SPS Proton Bunch Compression Studies for AWAKE

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Outline

Introduction & motivation

Measurements

- Conditions in the CERN SPS
- Results

Simulations

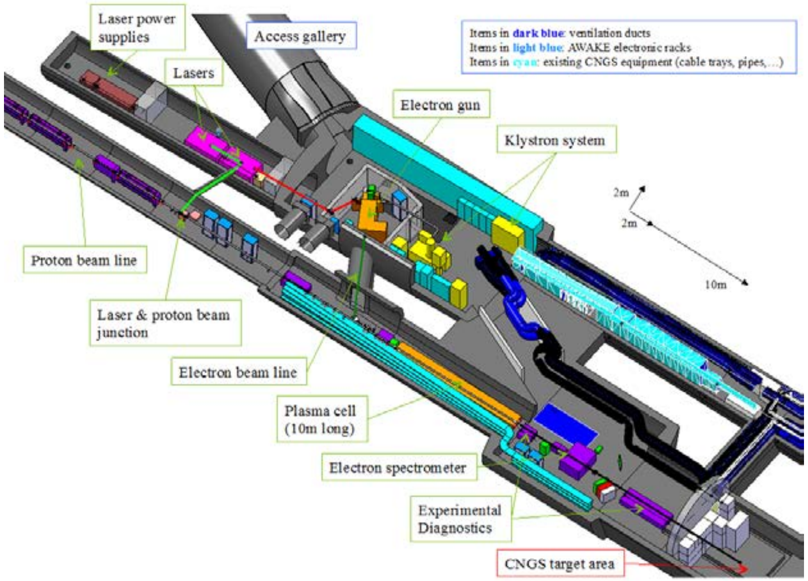
- Expected maximum peak current

Summary

Introduction

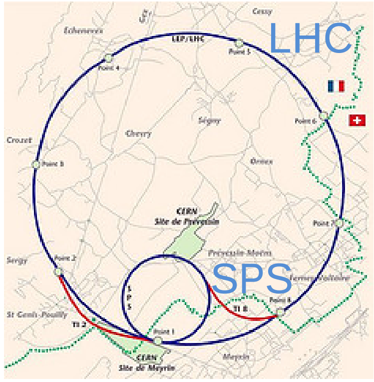
AWAKE is a proton-bunch driven plasma wakefield acceleration experiment

Location	CERN SPS, extraction at CNGS site
Proton bunch	300—400 GeV, high-brightness beam



← Layout of the AWAKE experimental area at the SPS CNGS site

SPS and LHC rings at CERN →



Studies & their motivation

Experimental studies

Measurements of the SPS proton bunch parameter space

AWAKE 'Wish list'	Highest possible peak current, smallest possible transverse emittance
Design parameters	$N_b = 3\times10^{11}$ p, σ_z = 12 cm = 0.4 ns, σ_r = 0.02 cm, ε_{bn} = 3.5 mm mrad

First simulation studies

How much can the peak current be improved?

RF voltage upgrade	More voltage, shorter bunches
LLRF upgrade	Enables a jump to the unstable phase

EXPERIMENTAL STUDIES:

MEASUREMENT CONDITIONS

Measurements

Measurement conditions

Energy 450 GeV (SPS flat top)

Main RF V_{200MHz} = 8 MV maximum (12 MV in ~2019)

4th harm. RF V_{800MHz} = 0.8 MV maximum (1.2 MV in 2015)

used for longitudinal stability

Tested two optics with different transition energies

Q20 optics $\gamma_T = 18$

Q26 optics $\gamma_T = 22.8$

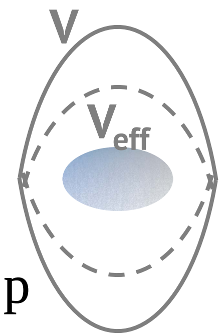
Q20 is better for stability, but for the same emittance and same RF voltage the bunches are longer

Limitations and cures

Main limitations to increase the brightness

Limited RF voltage

Intensity effects that occur at the high intensities demanded by AWAKE

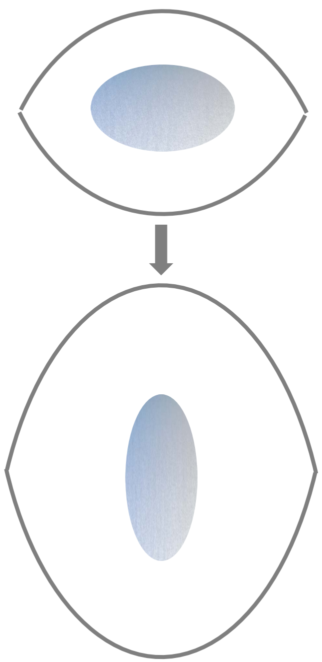


Potential-well distortion	Beam-induced voltage (~ N) → reduced V_{eff} → longer bunches
Beam instabilities	Uncontrolled emittance blow-up *Cures: lower γ_T, 800 MHz RF, controlled ε_L blow-up*
Space-charge effect	In the SPS injectors & SPS flat bottom → Transverse emittance blow-up *Cures investigated in the LIU project*

