21 June 2017

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The Resonant Multi-Pulse Ionization Injection

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EUPRAXIA Meeting, DESY, 19-23 June 2017

Outlook

- High-quality bunches generation roadmap
- The new Resonant Multi-Pulse Ionization injection
- 265 MeV and >1 GeV high-quality [dE/E=0.5%, 0.08 mm mrad] electron bunches
- Linear vs Circular polarization (Driver pulse)
- Second vs Third harmonics of Ti:Sa (Ionization pulse)
- FEL preliminary results
- Towards experimental demonstration at ILIL-PW

Outlook

The new Resonant Multi-Pulse Ionization Injection is a SINGLE LASER System (e.g. Ti:Sa) scheme that can generate extremely good-quality bunches.

RMPII with ONE
250 TW Ti:Sa

6.5J in 30fs, n=5e17/cm^3
(more options with
less power
are available)

Low Energy INJECTOR
(NO pulse guiding required)

265MeV, 0.5%,
0.08 mmmrad, 0.9KA

Options to increase current available

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

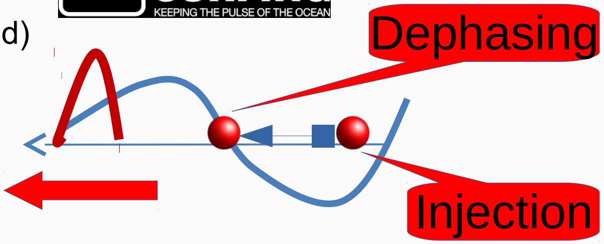
1-2 GeV, 0.22% SLICE,
0.5%, 0.08 mmmrad, 0.9KA

High-quality bunches generation roadmap

Low energy spread/emittance bunches require *accurate control* in

- **Particle's injection (either internal trapping or external injection)**

  At injection/trapping **transverse emittance** ε_n must be very low (<<1 mm mrad)

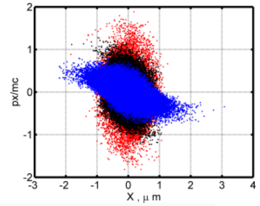


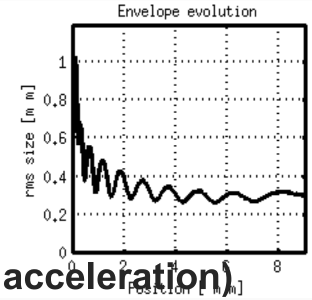
- **Phase evolution (longitudinal position variation into the bucket)**

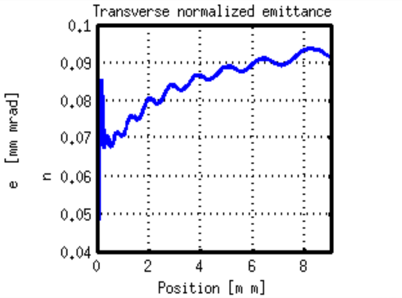
  Dephasing length $L_{deph} \approx \lambda_p^3 / \lambda_0^2 \cong \lambda_0 (n_c / n_e)^{3/2}$

- **Betatron oscillation induced emittance growth**

  Matched radius $r_{matched}(s) \cong \sqrt[4]{\frac{1}{\gamma(s)}} \cdot \sqrt{\frac{\varepsilon_n(s)}{k_{ext}(s)}}$

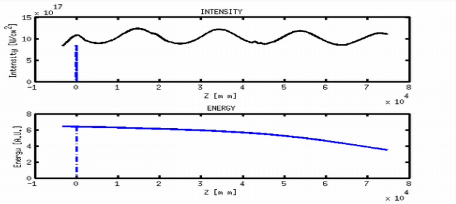






- **Laser pulse guiding, pump depletion (only for high energy acceleration)**

Diffraction is compensated by positive-lens effect of plasma channels (and nonlinear effects)



- **Beam loading** detrimental effects must be reduced

- **Bunch extraction from the plasma and beam optics**

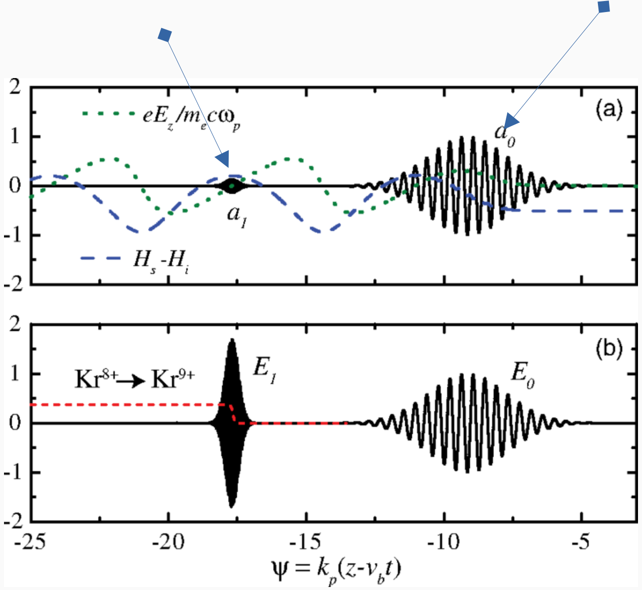
  Phase/amplitude variation of wakefield @ plasma exit; space charge issues;
- Possible strong deviations OF FORCES from azimuthal symmetry
- Standard beam optics/plasma lens optimization after plasma exit

Not (yet) implemented

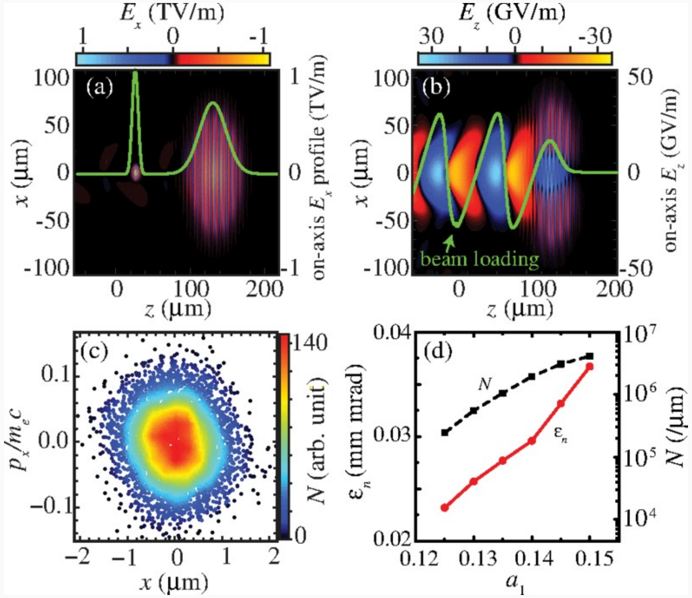
The "two-colour" ionization injection scheme

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 [sinchronized] laser systems: a long-wavelength (e.g. CO2) for wake driving and a short (e.g a frequency doubled Ti:Sa) for electron extraction.

Doubled Ti:Sa ionizing pulse *CO2 driver pulse*



ΔE/E rms= 2.8%, E=50 MeV

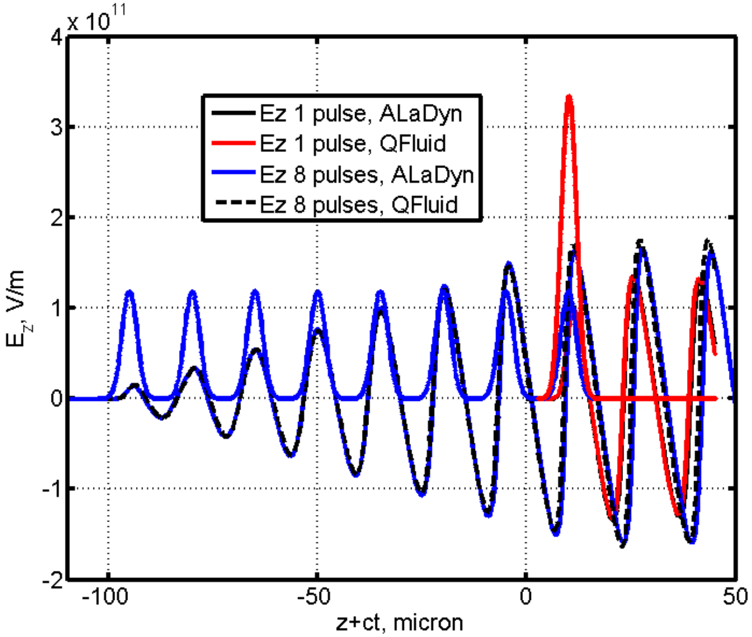


The CO2 pulse is needed because the long wavelength assures a large amplitude Wakefield though the electric field is lower than the ionizing threshold for Kr9+

Multi-Pulse LWFA is available!

