Online Tuning of Storage Ring Nonlinear Dynamics

and Fast ORM Measurement at SIRIUS

Optics Tuning and Corrections for Future Colliders Workshop

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on behalf of the LNLS Accelerator Physics Group

Introduction

Online tuning of storage ring non-linear dynamics

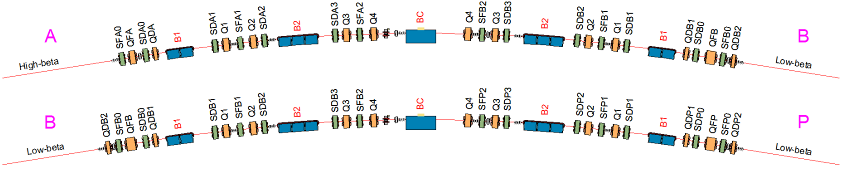
Fast ("AC") Measurement of Orbit Response Matrix

SIRIUS storage ring

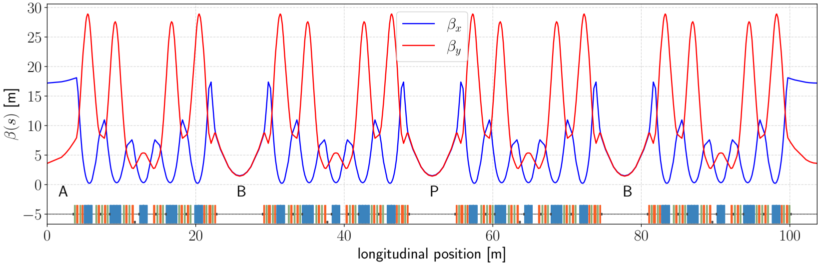
4th generation storage ring based synchrotron light source with 250 pm rad emittance. Designed, built and operated by the Brazilian Synchrotron Light Laboratory (LNLS), at the Brazilian Center for Research in Energy and Materials (CNPEM), Campinas, Brazil.

Parameter		Currently	Phase I
Energy	E_0	$3\,\mathrm{GeV}$	
Current	I_0	$100\,\mathrm{mA}$	$350\,\mathrm{mA}$
Operation mode		Top-up	
Lifetime	τ	$15\,\mathrm{h}$	$> 10\,\mathrm{h}$
RF Cavities		1 NC	2 SC + HC
RF Voltage	$\hat{V}_{\mathrm{rf}}$	$1.5\,\mathrm{MV}$	$3.0\,\mathrm{MV}$
RF Frequency	f_{rf}	$499.667\,\mathrm{MHz}$	
Harmonic Number	h	864	
Momentum compaction factor	α	1.6×10^{-4}	
Energy Spread	σ_δ	8.5×10^{-4}	
Bunch length	σ_z	$2.5\,\mathrm{mm}$	$12\,\mathrm{mm}$
Energy loss p/ turn	U_0	$470\,\mathrm{keV}$	$870\,\mathrm{keV}$

20×5BA lattice, with 5-fold symmetric high (A) and low (B, P) betatron functions sections: 1 Superperiod = A-B-P-B



Sirius v21



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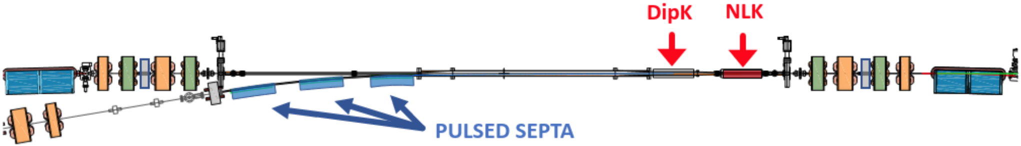
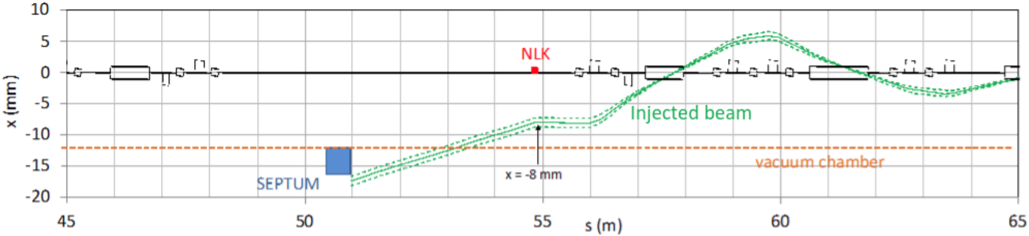
Off-axis injection scheme





