ESRF Status and Plans

S. White

Material from: N. Carmignani, L. Carver, S. Liuzzo, T. Perron, A. Sauret, P. Borowiec, M. Dubrulle, M. Morati, V. Serriere, A. D'Elia, L. Hardy, T. Brochard, D. Baboulin, G. Le Bec, C. Benabderrahmane

ESRF | The European Synchrotron

OUTLINE

ESRF-EBS accelerator complex

ESRF-EBS operation status

Storage ring improvements

Injection and injectors upgrade

New Linac project

ESRF ACCELERATOR COMPLEX

Light source in operation since 1994 located in Grenoble, France:

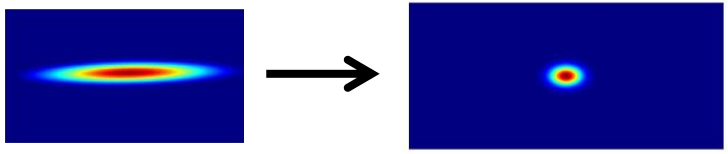
- **33 Insertion Devices (ID) end stations**
- **16 Bending Magnets (BM) end station**
- **1 Cryo-Electron Microscope (Cryo-EM)**

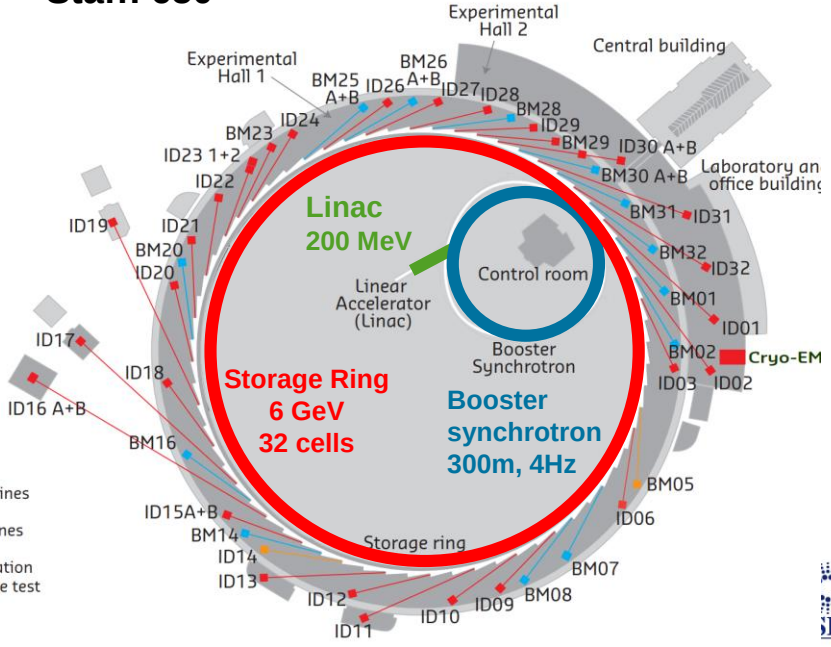
22 partner nations:

- **Annual budget: 100 million euros**
- **Staff: 650**

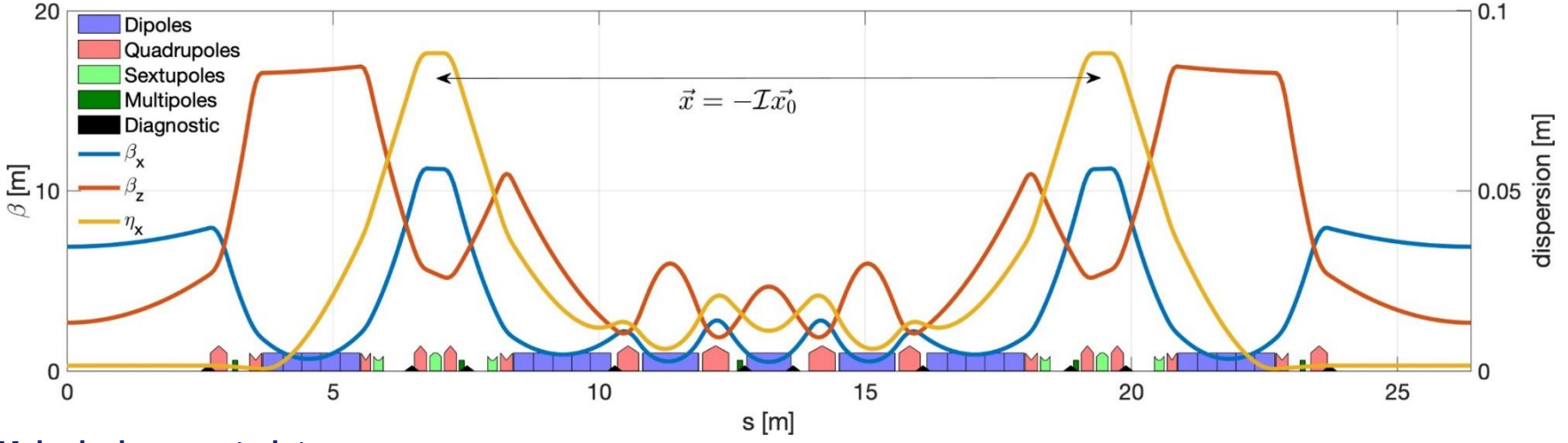
The ESRF Extremely Brilliant Source upgrade:

- Decrease the horizontal emittance
- Increase the source brilliance
- Increase the source coherence



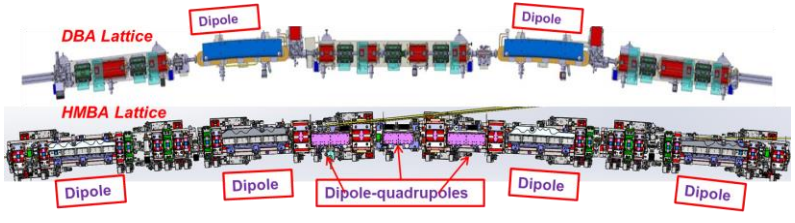


HMBA LATTICE



Main design constraints are:

- Horizontal equilibrium emittance of <150 pm.rad
- Fit existing tunnel and infrastructure and maintain beamlines
- Use existing injectors chain
- Minimize energy loss and power consumption



31 magnets per cell instead of 17

HMBA technical solutions:

