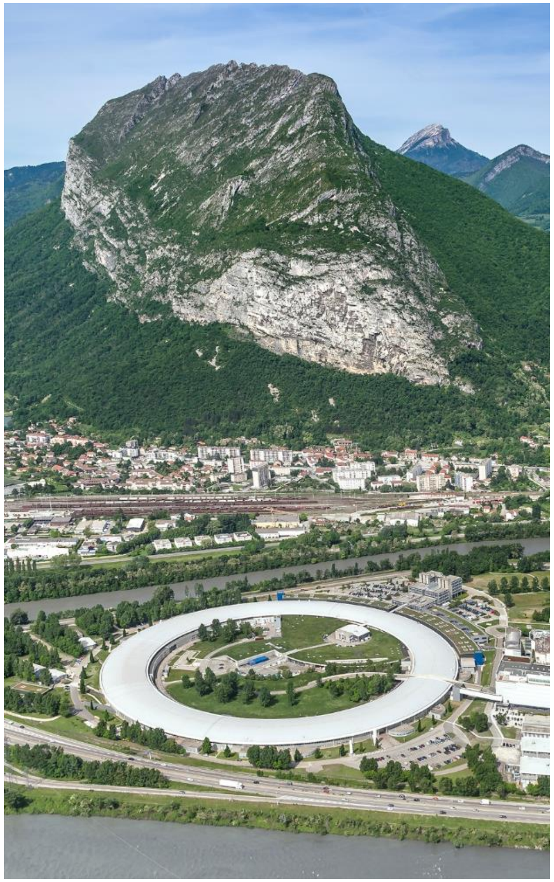
ESRF | The European Synchrotron



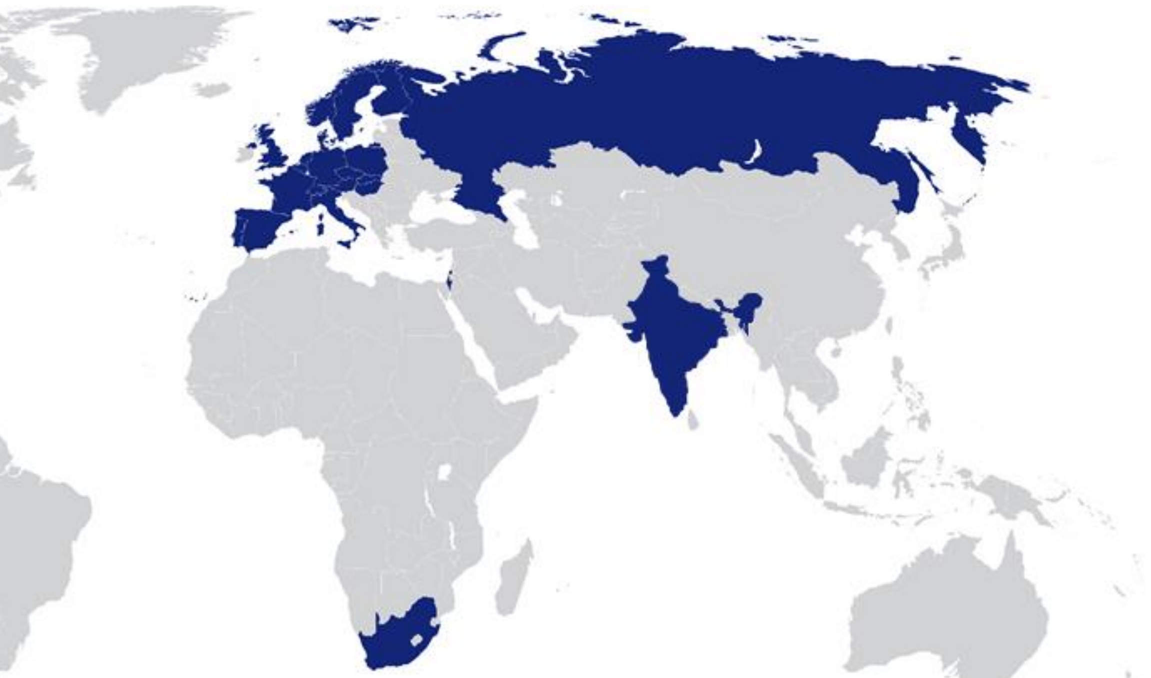
1) General presentation

2) The ESRF today

3) The ESRF Upgrade

Monday 15 January 2018
JUAS 2018 Revol Jean-Luc

A MODEL OF INTERNATIONAL COOPERATION: 22 PARTNER NATIONS

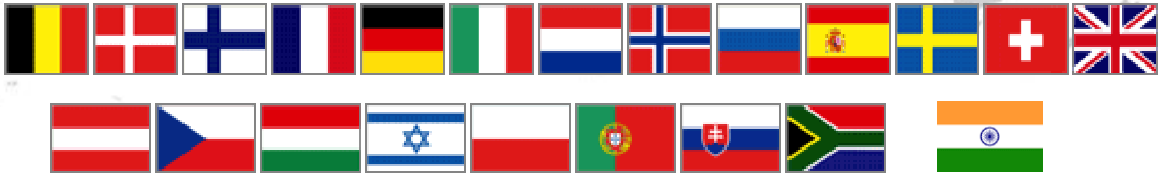


13 Member states:

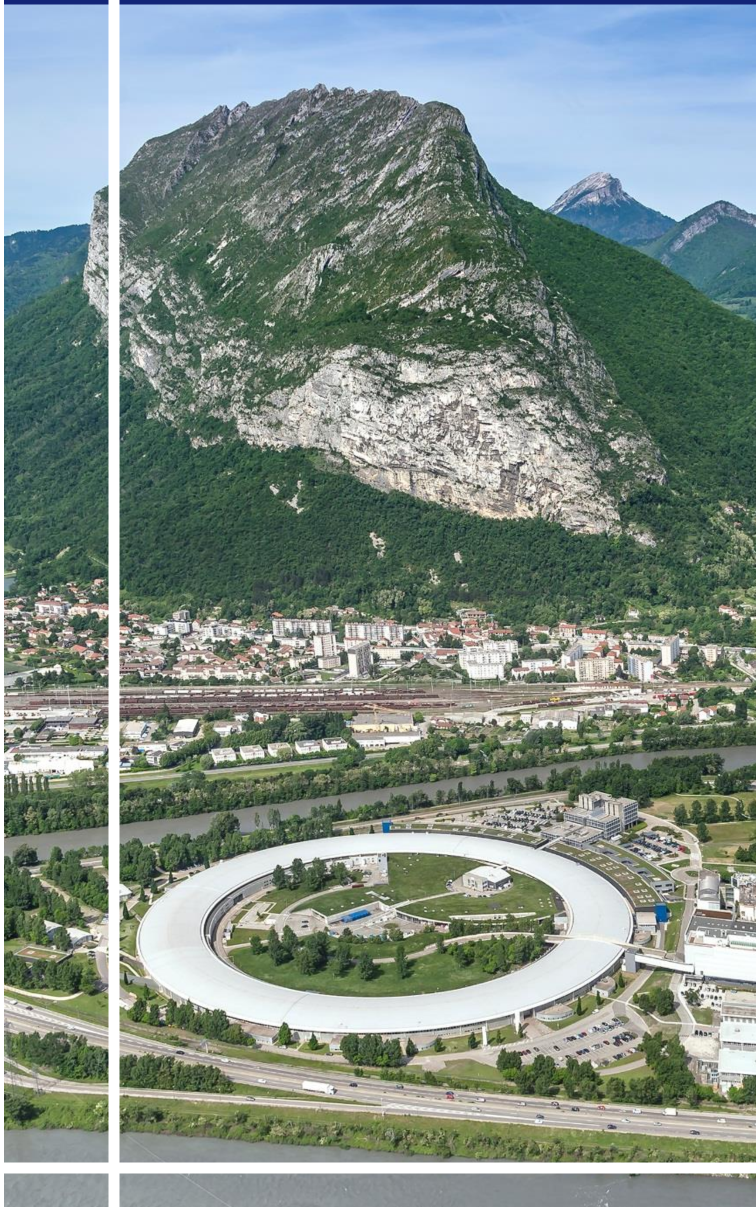
France	27.5 %
Germany	24 %
Italy	13.2 %
United Kingdom	10.5 %
Russia	6 %
Benesync (Belgium, The Netherlands)	5.8 %
Nordsync (Denmark, Finland, Norway, Sweden)	5 %
Spain	4 %
Switzerland	4 %

9 Associate countries:

Israel	1.5 %
Austria	1.3 %
Centralsync (Czech Republic, Hungary, Slovakia)	1.05 %
Poland	1 %
Portugal	1 %
India	0.66 %
South Africa	0.3 %

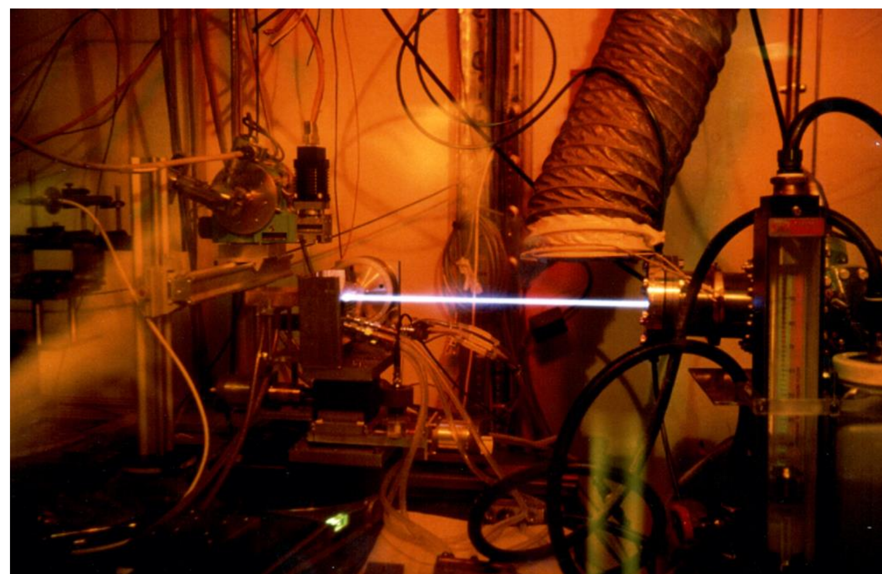


22 partner nations
Annual budget: **100 million euros**
Staff: **630 people, 40 different nationalities**
Legal status: **Private civil company subject to French law**



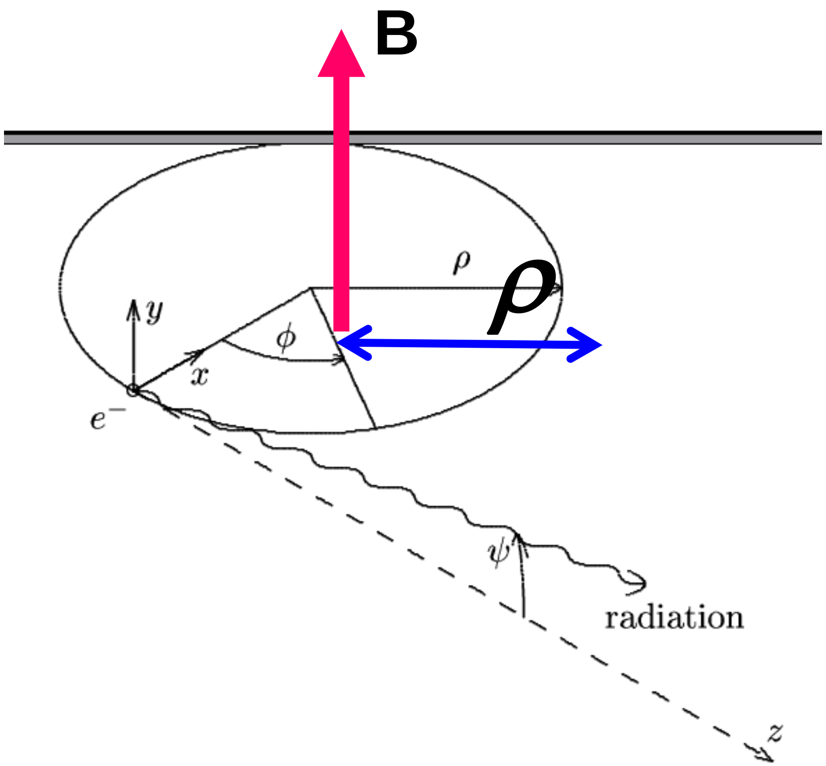
ESRF
The European Synchrotron

The ESRF today



PRINCIPLE

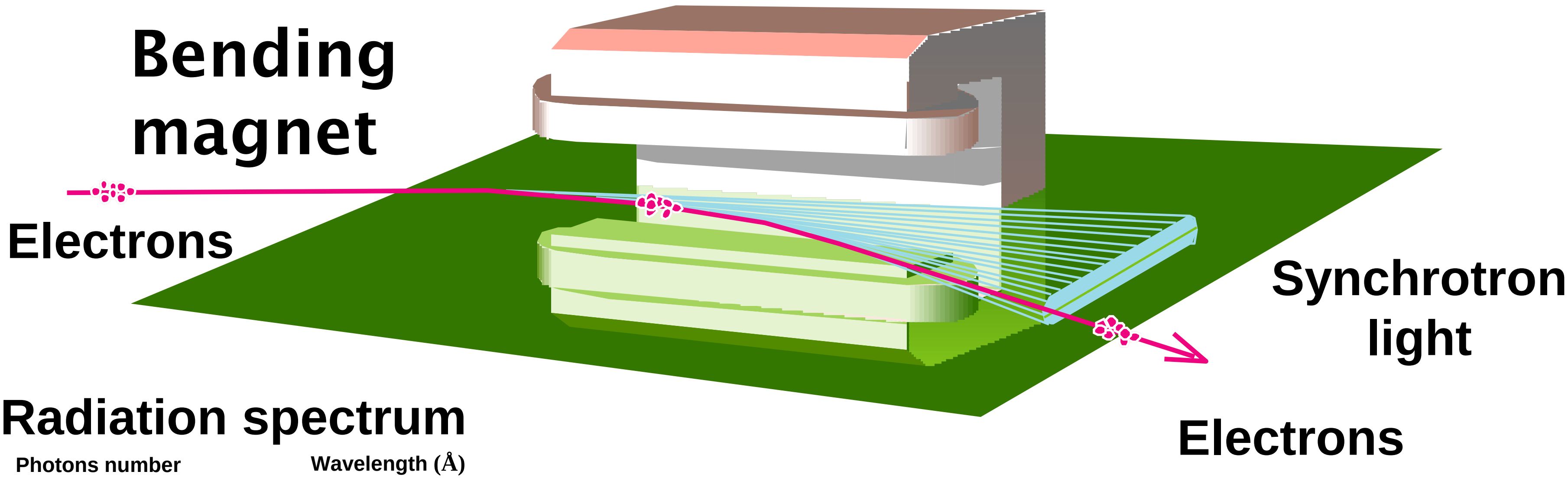
- When a charged particle is deviated in a magnetic field, it loose energy by emitting electromagnetic radiation (photons),call synchrotron radiation, tangent to the trajectory.



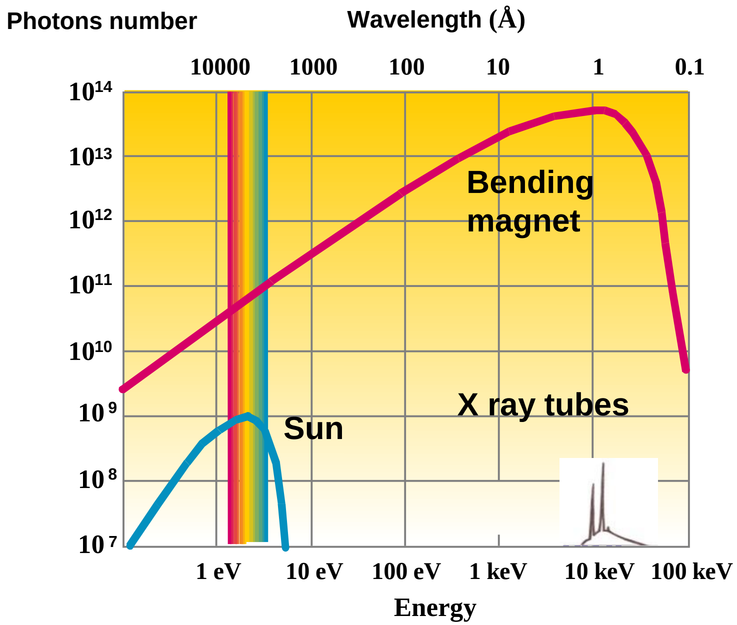
$$P \propto \left(\frac{E}{mc^2}\right)^4 \frac{I}{\rho}$$

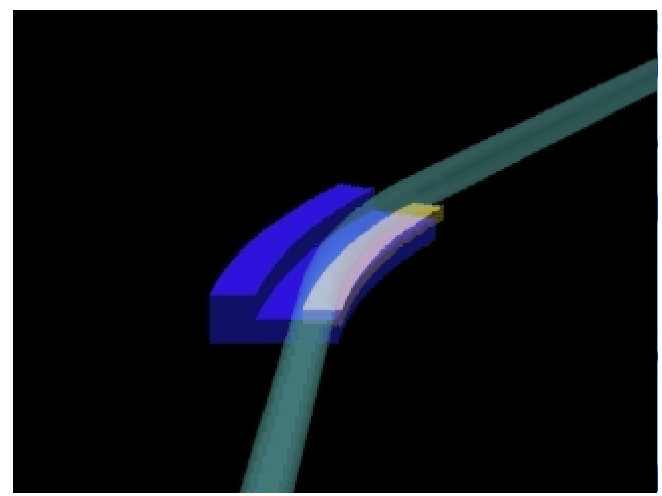
Large difference between electrons and protons !

Scale with the square of the energy!



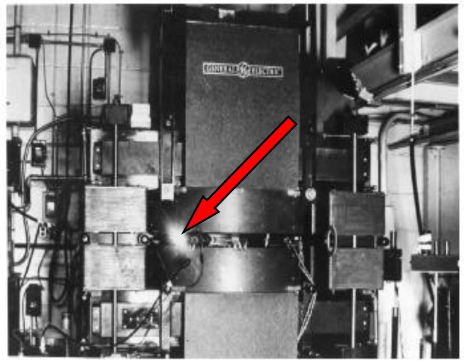
Radiation spectrum



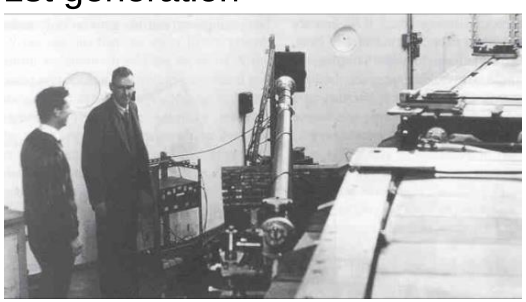


FROM PARASITIC USE TO DEDICATED USER FACILITY

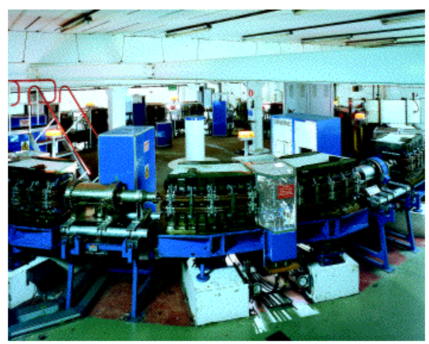
1947: First observation of synchrotron radiation



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

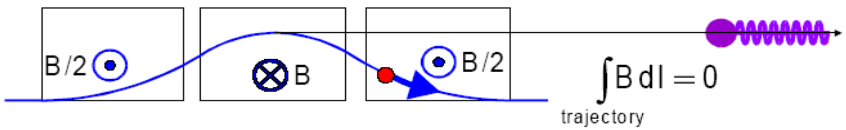


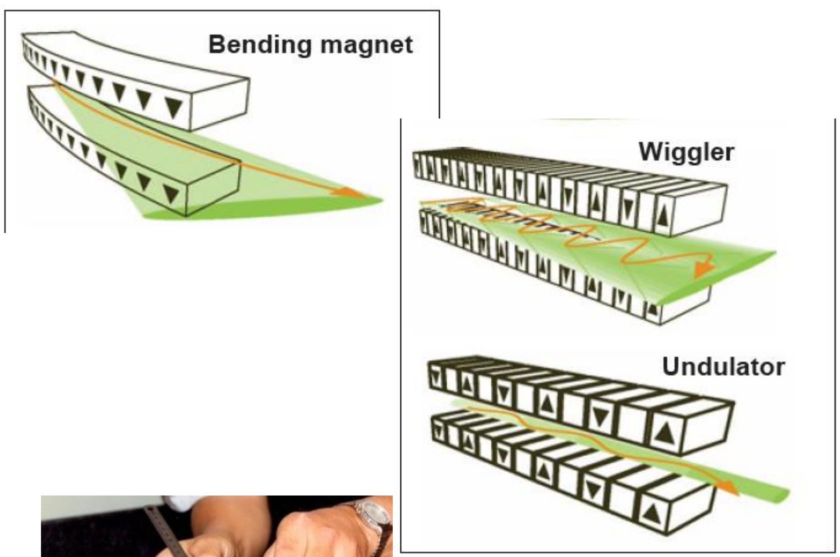
1981: SRS (UK) 1st dedicated X ray light source
2nd generation

