

Summary of LIU 1/2 Day Space Charge Workshop

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Abstract

On the 7th of October 2015 we have convened at CERN an internal review on space charge studies for the LHC pre-accelerators in view of the LIU project. There have been two introductory talks and one talk for each of the machines: LEIR, PSB, PS & SPS. The general outcome of the SC experimental and simulation studies starting in 2011 and future studies up to the end of 2018 are being summarized in this note.

Introduction

Since spring 2011 we have started the CERN SC working group. The idea has been to revive the expertise in our group on SC issues and from the start in conjunction with the non-linear dynamics of the various machines. During these 4.5 years we have completed the preparation phase for the SC LIU studies while at the same time doing as much SC studies as possible. The main issues have been:

- Choose an adequate code for our studies both for the frozen and self-consistent mode.
- Benchmarking of the codes of interest using the GSI benchmarking suite.
- Preparing relevant machine experiments to benchmark our codes. In particular we have defined “master” experiments for each machine that we will study with our world-wide collaborators.
- Collaborating with SC experts from various laboratories around the world. In particular, convening with them at international workshops (up to now 4).
- Two weekly meetings to discuss the progress of work and to spread the knowledge about SC & nonlinear issues.
- A total of 13 educational talks have been given from local and international experts from our community.

We have agreed to have this internal review on the 7th of October and 31 participants have registered for this event. Besides the 6 talks that have been given we also convened to prepare an ad-hoc summary. Like for all other SC workshops at CERN we also need a written document to properly document the achievements of the past years and a plan for detailed studies that are foreseen during the upcoming 3 years after which the LIU project will most likely be terminated.

In this note we present a section about LIU requirements together with the study progress report. A second section is dedicated to future studies required by LIU and a last section discusses detailed future studies with a preliminary timetable.

Results from the Preparatory LIU Phase – 2011-2015

LIU SC Requirements

From the LIU perspective there are 2 main points:

- (I) Space charge plays a key role at several stages along the LHC injection chain
 - PSB: Injection process; determines achievable brightness.
 - LEIR: Possible key role in losses at RF capture/start of acceleration.
 - PS: Injection plateau: Do we fully understand the present limitation and extrapolate for future operation? Handling of longitudinal parameters from the PSB.
 - SPS: Injection plateau for both protons and ions.
- (II) Space charge determines the LIU beam performance and predictions need to be addressed with:
 - Machine studies.
 - Simulations with existing codes.
 - In-house development of new tools to explore the regimes of our interest.

CERN's SC Working Group

The main work items for the SC Working Group have been code, machine modeling and experiments:

- (I) Codes
 - MAD-X has been equipped with SC in frozen and adaptive mode. Presently, a benchmarking is in progress for the PS “master” experiment together with “Micromap”, a truly frozen SC code from GSI.
 - The code “pyORBIT” is our main workhorse for self consistent SC treatment but it also allows for intermediate set-ups including the frozen mode. A full benchmarking will be performed by our PhD student Malte Titze.
- (II) Machine Models

- A lot of progress has been done concerning the linear & non-linear models of our accelerators.
- These models require precision measurements at the machines, either magnetic measurements and/or construction of effective models via the proposed and partially performed CERN “master” experiments.

Studies at the PSB

- (I) Main question: can we achieve 2x brightness with Linac4?
- Simulations finished. They confirm so.
 - Confirmed linearity of the curve emittance vs. intensity & dependence on longitudinal emittance.
 - Explored different working points to get extra margin.
 - Influence of the injection chicane on beam dynamics with space charge studied.
 - Full blown simulations including also multi-turn H- injection & optimized longitudinal parameters completed (as of today).
 - Benchmarking with current injection started: new set of measurements followed by simulations.
- (II) Studies for High intensity beams (ISOLDE): what is the max intensity within a given emittance and losses constrains? Ongoing.
- Proposal of a new collimator to replace the existing aperture restriction.
 - Study of shaving at the new collimator to achieve low emittances.
- (III) Experiments at 160 MeV and benchmark with PTC-Orbit completed.
- Interaction with half-integer
 - Interaction with the integers
 - Effect of chromaticity
- (IV) Tune scans to identify machine resonances done.
- (V) Linear Model of the PSB available, but should be updated after the realignment campaign of 2013-2014.
- (VI) Code development:

- Extensive benchmark and debug of “PTC-Orbit” done.
- "PTC-Orbit" still our preferred option until issues with the PTC interface will be finalized in “pyOrbit”.

