High-quality GeV-scale electron bunches with the Resonant Multi-Pulse Ionization injection

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The Resonant Multi-Pulse Ionization injection

- 265 MeV and >1 GeV high-quality \([dE/E=0.5\%, \ 0.08 \ \text{mm mrad}]\) electron bunches with tunable duration
- Higher harmonics of Ti:Sa (Ionization pulse)
- FEL preliminary results

Towards experimental demonstration at ILIL-PW

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ILIL Lab top view

Existing layout (10 TW)  Upgrade (250 TW)

Control room

10 TW Interaction  Laser front-end  Power amplifier

250 TW Interaction

37 m
# 250 TW Ti:Sa laser commissioning

| MAIN BEAM | Front-end | 1st Phase | 2nd Phase |
|-----------|-----------|-----------|-----------|
| Wavelength (nm) | 800 | 800 | 800 |
| Pump Energy (J) | 1.8 | 12 | 24 |
| Pulse Duration (fs) | 40 | 30 | 25 |
| Energy Before Compression (J) | 0.4 | 4.7 | 7.9 |
| Rep. Rate (Hz) | 10 | 1 | 2 |
| Max intensity on target (W/cm²) | 2×10^{19} | 2×10^{20} | >4×10^{20} |
| Contrast@100ps | >10^{9} | >10^{9} | >10^{10} |
| Beam Diameter (mm) | 36 | 100 | 100 |
ReMPI is a SINGLE LASER System (e.g. Ti:Sa) LWFA scheme that can generate extremely good-quality bunches \textit{with tunable duration}.

### ReMPI with ONE 250 TW Ti:Sa

**Low Energy INJECTOR**
(NO pulse guiding required)

- 265MeV, 0.5%,
- 0.08 mmmrad, 0.9KA

**Options to increase current and decrease the emittance are available**

**Full INJECTOR/ACCELERATOR**
(In a single stage)
(Pulse Guiding required)

- 1-2 GeV, 0.22% SLICE,
- 0.5%, 0.08 mmmrad, 0.9KA

**Options to increase energy are available**

**BASELINE PARAMETERS**

- 6.5J in 30fs, \( n = 5 \times 10^{17} / \text{cm}^3 \)
- (more options with less power are available)
Two-colour injection [L. L. Yu et al. PRL 112 (2014)] is a very promising scheme aiming at generating extremely low-emittance bunches but requires two synchronized laser systems: a long-wavelength (e.g. CO2) for wake driving and a short (e.g. a frequency doubled Ti:Sa) for electron extraction.

The CO2 pulse is needed because the long wavelength assures a large amplitude Wakefield though the electric field is lower than the ionizing threshold for Kr9+

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The Resonant Multi-Pulse Ionization injection [P. Tomassini et al., accept. for pub. on PoP (Oct. 2017)] is a new bunch injection scheme aiming at generating extremely low-emittance bunches [currently as low as 0.08 mm mrad but in can be further reduced]

ReMPI requires ONE short-pulse 100-TW class (e.g Ti:Sa) laser system. Since a unique very large-amplitude Ti:Sa pulse would fully ionize the atoms (Ar8+ in our selected example), the pulse is shaped as a resonant sequence of sub-threshold amplitude pulses.
The multi-pulse approach to LWFA has been proposed so far [D. Umstadter et al, PRL 72, (1994)]. A multi-pulse train can generate plasma waves with larger amplitude than those driven by a single pulse with the same energy.

Two possible pulse-shaping schemes have been proposed very recently.

Older methods include either multiple beam-splitters setup or phase masks.
MP-LWFA is under active investigation

Ideas for MP-LWFA (at 10 Hz and kHz) GeV-scale accelerators have already been presented here

- S.M. Hooker presented last results on MP-LWFA on WP1 on Monday
  See Cawley et al. PRL 119 (2017)

- Roman Walczak presented a MP-LWFA at GeV scale and kHz rep. rate on WP5 on Tuesday

- Posters in Sessions I and II have been devoted to both ReMPI and MP-LWFA
ReMPI trapping analysis

Pulse-train amplitude must be above the trapping threshold for the extracted electrons

\[ E_{\text{norm}} = \frac{E_z}{E_0}; E_0 = mc \omega_p / e \]

E. Esarey et al.; Phys. Plasmas 2 (1997)
P. Tomassini et al, PoP (2017)

Trapping analysis with commonplace parameters reveals that optimal trapping is reached with \( a_0 > 1.6 \) in a single pulse setup. This value is close to Ionization threshold \( \text{N}^{5+} \rightarrow \text{N}^{6+} \).

