High-Brightness Challenges for the Operation of the CERN Injector Complex

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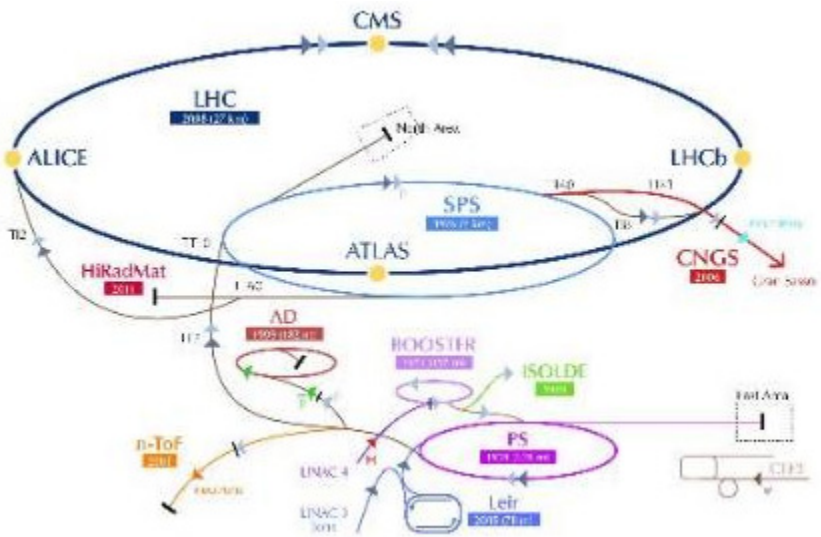
CERN's LHC Injector Chain

today

protons
- Linac2 (50 MeV p)
- PS Booster (1.4 GeV p)
- Proton Synchrotron (PS) (26 GeV p)
- Super Proton Synchrotron (SPS)

ions
- Linac3
- LEIR
- Proton Synchrotron (PS)
- Super Proton Synchrotron (SPS)



after LS2*

protons
- Linac4 (160 MeV H-)
- PS Booster (2 GeV p)
- Proton Synchrotron (PS) (26 GeV p)
- Super Proton Synchrotron (SPS)

* second long LHC shutdown 2019/20

LHC Type Beams from the Injectors

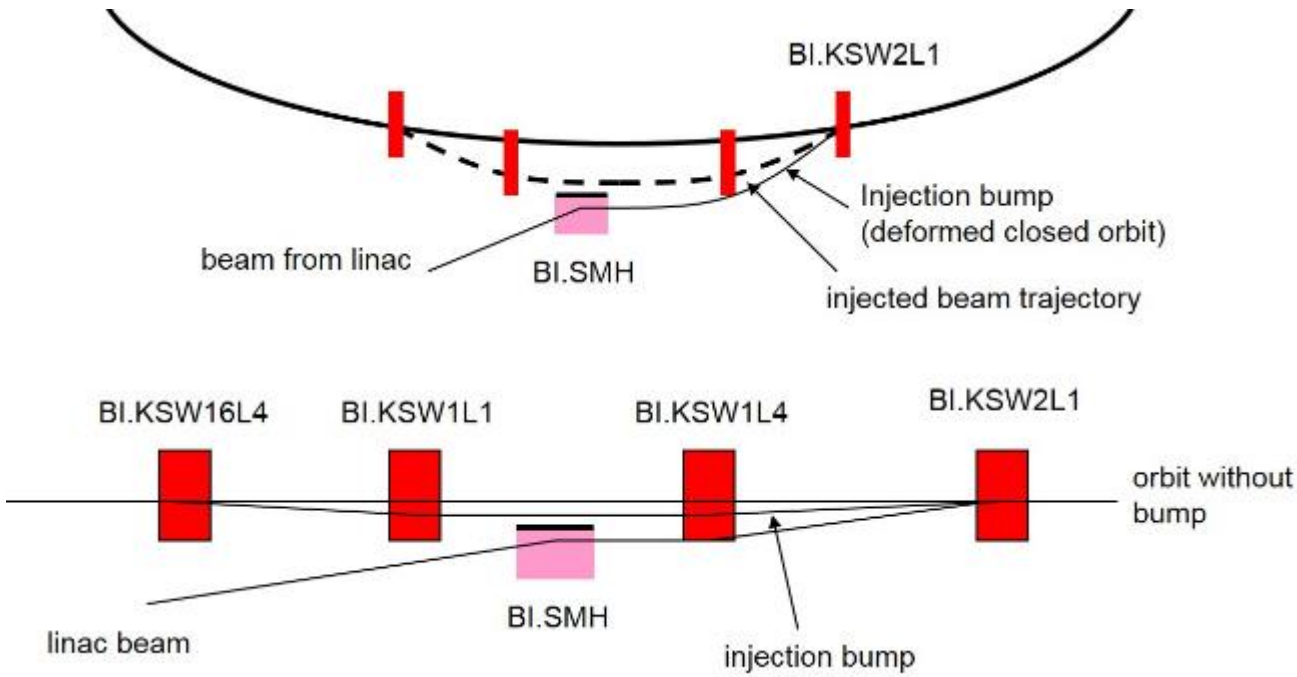
the challenge for LHC type beams is high brightness (not high intensity!)

<u>single bunch beams:</u>
low-intensity low emittance single bunch for LHC setting up

<u>multi bunch beams for physics:</u>
different production schemes

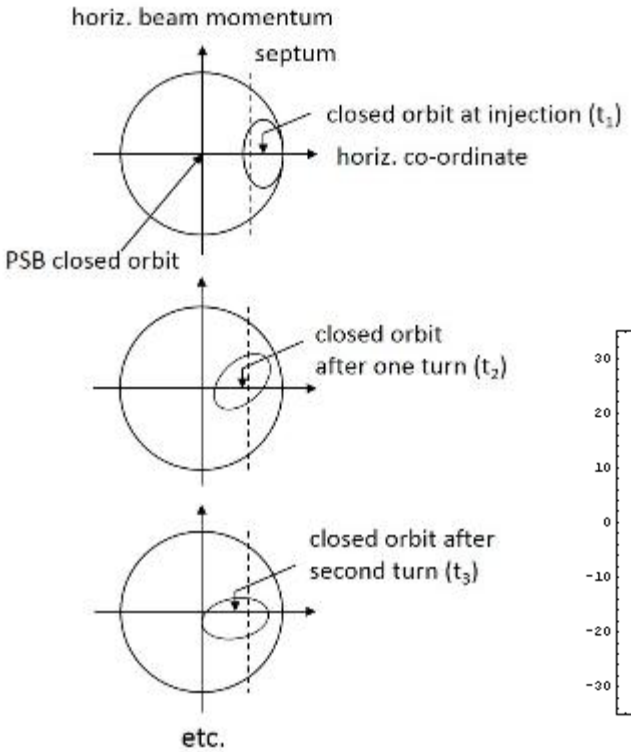
- **standard beam LHC25; main production beam for the LHC**
- **BCMS** (Batch Compression, Merging and Splitting) **variant to increase beam brightness**
- 8b4e and BCS variant; set up in 2017 to mitigate LHC vacuum issues

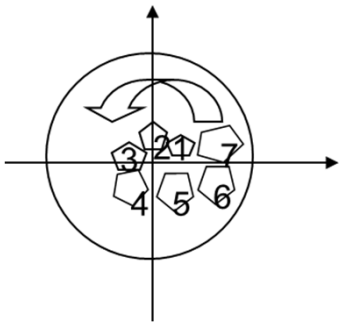
Present Linac2-PSB Multi-Turn Injection

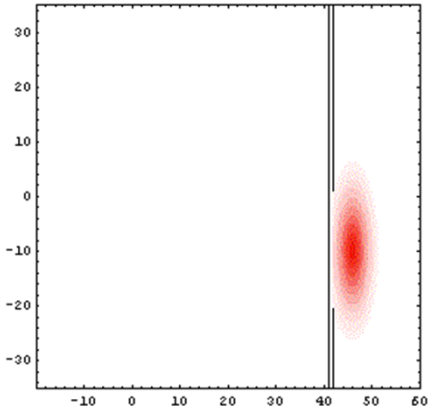


1. injection bump generated using four slow bumpers
2. injection bump moves slowly back towards closed orbit
3. beam from Linac2 is deflected on the (moving) orbit by a septum

