Experiences with SIRIUS Booster

Fernando Henrique de Sá
On behalf of the LNLS Accelerator Physics Group

Injectors for Storage Ring Based Light Sources
Karlsruhe, 6-8 of March 2024

SIRIUS – 4GSR in Operation

SIRIUS design parameters

Energy	3.0	GeV
Circumference	518.4	m
Emittance	250	pm.rad
Current (top-up)	350	mA

- Green-field facility
- Construction: 2012 – 2020
- Cost: US$ 500M (~85% spent in Brazil)
- 1st regular users call: Nov. 2022
- 10 beamlines in operation
- 100 mA in top-mode mode, uniform fill
- Phase-1 (end of 2024): 14 beamlines

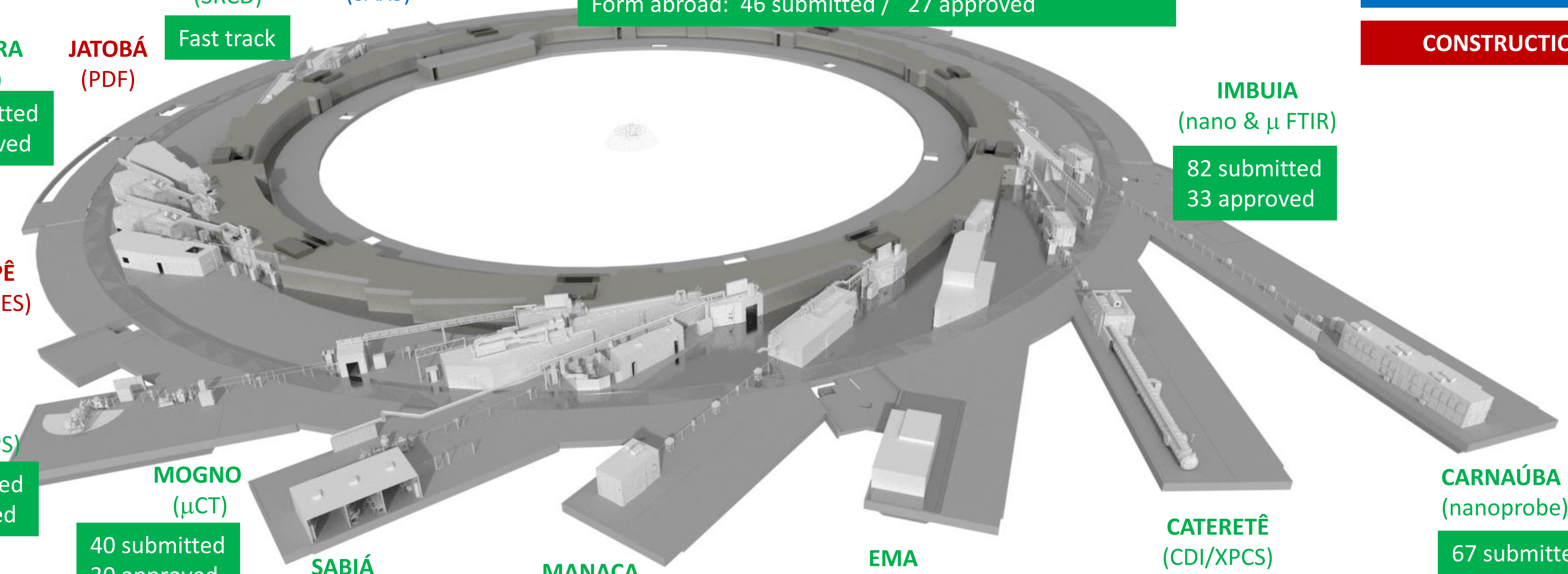
SIRIUS Beamlines – Phase 1

https://www.lnls.cnpem.br/beamlines/

Third Cycle of Proposals (1S 2024)

Total: 422 submitted / 225 approved
From Brazil: 376 submitted / 198 approved
Form abroad: 46 submitted / 27 approved

OPERATION
INSTALLATION
CONSTRUCTION



CEDRO
(SRCD)
Fast track

SAPUCAIA
(SAXS)

PAINEIRA
(XPD)
46 submitted
36 approved

JATOBÁ
(PDF)

QUATI
(XAFS)

SAPÊ
(ARPES)

IPÊ
(RIXS/ XPS)
45 submitted
26 approved

MOGNO
(µCT)
40 submitted
30 approved

SABIÁ
(XMCD/PEEM)
18 submitted
15 approved

MANACA
(MX)
Fast track

EMA
(Extreme Cond.)
83 submitted
20 approved

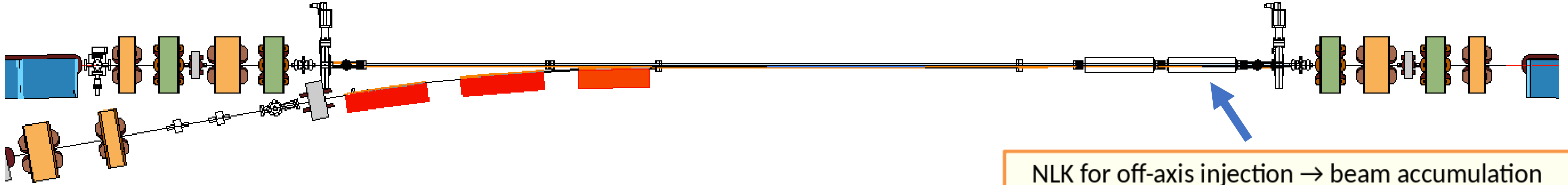
CATERETÊ
(CDI/XPCS)
41 submitted
24 approved

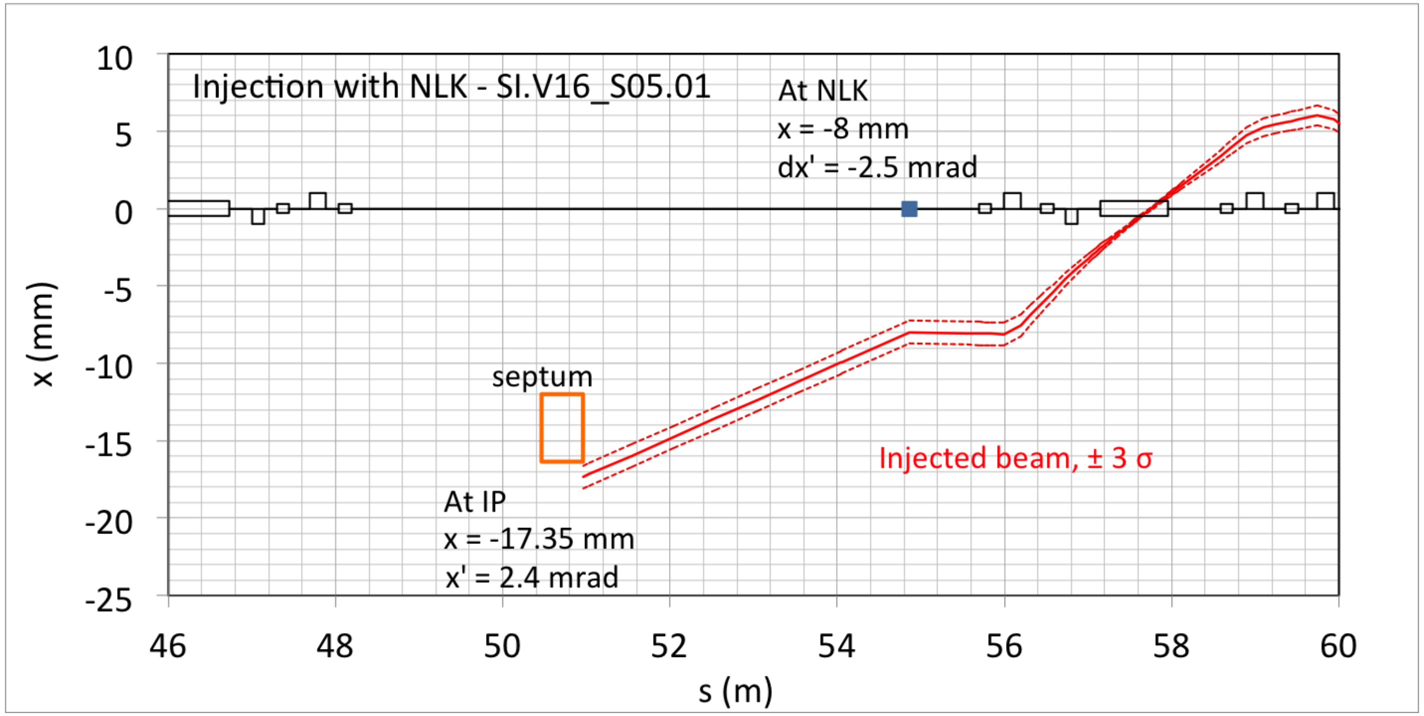
CARNAÚBA
(nanoprobe)
67 submitted
41 approved

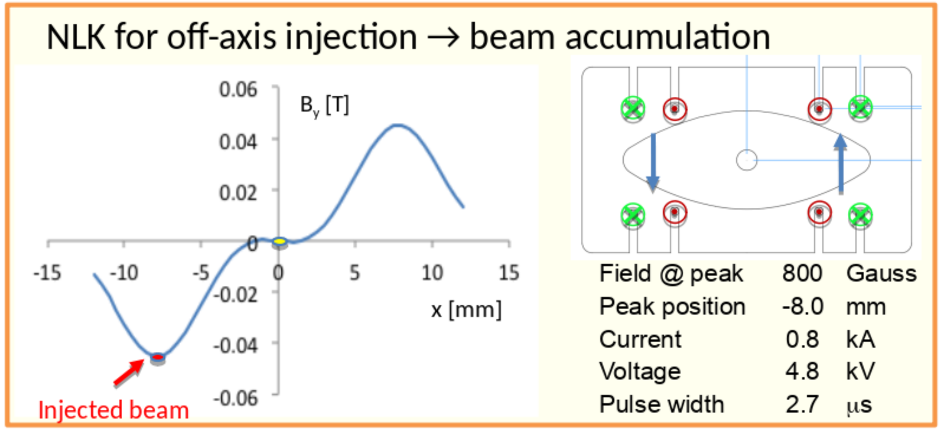
IMBUIA
(nano & µ FTIR)
82 submitted
33 approved

