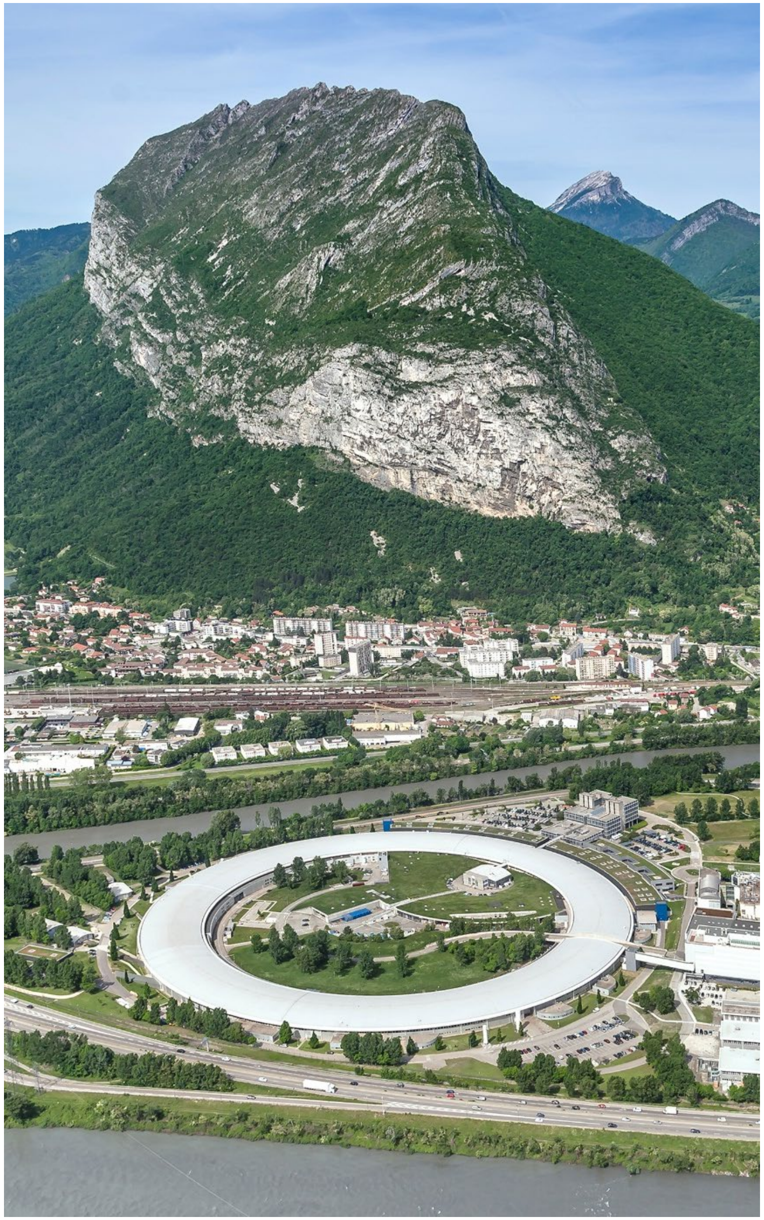


Alignment for the ESRF Extremely Brilliant Source (EBS)

D. Martin

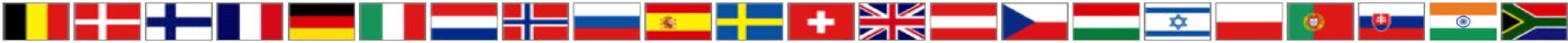
martin@esrf.fr

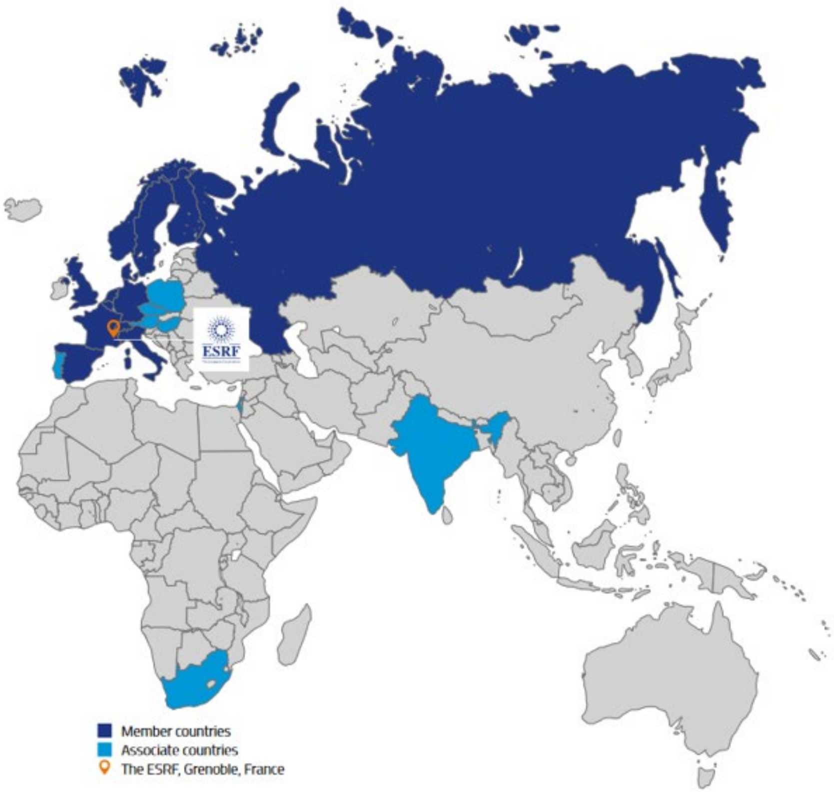
3DMC – Bilbao

28 September 2023

3DMC 3D METROLOGY CONFERENCE

THE ESRF





The ESRF is a synchrotron radiation light source.

It provides the world's brightest X-rays.

The X-rays are used to unveil the structure of materials and the mechanisms of life down to the atomic scale.

Founded in **1988**

21 partner countries

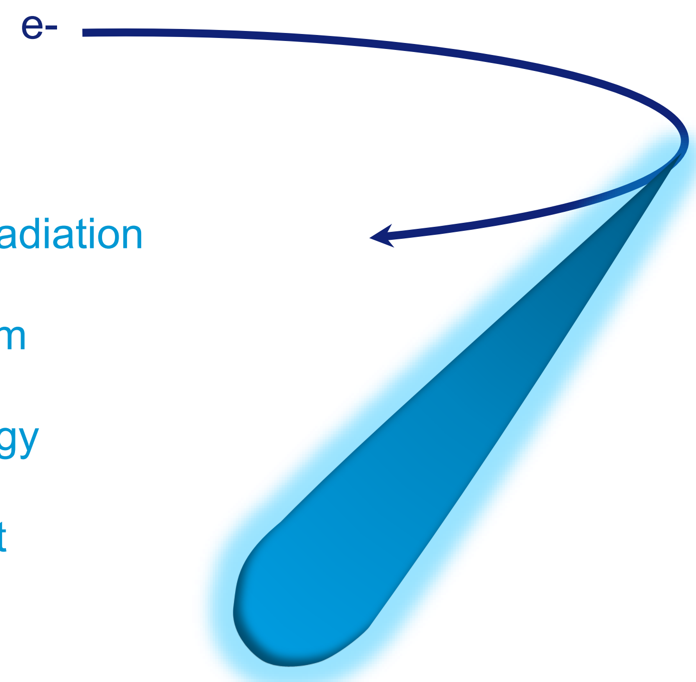
700 staff from more than **40** countries

9 000 users each year

2 000 scientific publications each year

30% of research carried out with industrial partners

WHAT IS SYNCHROTRON RADIATION?



When electrons are accelerated they generate synchrotron radiation

Synchrotron radiation is light on the electromagnetic spectrum

The wavelength of this light is a function of the electron energy

The ESRF electron velocity is very close to the speed of light

So the wavelength of the light is in the hard X-ray regime

The wavelengths of X-rays are small so they can be used to look at the atomic structure of matter

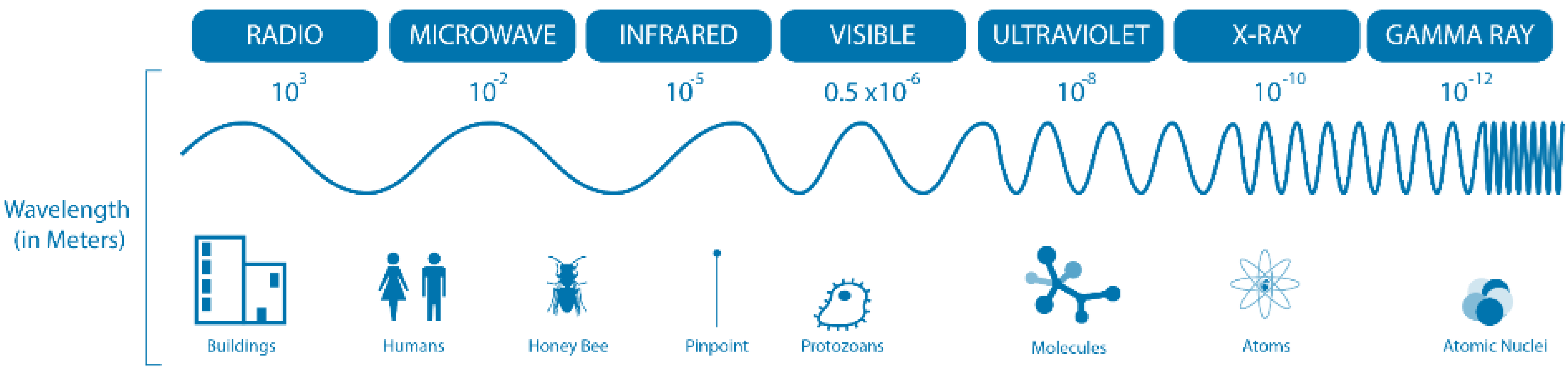
THE ELECTROMAGNETIC SPECTRUM

INFRARED 720-850nm

VISIBLE 440-640nm

ULTRAVIOLET 335-365nm

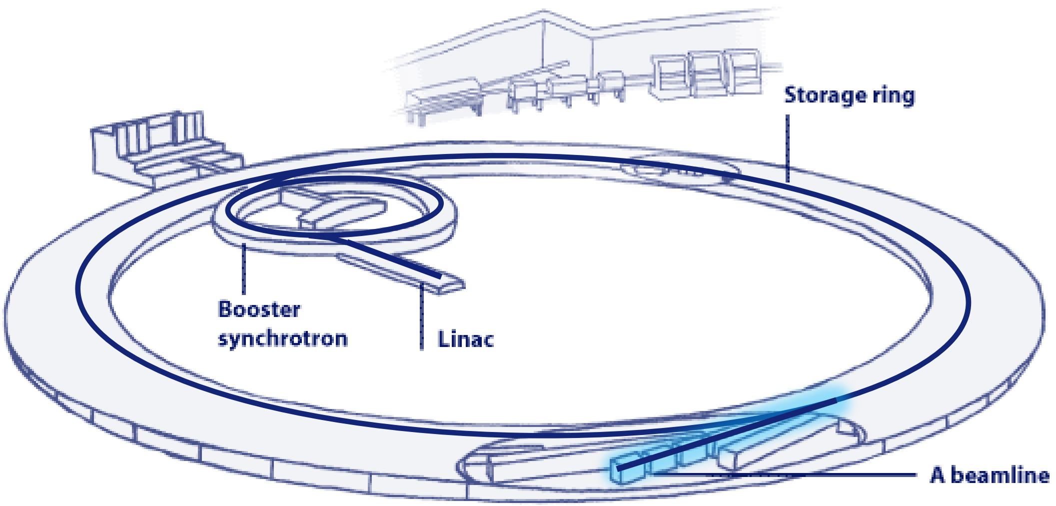
X-RAY 0.025 nm



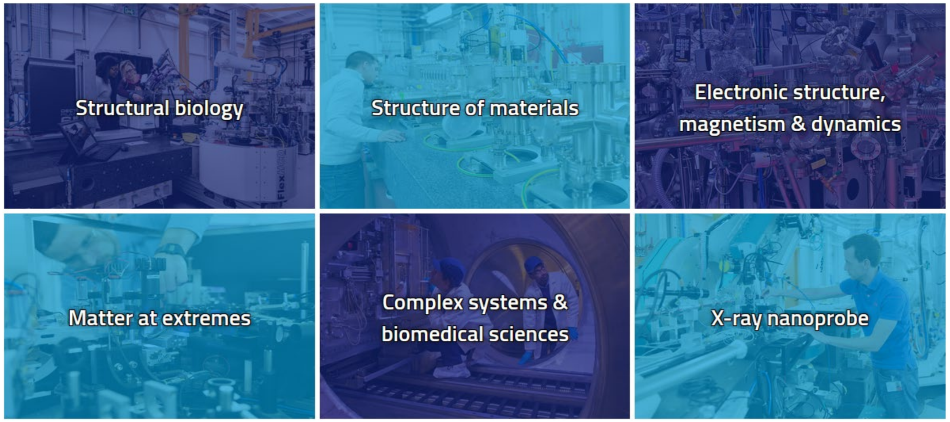
WHAT IS A SYNCHROTRON RADIATION LIGHT SOURCE?

