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28 September 2017

EAAC17
24-30 September, Isola d'Elba

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ISTITUTO NAZIONALE DI OTTICA

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

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Outlook

- The ILIL@CNR laboratory
- The Resonant Multi-Pulse Ionization injection
- 265 MeV and >1 GeV high-quality [dE/E=0.5%, 0.08 mm mrad] electron bunches with tunable duration
- Higher harmonics of Ti:Sa (Ionization pulse)
- FEL preliminary results
- Towards experimental demonstration at ILIL-PW

Intense Laser Irradiation Laboratory @ CNR Pisa

http://ilil.ino.it

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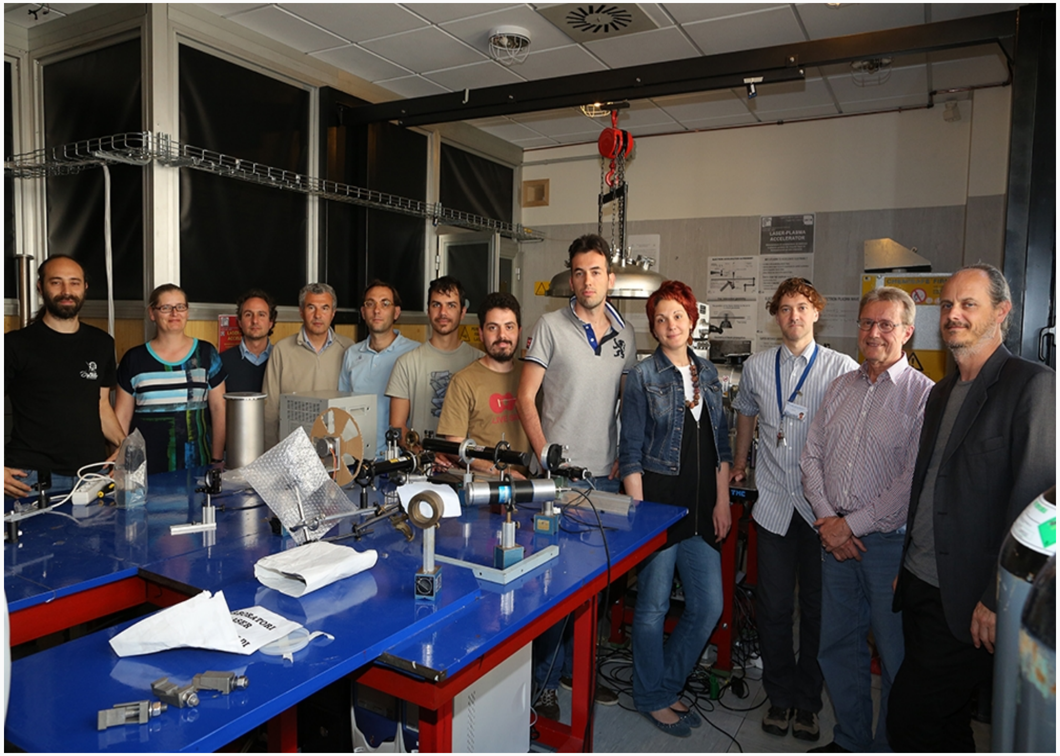

* Also at INFN

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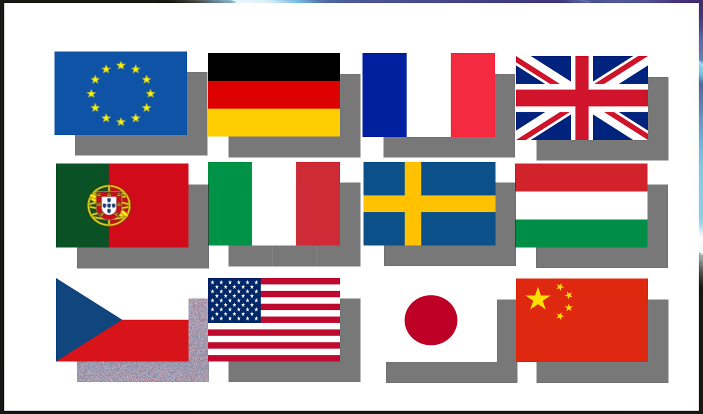
EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

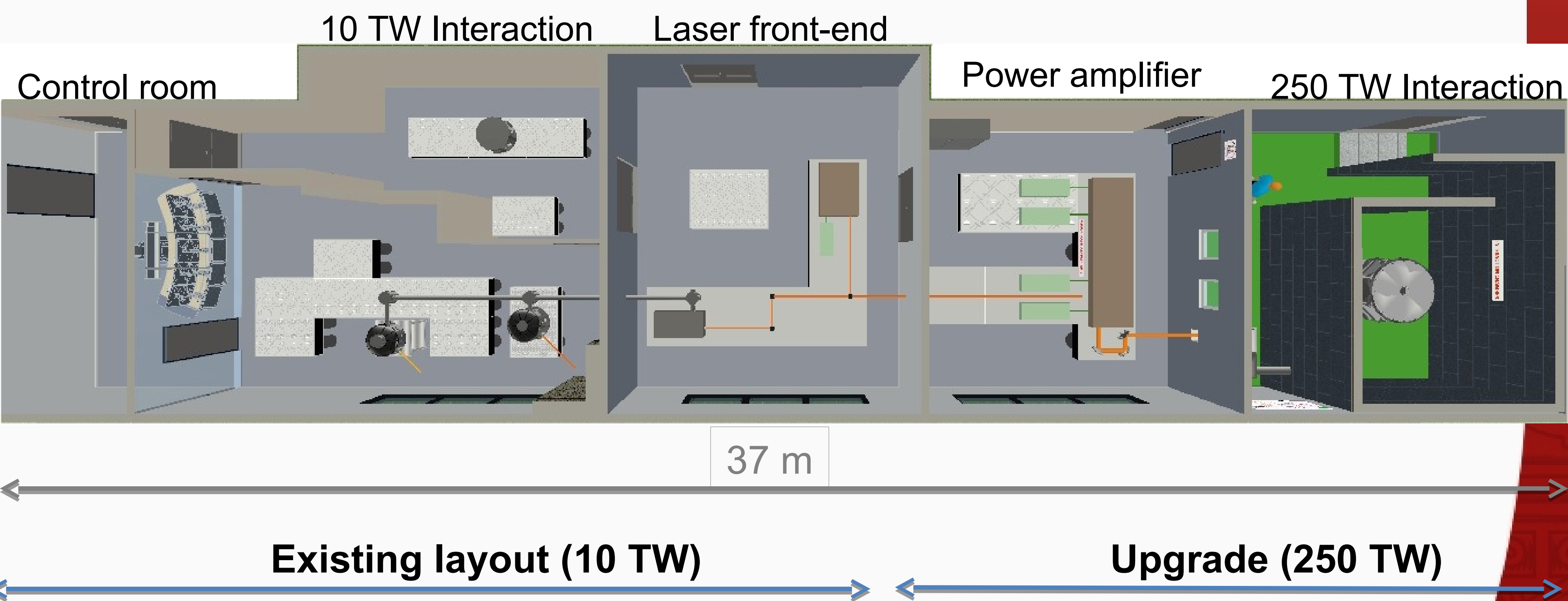
A new infrastructure design study (H2020) for a plasma driven X-ray FEL



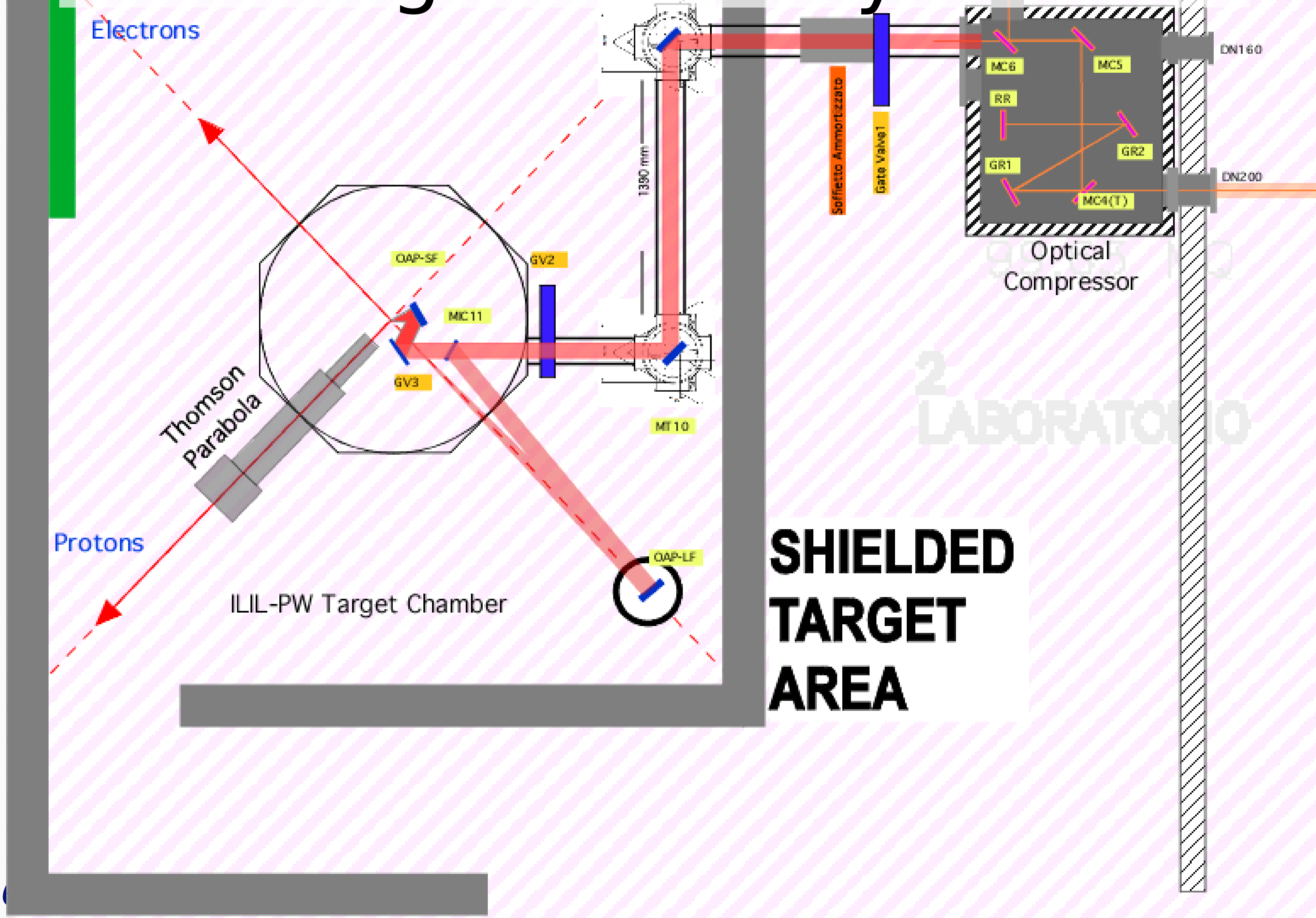
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