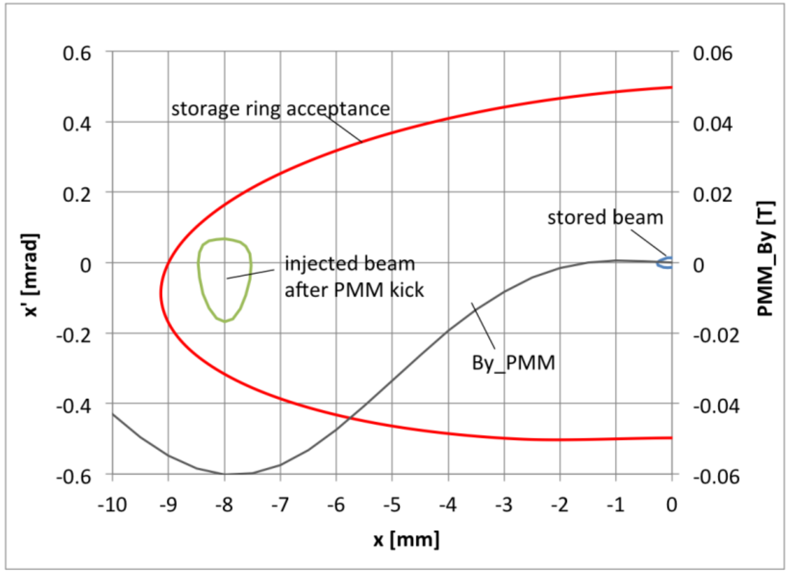
Courtesy: Harry Westfahl

Storage Ring Injection





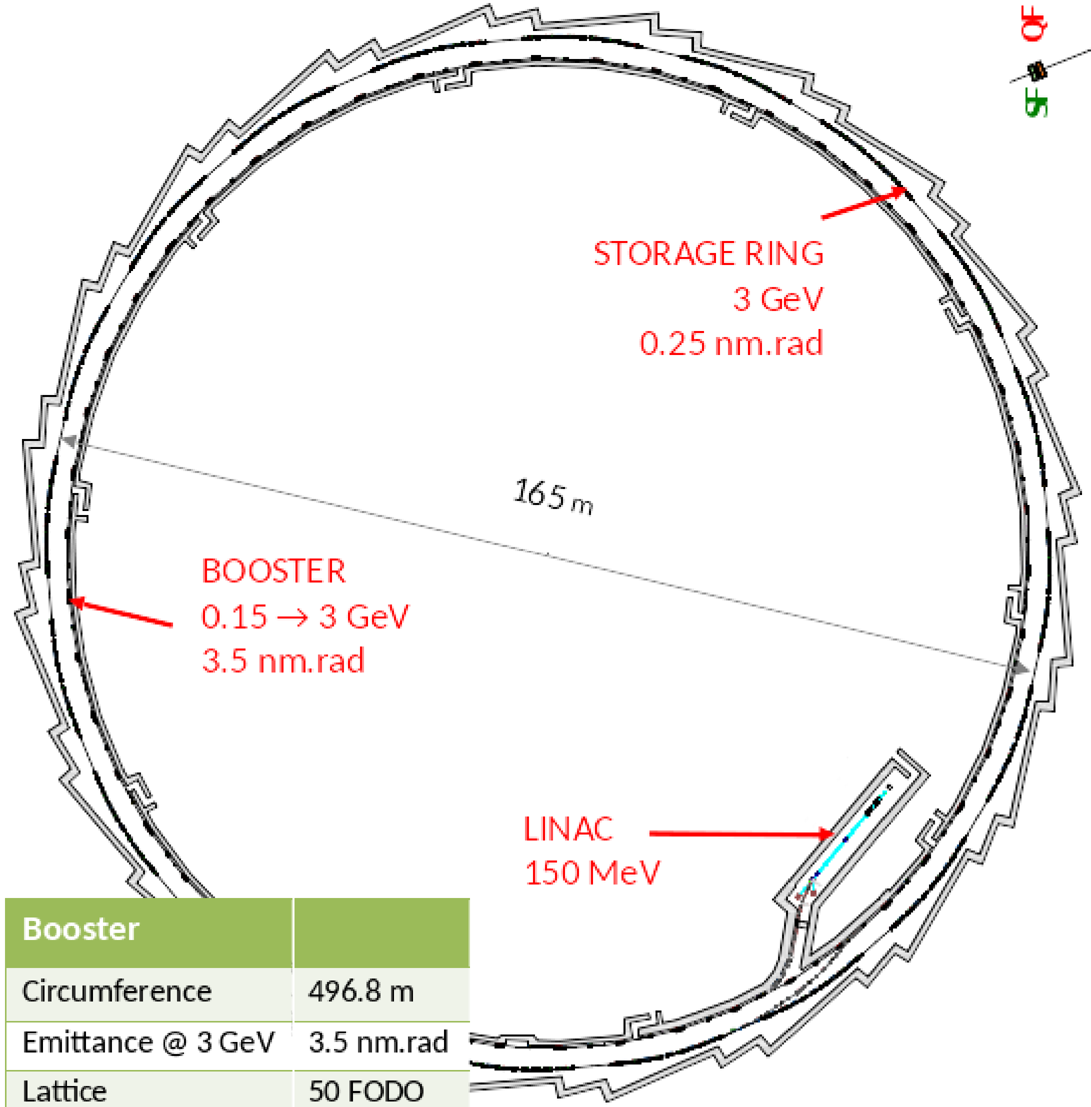




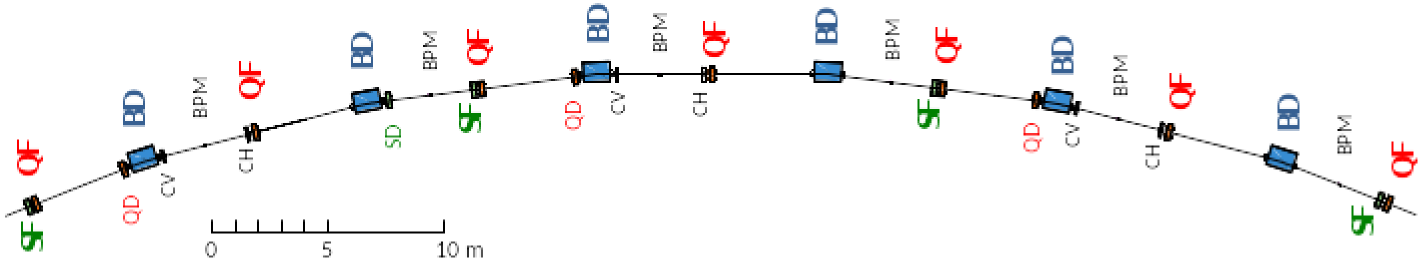
Low emittance booster required!

Booster Design

Lattice Design



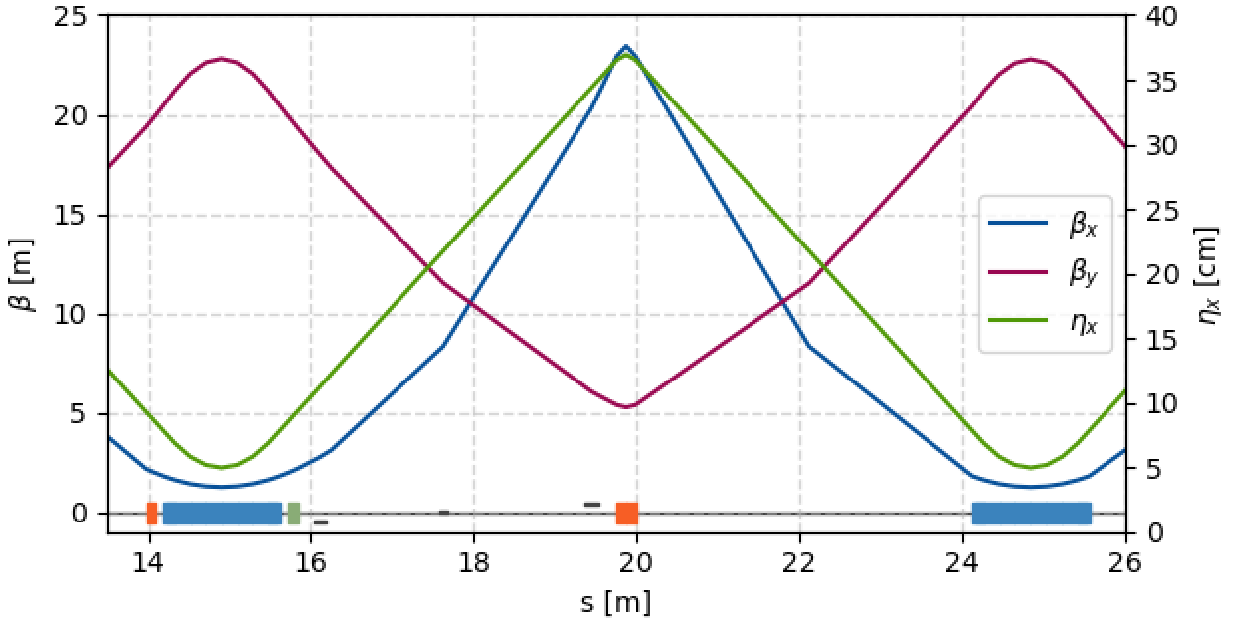
Booster	
Circumference	496.8 m
Emittance @ 3 GeV	3.5 nm.rad
Lattice	50 FODO
Cycling frequency	2 Hz

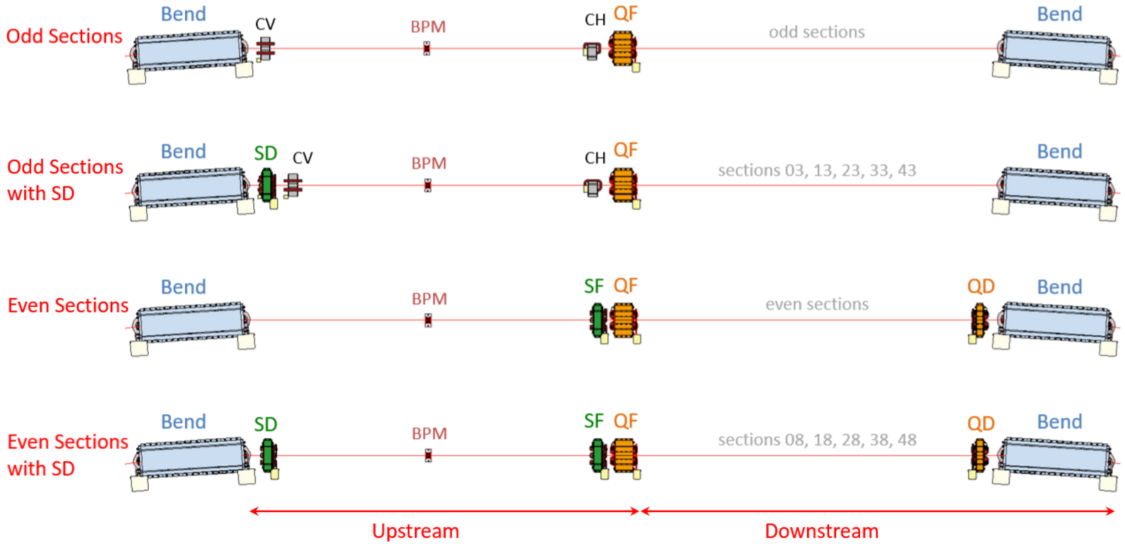


- Dipoles with defocusing quadrupole and sextupole components;
- Large spaces between magnets:
  - enough room for RF cavity and injection/extraction systems;
- Symmetric lattice, without non-dispersive straigth sections:
  - simpler, cheaper and with uniform distance to storage ring;
- Compact magnets:
  - supported by girders attached to inner walls of tunnel;

