HYBRID MULTI BEND ACHROMAT: FROM SuperB TO EBS

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Abstract

The Hybrid Multi Bend Achroma:from SuperB to EBS. The motivations and rationale at the basis of the Hybrid Multi Bend Achromat (HMBA) lattice and its evolution through the years are presented. Its implementation in the ESRF Extremely Brilliant Source (EBS) upgrade is also shown.

HISTORY OF THE HYBRID MULTI BEND ACHROMAT (HMBA)

The HMBA lattice origins from the need of low emittance rings for the SuperB project (2006) [1]. The high luminosity of the SuperB relied on the use of the large Piwinsky angle [2] and crab waist scheme [3]. 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).

In 2006 the basic scheme for high luminosity factories was to have bunches as short as possible to overcome the hourglass limitation. Figure 1 [4], shows the different collision schemes.

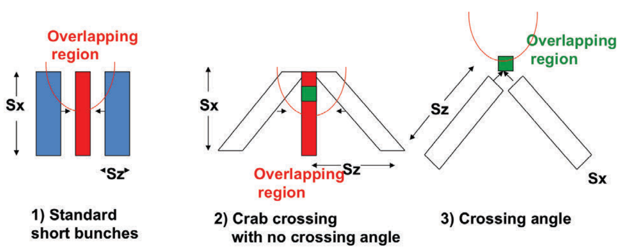

Figure 1: Collision schemes.

At equal luminosity:

- case 2) has longer bunch, the longitudinal overlap happens in the same area as in case 1)
- case 3) has longer bunch and smaller σ_x.
- At any given time case 2) and case 3) have the same overlapping region (green square in Fig. 1)

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. For this reason a strong synergy with the Synchrotron Light Sources Accelerator Community started.

In order to decrease beam-beam effects due to the crossing angle it is required to: 1) increase the crossing angle (at the expenses of luminosity) and 2) 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 beam-beam effect in the section were the beams do overlap is reduced
- The beam-beam effect in the sections were the beams do not overlap is greatly reduced

It is very important to notice that with large crossing angle (case 3) of Fig. 1) X and Z (transverse and longitudinal) quantities are swapped. Short bunches are no more needed since the Interaction Region (IR) length is given by $\sigma_z = \sigma_x/\theta$ (where $\sigma_{x,z}$ are the radial and longitudinal beam sizes and θ the crossing angle) as shown in Fig. 2.

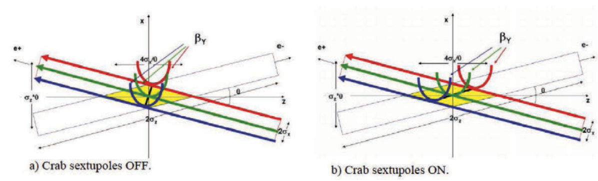

Figure 2: Crab waist and large crossing angle.

In the crab waist the vertical waist has to be a function of x. It must be at $z = 0$ for particles at $-\sigma_x$ ($-\sigma_x/2$ at low current) and at $z = \sigma_x/\theta$ for particles at $+\sigma_x$ ($\sigma_x/2$ at low current). 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.

Lattice Development From SuperB To EBS

The lattice of the SuperB rings in 2008 and 2009 is presented in Fig. 3 and Fig. 4.

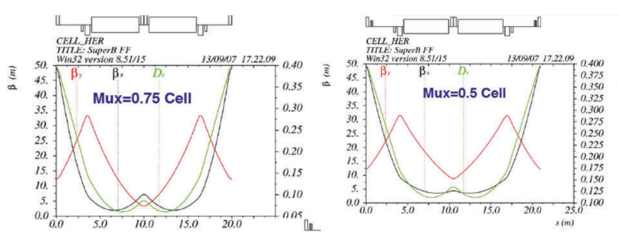

Figure 3: SuperB Lattice cells in 2008

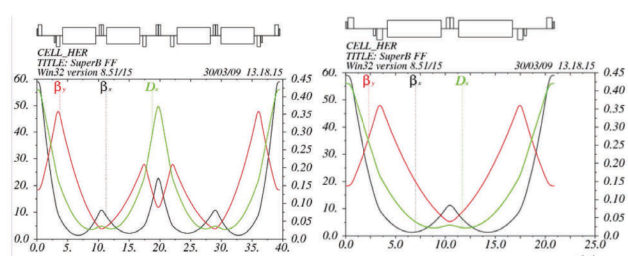

Figure 4: SuperB Lattice cells in 2009

After the first Low Emittance Ring Workshop [5] the lattice further evolved (see Fig. 5) following the design adopted for the MAXIV light source [6].