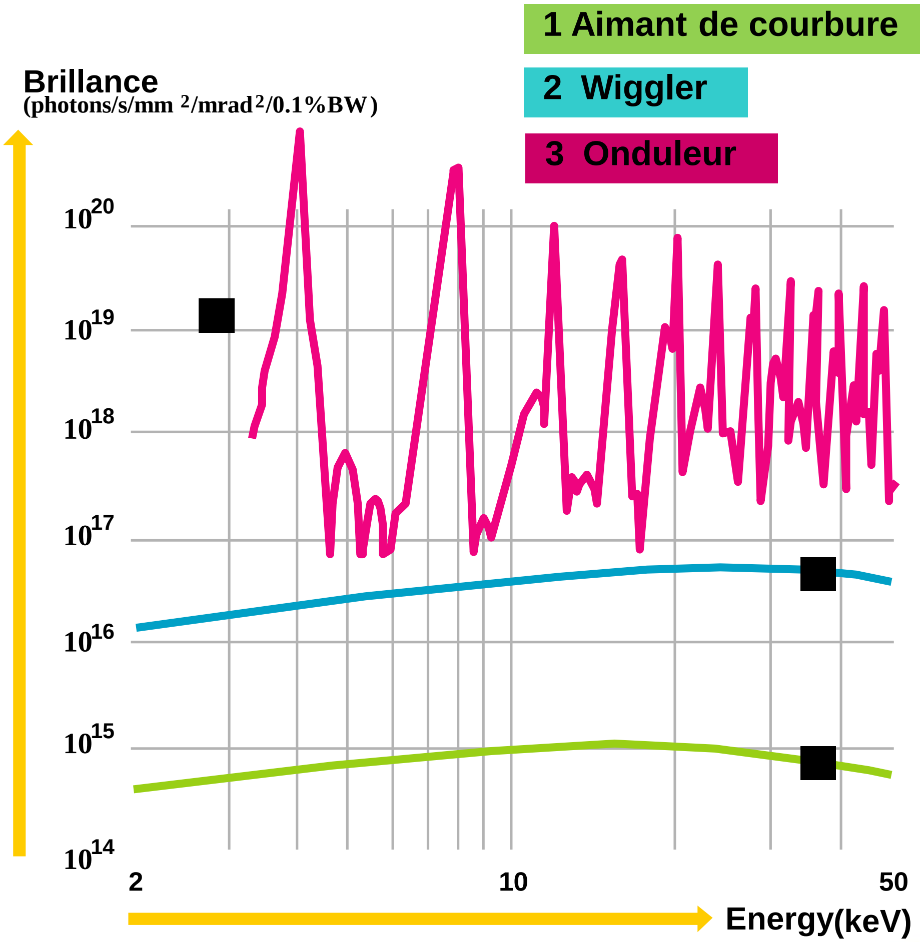


1994: Inauguration of the l'ESRF, The first X ray light source of the 3rd generation

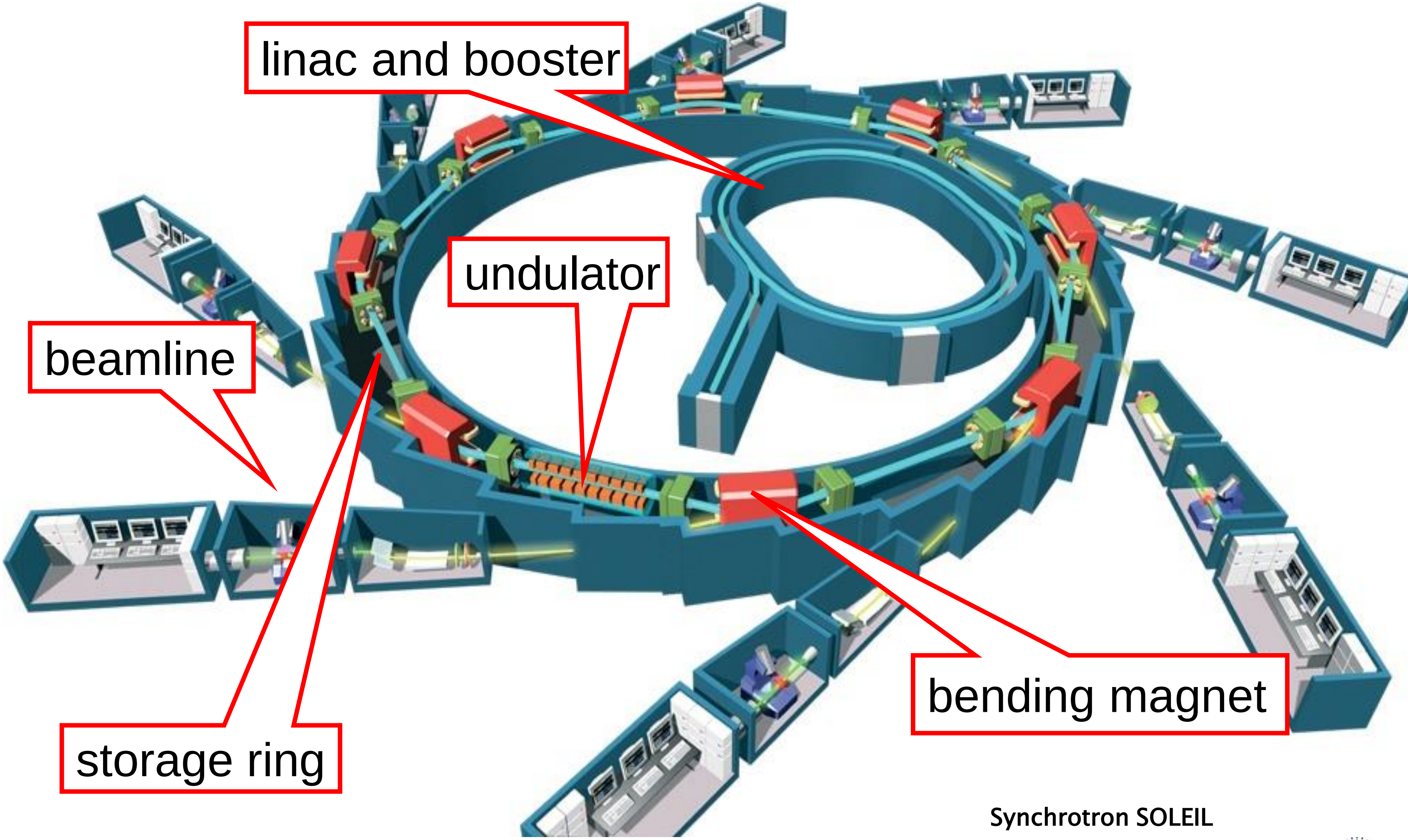
Insert permanent magnets to provide an alternative magnetic field to bend the trajectory.







A TYPICAL USER FACILITY



Synchrotron SOLEIL

BRILLIANCE OF LIGHT SOURCES

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

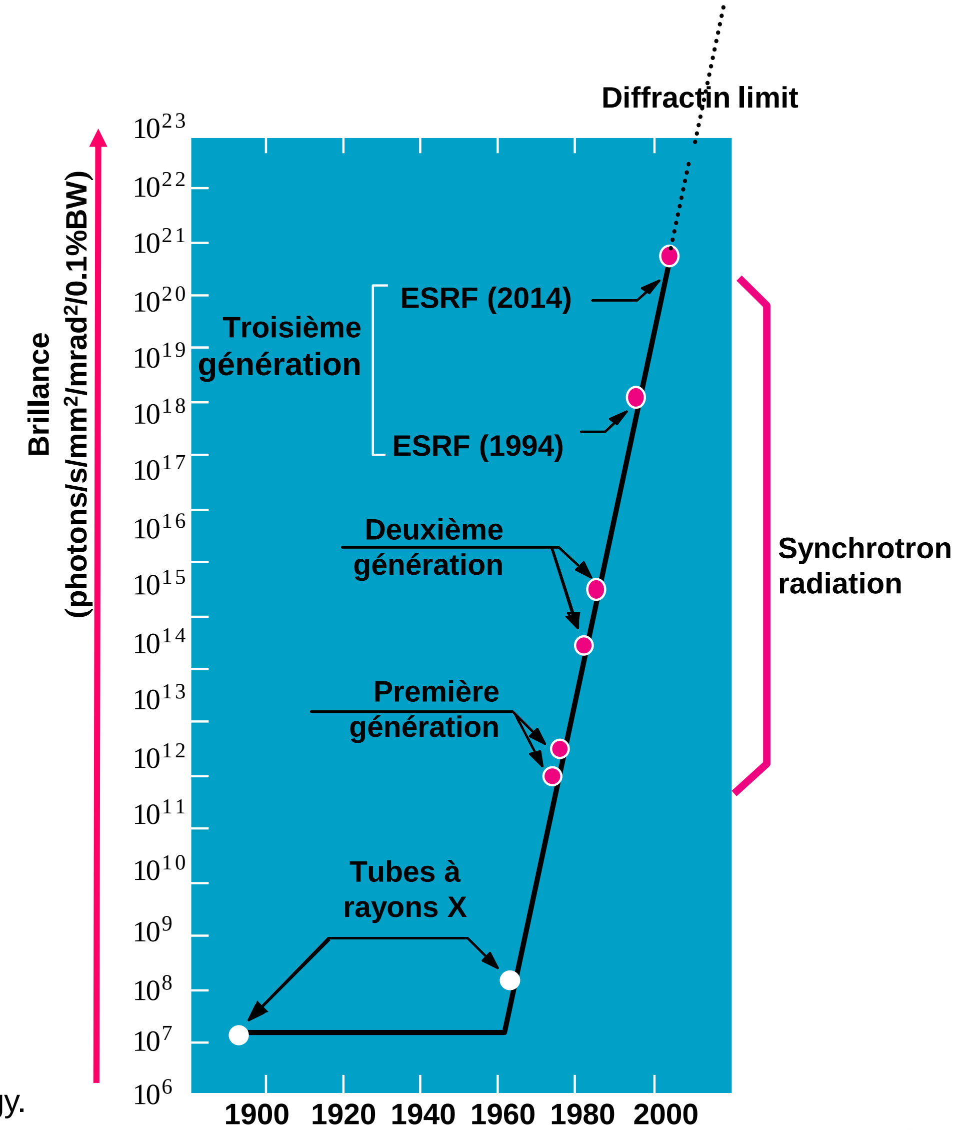
Brilliance =
photons /s / mm² /mrad² /0.1% bandepassante

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 …





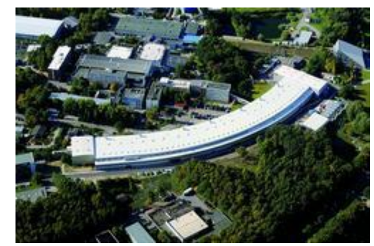

High energy rings (≥ 6.GeV)

SPRING 8

ESRF Upgrade

APS Upgrade

Petra III



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

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

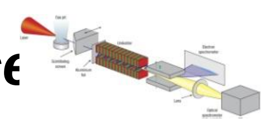
LCLS

SACLA

European XFEL

Fermi

Laser plasma acceleration: 5th generation light source



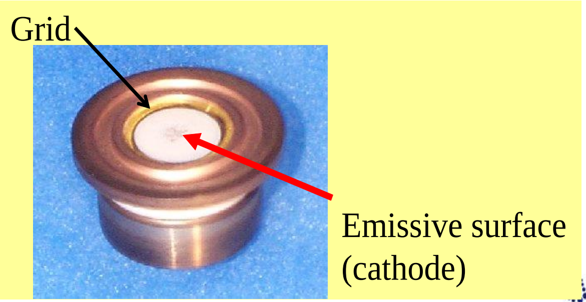
THE ACCELERATOR COMPLEX

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

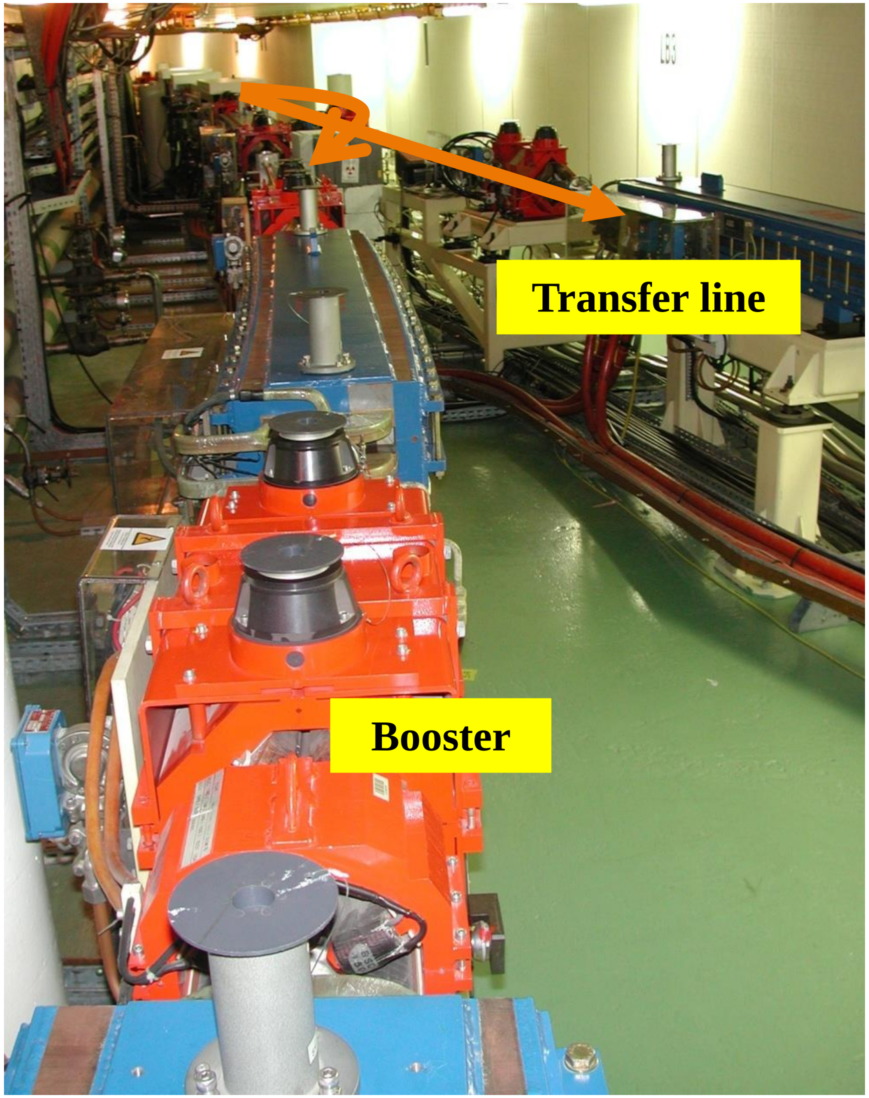
THE SYNCHROTRON (OR BOOSTER)

Goal: Accelerate the electrons from 200 MeV to 6 GeV

Cycle: period of 250 msec

Length: 300 metres

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

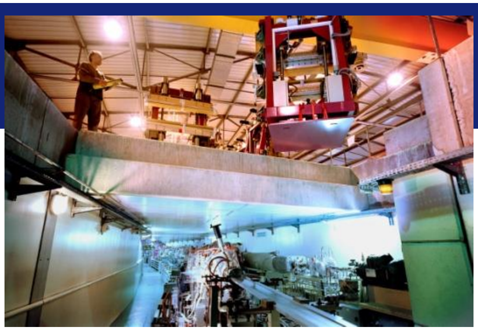


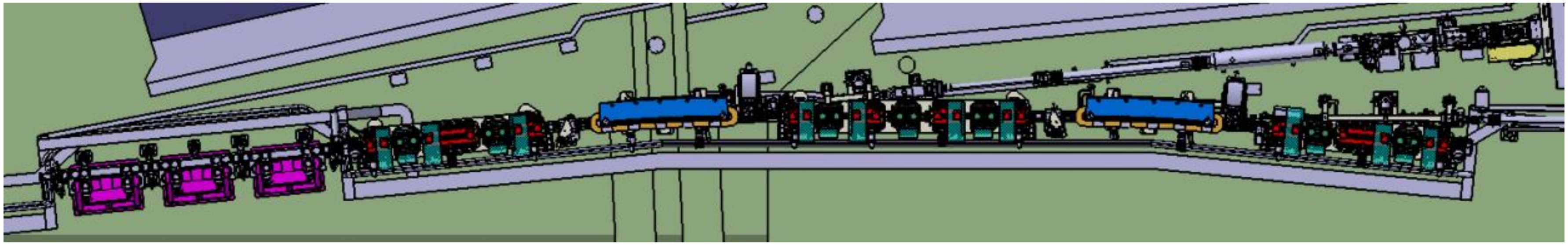
Goal:

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

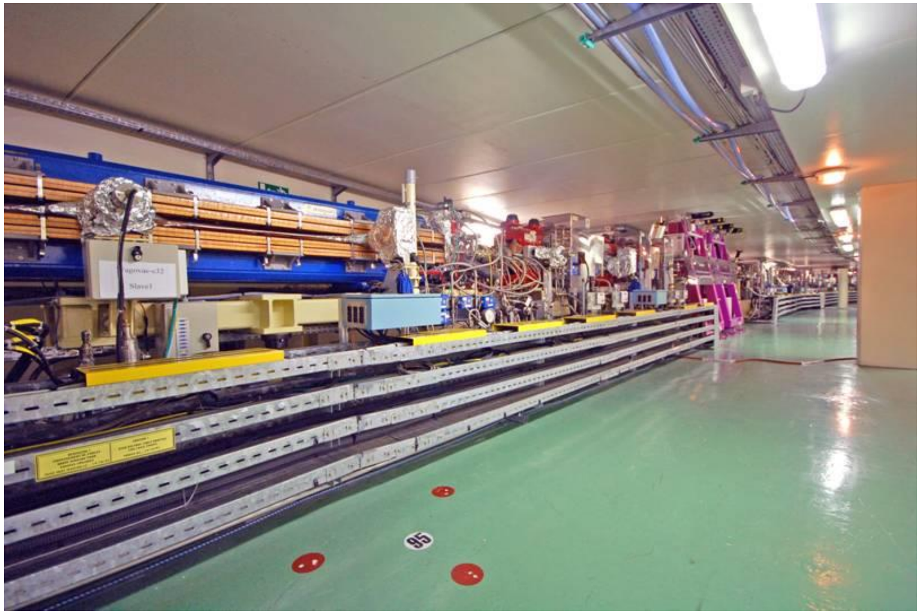
- 5 bending magnets (powered in serie with Booster dipoles)
- 14 quadrupoles
- 9 insertable screens
- Beam Position Monitors
- Synchrotron radiation screens (1 screen / dipole)
- Length: 65 metres

THE STORAGE RING



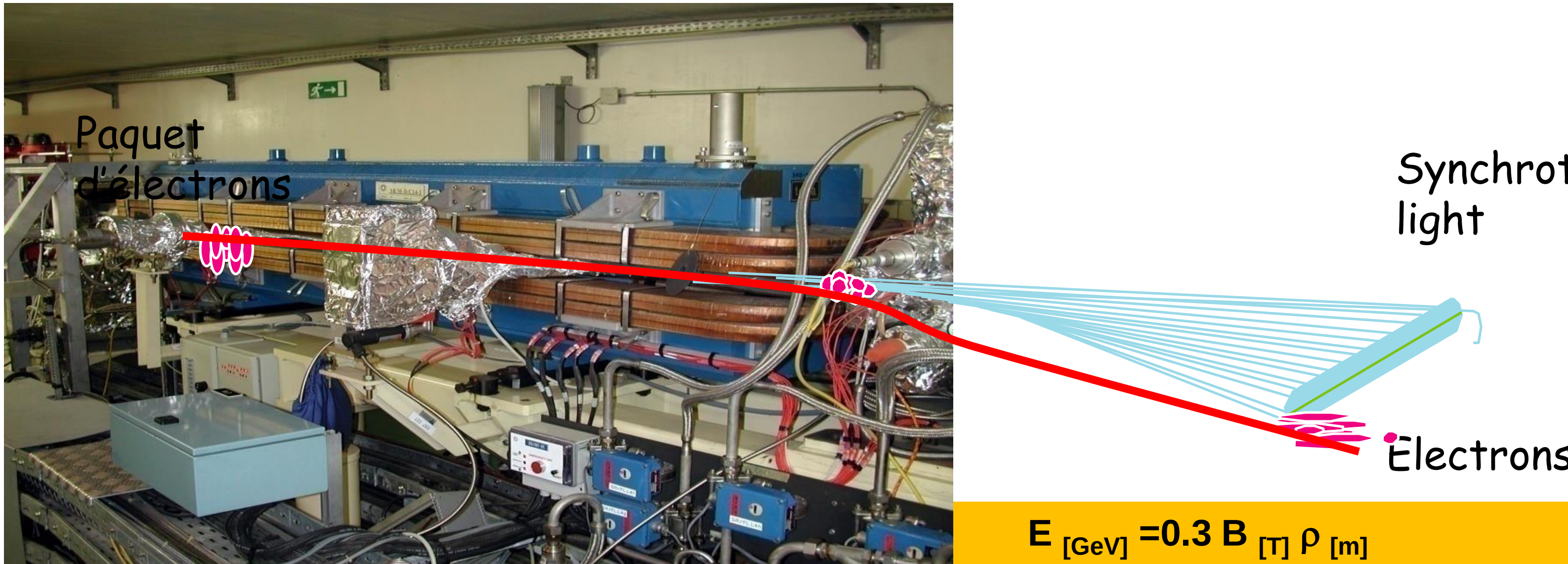


- Circumference: 844 metres
- 16 super-periods of 2 mirror cells➔ 32 cells
- Energy: 6 GeV
- Nominal intensity: 200 mA
- Emittance: 4nm rad
- Usual coupling : 0.1 %



THE STORAGE RING BENDING MAGNETS

64 bending magnets (dipoles)



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

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

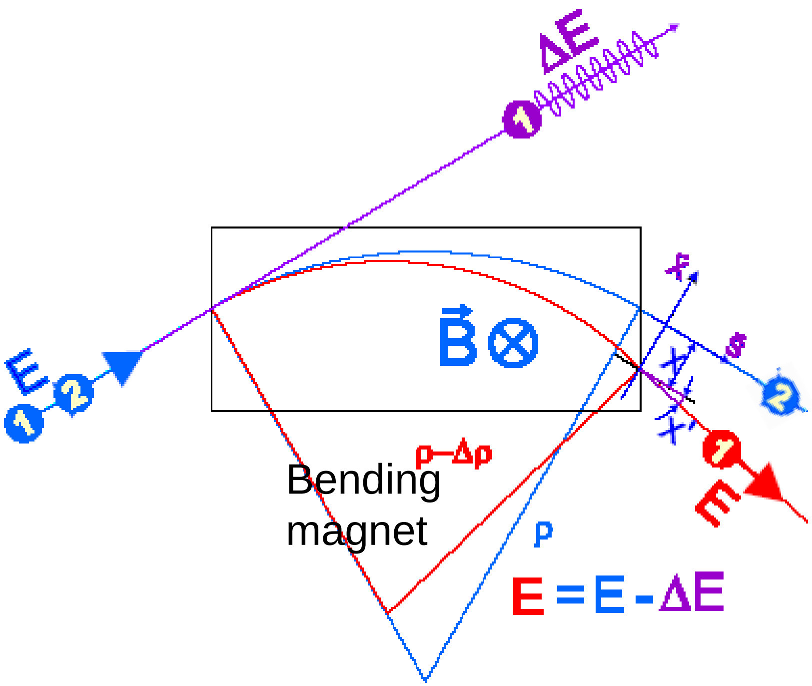
Energy lost per turn of ring by one electron

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

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



<u>Electron 2</u> emits Δe at the exit of the bending magnet.

