Longitudinal injection into low-emittance ring: A novel scheme for SOLEIL upgrade

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I. Introduction
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I. Introduction

Low-$\varepsilon$ lattice investigation is under way @ SOLEIL, with a new step of increasing the symmetry (one type of straight section). 2 kinds of lattices are under study:

- $\varepsilon_x > 100$ pm.rad with a large dynamic aperture (off-axis injection)
- $\varepsilon_x < 100$ pm.rad with small dynamic aperture (on-axis injection).

This talk deals with the latter case.

**On-axis injection**

This presentation aims to propose an alternative solution to On-axis injection, other than:

- the swap out method.
- the use of a very fast transverse kicker.

**Longitudinal injection**

It starts with the longitudinal injection scheme developed by the SLS group.
II. Longitudinal injection: recall of SLS scheme

- applied to MAX IV

A transparent injection is presented where the injected beam is longitudinally separate from the stored beam by $\Delta \varphi = -\pi$.

The longitudinal acceptance phase-space looks like a “golf club” and allows a specific off-momentum beam to be naturally trapped and merged into the circulating beam.
II. Longitudinal injection: recall of SLS scheme

- applied to MAX IV

100 MHz RF system: bunch spacing = 2 x 5 ns

As a first step, short pulse kickers place the injected beam on-(chromatic) axis

M. Aïba et al., PRST AB 18, 020701 (2015)
II. Longitudinal injection: recall of SLS scheme

- applied to SOLEIL Upgrade:

SOLEIL synchrotron
- Linac injector: 100 MeV
- Booster: 157 m outside SR tunnel
- Storage Ring: 354 m, 2.75 GeV
- RF system: cryogenic, 352.2 MHz
II. Longitudinal injection: recall of SLS scheme

- Applied to SOLEIL Upgrade:

  Example of prospect lattice with very low H. emittance.

\[ \varepsilon_x = 45 \text{ pm.rad} \]

SOLEIL synchrotron
- Linac injector: 100 MeV
- Booster: 157 m outside SR tunnel
- Storage Ring: 354 m, 2.75 GeV
- RF system: cryogenic, 352.2 MHz

- 16 periods, 354 m, 2.75 GeV
- Working point = (73.43, 42.11)
- \((\beta_x, \beta_z)_{sp} = (2.5, 2.8) \text{ m with straight = 5.655 m}\)
- Max \(K1 = 10 \text{ [m}^{-2}] \Rightarrow 92 \text{ T/m @2.75 GeV}\)
- Combine sextupole into quad and bends
- Bends: (0.65 T, 49 T/m, 7183 T/m²) @2.75 GeV

Hung Chun Chao, IPAC 2017
II. Longitudinal injection: recall of SLS scheme

- applied to SOLEIL Upgrade

Motion in the longitudinal phase space (Accelerator Toolbox tracking)

Taking into account radiation and damping.
II. Longitudinal injection: recall of SLS scheme

- applied to SOLEIL Upgrade

*Motion in the longitudinal phase space (Accelerator Toolbox tracking)*

In the case of SOLEIL, rise/fall time requirement for the fast transverse kicker = 1.4 ns for a few mrad strength.

It is far beyond the today state of the art.

352 MHz RF system: bunch spacing = 2 x 1.4 ns
III. Longitudinal injection: new scheme

Instead, we propose to use 2 kinds of “Non-Linear Kicker” (NLK):

- A **Transverse Non-Linear Kicker** (or Multipole Injection Kicker MIK) with no constraint in duration, to place the injected beam on a chromatic orbit and then perform an on- (chromatic) axis injection. It assumes:
  - The injected beam is off-momentum ($\delta_{\text{inj}}$)
  - It exists a H. dispersion bump in the lattice
    - This bump may be especially created @ MIK position → breaks the symmetry of the ring → the lower bump the better
    - Or use of the natural “low” dispersion

In both cases, **high** $\delta_{\text{inj}}$ is needed to get a reasonable chromatic orbit @ MIK (*chromatic Closed Orbit > 4 mm*).