EuPRAXIA kick-off meeting in Pisa, July 2016

ILIL Lab top view



Target Area Layout



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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)	2x10^19	**2x10^20**	>4x10^20
Contrast@100ps	>10^9	**>10^9**	>10^10
Beam Diameter (mm)	36	**100**	100

INFN

The **Resonant Multi-Pulse Ionization injection** scheme outlook

ReMPI is a SINGLE LASER System (e.g. Ti:Sa) LWFA scheme that can generate extremely good-quality bunches *with tunable duration*.

ReMPI with ONE 250 TW Ti:Sa

BASELINE PARAMETERS

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 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

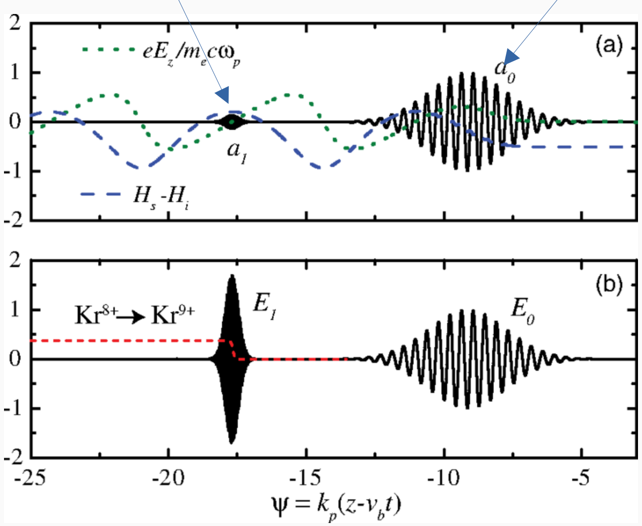
Options to increase energy are available

We start from the "two-color" ionization injection scheme

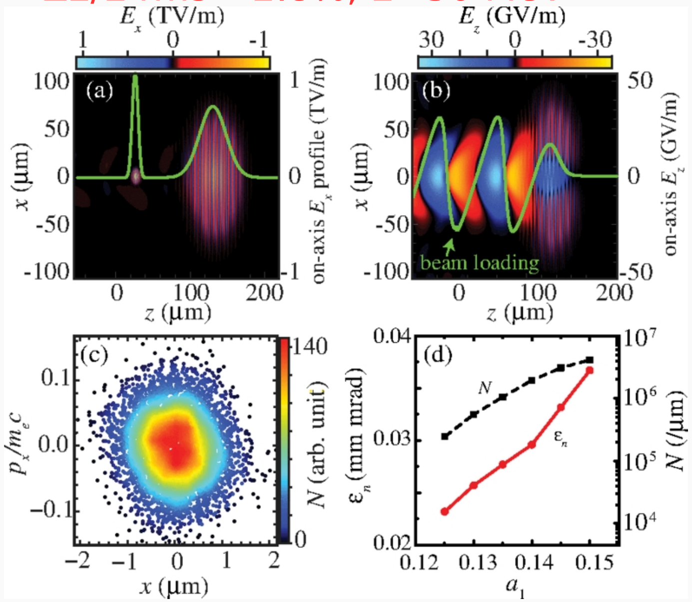
Two-colour injection [L. L. Yu et al. PRL 112 (2014)] is a very promising scheme aiming at generating extremely low-emittance bunches but requires two [sinchronized] laser systems: a long-wavelength (e.g. CO2) for wake driving and a short (e.g a frequency doubled Ti:Sa) for electron extraction.

Doubled Ti:Sa ionizing pulse

C02 driver pulse



$\Delta E/E$ rms= 2.8%, E=50 MeV

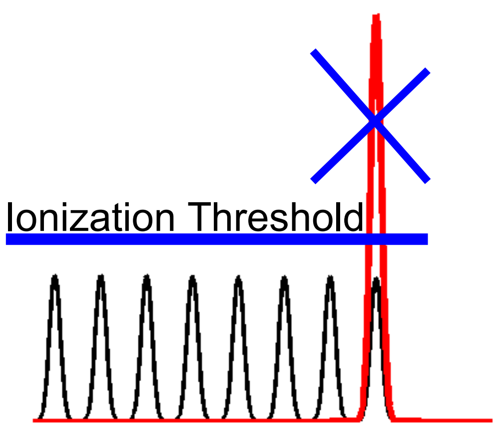


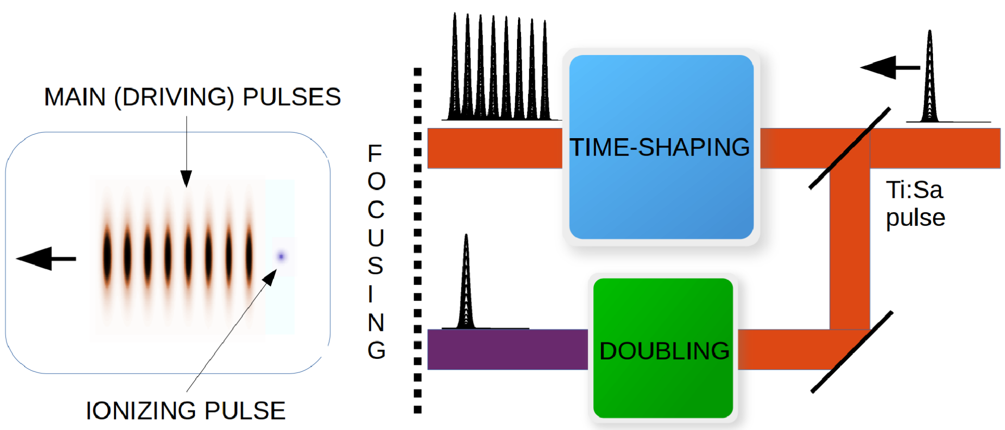
The CO2 pulse is needed because the long wavelength assures a large amplitude Wakefield though the electric field is lower than the ionizing threshold for Kr9+

The new injection scheme: Resonant Multi-Pulse Ionization Injection

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 <u>resonant</u> sequence of sub-threshold amplitude pulse**s.

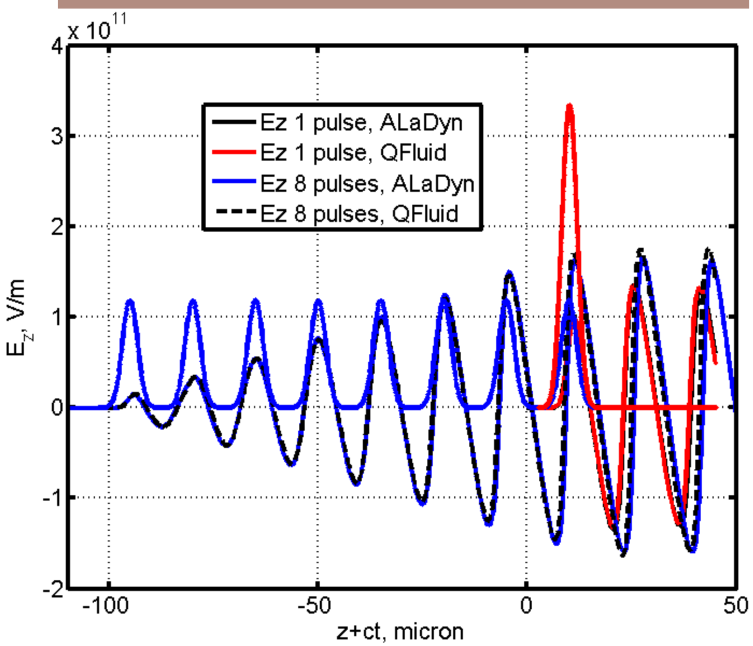




Multi-Pulse LWFA is available NOW !