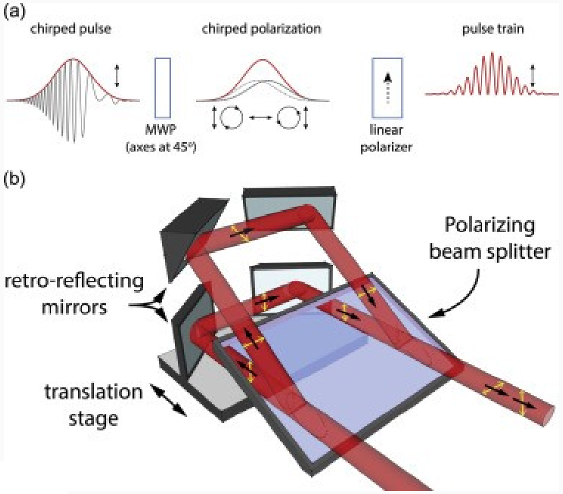
The multi-pulse approach to LWFA has been proposed so far [D. Umstadter et al, PRL 72, (1994)]. A multi-pulse train can generate plasma waves with larger amplitude than those driven by a single pulse with the same energy.

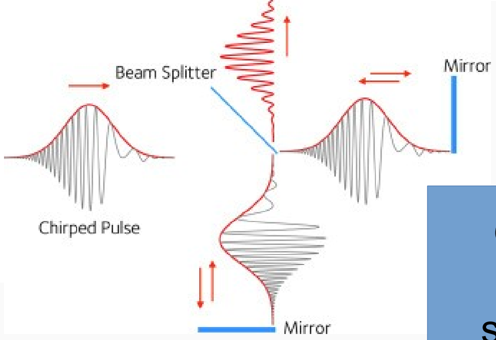
AlaDyn code, PIC 2D slice



QFluid code (self- consistent hybrid fluid+kinetic, 2D CYL)

Two possible pulse-shaping schemes have been proposed very recently



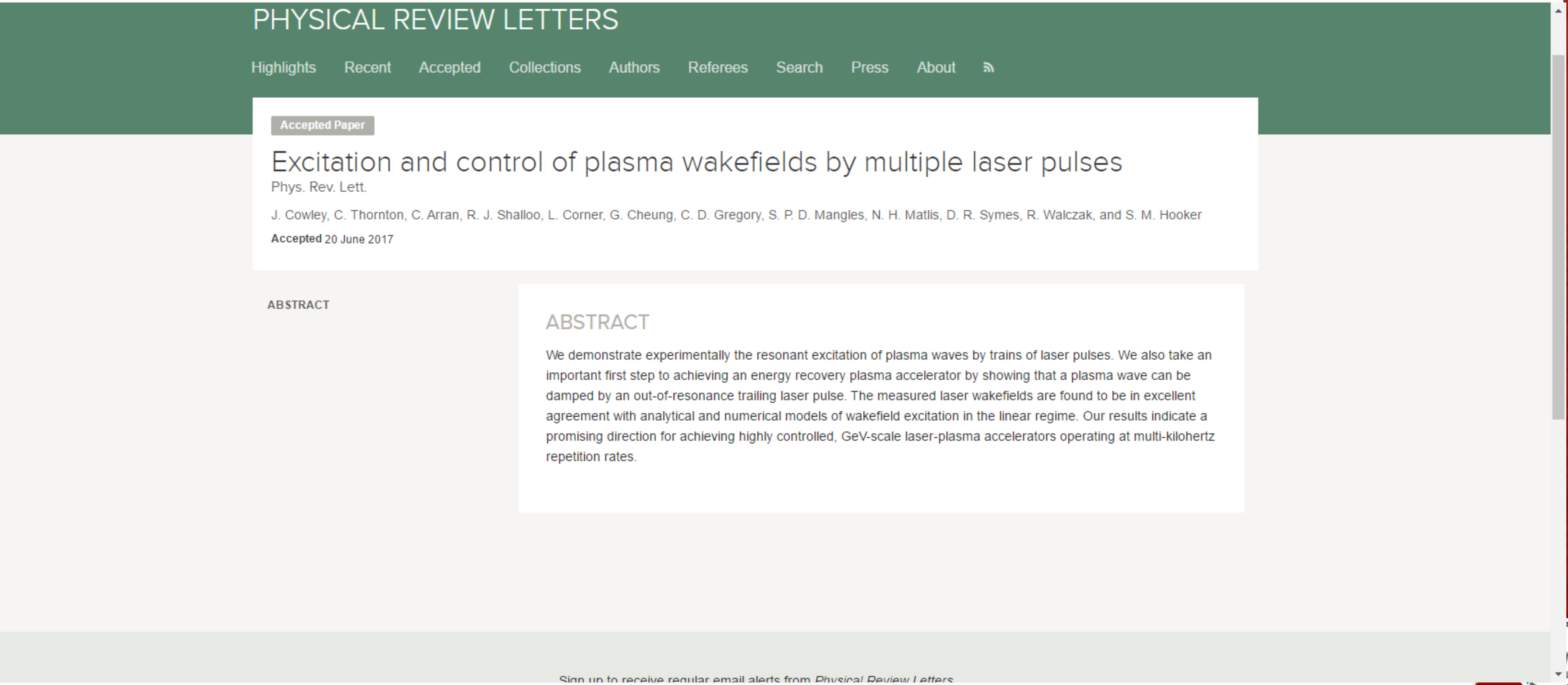


R.J. Shallow et al,
NIM A 829 (2016)

Older methods include either multiple beam-splitters setup or phase masks

BRAND NEW MP-LWFA scheme

- Accepted in PRL yesterdey!
- Uses a Michelson interferometer to induce beating



Excitation and control of plasma wakefields by multiple laser pulses

Phys. Rev. Lett.

J. Cowley, C. Thornton, C. Arran, R. J. Shalloo, L. Corner, G. Cheung, C. D. Gregory, S. P. D. Mangles, N. H. Matlis, D. R. Symes, R. Walczak, and S. M. Hooker

Accepted 20 June 2017

ABSTRACT

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We demonstrate experimentally the resonant excitation of plasma waves by trains of laser pulses. We also take an important first step to achieving an energy recovery plasma accelerator by showing that a plasma wave can be damped by an out-of-resonance trailing laser pulse. The measured laser wakefields are found to be in excellent agreement with analytical and numerical models of wakefield excitation in the linear regime. Our results indicate a promising direction for achieving highly controlled, GeV-scale laser-plasma accelerators operating at multi-kilohertz repetition rates.

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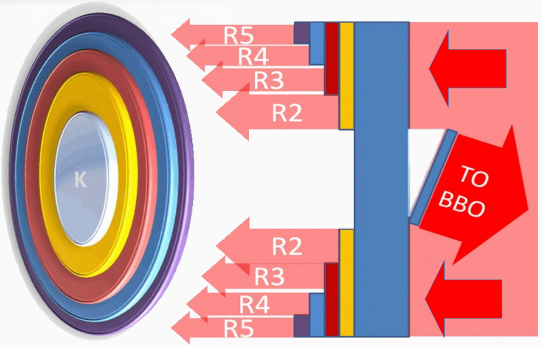
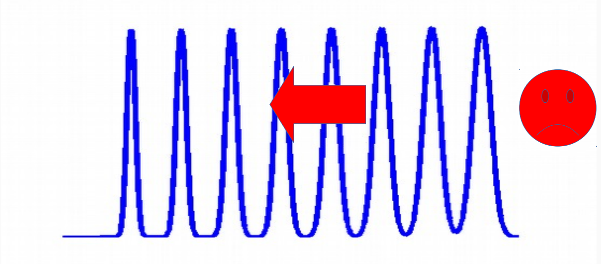
C3ANDEL (**C**omb by **C**hirp **C**ompensated **AN**nular **DE**lay **L**ine)

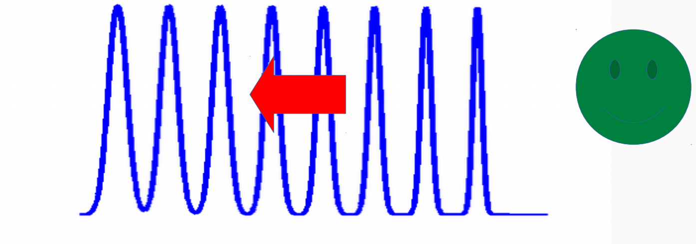


- **The pulse is time shaped with an annular delay line of fused silica.**
- **Each ring thickness is accurately determined by the selected delay of the sub-pulse**

- **Natural pulses lengthening is in the wrong direction (the longer pulses should arrive first [D. Umstadter et al, PRL 72, (1994)]).**



CHIRP COMPENSATION



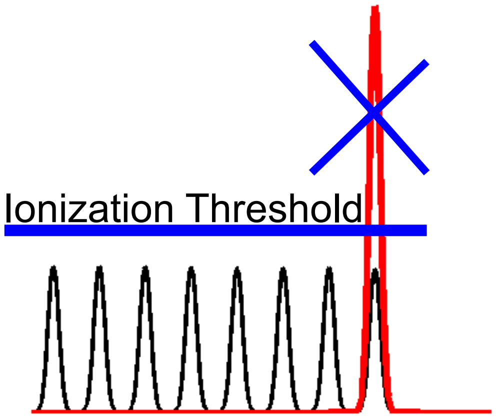
- **The use of a negative chirp (shorter wavelengths on the head of the pulse) will compensate for the lengthening of the last pulse.**

