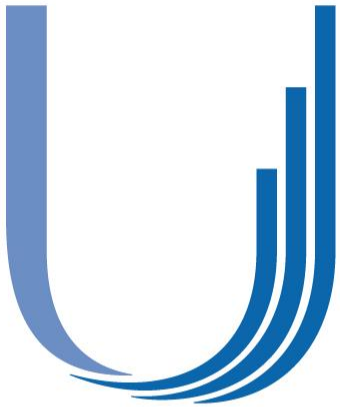
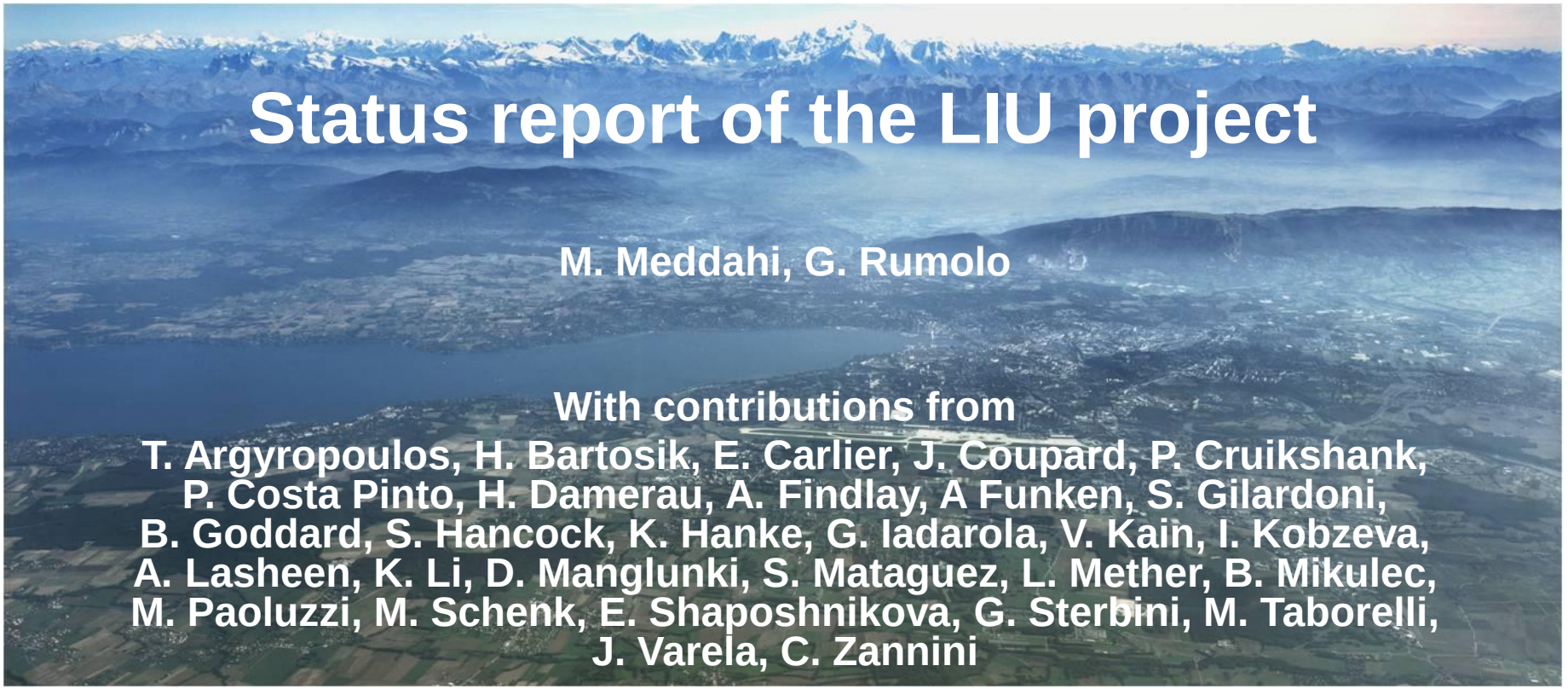


LHC Injectors Upgrade



LHC Injectors Upgrade

Status report of the LIU project

M. Meddahi, G. Rumolo

With contributions from

T. Argyropoulos, H. Bartosik, E. Carlier, J. Coupard, P. Cruikshank, P. Costa Pinto, H. Damerau, A. Findlay, A Funken, S. Gilardoni, B. Goddard, S. Hancock, K. Hanke, G. Iadarola, V. Kain, I. Kobzeva, A. Lasheen, K. Li, D. Manglunki, S. Mataguez, L. Mether, B. Mikulec, M. Paoluzzi, M. Schenk, E. Shaposhnikova, G. Sterbini, M. Taborelli, J. Varela, C. Zannini

CERN

Outline

- **Introduction**
  - Goals and timelines of the LIU project
  - Outcome of Cost & Schedule Review in March 2015
- **Protons:**
  - LIU baseline as of 1/1/15 and expected Injector performance
  - Recent decisions on LIU pending items
  - Impact of proposed baseline changes
- **Ions:**
  - LIU baseline performance vs. HL-LHC desired parameters
  - Injector limitation and ongoing activities
- **Conclusions**

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Goals and means of the LIU project

Increase intensity/brightness in the injectors to match HL-LHC requirements

⇒ Enable Linac4/PSB/PS/SPS to accelerate and manipulate higher intensity beams (efficient production, space charge & electron cloud mitigation, impedance reduction, feedbacks, etc.)