100% efficiency with $x = -9$ mm DA

88% efficiency observed

RCDS Dynamic Aperture Optimization Setup

Robust conjugate direction search (RCDS) for DA optimization:

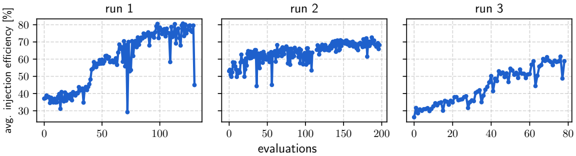
- objective function:
  - avg. injection efficiency of 5 pulses @ 2 Hz ($\sigma \approx 1\%$)
  - beam steered to the DA border to reduce efficiency
  - kick resilience optimization $\not\Rightarrow$ injection efficiency optimization
- available knobs: 21 sextupole families
  - chromaticity response matrix nullspace singular-vectors (13, 17 knobs)
  - 13 free families + 6 compensation families
- Tuning in 3 machine working points: higher fractional tunes to reduce amplification factors and improve orbit stability

More details:
M. M. S. Velloso, M. B. Alves, L. Liu, X. R. Resende, F. H. de Sá, and X. Huang, in *Proc. IPAC'23* Venezia, 05 2023, pp. 3222-3226. WEPL087 paper
About RCDS:
X. Huang, J. Corbett, J. Safranek, J. Wu, *Nucl. Instr. Meth.*, vol 726, pp.77-83, 2013.
X. Huang, J. Safranek, *Phys. Rev. ST Accel. Beams*, vol 18, p.18
Implementations:
- `https://github.com/SPEAR3-ML/RCDS.git`
- apsuite/optimization/rcds.py

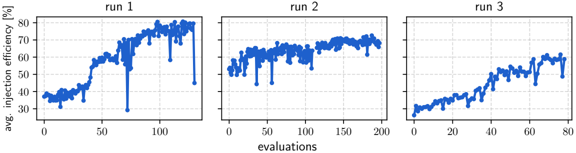
SIRIUS sextupole families

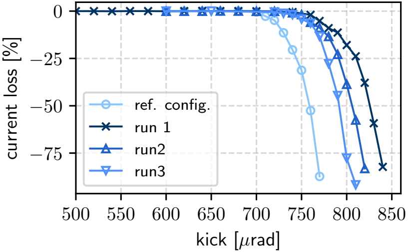
achromatic	SFA0, SDA0, SFB0, SDB0, SDP0, SFP0
chromatic	SDA1, SFA1, SDA2, SFA2, SDA3, SDB1, SFB1, SDB2, SFB2, SDB3, SFP1, SDP1, SDP2, SFP2 SDP3

Tuning at $\nu_x = 49.08, \nu_y = 14.14$ (Working Point 1)

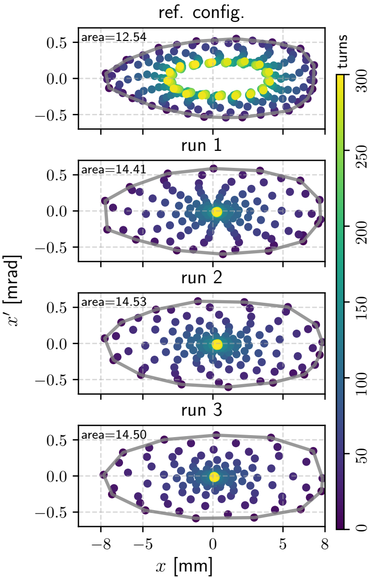


Tuning at $\nu_x = 49.08, \nu_y = 14.14$ (Working Point 1)

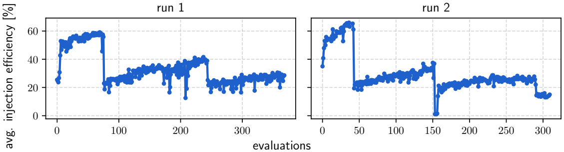




configuration	injection efficiency [%]	lifetime @ 60 mA
ref-config	88 ± 8	21 hrs
run 1	91 ± 1	
run 2	98 ± 1	20 hrs
run 3	87 ± 3	



Tuning at $\nu_x = 49.20, \nu_y = 14.25$ (Working Point 2)