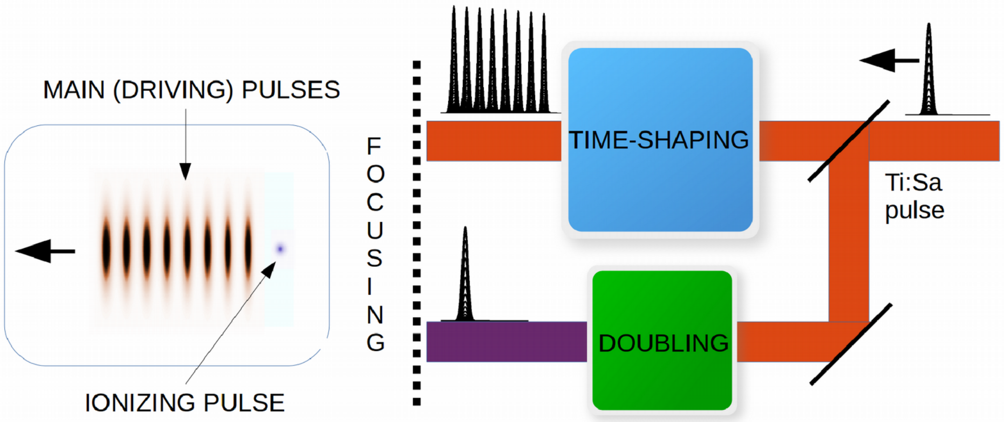
- **A tilted pick-up mirror for the Injection Pulse is placed in the center of the rings.**

A new injection scheme: Resonant Multi-Pulse Ionization Injection

The Resonant Multi-Pulse Ionization injection [P. Tomassini et al, 2017 (submitted)] is a new bunch injection scheme aiming at generating extremely low-emittance bunches [as low as 0.07 mm mrad]

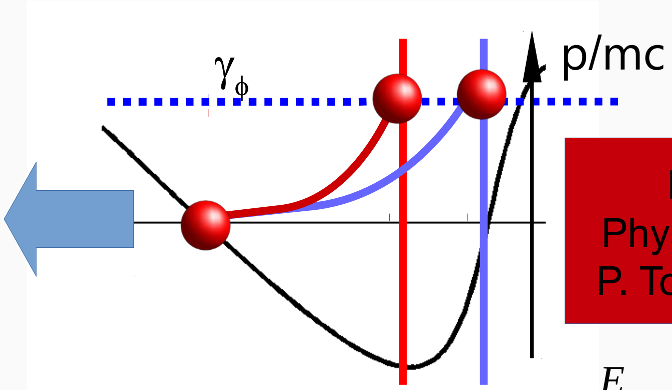
RMPII requires ONE short-pulse 100-TW class (e.g Ti:Sa) laser system. Since a unique very large-amplitude Ti:Sa pulse would fully ionize the atoms (Ar8+ in our selected example), the pulse is shaped as a <u>resonant</u> sequence of sub-threshold amplitude pulses.





RMPII trapping analysis

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



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

$$E_{norm} = E_z / E_0 \,;\, E_0 = mc\,\omega_p / e$$

$$E^2_{norm}/2 + \beta_{ph}\sqrt{(1+E^2_{norm}/2)^2 - 1} > 1 - 1/\gamma_{ph}$$

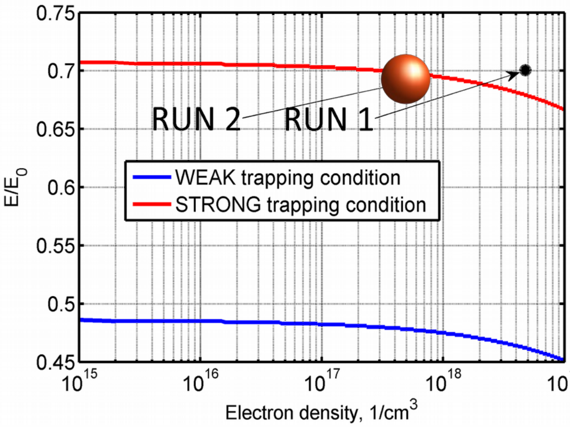
$$2\beta_{ph}\sqrt{(1+E^2_{norm}/2)^2 - 1} > 1 - 1/\gamma_{ph}$$

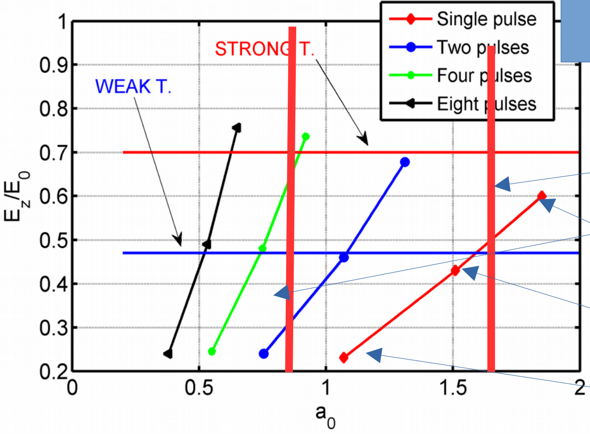
STRONG trapping
WEAK trapping

Trapping analysis with commonplace parameters reveals that optimal trapping is reached with **a0>1.6** in a single pulse setup. This value is close to Ionization threshold **N5+→N6+**.

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

To get advantage of the lower Ui of Ar8+→Ar9+ (Ui=422 eV) at least a 4-pulses train is needed





- Ionization thr. N5+->6+
- Ionization thr. Ar8+->9+

- 7.5J
- 5.0J
- 2.5J

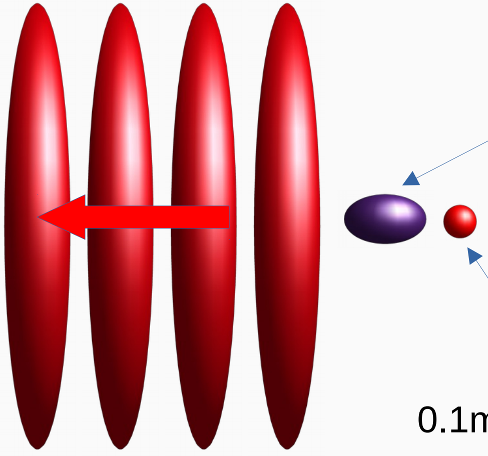
RMPII ionization analysis

The frequency-doubled minor portion of the pulse acts as "ionizing pulse" as in two-colour ionization.

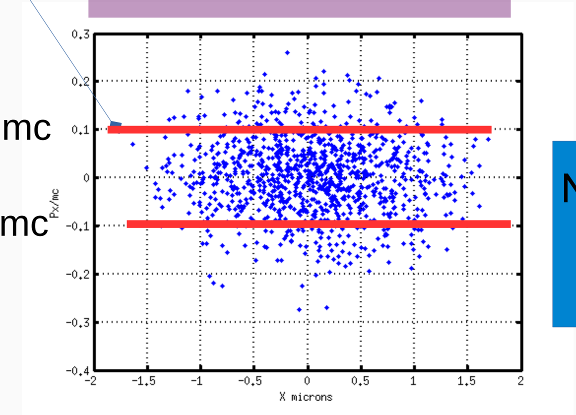
The key concept is that of "minimal transverse momentum rms" $p_{tr}/mc \simeq \Delta\, a_{0e}$
where $\Delta = \sqrt{a_{0e}/a_c}\,;\; a_c = 0.107\left(U_I/U_H\right)^{3/2}\lambda$

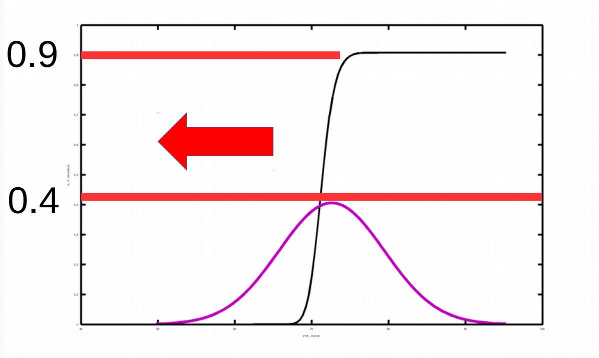
To reduce emittance a tightly focused beam is chosen

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



$w0_{ion}$=3.5-4.5 μm
λ_{ion}=0.4 μm
$Z_{R,ion}$=100-160 μm
T_{ion}=50 fs; a0=0.4





Ionization Ar8+->Ar9+

Newborn electrons (one time-step)
transverse phase space
eps_n=0.05 mm mrad

QFluid4 in brief

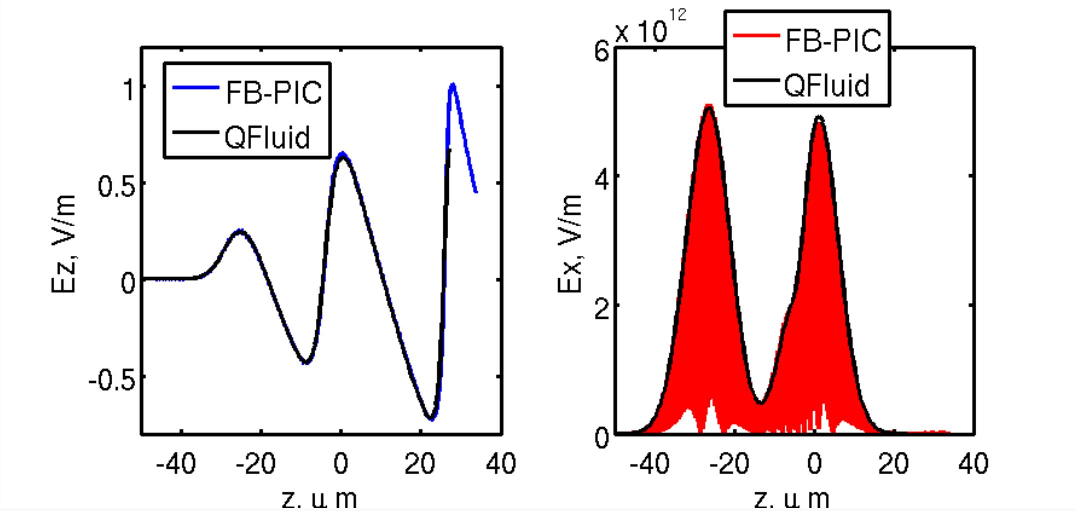
QFluid is a 2D CYLINDRICAL hybrid code for LWFA and PWFA in the plasma fluid and quasi-static regime that is suitable for long propagation simulations.