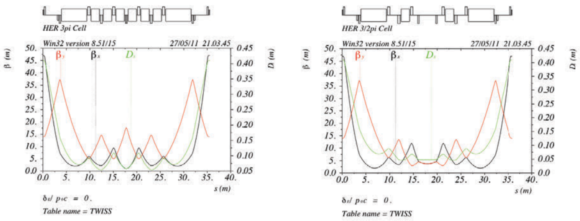

Figure 5: SuperB Lattice cells in 2011. Cell1 (left), Cell2 (right)

An alternating sequence of Cell1 ($\mu_x = 1.5$, $\mu_y = 0.5$) and Cell2 ($\mu_x = 1.215$, $\mu_y = 0.688$) composed the whole lattice. An undulator insertion with a length of 3.5 m and $\beta_{x,y} = 3.2$ m could also be added. The optics kept flexible to changes of β's and phase advance.

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

Figure 6 shows the ESRF accelerators layout as of today.

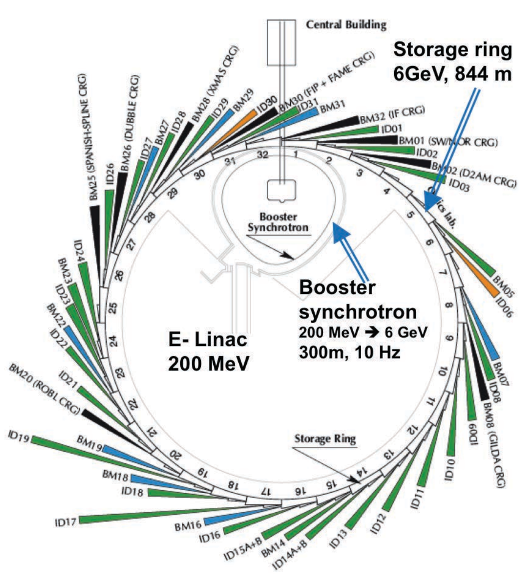

Figure 6: ESRF light source

The lattice is composed of 32 Double Bend Achromat (DBA) cells, giving a natural emittance of $\epsilon_x = 4$ nm. The ESRF provides X-rays to 42 beamlines (12 from dipoles and 30 form undulators).

EXTREMELY BRILLIANT SOURCE (EBS): ESRF ACCELERATOR UPGRADE

The Accelerator Upgrade Phase II aims to substantially decrease the storage ring equilibrium horizontal emittance in order to: 1) increase the source brilliance and 2) increase the 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 Insertion Device (ID) 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.
- **Maintain standard User-Mode Operations until the day of shut-down for installation.**

Figure 7 [7] shows the evolution of light sources in terms of emittance and how, several facilities will implement low horizontal emittance lattices by the next decade.

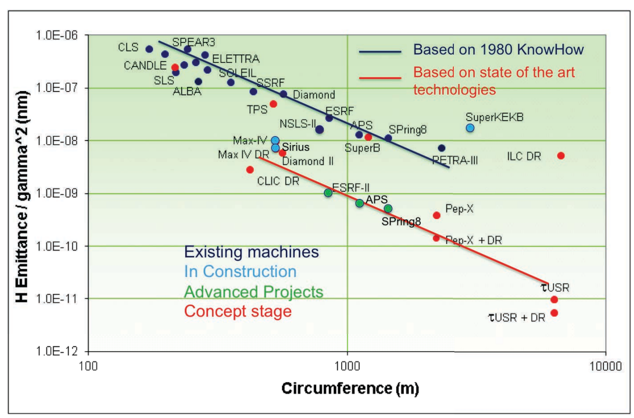

Figure 7: Low emittance rings trend

In the case of ESRF the brilliance, coherent fraction and spectrum of the radiation evolve as detailed in [8] [9].

Evolution of the Multi Bend Lattice

The ESRF DBA cell (see Fig. 8) is used by many 3rd generation synchrotron radiation sources and features a local dispersion bump (originally closed) for chromaticity correction.