- Longer and weaker “Multi-Bends”: combined function magnets with low
- dispersion + longitudinal gradient permanent dipoles
- Dispersion bump with -I transform: weaker, fewer sextupoles with partial compensation of aberrations for improved lifetime and acceptance

ESRF-EBS design:

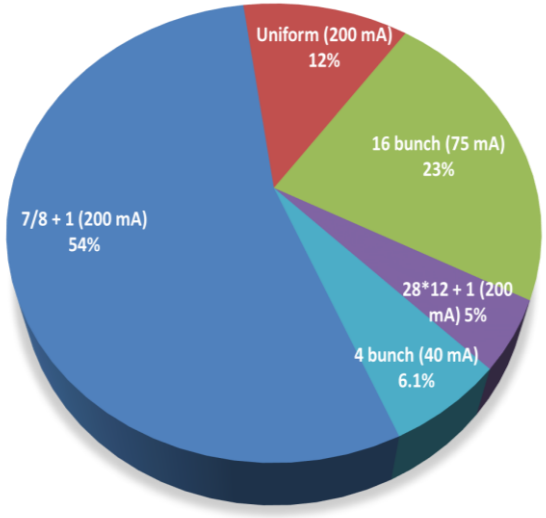
- **Horizontal emittance ~135 pm.rad**
- **Touschek Lifetime ~20h**
- **Injection efficiency >90%**

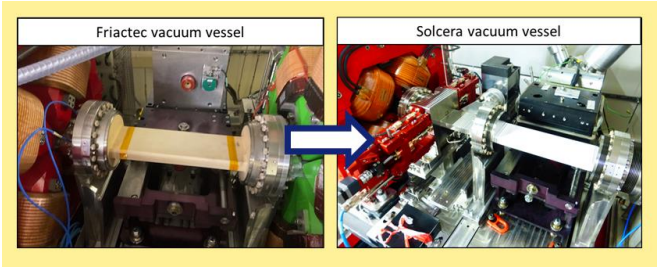
OPERATION MODES

	7/8 + 1	Uniform	28*12+1 (Hybrid)	16 bunch	4 bunch
I_{max} (mA)	192+8	200	192 + 8	75	40
Lifetime (h)	➢ 20	~ 25	> 16	~ 5.5	~ 5
ε_v (pm)	10	10	20	20	40
Nominal Reached on	13/09/22	21/11/20	14/11/22	23/08/22	05/12/22

** Intensity limitation for timing modes due to mech. weakness of the kicker ceramic chambers*
** Vertical emittance artificially increased from 1 pm rad for an operational lifetime*

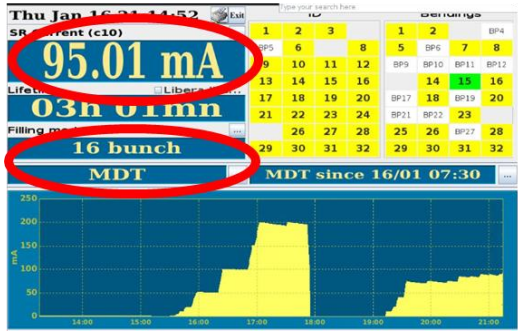
** All timing modes delivered with a purity of 10^{-9} with cleaning process in the booster*





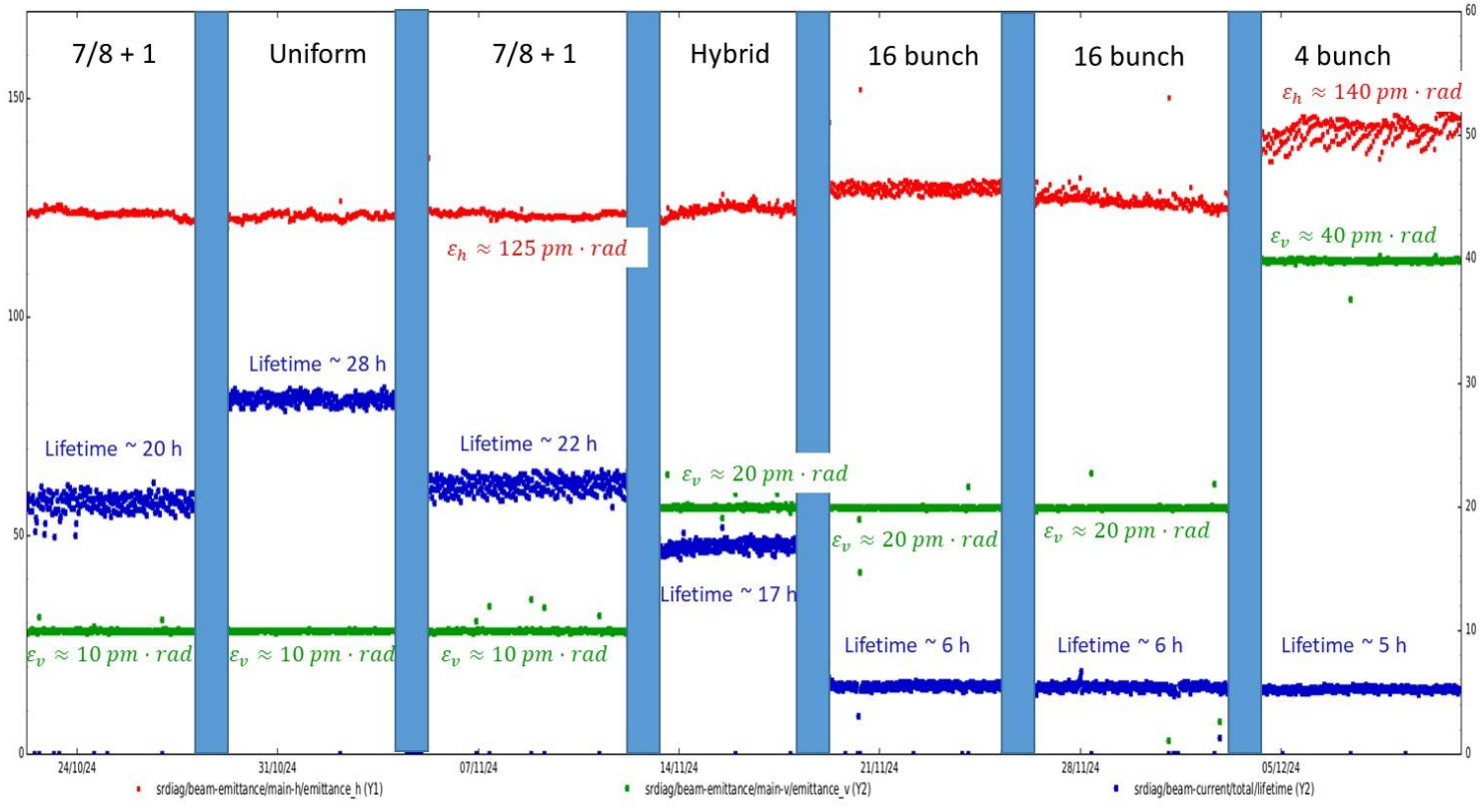
New ceramic chambers finally installed and validated

And …on 16th January 2025 !