➔ *same energy when crossing the magnet*

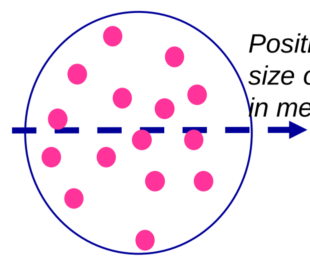
➔ *stay on the reference trajectory*

<u>Electron 1</u> emits ΔE at the entrance of the bending magnet.

➔ *lower energy when crossing the magnet*

➔ *larger curvature*

<u>**A horizontal beam size and divergence (or emittance)**</u>
<u>**and an energy spread is created**</u>.



The beam emittance is the <u>**surface**</u> occupied by the beam in size and divergence.

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

THE STORAGE RING QUADRUPOLE MAGNETS

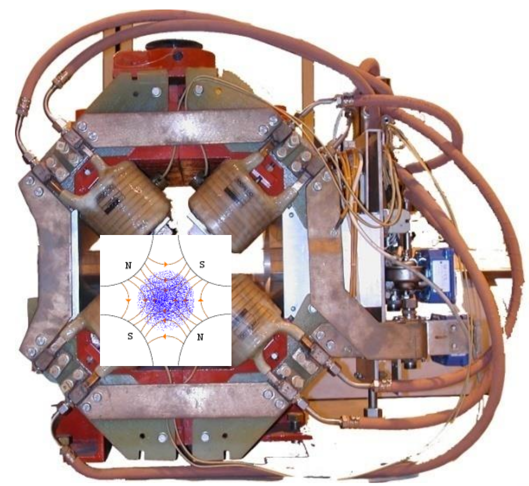
256 quadrupoles shared in 6 families

Name	Number
QF2	32
QD3	32
QD4	64
QF5	64
QD6	32
QF7	32

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

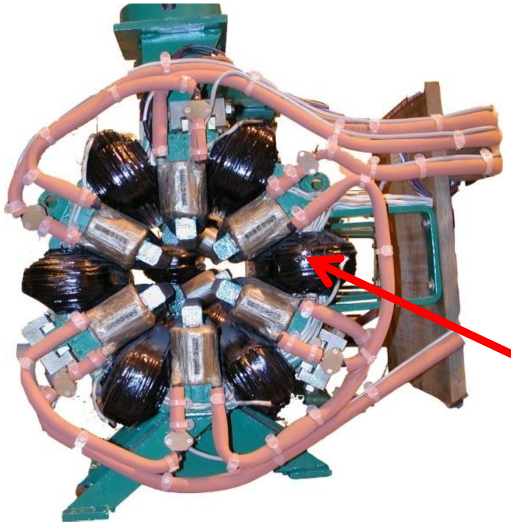
The quadrupole settings are also important for:

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



THE STORAGE RING SEXTUPOLE MAGNETS

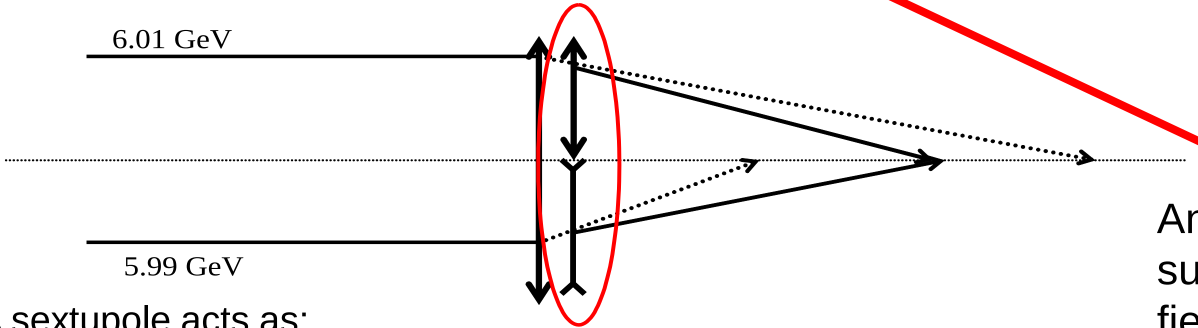
224 sextupoles shared in 7 families



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

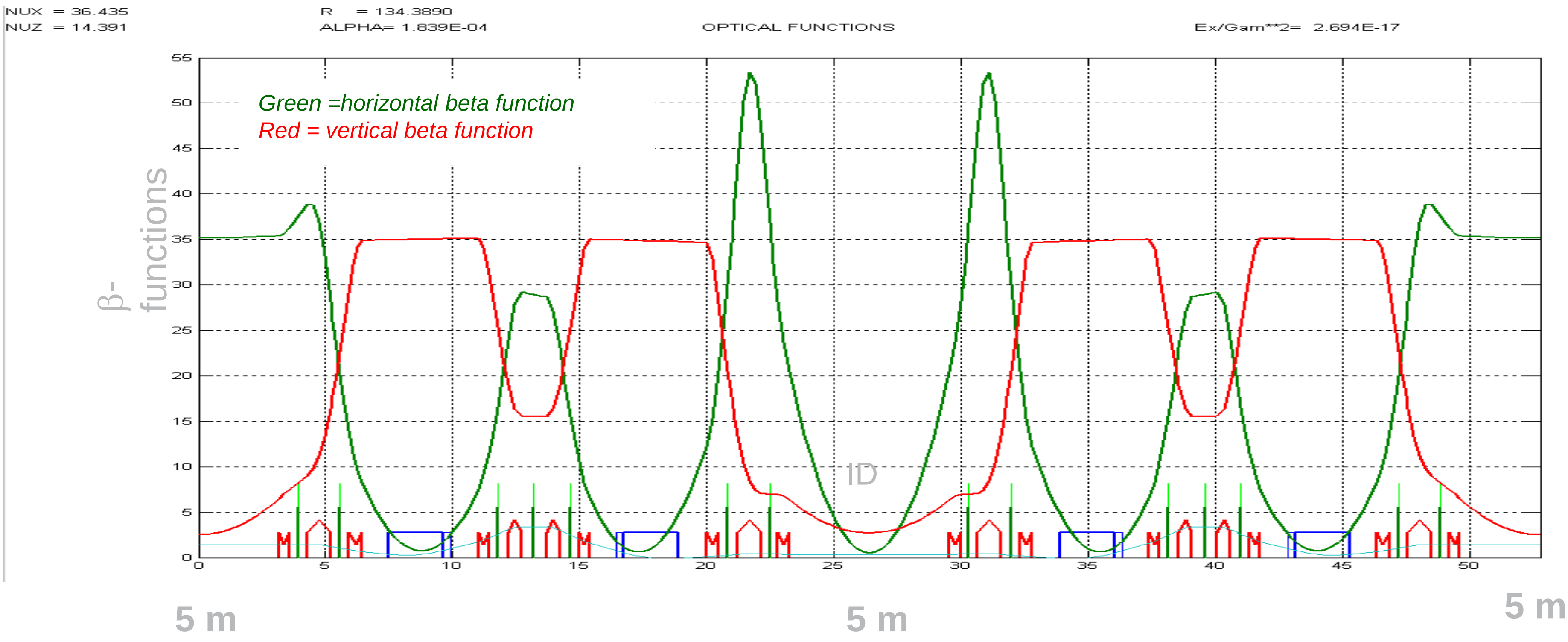


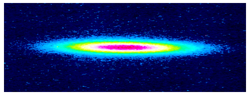
And steerers (3 power supplies to get a H or V field)

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





ESRF Horizontal emittance = 4 nm.rad

ESRF vertical emittance = 5pm

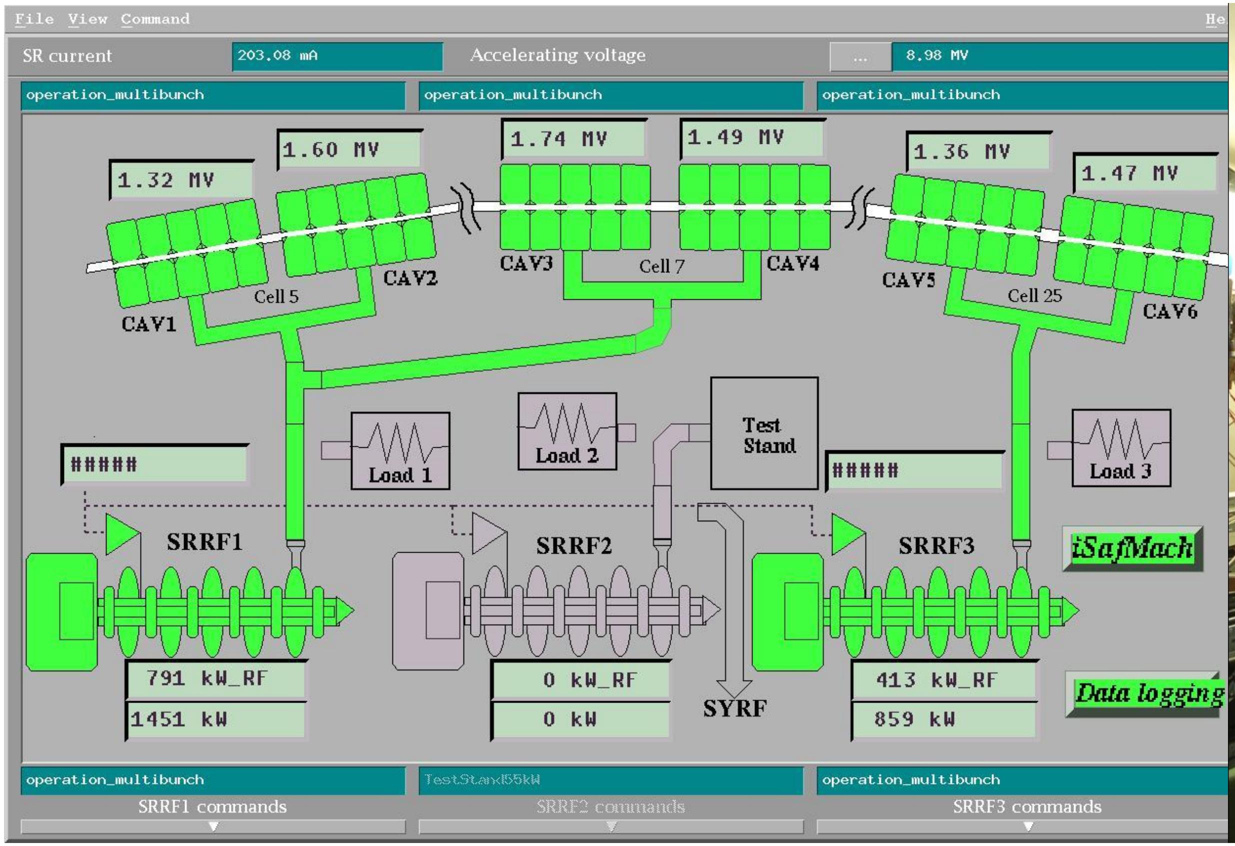
Vertical emittance is determined by the coupling to the horizontal motion due to magnet or alignment imperfections.

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

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

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)

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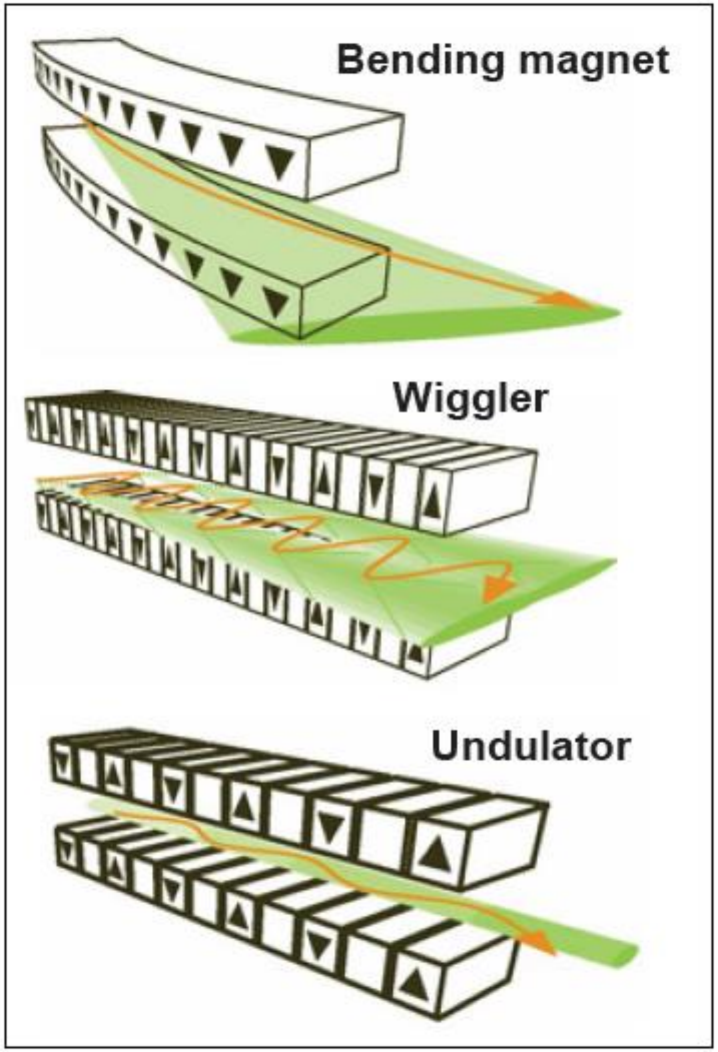
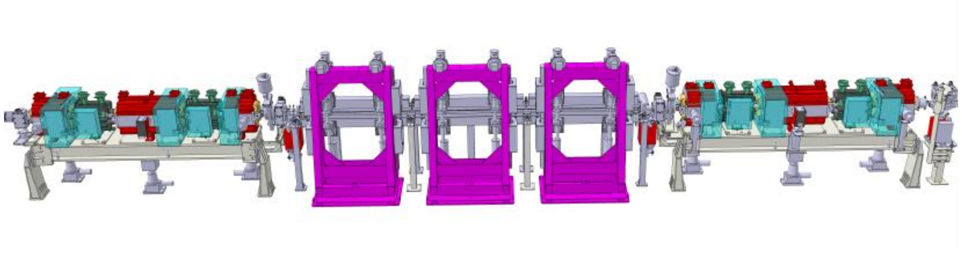
INSERTION DEVICES

INSERTION DEVICES

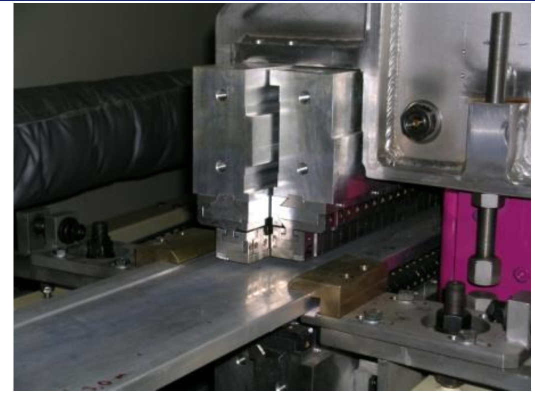


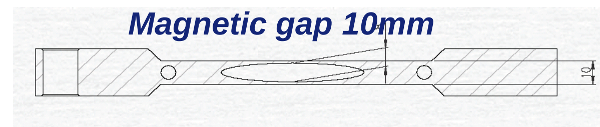
Goal: produce X-rays with specific properties which are different from those emitted by the dipoles, for example, tuneable energy spectrum, polarisation, higher brilliance...



INSERTION DEVICES

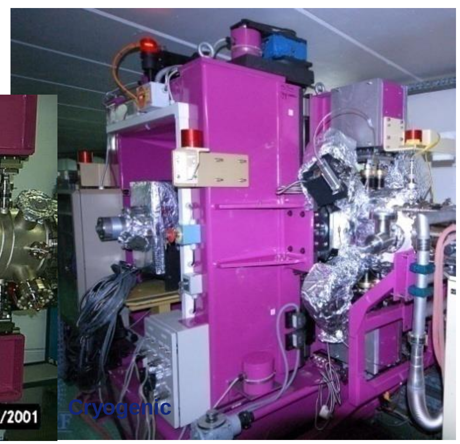
In-air *length =1.64 m*





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

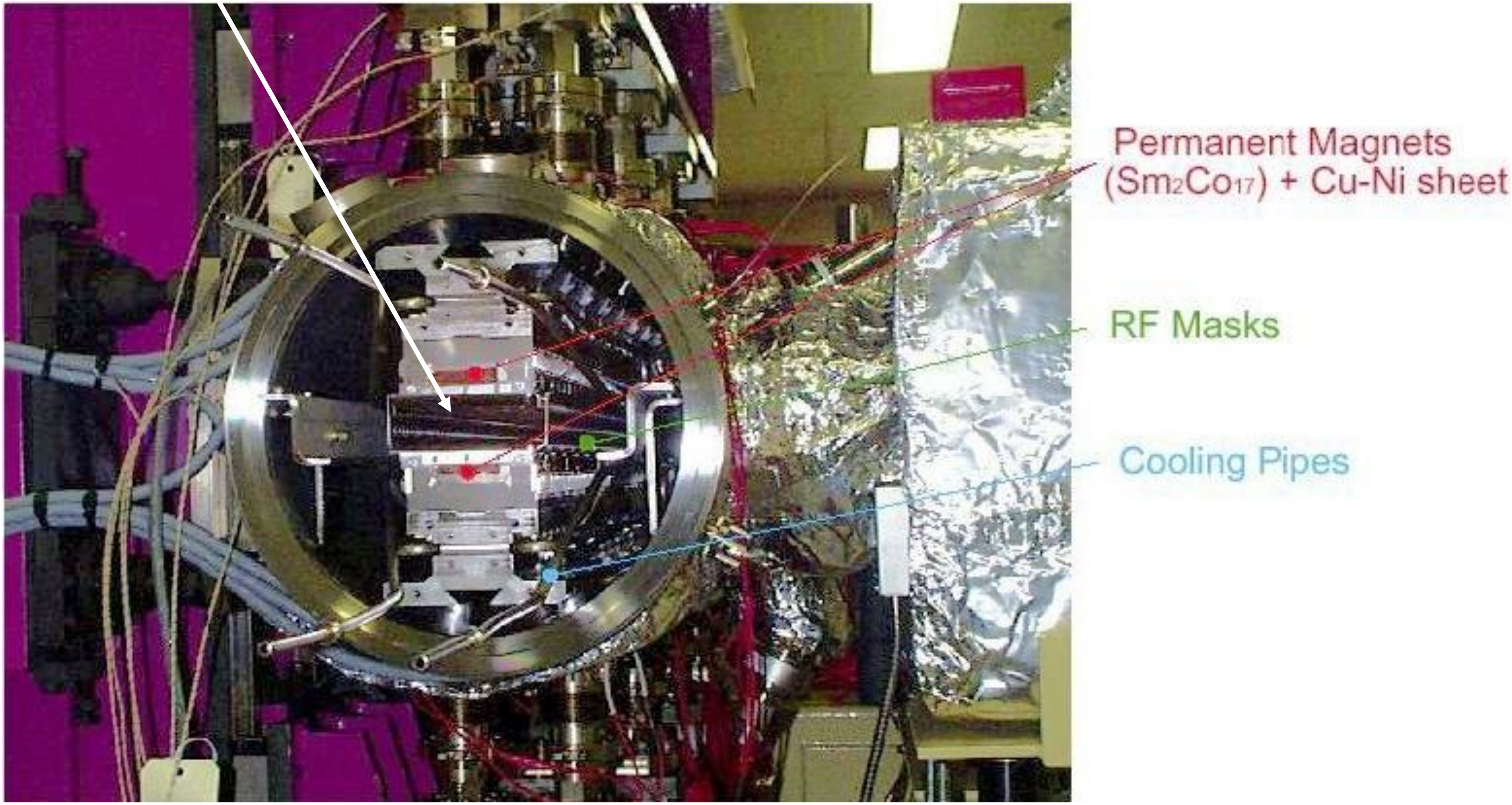
But less than 100 kW is used!!

