Hybrid Multi Bend Achromat: from SuperB to EBS

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Pantaleo Raimondi, ESRF

ESRF | The European Synchrotron

HYBRID MULTI BEND ACHROMAT (HMBA): HISTORY

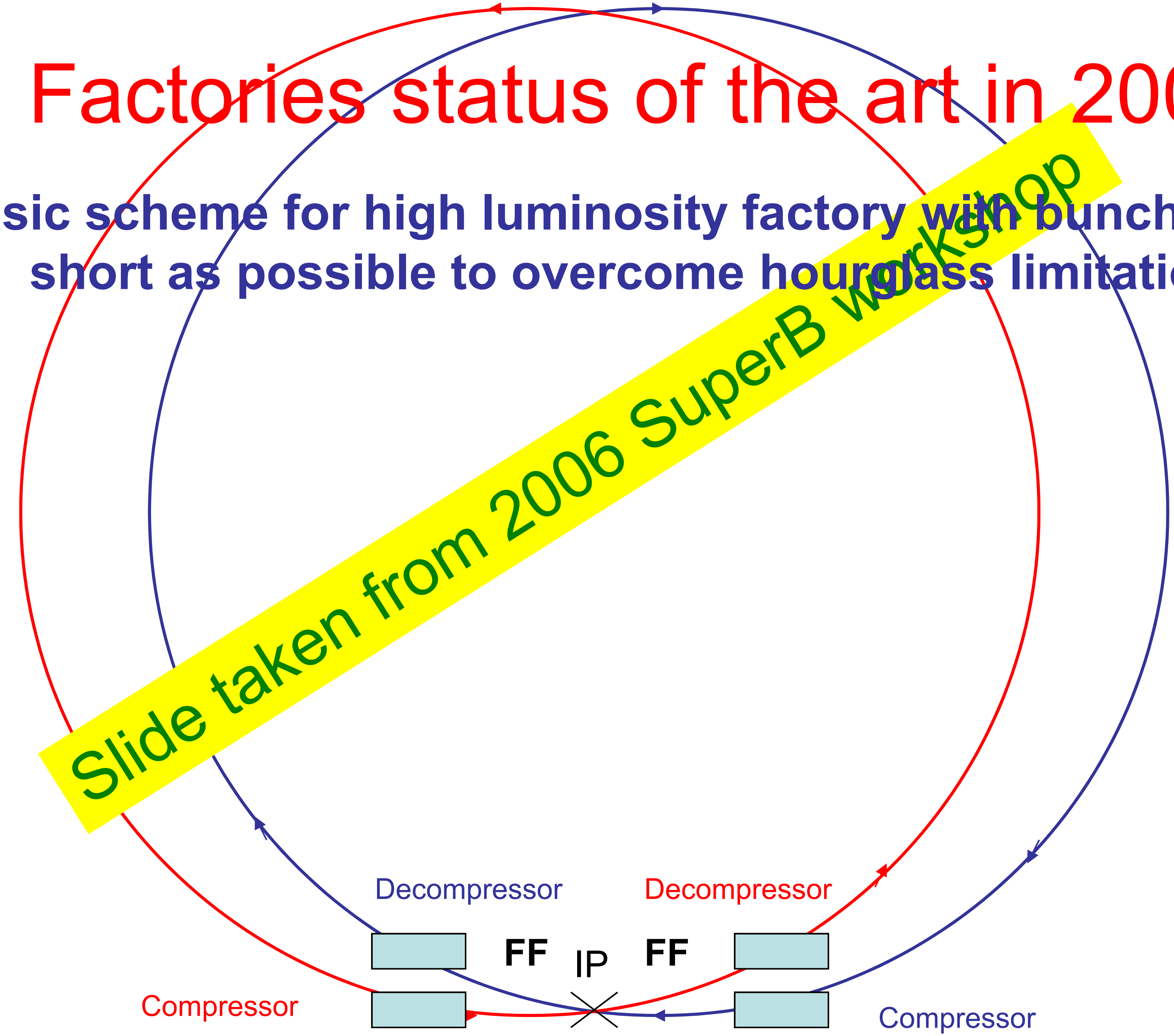
- **The HMBA lattice origins from the need of low emittance rings for the SuperB project (2006)**
- **The high luminosity of the SuperB relied on the use of the large Piwinsky angle and crab waist scheme**
- **With respect to ALL the circular lepton colliders built and studied up to 2006, a fundamental difference is that the optimal horizontal emittance is basically ZERO (when beam-beam effects are dominant)**
- **Moreover the luminosity is so high that the beam lifetime becomes a strong limitation to the ultimate performances of the colliders**
- **All the colliders based on this concept have to develop low emittance lattices with large dynamic aperture**

Strong synergy with the Synchrotron Light Sources Accelerator Community

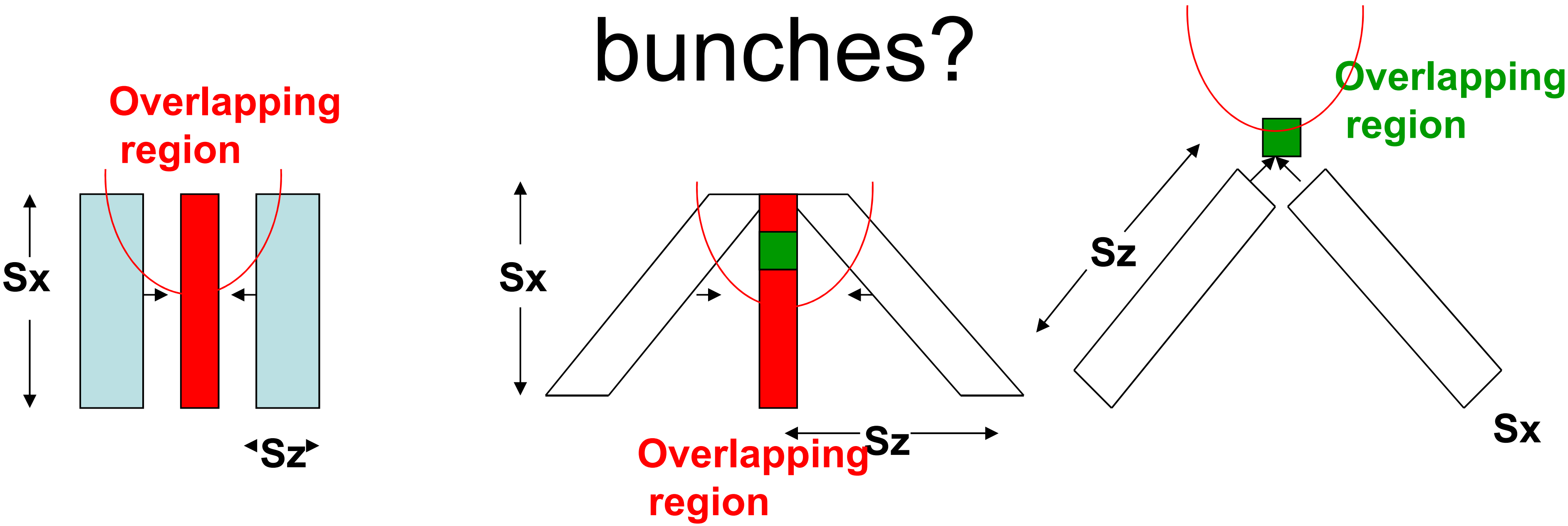
Factories status of the art in 2006

Basic scheme for high luminosity factory with bunches as short as possible to overcome hourglass limitation

Slide taken from 2006 SuperB workshop



Do we need to compress the bunches?



1) Standard short bunches

2) Crab crossing with no crossing angle

3) Crossing angle

All cases have the same luminosity:

(2) has longer bunch, longitudinal overlap happens in the same area as in (1)

(3) has longer bunch and smaller σ_x

2006 SuperB workshop

At any given time (2) and (3) have the same overlapping region

In order to decrease beam-beam effects due to the crossing angle:

- increase the crossing angle (at the expenses of luminosity)
- Introduce the "*crab waist*" concept:

- All components of the beam collide at a minimum β_y
- The 'hourglass' is reduced and the geometric luminosity is higher
- The bb effect in the section were the beams do overlap is reduced
- The bb effect in the sections were the beams do not overlap is greatly reduced

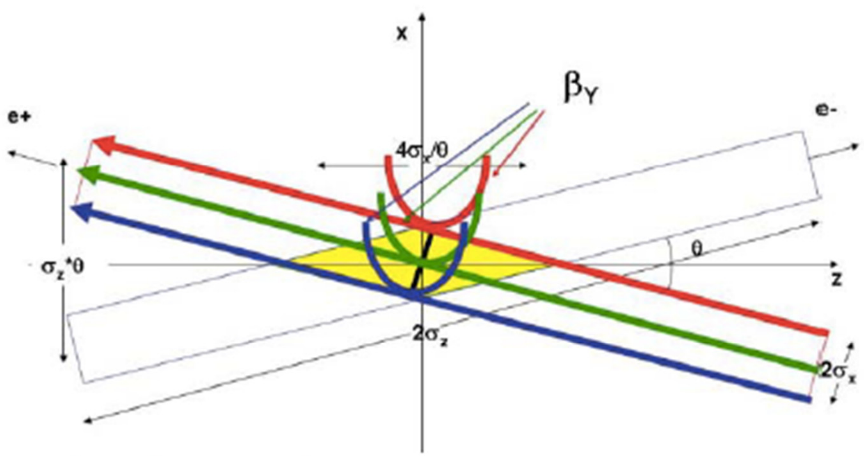
Preliminary tracking results are extremely promising

2006 SuperB workshop

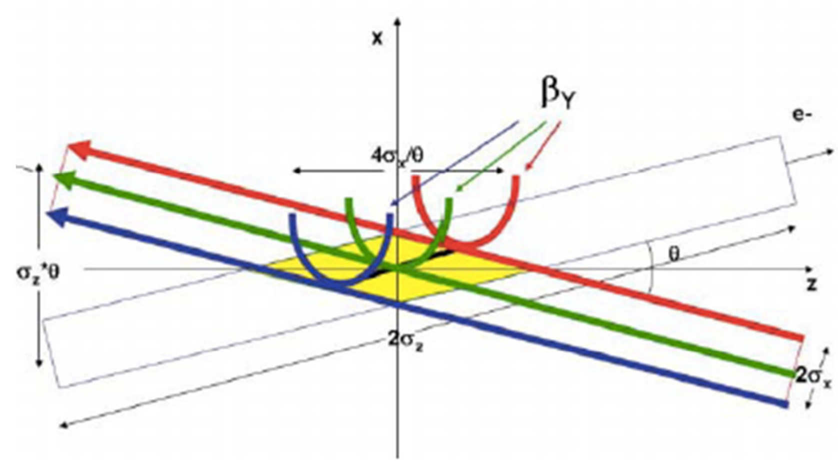
With large crossing angle X and Z quantities are swapped

Very important!!!

Short bunches are no more needed since the IR length is given by $\sigma_z = \sigma_x/\theta$



a) Crab sextupoles OFF.



b) Crab sextupoles ON.

Crab waist: vertical waist has to be a function of x:

Z=0 for particles at $-\sigma_x$ ($-\sigma_x/2$ at low current)

Z= σ_x/θ for particles at + σ_x ($\sigma_x/2$ at low current)

2006 SuperB workshop

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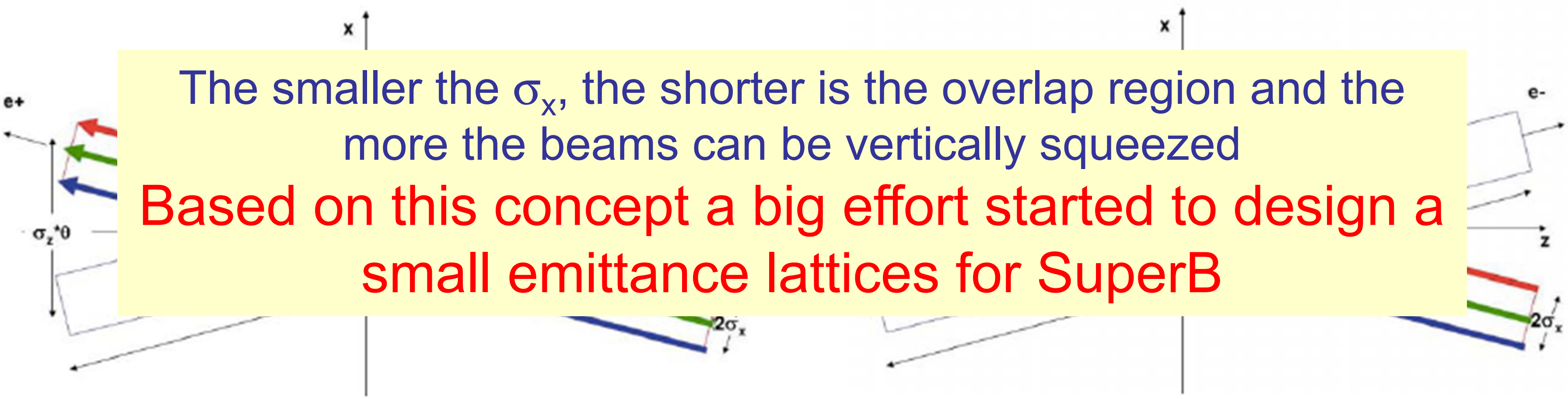


The smaller the σ_x, the shorter is the overlap region and the more the beams can be vertically squeezed

Based on this concept a big effort started to design a small emittance lattices for SuperB

a) Crab sextupoles OFF.

b) Crab sextupoles ON.

Crab waist: vertical waist has to be a function of x:

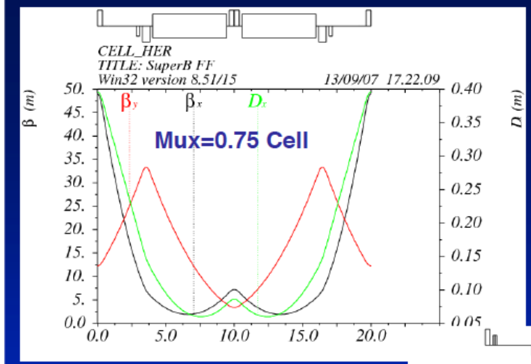
$Z=0$ for particles at $-\sigma_x$ ($-\sigma_x/2$ at low current)

$Z=\sigma_x/\theta$ for particles at $+\sigma_x$ ($\sigma_x/2$ at low current)

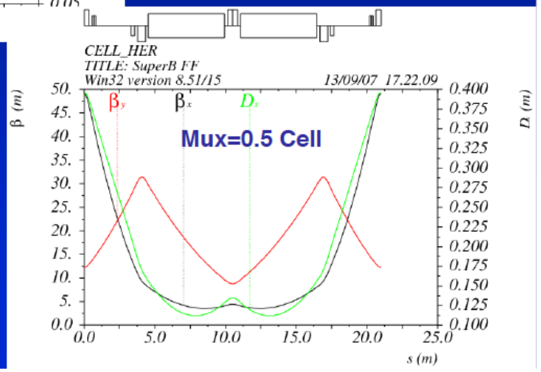
2006 SuperB workshop

LATTICE DEVELOPMENT: FROM SUPERB TO EBS

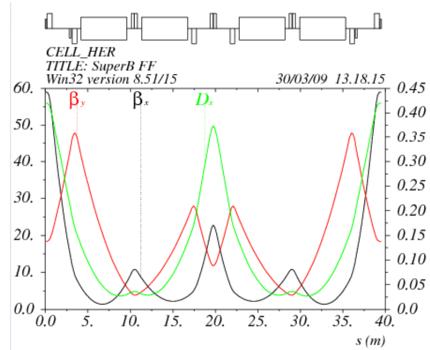
M. Biagini



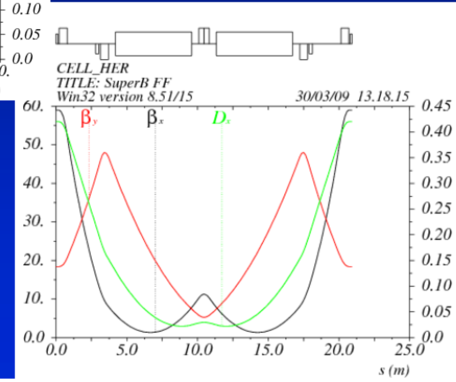
Arc cells layout
Alternating Sequence of these cells