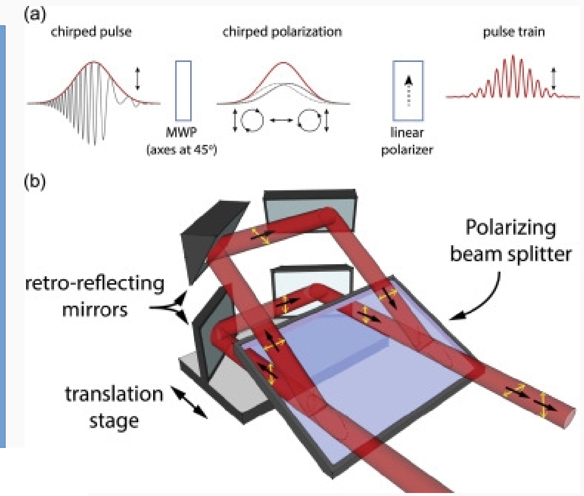
The multi-pulse approach to LWFA has been proposed so far [D. Umstadter et al, PRL 72, (1994)]. A multi-pulse train can generate plasma waves with larger amplitude than those driven by a single pulse with the same energy.

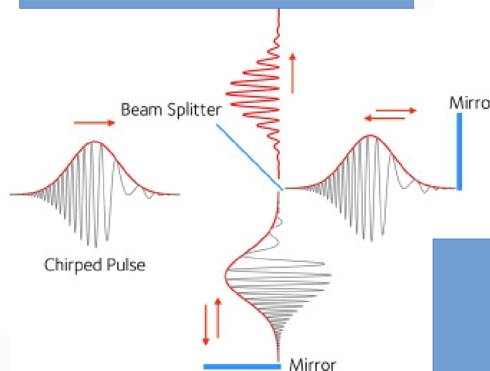
AlaDyn code, PIC 2D slice



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

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

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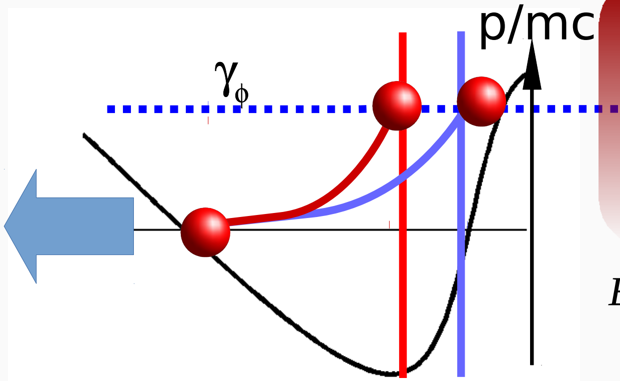
ReMPI trapping analysis

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, PoP (2017)

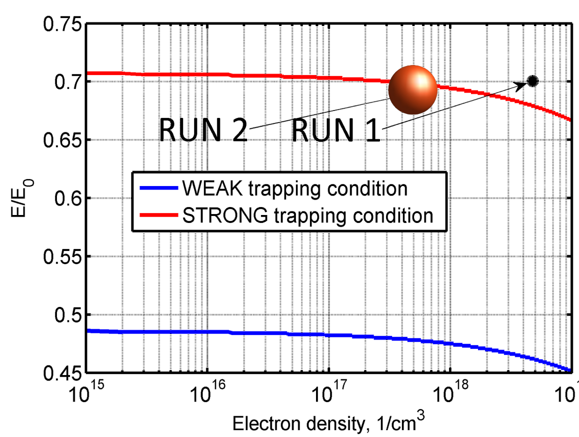
$$E_{norm}=E_z/E_0\,;E_0=mc\,\omega_p/e$$

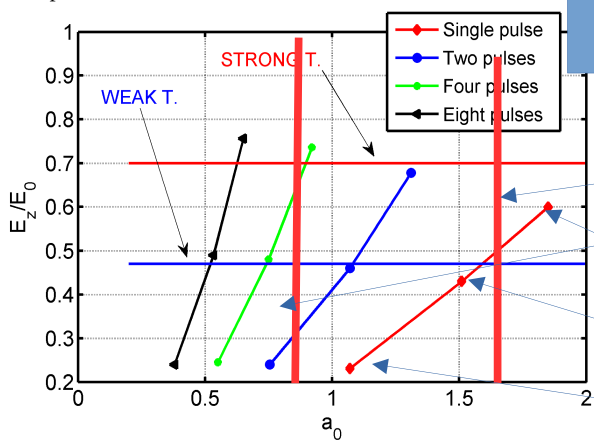
$$E_{norm}^2/2+\beta_{ph}\sqrt{(1+E_{norm}^2/2)^2-1}>1-1/\gamma_{ph}$$ STRONG trapping

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

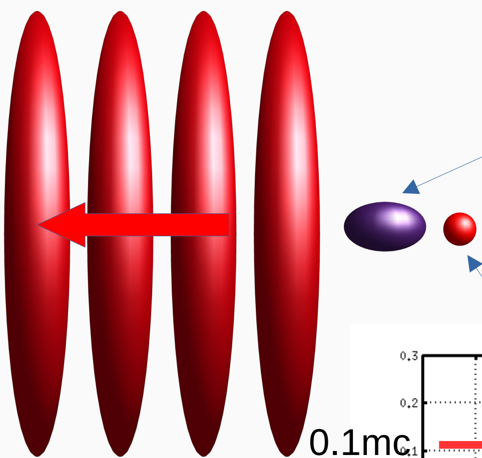
ReMPI ionization analysis

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

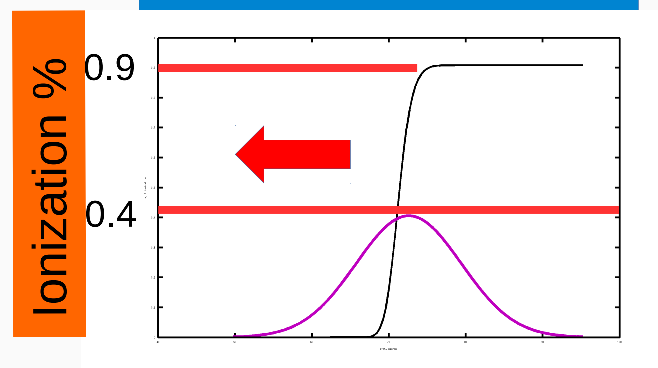
The key concept is that of "minimal transverse momentum rms" $p_{tr}/mc \simeq \Delta a_{0e}$
where $\Delta = \sqrt{a_{0e}/a_c}; a_c = 0.107 (U_I/U_H)^{3/2} \lambda$

To reduce emittance a tightly focused beam is chosen

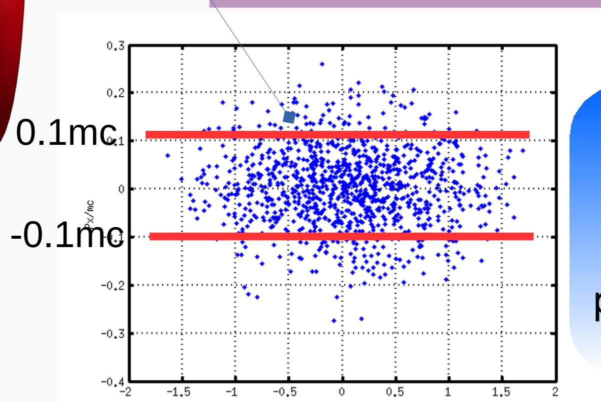
C.B. Schroeder et al.,
PRAB 17 (2014)
P. Tomassini et al (2017)



$w0_{ion}$=3.5-4.5 μm
λ_{ion}=0.4 μm
$Z_{R,ion}$=100-160 μm
T_{ion}=40 fs; a0=0.4



Ionization Ar8+->Ar9+



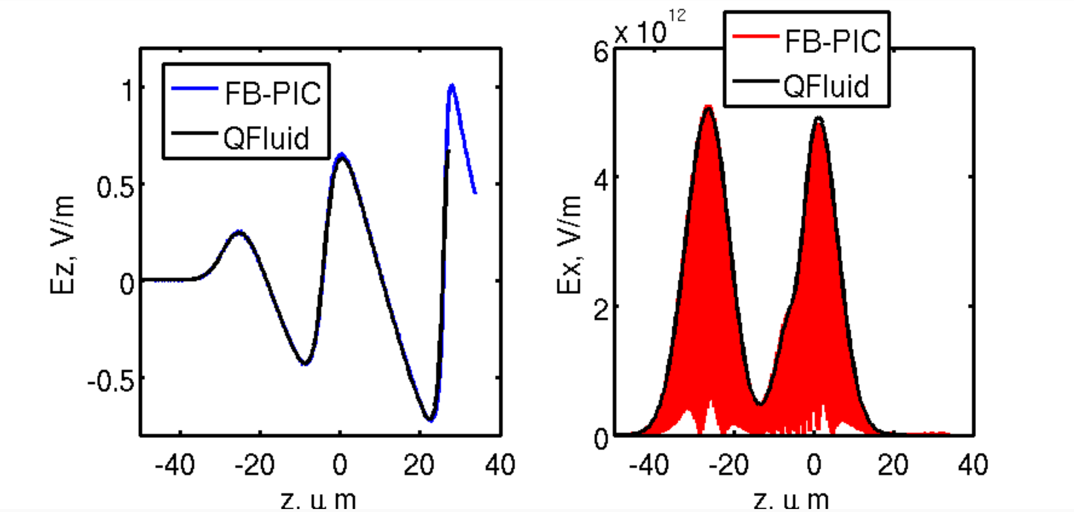
Newborn electrons (one time-step) transverse phase space **eps_n=0.051 μm** in good agreement with eps_n=0.053 mm predicted by the model of **Schroeder et al.**,