Present Linac2-PSB Multi-Turn Injection







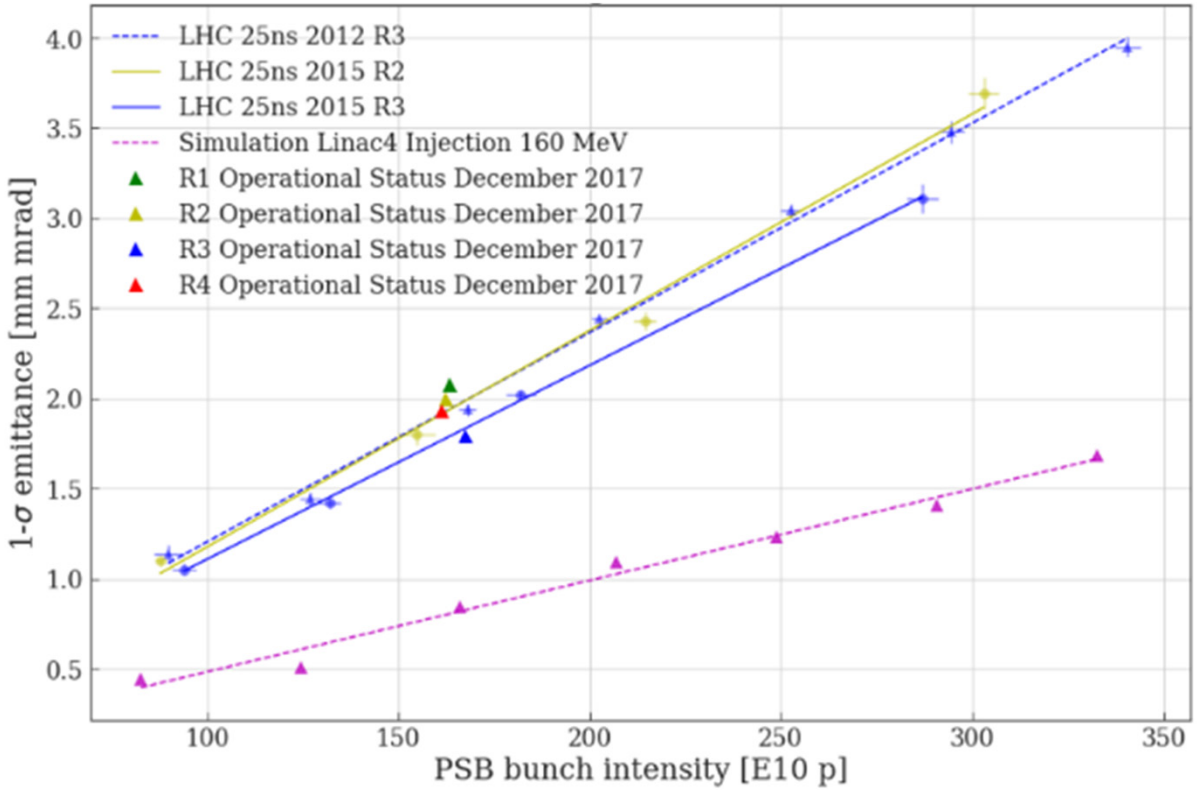
as this process takes place, subsequent linac beam "slices" are injected, with increasing oscillation amplitude around the instantaneous closed orbit ("horizontal stacking")

beamlets are now "polygons", as they have undergone several cuts

they spiral up around the (moving) closed orbit, leading to a density distribution which is dense in the core and less dense in the outer part

- presently about 50% of the beam coming from Linac2 is lost at injection
- the transverse beam emittance is a linear function of the number of injected turns

PSB Emittance vs Intensity



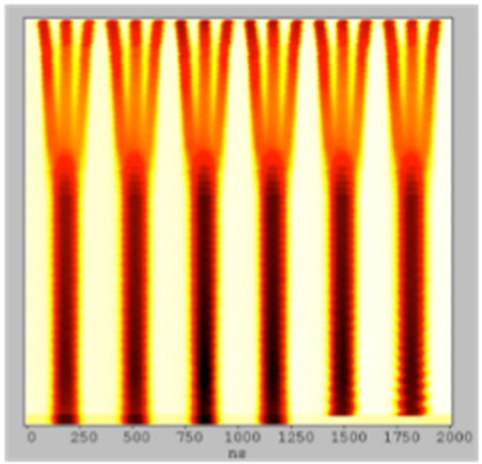
Standard 25 ns Spacing Beam

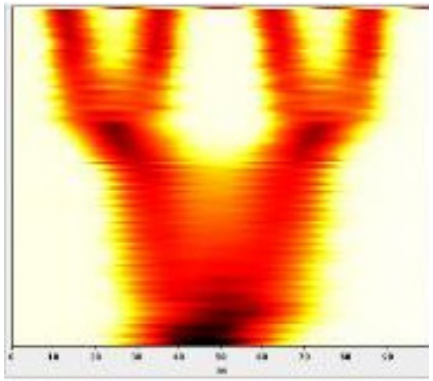
The PSB receives two consecutive injections from Linac2, one filling all four rings with one bunch each (h=1) and a second injection filling only two of the four rings. With this scheme the PSB produces six bunches at 1.4 GeV energy, which are transferred in two extractions (4 + 2 bunches) to the PS.

In the PS the beam is accelerated to a top energy of 26 GeV and at the same time the bunches are longitudinally split. This scheme employs consecutively the RF harmonics 21, 42 and 84, which leads to a 12-fold splitting of each bunch. The resulting number of bunches produced from the six bunches coming from the PSB is hence 72.

Standard 25 ns Beam: RF Manipulations in the PS

<u>from PSB:</u>
1.4 GeV
τ_l = 183 ns
ε_l = 1.27 eVs
$N_b = 16.5 \times 10^{11}$
bunches: 6





<u>extracted to SPS:</u>
26 GeV
ε_l = 0.35 eVs
$N_b = 1.3 \times 10^{11}$
split factor: 12
bunches: 72

RF harmonics @ 2.5 GeV:
7 - 14 -21

RF harmonics @ 26 GeV:
21 - 42 - 84

BCMS Beam – A Way to push Brightness

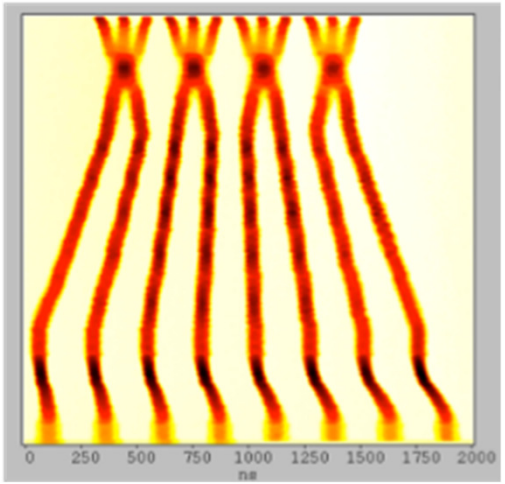
In the BCMS* scheme, instead of taking six PSB bunches into H7, the PS takes eight bunches into H9. The total intensity is then distributed across eight PSB bunches rather than six ones. Accordingly, the injected intensity per ring and the transverse emittance can be reduced.

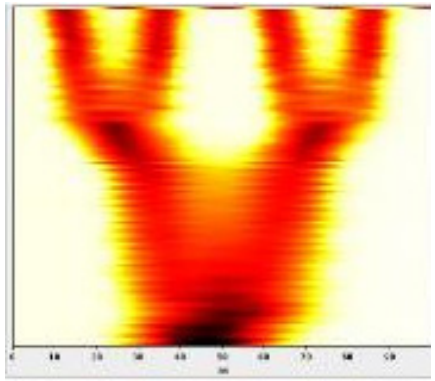
In the PS, first, a compression is performed by incrementing the harmonic number from H9 to H14. Then, a bunch merging puts the harmonic number back to seven. From this point, the RF gymnastics are similar to the nominal beam, with the bunches split in three, then two and two again. The number of bunches produced is different from the normal scheme: eight bunches are merged into four, multiplied by three, two and two again. The result is 48 bunches spaced by 25 ns.