SuperB arc lattice 2008



Arc Cells
Alternating sequence of these cells

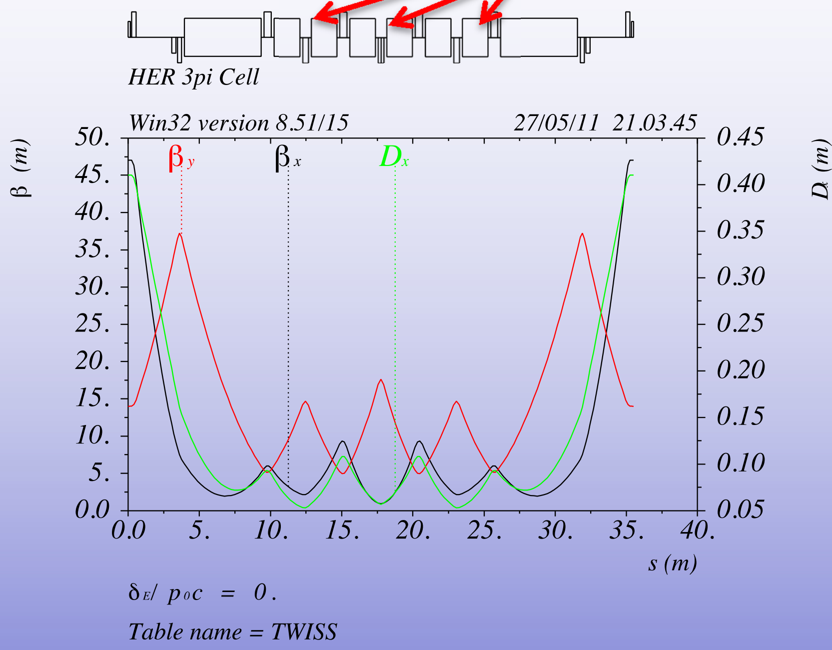


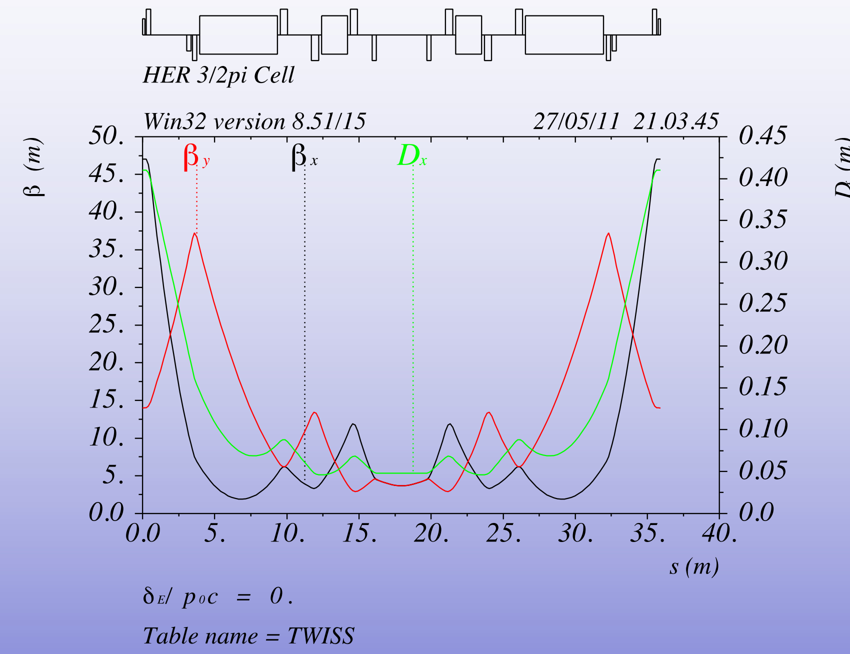
Distances between magnets compatible with PEP hardware
All K-values in range

SuperB arc lattice 2009

SuperB lattice after 1° Low emittance workshop (2011, CERN)

Two dipoles broken in 6 (a la MAXIV)





Alternating sequence of:

- Cell1 $\mu_x = 1.5$, $\mu_y = 0.5$
- Cell2 $\mu_x = 1.215$, $\mu_y = 0.688$

Undulator insertions: length = 3.5m $\beta_{x/y} = 3.2$m

Optics flexible to change beta's and μ's

HYBRID MULTI BEND ACHROMAT: HISTORY

"If the mountain won't come to you, you must go to the mountain"

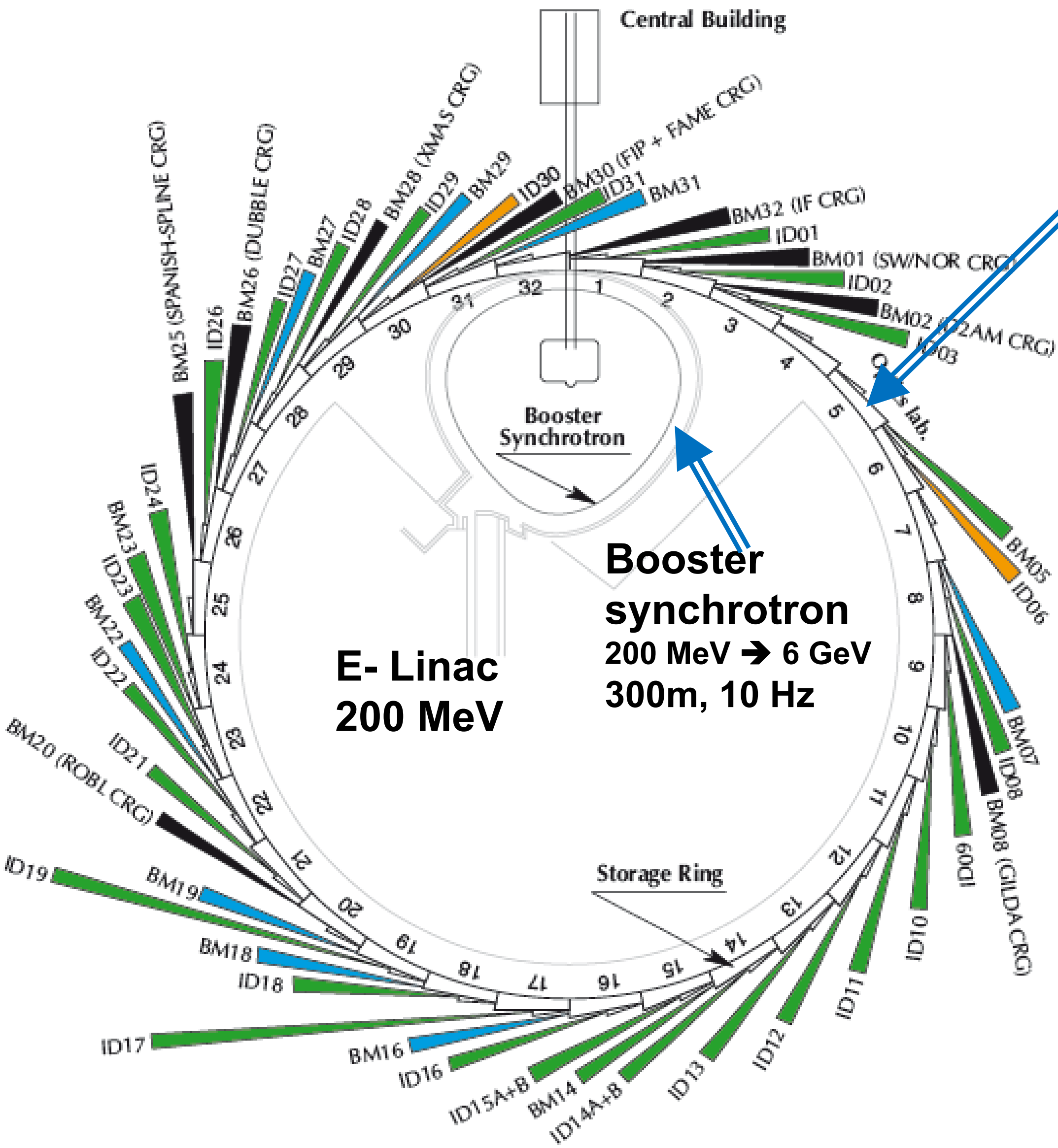
In 2012 I moved to ESRF

At ESRF there was immediate interest and enthusiasm on the potential of the SuperB ARCs design for 4th generation Synchrotron based light sources

The lattice was further improved and adapted to ESRF, thus resulting in the final HMBA version

The ESRF team has been working ever since to make it REAL

ESRF TODAY



Storage ring
6GeV, 844 m

Energy	GeV	6.04
Multibunch Current	mA	200
Horizontal emittance	nm	4
Vertical emittance	pm	3.5

32 straight sections

DBA lattice

42 Beamlines

12 on dipoles

30 on insertion devices

72 insertion devices:
55 in-air undulators, 6 wigglers,
11 in-vacuum undulators, including
2 cryogenic

Extremely Brilliant Source: Accelerator Upgrade

The Accelerator Upgrade Phase II aims to:

- Substantially decrease the Store Ring Equilibrium Horizontal Emittance
- Increase the source brilliance
- Increase its coherent fraction

In the context of the R&D on “Ultimate Storage Ring”, the ESRF has developed a solution, based on the following requirements and constraints:

- Reduce the horizontal equilibrium emittance from 4 nm to less than 140 pm
- Maintain the existing ID straights beamlines
- Maintain the existing bending magnet beamlines
- Preserve the time structure operation and a multibunch current of 200 mA
- Keep the present injector complex
- Reuse, as much as possible, existing hardware
- Minimize the energy lost in synchrotron radiation
- Minimize operation costs, particularly wall-plug power
- Limit the downtime for installation and commissioning to less than 18 months.

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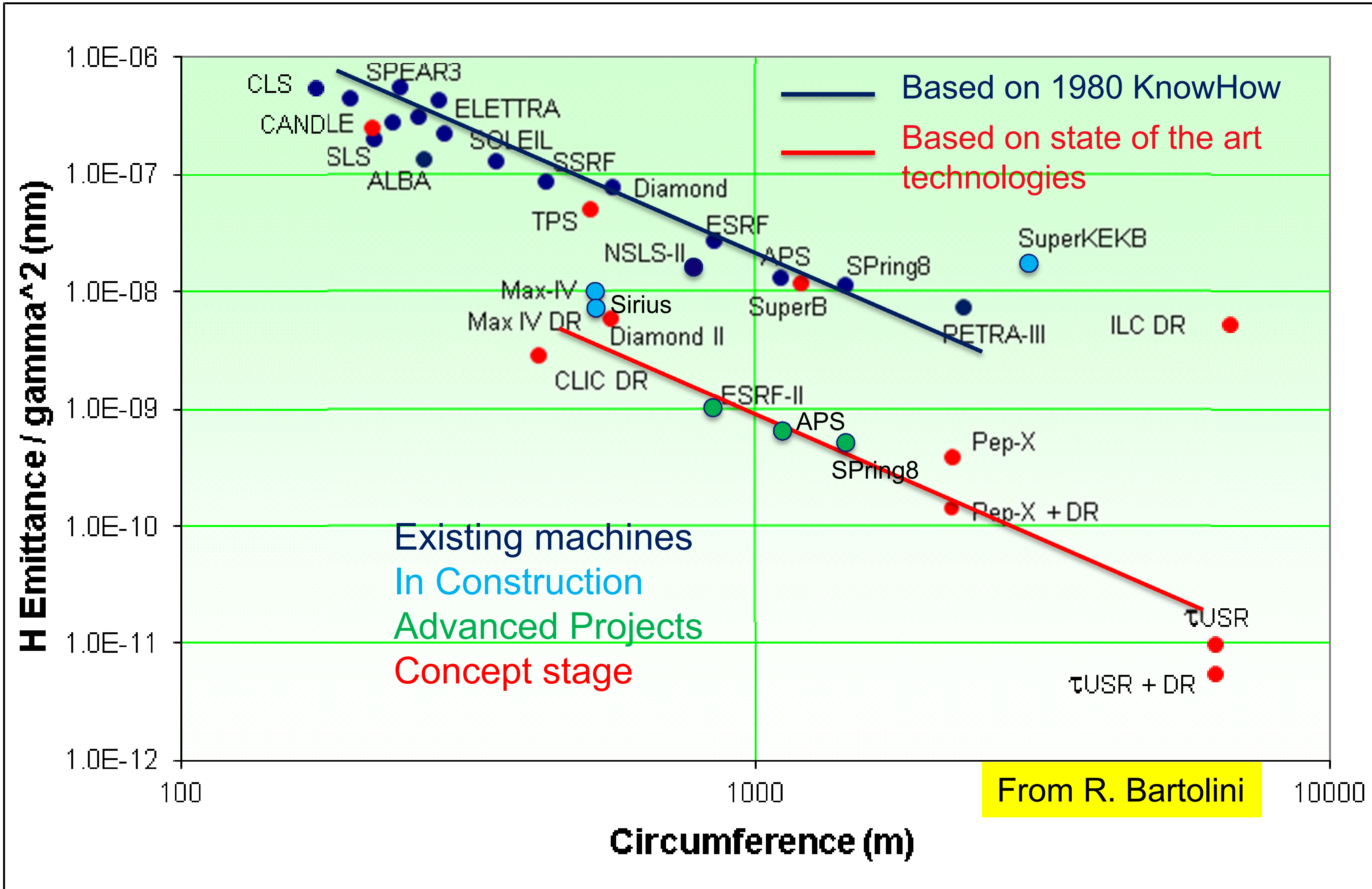
Maintain standard User-Mode Operations until the day of shut-down for installation

LOW EMITTANCE RINGS TREND



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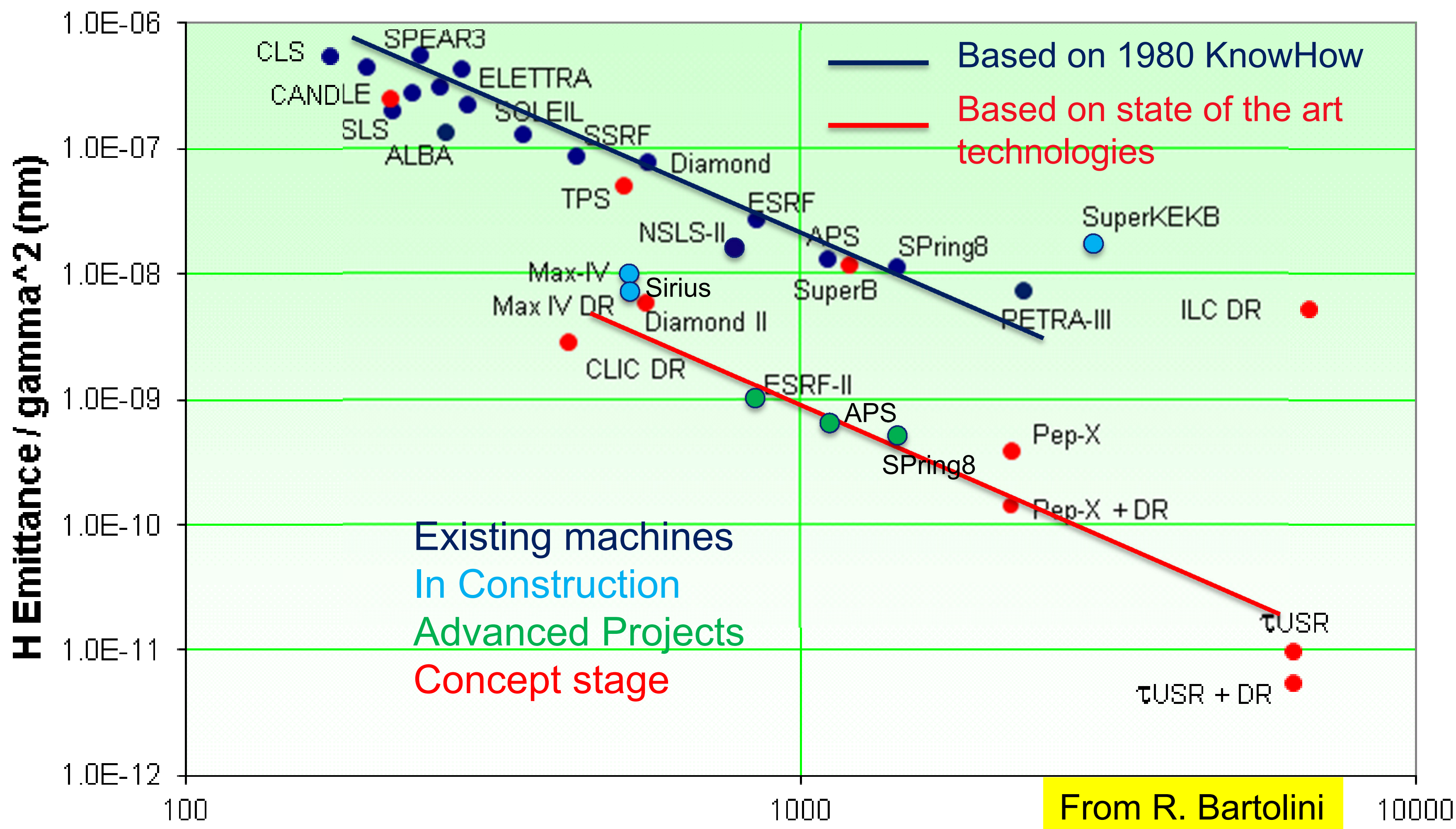
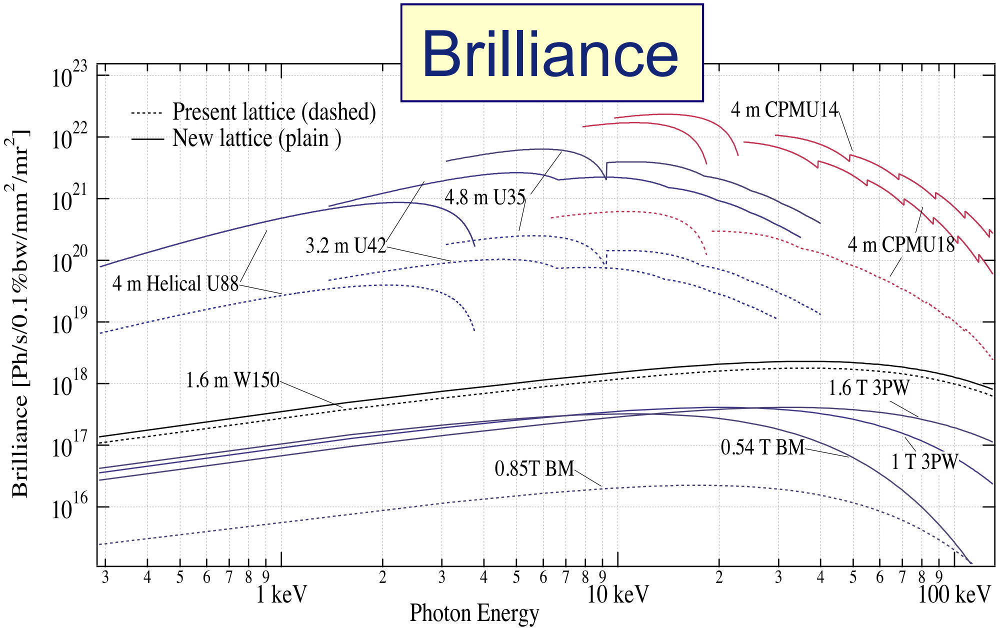