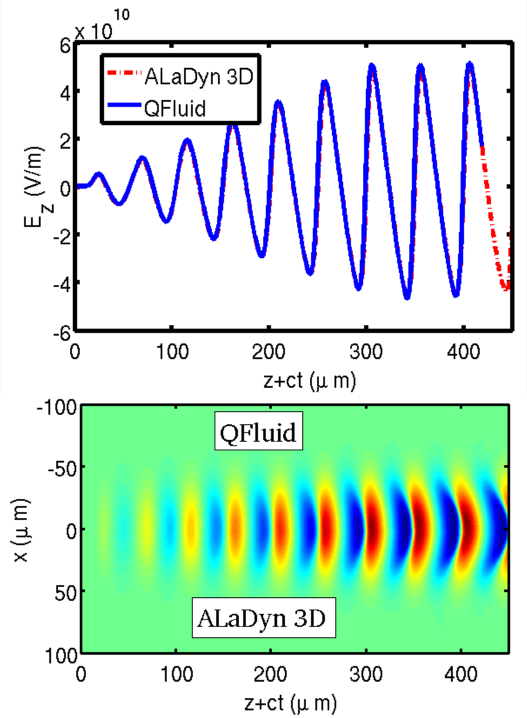
QFluid4 in brief

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 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 <u>Validated with EPOCH, AlaDyn and FB-PIC (also in the multi-pulse case)</u>

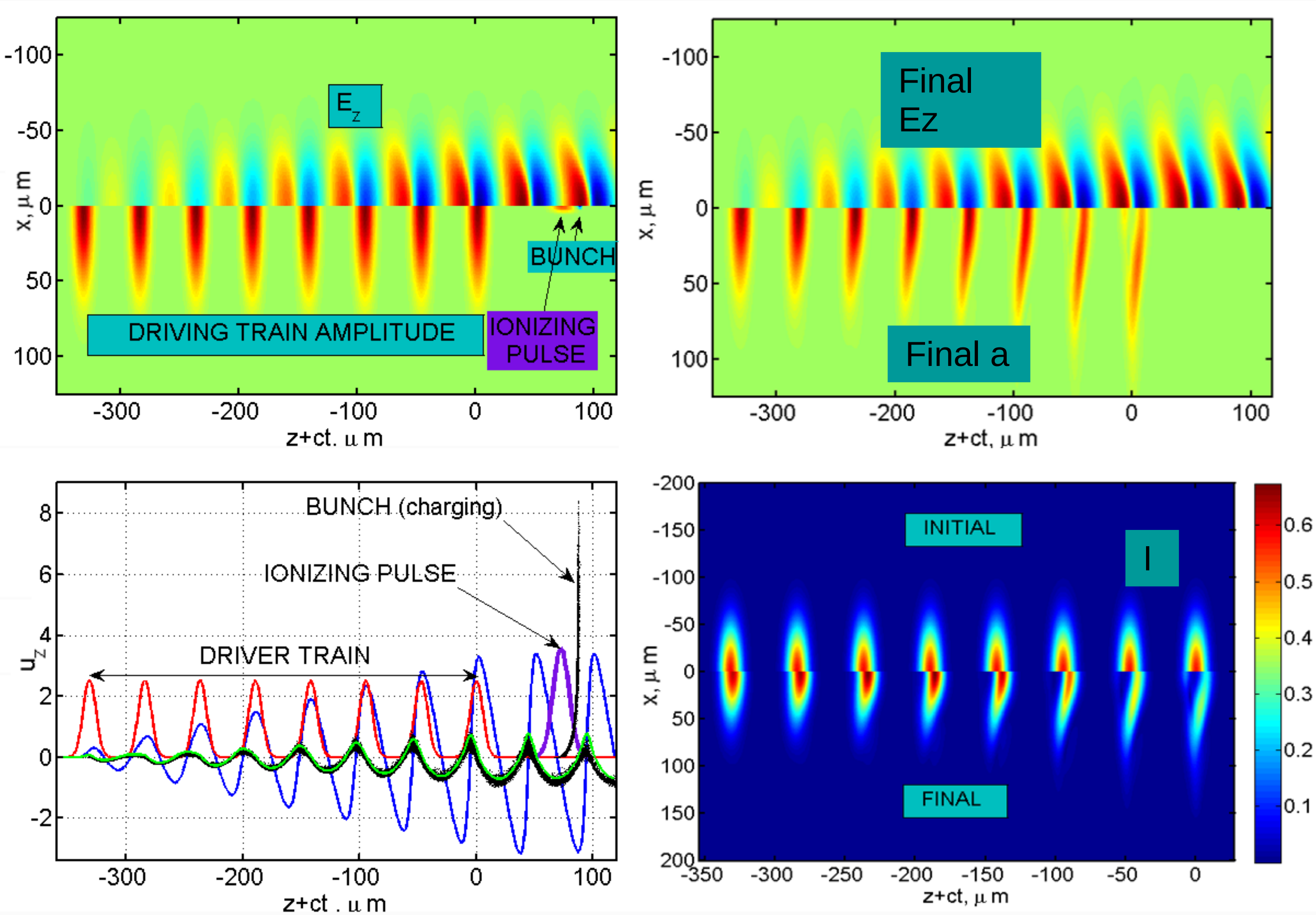




Thanks to M. Kirchen and R. Lehe for support with FB-PIC

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

$E = 12\,mJ$

$T = 35\,fs$

$w_0 = 3.5\,\mu m$

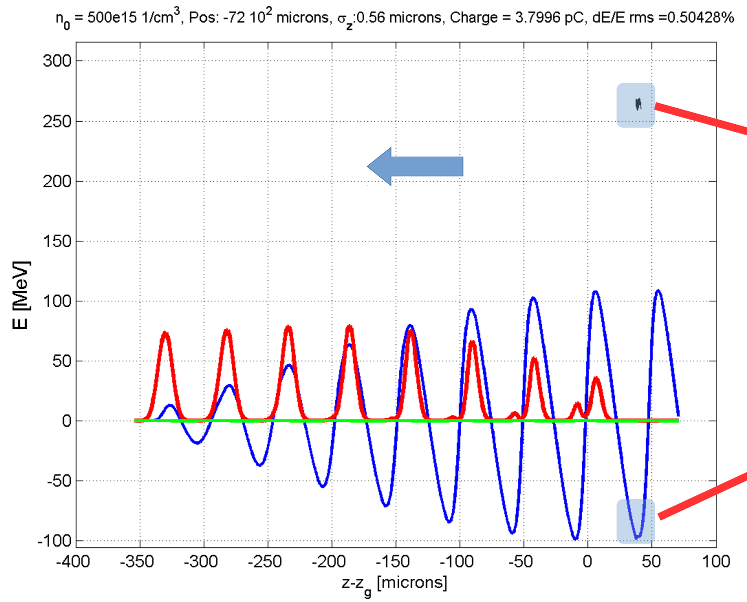
$a_0 = 0.41$

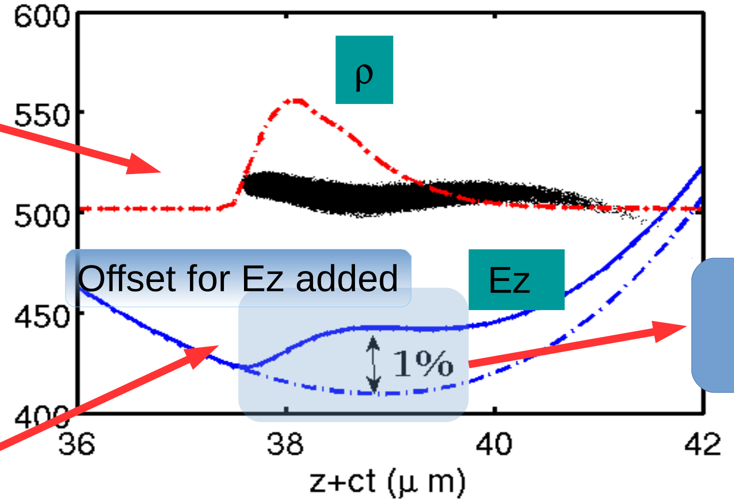
BOX

$\delta r = \delta z = 0.05\,\mu m$

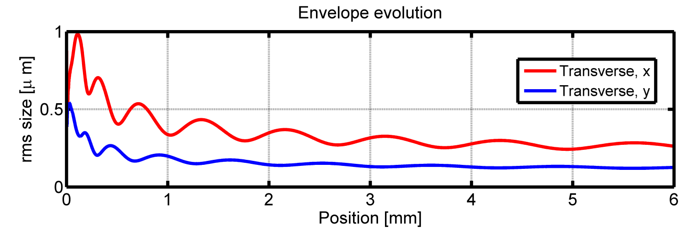
SETUP A (INJECTOR) -Final Bunch quality

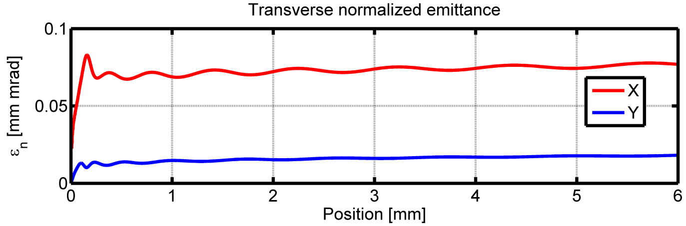
After about 6mm of acceleration the 265 MeV beam possesses an outstanding beam-quality: dE/E = 0.5%, eps_n<0.08 mm mrad,





BEAM LOADING





MATCHED BEAM

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

$$(\delta E/E)_{rms}=5\cdot10^{-3};\delta\theta_{rms}=0.4\,mrad$$

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

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

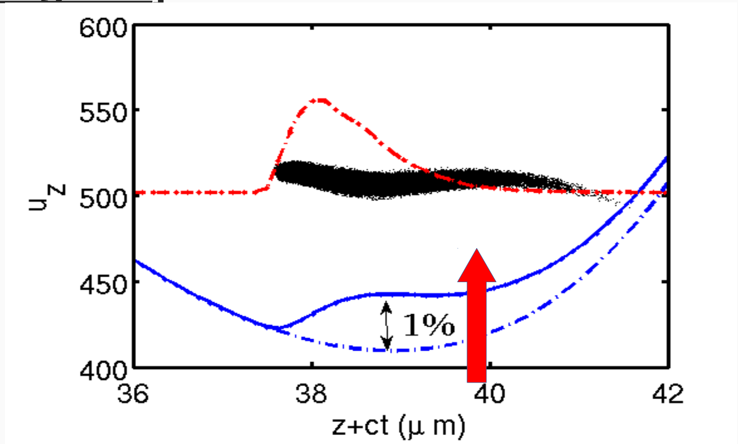
SETUP A (INJECTOR) – Increase Charge?