$2 kW/mm^2$ at 200 mA

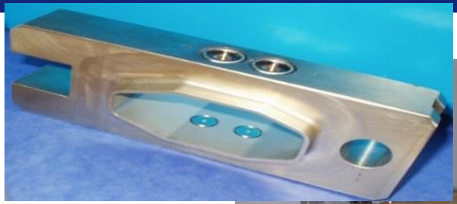
8000 kW of Electrical power is needed to produce it!!
Efficiency: 2% !

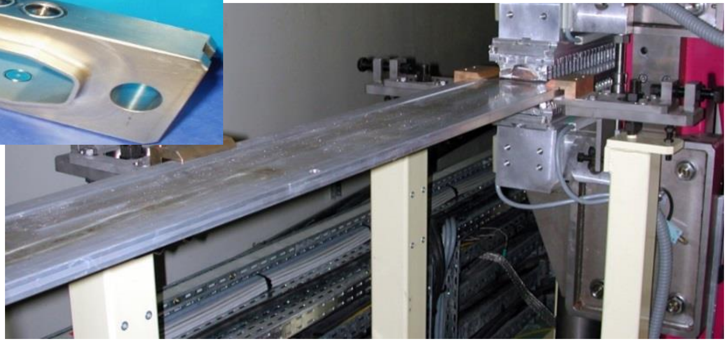
IN-VACUUM UNDULATORS

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



THE VACUUM SYSTEM





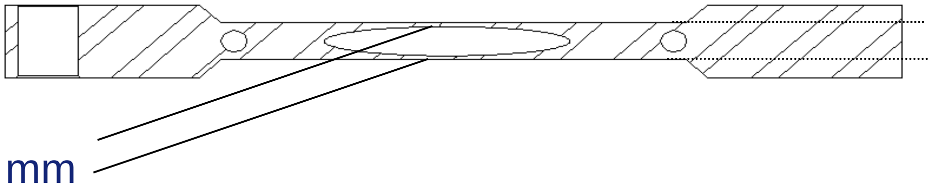
Goal: control and maintain an excellent vacuum level in the storage ring:

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.

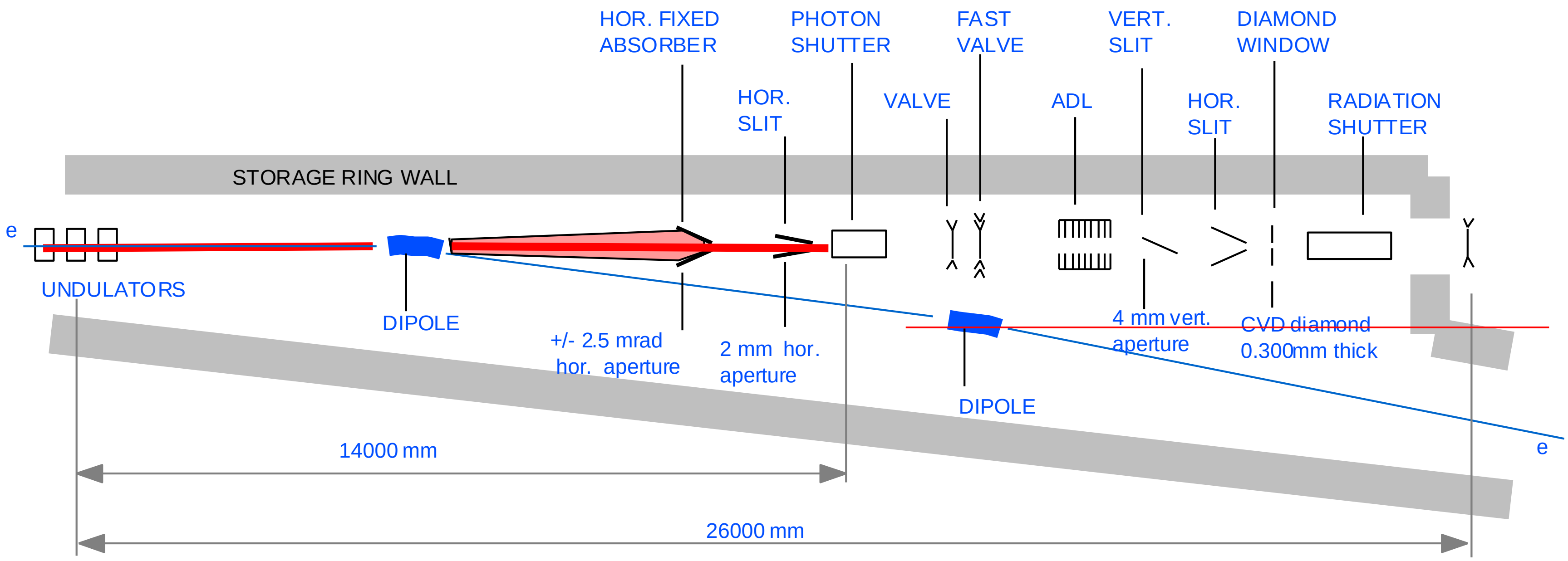
ID chambers

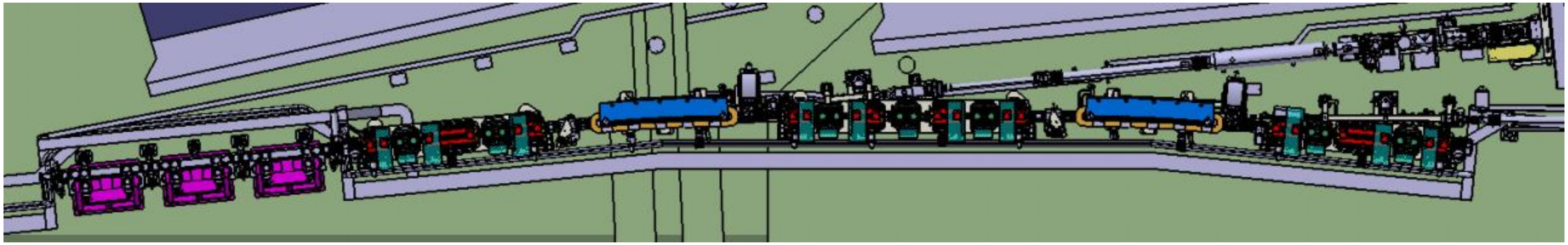
Length = 5 metres et 6 metres



- 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.

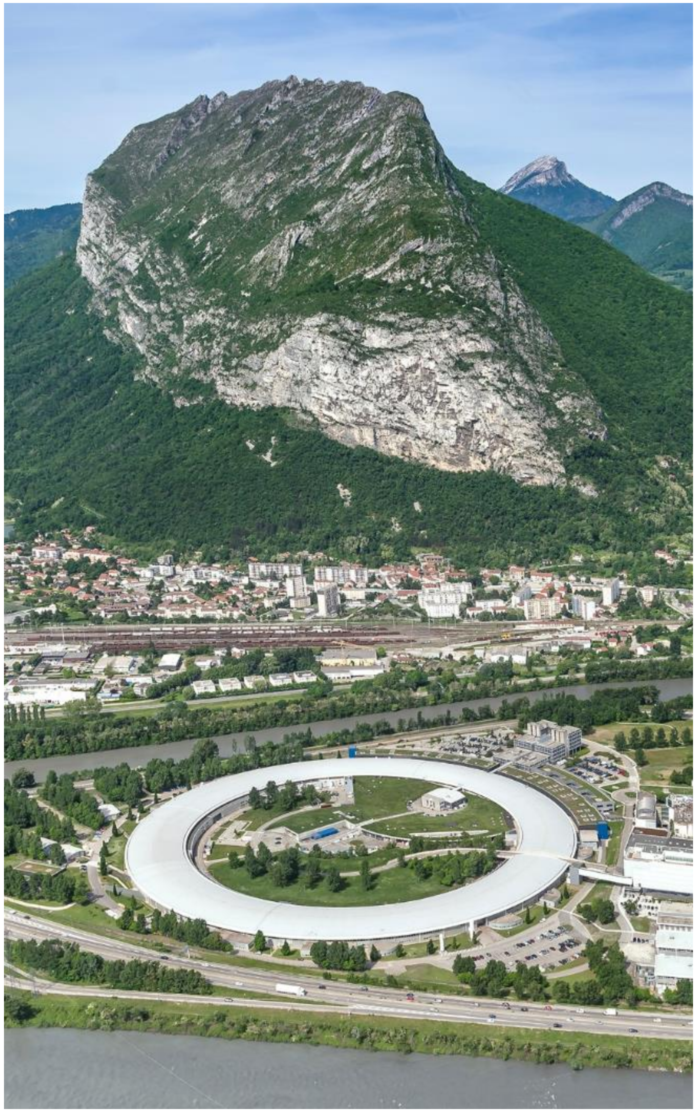
THE STORAGE RING FRONT ENDS





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

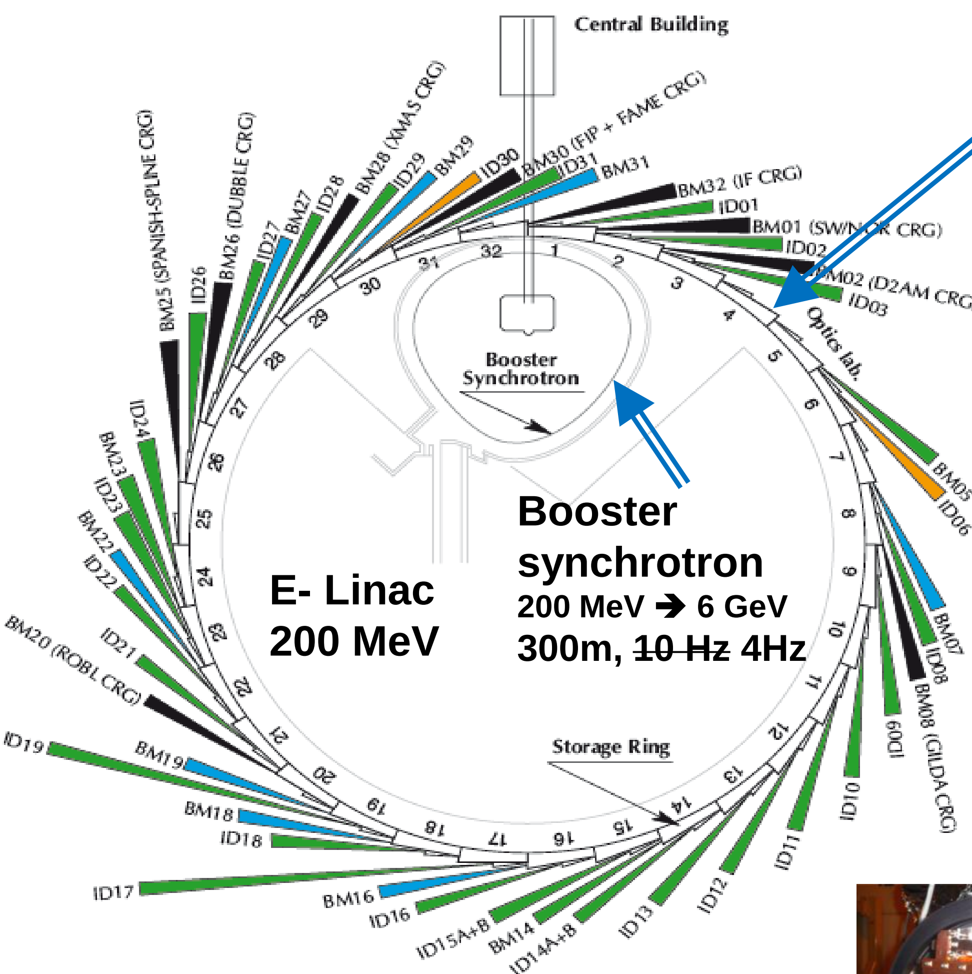
THE ESRF TODAY



ESRF

Operation

ESRF TODAY



Storage ring
6GeV, 844 m

E- Linac
200 MeV

Booster synchrotron
200 MeV ➔ 6 GeV
300m, ~~10 Hz~~ 4Hz

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

32 straight sections

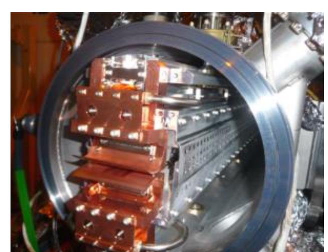
DBA lattice

42 Beamlines

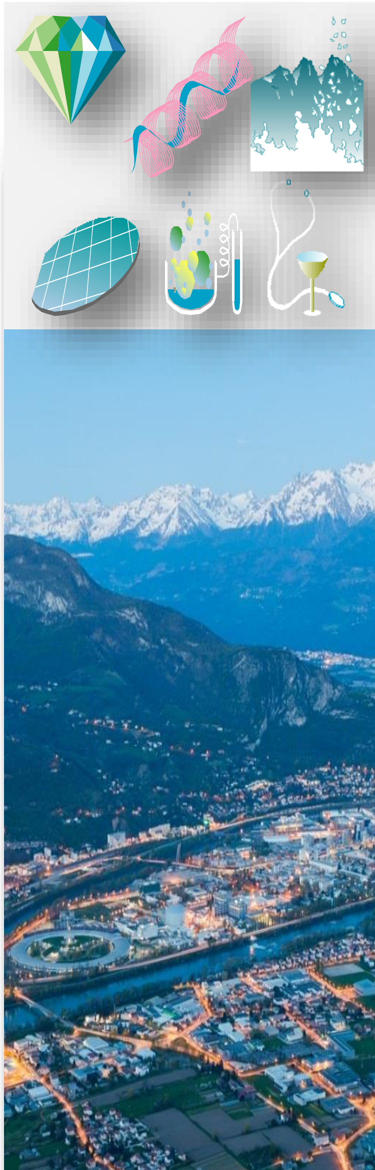
12 on dipoles

30 on insertion devices

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



OPERATION : MACHINE STATISTICS FOR 2014-2017



Throughout 2017, the ESRF delivered 5380 hours of beamtime to its users, out of the 5502 planned

	2014	2015	2016	2017
Availability (%)	99.11	98.53	99.06	**98.28**
Mean Time Between Failures (hrs)	105.5	93.6	93.8	**64.7**
Mean duration of a failure (hrs)	0.94	1.37	0.88	**1.12**

2014: 52 Failures / 2015: 59 Failures / 2016: 59 Failures / 2017: 85 Failures

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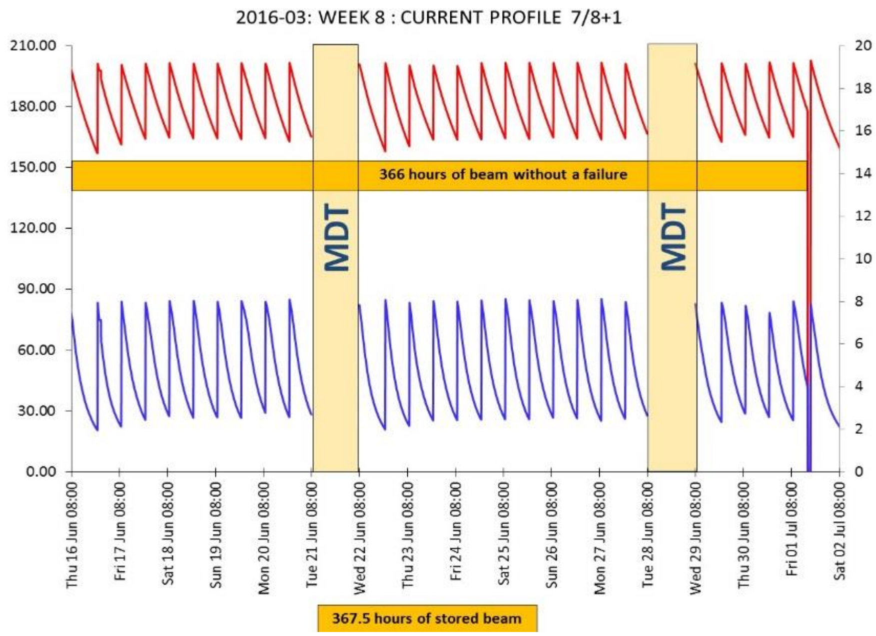
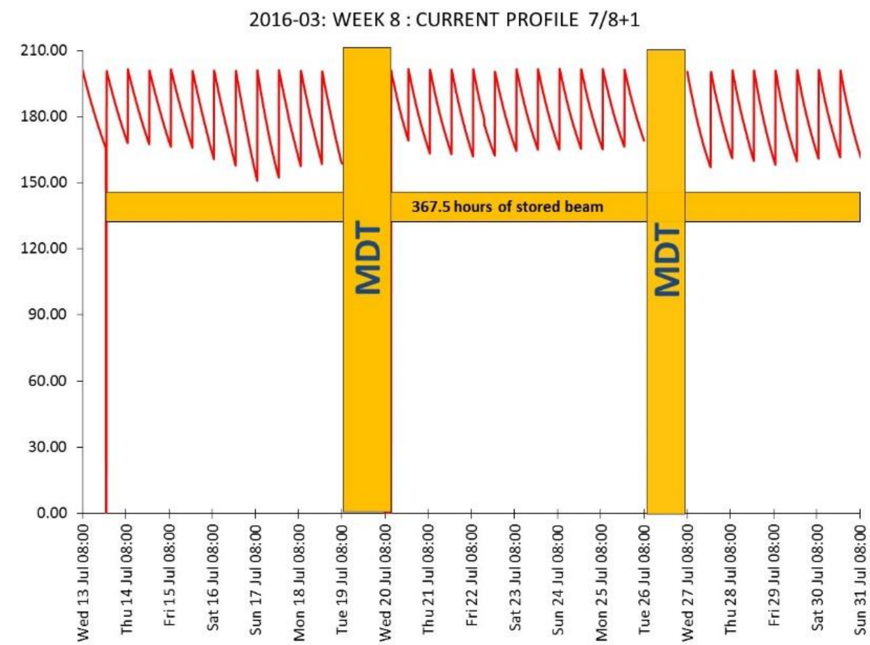
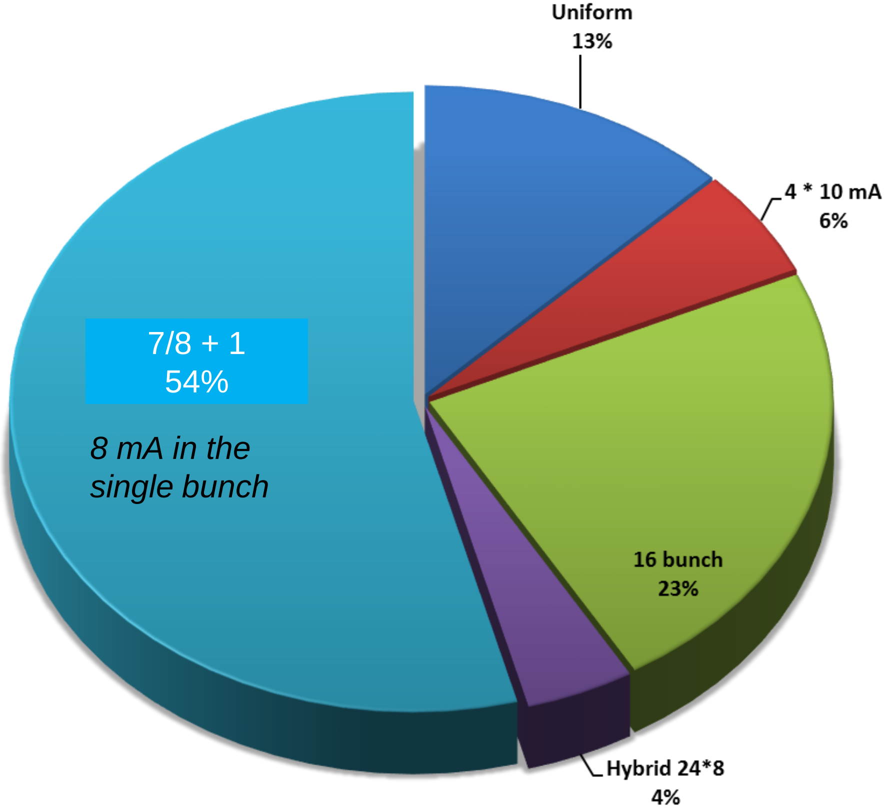
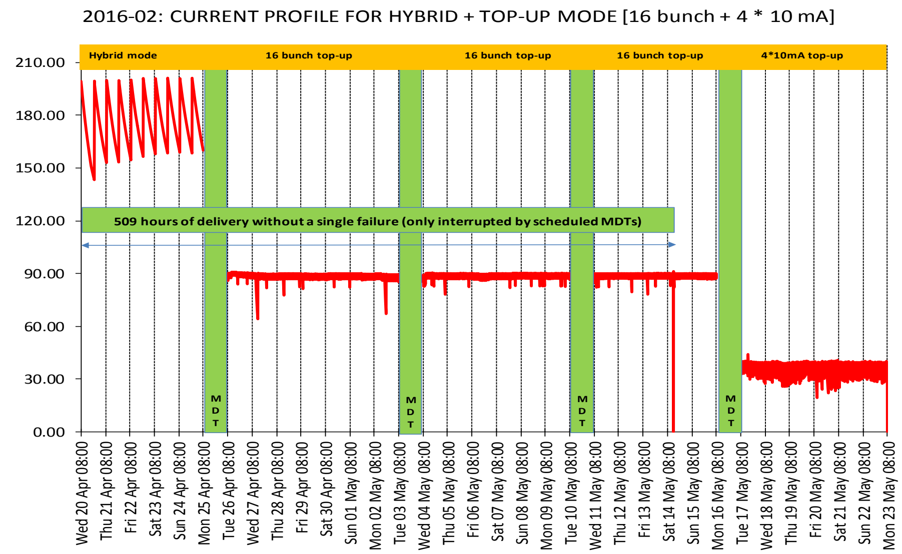
JUNE – JULY 2016: long periods of deliveries without any failures