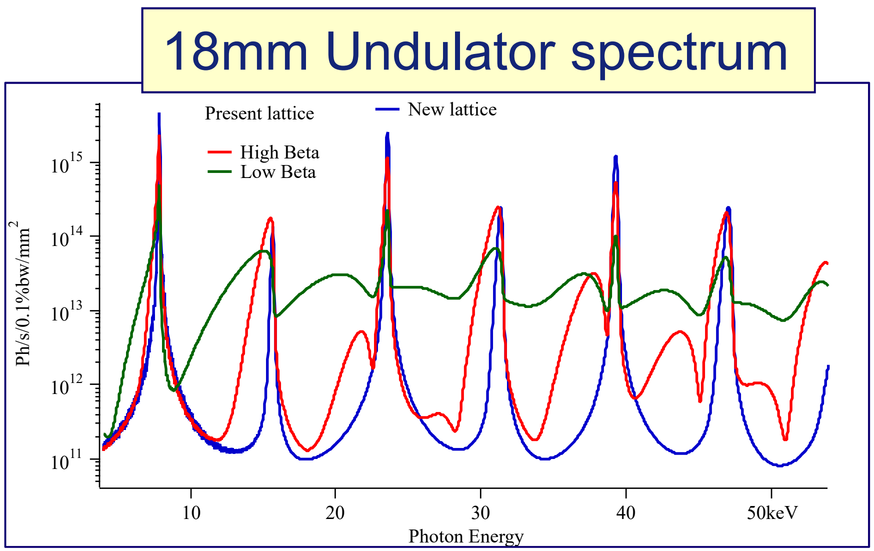
Several facilities will implement low horizontal emittance lattices by the next decade

BRILLIANCE AND COHERENCE INCREASE

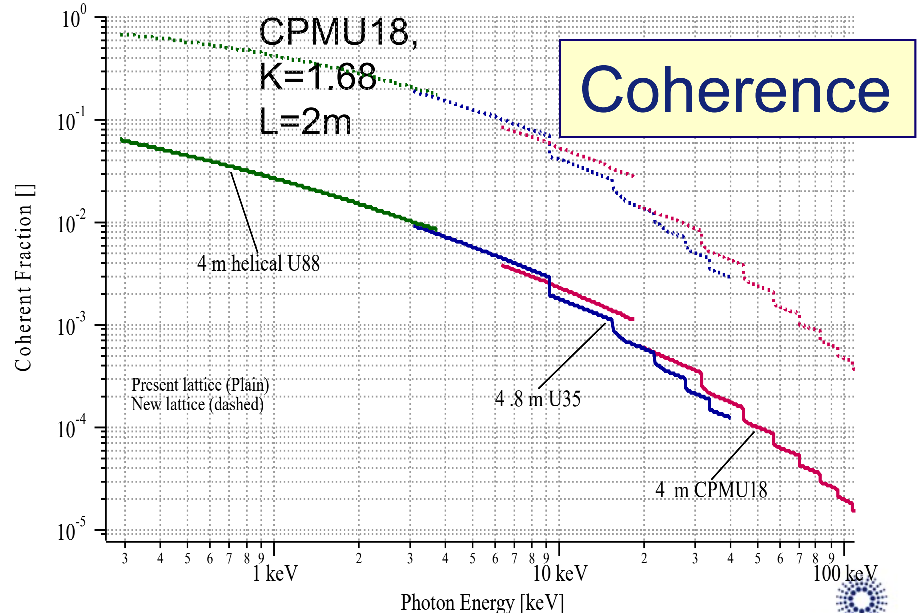


Hor. Emittance [nm]	4	0.135
Vert. Emittance [pm]	4	5
Energy spread [%]	0.1	0.09
β_x[m]/β_z [m]	37/3	6.9/2.6

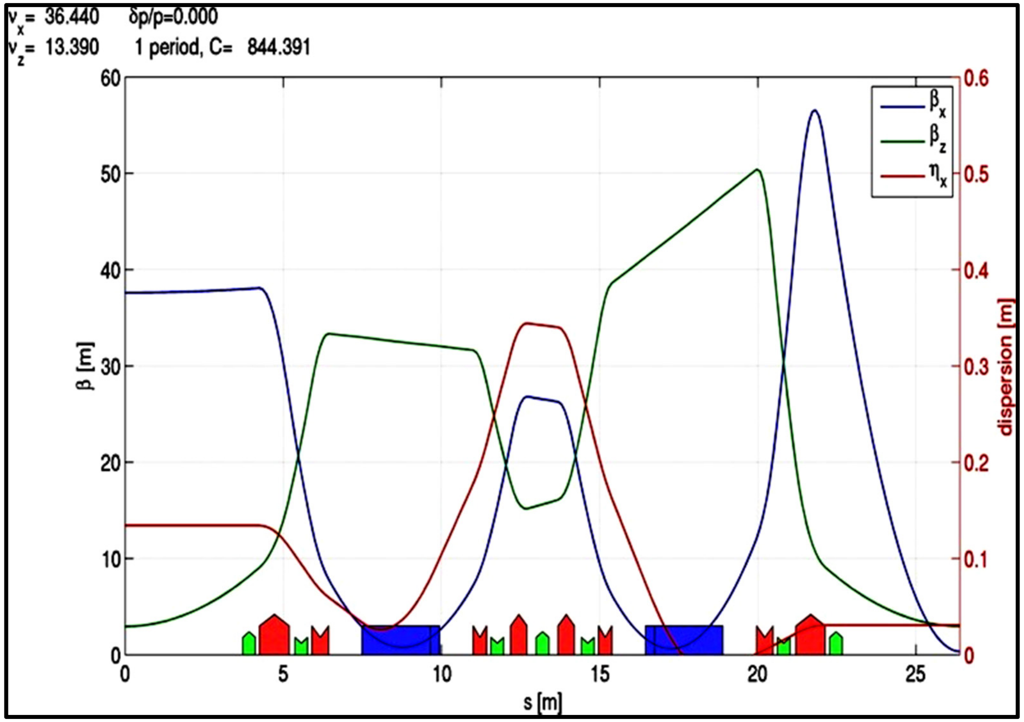
Source performances will improve by a factor 50 to100



Undulator: CPMU18, K=1.68 L=2m



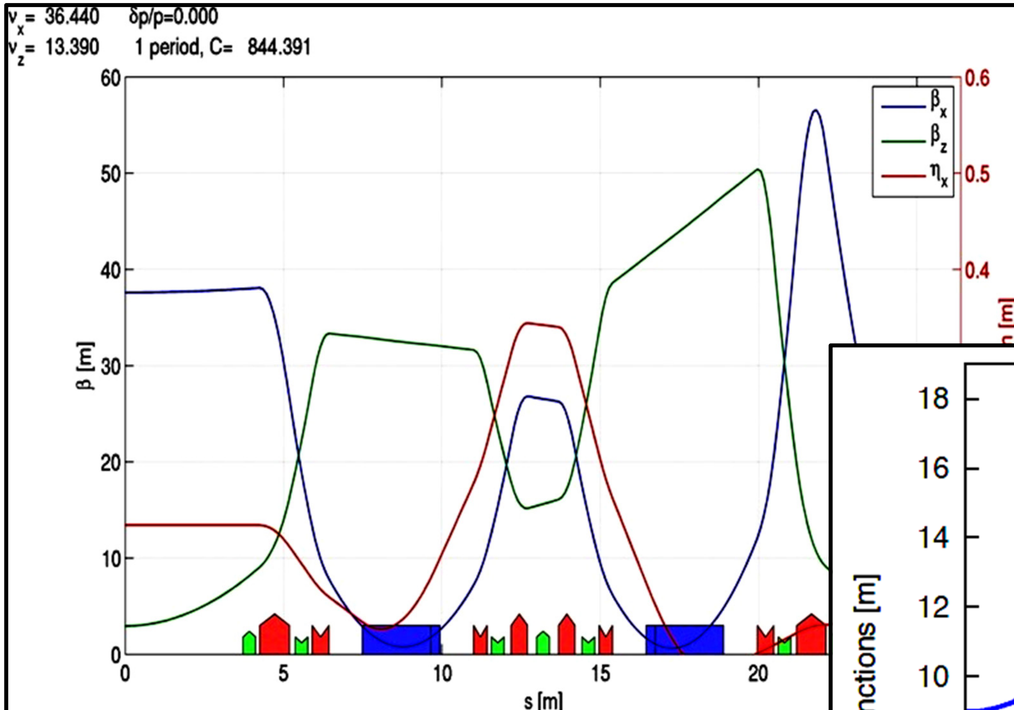
THE EVOLUTION TO MULTI-BEND LATTICE



Double-Bend Achromat (DBA)

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

THE EVOLUTION TO MULTI-BEND LATTICE



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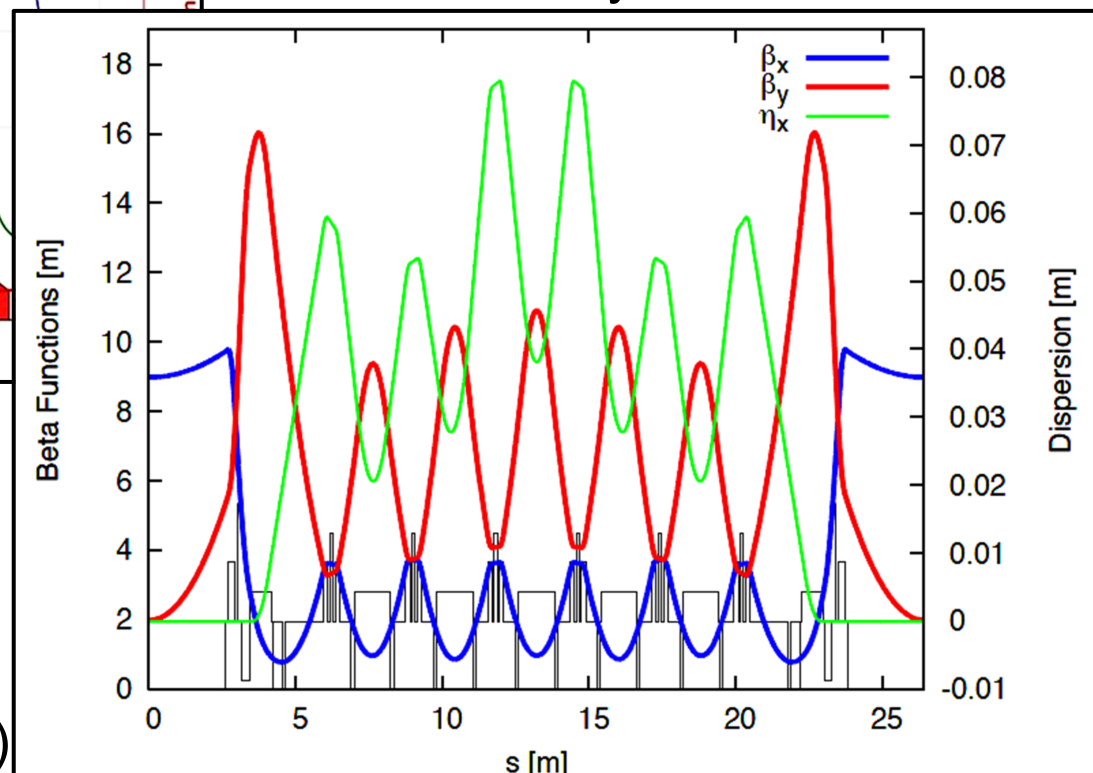
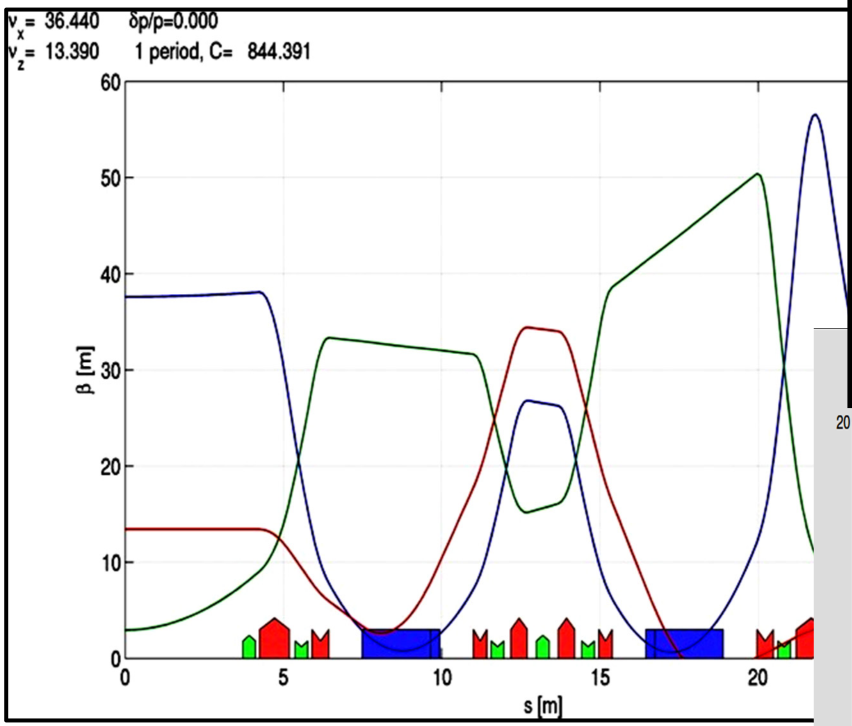


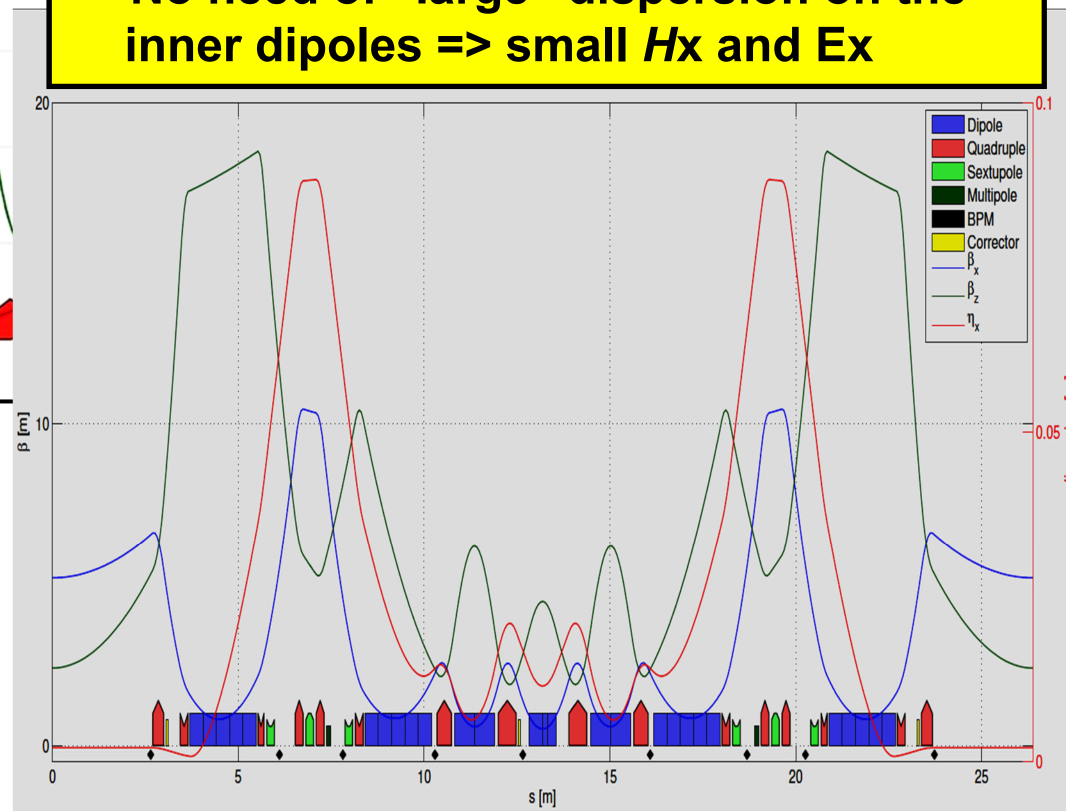
Multi-Bend Achromat (MBA)

