EuPRA\textsc{XIA}@SPARC\textunderscore\textsc{LAB}
Start to end Simulations

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on behalf of WA1- Beam Physics collaboration team
Outline

WA1 : Activities and Roadmap to TDR update

S2E Simulations progress and results

Conclusions
• The installation of the new five AC922 units for the plasma simulations is ongoing from **Sept. 10th 2021**.
• The infiniband connection cards and switches for the cluster setup must be purchased.
• The purchase procedure of the WS rack module for Linac simulations has been finalized on **Oct. 20th 2021**, delivery in one month.
Activities with the Architect code-WP9 (P. Santangelo)

- Investigation (and solution) of (known) intermittent problems
- Parallelization of much of the code using OpenMP

Result: (July release)

<table>
<thead>
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<th>distance (um)</th>
<th>100</th>
<th>1000</th>
<th>10000</th>
<th>60000</th>
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<tr>
<td>serial (seconds)</td>
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<td>1720</td>
<td>17426</td>
<td>103789</td>
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<td>16</td>
<td>48</td>
<td>372</td>
<td></td>
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</tr>
</tbody>
</table>

- The new version is better, with 6 speedups on eight processors
- The parallel code produces results «visually» as the same as the serial code
- First Architect tests now possible on long times and distances
- Multiple runs of parallel code in the same machine
  (not immediate but it works well)
- More to investigate: parallel method for the "current deposition" of bunches
  - particles are only in bunches
  - the position of the particles is limited to a small part of the grid
Magnets & PS design-WP17 (L. Sabatini, A. Vannozzi)

WORK IN PROGRESS:
- **DIPOLES:** magnetic design ready for:
  - BLH (4x laser heater chicane)
  - BC (4x compressor chicane)
  - DIPSPL (first spectrometer)
- **QUADRUPOLES:** magnetic design ongoing for all the three families ⇒ Optimization
- Control System for power supplies: first estimation of specs.

WHAT NEXT:
- **DIPOLES:**
  - detailed magnetic design including quality and harmonic analysis
  - review of magnetic design with BD by providing field maps
- **QUADRUPOLES:**
  - focus on integrated quadrupole (the one including steering and diagnostics)
- DUMP dipoles
Roadmap to TDR update (from last WA meeting)

Upcoming milestones

July 2021 machine layout «coarse» finalization in terms of :

- Number and type of undulators
- Number and type of transfer lines
- Spectrometer /extraction lines
- 5GeV plasma acceleration line
- Submitted to «first magnets design and feasibility verification (April-May 2021)»

Not completed -> delay to be quantified

Personnel

- Between end of May and beginning of October: two less full-time people for WP1-WP2
- One full-time people on parental leave from July 2021 at least until February 2022 on WP1
- One part-time people on WP1 now more devoted to SPARC_LAB restart and new parts commissioning

- Under negotiation in these days:
  - Two senior and One Postdoc part –time (30%) from other structures/projects for WP1
  - 2-3 students from the 37th PhD Course in Accelerator Physics (Sapienza University- Sept 9th 2021) for WP1-WP2-WP17
S2E Simulations progress and results

• With the available resources both of computing power and personnel, two main topics were given priority and efforts:

  – Energy spread compensation scheme for plasma acceleration (WoP1 Linac working point)
  – Bunch compression scheme for the 200pC beam from Linac (WoP2), i.e. chicane vs dogleg comparison
On the basic all-in-one layout: (A Giribono)

- E_{\text{max}}=1.03 \text{ GeV} for all X-band configuration (w 10\% contingency on Kly output power)
- L_{\text{max}}\approx 60 \text{ m (ex. 59.52 m)} from cathode + 1 m distance from the wall vs 59 m nominally available
- Extremely tight in:
  - plasma in\&out matching
  - Diagnostic sections for beam characterization
  - No room for doglegs upstream the undulator
Update on beam dynamics simulations for WoP1 and WoP2

- WoP1 → comb beam re-optimised with ASTRA (NB: X-band $E_{\text{acc}}=40$ MV/m for beam quality preservation)
  - red: Tstep
  - Blue ASTRA
WoP 1-PWFA
WoP1- PWFA previous results (where we were)