A simple two-pulses train allows us to deal with Nitrogen (\( U_i = 552 \) eV)

To get advantage of the lower \( U_i \) of \( \text{Ar}^{8+} \rightarrow \text{Ar}^{9+} \) (\( U_i = 422 \) eV) at least a 4-pulses train is needed

- Ionization thr. \( \text{N}^{5+} \rightarrow \text{N}^{6+} \)
- Ionization thr. \( \text{Ar}^{8+} \rightarrow \text{Ar}^{9+} \)
- 7.5J
- 5.0J
- 2.5J
The frequency-doubled minor portion of the pulse acts as “ionizing pulse” as in two-color ionization.

The key concept is that of “minimal transverse momentum rms” $p_{tr}/mc \approx \Delta a_{0e}$ where

$$\Delta = \sqrt{a_{0e}/a_c}; \quad a_c = 0.107 \left( U_i/U_H \right)^{3/2} \lambda$$

To reduce emittance a tightly focused beam is chosen

$w_0_{ion} = 3.5-4.5 \, \mu m$

$\lambda_{ion} = 0.4 \, \mu m$

$Z_{R,ion} = 100-160 \, \mu m$

$T_{ion} = 40 \, fs; \quad a0=0.4$

C.B. Schroeder et al.,
PRAB 17 (2014)
P. Tomassini et al (2017)

Ionization Ar8+->Ar9+

Newborn electrons (one time-step) transverse phase space $\epsilon_{n}=0.051 \, \mu m$ in good agreement with $\epsilon_{n}=0.053 \, \mu m$ predicted by the model of Schroeder et al.
QFluid is a 2D CYLINDRICAL hybrid code for LWFA and PWFA in the plasma fluid and quasi-static regime that is suitable for long propagation simulations.

Laser pulse evolution is solved with the Envelope Evolution Approximation (second time derivative included!) Plasma dynamics is solved via the pseudo-potential computation in the QSA. Electrons of the beam move as macro-particles under the 3D force that includes the ponderomotive effect.

NOTE: Qfluid can’t be properly used with fast varying density profiles Validated with EPOCH, ALaDyn and FB-PIC (also in the multi-pulse case)

Thanks to M. Kirchen and R. Lehe for support with FB-PIC
A first possible parameters set is presented here. It is intended either as a bunch injector or a 100 MeV-class accelerator. A flat-density (no guiding) Ar+8 pre-plasma is assumed.

PLASMA
\[ n_0 = 5 \times 10^{17} \text{ cm}^{-3} \]

DRIVER
\[ E = 0.83 \times 8 \text{ J} \]
\[ T = 30 \text{ fs} \]
\[ w_0 = 45 \mu m \]
\[ a_0 = 0.61 \]

IONIZATION
\[ E = 12 \text{ mJ} \]
\[ T = 35 \text{ fs} \]
\[ w_0 = 3.5 \mu m \]
\[ a_0 = 0.41 \]

BOX
\[ \delta r = \delta z = 0.05 \mu m \]
After about 6mm of acceleration the 265 MeV beam possesses an outstanding beam-quality: \( \frac{dE}{E} = 0.5\% \), \( \epsilon_n < 0.08 \text{ mm mrad} \),

\[ Q = 3.8 \text{ pC} \]
\[ I_{\text{peak}} = 0.9 \text{ kA} \]

\[ \left( \frac{\delta E}{E} \right)_{\text{rms}} = 5 \cdot 10^{-3} \]
\[ \delta \theta_{\text{rms}} = 0.4 \text{ mrad} \]

\[ \epsilon_{nx} = 0.078 \text{ mm mrad} \]
\[ \epsilon_{ny} = 0.018 \text{ mm mrad} \]

\[ \sigma_l = 0.56 \mu m \]
\[ \sigma_r = 0.23 \mu m \]
SETUP A (INJECTOR) – Increase Charge?