* Batch Compression, Merging and Splitting

BCMS Beam: RF Manipulations in the PS

<u>from PSB:</u>
1.4 GeV
τ_l = 150 ns
ε_l = 0.92 eVs
$N_b = 7.8 \times 10^{11}$
bunches: 8



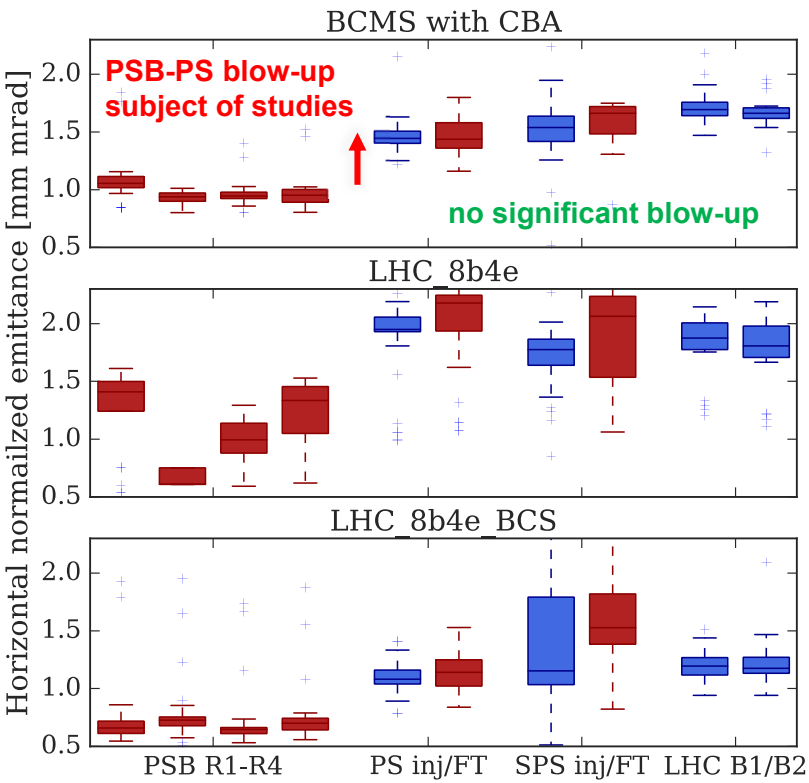


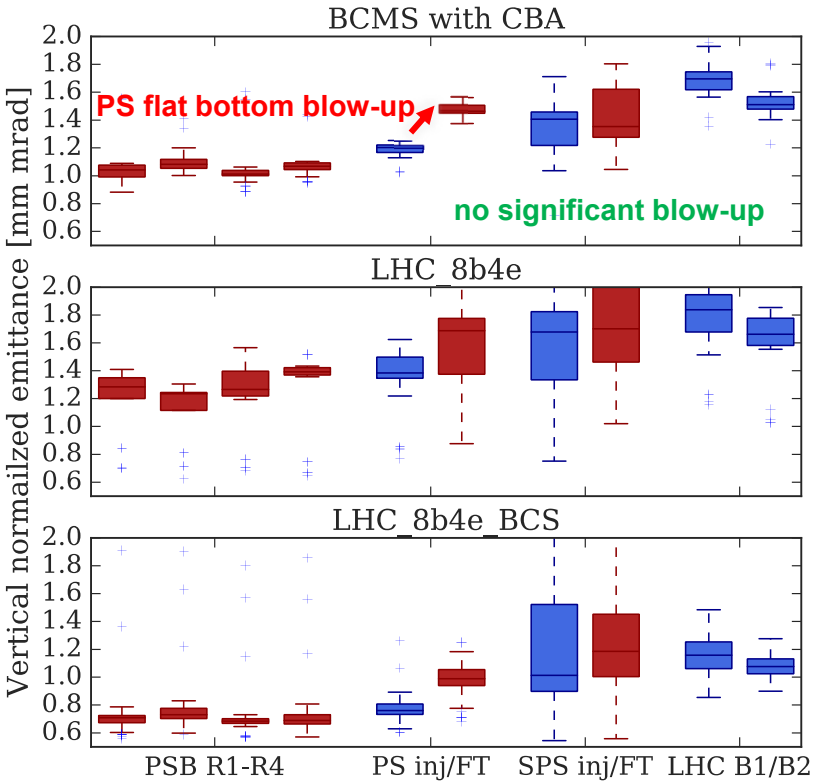
<u>extracted to SPS:</u>
26 GeV
ε_l = 0.35 eVs
$N_b = 1.3 \times 10^{11}$
split factor: 6
bunches: 48

RF harmonics @ 2.5 GeV:
9 - 14 - 7 -21

RF harmonics @ 26 GeV:
21 - 42 - 84

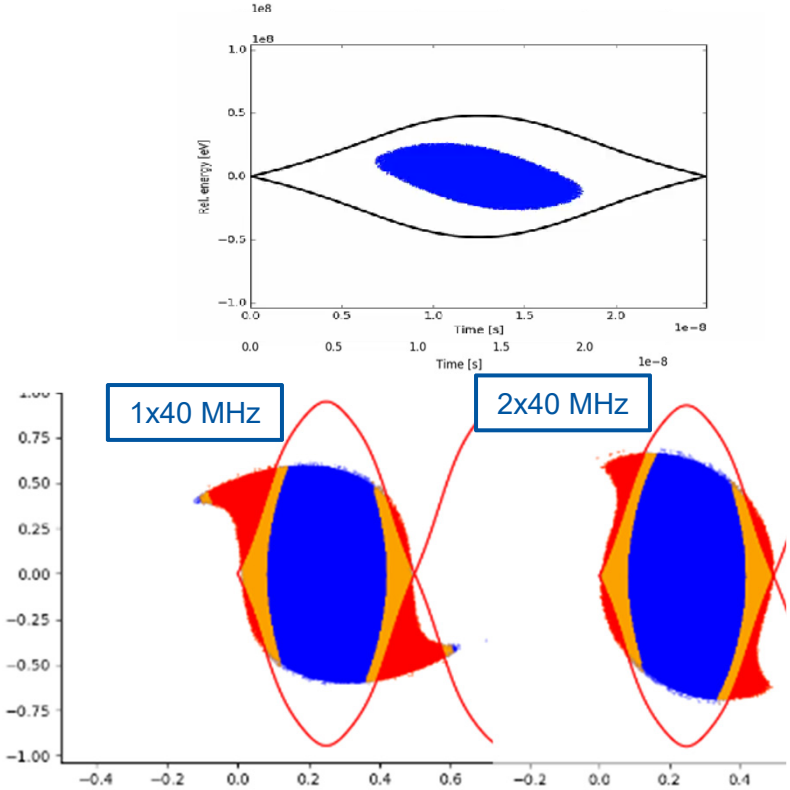
PSB-PS-SPS Transfer: Transverse Plane





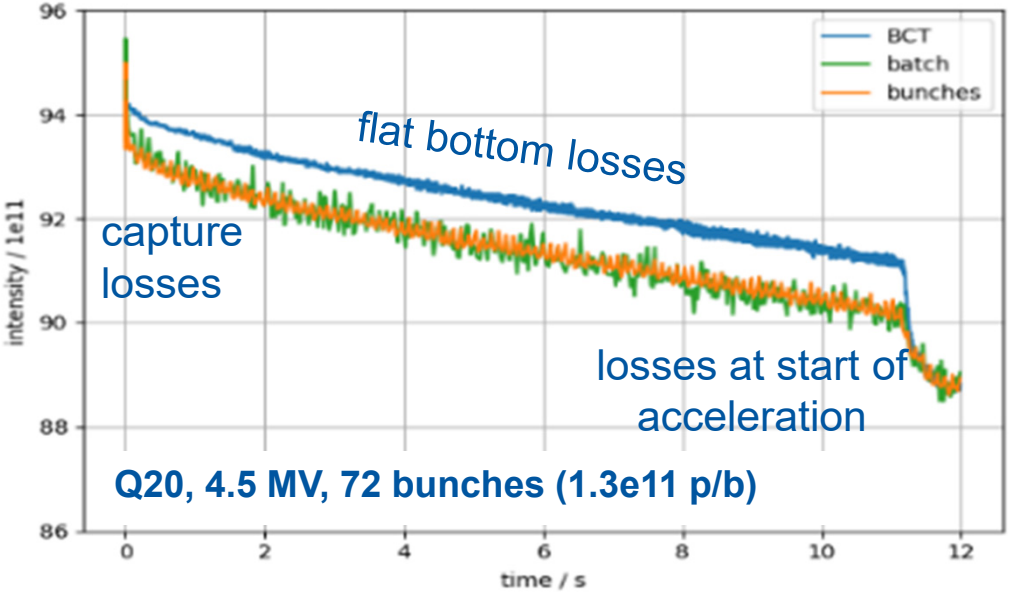
PS-SPS Transfer: Longitudinal Plane

- bunch rotation in PS using 1x40 MHz + 2x80 MHz cavities to fit bunches into 5 ns SPS RF bucket
- development of uncaptured tails due to non-linear forces
- clear improvement by pulsing **2x40 MHz** cavities,
  routinely used in 2017 operation
- further bunch rotation optimization (80 MHz phase switch / 3rd cavity) shows only minor improvements