A synchrotron radiation light source is composed of two main elements:

- A particle accelerator that accelerates electrons e^- to nearly the speed of light, and
- Beamlines that use the synchrotron radiation generated by the accelerator to study matter.



General applications of synchrotron radiation at the ESRF



The linear accelerator (linac) accelerates the electrons from rest mass to 100 MeV

The booster accelerates the electrons from 100MeV to 6GeV

The storage ring (SR) keeps the electrons circulating at 6GeV for many hours

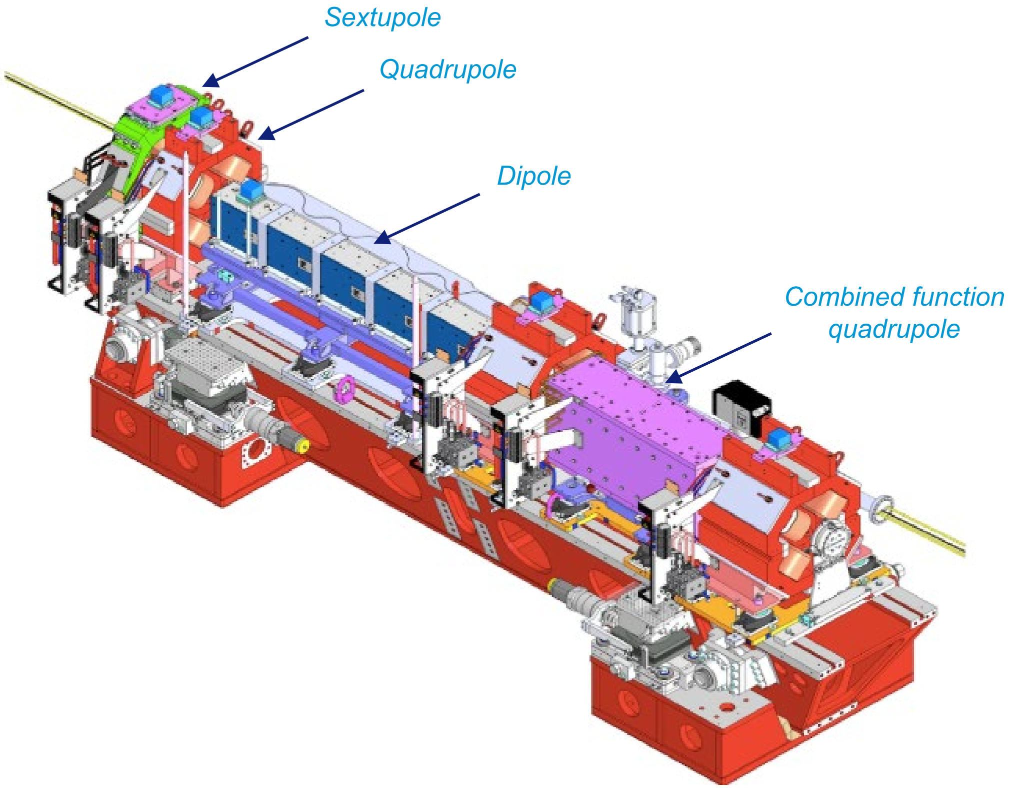
The 6GeV electrons produce synchrotron radiation in a tangential direction to the e^- beam travel

More importantly, special assemblies of magnets called insertion devices (IDs) make the 6GeV electrons oscillate about their orbit, producing very bright and collimated X-rays.

The X-rays are used on the beamlines to study matter.

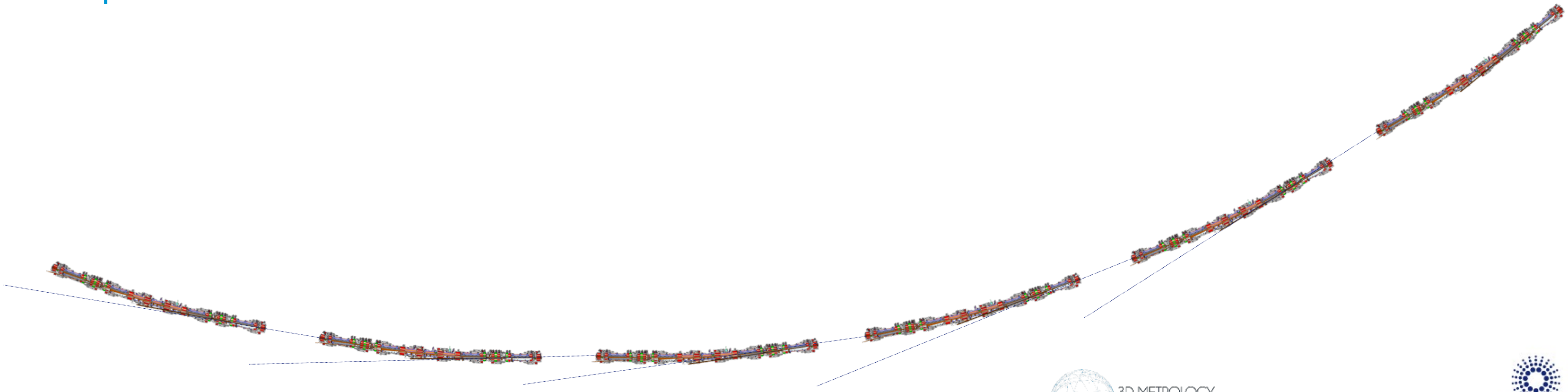
WHAT IS THE SR ACCELERATOR AND HOW DOES IT WORK?

An accelerator is composed of a repeating array of magnets. The array of magnets is referred to as the lattice. At the ESRF, the lattice comprises 32 cells. Each cell is composed of 4 girders and a total of 49 magnets …



Different magnets have different functions. Simplistically, for the main magnet families:

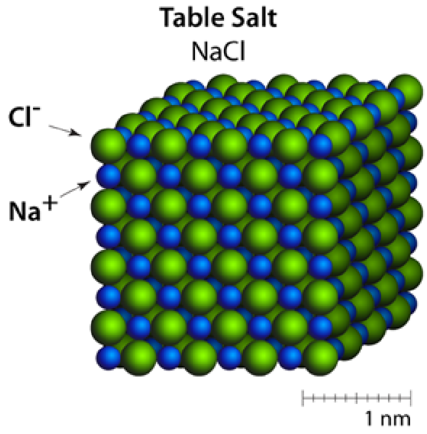
- The dipoles change the e- beam direction.
- The quadrupoles focus the e- beam.
- The sextupoles correct the e- beam.

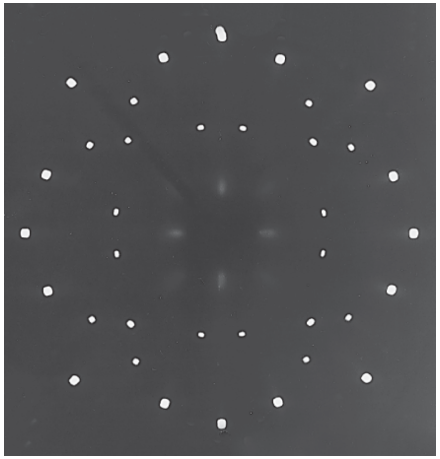


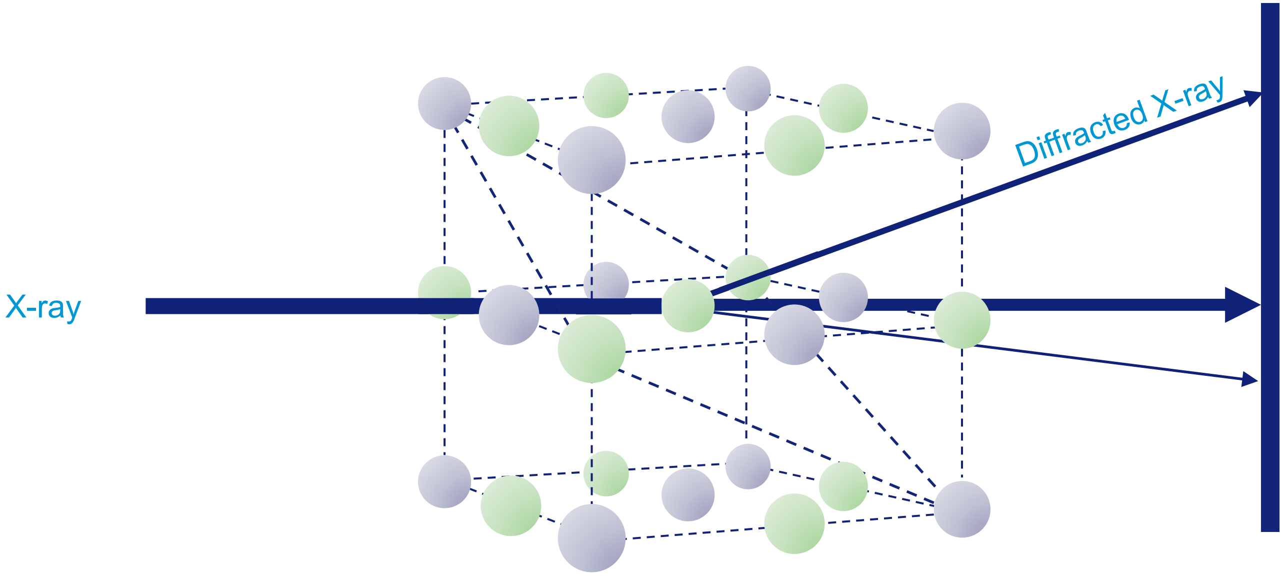
SO HOW ARE X-RAYS USED AT THE ESRF?

A good example of the type of science made at the ESRF is crystallography using X-ray diffraction.

A **crystal** is a solid material whose constituent atoms, molecules or ions, are arranged in a **highly ordered microscopic structure**, forming a **lattice** that extends in all directions.