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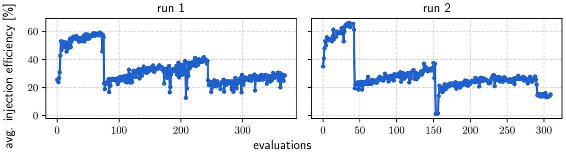
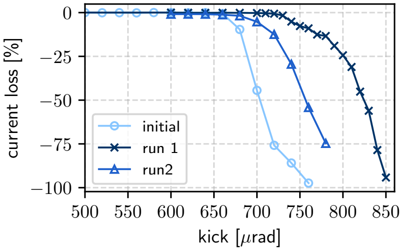
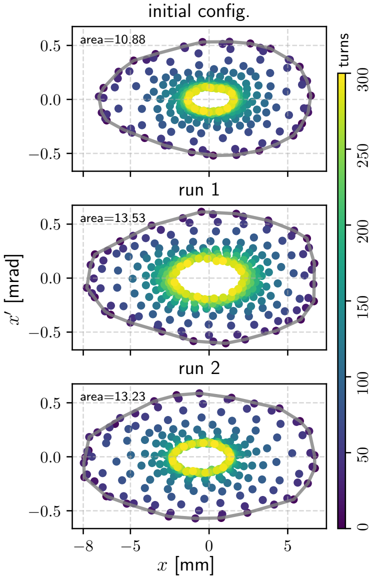
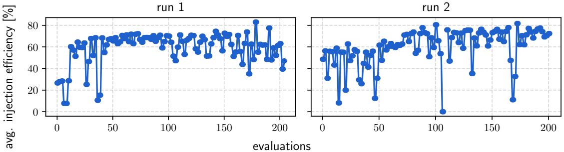




configuration	injection efficiency [%]	lifetime @ 60 mA
non-optimized	51 ± 1	18 hrs
run 1	79 ± 3	21 hrs
run 2	65 ± 1	



Tuning at $\nu_x = 49.16, \nu_y = 14.22$ (Working Point 3)



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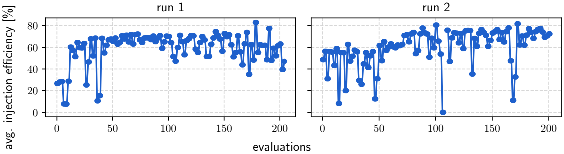
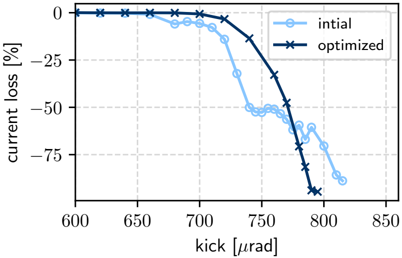
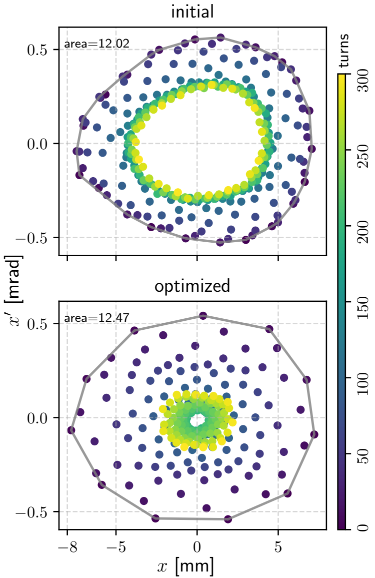


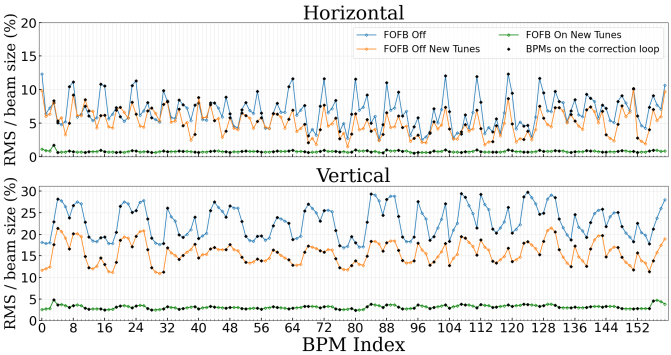




configuration	injection efficiency [%]	lifetime @ 60 mA
non-optimized		
optimized	93 ± 3	19.5 hrs

Orbit stability improvements

WP 3 contributed for SIRIUS recent achievement of reaching $< 1\%\ \sigma_x$ and $< 4\%\ \sigma_y$ orbit rms variations in the horizontal and vertical planes, respectively.



L. Liu *et al.*, "Status of SIRIUS operation with users", presented at the IPAC'23, Venice, Italy, May 2023, paper WEOGA2.