All design parameters achieved!

ALL ESRF MODES IN ONE GRAPH

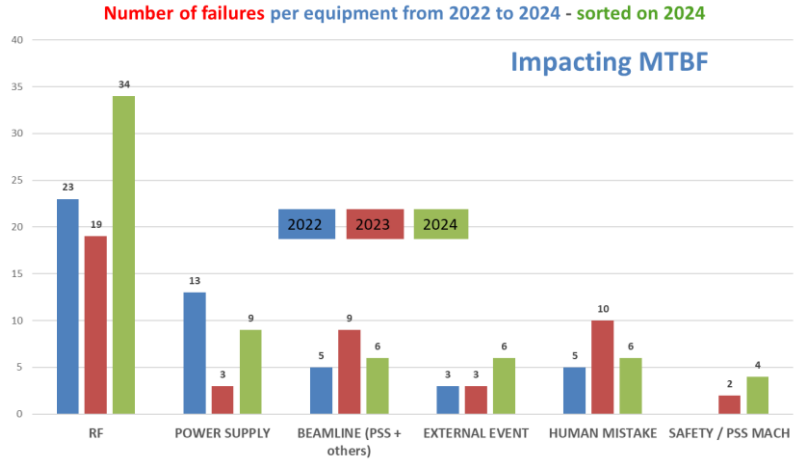


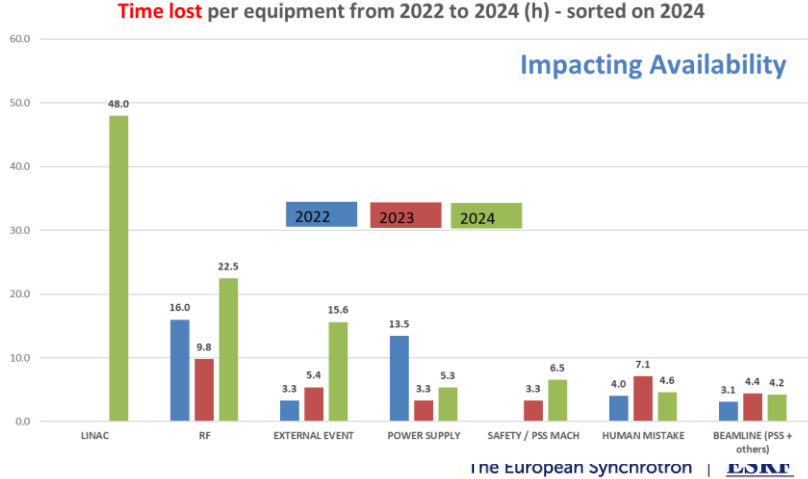
Injection efficiency in USM varies between 60% and 80% depending on the mode

FAILURES AND AVAILABILITY

MACHINE – USM	2020	2021	2022	2023	2024
Availability (%)	96.08	96.35	99.06	99.28 *(97.85)	*97.92*
Mean Time Between Failures (hrs)	46.00	66.4	88.5	107.1 *(105.6)	*76.2*
Mean duration of a failure (hrs)	1.80	2.42	0.83	0.77	*1.59*

* Without compensation





Overall performance improving, main source of failures are RF sytems

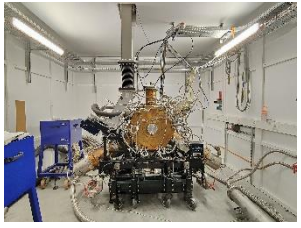
Power supply hotswap system now fully deployed

2024: 48h downtime due to single linac failure

STORAGE RING IMPROVEMENT – RF SYSTEMS

Replacement of 352 MHz 1.1 MW klystrons by SSA power sources:

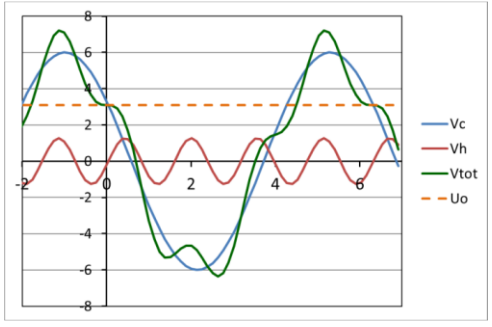
- **Major infrastructure work needed (pipe, holes, cables, cooling, …)**
- **SAT performed either with EBS mono-cell cavity of on a load**
- **SSA0 delivered, tests and validation ongoing**

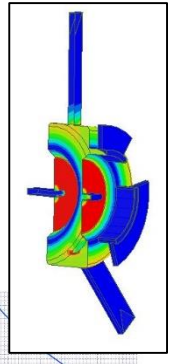


4TH HARMONIC CAVITY PROJECT

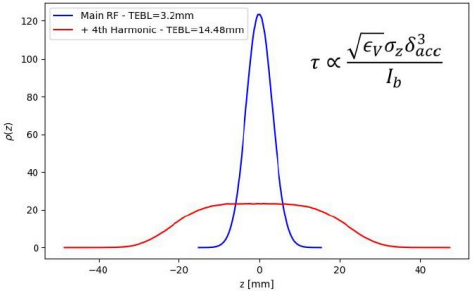
Implementation of harmonic cavities to increase lifetime has several benefits:

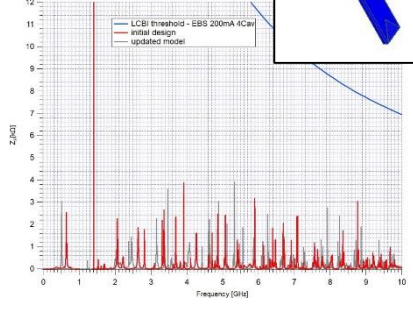
- Fewer shorter injections
- Reduced losses on ID gaps
- Reduced beam induced heating





