LEBT lines: simulations and experimental results

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Outline

1. **Introduction**
2. **The LIPAc source & LEBT commissioning**
3. **SILHI source & LEBT commissioning**
4. **Conclusions & Perspectives**

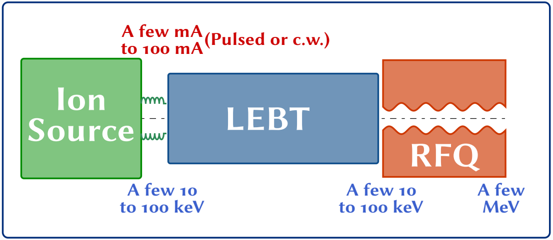
Outline

1. **Introduction**
   - Space charge compensation
   - LEBT simulations performed in CEA-Saclay
2. The LIPAc source & LEBT commissioning
3. SILHI source & LEBT commissioning
4. Conclusions & Perspectives

Introduction

Ion sources and LEBT in a linear accelerator

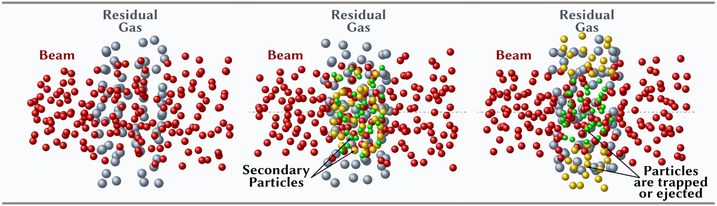
Ion source & LEBT
3 Introduction
SCC
LEBT Simulations
LIPAc injector
Requirements
LEBT Layout
Experimental setup
Experimental results 10% dc
Emittance vs Intensity
Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion
SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience
Conclusion



- **Beam production:** ion source
- **Beam transport, selection and adaptation:** LEBT
- **Beam qualification (usually):** beam diagnostics

- **Optimize** beam transmission through RFQ
- **Minimize** emittance growth
- **Deal** with high beam power

The space charge compensation (SCC) regime



Example

Consider a proton beam propagating through an H_2 residual gas.

$$p + H_2 \rightarrow p + e^- + H_2^+$$

With $n_{gas}/n_{beam} \gg 1$, with n_{gas} and n_{beam} the gas and beam density.

Space charge compensation is...

- Partial.
- Not uniform longitudinally and radially (nonlinear field).
- Time dependent (pressure dependent).

Ion source & LEBT

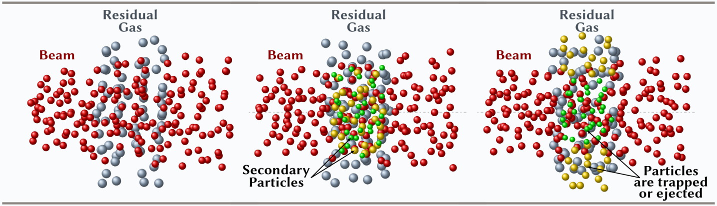
Introduction
4 SCC
LEBT Simulations

LIPAc injector
Requirements
LEBT Layout
Experimental setup
Experimental results 10% dc
Emittance vs Intensity
Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion

SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience

Conclusion

The space charge compensation (SCC) regime



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Ion source & LEBT
Introduction
4 SCC
LEBT Simulations
LIPAc injector
Requirements
LEBT Layout
Experimental setup
Experimental results 10% dc
Emittance vs Intensity
Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion
SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience
Conclusion

LEBT simulations performed in CEA-Saclay

Ion source extraction: Axcel INP

- Electrode geometry
- No space charge compensation

LEBT & RFQ: TraceWin

- Multiparticle PIC code
- Transport with space charge compensation dependant of z
- Transport with space charge compensation fiedl map

LEBT: SolMaxP or Warp (J.L. Vey, D. Grote et al.)