Energy spread and emittance with Q=3.8 pC are very low so the natural question is

If we want to use the bunch as a pre-accelerated bunch suitable for energy boosting, is it possible to increase its charge?

So answer is YES (nonlinear emittance increase due to bunch hopping not included) BUT energy spread will increase to above 1% for a 10pC bunch [beam loading compensation in progress]

\[
Q \propto w_{ion}^4, \quad \epsilon_{n} \propto w_{ion}^4
\]

Nonlinear effects will Increase emittance
To extend the acceleration beyond one Rayleigh length guiding with a preformed channel is assumed. A capillary is placed close to gas-jet nozzle to assure a gentle transition from a flat (pure Ar) plasma to a He plasma channel.

**Gas-Jet nozzle**
265MeV injector

**He filled capillary**

**BUNCH B** - 3cm
1.15 GeV, 0.81% rms, 
\( \varepsilon_n = 0.08 \text{ mm mrad} \)

**BUNCH D** - 8cm
1.9 GeV, 0.67% rms, 
\( \varepsilon_n = 0.08 \text{ mm mrad} \)
A single capillary filled with Argon could be a valid alternative to the gas-jet+capillary since the Intensity threshold for Ar9+ is \( I_{tr}=1.4\times10^{18}\text{W/cm}^2 \) (no strong defocusing from further ionization occur).
2D (cyl) maps
Longitudinal phase-space+fields

$n_0 = 500s15 \text{ 1/cm}^3$, Pos: -3 \times 10^2 \mu \text{m}, \sigma_z = 0.64 \mu \text{m}, Q = 4.2718 \text{ pC}, \sigma_z/E = 14.8422\%
Driver(s) evolution

INJECTED

EVOLVED
Minimum energy spread is reached after about 3.5 cm of acceleration with mean energy of 1.3 GeV, dE/E = 0.5%, eps_n=0.08 mm mrad,

\[ Q = 4.3 \text{ pC}; I_{\text{peak}} = 0.85 \text{ kA} \]

\[ (\delta E/E)_{\text{rms}} = 5 \cdot 10^{-3}; \delta \theta_{\text{rms}} = 0.2 \text{ mrad} \]

\[ \epsilon_{nx} = 0.081 \text{ mm mrad}; \epsilon_{ny} = 0.021 \text{ mm mrad} \]

\[ \sigma_l = 0.66 \mu \text{m}; \sigma_r = 0.20 \mu \text{m} \]

\[ L_{\text{CRHOM}} = \frac{\gamma \sigma_r^2}{(\delta E/E)\epsilon_n} \approx 26 \text{ cm} \]

M. Migliorati et al.
PRST-AB 16 (2013)
SLICE analysis for Bunch C

Slice analysis with coherence length $l_c=0.05$ micron (See FEL slices below) reveals a slice energy spread of $\frac{dE}{E_{slice}}=0.22\%@peak$ current  (integrated $\frac{dE}{E} = 0.5\%$),

$$\left(\frac{\delta E}{E}\right)_{SLICE} \text{rms} = 2.2 \cdot 10^{-3} @ peak$$

$I = 0.85\ KA @ peak$
ReMPI bunch length flexibility.

The optimal bunch length depends on the application of the bunch, of course.

- For most of FEL application the length should be of micrometer size to reduce slippage effects.
- For Thomson/Compton backscattering applications with sub-fs duration bunch length should be lower than 0.3 μm

An injection scheme with flexible (and easily tunable) bunch length is therefore optimal for multi-purpose facilities.

- ReMPI can generate [with the parameters currently explored] bunches [and thus radiation] with duration tunable in the range 360 as<t (rms)< 2 fs
Bunch trapping and compression, 1D theory.

In the 1D QSA limit [we are not too far from that in the current working points] the conserved Hamiltonian can be written as

\[ a^2 \ll 1 \quad H(\psi, \gamma) = \gamma (1 - \beta \beta_{\phi}) - \varphi(\psi) \]

where \( \Psi = k_p (z - \beta \phi ct) \) is the phase of the electron in the bucket.