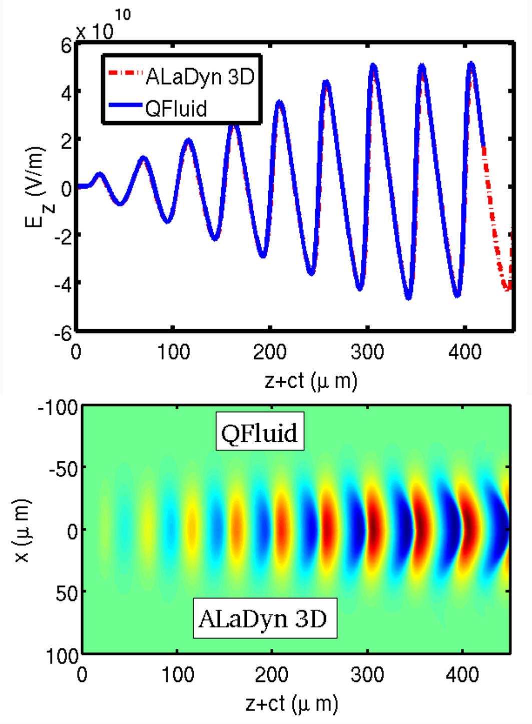
Laser pulse evolution is solved with the Envelope Evolution Approximation (second time derivative included!)

Plasma dynamics is soved via the pseudopotential computation in the QSA

Electrons of the beam move as macroparticles under the 3D force that includes the ponderomotive effect.

NOTE: Qfluid can't be properly used with fast varying density profiles (as those @ plasma exit.Validated with EPOCH, AlaDyn and FB-PIC (also in the multi-pulse case)

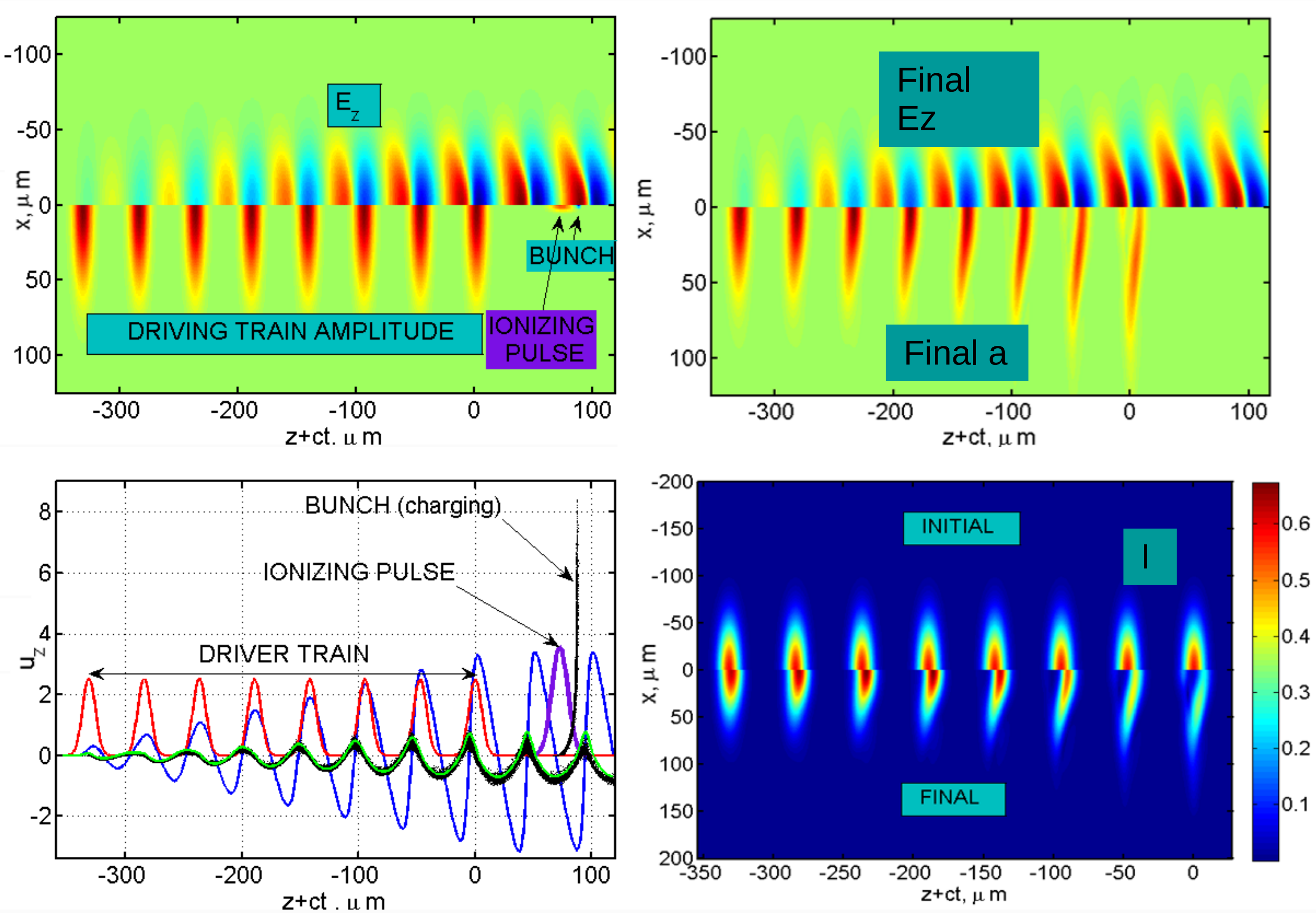




Thanks to M. Kirchen (DESY) FB-PIC

SETUP A -INJECTOR (not guided)

