PAUL SCHERRER INSTITUT

PSI

Volker Schlott, Paul Scherrer Institut

Diagnostics for LESR Injectors

IFAST Workshop on Injectors for Storage Ring based Light Sources

KIT, Karlsruhe, Germany, March 6th – 8th 2024

PAUL SCHERRER INSTITUT

Overview

- **Introduction**
- **Injector Diagnostics Requirements**
- **Diagnostics Systems**

  … Overview

  … Beam Position Monitors

  … Profile Monitors – Screens and Synchrotron Light

  … Loss Monitors

  … Current, Charge and Bunch Pattern Monitors
- **Conclusions**

Acknowledgements 😀 😘 😀

This presentation is based on discussions and information material provided by many dear colleagues!

Special thanks go to…:

… Cigdem Ozkan-Loch

… Jonas Kallestrup

… Boris Keil

… and PSI mechanical engineering for CAD drawings

Some General Remarks on LESR Injectors

Typical storage ring based light source injectors consist of…

→ **a low energy** (up to some hundred MeV) **LINAC**

→ **a LINAC to booster transfer line (LBTL)**

→ **a** (full energy) **booster synchrotron**

→ **a booster to storage ring transfer line (BRTL)**

SRLS injectors are typically operated at a few Hz for…

→ **storage ring filling**
(as fast as possible from scratch up to full current)

→ **"top up" operation**
(frequent filling to keep the current dead band of a few mA → ~ 10 shots every 5 minutes)

PAUL SCHERRER INSTITUT

Requirements for SRLS Injector Diagnostics

LINAC and Transfer Lines

→ **single-shot** and **shot-to-shot** measurements of **single bunches** and **bunch trains**

→ provide input for **beam dynamics applications** to set-up and optimize LINAC
(e.g. cathode and gun characterization, emittance and energy spread measurements)

→ **monitoring** of transmission, energy stability and injection points / angles

→ **allow** for **beam-based feedbacks** to compensate drifts and minimize losses

Booster Synchrotron

→ **measurement** of **orbit** along the ramp to **allow** for **orbit correction**

→ provide **tune** information along the ramp
(tune kicker and turn-by-turn BPM mode or multi-bunch feedback system)

→ measurement and monitoring of **losses** and **transmission**

Overview of SRLS Injector Diagnostics Systems

LINAC and Transfer Lines (LBTL and BRTL)

Parameters	Devices	Measurement Mode(s)
Bunch Pattern	- coaxial Faraday cup - wall current monitor - fast current transformer - broadband pick-up	- single bunches and bunch trains at a few Hz - tens of ps to a few μs resolution - read-out of waveforms by (ultra) fast digitizers and/or oscilloscopes
Bunch Charge **Beam Current** **Transmission**	- ICT and BCM - BPM sum signal	- single bunches and bunch trains at a few Hz - absolute and relative charge measurement
Beam Position	- (resonant) stripline and button type BPMs	- single-shot at a few Hz for single bunches - average position for bunch trains
Transverse Profile	- screen monitors - synchrotron radiation monitors	- single shot image acquisition at a few Hz - tens of mm AoI for beam finding / threading - few tens of μm to a few μm spatial resolution for ε-measurement in LINAC and BRTL
Beam Loss	- scintillators & PMs - Cerenkov fibers & PMs	- beam loss detection and monitoring at selected locations - monitoring of beam loss pattern along transfer lines and injection areas

Overview of SRLS Injector Diagnostics Systems

Booster Synchrotron

Parameters	Devices	Measurement Mode(s)
Beam Current **Transmission**	- NPCT (MPCT) - BPM sum signal	- sub-ms absolute beam current measurement along the ramp - relative current measurement (e.g. turn-by-turn)
Beam Position	- button type pick ups	- turn-by-turn beam position for commissioning - averaged beam positions along the ramp (lower BW / higher resolution "ramp modes") - BPM readings can be used for orbit correction
Tune	- dedicated tune pick up - tune (stripline kicker)	- tune measurements along the ramp
Transverse Profile	- screen monitors - synchrotron radiation monitors	- screens (2) at the injection for position and angle control (30 mm AoI, 100 µm resolution) - a few more screens and/or synchrotron radiation monitors for observing beam profiles (in case of trouble shooting)
Beam Loss	- scintillator BLMs - longitudinal LMs	- beam loss detection and monitoring at selected locations - monitoring of beam loss pattern at injection areas

BPMs – LESR LINAC and Transfer Lines

Requirements, Boundary Conditions and Evaluation

→ **single-shot** and **shot-to-shot** measurements of **single bunches** and **bunch trains**

→ **spatial resolution requirements** are **moderate** (~ 100 µm) in LINAC and LBTL but **much more challenging** (~ 10 µm for low charges (≤ 150 pC) during top -up) in BRTL

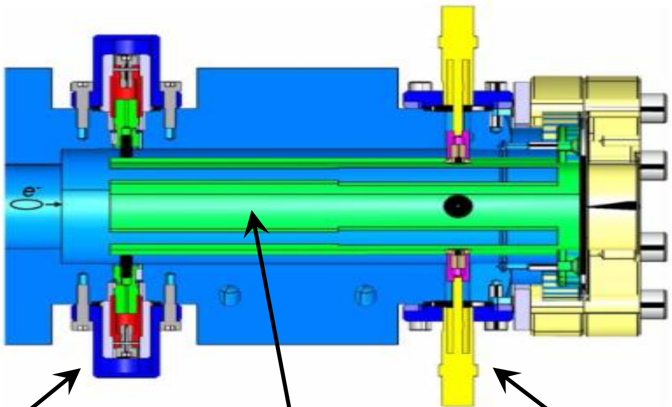
→ if possible, make use of the **same BPM electronics** in the **injector** as for the **storage ring**