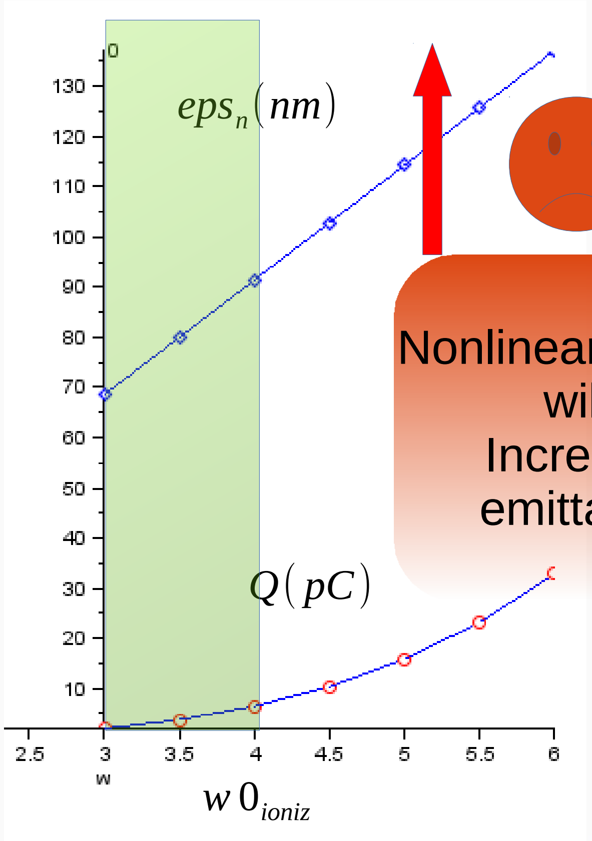
Energy spread and emittance with Q=3.8 pC are very low so the natural question is

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

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

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]





Nonlinear effects will Increase emittance

SETUP B,D – (guided) GeV-class

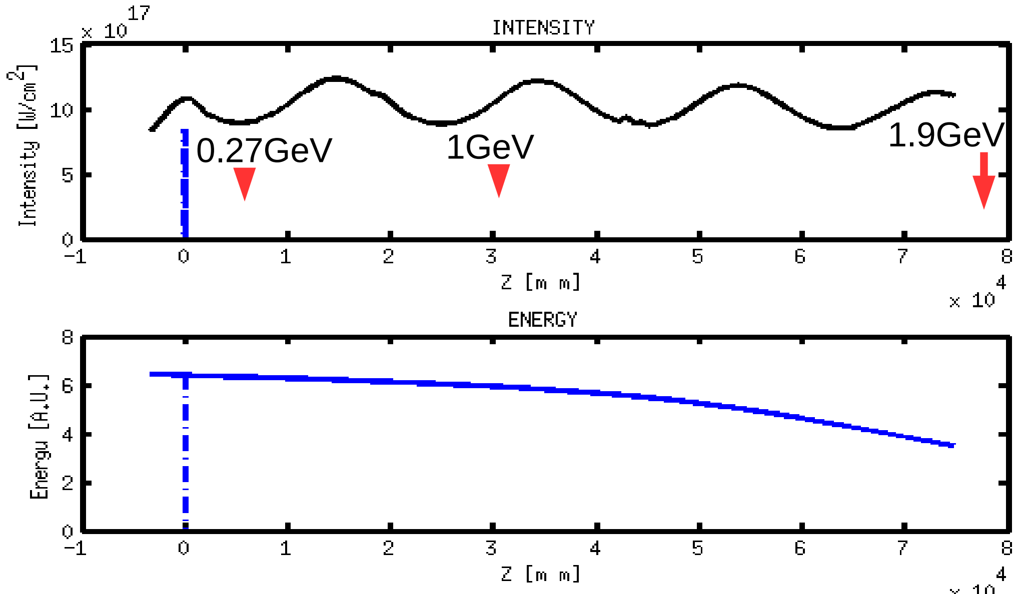
To extend the acceleration beyond one Rayleigh length guiding with a preformed channel is assumed. A capillary is placed close to gas-jet nozzle to assure a gentle transition from a flat (pure Ar) plasma to a He plasma channel

Gas-Jet nozzle
265MeV injector

He filled capillary

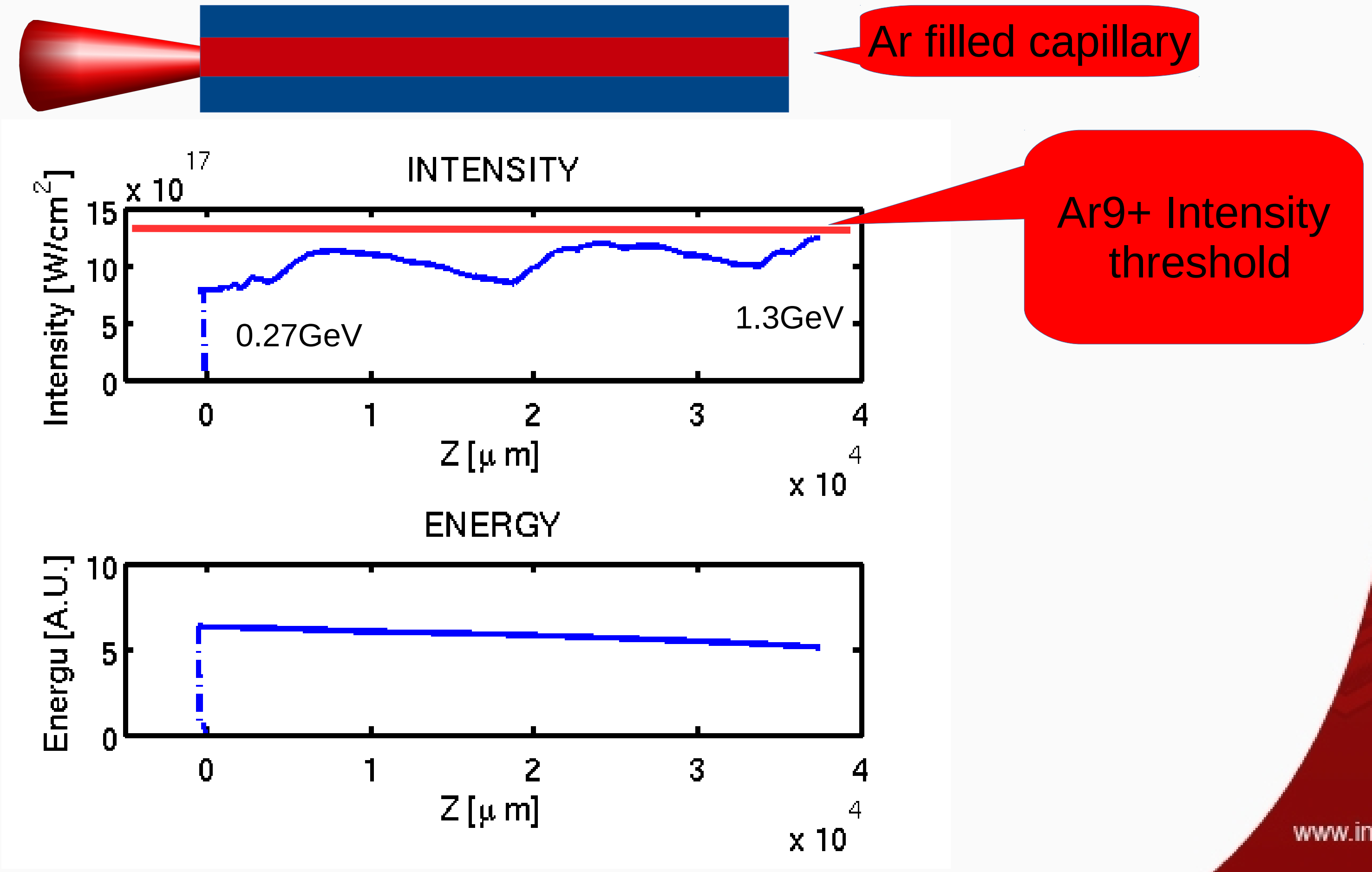
BUNCH B- 3cm
1.15 GeV, 0.81% rms,
ε_n= 0.08 mm mrad

