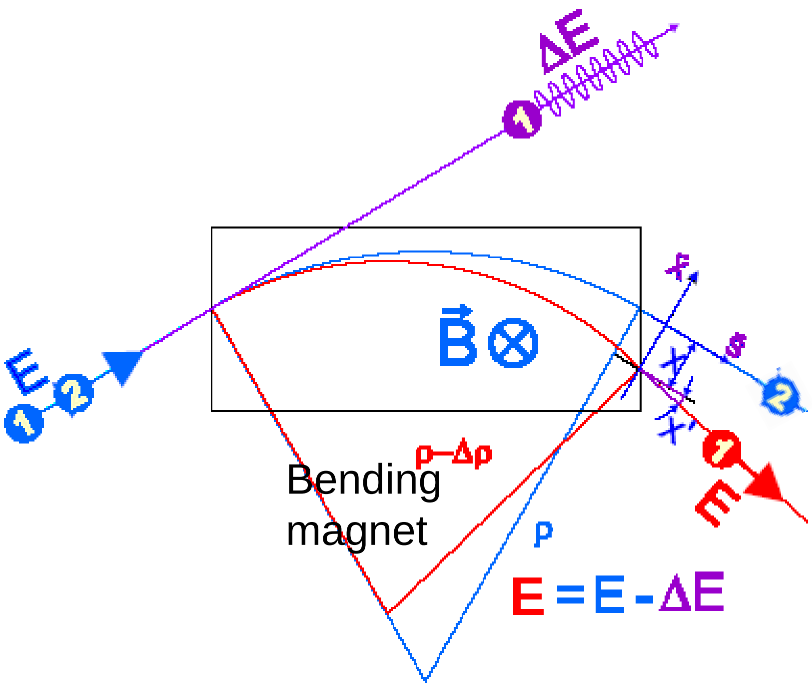
Energy lost per turn of ring by one electron

$$\Delta E_{[keV]} = 88.5 \frac{E^4_{[GeV]}}{\rho_{[m]}} = \mathbf{4.6\ MeV}$$

The power radiated around the length of the ring bending magnets by a current of 200 mA = 920 kW

Numbers :	64 (2 per cells)
Bending angle :	5.625 °
Magnetic field :	0.8612 Tesla
Number of family :	1
Nominal intensity :	714.993 A

GENERATION OF AN HORIZONTAL EMITTANCE BY RADIATION



Electron 2 emits Δe at the exit of the bending magnet.

➔ *same energy when crossing the magnet*

➔ *stay on the reference trajectory*

Electron 1 emits ΔE at the entrance of the bending magnet.

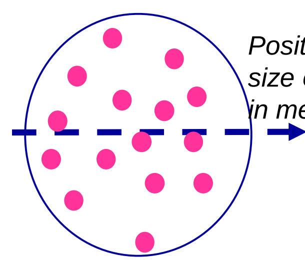
➔ *lower energy when crossing the magnet*

➔ *larger curvature*

A horizontal beam size and divergence (or emittance) and an energy spread is created.

Angle or divergence or X' in radian

The beam emittance is the **surface** occupied by the beam in size and divergence.



Position or size or X in meter

$$\varepsilon_{x[m*rad]} = \frac{1}{\pi}\oiint dx\,dx'$$

THE STORAGE RING QUADRUPOLE MAGNETS

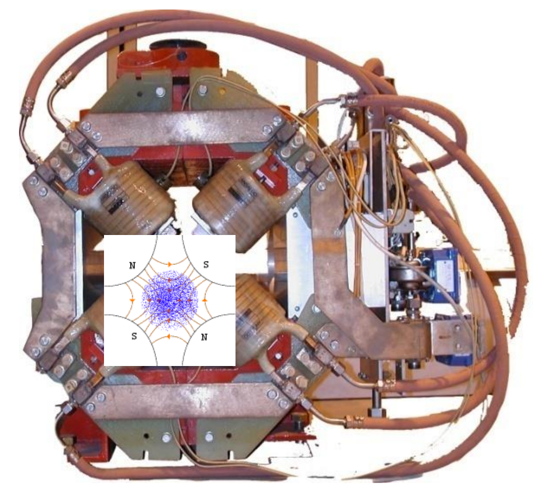
256 quadrupoles shared in 6 families

Name	Number	Intensity
QF2	32	216.730 A
QD3	32	-334.022 A
QD4	64	- 415.454 A
QF5	64	411.798 A
QD6	32	- 491.497 A
QF7	32	375.181 A

The goal of the **quadrupoles** is to focus the electron beam so as to maintain its size as small as possible

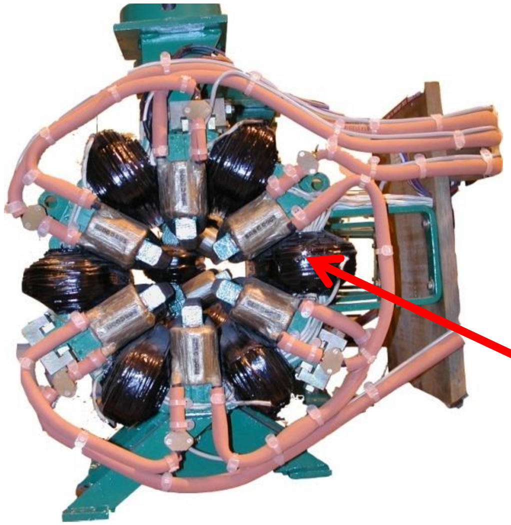
The quadrupole settings are also important for:

- the tune values,
- the beam size,
- the injection speed,
- the betatronic resonances, etc



THE STORAGE RING SEXTUPOLE MAGNETS

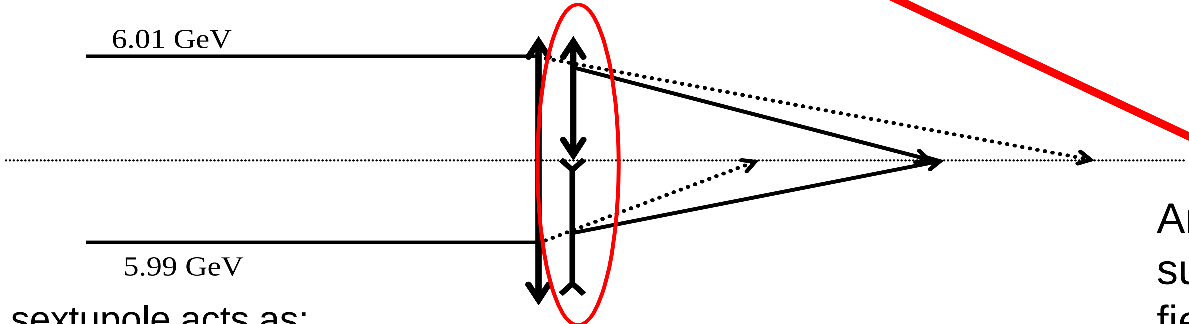
224 sextupoles shared in 7 families



Name	Number
S4	32
S6	32
S13	32
S20	32
S19	32
S22	32
S24	32

Their settings are important for:

- the chromaticities,
- the betatronic resonances
- the dynamic aperture,
- and therefore the beam lifetime



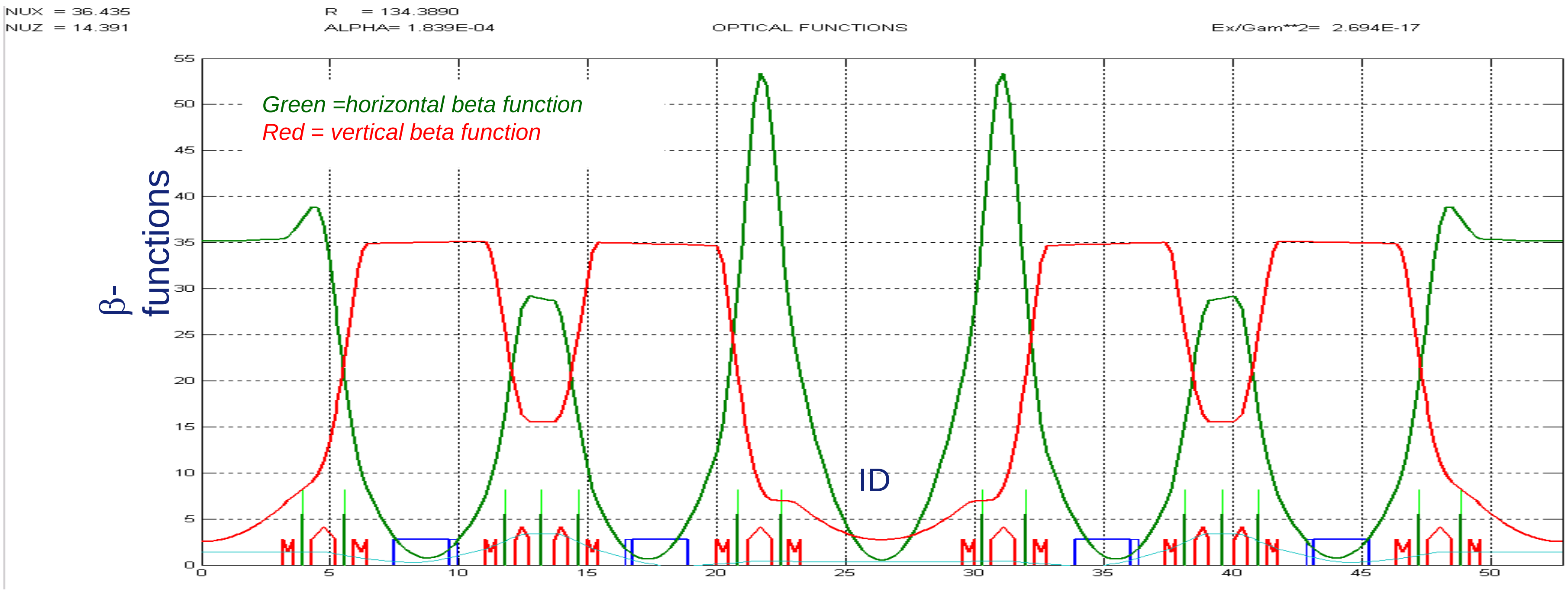
And steerers (3 power supplies to get a H or V field)

A sextupole acts as:

- A focusing quadrupole for the electrons which have a higher energy

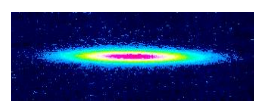
- A defocusing quadrupole for the electrons which have a lower energy

THE ESRF STORAGE RING LATTICE



5 m **5 m** **5 m**

Even cells



Odd cells

ESRF Horizontal emittance = 4 nm.rad

ESRF vertical emittance = 5pm

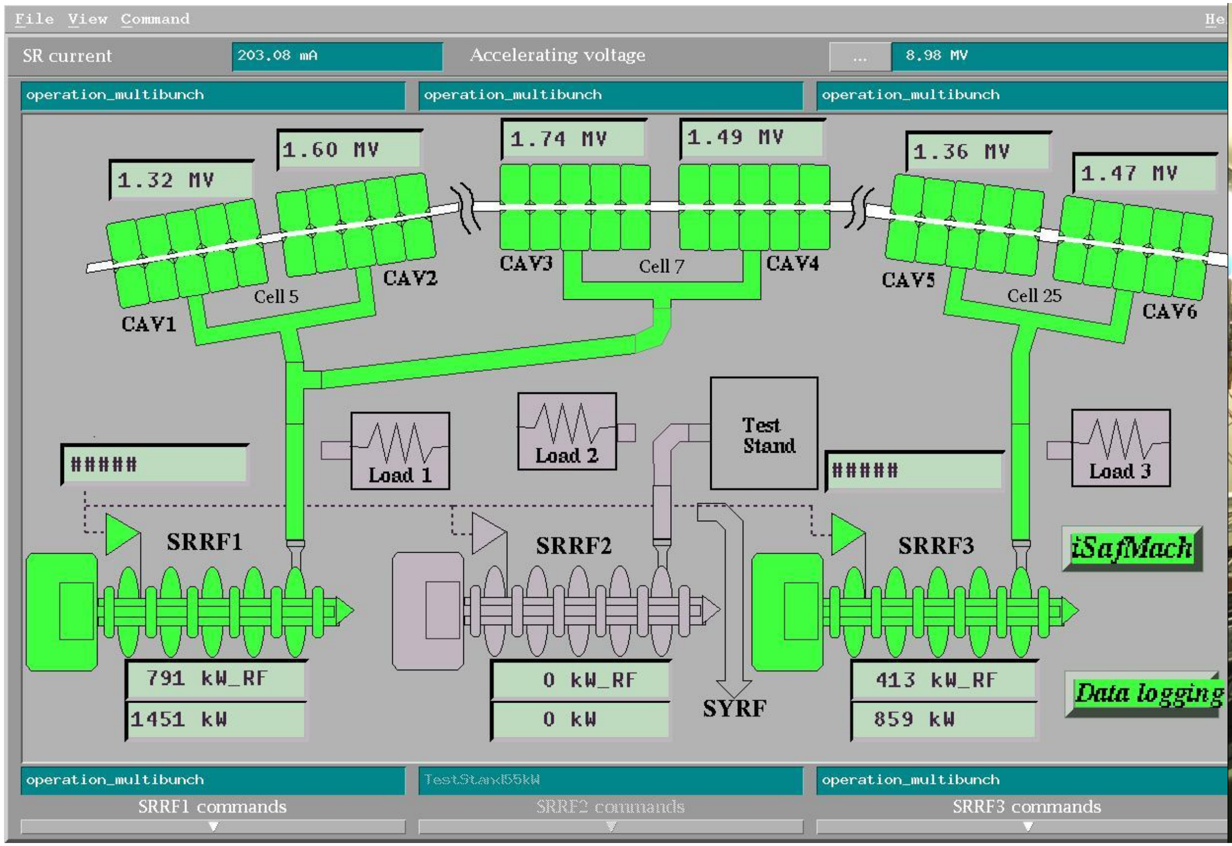
Vertical emittance is determined by the coupling to the horizontal motion due to magnet or alignment imperfections.

$$\sigma_x = \sqrt{\varepsilon_x \beta_x} \qquad \sigma'_x = \sqrt{\varepsilon_x / \beta_x}$$

$$\sigma_y = \sqrt{\varepsilon_y \beta y} \qquad \sigma'_y = \sqrt{\varepsilon_y / \beta_y}$$

Taille *Divergence*

THE STORAGE RADIOFREQUENCY SYSTEM



Goal: compensate the energy loss turn / turn by the electrons, following the synchrotron radiation emission, i.e., 4.8 MeV (with all insertion devices)

THE STORAGE RADIOFREQUENCY SYSTEM

For a beam intensity of 200mA :

6 active cavities (1 klystron powers 4 cavities, the second one powers 2 cavities)
Accelerating voltage : 9 MV
Voltage / cavity : 1.5 MV
Klystron total power : 1.3 MW (1MW for beam + 42 kW/cavity+20kW reflected)

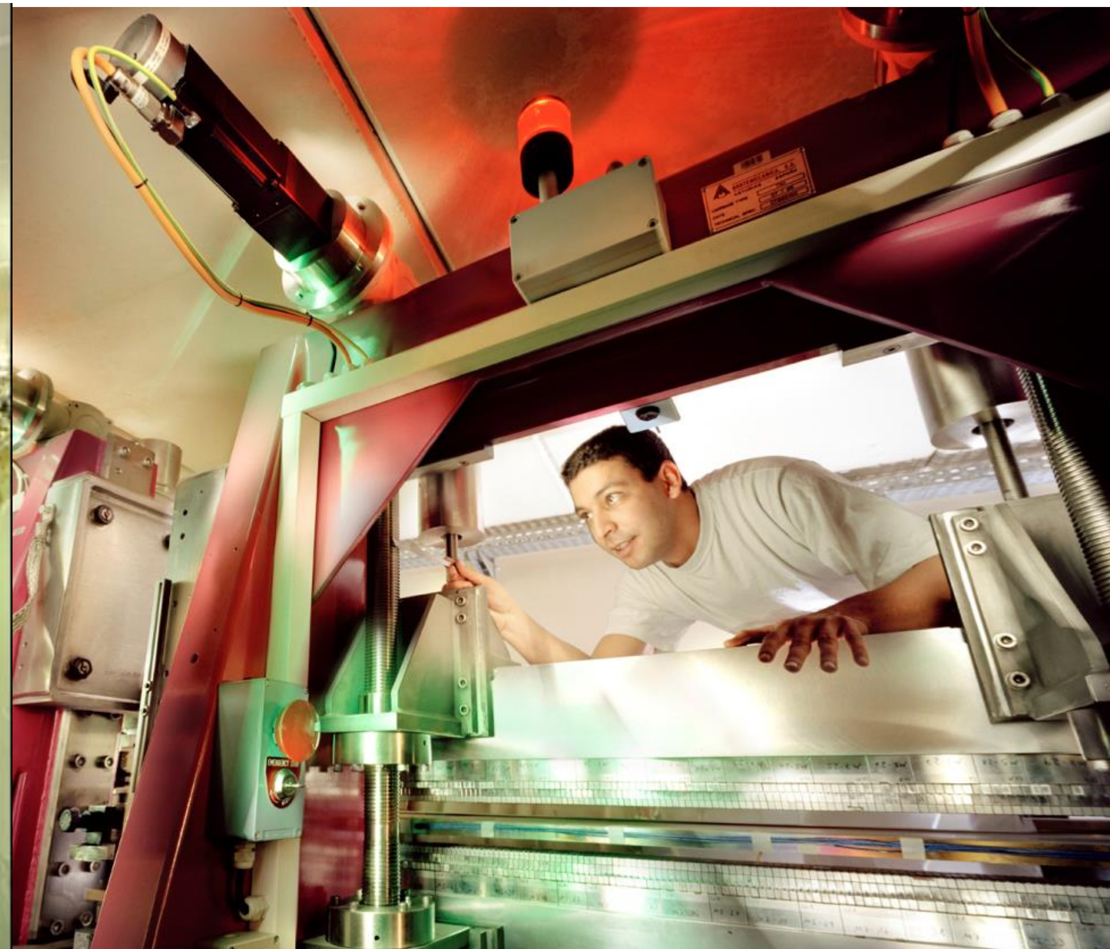
• **macroscopic**: the RF frequency imposes the maximum number of bunches on the circumference.

$$h = \Delta \frac{F_{RF}}{F_{rev}} = 352 \text{ MHz} / 355 \text{ kHz} = 992$$

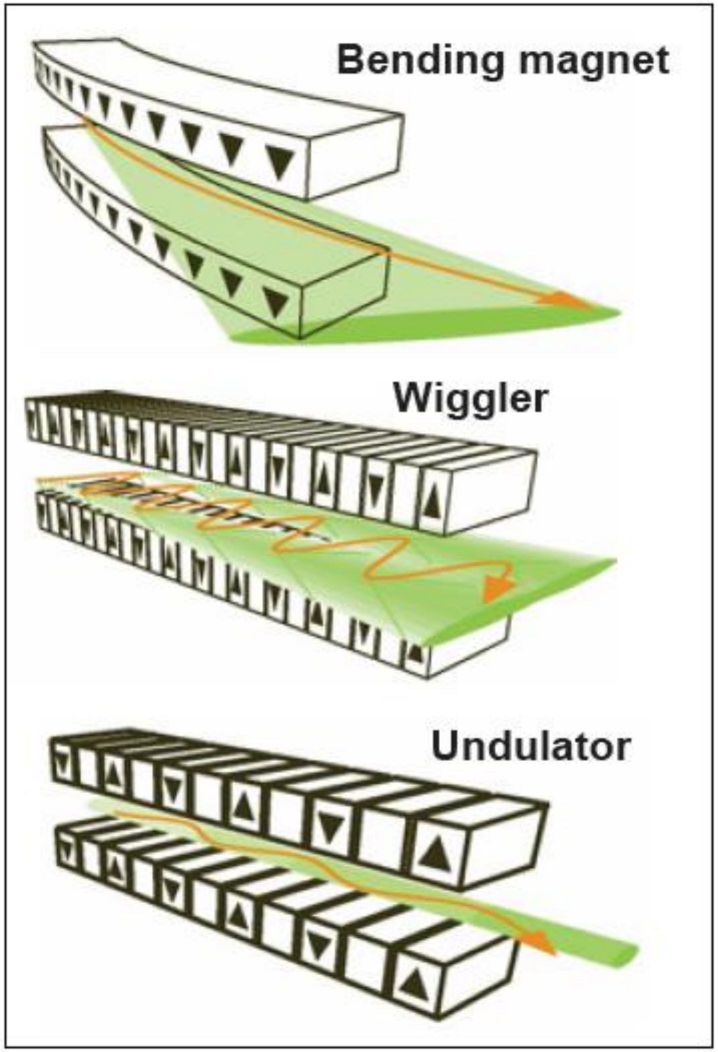
• **microscopic**: the RF frequency imposes the revolution time of the reference particle. For a given field of the bending magnets, it defines the length of the trajectory and therefore the energy of the reference particle.

With ESRF data, a difference of 3.5 KHz (10^{-5}) will induce an horizontal displacement of the beam of 18 mm, visible on the screens.

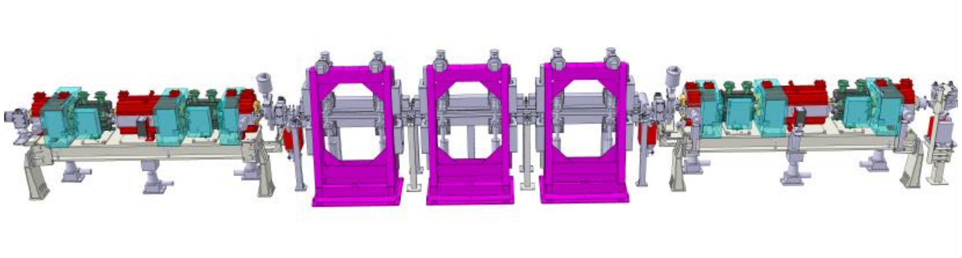
INSERTION DEVICES



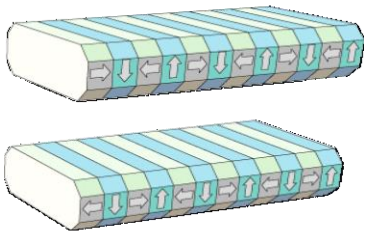
INSERTION DEVICES

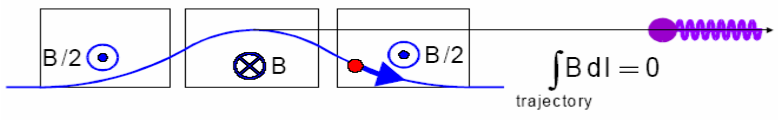


Goal: produce X-rays with specific properties which are different from those emitted by the dipoles, for example, tuneable energy spectrum, polarisation, higher brilliance...



Generally designed « on request » for a given beamline

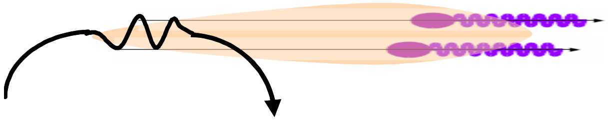




Two main families:

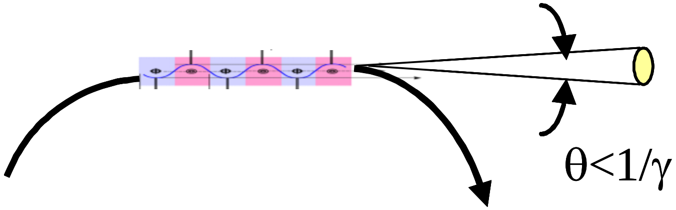
Wigglers : Small number of periods, higher magnetic fields

They produce ‘hard’ X rays (E>10 keV).

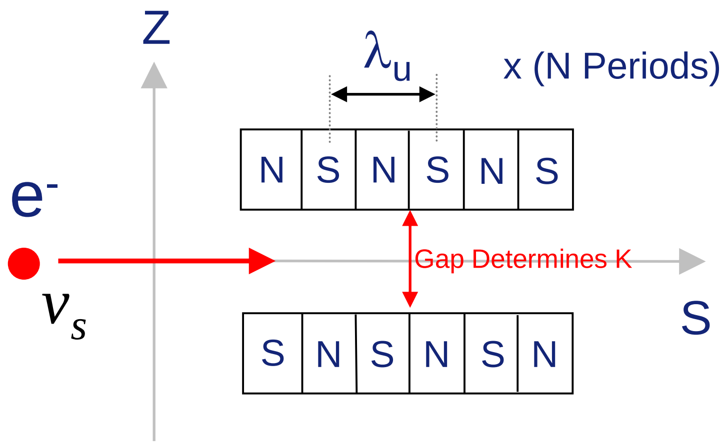


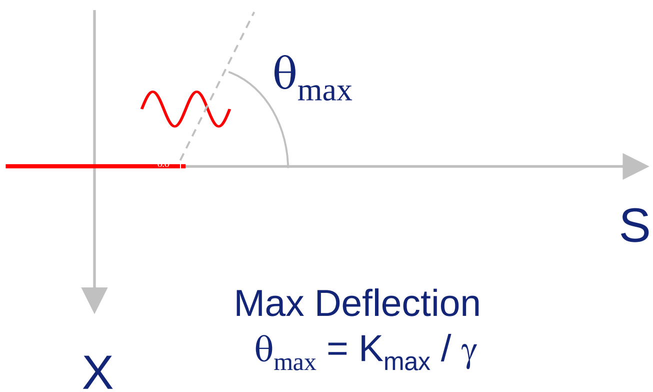
Undulators : Great number of periods .

Larger flux induced by in interference properties..



INSERTION DEVICES





Max Deflection
$\theta_{max} = K_{max} / \gamma$

Undulator: K < 3

Wiggler: K >3

The electron takes a sinusoidal path, with a max angular deflection given by K/γ, where K is the deflection parameter given by;

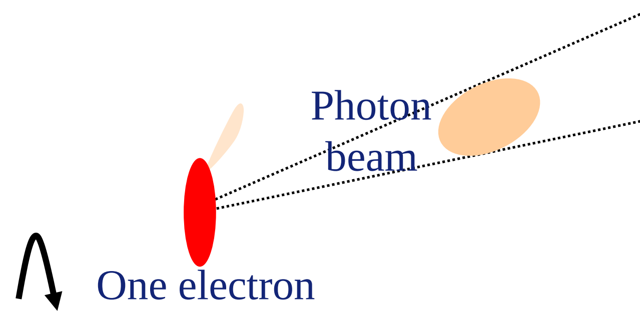
$$K = 0.0934\ \lambda_u\ [mm]\ B_{peak}\ [T]$$

In case of undulator ,K ~ 1-2

θ max has to be compared with 1/γ

Narrow cone of natural emission angle 85μrad *(0.005 degree)* at 6 GeV

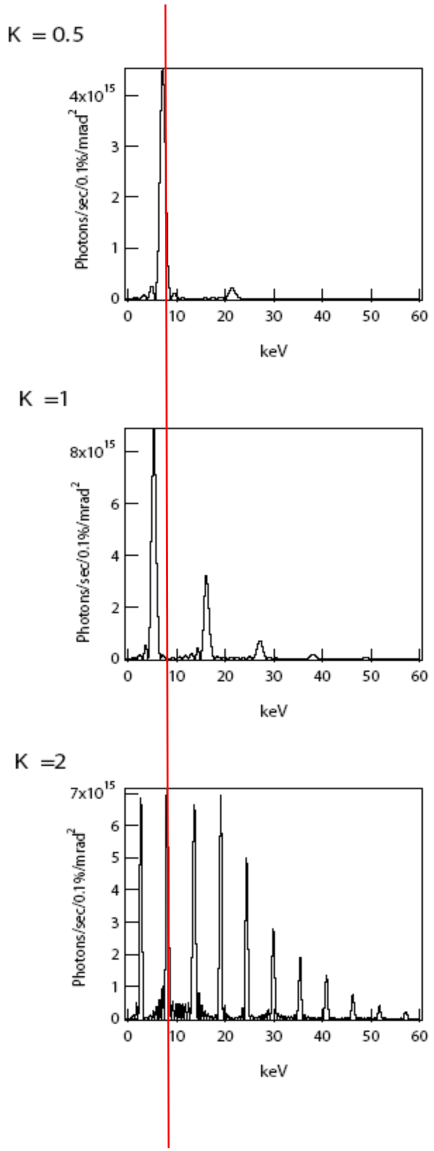
170μrad *(0.01 degree)* at 3 GeV



$$\Psi = \frac{1}{\gamma} = \frac{1}{E/E_0}$$

E_0=0.5 MeV

E = 6 GeV



The deflecting angle is a function of the periodicity and the magnetic field

$$K = 0.0934\ \lambda_u\ [mm]\ B_{peak}\ [T]$$

In case of undulator ,K ~ 1-2

The energy of the fundamental on axis is given by

$$\varepsilon_{[keV]} = 0.9.50\ \frac{E^2_{[GeV]}}{\left(1+K^2/2\right)\lambda_{u[cm]}}$$

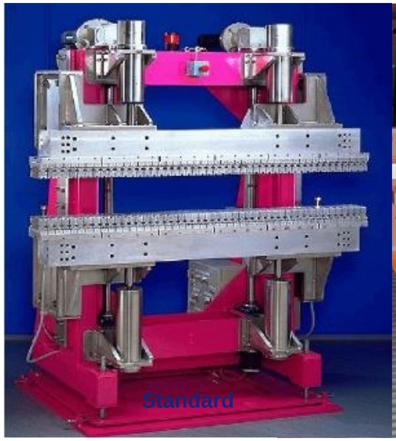
If ***K increases*** *the* ***energy*** *fundamental peak of the undulator* ***decreases****.*

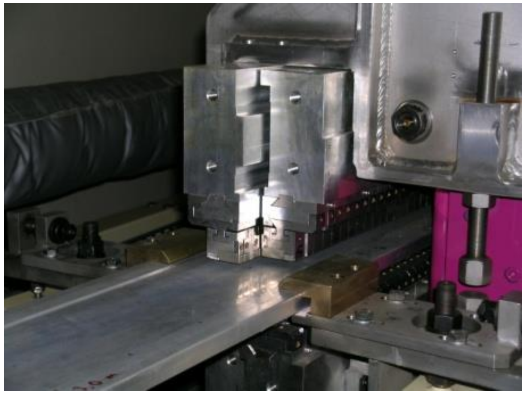
The total emitted power is:

$$P_{[kW]} = 0.633 E_{electron[GeV]} B^2_{peak\,[T]} * L_{[m]} * I_{[A]}$$

The undulator conception is defined by the beamline requirements

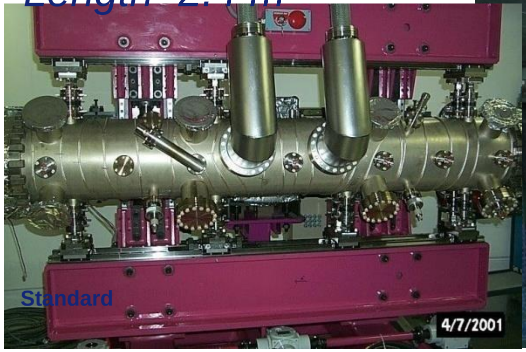
In-air *length =1.64 m*





Magnetic gap 10mm

In-vacuum
Length=2.4 m



(2.4 m flenge to flange , 2m magnetic asembly)

Power generated by one undulator (1.6 m) = 3kW

Available power = 250 kW

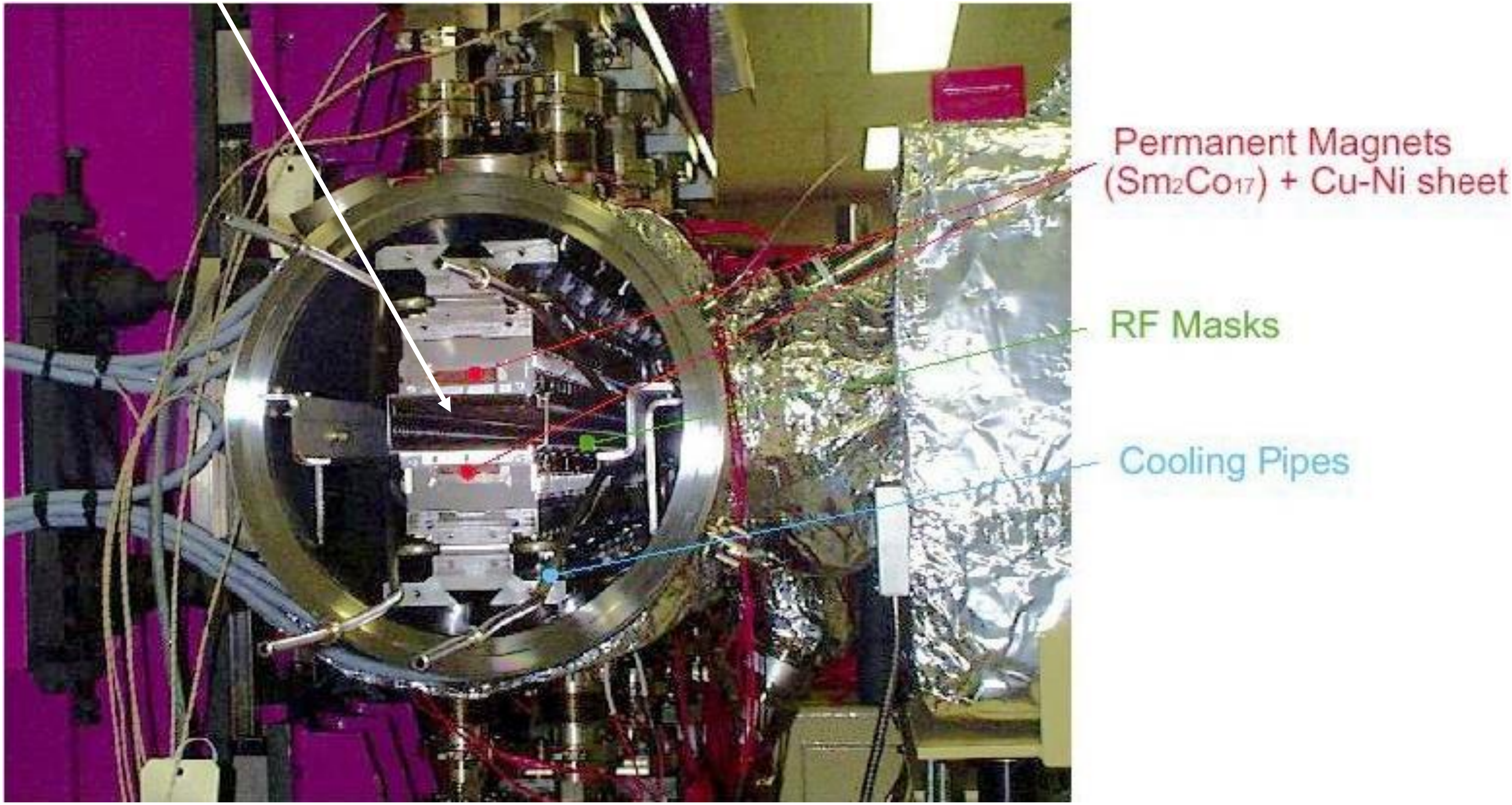
But less than 100 kW is used!!

