Low Emittance Lattice Design

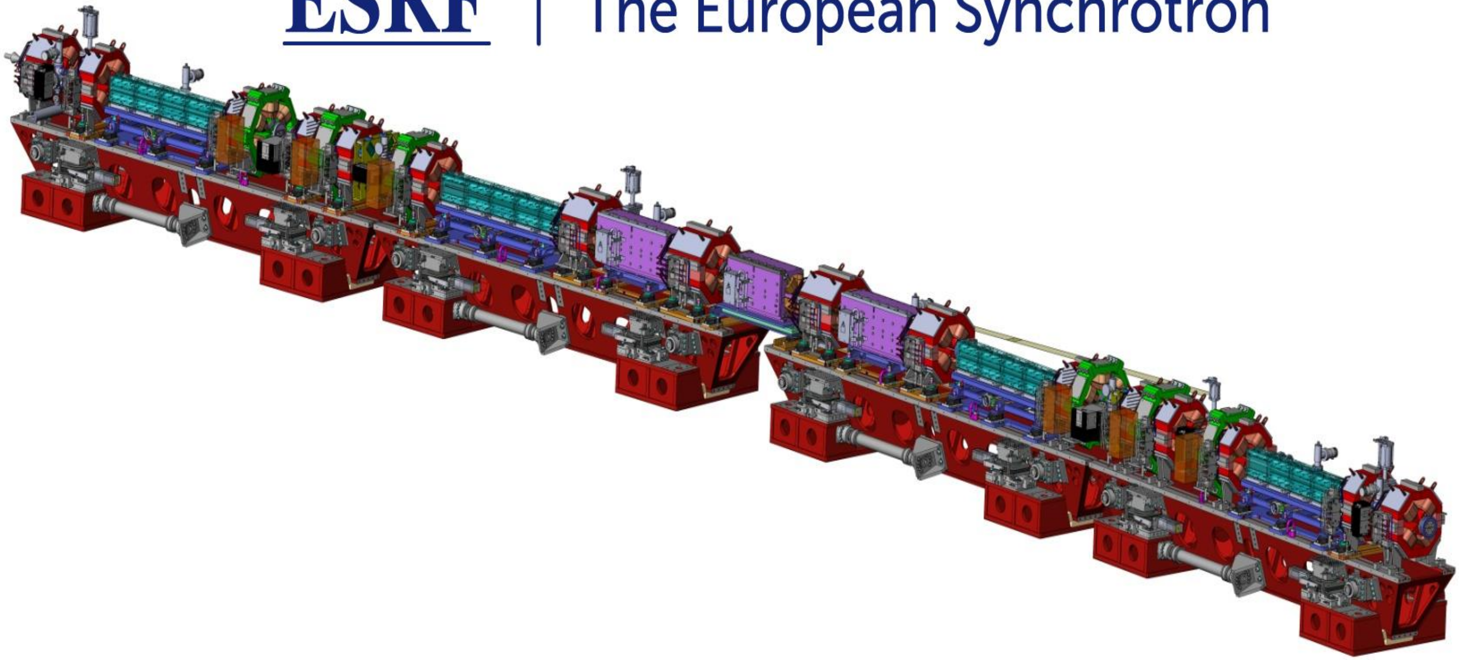
Barcellona, April-23-24 2015

ESRF Phase II Accelerator Upgrade

Pantaleo Raimondi

On behalf of the Accelerator Project Phase II Team

ESRF | The European Synchrotron



Accelerator Upgrade Phase II

The Accelerator Upgrade Phase II aims to:

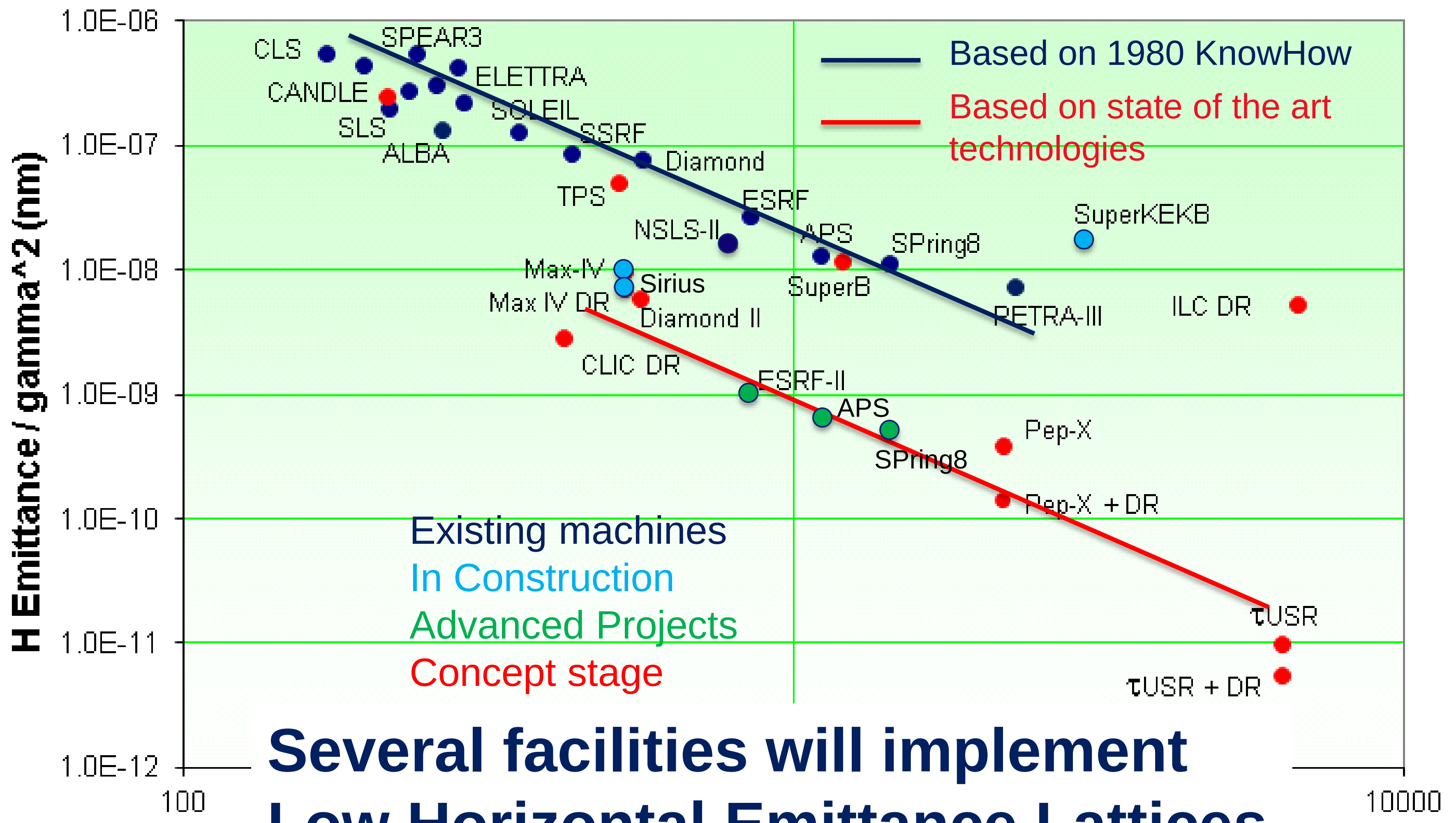
- Substantially decrease the Store Ring Equilibrium Horizontal Emittance
- Increase the source brilliance
- Increase its coherent fraction.

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 19.5 months.

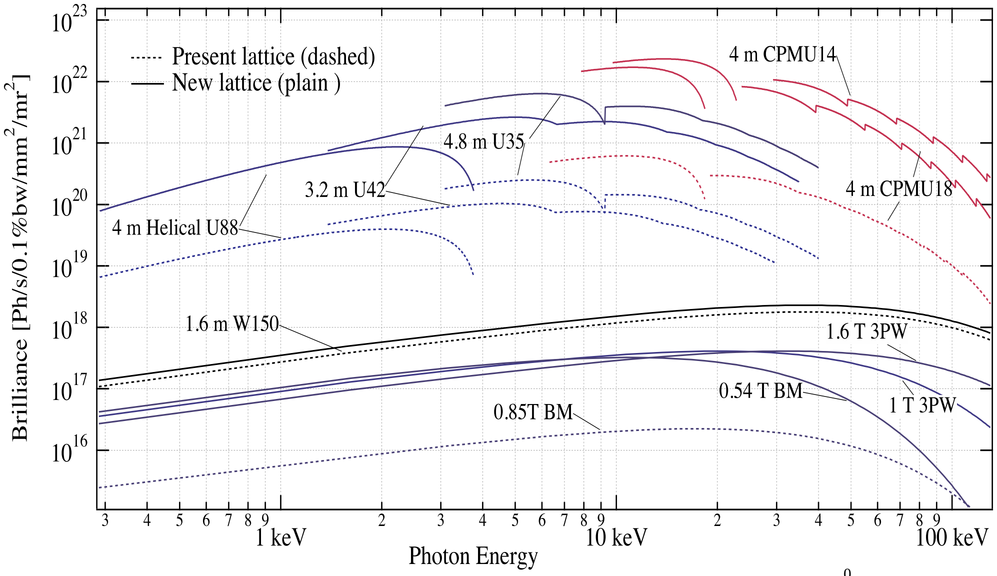
Maintain standard User-Mode Operations until the day of shut-down for installation

LOW EMITTANCE RINGS TREND



Several facilities will implement Low Horizontal Emittance Lattices by the next decade

BRILLIANCE AND COHERENCE INCREASE

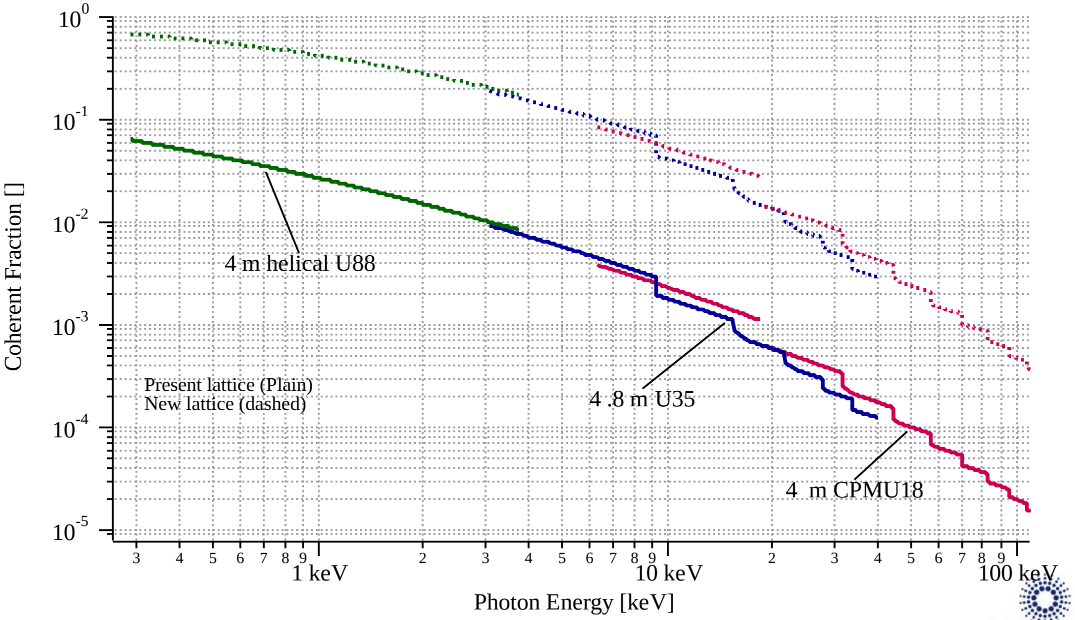


Brilliance

Source performances will improve by a factor 50 to100

Hor. Emittance [nm]	**4**	**0.15**
Vert. Emittance [pm]	**3**	**2**
Energy spread [%]	**0.1**	**0.09**
β_x[m]/β_z [m]	**37/3**	**4.3/2.6**

Coherence



BENDING MAGNETS SOURCE: 2-POLE, 3-POLE OR SHORT WIGGLERS

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

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

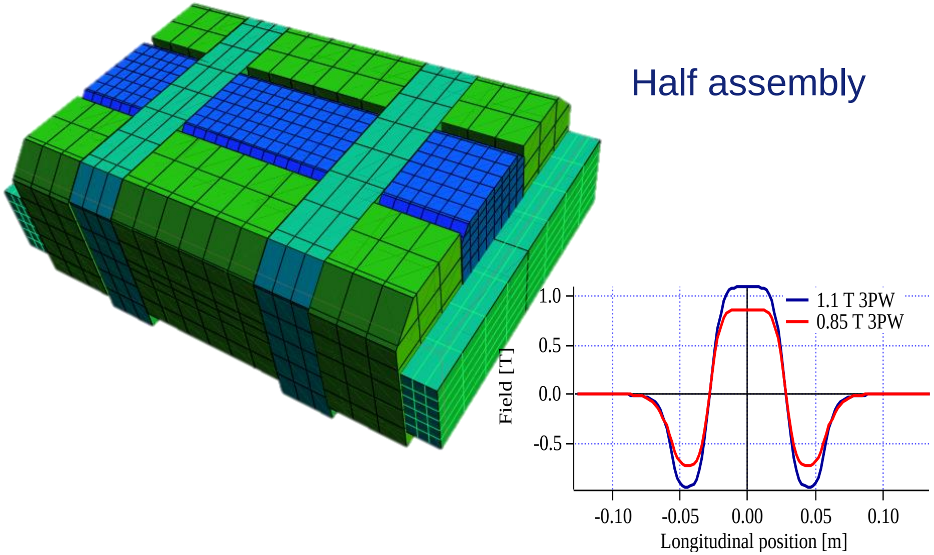
Conflict with hard X-ray demand from BM beamlines

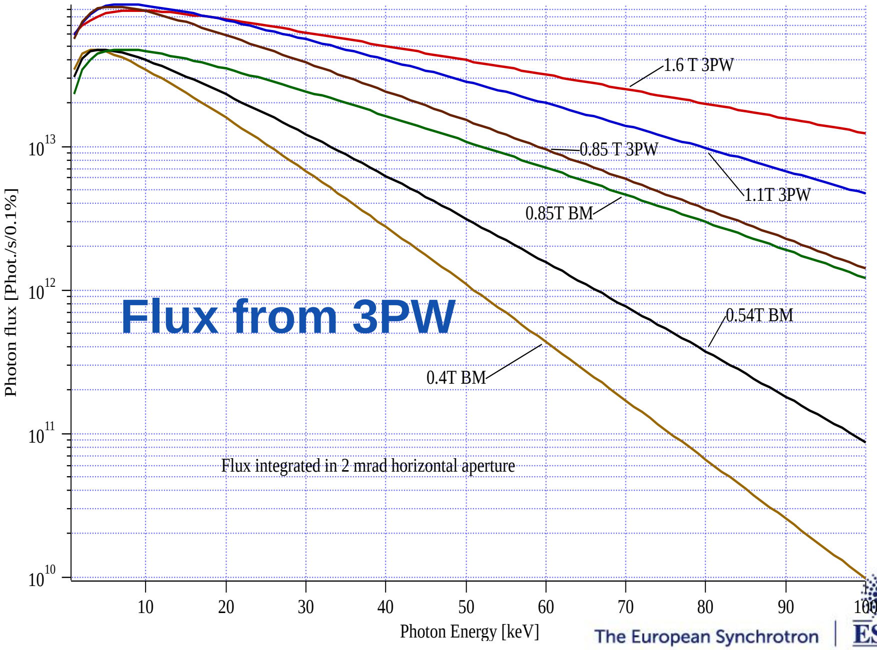
ESRF will go from 0.85 T BM to 0.54 T BM