Linear Optics

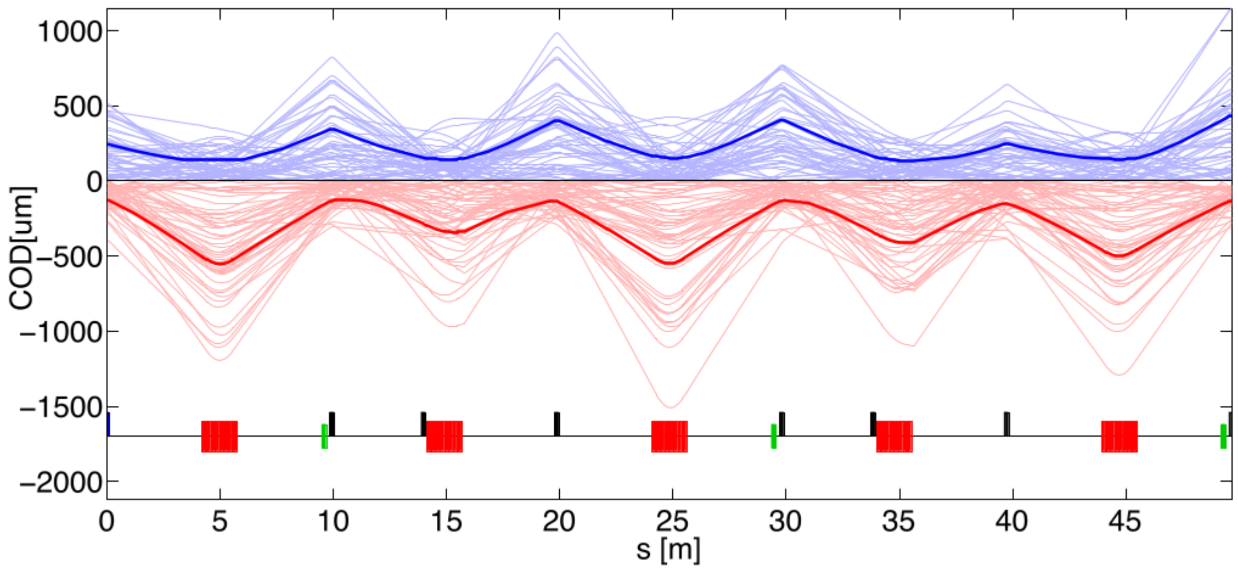
Circumference	496.8 m
Harm. Number	828
Tunes	(19.20, 7.31)
Chromaticities	(0.5, 0.5)
Nat. Chrom.	(-33.7, -13.9)
Mom. Compaction	**7.2×10^{-4}**
Nat. Emitt.@3GeV	**3.5 nm.rad**
Nat. En. Spread@3GeV	0.09 %
Nat. Bun. Len.@3GeV	11.2 mm





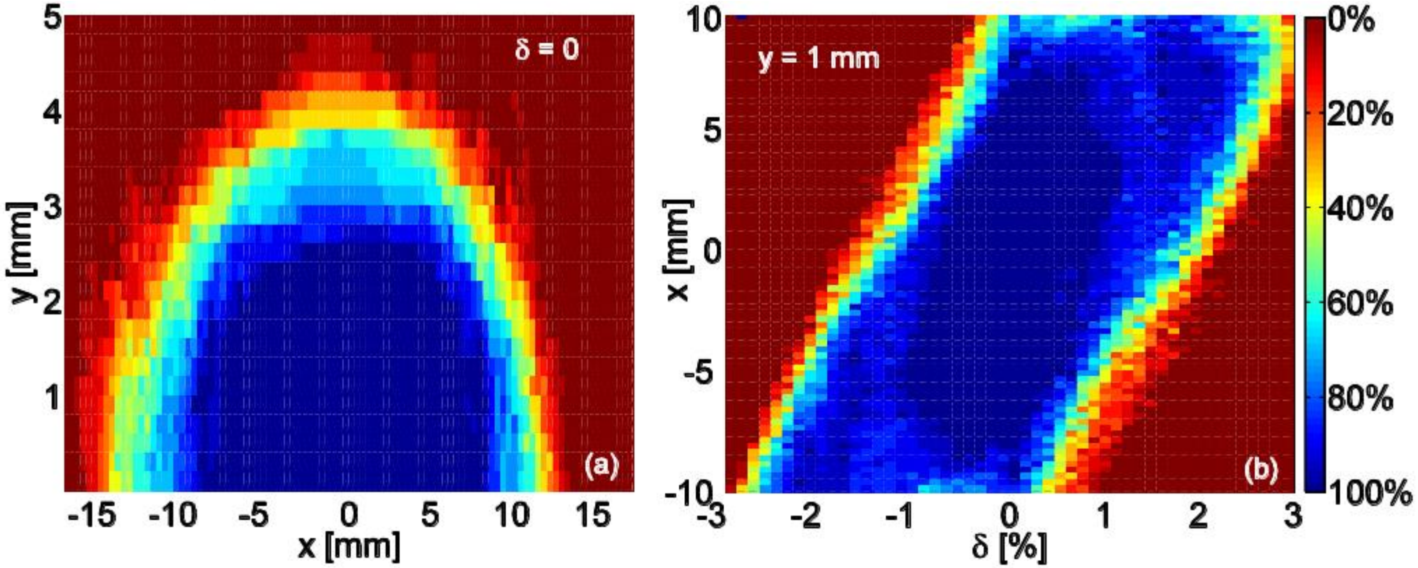
- Optimized for low emittance → low momentum compaction;
- Nominal linear optics with 50 dipoles and 50 QFs;
- Nominal chromaticity adjusted to 0.5 with 25 SF sexts and dipoles;
- Tune and chromaticity correction with 25 QD quads and 10 SD sexts;
- Orbit Correction with 50 BPMs, 25 CH and 25 CV magnets;
- BPMs are not placed close to peaks of optical funcions;

Orbit Correction and Dynamic Aperture

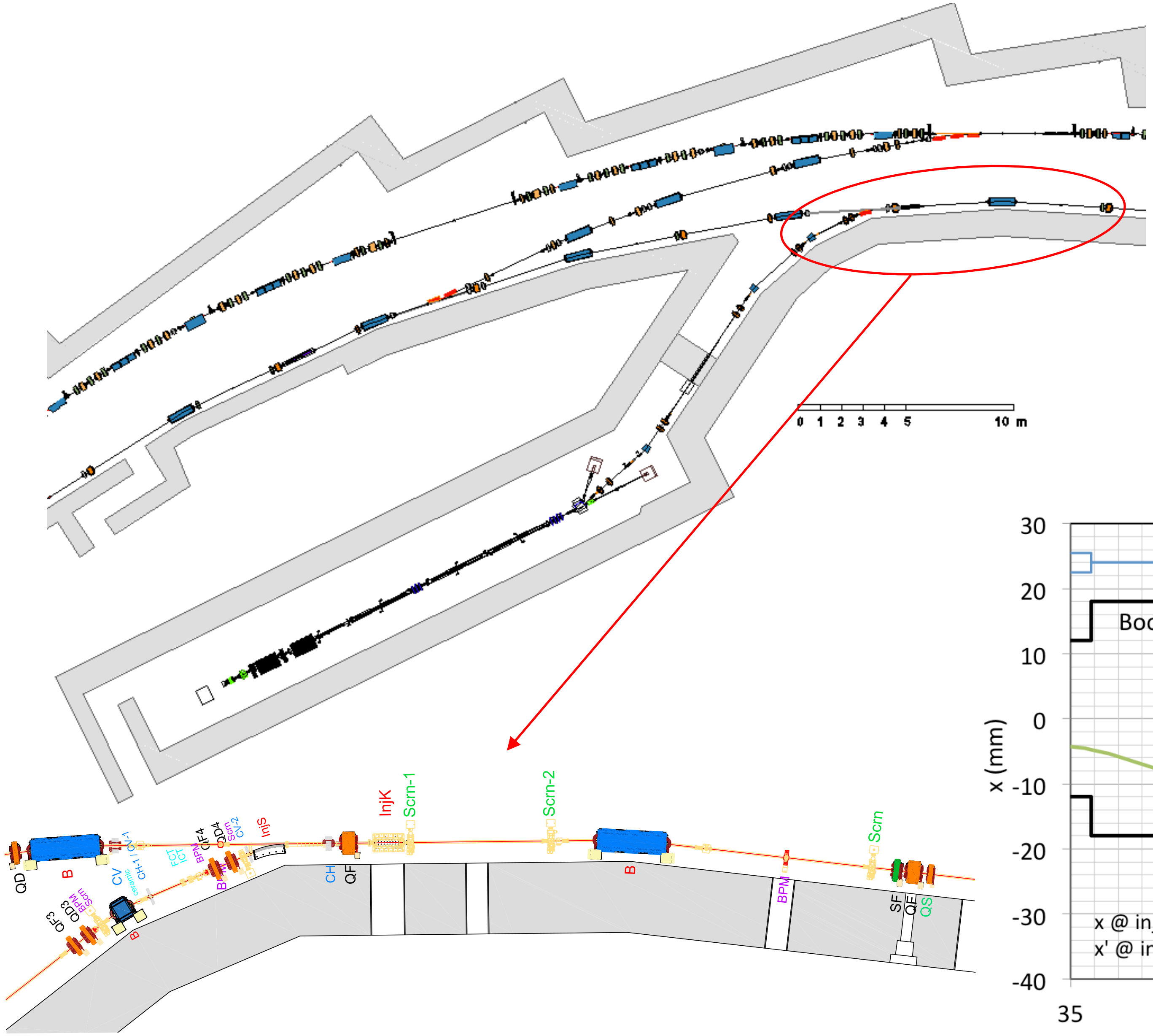


Error	Dipole	Quad.	Sext.
Alignment x, y	160 um		
Rotation Roll	0.8 mrad		
Excitation	0.15 % (grad. 2.4 %)	0.3 %	0.3 %
Mult. Normal	~$4x10^{-4}$		
Mult. Skew	~$1x10^{-4}$		