- Self consistant PIC code
- Beam interaction with residual gas and beam pipe
- Transport of beam and secondary particles

Introduction
SCC
5 LEBT Simulations
LIPAc injector
Requirements
LEBT Layout
Experimental setup
Experimental results 10% dc
Emittance vs Intensity
Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion
SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience
Conclusion

LEBT simulations performed in CEA-Saclay

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Ion source & LEBT

Introduction
SCC
5 LEBT Simulations

LIPAc injector
Requirements
LEBT Layout
Experimental setup
Experimental results 10% dc
Emittance vs Intensity
Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion

SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience

Conclusion

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Introduction
SCC
5 LEBT Simulations
LIPAc injector
Requirements
LEBT Layout
Experimental setup
Experimental results 10% dc
Emittance vs Intensity
Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion
SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience
Conclusion

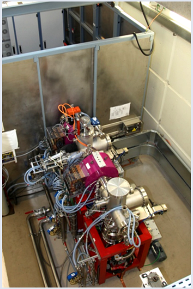
Outline

1. Introduction
2. The LIPAc source & LEBT commissioning
   - Requirements
   - LEBT Layout
   - Experimental setup
   - Experimental results 10% dc
   - Emittance vs Intensity
   - Emittance vs solenoids
   - Simulations conditions
   - Simulations results
   - LIPAc commissioning conclusion
3. SILHI source & LEBT commissioning
4. Conclusions & Perspectives

Linear IFMIF Prototype Aceelerator (LIPAc) source & LEBT

Requirements

- D^+ beam.
- Continuous beam.
- Energy: 100 keV.
- Intensity: 140 mA.
- Final emittance: $\leqslant 0.3\ \pi$ mm.mrad
- Twiss parameters at the RFQ entrance: $\leqslant$ 10% mismatch.

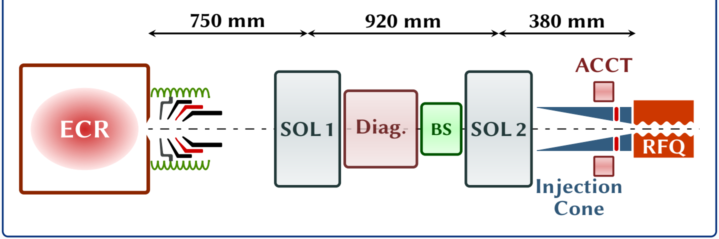


Commissioning

- Commissioning in Saclay: March to November 2012.
- Status: remounting in Rokkasho.
- Start of beam commissioning in Rokkasho: July 2014.

Ion source & LEBT

Introduction
SCC
LEBT Simulations
LIPAc injector
7 Requirements
LEBT Layout
Experimental setup
Experimental results 10% dc
Emittance vs Intensity
Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion
SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience
Conclusion



LIPAc source & LEBT setup

- Electron Cyclotron Resonance ion source (2.45 GHz), SILHI-like.
- 5 electrodes extraction system (electrode plasma: ϕ12 mm).
- LEBT with 2 solenoids.
- RFQ injection cone (ϕ12 mm) with an electron repeller.
- Space charge compensation regime.
- Total length: 2.05 m

Ion source & LEBT

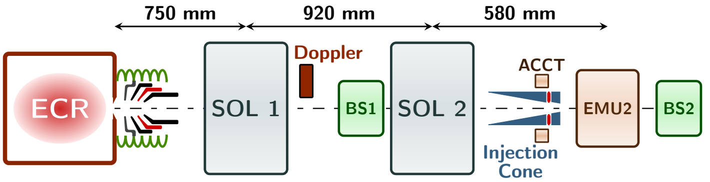
Introduction
SCC
LEBT Simulations

LIPAc injector
Requirements
LEBT Layout
Experimental setup
Experimental results 10% dc
Emittance vs Intensity
Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion

SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience

Conclusion

LIPAc source & LEBT
Experimental setup for beam commissioning



Beam Diagnostics

Beam intensity: ACCT, Beam Stop 1, Beam Stop 2 (auto polarisation).

Total extracted current: Current on the High Voltage power supply.

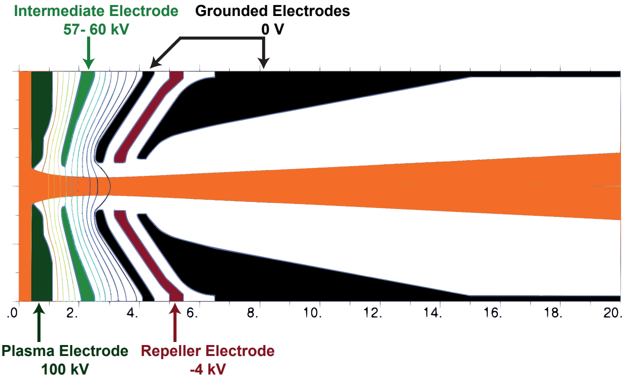
Emittance value: Emittance Measurement Unit (Allison scanner).