Equation of motion for the phase and the relativistic factor are

\[ \frac{1}{k_p c} \frac{d\gamma}{dt} = \frac{\partial \varphi}{\partial \psi} = -\frac{E_z}{E_0}; \quad \frac{1}{k_p c} \frac{d\psi}{dt} = 1 - \frac{\beta_{\phi}}{\beta} \]

Electrons born approximately at rest with the extraction phase \( \Psi_e \), where the normalized potential is \( \phi_e = \phi(\Psi_e) \) and slip back in the wake up to reaching the wake's speed at the trapping phase \( \Psi_t \), where the potential is \( \phi_t = \phi(\Psi_t) \). Since \( \beta = \beta_{\phi} \) we get

\[ H(\psi_e, 1) = 1 - \varphi_e = H(\psi_t, \gamma) = 1/\gamma - \varphi_t \]

\[ \varphi_t = \varphi_e + 1/\gamma - 1 \]

By differentiating \* with respect to the phase we get the simple relationship

\[ \sigma(z_t) \simeq \sigma(z_e) \frac{(E_z + 1/2 \partial_{\psi} \delta \psi)_e}{(E_z + 1/2 \partial_{\psi} \delta \psi)_t} \]
Setting up the bunch duration from 360 as (rms) to <2fs (rms)

The final bunch duration can be *easily tuned just by selecting the appropriate delay* of the ionizing pulse from the drivers train.

- The **minimum length** is obtained by placing the peak of the ionizing pulse close to the phase of the null electric field (say $\Psi=\kappa_p(z+ct)=0$). As the ionizing pulse moves away from the $\Psi = 0$ phase bunch length increases.
- Setting up the appropriate phase of the ionizing pulse into the bucket the selected bunch length is obtained.

**Initial length 1.56 $\mu$m**

- Case $\Psi=0.06$ (RED): $E_z$ (final length **0.12** $\mu$m)
- Case $\Psi=0.26$ (GREEN ): final length **0.27** $\mu$m
- Case $\Psi=0.52$ (GREEN ): final length **0.57** $\mu$m
SECOND vs HIGHER harmonics (Ionization)

After the ionization pulse passage, the extracted particles possess transverse momentum that essentially depends on pulse amplitude.

\[ p_{tr} / mc \simeq a_{0 \text{ion}}^{3/2} \lambda^{-1/2} \propto \lambda, \text{[QUIVERING, UNCORRELATED]} \]

\[ p_{tr} / mc \propto a_{0 \text{ion}}^2 \propto \lambda^2, \text{[PONDEROMOTIVE, CORRELATED]} \]

With the same BBO crystal used for the 2\(^{nd}\) harmonics it is possible (and experimentally feasible) to generate a 3\(^{rd}\) harmonics. Only phase-matching angle and efficiency change. With a 1st→3rd harmonics conversion efficiency of 8\% and 150mJ of incoming 0.8 energy a pulse delivering 12mJ @267nm.

Since minimum emittance scales as \(a_0\) (correlated x-px give no contribution) we expect that (WITH NO SPACE-CHARGE included) the emittance scales as \(\lambda^{-1.5}\).

SAME parameters a C-bunch, but emittance after the injection phase is now 0.045 mm mrad (III harm.) instead of 0.07 mmmrad (II harm.) Not negligible space-charge effects Are present.
What's missing and what are we going to do

The simulations have been performed with a 2D cylindrical code in the QSA, with benchmarks with ALaDyn and FB-PIC.

- Deviations from cylindrical symmetry due to the injected charge are present. **Beam loading is currently small so the non-symmetric contribution is very low.** A more detailed analysis requires, however, the use of either a quasi-3D code (FP-PIC, probably) or a full 3D PIC code (AlaDyn).

- Beam degradation @ plasma exit must be accurately estimated. In order to do that more simulation with ALaDyn 3D have been scheduled.