Options	Pros	Cons
Button-type	– make use of similar BPM pick-up HW from booster and storage ring	– low signal levels & limited resolution for single bunches in top-up mode
Cavity-type	– highest signal levels and potentially best resolution (especially for low charge single bunches in top-up mode)	– different type of BPM pick-up as in booster and storage ring – different type of BPM electronics – only limited (linear) meas. range
Matched Stripline	– high signal levels (up to 10 x button-type) – large measurement range – same BPM electronics in whole facility (but energy / signal level lost in input ringing filter)	– different type of BPM pick-up as in booster and storage ring
Resonant Stripline	– higher signal levels than MS (10+ x button-type) – large measurement range – same BPM electronics in whole facility (pick-up res. frequency matches input ringing filter)	– different type of BPM pick-up as in booster and storage ring

Transfer Line BPMs – Resonant Striplines *

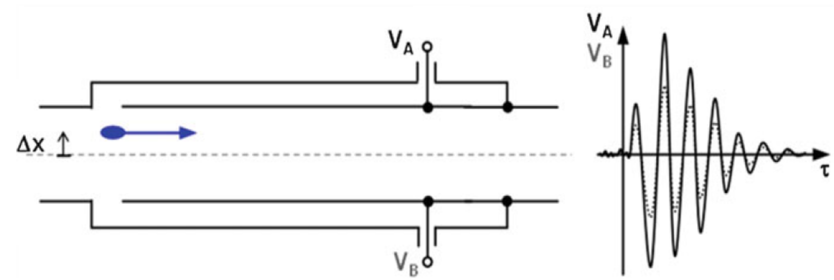
* A. Citterio et al., Proc. DIPAC'09, Basel, Switzerland, MOPD12, p. 71

Mechanical Design

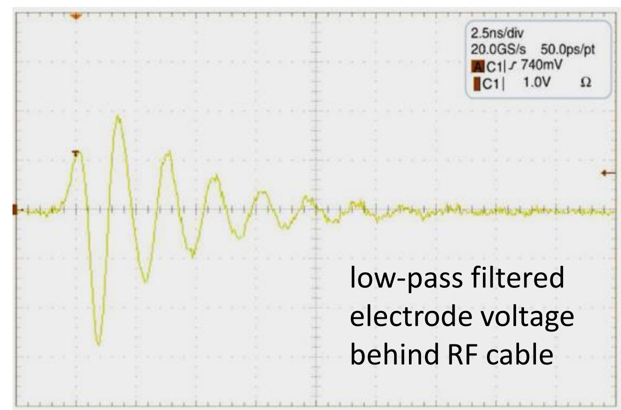


tuning pin   striplines   N-type feedthrough

Schematic and Signal Waveform (one plane)



500 MHz resonance



- **resonant frequencies** f_M and f_D **@ 500 MHz** (< 1 MHz BW)
- **loaded Q ≈ 7,** measured **sensitivity ≈ 1.5 dB/mm**
- **crosstalk** (for orthogonal dipole modes) ≈ **0.1%**
- **beam aperture 38 mm, stripline length** tuned to **138.4 mm**

For SLS 2.0 BRTL **single bunch / single shot position resolution** using the **turn-by-turn mode** of the ***"DBPM3"*** BPM electronics and the **500 MHz resonant striplines** is in the order of **10 µm RMS** for **typical top-up charges** of **150 pC**

PAUL SCHERRER INSTITUT

BPMs – LESR Booster Synchrotron

→ sufficient number of **button-type BPMs** to be placed in the booster synchrotron for **orbit** and **tune measurement** and **correction**

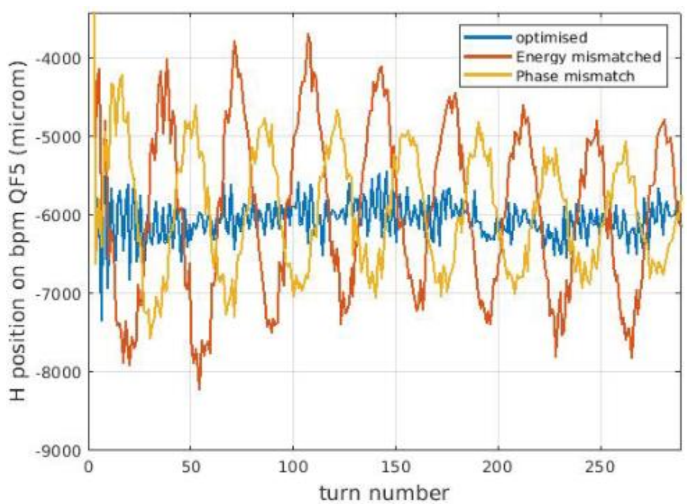
→ **booster BPM system** should provide **turn-by-turn** and **"ramped-mode"** position data for **injection studies** and **beam orbit measurements / corrections** along the ramp

→ **spatial resolution requirements** are **moderate**: **$\mathcal{O}$ (100 µm)** for "turn-by-turn" data and **$\mathcal{O}$ (10 µm)** for orbit measurements along the ramp (for top-up currents)

→ **BPM sum signals** can be used as a **"turn-by-turn" current / transmission monitor**

→ **tune measurement** is provided by a **stripline kicker** and a dedicated **"turn-by-turn" BPM**

<u>Some Examples</u> (from the upgraded ESRF EBS booster*)



* **M. Cargnelutti et al., Proc. IPAC'15, Richmond, VA, USA, MOAB3, p.24**
  N. Carmignani et al., Proc. IPAC'21, Campinas, SP, Brazil, MOPAB051, p. 221

<u>"turn-by-turn" BPM data for injection optimization</u>

→ synchrotron oscillations of the beam entering the booster for three different cases:

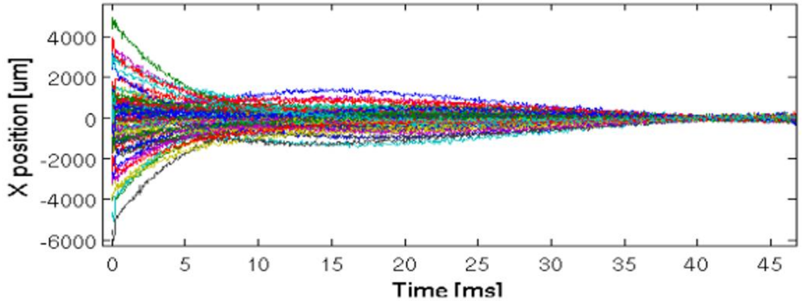
blue: optimized
yellow: phase mismatch
brown: energy mismatch

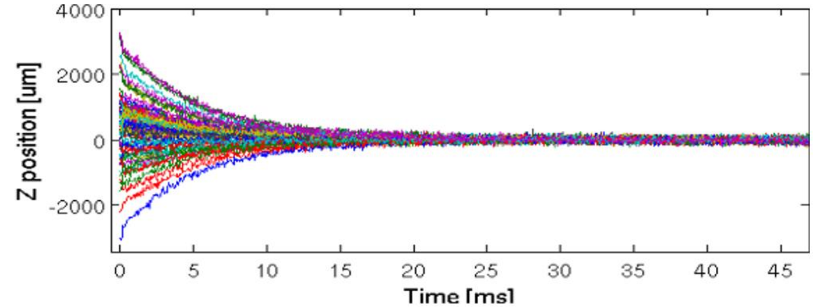
BPMs – LESR Booster Synchrotron

Some More Examples (from the upgraded ESRF EBS booster*)

beam position from all booster BPMs

(position offset of each BPM has been removed)

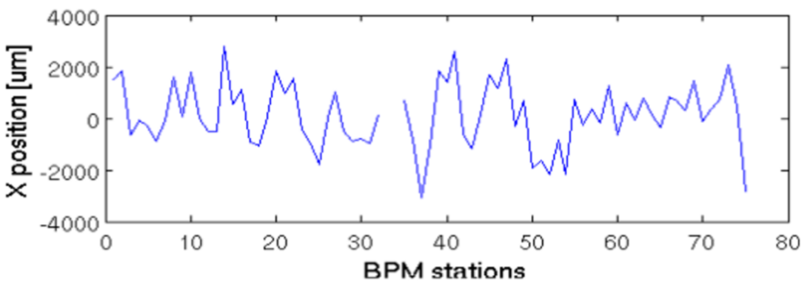


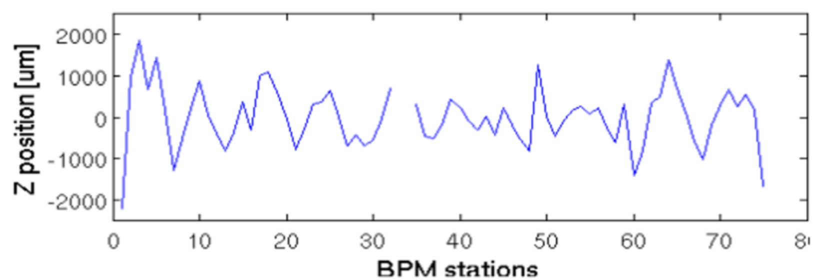


→ lower bandwidth (increased decimation) provides higher resolution (here x 64 for covering the booster ramp)

booster beam orbit measurement

(beam positions have been taken 20 ms after injection)



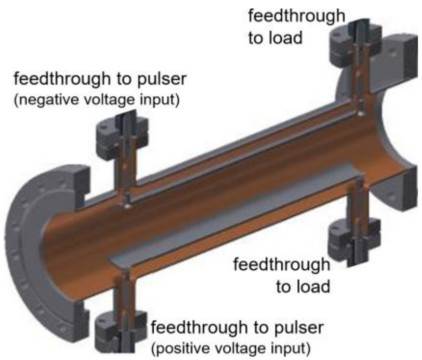


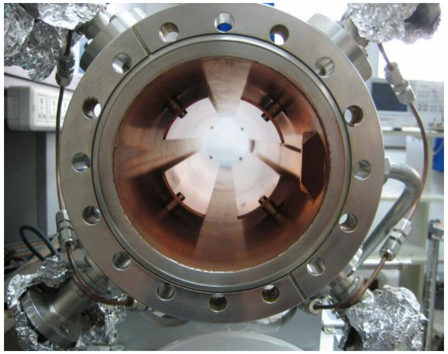
* M. Cargnelutti et al., Proc. IPAC'15, Richmond, VA, USA, MOAB3, p.24
N. Carmignani et al., Proc. IPAC'21, Campinas, SP, Brazil, MOPAB051, p. 221

LESR Booster Tune Measurement

Stripline Kicker *

schematic of SL kicker (one plane) and image (two planes)