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

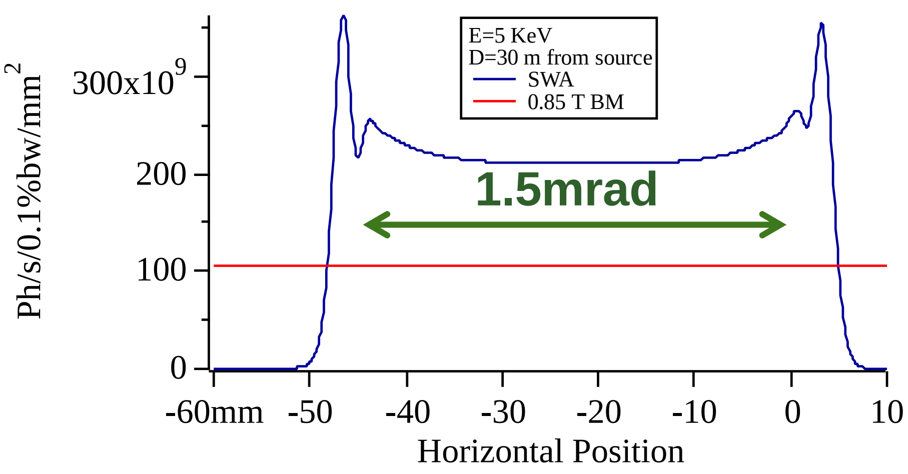
- Field Customized
- Large fan with flat top field
- 2 mrad feasible for 1.1 T 3PW
- Mechanical length ≤ 150 mm

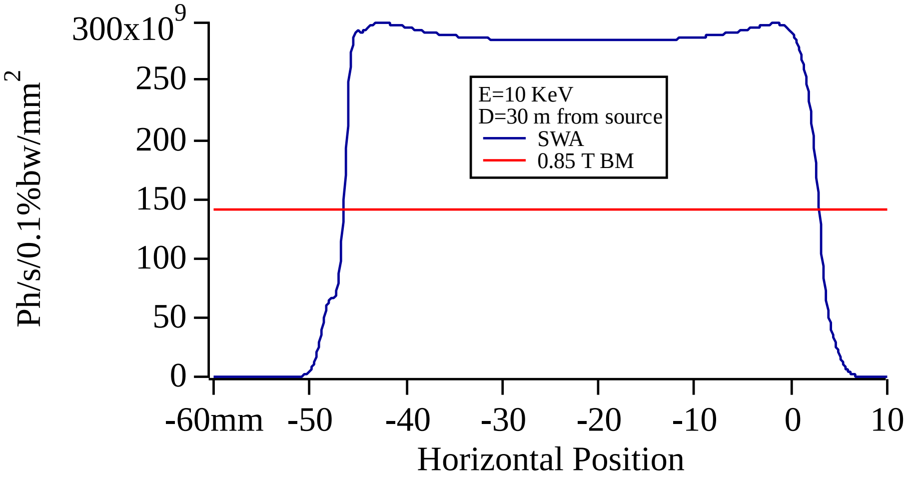
- Source shifts longitudinally by ~3m
- Source shifts horizontally by ~1-2cm

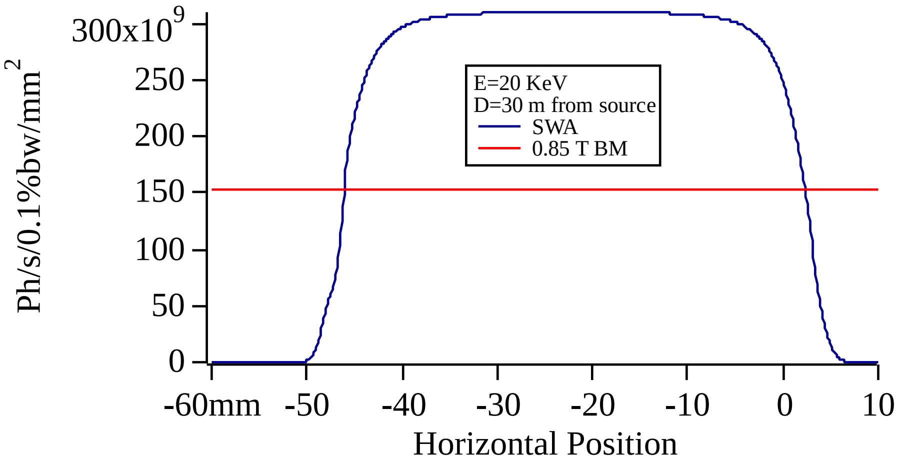


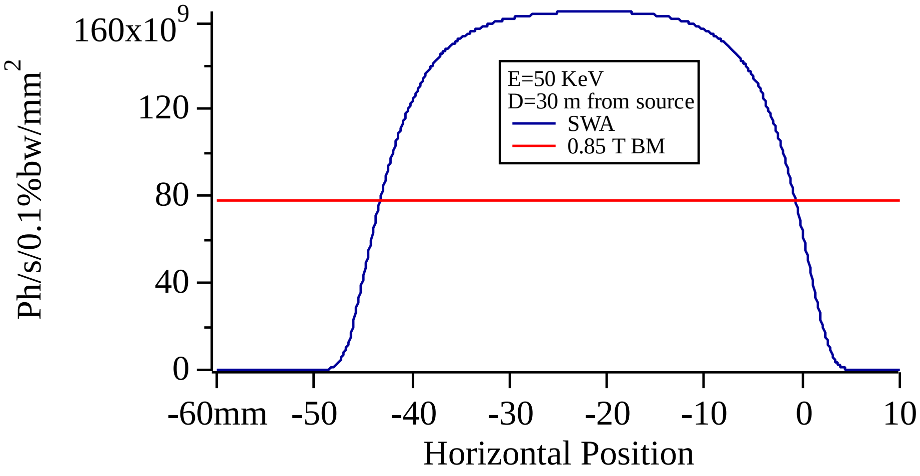


Short WIGGLERS SWs
Transverse photon beam profiles with residual interferences



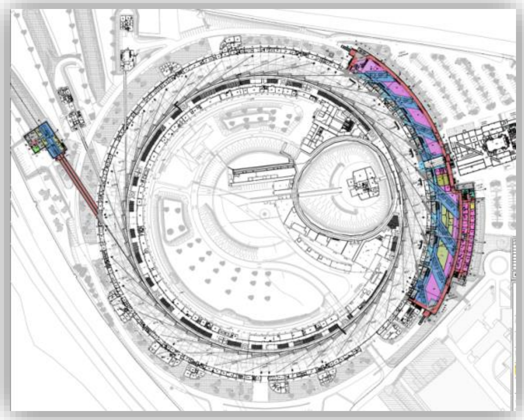




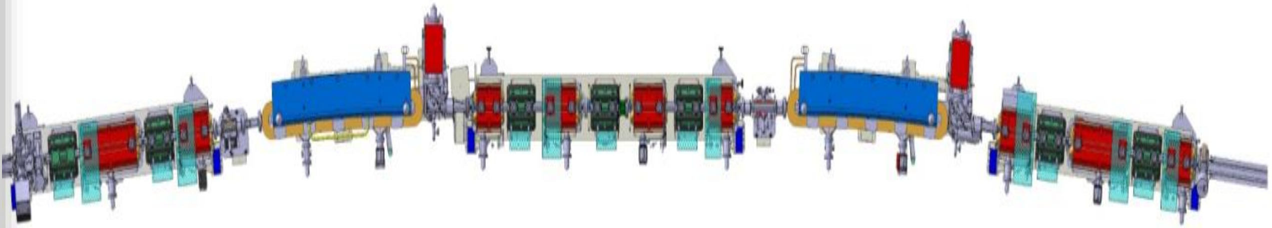


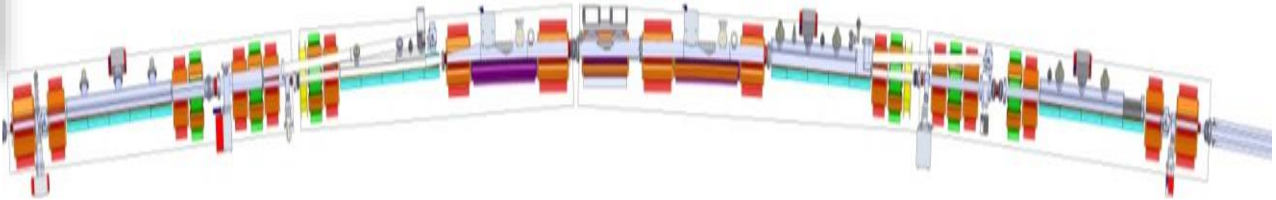
Joel Chavanne

ESRF Phase II Upgrade at the Bone



Present ESRF Arc Layout: Ex=4nm





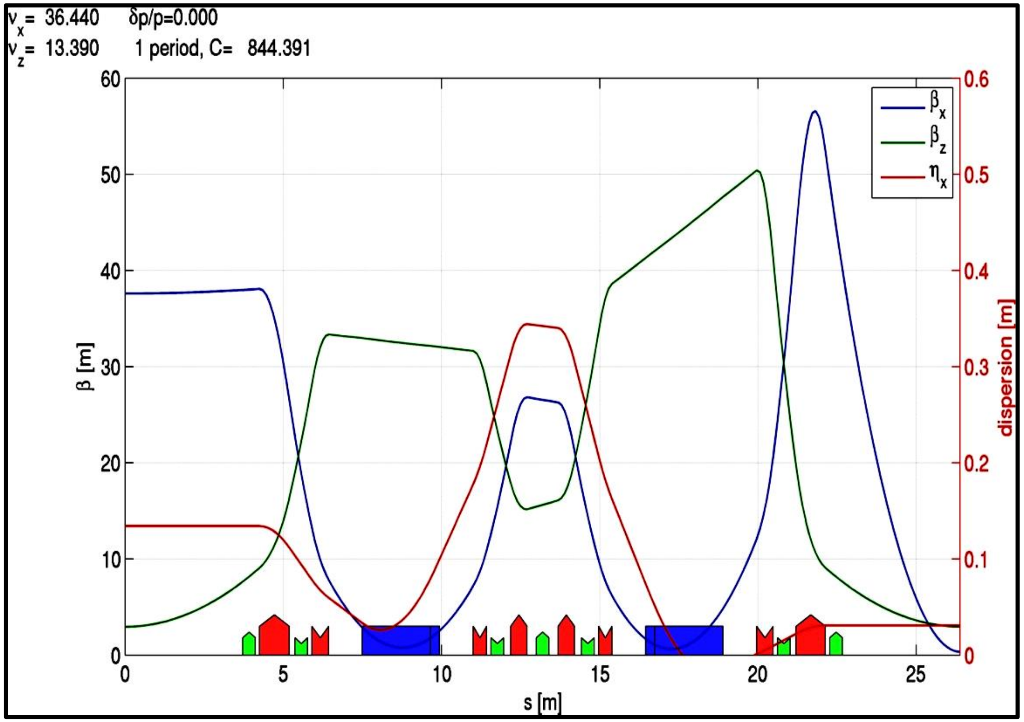
New Low Emittance Layout: Ex=0.135nm

The 844m Accelerator ring consists of 32 identical Arcs.

Each Arc is composed by a well defined sequence of Magnets, Vacuum Components (vacuum vessel, vacuum piumps etc), sensors (diagnostic) etc.

All the Arcs will be replaced with a completely new Layout

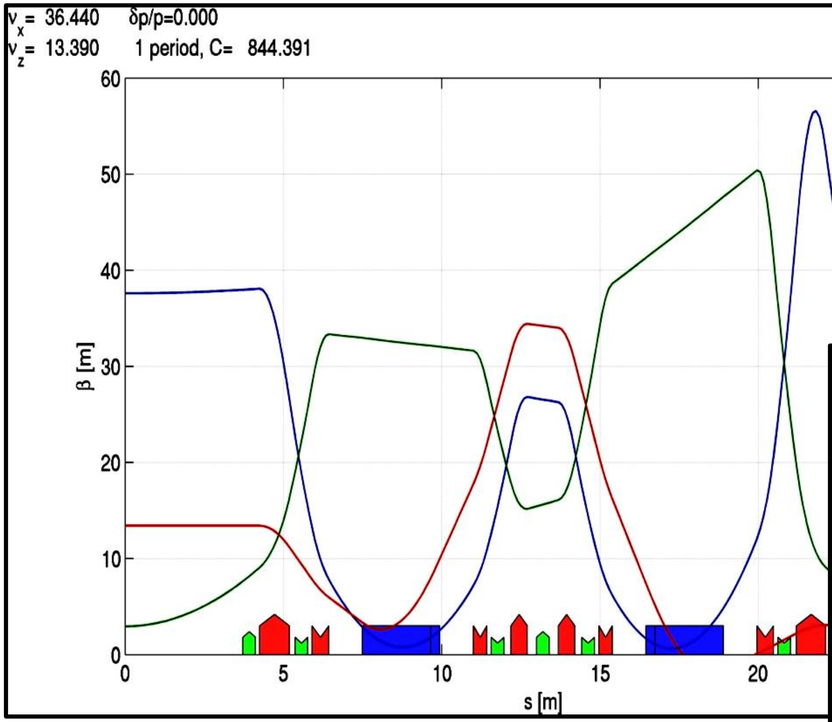
THE EVOLUTION TO MULTI-BEND LATTICE



Double-Bend Achromat (DBA)

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

THE EVOLUTION TO MULTI-BEND LATTICE

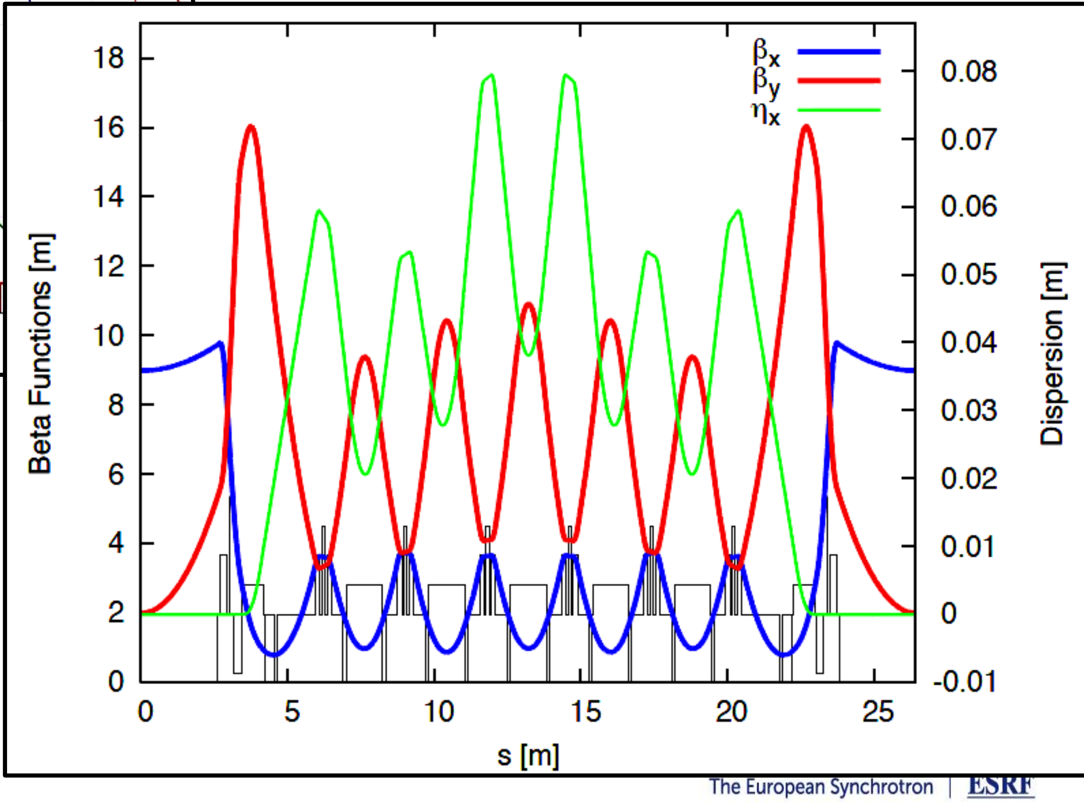


Double-Bend Achromat (DBA)