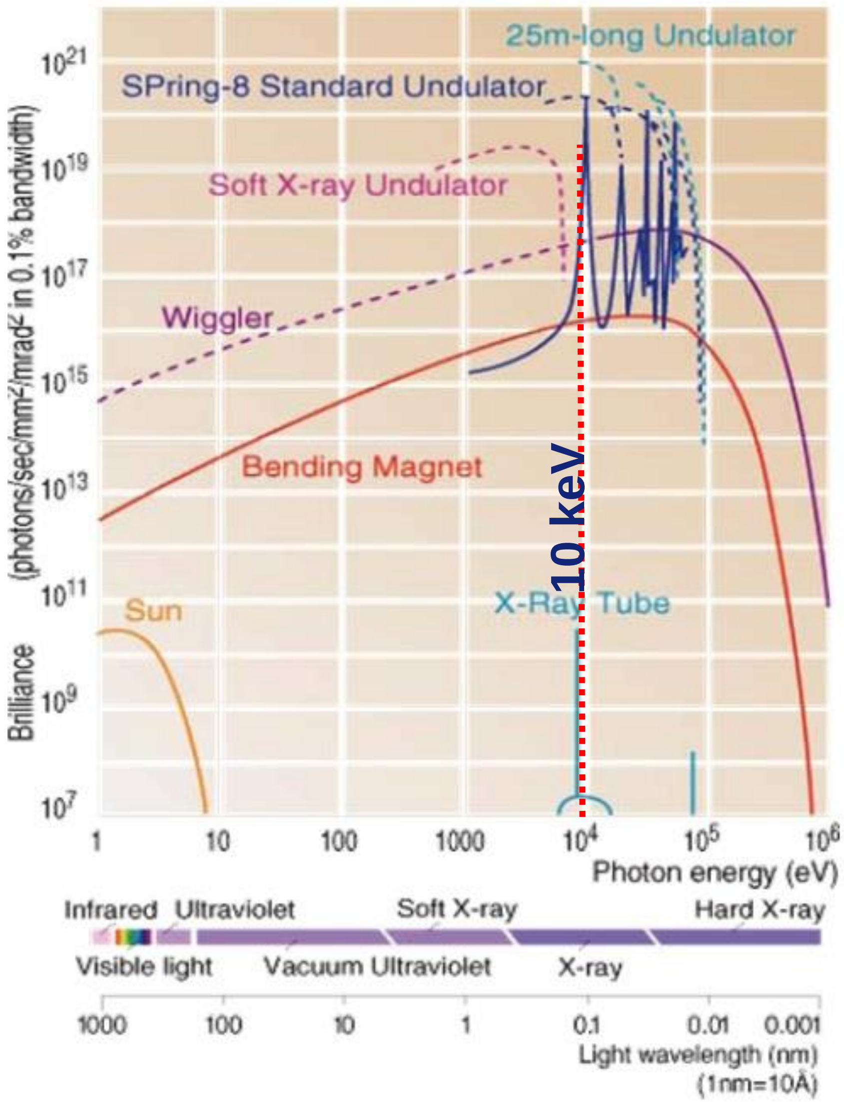
$2kW/mm^2$ at 200 mA

8000 kW of Electrical power is needed to produce it!!
Efficiency: 2% !

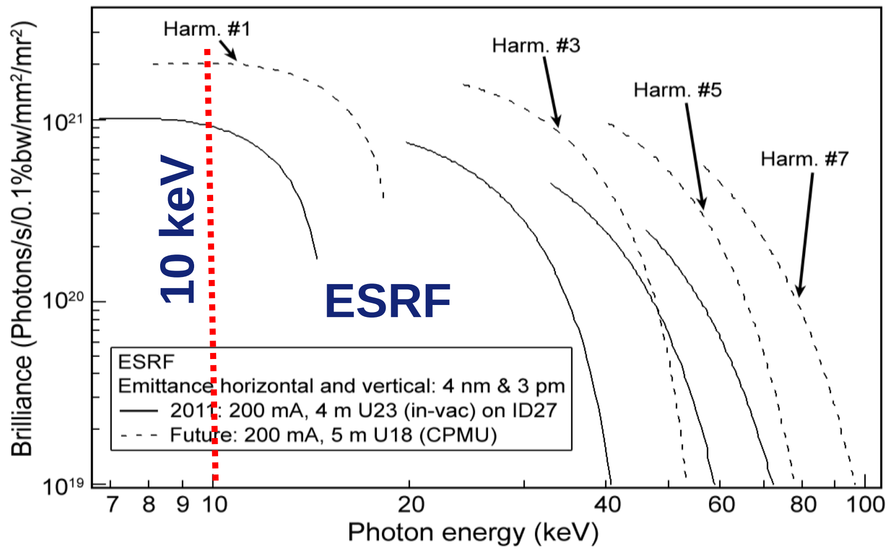
IN-VACUUM UNDULATORS

The jaws of the in-vacuum undulators can be closed down to 5 mm

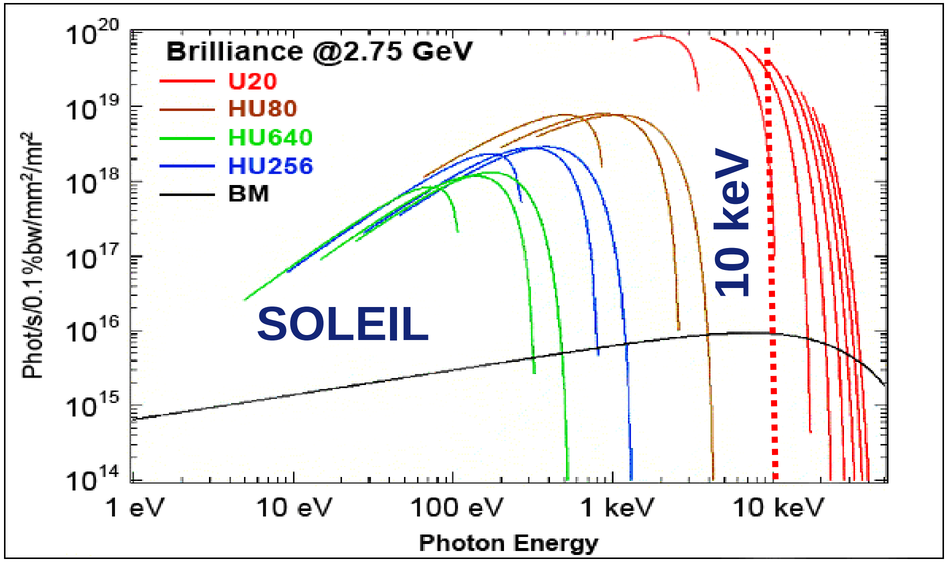




25m-long Undulator
SPring-8 Standard Undulator
Soft X-ray Undulator
Wiggler
Bending Magnet
Sun
X-Ray Tube
10 keV
Brilliance (photons/sec/mm²/mrad² in 0.1% bandwidth)
Photon energy (eV)
Infrared
Ultraviolet
Soft X-ray
Hard X-ray
Visible light
Vacuum Ultraviolet
X-ray
Light wavelength (nm)
(1nm=10Å)

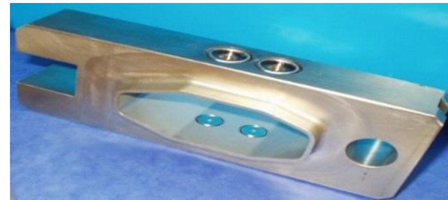


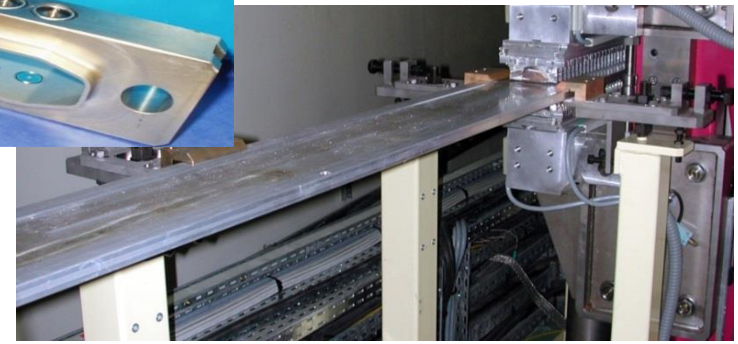
Harm. #1
Harm. #3
Harm. #5
Harm. #7
10 keV
ESRF
ESRF
Emittance horizontal and vertical: 4 nm & 3 pm
2011: 200 mA, 4 m U23 (in-vac) on ID27
Future: 200 mA, 5 m U18 (CPMU)
Brilliance (Photons/s/0.1%bw/mm²/mr²)
Photon energy (keV)



Brilliance @2.75 GeV
U20
HU80
HU640
HU256
BM
10 keV
SOLEIL
Phot/s/0.1%bw/mm²/mr²
1 eV
10 eV
100 eV
1 keV
10 keV
Photon Energy

Goal: control and maintain an excellent vacuum level in the storage ring:

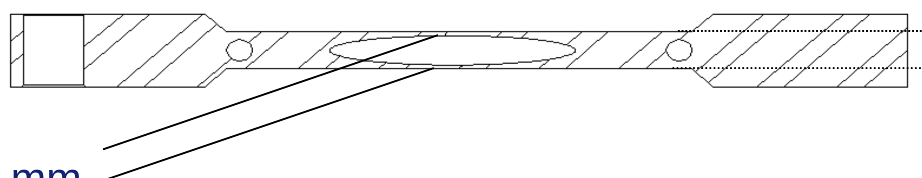




10^{-10} mbar without beam (static pressure)
10^{-9} mbar with beam (dynamic pressure)

- This vacuum level is ensured by the ionic pumps, NEG coating
- The pressure control is done with Penning gauges.

ID chambers



- Extruded aluminium
- The internal side of these vacuum vessels is covered with a thin coat of NEG material (Non Evaporable Getter) made of an alloy of Titanium, Zirconium, Vanadium. The particularity of this alloy is to trap chemically certain molecules (mainly CO and CO2) acting as vacuum pumps.

Decrease of the stored current is a function of:

$$\frac{1}{\tau} = -\frac{1}{I}\frac{dI}{dt}$$

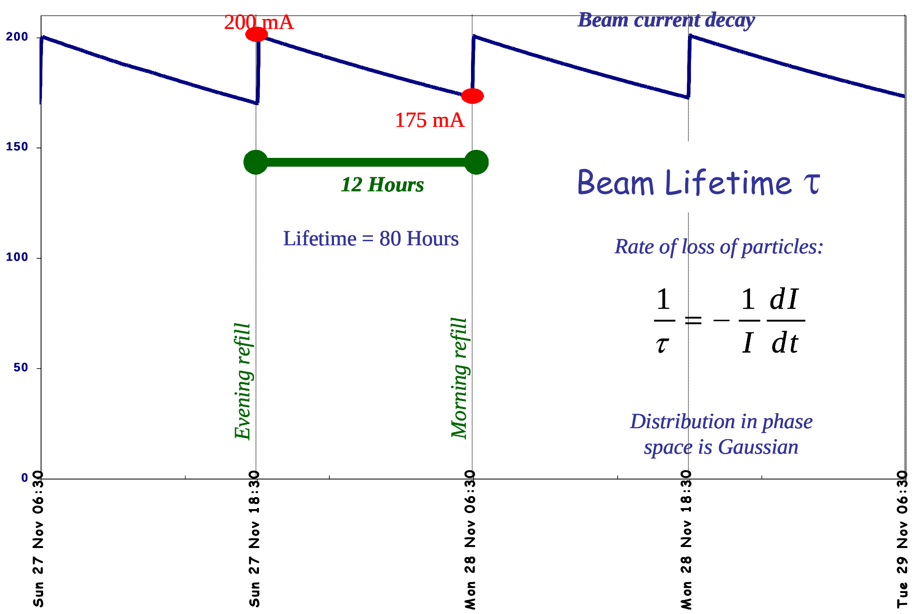
- Vacuum quality
  - ➔ *Probability of collision with residual gas*
- Number of electrons per bunch (i.e. total current)
  - ➔ *Probability of collision within the bunch*
- Lattice
  - ➔ *Transverse and longitudinal dynamic acceptance*
- Size of the vacuum chamber
  - ➔ *Physical transverse acceptance*

$$\frac{1}{\tau} = \sum_i \frac{1}{\tau_i}$$

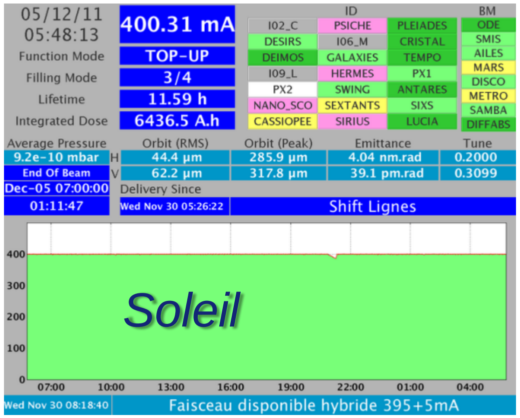
Large change in current:

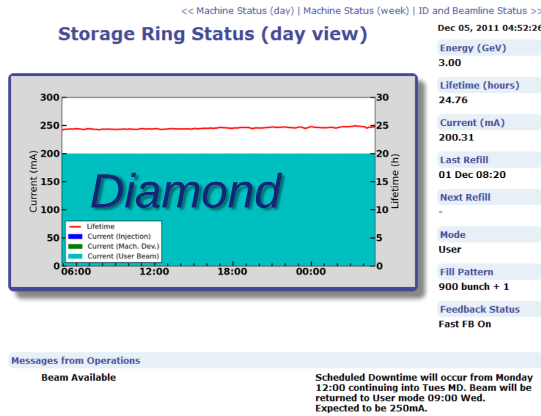
➔ Large variation ofthe heat load on the optics

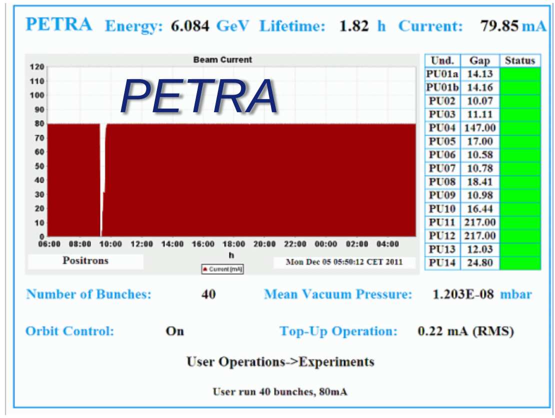
➔ Detrimental to the position stability on the sample

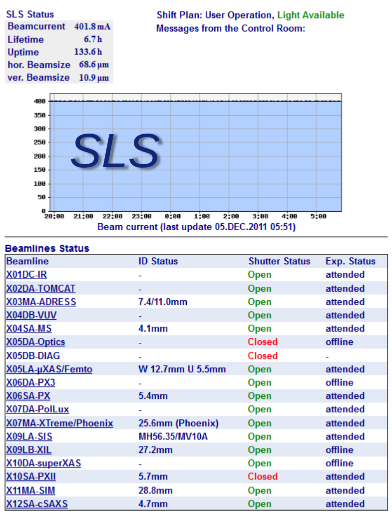


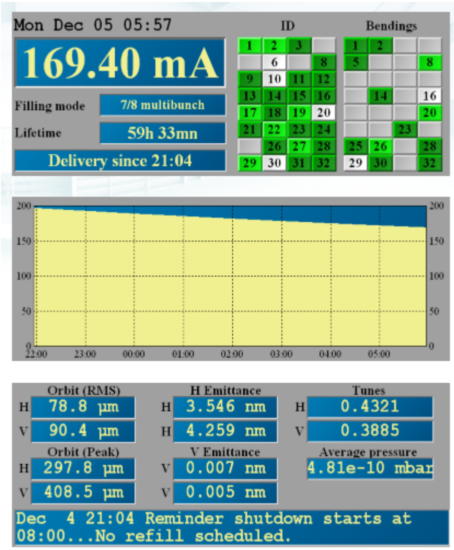
TOP-UP

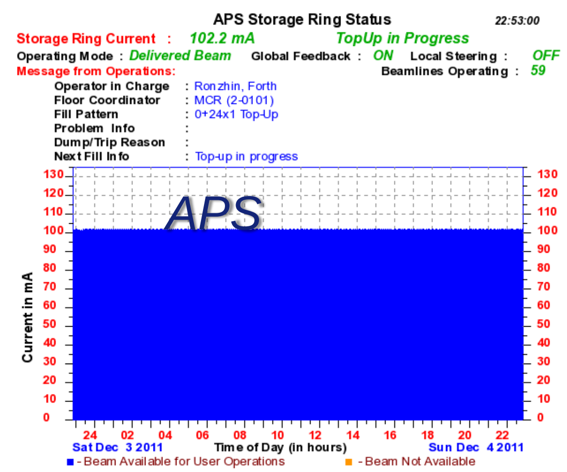

05/12/11
05:48:13
400.31 mA
Function Mode
TOP-UP
Filling Mode
3/4
Lifetime
11.59 h
Integrated Dose
6436.5 A.h
Average Pressure
9.2e-10 mbar
End Of Beam
Dec-05 07:00:00
01:11:47
Orbit (RMS)
44.4 µm
62.2 µm
Orbit (Peak)
285.9 µm
317.8 µm
Emittance
4.04 nm.rad
39.1 pm.rad
Tune
0.2000
0.3099
Delivery Since
Wed Nov 30 05:26:22
Shift Lignes
Soleil
Wed Nov 30 08:18:40
Faisceau disponible hybride 395+5mA


<< Machine Status (day) | Machine Status (week) | ID and Beamline Status >>
Storage Ring Status (day view)
Dec 05, 2011 04:52:26
Diamond
Energy (GeV)
3.00
Lifetime (hours)
24.76
Current (mA)
200.31
Last Refill
01 Dec 08:20
Next Refill
Mode
User
Fill Pattern
900 bunch + 1
Feedback Status
Fast FB On
Messages from Operations
Beam Available
Scheduled Downtime will occur from Monday 12:00 continuing into Tues MD. Beam will be returned to User mode 09:00 Wed. Expected to be 250mA.

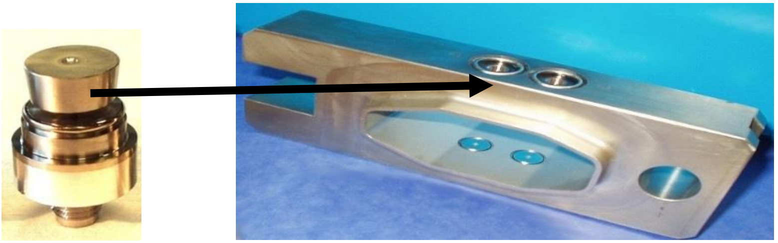

PETRA Energy: 6.084 GeV Lifetime: 1.82 h Current: 79.85 mA
PETRA
Number of Bunches: 40
Mean Vacuum Pressure: 1.203E-08 mbar
Orbit Control: On
Top-Up Operation: 0.22 mA (RMS)
User Operations->Experiments
User run 40 bunches, 80mA


SLS Status
Shift Plan: User Operation, Light Available
Messages from the Control Room:
Beamcurrent 401.8 mA
Lifetime 6.7 h
Uptime 133.6 h
hor. Beamsize 68.6 µm
ver. Beamsize 10.9 µm
SLS
Beam current (last update 05.DEC.2011 05:51)
Beamlines Status

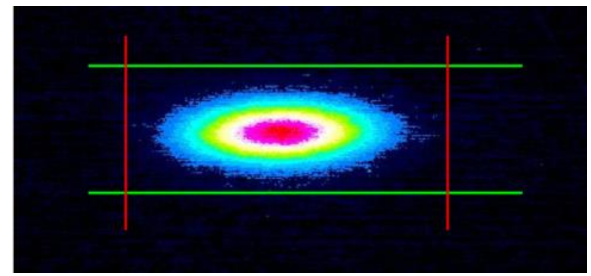

Mon Dec 05 05:57
169.40 mA
Filling mode
7/8 multibunch
Lifetime
59h 33mn
Delivery since 21:04
ID
Bendings
Orbit (RMS)
H Emittance
Tunes
78.8 µm
90.4 µm
3.546 nm
4.259 nm
0.4321
0.3885
Orbit (Peak)
V Emittance
Average pressure
297.8 µm
408.5 µm
0.007 nm
0.005 nm
4.81e-10 mbar
Dec 4 21:04 Reminder shutdown starts at 08:00...No refill scheduled.


APS Storage Ring Status
22:53:00
Storage Ring Current : 102.2 mA
TopUp in Progress
Operating Mode : Delivered Beam
Global Feedback : ON
Local Steering : OFF
Message from Operations:
Beamlines Operating : 59
Operator in Charge : Ronzhin, Forth
Floor Coordinator : MCR (2-0101)
Fill Pattern : 0+24x1 Top-Up
Problem Info :
Dump/Trip Reason :
Next Fill Info : Top-up in progress
APS
Current in mA
Sat Dec 3 2011
Time of Day (in hours)
Sun Dec 4 2011
- Beam Available for User Operations
- Beam Not Available

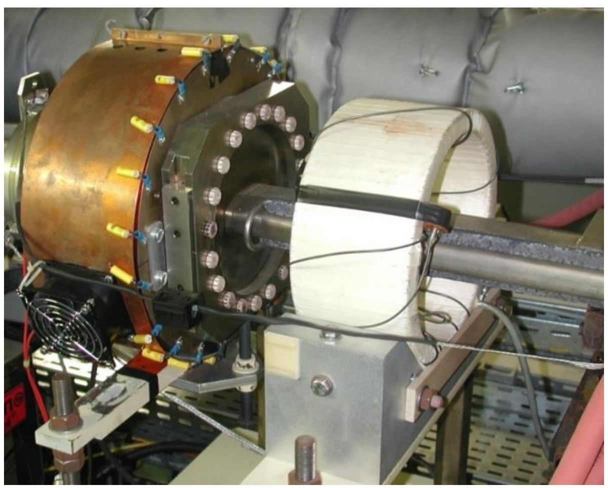
THE STORAGE RING BEAM DIAGNOSTICS



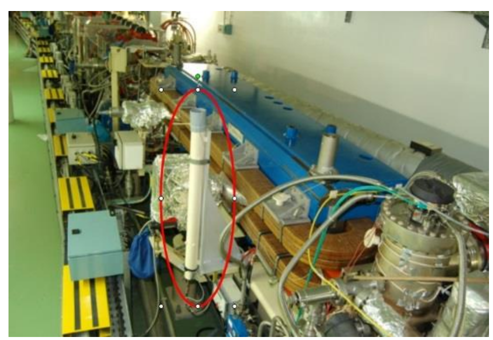
224 Beam Position Monitors to measure the positions of the electron beam center of mass in the horizontal et vertical planes



Beam imaging system to visualize the transverse profile of the electron beam in a bending magnet and compute its emittance.



Current transformers to measure the beam intensity



Beam Loss Monitors to locate the losses resulting from a scraping effect of the beam on the vacuum vessels or due to locally moderate vacuum level

BEAM STABILITY PERFORMANCE

Position stability should be studied on

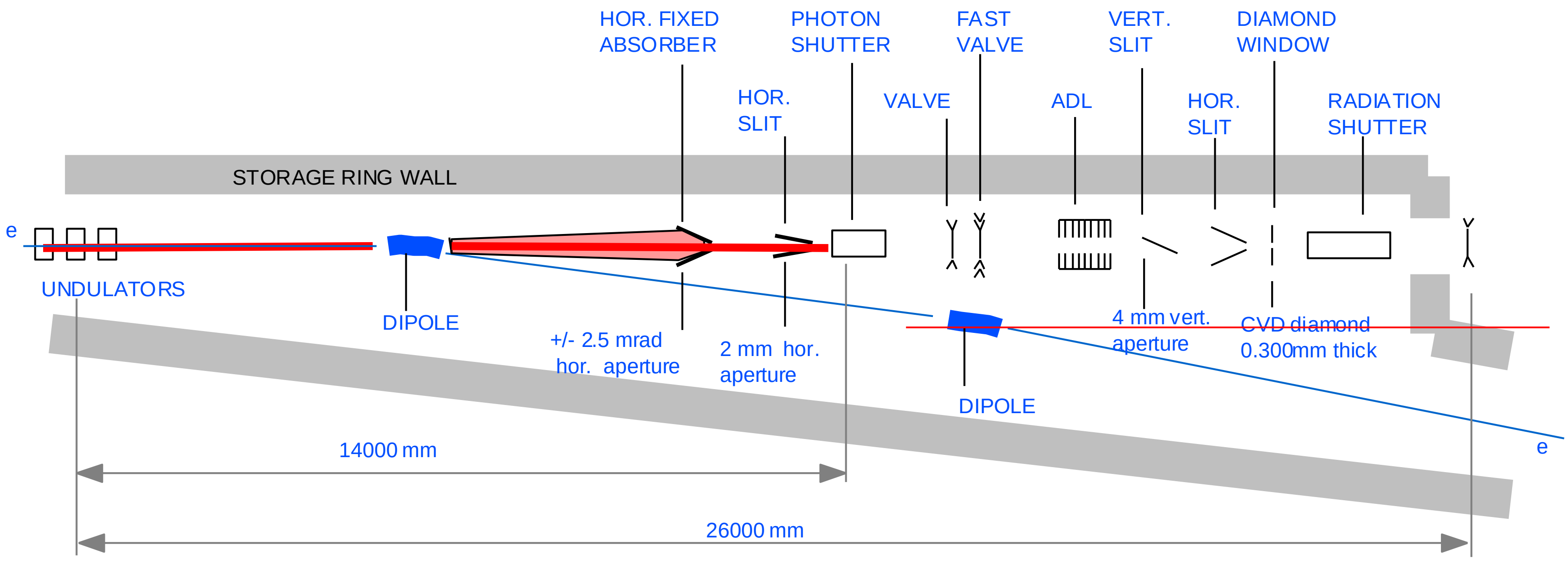
- Short term
  - ➔ Reduction of the perturbations!
  - ➔ Fast Orbit Feedback
- Medium term
  - ➔ Closed orbit correction
- Long term
  - ➔ Magnets realignment

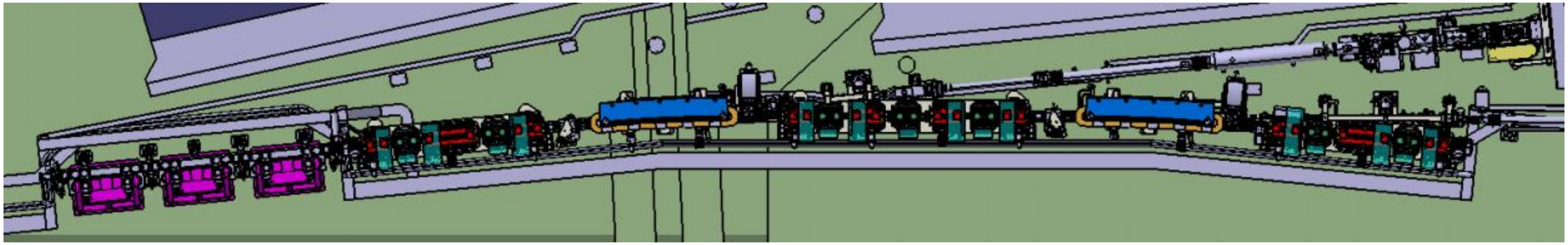
	Horizontal		*Vertical*
Emittances	4 nm		30 pm
β function	2.5	35	2.5
Beam size	45 µm	380 µm	9 µm
Required stability	**4.5 µm**	**38 µm**	**0.9 µm**

Stability criteria mostly achieved in horizontal but more critical in the vertical plane.