⇒ Upgrade the injectors of the ion chain (Linac3, LEIR, PS, SPS) to produce beam parameters at the LHC injection that can meet the luminosity goal

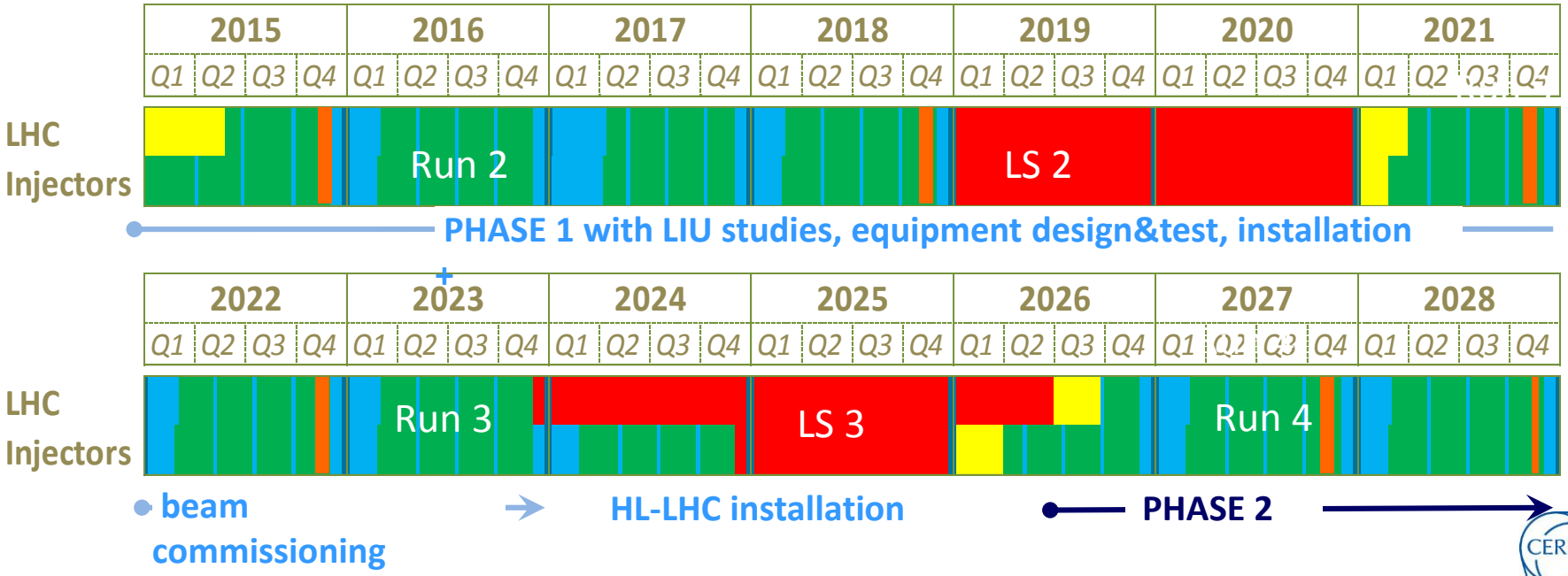
Increase injectors' reliability and lifetime to cover HL-LHC run (until ~2035!) closely related to CONSolidation

⇒ Upgrade/replace ageing equipment (power supplies, magnets, RF, EL, CV…)

⇒ Improve radioprotection measures (shielding, ventilation…)

Timelines of LIU

- **LIU machine studies during Run 2 until LS2**
  - Beam and simulation studies (e.g. space charge, e-cloud mitigation, instabilities)
  - Design, procurement and test of equipment (e.g. protection devices)
- **LIU installations and hardware work during (E)YETS's, but mainly during LS2**
- **Beam commissioning of LIU beams**
  - **Pb ion beams** need to be ready by **2021 Pb-Pb ion run**
  - **Proton beams** during **Run 3** to be ready after **LS3**



LIU proton baseline as of 1/1/15

- **PSB:**
  - Double brightness with injection from Linac4
  - Acceleration to 2 GeV with upgraded main C02+C04 RF systems or replacement by Finemet cavity based RF system, and new main power supply

- **PS:**
  - Injection at 2 GeV to mitigate space charge
  - Newly installed and upgraded longitudinal feedbacks (impedance reduction and against CBI)

- **SPS:**
  - Power upgrade of the main 200 MHz RF system (plus double available 800 MHz voltage, and new LL RF system)
  - Electron cloud mitigation through a-C coating (baseline) or beam induced scrubbing
  - Removal of limits of beam dump and protection devices

LIU ion baseline as of 1/1/15

- **Source & Linac3:**
  - Increase beam current by improving Low Energy Beam Transport (LEBT)
  - Linac3 repetition rate: 5 Hz → 10 Hz
- **LEIR:**
  - Increase number of injections with increased beam cooling rate
  - Understand and mitigate large beam losses at RF capture
- **PS:**
  - Bunch splitting to produce 4 bunches with 100 ns bunch spacing
- **SPS:**
  - Mitigate beam degradation at flat bottom
  - Upgrade SPS injection system with 100 ns rise time
  - Longitudinal slip-stacking → 50 ns bunch spacing

Outcome of Cost & Schedule review 9-11/3/15

- **General remarks from reviewers**
  - Budgets are correctly assembled and adequate
  - Schedule is generally well defined and realistic
  - Significant ramp up of effort in the next 2 years requires close tracking of resources
  - General concern about retiring expertise / expertise availability
- **Linac4 recommendations**
  - RFQ spare
- **PSB recommendations**
  - Schedule the removal of old cables as soon as possible
  - Start installation of equipment for PSB upgrade as soon as possible to alleviate LS2 schedule problem

Presently mitigated by decision to postpone LS2 by 6 months and extend it by 6 months to reduce schedule risk

- **PS recommendations**
  - None
- **SPS recommendations**
  - Items for cost saving (1) partial aC coating (2) internal instead of external new beam dump
  - Include the shielding of SPS flanges in the LIU baseline (impedance reduction)

Outcome of Cost & Schedule review 9-11/3/15

- **IONS remarks & recommendations**
  - The requirement for the ion upgrade of the injectors is not well understood. Luminosity goal and number of Pb-Pb runs on which this has to be delivered need to be defined. A common point and exact specifications could not be achieved during the meeting
  - The path to a higher Pb intensity is not clear due to an intensity limit in LEIR. Beam studies to understand this limit are required before the upgrade plan can be finalised
  - No clear mitigation plan has been identified if the intensity limit in LEIR cannot be resolved
  - A new 100 ns SPS injection kicker provides only marginal increase in luminosity

A combined LIU/HL-LHC effort was launched to define the scope of the upgrade and translate it into desired sets of beam parameters at the SPS extraction