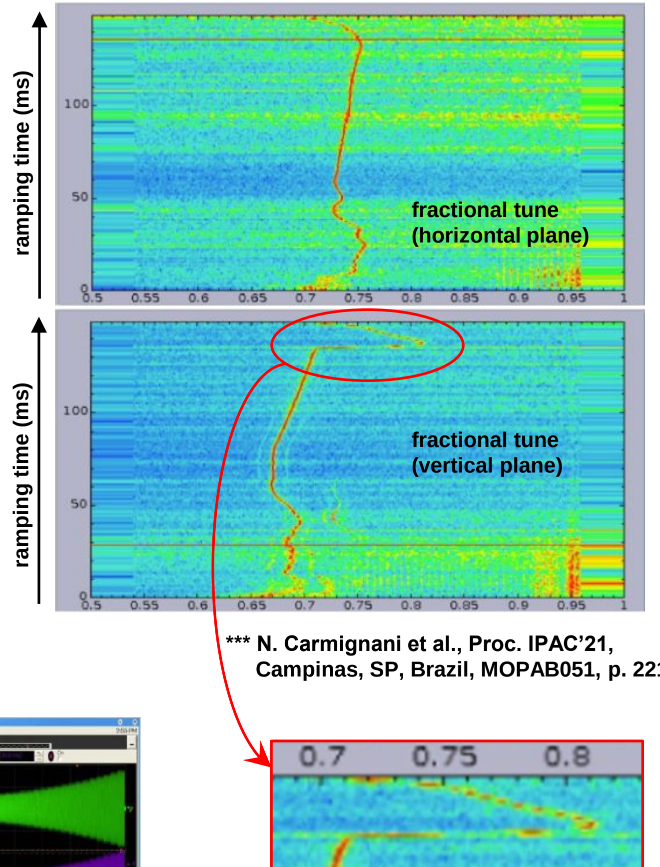




* From J. Byrd, Stripline Pickups and Kickers, USPAS June 2009

Measurement Example

from the upgraded ESRF EBS booster***



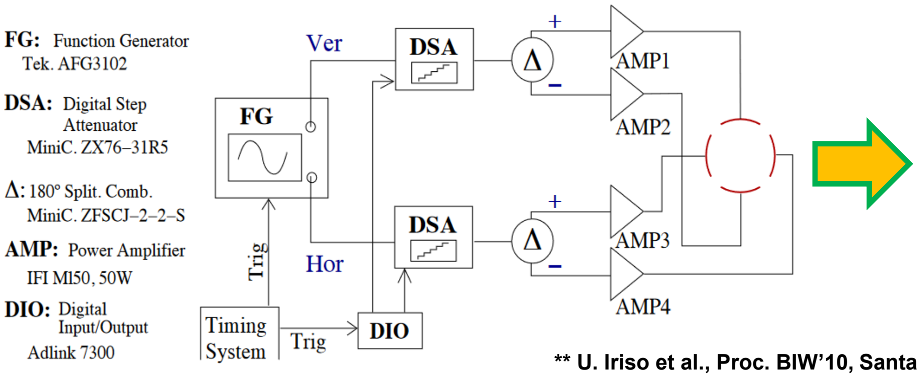
*** N. Carmignani et al., Proc. IPAC'21, Campinas, SP, Brazil, MOPAB051, p. 221

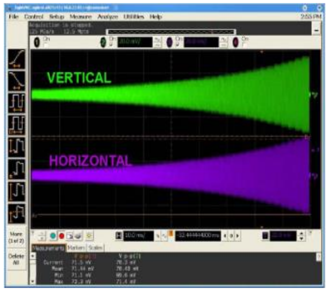
emittance exchange

vertical tune change by ≈ 0.1 within 0.7 ms at extraction time of ≈ 140 ms

Beam Excitation **

using white noise and increasing kick strength synchronized with beam energy on the ramp