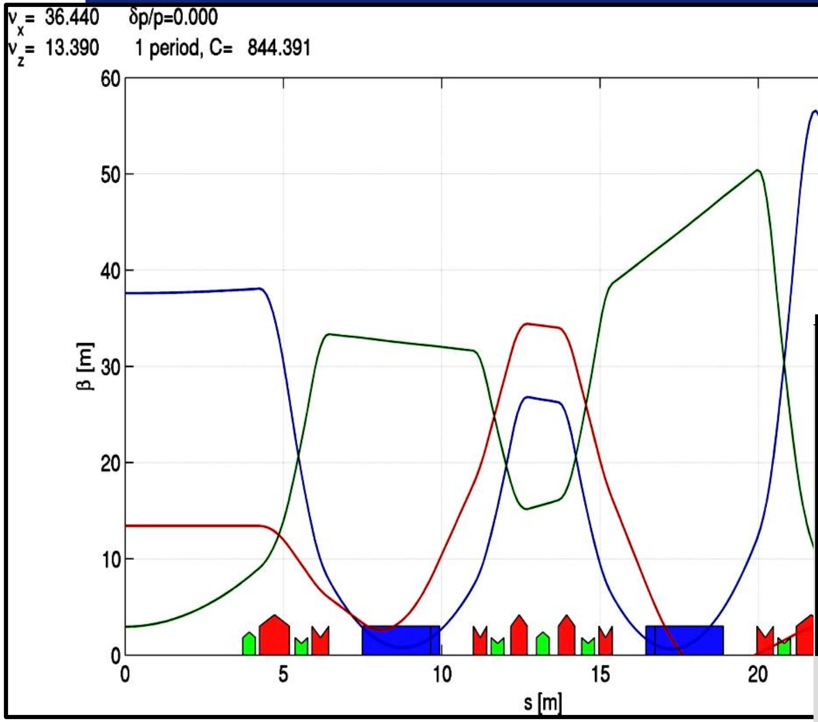
- Many 3rd gen. SR sources
- Local dispersion bump (originally closed) for chromaticity correction

Multi-Bend Achromat (MBA)

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

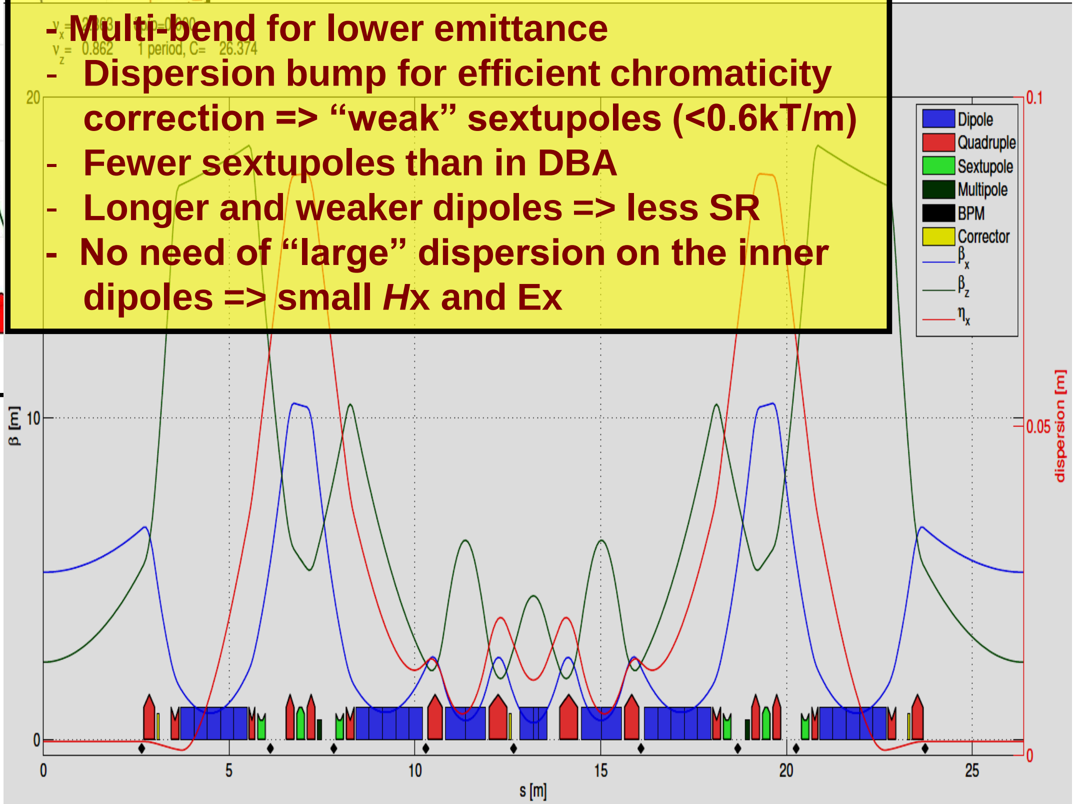


THE HYBRID MULTI-BEND (HMB) LATTICE



ESRF existing (DBA) cell

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

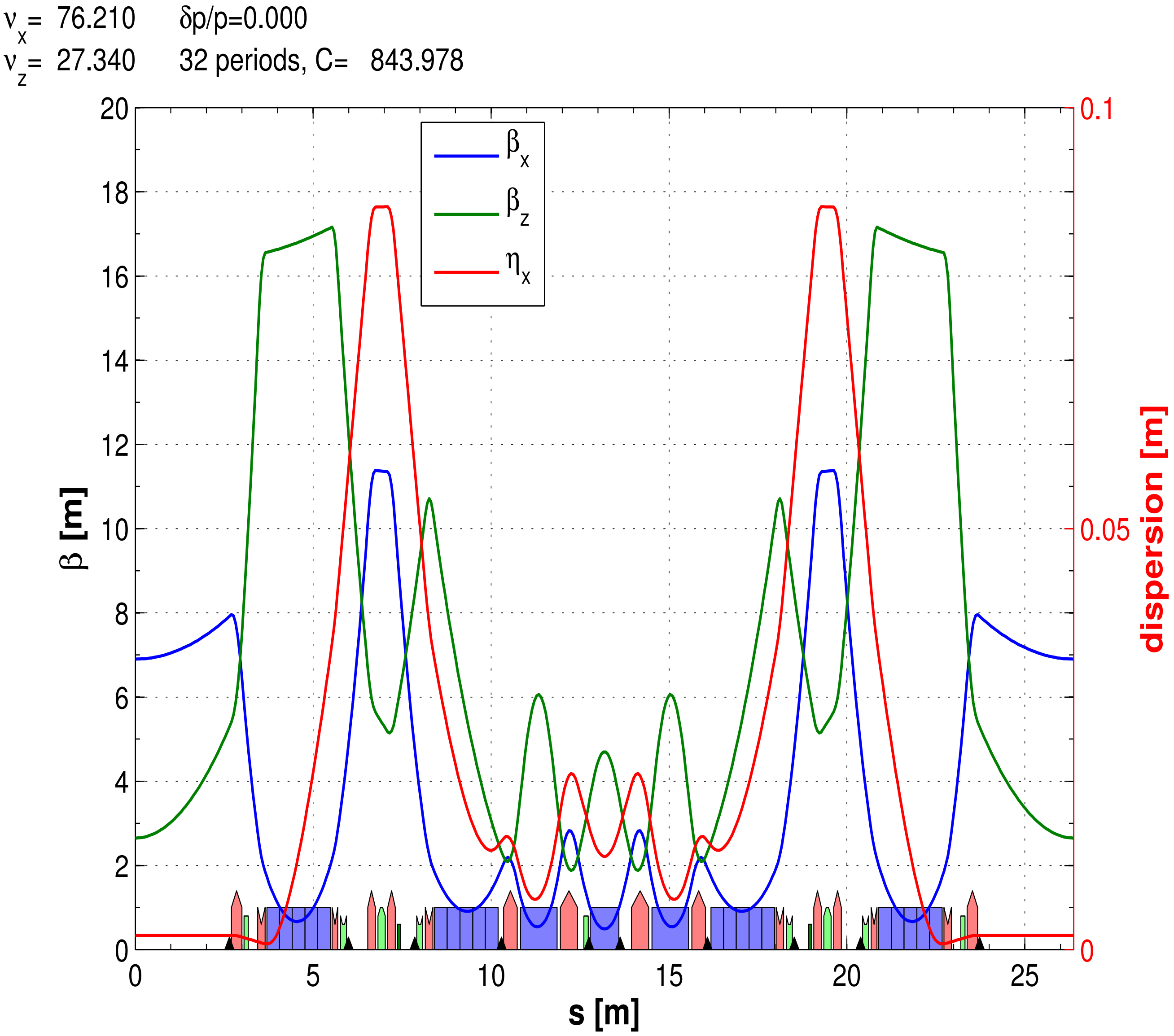


- **Multi-bend for lower emittance**
- **Dispersion bump for efficient chromaticity correction => “weak” sextupoles (<0.6kT/m)**
- **Fewer sextupoles than in DBA**
- **Longer and weaker dipoles => less SR**
- **No need of “large” dispersion on the inner dipoles => small *H*x and Ex**

Proposed HMB cell

- Ex = 140 pm•rad
- tunes (75.60, 27.60)
- nat. chromaticity (-92, -82)

LATTICE EVOLUTION: S28B OPTICAL FUNCTIONS



Natural equilibrium emittance:

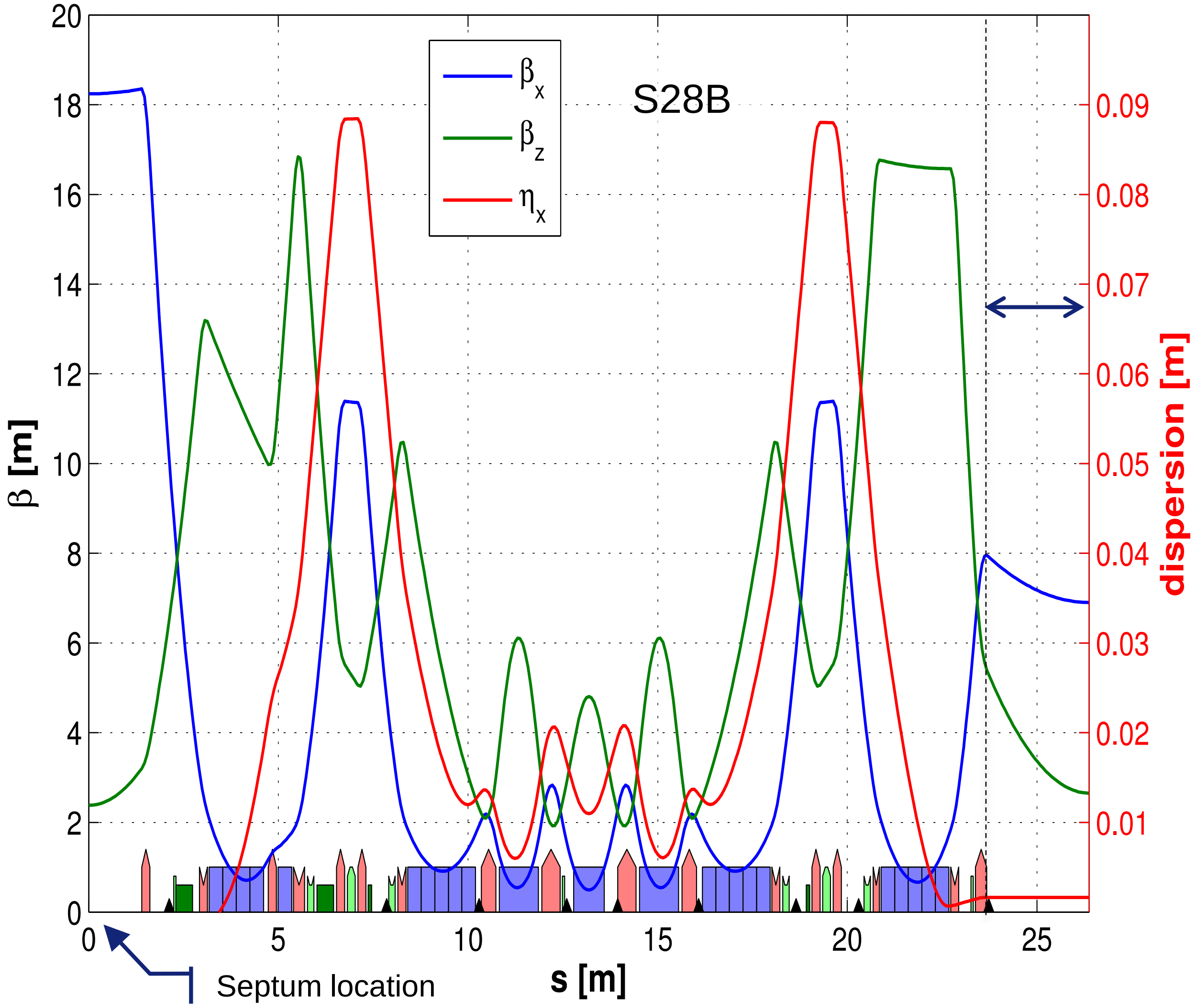
ε_{x0} = 134 pm

Emittances with 5 pm coupled into the vertical plane and 0.5 MV radiation losses from IDs:

ε_x = 107 pm

ε_z = 5 pm

INJECTION CELL: S28B



Septum location

- 2 quadrupoles in the straight section,
- The global phase advance is still strictly identical to the standard cell,
- However the tuning of the whole cell is slightly different, giving more flexibility for the injection tuning.

LINEAR AND NONLINEAR OPTIMIZATIONS

Linear and nonlinear optimizations have been done with the multi-objective genetic algorithm NSGA-II, to maximize Touschek lifetime and dynamic aperture.

Lifetime and dynamic aperture are computed on 10 different errors seeds.

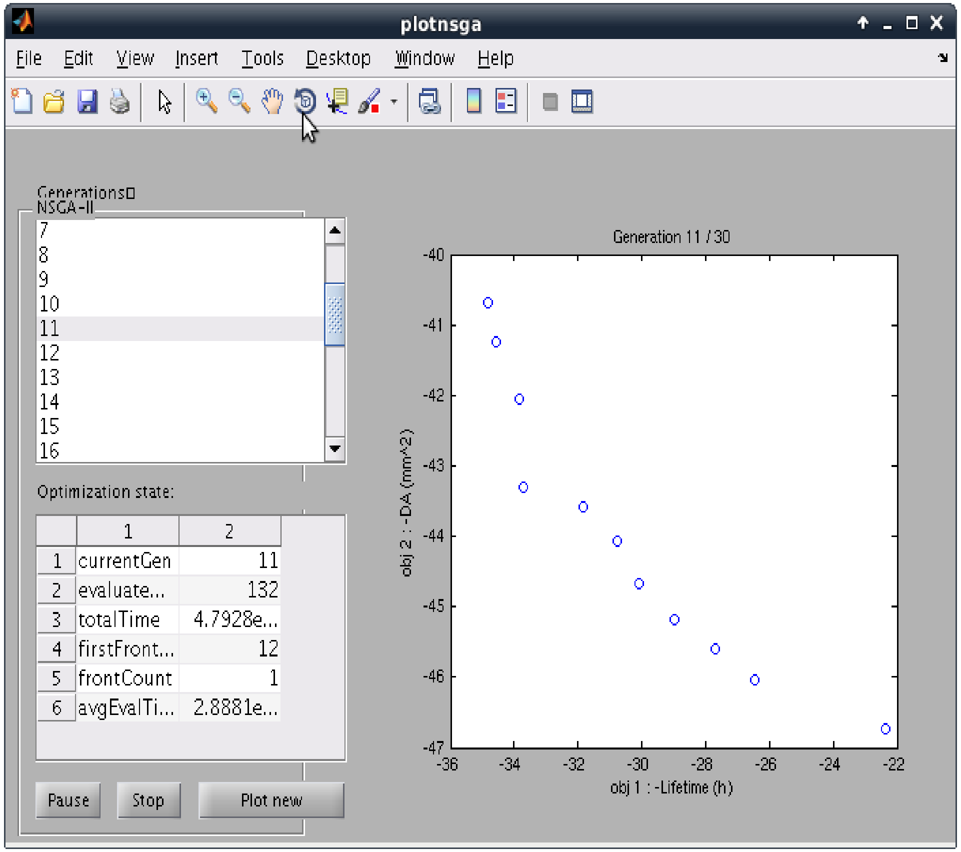
Sextupoles: from 6 to 3 families, weaker and shorter.

Octupoles: from 2 to 1 family, weaker and shorter.