SPS Losses

- losses at capture, flat bottom, and acceleration start
- capture losses mostly due to longitudinal distribution after bunch rotation in PS (transfer from 40 MHz to 200 MHz buckets …) and RF transients during first few ms in SPS
- losses out of bucket on SPS flat bottom due to particles close to separatrix (full bucket)
- minimizing capture losses by increasing RF voltage in SPS is limited by
  - unmatched distribution results in larger longitudinal emittance
  - momentum acceptance
  - RF voltage for maintaining bucket area during the ramp



Main Limitations for LHC Type Beams

Brightness limit delivered by the PSB

- transverse emittance depends linearly on the intensity

Limited longitudinal emittance extracted from PSB

- rise time of the recombination kickers
- blow-up observed at PS injection for large momentum spread

Space charge on the PS flat bottom

- large tune spread, limited by resonances
- need to keep bunch intensity low to preserve brightness

Longitudinal emittance at PS extraction set to 0.35 eVs

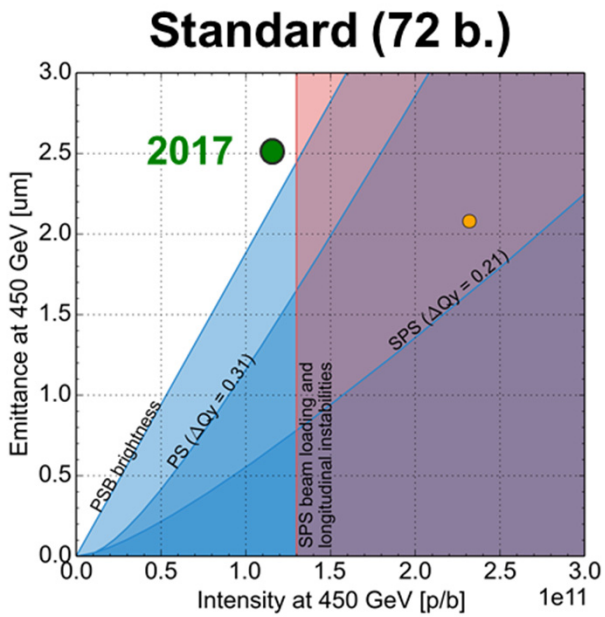
- keep losses in the SPS under control; longitudinal stability

Summary of 2017 Performance

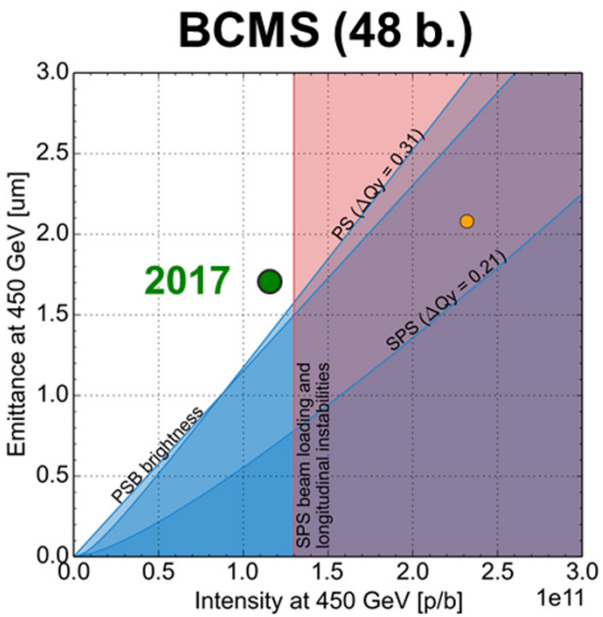
	Intensity [1e11 p/b]	Emittance [um]	pattern
25 ns standard (like 2017)	1.15	2.5 (2.4)	1-4 x 72 → 288
25 ns standard (high intensity)	1.30	2.8 (2.7)	1-4 x 72 → 288
25 ns BCMS (like 2017)	1.15	1.7 (1.4)	1-3 x 48 → 144
25 ns BCMS (high intensity)	1.30	1.9 (1.6)	1-3 x 48 → 144
8b4e standard (like 2017)	1.20	1.8 (1.6)	1-3 x 56 → 168
8b4e standard (high intensity)	1.60	2.4 (2.1)	1-3 x 56 → 168
8b4e BCS (like 2017)	1.25	1.15 (1.0)	1-4 x 32 → 128
8b4e BCS (high intensity)	1.60	1.55 (1.2)	1-4 x 32 → 128

blue: theoretical achievable

Limitation Diagrams for 2017 Beams



1.15e11 / 2.5 um



1.15e11 / 1.7 um

2017 performance close to limitations!

LIU Upgrade

Today the injector complex provides LHC beams well within (and beyond!) the original specifications

The High-Luminosity LHC Project requests beams with parameters out of today's reach

The LHC Injectors Upgrade (LIU) has been put in place to enable the injector complex to deliver the requested high-brightness beams

The LIU project consists of the following building blocks:

Linac4:

- higher energy reduces space charge effects at PSB injection
- H^- stripping injection is essentially loss free and allows to tailor beam emittance

PSB:

- energy upgrade from 1.4 GeV to 2.0 GeV reduces space charge effects at PS injection
- numerous other upgrade items (power supplies, RF, instrumentation, …)

PS:

- increase of the injection energy to 2.0 GeV
- numerous other upgrade items (power supplies, RF, instrumentation, …)

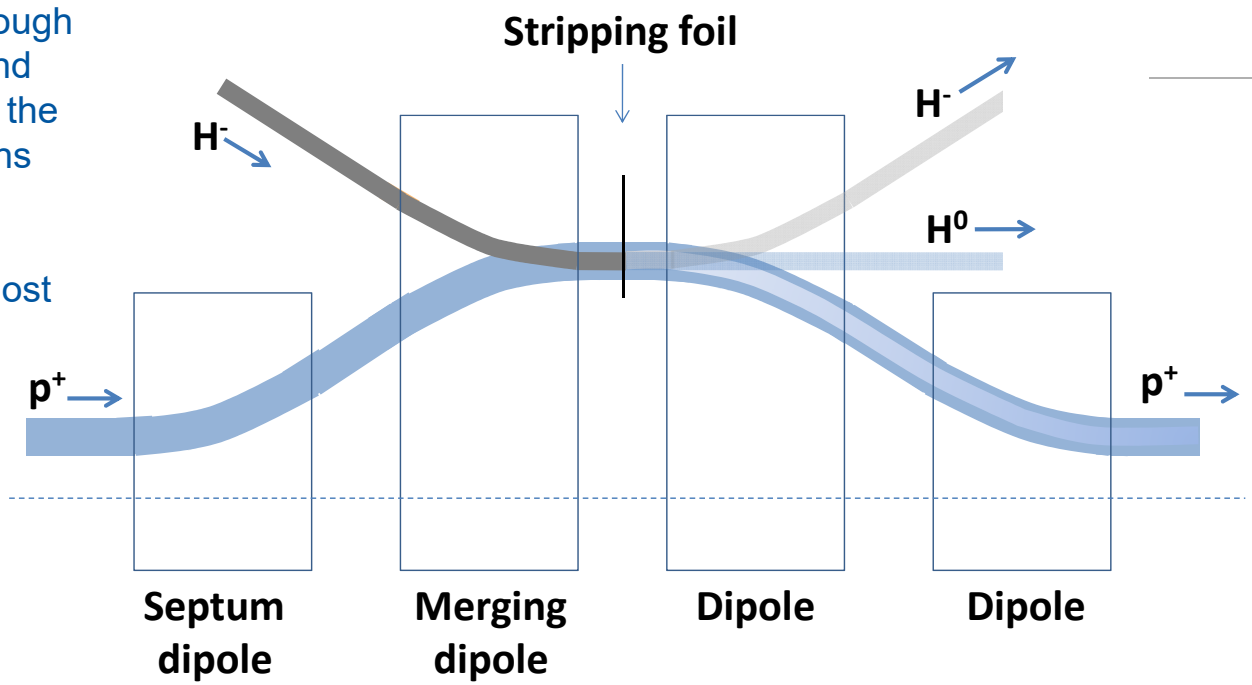
SPS:

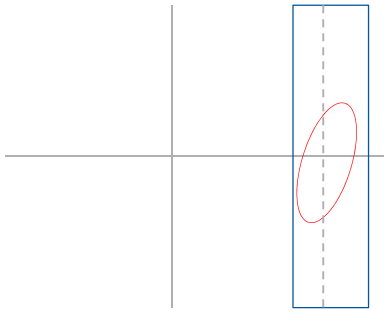
- numerous other upgrade items (coating, RF, instrumentation, …)

H- Injection with Linac4

H- ions pass through a stripping foil and are merged with the circulating protons