	Horizontal	*Vertical*
10% Beam size	**38 µm**	**0.9 µm**
One week	**11 µm**	**8 µm**
One day	**5 µm**	**2 µm**
One hour	**5 µm**	**2 µm**
One minute	**5 µm**	**2 µm**
One second	**2 µm**	**1 µm**

THE STORAGE RING FRONT ENDS





Goal: Drive the X-rays produced either by the dipoles, or by the insertion devices, from the storage ring to the beam line.

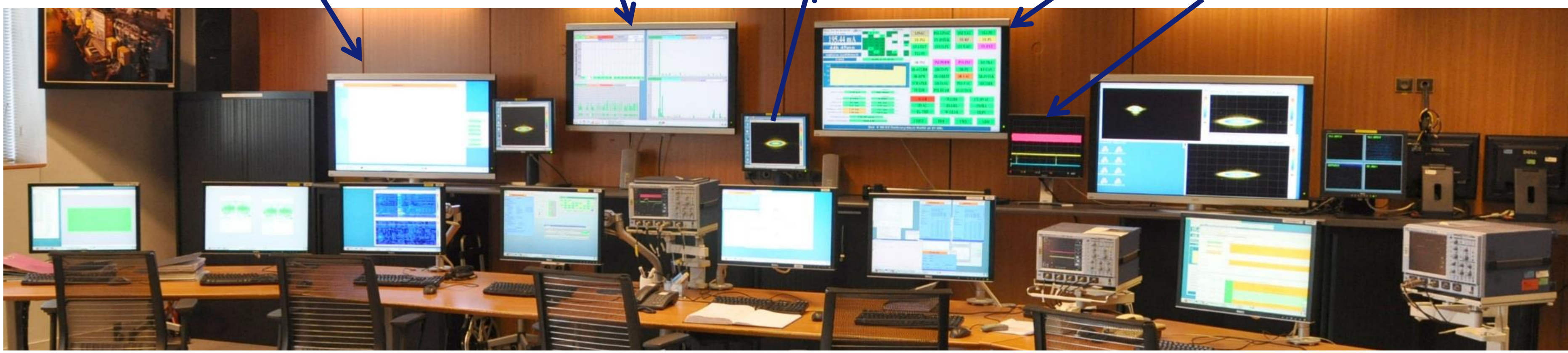
THE ESRF CONTROL ROOM

Current, emittances, lifetime monitoring

Radiation monitors

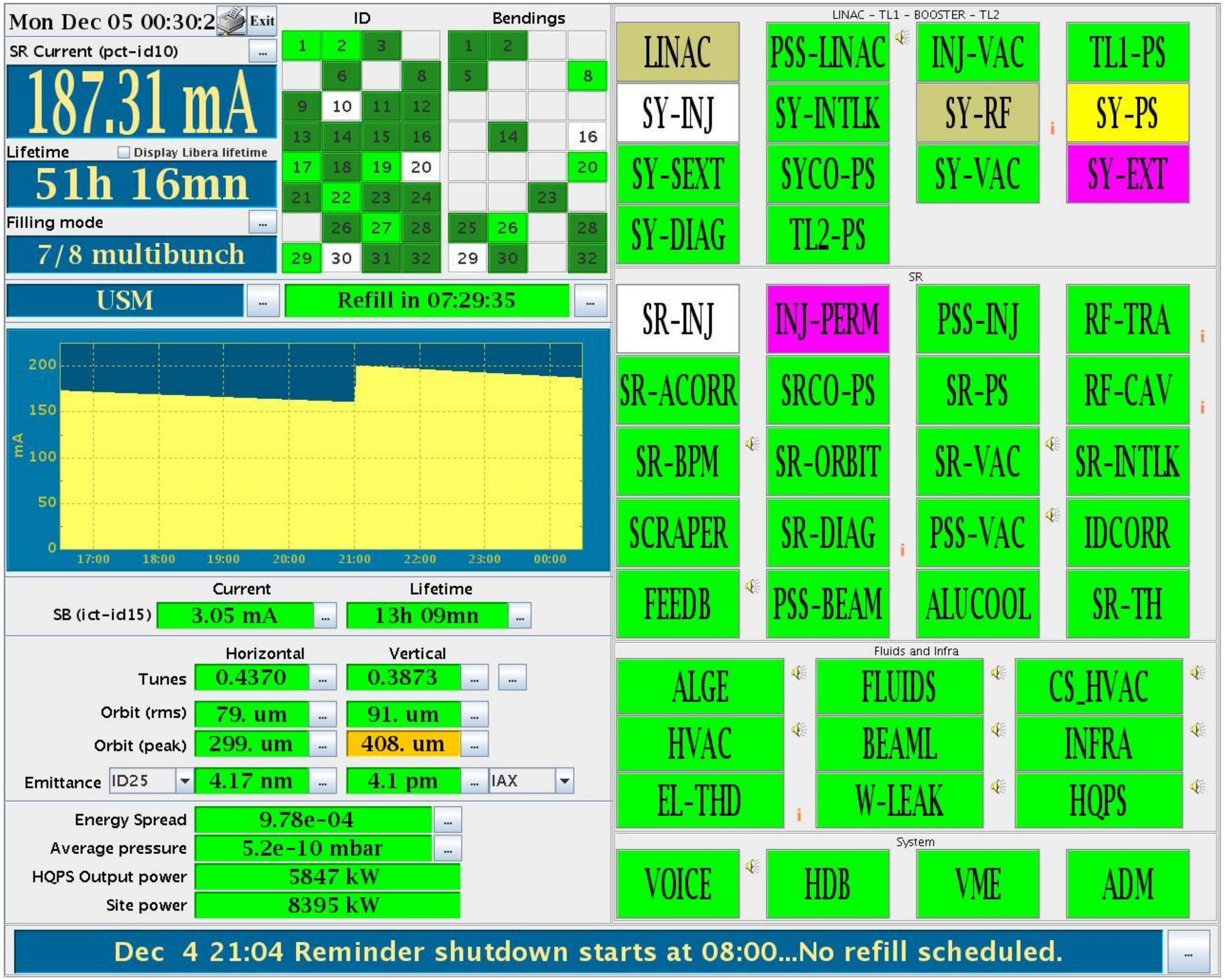
Main synoptic

Filling pattern

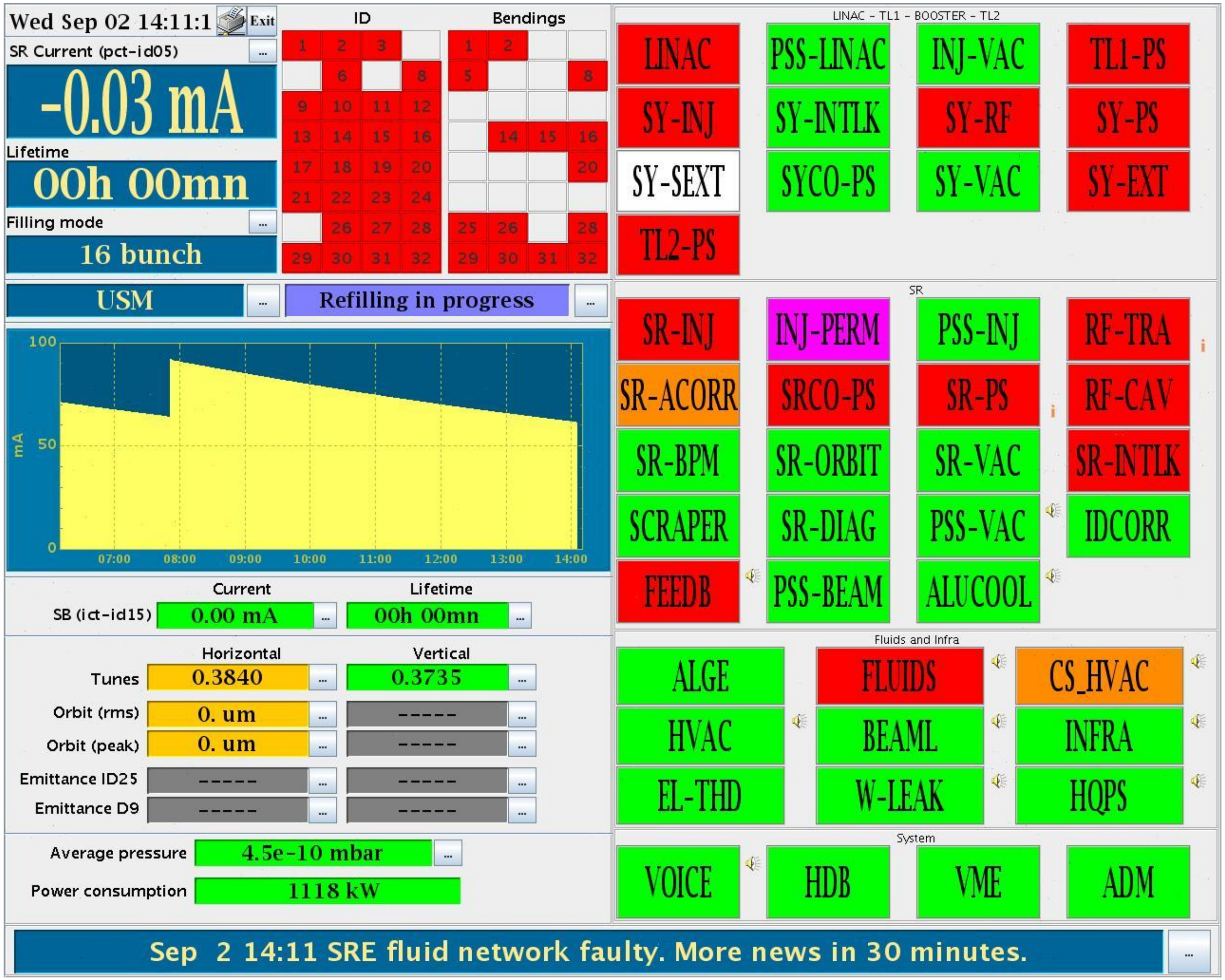


- Control of the accelerator equipmenrs
- Réinjections
- Beam parameters monitoring
- Fault and failures control and analysis

ACCELERATOR OPERATION



When everything is fine!



In case of fault !!

OPERATION : MACHINE STATISTICS FOR 2013-2016

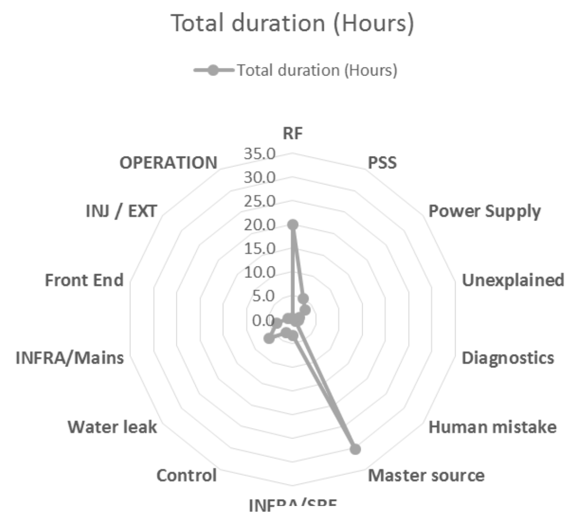
	2013	2014	2015	2016 (Until 22 November 2016)
Availability (%)	98.93	99.11	**98.53**	**99.06**
Mean Time Between Failures (hrs)	79.70	105.5	**93.6**	**93.8**
Mean duration of a failure (hrs)	0.86	0.94	**1.37**	**0.88**

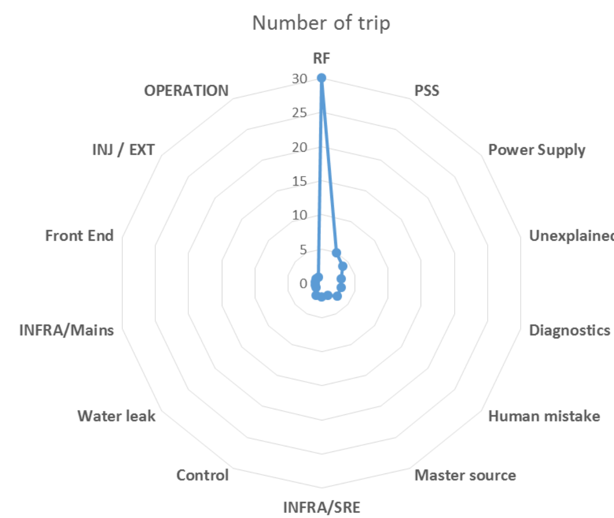
2014: 52 Failures ➔ 1 every 4.4 days
2015: 59 Failures ➔ 1 every 3.9 days
2016: 59 Failures

USM : 5544 hours (63.3%)
SD : 1944 hours (22.2%)
MDT : 1272 hours (14.5%)

OPERATION 2015: FAILURE DISTRIBUTION PER EQUIPMENT

	Number of trip	Total duration (Hours)	Average duration
RF	30	20.0	0.7
PSS (Beamlines)	5	5.0	1.0
Power Supply	4	3.3	0.8
Unexplained	3	1.4	0.5
Diagnostics	3	1.2	0.4
Human mistake	3	0.8	0.3
Master source	2	30.3	15.2
INFRA/SRE	2	3.3	1.7
Control	2	3.1	1.5
Water leak	1	6.4	6.4
INFRA/Mains	1	3.5	3.5
Front End	1	1.1	1.1
INJ / EXT	1	0.3	0.3
OPERATION	1	0.2	0.2
Grand Total	59	79.9	





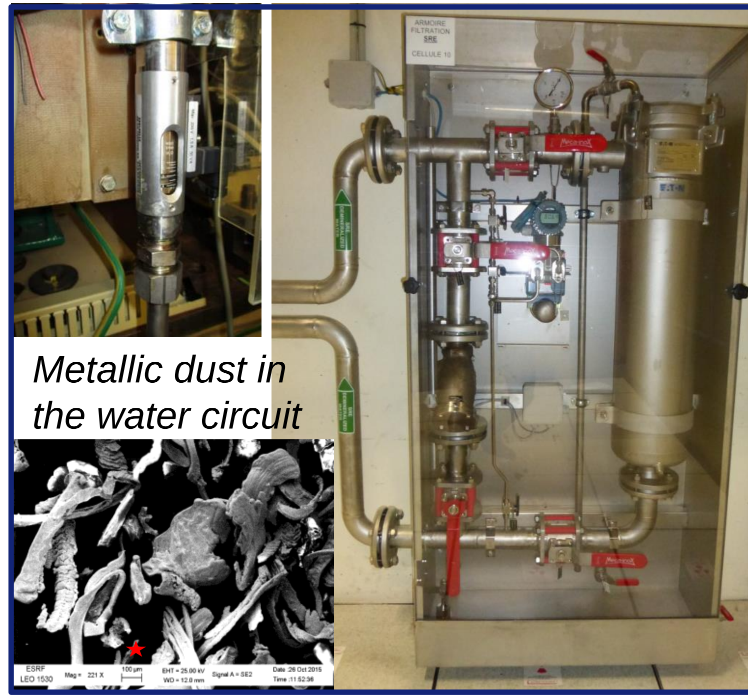
Preliminary statistics for 2016: 50% of failures due to RF

DISASTER GALLERY….

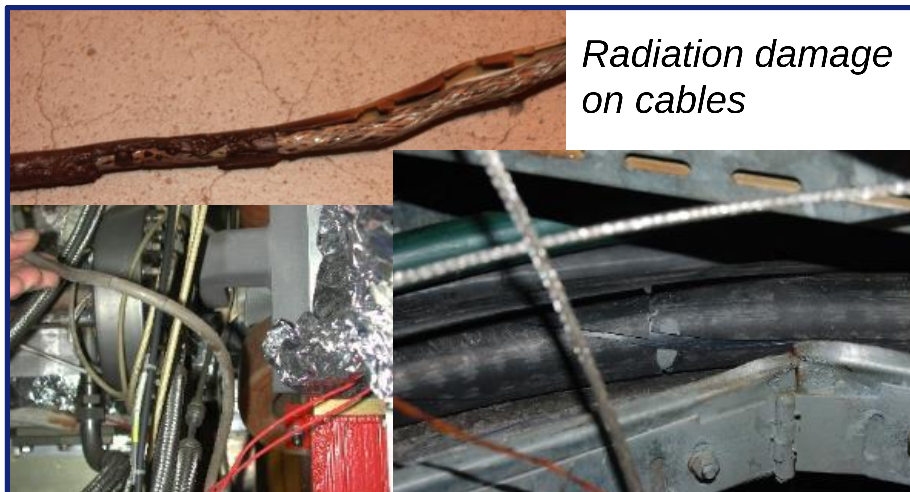
October 2015

Magnet water cooling hoses

Magnet PS circuit breaker short circuit

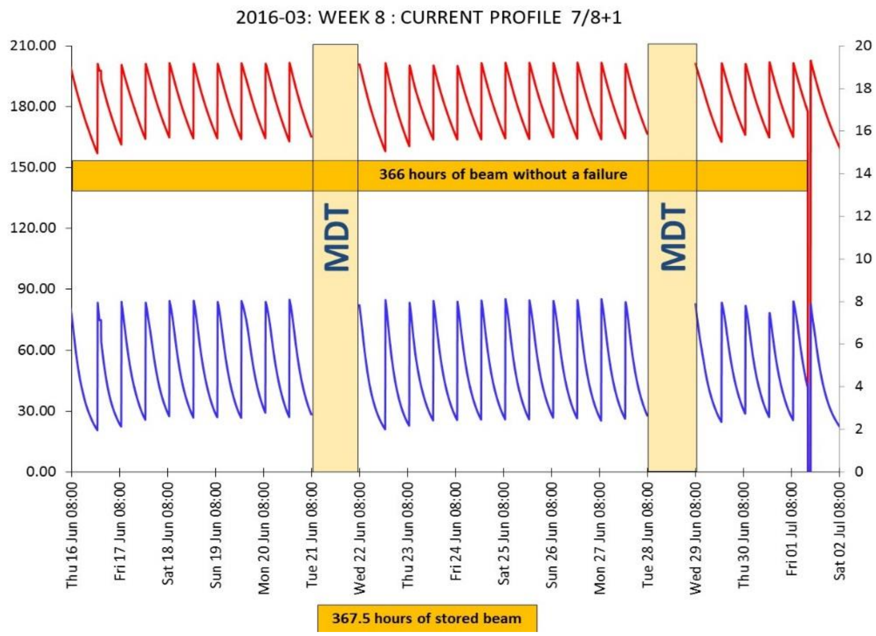


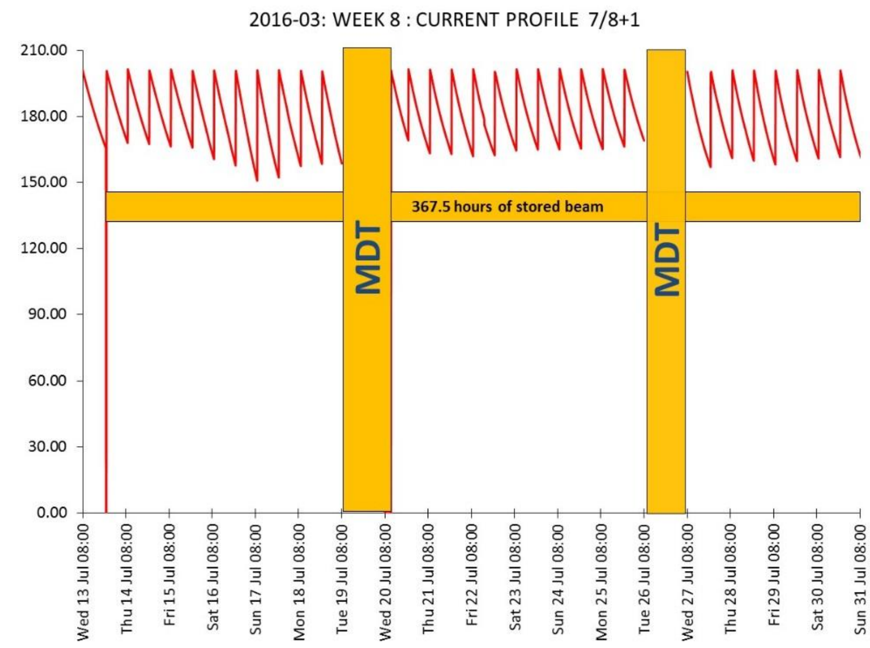
Metallic dust in the water circuit



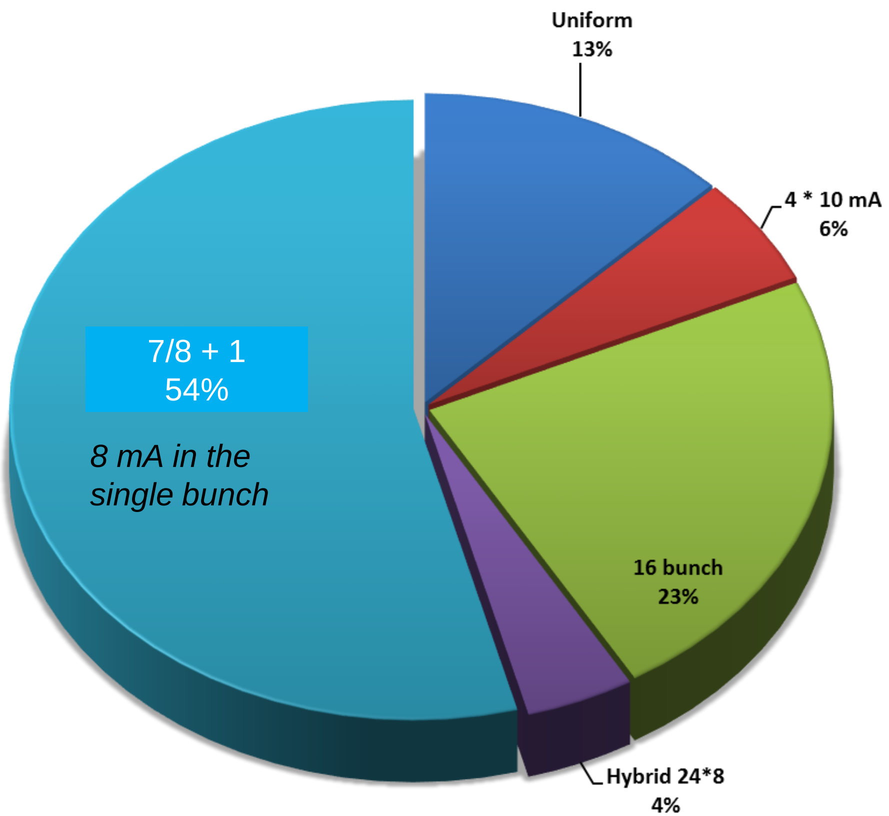
Radiation damage on cables

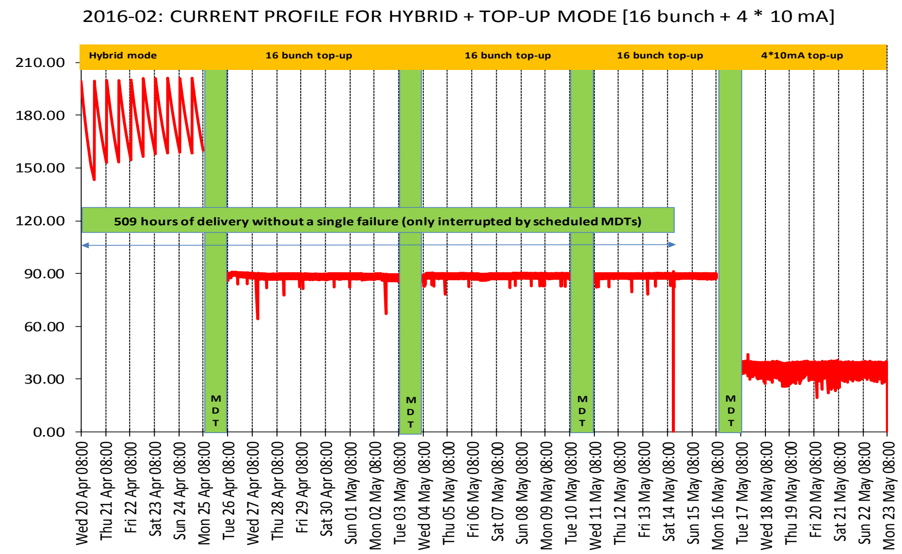
JUNE – JULY 2016 with long periods of deliveries without a failure!





