Advanced beam dynamics experiments at SPARC

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on be half the SPARC group
SPARC layout

VB cavity for low energy bunch compression and solenoids to emittance compensation

photocathode laser room

Gun 1.6 SW 130MV/m

linac - TW S-band

New beam lines under installation: Thoson – PWFA – LWFA

FLAME laser input line

6 unadulators

<table>
<thead>
<tr>
<th>Period</th>
<th>2.8 cm</th>
</tr>
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<tbody>
<tr>
<td>Undulator length</td>
<td>2.156 m</td>
</tr>
<tr>
<td>No of Periods</td>
<td>77</td>
</tr>
<tr>
<td>Gap (nom./min/max)</td>
<td>0.958 / 0.6 / 2.5 cm</td>
</tr>
<tr>
<td>K (nom./max/min)</td>
<td>2.145 / 3.2 / 0.38</td>
</tr>
<tr>
<td>Remanent field</td>
<td>1.31 T</td>
</tr>
<tr>
<td>Blocks per period</td>
<td>4</td>
</tr>
<tr>
<td>Block size (h x l x w)</td>
<td>2 x 0.7 x 5 cm</td>
</tr>
</tbody>
</table>
SPARC Velocity Bunching applications

Progress towards high brightness beam:
- Gun RF pulse shaping 130MV/m
- VB time jitters <100fs
New RF pulse shaping for Gun feeding

**Goals:**
- Increase the gun accelerating gradient
- Maintain the residual phase noise, respect to the main oscillator, below 100fs
- Have a breakdown rate as low as possible

**Solution:**
- In the first 3us the RF level is kept as low as possible to make the PLL (Phase Locked Loop) working
- The RF is brought to the maximum level in the last 0.8 us

Before (11 MW - 112 MV/m – 4.7 MeV)

Now (14 MW - 130MV/m – 6.2 MeV)

M. Bellaveglia, M. Ferrario, A. Gallo, RF pulse shaping optimization to drive low emittance RF photoinjector, to be published
Laser Comb: beam echo generation of a train bunches

- M. Ferrario, M. Boscolo et al., Int. J. of Mod. Phys. B, 2006 (Taipei 05 Workshop)
A train of laser pulses at the cathode by birefringent crystal

The technique used for this purpose relies on a birefringent crystal, where the input pulse is decomposed in two orthogonally polarized pulses (ordinary, extraordinary) with a time separation proportional to the crystal length.

Different crystal thickness are available (10.353 mm in this case).

Putting more crystals, one can generate bunch trains (e.g. 4 bunches).

The intensity along the pulse train can be modulated (e.g. PWFA)

\[ \Delta \tau = \left( \frac{1}{v_{go}} - \frac{1}{v_{ge}} \right) L_1 \]
Experimental results
Systematic analysis by simulations

**Free parameters:**
- Gun injection phase
- VB injection phase
- Bz field Gun Solenoid
- Bz field $T_{w_{\text{cavity}}} \text{N. 1}

**Initial parameters:**
- $T_{\text{separation}}$ at chathode = 4.27 ps
- $Q = 80 \text{ pC} + 80 \text{ pC}$
- $\sigma_x = \sigma_y = 400 \mu m$
- $T_{w_{\text{cavity}}} \text{ II–III on crest}

**Final Condition:**
- $T_{\text{separation}} \approx 1 \text{ ps}$
- current I = current II
- Minimum total rms $\epsilon$

The minimum total projected emittance (measurable) corresponds to a similar behaviour of both sub-bunches (emittance and current).
Two bunches train characterization $Q_t=166$ pC (92+78) on crest

Remarkable agreement

$\varepsilon_{x,y}(100\%) = 0.8,1.1$ mm-mrad, $E_{\text{spread}}$ for each pulse $< 0.1\%$ (170 MeV)

$\varepsilon_{x,y} (90\%) = 0.5,0.5$ mm-mrad, $\sigma t_1 \approx \sigma t_2 \approx 1$ ps