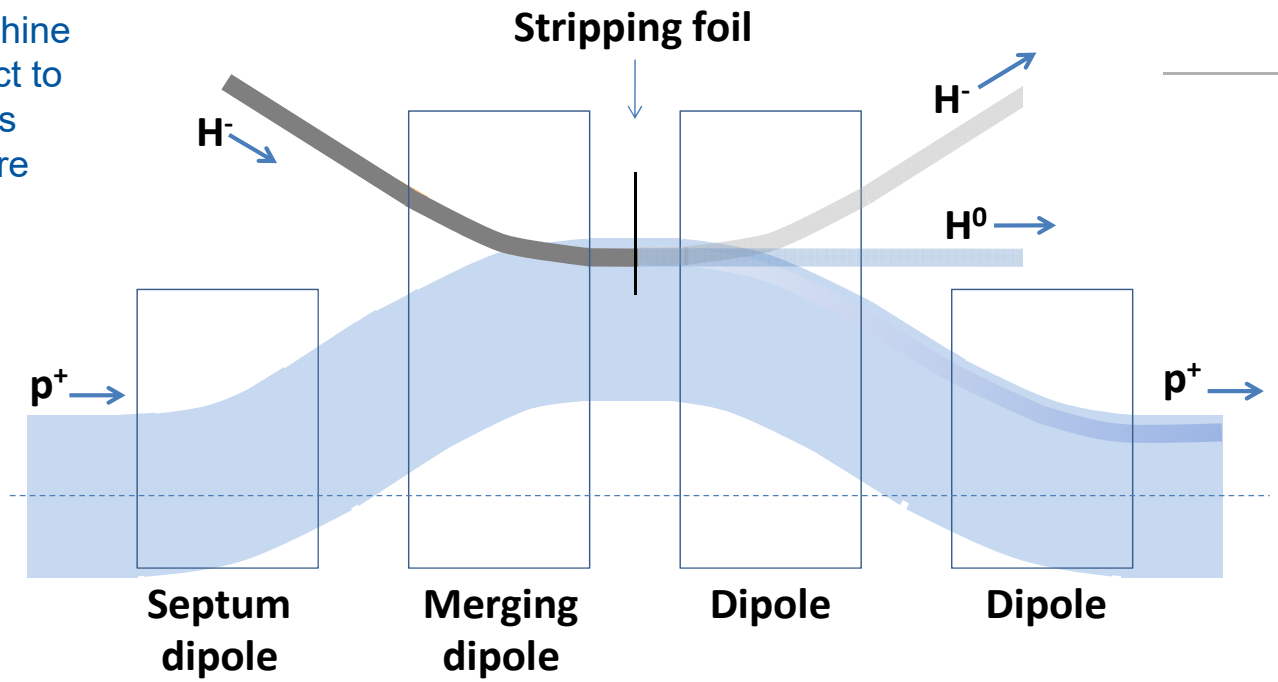
98 % stripping efficiency → almost loss-free

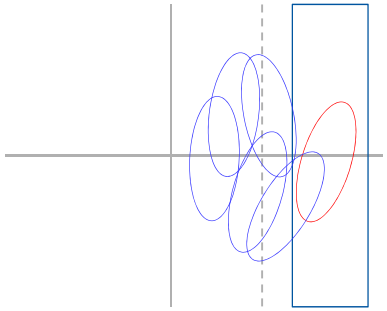




H- Injection with Linac4

shifting the machine orbit with respect to foil (painting) fills machine aperture with beam

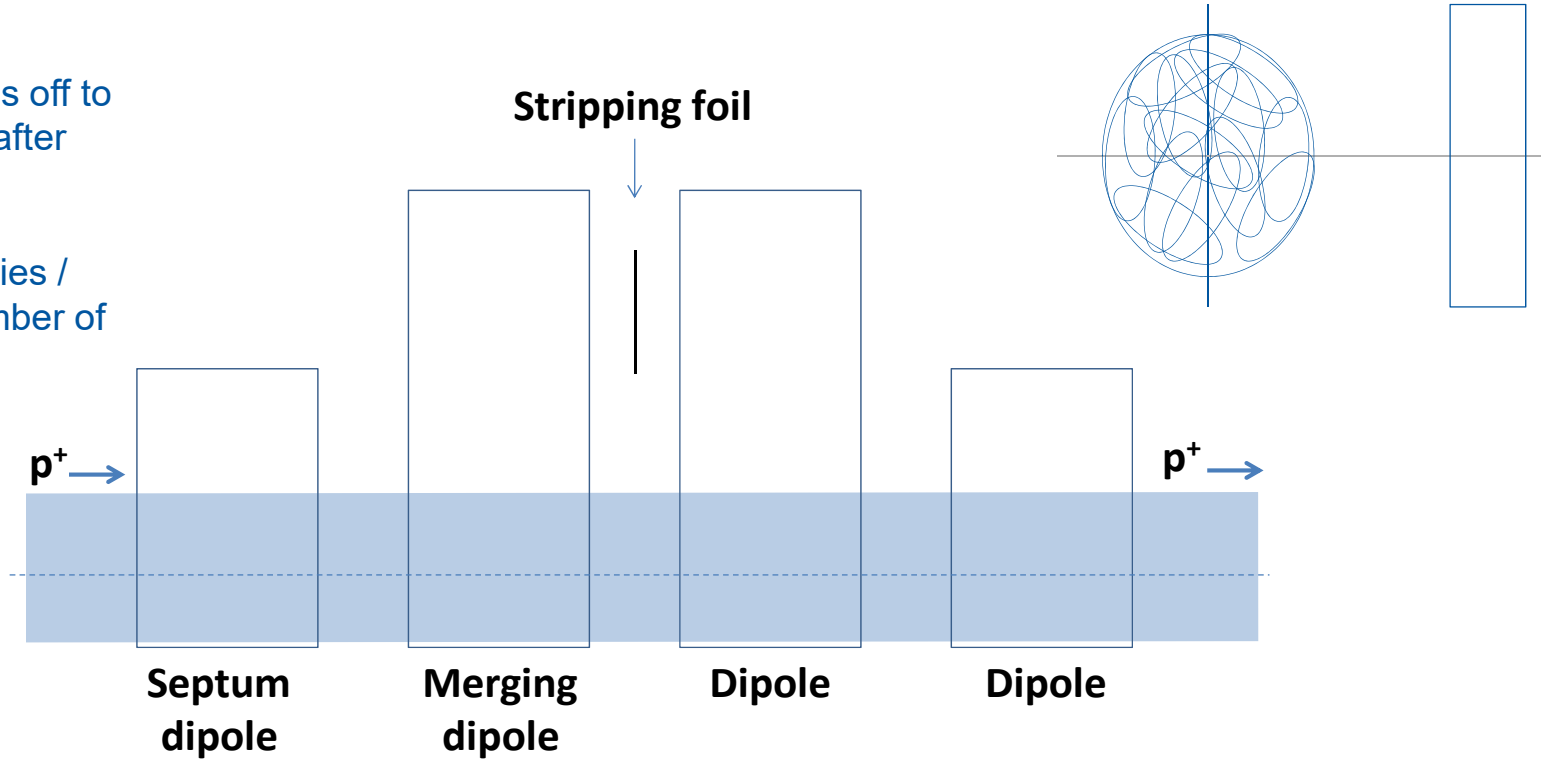




H- Injection with Linac4

chicane switches off to zero amplitude after injection

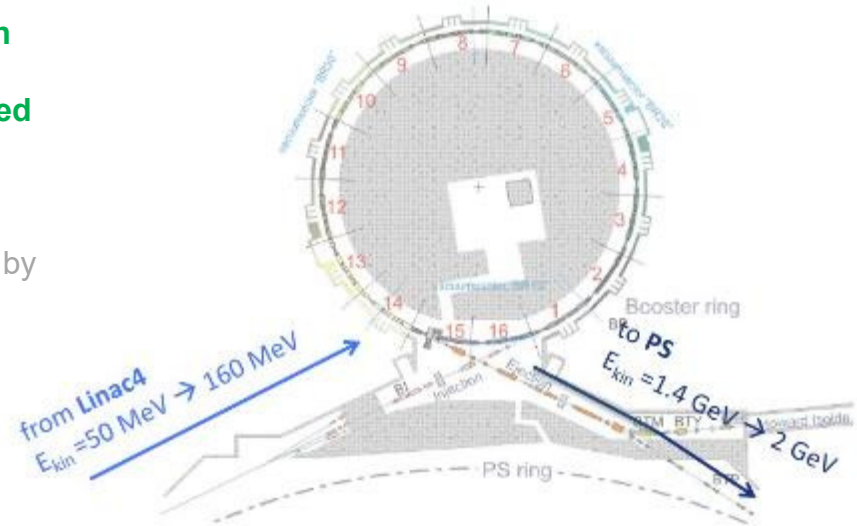
different intensities / emittances: number of injected turns from 1 to 100