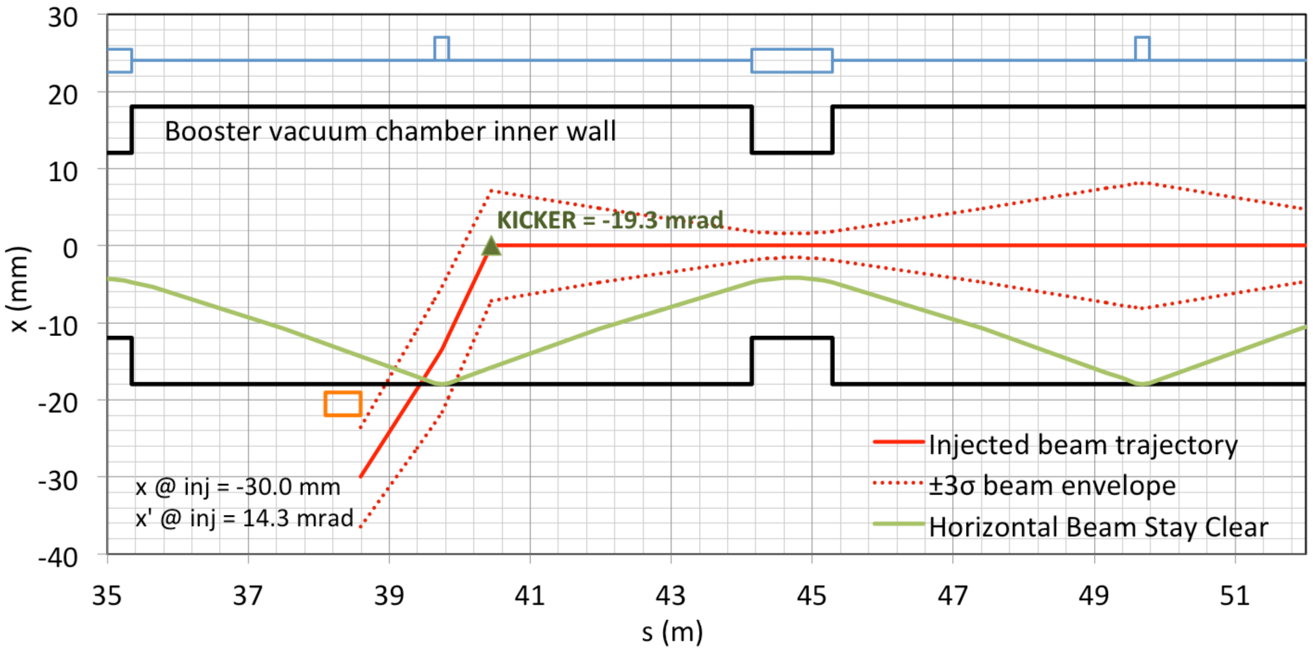
- Simulations with realistic errors;
- Low residual orbit;
- Good dynamic aperture and momentum aperture;



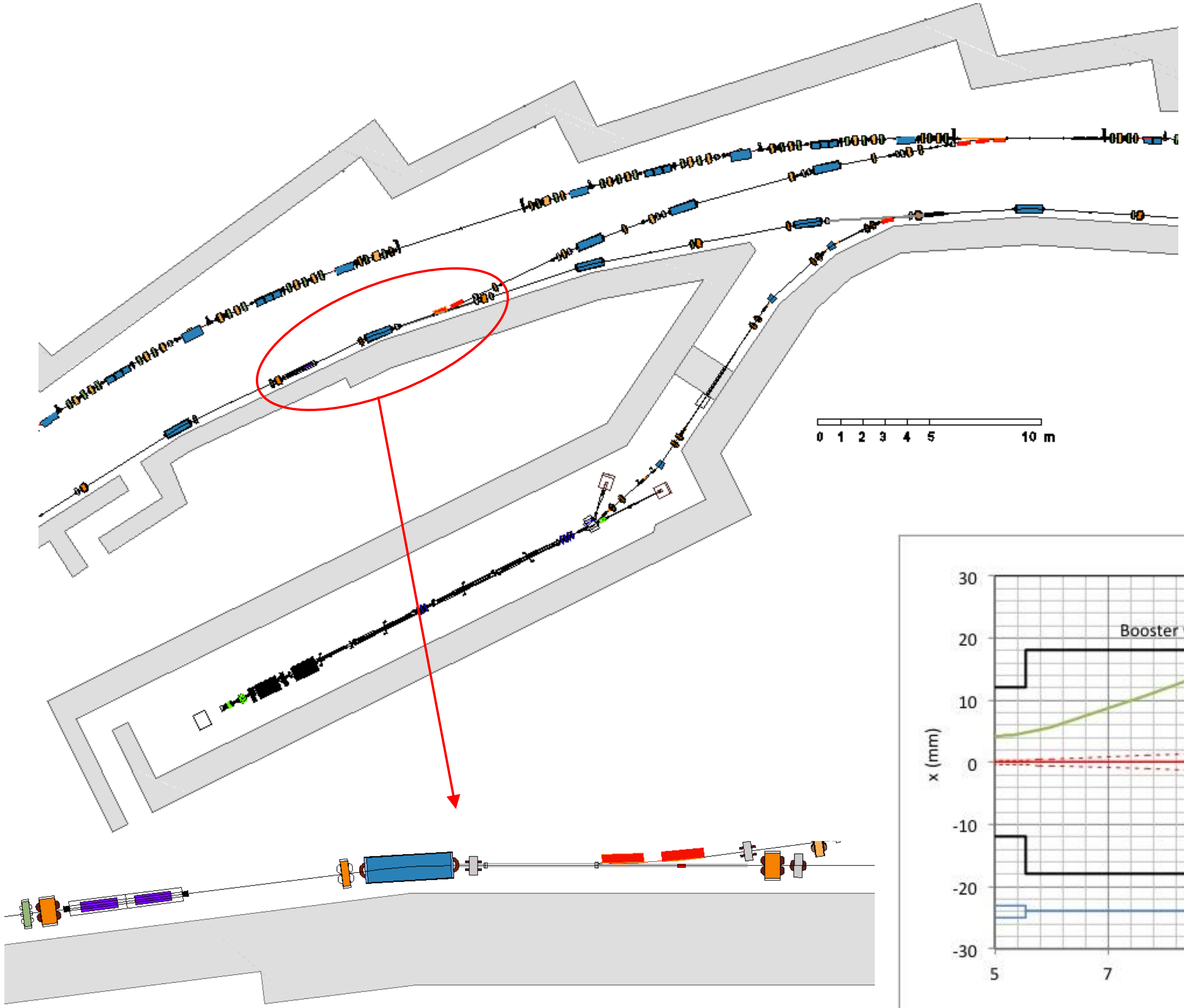
Injection System



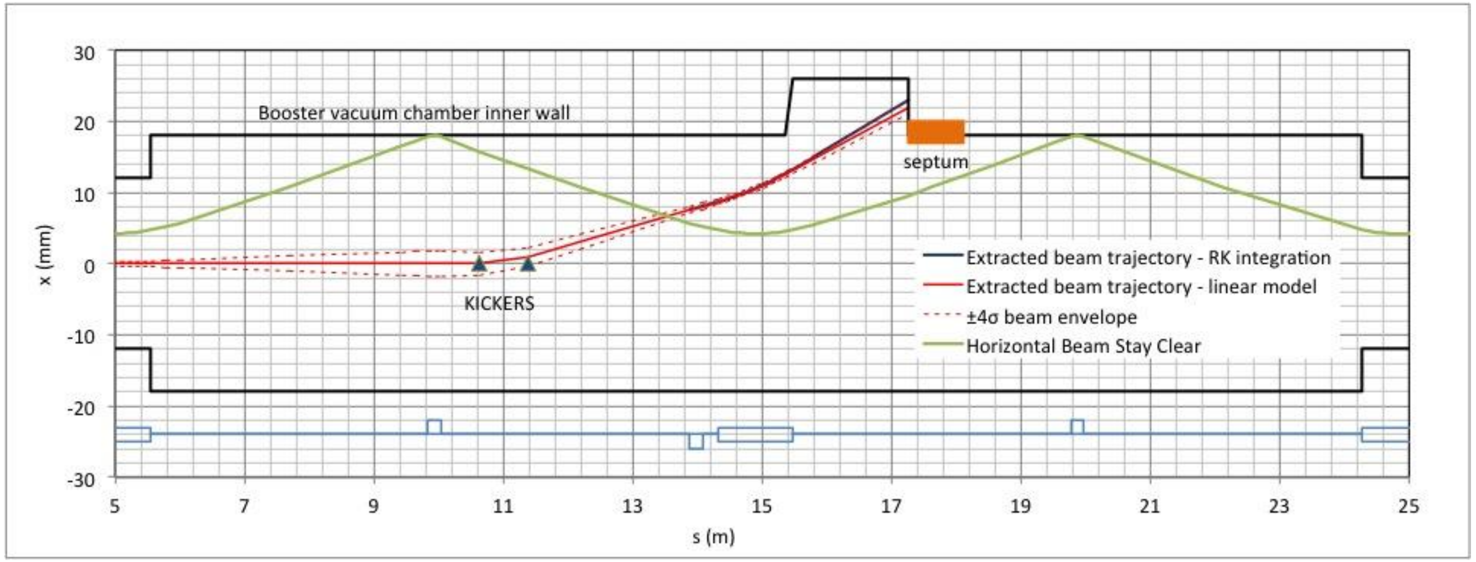
- Linac beam @ 150 MeV: $\varepsilon_{x,y}$ = 170 nm.rad, σ_δ = 0.5%;
- Geometry requires strong septum (21.5°) and kicker (19.3 mrad);
- Optics (β, α, η, η') at end of TL matched to booster optics;
- Booster horizontal acceptance:
  - 4-σ of beam size;
  - 1 mm of orbit distortion;
  - 4.5 mm of transverse oscillations
  - 1.5% of energy oscillation;
- Three screens were considered to help checking optics matching;
- 100% of ramp efficiency in commissioning simulations.