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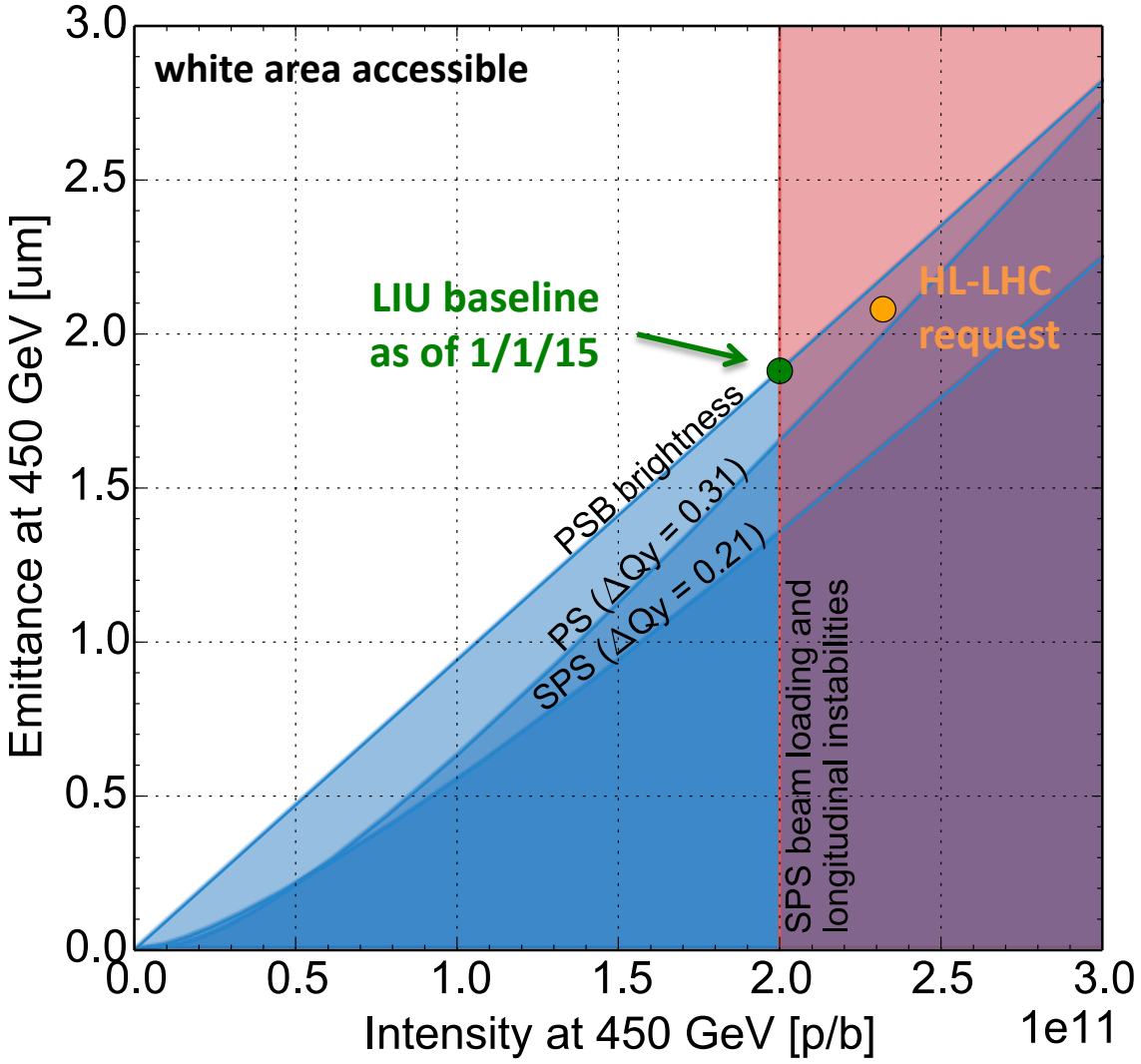
LIU performance reach



- **Baseline as of 1/1/15**
  - Linac4 + 160 MeV PSB injection
  - 2 GeV PS injection energy
  - 200 MHz SPS RF upgrade
  - Full SPS aC coating
  - Upgrade of protection devices & SPS beam dump

budget	PS	SPS
losses	5%	10%
blow-up	5%	10%

… based on 2012 experience

Review on Finemet cavities

- **Finemet cavities for PSB**
  - **Scope:** Upgrade the RF system by replacing existing C02 and C04 cavities by Finemet system to reach extraction energy of 2 GeV; possibility of replacing also C16 under st
  - **MD results:** All present means to manipulate the beam demonstrate igital LLRF version for Finemet in operation on R4, including impedance rmonics
  - **Committee comments:** The Finemet systems will bility for allocating the voltage at most pertinent frequency and become possible

Finemet technology as baseline has been fully endorsed for the PSB (including the replacement of C16) and for the PS

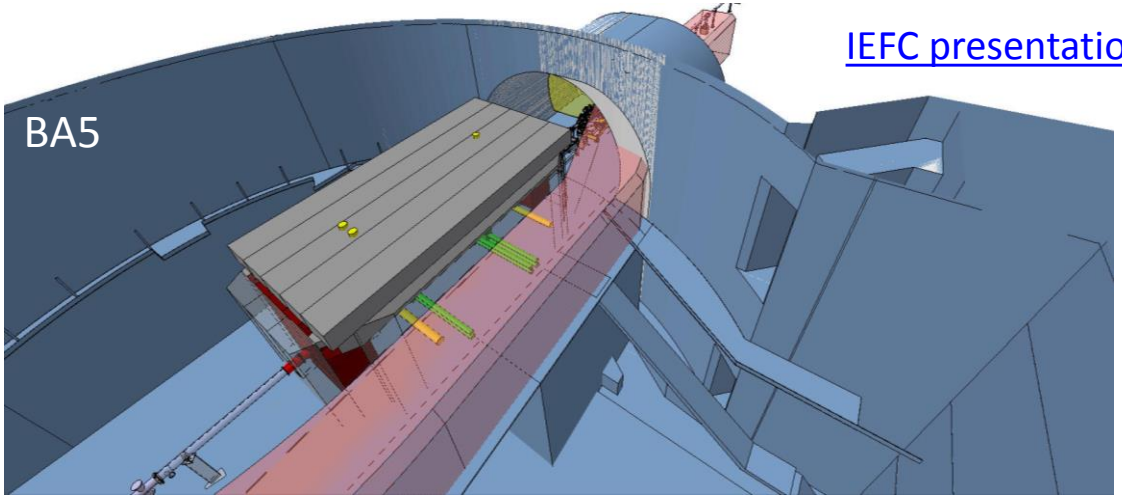
- **Finemet cavity a or PS**
  - **Scope:** and longitudinal damper to cure coupled-bunch instabilities with LHC acceleration and on flat-top to reach LIU performance
  - **MD result** amping of coupled-bunch oscillations with Finemet cavity was demonstrated giving confidence in the concept and the defined specifications
  - **Committee comments:** Implementation shall proceed as soon as possible to get benefits before LS2 and simplify setting-up after LS2