Beam proportion: Doppler shift measurement.

Ion source & LEBT
Introduction
SCC
LEBT Simulations
LIPAc injector
Requirements
LEBT Layout
Experimental setup
Experimental results 10% dc
Emittance vs Intensity
Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion
SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience
Conclusion

The ion source extraction system

Introduction
SCC
LEBT Simulations
LIPAc injector
Requirements
LEBT Layout
10 Experimental setup
Experimental results 10% dc
Emittance vs Intensity
Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion
SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience
Conclusion



Plasma electrode diameter: 12 mm

Experimental results at 10% duty cycle

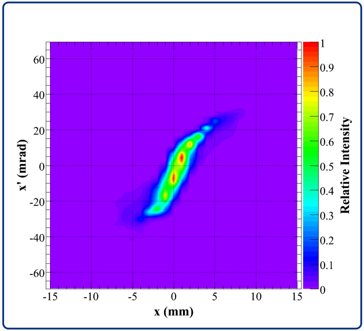
Ion source & LEBT

Introduction
SCC
LEBT Simulations

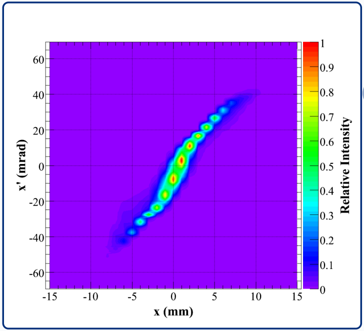
LIPAc injector
Requirements
LEBT Layout
Experimental setup
11 Experimental results 10% dc
Emittance vs Intensity
Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion

SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience

Conclusion



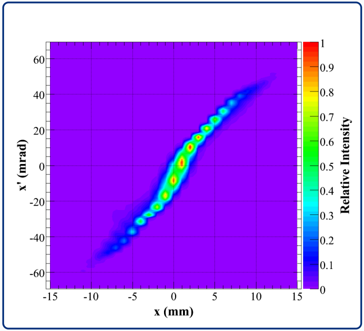
I_{BS} = 110 mA $\epsilon = 0.15\ \pi.mm.mrad$



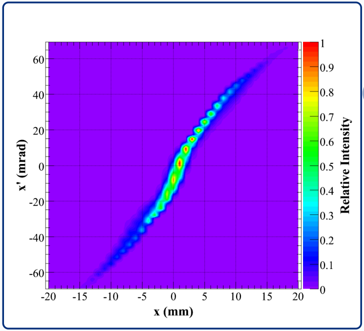
I_{BS} = 130 mA $\epsilon = 0.17\ \pi.mm.mrad$

Experimental results at 10% duty cycle

Ion source & LEBT
Introduction
SCC
LEBT Simulations
LIPAc injector
Requirements
LEBT Layout
Experimental setup
12 Experimental results 10% dc
Emittance vs Intensity
Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion
SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience
Conclusion



I_{BS} = 140 mA $\epsilon = 0.2\ \pi.mm.mrad$



I_{BS} = 150 mA $\epsilon = 0.26\ \pi.mm.mrad$

Experimental results at 10% duty cycle
Summary

Particles: D^+ – Extraction Voltage: 100 kV
Pulse Length: 10 ms – Repetition rate: 10 Hz.

I_{BS} (mA)	I_{Tot} (mA)	D^+ proportion (%)	U_{IE} (kV)	ϵ ($\pi.mm.mrad$)
100	125	80	40	0.14
110	133	83	40	0.15
120	141	85	40	0.16
130	148	88	40	0.17
140	155	90	40	0.2
150	165	91	40	0.26

Ion source & LEBT

Introduction
SCC
LEBT Simulations

LIPAc injector
Requirements
LEBT Layout
Experimental setup
13 Experimental results 10% dc
Emittance vs Intensity
Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion

SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience

Conclusion

Emittance vs total extracted current

Introduction
SCC
LEBT Simulations
LIPAc injector
Requirements
LEBT Layout
Experimental setup
Experimental results 10% dc
14 Emittance vs Intensity
Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion
SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience
Conclusion

I_{BS} (mA)	I_{Tot} (mA)	U_{IE} (kV)	Duty Cycle (%)	ϵ ($\pi.mm.mrad$)
110	133	40	10	0.15
100	134	40	30	0.14
140	155	40	10	0.2
120	151	40	30	0.19
140	170	40	30	0.39
140	170	43	30	0.32
140	170	43	50	0.33
140	176	42	cw	??