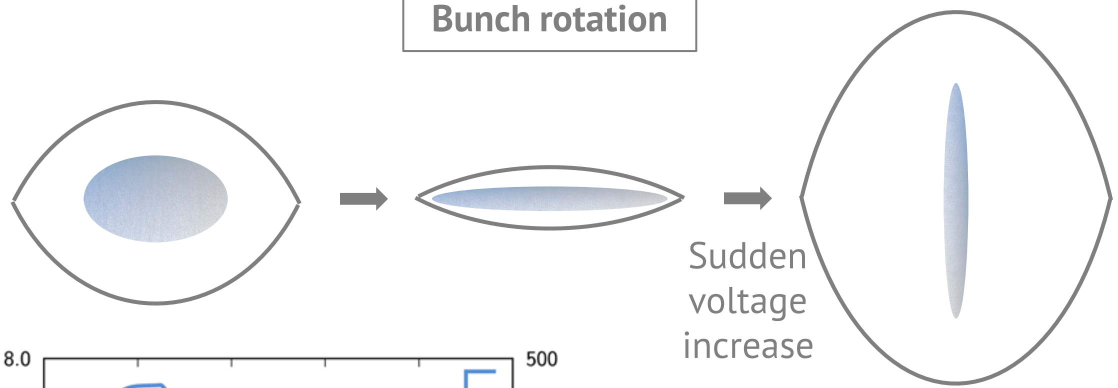
Bunch rotation

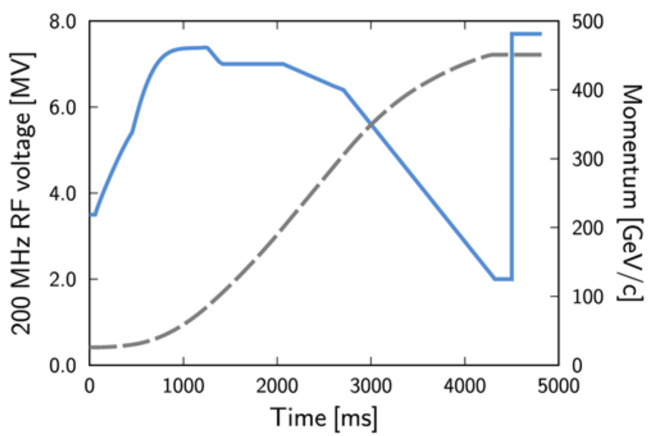
During the measurements, we used bunch rotation in longitudinal phase-space to shorten the bunches

Adiabatic voltage increase



Bunch rotation





Voltage programme and beam momentum during the measurements

EXPERIMENTAL STUDIES:

RESULTS OBTAINED WITH THE Q20 OPTICS

Longitudinal stability

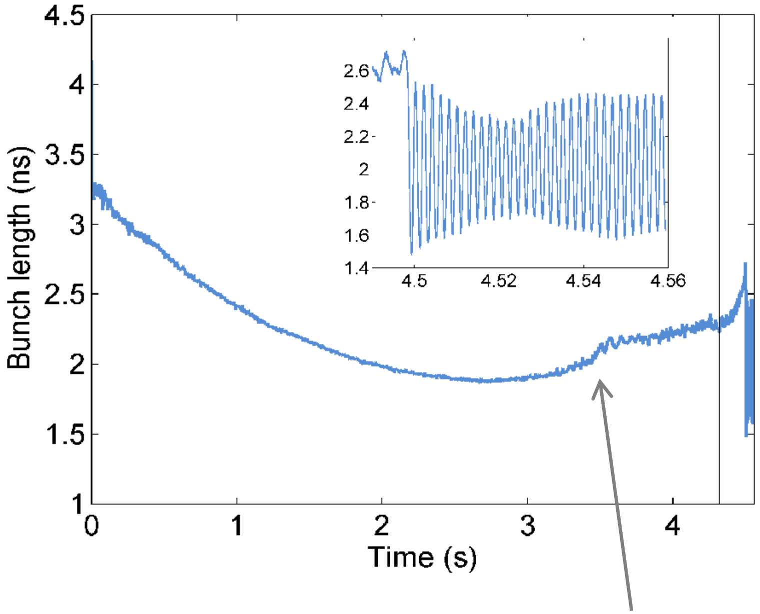
Even in the Q20 optics:

Beam instabilities $\gtrsim 3\times10^{11}$ p

A small controlled ε_L blow-up could help to stabilise the beam

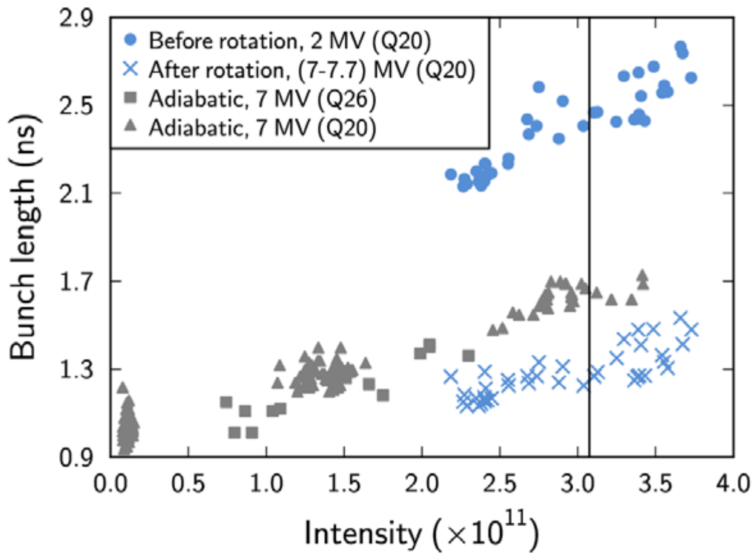
→ Better reproducibility

→ But: longer bunches



Bunch length increase due to uncontrolled emittance blow-up

Bunch length and peak current



Bunch length (4 sigma Gaussian fit) achieved adiabatically
or using bunch rotation

Vertical line: threshold of stability
Rotation reduces τ by ~20 %

Peak current

At the design intensity 3×10^{11}

Average $\tau_{4\sigma}$	1.3 ns (σ = 10 cm)
Average I_{peak}	(59 ± 4) A

At higher intensity, ~3.7×10^{11}

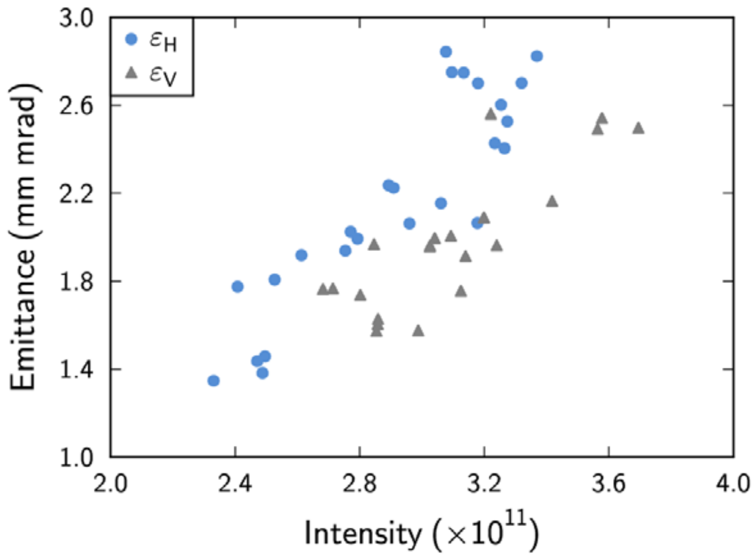
Shortest $\tau_{4\sigma}$	1.4 ns (σ = 11 cm)
Highest I_{peak}	(67 ± 7) A

Bunch length vs. intensity

Strong increase of τ with N

Probably a large portion is due to microwave instability

Transverse emittance



Horizontal and vertical normalised rms emittances

Measurement accuracy: ± 20 %
The beam is expected to be round

Transverse emittance vs. intensity

The increase is roughly linear

The slope is determined by:

- Space charge in the injectors
- Injection losses ∝ intensity

At the design intensity 3×10^{11}

- Smallest $\varepsilon_{H,V}$ 1.9 mm mrad

Optics comparison

Scaling of intensity thresholds of stability

Transverse-mode coupling instability $\propto \eta\varepsilon_L$

Loss of Landau damping $\propto \eta\varepsilon_L^{5/2}$

Where $\eta = \gamma_T^{-2} - \gamma^{-2}$ is the slippage factor

Performance of the Q20 compared to the Q26 optics

Better transverse and longitudinal beam stability

Transverse size	Smaller
Bunch length	Similar *less blow-up but longer τ for the same $V \propto \eta$*