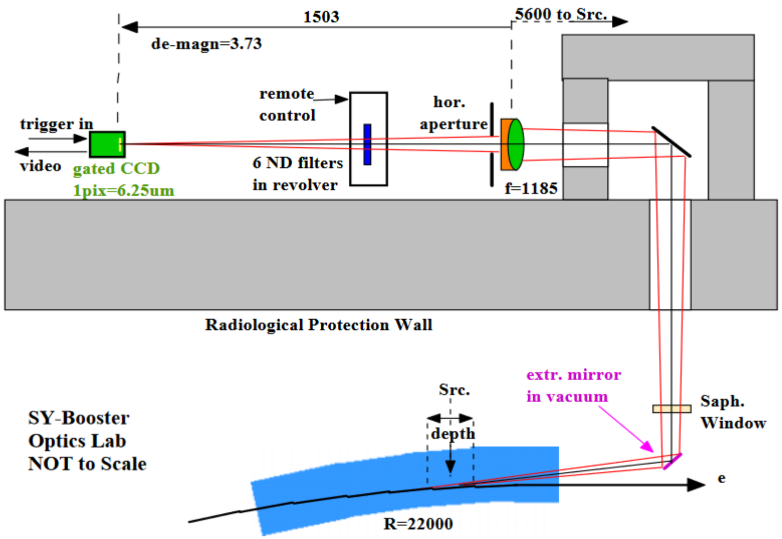


** U. Iriso et al., Proc. BIW'10, Santa Fe, NM, USA, TUPSM073, p. 350

LESR Booster – Beam Profile Measurements

Synchrotron Light Extraction

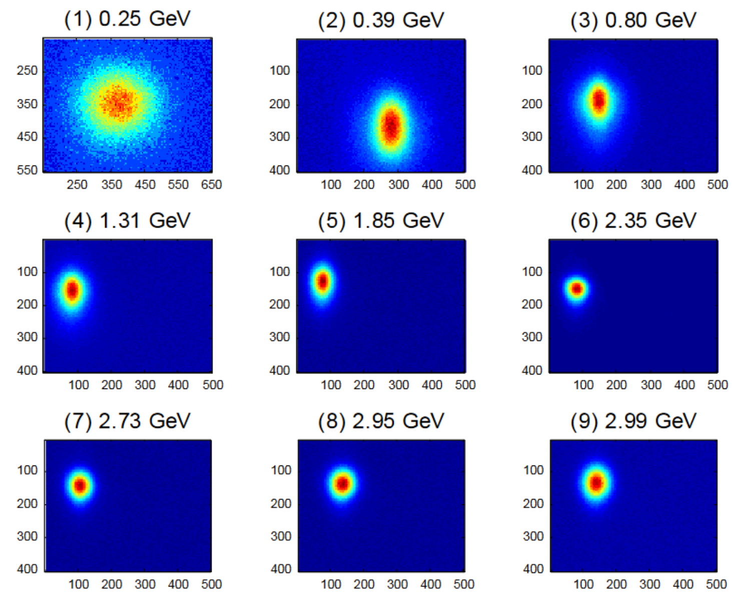
top view from the ESRF EBS booster *

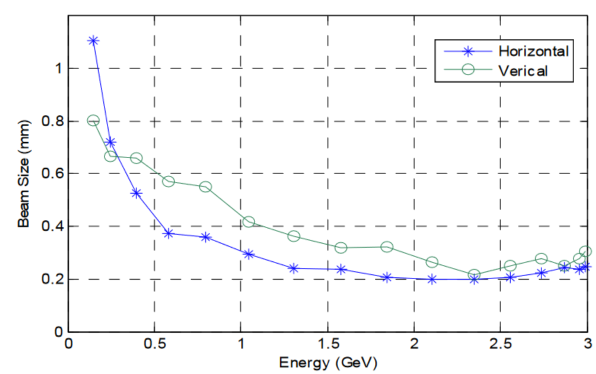


* B.K. Scheidt, Proc. DIPAC’05, Lyon, France, POM002, p. 24

Synchrotron Light Profiles

from TPS booster along the ramp (9 µm / pixel) **

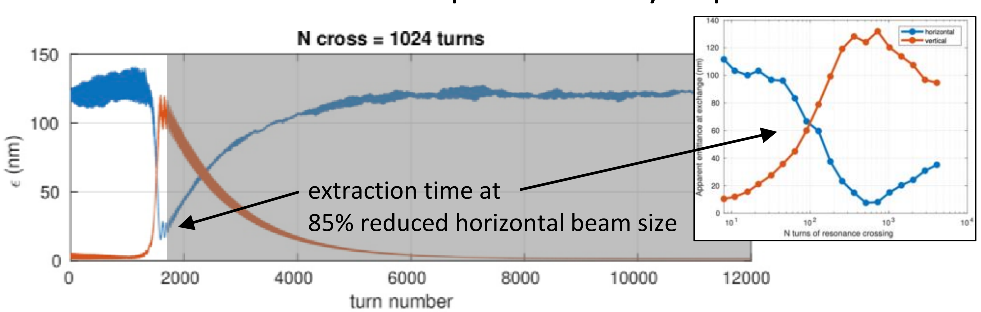




** P.C. Chiu et al., Proc. IBIC’15, Melbourne, Australia, MOBLA01, p. 1

Emittance Exchange

on the ESRF EBS booster ramp observed by SL profile monitor ***



*** N. Carmignani et al., Proc. IPAC’21, Campinas, SP, Brazil, MOPAB051, p. 221

LESR Transfer Lines – Screen Monitors

courtesy of Cigdem Ozkan-Loch

Screen Monitors for SLS 2.0 BRTL

a dispersion-free beam path has been integrated in the SLS 2.0 BRTL for ε measurement

	screen monitor for ε measurement	screen monitor for ΔE/E measurement	screen monitor as "beam finder"
minimum beam size	10 µm with ε_h = 2 nm	700 µm with ε = 12.5 nm energy dispersion = 0.085%	not defined
screen resolution	< 10 µm	10 µm to measure ΔE/E with 3% precision	10 µm
field of view	20 mm x 20 mm	20 mm x 20 mm	20 mm x 20 mm
charge sensitivity	< 10 pC (@ 2.7 GeV)	< 10 pC (@ 2.7 GeV)	< 10 pC (@ 2.7 GeV)

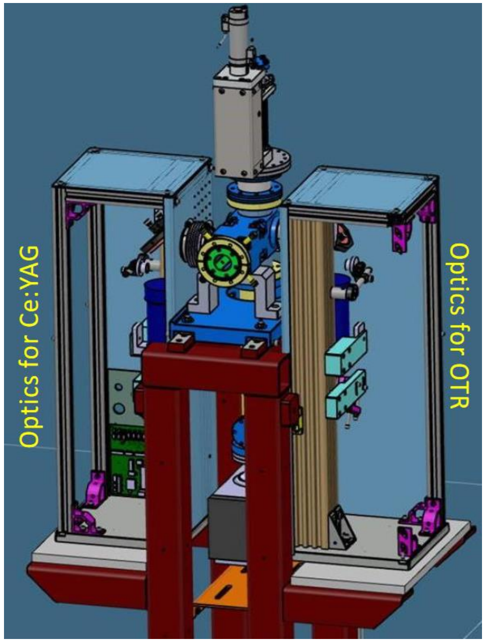
→ **Ce:YAG screens** as beam finder for low charge beams with limited spatial resolution

→ **OTR screens** for high resolution / precision measurements (ε and ΔE/E)

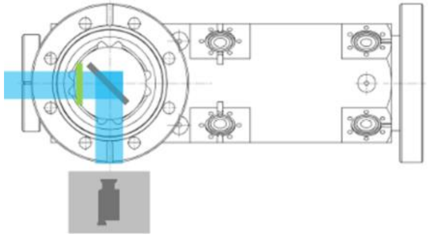
→ **separate optics boxes** at ε and ΔE/E measurement station for high resolution and high sensitivity

→ **camera** mounted **in Scheimpflug geometry** to correct for focal plane of OTR screen (@ 45° to beam and camera)

Optics Set-up for "BRTL ε-Screen"

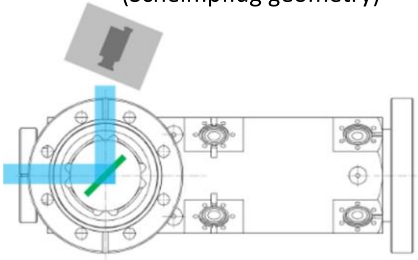


Light Out-coupling for Ce:YAG

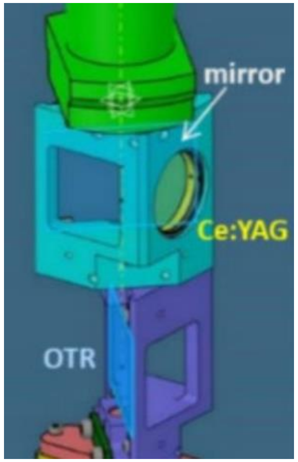


Light Out-coupling for OTR

(Scheimpflug geometry)