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

$n_0 = 5\,10^{17}\,1/cm^3$

DRIVER

$E = 0.83\,x\,8\,J$

$T = 30\,fs$

$w_0 = 45\,\mu m$

$a_0 = 0.61$

IONIZATION

$E = 12\,mJ$

$T = 35\,fs$

$w_0 = 3.5\,\mu m$

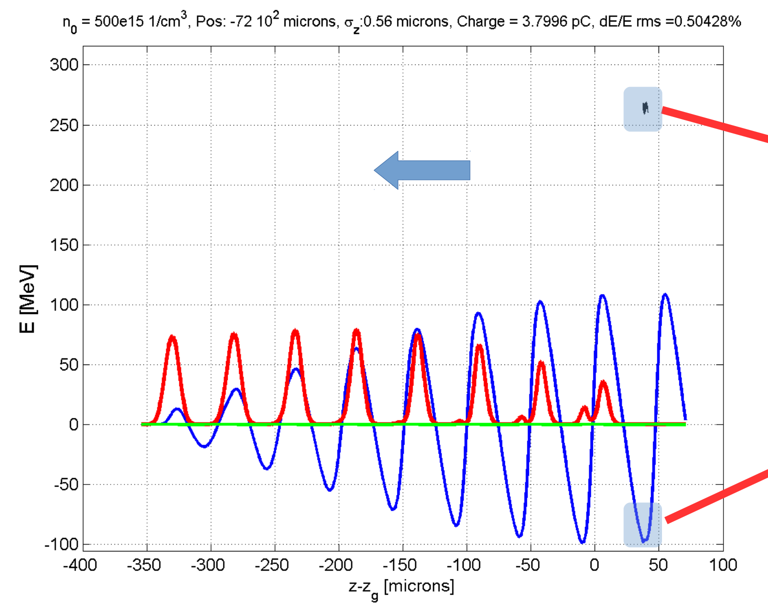
$a_0 = 0.41$

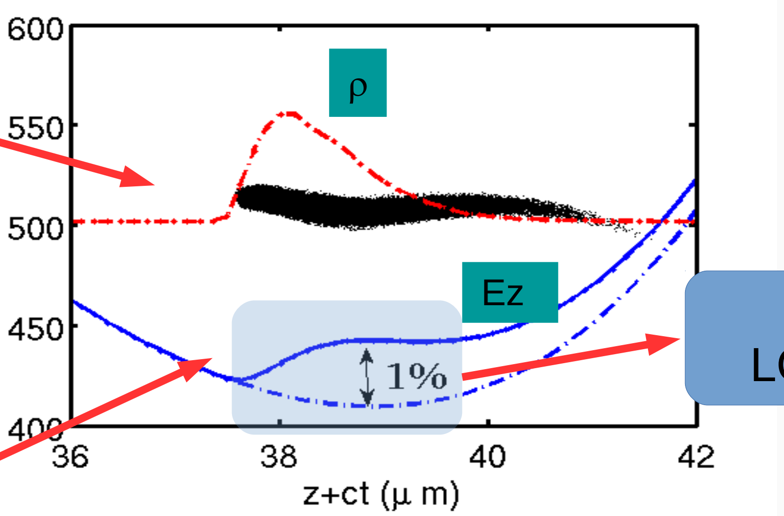
BOX

$\delta r = \delta z = 0.1\,\mu m$

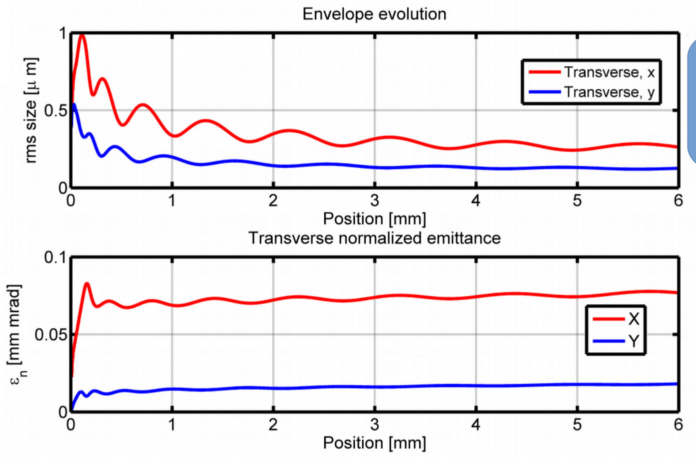
SETUP A (INJECTOR) -Final Bunch quality

After about 6mm of acceleration the 265 MeV beam possesses an outstanding beam-quality: dE/E = 0.5%, eps_n<0.08 mm mrad,





BEAM LOADING



MATCHED BEAM

$$Q = 3.8\,pC\,;\,I_{peak} = 0.9\,kA$$

$$\left(\delta E/E\right)_{rms} = 5\cdot 10^{-3}\,;\,\delta\theta_{rms} = 0.4\,mrad$$

$$\epsilon_{nx} = 0.078\,mm\cdot mrad\,;\,\epsilon_{ny} = 0.018\,mm\cdot mrad$$

$$\sigma_l = 0.56\,\mu\,m\,;\,\sigma_r = 0.23\,\mu\,m$$

SETUP A (INJECTOR) – Increase Charge?

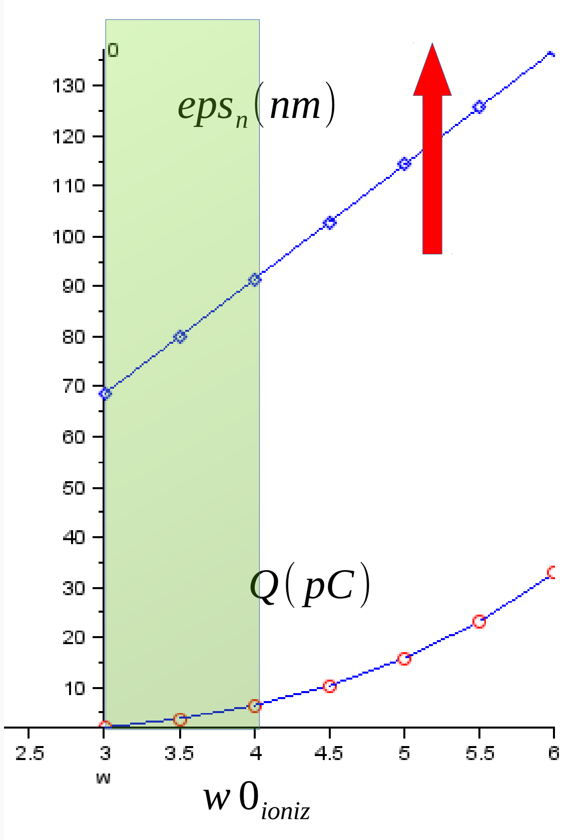
Energy spread and emittance with Q=3.8 pC are very low so the natural question is

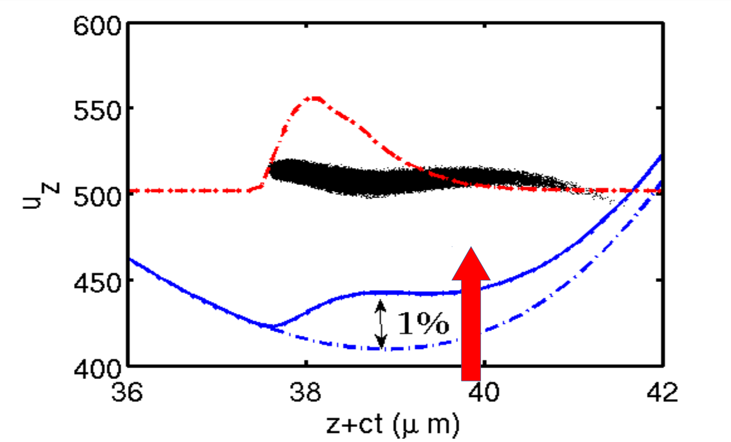
If we want to use the bunch as a pre-accelerated bunch suitable for energy boosting, is it possible to increase its charge?

$Q \propto w_{0\,ion}^4$ $eps_n \propto w_{0\,ion}$

☺

So answer is <u>YES</u> (nonlinear emittance increase due to bunch hopping not included) BUT energy spread will increase to above 1% for a 10pC bunch





SETUP B,D – (guided) GeV-class

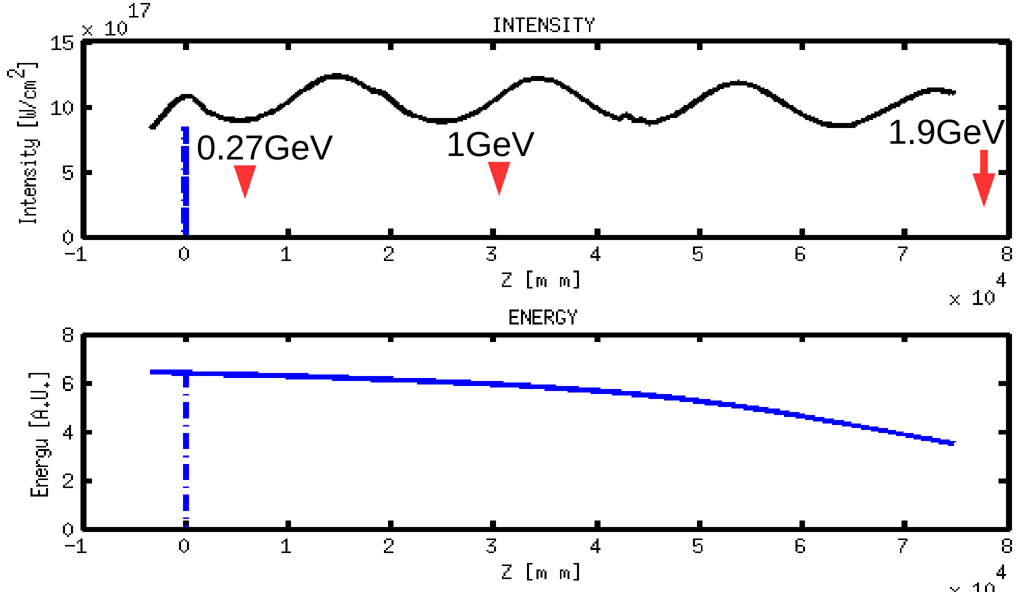
To extend the acceleration beyond one Rayleigh length guiding with a preformed channel is assumed. A capillary is placed close to gas-jet nozzle to assure a gentle transition from a flat (pure Ar) plasma to a He plasma channel

Gas-Jet nozzle
265MeV injector

He filled capillary

BUNCH B- 3cm
1.15 GeV, 0.81% rms,
ε_n= 0.08 mm mrad

BUNCH D- 8cm
1.9 GeV, 0.67% rms,
ε_n=0.08 mm mrad



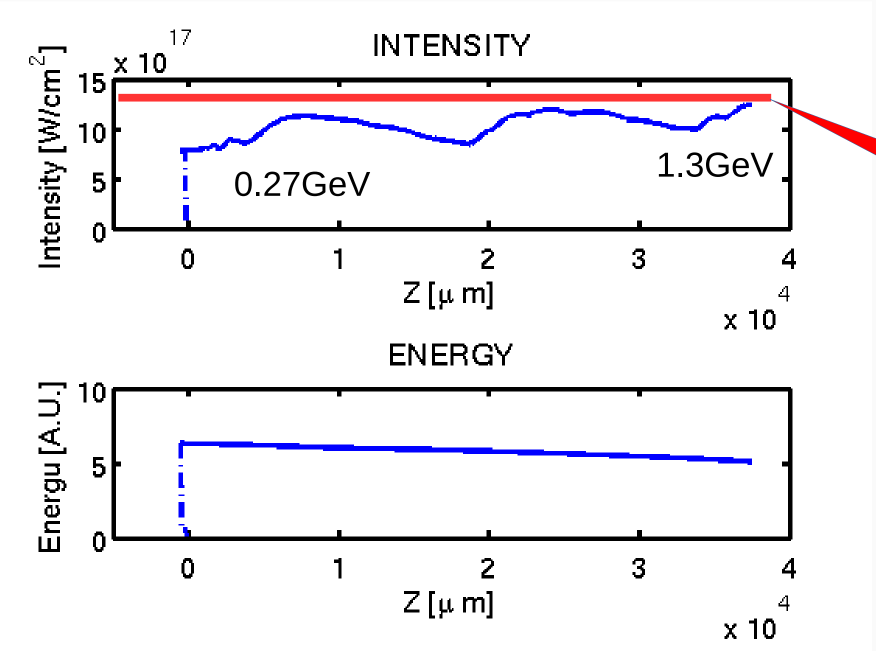
SETUP C – (guided) GeV-class

A single capillary filled with Argon could be a valid alternative to the jes-jet+capillary since the Intensity threshold for Ar9+ is I_tr=1.4e18W/cm^2 (no strong defocusing from further ionizatio occur)