- A **Longitudinal Non-Linear Kicker** to improve the capture of this high momentum beam.

III. Longitudinal injection: new scheme

- Create a “longitudinal NLK”
  
  = Additional RF pulse that will:
  - Reduce the injected off-momentum deviation as quickly as possible and let enter the particles into the longitudinal bucket
  - Keep the stored beam unaffected, in terms of centroid position and bunch length.
III. Longitudinal injection: new scheme

Create a “longitudinal NLK”

= Additional RF pulse that will:
  - Reduce the injected off-momentum deviation as quickly as possible and let enter the particles into the longitudinal bucket
  - Keep the stored beam unaffected, in terms of centroid position and bunch length.

Main 352 MHz RF pulse

\[ V_{\text{main}} = 1 \, \text{MV} \]
\[ U_0 = 360 \, \text{keV/turn} \]
III. Longitudinal injection: new scheme

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- Main 352 MHz RF pulse
  \[ V_{\text{main}} = 1 \text{ MV} \]
  \[ U_0 = 360 \text{ keV/turn} \]

- Additional 352 MHz pulse
  Shifted by \( \phi_s \)
  \[ V_{\text{add}} \sim 1 \text{ MV} \]

- Correction by 3rd harmonic
  \[ V_{3\text{rd}} = V_{\text{add}} / 3 \]
III. Longitudinal injection: new scheme

- Create a “longitudinal NLK”

  - Additional RF pulse that will:
    - Reduce the injected off-momentum deviation as quickly as possible and let enter the particles into the longitudinal bucket
    - Keep the stored beam unaffected, in terms of centroid position and bunch length.

- Stored beam doesn’t see any change

- Off-phase particles see an additional kick.

- Process must be stopped as soon as injected particles reach the synchronous phase
III. Longitudinal injection: new scheme

- Create a “longitudinal NLK”
  - Additional RF pulse that will:
    - Reduce the injected off-momentum deviation as quickly as possible and let enter the particles into the longitudinal bucket
    - Keep the stored beam unaffected, in terms of centroid position and bunch length.

In practice, stored beam will be lengthened with the 3\textsuperscript{rd} harmonic, which suggests that 3 HC already exists and can be also used for NLK scheme.

Main RF pulse
III. Longitudinal injection: new scheme

- Create a “longitudinal NLK”

  - Additional RF pulse that will:
    - Reduce the injected off-momentum deviation as quickly as possible and let enter the particles into the longitudinal bucket
    - Keep the stored beam unaffected, in terms of centroid position and bunch length.

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New total RF pulse
III. Longitudinal injection: new scheme

- Effect of the “longitudinal NLK”
  - Standard $V_{RF}$

![Graph showing the effect of standard $V_{RF}$ on a particle with zero betatron amplitude]
III. Longitudinal injection: new scheme

- Effect of the “longitudinal NLK”
  - Switch on $V_{RF \text{ add}} = 1 \text{ MV}$,
  - Switch off when particle passes $\varphi_s$

![Graph showing particle behavior with zero betatron amplitude](image.png)
III. Longitudinal injection: new scheme

- **Effect of the “longitudinal NLK”**

  Simulate realistic injected beam from Booster:

  Considering a basic MBA lattice for Booster with $\varepsilon_x = \varepsilon_z = 10 \text{ nm.rad}$, $\sigma_s = 35 \text{ ps}$

  - Switch on $V_{RF \text{ add}} = 1 \text{ MV}$,
  - Switch off when “mean phase” $= \varphi_s$

Injected beam with adapted $\beta$ functions
III. Longitudinal injection: new scheme

- Effect of the “longitudinal NLK”

Simulate realistic injected beam from Booster:

Considering a basic MBA lattice for Booster with $\varepsilon_x = \varepsilon_z = 10 \text{ nm.rad}$, $\sigma_s = 35 \text{ ps}$

- Considering the stored beam lengthening with the 3rd HC.