The Multi Bend Achromat used for MAXIV (see Fig. 9), has no dispersion bump, and its value is a trade-off between emittance and sextupoles strengths for Dynamic Aperture (DA). The Hybrid Multi-Bend Achromat (HMBA) lattice features:

- Multi-bend for lower emittance
- Dispersion bump for efficient chromaticity correction, and thus weak sextupoles (<0.6 kT/m)
- Fewer sextupoles than in DBA

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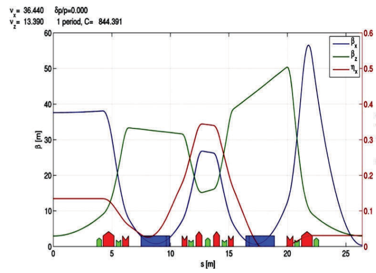

Figure 8: Double Bend Achromat

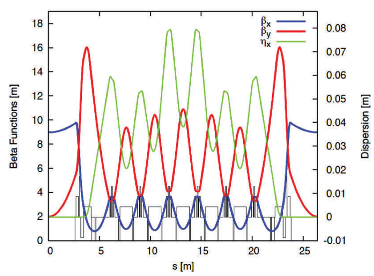

Figure 9: Multi Bend Achromat (MAXIV)

- Longer and weaker dipoles and thus less Synchrotron Radiation
- No need of "large" dispersion on the inner dipoles, giving small invariant $\mathcal{H}_x$ and thus small ϵ_x.

The proposed HMBA lattice has a natural horizontal emittance of $\epsilon_x = 133$ pm, tunes working point at (76.21, 27.34) and natural chromaticity (−99, −82). The lattice cell is shown in Fig. 10.

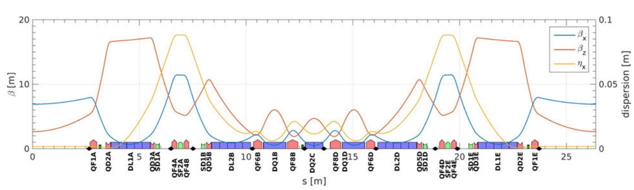

Figure 10: Hybrid Multi Bend Achromat

TECHNICAL CHALLENGE

Magnets

The magnets system is described in detail in [10]. The required magnets are:

- 132 permanent magnet (Sm_2Co_{17}) dipoles with field between 0.16 T and 0.65 T,
- 398 quadrupoles with gradients about 52 T m^{-1}
- 128 high gradient quadrupoles, 90 T m^{-1} and 12.5 mm bore radius
- 99 combined dipole-quadrupoles, 0.54 T and 34 T m^{-1}
- 196 sextupoles with strength about 1500 T/m^2
- 64 octupoles, strength 30 kT/m^3
- 100 correctors, for horizontal and vertical steering and coupling correction.

The mechanical design of the above magnets is in the final drawing phase. Large positioning pins have been included for opening repeatability and tight tolerances have been set on pole profiles (±20 µm). Prototypes of these magnets have been delivered between September 2014 and spring 2015.

Figure 11 shows that all magnets cope with the requirements of 11 mm stay clear from pole to pole for optimal synchrotron radiation handling.

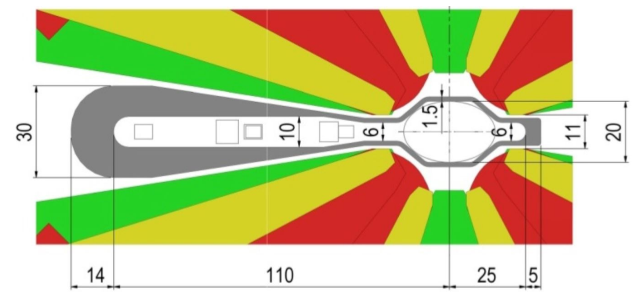

Figure 11: Vacuum chamber and magnet sections.

The longitudinal gradient dipoles are made of 5 modules (see Fig. 12). The lower field module has a larger gap to allow the installation of an absorber. The engineering and prototyping of this magnets is completed. The magnets will be built directly by ESRF.

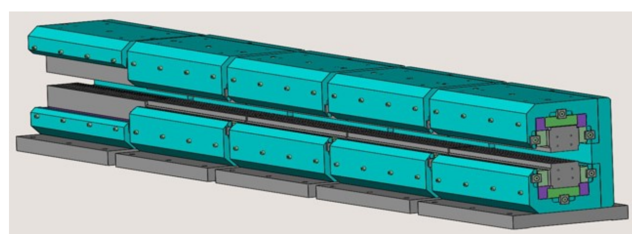

Figure 12: Longitudinal gradient dipole.

Dipole quadrupoles (zeroth order design started from a HERA injection septum quadrupole [11]) are machined out of 7 solid iron plates. The poles are curved longitudinally for a maximum stay clear and good field region (7 mm) as depicted in Fig. 13.