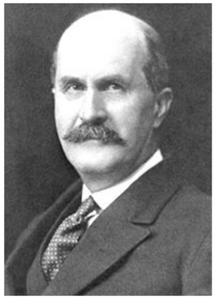


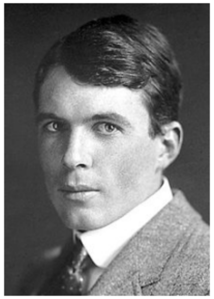


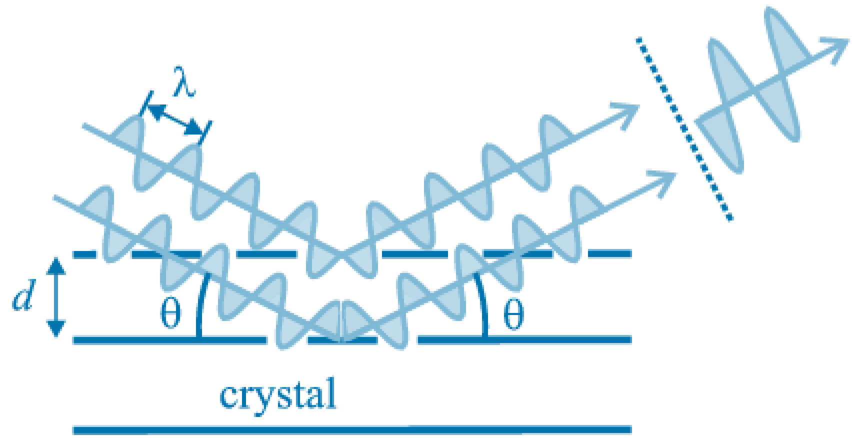


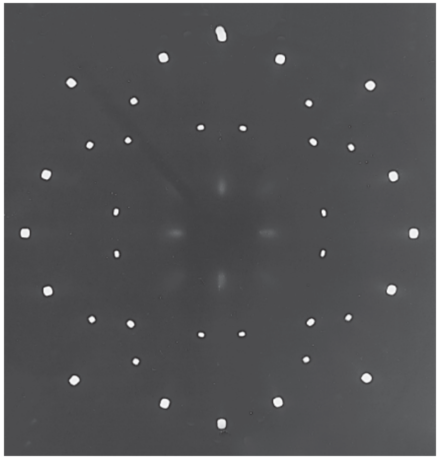
The atoms comprising the crystal structure form planes. When X-rays are incident on these crystal planes they are diffracted and produce a characteristic pattern of spots

BRAGG'S LAW









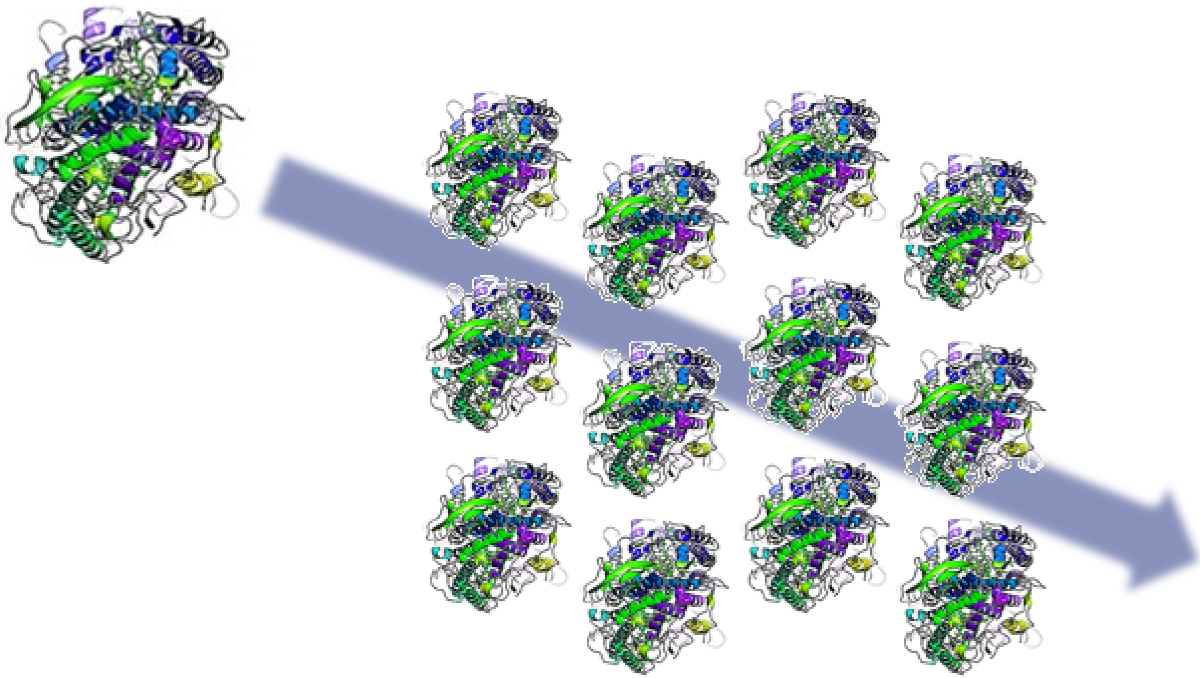
$$n\lambda = 2d\sin\Theta$$

Bragg's law provides an elegant and powerful description of diffraction from crystals.

It describes how constructive interference leads to the pattern of X-ray diffraction spots.

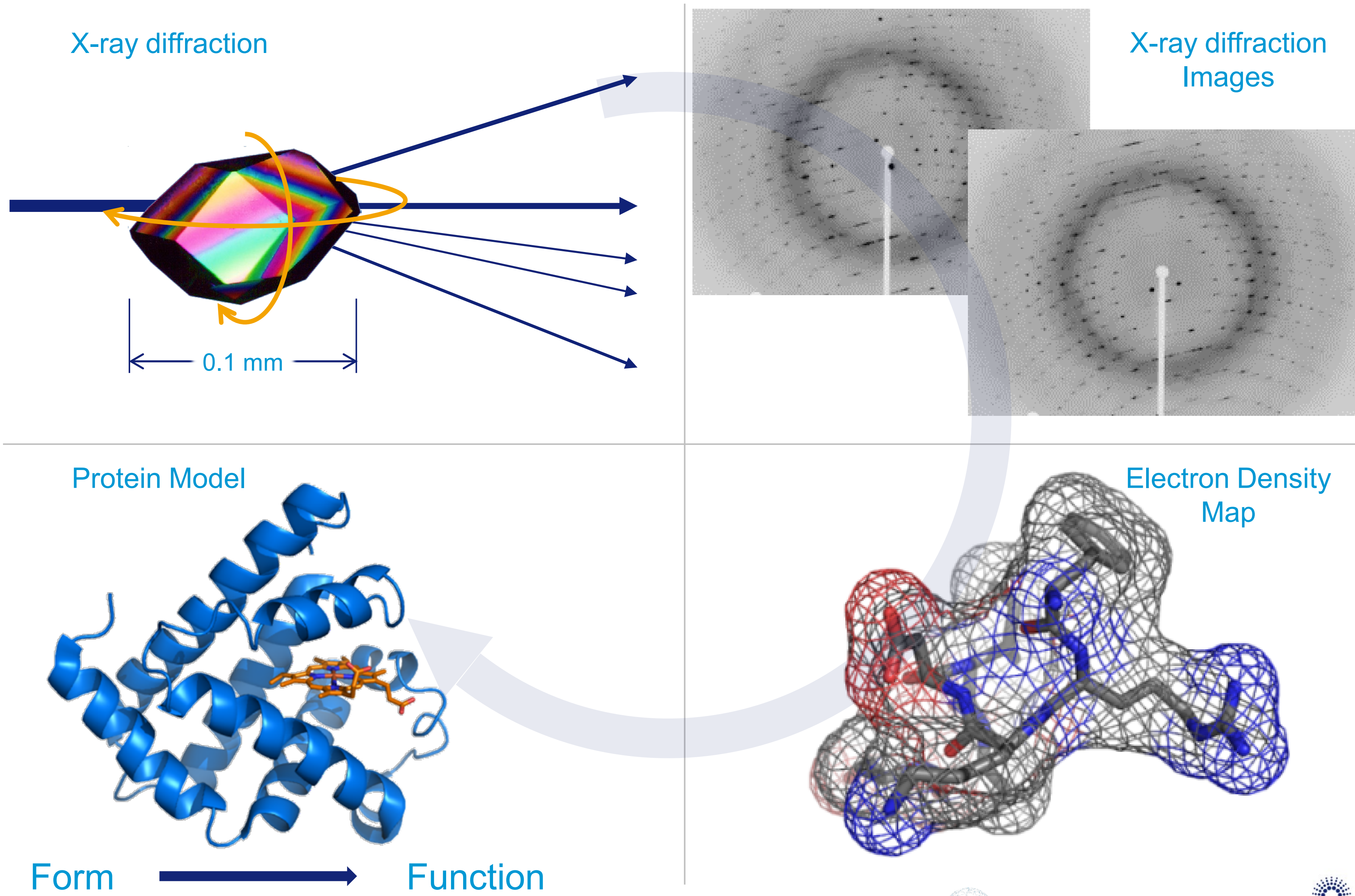
Qualitatively, the diffraction picks up a *specific distance* in real-space, and transforms it into a frequency in *reciprocal space*.

CRYSTALLOGRAPHY WITH LARGE MOLECULES



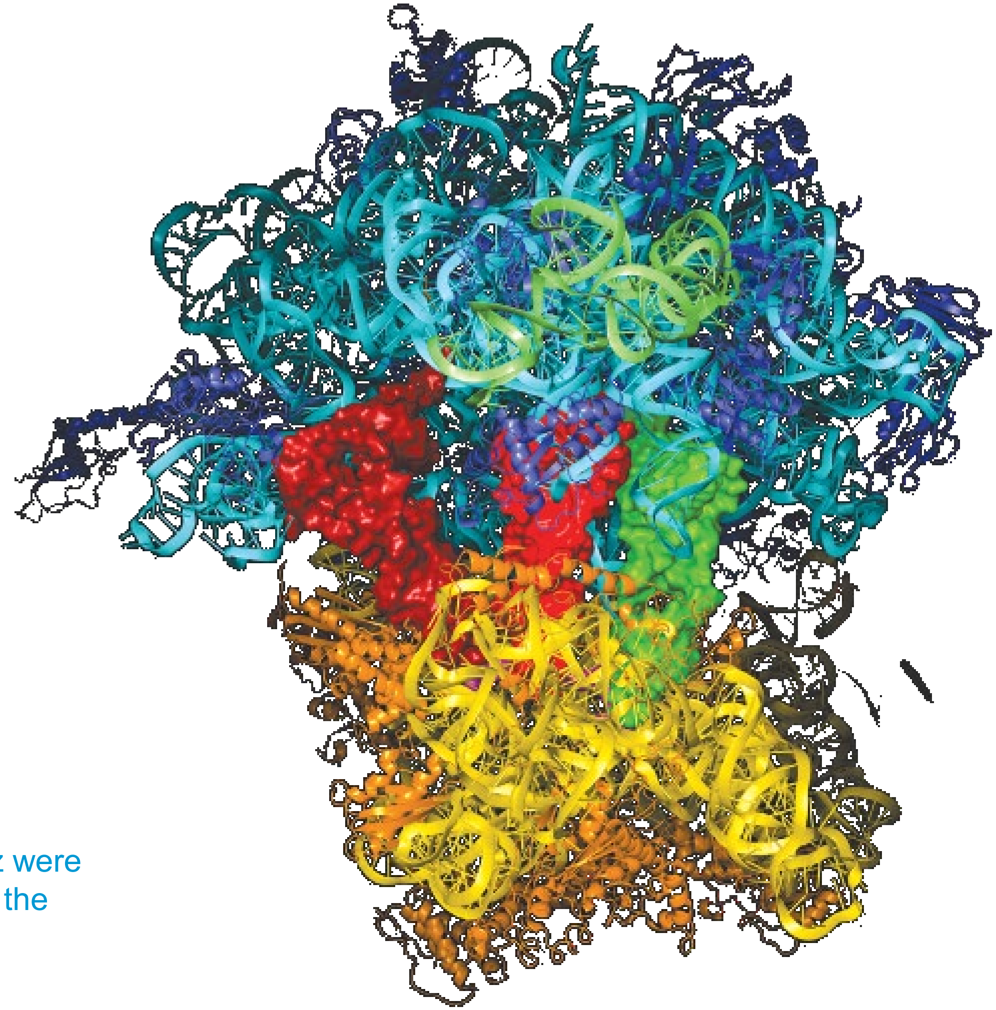
The same
techniques can be used
to image complex systems such as proteins

X-RAY CRYSTALLOGRAPHY METHOD



THE RIBOSOME

This technique has led to the discovery of some fantastically complex structures like the ribosome.