OPERATION: FILLING MODES IN 2016



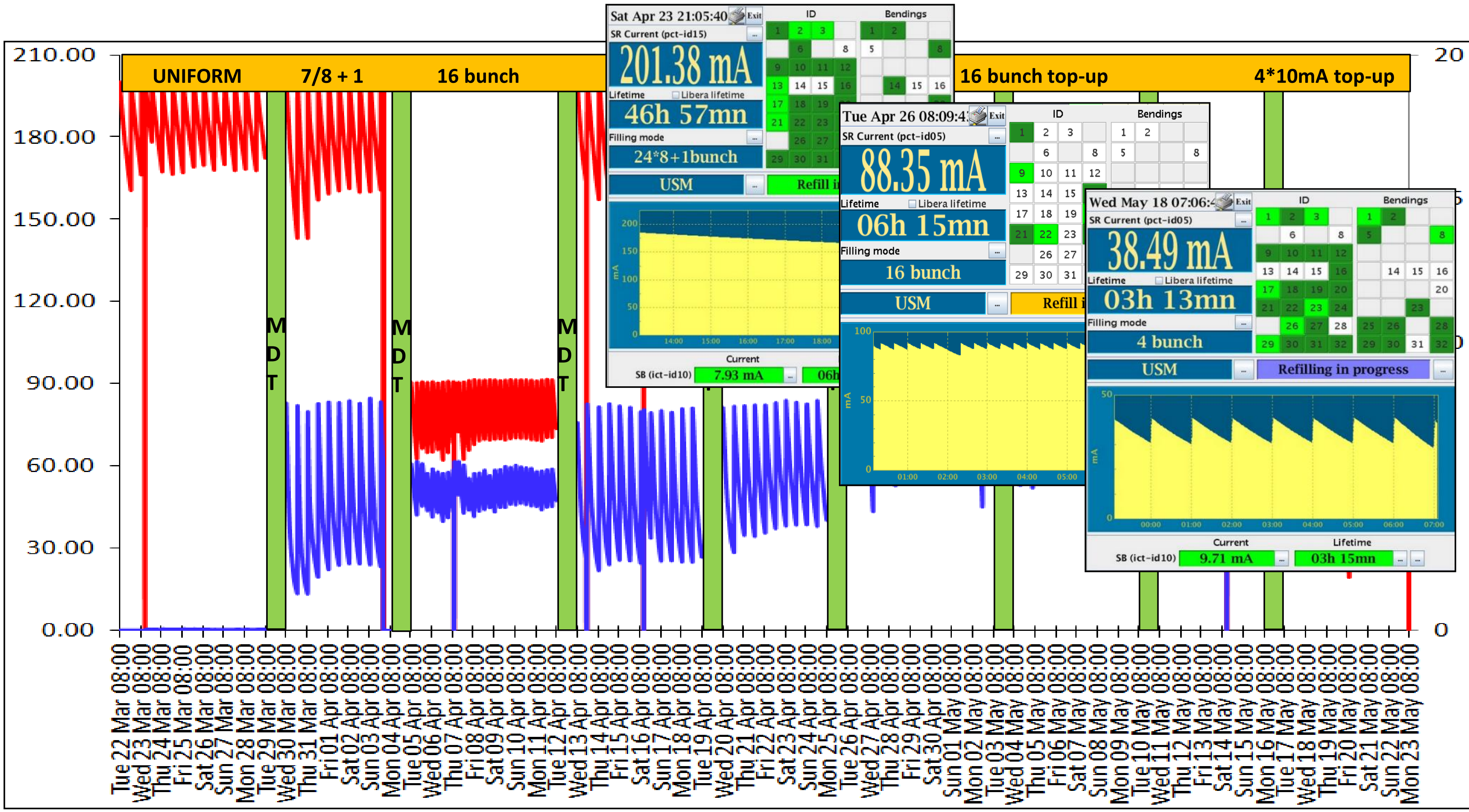


16 Bunch in top-up since 26 April 2016

I max = 90 mA,
Refill every 20 mn, delta I = 5 mA,
Vertical emittance < 10 pm

skipped refills <2%

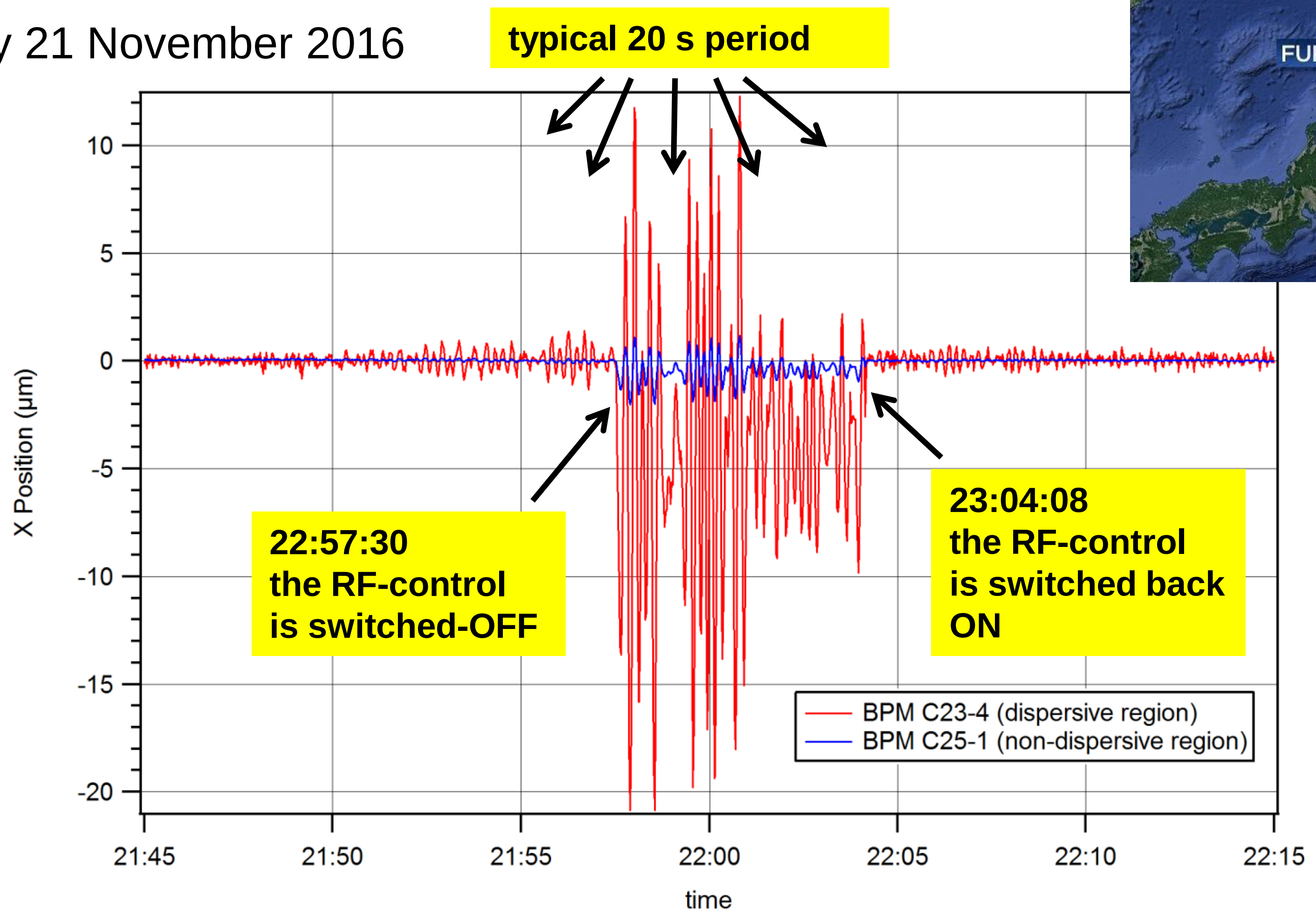
OPERATION : MACHINE

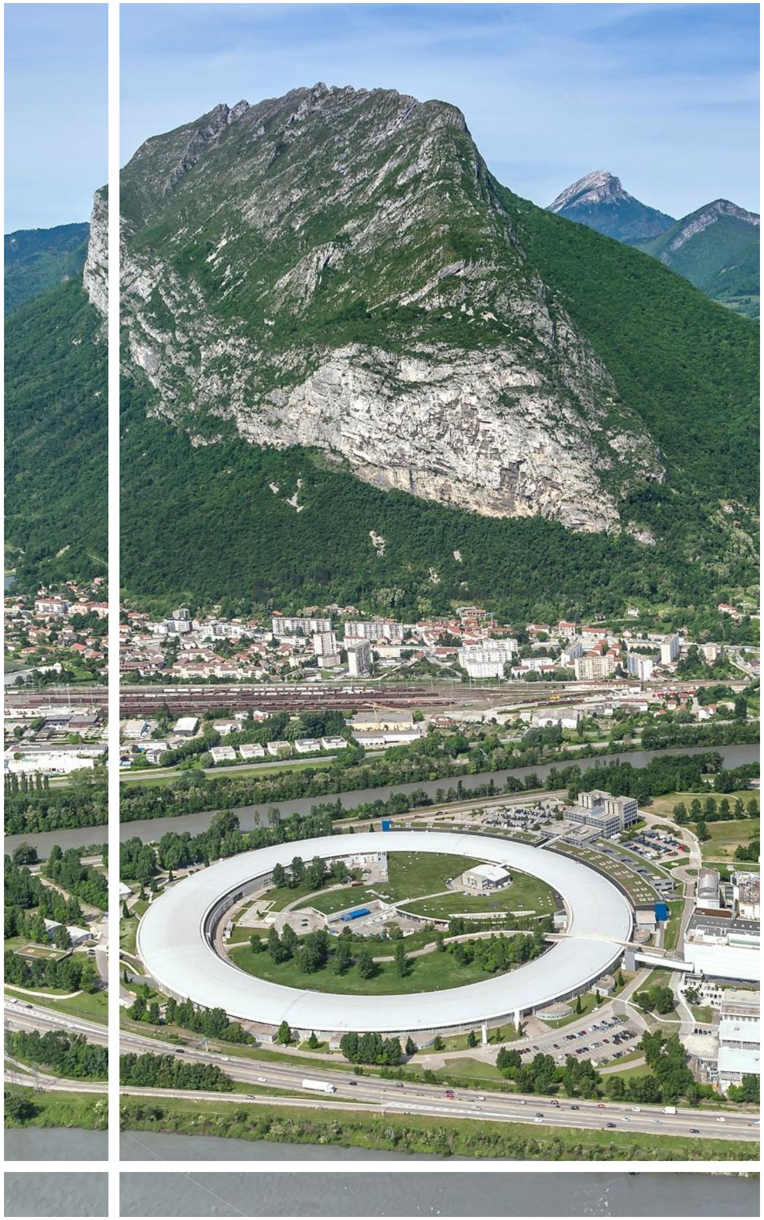


24 days of delivery without a failure

JAPANESE EARTHQUAKE – PERTURBATION REDUCTION WITH RF CONTROL

Sunday 21 November 2016

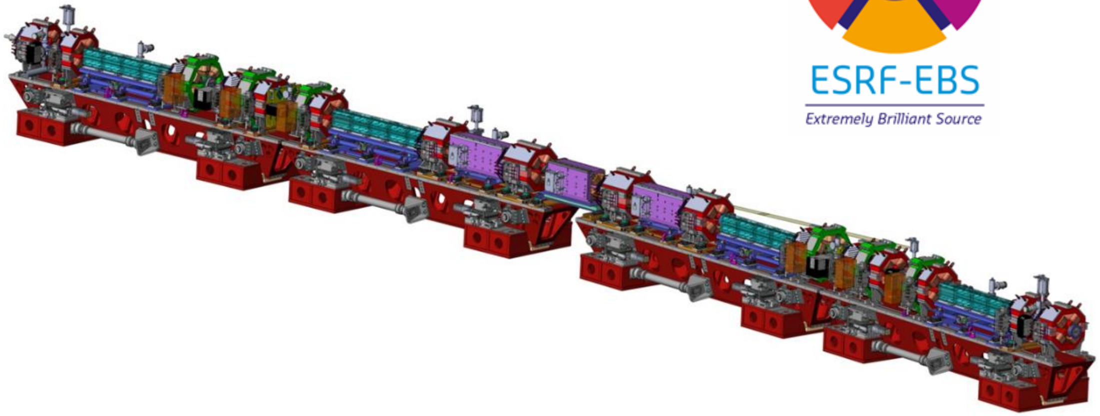




ESRF
The European Synchrotron

Upgrade

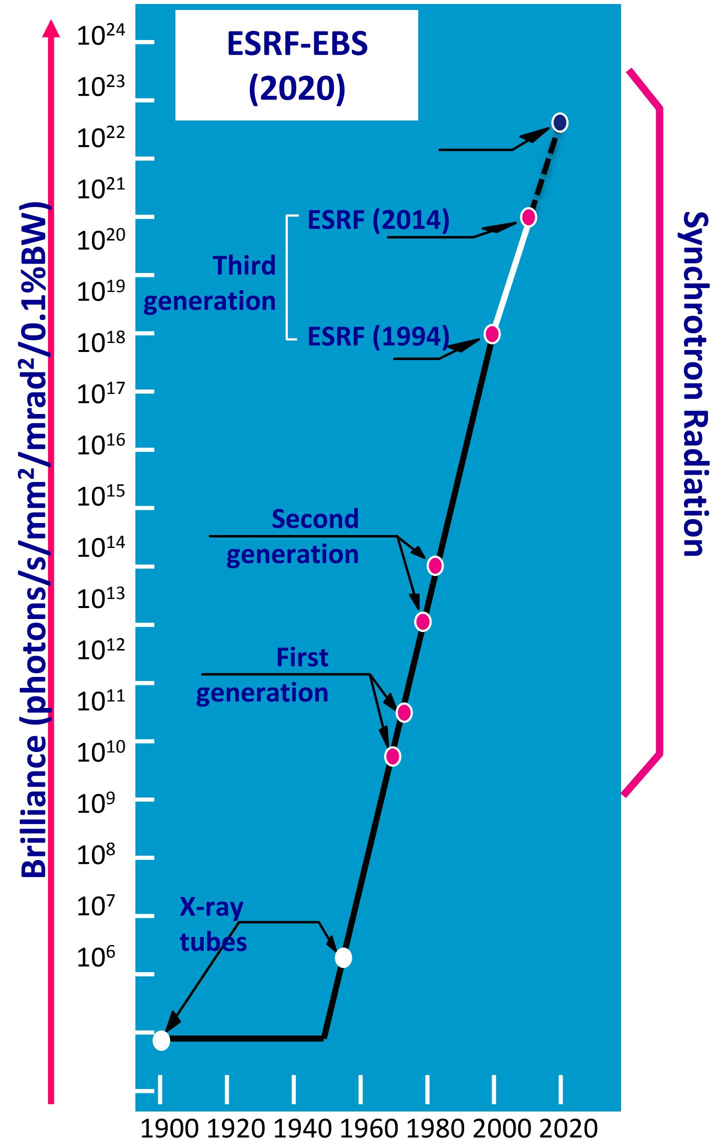
ESRF-EBS
Extremely Brilliant Source



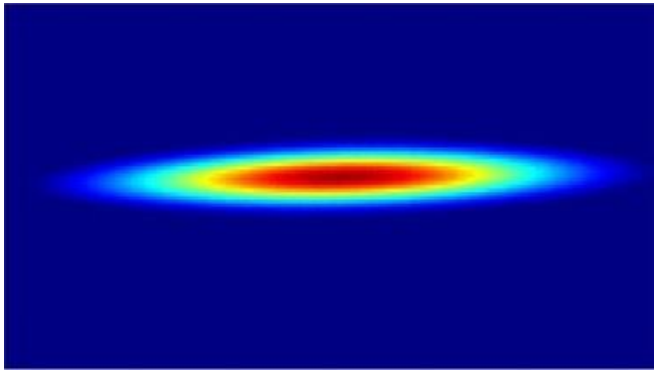
ESRF-EBS
Extremely Brilliant Source

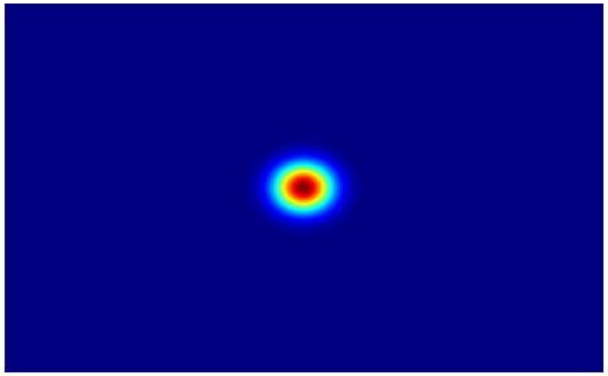
ESRF Extremely Brilliant Source
ESRF-EBS – 150 M€ (2015-2022)

- ~100 times more brilliant and coherent X-rays
- Programme to exploit the qualities of this new and unique extremely brilliant X-ray source:
  - Creation of new beamlines
  - Innovative detector programme
  - « Data as a Service » strategy



Reduce the **horizontal** emittance from **4nm** to **0.14nm**



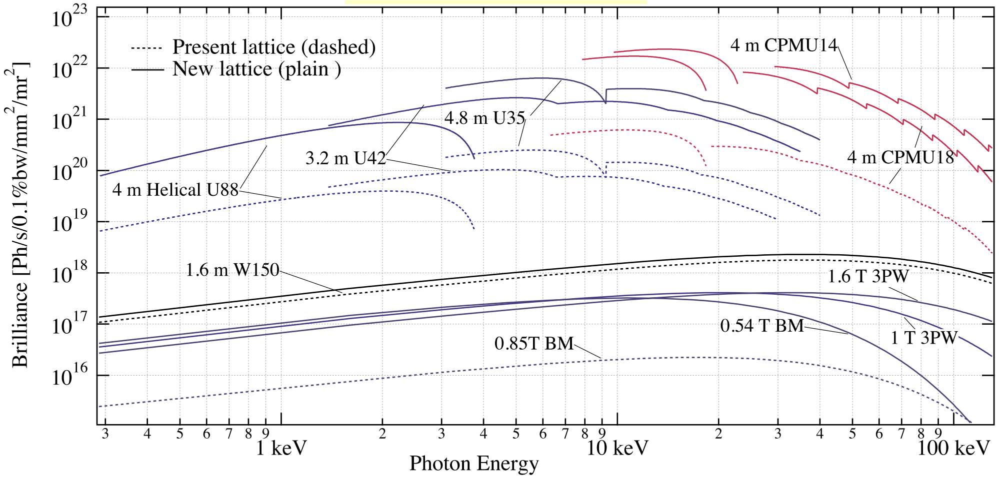


Beam-line experiments can benefit from :

an increase in brilliance
an increase of coherence
(the coherent fraction, in hor. plane)

BRILLIANCE AND COHERENCE INCREASE

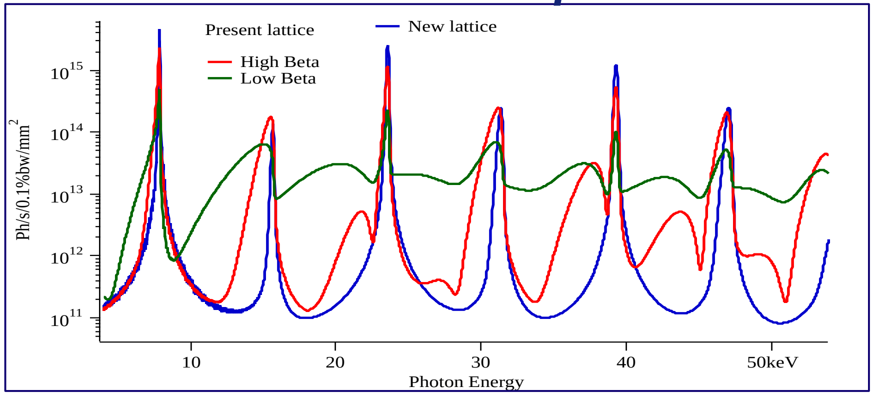
Brilliance



Hor. Emittance [nm]	4	0.135
Vert. Emittance [pm]	4	5
Energy spread [%]	0.1	0.09
β_x[m]/β_z [m]	37/3	6.9/2.6

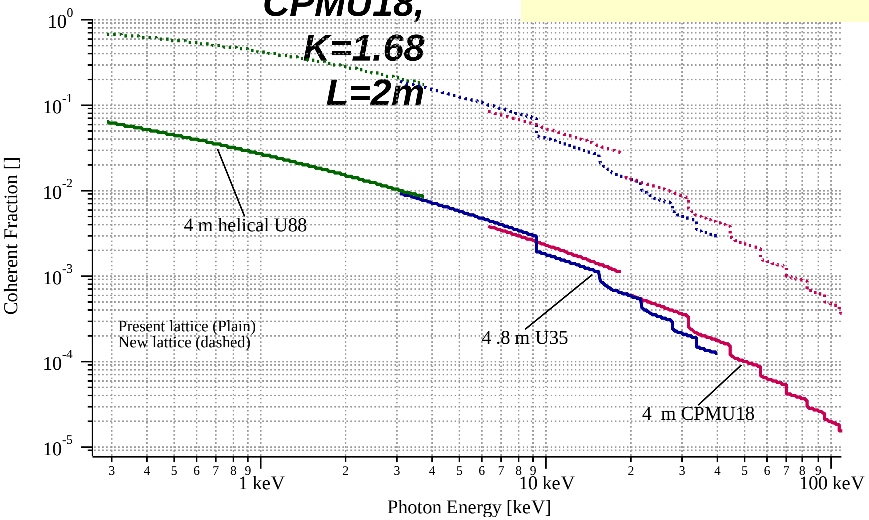
Source performances will improve by a factor 50 to100

18mm Undulator spectrum



Undulator: CPMU18, K=1.68 L=2m

Coherence



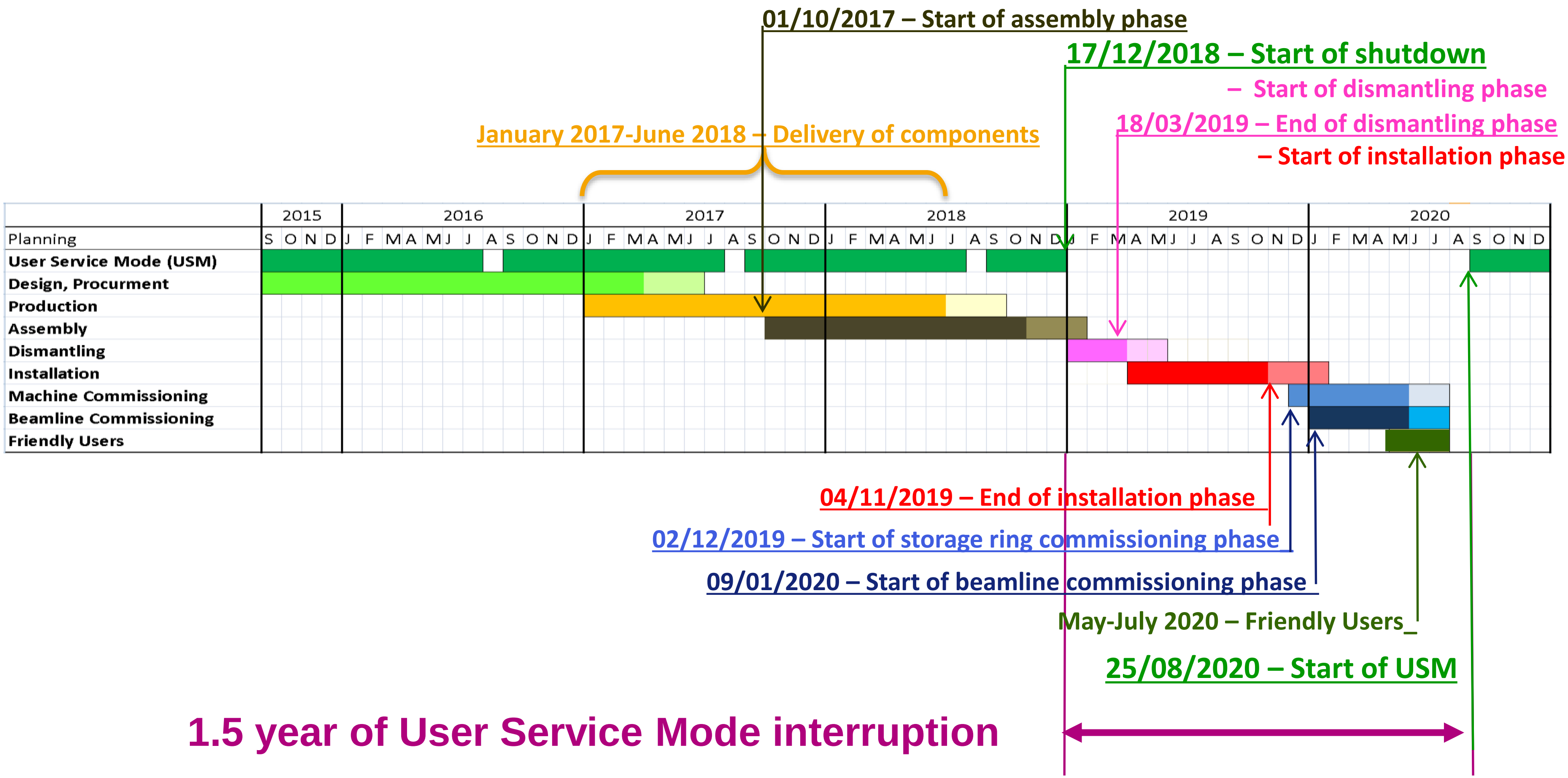
EXTREMELY BRILLIANT SOURCE: ACCELERATOR UPGRADE

The Extremely Brilliant Source Project aims to:

- Substantially decrease the Store Ring Equilibrium Horizontal Emittance
- Increase the source brilliance
- Increase its coherent fraction
- Must fit in the same tunnel : same circumference as much as possible
- Keep the electron energy (6 GeV)
- IDs at same locations: keep Beamlines where they are
- Maintain the existing bending magnets beamlines
- Preserve the time structure operation and a multibunch current of 200 mA
- Re-use injector complex
- Limit the downtime for installation and commissioning to less than 18 months

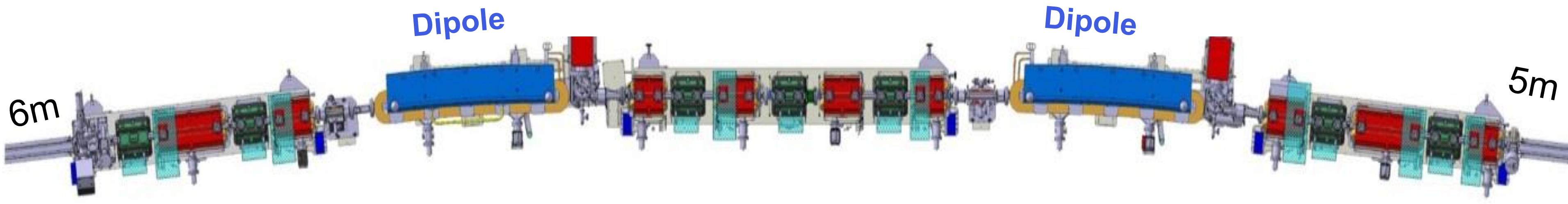
Maintain standard User-Mode Operations until the day of shut-down for installation

OPERATION AND EBS EBS PROJECT PLAN (2015-2020)



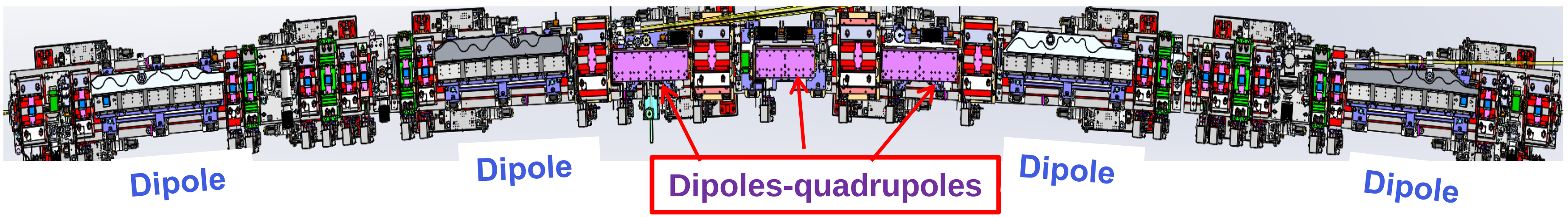
- **Present ESRF lattice**

32 cells, Double Bend Achromat = (2 dipoles + 15 quad. sext.) per cell
ID length = 5 m (standard) / 6m / 7m



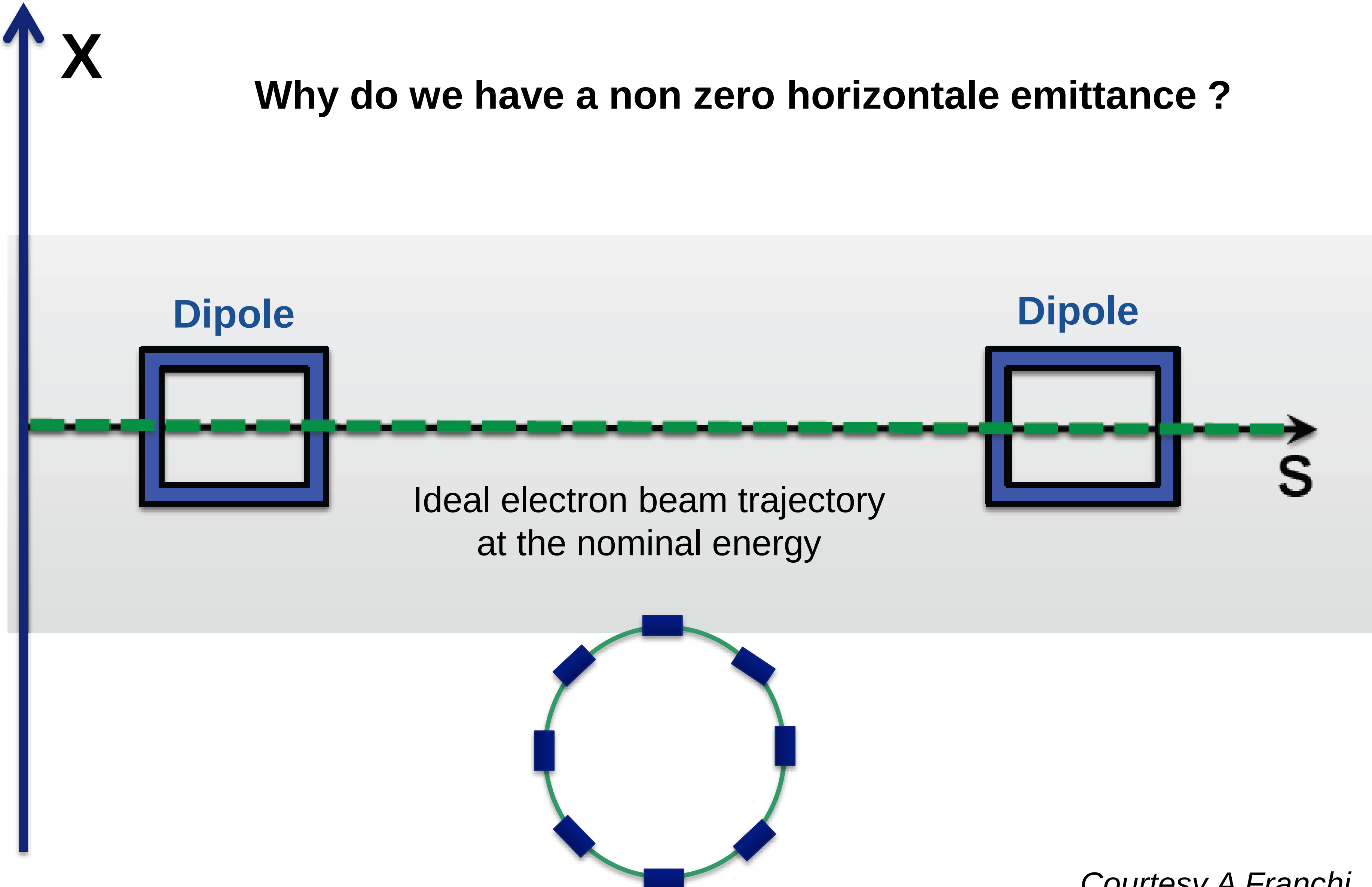
- **ESRF EBS lattice**

Hybrid 7 Bend Achromat = (4 dipoles + 3 dipoles-quad + 24 quad., sext., oct.) per cell
ID length = 5 m



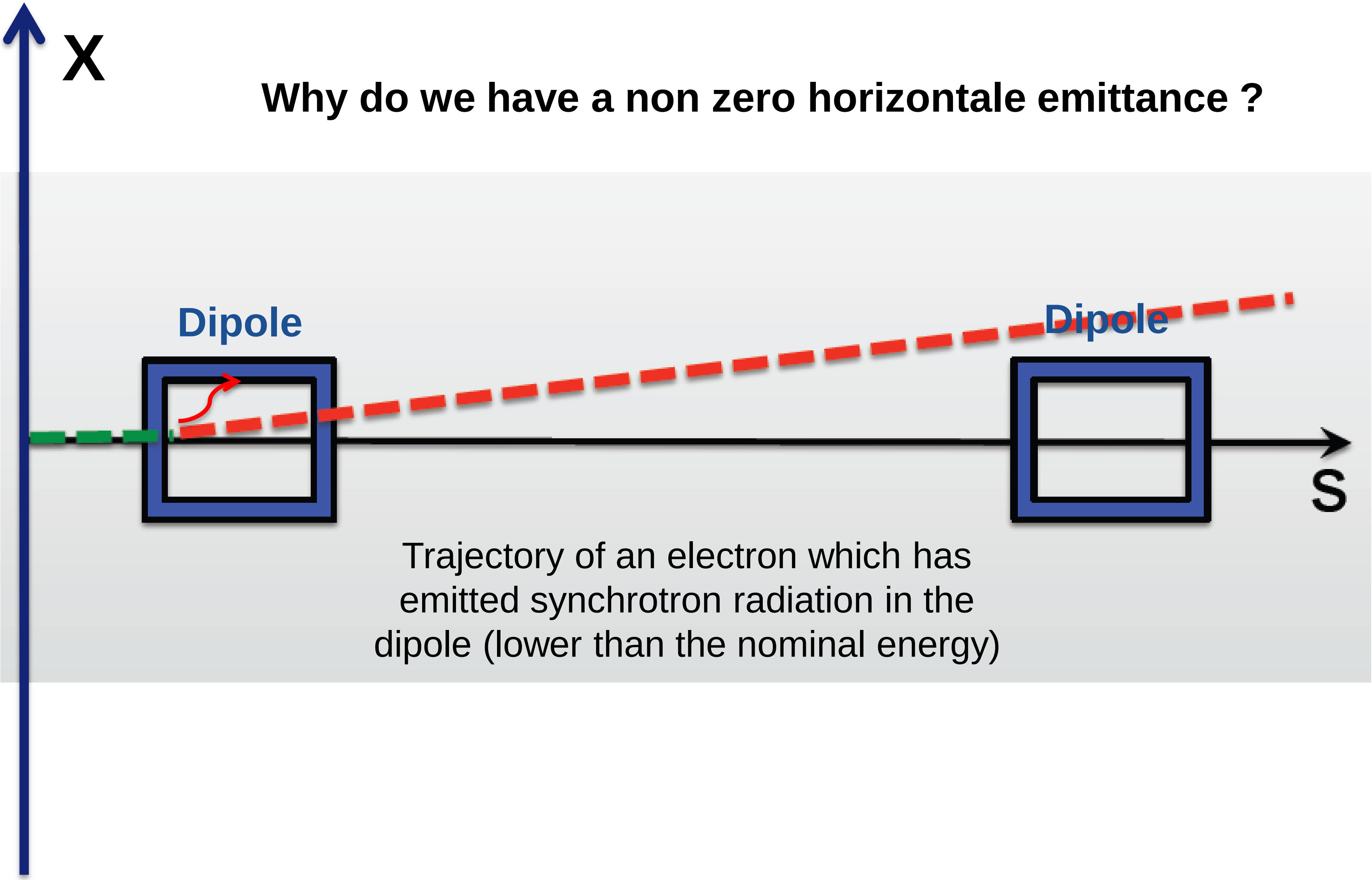
31 magnets per cell instead of 17 currently
Free space between magnets (total for one cell): **3.4m** instead of **8m** today !!

Why do we have a non zero horizontale emittance ?