Screen Holder with Ce:YAG and OTR

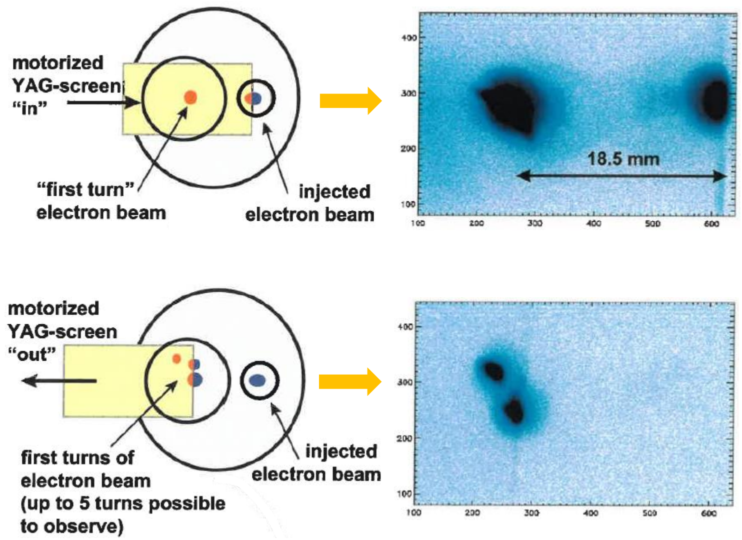


LESR Screens for Injection and 1^{st} Turn(s)

- screens are not popular nor widely used **in storage rings** (impedance, heat load…)
- first turn(s) **during commissioning can be considered as** transfer line diagnostics
  - → one screen directly behind injection septum can be helpful for observing beam position (relative to septum), beam matching and injection point
  - → a second screen in injection straight to adjust the kick / injection angle

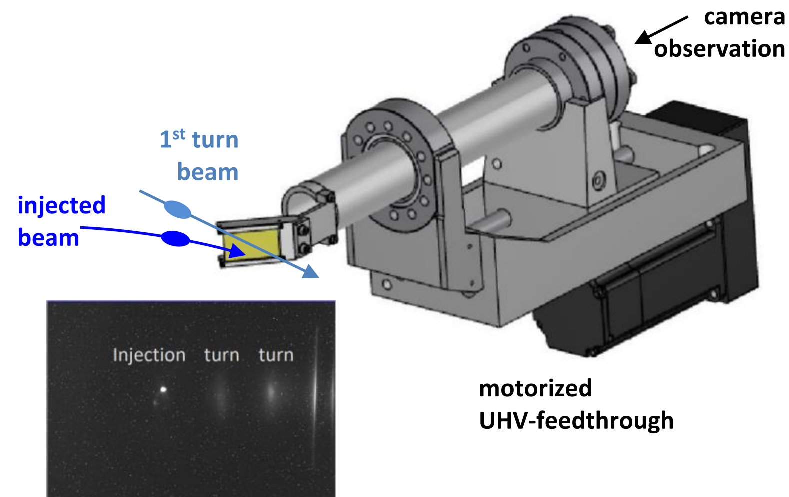
First Turns in SLS Booster

images taken during booster commissioning in 2000



SLS Storage Ring Injection

screen monitor to observe injection and 1^{st} turn(s)

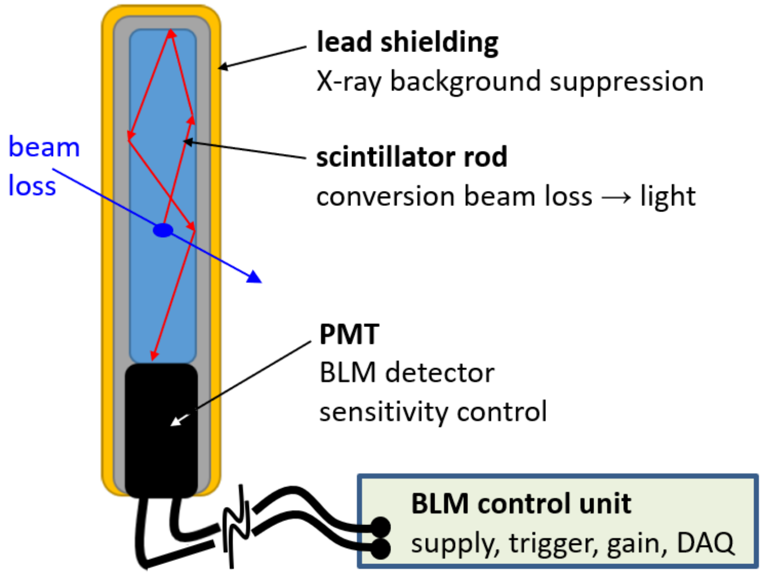


courtesy of Cigdem Ozkan-Loch

screen(s) can be helpful for “trouble shooting” but turn-by-turn BPMs are the working horses…!!!

Localized Loss Monitors – Scintillators and PMT

courtesy of E. Buratin, Kees Scheidt (ESRF-EBS) and L. Torino (ALBA)



BLM sensitivity & calibration

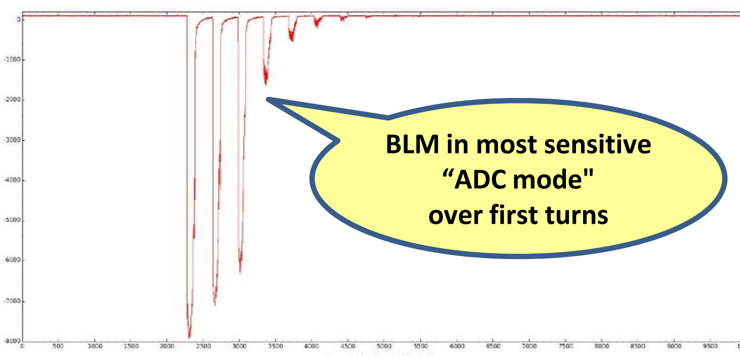
PMT: blue light

gain: PMT voltage

DAQ: ADC calibration

system: Ce137 source in-situ

Commissioning: First Turn(s)