Ada Yonath, Venkatraman Ramakrishnan and Thomas Steitz were awarded the 2009 Nobel prize in Chemistry for their work on the ribosome

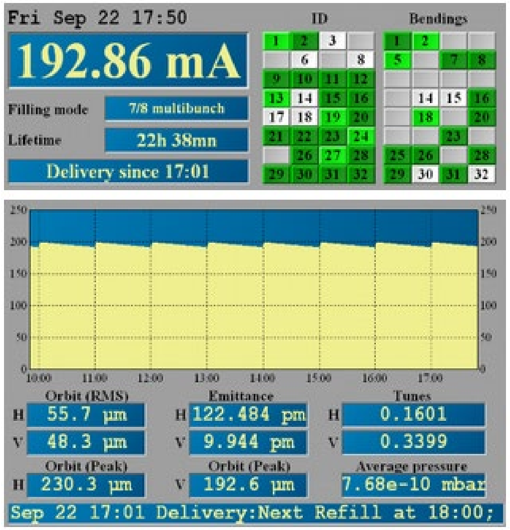
20 nm

Where does 3D metrology fit into this?

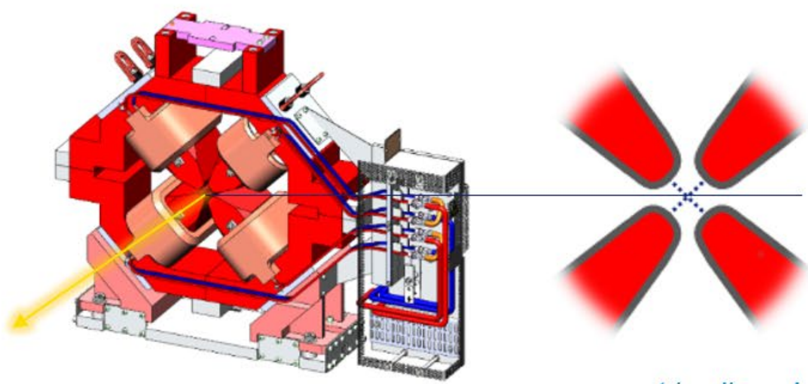
Typically electrons circulate in the SR for days. New electrons are injected (topped up) every hour*.

All of the time they are circulating, the electrons must stay within a sub-millimetric path. Any disturbance will cause them to oscillate and rapidly be lost.

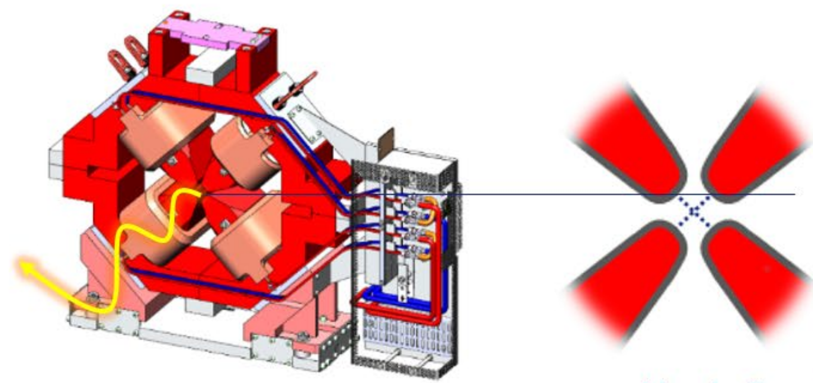
**In an 8 hour shift, 6 GeV electrons travel nearly 9 billion km in the ESRF Storage Ring*



Machine status

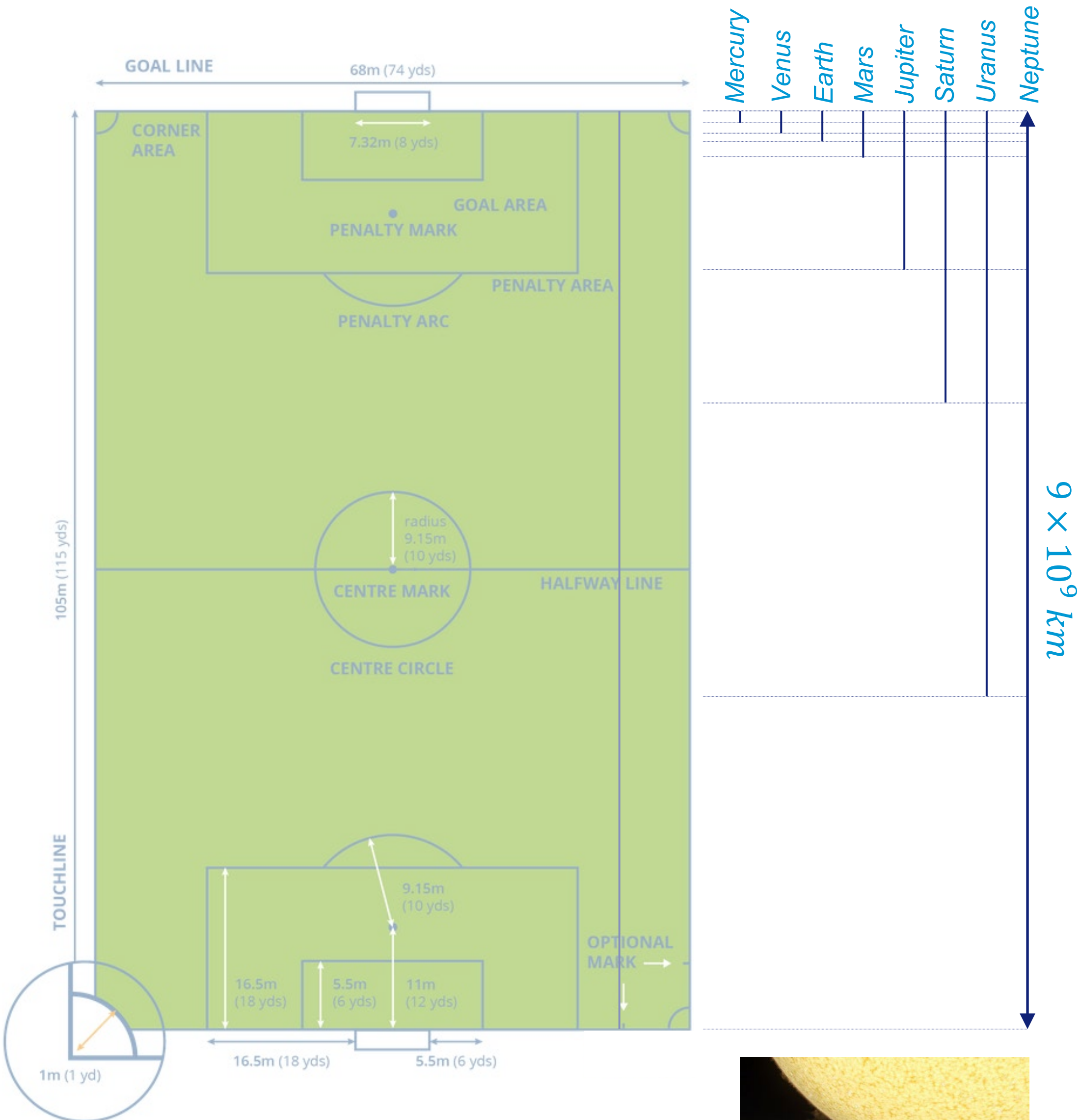


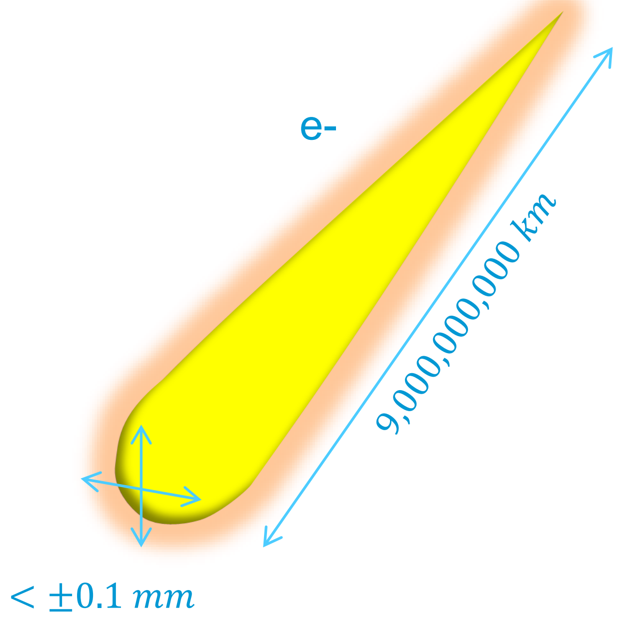
magnet is aligned

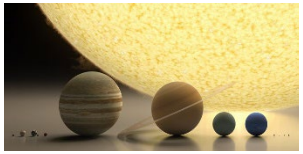


magnet is misaligned

$9x10^9$ km IS THE DISTANCE ACROSS THE ORBIT OF NEPTUNE!







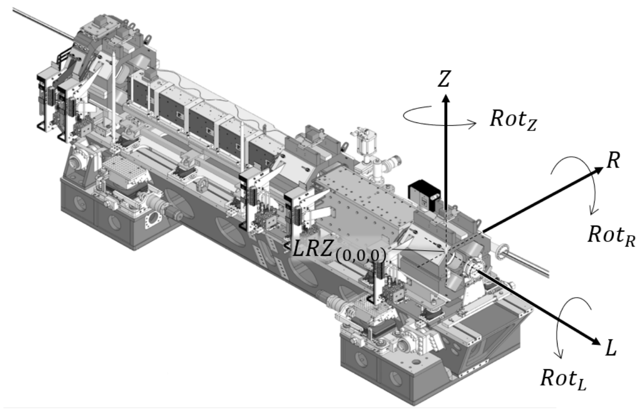
Electrons must effectively stay in a virtual cylinder of radius less than 0.1 mm and $9x10^9$ km long over 8 hours!

EBS ALIGNMENT CONSTRAINTS

There were **two key constraints** for EBS

first respect the magnet (and other) alignment tolerances

Machine	U(L) [µm]	U(R) [µm]	U(Z) [µm]
Long. Varying field dipoles	1000	>100	>100
High gradient quadrupoles, Combined function dipoles	500	60	60
Medium gradient quads	500	100	85
Sextupoles	500	70	50
Octupoles	500	100	100



Maximum permissible error 2.5σ

… and **second** ensure the new machine was in the same place as the old machine to minimize disturbance to the functioning beamlines.

ALIGNMENT TOLERANCES – WHAT DO THEY MEAN?