PSB Upgrade

upgrade of PSB injection from 50 MeV protons to 160 MeV H- with increased intensity

- re-build injection line for 160 MeV
- replace injection septum by stripping foil
- injection bumps
- diagnostics
- …

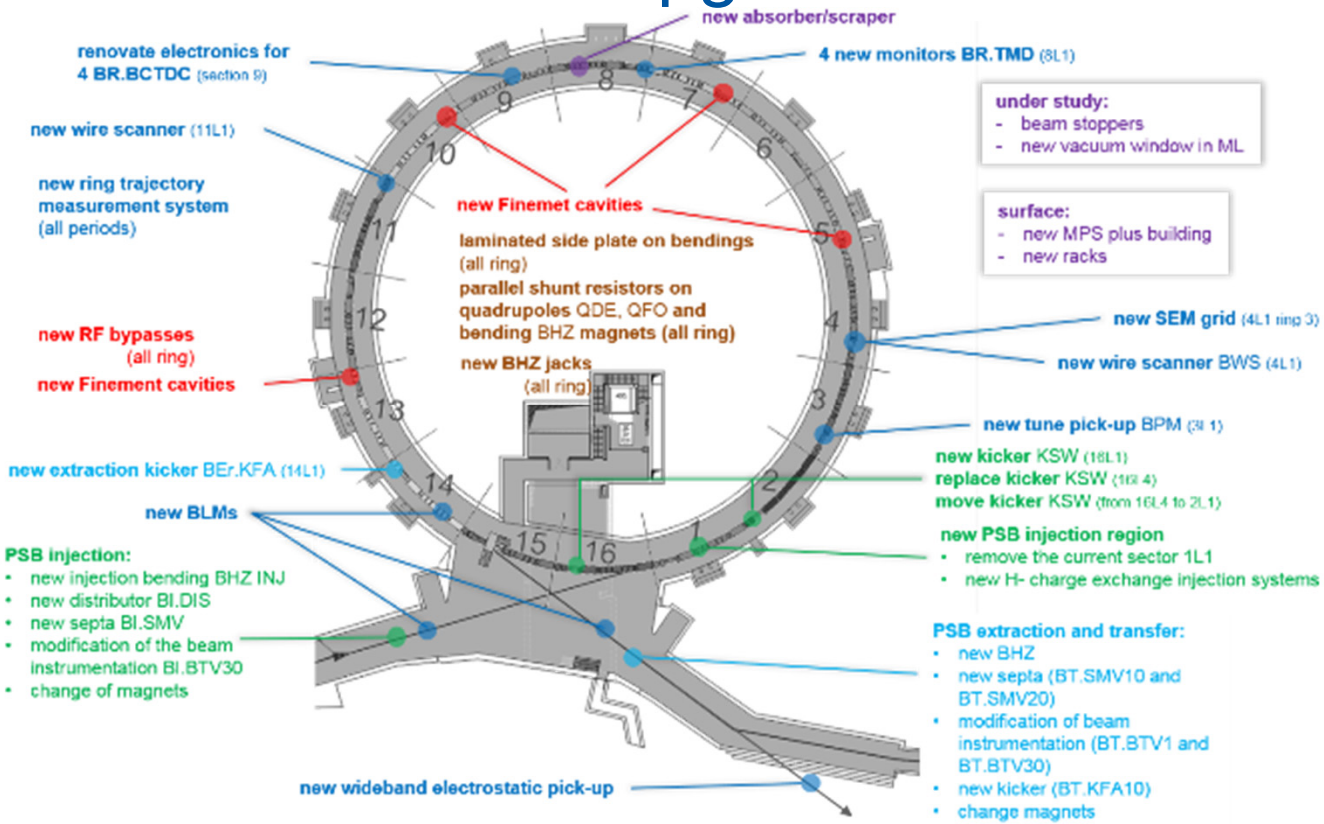


upgrade of PSB rings and extraction / transfer from 1.4 GeV to 2.0 GeV

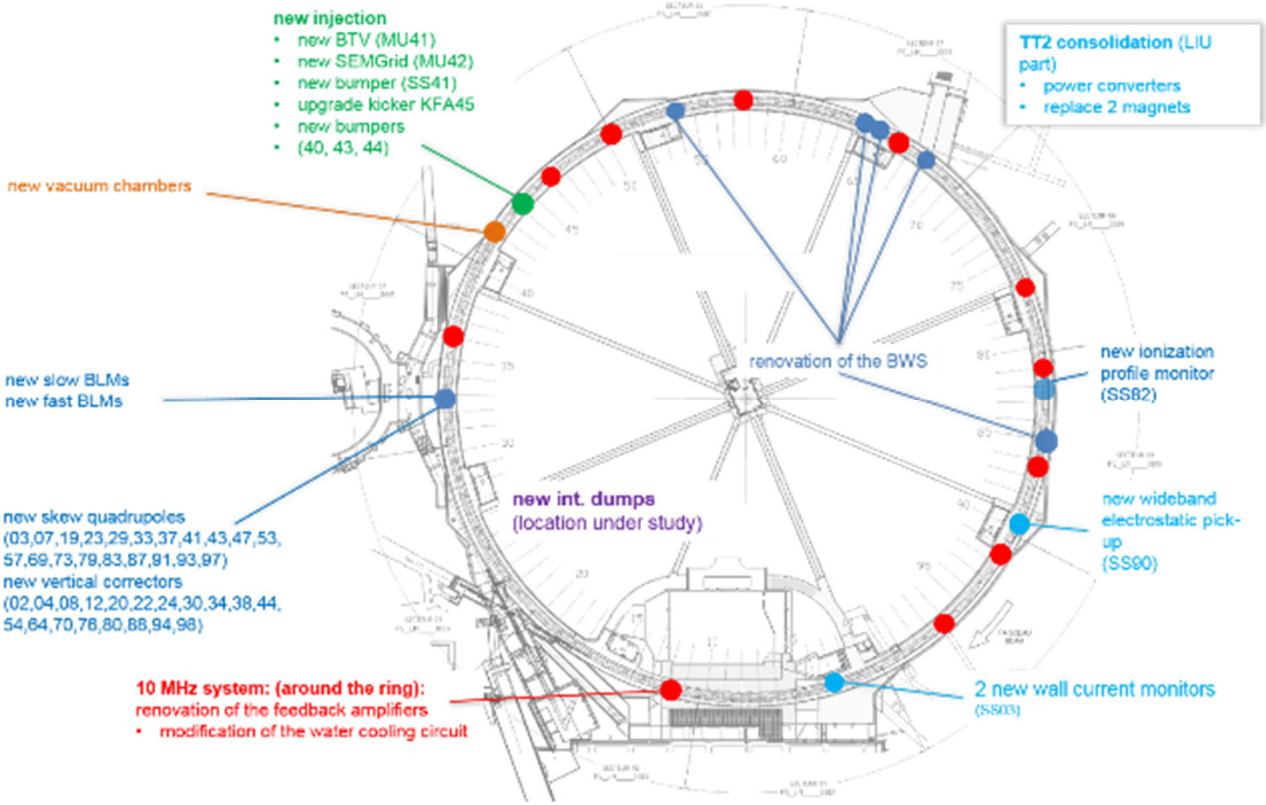
- replace main power supply
- replace number of smaller power supplies
- new extraction and recombination elements
- …

1. **increased injection energy from Linac4 and new injection scheme**
   → higher injection energy (160 MeV) leads to increased brightness
   → essentially loss free and allows to tailor emittances
2. **increased PSB top energy (2 GeV)**
3. **increased PS injection energy (2 GeV)**
   → reduces space charge effects at PS injection

PSB Upgrade


new absorber/scraper
renovate electronics for 4 BR.BCTDC (section 9)
4 new monitors BR.TMD (8L1)
under study:
- beam stoppers
- new vacuum window in ML
new wire scanner (11L1)
new ring trajectory measurement system (all periods)
new Finemet cavities
laminated side plate on bendings (all ring)
parallel shunt resistors on quadrupoles QDE, QFO and bending BHZ magnets (all ring)
surface:
- new MPS plus building
- new racks
new SEM grid (4L1 ring 3)
new wire scanner BWS (4L1)
new RF bypasses (all ring)
new Finemet cavities
new BHZ jacks (all ring)
new tune pick-up BPM
new extraction kicker BEr.KFA (14L1)
new kicker KSW (16L1)
replace kicker KSW
move kicker KSW (from 16L4 to 2L1)
new BLMs
new PSB injection region
• remove the current sector 1L1
• new H- charge exchange injection systems
PSB injection:
• new injection bending BHZ INJ
• new distributor BI.DIS
• new septa BI.SMV
• modification of the beam instrumentation BI.BTV30
• change of magnets
PSB extraction and transfer:
• new BHZ
• new septa (BT.SMV10 and BT.SMV20)
• modification of beam instrumentation (BT.BTV1 and BT.BTV30)
• new kicker (BT.KFA10)
• change magnets
new wideband electrostatic pick-up