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



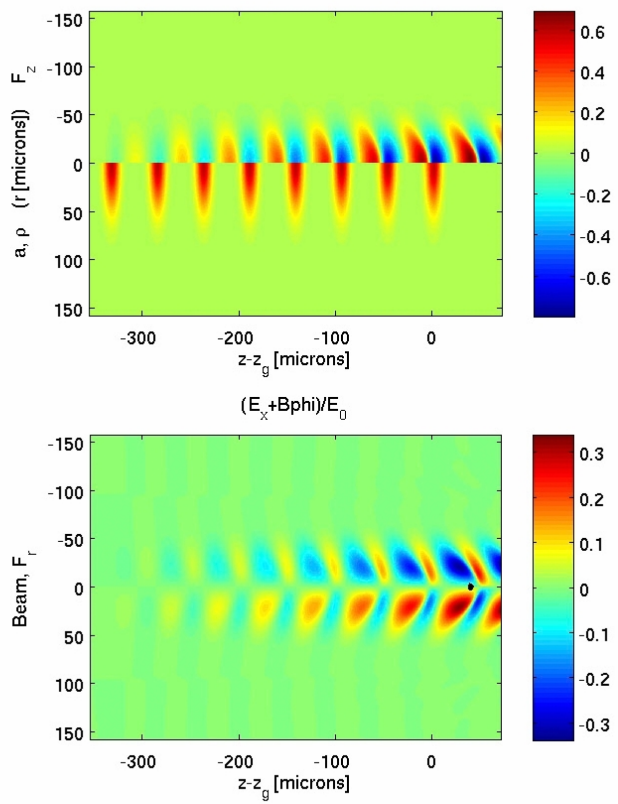
SETUP C – (guided) GeV-class

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



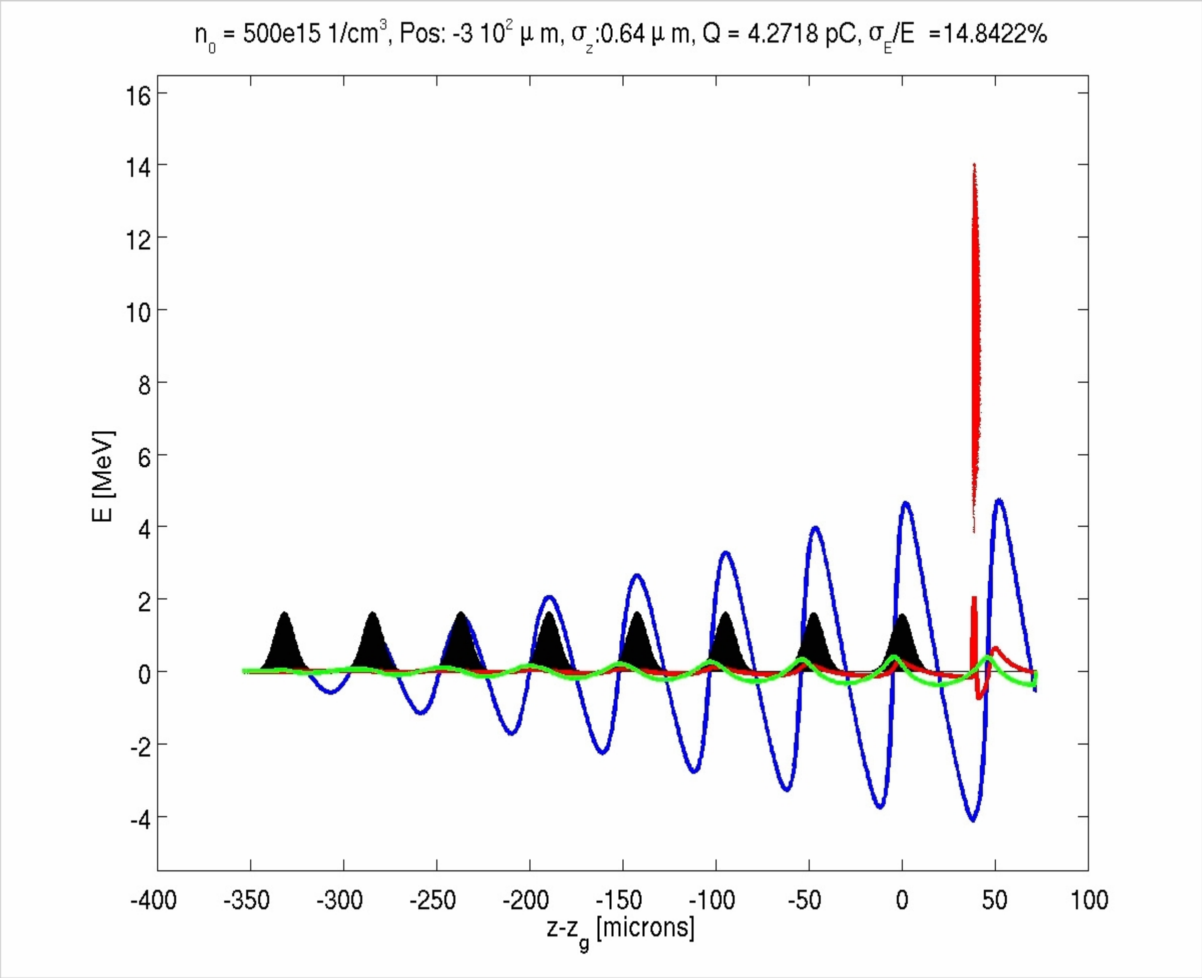
2D (cyl) maps

QFluid4.3 Linear polarization

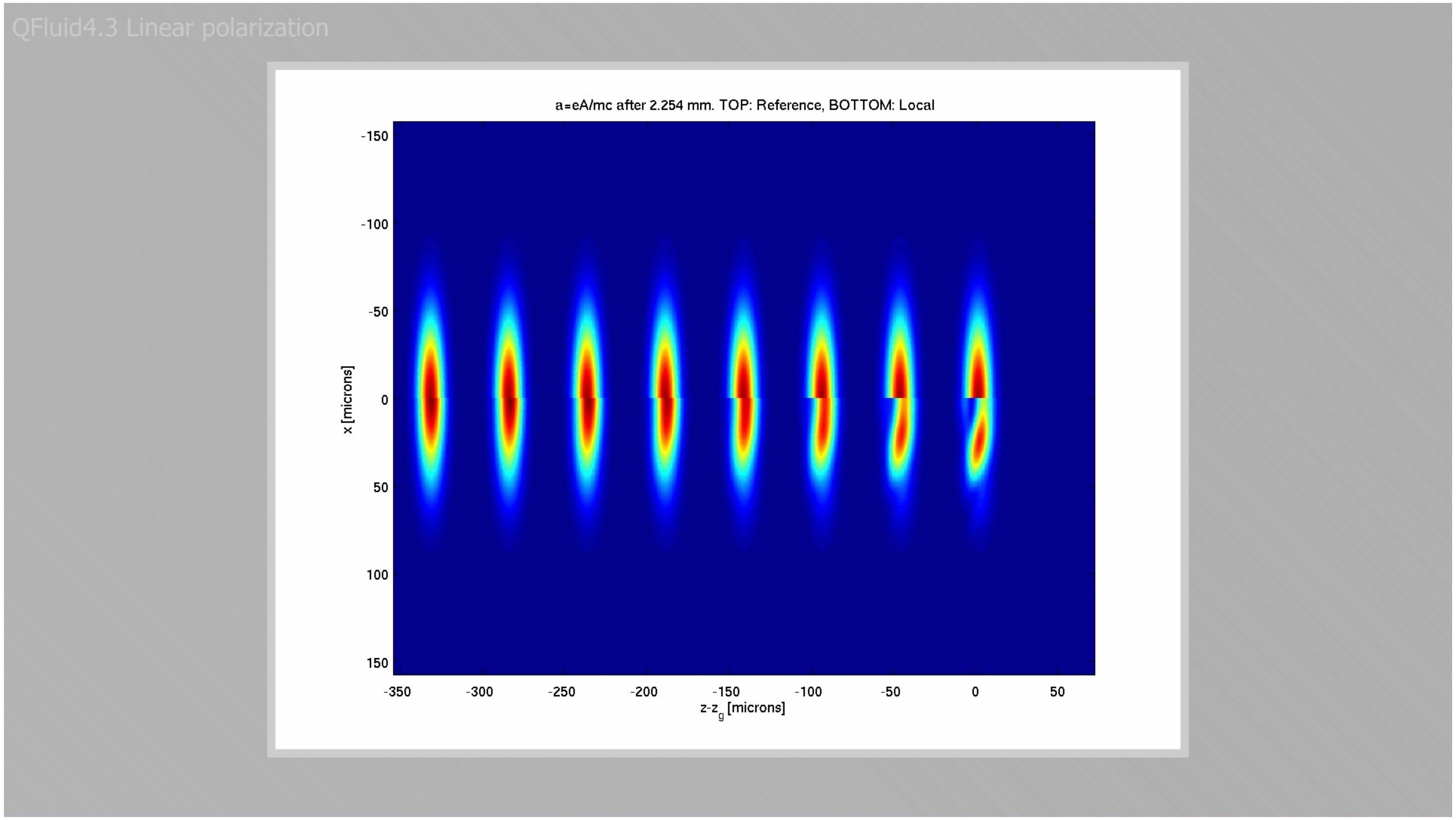


Longitudinal phase-space+fields

QFluid4.3 Linear polarization



Driver(s) evolution

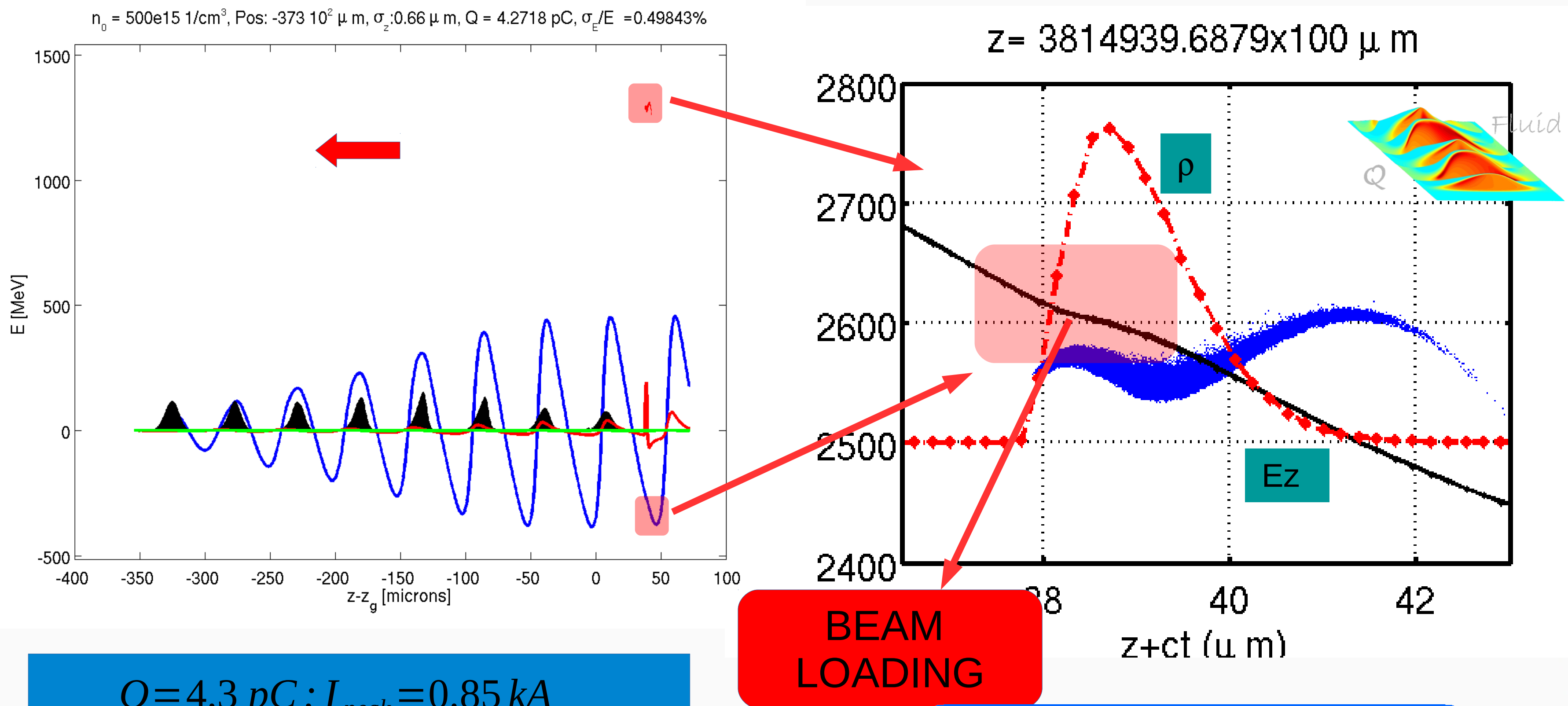


INJECTED

EVOLVED

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,



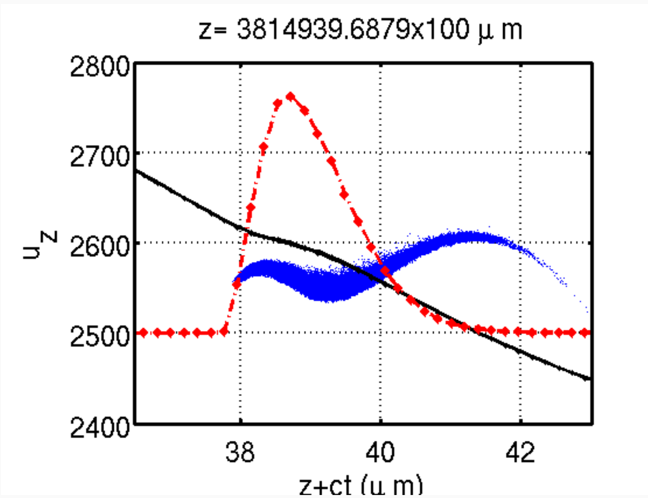
$$Q=4.3\,pC\,;I_{peak}=0.85\,kA$$
$$(\delta E/E)_{rms}=5\cdot 10^{-3};\delta\theta_{rms}=0.2\,mrad$$
$$\epsilon_{nx}=0.081\,mm\cdot mrad\,;\epsilon_{ny}=0.021\,mm\cdot mrad$$
$$\sigma_l=0.66\,\mu m\,;\sigma_r=0.20\,\mu m$$

$$L_{CRHOM}=\frac{\gamma\sigma_r^2}{(\delta E/E)\epsilon_n}\simeq 26\,cm$$

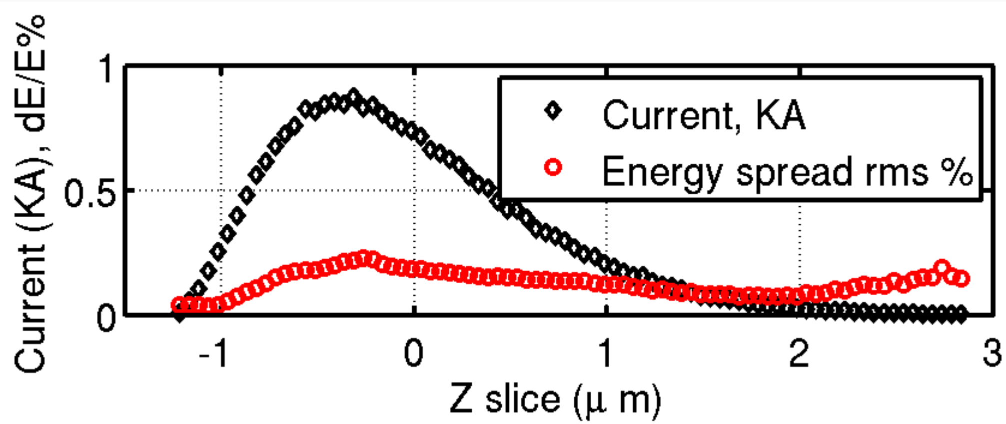
M. Migliorati et al.
PRST-AB 16 (2013)

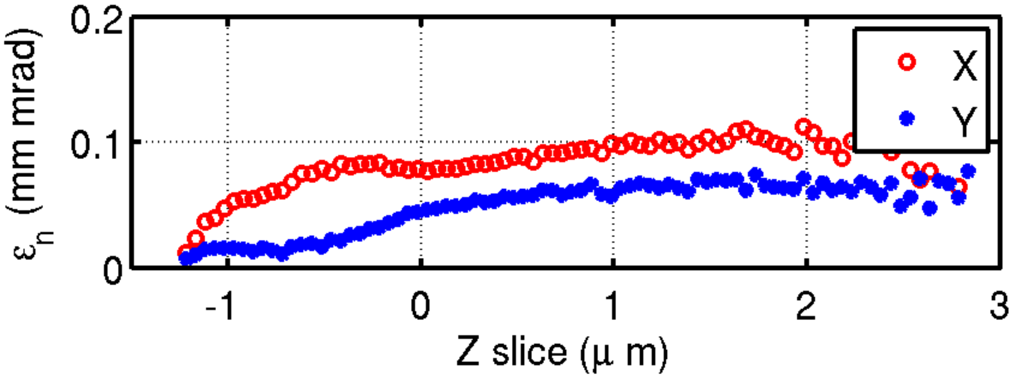
SLICE analysis for Bunch C

Slice analysis with coherence length l_c=0.05 micron (See FEL slices below) reveals a slice energy spread of dE/E_slice=0.22%@peak current (integrated dE/E = 0.5%),



$$(\delta E/E)_{SLICE}\, rms = 2.2\cdot 10^{-3} @\, peak$$
$$I = 0.85\, KA @\, peak$$