Need to increase U_{IE} for high total extracted current.

Emittance vs total extracted current

I_{BS} (mA)	I_{Tot} (mA)	U_{IE} (kV)	Duty Cycle (%)	ϵ ($\pi.mm.mrad$)
110	133	40	10	0.15
100	134	40	30	0.14
140	155	40	10	0.2
120	151	40	30	0.19
140	170	40	30	0.39
140	170	43	30	0.32
140	170	43	50	0.33
140	176	42	cw	??

Need to increase U_{IE} for high total extracted current.

Introduction
- SCC
- LEBT Simulations

LIPAc injector
- Requirements
- LEBT Layout
- Experimental setup
- Experimental results 10% dc
- Emittance vs Intensity
- Emittance vs solenoids
- Simulations conditions
- Simulations results
- Conclusion

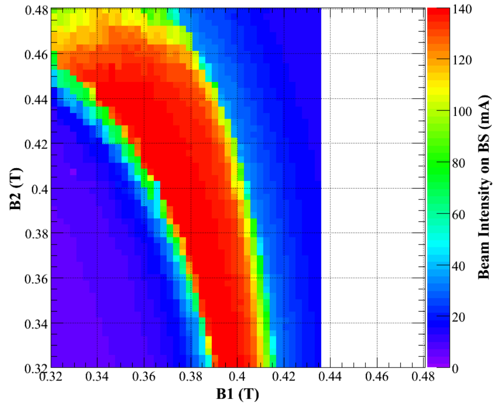
SILHI
- Requirements
- LEBT Layout
- Experimental results
- Simulations strategy
- Simulation results
- Simulation vs Experience

Conclusion

Emittance vs solenoids magnetic field

Introduction
SCC
LEBT Simulations
LIPAc injector
Requirements
LEBT Layout
Experimental setup
Experimental results 10% dc
Emittance vs Intensity
15 Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion
SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience
Conclusion

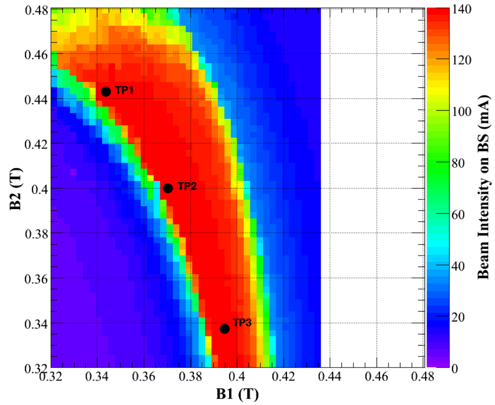
Extraction voltage: 100 kV – Duty cycle: 10%.



I_{BS} = 141 mA – I_{Tot} = 165 mA – U_{IE} = 43 kV

Emittance vs solenoids magnetic field

Extraction voltage: 100 kV – Duty cycle: 10%.



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Emittance vs solenoids magnetic field

Introduction
SCC
LEBT Simulations
LIPAc injector
Requirements
LEBT Layout
Experimental setup
Experimental results 10% dc
Emittance vs Intensity
Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion
SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience
Conclusion

Extraction Voltage: 100 kV – Duty cycle: 10%.
I_{BS} = 141 mA – I_{Tot} = 165 mA – U_{IE} = 43 kV

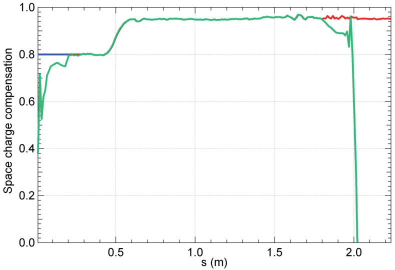
TP	B1 (A)	B1 (A)	ϵ ($\pi.mm.mrad$)
TP1	0.35	0.44	0.36
TP2	0.37	0.40	0.26
TP3	0.40	0.34	0.23