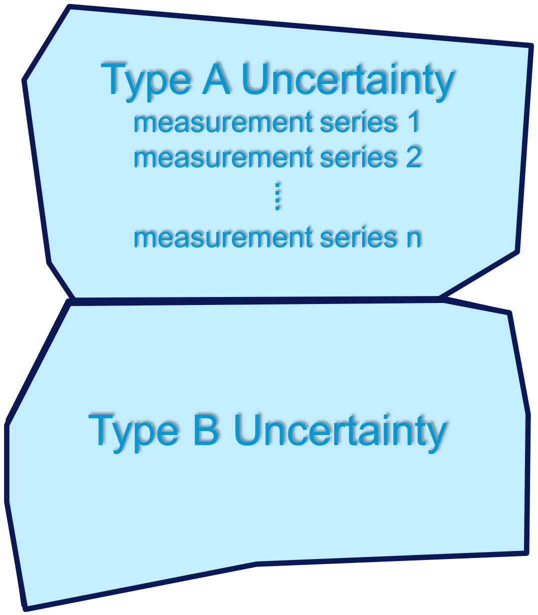
Machine	U(L) [µm]	U(R) [µm]	U(Z) [µm]
Long. Varying field dipoles	1000	>100	>100
High gradient quadrupoles, Combined function dipoles	500	60	60
Medium gradient quads	500	100	85
Sextupoles	500	70	50
Octupoles	500	100	100

Early on it was decided that these tolerances included all possible errors, and notably:

- Fiducialisation,
- Alignment on the girder including:
  - opening and closing of magnets,
  - girder rectitude,
- Transportation,
- Alignment in the tunnel,
- …

It was also decided the most appropriate way to determine the overall uncertainty was to follow the methodology for an uncertainty calculation outlined in the Guide to the Uncertainty in Measurement – the GUM*.

**available at https://www.bipm.org/en/publications/guides/gum.html*



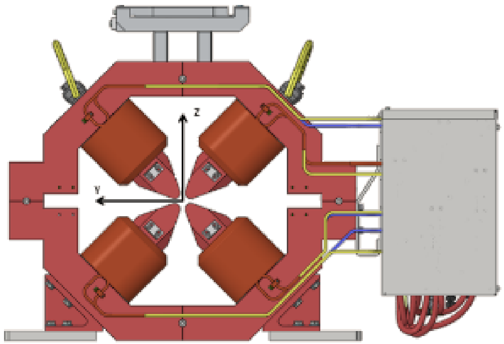
measurement uncertainty
non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used

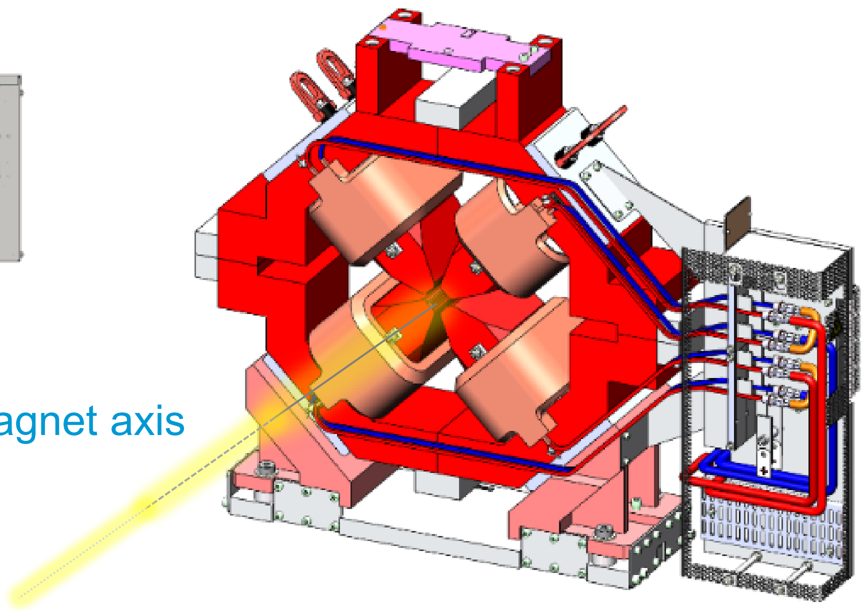
$$U = \sqrt{Type\ A^2 + Type\ B^2}$$

An uncertainty calculation is generally done in a characteristic manner

FIDUCIALISATION

For a magnet, we are interested in putting the magnet axis in the right place

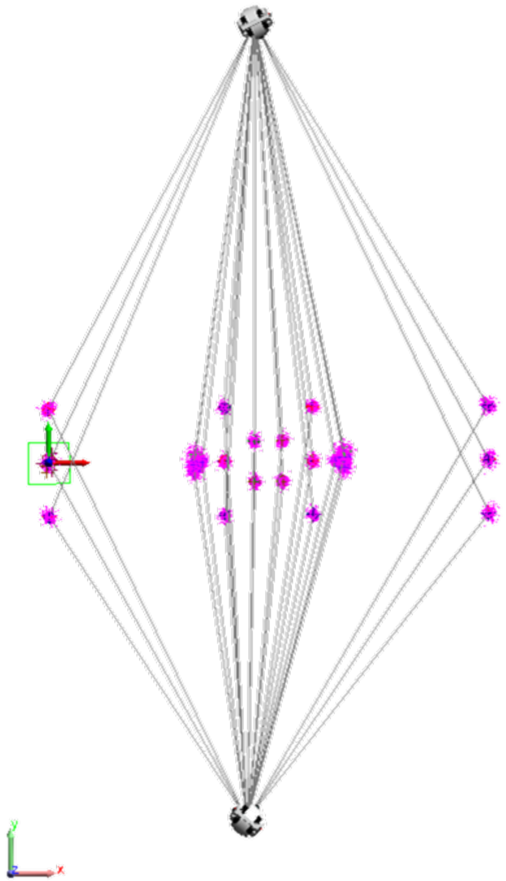


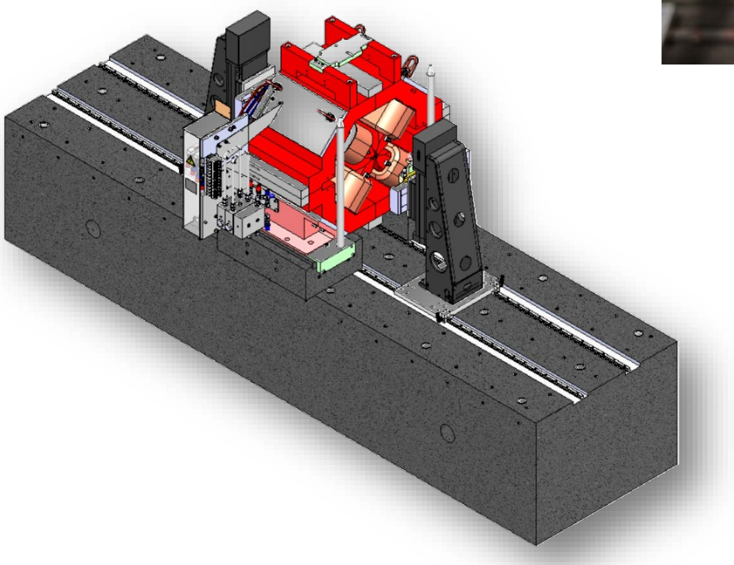


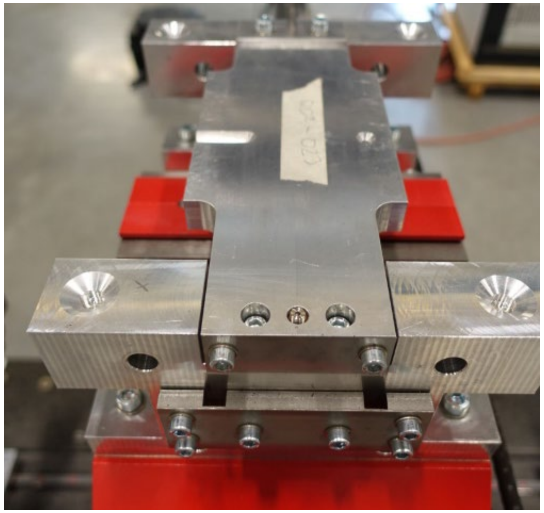
But we cannot *see* the magnet axis

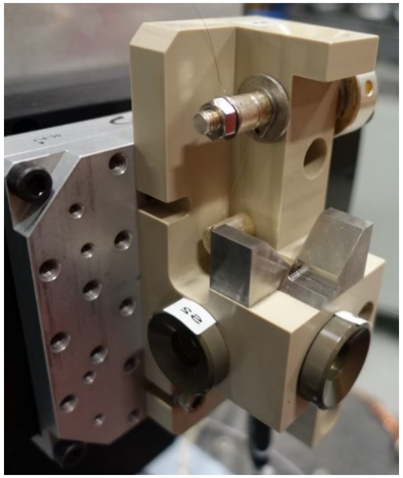
So we have to reference it with respect to something we can see.

The magnet reference points were determined from two laser tracker stations.









FIDUCIALISATION UNCERTAINTY

	U(L) [µm]	U(R) [µm]	U(Z)[1] [µm]	U(Z)[2] [µm]
Laser Tracker				
Wire position	13	15	18	18
Measurement	9	10	9	9
Repeatability	3	3	12	12
Magnet measurements		4	4	4
Magnetic Fiducialisation		*20*	*20*	*20*
Magnet Shim Determination				*20*
Total	**16**	**26**	**31**	**37**

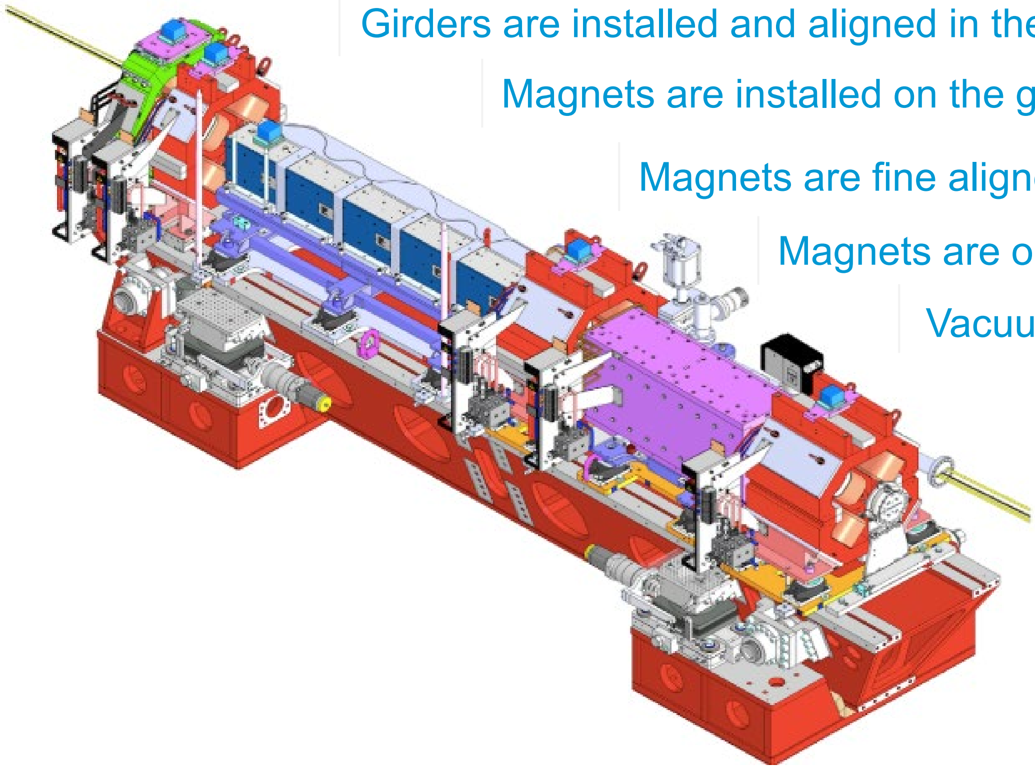
Shims were used to align certain magnets:
1) High gradient quadrupoles, Combined function dipoles
2) Medium gradient quadrupoles, sextupoles and octupoles

We combine all of these errors/uncertainties to determine the fiducialisation uncertainty contribution.