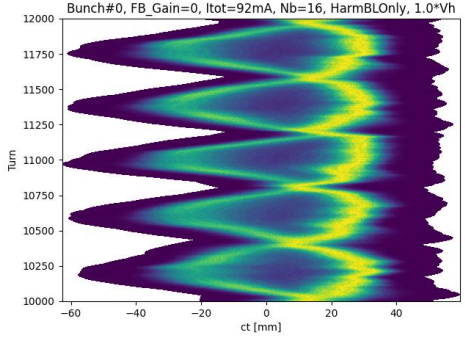
Initially considered a 2-cell cavity design, now moved to 1-cell design to simplify cooling circuits





Considered at ESRF-EBS for equidistant modes (timing + uniform);

- Collective effects and instabilities
- Transient beam loading for hybrid modes



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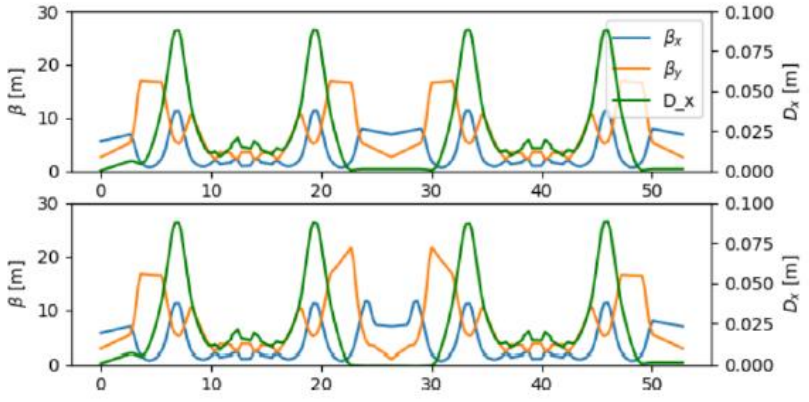
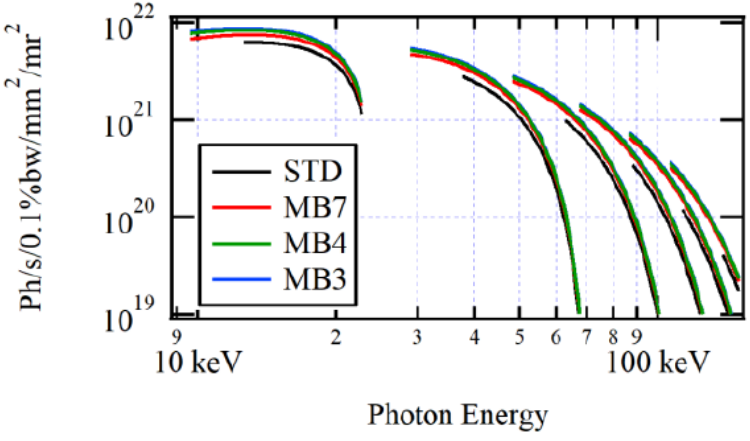
BRILLIANCE INCREASE

Request for beam lines to reduce ID gaps: criteria for ESRF, operate at constant losses on the gap





Energy [keV]	STD	MB7	MB4	MB3
	[10^{21} photons/s/0.1%/mm^2/mrad^2]			
12.6	6.27	7.46	8.35	8.74
50	1.07	2.34	2.56	2.65
100	0.143	0.334	0.363	0.374

Mini-beta optics designed for ESRF-EBS:

- Most of the gain from reduction of the ID gap
- Horizontal beta matching does not contribute significantly to the brilliance

BRILLIANCE INCREASE

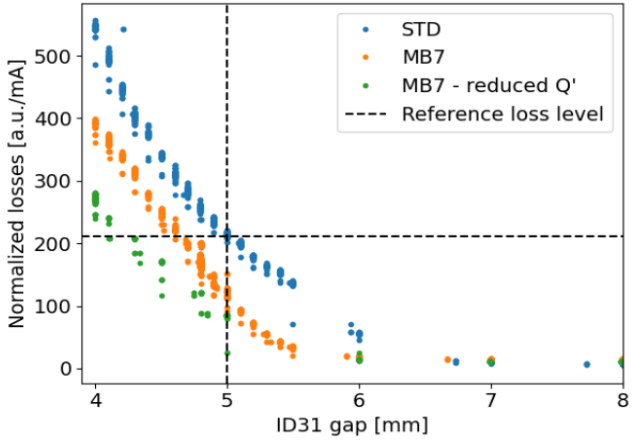
Brilliance increases as expected but losses do not scale with beta function as expected

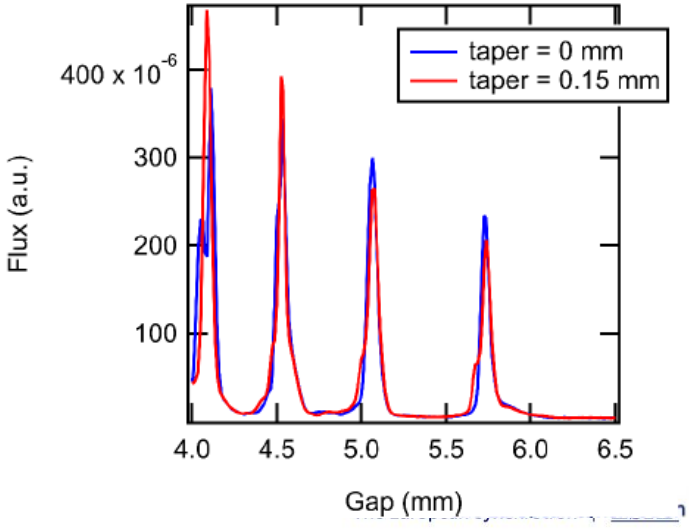
Mini-beta optics do not seem to be the most promising option to close ID gaps:

- Touschek losses increased with gap reduced to 4mm
- Injection efficiency reduced by ~10% with gap closed at 4mm

Operation with low ID gap is presently not possible:

- HALO reduction: **low Q' optics + HC**
- **High brilliance uniform mode?**
- Alternative injection scheme: **shared oscillation using fast stripline kickers**





INJECTORS - LINAC CONSOLIDATION

No spares of:

1. Gun body but cathodes on stock
2. Accelerating section

Other components are available, some partially assembled

Fall back scenario 1 (modulator 1 or modulator 2 out of order):
Modulator 3 can replace Modulator 1 or 2. Switching between modulators takes around 2 hours (2 skipped refills).