@ Photoinjector exit: $<E>=91.5$ MeV

- Transverse (up) and longitudinal (down) phase space at the Photoinjector exit

\[ \gamma e_x = 1.70 \mu m \]

\[ \sigma_z = 79 \mu m, \sigma_{E} \langle E \rangle = 0.95\% \]

- Transverse (left) and longitudinal (right) slice analyses at the Photoinjector exit

@ Plasma exit: $E\approx1$ GeV

However, an effort is needed to improve the value of the projected energy spread in order to increase the efficiency of the radiation source.
Previous results on Stability

(A. Del Dotto)

Witness beam final energy and energy spread as a function of the Driver-Witness separation

- $n_p = 10^{16} \text{ cm}^{-3}$
- $\lambda_p = 334 \mu\text{m}$

- $D - W$ separation: $167 \mu\text{m}$
- $D - W$ separation: $173 \mu\text{m}$
- $D - W$ separation: $180 \mu\text{m}$
- $D - W$ separation: $183 \mu\text{m}$
- $D - W$ separation: $187 \mu\text{m}$
- $D - W$ separation: $193 \mu\text{m}$
- $D - W$ separation: $200 \mu\text{m}$

Witness beam final energy and energy spread as a function of the Driver-Witness separation
New beams from Photoinjector: 
0.8 kA on Witness & reverse slope for Wit energy spread

From Photoinjector

At Linac exit

Case 1

Case 2

Case 3 (Chicane ON for better separation)

As suggested by Rev. Committee and needed for long space manipulation.

C. Vaccarezza, EuPRAXIA@SPARC_LAB Review Committee, Oct 26th, 2021
WoP1 $I_w=800$ A

(S. Romeo)

Start to end simulation from

Elegant data:
- Simulation with Architect code
- 40 cm propagation in plasma channel
- Density scan to optimize the energy spread

**Witness parameters**

$$\sigma_{x,y} = 2.6, 2.8 \, \mu m$$
$$\sigma_z = 5.11 \, \mu m$$
$$\varepsilon_n(x,y) = 1.2, 1.0 \, \text{mm mrad}$$
$$\gamma = 921$$
$$\sigma_E = 0.076\%$$
$$I \approx 800 \, A$$
First results $I_w = 800$ A

Density scan result (Energy/spread)

Best result 0.87 G/V/m  0.35% energy spread

First results $I_w = 800$ A
Transverse Matching for $n_p = 1.2 \cdot 10^{16} \text{ cm}^{-3}$

Results show a transverse mismatching

$$\beta_m = \frac{\sqrt{2\gamma}}{k_p} \approx 2.1 \text{ mm}$$

- $\beta_{x,y} = 5.2, 6.8 \text{ mm}$
- Emittance increase of a factor 4-5 due to betatron dephasing
- Could be solved by means of plasma ramps
Witness LPS

- We are working in over beam loading regime
- Minimum energy spread corresponds to pure non-linear contribution of plasma wake
- Longitudinal phase space is not flat in the witness core
- Strategies for energy spread mitigation are still under investigation
Slice analysis:
Option 2: Plasma pre-chirper (A.R. Rossi)

We are investigating the possibility to pre-compensate the energy chirp by using a higher plasma density stage. Back of the envelope, 1D evaluations seem to qualitatively confirm the possibility to pre-compensate energy chirp.

\[ n_0 = 9 \times 10^{18} \text{ cm}^{-3} \]

Pre-compensation for the excess beam loading case

Driver far off resonance and scarcely affected by plasma field.

Driver closeup

Witness closeup

NB: all units are normalized. Current profiles are in a.u. D and W profiles are do not have the same scale.
Pre-compensation for the excess beam loading case

\[ n_0 = 4 \times 10^{18} \, cm^{-3} \]

NB: all units are normalized. Current profiles are in a.u.