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

THE HYBRID MULTI-BEND ACHROMAT (HMBA) LATTICE

- **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**

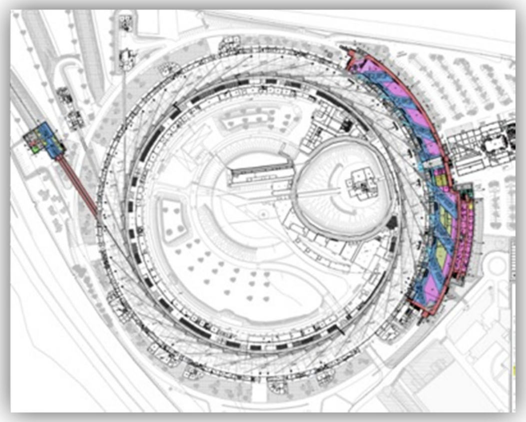


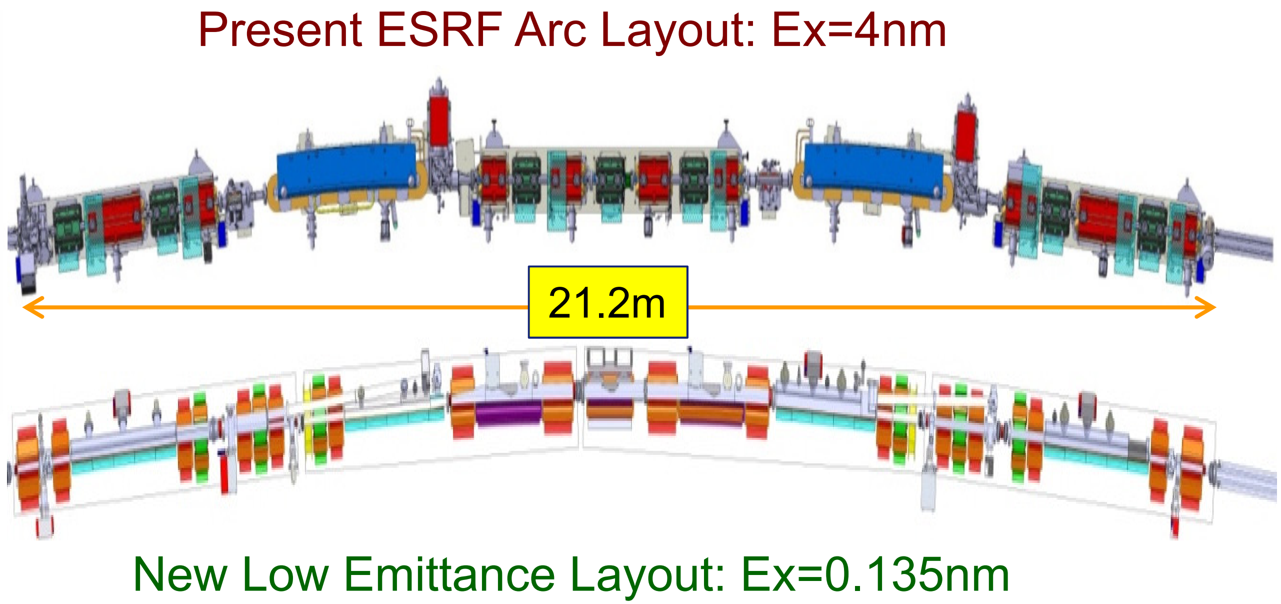


Proposed HMBA cell

- ε_x = 133 pm•rad
- tunes (76.21, 27.34)
- nat. chromaticity (-99, -82)

ESRF Phase II Upgrade at the Bone





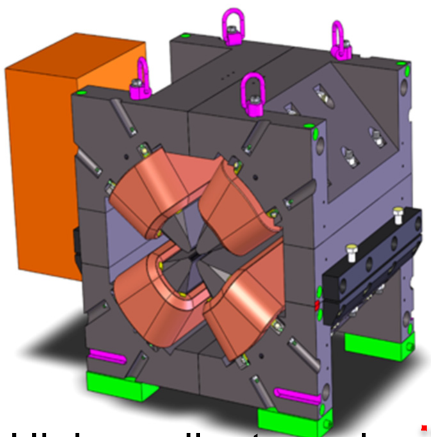
The 844m Accelerator ring consists of:

- 32 identical Arcs 21.2m long
- 32 straight sections 5.2m long equipped with undulators and RF

Each Arc is composed by a well defined sequence of Magnets (dipoles, quadrupoles etc), Vacuum Components (vacuum vessel, vacuum pumps etc), Diagnostic (Beam Position Monitors etc) etc.

All the Arcs will be replaced by a completely new Layout

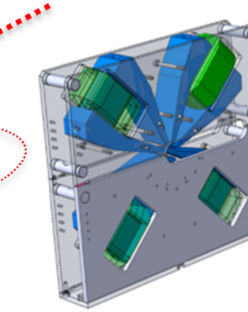
Technical challenge: Magnets System



Mechanical design final drawing phase

- Large positioning pins for opening repeatability
- Tight tolerances on pole profiles
- Prototypes delivered in the period September 2014-Spring 2015

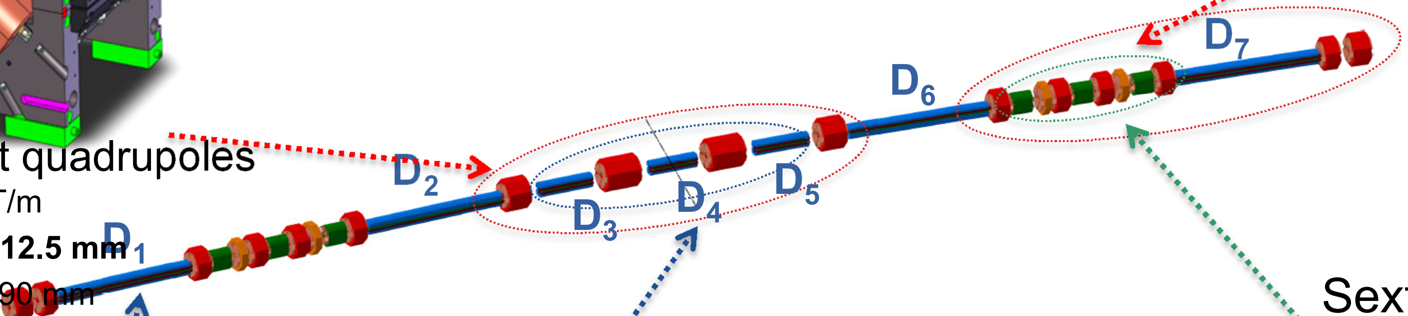
Quadrupole
Around 52Tm^{-1}



Octupoles

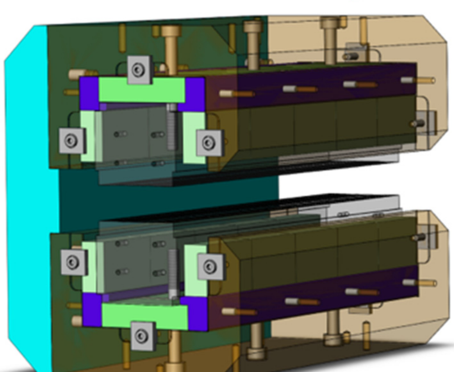
High gradient quadrupoles

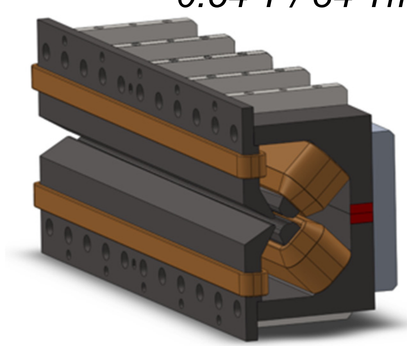
- Gradient: 90 T/m
- **Bore radius: 12.5 mm**
- Length: 390/490 mm
- Power: 1-2 kW

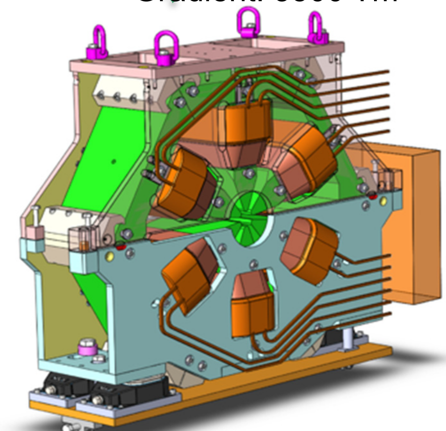


Sextupoles
Length 200mm
Gradient: 3500 Tm^{-2}

Combined Dipole-Quadrupoles
0.54 T / 34 Tm^{-1} & 0.43 T / 34 Tm^{-1}





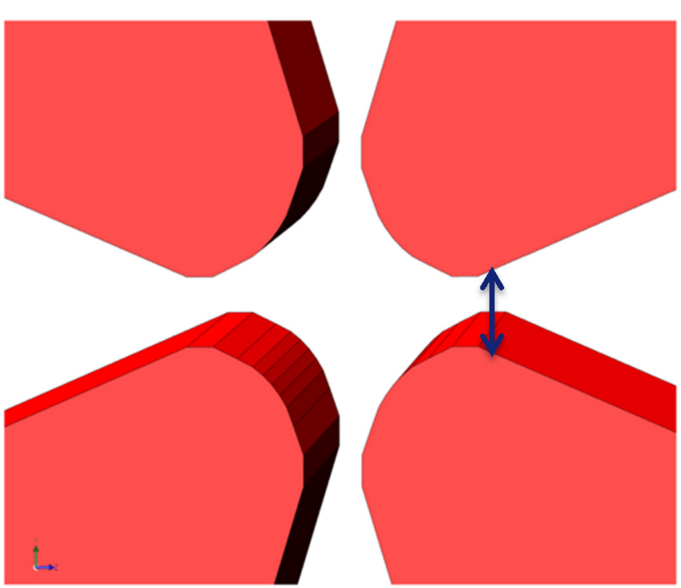


Permanent magnet (Sm_2Co_{17}) dipoles
longitudinal gradient 0.16 – 0.65 T, magnetic gap 25 mm
1.8 meters long, 5 modules

Gael Le Bec

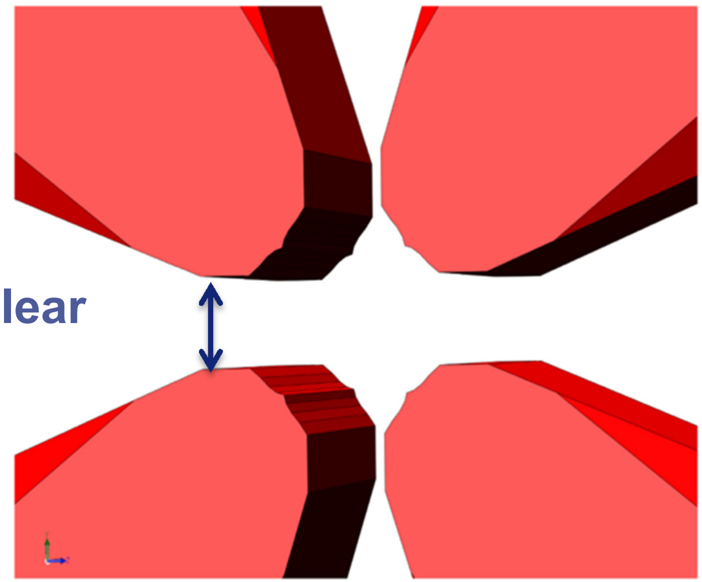
Pole shape optimization

Imposed 11mm stay clear from pole to pole for all magnets for optimal synchrotron radiation handling

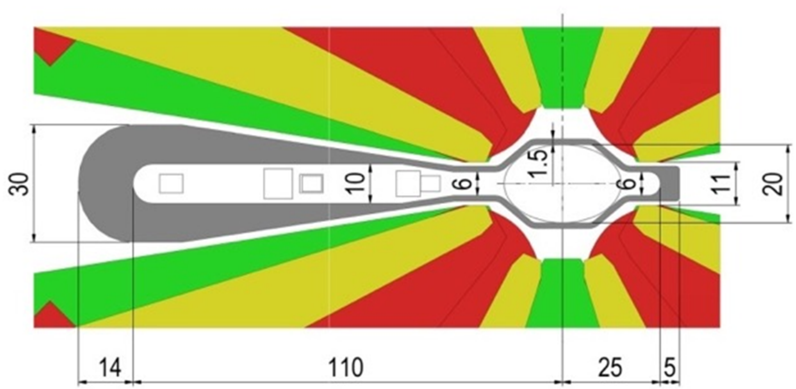


Low gradient pole profile

11mm stay clear



High gradient pole profile

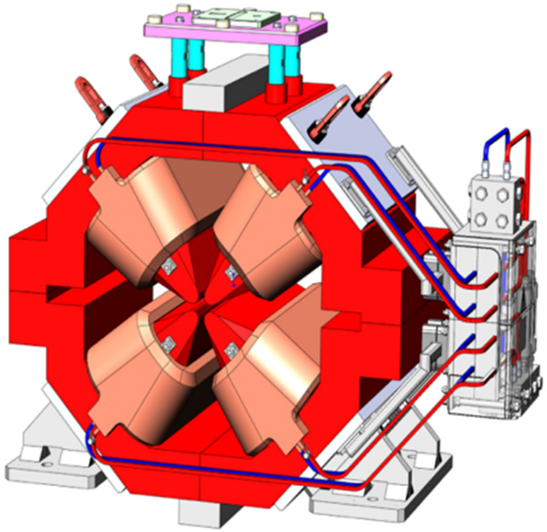


Vacuum chamber and magnets sections

QUADRUPOLES

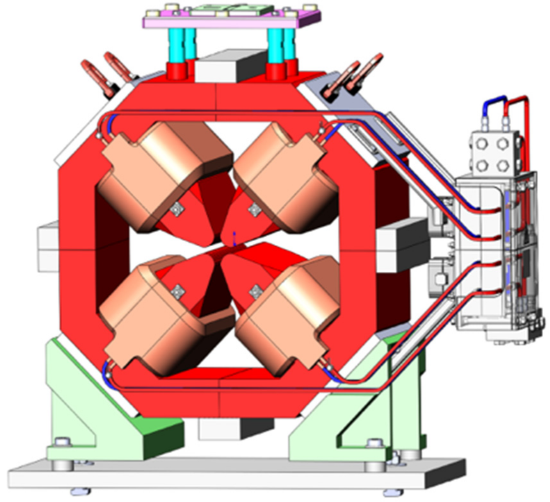
High Gradient

- 91 T/m gradient, 388 – 484 mm length
- 12.7 mm bore radius, 11 mm vertical gap
- 1.4 – 1.6 kW power consumption



Moderate Gradient

- Up to 58 T/m gradient, 162– 295 mm length
- 16.4 mm bore radius, 11 mm vertical gap
- 0.7 – 1.0 kW power consumption



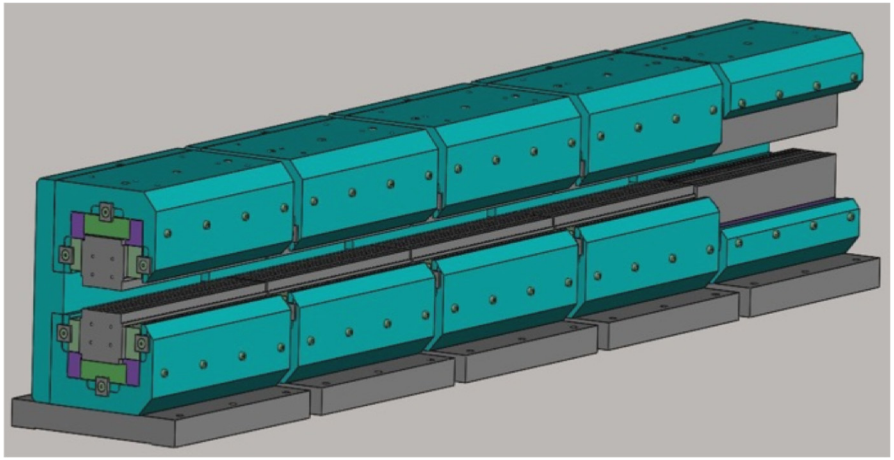
DIPOLES WITH LONGITUDINAL GRADIENT

Better longitudinal matching η_x-β_x in the dipoles (Y. Papaphilippou)

Optimal η_x in the straight section is close to 0

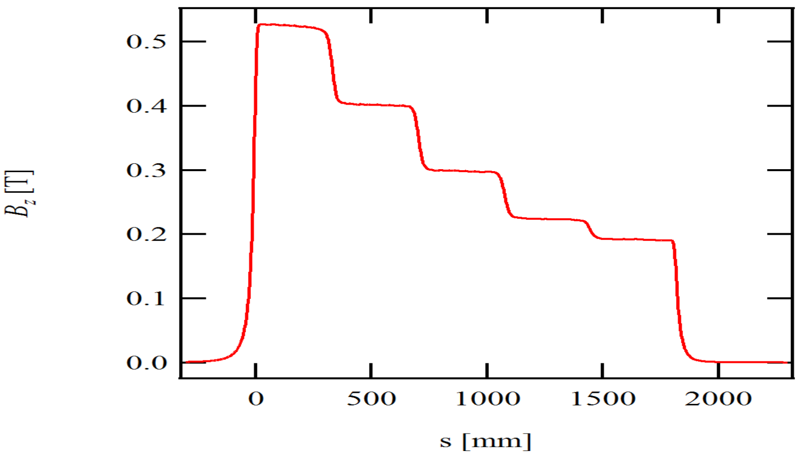
Larger η_x at the sextupoles

Smaller ε_x

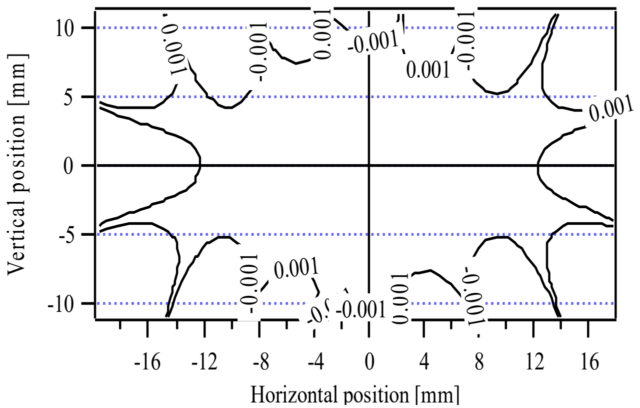


Specifications

- 0.17 – 0.67 T field
- 5 modules of 357 mm each
- Larger gap for the low field module
- Allows the installation of an absorber