Tunes: 76.21 27.34

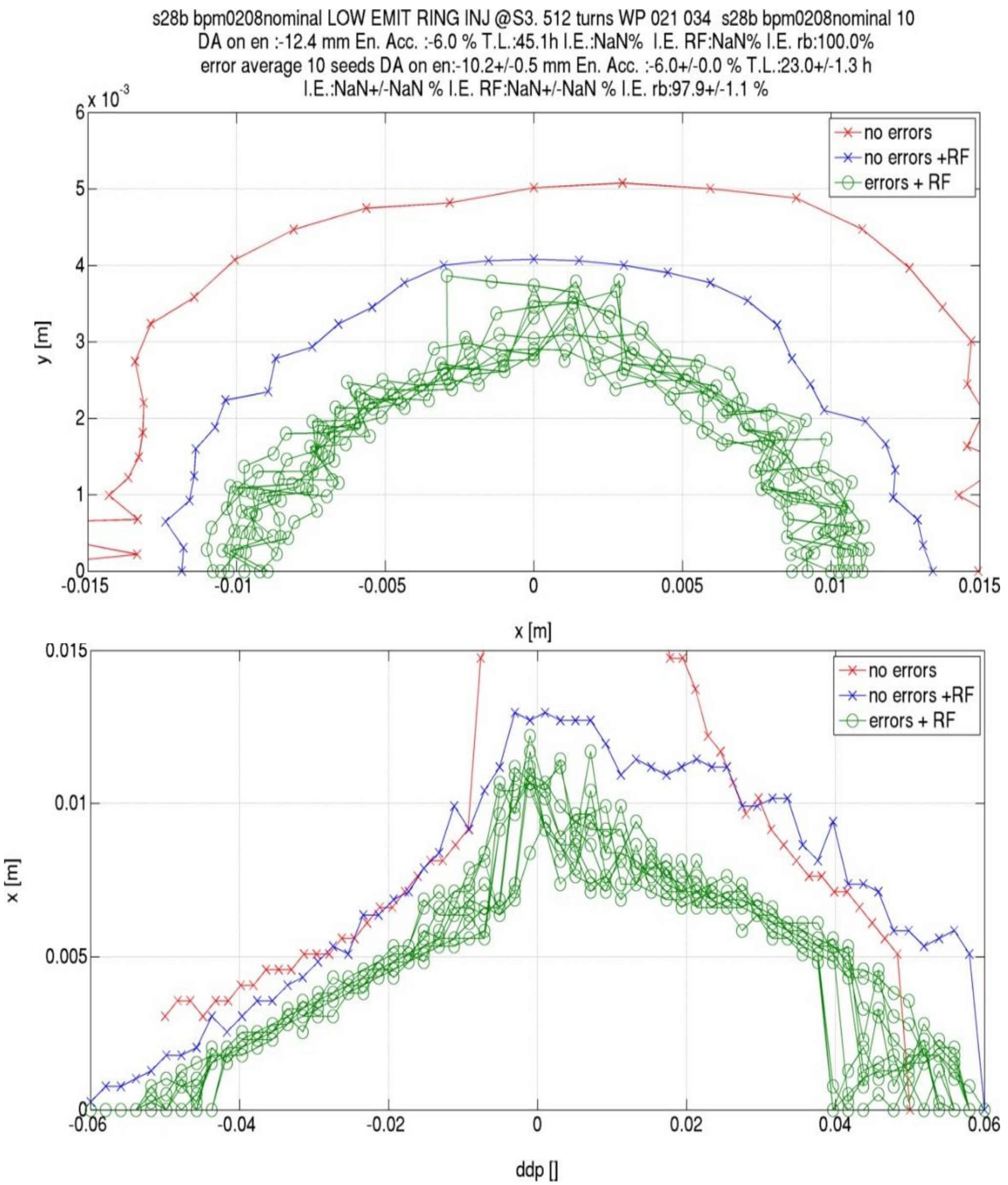
Linear matching parameters: $\beta_{x\ ID}$ = 6.9m

Chromaticities: 6, 4



	1	2
1	currentGen	11
2	evaluate...	132
3	totalTime	4.7928e...
4	firstFront...	12
5	frontCount	1
6	avgEvalTi...	2.8881e...

LIFETIME OF S28B



S28A

DA -8.1mm@S3

TLT ~ 13h.

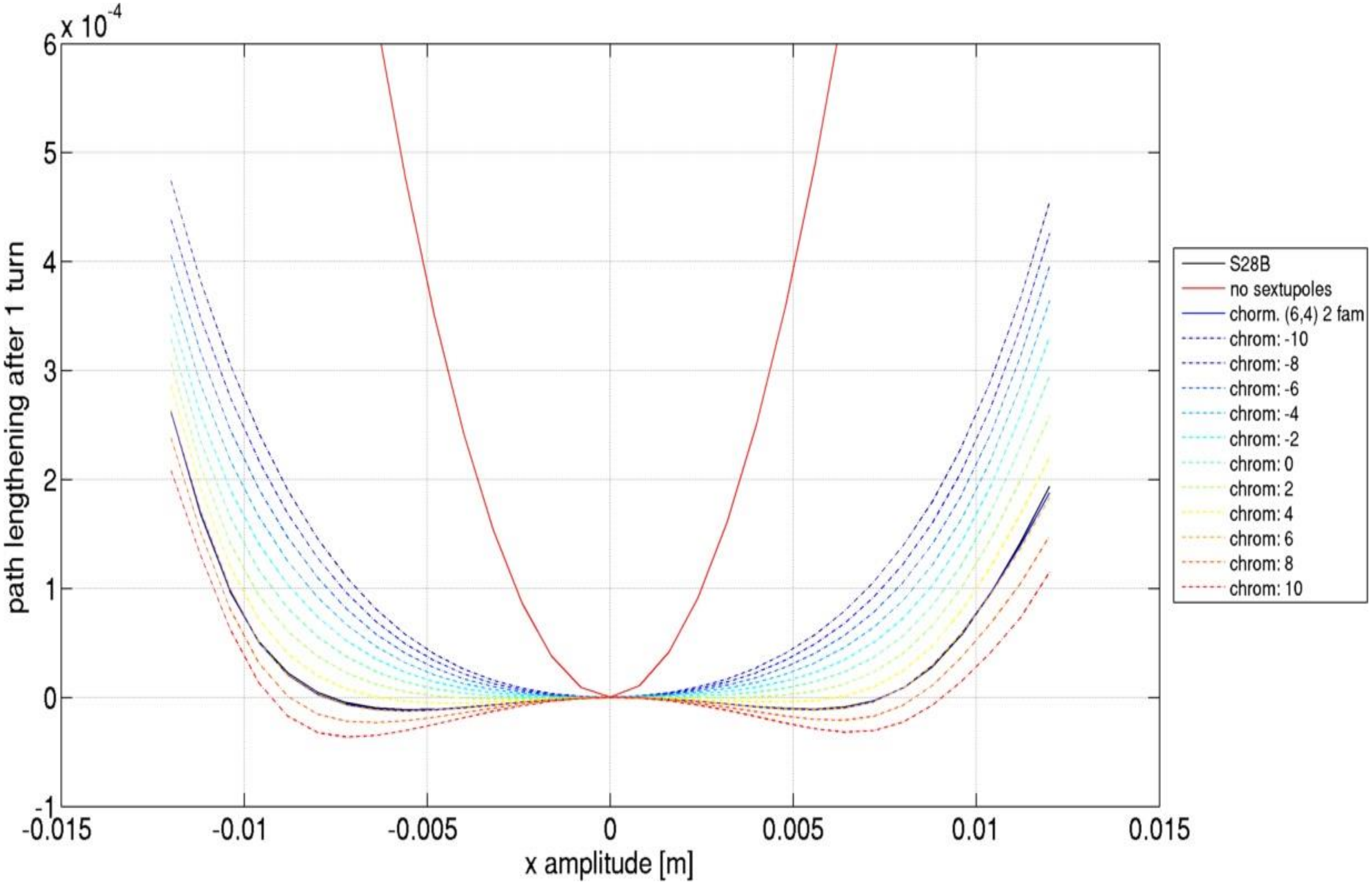
S28B

DA -10mm@S3

TLT ~ 21h

e_y=5pm	ESRF	Upgrade
7/8 multibunch	64 h	21 h
16 bunch	6 h	2.1 h
4 bunch	4 h	1.4 h

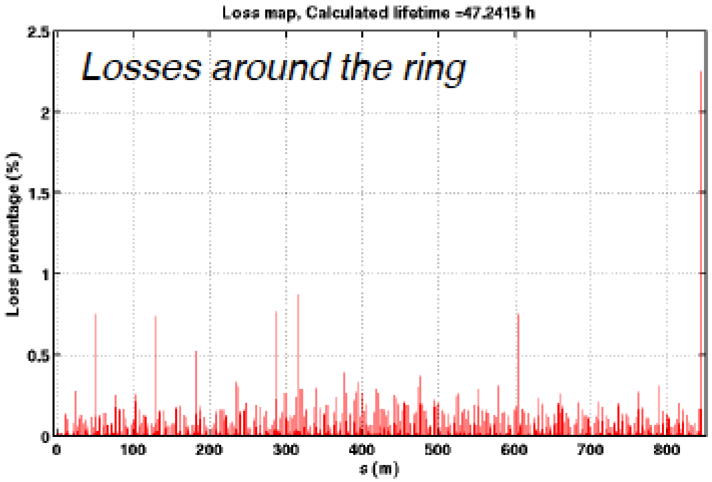
PATH LENGTHENING VS AMPLITUDE AND CHROMATICITY

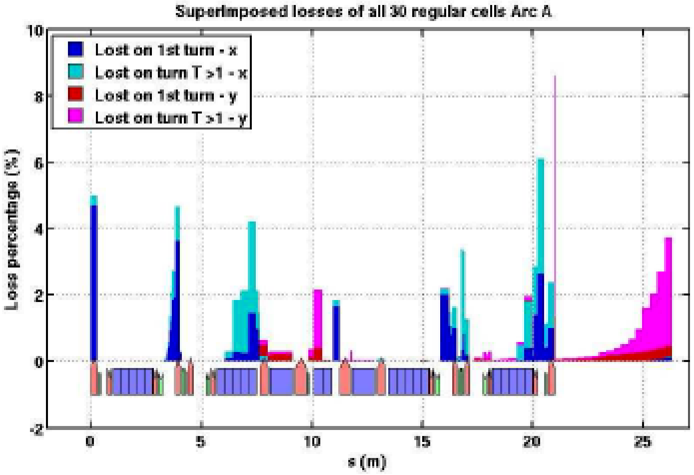


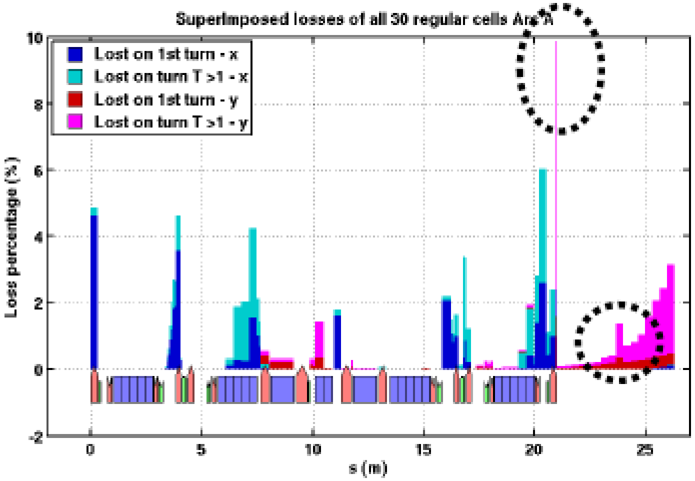
The path lengthening with amplitude effect strongly depends on the chromaticity, especially at low amplitude.

COLLIMATION OPTIMIZATION TO DECREASE LOSSES IN THE IDS

Losses in S28B without errors


Losses around the ring

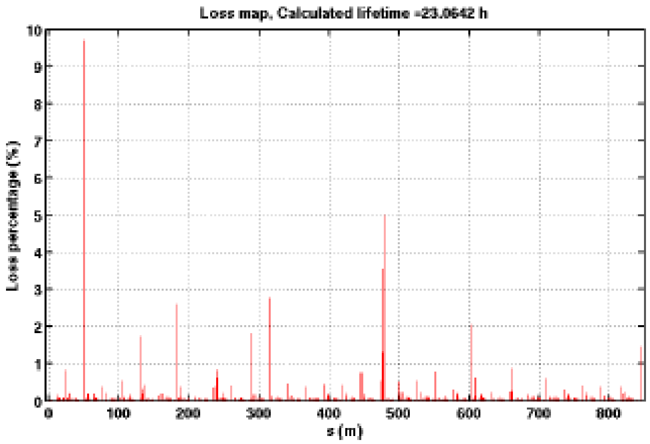

Superimposed regular cells, ± 4 mm vertical aperture in all straight sections

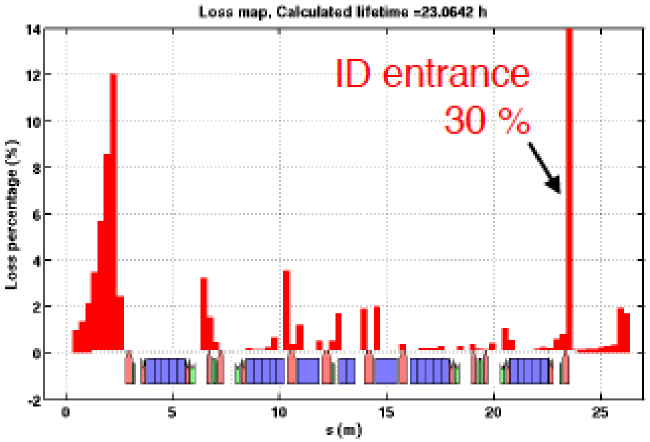

Aperture reduction to ± 3 mm at the 12 in-vacuum undulators locations

- 12 aperture restrictions have been inserted at the entrance or middle of straight sections to figure the in-vacuum insertion devices locations, impacting the distribution.