Fall back scenario 2 (section 2 out of order):
100 MeV injection with section 1 only has been validated as possible.

Other interventions require much longer down time.

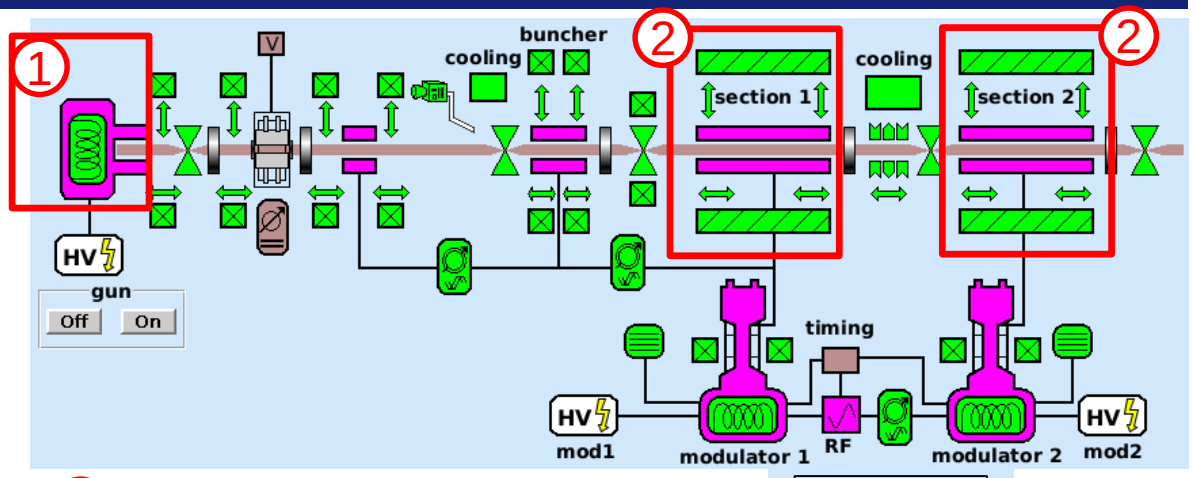
No simple fall back scenario if:

- Leak into VAC of any section (cavities of sections are not brazed, they are just screwed together)
- Section 1 failure (i.e. solenoid), (100 MeV injection with section 2 only is not possible)

Working section needs to be installed on the first position

Strong motivation to increase the reliability level.

SAT: autumn 2025



2 *Accelerating sections in operation since 1988*

3 Modulator 3 (backup for Mod.1 or 2)

Implemented actions:

- Purchase of new accelerating section -> **CFT awarded by Research Instruments GmbH, delivery September 2025, kick-off meeting already held**
- Purchase of RF Unit which consists: **solid state modulator**, HV transformer, focusing coils with PS, RF driver, control unit, Canon klystron. -> **CFT awarded by Nodica Group (former Scandinova AB), delivery September 2025, kick-off meeting already held**
- Purchase of vacuum chamber to replace any section -> **delivered**
- Machining of the gun body -> **to be launched**

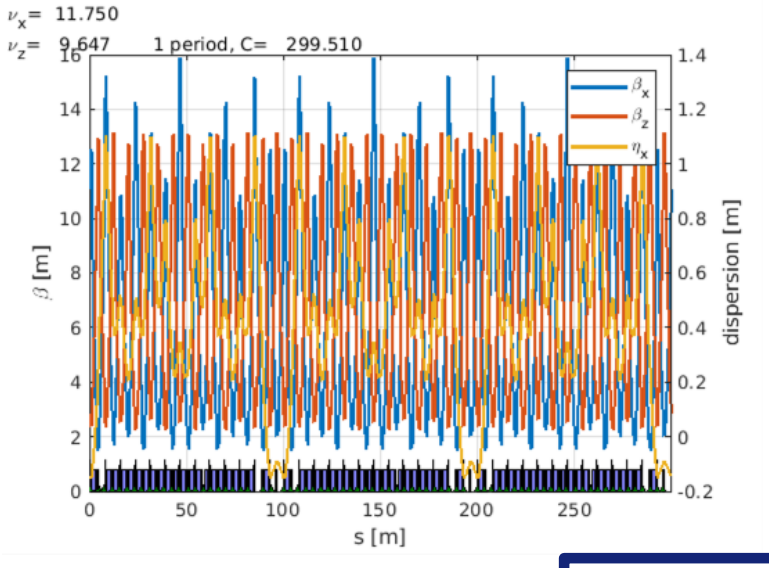
BOOSTER LIGHT UPGRADE

In 2022, several options for a light upgrade of the booster have been studied and the options are presented in at IPAC22: *Options for a Light Upgrade of the ESRF Booster Synchrotron Lattice (T. Perron)*

The basic idea is to increase the number of quadrupole families from 2 to more (4, 5 or 6) to reduce horizontal emittance. This was initially proposed by P. Raimondi.