Studies at the PS

- (I) Space-charge limit understood:
- (II) 8th order systematic resonance in vertical plane and integer limiting maximum Laslett tune shift to about $|0.31|$ considered maximum budget allocated for LIU beam production, but compatible with LIU needs.
- (III) Mitigation measurements, on top of increase of the injection energy to 2 GeV being explored and should be explored in the future:
 - Longer bunches.
 - Hollow bunches.
 - Different integer tunes at injection.

Studies at the SPS

- (I) Main experimental results:
 - Space charge itself acceptable for LIU parameters for standard 25 ns beam and BCMS beams.
 - No limiting resonance up to $Q_y = 20.33$ found tune spreads of up to 0.33 possible?
 - Detailed measurements of the machine non-linearities.
- (II) Effective non-linear model
 - Measurements of non-linear chromaticity (Q_{20} & Q_{26}).
 - Measurements of amplitude detuning (Q_{20} & Q_{26}).
 - Determine systematic multipole components in main magnets to reproduce measured non-linearities.
- (III) Space charge benchmarking with single bunch beams
 - Experiments with single bunch high brightness beams close to 3rd and 4th order resonances excited in a controlled way (observables are emittance growth and losses).

- Tune scan (static tunes) with single bunch high brightness beams in Q20 operational conditions to identify interesting working point region and detrimental resonances (observables are emittance growth and losses during a few seconds beam storage).

Studies at LEIR

Intensity machine studies have been performed but the cause of large losses during RF capture have not yet been understood. In particular, we do not yet know if these losses are caused by SC.

LIU Requests – 2015-2018

(I) PSB: Request from LIU: Double the brightness

- Not feasible today, needs injection at 160 MeV
- Ok from simulations (and good benchmark code Vs. measurements at 160 MeV).
- Measurements & code benchmark of the present 50 MeV injection, to validate the simulations, required and ongoing.
- Exploitation of the non-linear correctors, available but not used, to be explored. Measurements and simulations required.

(II) PS: Request from LIU: SC tune spread of at least 0.31 at 2 GeV

- Current achievement: 0.31 at 1.4 GeV.
- Conjecture: interaction between SC and non-linearities are equivalent between the 2 injection energies, margin required.
- Margin: hollow beam; different integers at injection; different injection optics, simulation required.
- Interaction between SC and head-tail instability, simulations required including SC direct, instability and feedback.

(III) SPS: Request from LIU: SC tune spread of 0.21 for 25 ns beam

- What is the brightness limit for other beam variants (e.g. 8b+4e)?
- Current achievement: 0.21 with 50 ns beam. Same needed for 25 ns beam (potentially in presence of electron cloud).
- The 25 ns beam with the desired brightness is not yet available from pre-injectors.

- Detailed MDs at SPS being performed to construct a trustworthy effective model with the aim of simulating the case of the 25 ns beam including electron cloud. The brightness limit for other beam variants will be studied with single bunch beams.

Future Systematic Studies – 2015-2018

SC Working Group

(I) Code development

- Complete the porting of all “PTC-ORBIT” features to the new “pyORBIT” PIC code.
- A “SixTrack” SC tracker is being developed that may allow for best speed for the frozen mode.
- Development work is continuing for our own PIC SC code “Py-HEADTAIL”.

(II) Systematic SC Studies should now be performed for our machines at least for the next 3 years. Planning and discussions of the results will continue on a regular basis in the bi-weekly SC WG meetings.

(III) To this end we have two PhD students and a fellow as of middle of 2016.

(IV) We have also plans for optimization of our computer resources: Ideally we are hoping to get access to 50% of a 4'000 core machine which is in a discussion phase in the IT department. Compared to our present cluster this would allow a 5.6 speed-up and 10 jobs in parallel. A smaller cluster at CNAF for 2/3 jobs (max 500 cores) should be 2 times faster.

LEIR & SPS: Ions – 2015-2018

(I) LEIR:

- Beam parameter characterization along flat bottom and during capture/start of acceleration.
- Dynamic working point scan on flat bottom (“loss maps”) to identify relevant resonances.

- Dependence of beam lifetime on transverse emittance (using blow-up by transverse damper or reduced e-cooler efficiency).
- Study RF capture on different RF harmonics configurations (bunch lengthening, shortening, different harmonics).
- Identify if space charge plays a role in the intensity limitation.