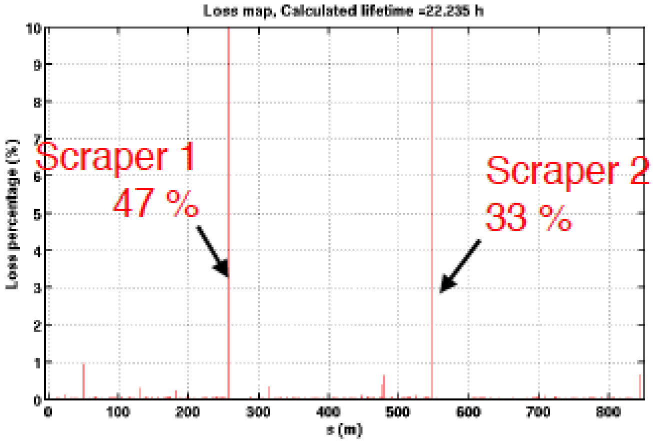
COLLIMATION OPTIMIZATION TO DECREASE LOSSES IN THE IDS

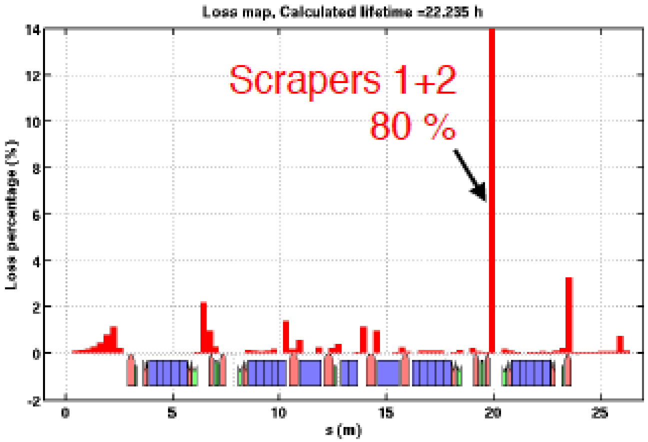
80% of the losses are relocated on the scrapers for 4% lifetime reduction:





No scrapers

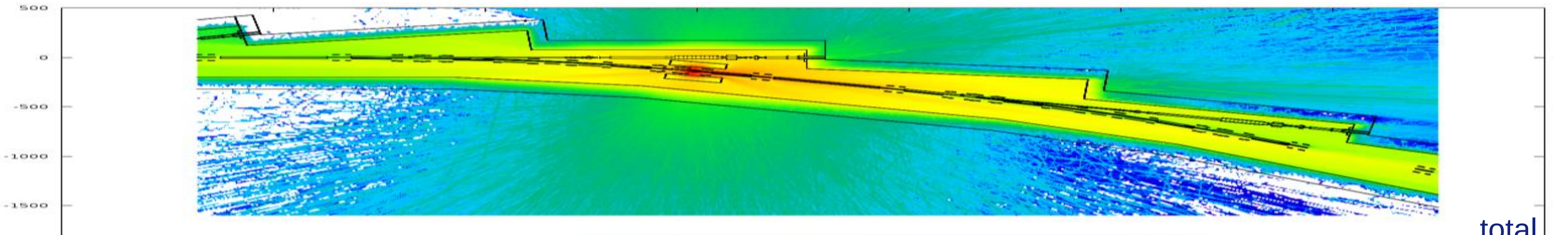




Two scrapers in DR_37 of cells 13 and 24

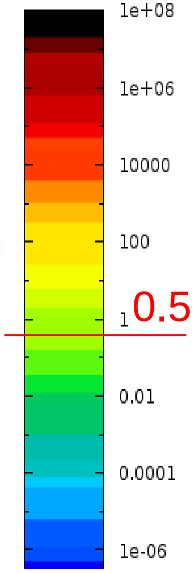
COLLIMATOR SHIELDING

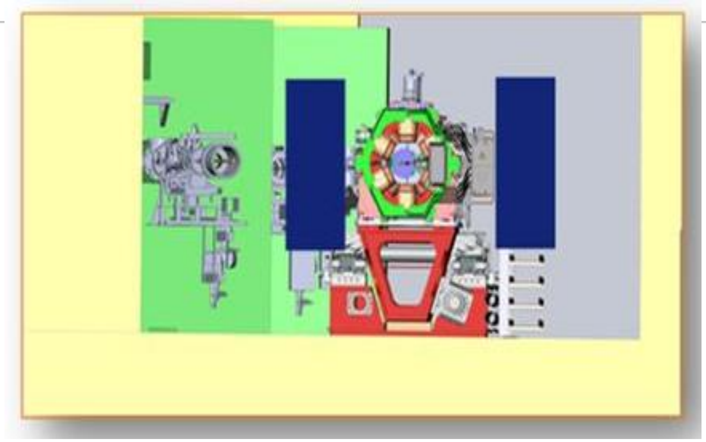
50 CM LEAD LOCAL SHIELDING



total

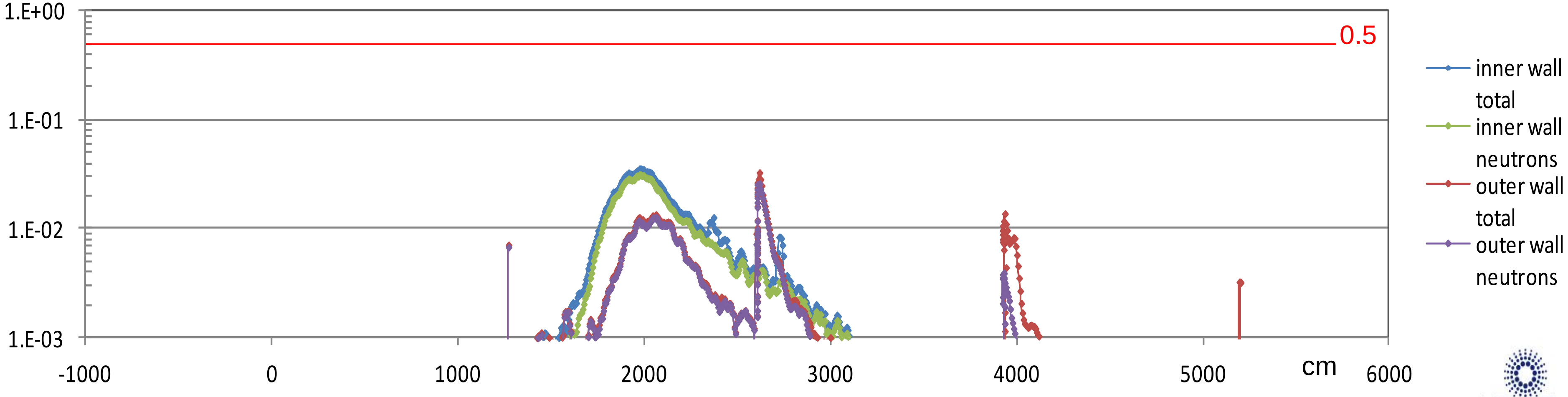
µSv/h



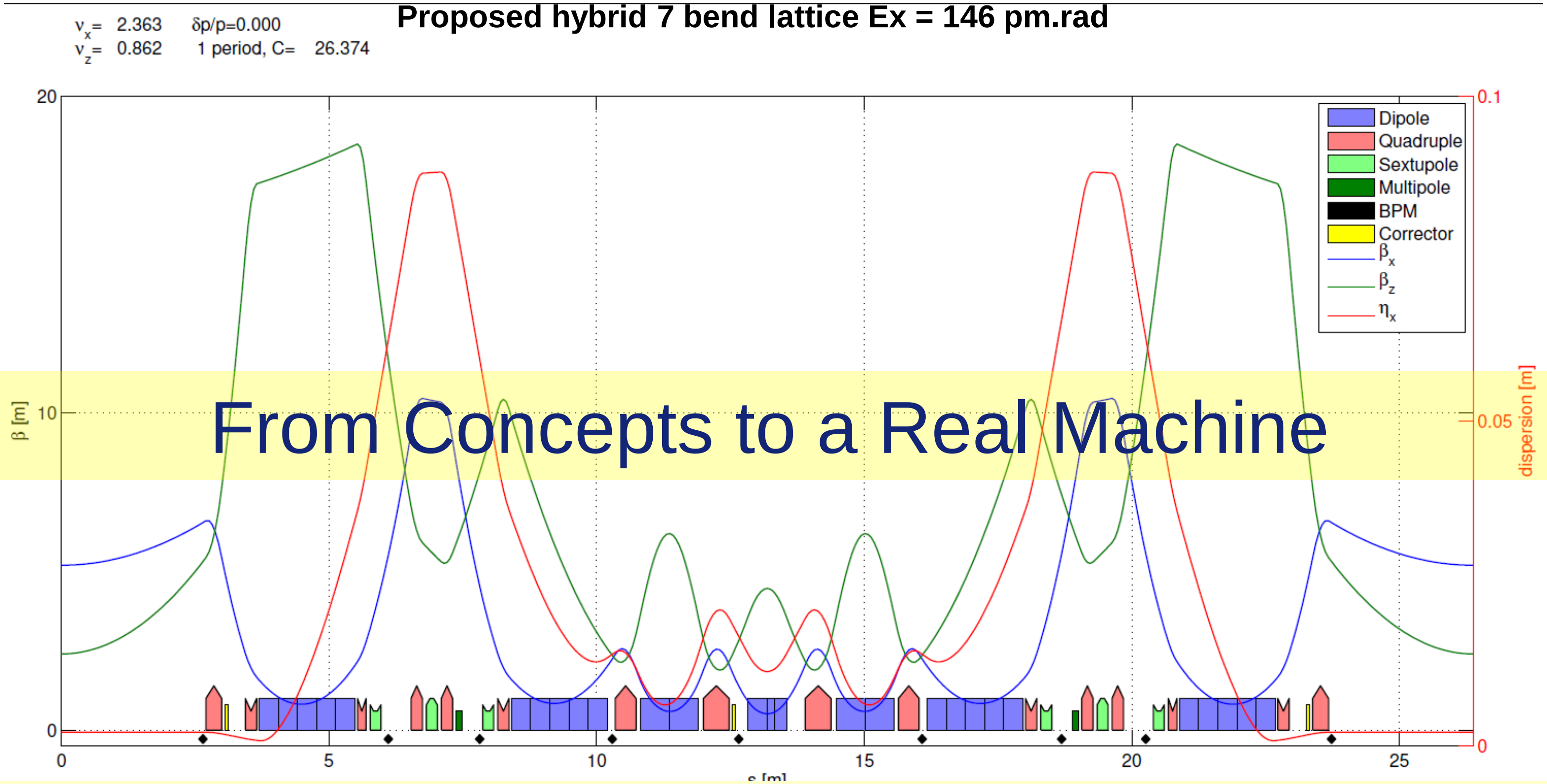


neutrons

ambient dose equivalent rate (µSv/h)



The ESRF Low Emittance Lattice



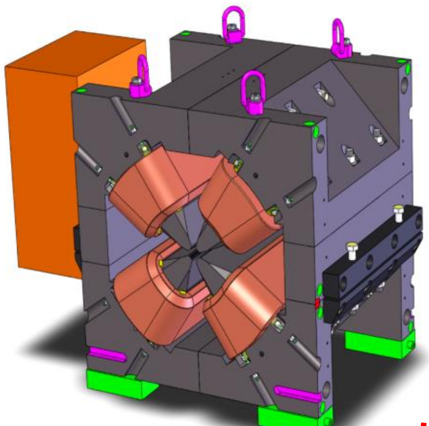
Proposed hybrid 7 bend lattice Ex = 146 pm.rad

From Concepts to a Real Machine

<u>Several iterations made between:</u>

- Optics optimization: general performances in terms of emittance, dynamic aperture, energy spread etc…
- Magnets requirements: fields, gradients…
- Vacuum system requirements: chambers, absorbers, pumping etc
- Diagnostic requirements
- Bending beam lines source

Technical challenge: Magnets System

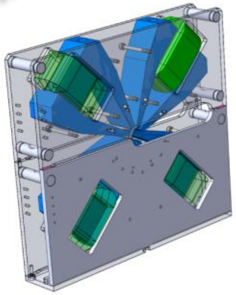


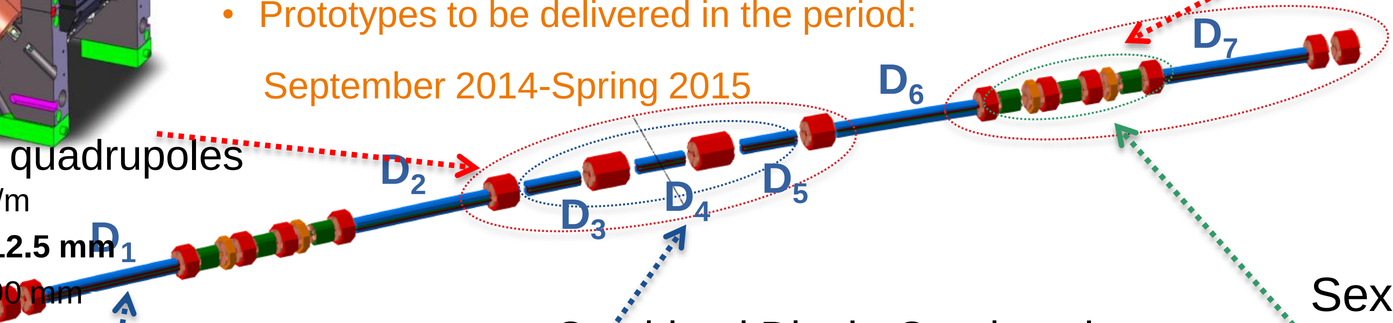
Mechanical design final drawing phase

- Soft iron, bulk yoke
- Large positioning pins for opening repeatability
- Tight tolerances on pole profiles
- Prototypes to be delivered in the period: September 2014-Spring 2015

Quadrupole

Around 52Tm^{-1}





High gradient quadrupoles

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

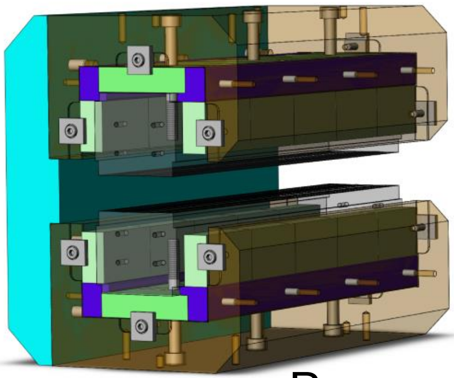
Combined Dipole-Quadrupoles

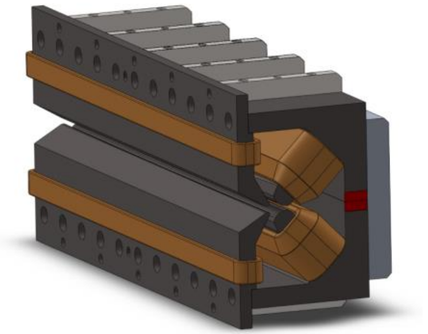
0.54 T / 34 Tm^{-1} & 0.43 T / 34 Tm^{-1}