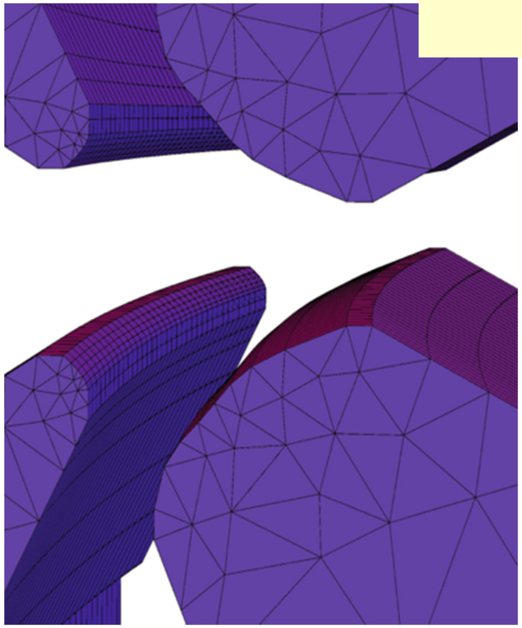


Longitudinal field distribution

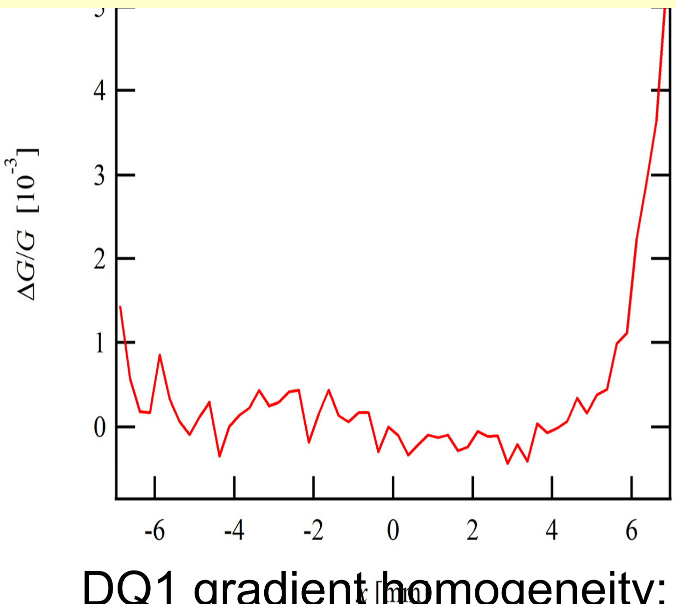


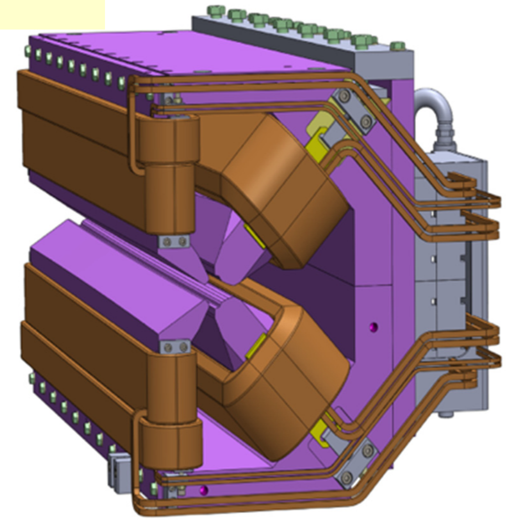
Measured field integral homogeneity (one module)

Zeroth order design started from a HERA injection septum quadrupole



DQ1 pole shape





DQ1 gradient homogeneity:

Integration of trajectory along an arc

DQ1: 1.028 m, 0.57 T, 37.1 T/m

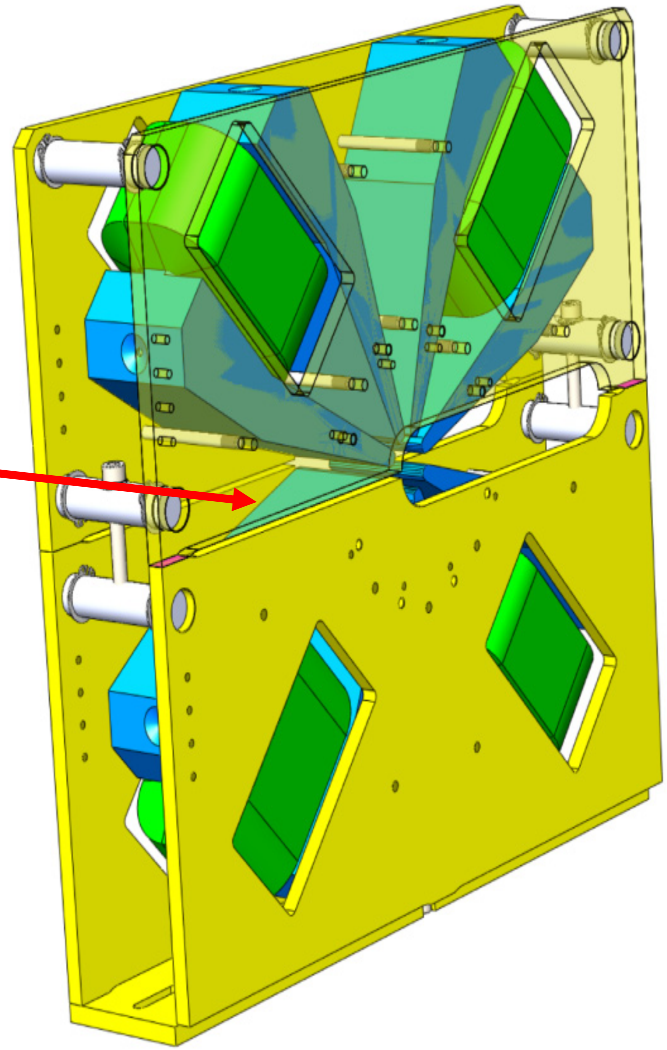
$\Delta G/G$ < 1% (GFR radius 7 mm)

DQs are machined in 7 solid iron plates

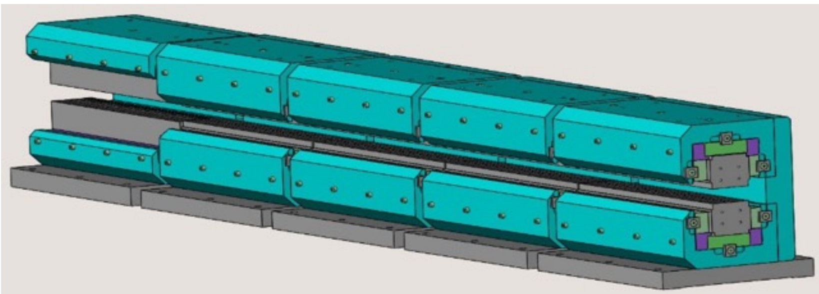
Poles curved longitudinally for maximum stay clear and good field region

Specifications

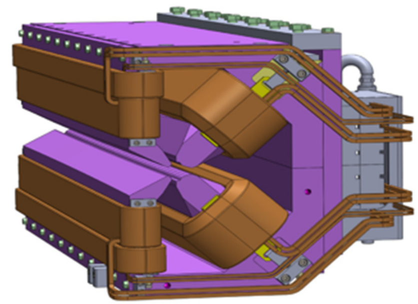
- 48 kT/m^3 nominal strength (70 kT/m^3 maximum)
- 90 mm length
- 4 Water cooled coils at the return-field yoke
- Allows for the required stay-clear for Synchrotron Radiation fans



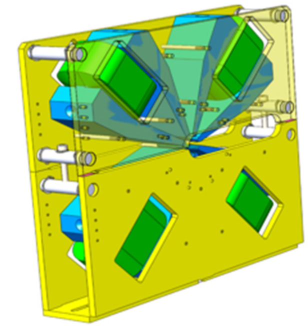
ESRF EBS (2015-2022): MAGNETS PROCUREMENT



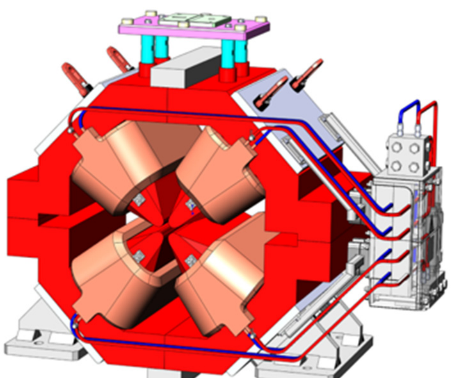
132 dipoles



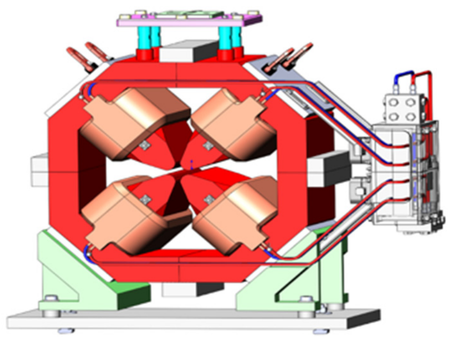
99 dipole-quadrupoles



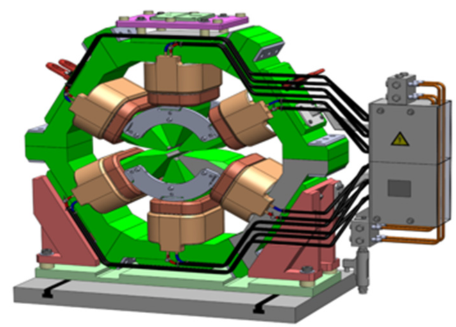
66 octupoles



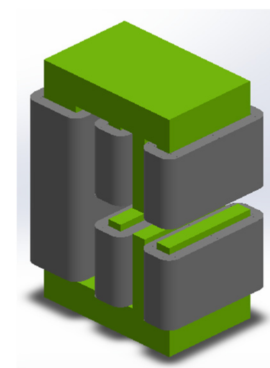
398 moderate gradient quadrupoles



130 high gradient quadrupoles



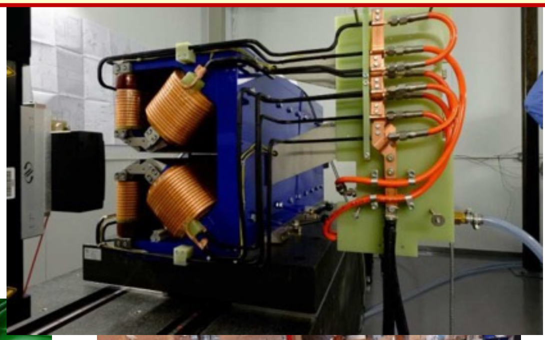
196 sextupoles

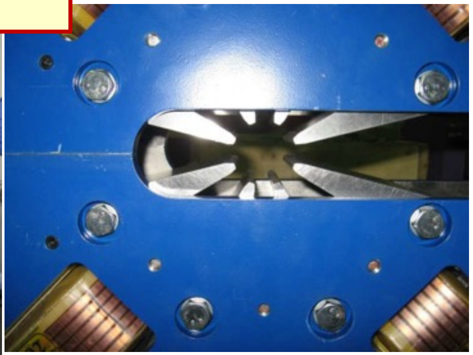


100 correctors

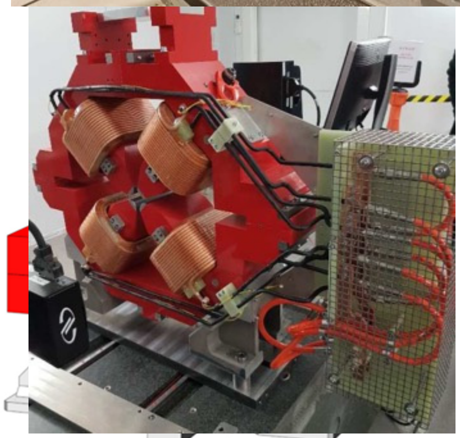
ESRF EBS (2015-2022): MAGNETS PROCUREMENT

All contracts in place, magnets in fabrication
FAT for HG-Quads, Sextupoles and correctors last week
All FAT completed
More than 1000 Magnets to be procured by the end of 2018





66 octupoles



398 moderate gradient quadrupoles

130 high gradient quadrupoles

196 sextupoles

100 correctors

IMPLEMENTATION IN CHARTREUSE HALL

Module’s Yokes

Dipole assembly area

IMPLEMENTATION IN CHARTREUSE HALL

PM Dipoles are being assembled by ESRF staff
More than 650 Magnets Modules for a total of about 130 5-Module dipoles

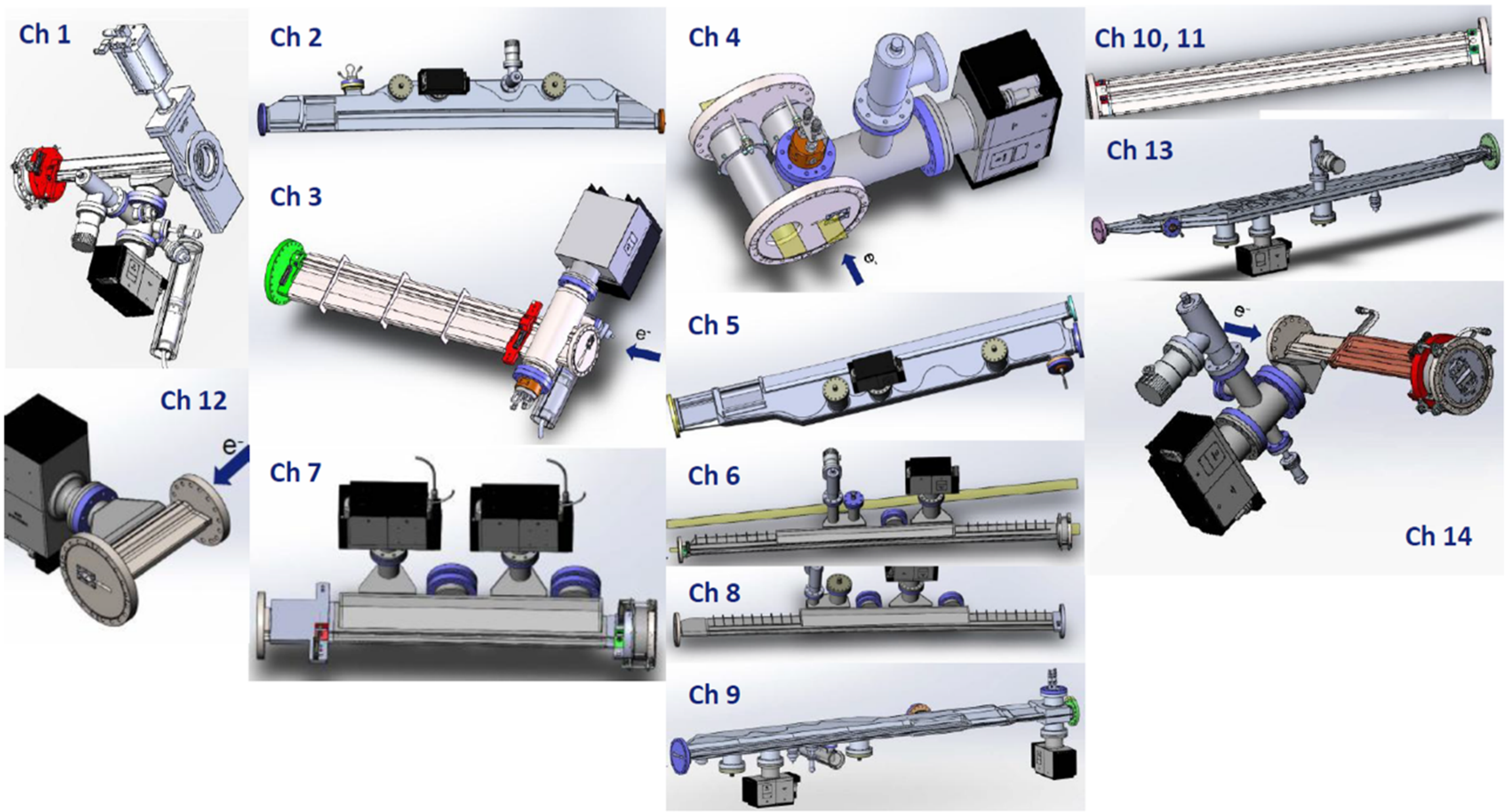
PM assembly tool

~50 dipoles out of 128 already completed

Module's Yokes

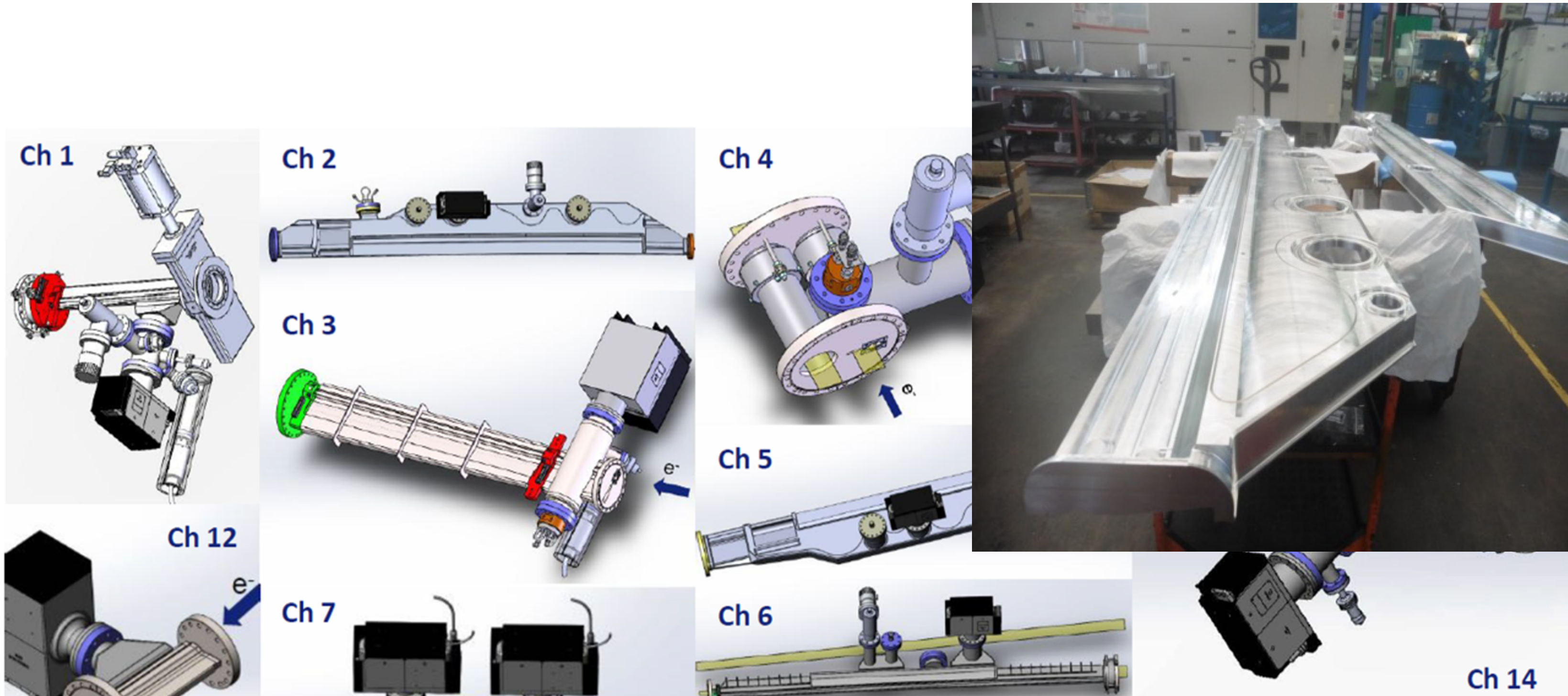
Dipole assembly area

ESRF EBS (2015-2022): VACUUM CHAMBERS PROCUREMENT



Courtesy of ASD-FE, ISDD-MEG & TID-VG

ESRF EBS (2015-2022): VACUUM CHAMBERS PROCUREMENT



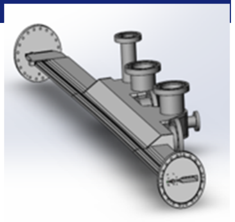
All contracts in place, chambers in fabrication
FAT for aluminium chambers: December 2016
All FAT completed
More than 450 Vacuum Chambers to be procured by the end of 2018