OPERATION: FILLING MODES IN 2016



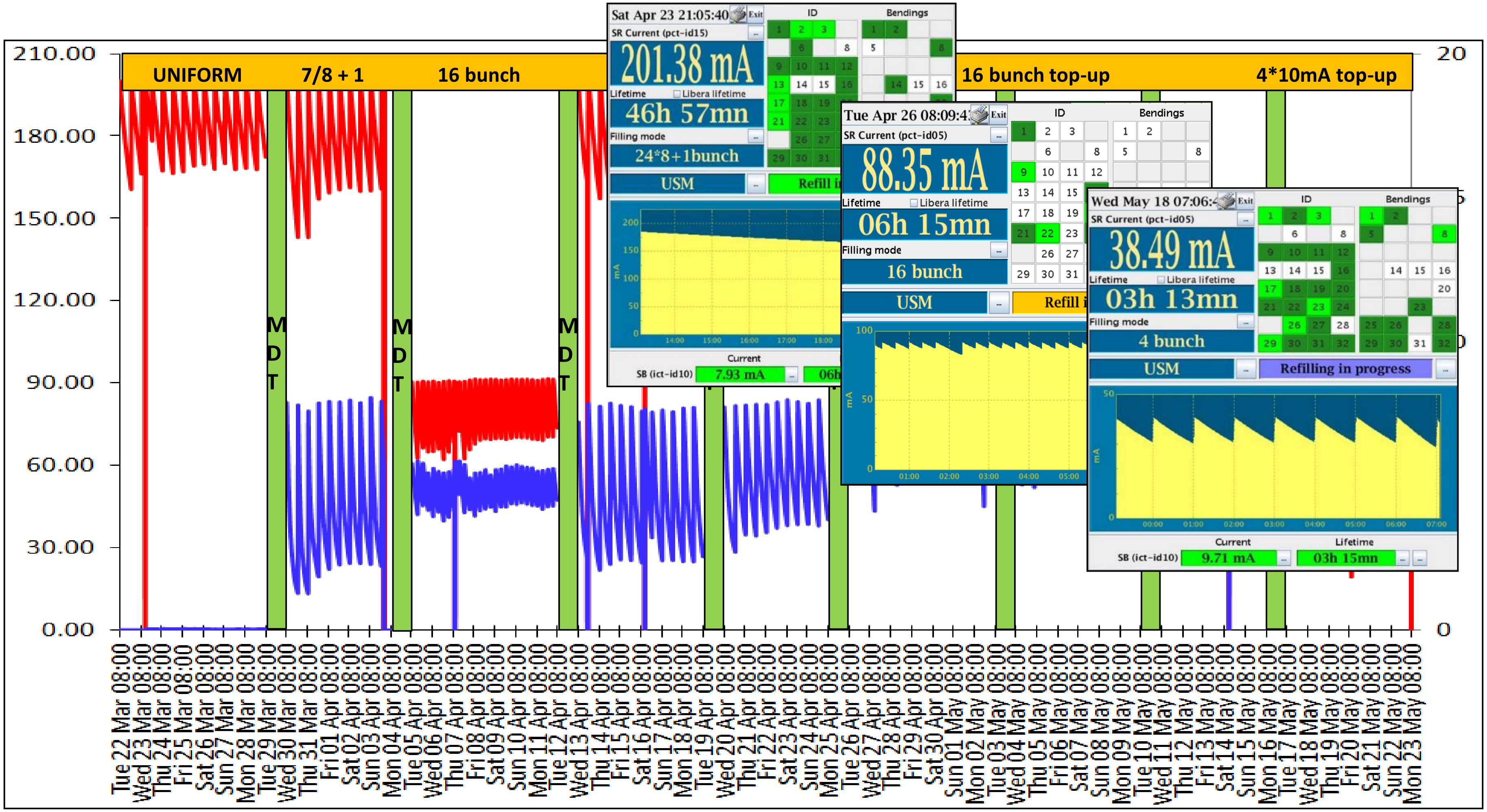


16 Bunch in top-up since 26 April 2016

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

skipped refills <2%

OPERATION : MACHINE



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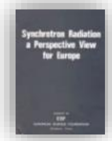
ESRF-EBS: The Extremely Brilliant Source Project

ESRF-EBS
Extremely Brilliant Source

ESRF | The European Synchrotron

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 on time and within budget
- **1998** 40 beamlines on time and within budget

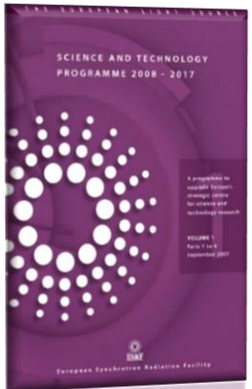
- **2009-2015** Upgrade Programme Phase I on time and within budget

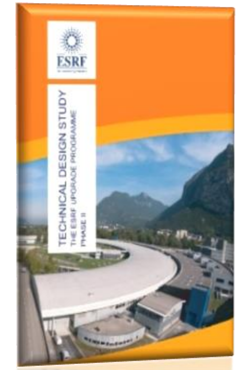
- **2012** New design for the storage ring

- **2015** Upgrade Programme Phase II: ESRF-EBS

ESRF UPGRADE PROGRAMME: AN AMBITIOUS PROGRAMME TO PREPARE THE FUTURE

Purple Book January 2008





Orange Book January 2015

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

- 19 new beamlines, many specialised in *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

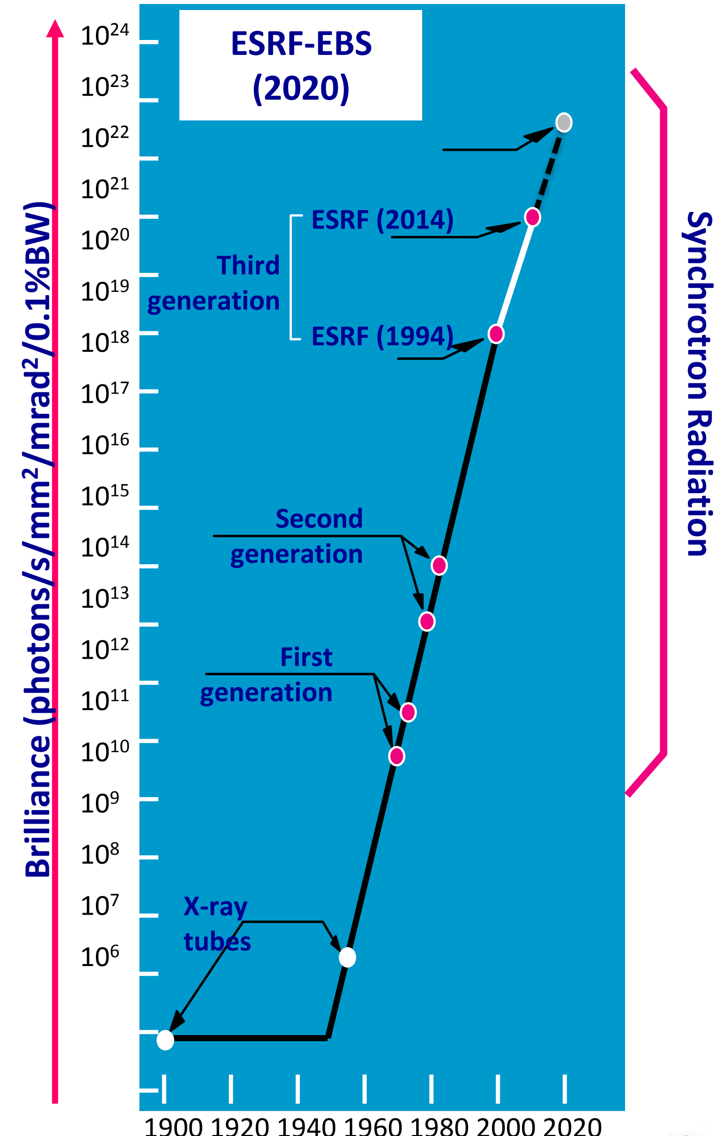
ESRF-EBS: AN AMBITIOUS NEW STANDARD FOR SYNCHROTRON STORAGE RINGS

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

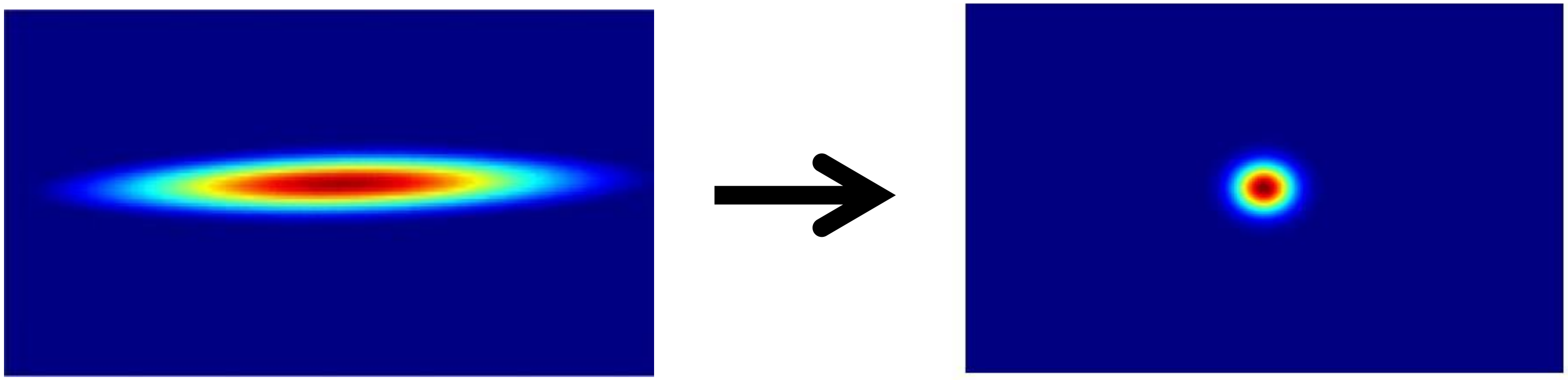
ESRF-EBS
Extremely Brilliant Source

- ~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

Budget for the source only: 104 M€



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)

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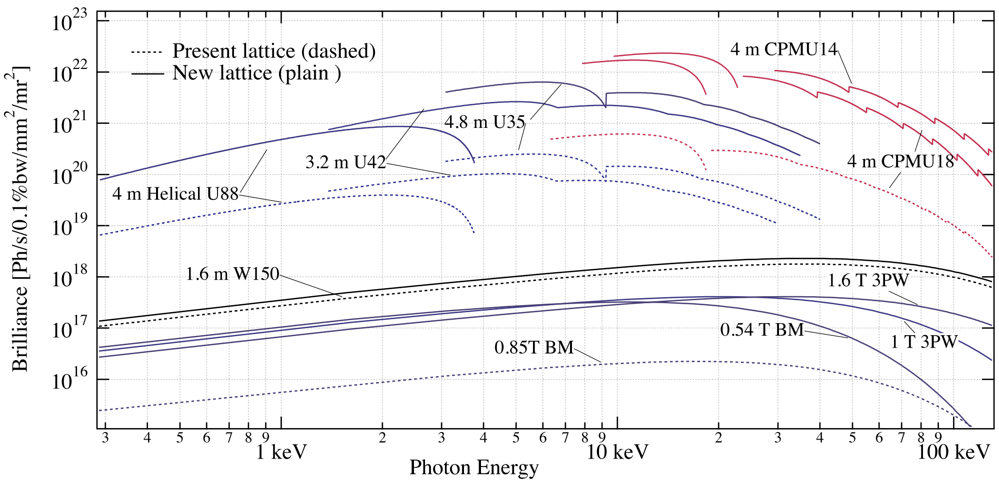
BRILLIANCE AND COHERENCE INCREASE

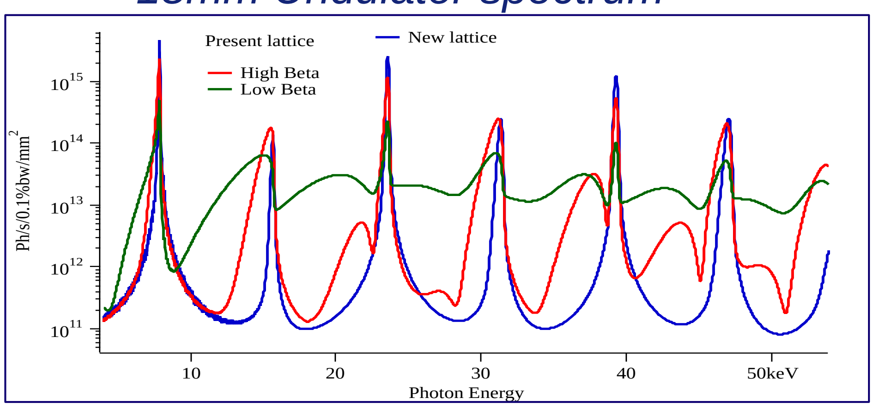
Brilliance



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

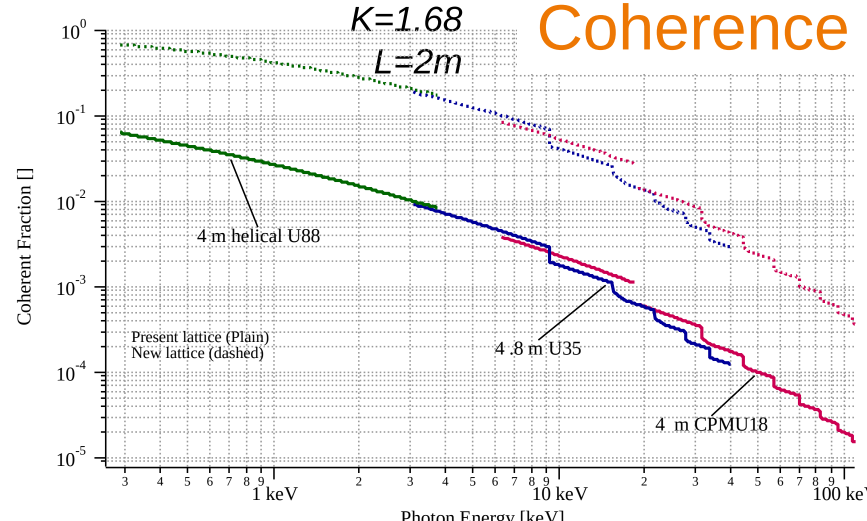
Source performances will improve by a factor 50 to100

18mm Undulator spectrum



Undulator: CPMU18, K=1.68 L=2m

Coherence



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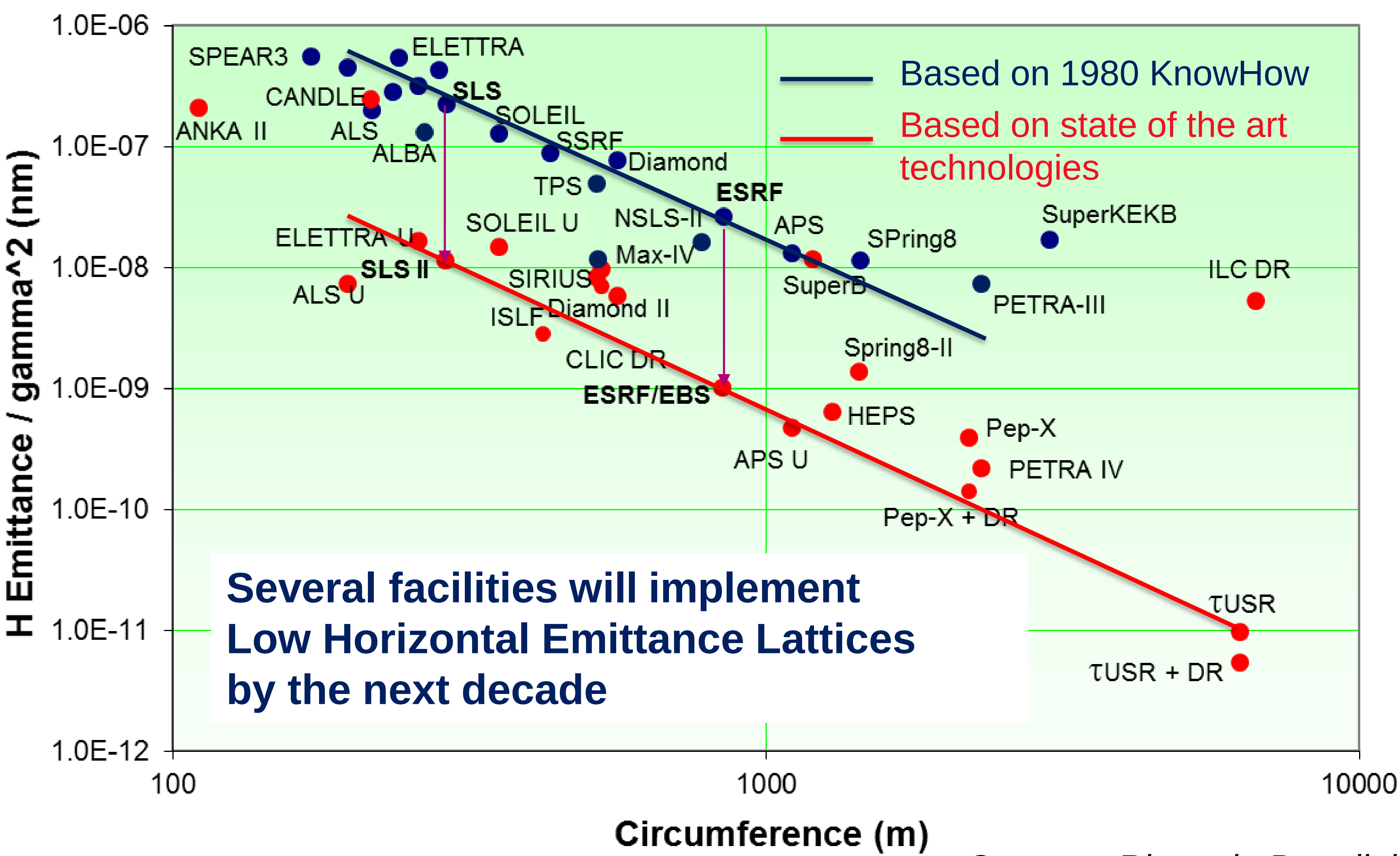
LOW EMITTANCE RINGS TREND