This is the first of several contributions to the overall alignment uncertainty…

Reference: G. Le Bec, J. Chavanne, L. Lefebvre, D. Martin, and C. Penel, "Magnetic Measurements and Fiducialisation of the ESRF-EBS Magnets", in Proc. 11th Int. Particle Accelerator Conf. (IPAC'20), Caen, France, May 2020, paper THVIR09, pp. XX-XX

GIRDER ASSEMBLY



Girders are installed and aligned in the horizontal plane

Magnets are installed on the girder 0.5 mm

Magnets are fine aligned 0.05 mm

Magnets are opened

Vacuum string is installed

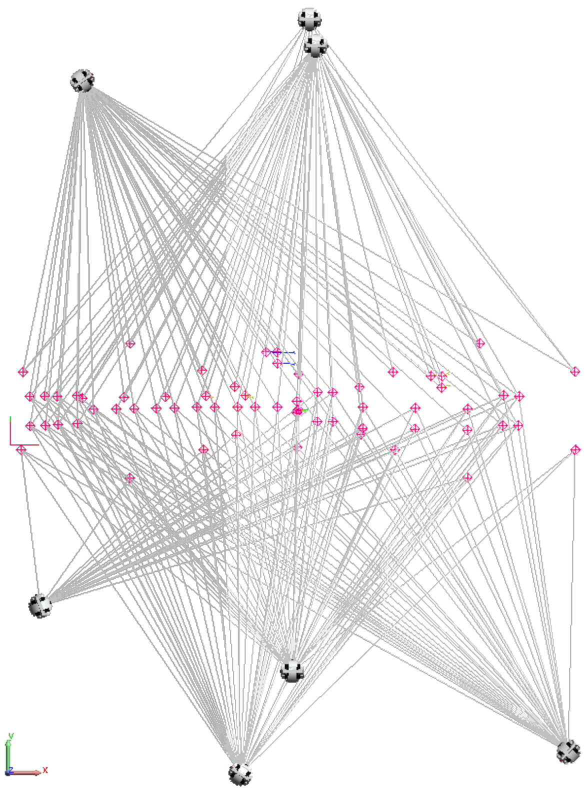
BPMs aligned 0.1 mm

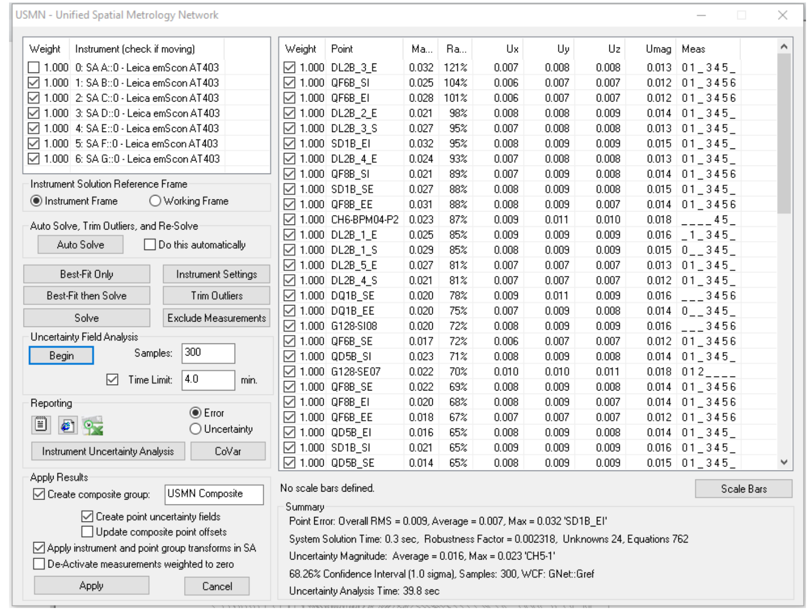
Magnets are closed

Fine magnet alignment check and survey

Assembly was made at ESRF01 – a dedicated building

GIRDER ALIGNMENT UNCERTAINTY



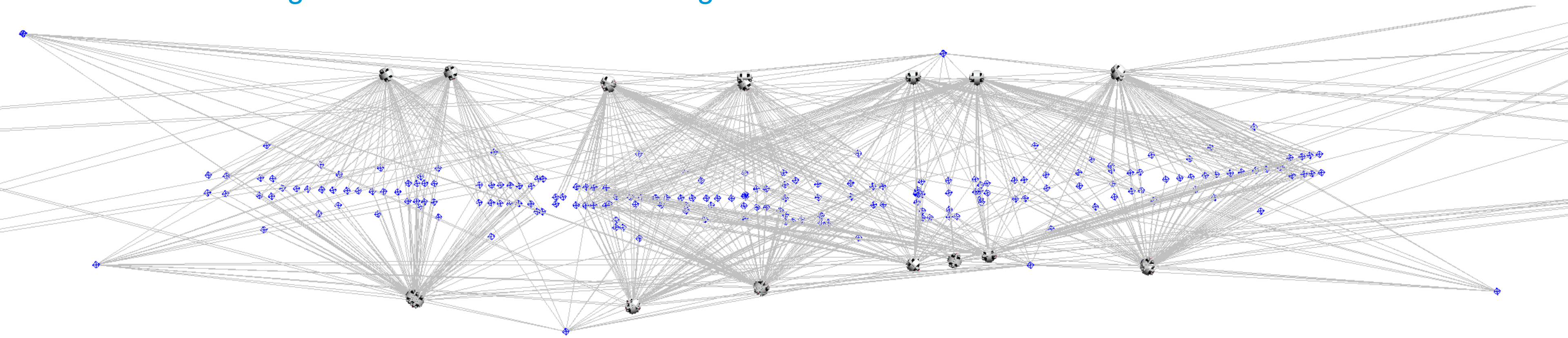


	U(L) [µm]	U(R) [µm]	U(Z) 1) [µm]	U(Z) 2) [µm]
Measurements	6	7	6	6
Difference to nominal	126	24	25	25
Overall uncertainty		14	17	17
Magnet Opening/Closing	8	5	7	7
Girder rectitude				8
Total	**126**	**29**	**31**	**31**

Shims were used to align certain magnets:
1) High gradient quadrupoles, Combined function dipoles
2) Medium gradient quadrupoles, sextupoles and octupoles

EFFECT OF STORAGE, TRANSPORTATION, INSTALLATION AND BAKEOUT

After the installation and initial alignment in the tunnel all of the girders were remeasured like they were during in ESRF01. This was done again after the bakeout was finished in the tunnel.



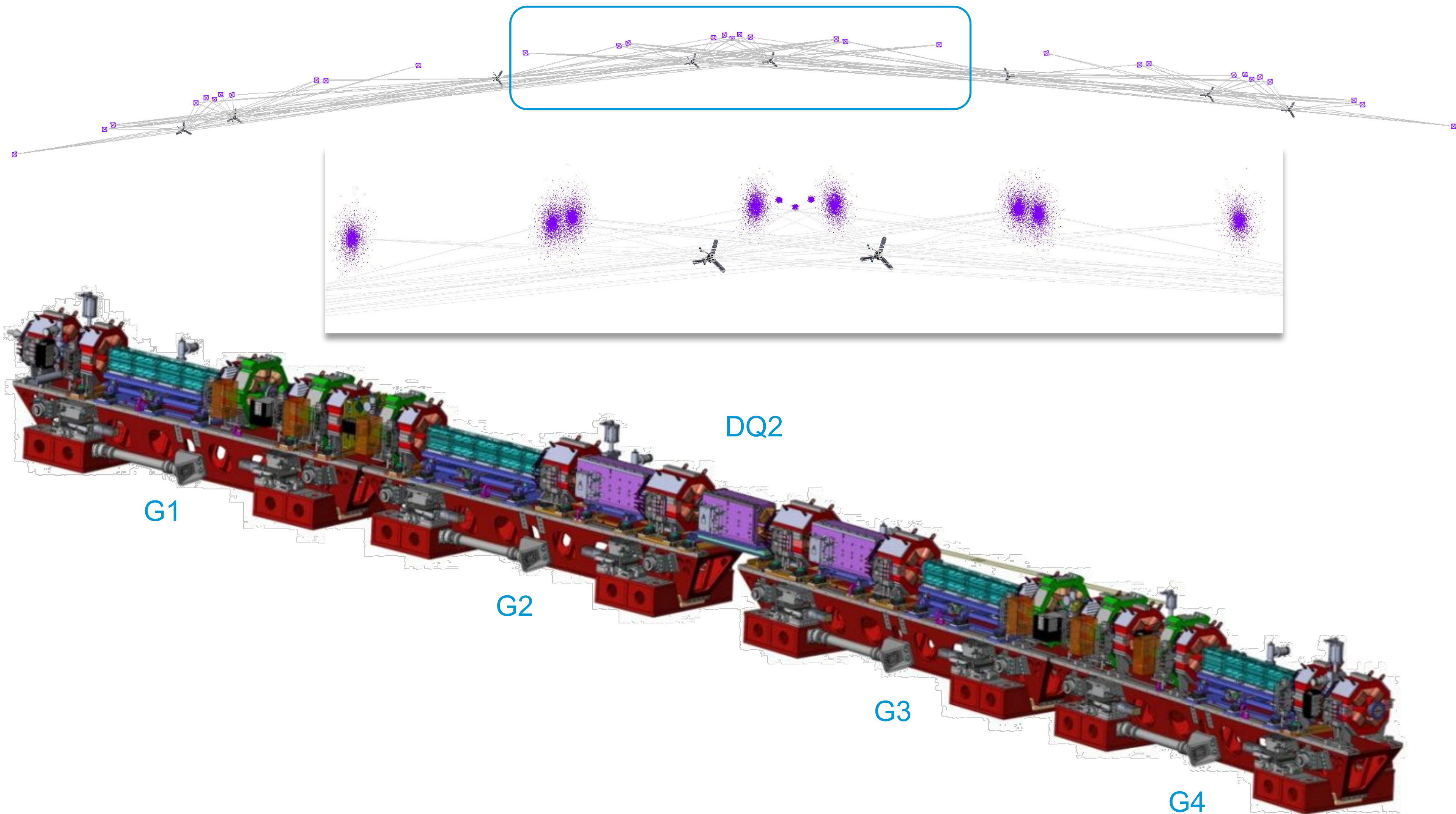
The magnet positions were then adjusted onto the magnet positions measured at ESRF01.