Gas-Jet nozzle
265MeV injector

He filled capillary

Ar filled capillary



Ar9+ Intensity
threshold

2D (cyl) maps

Longitudinal phase-space+fields

Driver(s) evolution

INJECTED

EVOLVED

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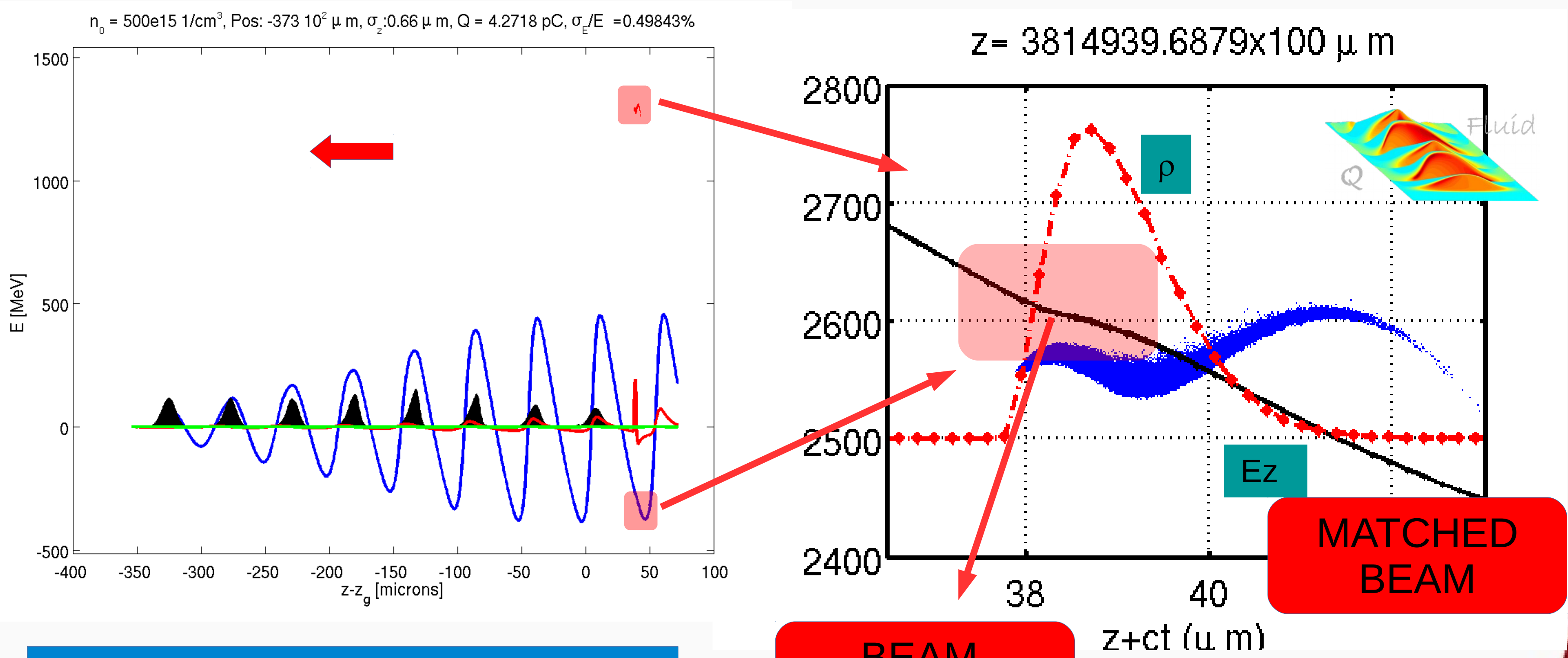
SETUP C (Guided) -Final Bunch quality

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,



MATCHED BEAM

BEAM LOADING

$$Q=4.3\,pC\,;\,I_{peak}=0.85\,kA$$

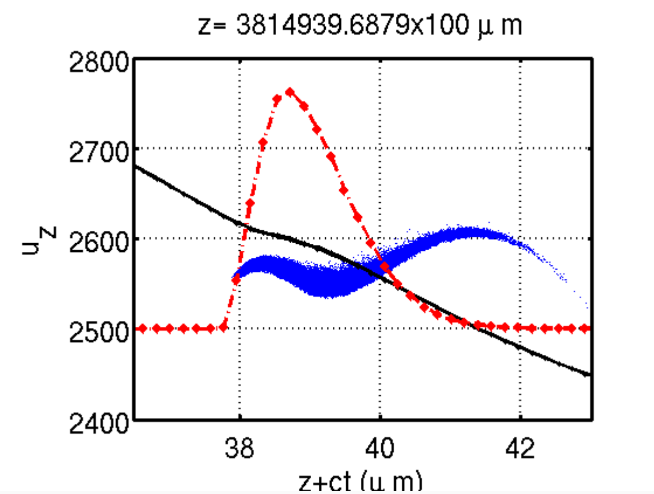
$$(\delta E/E)_{rms}=5\cdot10^{-3};\,\delta\theta_{rms}=0.2\,mrad$$

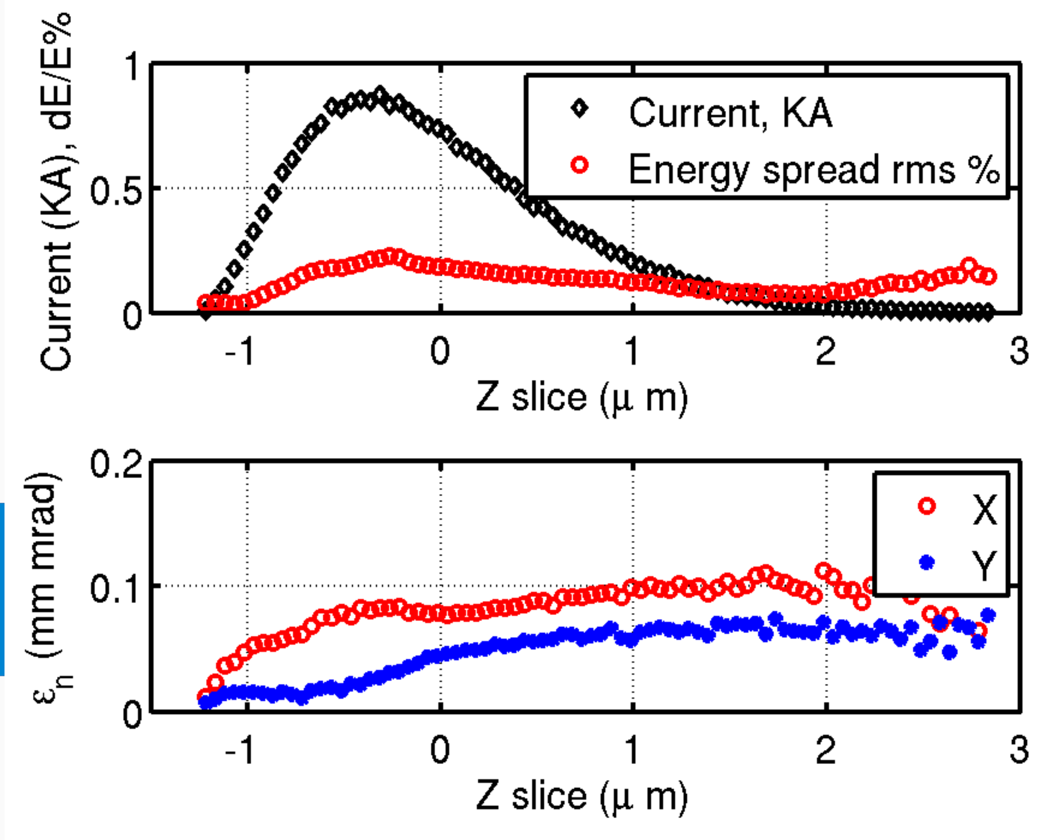
$$\epsilon_{nx}=0.081\,mm\cdot mrad\,;\,\epsilon_{ny}=0.021\,mm\cdot mrad$$

$$\sigma_l=0.66\,\mu m\,;\,\sigma_r=0.19\,\mu m$$

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 dE/E_slice=0.22%@peak current (integrated dE/E = 0.5%),





$$(\delta E/E)_{SLICE}\, rms = 2.2\cdot 10^{-3}\, @\, peak$$

$$I = 0.85\, KA\, @\, peak$$

LINEAR vs CIRCULAR polarizations (Driver)

The use of circular polarization can help in either reducing the number N of pulses or increasing the intensity of the driver(s).