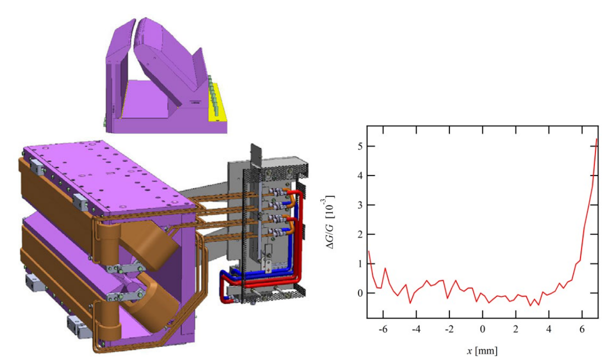

Figure 13: Combined function magnet design and field quality along electron trajectory.

All contracts are in place and magnets are in fabrication. FAT for High Gradient-Quads, Sextupoles and correctors was performed in May 2017. More than 1000 magnets will be procured by the end of 2018 (see [10]). Figure 14 shows batches of magnets ready for EBS.

Figure 14: Magnets procurement.

PM Dipoles are being assembled by ESRF staff. More than 650 Magnets Modules for a total of about 130 5-Module dipoles. About 50 dipoles out of 128 already completed. Figure 15 shows the assembly area.

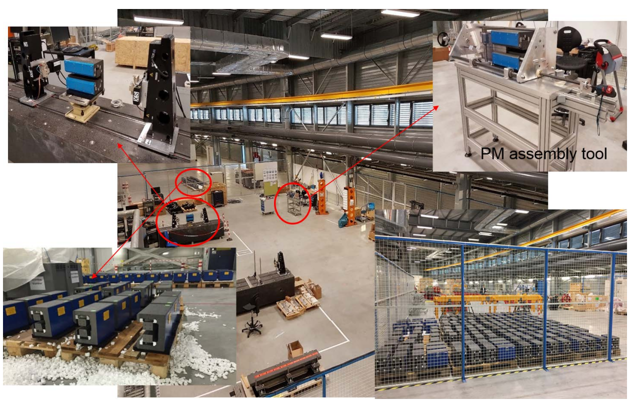

Figure 15: Permanent dipoles magnets assembly area.

Vacuum Chambers

The vacuum system is composed of more than 450 chambers to be procured in less than 3 years. There are 14 main families for the arc cells, and several specific chambers. All contracts are in place and the vacuum chambers are in fabrication. FAT for aluminum chambers performed in December 2016. As an example the chamber number 8 (see Fig. 16) is

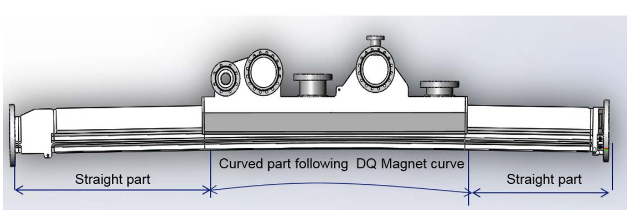

Figure 16: Vacuum chamber number 8

composed of 2 straight sections and a curved section to host the DQ magnet in the center. Two different profiles are used for the antechember in the two regions, in order to stiffen the structure and allow the installation of ports for pumps and absorbers. Images of the production of some of the chamber are reported in Fig. 17. The design for the Bellow RF fingers

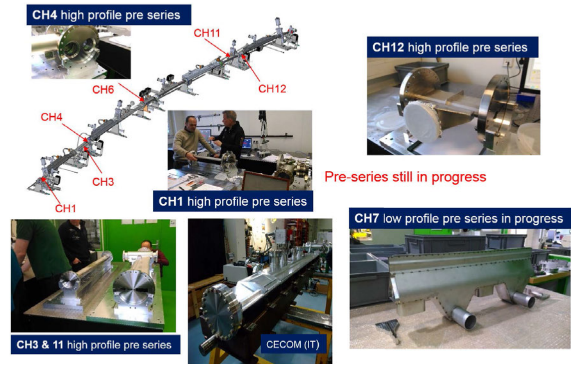

Figure 17: Vacuum chambers production

is now a patented ESRF design (see Fig. 18).