Survey	U(R) [µm]	U(Z) [µm]
ESRF01 (see girder alignment uncertainty)	14	17
After transport (3D adjustment on ESRF01)	17	20
After bakeout (3D adjustment on ESRF01)	19	21

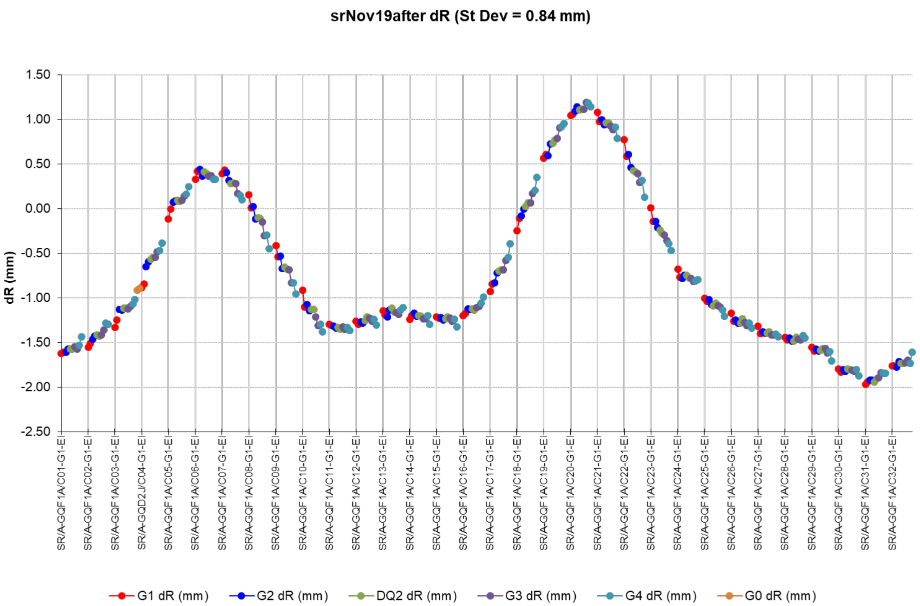
These results suggest the effect of transport was ~10 µm – and the effect of bakeout on the alignment less than that …

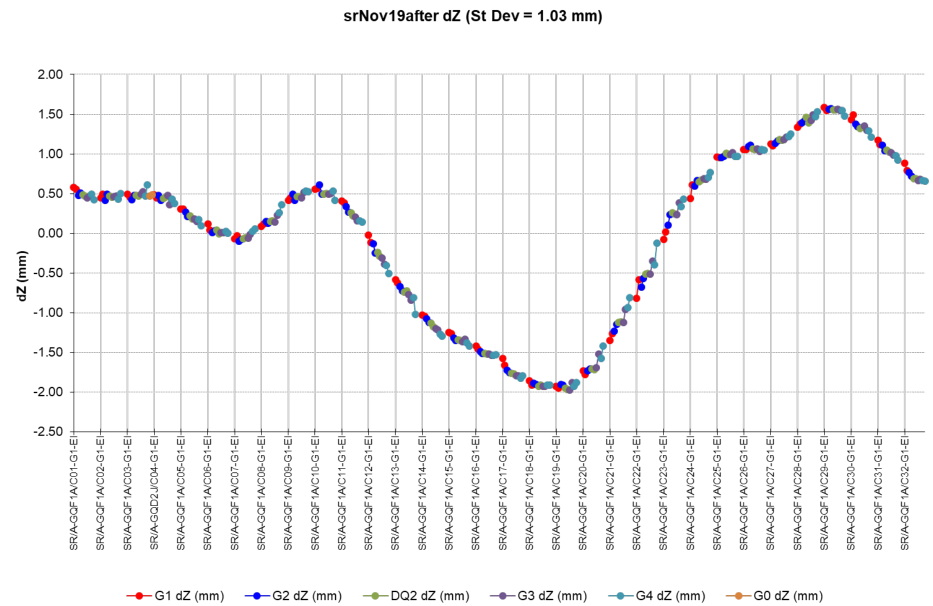
ESRF01 was the building where the girders were assembled.

GIRDERS IN THE TUNNEL

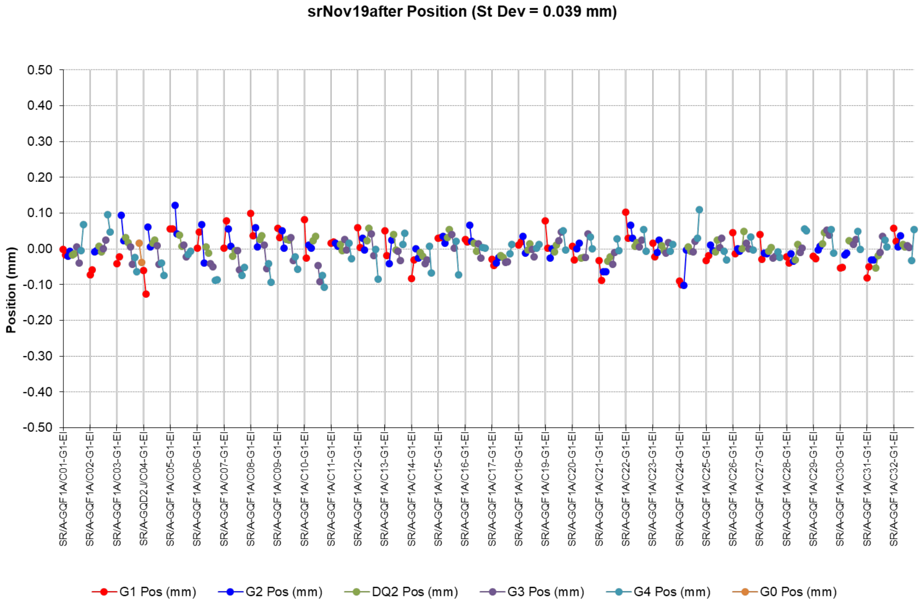


NOVEMBER 2019 AFTER FINAL ALIGNMENT

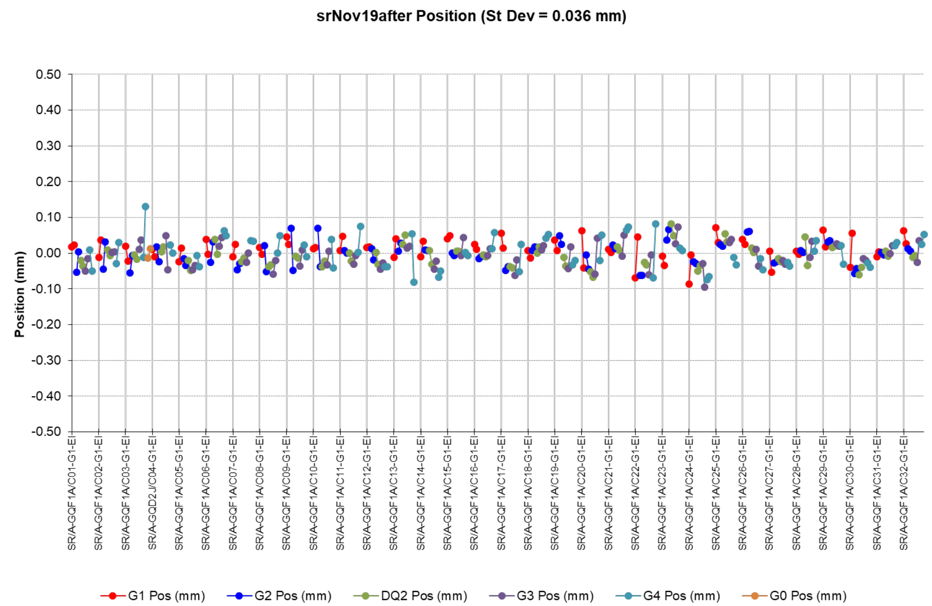




NOVEMBER 2019 AFTER FINAL ALIGNMENT - ERROR



U_R=39 um
U_Z=36 um



	U(R) [µm]	U(Z) [µm]
G1E, G4S	52	42
G1S, G2E, G3S, G4E	42	34
G2S, G3E	24	32
DQ2	23	30

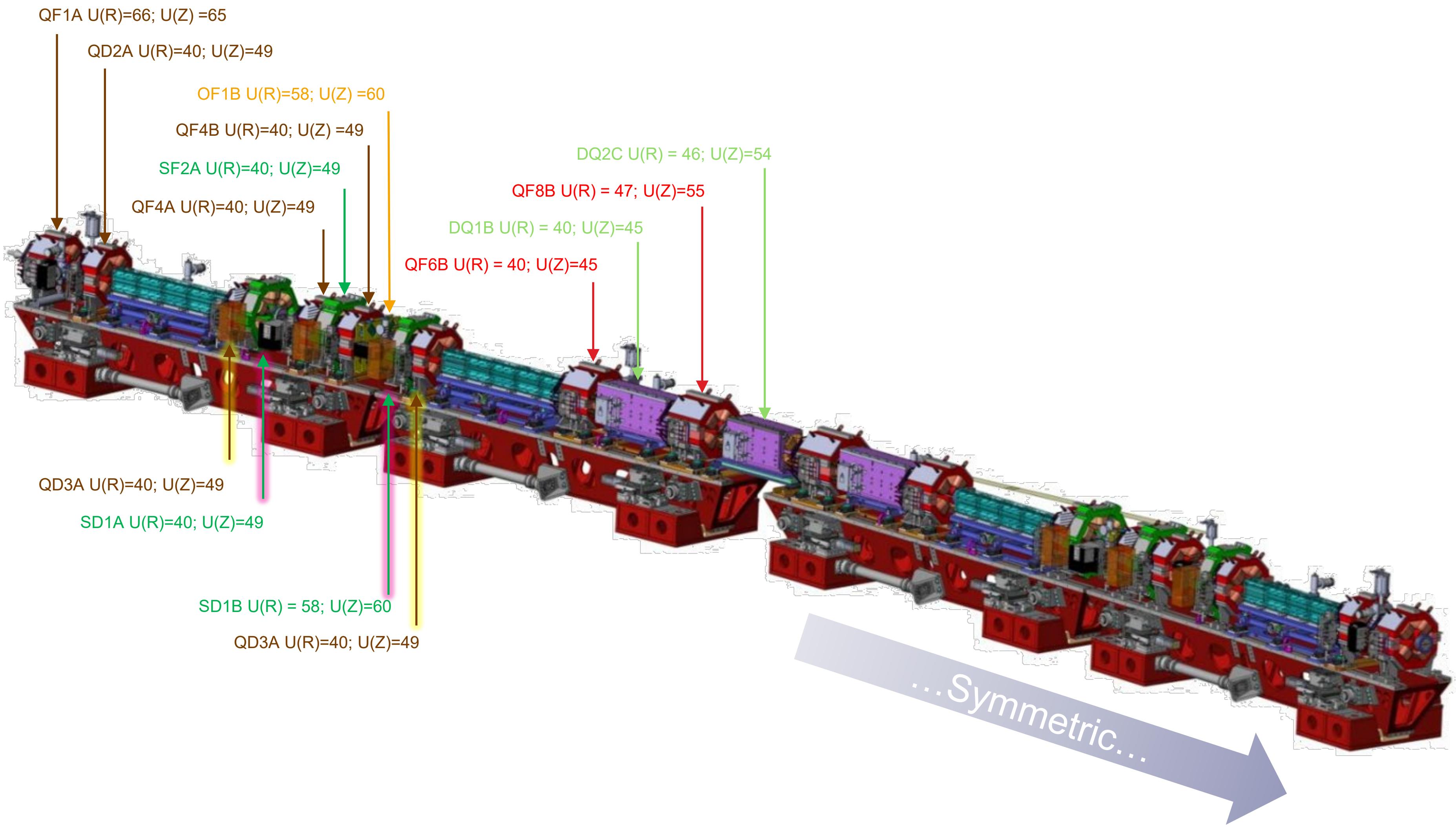
ALIGNMENT UNCERTAINTY BY MAGNET FOR ½ CELL – 2ND HALF IS SYMETRIC

Combined alignment uncertainties for the EBS machine using the U_R and U_Z from the previous slides are estimated to be:

Magnet type		*Nominal U(R) [µm]*	Measured U(R) [µm]	*Nominal U(Z) [µm]*	Measured U(Z) [µm]
QF1A	Med. Grad. Quad.	*100*	**66**	*85*	**65**
QD2A	Med. grad. quad.	*100*	**40**	*85*	**49**
QD3A	Med. Grad. Quad.	*100*	**40**	*85*	**49**
SD1A	Sextupole	*70*	**40**	*50*	**49**
QF4A	Med. Grad. Quad.	*100*	**40**	*85*	**49**
SF2A	Sextupole	*70*	**40**	*50*	**49**
QF4B	Med. Grad. Quad.	*100*	**40**	*85*	**49**
OF1B	Octupole	*100*	**58**	*100*	**60**
SD1B	Sextupole	*70*	**58**	*50*	**60**
QD3A	Med. Grad. Quad.	*100*	**40**	*85*	**49**
QF6B	High Grad. Quad.	*60*	**40**	*60*	**45**
DQ1B	Dipole-Quadrupole	*60*	**40**	*60*	**45**
QF8B	High Grad. Quad.	*60*	**47**	*60*	**55**
DQ2C	Dipole-Quadrupole	*60*	**46**	*60*	**54**
…Symmetric …					

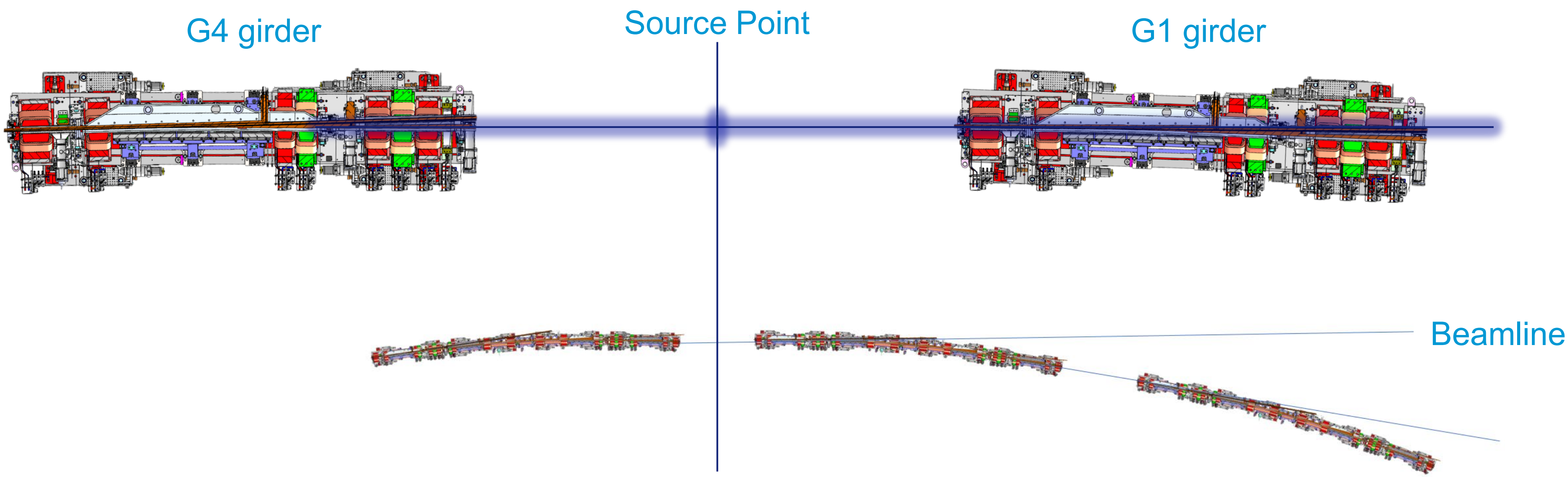
Note U(L) along the beam = 453 µm for a nominal value of 500m

ALIGNMENT UNCERTAINTY BY MAGNET

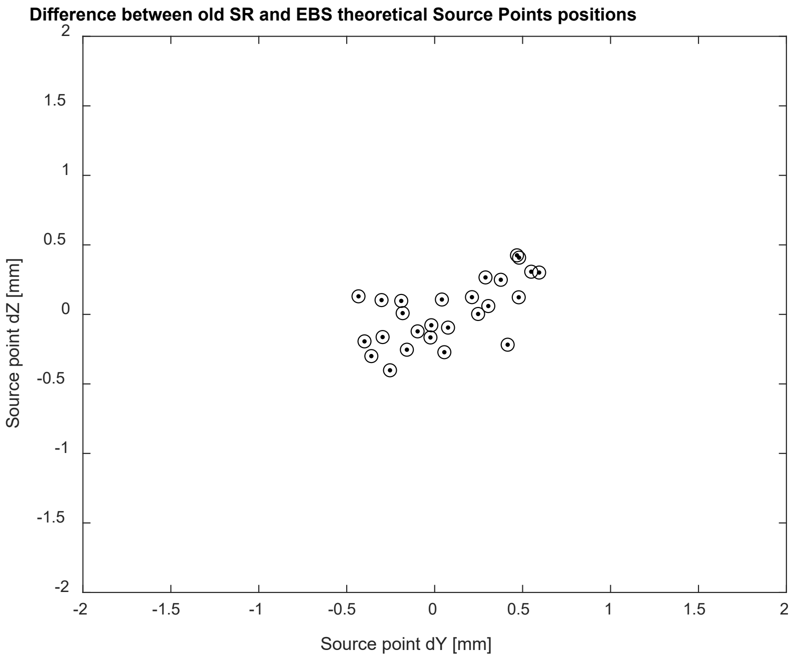


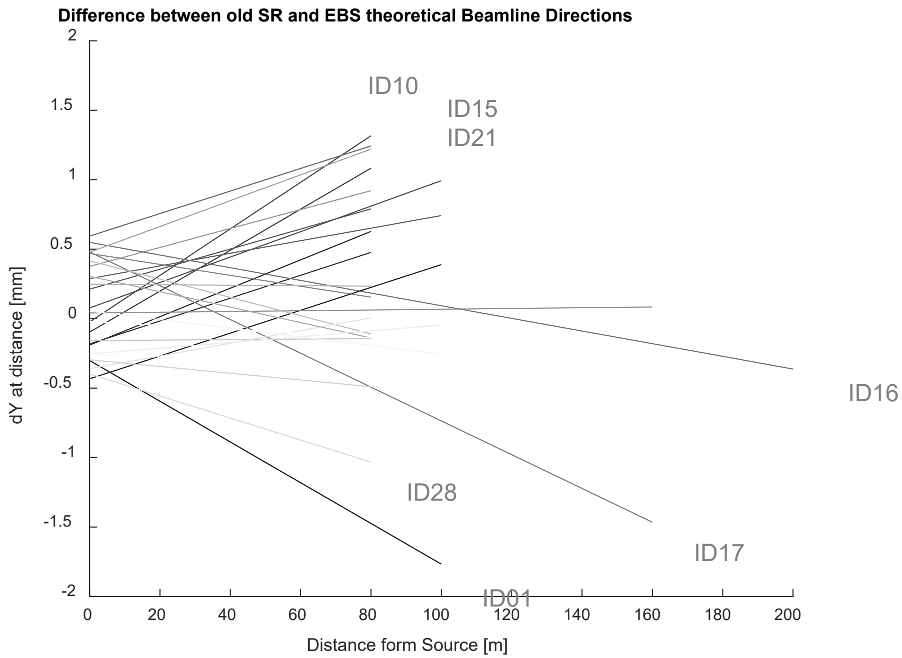
BEAMLINE POSITION CONSTRAINT

The constraint was to align the beamline source points and directions as they were in the old machine. The beamline direction is determined by the magnet positions on either side of the source point.



Recall the second major constraint – put the machine back where the old machine was…





RMS R [mm]	RMS Z [mm]	RMS Direction [urad]
0.32	0.22	8

ALIGNMENT UNCERTAINTY

Machine simulations estimate the alignment uncertainties to be less than these values. The SR alignment estimates were:

- rms quadrupole horizontal orbit → 22 to 42 µm
- rms quadrupole vertical orbit → 22 to 53 µm

P. Raimondi,et al., "Commissioning of the Hybrid Multi-Bend Achromat lattice at the European Synchrotron Radiation Facility" Phys. Rev. Accel. Beams 24, 110701 – Published 1 November 2021

Our estimates for alignment uncertainties are:

Medium gradient magnets

- U(R) = 40 to 66 um for a nominal value of 100 um
- U(Z) = 49 to 69 um for a nominal value of 85 um

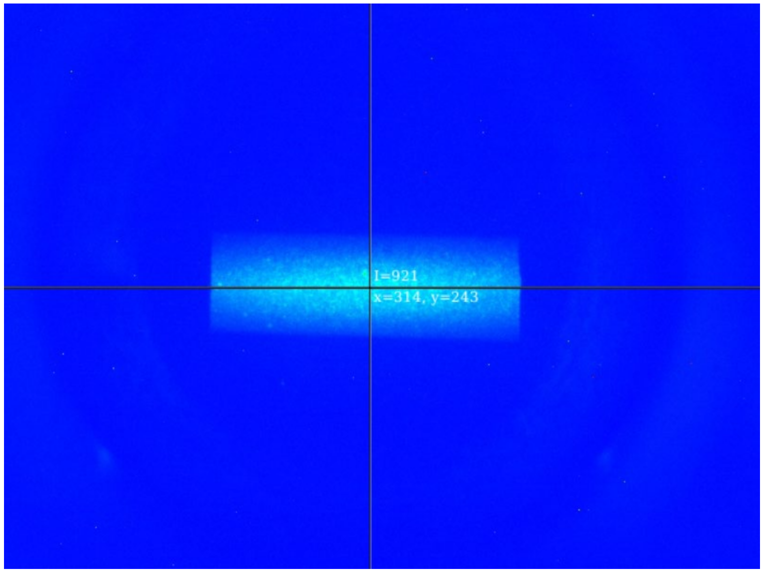
Sextupole magnets

- U(R) = 40 to 58 um for a nominal value of 70 um
- U(Z) = 49 to 60 um for a nominal value of 50 um

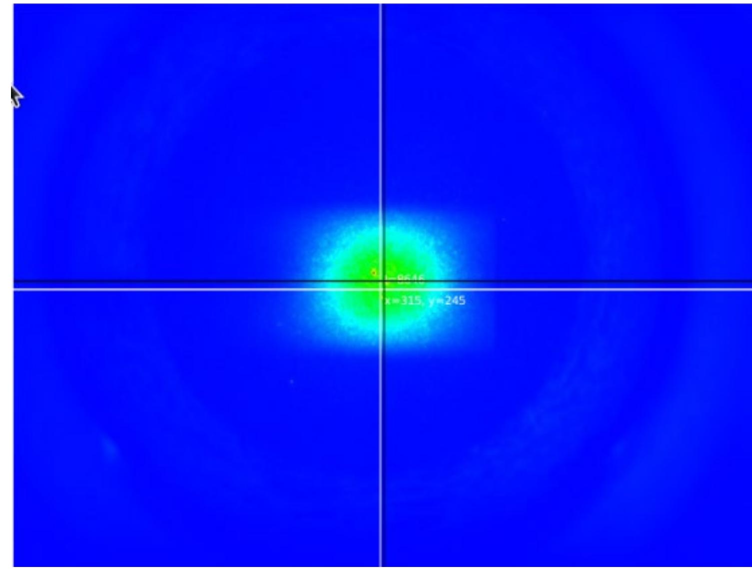
High gradient and combined function magnets

- U(R) = 40 to 47 um for a nominal value of 60 um
- U(Z) = 45 to 54 um for a nominal value of 60 um

Finally, the beamline source points were within 0.3 mm and 8 urad of their nominal positions.



Old SR
26 November 2018



EBS
30 January 2020

…The EBS X-ray beam at distances varying from 45 to 160m was found within fractions of millimetres from its position in December 2018…

E-mail Francesco Sette to all staff on 31/01/2020

Thank you for your attention…