Courtesy A Franchi

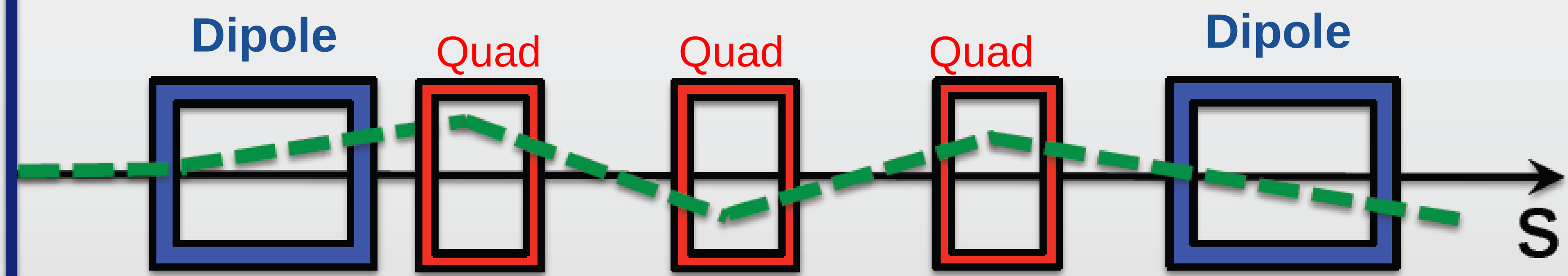
Why do we have a non zero horizontale emittance ?



Courtesy A Franchi

x

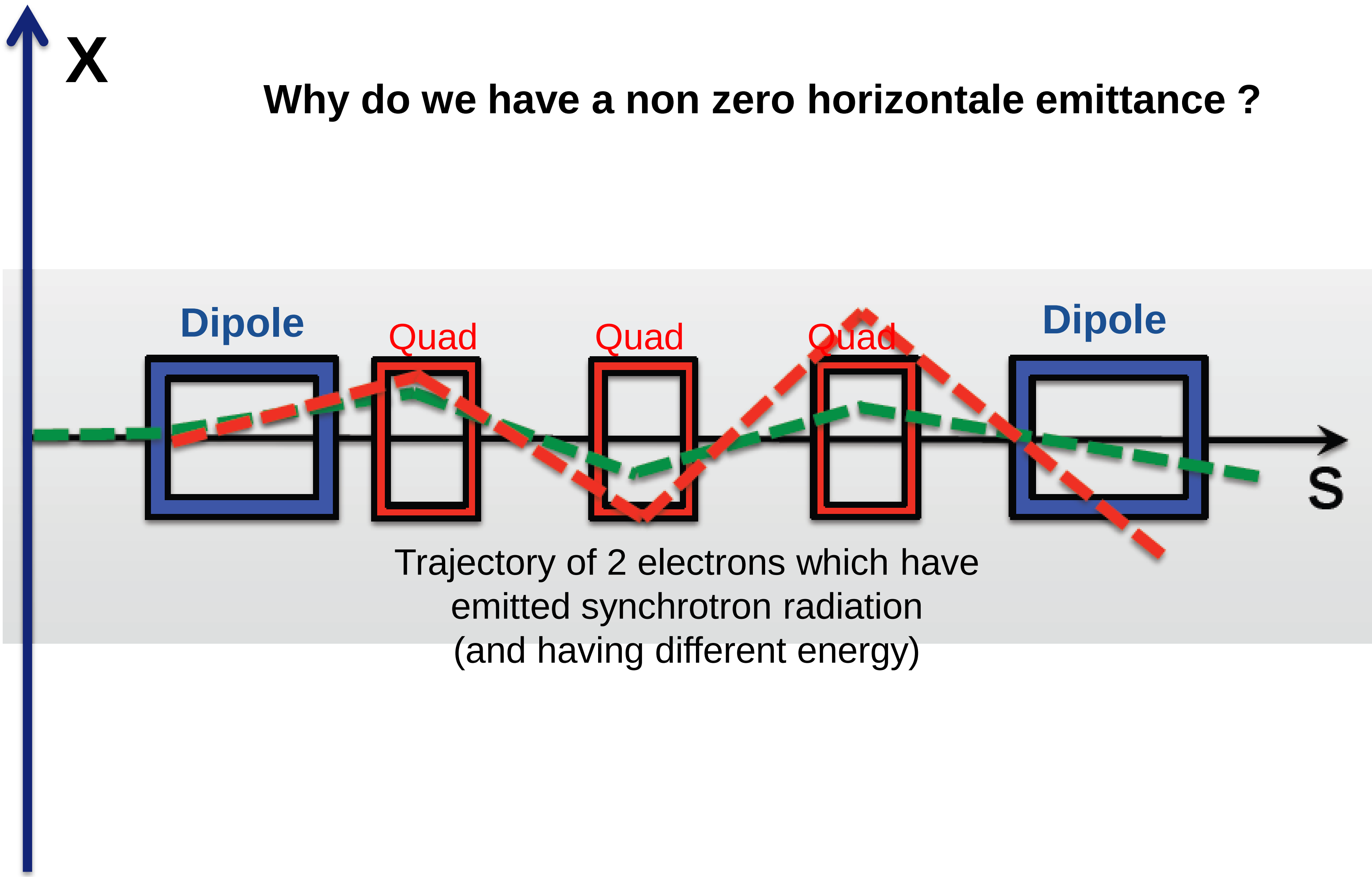
Why do we have a non zero horizontale emittance ?



Trajectory of an electron which has emitted synchrotron radiation in the dipole (lower than the nominal energy)

Corrected by quadrupole magnets

Courtesy A Franchi

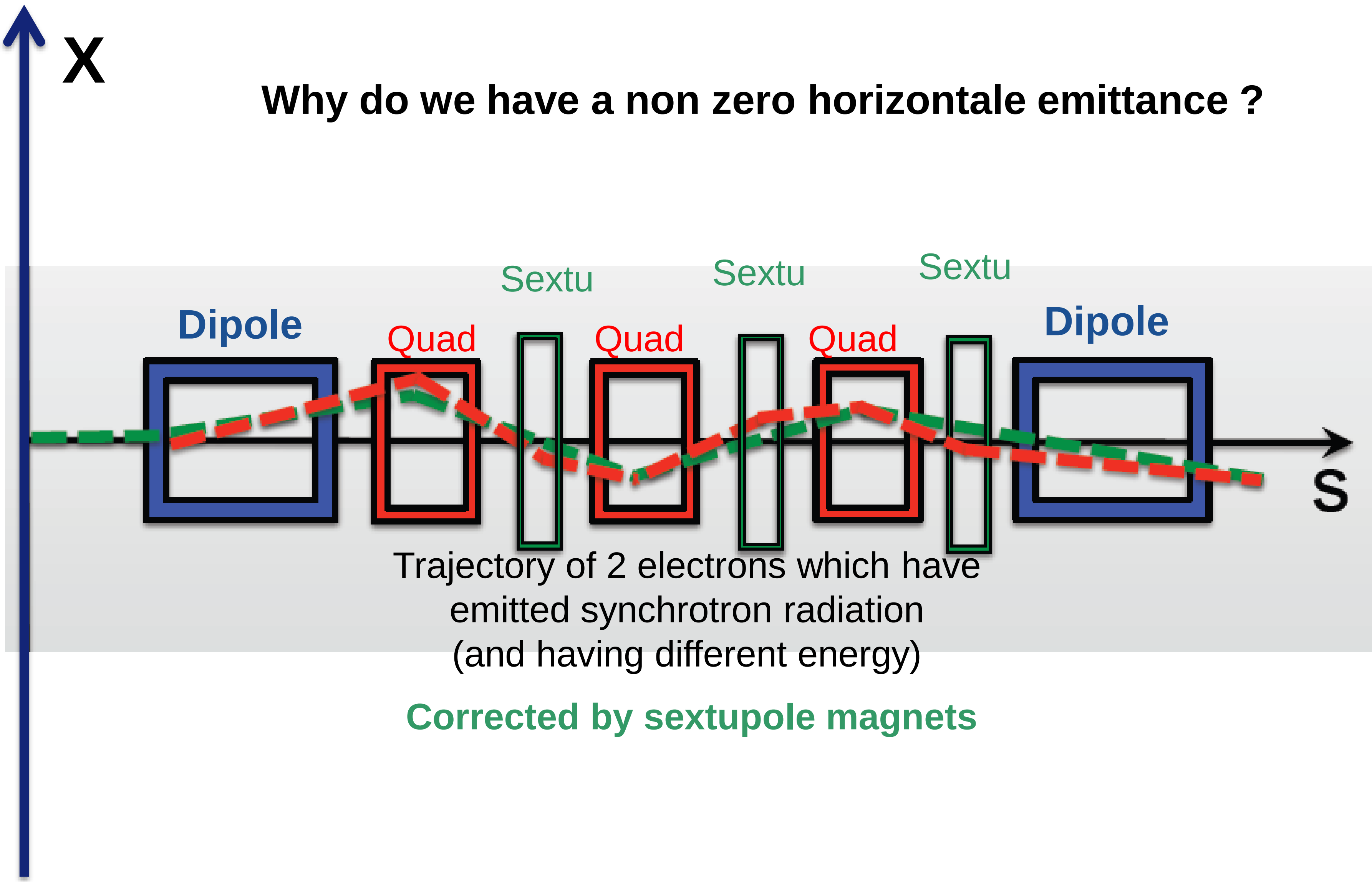


Why do we have a non zero horizontale emittance ?

Trajectory of 2 electrons which have emitted synchrotron radiation (and having different energy)

Courtesy A Franchi

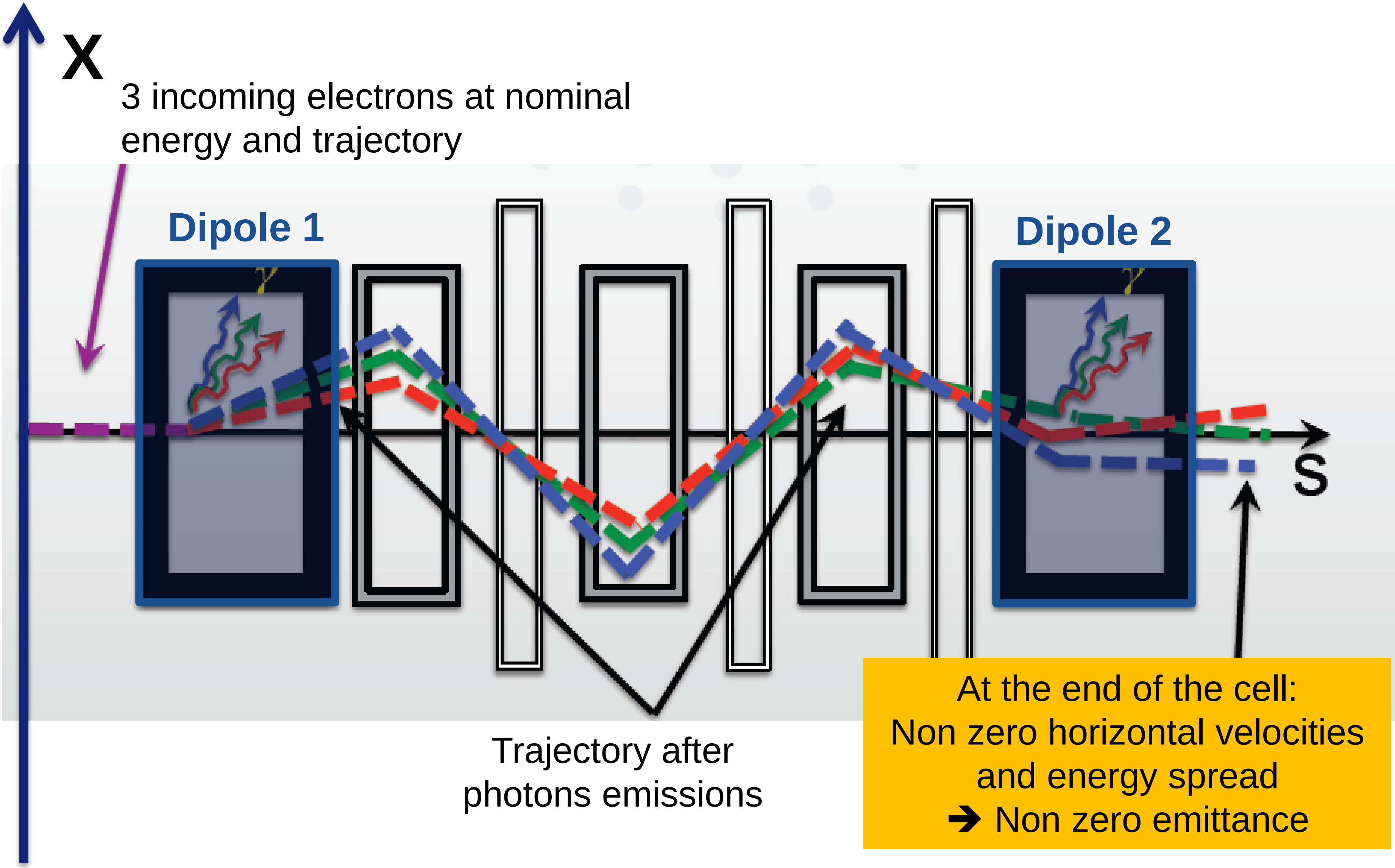
Why do we have a non zero horizontale emittance ?



Trajectory of 2 electrons which have emitted synchrotron radiation (and having different energy)

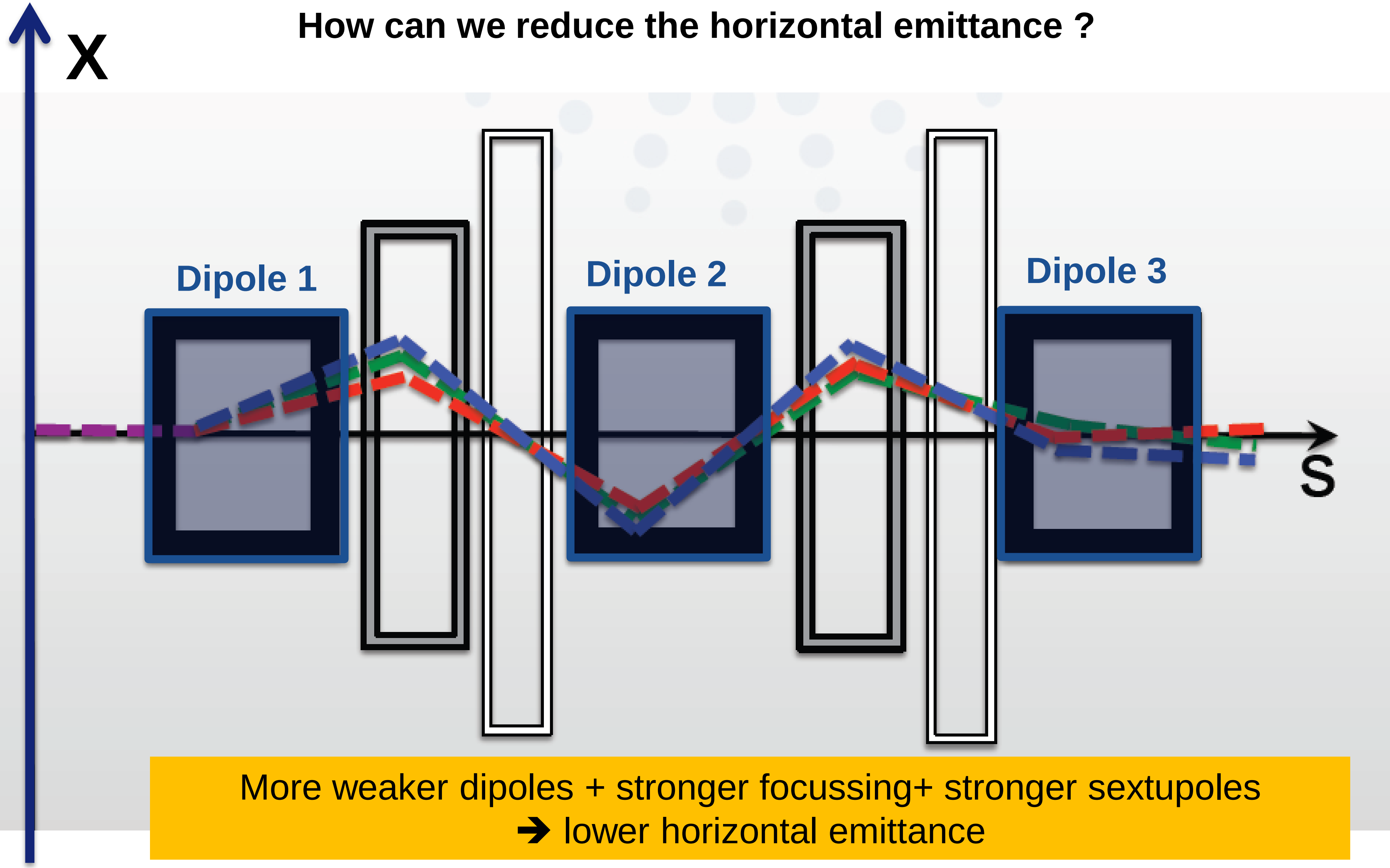
Corrected by sextupole magnets

Courtesy A Franchi



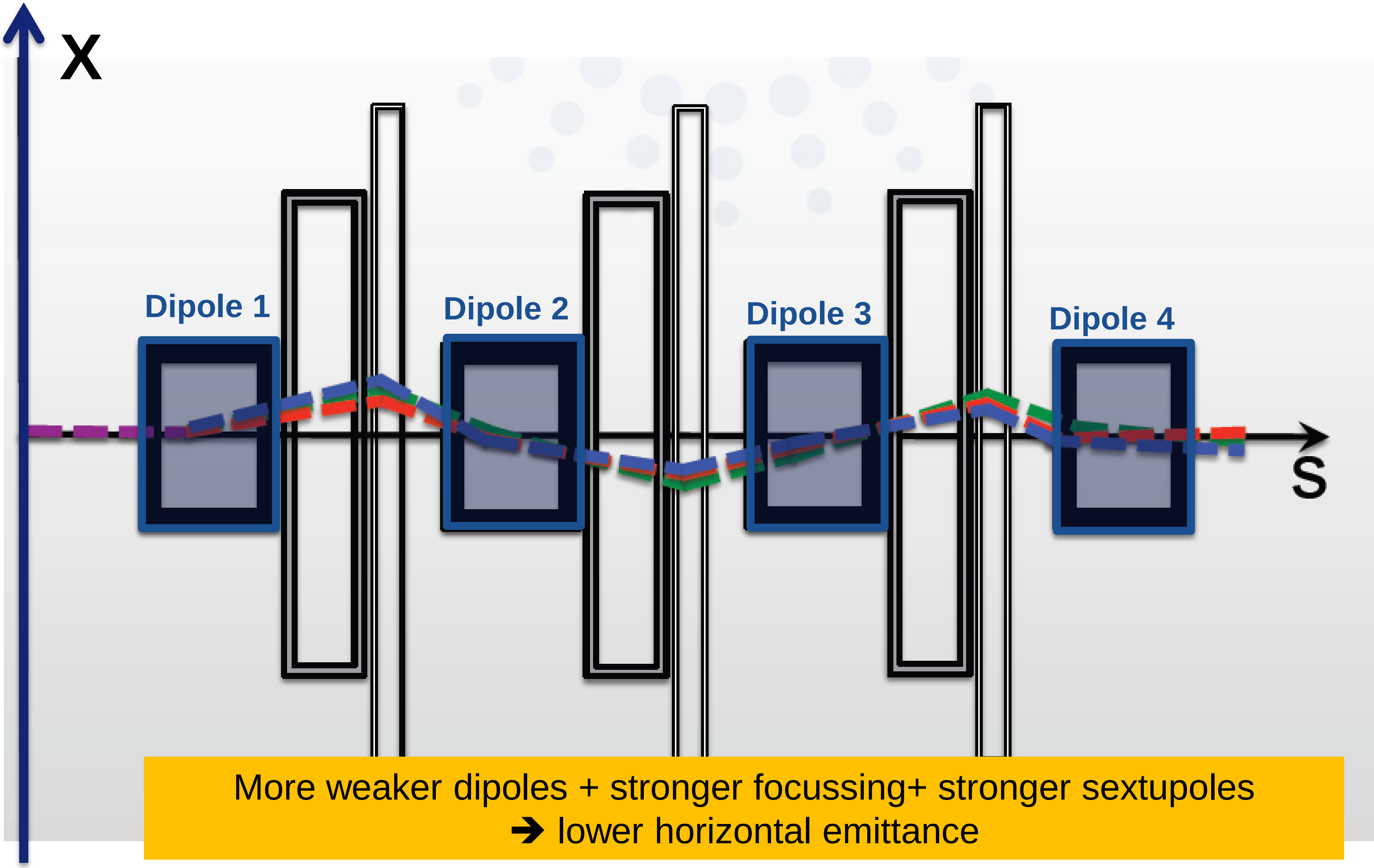
Courtesy A Franchi

How can we reduce the horizontal emittance ?



More weaker dipoles + stronger focussing+ stronger sextupoles
➔ lower horizontal emittance

Courtesy A Franchi

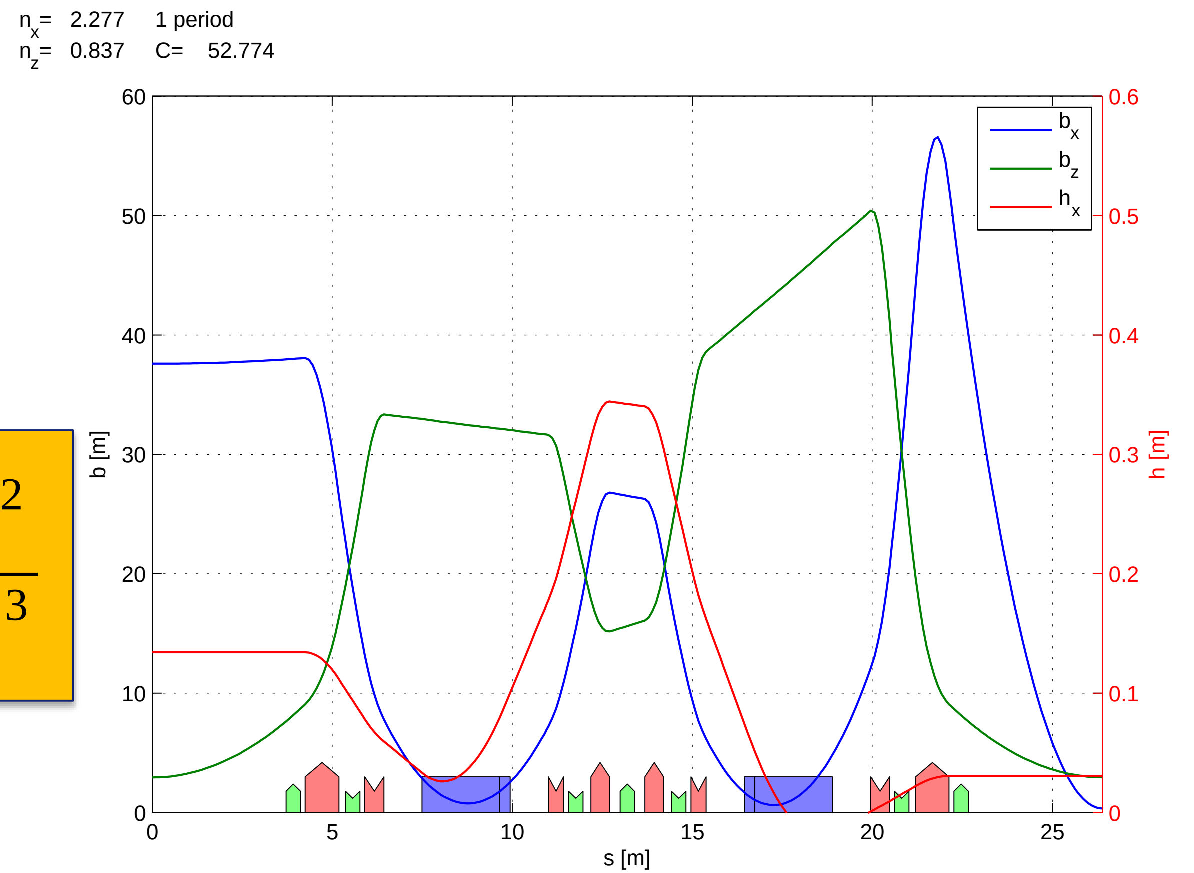


More weaker dipoles + stronger focussing+ stronger sextupoles
➔ lower horizontal emittance

Courtesy A Franchi

PRESENT ESRF LATTICE

Low emittance:
Careful tuning of β_x and η_x in the dipoles (where the radiation occurs)
β_x: envelope function
η_x: dispersion



How clever we are

Energy

$$\varepsilon_x = F(Lattice)\frac{E^2}{N^3}$$

Number of identical dipoles

Emittance reduction ➔ large number of bending magnets

- Increase the number of cells
  ➔ Large circumference
- Put more dipoles per cell
  ➔ Compact machine

Storage ring performance (current and future sources)

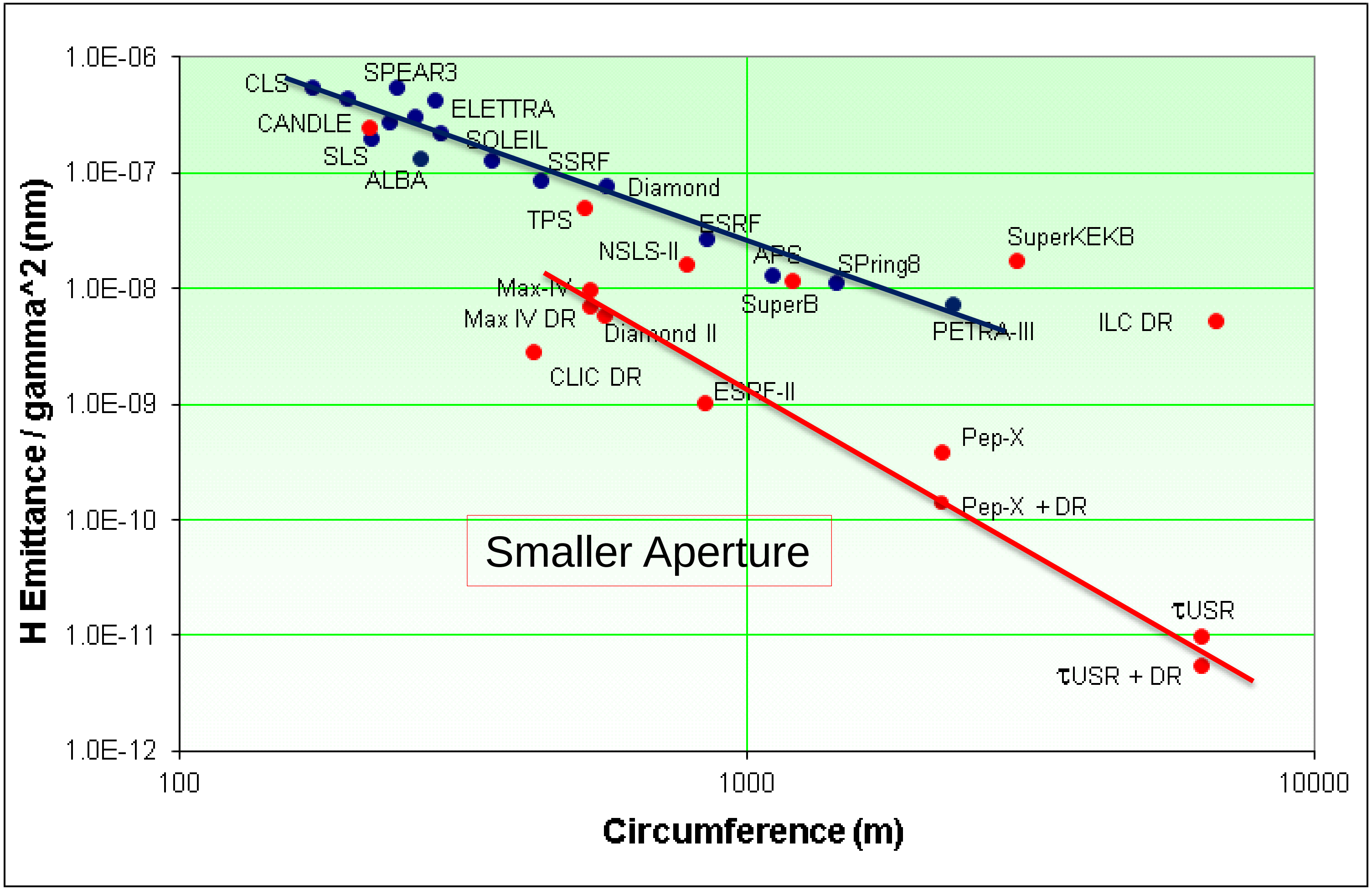
horizontal emittance

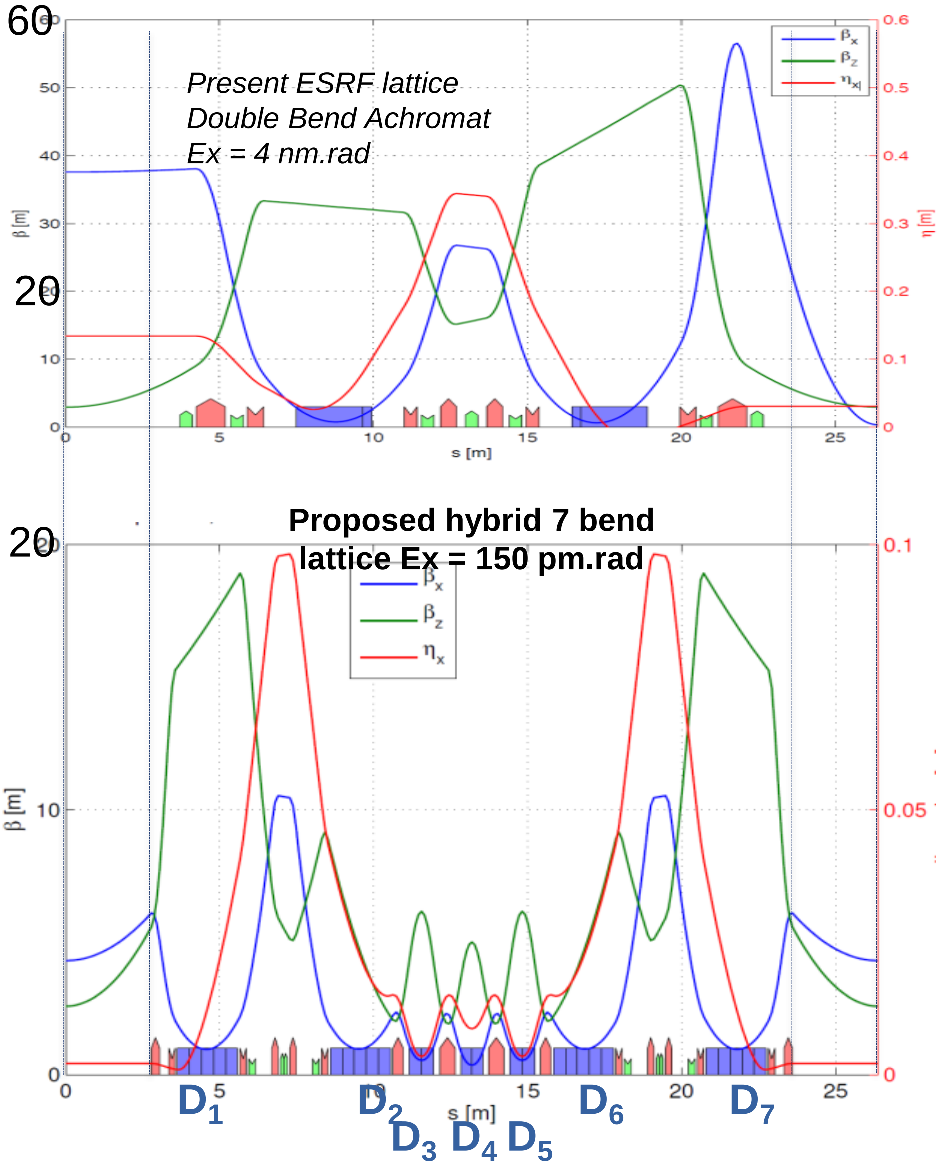
• ESRF	2BA	**4000** pm – 6 GeV, operational
• PETRA III	2BA	**1000** pm – 6 GeV, operational
• NSLS II	2BA	**~350** pm – 3 GeV, operational
• MAX IV	7BA	**~300** pm – 3 GeV, commissioning
• Sirius	5BA	**~250** pm – 3 GeV, in planning
• Spring-8	6BA	**~70** pm – 6 GeV, in planning
• ESRF	7BA	**~150** pm – 6 GeV, construction