Simulation conditions

Introduction
SCC
LEBT Simulations
LIPAc injector
Requirements
LEBT Layout
Experimental setup
Experimental results 10% dc
Emittance vs Intensity
Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion
SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience
Conclusion

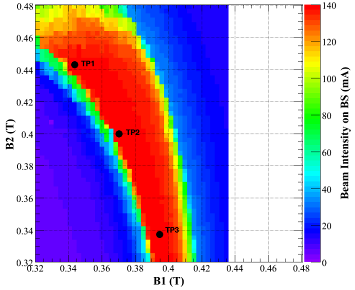
Codes used

- Source extraction with **Axcel-INP**.
- Space charge compensation profile with **SolMaxP**.
- Transport with **TraceWin**.

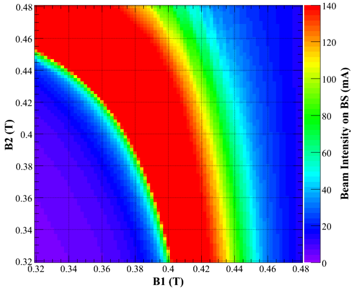


Adjustment of the space charge compensation profile to fit the data.

Solenoids variation
Experiment vs Simulation



Experiment

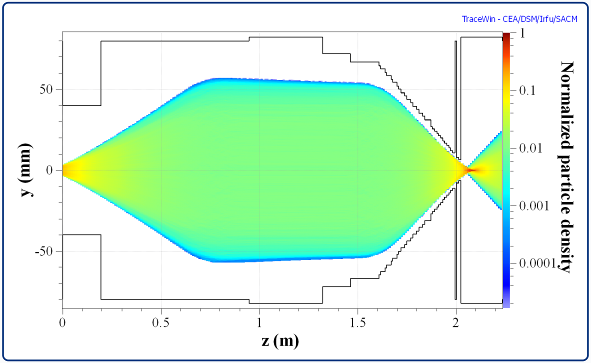


Simulation

Introduction
SCC
LEBT Simulations
LIPAc injector
Requirements
LEBT Layout
Experimental setup
Experimental results 10% dc
Emittance vs Intensity
Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion
SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience
Conclusion

Solenoids variation – Beam Density TP1

Ion source & LEBT
Introduction
SCC
LEBT Simulations
LIPAc injector
Requirements
LEBT Layout
Experimental setup
Experimental results 10% dc
Emittance vs Intensity
Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion
SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience
Conclusion



B1 = 0.35 A – B2 = 0.44 A

ϵ_{expe} 0.36 $\pi.mm.mrad$ – ϵ_{simu} 0.38 $\pi.mm.mrad$

Solenoids variation – Beam Density TP2

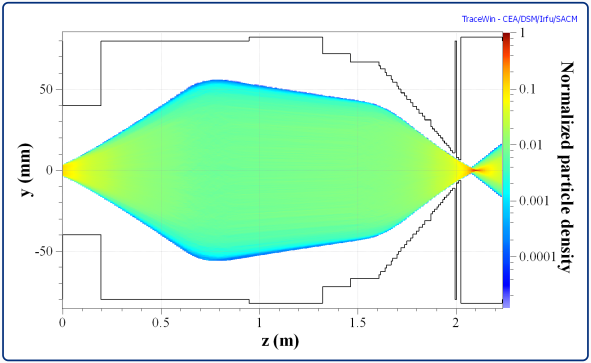
Ion source & LEBT

Introduction
SCC
LEBT Simulations

LIPAc injector
Requirements
LEBT Layout
Experimental setup
Experimental results 10% dc
Emittance vs Intensity
Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion

SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience

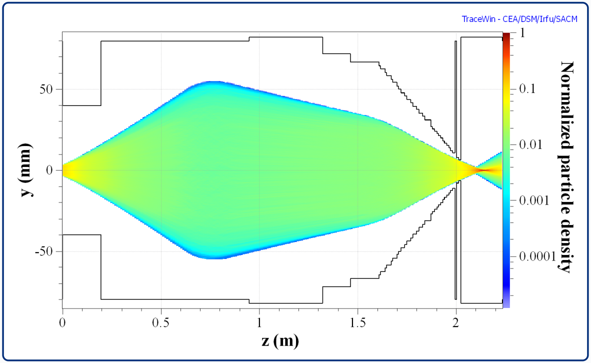
Conclusion



B1 = 0.37 A – B2 = 0.40 A

ϵ_{expe} 0.26 $\pi.mm.mrad$ – ϵ_{simu} 0.29 $\pi.mm.mrad$

Solenoids variation – Beam Density TP3



B1 = 0.40 A – B2 = 0.34 A

ϵ_{expe} 0.23 $\pi.mm.mrad$ – ϵ_{simu} 0.25 $\pi.mm.mrad$

Ion source & LEBT

Introduction
SCC
LEBT Simulations

LIPAc injector
Requirements
LEBT Layout
Experimental setup
Experimental results 10% dc
Emittance vs Intensity
Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion

SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience

Conclusion

LIPAc commissioning conclusion

Experiment

- An unprecedented 140 mA D^+ cw beam has been produced and transported.
- LIPAc injector meets the requirements at low duty cycle (and very close in cw).
- No showstopper to reach the specifications in cw.
- Beam commissioning should start in Rokkasho in July 2014.
- Emittance measurement will be done after the source

Simulation

- More work is needed to perform realistic self-consistent simulations.
- A numerical model gives reasonable agreement with experiments for beam intensity above 130 mA.
- Poor agreement with experiments below 120 mA.
- Simulation of source extraction system are not satisfactory.

Ion source & LEBT

Introduction
SCC
LEBT Simulations

LIPAc injector
Requirements
LEBT Layout
Experimental setup
Experimental results 10% dc
Emittance vs Intensity
Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion

SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience

Conclusion

Outline

1 Introduction

2 The LIPAc source & LEBT commissioning

3 SILHI source & LEBT commissioning
- Requirements
- LEBT Layout
- Experimental results
- Simulation strategy
- Simulation results
- Simulation vs Experience

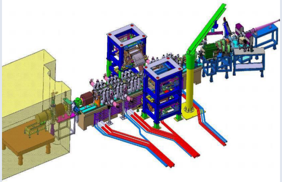
4 Conclusions & Perspectives

Requirements

- H^+ beam.
- Continuous beam.
- Energy: 95 keV.
- Intensity: 100 mA.
- Final emittance: $\leqslant 0.25\ \pi$ mm.mrad.

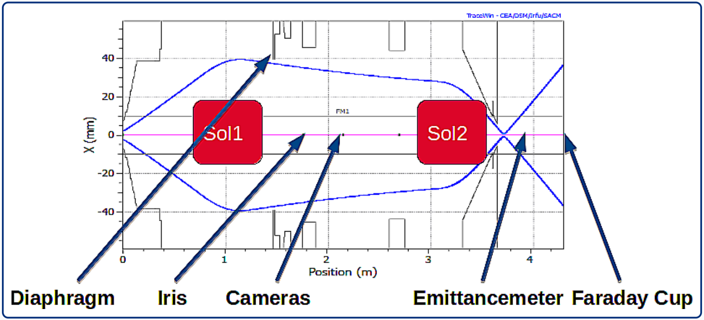
Commissioning

- Commissioning in Saclay: March to October 2013.
- Status: LEBT dismounted – RFQ mounting and cabling.
- Start of beam commissioning with RFQ: early 2015.



Ion source & LEBT

Introduction
SCC
LEBT Simulations
LIPAc injector
Requirements
LEBT Layout
Experimental setup
Experimental results 10% dc
Emittance vs Intensity
Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion
SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience
Conclusion



SILHI source & LEBT setup

- "Original" SILHI ECR ion source (2.45 GHz).
- 5 electrodes extraction system (electrode plasma: ϕ10 mm).
- LEBT with 2 solenoids.
- Space charge compensation regime.
- Total length: 3.5 m

Ion source & LEBT

Introduction
SCC
LEBT Simulations

LIPAc injector
Requirements
LEBT Layout
Experimental setup
Experimental results 10% dc
Emittance vs Intensity
Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion

SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience

Conclusion

Experimental results

Emittance vs Beam intensty

I_{FC} (mA)	SOL 1 (A)	Sol 2 (A)	ϵ ($\pi.mm.mrad$)
10	100	150	0.07
30	100	150	0.17
70	100	150	0.3
80	110	165	0.35

To be improved...

- Maintenance of the ion source has to be done to improve the performances.
- Alignment of the beam line to be checked.