Courtesy of ASD-FE, ISDD-MEG & TID-VG

LOW PROFILE STAINLESS STEEL CHAMBERS

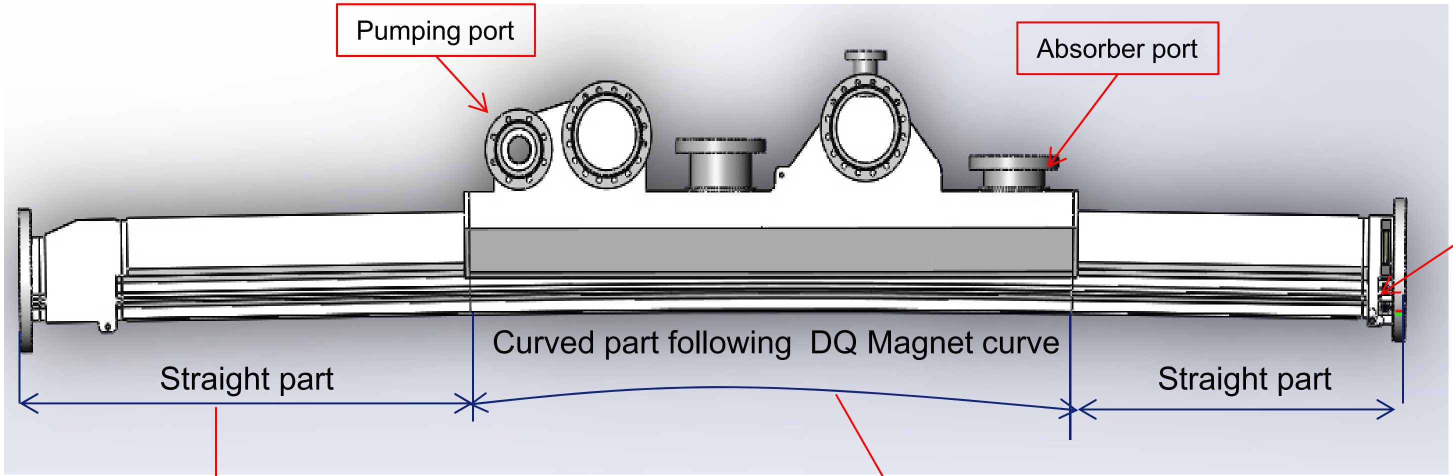
Material : 316 LN

Curved Chambers

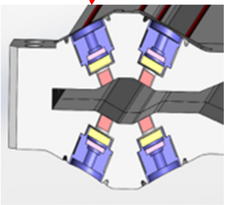


Pumping port

Absorber port

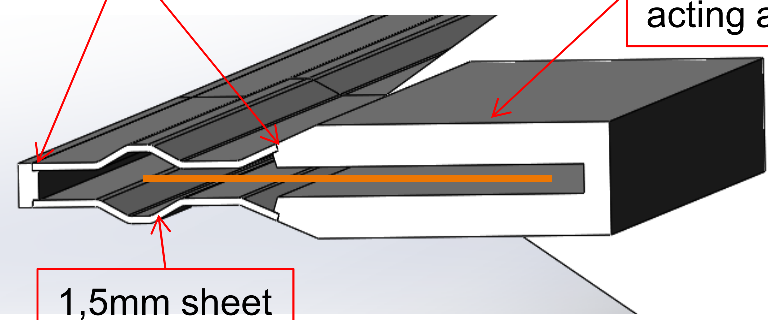


BPM Block



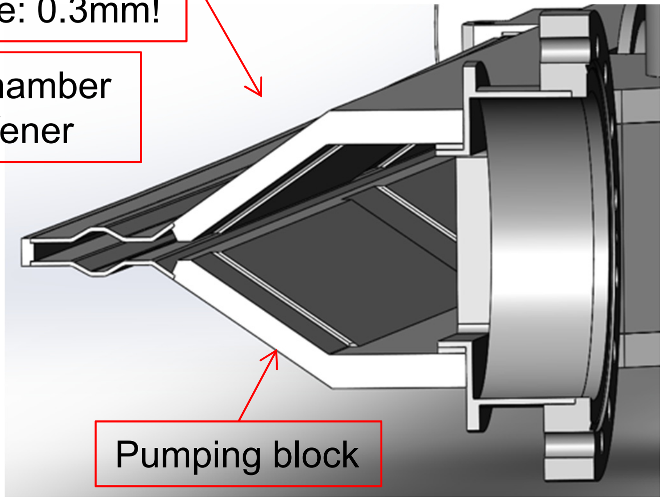
Requested shape tolerance: 0.3mm!

EB Welding

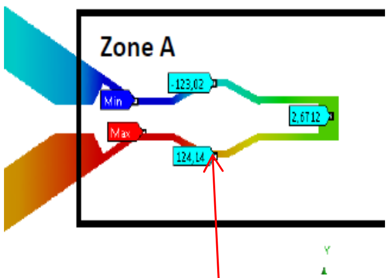


Thick ante-chamber acting as stiffener

1,5mm sheet



Pumping block



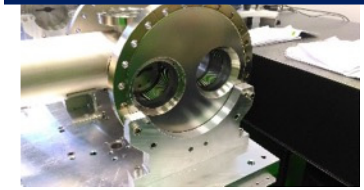
Deformation at the Beam area 0.125mm

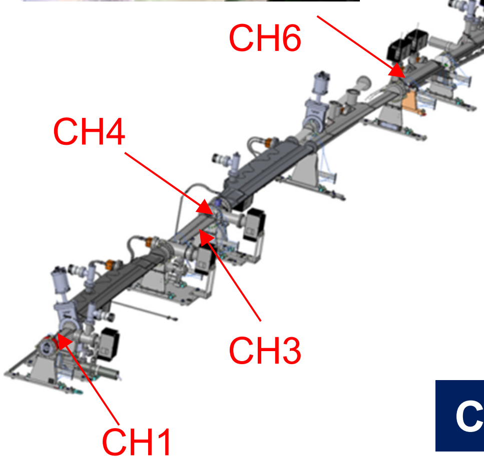
Joel Pasquaud

PRODUCTION – VACUUM CHAMBERS (STAINLESS STEEL)

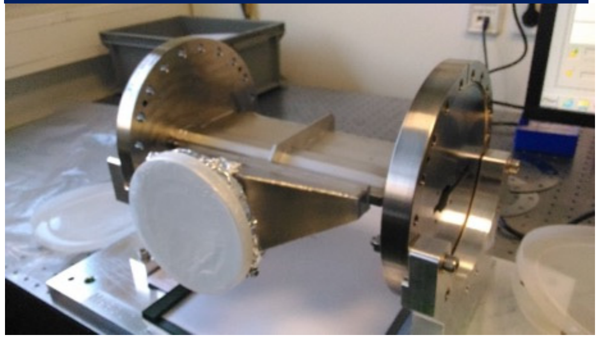
Stainless steel chambers: 2 contracts FMB (D)
CH14: 1 contract PINK (D)

CH4 high profile pre series



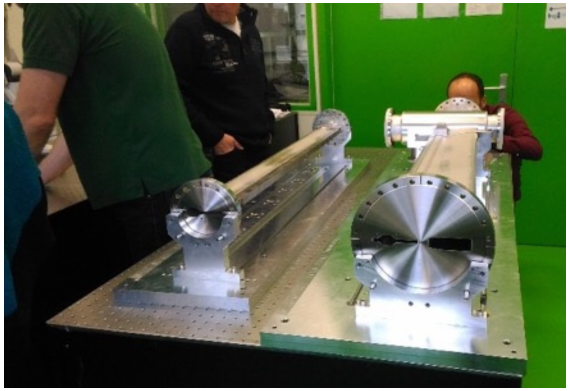


CH12 high profile pre series

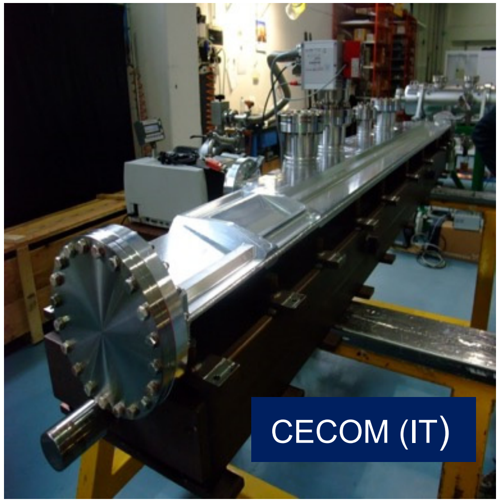


CH1 high profile pre series

Pre-series still in progress



CH3 & 11 high profile pre series

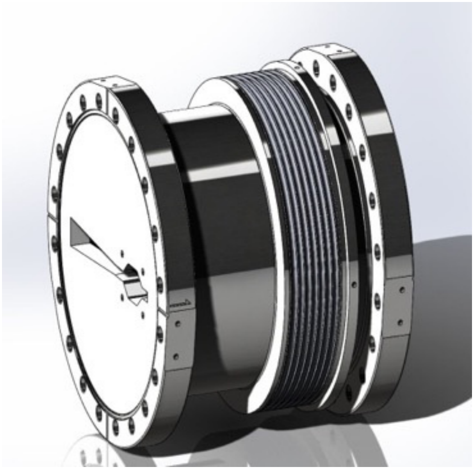


CH7 low profile pre series in progress

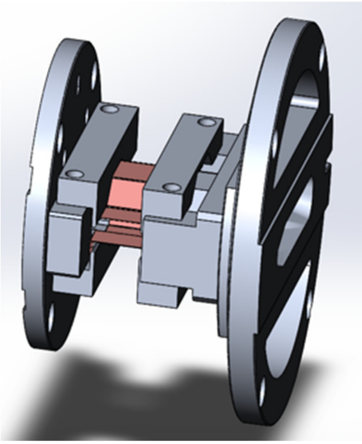
The European Synchrotron | ESRF

Courtesy of P Van Vaerenbergh, J Pasquaud, L Goirand

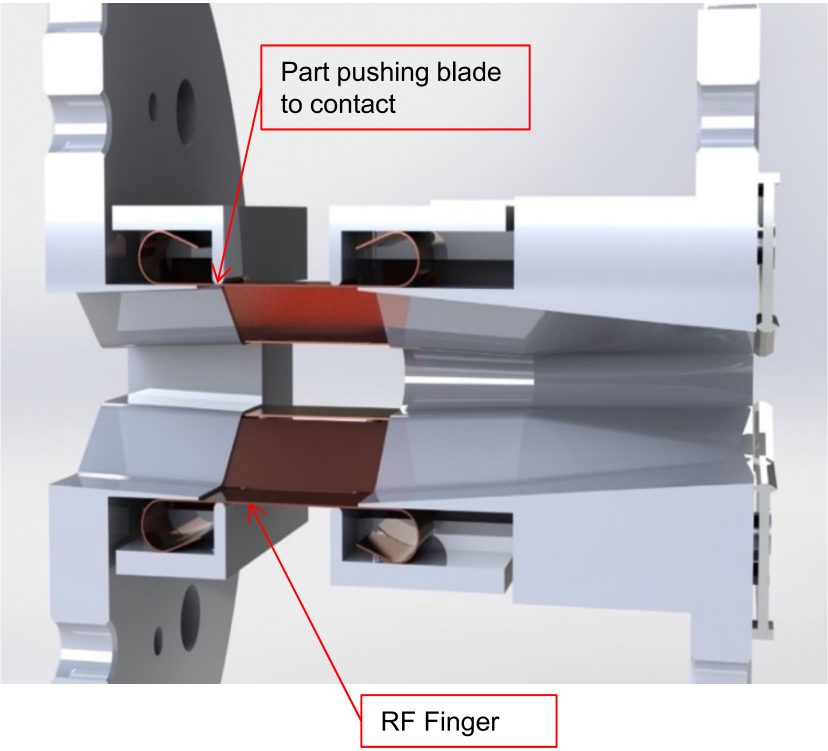
BELLOW RF FINGERS: ESRF DESIGN PATENTED



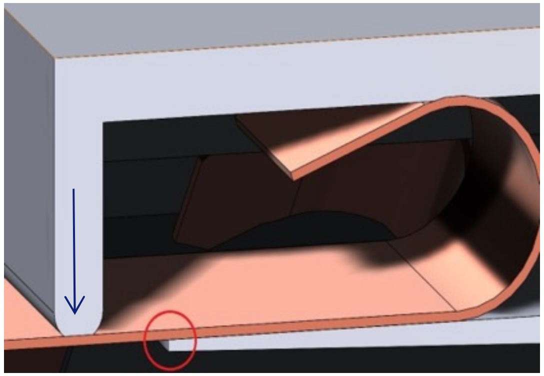
Bellow assembly



RF Finger assembly



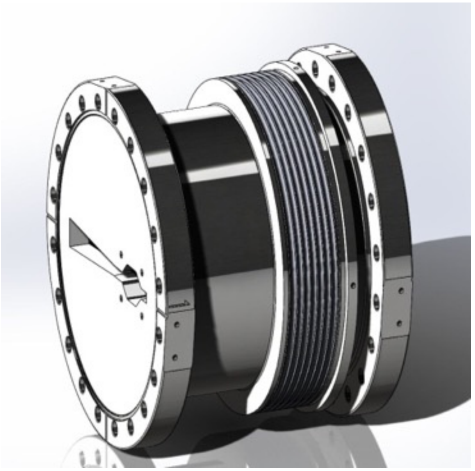
Blade contact



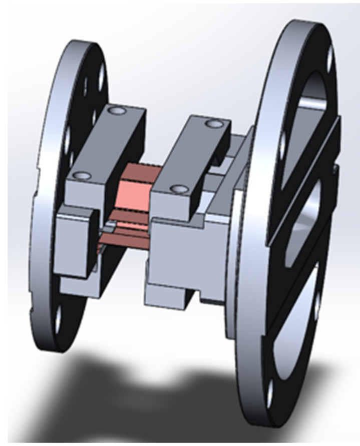
- Smooth transitions between profiles
- No change of the profile inside the RF fingers

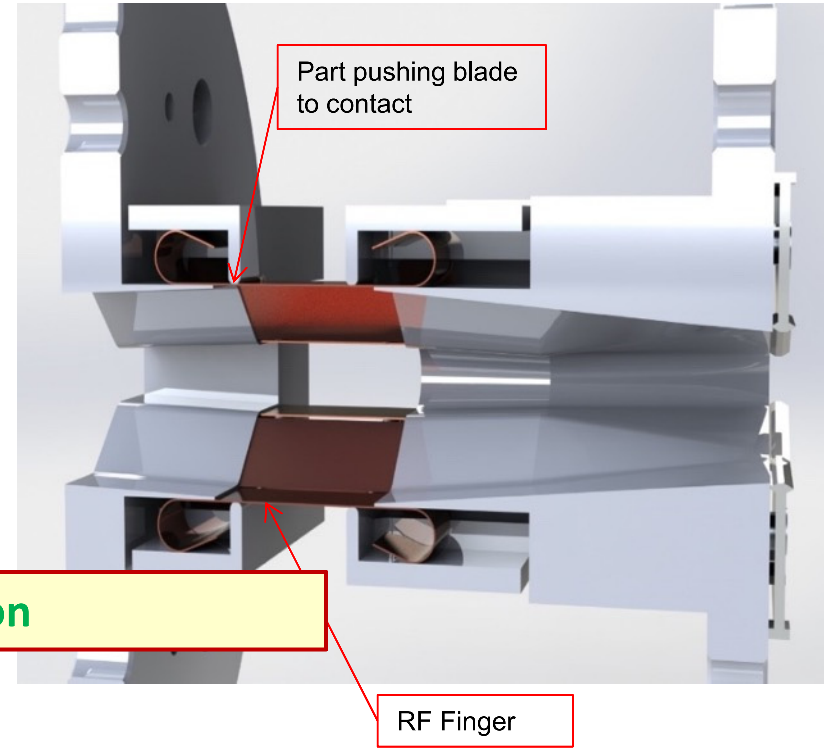
Courtesy of P Brumund, L Eybert, L Goirand