PS Upgrade

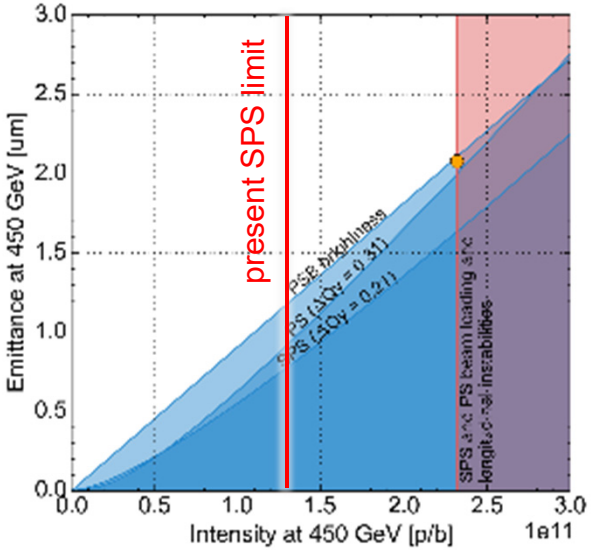

new injection
• new BTV (MU41)
• new SEMGrid (MU42)
• new bumper (SS41)
• upgrade kicker KFA45
• new bumpers
• (40, 43, 44)
TT2 consolidation (LIU part)
• power converters
• replace 2 magnets
new vacuum chambers
renovation of the BWS
new ionization profile monitor (SS82)
new slow BLMs
new fast BLMs
new int. dumps
(location under study)
new wideband electrostatic pick-up (SS90)
new skew quadrupoles
(03,07,19,23,29,33,37,41,43,47,53, 57,69,73,79,83,87,91,93,97)
new vertical correctors
(02,04,08,12,20,22,24,30,34,38,44, 54,64,70,76,80,88,94,98)
10 MHz system: (around the ring):
renovation of the feedback amplifiers
• modification of the water cooling circuit
2 new wall current monitors
(SS03)

SPS Upgrade

- **Main performance limitations of present machine**
  - Losses at injection and flat bottom / start of ramp
  - Intensity limitation due to lack of RF power for beam loading compensation
  - Longitudinal instabilities during ramp and flat top

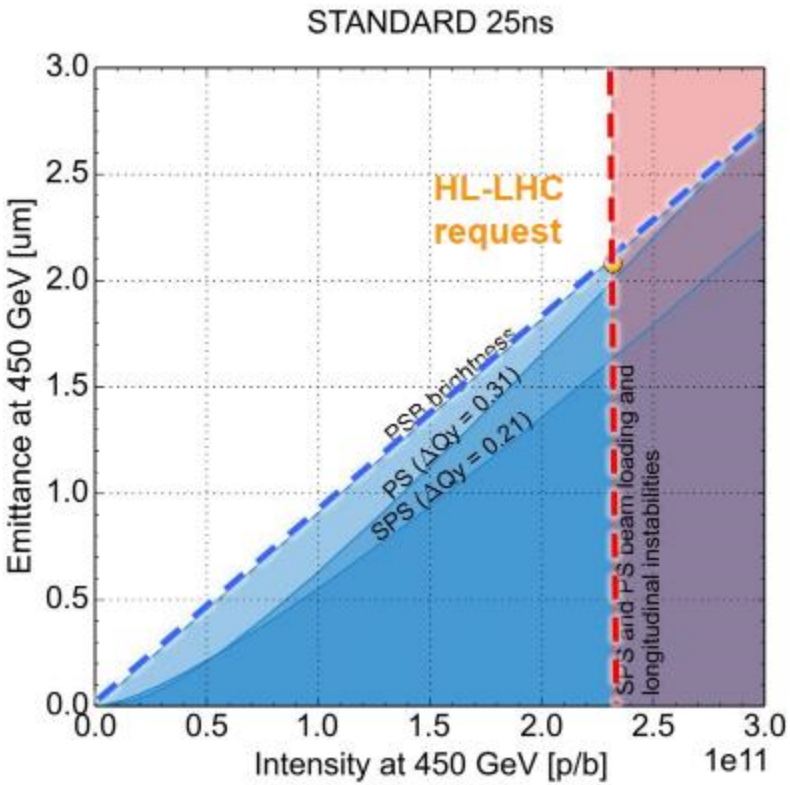
- **Main upgrade items for SPS**
  - 200 MHz RF system upgrade (including LLRF)
  - Electron cloud mitigation: amorphous Carbon (aC) coating
  - Impedance reduction (vacuum flanges & 630 MHz HOM)
  - New beam dump system in LSS5 and new design of protection devices to comply with target beam parameters

LIU (standard 25 ns)



- **Beam performance achievements in 2017**
  - LHC filling with up to 1.3e11 p/b within (close to LIU brightness but with 8b4e BCS* beam)
  - 2e11 p/b injected into SPS in trains of 48 and 72 bunches (BCMS* and standard*) and stored on 26 GeV/c flat bottom for studies of losses and emittance preservation

LIU Performance Reach for Protons



PSB brightness + intensity limitations in PS and SPS inferred from simulations

space charge limitation curves in PS and SPS based on assumed tune spreads and optimised beam parameters at transfers

High Brightness Operation with Ions

present challenges and post-LS2

Source, Linac3 & LEIR injection line:

- Develop automatic "source tuning" software to optimize source performance.
- Test mitigation measures to lead-oxidation limiting source lifetime.
- Continuous monitoring of the transfer line beam trajectory at injection crucial to detect beam characteristics variations from Linac3
- Consolidate Linac3 beam dynamics model

LEIR:

- Main limitations identified in 2015: space charge induced losses at RF capture.
- Intense measurements campaign identified detrimental space charge resonances.
- Line density flattening, resonance compensation -> Met HL-LHC specs since 2016.
- Gain intensity margins and ensure stable operation

PS & SPS:

- No major issues for transfer through PS (mainly RF manipulation)
- Baseline relies on SPS slip-stacking to deliver HL-LHC beam requirements
- In case of lower than expected performance alternative production scenarios are being investigated: 3 high intensity bunches from LEIR into PS
- Simulations with collective effects within 5% loss budget
- Slip stacking to be demonstrated in SPS after LS2 (LLRF upgrade needed)

High Brightness Operation with Ions

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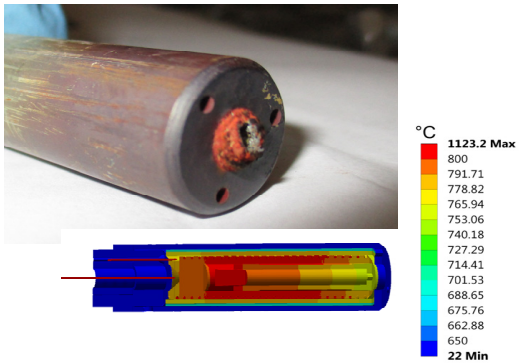