SIMULATION STUDIES WITHOUT INTENSITY EFFECTS:

MAXIMISING THE PEAK CURRENT

Adiabatic bunch shortening

About the simulations

No intensity effects were taken into account

Starting from	Matched bunch in a 2 MV flat top bucket
Initial ε_L	Same as in experiments with 3×10^{11} p

Adiabatic voltage increase

V_{max}	$\tau_{ejection}$	I_{peak} at 3×10^{11}
8 MV	1.50 ns	51 A
12 MV	1.35 ns	57 A

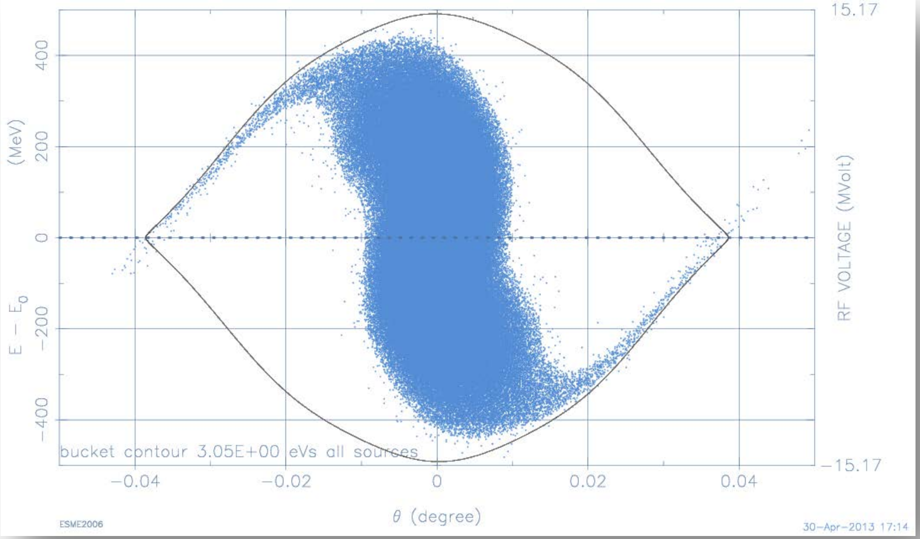
$$\tau \sim V^{-1/4}$$

The peak current assumes that the same bunch length can be achieved with intensity effects (implicitly included in ε_L)

Bunch compression (1)

Bunch rotation in longitudinal phase space

V_{max}	$\tau_{ejection}$	I_{peak} at 3×10^{11}
8 MV	1.16 ns	66 A
12 MV	0.93 ns	82 A