![Plot every 50 turns](Image)
III. Longitudinal injection: new scheme

- **Modeling realistic rise and fall time of the additional RF pulses**

  Switch on / off takes into account the loaded quality factor $Q_L$ of cavities:
  
  \[ \tau_L = \frac{2 Q_L}{2 \pi f_{RF}} \]

  One must consider:

  - How to get similar $\tau_L$ for 3rd HC compared to main RF
  - The phase control of main RF during voltage change

SOLEIL Upgrade, same cryogenic 352 MHz cavities as now

$Q_L < 10^5$, $\tau_L < 100 \mu s \sim 80$ turns
III. Longitudinal injection: new scheme

- Modeling realistic rise and fall time of the additional RF pulses

\[ V_{\text{add}} \]

\[ \text{time} \]

\[ \delta \% \]

\[ \text{Plot every 50 turns} \]

\[ \text{Phase / II} \]

\[ R_{\text{injection}} = 83\% \]

→ No significant impact on the injection efficiency
III. Longitudinal injection: new scheme

- Performance of the scheme:
  1) Dependency on injected beam bunch length:
  The shorter bunch length, the smaller the oscillation amplitude in $\delta$ during injection process.

![Graphs showing oscillation amplitude with different bunch lengths](image)

$\sigma_s = 35 \text{ ps}$

$\sigma_s = 5 \text{ ps}$

Same injection rate, but dissymmetry in momentum oscillation becomes larger when bunch length decreases.

$\varepsilon_{x \text{ inj}} = \varepsilon_{z \text{ inj}} = 10 \text{ nm.rad}$
III. Longitudinal injection: new scheme

- **Performance of the scheme:**
  2) **Dependency on injected beam emittances:**
     - Limitation comes from transverse acceptance at high momentum.

\[
\begin{align*}
\varepsilon_{x\,\text{inj}} &= \varepsilon_{z\,\text{inj}} = 10 \text{ nm.rad} \\
\varepsilon_{x\,\text{inj}} &= \varepsilon_{z\,\text{inj}} = 1 \text{ nm.rad}
\end{align*}
\]

= same behaviour in longitudinal plane

But losses at high momentum disappear.

\[\sigma_s = 5 \text{ ps}\]
IV. Longitudinal injection: challenges

- Increase dynamic aperture for large positive energy deviation.

New lattice optimized in terms of off-momentum transverse dynamic acceptance → confirms origin of losses at high momentum.

*TRACY III code (10³ turns)*

![Graph showing lattice and optimized lattice with δ = +6%](image-url)
IV. Longitudinal injection: challenges

- Take advantage of the dissymmetric energy oscillation to relax constraints on the DA for negative momentum.
  → Investigations are foreseen, using MOGA with specific objectives.

\[
\varepsilon_{x \text{ inj}} = \varepsilon_{z \text{ inj}} = 10 \text{ nm.rad}, \sigma_s = 5 \text{ ps}
\]
VI. Summary

Starting from the longitudinal injection described by SLS group, a novel scheme is proposed for an on-axis injection.

- It does not involve any fast transverse kicker, but a MIK with no time constraint.
- It uses cavities already installed: main RF and its 3rd harmonic with manipulation of phase and power during injection process.
- It doesn’t affect the stored beam, in terms of phase and bunch length.
- It aims at enhancing capturing of off-momentum particles by kicking them into the longitudinal bucket.
VI. Summary

Challenges:

- In SOLEIL case, adapt the present ‘high emittance’ Booster in order to reduce injected emittance and pulse length.

- Optimize the off-momentum dynamic aperture of the low-emittance lattice for (only) high positive momentum. Use of MOGA for this dissymmetric optimization.

- Ensure the appropriate horizontal dispersion @ MIK position to get the ‘few mm’ chromatic orbit, without reducing off-momentum DA.

- RF issues
Acknowledgments

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Thank you for your attention !
Backup slide

$\varepsilon_x = 45 \, \text{pm rad}$

$\varepsilon_x = 39 \, \text{pm rad}$

OPA code