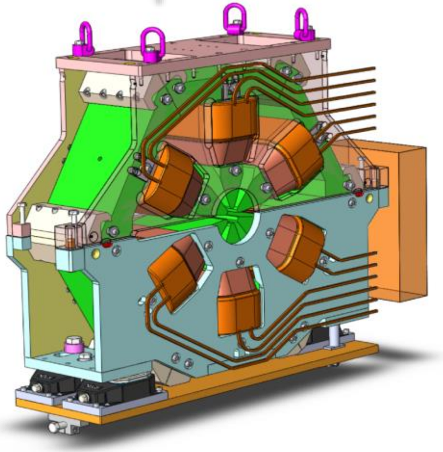
Sextupoles

Length 200mm

Gradient: 3500 Tm^{-2}







Permanent magnet (Sm_2Co_{17}) dipoles

longitudinal gradient 0.16 – 0.65 T, magnetic gap 25 mm

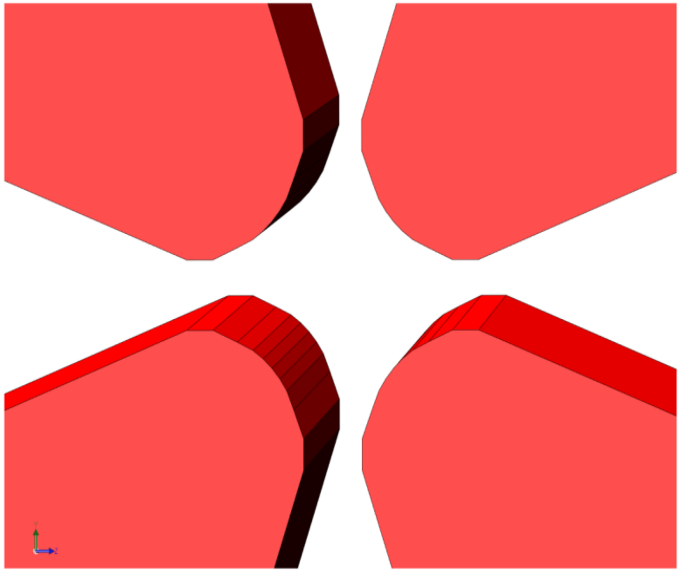
1.8 meters long, 5 modules

Gael Le Bec

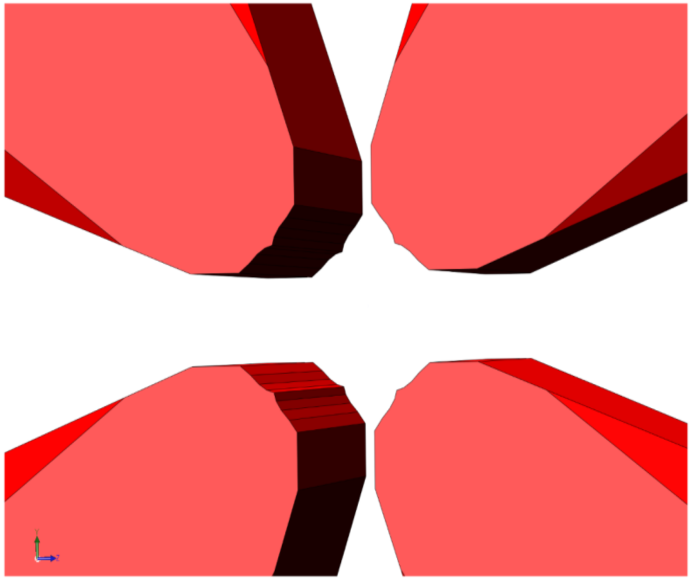
QUADRUPOLES

Pole shape optimization

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



Low gradient pole profile
QF1 magnet

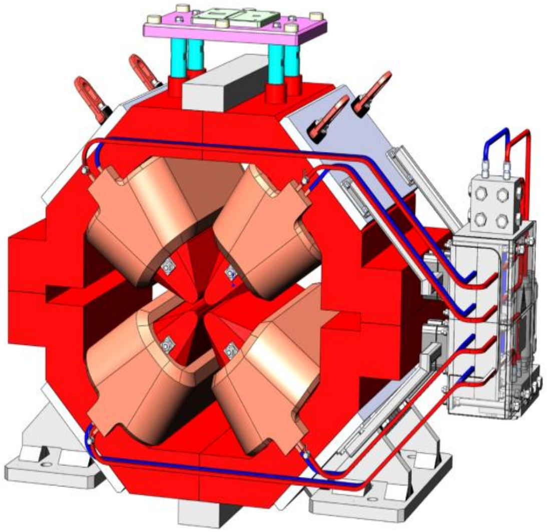


High gradient pole profile
QF8 magnet

QUADRUPOLES

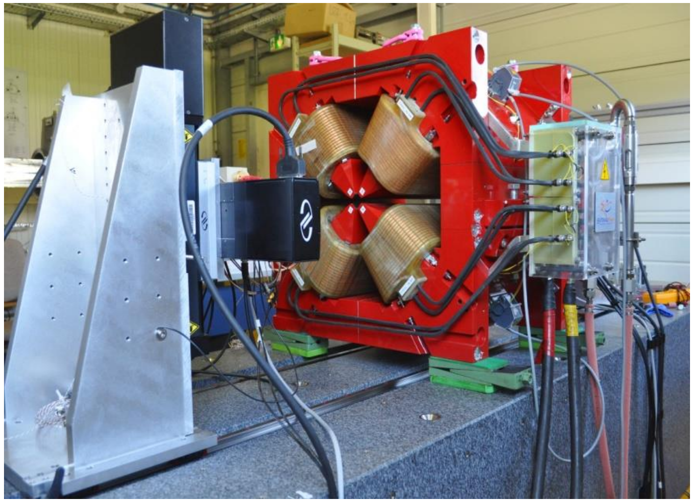
High Gradient

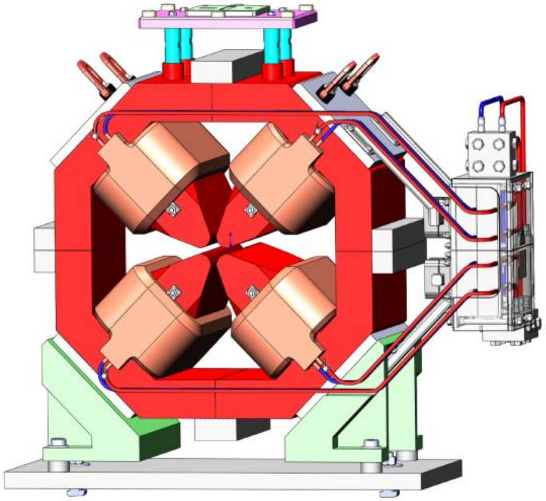
- 91 T/m gradient, 388 – 484 mm length
- 12.7 mm bore radius, 11 mm vertical gap
- 1.4 – 1.6 kW power consumption



HG Prototype

+/-20um pole accuracy





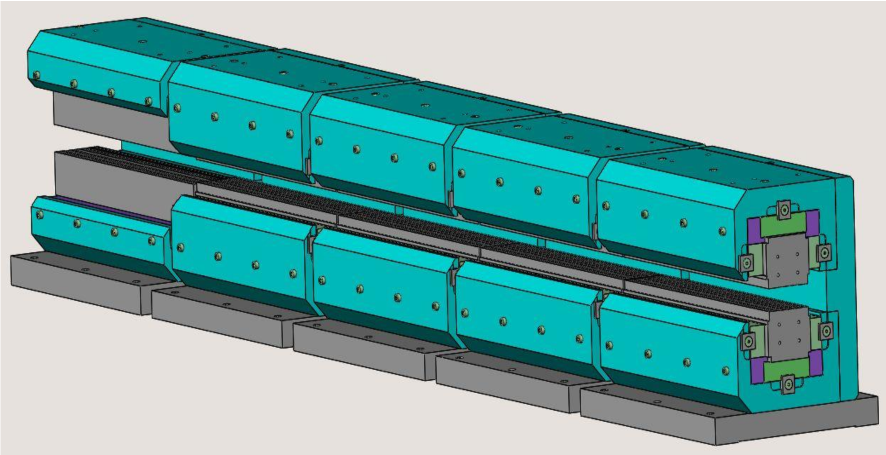
Moderate Gradient

- 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

DIPOLE WITH LONGITUDINAL GRADIENT

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

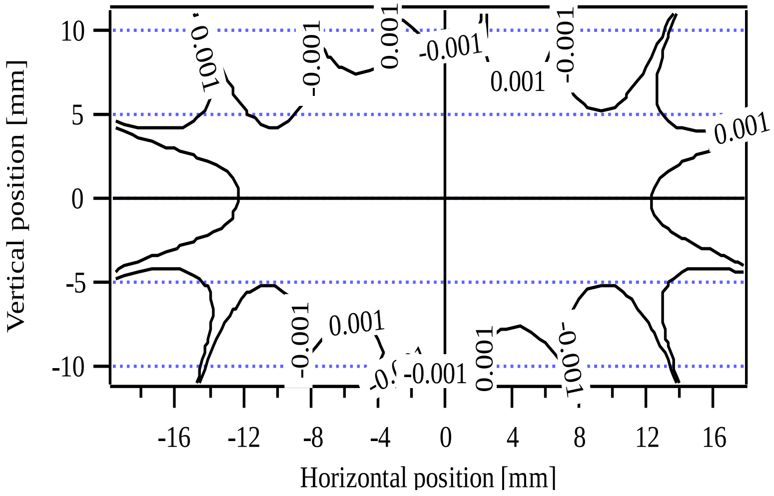


Engineering design

- Final drawings produced

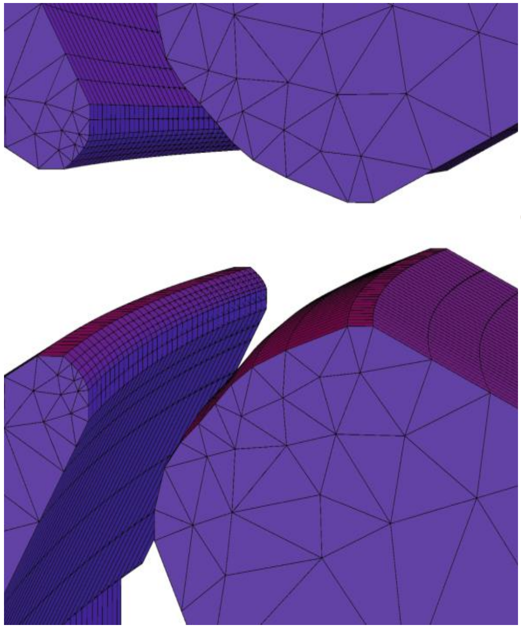
Prototyping

- Final prototype to be build in the coming months

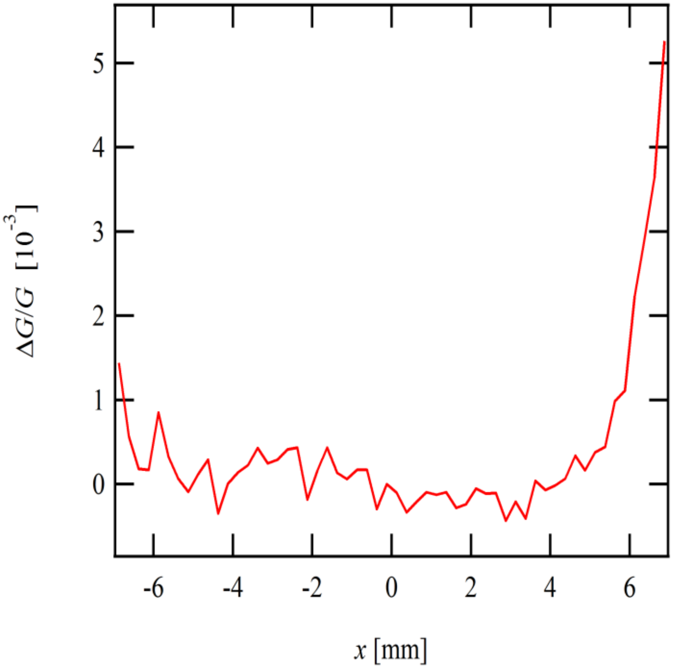


Measured field integral homogeneity (one module)

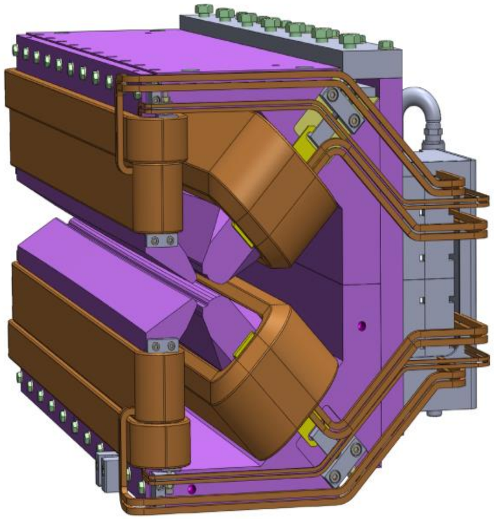
DIPOLE QUADRUPOLES



DQ1 pole shape



DQ1 gradient homogeneity:
Integration of trajectory along an arc



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

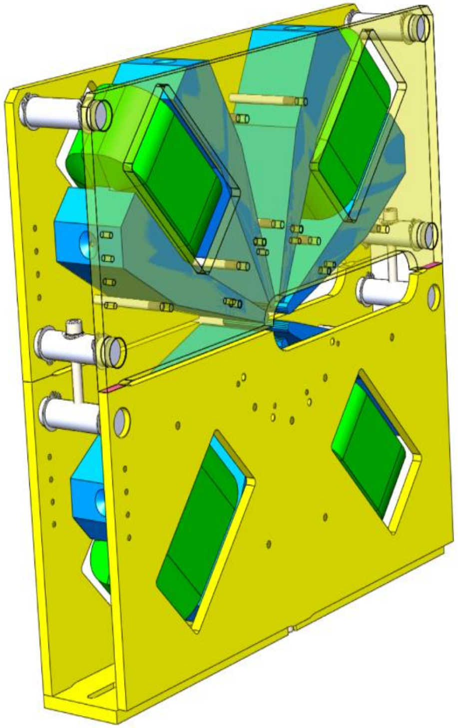
$\Delta G/G < 1\%$ (GFR radius 7 mm)

DQs are machined in 7 laminated iron plates

OCTUPOLES

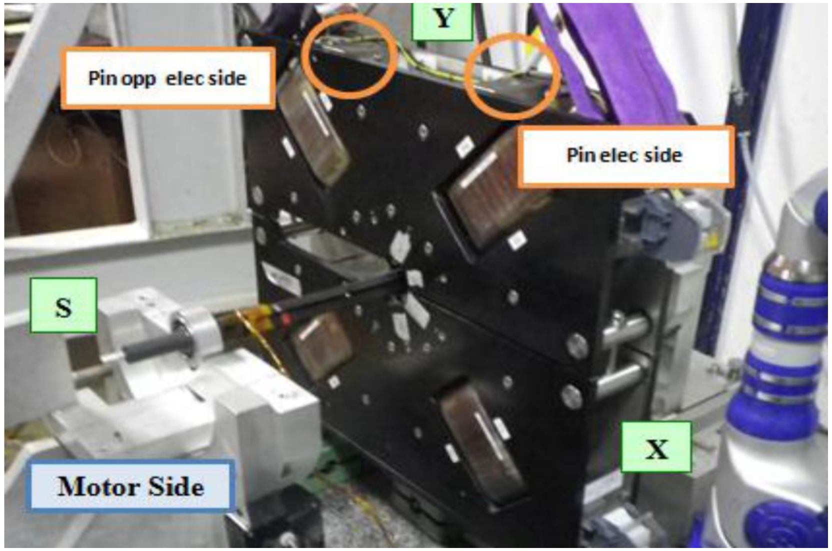
S28b specifications

- 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



Prototyping

- Air cooled prototype measured



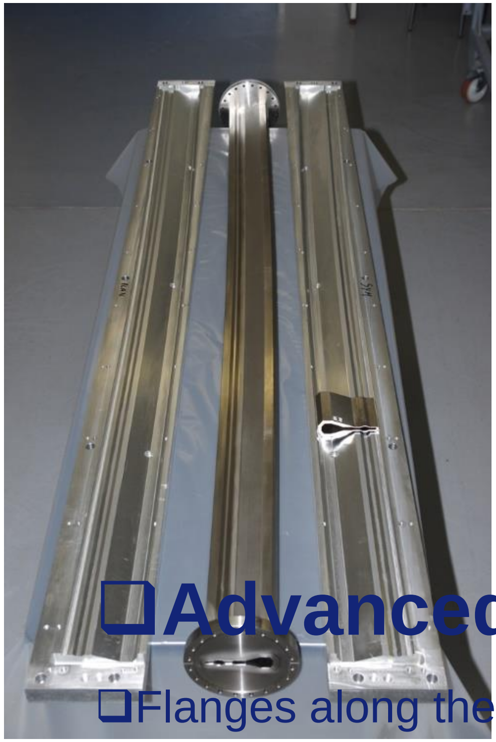
1) MAIN MAGNET POWER SUPPLIES

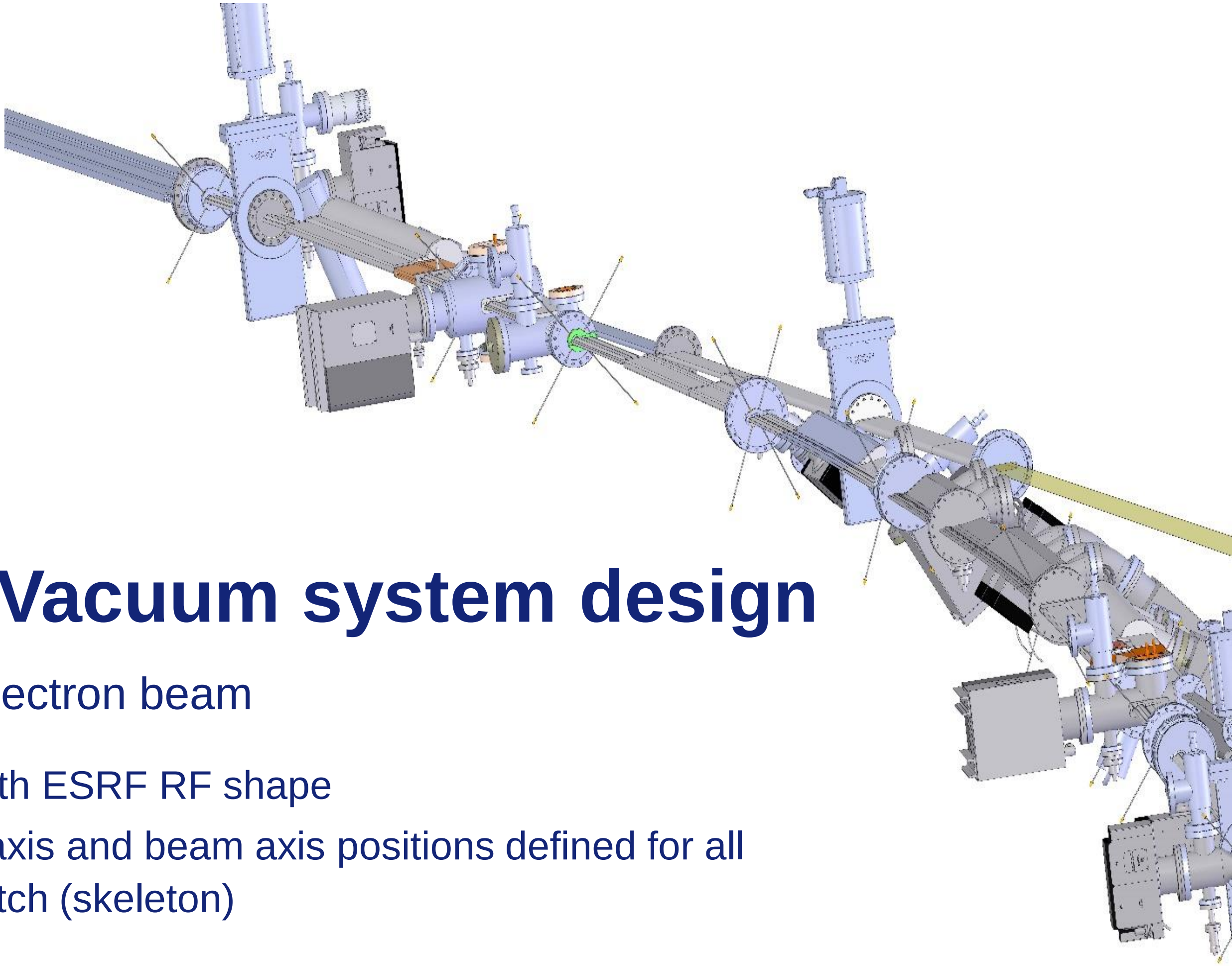
The following table has been updated to the last values of the WP2