BLM operation modes

fast ADC and sufficient buffer provides
turn-by-turn (even bunch-by-bunch) options

integration mode provides loss pattern along accelerator and allows "sanity-check" in reference to pre-defined loss rates

(e.g. "BLM drift control" in injector and transfer lines can be helpful for stable and reliable "top-up" operation)

LESR Injector Diagnostics – Loss Monitors

Longitudinal Loss Monitors – Cerenkov Fibers and PMT

courtesy of C. Ozkan-Loch (PSI)

→ similar to undulator lines in FELs, a **long Cerenkov** (quartz) **fiber** can be placed along the **LINAC**, **transfer lines** and **booster / storage ring injection regions**

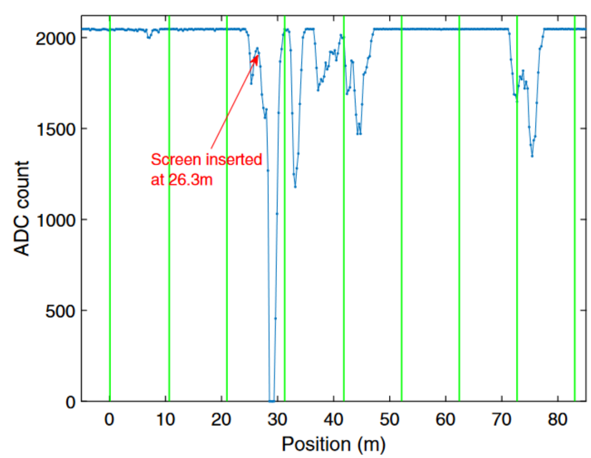
→ **beam losses** generate **light pulses** in the **quartz fiber**, which are detected by a **PMT** at one end of the fiber.

→ **multiple loss locations** generate **multiple light pulses** ($\mathcal{O}$ 10s of ns) per injection trigger

→ a **fast ADC** (> 500 MS/s) digitizes the loss signal as a waveform corresponding to the fiber length or the beam path, which is covered by the LLM

→ the **LLM spatial resolution** is in the order of **0.5 – 1 m**. **loss locations** can be "**calibrated**" by inserting screens valves at known locations along the beam path

Example of LLM Calibration from SwissFEL
from C. Ozkan-Loch et al., PRSTAB 23, 102804 (2020)



→ **LLMs** will be installed in **SLS 2.0**…:

LINAC – LBTL – booster injection
BRTL – storage ring injection

→ **LLMs** will be used for "**injector drift control**" in **SLS 2.0**

LESR Injector: Charge and Current Monitors

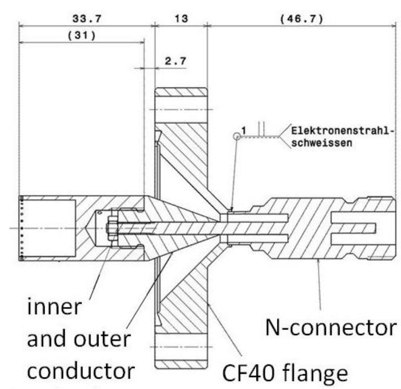
- **integrating current transformers** are absolutely calibrated standard devices for **beam charge** measurements in **LINACs and transfer lines**:
  - → e.g. ICT / BCM-IHR < 10 pC – 1 nC (single bunches and bunch trains)
- **parametric current transformers** are standard devices for circulating **beam current** measurements in **booster and storage rings**:
  - → e.g. NPCT 5 (1) µA / √Hz from DC (storage ring) to 10 kHz (booster ramps)
- **real-time determination of transmission efficiency** through injector complex provides important information of injector stability during commissioning and to-up operation
- **coaxial Faraday cups, wall current monitors** and **fast current transformers** provide time-resolved information of electron bunches and bunch patterns on a ps to ms scale