Ejection System



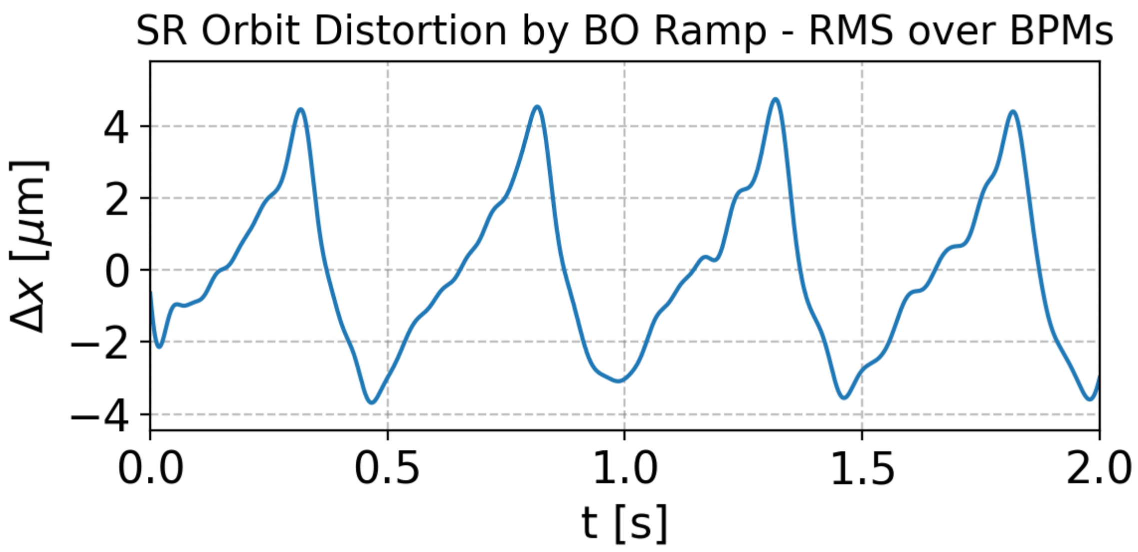
- Optics at beggining of TL matched to optical functions of booster (including dispersion and its derivative);
- Weaker ejection kicker (~2.1 mrad) and septa (~3.6°);

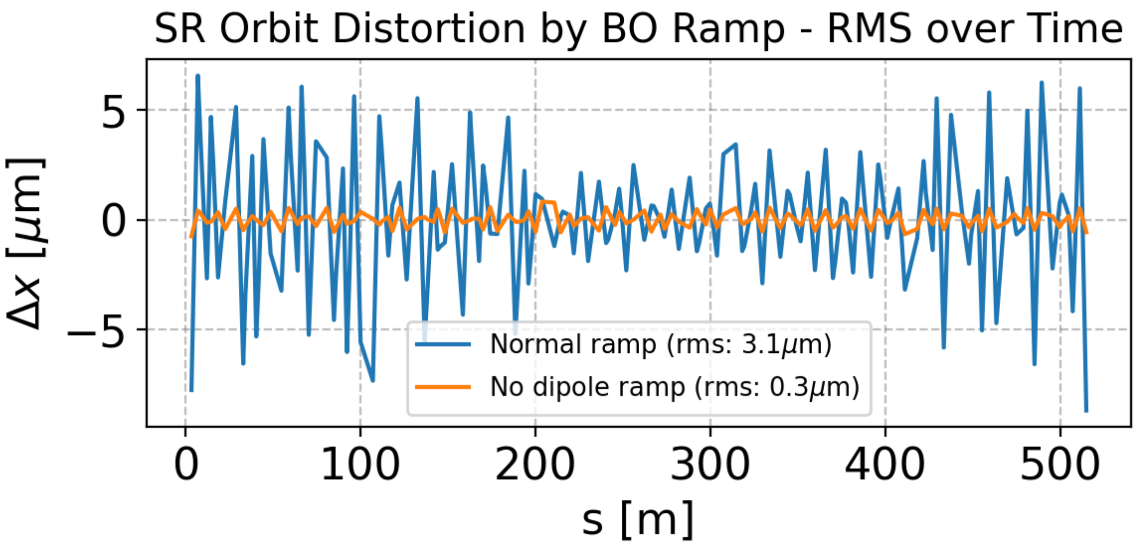


Commissioning

Booster and SR sharing same tunnel

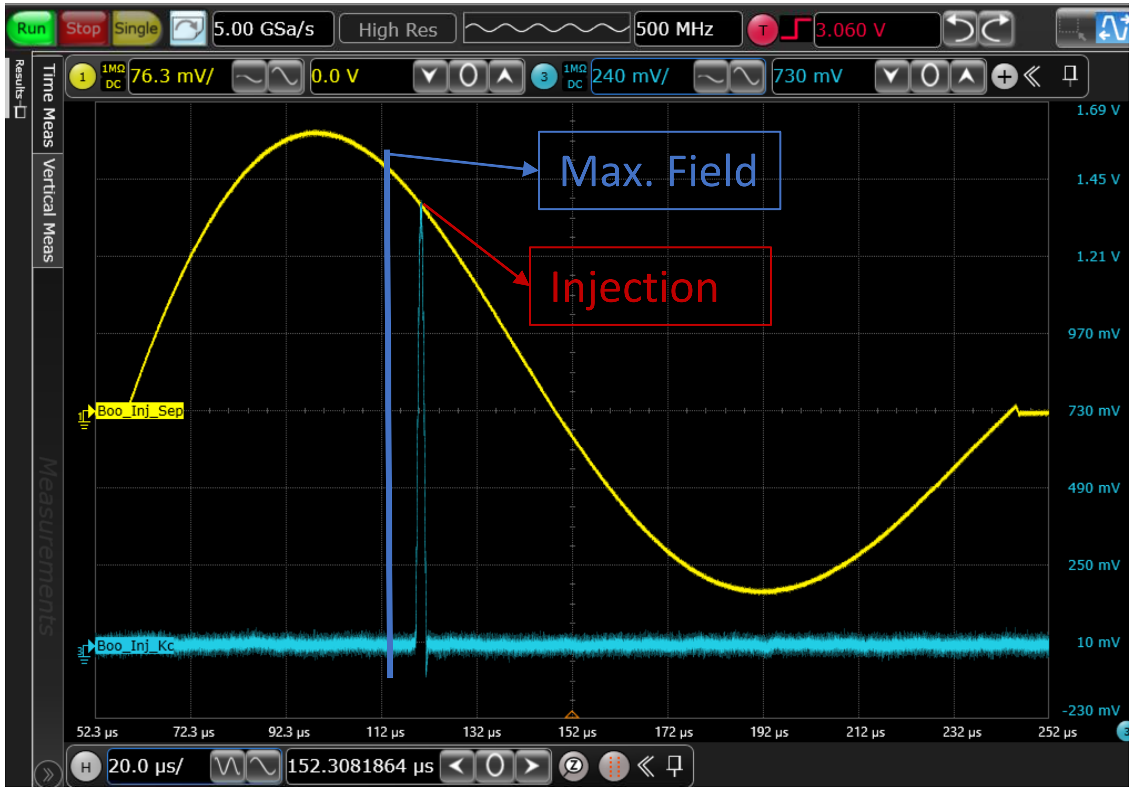
- Commissioning concurrently with the installation of the SR:
  - Intermitent commissioning schedules;
  - Facilities not well conditioned yet -> poor temperature stability;
  - Installation activities delaying commissioning:
    - Magnets and BPM cables inversion;
    - Mal-functioning power supplies;
    - SR permanent magnet temporarilly stored close to booster;
- Interference of SR power supplies on booster and TLs orbit:
  - SR magnets cable positions optimized to minimize magnetic field on booster under nominal operation currents for all PSs;
  - Only few SR PSs on -> no beam on booster;
  - Even with all SR PSs on, the booster orbit changes in comparison to when they are off;
- Interference of booster ramping on storage ring orbit:
  - Mainly on the horizontal plane;
  - Created by the dipoles;
  - Effectively attenuated by SR fast orbit feedback.