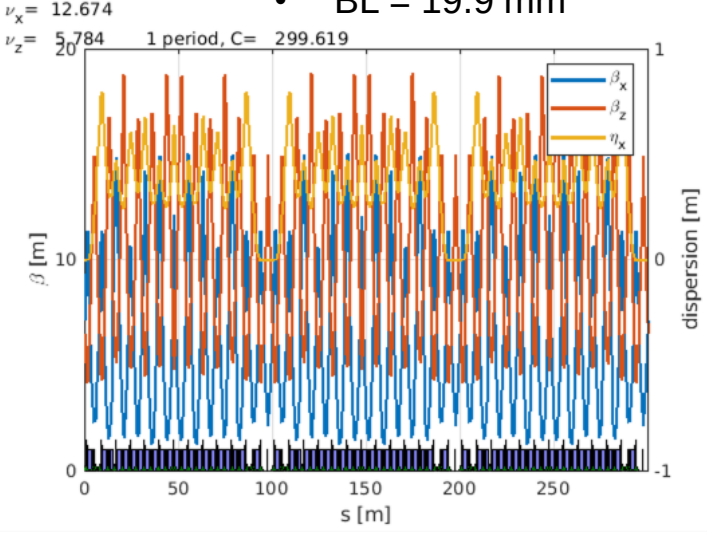
Present lattice
2 quad families

- 39 QD, 39 QF
- ε_x = 83.1 nm
- BL = 22.6 mm



New lattice
5 quad families

- 39 QD, 21 QF,
- 6 QF1, 6 QF2, 6 QF3
- ε_x = 59.6 nm
- BL = 19.9 mm

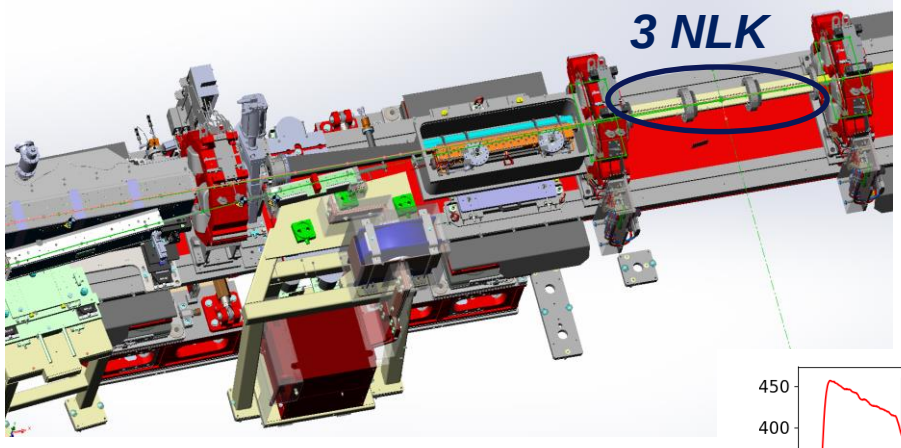


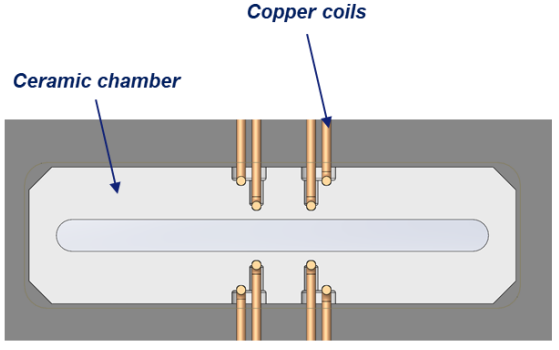
Installation: summer 2027

NON LINEAR KICKER INJECTION

Provide transparent injection:

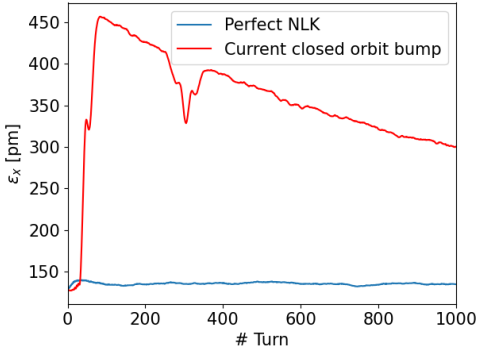
- Most beam lines cannot acquire data during injections
- NLK injection scheme found as the most promising option (can be combined with other methods)



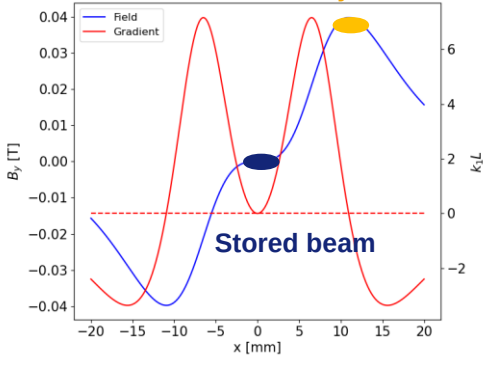


Cross-section of the proposed non-linear kicker.

Stored beam sees no field or gradient: injection perturbation suppressed
Field quality strongly depends on coils position: precise characterization required



Injected beam



PULSED MAGNETS MEASUREMENT BENCH

Developed dedicated pulsed magnets measurement bench:

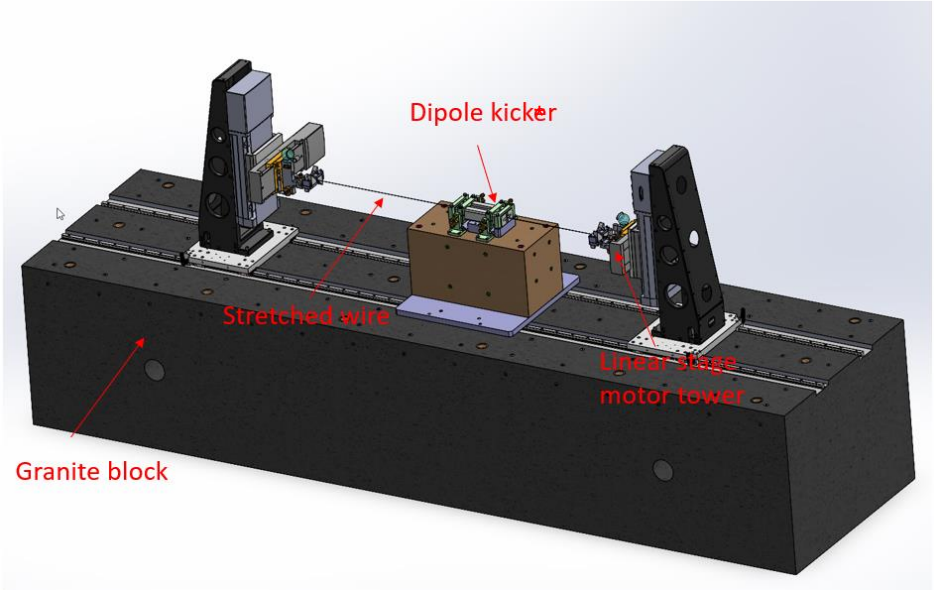
- Adaptation of stretched-wire measurement
- 2 loops for simultaneous measurement of horizontal and vertical planes
- Voltage (V) measured across loops and converted to magnetic flux value
- All multipoles reconstructed from 2D fit of measurement on a closed contour

Theoretically :

- **Faraday's law :** $$V = -\frac{d\varphi}{dt}$$
- **Magnetic flux :** $$\varphi = \int \mathbf{B} \cdot d\mathbf{S}$$

Wires arrangement

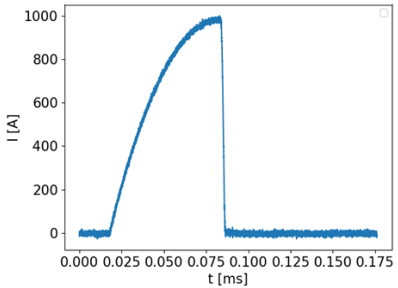
3D scheme of the magnetic test bench.