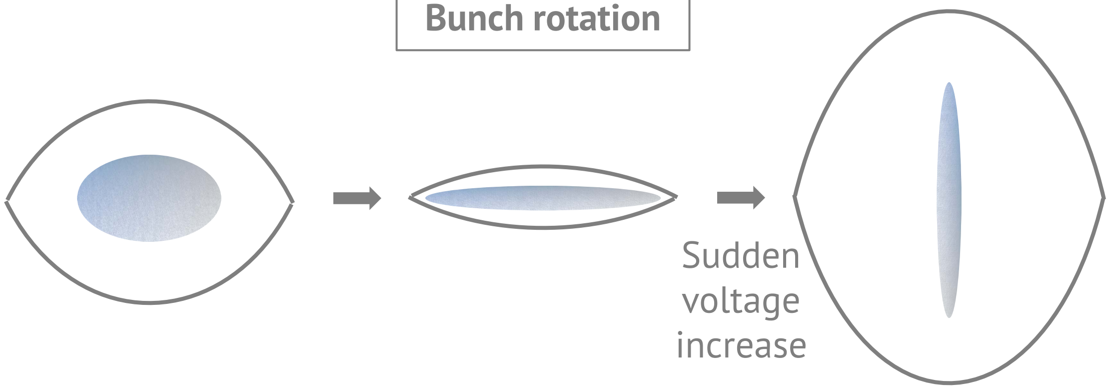


800 MHz RF doesn't affect much

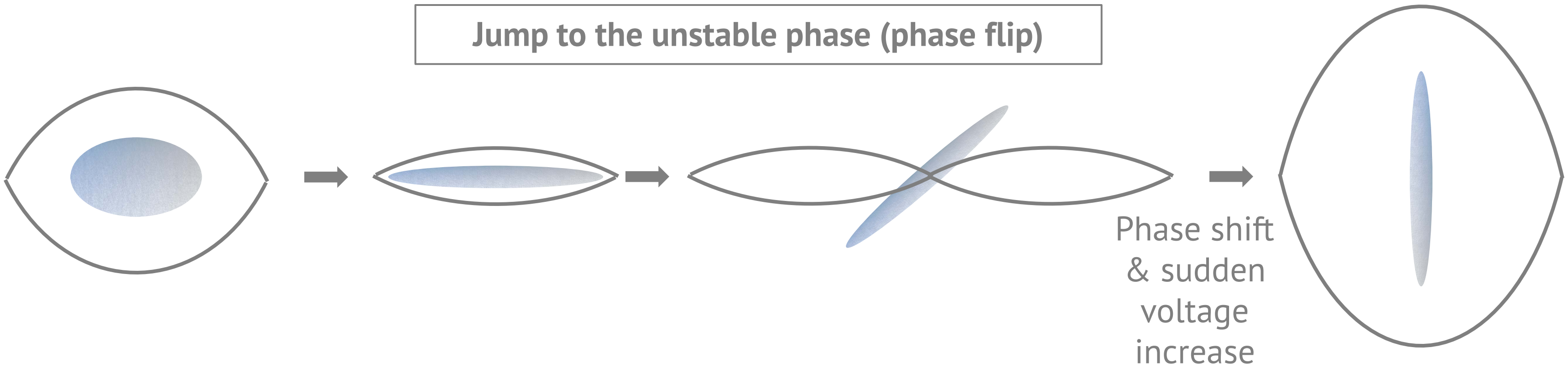
Can gain ~100 ps with a fast V rise (100 μs instead of 1 ms)

Jump to the unstable phase

Bunch rotation



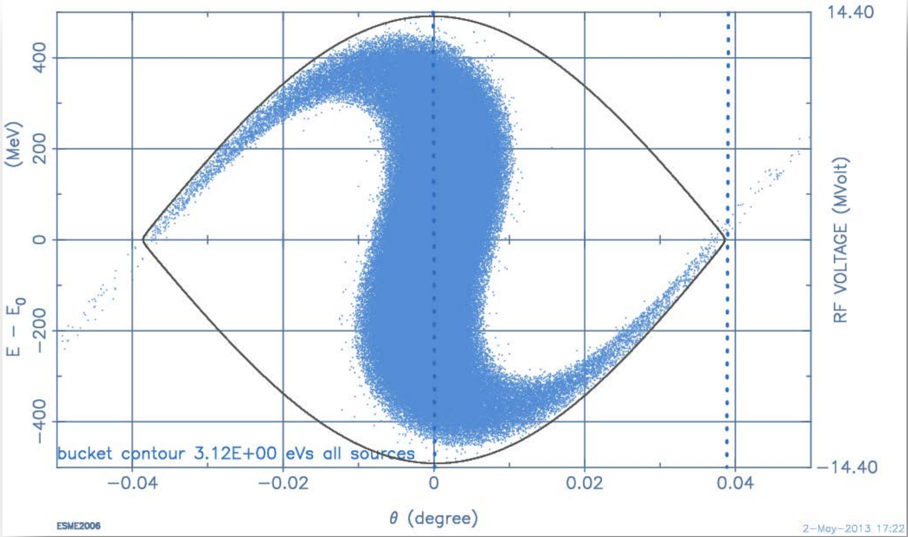
Jump to the unstable phase (phase flip)



Bunch compression (2)

Jump to the unstable phase (phase flip)

V_{max}	$\tau_{ejection}$	I_{peak} at 3×10^{11}
8 MV	0.98 ns	78 A
12 MV	0.85 ns	90 A



Effect of 800 MHz RF

single RF and double RF w/ 180° rel. phase give the same results; double RF in-phase: +100 ps

Summary

Short, high-intensity SPS proton bunches for AWAKE

Reliably achieved 59 A ($\tau_{4\sigma}$ = 1.3 ns, σ = 10 cm) at 3×10^{11} p

Design parameters 48 A ($\tau_{4\sigma}$ = 1.6 ns, σ = 12 cm) at 3×10^{11} p

Achievable with future upgrades

Up to 50 % more peak current (more V, better bunch compression)

Main limitations for higher brightness

Longitudinal beam instabilities

Steep increase in bunch length as a function of intensity

If the impedance source of this growth could be eliminated, further significant improvement in brightness should be possible

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THANK YOU!