Courtesy Riccardo Bartolini

EXTREMELY BRILLIANT SOURCE: ACCELERATOR UPGRADE

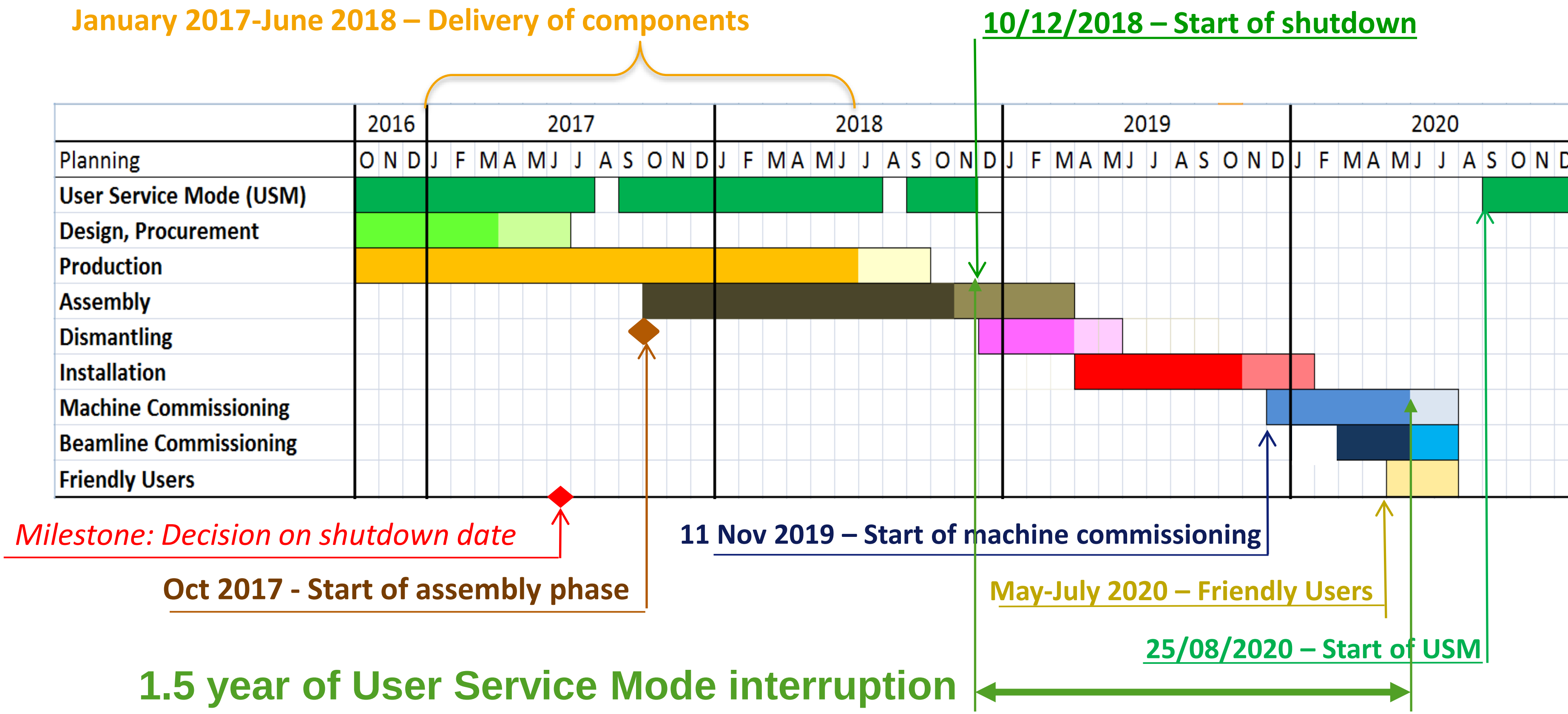
The Extremely Brilliant Source Project aims to:

- Substantially decrease the Storage 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 magnet 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 PROJECT PLAN (2015-2020)



2018 is a normal year for Operation

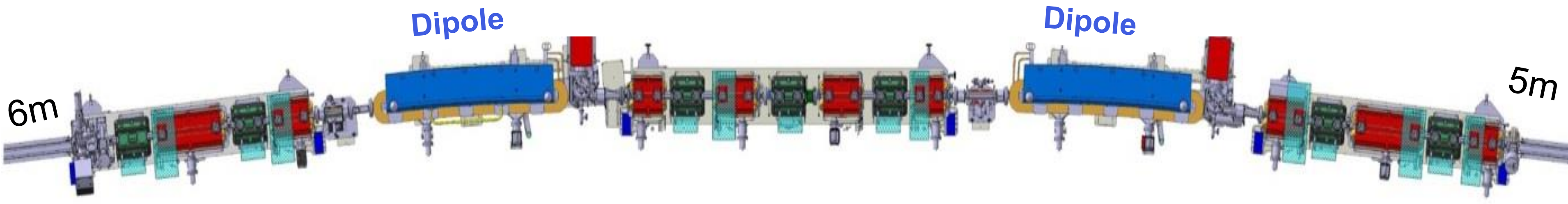
October	2017	Start of the girder assembly (estimated duration 1 year)
10 December	2018	Start of the long shutdown, dismantling starts
December	2019	Accelerator commissioning
March	2020	Beamline commissioning starts
25 August	2020	Back to USM

NEW LATTICE VS PRESENT ESRF LATTICE

▪ **Present ESRF lattice**

32 cells, Double Bend Achromat = (2 dipoles + 15 quad. sext.) per cell

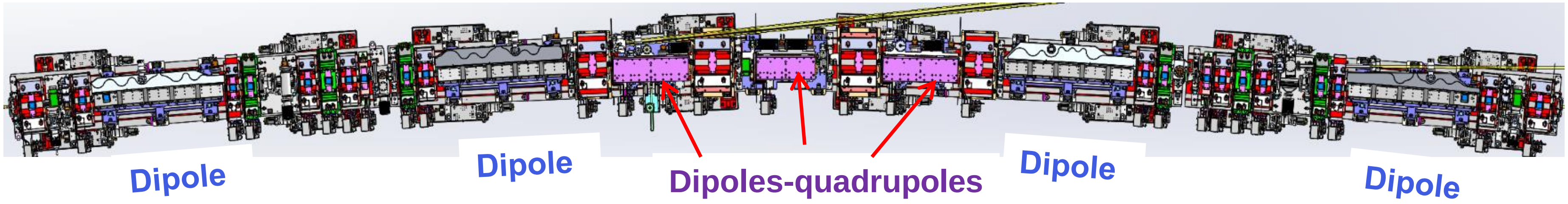
ID length = 5 m (standard) / 6m / 7m



▪ **ESRF EBS lattice**

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

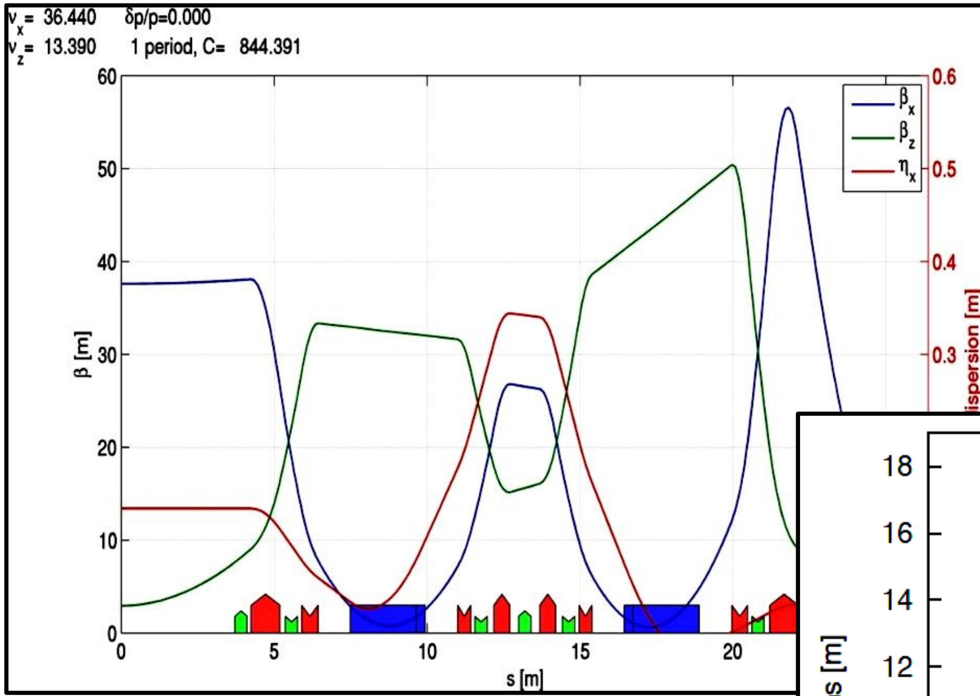
32 identical arcs 21.2 m long, ID length = 5 m



31 magnets per cell instead of 17 currently

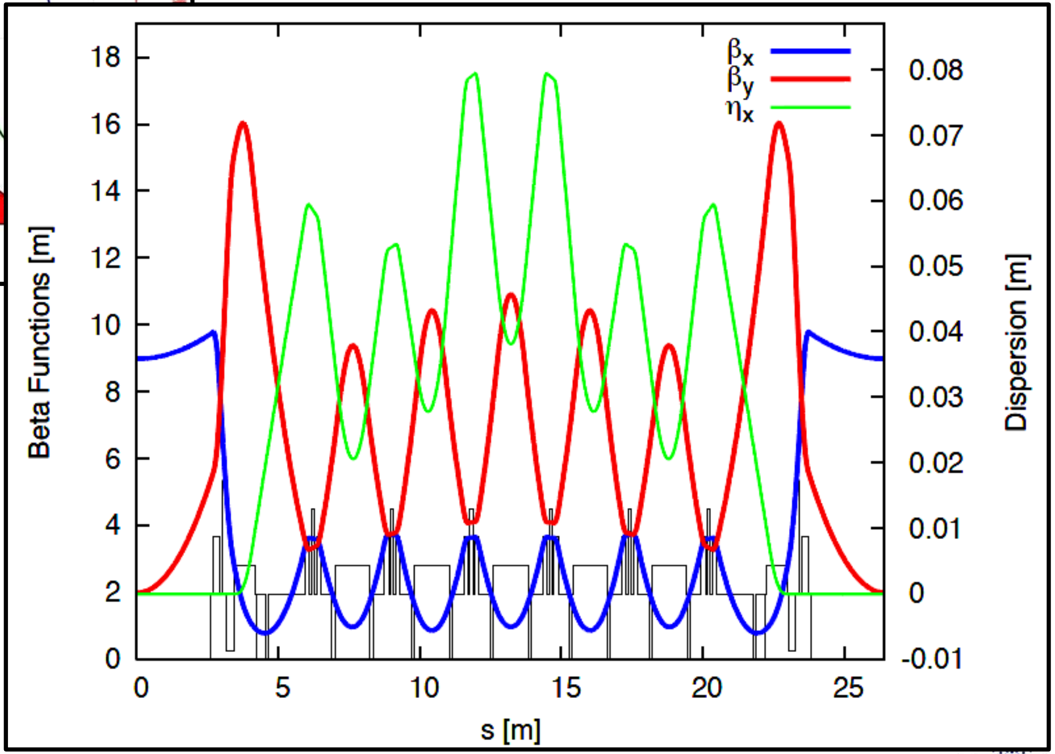
Free space between magnets (total for one cell): **3.4m** instead of **8m** today !!

THE EVOLUTION TO MULTI-BEND LATTICE



Double-Bend Achromat (DBA)

- Many 3rd gen. SR sources
- Local dispersion bump (originally closed) for chromaticity correction



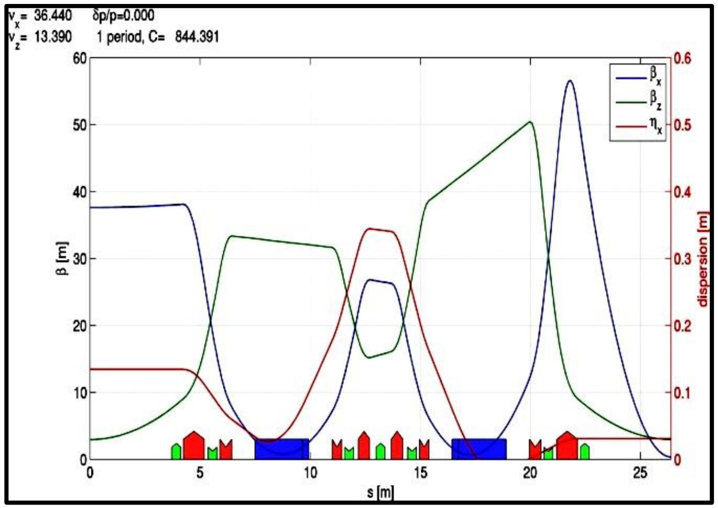
Multi-Bend Achromat (MBA)

- MAX IV and other USRs
- No dispersion bump, its value is a trade-off between emittance and sextupoles (DA)

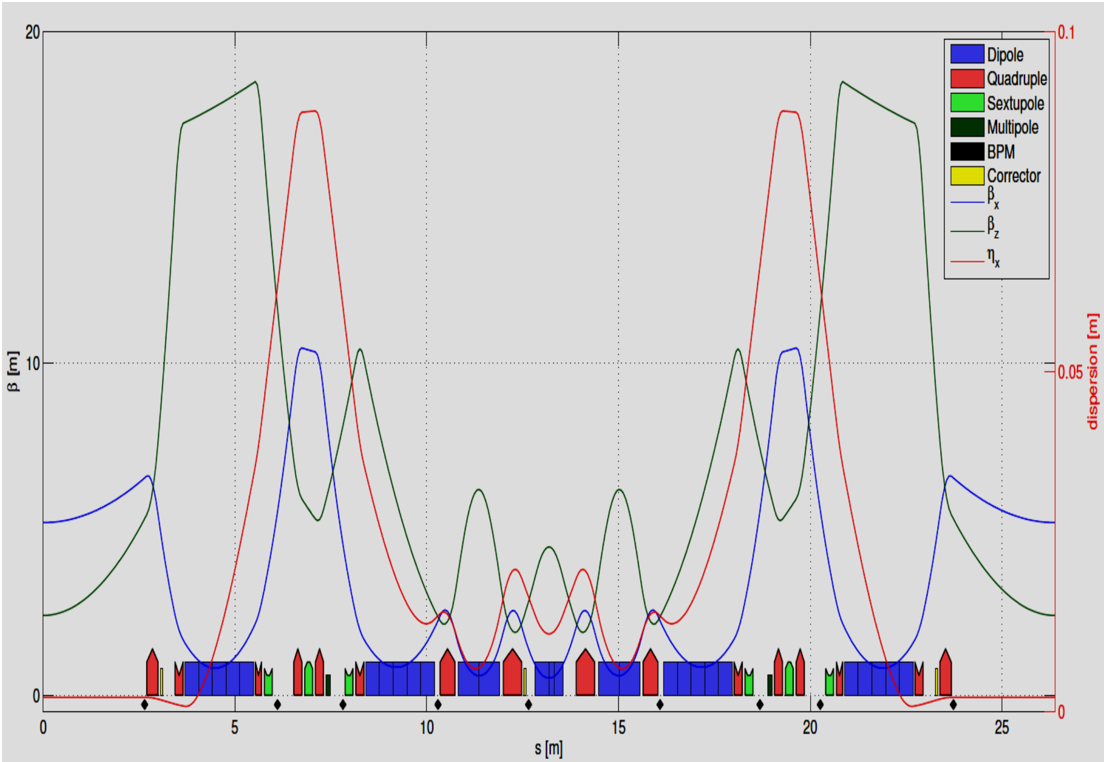
THE HYBRID MULTI-BEND (HMB) LATTICE

ESRF existing DBA cell

- Ex = 4 nm•rad
- tunes (36.44,13.39)
- nat. chromaticity (-130, -58)



- **Multi-bend for lower emittance**
- **Dispersion bump for efficient chromaticity correction => "weak" sextupoles (<0.6kT/m)**
- **Fewer sextupoles than in DBA**
- **Longer and weaker dipoles => less SR**
- **No need of "large" dispersion on the inner dipoles => small *H*x and Ex**

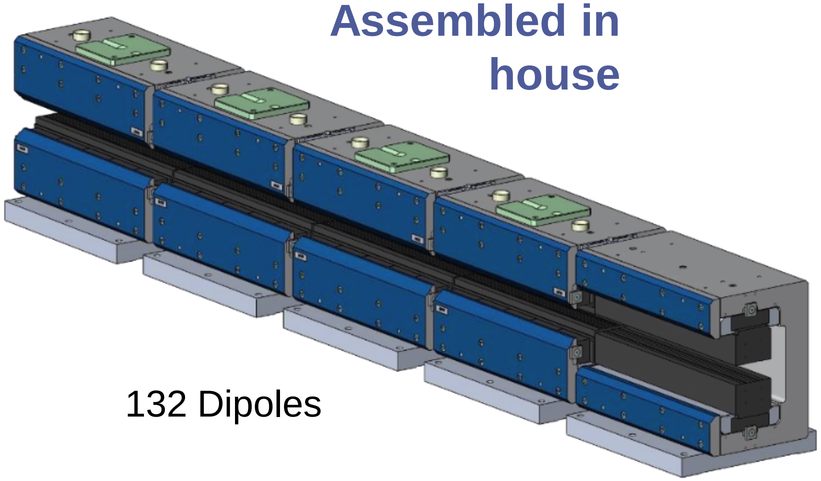


ESRF HMB cell

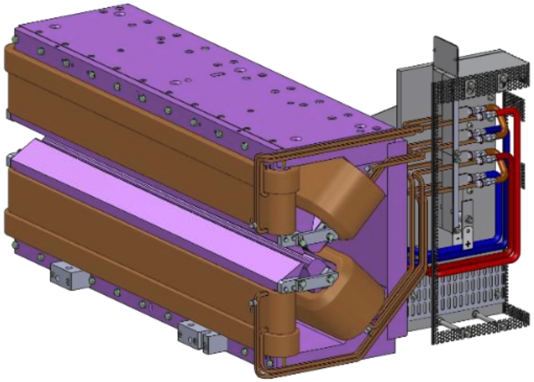
- Ex = 140 pm•rad
- tunes (76.21, 27.34)
- nat. chromaticity (-99, -82)

MAGNETS

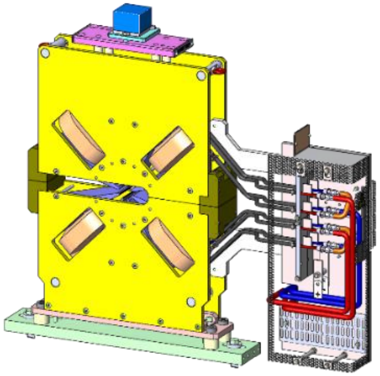
Assembled in house



132 Dipoles



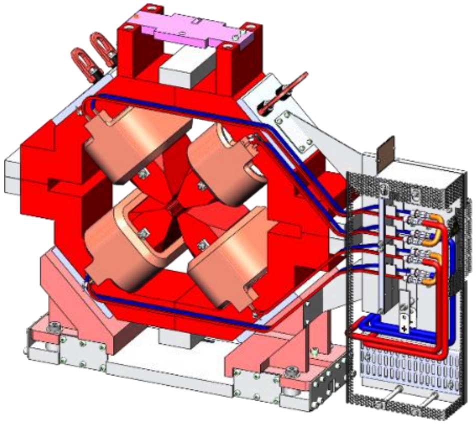
100 Dipole-quadrupoles

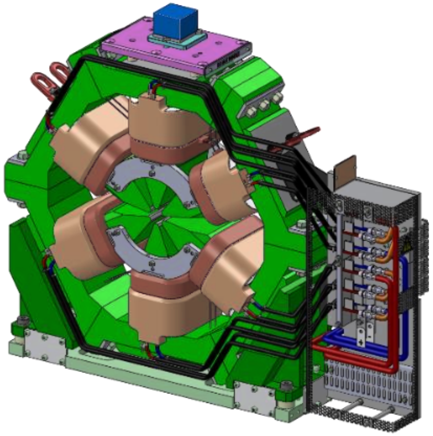


66 Octupoles

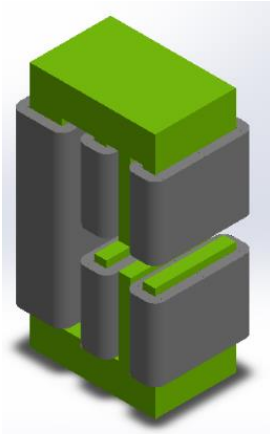
More than 1000 Magnets to procure in less than 3 years

