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

FLAME Laser

TRANSPORT TO SPARC

TARGET AREA

LASER INSTALLATION

POWER SUPPLIES YAG YAG YAG YAG YAG
The External Injection experiment @ SPARC_LAB

SPARC_LAB: the test facility

SPARC bunker
The External Injection experiment @ SPARC_LAB

SPARC_LAB: the test facility

- Dogleg
- THOMSON
- EXIN - PWFA
- COMB - PWFA
- Interaction point

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HBEB – San Juan 03/27/2013
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Choice of settings 1

**Laser parameters:**
- $E \leq 3.5 \text{ J on target}$
- $T_{\text{FWHM}} > 20 \text{ fs}$
- $\sigma_{tr} \geq 10 \text{ µm}$

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

**Beam line**
- VB and magnetic mixed compression

Many possible plasma waves regimes: $a_0 \leq 4.8$

Ionization energy is not a problem $\sim 10 - 100 \text{ of µJ/cm}$

Matching to/from plasma needed

The shorter the better but high current means high loading

Many “handles” for delivering good quality – high current bunches
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Choice of settings 2

Plasma wave regime

- **Linear**
  - 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.

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

- **Bubble**
  - 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.

\[ n = n_0 \left(1 + \frac{\Delta n}{n_0} \frac{r^2}{w^2}\right); \quad \frac{\Delta n}{n_0} = \frac{4}{(k_p w)^2} \]

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.
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

\[ k_{zi} = -\frac{u_s^2}{2k_0^2a^3} \frac{1 + \varepsilon_w}{\sqrt{\varepsilon_w - 1}} \]

where \( u_s = 2.405 \), a=cap. radius and \( \varepsilon_w = 2.25 \) dielectric constant for glass. For a=50 um \( L_d > 1.5 \) 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 $E_{\text{laser}} = 3.5\text{J}$

Linear regime
(beam loading)

Capillary diameter

Cavitation threshold

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

$R_{\text{cap}}(\mu\text{m})$
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**

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

**Linear regime** (beam loading)

**Capillary diameter**

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

Gas cell 3 cm

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

e-beam
(on axis, matching sought)
S2E simulation: plasma acceleration

Sample beam: \( \Delta t = 157 \text{ fs}, \sigma_x = 3.8 \mu m \).

\[ \sigma_x = 5.4 \mu m \]

\( E = 120 \text{ MeV} \)
\( E_{\text{acc}} = 1.6 \text{ GV/m} \)
\( \epsilon_{nx} = 4.5 \mu m \)

Charge loss = 8%

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

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- $\sigma_x = 5.4$ μm
- $E = 120$ MeV
- $E_{acc} = 1.6$ GV/m
- Charge loss = 8%
- $\Delta \gamma/\gamma = 4.5\%$
Laser guiding: capillary
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:
\[ B = \frac{q_s}{(\varepsilon_{nx}^2 \sigma_t \delta\gamma/\gamma \times 1000)} \]

\( \Delta t \): 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

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

Reference beam transport and parameters
S2E simulation: plasma acceleration

Reference beam

\[ \sigma_x = 2.0 \, \mu m \]

\[ E = 630 \, \text{MeV} \]

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\[ \epsilon_{nx} = 3.5 \, \mu m \]

\[ \Delta \gamma/\gamma = 7.7 \% \]
S2E simulation: plasma acceleration

Reference beam

$\varepsilon_{nx} \ (\mu m)$

$\delta \gamma / \gamma \ (%)$

$E = 630 \ MeV$

$\Delta \gamma / \gamma = 7.7 \%$
S2E simulation: plasma acceleration

\[ \varepsilon_n = 3.5 \ \mu m \]
\[ \sigma_x = 2.0 \ \mu m \]
\[ E = 630 \ \text{MeV} \]
\[ \Delta \gamma/\gamma = 7.7 \% \]
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.