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**

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Bunch trapping and compression, 1D theory .

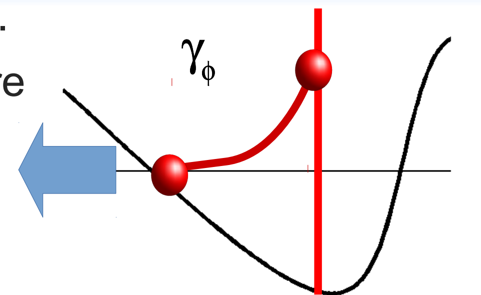
In the 1D QSA limit [we are not too far from that in the current working points] the conserved Hamiltonian can be written as

$$a^2 \ll 1 \qquad H(\psi,\gamma)=\gamma(1-\beta\beta_\varphi)-\varphi(\psi)$$

E.Esarey & M. Pillov, PoP **2** 1432 (1995)

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

$$\frac{1}{k_p c}\frac{d\gamma}{dt}=\frac{\partial\varphi}{\partial\psi}=-E_z/E_0;\ \frac{1}{k_p c}\frac{d\psi}{dt}=1-\frac{\beta_\varphi}{\beta}$$



- Electrons born approximately at rest with the extraction phase Ψ_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 Ψ_e where the potential is $\phi_t = \phi(\Psi_t)$. Since $\beta=\beta_\phi$ we get

$$H(\psi_e,1)=1-\varphi_e=H(\psi_t,\gamma_\varphi)=1/\gamma_\varphi-\varphi_t \Rightarrow \varphi_t=\varphi_e+1/\gamma_\varphi-1 \quad *$$

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

Final bunch length

$$\sigma(z_t)\simeq\sigma(z_e)\frac{(Ez+1/2\,\partial_\psi Ez\,\delta\psi)_e}{(Ez+1/2\,\partial_\psi Ez\,\delta\psi)_t}$$

Setting up the bunch duration from 360 as (rms) to <2fs (rms)