524 Quadrupoles
(132 HG, 392 MG)





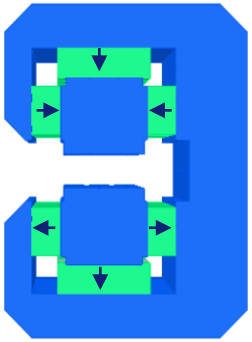
196 Sextupoles

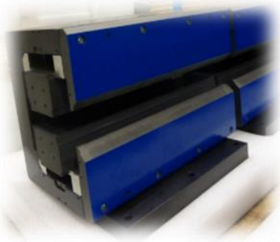


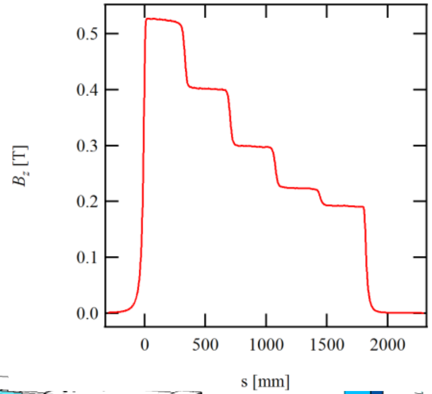
98 Correctors

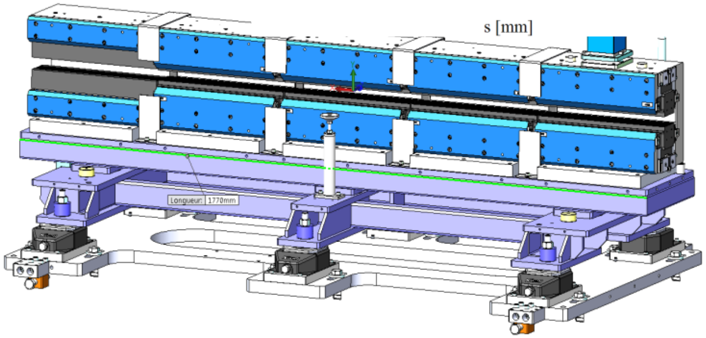
DIPOLES WITH LONGITUDINAL GRADIENT [132]

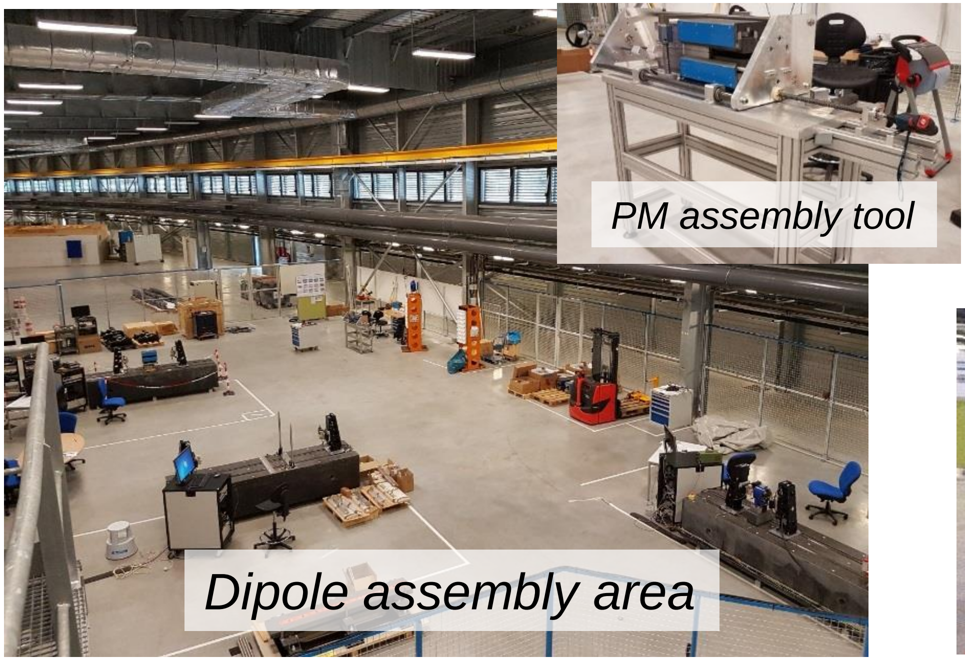
- Each dipole based on 5 PM modules
- Strength 0.67-0.17 T &
- Iron length 1788 mm
- 25.5 – 30.5 mm GAP
- Iron: Pure Iron
- Permanent magnet Sm_2Co_{17}









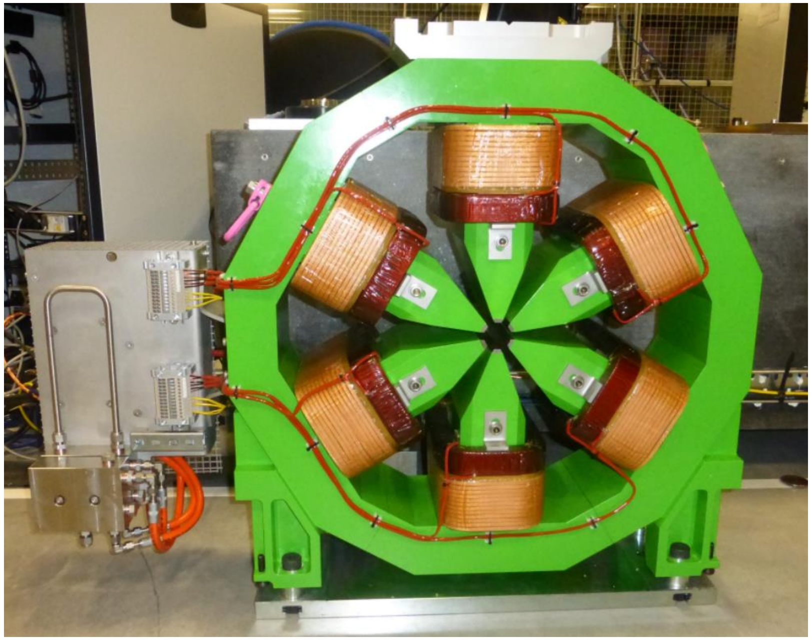

Dipole assembly area

PM assembly tool

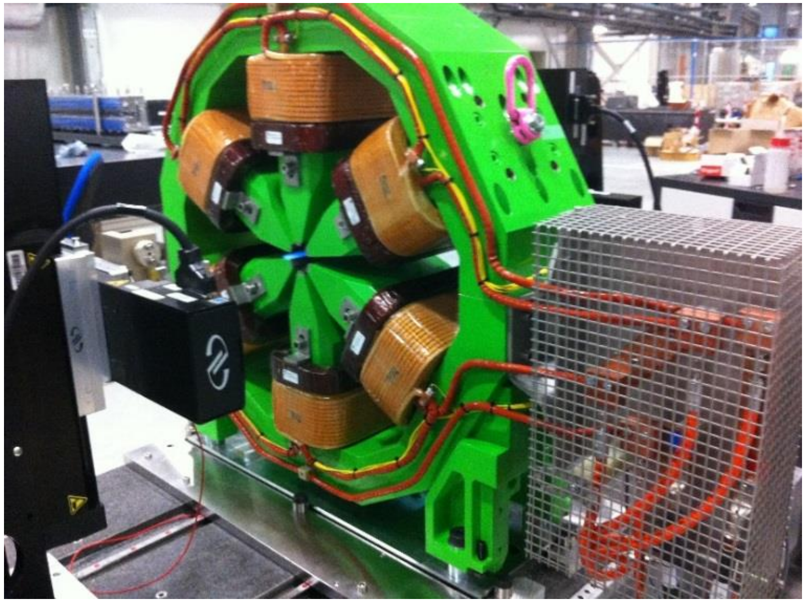
Around 6000kg of PM, 660 Iron modules,
Half of the 128 magnets already assembled

SEXTUPOLES [196]

- 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



First series magnet batch delivered



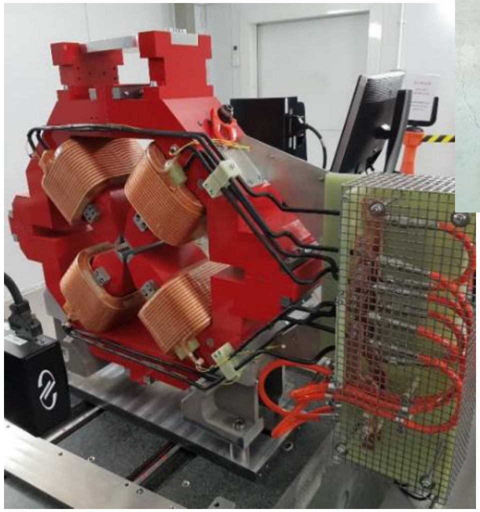
QUADRUPOLES

High Gradient *[130]*

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

First series magnet batch delivered

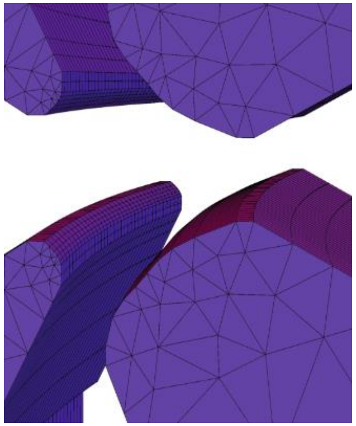
Moderate Gradient *[398]*

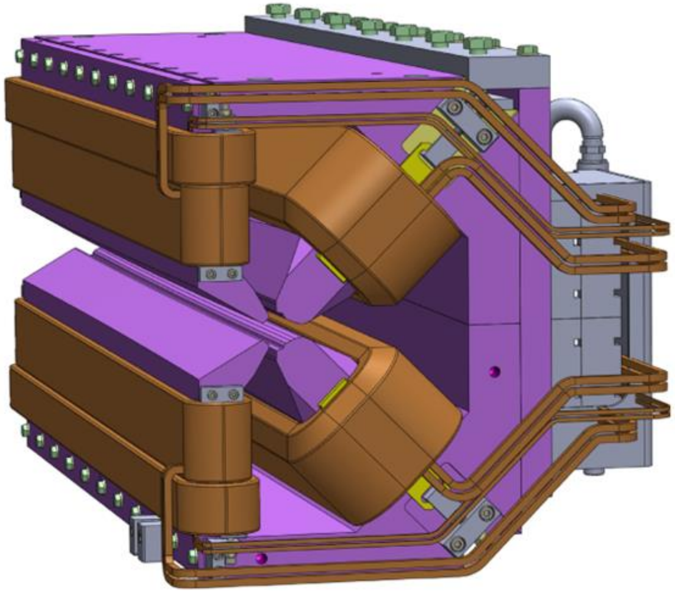


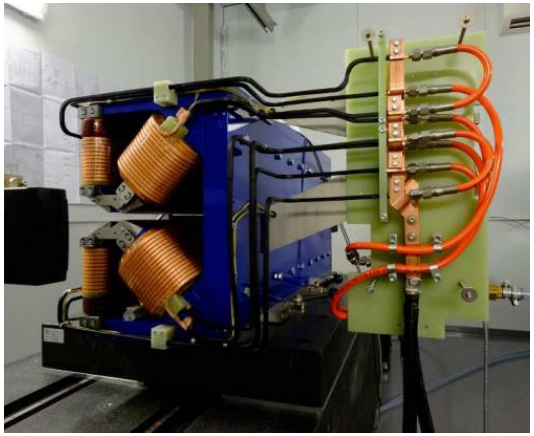
- 4 types
- Up to 54 T/m gradient, 162– 295 mm length
- 16.4 mm bore radius
- 0.7 – 1.1 kW power consumption

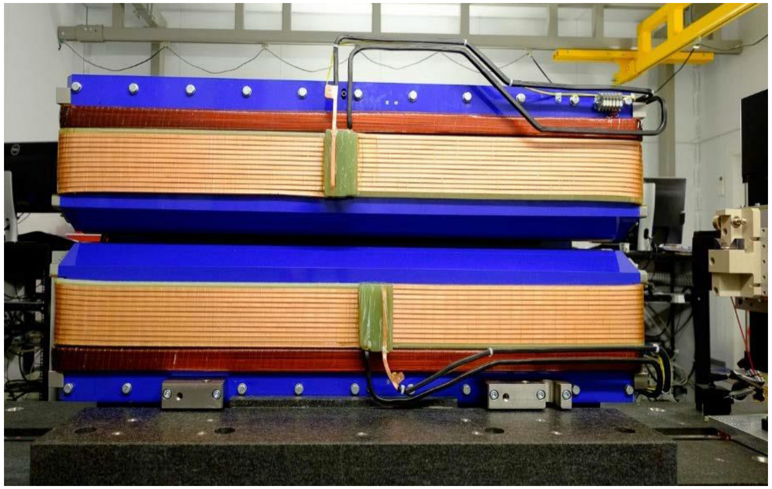
DIPOLE QUADRUPOLES [99]

- 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





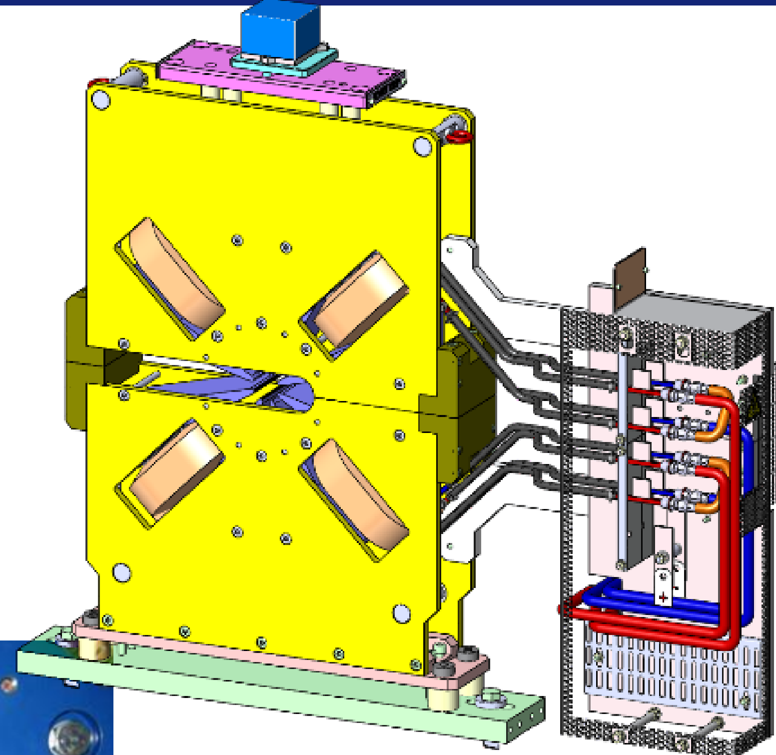


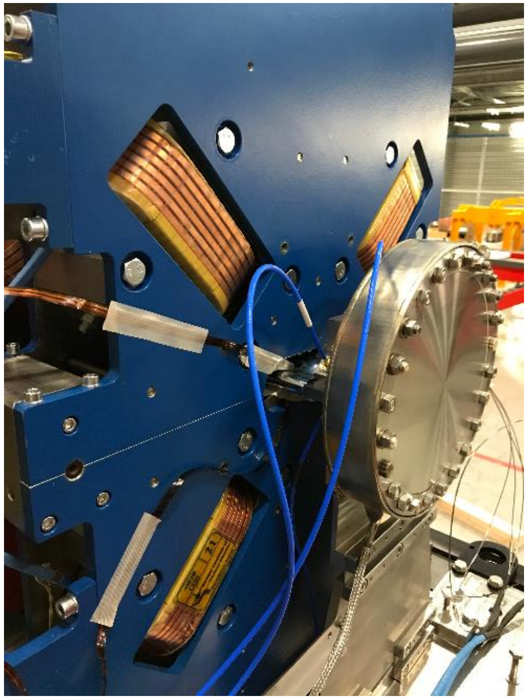


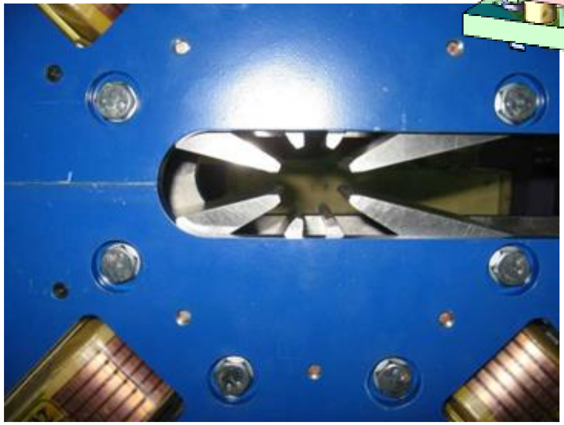
Pre-series magnet delivered

OCTUPOLES [66]

- 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



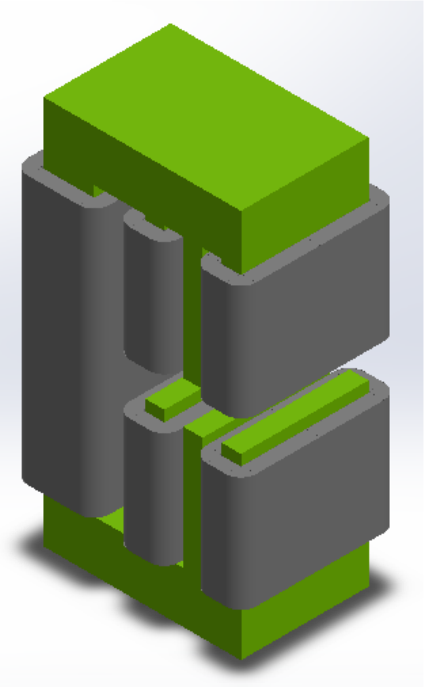




Series production

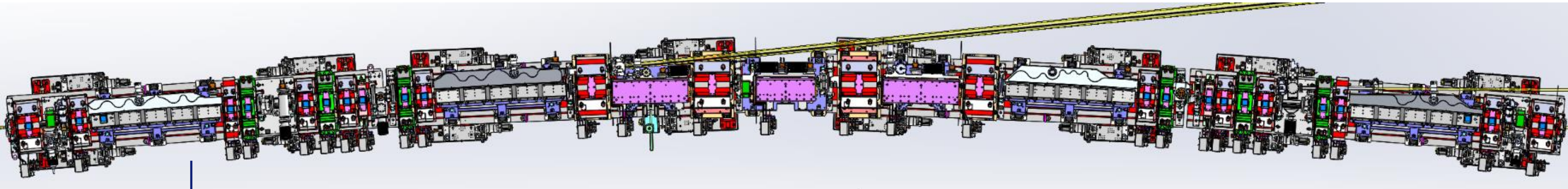
CORRECTORS [100]

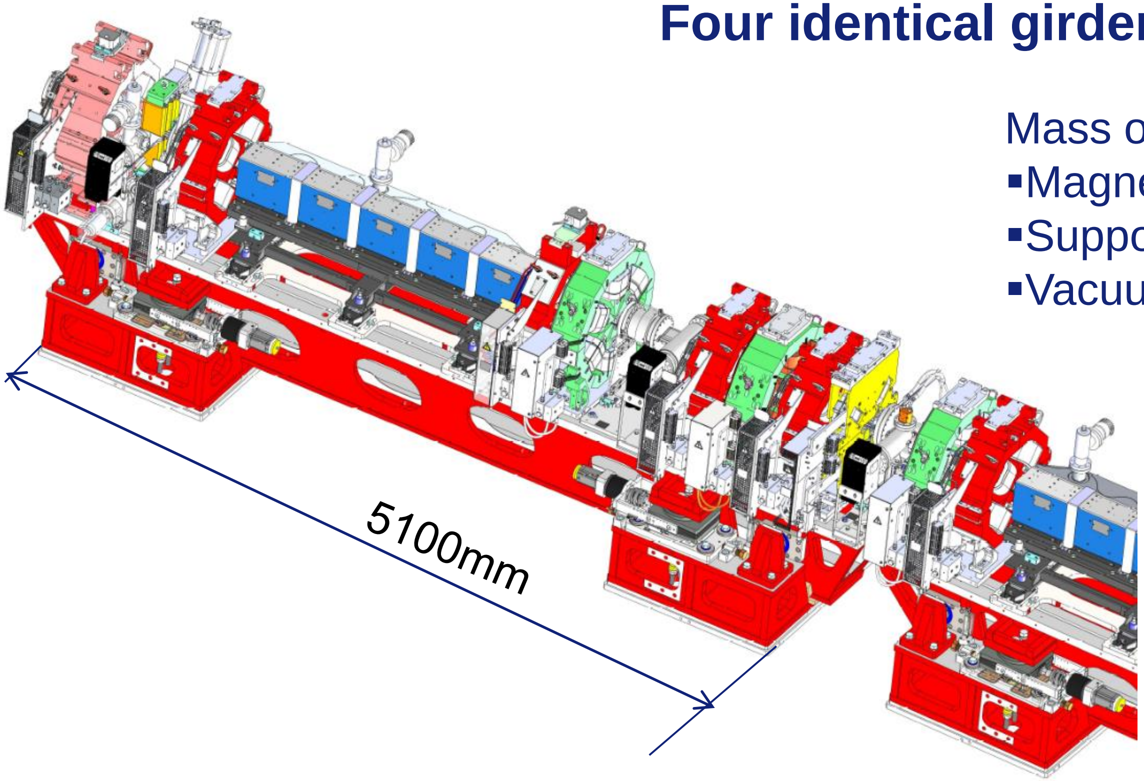
- Horizontal: 0.1 T.mm
- Vertical 0.1 T.mm
- Skew quadrupole: 0.12 T
- 25.5 mm gap mm bore radius