Almost linear increase of brightness down to 50-100pm emittance.
For lower emittance the gain becomes less than linear due to:

- the diffraction limit
- mismatch of the electron beam with the X-ray beam

LOW EMITTANCE RINGS TREND





Bleu: Dipoles Red: Quadrupoles Green: sextupoles

@ 7 bending magnets D_{1to7}
➔ reduce the horizontal emittance

@ Space between D_1-D_2 and D_6-D_7
β-functions and dispersion allowed to grow
➔ chromaticity correction
with efficient sextupoles

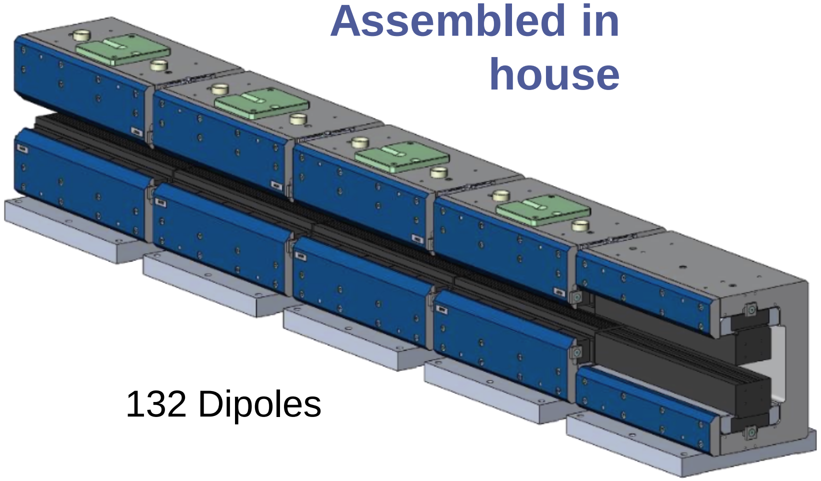
@ Dipoles D_1, D_2, D_6, D_7
➔ longitudinally varying field to further reduce emittance

@ Central part alternating
➔combined dipole-quadrupoles$D_{3\text{-}4\text{-}5}$
➔high-gradient focusing quadrupoles

@ D_4 (0.34T) and D_5 (0.85T)
➔Source points for BM beamlines

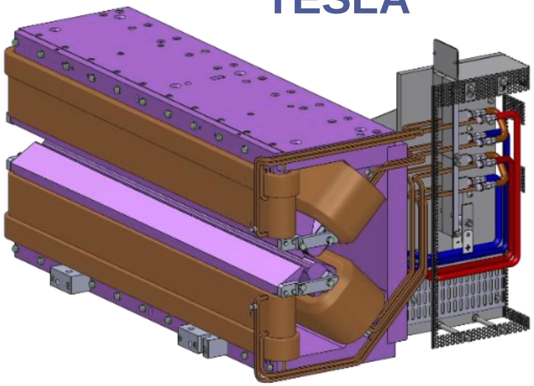
MAGNETS

Assembled in house



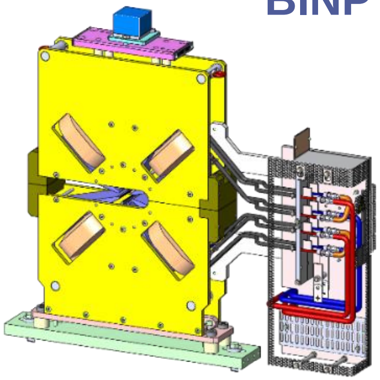
132 Dipoles

TESLA



100 Dipole-quadrupoles

BINP



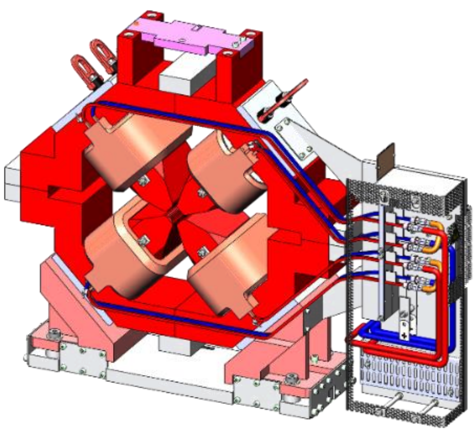
66 Octupoles

More than 1000 Magnets to procure in less than 3 years

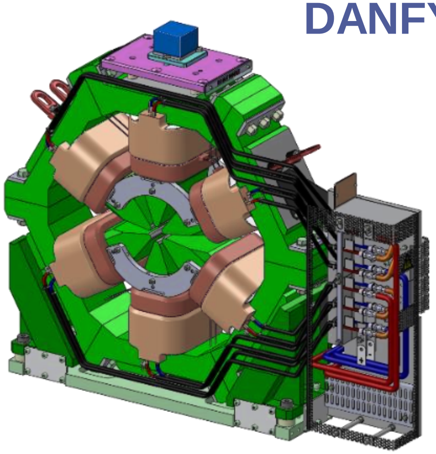
TESLA
(MG)

524 Quadrupoles
(132 HG, 392 MG)

DANFYSIK
(HG)

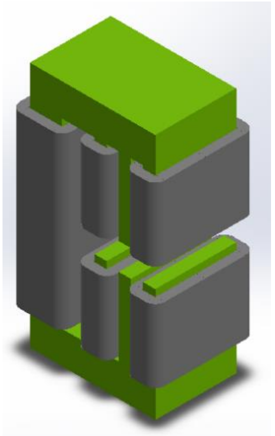


DANFYSIK



196 Sextupoles

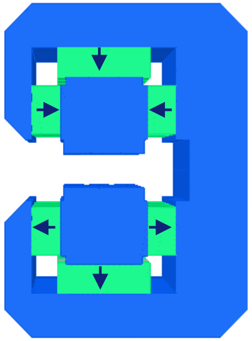
SEF

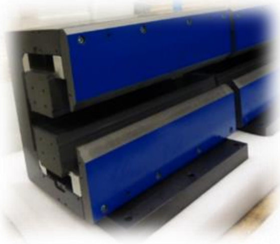


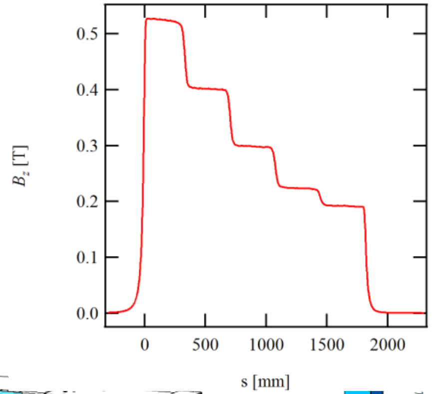
98 Correctors

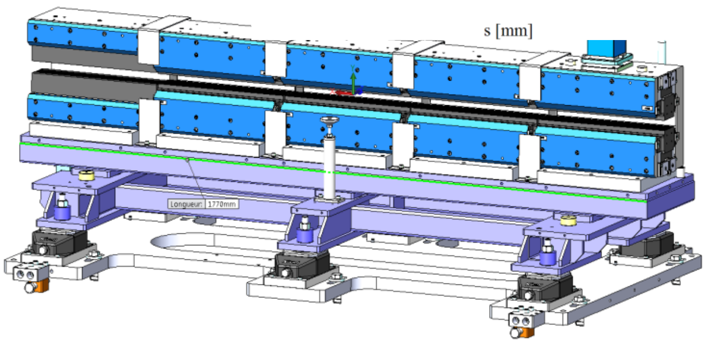
DIPOLES

- Each dipole based on 5 PM modules
- Strength 0.67-0.17 T &
- Iron length 1788 mm
- 25.5 – 30.5 mm GAP
- Iron: Pure Iron
- Permanent magnet Sm_2Co_{17}

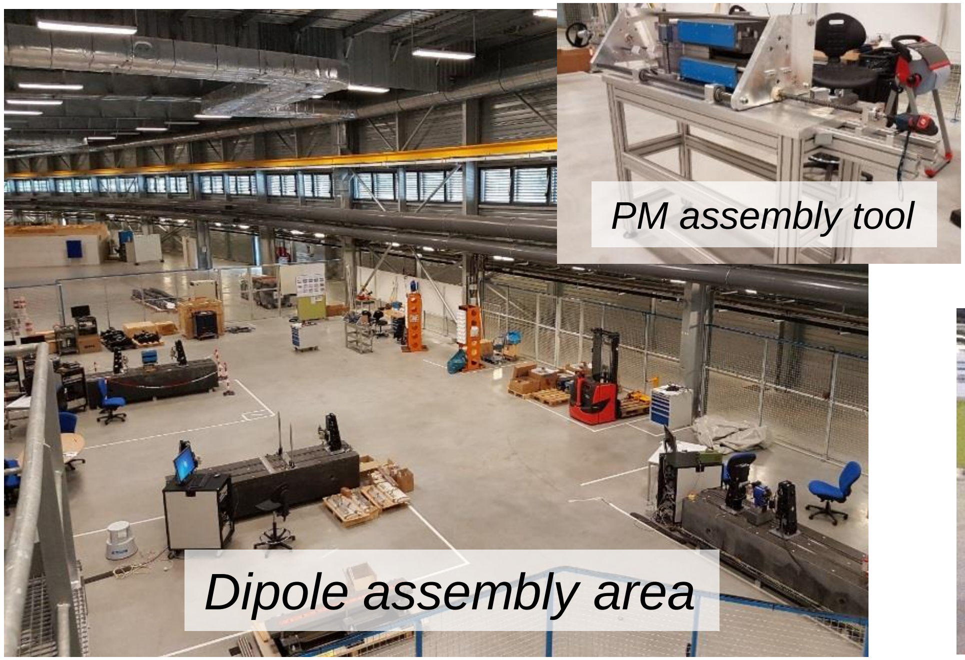








Around 6000kg of PM, 660 Iron modules,
Partially delivered

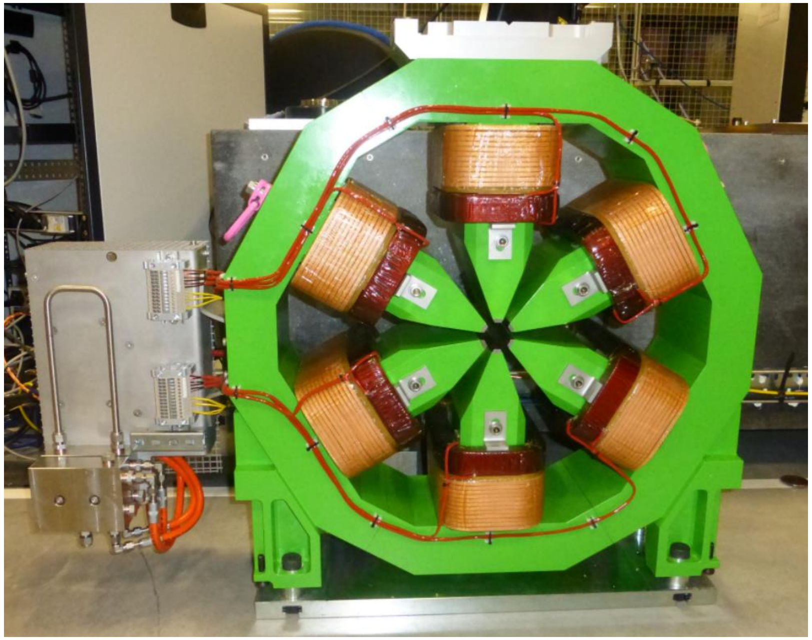


Dipole assembly area

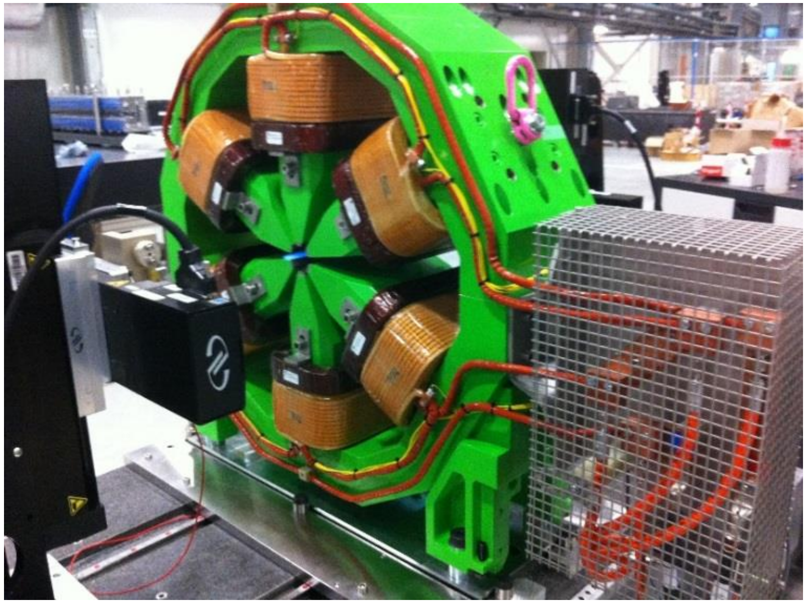
PM assembly tool

SEXTUPOLES

- 2 types
- 1700 T/m^2 gradient, 166 – 200 mm length
- 19.2 mm bore radius
- 0.5 kW power consumption
- Including additional correction coils



Pre-series magnet delivered



QUADRUPOLES

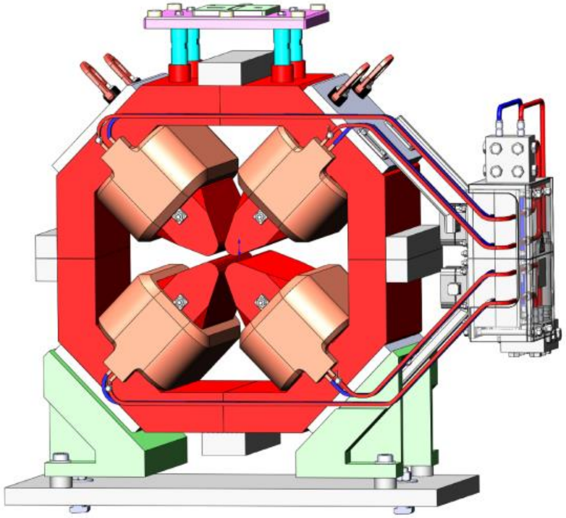
High Gradient

- 2 types
- 89 & 87 T/m gradient
- 388 – 484 mm length
- 12.7 mm bore radius
- 1.9 & 1.7 kW power consumption

Pre-series magnet delivered

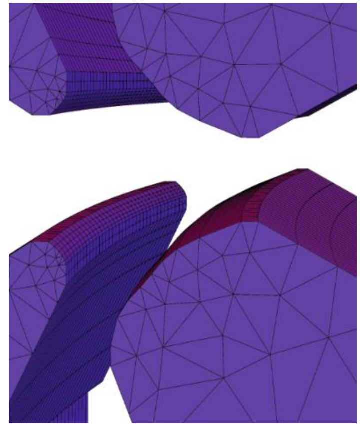
Moderate Gradient

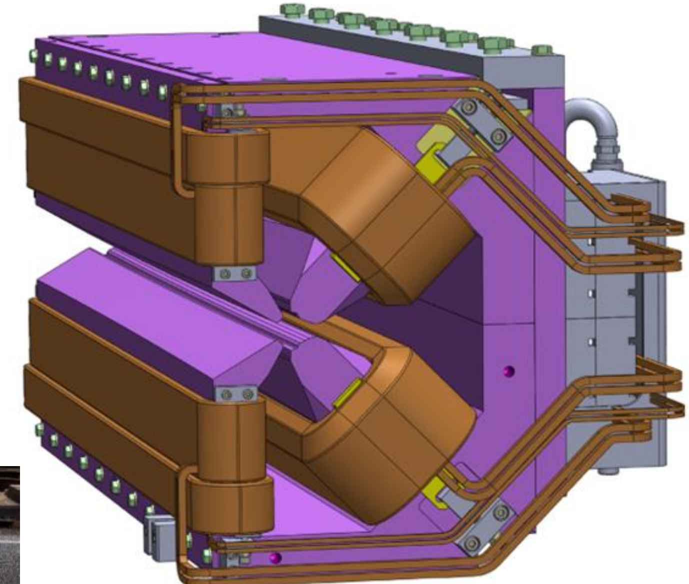
- 4 types
- Up to 54 T/m gradient, 162– 295 mm length
- 16.4 mm bore radius
- 0.7 – 1.1 kW power consumption

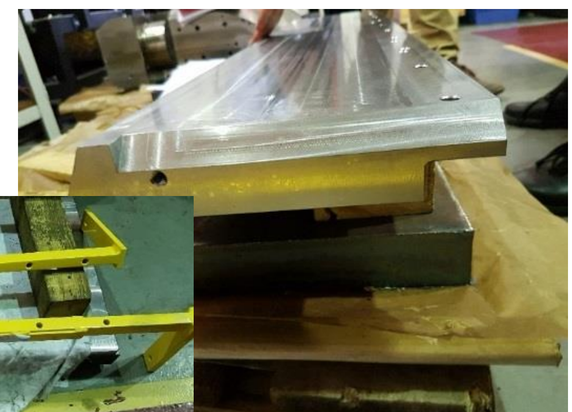


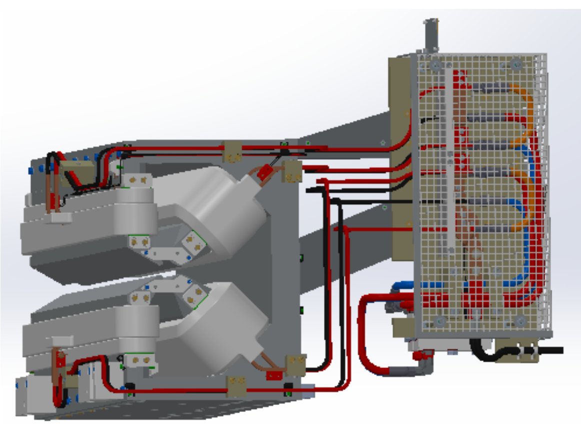
DIPOLE QUADRUPOLES

- 2 types
- Nominal dipole 0.55 – 0.39 T
- Nominal gradient 36-39 T/m
- 1028-800 mm
- 18.6 mm bore radius
- 1.6- 1.2 kW power consumption
- Poles longitudinally curved





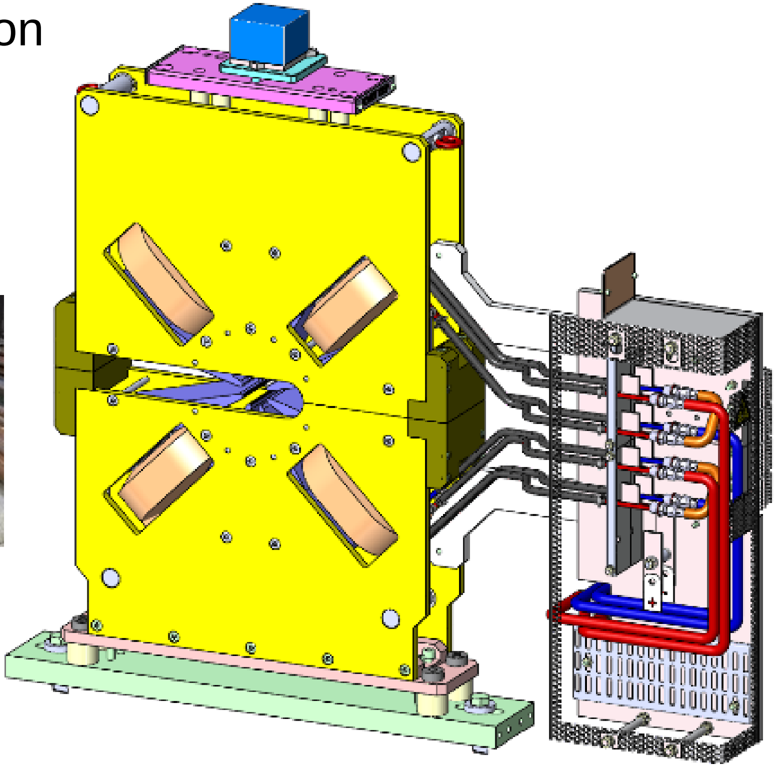




Pre-series magnet in production

OCTUPOLES

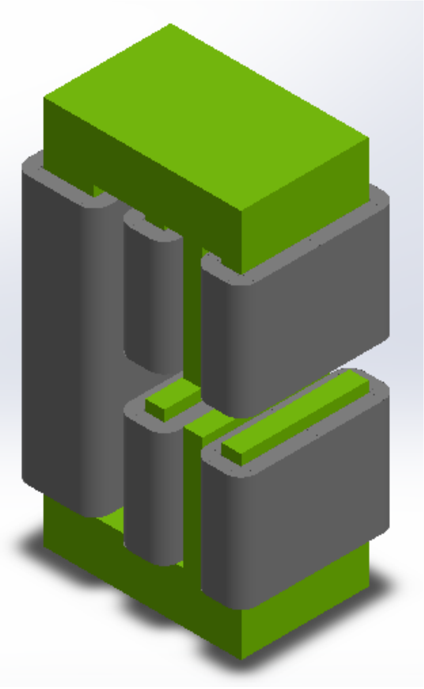
- 36900 T/m3 gradient, 90 mm length
- 18.6 mm bore radius
- 0.1 kW power consumption
- Allows the required stay clear for Synchrotron radiation fan



Pre-series magnet in production

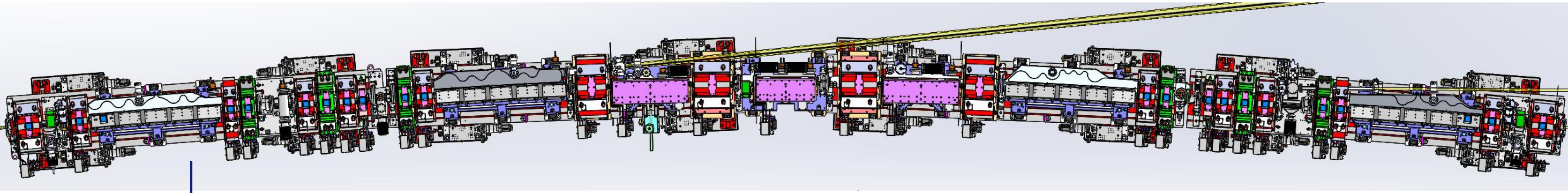
CORRECTORS

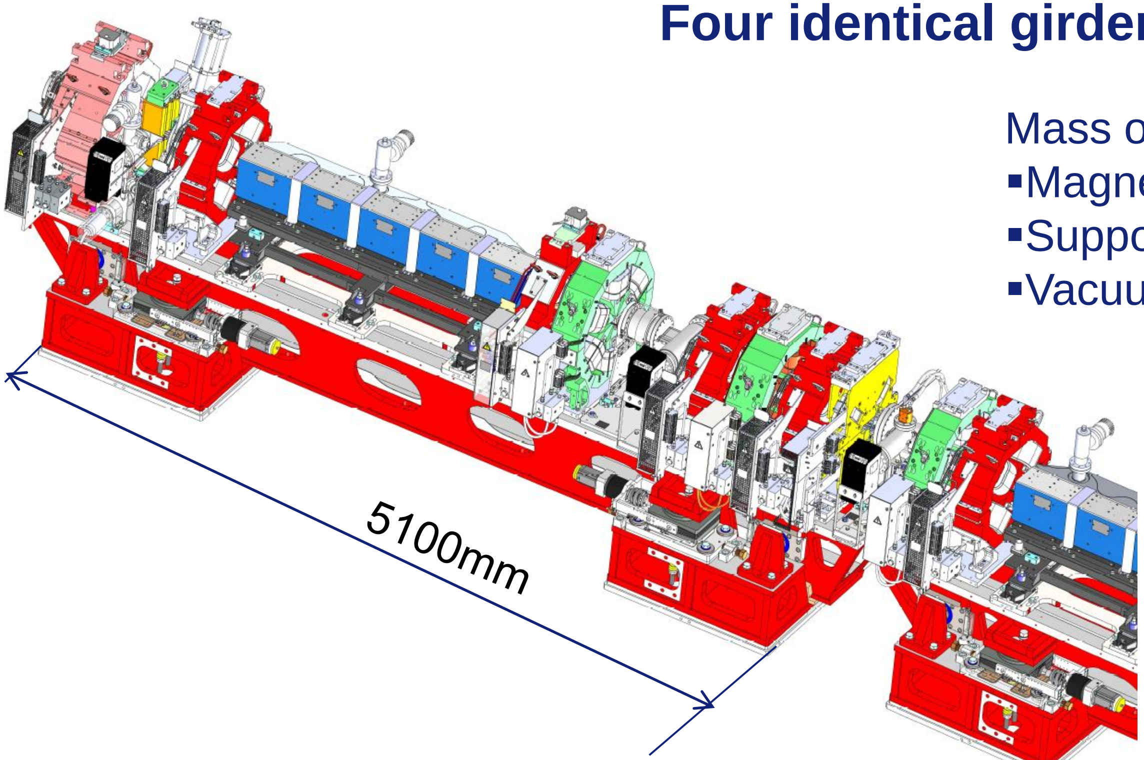
- Horizontal: 10 T.mm
- Vertical 10 T.mm
- Skew quadrupole: 0.12 T
- 25.5 mm gap mm bore radius



Pre-series magnet delivered

GIRDERS





Four identical girders per cell

Mass of:
- Magnetic elements
- Supports
- Vacuum equipements

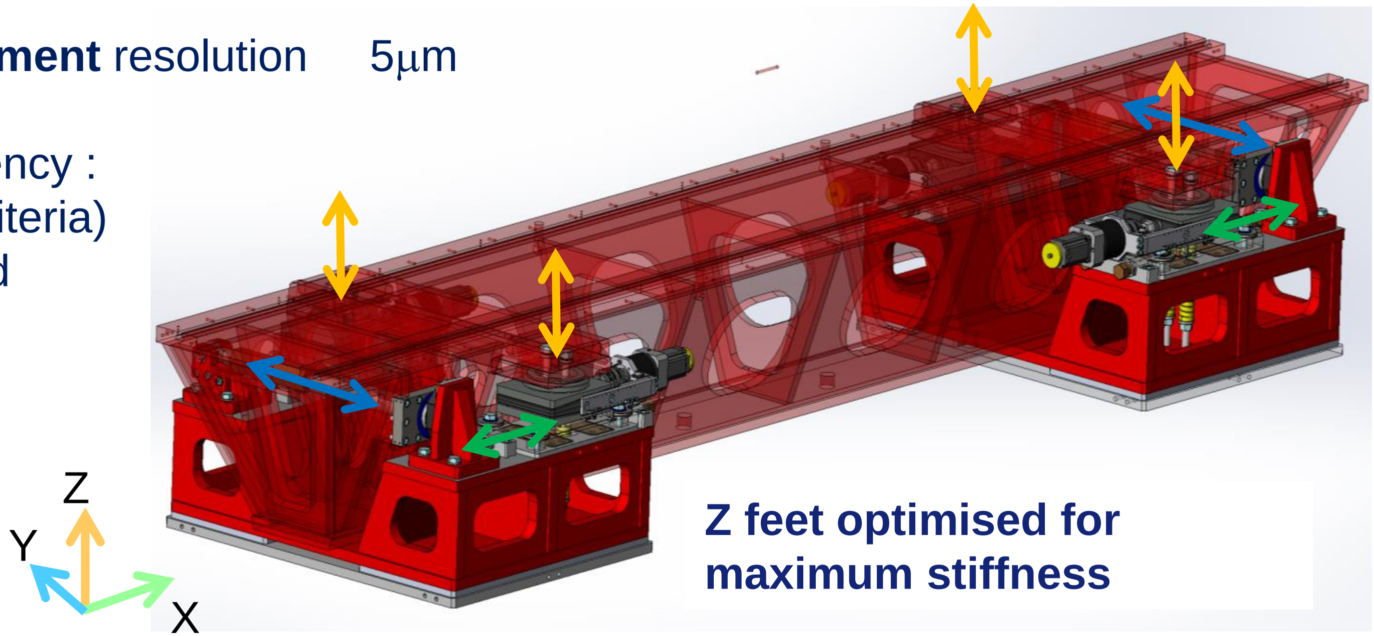
6-7T/girder

GIRDERS

- Girder supported by 4 adjustable Z feet made of motorised wedges
- Y adjustment by 2 manual jacks pushing the girder

	HORIZONTAL (Y)	VERTICAL (Z)
Girder to girder	50 μm	50 μm

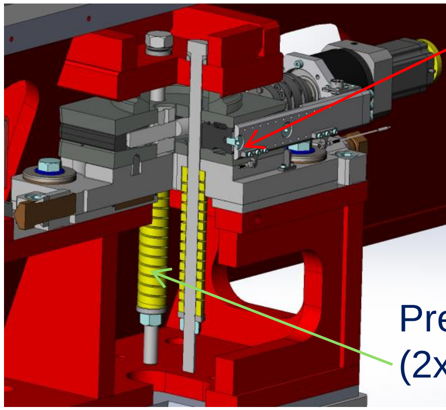
- **Motorized Z adjustment** resolution 5μm
- **Manual Y adjustment** resolution 5μm
- 1st natural frequency :
  - 50Hz (design criteria)
  - 49 Hz measured