full review on Indico

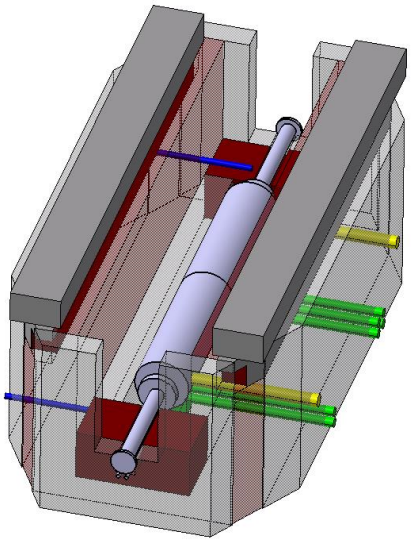
New SPS beam dump system in LSS5

- **Motivations**
  - More robust dump block (TIDVG) design to cope with LIU beams and high power FT beams
  - Decouple dump from LSS1 injection systems to reduce residual dose rate

- **Internal beam dump as new LIU baseline**
  - Keep all robust features of existing dump system: simple and reliable
  - One absorber block for all beams from 14 to 450 GeV (no 'forbidden energy zone')
  - Specially designed containment/shielding volume → significantly reduced activation and dose to personnel to improve ALARA during interventions on dump system and surrounding equipment
  - Concept fully validated including feasibility of installation during LS2 (some points still under discussion: decommissioning of water cooled cables, new locations for instrumentation in LSS5)

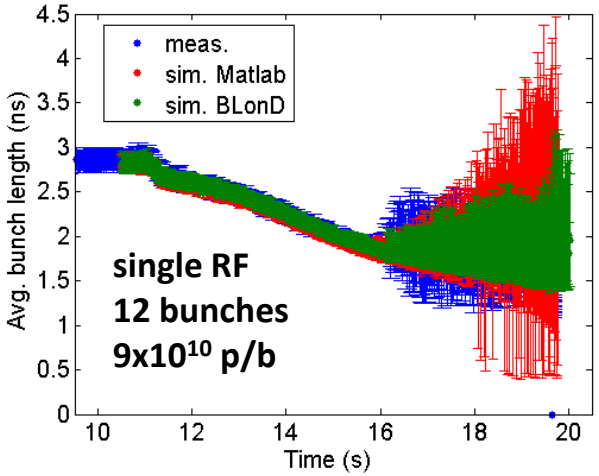


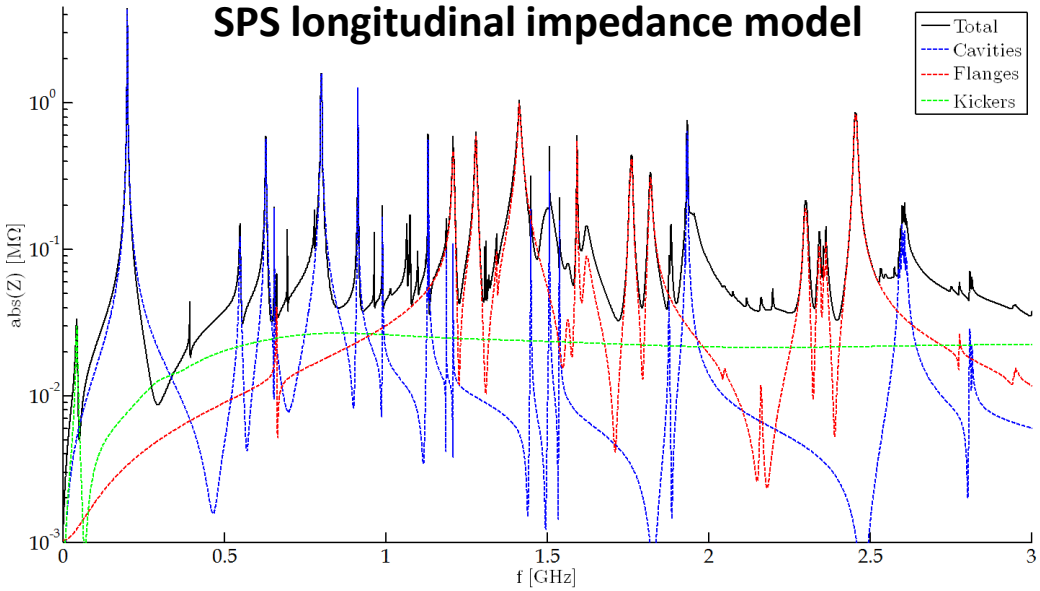
IEFC presentation



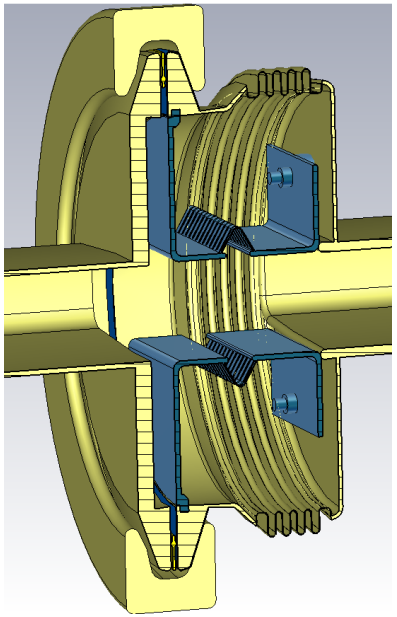
SPS longitudinal impedance reduction

- **Longitudinal instability during ramp and flat top**
  - Expected to limit the LIU performance even after RF upgrade
  - Lower threshold for multi-bunch compared to single bunch
- **Search for critical longitudinal impedance**
  - Large contribution to total impedance from vacuum flanges
  - **Shielding the vacuum flange transitions** proposed solution