Series production

GIRDERS





Four identical girders per cell

Mass of:
- Magnetic elements
- Supports
- Vacuum equipements

6-7T/girder

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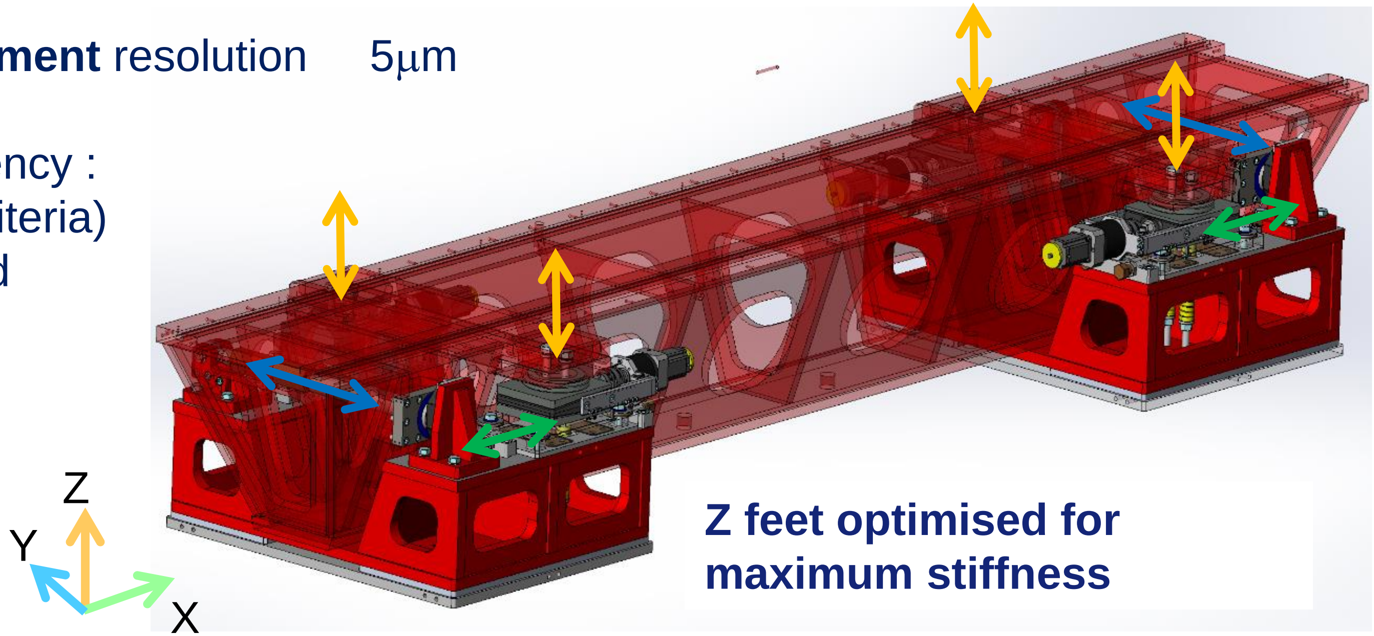
GIRDERS

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

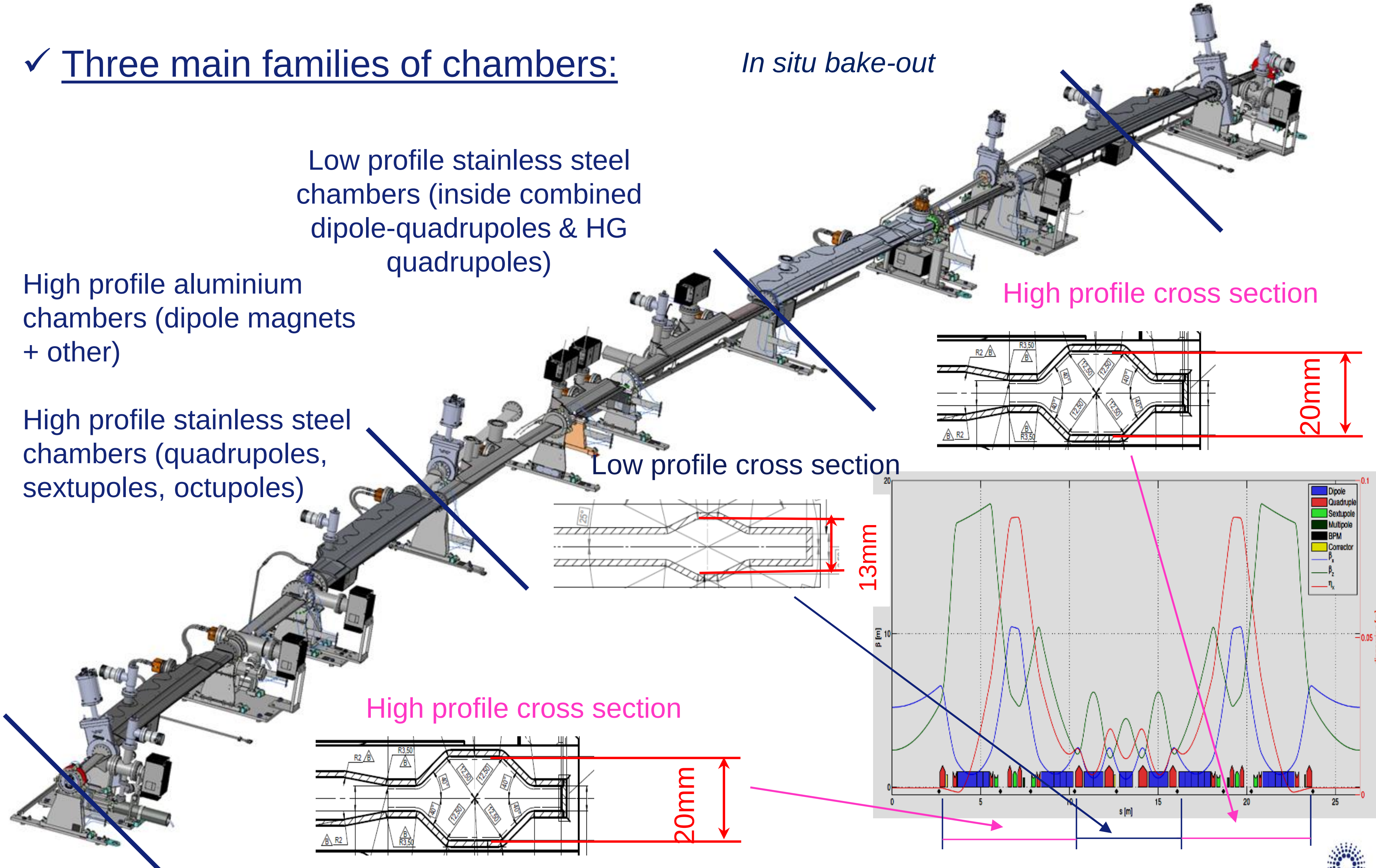
	HORIZONTAL (Y)	VERTICAL (Z)
Girder to girder	50 μm	50 μm

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



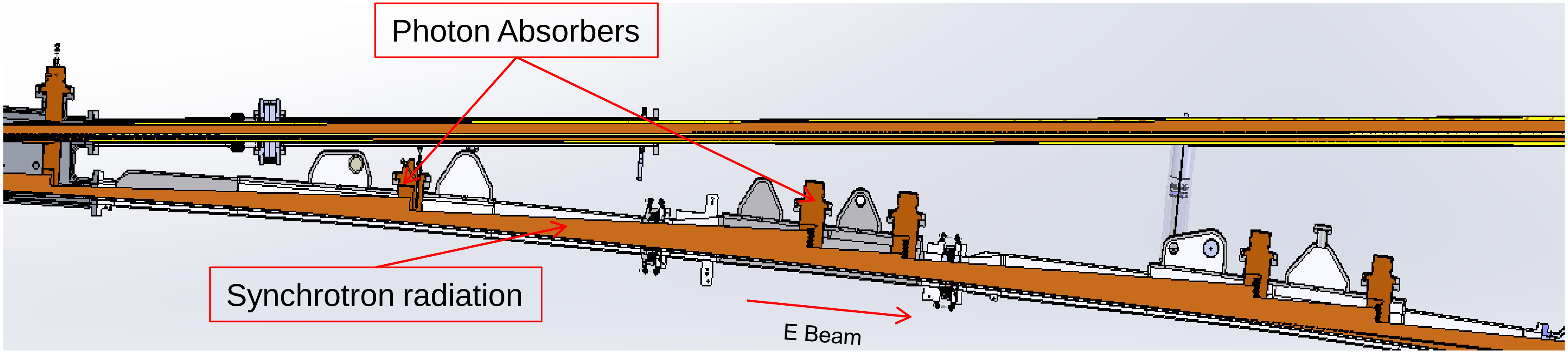
VACUUM CHAMBERS

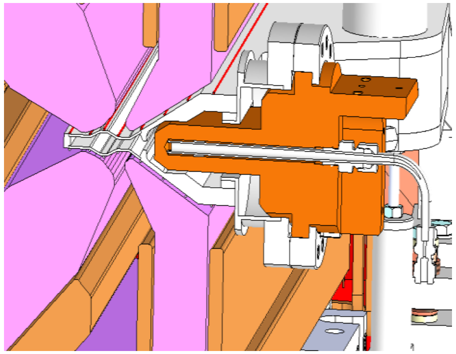
✓ Three main families of chambers:



PHOTON ABSORBERS

- ~391 absorbers (including crotch absorbers, without injection cell specials)
- Total power to be absorbed: 504.5 kW (30 x 15.795 kW + 2x 15.314) kW
- Power density: 10 to 110 W/mm2 (normal to beam)
- => moderate power parameters compared to current ESRF
- Scattered radiation blocked in the absorber to avoid chamber cooling





Absorber flange mounted on the ante-chamber

Tight space constraints

-CuCr1Zr as an alternative to Glidcop

- Integrate the CF flange in the CuCr1Zr absorber body (Sharma Sushil idea)

Pre-series delivered, absorbers in series production

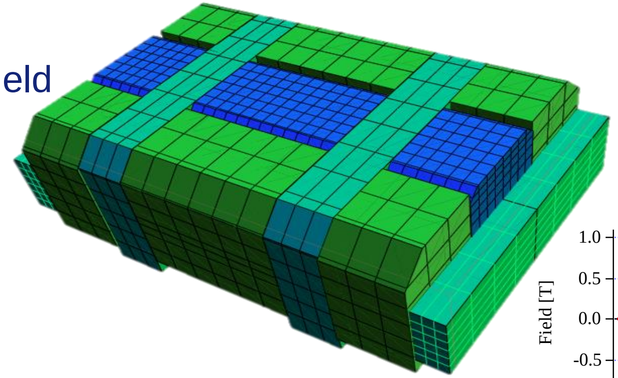
BENDING MAGNETS SOURCE: 1- POLE BM, 2-POLE & 3-POLE WIGGLERS

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

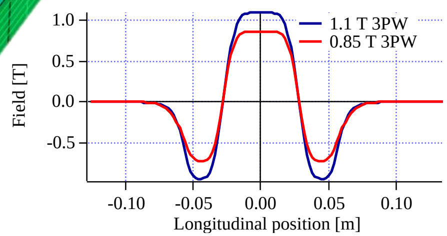
Increased number of bending magnets / cell => BM field reduction

Conflict with hard X-ray demand from BM beamlines

ESRF will go from 0.85 T BM to 0.54 T BM



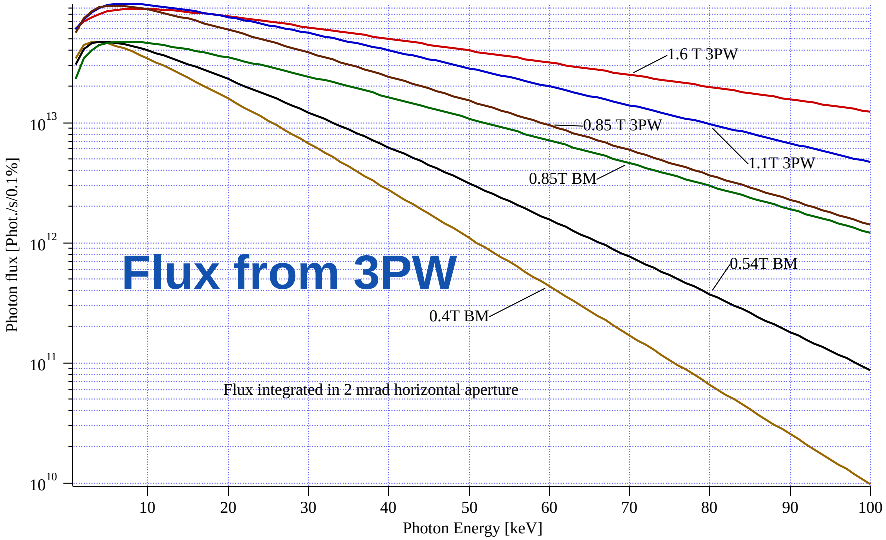
Half assembly



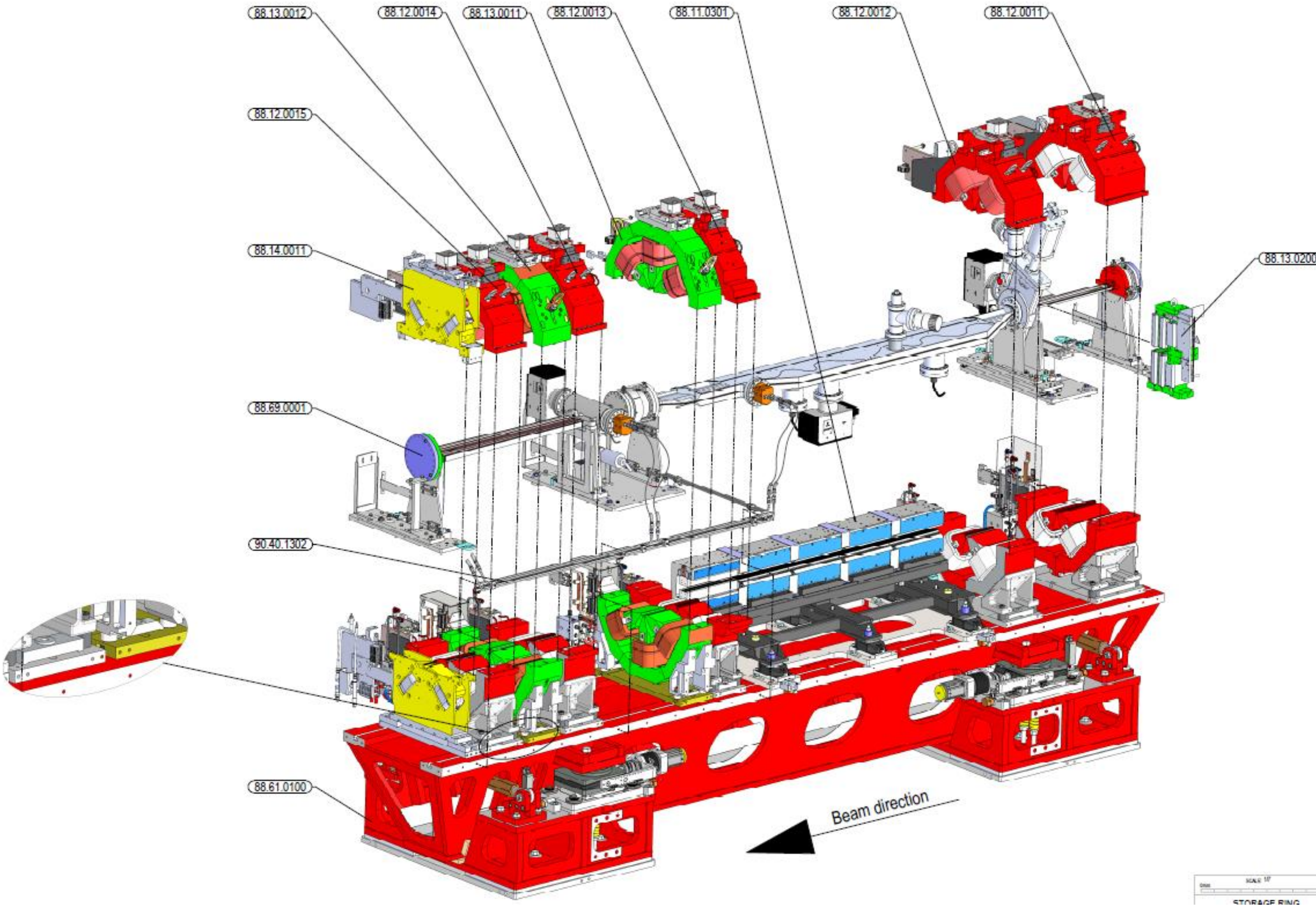
The BM Sources will be replaced by dedicated 1-Pole short super bend, 2-Pole or 3-Pole Wigglers

- 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



COMPLETE GIRDER DISASSEMBLED VIEW



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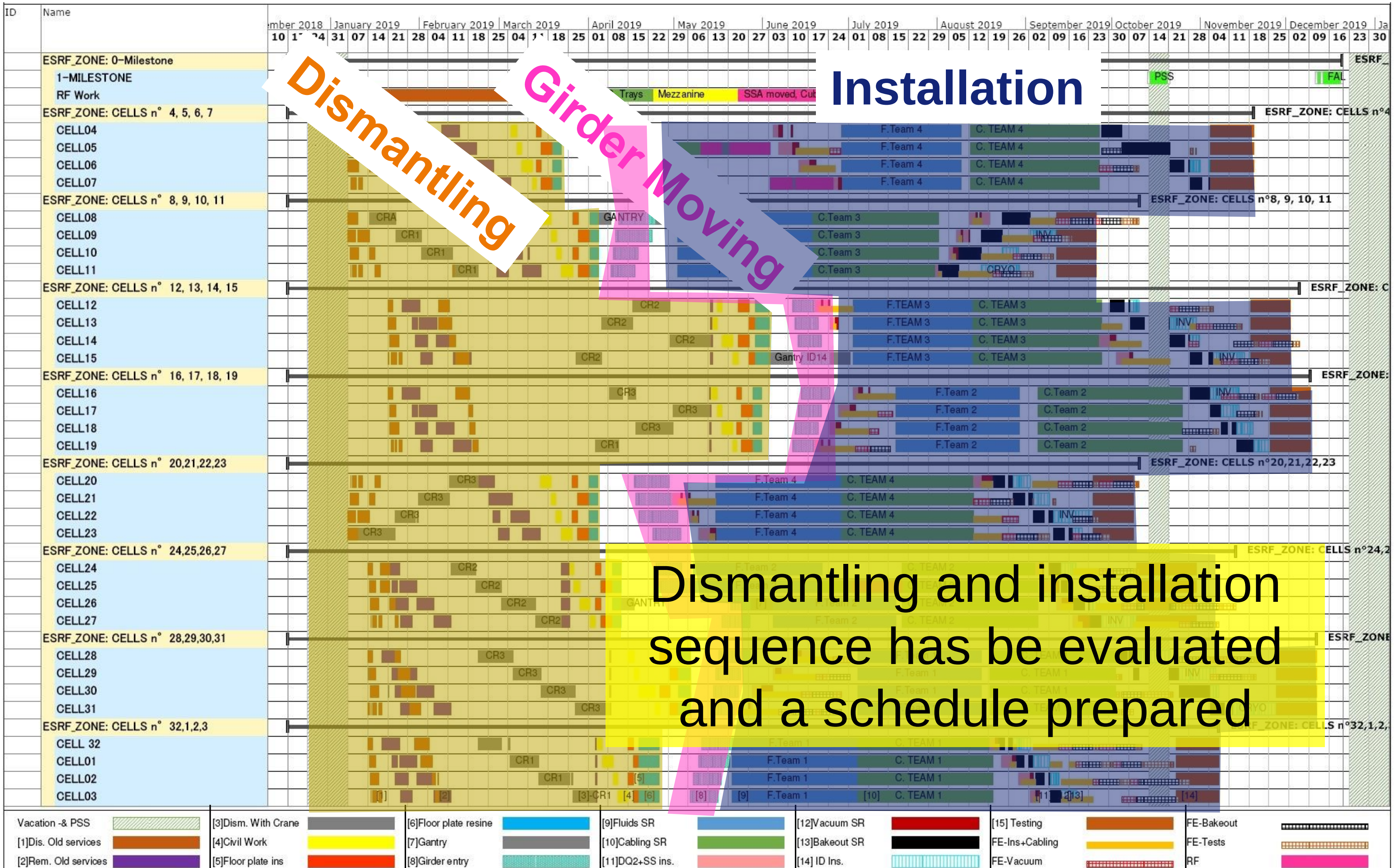
FULL CELL MOCKUP

The four girders are now assembled with the pre-series components:

- No major problems encountered with the different components; everything fits together
- Minor modifications required to the suppliers for the series production

- The overall assembly procedure has been validated
- Detailed and optimised procedures are under preparation

DISMANTLING & INSTALLATION PLANNING



Dismantling and installation sequence has be evaluated and a schedule prepared

CONCLUSION

EBS project running in parallel with ESRF operation

- **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 almost completed**

  ➔ Schedule now heavily linked to external manufacturers
- **Mock-up cell completed**
- **Assembly to be started**
- **Dismantling/installation/commissioning in preparation**

At this stage, no major show stopper identified.

MANY THANKS FOR YOUR ATTENTION