SLS LINAC Coaxial F-Cup

90° insertable version

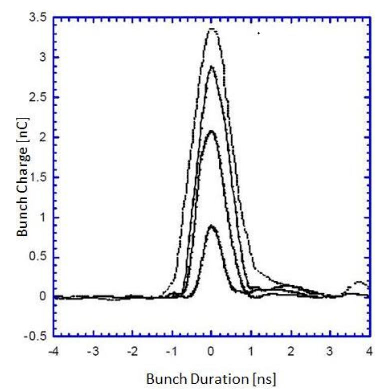
Coaxial Faraday Cup

integrated in a CF flange as low energy beam stop



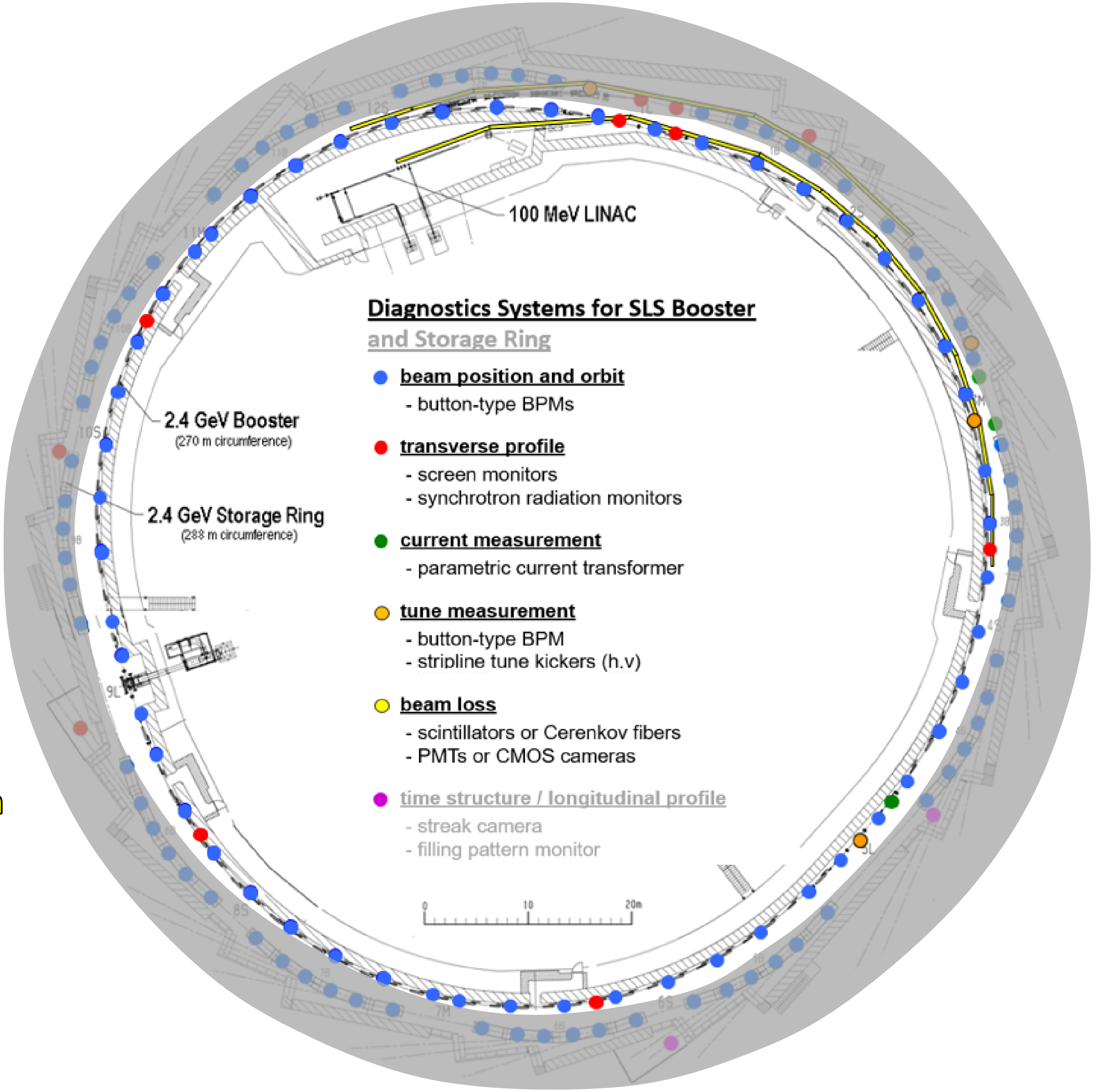
SLS LINAC Gun Emission

bunch length and charge as function of gun bias settings



LESR SLS Booster Diagnostics – Overview

- 54 button-type BPMs
- 1 current transformer
- 1 tune kicker (diagonal)
- 1 tune BPM
- 2 screen monitors (at injection)
- 3 screen monitors (around ring)
- 3 synchrotron light ports
- BLMs and LLM at injection



LESR Transfer Line Diagnostics

Example: SLS 2.0 BRTL aiming for good SR injection control

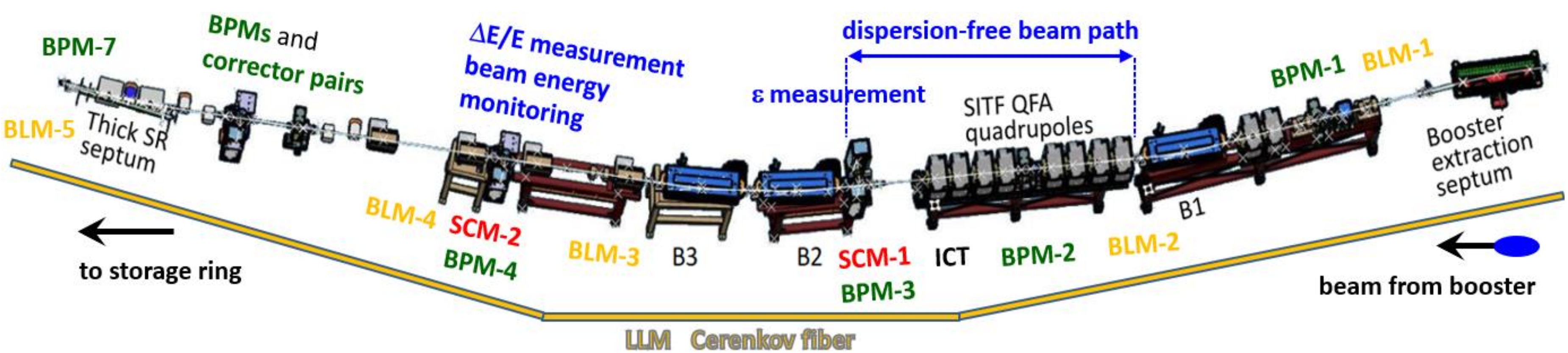
→ **matching** from booster synchrotron to storage ring

→ **dispersion-free beam path** allows for ε and **Twiss parameter measurement** (strong SITF QFA quadrupoles and **SCM-1** in front of B2)

→ **high dispersion** at location of **SCM-2** / **BPM-3** allows for **ΔE/E measurement** and **monitoring** of **energy stability**

→ **BPM** and **corrector pairs** in front of thick septum allow for good **control** of **injection point** and **angle** supported by **high resolution "witness BPM"** (**BPM-7**) behind thick septum

→ **beam loss monitors** at selected locations and **longitudinal loss monitor** along BRTL and storage ring injection region to **monitor** and **optimize beam losses** and **loss pattern**



PAUL SCHERRER INSTITUT

Conclusions

- **Injectors are often "re-used", and they are much less challenging than the new or upgraded generation of low emittance storage rings ☺ ☺ ☺**

  However, …

  → existing diagnostics systems should be improved and/or refurbished

  → new or adequate diagnostics systems should be introduced if and where necessary

- **High resolution Profile Monitors and BPMs in combination with BLMs are required to…**

  → determine beam parameters (e.g. in case of emittance exchange)

  → tune and monitor position and angle of injected beams

  → monitor drifts in LINAC and transfer lines
  (especially during "top-up operation)

Thank You !!!

… for your patience and attention ☺☺☺