BELLOW RF FINGERS: ESRF DESIGN PATENTED



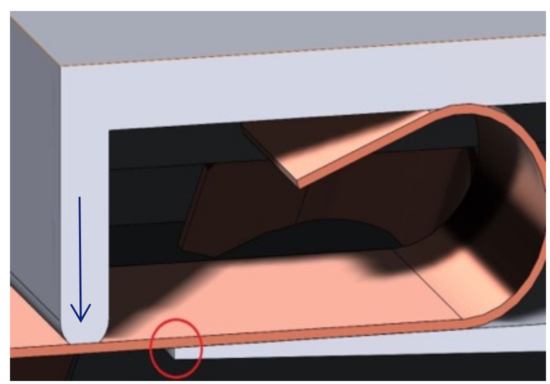
Bellow assembly





In fabrication

Blade contact

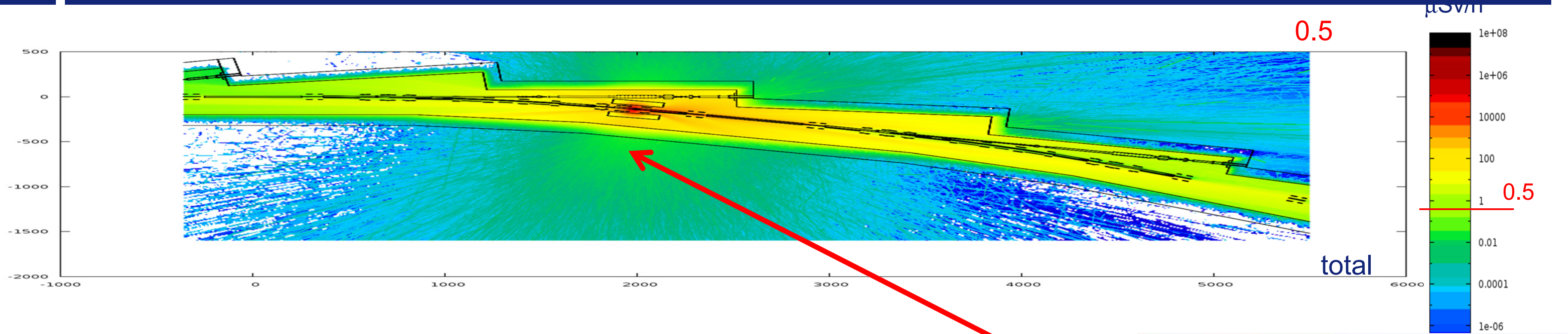


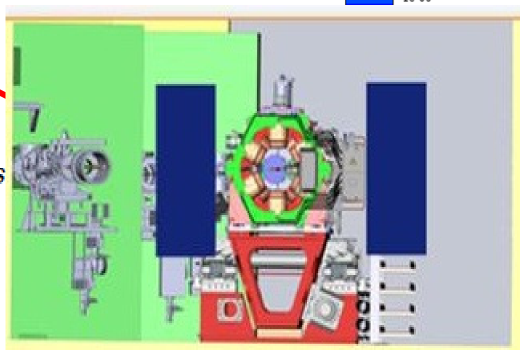
- Smooth transitions between profiles
- No change of the profile inside the RF fingers

Courtesy of P Brumund, L Eybert, L Goirand

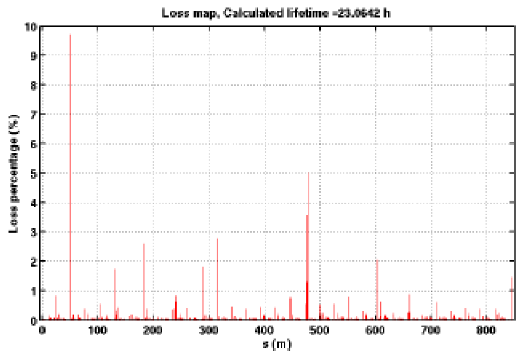
COLLIMATOR SHIELDING

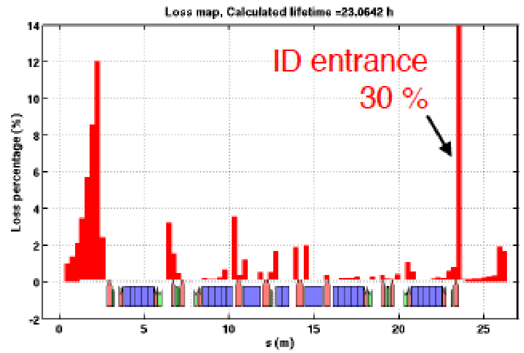
50 CM LEAD LOCAL SHIELDING



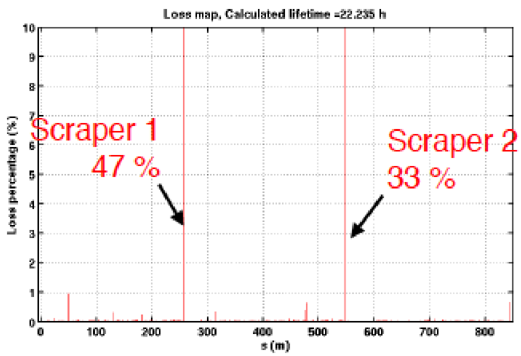


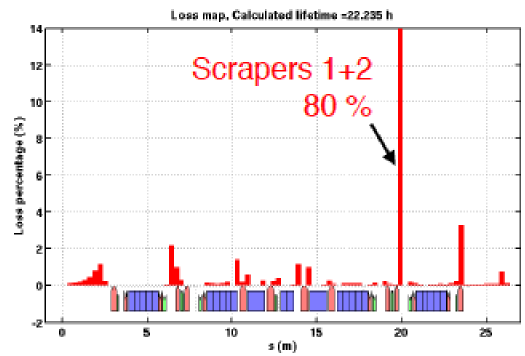
80% of the losses are relocated on the scrapers for 4% lifetime reduction:





No scrapers

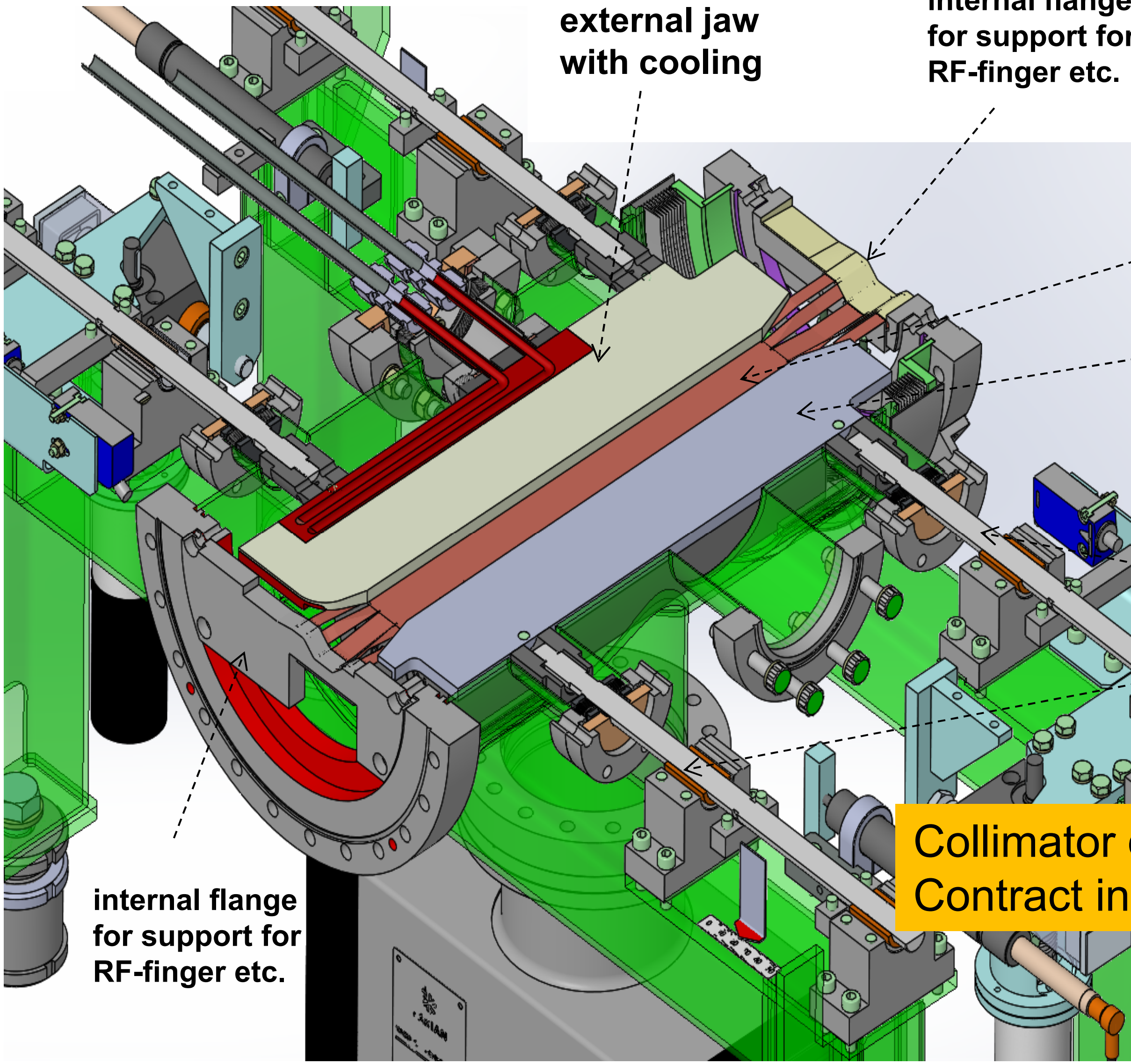




Two scrapers in DR_37 of cells 13 and 24

cm

COLLIMATOR FOR CH.#12 IN CELLS 13 AND 24

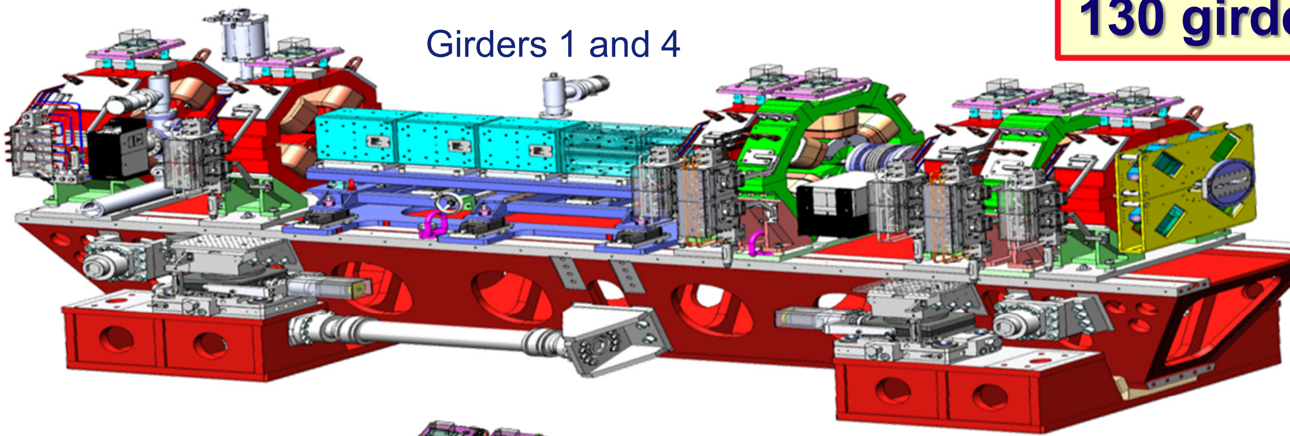


Collimator design completed
Contract in place by Dec 2017

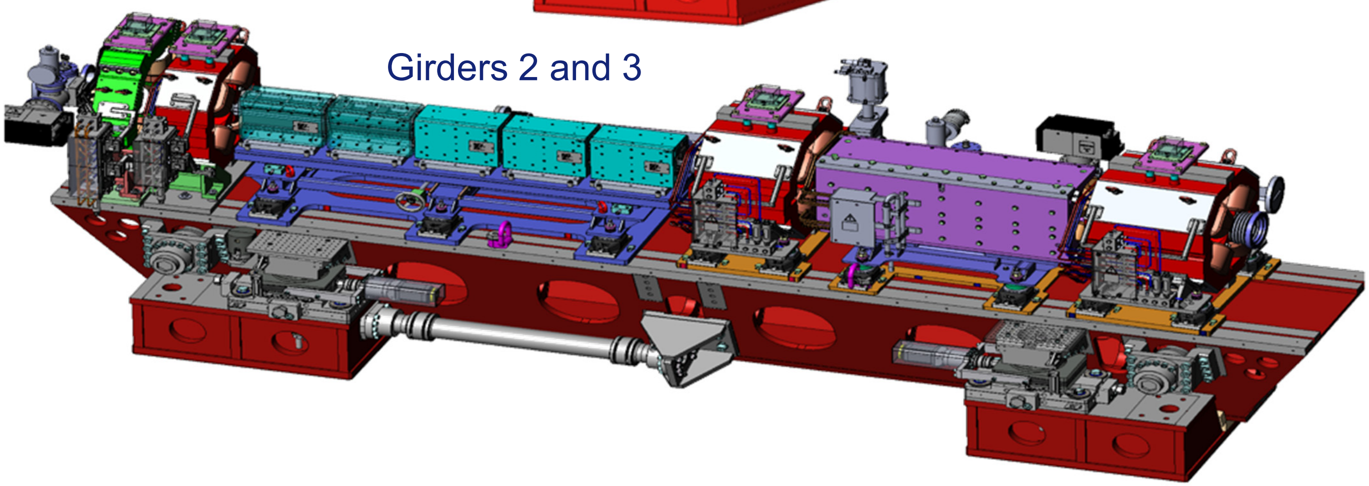
ESRF EBS (2015-2022): GIRDERS PROCUREMENT