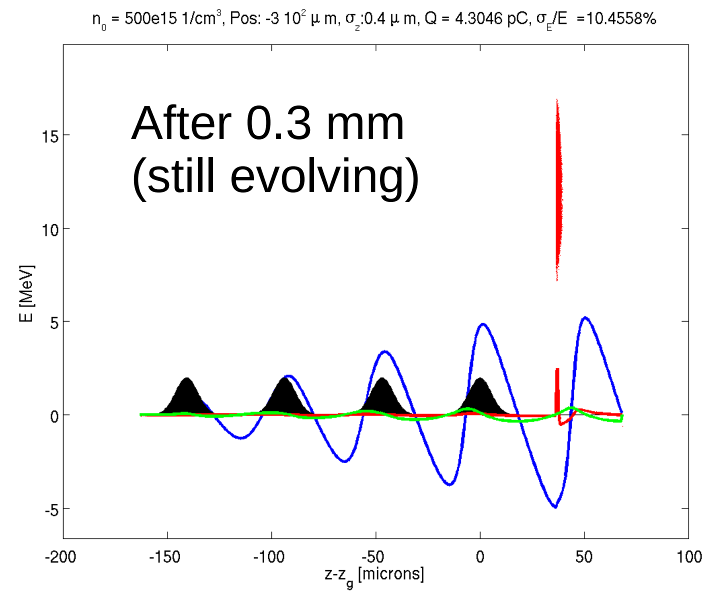
CAUTIONARY NOTE: Some authors [CITE]claim that non-adiabatic effects can modify the outcomes of ADK model especially for circularly polarized pulses. Is there a detailed experimental comparison between linear and circular polarization for the same parameters used here? [30-50fs, a0=0.6-0.8]?

Analytical/numerical results from ADK theory [P. Tomassini 2017] show that the saturation intensity I_C (circular pol.) for Ar9+ is related to I_L (linear pol.) as

$$I_C \simeq 1.7\, I_L$$

TEST RUN with 4 pulses. Same parameters as before but in circular polarization

Snapshot after 300 micron (same results as with an 8-pulses train)



After 0.3 mm
(still evolving)

SECOND vs THIRD harmonics (Ionization)

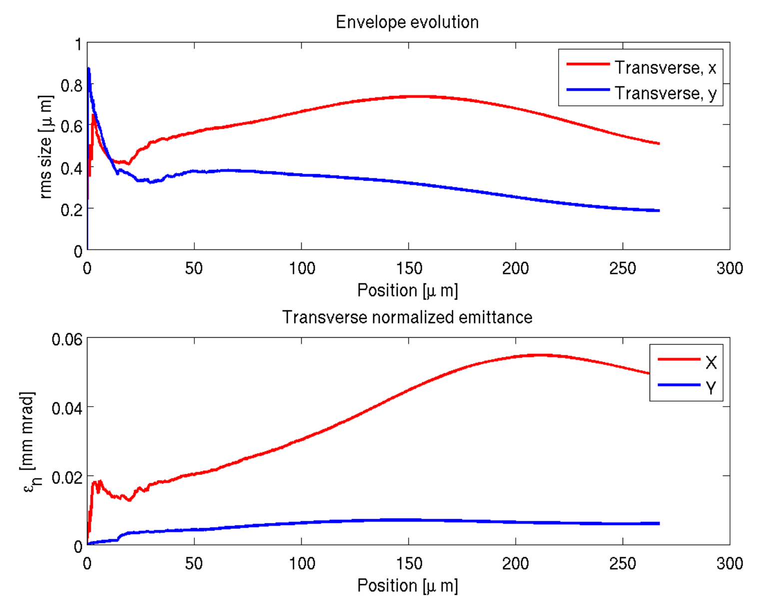
After the ionization pulse passage, the extracted particles possess transverse momentum that essentially depends on pulse amplitude.

$$p_{tr}/mc \propto a_{0\,ion} \propto \lambda^{-1} [QUIVERING, UNCORRELATED]$$
$$p_{tr}/mc \propto a_{0\,ion}^{2} \propto \lambda^{-2} [PONDEROMOTIVE, CORRELATED]$$

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 a0 (correlated x-px give no contribution) we expect that (WITH NO SPACE-CHARGE included) **the emittance scales as 1/λ.**

SAME parameters a C-bunch, but emittance after the injection phase is now 0.05 mm mrad (III harm.) instead of 0.07 mmmrad (II harm.) Not negligible space-charge effects Are present.



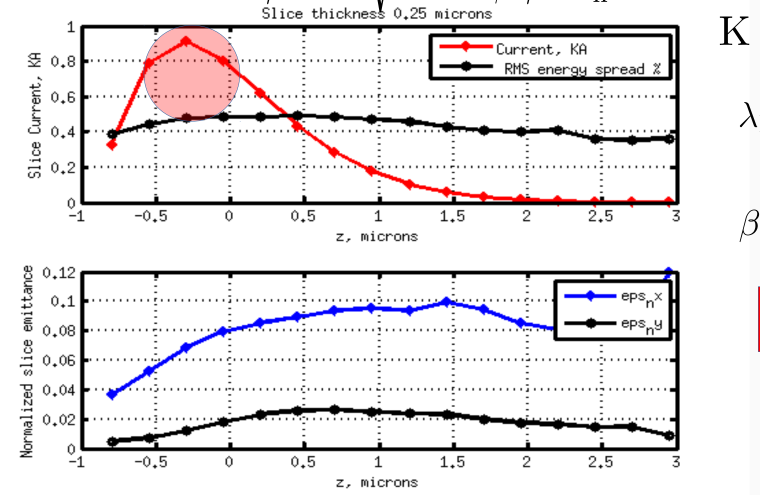
FEL preliminary results

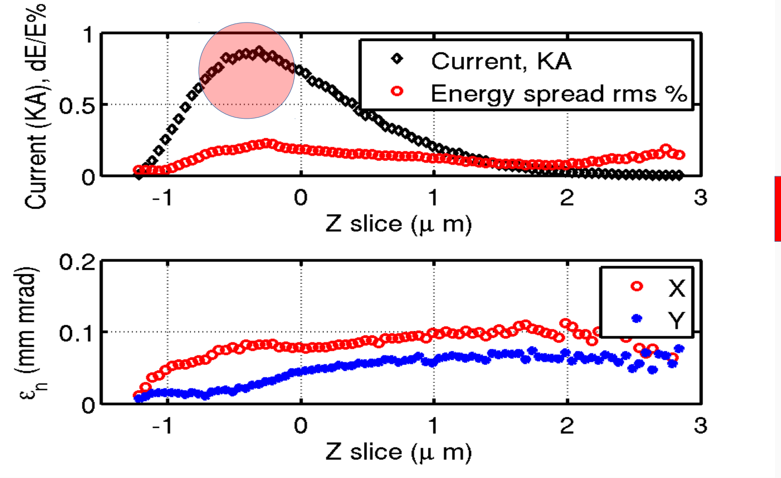
Detailed FEL simulation are ongoing. Preliminary analytical results with bunches A (0.265 GeV) and B (1.0GeV) are shown here. Slice analysis is necessary to fully understand coherent spikes generation and lasing.

$$\rho = \frac{8.36\times10^{-3}}{\gamma}\sqrt[3]{\lambda_U^2\frac{I_{peak}[A]}{2\pi\beta\gamma^{-1}\varepsilon_n}K^2 f_B^2(K)}$$

Bunch parameters

	A	B	C
Bunch parameters			
beam energy [GeV]	0.265	1.15	1.3
long. beam size (rms) σ_L [μm]	0.56	0.25	0.655
current intensity [A]	812	2200	785
norm. emittance [mm×mrad]	0.078	0.08	0.08
energy spread σ_E/E (%)	0.65	0.81	0.5
Common FEL parameters			
undulator magnetic field [T]	1		
undulator period [cm]	1.4		
deflection parameter	1.3		
Output FEL parameters			
FEL wavelength [nm]	48	2.6	2.0
Twiss β [m]	1.26	5.45	6.16
Pierce parameter ρ	0.009	0.003	0.0018
inh. broad. gain length [m]	0.096	1.38	2.14
saturation power [MW]	2291	323	86
saturation length [m]	2.5	33	49
coherence length [μm]	0.25	0.04	0.05
sat. power with slippage [MW]	995	253	82





$$K \simeq 0.94\, B[T]\, \lambda_U[cm]$$

$$\lambda_{FEL} = \frac{\lambda_U}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

$$\beta_{Twiss}[m] = \frac{\sqrt{2}\,\gamma}{2\pi K}\lambda_U[m]$$

BUNCH A

BUNCH C

FEL preliminary results

Gain length

$$\mathrm{L_G} = \left[1 + \frac{0.641}{\rho^2}\left(\frac{\sigma_\mathrm{E}}{\mathrm{E}}\right)^2\right] \exp\left[\frac{0.136}{\rho^2}\left(\frac{\sigma_\mathrm{E}}{\mathrm{E}}\right)^2\right] \frac{\lambda_\mathrm{U}}{4\pi\sqrt{3}\rho}$$