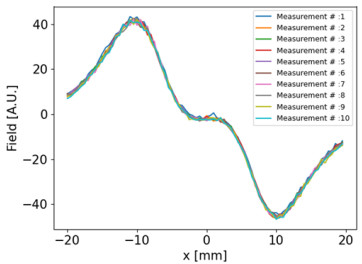
NON LINEAR KICKER MEASUREMENTS

Existing SOLEIL NLK installed on the bench for validation

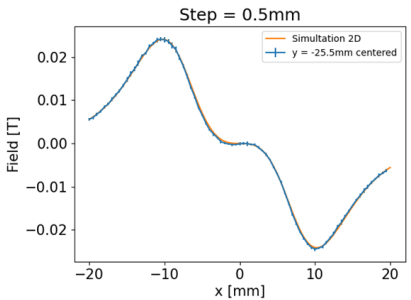
Use ESRF injection kickers power supplies (2kA)



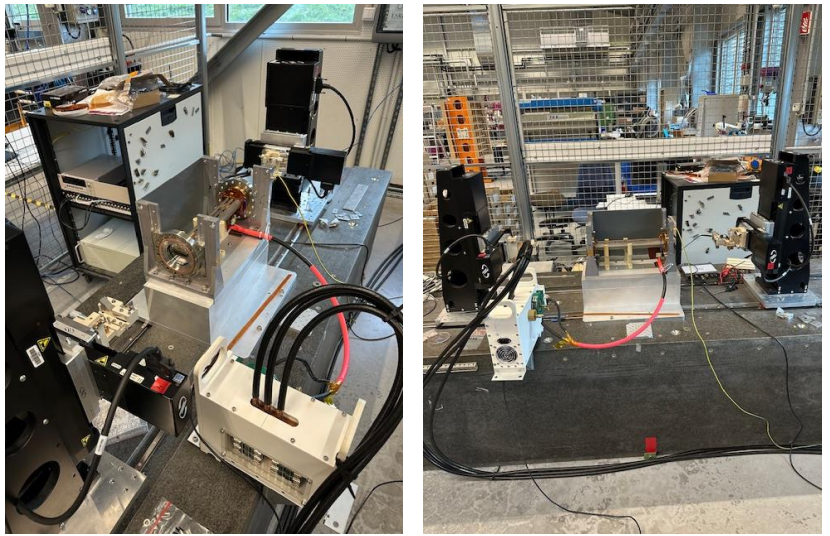
Current profile delivered by the power supply.



Reproducibility of the measurements.



Agreement of experimental data with the simulated SOLEIL'NLK field.



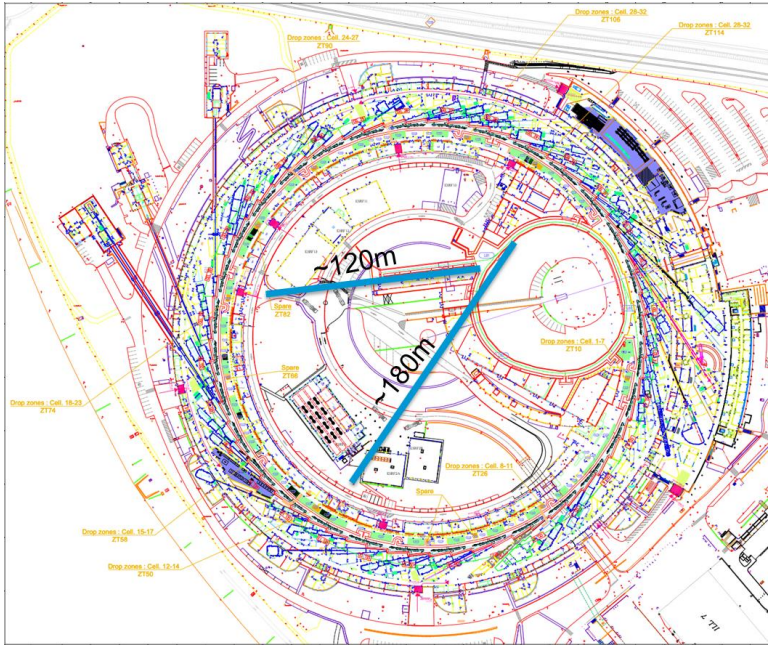
Test bench with SOLEIL NLK

Beam tests: summer 2026
Installation: summer 2028 (earliest)

A NEW 6 GEV LINAC?

Presently considering a complete upgrade of our injectors with a full energy linac: limited space available, high gradient technologies could be a solution

- Complete **renewal of obsolete injectors** providing low emittance injected beams (<1nmrad, **>40 times smaller than the present injectors,** <1mm bunch length **>10 times shorter bunch,** 0.6mA/bunch)
- Enable **ultra-low emittance / low aperture / low gaps** SR lattice design by relaxing constraint on DA.
- Demonstrate **state-of-the-art** compact technology for users facilities injectors
- Enable **transparent on-axis off-energy** accumulation with ultra short injected beam (with ultra-fast kicker).
- Enable new science making use of the linac electron beam (short pulse e^-, FEL)



