The External Injection experiment @ SPARC_LAB

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on behalf of the SPARC_LAB team
EXIN goals

- Demonstrate an energy increase preserving as much as possible beam 6D volume.
- Stability.
- Reproducibility.
- Everything above in the easiest way (leading philosophy).

Highest energy record in LWFA is NOT a goal!
SPARC_LAB: the test facility
SPARC_LAB: the test facility

SPARC bunker
SPARC_LAB: the test facility
The External Injection experiment @ SPARC_LAB

Choice of settings 1

Laser parameters:
- \( E \leq 3.5 \text{ J on target} \)
- \( T_{\text{FWHM}} > 20 \text{ fs} \)
- \( \sigma_{\text{tr}} \geq 10 \mu\text{m} \)

E-beam parameters:
- \( E = 70 - 150 \text{ MeV} \)
- \( L_{\text{FWHM}} > 5 \text{ fs} \)
- \( \varepsilon_{\text{nt}} : \text{few } \mu\text{m} \text{ (hopefully)} \)
- \( \sigma_{\text{tr}} : \text{as per emittance} \)
- \( \delta\gamma/\gamma : \text{not critical} \)
- \( Q > 20 \text{ pC} \)

Beam line
- VB and magnetic mixed compression
- Many “handles” for delivering good quality – high current bunches

Many possible plasma waves regimes: \( a_0 \leq 4.8 \)

Ionization energy is not a problem \( \sim 10 - 100 \text{ of } \mu\text{J/cm} \)

Matching to/from plasma needed
The shorter the better but high current means high loading
Choice of settings 2

Plasma wave regime

Linear

Mildly non linear

Bubble

Easier and more stable but beam loading can be very important (beam driver). Would require the capability to manage bunches with a currents in up to few tens of Amps.

Fields are quite intense so performances can be very interesting. Beam loading is manageable with bunch currents up to few hundreds of Amp.

The hardest to implement and manage, due to high sensitivity to jitters. Highest performances and beam loading is not a problem up to few kAmps. Possible in future.
Choice of settings 3

Gas cell: no guiding.

To guide or not to guide

Laser guiding over a distance much longer than natural Rayleigh length

Capillary: guiding by boundary conditions. Laser matching critical.

\[ n = n_0 \left( 1 + \frac{\Delta n}{n_0} \frac{r^2}{w^2} \right) \]

\[ \frac{\Delta n}{n_0} = \frac{4}{(k_p w)^2} \]

Transverse plasma tapering: like a graded index optical fibre.

Excluded by the philosophy of the easiest way

Just a box to confine the gas. Easy, but very limited in length.
Choice of settings 3

To guide or not to guide continued

A few data about monomode laser guiding
in glass capillaries*:

The matching condition of the laser pulse to the capillary is:

$$w_0 = 0.645a$$

meaning that 98% of laser energy is coupled to the cap. The coupled mode is the EH\(_{11}\), which is the closest to the TEM\(_{00}\).

The characteristic length \(L_d\), for monomode guiding of EH\(_{11}\), over which laser energy is reduced to 1/e the initial value, is the inverse modulus of

$$k_{zi} = -\frac{u_s^2}{2k_{20}a^3} \frac{1 + \varepsilon_w}{\sqrt{\varepsilon_w - 1}}$$

where \(u_s = 2.405\), \(a = \text{cap. radius}\) and \(\varepsilon_w = 2.25\text{dielectric constant for glass}\). For \(a = 50 \text{ um}\) \(L_d > 1.5 \text{ m}\).

Damaging threshold of glass with grazing incidence > 10\(^{16}\) W/cm\(^2\).

* B. Cross et al., PRE 65, 026405 (2002).
Choice of parameters: physical constraints

Assuming $E_{\text{laser}} = 3.5\text{J}$

$n_0 \times 10^{18} \text{cm}^{-3}$

Cavitation threshold

Linear regime (beam loading)

Capillary diameter

$R_{\text{cap}} \text{(\mu m)}$
Choice of parameters: practical constraints

Assuming $E_{\text{laser}} = 3.5 \text{J}$

Increasing densities imposes lower tolerances on every possible jitter, slippage becomes an issue and short bunches are hard to produce.