130 girders,10-12t each

Girders 1 and 4

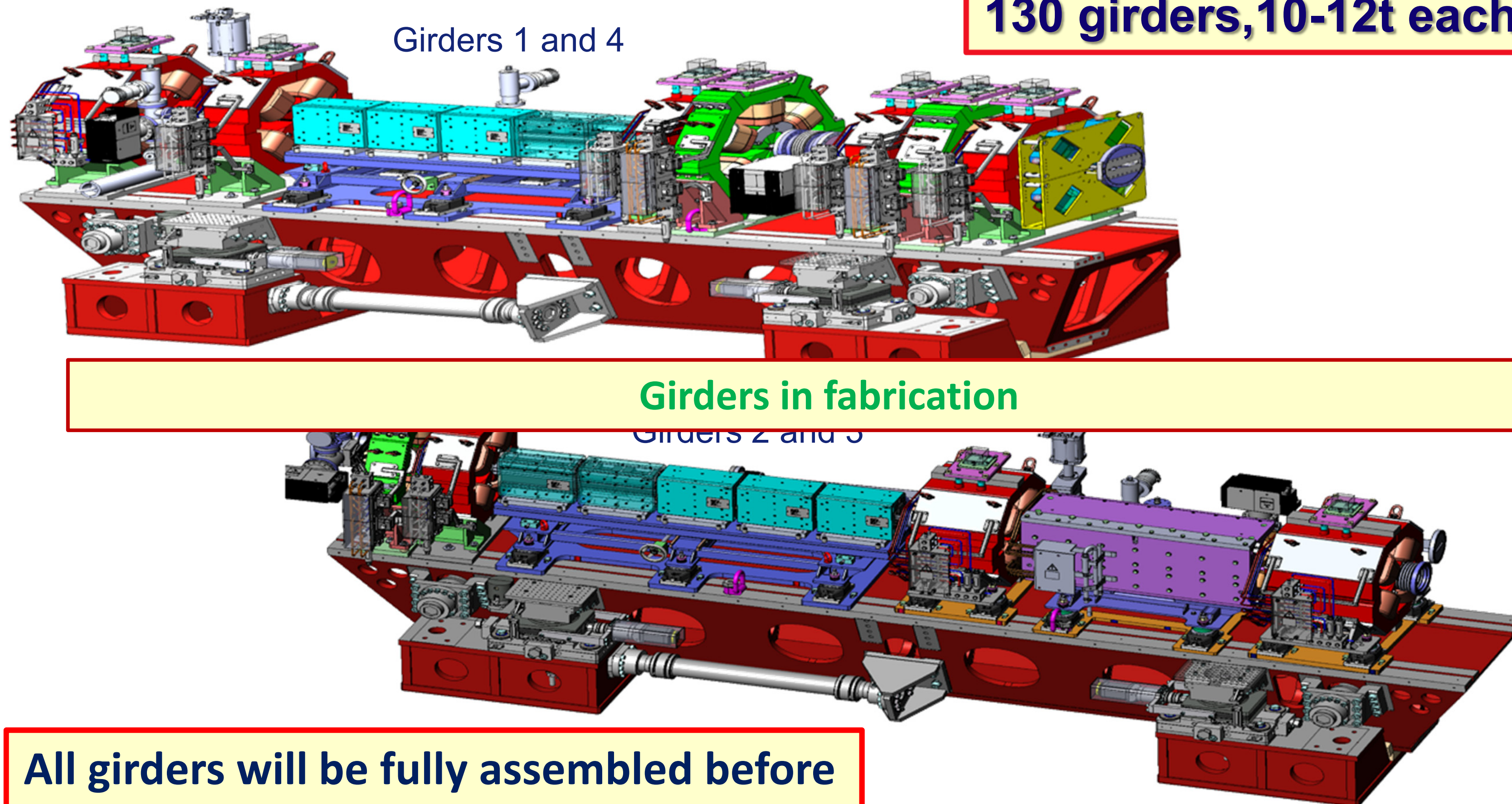


Girders 2 and 3



ESRF EBS (2015-2022): GIRDERS PROCUREMENT

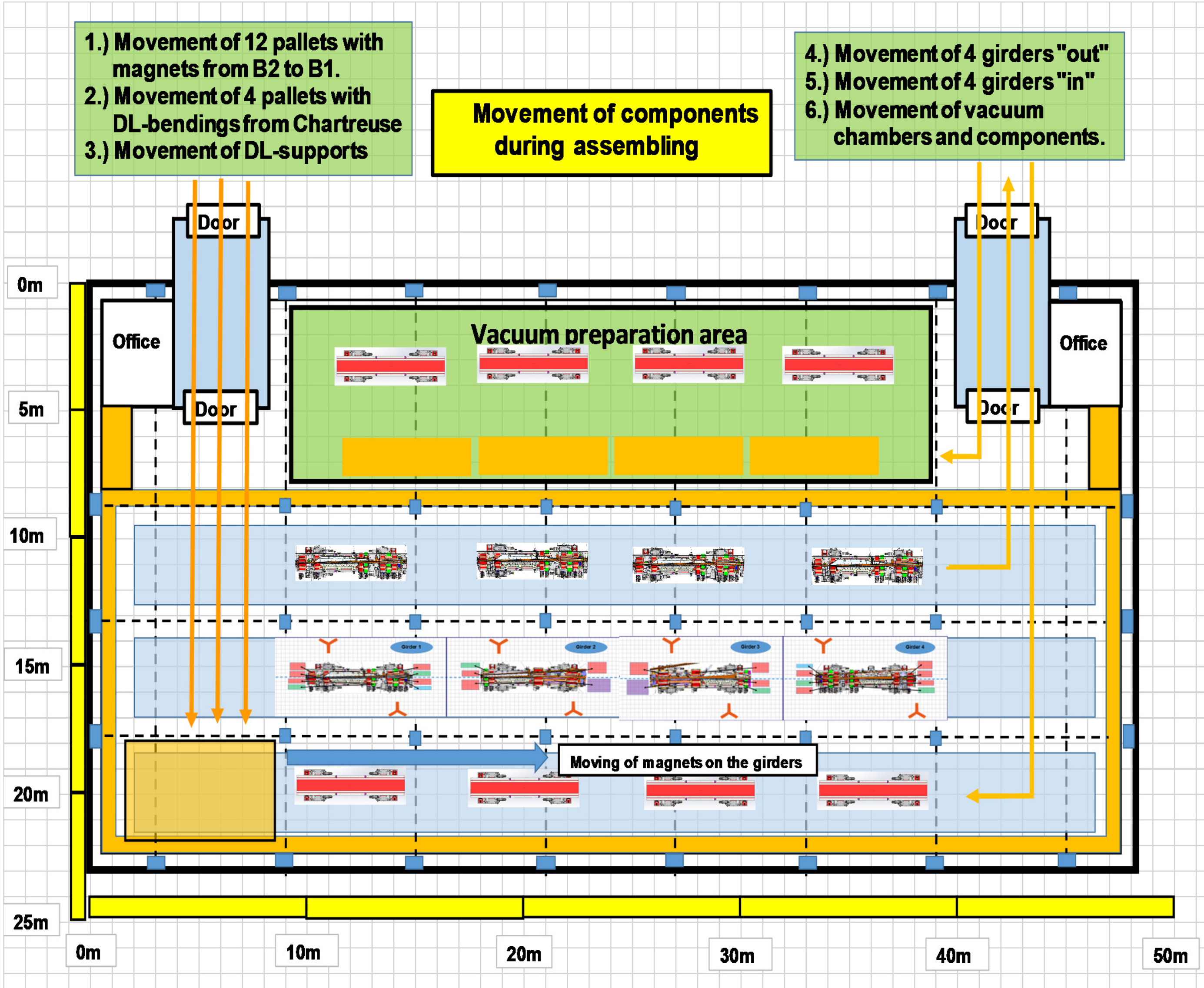
130 girders,10-12t each



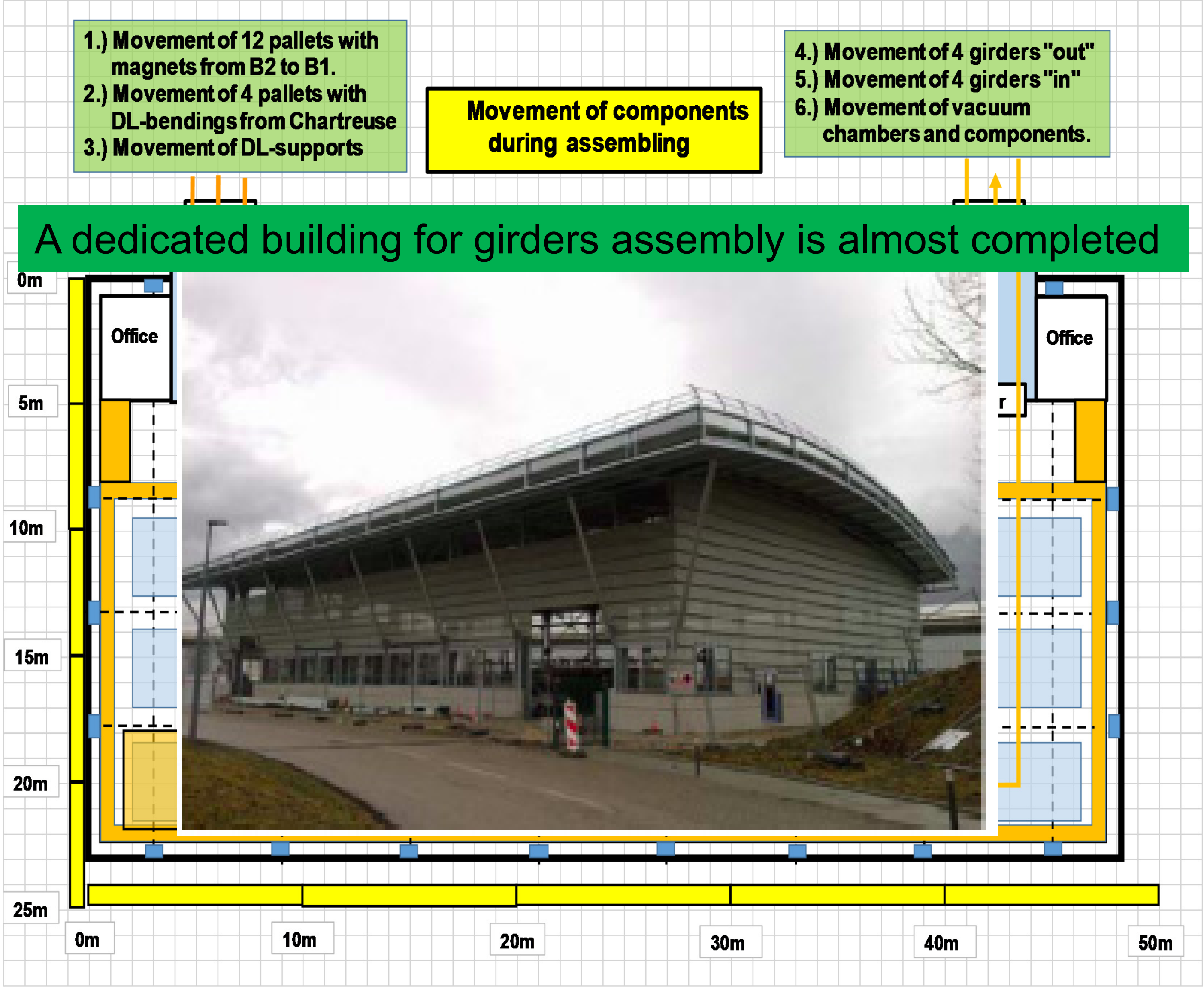
Girders in fabrication

All girders will be fully assembled before starting the shutdown for installation

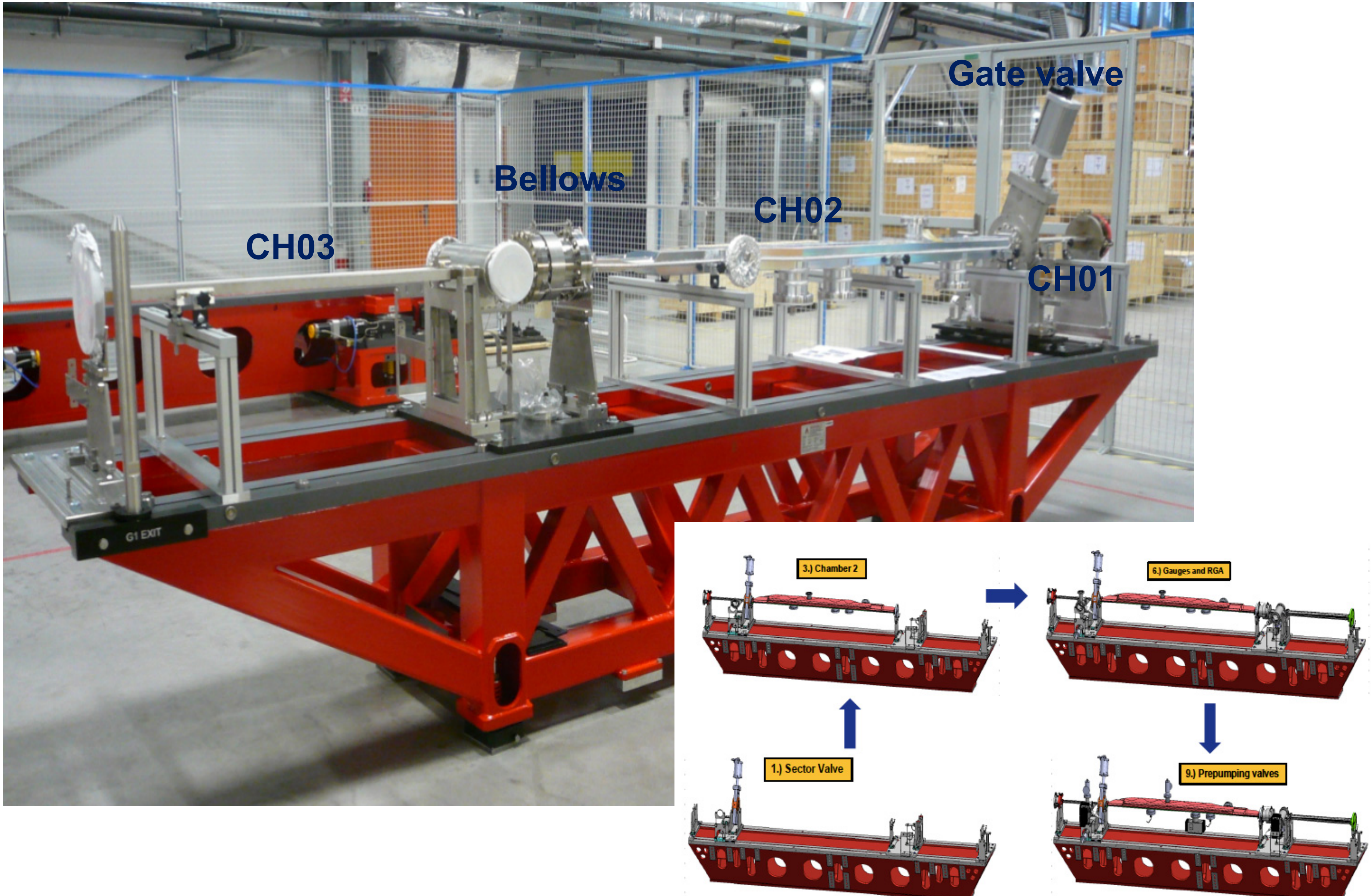
GIRDERS ASSEMBLY



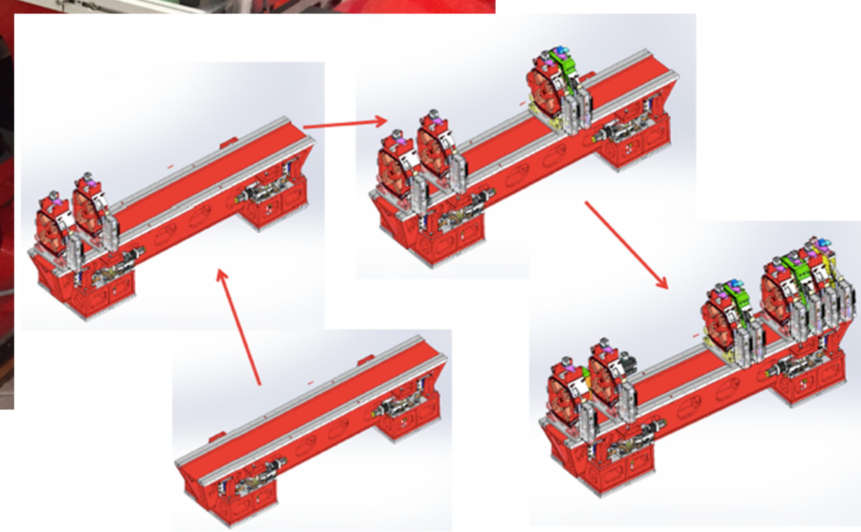
GIRDERS ASSEMBLY



VACUUM ASSEMBLY: GIRDER 1

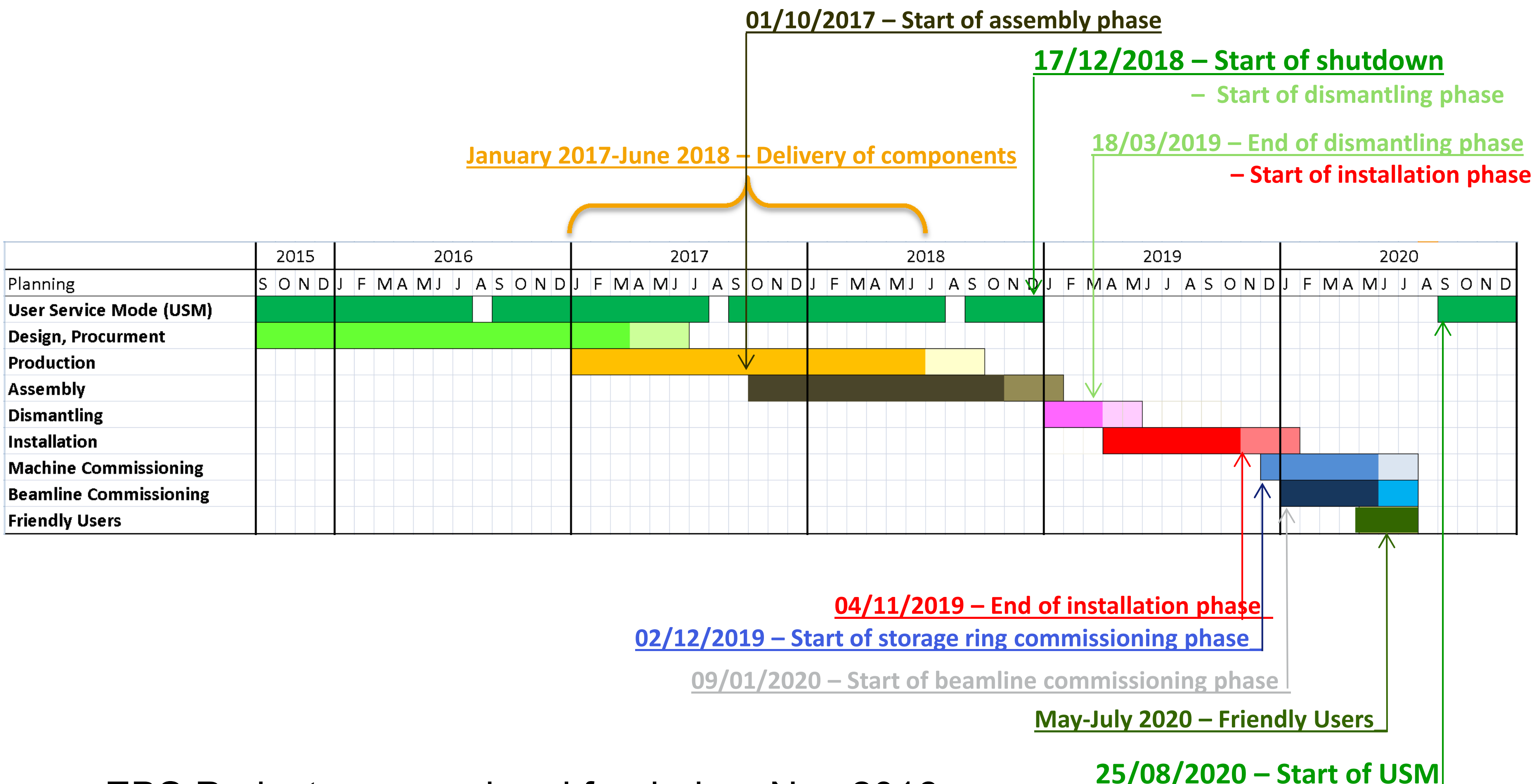


MAGNETS ASSEMBLY: GIRDER 3



EBS MASTER PLAN (2015-2020)

Master Plan and Major Milestones



EBS Project approved and funded on Nov 2016

Start of the project Jan 1st 2015

CONCLUSIONS

- ➢ **HMBA is the result of a worldwide effort to design high performances low emittance rings**
- ➢ **Many well established concepts are fully integrated in the design:**
  - **SLC-FF-like sextupole –I cancelation**
  - **Multi bend cells**
  - **Special magnets: longitudinal and transverse gradient dipoles**
  - **Multi objective optimization**

- ➢ **ESRF has taken the challenge of engineering it and making it real**
- ➢ **The project is in a very advanced status of realization**
- ➢ **The accelerator and science communities is looking forward to the completion of EBS with great expectations**

Many facilities around the world are considering the concepts of HMBA in order to build even better machines