Z feet optimised for maximum stiffness

GIRDERS

- Vertical movement

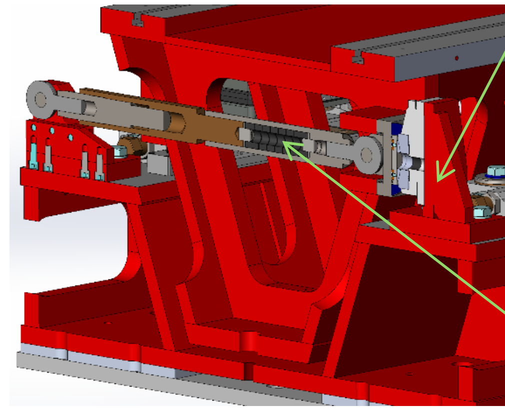


Motorized
Wedge Airloc

Z movement:
•Accuracy: 10.8µm
•Repeatability: 3.3µm
•Increment: 0.3µm

Preload springs
(2x0.7T)

- Horizontal movement



Wedge Nivell DK2

Horizontal Jacks functions:
▪horizontal adjustment
▪guiding the vertical movement
▪improoving the stiffness

«Pushing back» spring (3.5T)

Pre-series girder delivered by NORTEMECA and AVS

flatness 40µm

VACUUM CHAMBERS

✓ Three main families of chambers:

In situ bake-out

Low profile stainless steel chambers (inside combined dipole-quadrupoles & HG quadrupoles)

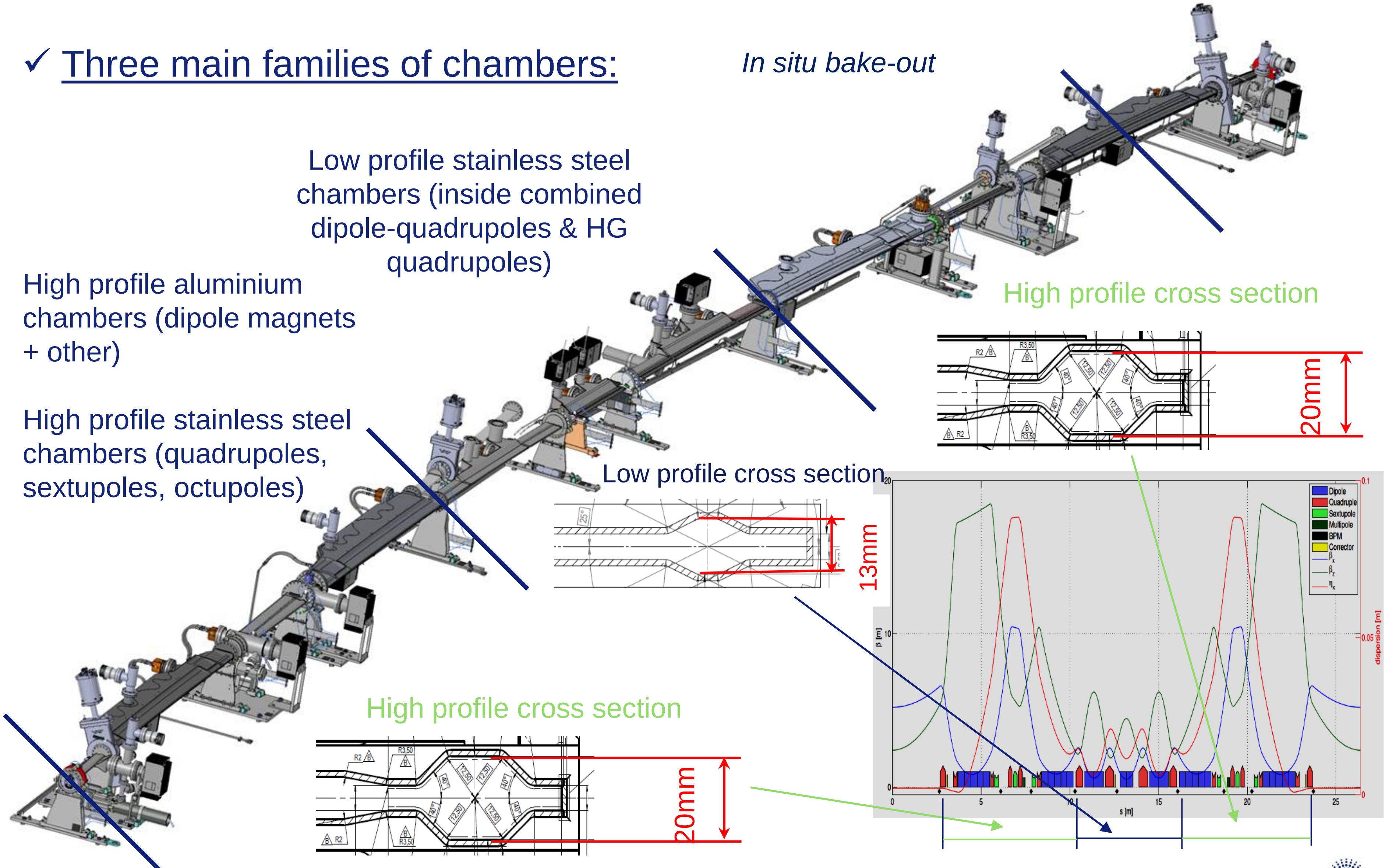
High profile aluminium chambers (dipole magnets + other)

High profile stainless steel chambers (quadrupoles, sextupoles, octupoles)

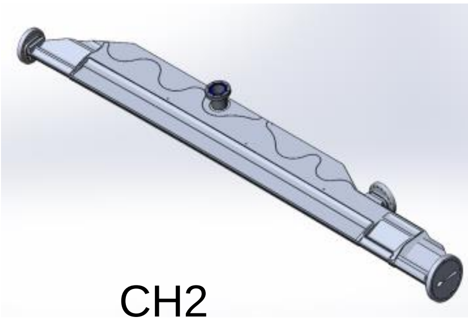
High profile cross section

Low profile cross section

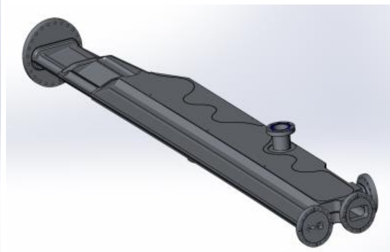
High profile cross section



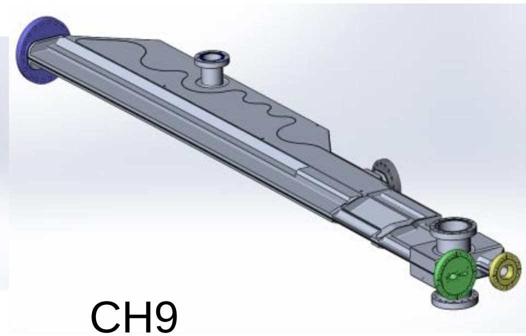
4 dipole chambers per cell made of Aluminum



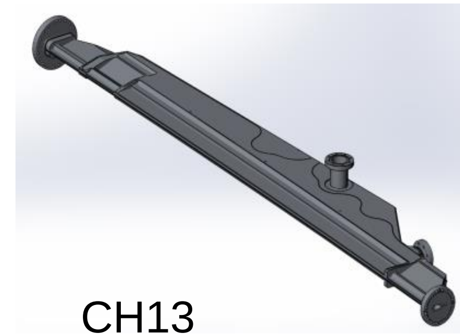
CH2



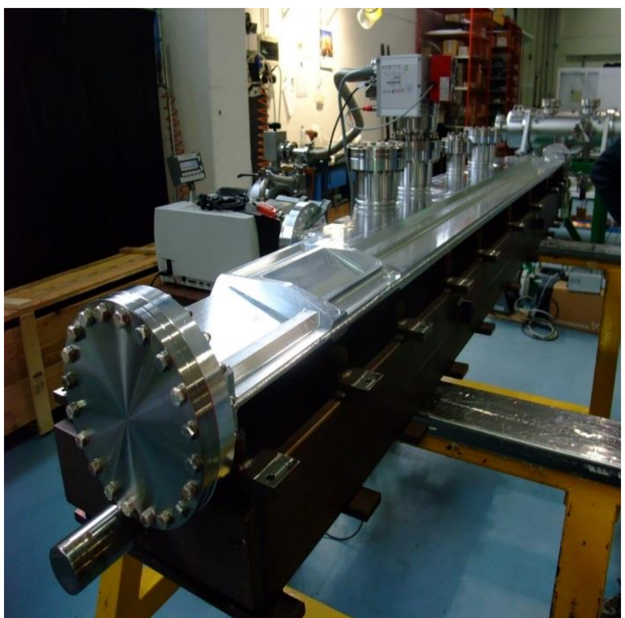
CH5



CH9



CH13

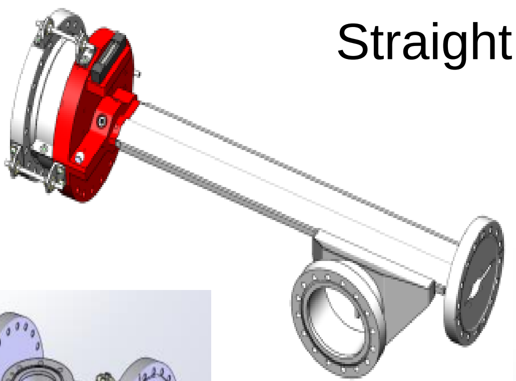


- Design completed
- Prototype done
- Manufacturing in progress

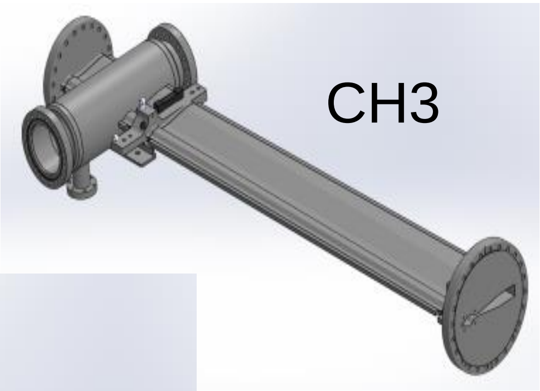
FAMILY 2: HIGH PROFILE STAINLESS STEEL CHAMBERS

Straight Chambers

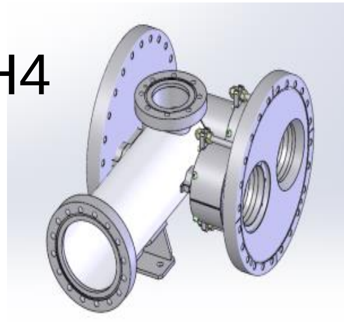
CH1



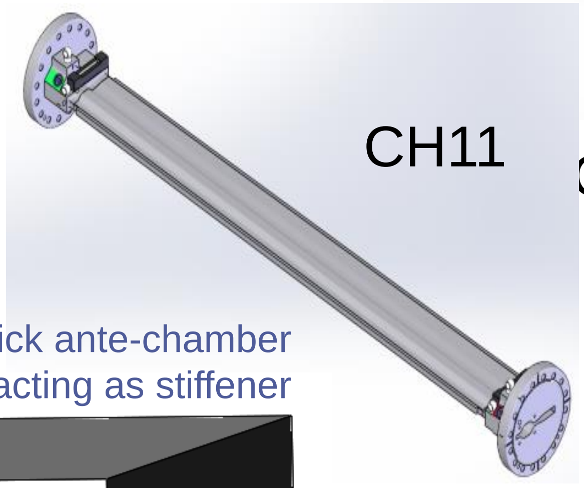
CH3



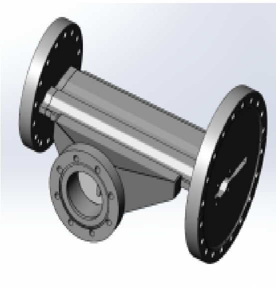
CH4



CH11

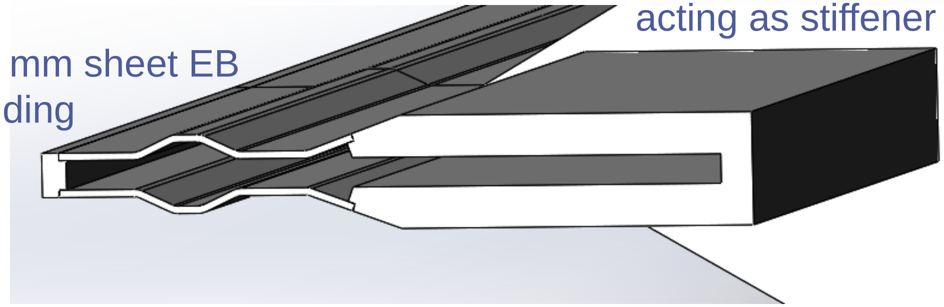


CH12

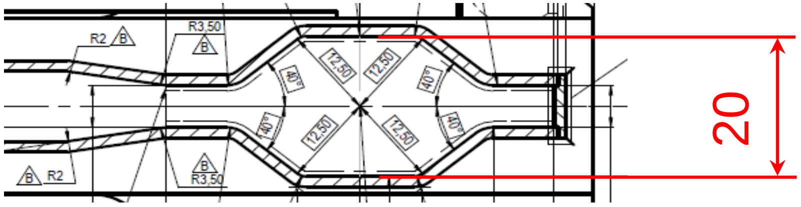


Thick ante-chamber acting as stiffener

1.5 mm sheet EB welding

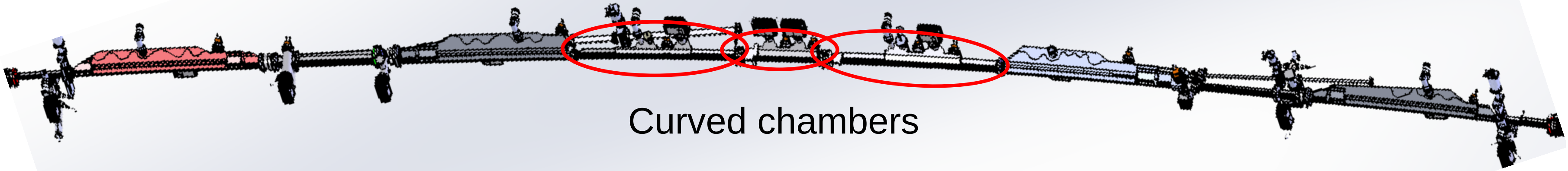


High profile cross section

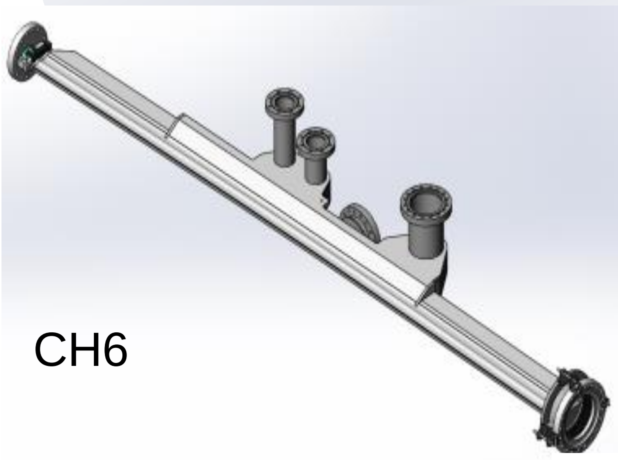


- Design completed
- Manufacturing in progress

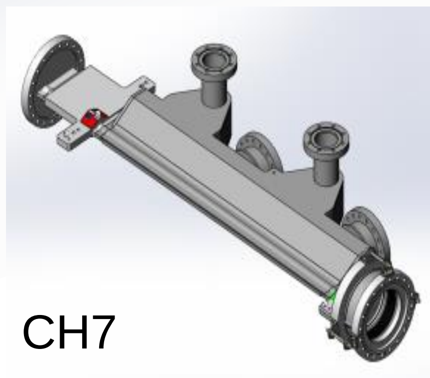
FAMILY 3: LOW PROFILE STAINLESS STEEL CHAMBERS



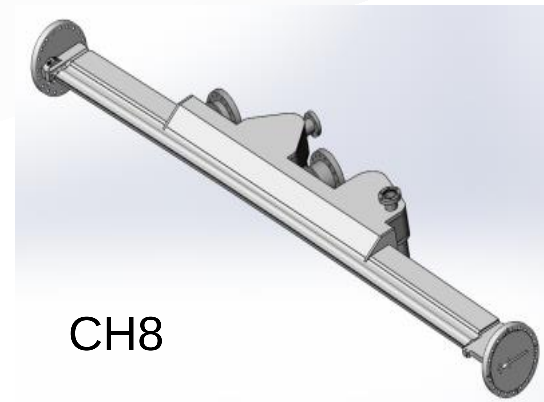
Curved chambers



CH6



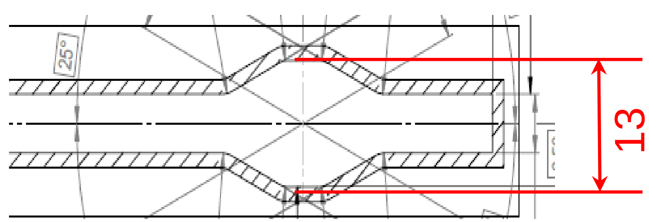
CH7

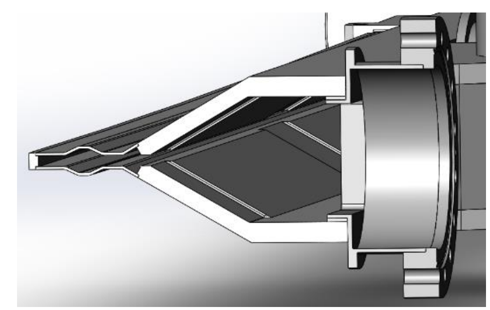


CH8

Low profile cross section (inside dipole-quadrupoles and HF quadrupoles)

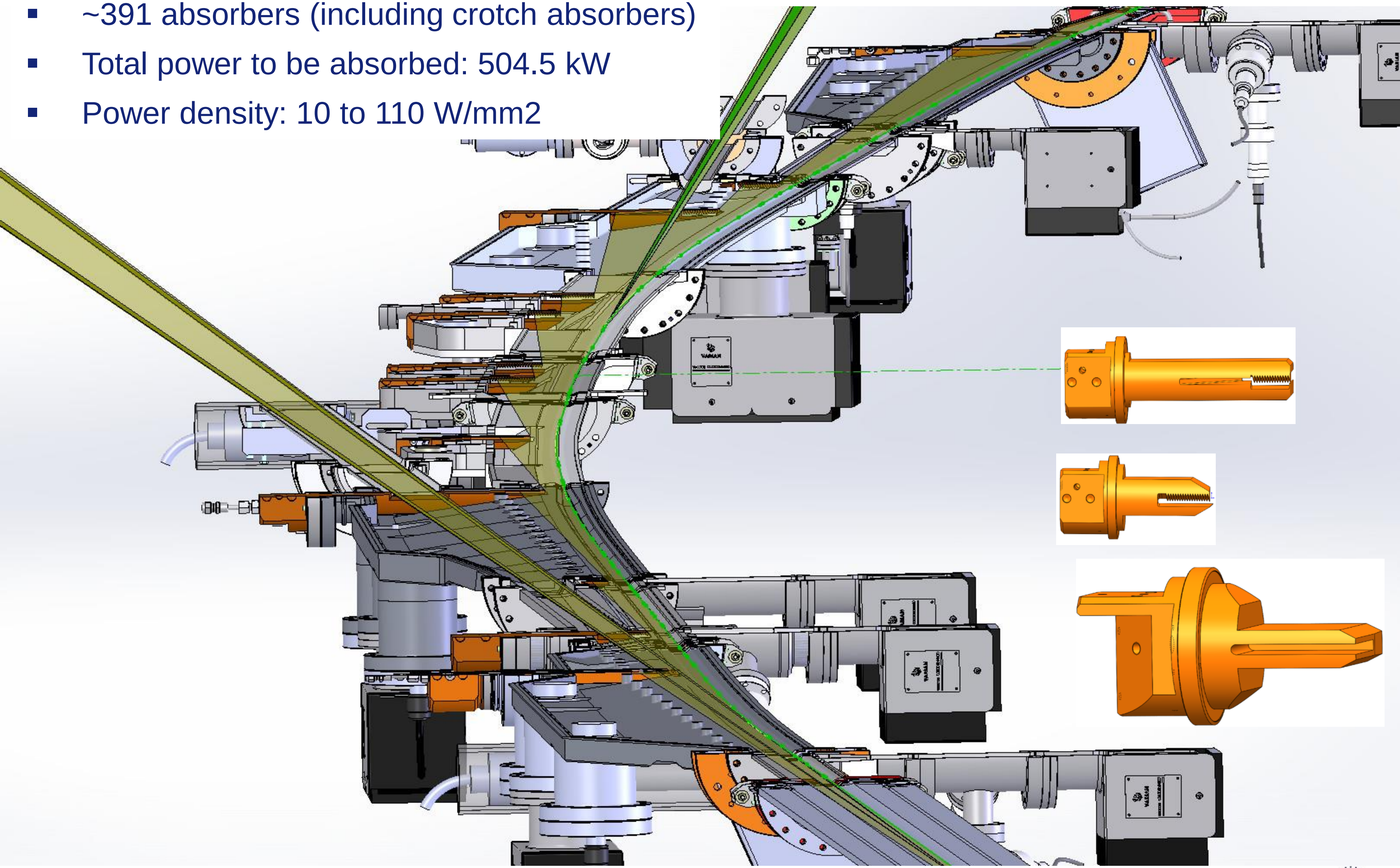
- Design complete
- Manufacturing in progress



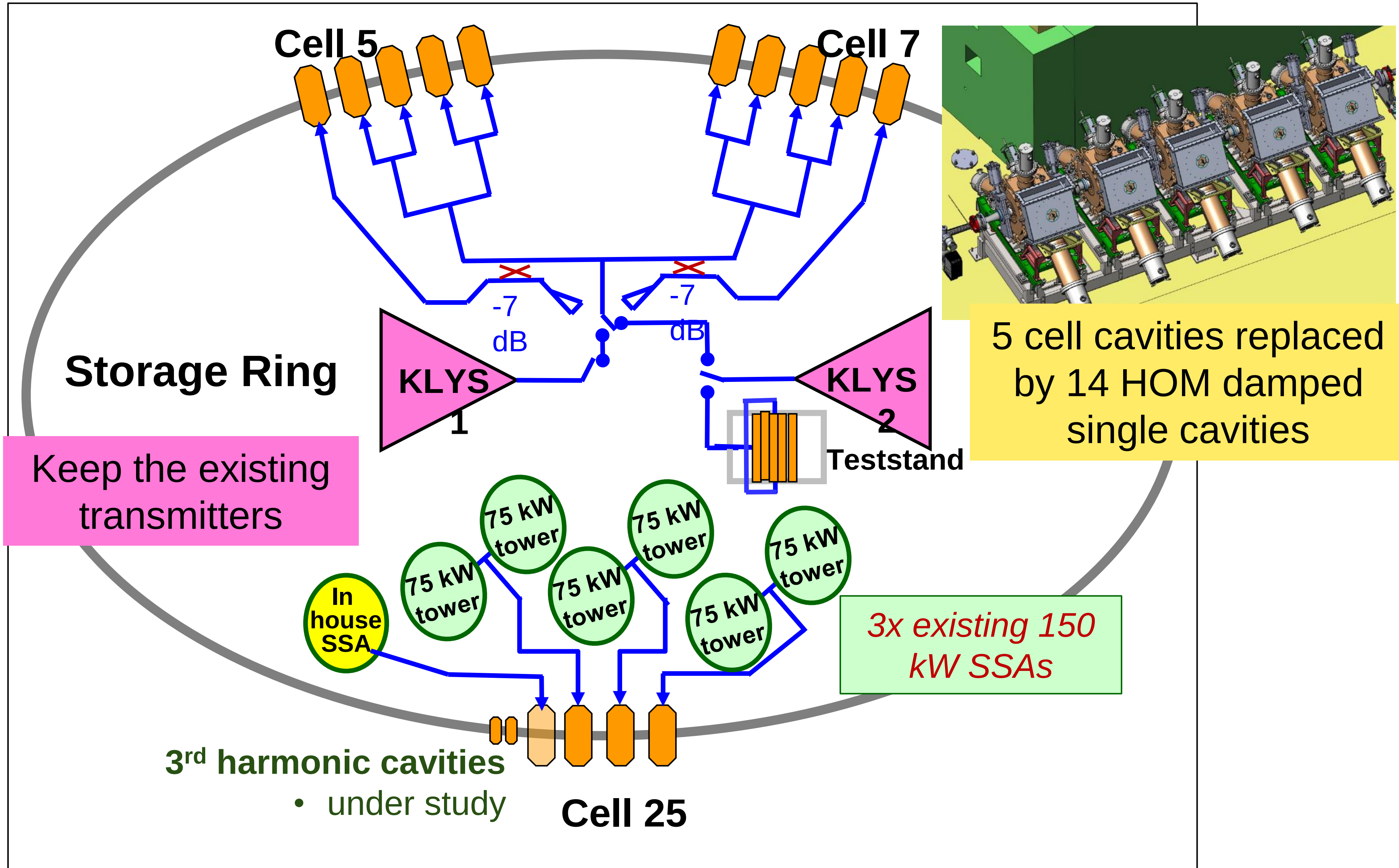


PHOTON ABSORBERS

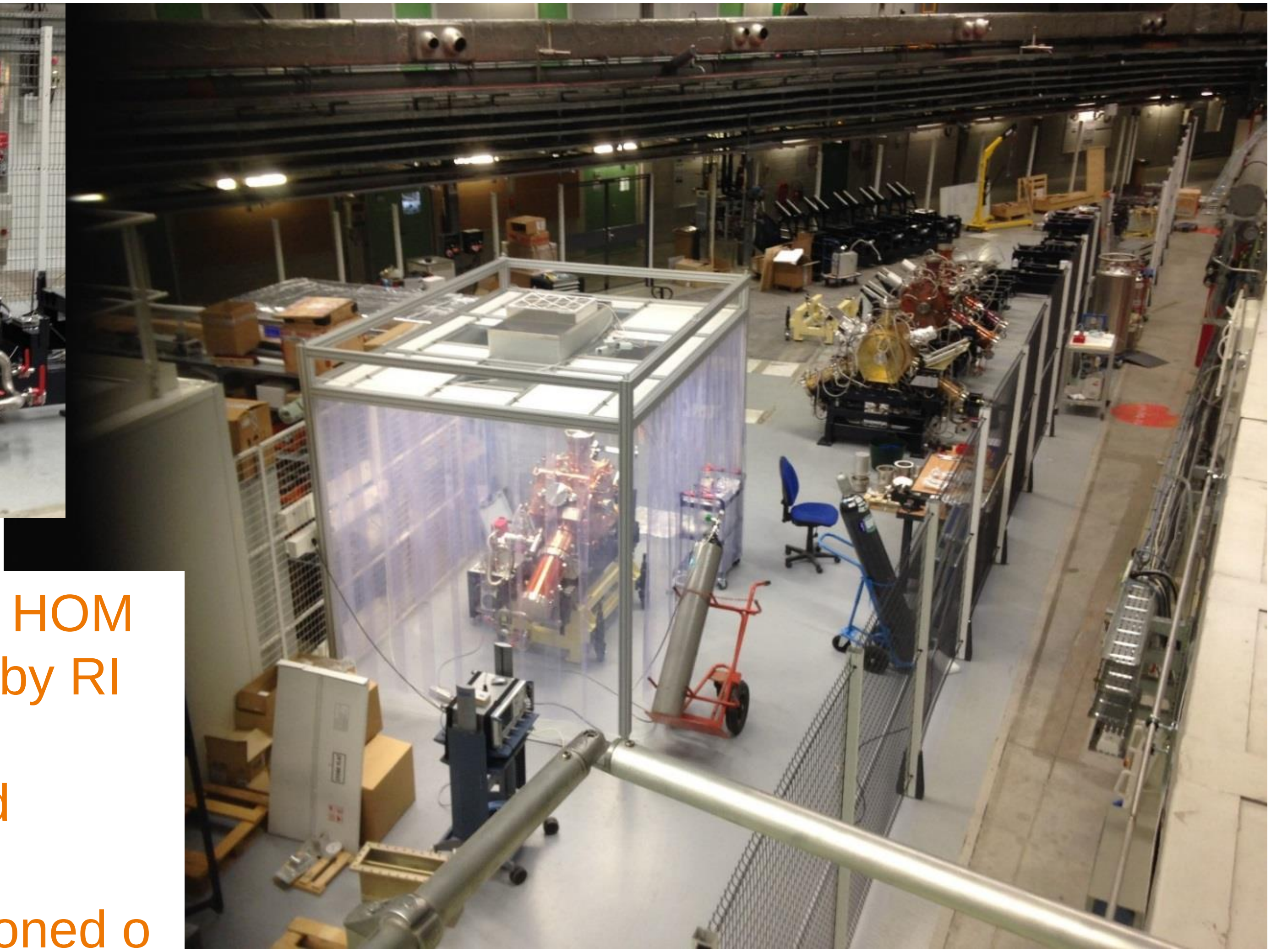
- ~391 absorbers (including crotch absorbers)
- Total power to be absorbed: 504.5 kW
- Power density: 10 to 110 W/mm2



RF LAYOUT


Cell 5
Cell 7
Storage Ring
KLYS 1
KLYS 2
-7 dB
-7 dB
Teststand
Keep the existing transmitters
5 cell cavities replaced by 14 HOM damped single cavities
75 kW tower
75 kW tower
75 kW tower
75 kW tower
75 kW tower
75 kW tower
In house SSA
3x existing 150 kW SSAs
3rd harmonic cavities
• under study
Cell 25

RF CAVITIES



Fabrication of 12 HOM damped cavities by RI

4 cavity delivered

2 cavities conditioned o 750 kV within 2 weeks

Cavity assembly area

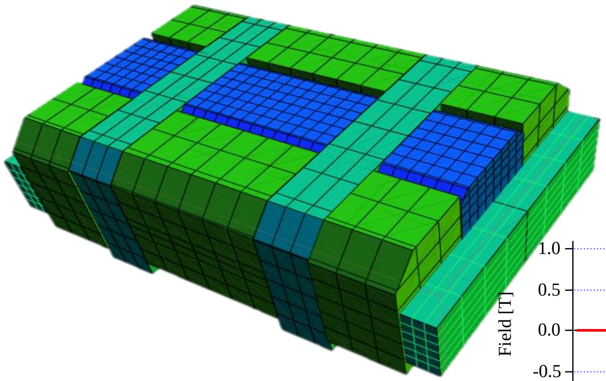
All new projects of diffraction limited storage rings have to deal with:

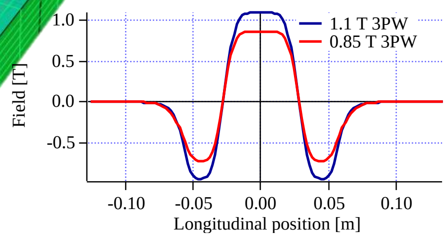
Increased number of bending magnets / cell => BM field reduction