Maximum compression VB phase $-90.4$

$T_{\text{sep.}} = 4.27$ ps

$\sigma_{t}-\text{pulses} \approx 150$ fs

$\sigma_x = \sigma_y = 400$ $\mu$m

$\sigma t=140$ fs

$\varepsilon_{x,y}(100\%) = 4.5,3.3$ mm-rad

$\varepsilon_{x,y} (90\%) = 3.6,2.6$ mm-rad

$E_{\text{spread}} 0.4\%$ and $0.25\%$ (110 MeV)

Energy separation $\approx 1.5$ MeV
Two bunches train characterization

Over-compression VB phase -95.6

\[ \sigma t \ I = 140 \text{ fs}, \sigma t \ II = 270 \text{ fs} \]

\[ T_{\text{separation}} \approx 0.8 \text{ ps} \]

\[ \varepsilon_{x,y}(100\%) = 6.2, 4.4 \text{ mm-rad} \]

\[ \varepsilon_{x,y}(90\%) = 5.8, 4.0 \text{ mm-rad} \]

Energy separation \( \approx 1.2 \text{ MeV} \)

<table>
<thead>
<tr>
<th></th>
<th>MEASUREMENTS</th>
<th>SIMULATIONS</th>
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</thead>
<tbody>
<tr>
<td>Total length (ps)</td>
<td>0.3998 ((\sigma/\sqrt{10}=0.0098))</td>
<td>0.3995</td>
</tr>
<tr>
<td>Time Separation (ps)</td>
<td>0.789 ((\sigma/\sqrt{10}=0.061))</td>
<td>0.7743</td>
</tr>
<tr>
<td>Energy Separation(MeV)</td>
<td>1.192 ((\sigma/\sqrt{10}=0.056))</td>
<td>1.4</td>
</tr>
<tr>
<td>Bunch 1 length (ps)</td>
<td>&lt;0.21 (res.)</td>
<td>0.0963</td>
</tr>
<tr>
<td>Bunch2 length (ps)</td>
<td>0.172 ((\sigma/\sqrt{10}=0.022))</td>
<td>0.1108</td>
</tr>
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</table>
FEL Comb at SPARC (two bunches train)

\[ dt = \frac{\lambda^2}{\Delta \lambda} \]

From the spectrum \( dt \approx 0.615 \text{ ps} \); comparable with data

\[ <dt> = 0.8 \text{ ps} \]
Four pulses COMB structure (200 pC)

Laser pulse @ gun cathode

whole train length ≈ 9 ps
σ_t (per spike) ≈ 200 fs
Click to play movie
4 comb pulses and long phase space rotation

Over-compression region: The sub-bunches are well separated; their distance can be controlled by VB phase injection.
4 comb pulses and long. phase space rotation

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THz radiation can be easily produced by means of CTR

It is difficult to put high charge in sub-ps bunches

A laser comb structure in the longitudinal laser profile can solve this problem
The SPARC THz source

Silicon Aluminated screen (40 nm coating)

CTR (SiO\textsubscript{2}) radiator

quartz window

90° off-axis parabolic mirrors

electron beam vacuum pipe

by Fourier trasforming

CTR spectrum

Interferogram

Martin-Puplet interferometer

- Operating spectral range: 100 GHz-5 THz
- It allows to reconstruct the beam profile
- First test with pyroelectric detector; foreseen Golay cell or bolometers

Interferogram spectrum

by Fourier transforming

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CTR (SiO₂)

quartz window

90° off-axis parabolic mirrors

detector

filters/polarizer

by Fourier trasforming

CTR spectrum

Interferogram

CTR spectrum

Interferogram

by Fourier transformation
Narrow THz radiation measured

Interferogram for bunches train show $2N-1$ peaks (inter-distance = sub-bunches distance)

$\Rightarrow$ Radiation spectrum is strongly suppressed outside the comb rep. frequency
Conclusion

• The SPARC linac has improved the machine stability and the gun gradient

• We have demonstrated, from experimental point of view, that one can control pulse spacing, length, current and energy separation by properly setting the accelerator.

• A very good agreement with simulations
Thanks for your attention