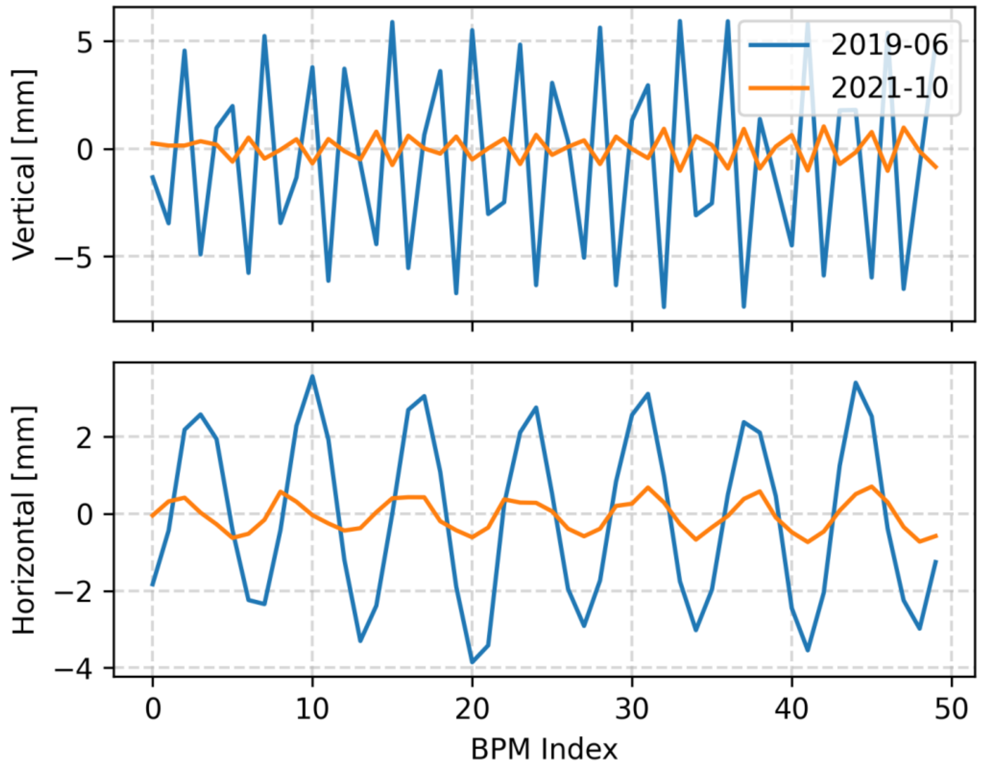


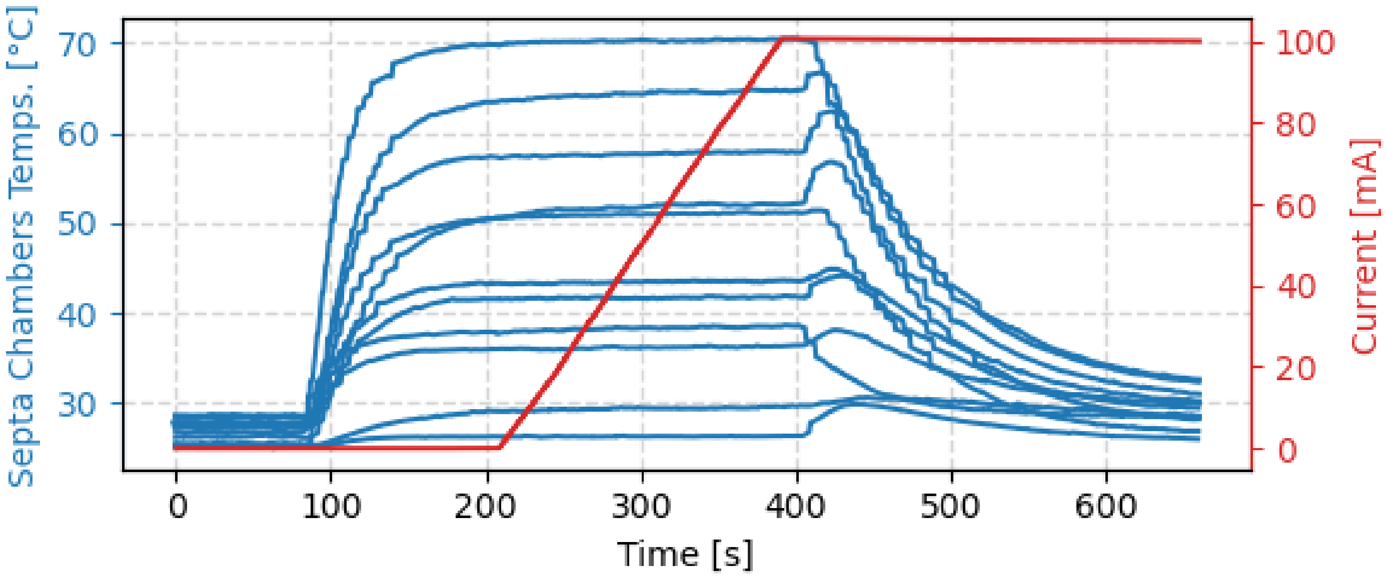


Septa Issues

- Strong effect of eddy current:
  - Peak of magnetic field displaced in relation to peak of current;
  - Strong quadrupole at injection septum → re-matching of TL;
  - Injection at 1/3 Hz due to temperature rise when pulsing at 2 Hz;
- Initially there was a large effect on orbit due to leak fields;







Orbit Issues

- Energy deviation variation along ramp:
  - **low momentum compaction** + **variation of velocity** → **energy deviation variation**;
  - Easy to miss in design stage:
    - slippage factor ≈ momentum compaction even at low energies;
    - For the SIRIUS booster $1/\gamma^2 \sim 1.3\times10^{-5}$ @150MeV, while $\alpha = 7.2\times10^{-4}$
  - The orbit correction system ineffective:
    - booster and the SR have the same master RF oscillator;
  - Booster realigned to correct energy deviation at low energy: improve ramp eff.;

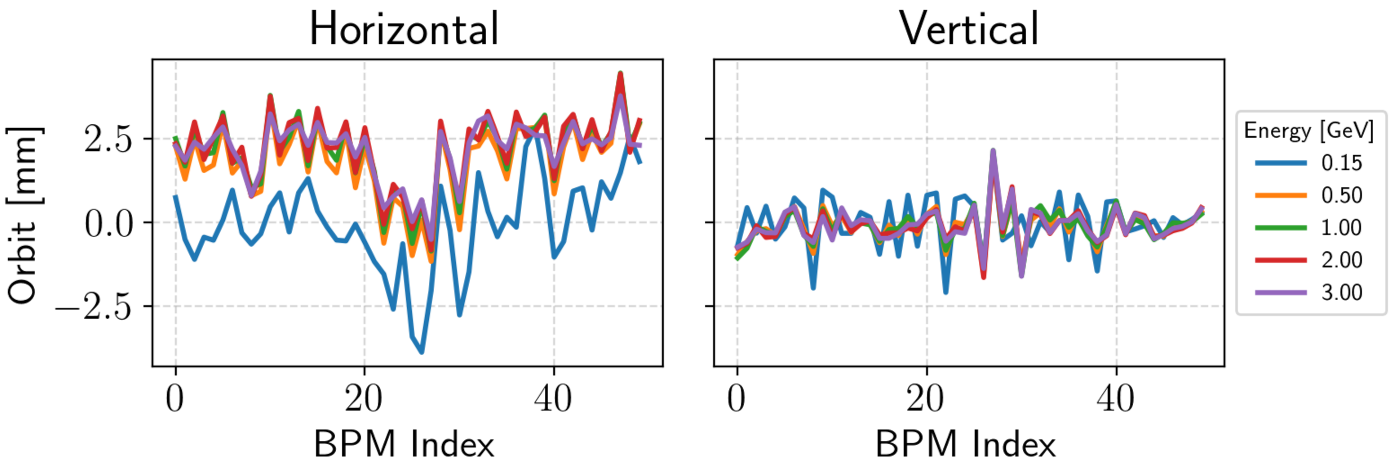
$$T_0 = hT_{\mathrm{RF}}$$

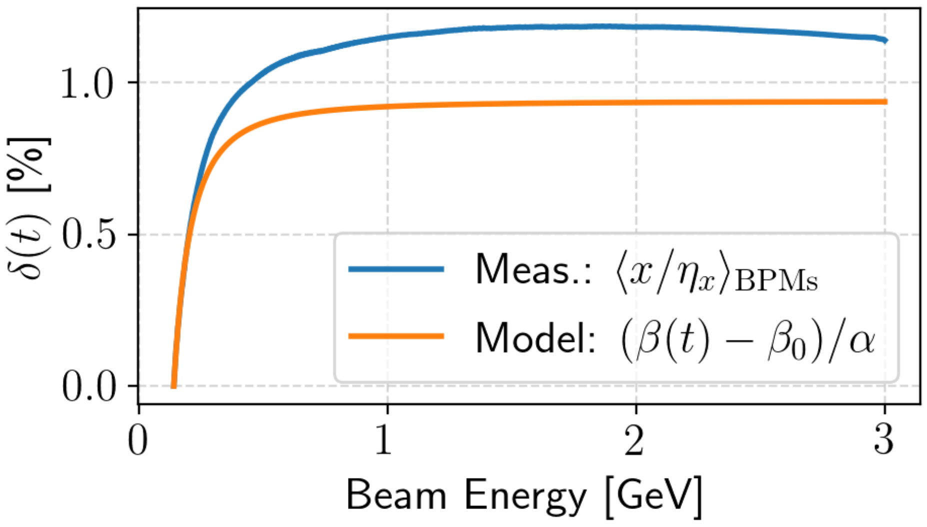
$$L(t) = v(t)T_0$$

$$L_0\left(1+\alpha\delta\right) = \left(\beta + \frac{1}{\beta\gamma^2}\delta\right)cT_0$$

$$\delta(t) = \frac{\beta(t)-\beta^*}{\alpha}$$

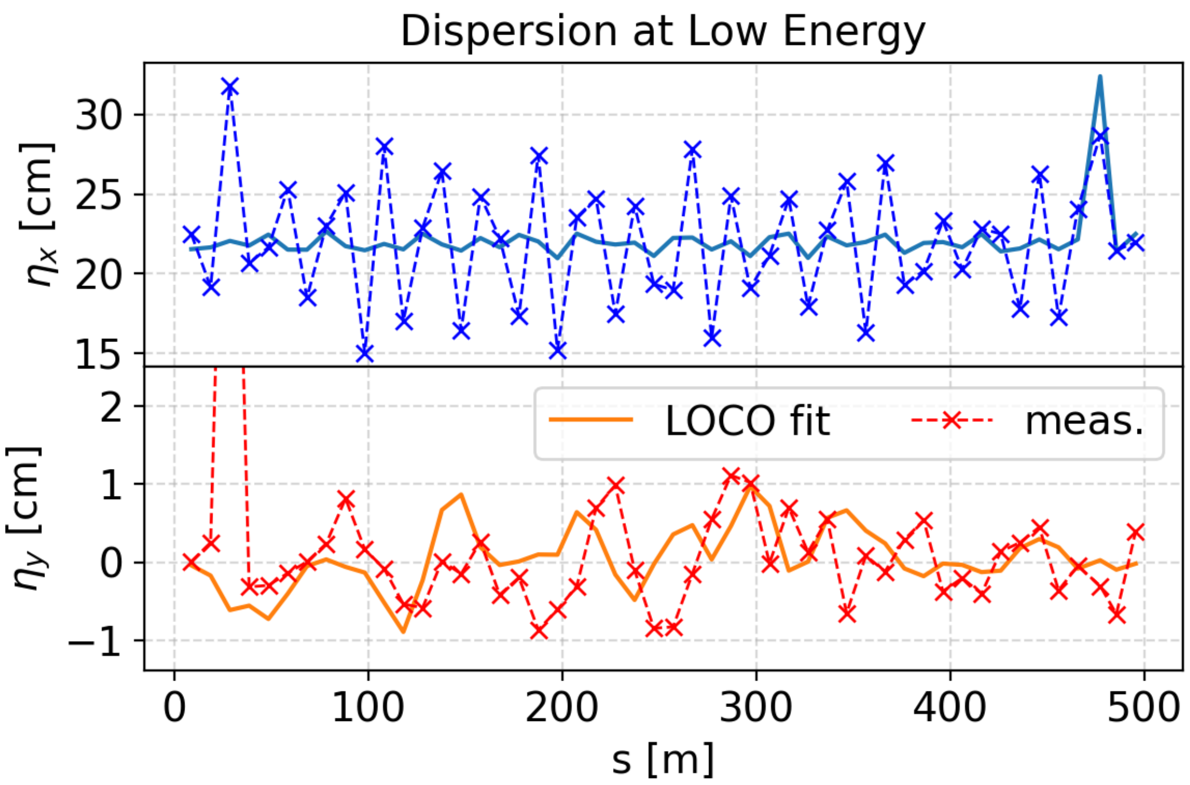
- Large residual horizontal orbit due to small number of HCMs:
  - Not predicted by simulations from design stage;
  - Similar orbit signature along ramp;
  - Possibly related to sorting of magnets installation order (correlated errors);
  - Ongoing studies to add corrector magnets and/or realign some magnets.