Conflict with hard X-ray demand from BM beamlines

ESRF will go from 0.85 T BM to 0.54 T BM

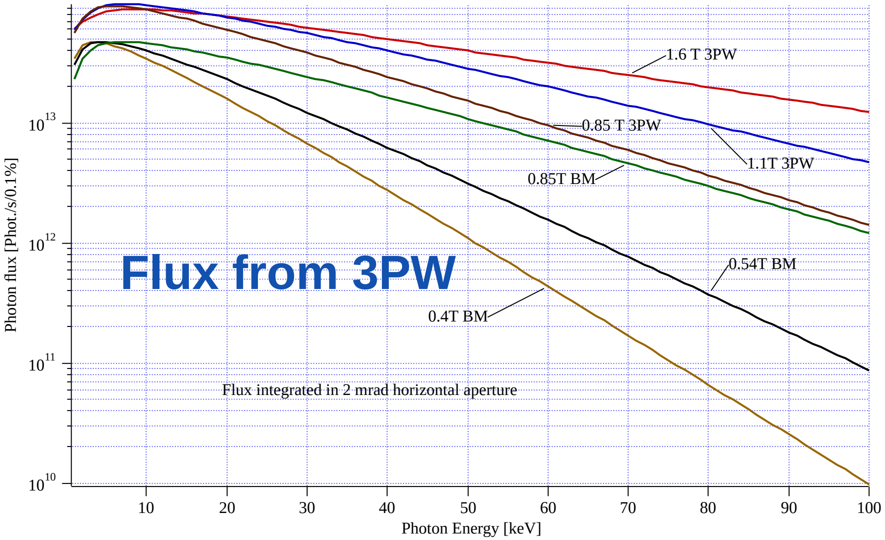
The BM Sources will be replaced by dedicated 2-Pole or 3-Pole Wigglers



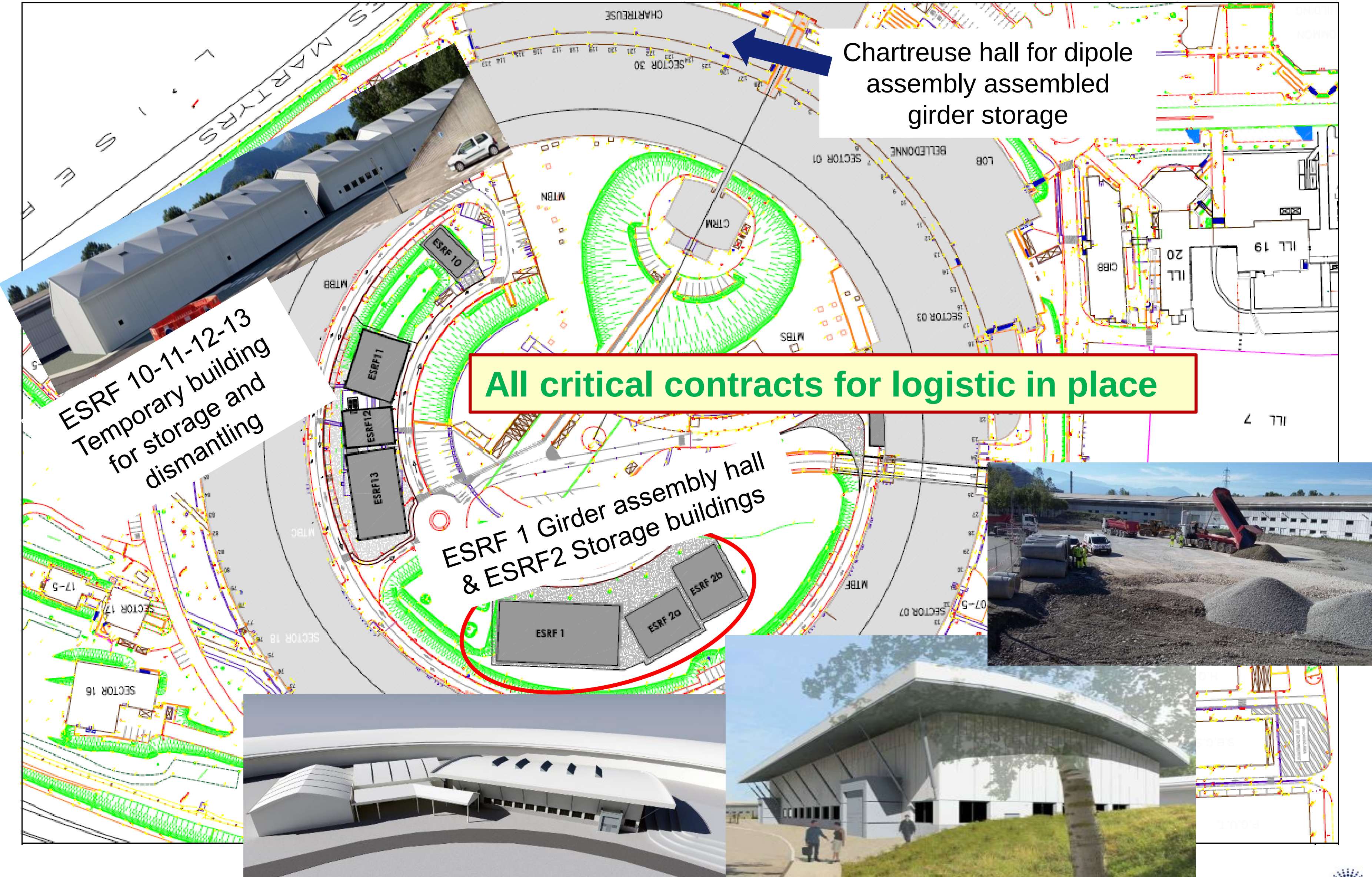


- Field Customized
- Large fan with flat top field
- 2 mrad feasible for 1.1 T 3PW
- Mechanical length ≤ 150 mm

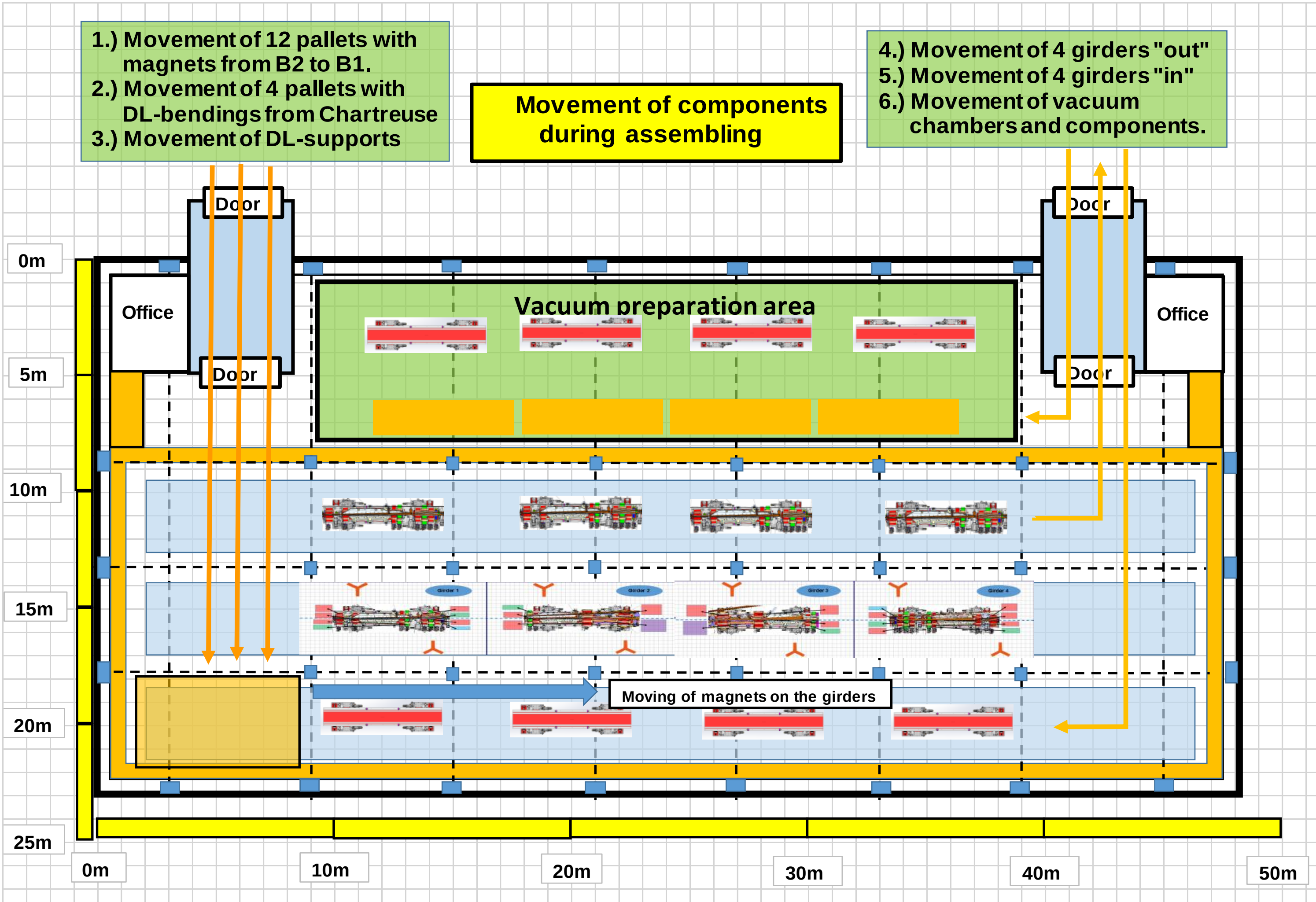
- Source shifts longitudinally by ~3m
- Source shifts horizontally by ~1-2cm



BUILDINGS FOR THE ASSEMBLY AND INSTALLATION PHASE

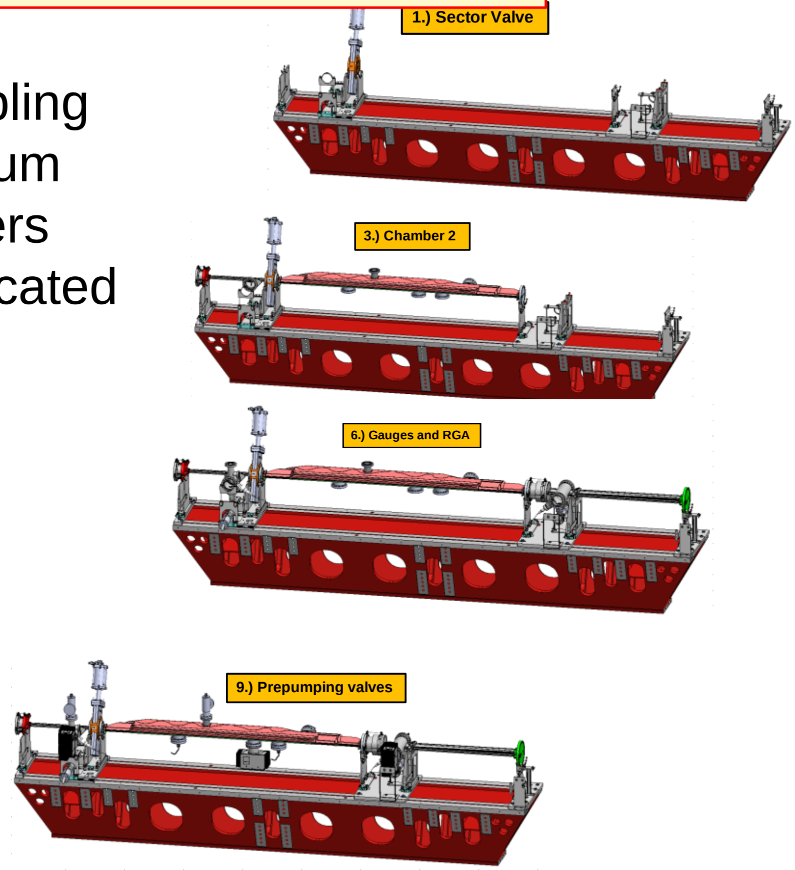


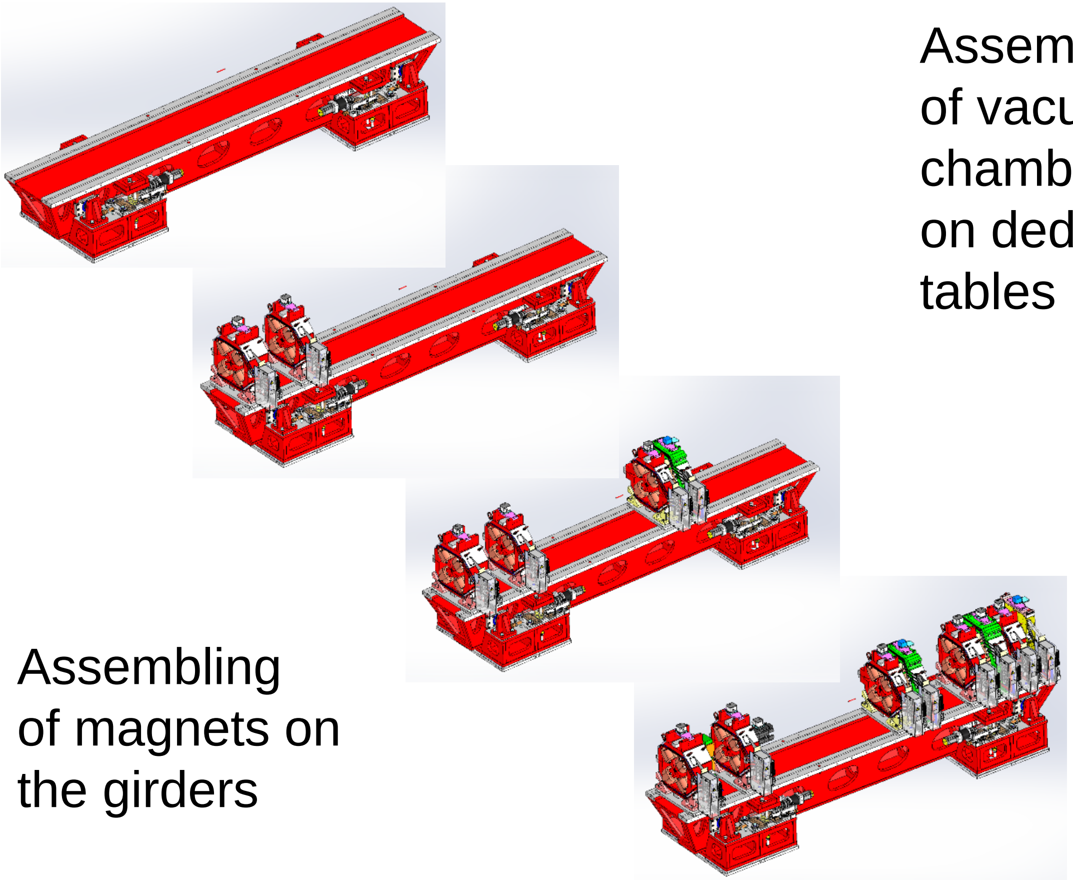
GIRDERS ASSEMBLY IN ESRF01



All the girders will be assembled in ESRF1 (Sep 2017 - Oct 2018) and stored mainly in the Chartreuse hall before the Long Shutdown

Assembling of vacuum chambers on dedicated tables



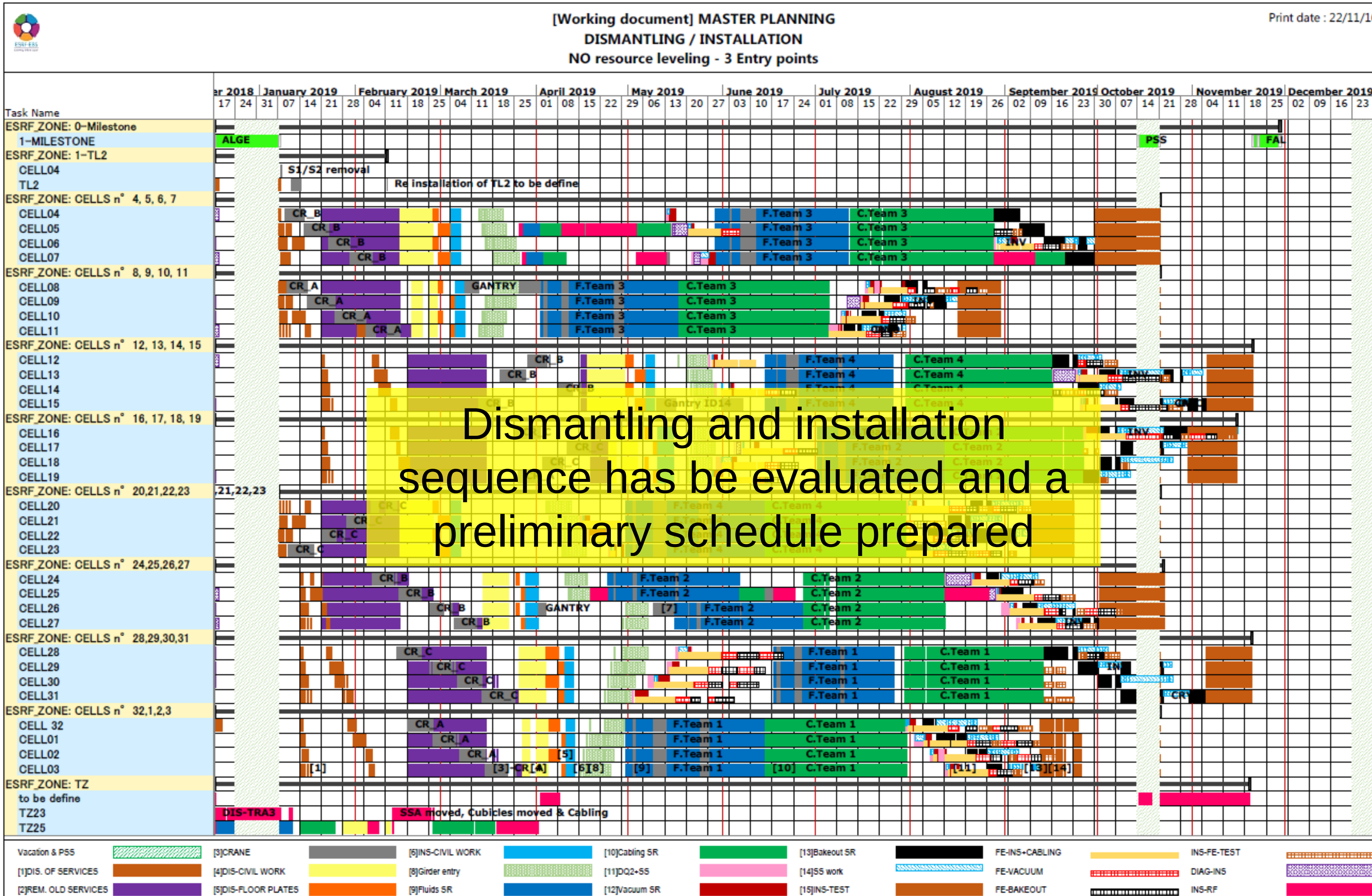


Assembling of magnets on the girders

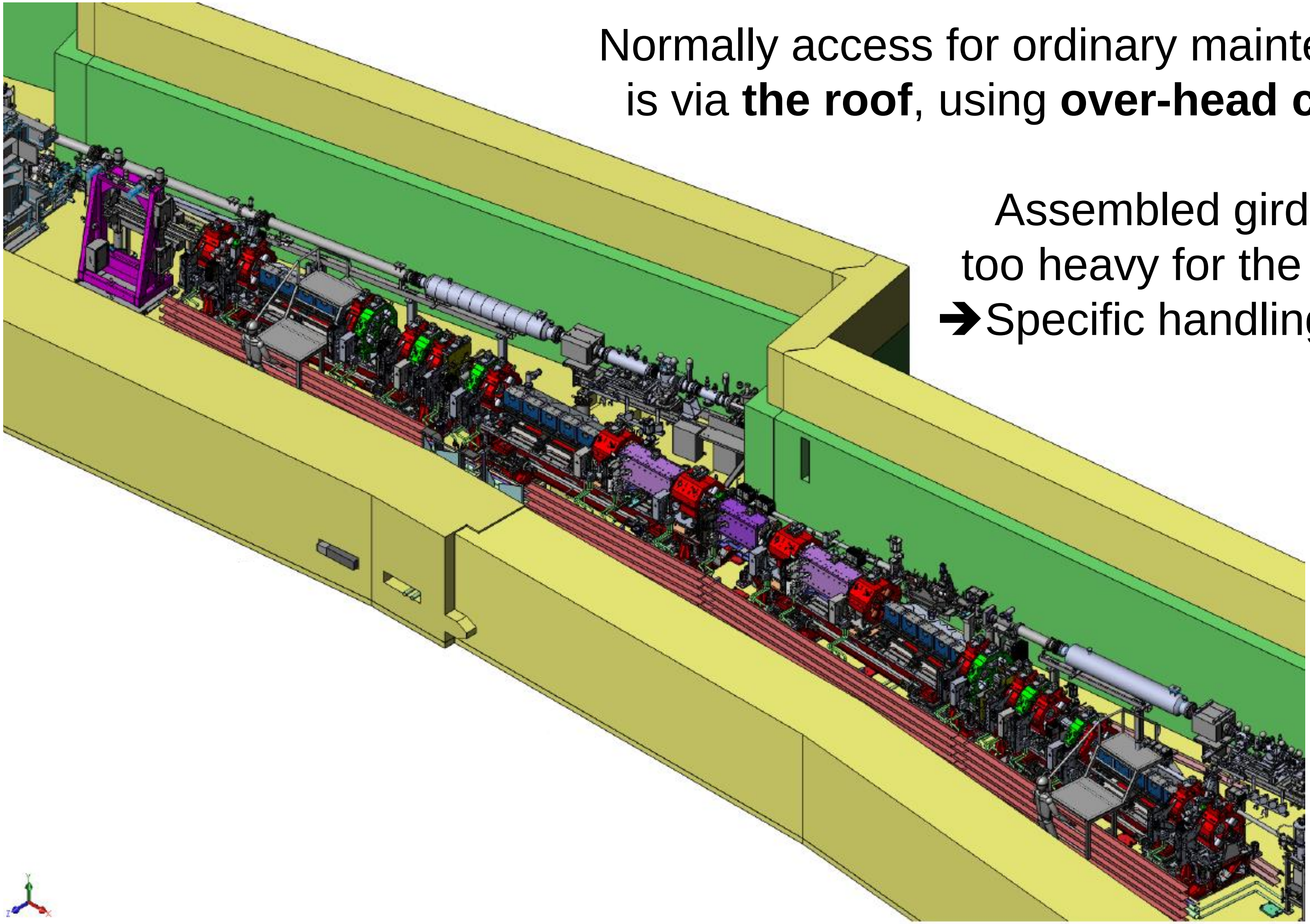
Then opening of magnets and add the whole vacuum section,… alignment,…..

- The tunnel must be cleaned up prior the installation of the new machine.
- Some work/upgrade will be anticipated prior the long shutdown
- The existing machine will be dismounted using the cranes
- Each component of the present storage ring must be fully dismounted, radiation measured, traced and stored following French safety regulation.
- Some civil work needed prior rolling the new girders.

DISMANTLING & INSTALLATION PLANNING



Dismantling and installation sequence has be evaluated and a preliminary schedule prepared



Normally access for ordinary maintenance is via **the roof**, using **over-head cranes,** but ….

Assembled girders are too heavy for the cranes

➔Specific handling tools.

PROGRESS OF EBS

EBS officially started on January 1st 2015

- **No impact on user operation**
- **Continuation of the development (injector, top-up, cryo undulators,…)**

Project execution progression:

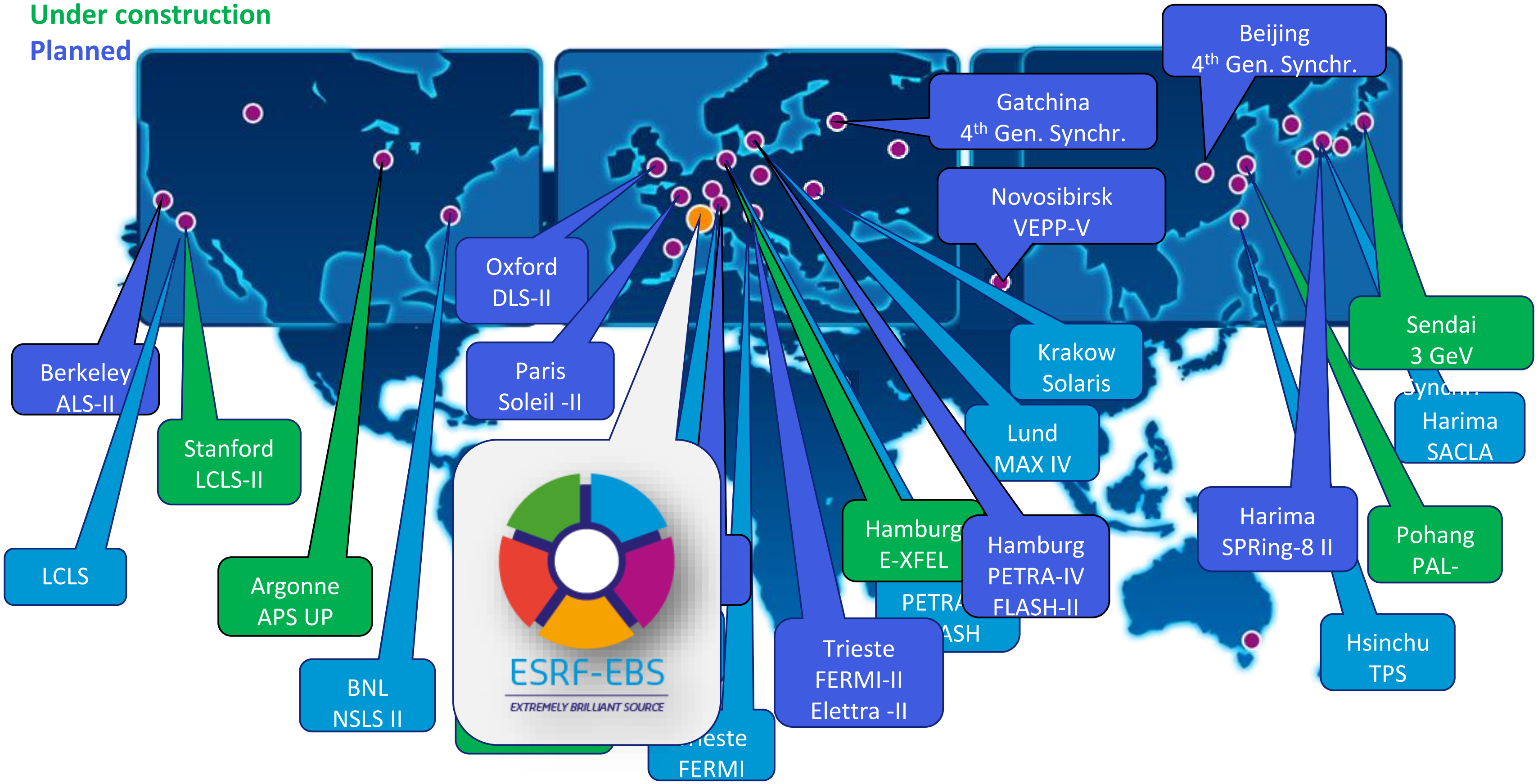
- **Engineering Design virtually completed**
- **Procurement in full swing**
- **Delivery of all pre-series components expected by end 2016/ start 2017**

  ➔ Schedule now heavily linked to external manufacturers!
- **Assembly to be started in less than 1 year (mock spring 2017)**
- **Dismantling/installation/commissioning in preparation**

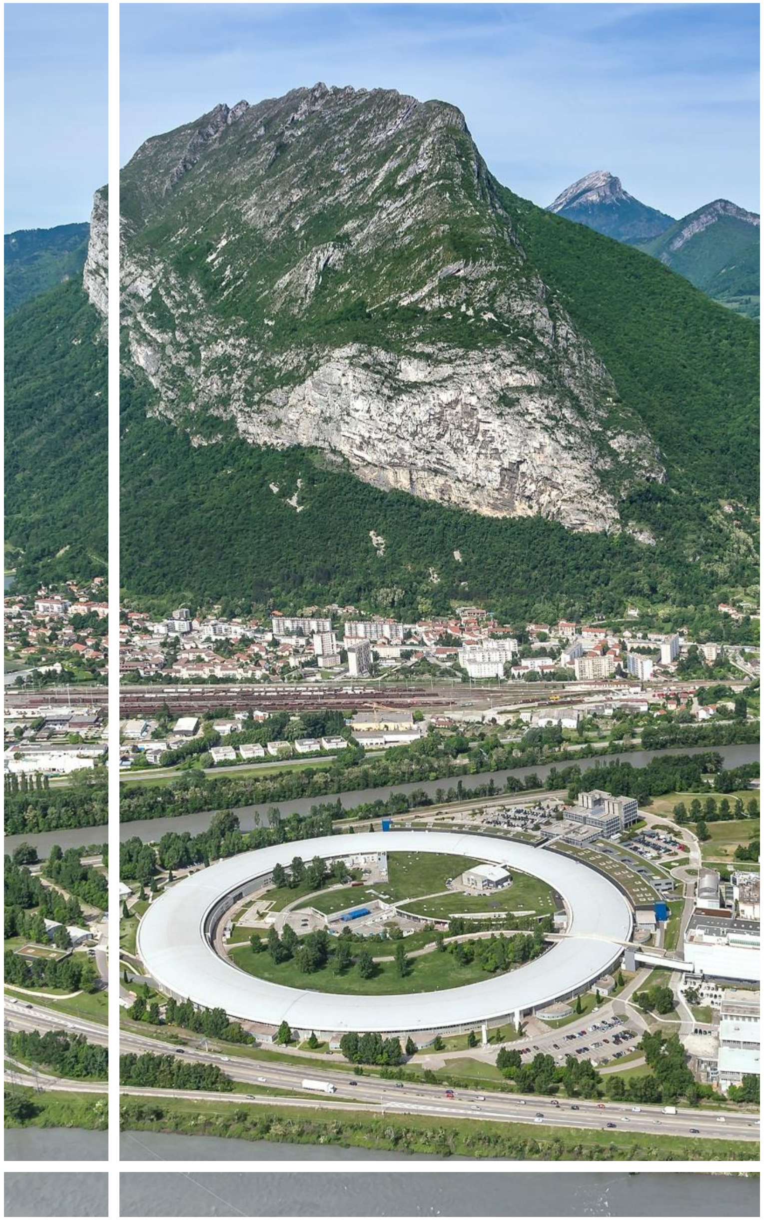
At this stage, no major show stopper identified.

Major new projects in X-ray science

Operational
Under construction
Planned



➔ A bright future for students!!!



ESRF
The European Synchrotron

Many thanks for your attention