Saturation Power

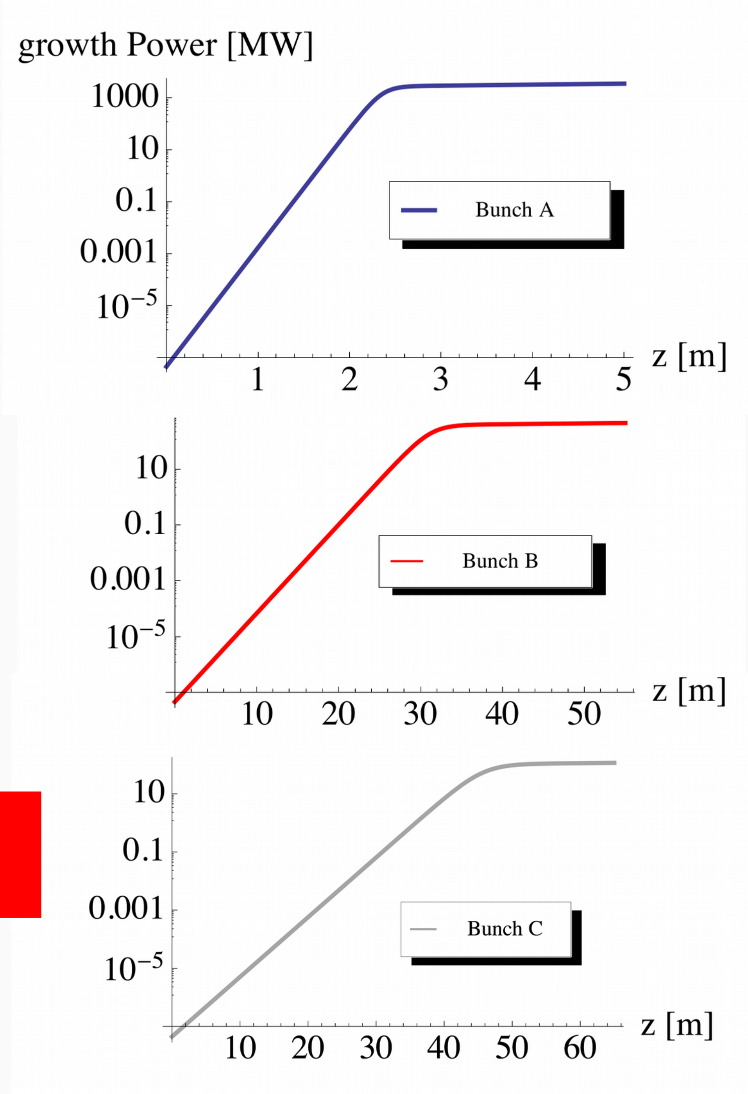
$$\mathrm{P_S} = \sqrt{2}\,\Phi\left(\rho, \frac{\sigma_\mathrm{E}}{\mathrm{E}}\right) \rho\, \mathrm{P}_{e\text{-beam}}$$

Coherence length

$$\mathrm{L_C} = \frac{\lambda_\mathrm{FEL}}{4\pi\sqrt{3}\rho}$$

Slippage corrections

$$\tilde{\mathrm{P}}_\mathrm{S} = \left(1 - \mathrm{e}^{-0.25\,\frac{\sigma_\mathrm{L}}{\mathrm{L_C}}}\right) \mathrm{P_S}$$

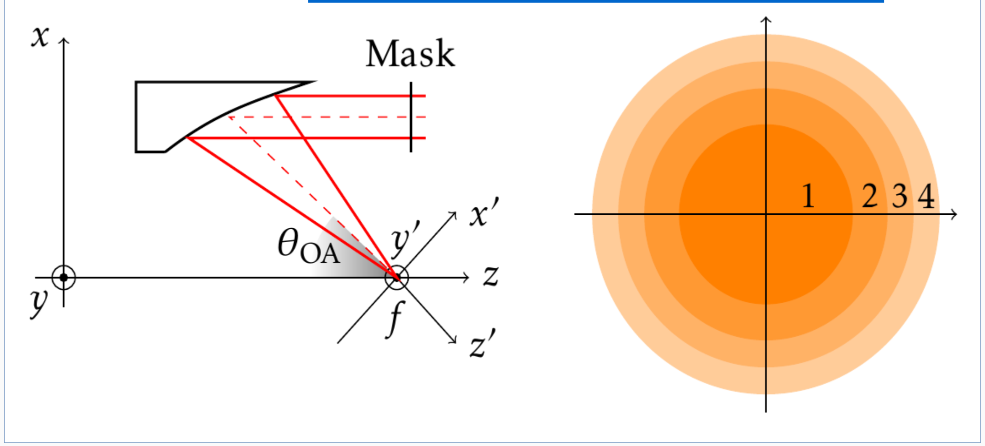


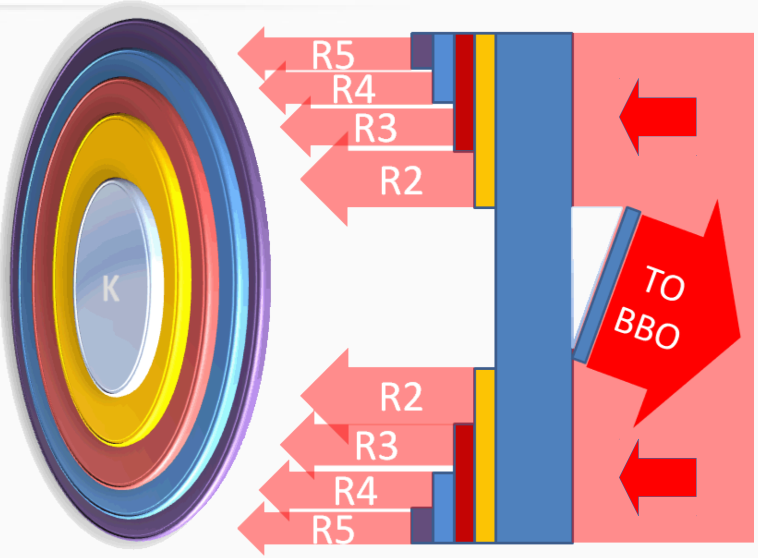
FEL results from G. Dattoli and F. Nguyen ENEA, Frascati

BOOKLET for FEL design,
G.Dattoli et al
http://fel.enea.it/booklet/pdf/
Booklet_for_FEL_design.pdf

C3ANDLE working status

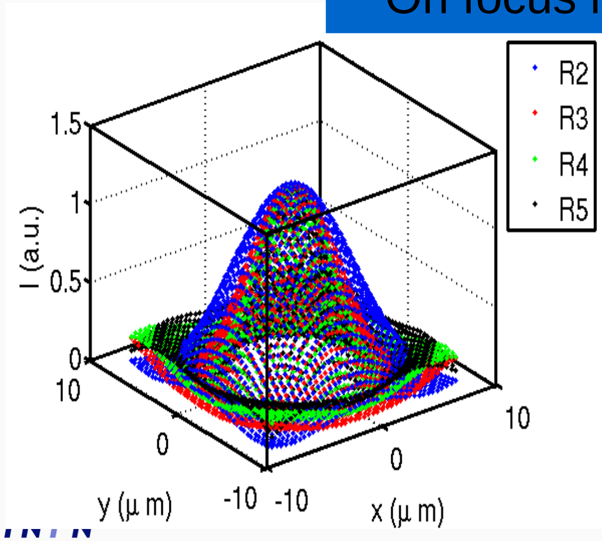
Delay masks with tuned thickness and radii

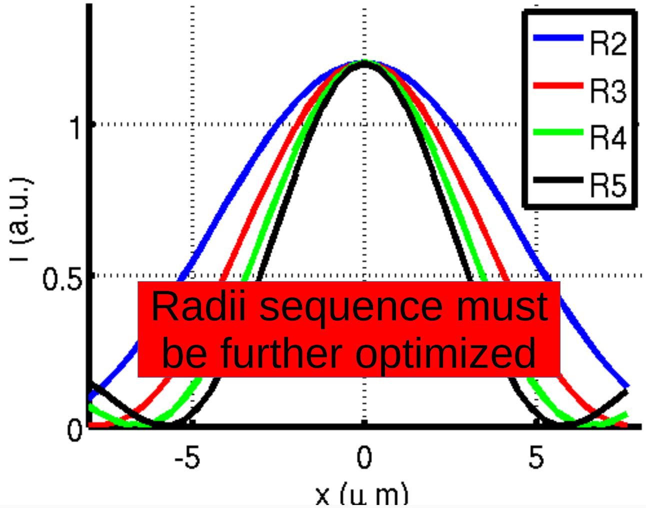




SIDE VIEW

On focus intensities





Radii sequence must be further optimized

PARAMETERS
n0=5e17 1/cm3

Substrate:
l0=0.5mm
Rings:
Δl=0.104 mm
BBO:
L=0.2mm

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)**
- **Charge can be increased to meet EUPRAXIA requirements (INJECTOR) but emittance and energy spread will increase. More simultions are required**
- **Bunch quality is outstanding, mainly concerning emittance (below 0.1 mm mrad along E and 0.02 mm mrad along B)**
- **FEL preliminary results show that those bunches are suitable for lasing, generating a few-spikes radiation.**
- **We are working on the choice of the pulse time shaper. A possible configuration with delay masks is being studied.**
- **Bunch quality can be further optimized by changing the trapping point [in progress]**