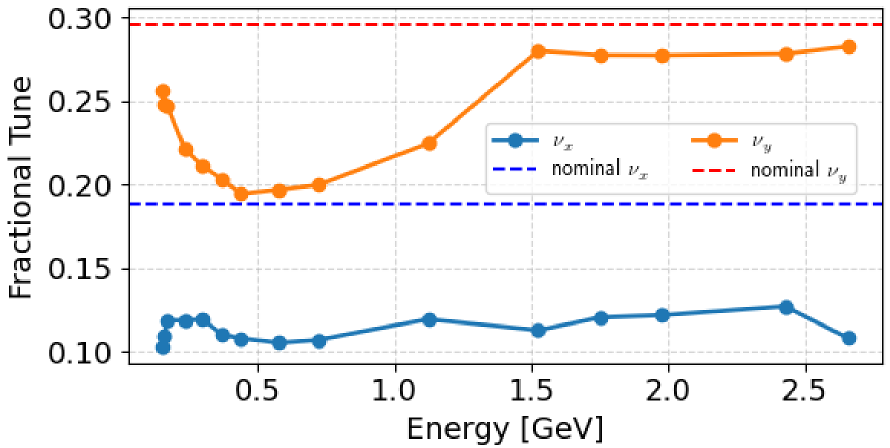


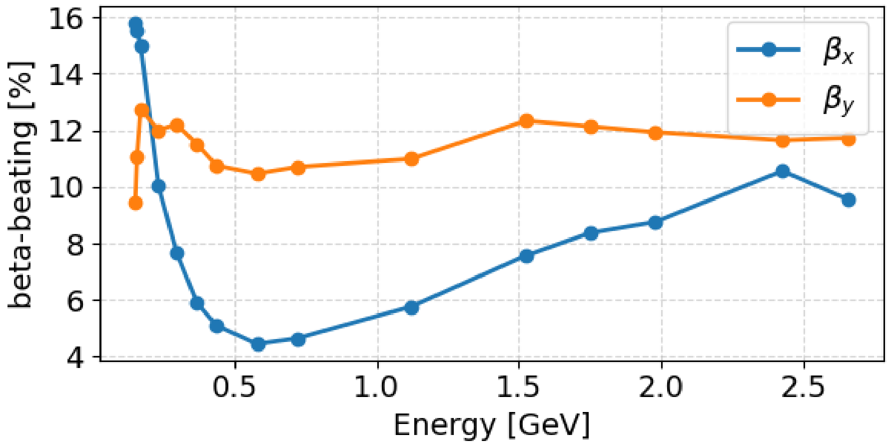


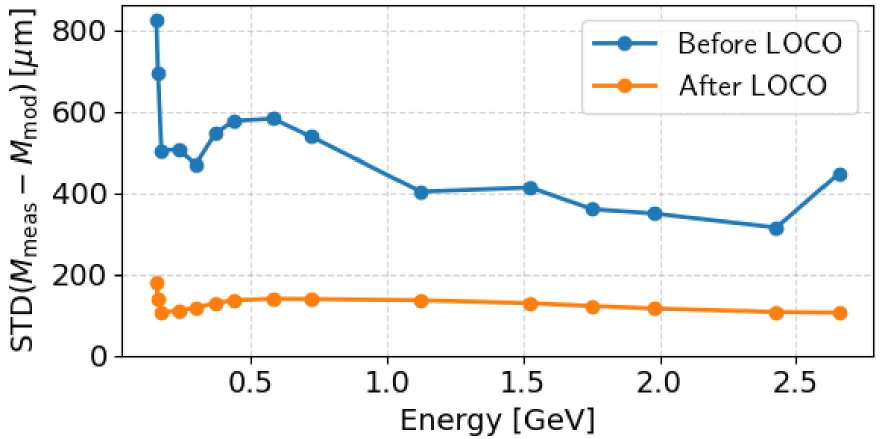
Optics Characterization

- Orbit response matrix measured along all ramp;
- LOCO fitting at some points (without using dispersion data);
- Tunes and beta-beating predicted by model:
  - Large beta-beating, but results are ok for a booster;
- Dispersion measured at low energies:
  - Difference to LOCO fitted model is not alarming;

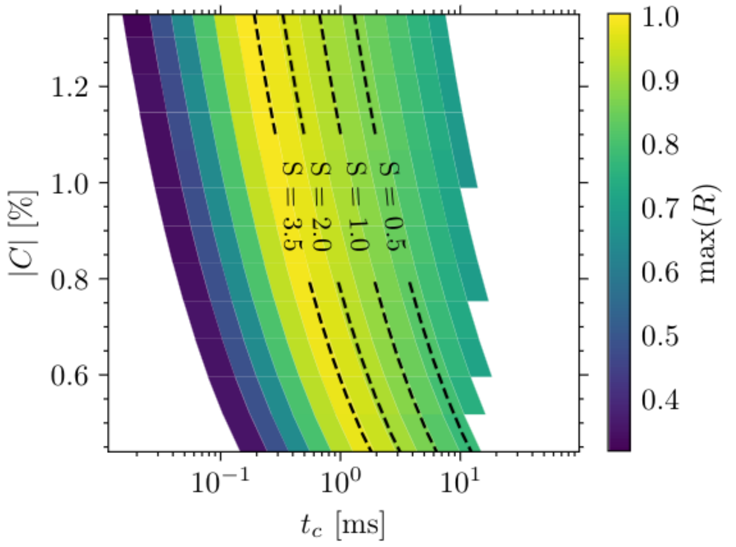




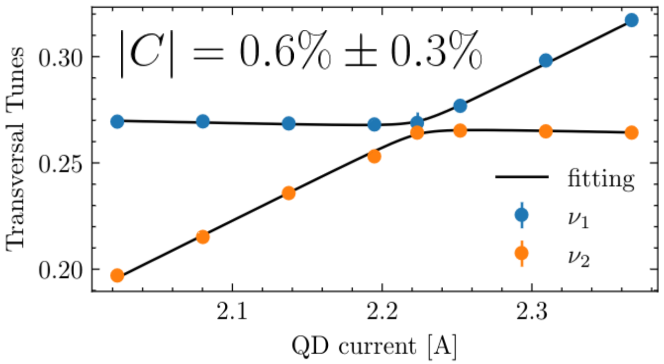


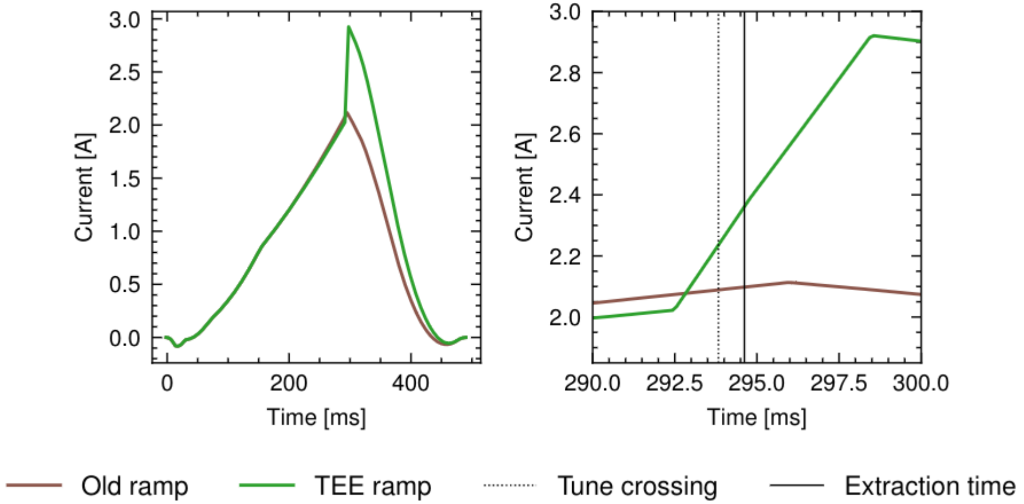


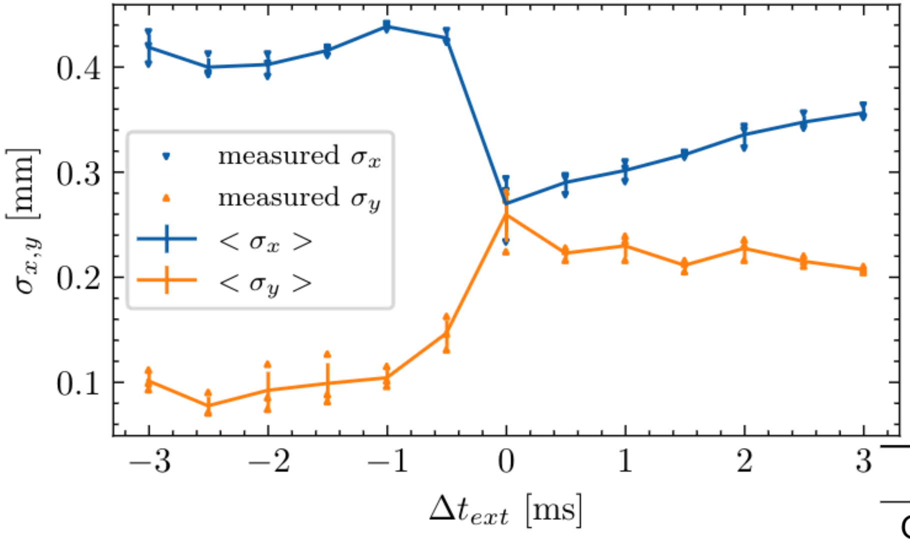
Transverse Emittance Exchange (TEE)



$$S = \frac{\dot{\Delta}}{|C|^2} \qquad R = 1 - \frac{\epsilon_x - \epsilon_{y0}}{\epsilon_{x0} - \epsilon_{y0}}$$



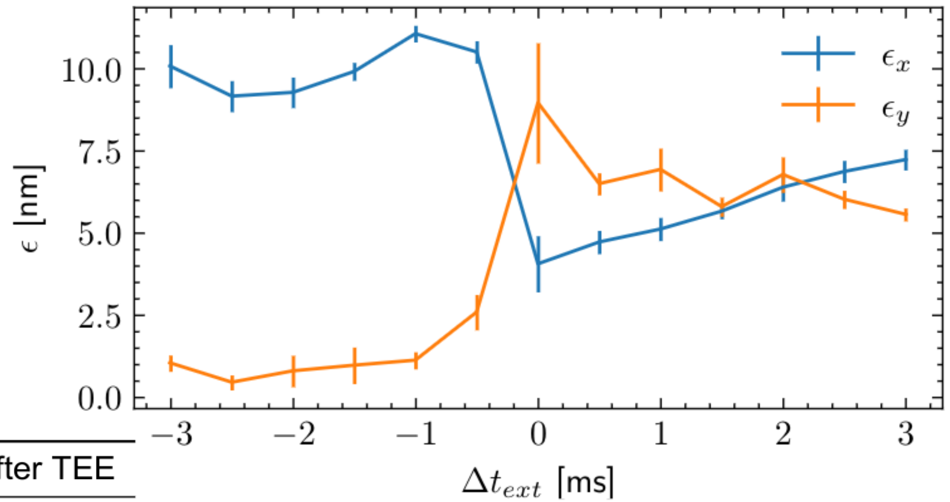




$$\epsilon_{x,y} = \frac{\sigma_{x,y}^2 - (\sigma_\delta \eta_{x,y})^2}{\beta_{x,y}}$$