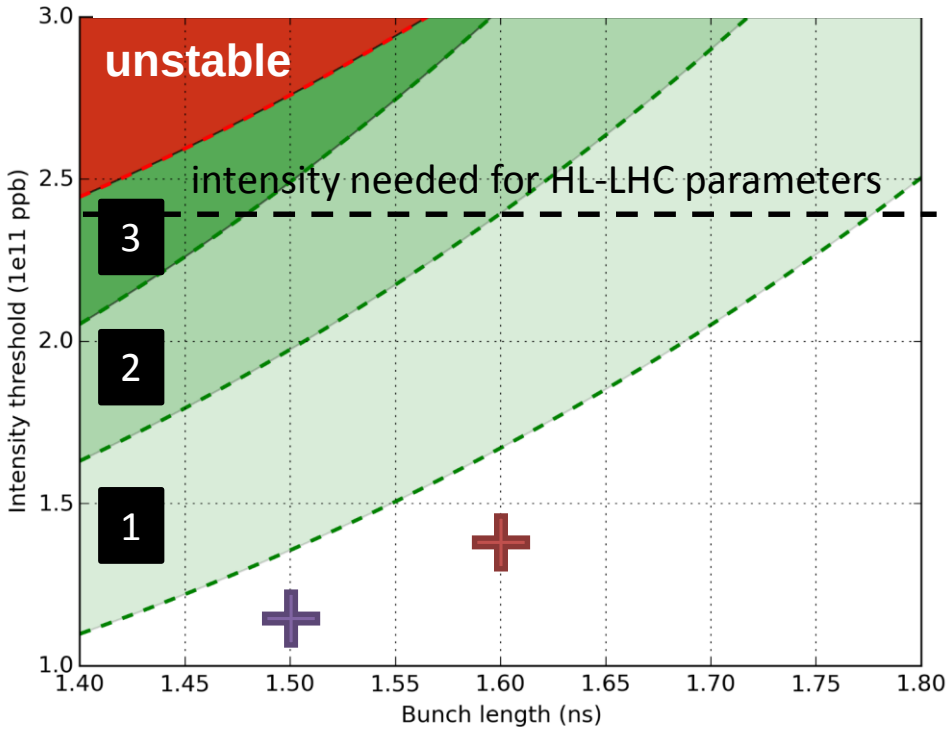




QF-type flange shielded



SPS longitudinal impedance reduction



36 bunches measured instability threshold (2015)

72 bunches measured instability threshold (2012)

Impedance reduction gain:

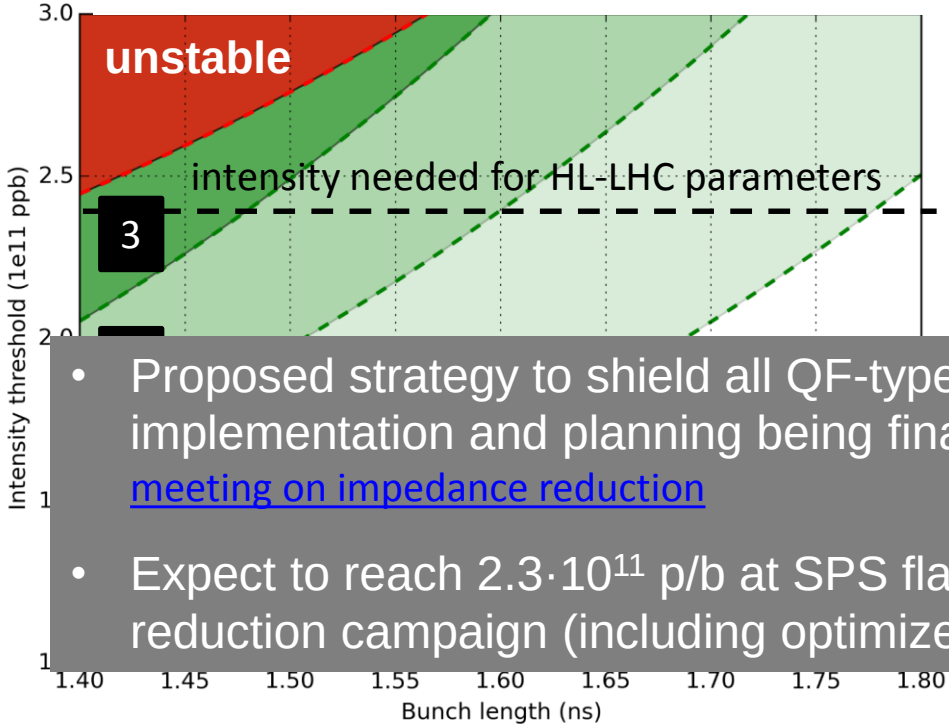
1: Flanges QF-type + HOM 630MHz

2: (1) + MKP

3: (2) + Flanges QD-type + other HOMs

- **Multi-bunch simulations (24 bunches) with double RF**
  - **Significant improvement of stability with shielded QF-type flanges together with damping of HOMs of 200 MHz cavity (which drive instability with slightly lower intensity threshold)**
  - Beneficial effect from shielding QD-type flanges at much higher intensities
  - No simulations with feed-back and damper loops yet

SPS longitudinal impedance reduction



+ **36 bunches measured instability threshold (2015)**

+ **72 bunches measured instability threshold (2012)**

Impedance reduction gain:

30MHz

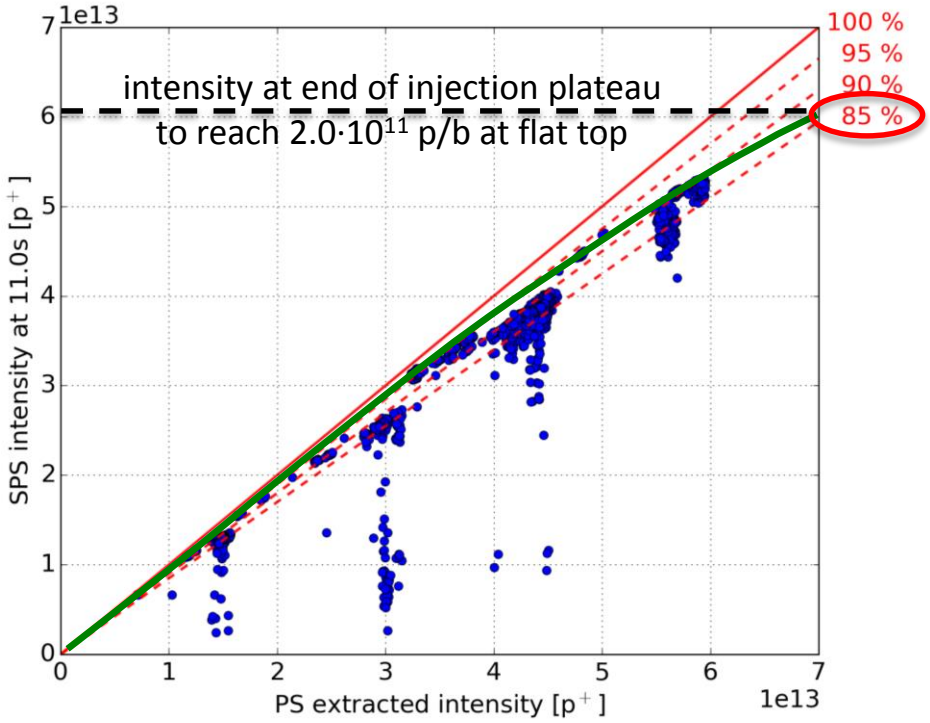
ther HOMs

- Proposed strategy to shield all QF-type flanges – technical implementation and planning being finalized [LIU-SPS coordination meeting on impedance reduction]
- Expect to reach $2.3 \cdot 10^{11}$ p/b at SPS flat top after impedance reduction campaign (including optimized HOM damping)

- **Multi-bunch simulations (24 bunches) with double RF**
  - **Significant improvement of stability with shielded QF-type flanges together with damping of HOMs of 200 MHz cavity (which drive instability with slightly lower intensity threshold)**
  - Beneficial effect from shielding QD-type flanges at much higher intensities
  - No simulations with feed-back and damper loops yet

SPS scrubbing vs. coating review

- **Results from high intensity scrubbing runs 2015**
  - Horizontal coupled bunch instability can be stabilized with transverse damper, high Q' + Octupoles
  - No sign of e-cloud induced blow-up along the bunch train
  - **Impact on beam brightness (need to inject higher intensity to compensate for losses)**



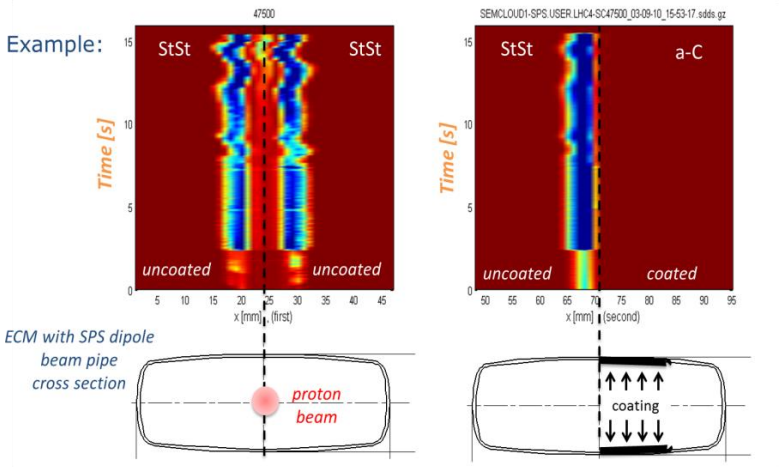
Extrapolation for 2·10^{11} p/b at flat top

- Expect 15% losses on injection plateau mostly due to e-cloud
- Assume losses at beginning of ramp + scraping remain ~5% (LIU RF upgrade)
- **20% total losses (~1.5·10^{13} p+/cycle)**
- **Compared to SPS loss budget of 10%, the additional 10% losses effectively result in 10% reduced brightness**

SPS scrubbing vs. coating review

- **Results from high intensity scrubbing runs 2015**
  - Horizontal coupled bunch instability can be stabilized with transverse damper, high Q' + **Octupoles**
  - No sign of e-cloud induced blow-up along the bunch train
  - **Impact on beam brightness (need to inject higher intensity to compensate for losses)**
  - With experience to date, LIU and HL-LHC performance goals not guaranteed with scrubbing only

- **Status of aC coating technology**
  - In general the technology is well developed
  - Suppression of e-cloud effect demonstrated
  - In-situ coating for MBB is being developed
  - Remaining issues for industrialization (e.g. cleaning with oxygen plasma prior to coat) being addressed



- **Review recommendation**
  - Make aC coating of MMB dipoles the baseline until there is high confidence that scrubbing can establish LIU and HL-LHC performance goals

[full review on Indico]