**Choosen working point**

- $R_{\text{cap}} = 60 \text{ µm}$
- $n_0 = 10^{17} \text{cm}^{-3}$

**Laser pointing, capillary damage, other jitters, ...**

**Capillary diameter**

**Beam loading**

**Linear regime (beam loading)**

**Cavitation threshold**
S2E simulation: beam production

Compression factor: 7

A. Bacci
S2E simulation: beam transport

Transport has been performed using ELEGANT with space charge effects turned OFF, from the end of the second accelerating structure at 8.66 m from cathod.

Envelopes

Twiss parameters

Emittance

C. Vaccarezza
Transport has been performed using ELEGANT with space charge effects turned OFF, from the end of the second accelerating structure at 8.66 m from cathod.

Final beam parameters: $\sigma_x \approx \sigma_y = 12.7 \, \mu m$, $\sigma_z = 9.8 \, \mu m$, $\varepsilon_x = 2.7 \, \mu m$, $\varepsilon_y = 0.4 \, \mu m$, $E = 71$ MeV, $\delta \gamma / \gamma = 0.2\%$.
Very mild compression: $cf = 2$.
Non particular optimization.
X emittance overestimated!
S2E simulation: plasma acceleration

Simulation tool: QFLUID2 by P. Tomassini

- 2D cylindrical.
- Plasma is a fluid.
- Supports mildly non-linear regimes.
- Laser evolution is self consistent and uses envelope approximation.
- Beam loading effects are included.
S2E simulation: plasma acceleration
S2E simulation: plasma acceleration

Some features

- Effect of defocusing field before slippage
- Effects of beam loading
- Focussing is not constant over bunch length
No laser guiding: gas cell
S2E simulation: plasma acceleration

Simulation geometry: gas cell

Laser
(on axis, $w_0=61$ um,
$L_R=1.5$ cm)

e-beam
(on axis, matching sought)

Gas cell 3 cm
S2E simulation: plasma acceleration

Sample beam: $\Delta t = 157$ fs, $\sigma_x = 3.8$ $\mu$m.

$\sigma_x = 5.4$ $\mu$m

$E = 120$ MeV

$E_{\text{acc}} = 1.6$ GV/m

$\epsilon_{nx} = 4.5$ $\mu$m

Charge loss = 8%

$\Delta \gamma/\gamma = 4.5$ %
S2E simulation: plasma acceleration

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$E = 120$ MeV 

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Charge loss = 8% 

$\Delta \gamma/\gamma = 4.5\%$
Laser guiding: capillary
S2E simulation: plasma acceleration

Simulation geometry: capillary

- Capillary 10 cm
- Laser (on axis but slightly unmatched)
- Gas leakage 5 mm
- e-beam (on axis, matching sought)
S2E simulation: plasma acceleration

Parameters scan results

Figure of merit:
\[ B = q_s / (\varepsilon_{nx}^2 \sigma_t \delta\gamma/\gamma \times 1000) \]

\( \Delta t \): injection phase
\( \sigma_x \): bunch envelope

Charge loss from 10% to 65%

Selected reference beam:
\( \Delta t = 182 \) fs
\( \sigma_x = 3.8 \) \( \mu \)m
S2E simulation: plasma acceleration

Reference beam transport and parameters

- $\sigma_x = 2.0 \, \mu m$
- $E = 630 \, \text{MeV}$
- $E_{\text{acc}} = 5.6 \, \text{GV/m}$
- $\varepsilon_{nx} = 3.5 \, \mu m$
- $\Delta\gamma/\gamma = 7.7 \%$
S2E simulation: plasma acceleration

Reference beam transport and parameters

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S2E simulation: plasma acceleration

Reference beam

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S2E simulation: plasma acceleration

Reference beam

- Reference beam parameters:
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  - $\sigma_x = 2.0 \mu m$
  - $E = 630$ MeV
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![Graph showing beam characteristics](image)
S2E simulation: plasma acceleration

Reference beam

$\varepsilon_{nx} = 3.5 \, \mu m$

$\sigma_x = 2.0 \, \mu m$

$E = 630 \, \text{MeV}$

$\Delta \gamma / \gamma = 7.7 \%$
Conclusions

- Simulations for the external injection experiment at SPARC_LAB are ongoing and yield promising results
- Further optimizations of whole S2E simulations is needed
- Interaction chamber and diagnostics station design is ongoing
- We need to find a way to match the bunch to the plasma
- First experimental results are scheduled for beginning of 2015

Thanks for your attention