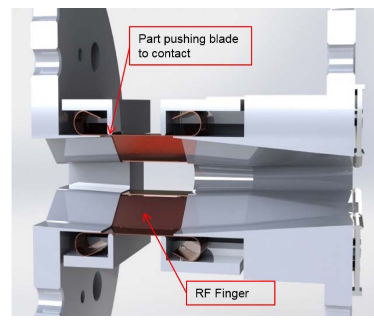

Figure 18: Bellow RF fingers: ESRF design patented

Collimators

A detailed study of the Touschek losses in the lattice showed that vertical losses at the undulators can be concentrated (up to 80%) using two horizontal scrapers. The details of this study are described in [12, 13]. Figure 19 shows the effect of the collimators on the losses over one cell.

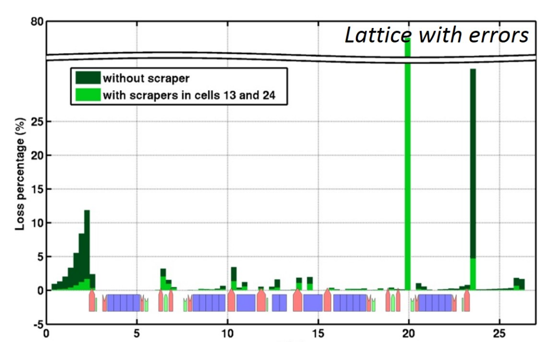

Figure 19: Losses simulated along the cell with and without collimators for a lattice with errors.

The design of the collimator is now completed and a contract will be placed by December 2017. The design is presented in Fig. 20 and will require local shielding.

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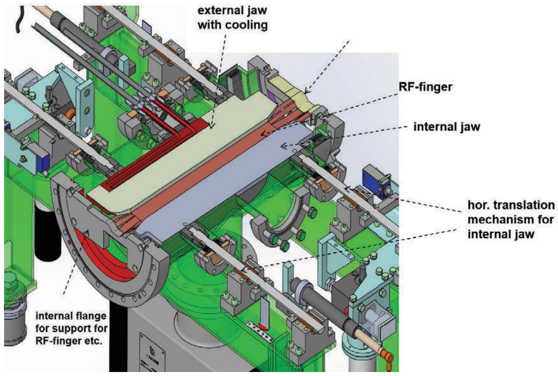

Figure 20: Collimators design.

Girders

All 130 girders (10-12 tons each) will be fully assembled before starting the shutdown for installation. Figure 21 shows an example.

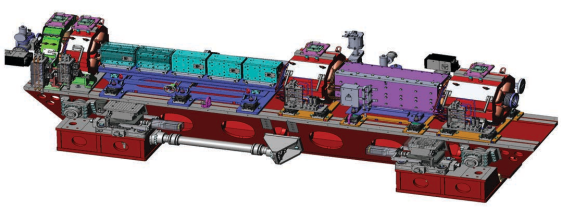

Figure 21: Girders design.

A dedicated building for Girder assembly is almost completed. Figures 22 and 23 show images of the assembly process.

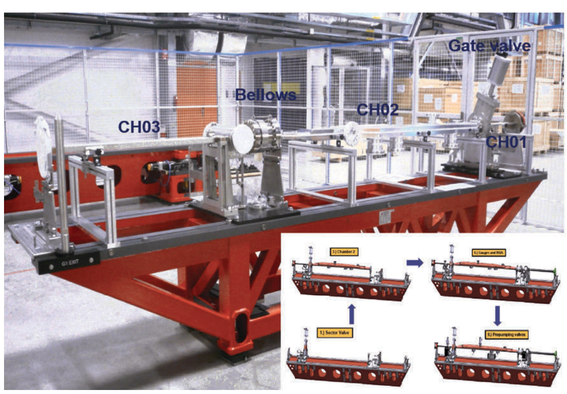

Figure 22: Vacuum assembly on dedicated girder.

MASTER SCHEDULE

The main steps in the master schedule are:

- January 2017 to June 2018: delivery of the components
- 01/10/2017: start of the assembly phase
- 17/12/2018: start of the machine shutdown and dismantling
- 18/03/2019: end of dismantling phase and start of installation phase

Figure 23: Assembly of magnets on the girder 3.

- 04/11/2019: end installation phase
- 02/12/2019: start of storage ring commissioning
- 09/01/2020: start of beamlines commissioning
- May-July 2020: Friendly users
- 25/08/2020: start of user standard mode

EBS Project has been approved and funded on November 2016 and started in January 1st 2015.

CONCLUSION

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-Final Focus-like [14] sextupole $-\mathcal{I}$ cancellation
- 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 today 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.

ACKNOWLEDGMENT

The work presented in this paper is the outcome of the collaboration of all the divisions at ESRF an contains contributions from external experts and the scientific community.

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