- Beam-loading must be tackled to let the beams have charge of tens of pC.
FEL analytical results

Gain length

\[ L_G = \left[ 1 + \frac{0.641}{\rho^2} \left( \frac{\sigma_E}{E} \right)^2 \right] \exp \left[ -\frac{0.136}{\rho^2} \left( \frac{\sigma_E}{E} \right)^2 \right] \frac{\lambda_U}{4\pi \sqrt{3\rho}} \]

Saturation Power

\[ P_S = \sqrt{2} \, \Phi \left( \rho, \frac{\sigma_E}{E} \right) \rho \, P_{e\text{-beam}} \]

Coherence length

\[ L_C = \frac{\lambda_{\text{FEL}}}{4\pi \sqrt{3\rho}} \]

Slippage corrections

\[ \tilde{P}_S = \left( 1 - e^{-0.25 \frac{\sigma_L}{L_C}} \right) P_S \]

PLEASE NOTE

This is NOT a start-to-end simulation.
1) Exit from the plasma is missing
2) Beam transport is ideal with a full preservation of beam-quality.
FEL preliminary results

Detailed FEL simulation are ongoing. Preliminary analytical results with bunches A (0.265 GeV) and B (1.0 GeV) are shown here. Slice analysis is necessary to fully understand coherent spikes generation and lasing.

\[
\rho = \frac{8.36 \times 10^{-3}}{\gamma} \sqrt[3]{\frac{\lambda_u^2 I_{\text{peak}}[A]}{2\pi \beta \gamma^{-1} \varepsilon_n}} K^2 f_B^2(K)
\]

\[K \approx 0.94 \, B[T] \, \lambda_u[cm]
\]

\[\lambda_{\text{FEL}} = \frac{\lambda_u}{2\gamma^2} \left(1 + \frac{K^2}{2}\right)
\]

\[\beta_{\text{Twiss}}[m] = \frac{\sqrt{2} \gamma \lambda_u}{2\pi K}
\]

**BUNCH A**

| Bunch parameters | A     | B     | C     |
|------------------|-------|-------|-------|
| beam energy [GeV]| 0.265 | 1.15  | 1.3   |
| long. beam size (rms) \(\sigma_L\) [\(\mu\)m] | 0.56  | 0.25  | 0.655 |
| current intensity [A] | 812   | 2200  | 785   |
| norm. emittance [mm\(\times\)mrad] | 0.078 | 0.08  | 0.08  |
| energy spread \(\sigma_E/E\) (%) | 0.5   | 0.81  | 0.22  |

**Common FEL parameters**

| undulator magnetic field [T] | 1 |
| undulator period [cm]        | 1.4 |
| deflection parameter         | 1.3 |
FEL preliminary results

| Output FEL parameters               | A | B  | C  |
|-------------------------------------|---|----|----|
| FEL wavelength [nm]                 |  48 | 2.6 | 2.0 |
| Twiss $\beta$ [m]                   | 1.26 | 5.45 | 6.16 |
| Pierce parameter $\rho$             | 0.009 | 0.003 | 0.0018 |
| inh. broad. gain length [m]         | 0.086 | 1.38 | 0.702 |
| saturation power [MW]               | 2602 | 323 | 861 |
| saturation length [m]               | 2.3 | 33 | 17.7 |
| coherence length [$\mu$m]           | 0.25 | 0.04 | 0.05 |
| sat. power with slippage [MW]       | 1130 | 252 | 826 |

growth Power [MW]

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Bunch C
Towards experimental investigation of ReMPI@ILIL CNR

Two posters from L. Gizzi and G. Vantaggiato have been presented on Session 1
A coaxial time-splitter is under consideration.

Delay masks with tuned thickness and radii.

On focus intensities.

Radii sequence must be further optimized.

SIDE VIEW

PARAMETERS

\(n_0 = 5 \times 10^{17} \text{ 1/cm}^3\)

Substrate:
\(l_0 = 0.5 \text{ mm}\)

Rings:
\(\Delta l = 0.104 \text{ mm}\)

BBO:
\(L = 0.2 \text{ mm}\)
Conclusion

Resonant Multi-Pulse ionization injection is a new reliable method to obtain an injector/accelerator with a SINGLE 100-TW class Ti:Sa laser system.

Using Argon an 8-pulses scheme is capable to generate a 265MeV bunch in 6mm (gas-jet, flat profile), 1GeV in 3 cm and 2GeV in 10cm (guided).

Bunch quality is outstanding, mainly concerning emittance (below 0.1 mm mrad along E and 0.02 mm mrad along B).

We are working on the choice of the pulse time shaper. A possible configuration with delay masks is being studied.

Bunch length and quality can be further optimized by changing the trapping point [in progress].

THANK YOU FOR YOUR ATTENTION!