Comparison between Lu and two-sheath (TS) models

\[ \Lambda = 2\pi \sigma_x \sigma_y \alpha \]

\[ \Lambda_d \approx 2.25 \]

\[ \Lambda_w \approx 2.55 \]

Def. \( \Lambda = 2\pi \sigma_x \sigma_y \alpha \)

\( \Lambda_d \approx 2.25 \)

\( \Lambda_w \approx 2.55 \)

\[ E_z \]  
\[ E_z \]  
\[ E_z \]

\( E_z \) (Lu)  
\( E_z \) (TS)  
Non-linear regime

Propagation direction

NB: units are normalized. Only back portion of the bubble is shown. Witness current profile is flat with length = 0.5 (FWHM), while \( \sigma_z = 1 \) for driver. Plasma density is \( 10^{16} \) cm\(^{-3} \)

Considerations

- TS model is much more robust wrt injection phase and witness current value (not shown) compared to Lu’s
- Flat top current profile does NOT perform much worse than triangular profile in reducing energy spread

**Previous considerations allow to consider non-linear regime a viable way to deliver low energy spread beams**

C. Vaccarezza, EuPRAXIA@SPARC_LAB Review Committee, Oct 26th, 2021
On going:

- Systematic analysis of the space charge effect on the matching before and after the plasma acceleration (plus driver removal) to verify lattice acceptance and robustness (Astra & Tstep plus genetic optimizer)

- Same analysis for the dogleg TL and chicane to evaluate the splitted layout for plasma and all X-band linac.

- X-band cavity after the Gun: design and optimization with iterative BD simulations

- Diagnostic BD simulation to check the virtual measurements

- Microbunching instability budget and mitigation for all the options
  \[\Rightarrow\] LH system and diagnostic section finalization
WoP2- All X-band 200pC
Two layouts for comparison: up to now...

**a)**
- 2 s-band 1 s-band
- 8 x-band
- DL-compressor
- E~ 145 MeV-WoP2
- Exercise to "save" 1m on the Linac length

**b)**
- E~ 90 MeV-WoP1 (Comb beam)
- LH-chicane
- DL-compressor

- E~ 573 MeV-WoP2
- E< 0.996 GeV-WoP2 (200pC beam)
- E~ 1.1 GeV-WoP2 (200pC beam)
Case a) Chicane layout

Old

2 X-band section 0.9 m long $E_{\text{acc}}=60 \text{ MV/m}$

1 S-band 2 m long $E_{\text{acc}}=27 \text{ MV/m}$

8 X-band + 8 X-band $E_{\text{acc}}=60 \text{ MV/m}$

$L_{\text{tot}}=13 + 47.5 = 60.3 \text{ m } E=1 \text{ GeV}$

(...+ 2 X-band = 63 m $E=1.1 \text{ GeV}$)
Case b) Dogleg compressor with $R_{56} > 0$

- 1 S-band 2 m long
  - $E_{acc} = 27 \text{ MV/m}$
- 8 X-band + 8 X-band
  - $E_{acc} = 60 \text{ MV/m}$

$L_{tot} = 13 + 50 = 63 \text{ E=1 GeV}$

($...+ 2 \text{ X-band} = 65 \text{ m}$
$E=1.1 \text{ GeV}$)
Case c) Dogleg with $R_{56} < 0$ considered layout

1 S-band 2 m long
$E_{\text{acc}} = 27 \text{ MV/m}$

8 X-band + 8 X-band $E_{\text{acc}} = 60 \text{ MV/m}$

$L_{\text{tot}} = 13 + 47.5 = 64 \text{ E=1 GeV}$

(...+ 2 X-band =66 m E=1.1 GeV)

Case b) Dogleg compressor
w $R_{56} < 0$
$R_{56}=30$ mm:
Case a) $I=1.6$ kA slice analysis

Case a) Magnetic chicane

File: 200pC_1GeV_DL_noopt_chic_nolin_sband_noopt.outm.asci
Case a) I=700 A slice analysis

File= 200pC_1GeV_DL_noopt_chic_nolin_sband_700A.outm.asci

Case a) Magnetic chicane

File= 200pC_1GeV_DL_noopt_chic_nolin_sband_700A.outm.asci
For Comparison:

Case a) Magnetic Chicane $R_{56} = 30 \text{ mm}$

Case b) Dogleg Compressor $R_{56} = 18 \text{ mm}$

Case c) Dogleg Compressor $R_{56} = -40 \text{ mm}$
Conclusions

• Despite the personnel situation some of the BD main topics have been addressed for the considered WoP’s.
• Some of the presented configurations have been found suitable for the considered undulators.
• Next effort will be focused to improve the aspects still not compliant with lasing at 3-4 nm necessities.
Thanks for your attention