Introduction
SCC
LEBT Simulations
LIPAc injector
Requirements
LEBT Layout
Experimental setup
Experimental results 10% dc
Emittance vs Intensity
Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion
SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience
Conclusion

Experimental results

Emittance vs Beam intensty

I_{FC} (mA)	SOL 1 (A)	Sol 2 (A)	ϵ ($\pi.mm.mrad$)
10	100	150	0.07
30	100	150	0.17
70	100	150	0.3
80	110	165	0.35

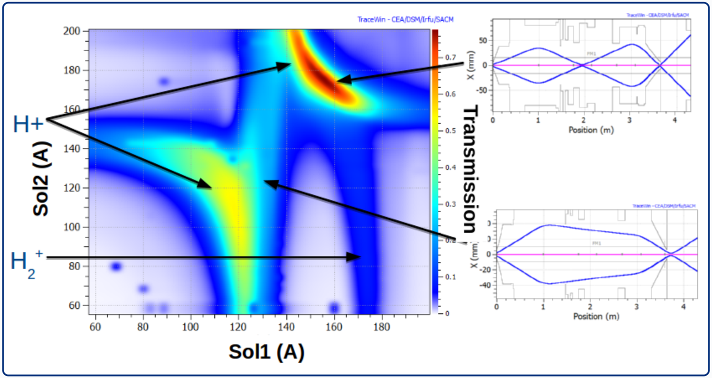
To be improved...

- Maintenance of the ion source has to be done to improve the performances.
- Alignment of the beam line to be checked.

Introduction
SCC
LEBT Simulations
LIPAc injector
Requirements
LEBT Layout
Experimental setup
Experimental results 10% dc
Emittance vs Intensity
Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion
SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience
Conclusion

Experimental results

Transmission vs Solenoid values



- Optimal LEBT transmission areas.
- Two focusing scheme can be seen.
- H^+ and H_2^+ beam dynamics.

Introduction
SCC
LEBT Simulations
LIPAc injector
Requirements
LEBT Layout
Experimental setup
Experimental results 10% dc
Emittance vs Intensity
Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion
SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience
Conclusion

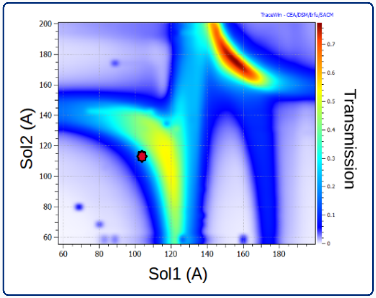
Simulation strategy

1. **Experiment: optimization** of the beam transmission through the cone. Solenoids values are fixed.
2. **Experiment: emittance** measurement.
3. **Simulation:** using TraceWin, **adjustment** of the beam initial conditions (α, β, ϵ) and degree of SCC to **fit** to the measured emittance.
4. **Simulation:** using TraceWin with the fitted parameters determination of **optimal solenoid values** for RFQ injection.
5. **Experimental validation:** Emittance measurement.
6. **Numerical validation:** SOLMAXP/Warp simulations.

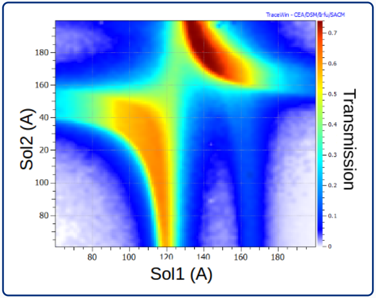
This method is simple an independent of:

- SOLMAXP/WARP simulations
- Ion source beam distribution calculated with AXCEL.