$\beta_x,\ \beta_y$	17.11 m, 6.60 m
$\eta_x,\ \eta_y$	−13 cm, 0 cm

$$R = 70\% \pm 10\%$$

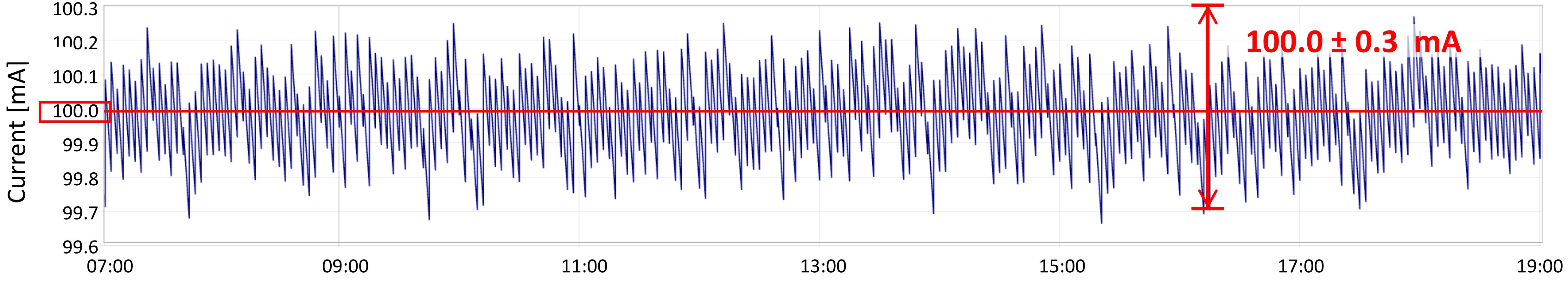


	Before TEE	After TEE
Optimized Inj. System	86 %	96 %
User shifts	75 %	82 %

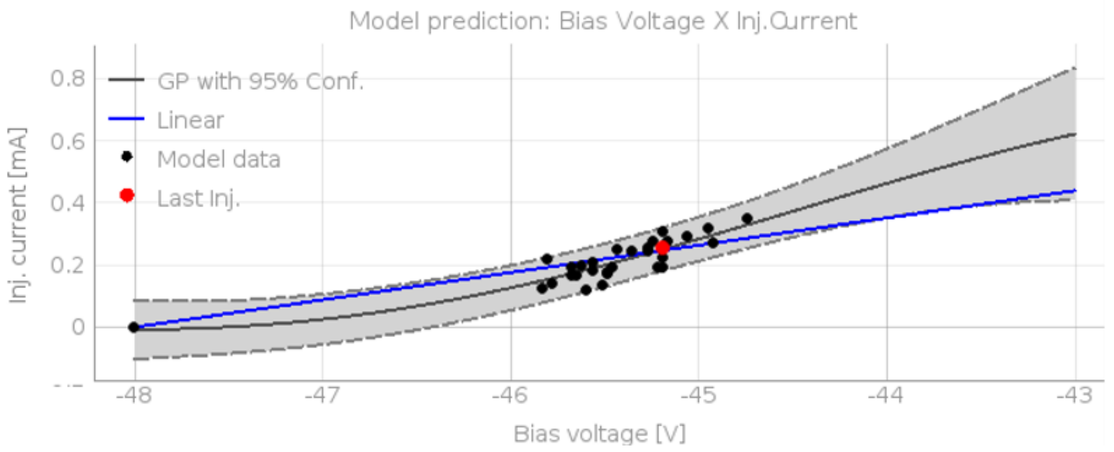
P. Kuske and F. Kramer, "Transverse Emittance Exchange for Improved Injection Efficiency", in Proc. IPAC'16, Busan, Korea, May 2016, pp. 2028–2031. doi:10.18429/JACoW-IPAC2016-WEOAA01

Current and Future Operation

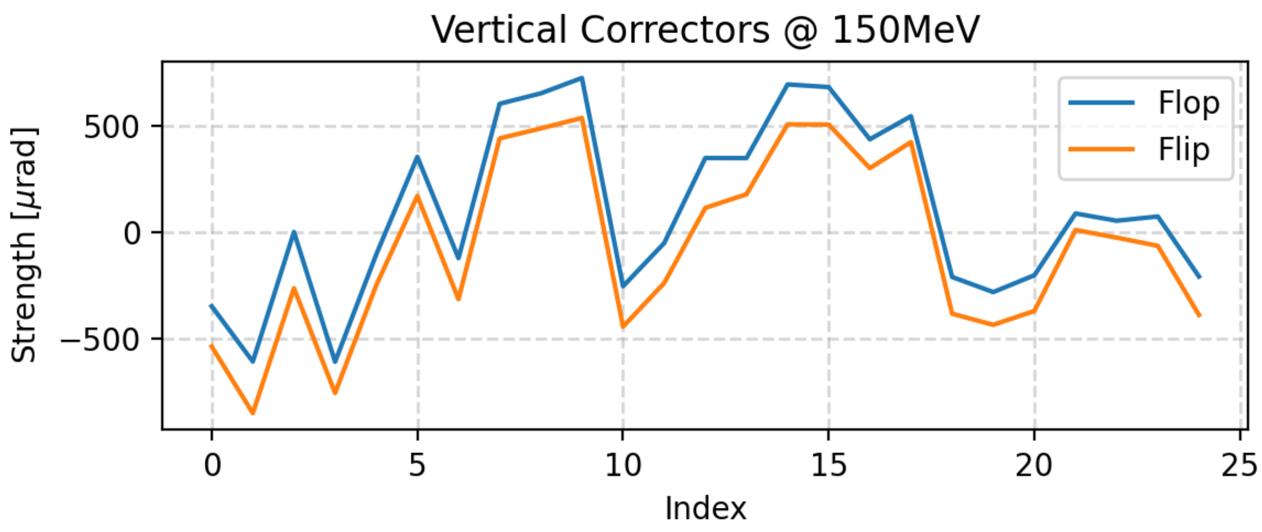
Current Operation in Top-up Mode



- Current operation performance:
  - Top-up mode: single-shot every 3 min;
  - Average injected current per pulse: 0.220 mA;
  - Control of injected current with Egun bias voltage.

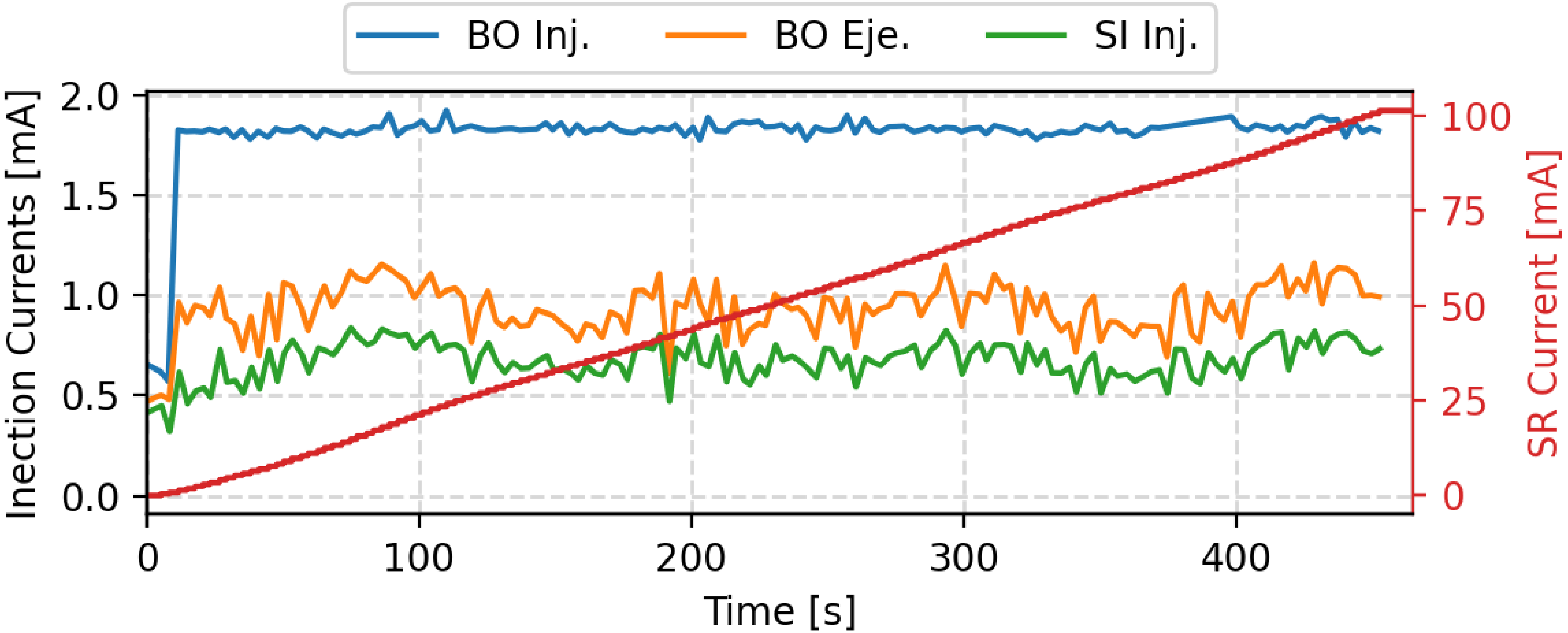


- Ocasionally BO vert. orbit changes between 2 states (flip-flop):
  - Correction signature imply field distributed along the ring;
  - Generally happens after machine maintenances;



Future Requirements for Operation

- In August 2024 SC RF cavities will be installed in the SR:
  - Stored current will probably increase to 200mA;
  - Lifetime is expected to be about half of present value;
  - Same injection scheme -> ~0.9mA per pulse;
- Multi-bunch needs optimization at high currents:
  - Linac was specified so that BO would ramp 1.7mA;
  - Today, maximum current delivered is ~1.1mA;
- Single-bunch injection:
  - Important to provide top-up operation with arbitrary fillings;
  - Not ready for operation. Very low efficiency (<10%);
  - Optimization also required for LINAC;



Summary

- A low-cost small emittance booster was designed:
  - Symmetric lattice and small number of magnet families and PSs;
  - Simple scheme for tune and chromaticity correction;
  - The number of corrector magnets was too small;
  - Small momentum compaction is an issue.
- In 2019 the booster commissioning was intervealed with the SR installation:
  - Intermitent scheduling. Main objective was to start SR commissioning ASAP;
  - Difficulty to perform detailed characterizations;
- From 2020 to last year a large effort was applied to the SR:
  - Increase of operation current, top-up;
  - Orbit stability, "transparent SR Injection", IDs installation and commissioning;
  - Little time dedicated to booster optimization;
- Booster performance meets current requirements;
- Work required to reach future operation demands:
  - Improvement of orbit correction;
  - Optimization of single-bunch mode;
  - Improvement of multi-bunch ramp efficiency at high currents;
  - Investigation of solutions to septa heating issues;

Thank you for your attention!

Thanks to Murilo Alves and all my colleagues that helped putting this presentation together.