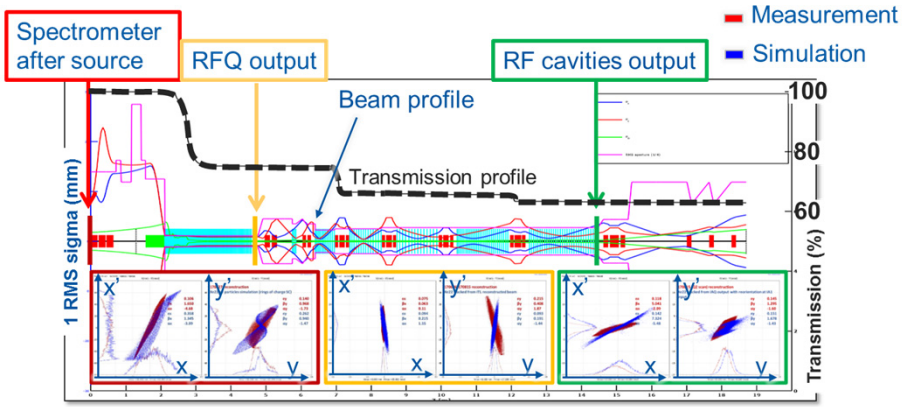

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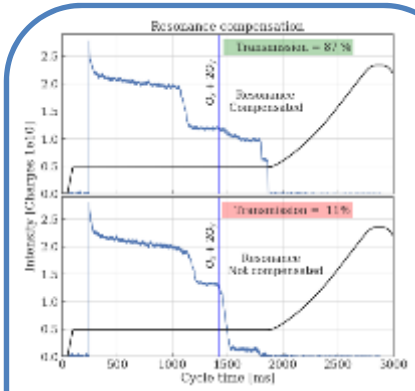
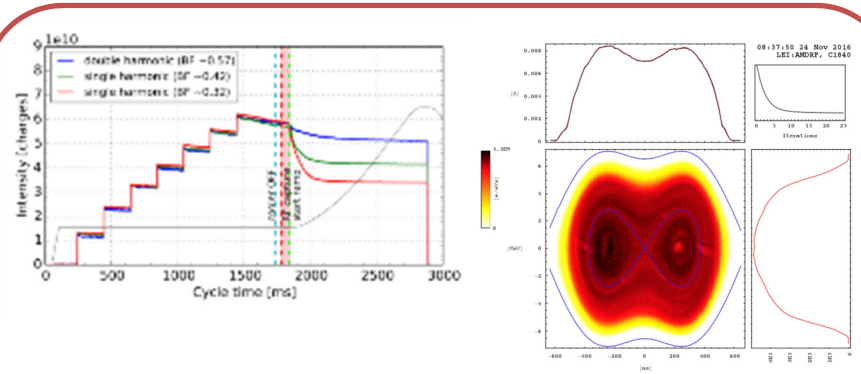
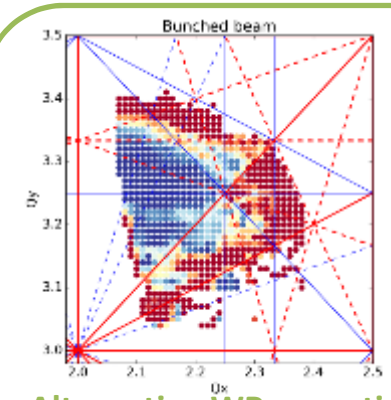


Lattice resonance compensation



Bunch profile optimization



Alternative WP operation

High Brightness Operation with Ions

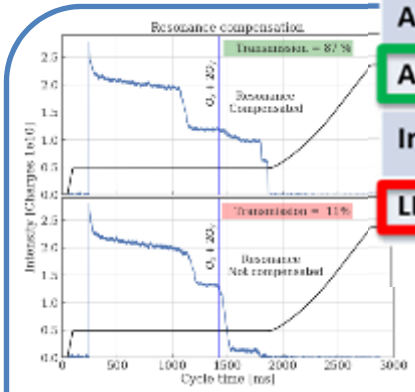
present challenges and post-LS2

LEIR:

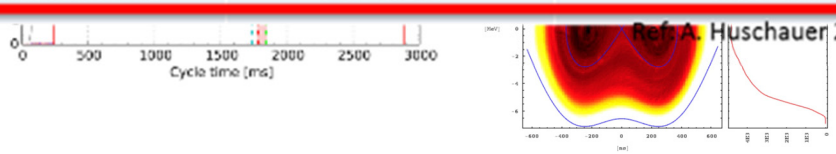
- Main limitations identified in 2015: space charge induced losses at RF capture
- Intense measurements campaign identified detrimental space charge resonances
- Line density f
- Gain intensity

LEIR parameters	Accumulated ions	Ions / bunch at extraction
Achieved 2015	15.5×10^8	6.0×10^8
Achieved 2016	19.1×10^8	8.1×10^8
Intensity record 2016	22.8×10^8	9.5×10^8
LIU/HL-LHC baseline	19.1×10^8	8.1×10^8

Average over the LHC 2016 run

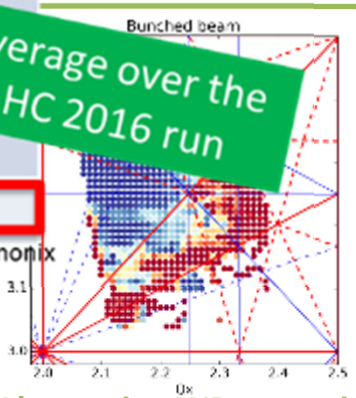


Lattice resonance compensation



Ref: A. Huschauer 2017 Chamonix

Bunch profile optimization



Alternative WP operation

High Brightness Operation with Ions

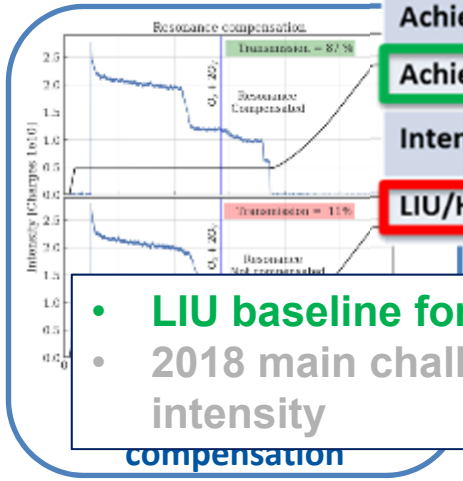
present challenges and post-LS2

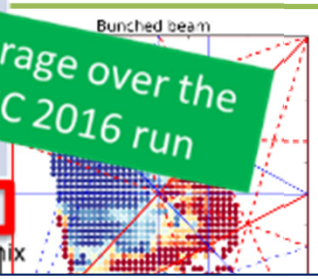
LEIR:

- Main limitations identified in 2015: space charge induced losses at RF capture
- Intense measurements campaign identified detrimental space charge resonances
- Line density f
- Gain intensity

LEIR parameters	Accumulated ions	Ions / bunch at extraction
Achieved 2015	15.5×10^8	6.0×10^8
Achieved 2016	19.1×10^8	8.1×10^8
Intensity record 2016	22.8×10^8	9.5×10^8
LIU/HL-LHC baseline	19.1×10^8	8.1×10^8

Average over the LHC 2016 run





Ref: A. Huschauer 2017 Chamonix

- **LIU baseline for beam intensity achieved since 2016**
- **2018 main challenge: machine stable and reproducible high performance at high intensity**

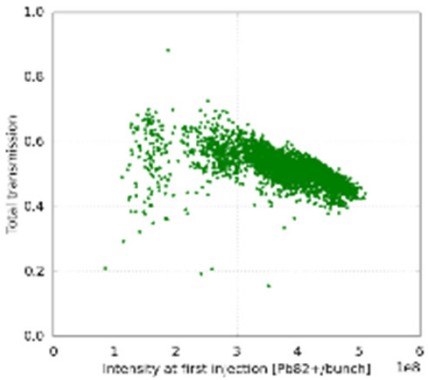
compensation

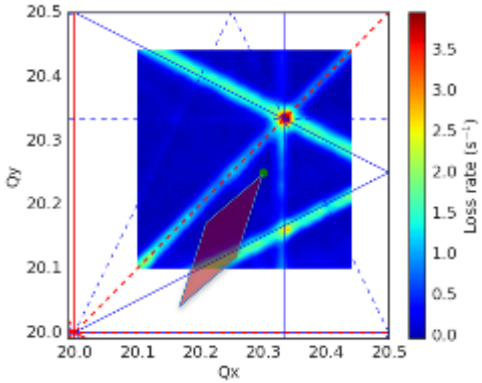
High Brightness Operation with Ions

present challenges and post-LS2

PS & SPS:

- No major issues for transfer through PS (mainly RF manipulation)
- Baseline relies on SPS slip-stacking to deliver HL-LHC beam requirements
- In case of lower than expected performance alternative production scenarios are being investigated: 3 high intensity bunches from LEIR into PS
- Simulations with collective effects within 5% loss budget
- Slip stacking to be demonstrated in SPS after LS2 (LLRF upgrade needed)





2015 data (12 SPS injections)

Summary

CERN's LHC injector complex delivers on a reliable and reproducible basis a variety of beams to the LHC within or beyond specifications

The beam spectrum comprises the "standard" production beams (25 ns and BCMS) as well as a variety of other beams for special purposes

In order to satisfy the future needs of the LHC in the High-Luminosity LHC era, the injectors are undergoing an ambitions upgrade program (**LIU, L**HC **I**njectors **U**pgrade project)

Implementation of the LIU upgrade will take place during the second long LHC shutdown (LS2) in 2019/20

With the LIU program put in place, the injectors will be enabled to satisfy the needs of the High-Luminosity LHC

The Future is Bright…

Thank you very much for your attention