Courtesy of Daniel Tavares

Summary

- Online tuning with RCDS was effective at optimizing injection efficiency
- Optimizing injection efficiency $\not\Rightarrow$ larger kick resiliency/larger phase portrait areas

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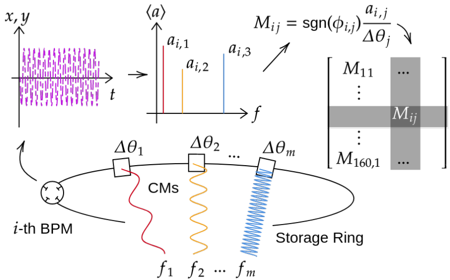
AC ORM Measurement



M.M.S. Velloso, M.B. Alves, and F.H. de Sá, "Fast Orbit Response Matrix Measurement via Sine-Wave Excitation of Correctors at SIRIUS", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 425–428.

- Fitting to i-th BPM data $u_i(t_j)$:

$$\begin{bmatrix} \cos(2\pi f_1 t_1) & \sin(2\pi f_1 t_1) & \dots \\ \cos(2\pi f_1 t_2) & \sin(2\pi f_1 t_2) & \dots \\ \vdots & \vdots & \\ \cos(2\pi f_1 t_n) & \sin(2\pi f_1 t_n) & \dots \end{bmatrix} \begin{bmatrix} b_{i1} \\ c_{i1} \\ \vdots \\ b_{im} \\ c_{im} \end{bmatrix} = \begin{bmatrix} u_i(t_1) \\ u_i(t_2) \\ \vdots \\ u_i(t_n) \end{bmatrix}$$

- Expected beam motion

$$\Delta u_i(t_n) = \sum_j a_{i,j} \sin(2\pi f_j t_n + \phi_{i,j})$$

$$a_{i,j} = \sqrt{b_{i,j}^2 + c_{i,j}^2}, \quad \phi_{i,j} = \mathrm{atan2}(b_{i,j}, c_{i,j}) \in (-\pi, \pi]$$

- ORM elements:

$$M_{ij} = \mathrm{sgn}(\phi_{i,j}) \frac{a_{i,j}}{\Delta\theta_j},$$

Measurements at SIRIUS storage ring

SIRIUS BPMs-CMs circuit

- 160 BPMs
- $n_x = 120$ CHs, $n_y = 160$ CVs, $n = n_x + n_y = 280$ CMs

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Measurement Procedure

- At each one of the **20 sectors**,
  - **6 CHs** $f_x = 3, 7, 13, 19, 29, 37$ Hz
  - **8 CVs** $f_y = 5, 11, 17, 23, 31, 41, 47, 59$ Hz
  - prime frequencies to easily distinguish nonlinear harmonics
  - 5 µrad strength, during 4 seconds.
  - integer number of oscillations, orthogonal harmonics

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- 30 mins for DC method
- $2.5 - 3$ mins AC method

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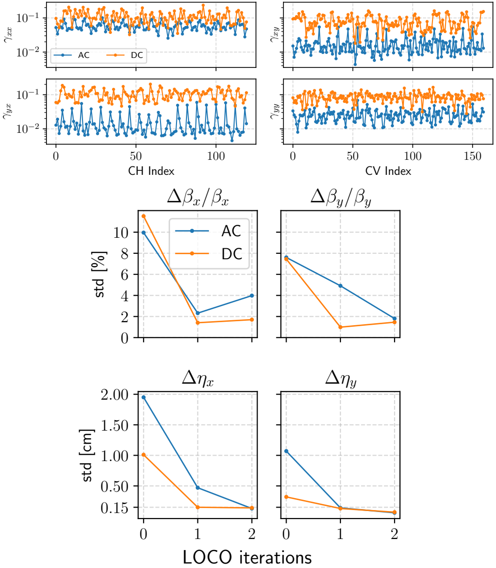

Thank you!

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FAPESP

LNLS Brazilian Synchrotron Light Laboratory sirius

CNPEM Brazilian Center for Research in Energy and Materials

MINISTRY OF SCIENCE TECHNOLOGY AND INNOVATION

BRAZILIAN GOVERNMENT BRASIL UNITING AND REBUILDING

Backup - AC ORM precision

$$\sigma_{ij}^2 = \frac{1}{N-1}\sum_{k=1}^{N}(M_{ij}^k - \langle M\rangle_{ij})^2, \quad \gamma_j = \sqrt{\left\langle \sigma_{ij}^2 \right\rangle_i}$$

Backup - NLK field profile