(II) SPS:

- Try to identify contribution of space charge on losses and blow-up at flat bottom.
- Calculate and estimate the expected tune spread from space charge.
- Experimental working point scan on long injection plateau with single bunch and multibunch beams (using bunch-by-bunch wire scanner measurements).
- Impact of “RF noise” from fixed frequency operation on losses.
- Comparison of the Q20 & Q26 optics.

PSB

(I) Curve emittance versus intensity with H- injection (mid 2016):

- Systematic simulations with injection chicane (done).
- Benchmark at 50 MeV:
 - Measurements (done).
 - Simulations including the present MT injection, model available, with no RF.
 - Model adiabatic RF capture in “PTC-ORBIT” / “pyOrbit” (early 2016).
 - Full benchmark code vs. measurements to give final validation of simulation results (mid 2016)

(II) High intensity and loss control (end 2017):

- Specify parameters for the new collimator (absorber) (end 2015).
- MDs finished (end 2016).
- Systematic studies concluded (end 2017).

(III) Linear and non-linear optics model(end 2018):

- Kick-response, needs to be redone after the realignment campaign (early 2016).
 - Demonstrate Turn-by-turn with AC Dipole excitation (end 2017).
 - Build non-linear model and provide resonance compensation scheme (end 2018)
- (IV) Getting extra-gain for LIU beams (end 2018):
- Effect of multipoles correctors (end of 2017).
 - Optimize machine working point including chromaticity (end 2018).
- (V) Effect of space-charge on instabilities (end 2018).
- (VI) Instrumentation: Most of the studies and measurements rely on:
- Turn-by-turn pick-up electronics in the ring, commissioning on-going.
 - Robustness of injection pick-ups measurements, under study.

PS

- (I) $8Q_v=50$ Intensity Decay
MDs foreseen, Simulations with full model, early in 2016.
- (II) Integer Resonance
MDs foreseen, with Simulations, early in 2016.
- (III) Single Particle Resonance Modeling
MDs foreseen, with Simulations, second part of 2016.
- (IV) Influence of Injection Bump on Resonance with Space Charge
no MDs foreseen, with Simulations, to be done 2015.
- (V) 7-7 Injection Tunes
MDs foreseen, Simulations with full model, to be done 2015.
- (VI) Repeat Scan vertical Emittance Blow-Up versus Laslett and versus Losses with Chromaticity corrected and Damper on
MDs foreseen, no Simulations, second part of 2016.

SPS – Protons

(I) Main questions to be answered

- Can we achieve and preserve the required brightness with 25 ns beams?
 - Interplay between space charge and electron cloud effects.
 - What is the optimal working point to minimize losses in presence of e-cloud? (working point changed in the past to optimize for space charge + e-cloud: G. Arduini et al. 2006).
 - How much can we reduce losses in presence of space charge and e-cloud (staged coating)?
- Can we cope with even higher beam brightness?
 - What is the maximum tune spread with acceptable losses and emittance growth for alternative beam production schemes (e.g. 8b+4e)?
 - What are the limiting resonances for Q_y larger than 20.25?
 - What is the optimal working point?
- What is the loss mechanism on flat bottom?
 - How do the losses scale with brightness and with intensity?
 - What can we do to minimize the losses?
- Can we reproduce the experimental observations in simulations?

(II) Studies 2015 – 2016

- Benchmarking experimental results with simulation codes (starting with frozen model).
- Study scaling of losses with beam parameters (transverse emittance, brightness, intensity, longitudinal emittance, ...).
- Try to understand and reproduce experimental observations using the SPS effective model established in previous item.
- Compare different space charge solvers and identify most suitable approach for studying beam behavior on long flat bottom.
- Determine maximum space charge tune spread compatible with allocated budgets for blow-up and losses.

(III) Studies 2015 – 2018

- Interplay between space charge and e-cloud

- Experimental tune scan studies to identify the best working point for high brightness in presence of electron cloud.
- Systematic experimental studies to understand the loss mechanism on SPS flat bottom (single high brightness bunch compared to 25 ns beams, influence of beam size, ...).
- Simulation campaign using effective SPS machine model including space charge and “best guess” e-cloud distribution around the machine.
- Impact of space charge on TMCI threshold
 - Experimental studies on the dependence of threshold on beam brightness.
 - Simulation campaign using existing SPS transverse impedance model.
- Q22 optics
 - Experimental tests of Q22 optics to demonstrated feasibility in case need to relax requirements on RF power during the low energy part of the ramp in Q20.
 - Study of high brightness beam performance