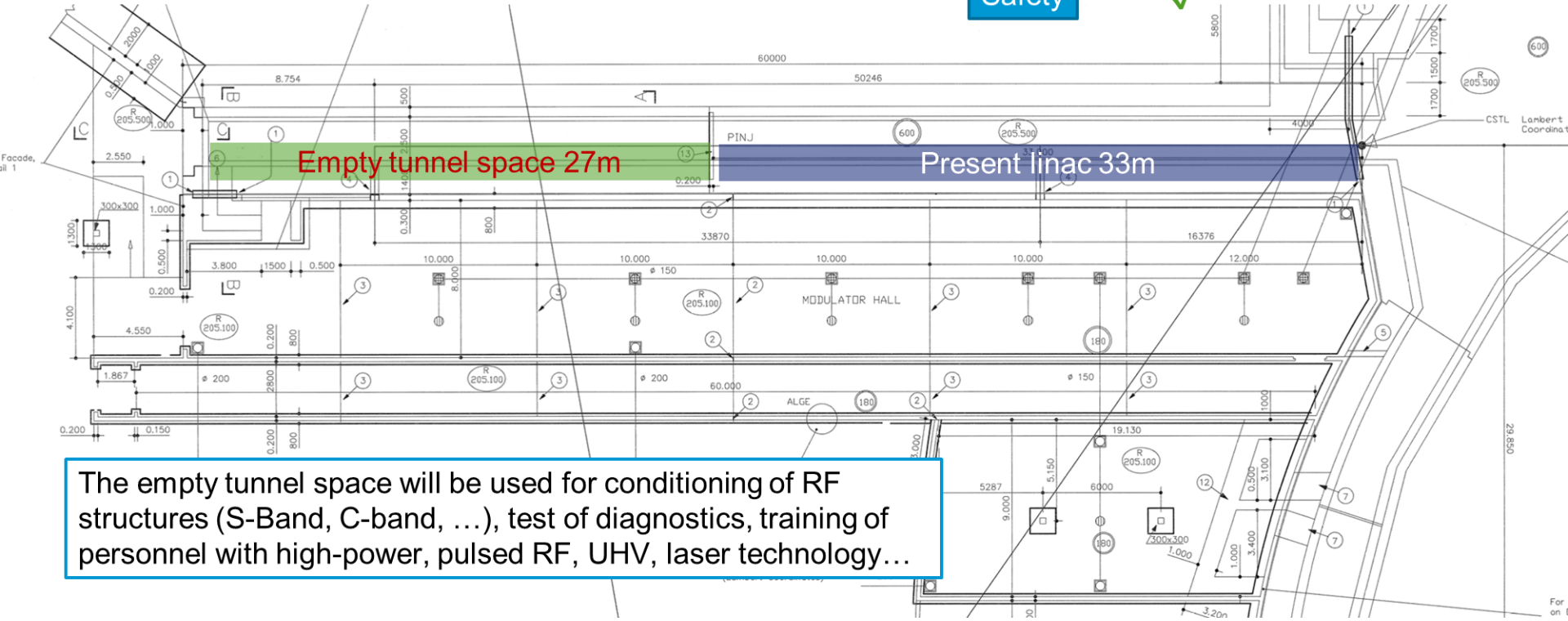
Possible site integration using C3 technology

FIRST STEP: LINAC TEST FACILITY

~0.5GeV C^3 demonstrator could fit in the empty tunnel and allows independent EBS operation

58m long tunnel ✓

Safety ✓



The empty tunnel space will be used for conditioning of RF structures (S-Band, C-band, …), test of diagnostics, training of personnel with high-power, pulsed RF, UHV, laser technology…

More in S. Liuzzo's presentation this afternoon

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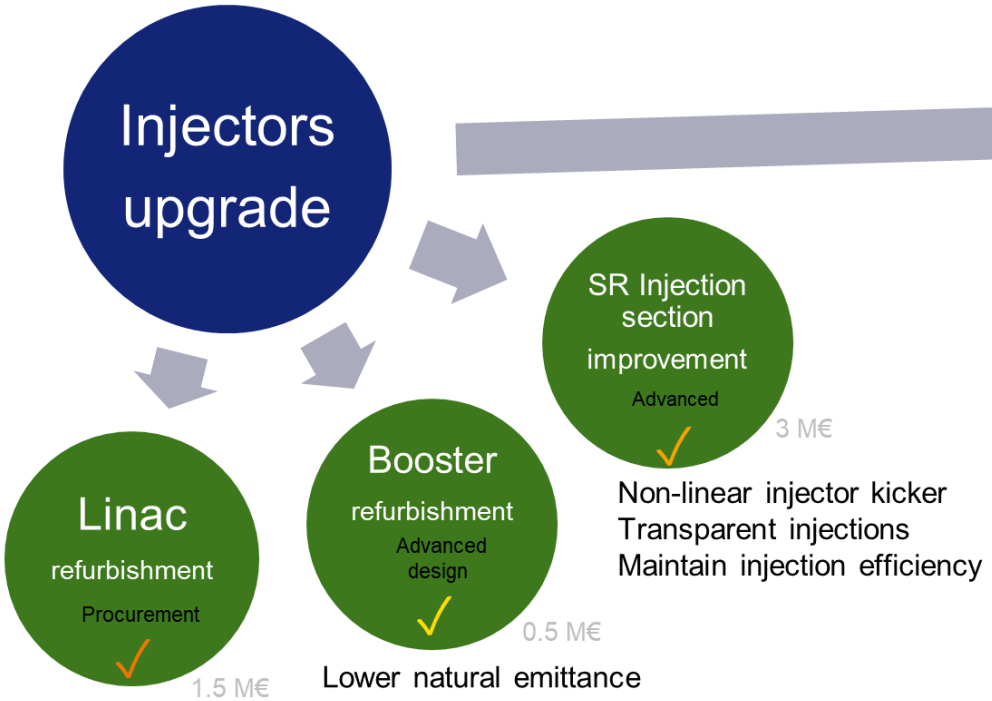
FULL PICTURE



Replace existing injectors with a full energy injector linac

Higher injection efficiency, lower injection perturbation, enable/facilitate future SR upgrades

6GeV + margin
> 600 pC (single bunch)
< 1 nm.rad at SR injection
< 0.1 % energy spread
< 1 mm bunch length
> 4 Hz repetition rate
Bunch spacing 2.8ns (in the SR)
Fits on site (maximum 180m)
As low energy consumption as possible
User facility grade :

- Reliability
- Reproducibility (turn on 1 month later and it works as before)
- Maintainability easy to repair or operate with failing component for long term

FEL option to be studied

SUMMARY

ESRF finally reached design parameters for all modes in 2024

Availability and reliability slowly improving

Short / mid-term improvement program:

- Linac refurbishment
- Replacement of klystrons by SSAs for SR main RF systems
- Implementation of 4th harmonic system for bunch lengthening
- Implementation of new booster lattice for emittance reduction
- Implementation of NLK injection for transparent top-up

Long term improvement: replacement of aging injectors, a new 6 GeV LINAC? Future facility upgrades?

MANY THANKS FOR YOUR ATTENTION