Simulation results
Transmission vs Solenoid values



Experiment



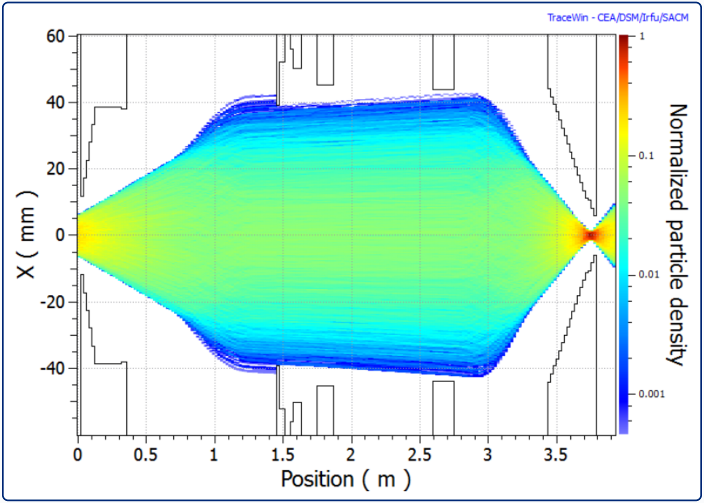
Simulation

Beam intensity: 40 mA

- Reasonable agreement.
- Discrepancies: alignment and steerers.
- RFQ optimal injection $\neq$ Maximal LEBT transmission

Simulation results

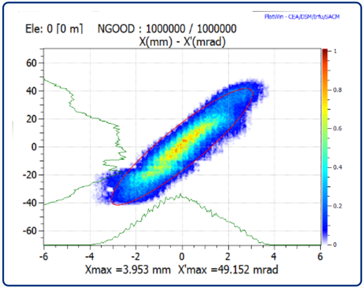
Beam transport

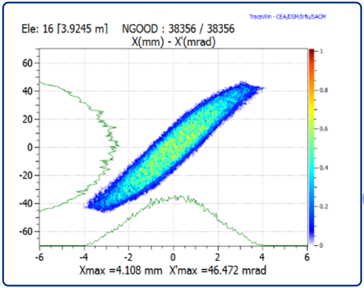


Introduction
SCC
LEBT Simulations
LIPAc injector
Requirements
LEBT Layout
Experimental setup
Experimental results 10% dc
Emittance vs Intensity
Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion
SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience
Conclusion

Simulation vs Experience
Emittance measurement

I_{CF} = 30 mA



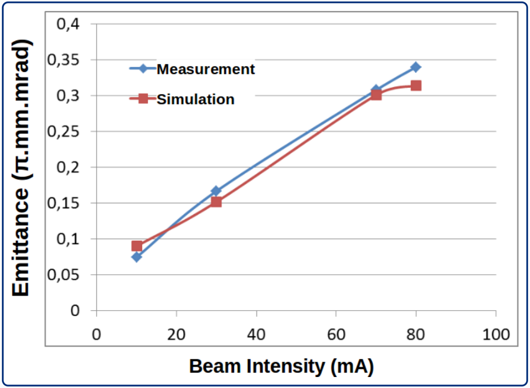


Experiment ϵ = 0.17 π.mm.mrad

Simulation ϵ = 0.15 π.mm.mrad

Simulation vs Experience

Emittance vs Beam intensity



SILHI LEBT simulations

- Simulations give good agreement with data.
- Validated with SOLMAXP and Warp.
- Model has to be tested with a 100 mA beam.

Ion source & LEBT

Introduction
SCC
LEBT Simulations
LIPAc injector
Requirements
LEBT Layout
Experimental setup
Experimental results 10% dc
Emittance vs Intensity
Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion
SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience
Conclusion

Outline

1 Introduction

2 The LIPAc source & LEBT commissioning

3 SILHI source & LEBT commissioning

4 Conclusions & Perspectives

Conclusions & Perspectives

Conclusions

- Self consistent codes gives qualitative results but are not yet predictive enough.
- SPIRAL2 D^+ source and LEBT commissioning has also been done in Saclay in 2012.
- All the sources and LEBT in Saclay are now dismounted.
- Commissioning of source and LEBT have to be anticipated.

Perspective

- Further work on simulations including SCC (degree of SCC, transient time): quantitative results are needed.
- More experiments will be done on LIPAc in Rokkasho.
- Development and commissioning of the FAIR p-linac source and LEBT will be done in Saclay.
- Measurements on a dedicated test bench in Saclay: BETSI (ESS chopper tests).

Conclusions & Perspectives

Ion source & LEBT

Introduction
SCC
LEBT Simulations

LIPAc injector
Requirements
LEBT Layout
Experimental setup
Experimental results 10% dc
Emittance vs Intensity
Emittance vs solenoids
Simulations conditions
Simulations results
Conclusion

SILHI
Requirements
LEBT Layout
Experimental results
Simulations strategy
Simulation results
Simulation vs Experience

Conclusion

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Thank you for your attention !