LIU-SPS proposed implementation strategy

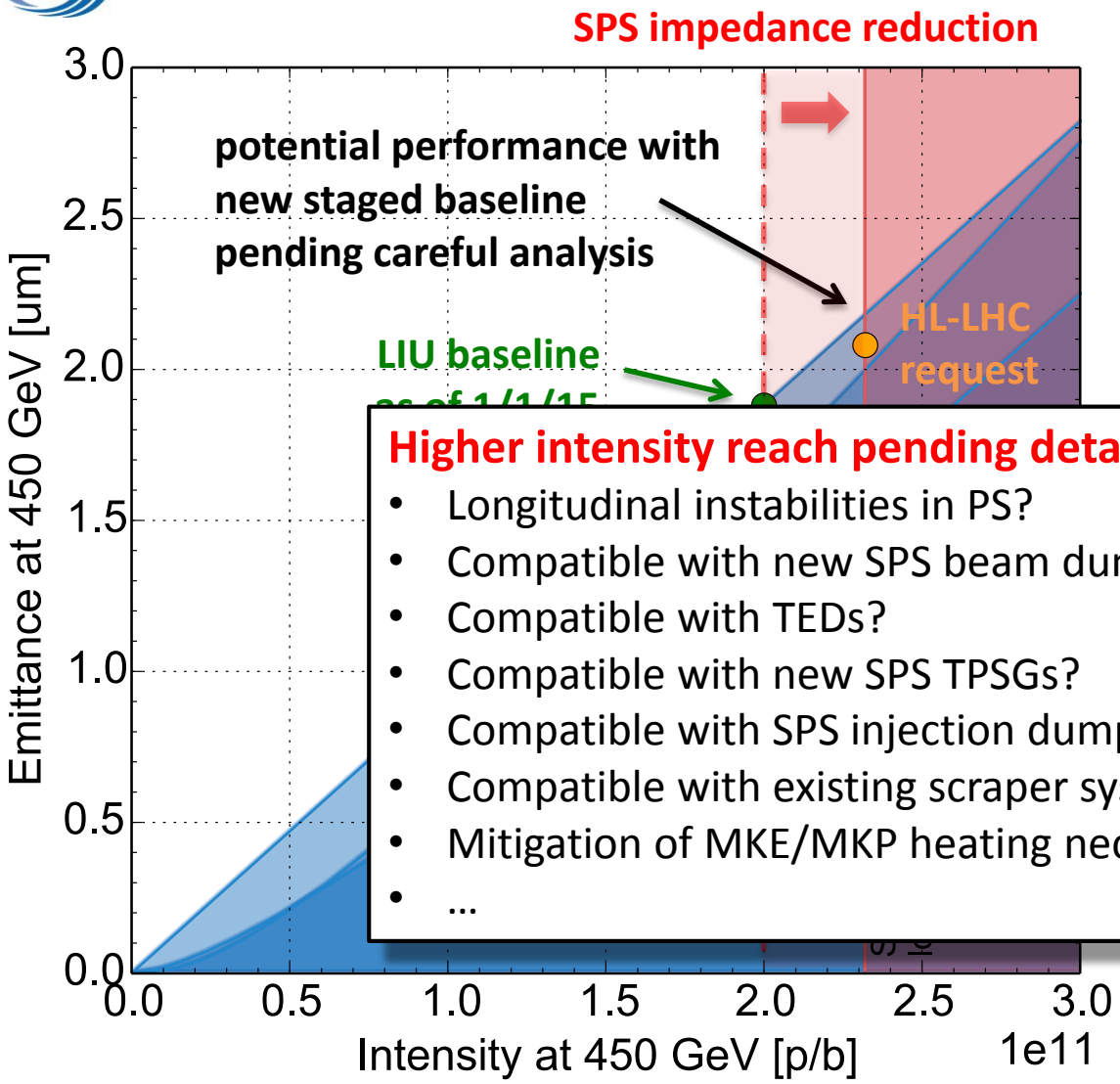
- **EYETS 16/17:**
  - Pilot (up to 1 arc) for coating QFs and QF SSS, in synergy with impedance reduction;
  - A few (4) MBB half-cells coated in-situ, to prototype the 'final' cleaning and coati chnology;
  - Replacement of some (10%) standard 156 mm drifts with coated cham
- **LS2:**
  - Complete coating of remaining QFs and QF S ith impedance reduction;
  - Pilot (1 arc) MBB coating, to debug f s and quality control;
  - Replacement of remainin rd drifts with coated chambers.
- **Run3:**
  - Evaluation of w ther these improvements, plus some improvements to the transverse damper and in combination with further scrubbing, are already enough to reach the performance target
- **LS3:**
  - If required, coating of remaining MBBs around the machine.

This strategy has been fully endorsed by the management

LIU-SPS Wideband Feedback system –US-LARP

- The goal of this important USLARP supported LIU-SPS project is to gain experience and develop the necessary expertise on how to build a wideband transverse feedback system and to demonstrate that it can damp intra-bunch motion for a 25 ns bunch train.
- Work is progressing as planned, in collaboration with John Fox' team – see presentation on Wed. 28/10 at 11h (W. Hofle / K. Li).
- A review is set for September 2016 to examine the results from the prototype system, the demonstration of its effectiveness and functioning and the future potential for deployment in SPS and other accelerators.
- A wideband feedback system is of great potential and the demonstration of its feasibility an important milestone on a path to a fully deployed system. When moving to the highest bunch intensities, new single bunch instabilities might be encountered and such a system is targeted to cure these. It is of high interest for the LHC, HL-LHC and as well for future accelerators.

Possible LIU performance reach



Higher intensity reach pending detailed analysis

- Longitudinal instabilities in PS?
- Compatible with new SPS beam dump system?
- Compatible with TEDs?
- Compatible with new SPS TPSGs?
- Compatible with SPS injection dump?
- Compatible with existing scraper system?
- Mitigation of MKE/MKP heating necessary?
- …

- **Baseline as of 1/1/15**
  - Linac4 + 160 MeV PSB injection
  - 2 GeV PS injection energy
  - 200 MHz SPS RF upgrade
  - Full SPS aC coating
- **Proposed new staged**

njection energy

PS RF upgrade

dance reduction (LS2)

S aC coating (LS2) +
ubbing (Run3)

+/-

maining aC coating
(LS3) if scrubbing not sufficient
to reach target parameters

Implications of proposed staged baseline

- **Direct consequences of limited SPS coating during LS2**
  - May need to inject (at least temporarily) very high intensities into the SPS in order to explore our desired beam parameters and accept larger losses
  - Need to study how to best cope with the losses → reinvestigate need for SPS collimation system (ongoing)
  - Need to check if there are limitations for injected intensity and beam brightness in the SPS (e.g. from injection dump)
  - Are the pre-injectors ready to deliver the higher beam intensity?

- **Staged approach gives some optimism for matching the HL-LHC requirements before LS3, with a path to the full solution to deploy in LS3 if needed**
  - Post-LS2 beam performance will steer possible further interventions in the injectors in the next (E)YETs and LS3
  - Compatibility of MBB coating with LS3 duration (12 months) and available resources to be checked
  - This implies that maybe the target parameters will be reached only after LS3

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Parameter table @ SPS extraction

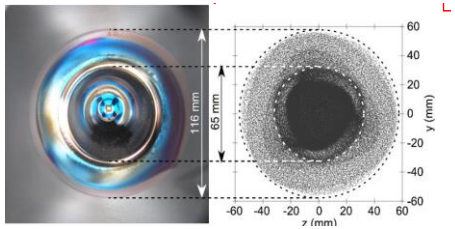
CASE	A	B	C	D	E
Parameters	**Request HL-LHC**	**LIU baseline**	**LIU Baseline and new SPS ion injection**	**LIU baseline with increased bunch intensity to reach C performance**	**HL-LHC operation without LIU Ion upgrade**
Bunch spacing (basic)	50 ns	50 ns	50 ns	50 ns	100/225 ns
Number of bunches	~1200	820	1200	820	420
Bunch intensity (RMS)	2.1×10^{8}	1.55×10^{8}	1.55×10^{8}	$\sim 1.75 \times 10^{8}$	2.2×10^{8}
Needed LEIR intensity upgrade	+90%	+40%	+40%	+60%	+0%
Normalised emittance (x and y) (mean)	1.3×10^{-6} m	1.1×10^{-6} m	1.1×10^{-6} m	1.1×10^{-6} m	1.1×10^{-6} m
Max. yearly achievable integrated luminosity	2.6 nb^{-1}	1.2 nb^{-1}	1.7 nb^{-1}	1.7 nb^{-1}	0.8 nb^{-1}