Type	Name	07/04/2015 quantity per cell	NOMINAL FIELD VALUES Length [m]	dB/dx [T/m]	lattice	Electrical design Power [kW]	Voltage [V]	Current [A]	PS design OVfactor	Imax	Watts Pnom	Watts Pmax	nom Watts cell	maxWatt P total cell
Quadrupole, mod. gradient	QF1	2	0.349	53.7		0.97	11.0	88.4	1.2	103	1081	1459	2161	2918
Quadrupole, mod. gradient	QD2	2	0.266	51.5		0.97	9.9	98.3	1.2	119	1109	1628	2218	3257
Quadrupole, mod. gradient	QD3	2	0.216	46.5		0.68	7.7	88.4	1.2	119	789	1422	1579	2843
Quadrupole, mod. gradient	QF4	4	0.216	51.5		0.97	9.9	98.3	1.2	119	1109	1628	4437	6514
Quadrupole, mod. gradient	QD5	2	0.212	52.5		0.97	9.9	98.3	1.2	117	1109	1567	2218	3134
Total		**12**											**12614**	**18666**
Quadrupole, high gradient	QF6	2	0.36	95.2		1.36	15.1	90.4	1.1	99	1480	1790	2959	3581
Quadrupole, high gradient	QF8	2	0.48	96.2		1.56	17.5	89.0	1.1	98	1671	2022	3343	4045
Total		**4**											**6302**	**7625**
Dipole-Quadrupole, high field	DQ1	2	1.11	37.54	33.9	1.47	17.2	85.5	1.2	103	1571	2263	3143	4526
Dipole-Quadrupole, mod field	DQ2	1	0.77	37.04	33.7	1.11	12.3	89.9	1.2	108	1223	1762	1223	1762
Total		**3**											**4366**	**6288**
Sextupole, long	SD	4		4500	4300	0.91	10.6	86.0	1.1	98	1012	1315	4049	5262
Sextupole, long	SF	2				0.91	10.6	86.0	1.1	98	1012	1315	2024	2631
Total		**6**											**6073**	**7892**
Octupole	OF1-2	2	0.114		7013	0.35	3.3	107.3	1.2	129	517	744	1034	1489
Total		**2**											**1034**	**1489**
		27	Total PS power for one cell for main electromagnets										**30.4** **kW**	**42.0** **kVA**

	magnet	coils	type	PS/Magnet	PS /cell	current	DC voltage	Power
corrector AC+DC (5 independent coils)	3	5	AC+DC	3	9	2A	13V	26W
Sextupole, short correctors	6	6	DC	4	24	2A	11V	22W
Total number of cell		51			**33**			

VACUUM CHAMBERS



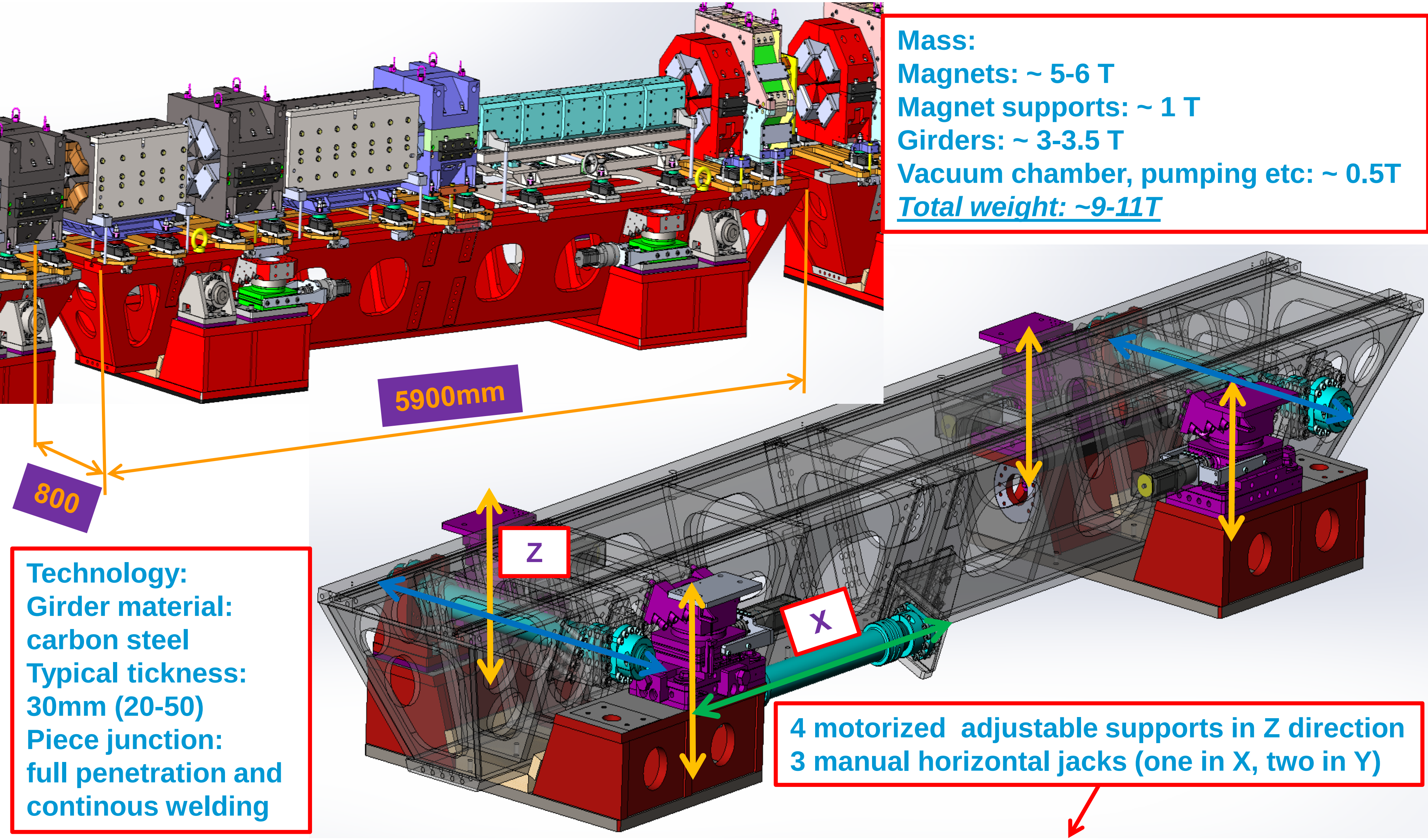


❑Advanced Vacuum system design

- ❑Flanges along the electron beam
  - ❑ CF flanges 316LN with ESRF RF shape
  - ❑ Longitudinal, flange axis and beam axis positions defined for all chambers in one sketch (skeleton)
- ❑Body
  - ❑ Stainless steel 316LN machined in two half parts and EB welded in the horizontal plan

Jean-Claude Biasci

GIRDER DESIGN, THE ORTHOGONAL HEPTAPOD



Mass:
Magnets: ~ 5-6 T
Magnet supports: ~ 1 T
Girders: ~ 3-3.5 T
Vacuum chamber, pumping etc: ~ 0.5T
Total weight: ~9-11T

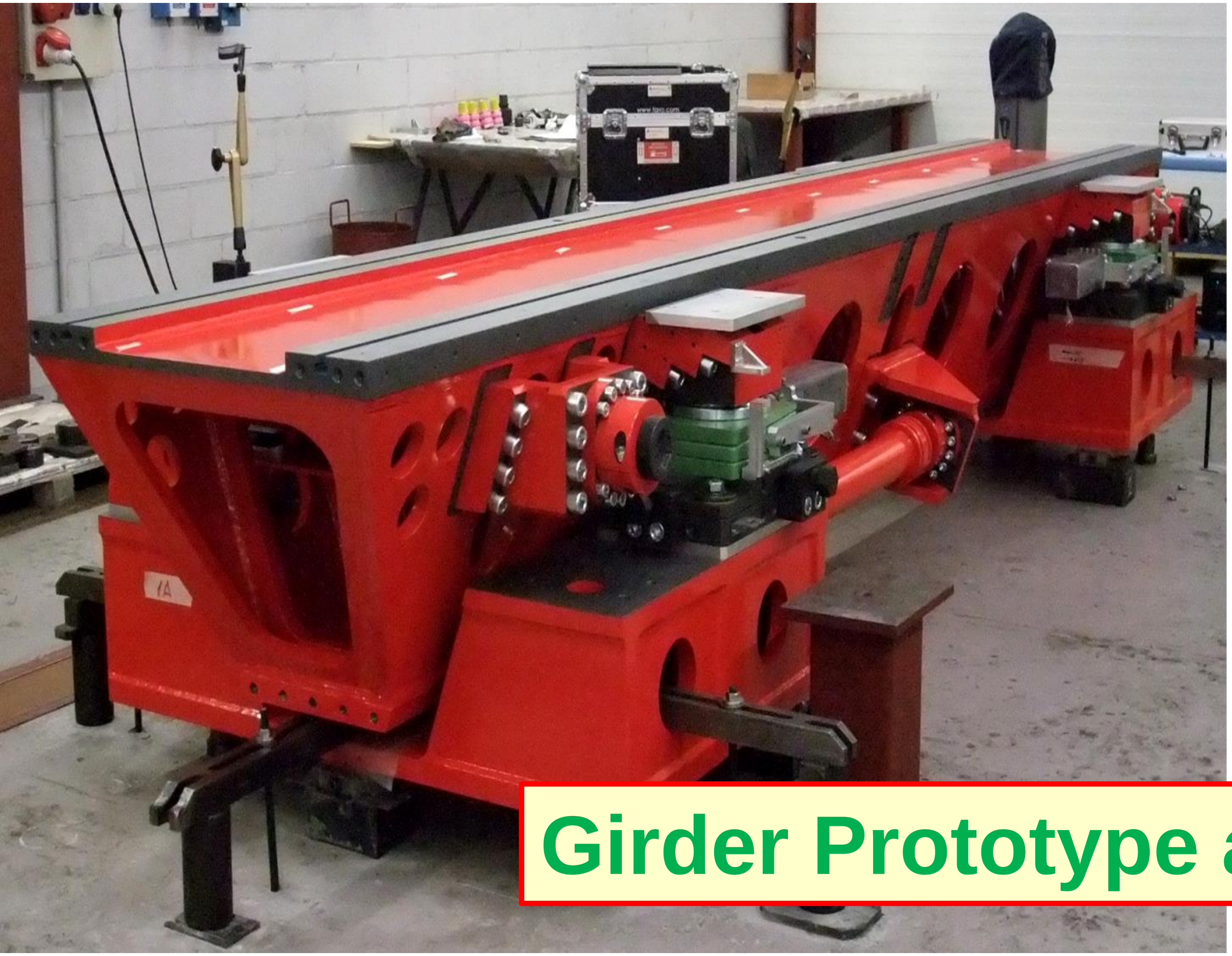
Technology:
Girder material:
carbon steel
Typical tickness:
30mm (20-50)
Piece junction:
full penetration and
continous welding

4 motorized adjustable supports in Z direction
3 manual horizontal jacks (one in X, two in Y)

Filippo Cianciosi

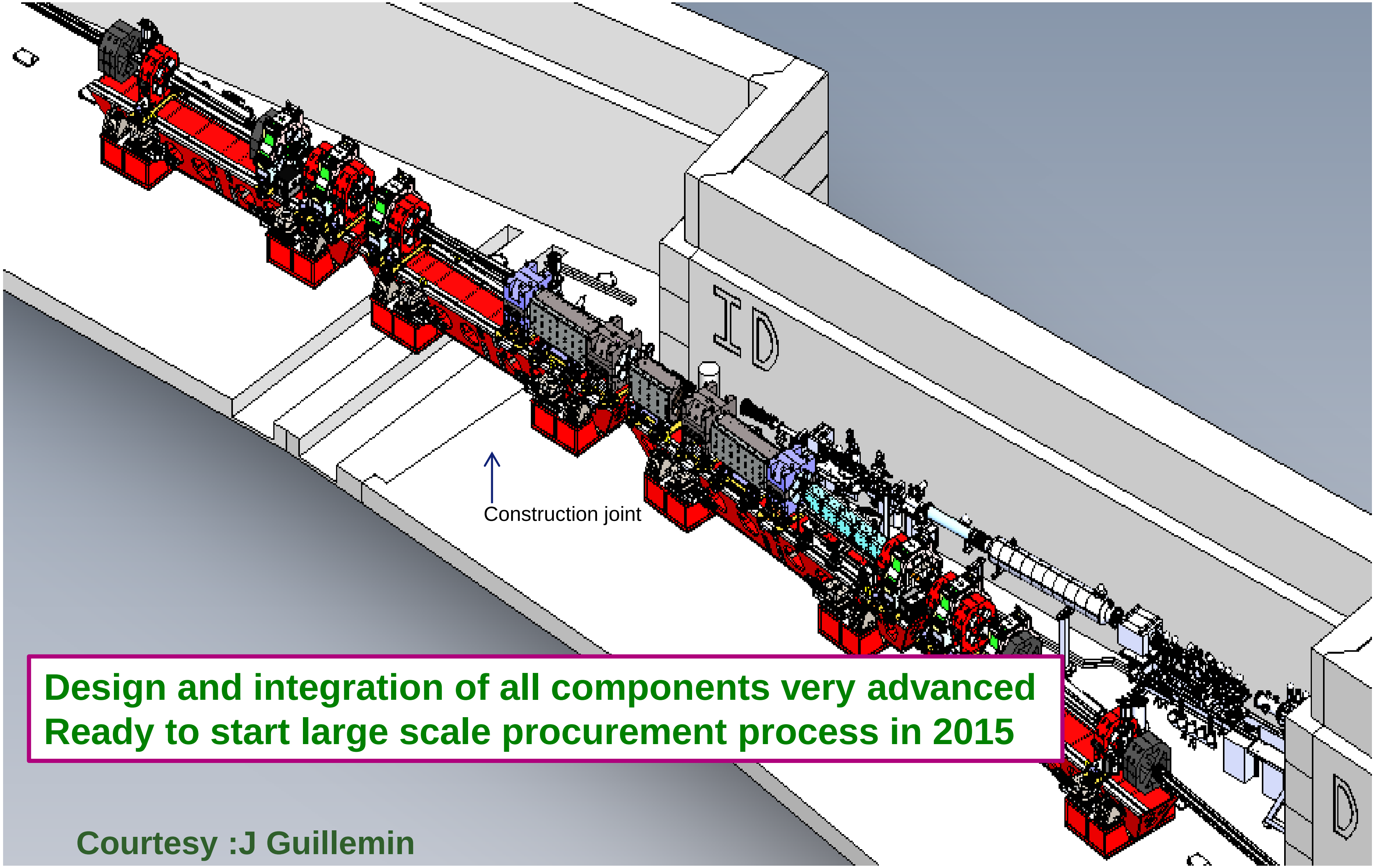
PRE-DELIVERY TEST AT NORTEMECANICA 08/04/2015 1/2

-Assembly test (made by Nortemecanica), no relevant problems.
-The Y movement with the jacks is smooth, the resolution is better than 10µm, the effort small
-The Z movement with the wedges is smooth, the (manual) resolution better than 10µm but the effort bigger than the one in the Airloc's datasheet