- HL-LHC parameters based EDMS document 1525065 v.0.3 by J. Jowett
- EDMS document 1533832 LIU beam parameters, in collaboration with J. Jowett (*in preparation*)

→ LIU could produce **up to 2/3 of the HL-LHC desired luminosity goal**, depending on the removal of the LEIR intensity limitation or staged SPS kicker upgrade

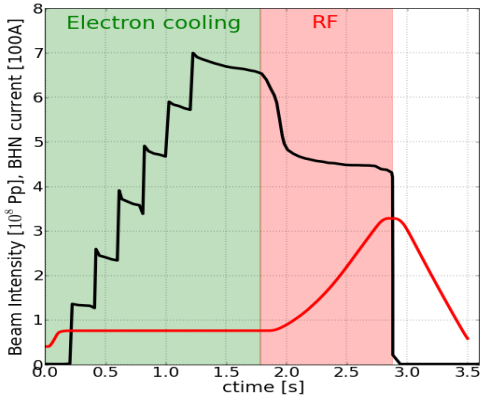
Main complex limitations

- **Linac3 reduced maximum current**

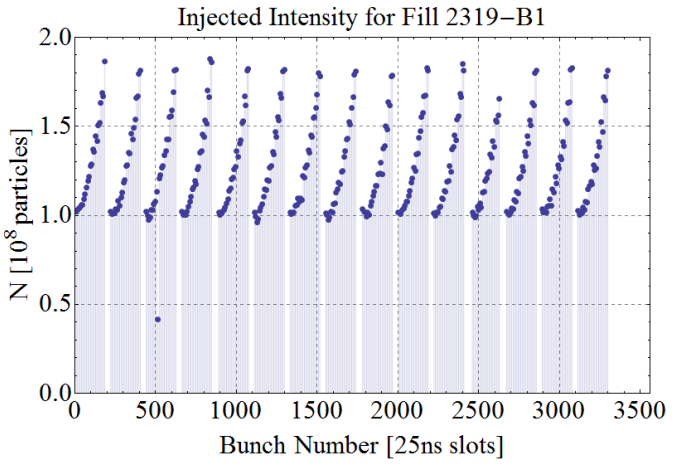


  - Larger number of injections in LEIR → longer cycles → longer SPS FB

- **LEIR maximum intensity due to losses at capture**
  - Bottleneck limiting maximum performances of the complex



- **Losses/emittance degradation at SPS FB due to IBS-TSK-like effect**
  - Intensity decreases along the batch imprinting pattern on LHC specific luminosity



Path of studies and actions

- **Linac3**
  - About 20% improvement in transmission in the low energy part expected by installing new electrostatic lens (Einzel lens) and increasing aperture between source and first solenoid (YETS 2015-16)
  - 10 Hz repetition rate operation to increase injection rate in LEIR (YETS 2015-16), before LS2 limited by CV, however extended testing possible

- **LEIR performance**
  - Main bottleneck is loss at RF capture. Mechanism still being investigated (space charge?)
  - Electron cooling with double current for faster cooling rate proved with Ar, further tests with Pb in 2016
  - Full machine model with detailed optics including impedance and e-cooler not yet available, planned for 2016 development

- **SPS flat bottom beam degradation**
  - Studies in 2012-13 showed that losses along the batch seems to be more caused by IBS or Touschek-like effect mixed with direct space-charge and RF-noise
  - More studies in 2015 on Q20, RF noise reduction, 2nd harmonic to increase longitudinal acceptance, bunch length sensitivity

- **SPS slip stacking**
  - No showstopper identified, implementation in LS2
  - Resources available in 2016 to develop LLRF, continue simulation work, study final bunch rotation
  - Tests foreseen prior to LS2 to investigate beam lifetime without phase loop, define the momentum aperture, test and optimise the RF programs

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  - 10 Hz repetition rate operation to increase injection rate in LEIR (YETS 2015-16) [illegible] LS2 limited by CV, however extended testing possible

- **LEIR performance**
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  - Electron cooling with double current for faster [illegible] in 2016
  - Full machine model with detailed optics [illegible] available, planned for 2016 development

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  - Resources available in 2016 to develop LLRF, continue simulation work, study final bunch rotation
  - Tests foreseen prior to LS2 to investigate beam lifetime without phase loop, define the momentum aperture, test and optimise the RF programs

- Extensive program in place to study the current intensity limitation in LEIR
- Progress on the understanding by the end of the year – important input for the next steps

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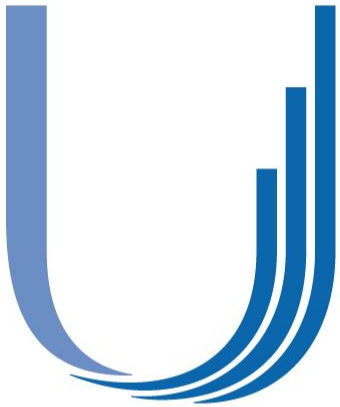
Conclusions

- **LIU baseline program as of 1/1/15**
  - Protons: Can produce beams with the desired brightness, but intensity 15% lower
  - Ions: Clarify scope together with HL-LHC

- **New for protons**
  - Finemet cavities endorsed as baseline for PSB (C02, C04 and also C16) and PS
  - SPS impedance reduction to be included in baseline
    - Prospect of extending intensity reach close to HL-LHC request pending careful analysis of other potential limitations
  - New internal dump for SPS
  - Staged deployment of aC coating for MBB chambers in synergy with impedance reduction
    - Maybe HL-LHC target parameters achieved only after LS3 and possibly need to cope with increased losses in SPS during Run3

- **New for ions**
  - Joint LIU/HL-LHC exercise to define set of desired beam parameters at LHC injection and upgrade scenarios → Target up to 2/3 of desired integrated luminosity
  - Extensive program of studies in place to analyse present injector limitations



LHC Injectors Upgrade

Thank you for your attention!