Girder Prototype at ESRF

SYSTEM INTEGRATION – MACHINE LAYOUT IN THE TUNNEL



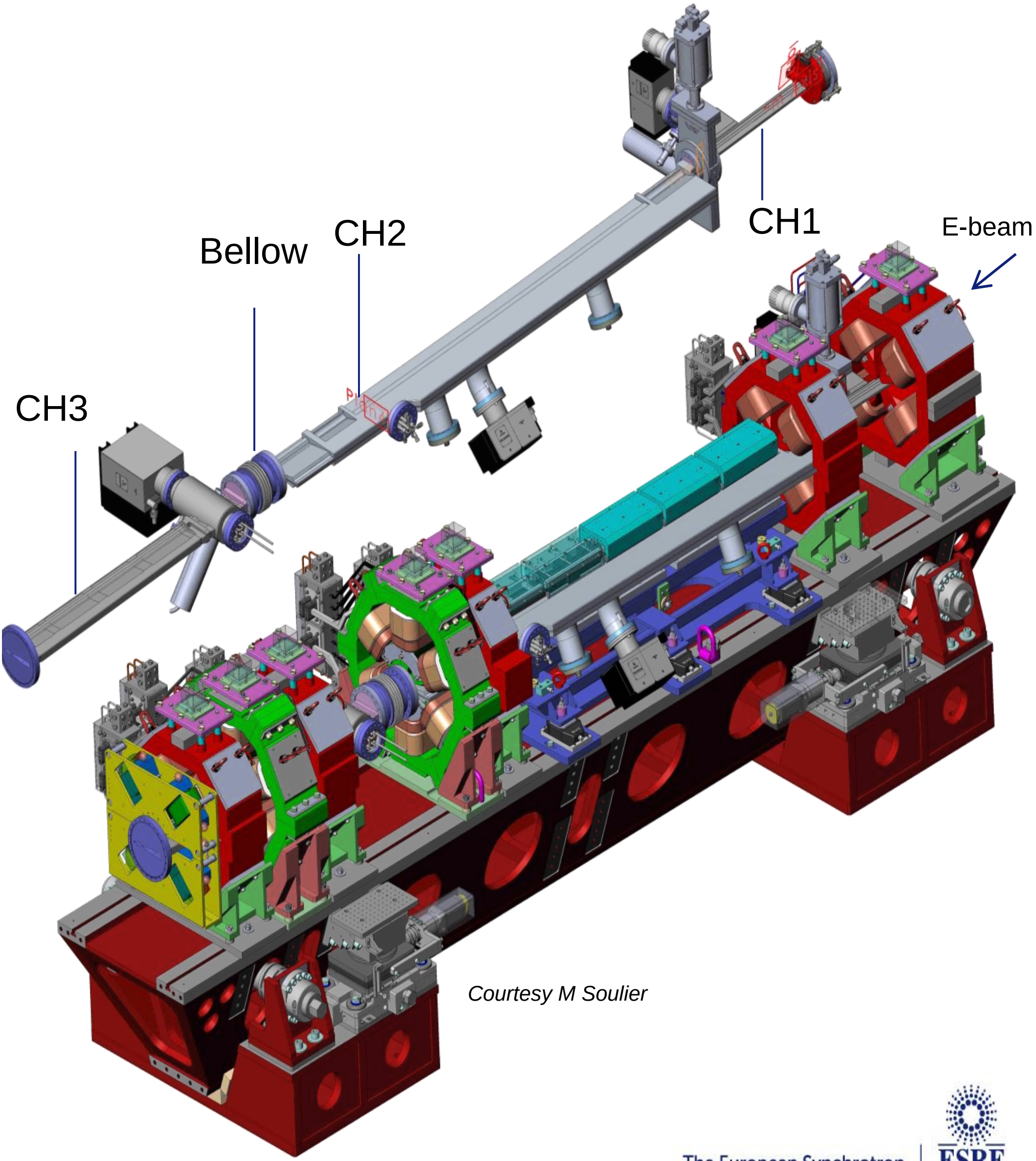
Design and integration of all components very advanced
Ready to start large scale procurement process in 2015

Courtesy :J Guillemin

SYSTEM INTEGRATION: GIRDER 1 (&4)

	CH1	CH2	CH3
Length [mm]	750.9	2627	1420.9
Material	316LN sheet	AL	316LN sheet
Bellow/RF fingers	1		-
Absorber	-	CH2 1-1	Crotch 1 CH3 1-1
BPM	BMP1		BPM2 BPM3

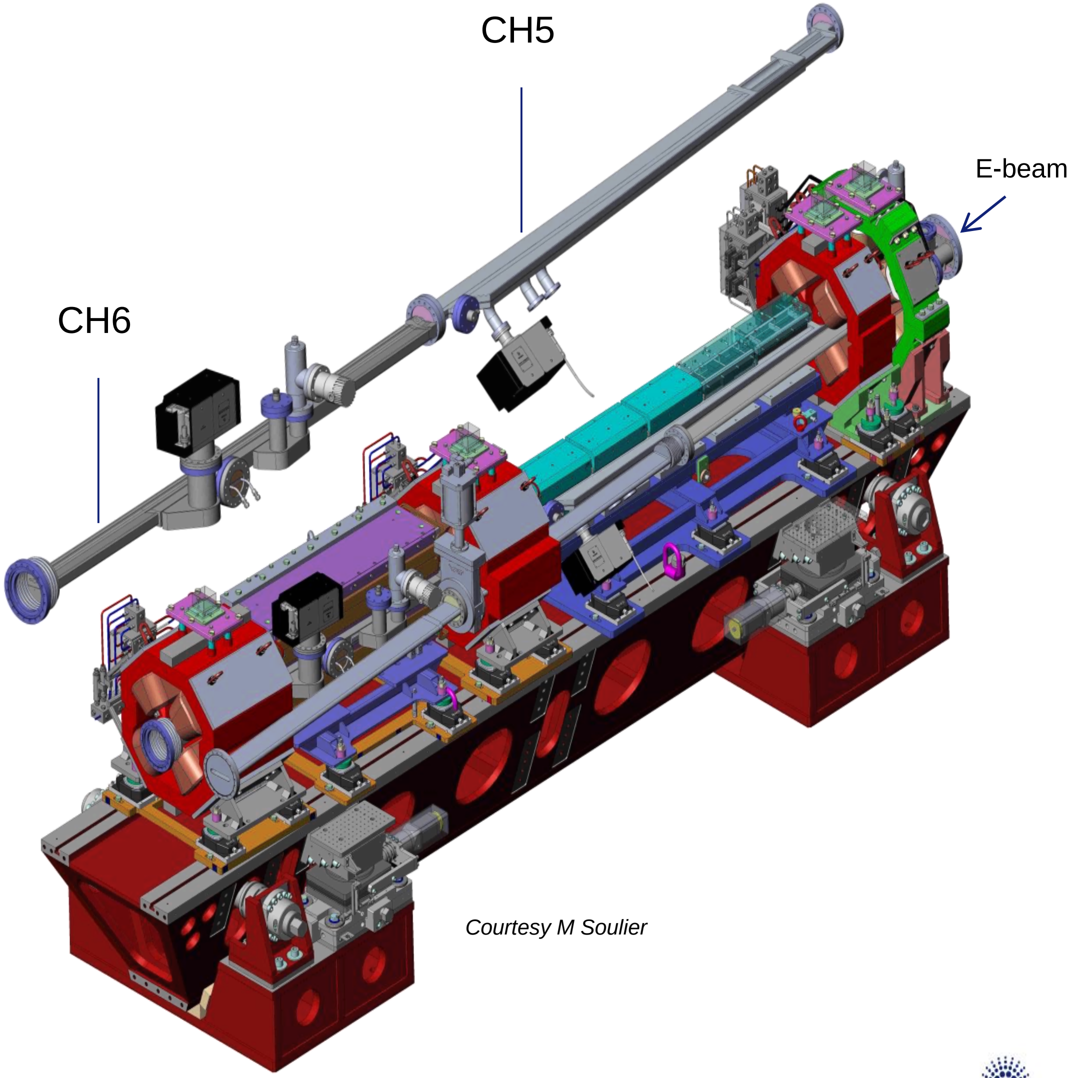
Red: fixed point



Courtesy M Soulier

SYSTEM INTEGRATION: GIRDER 2 (&3)

	CH5	CH6
Length [mm]	2408	2360
Material	AL	316LN sheet
Bellow/RF fingers	-	1
Absorber	CH5 1-1	CH6 1-1
BPM	-	BPM4



Courtesy M Soulier

PREPARING THE UPGRADE PHASE II

Orange Book

ESRF

TECHNICAL DESIGN STUDY
THE ESRF UPGRADE PROGRAMME
PHASE II

Technical Design Study (TDS)
Completed and submitted to:

Science Advisory Committee (SAC)

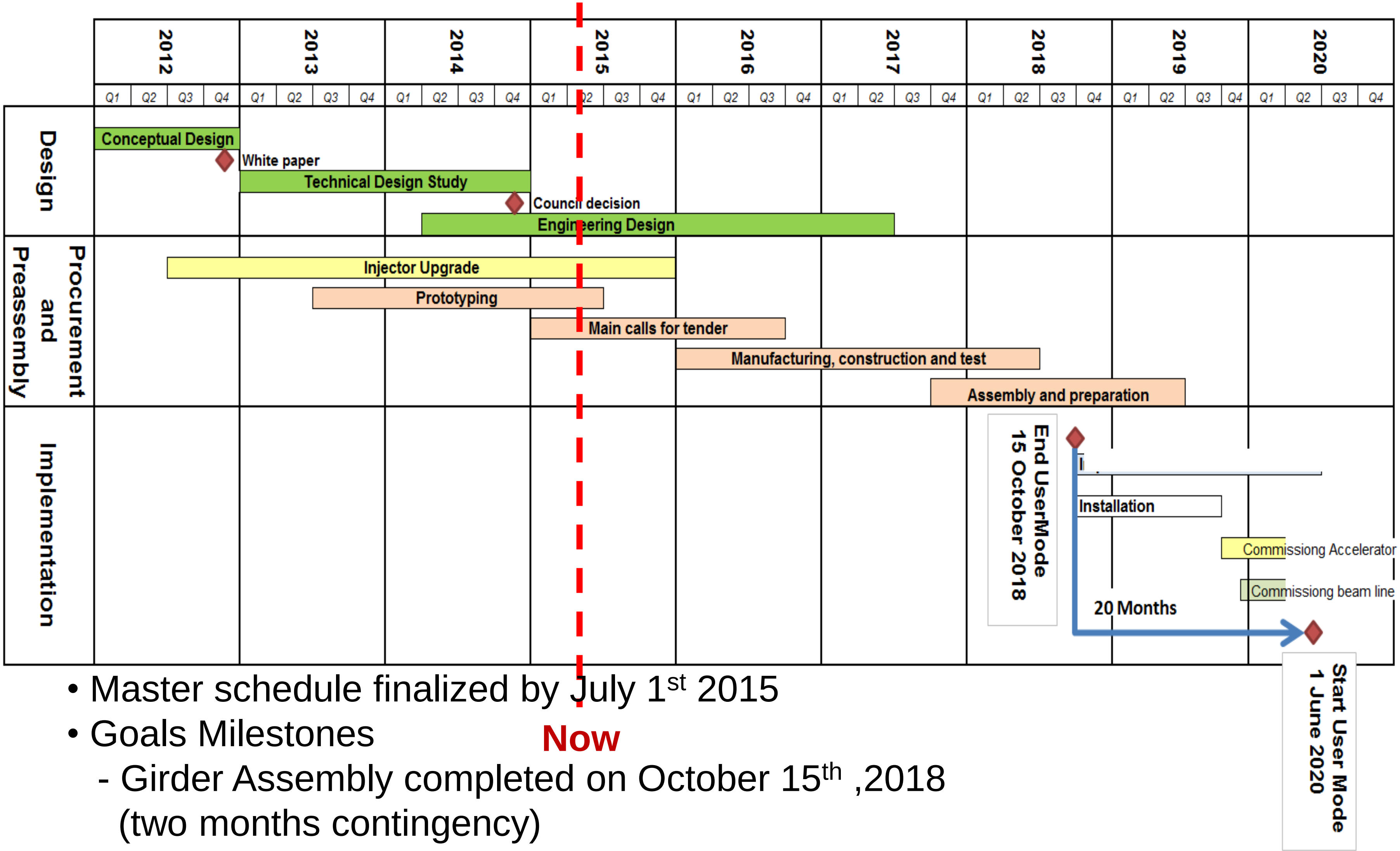
Accelerator Project Advisory Committee (APAC)

Cost Review Panel (CRP)

ESRF Council

All committees very positive
Project Approved and Funded
Official Start: Jan 1st 2015

OVERALL GENERAL PLANNING (TDS)



- Master schedule finalized by July 1st 2015
- Goals Milestones
  - Girder Assembly completed on October 15th ,2018 (two months contingency)
  - Shutdown for installation start on Dec 15th , 2018
  - User Mode Operation starts on June 1st, 2020 (about four months contingengy for installation and commissioning)

CONCLUSION (1)

❑ Project Officially Started on Jan 1st 2015

❑ Optics Optimized (More tuning (Design frozen) is forseen)

❑ Layout finalized

❑ Prototypes & manufacturers contacts in progress

❑ Accelerator Engineering well advanced

❑ All ESRF Divisions greatly supporting the Accelerator Upgrade Project

❑ A lot of the activities foreseen for the execution phase advanced already during 2014

❑ Tender process for serial production foreseen to start by Mid 2015

GREEN FIELD DLSR: GENERAL CONSIDERATIONS

❑ Current Upgrades forced to maintain existing layout

❑ General Ring Structure: Straight Sections interleaved with Arcs

❑ How to build the DLSR? Let’s start just listing the what is needed (not exhaustive):

0) 2pi total bend angle

1) Straight Sections

2) Matching SS-Arc

3) Minimum angle between SS

4) Chromaticity Correction

5) Low Emittance Lattice Arc

6) Injection section

The requirements for 1-to-6 are in general conflicting!

GREEN FIELD DLSR: GENERAL CONSIDERATIONS

1) Straight Sections:

How many?: 20-40

This number is mostly dictated by the optimal cost of the infrastructure w.r.t. the numebr of beamlines. Low energy ring costs much less, so in general fewer SS are found on them.

How long?: 2.5-3.5m

From last 20 years experience and IDs progress (e.g: revolver IDs, short period, low gaps) can we define the optimal length?

Two IDs in a SS (say 5m long) already cost a lot:

- Beta-Mismatch equivalent to a factor two in emittance (for DLSR)
- Minimum gap and minimum period larger (=> higher ring energy needed)

2) Matching SS-Arc

Matching is detrimental to: Emittance (Dipoles with Curl-H not ideal), Chromaticity

Canted Long SS require less Matching Section

GREEN FIELD DLSR: GENERAL CONSIDERATIONS

3) Minimum angle between SS

At the moment is:

“small” 4-6mrad for canted beamlines or

“large”: 2pi/SS_number

What is the minimum for not canted beamlines? 50-100mrad?

To be noted: Diamond DDBA has addressed and improved 1-2-3 on an existing ring!

4) Chromaticity Correction

Requires large betas, large dispersion, weak dipoles(as consequence)

5) Low Emittance Lattice Arc

Requires short dipoles, small dispersion, small beta_functions

6) Injection Section

Requires large beta_function and long Straight Section

GREEN FIELD DLSR: GENERAL CONSIDERATIONS

Presently the Arcs do all the 2-3-4-6 points simultaneously.

Could it make sense to do 2-3-4-6 somewhat separately?

- **Straight Sections Section**
- **Chromatic Correction Section**
- **Low Emittance Arc Section**
- **Injection Section**

MANY THANKS FOR YOUR ATTENTION