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

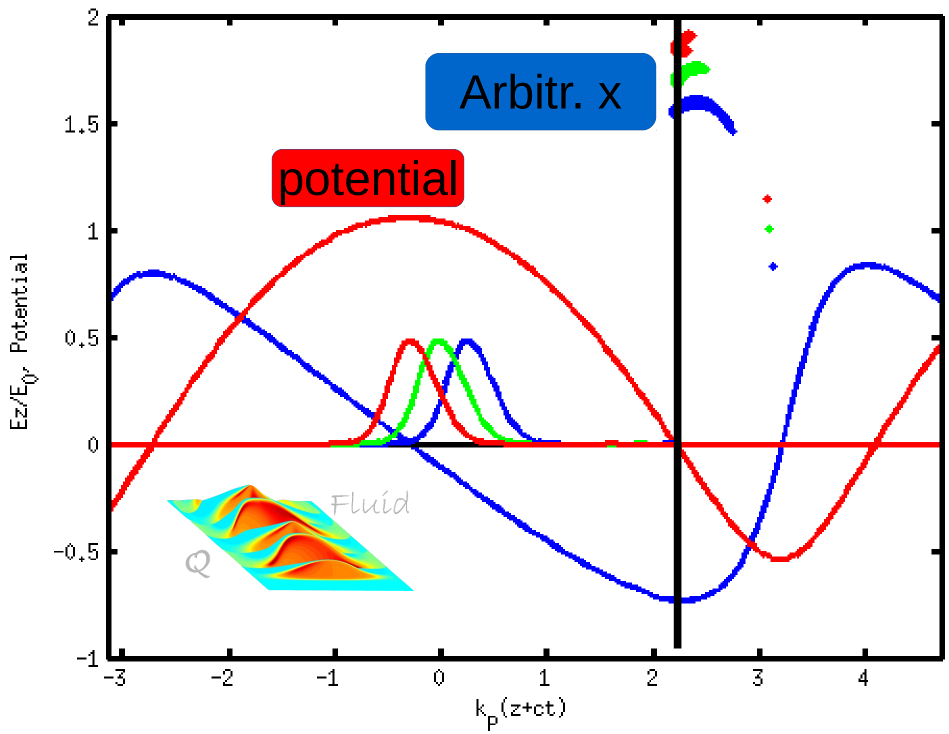
- The **<u>minimum length</u>** is obtained by placing the peak of the ionizing pulse close to the phase of the null electric field (say $\Psi = k_p(z+ct) = 0$). As the ionizing pulse moves away from the $\Psi = 0$ phase bunch length increases.
- Setting up the appropriate phase of the ionizing pulse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

<u>Initial length 1.56 μm</u>

Case Ψ=0.06 (RED):
Ez(final length **<u>0.12</u>** μm

Case Ψ=0.26 (GREEN):
final length **<u>0.27</u>** μm

Case Ψ=0.52 (GREEN):
final length **<u>0.57</u>** μm



SECOND vs HIGHER harmonics (Ionization)

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

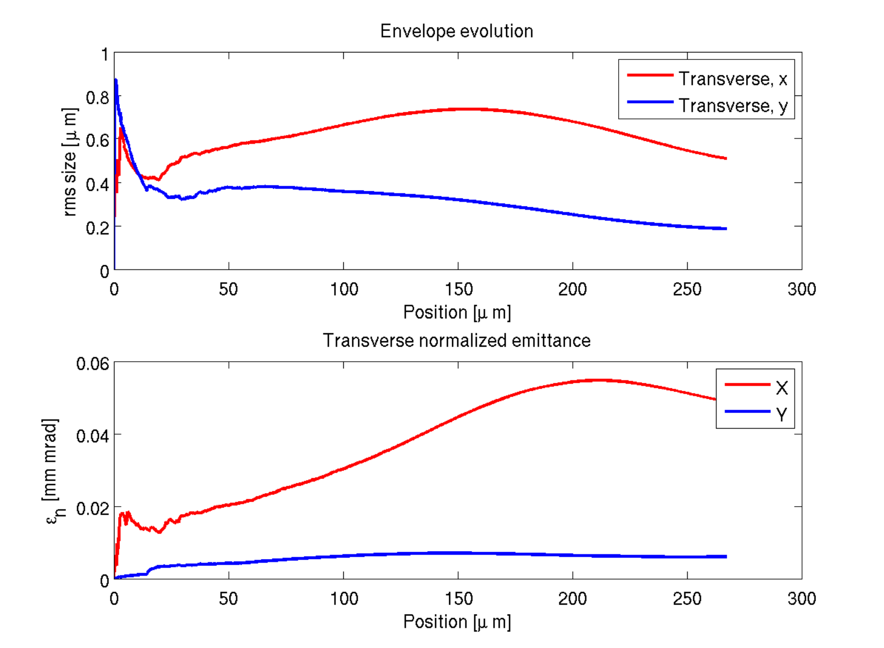
$$p_{tr}/mc \simeq a_{0\,ion}^{3/2} \lambda^{-1/2} \propto \lambda, [QUIVERING, UNCORRELATED]$$

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

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 $\lambda^{-1.5}$.**

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.

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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

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

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 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

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.

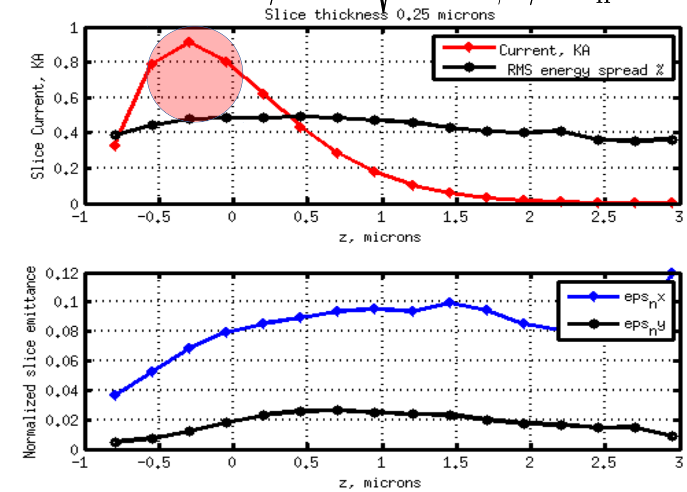
$$\rho = \frac{8.36\times10^{-3}}{\gamma}\sqrt[3]{\lambda_U^2\,\frac{I_{peak}[A]}{2\pi\beta\gamma^{-1}\varepsilon_n}\,K^2 f_B^2(K)}$$

Bunch parameters			
	A	B	C
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 (%)	0.5	0.81	0.22
Common FEL parameters			
undulator magnetic field [T]	1		
undulator period [cm]	1.4		
deflection parameter	1.3		

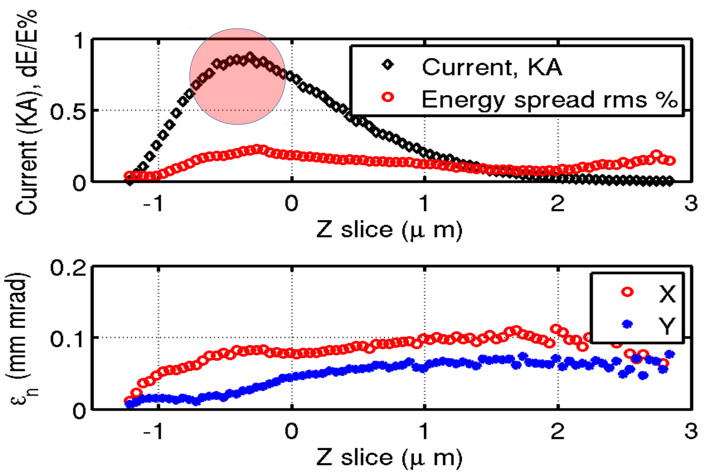
$$K \simeq 0.94\ B[T]\ \lambda_U[cm]$$

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

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



BUNCH A



BUNCH C

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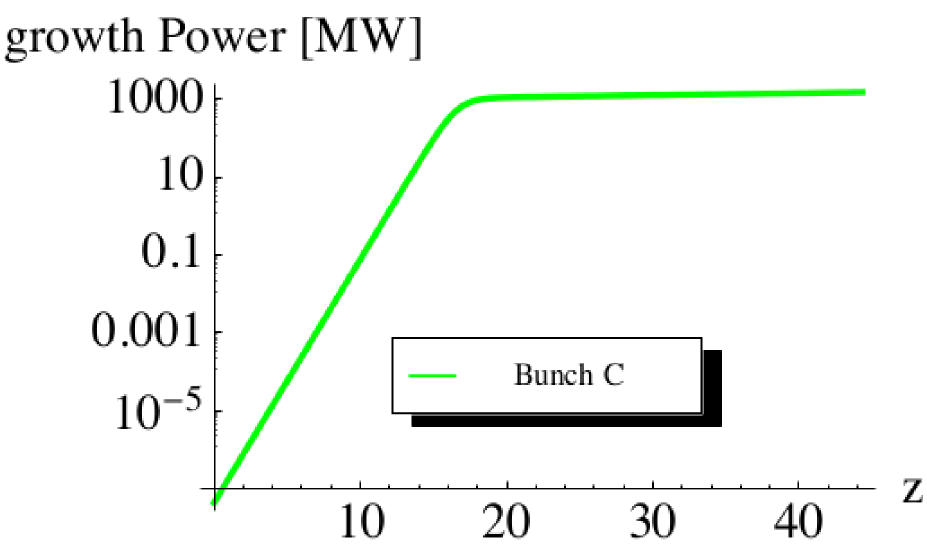
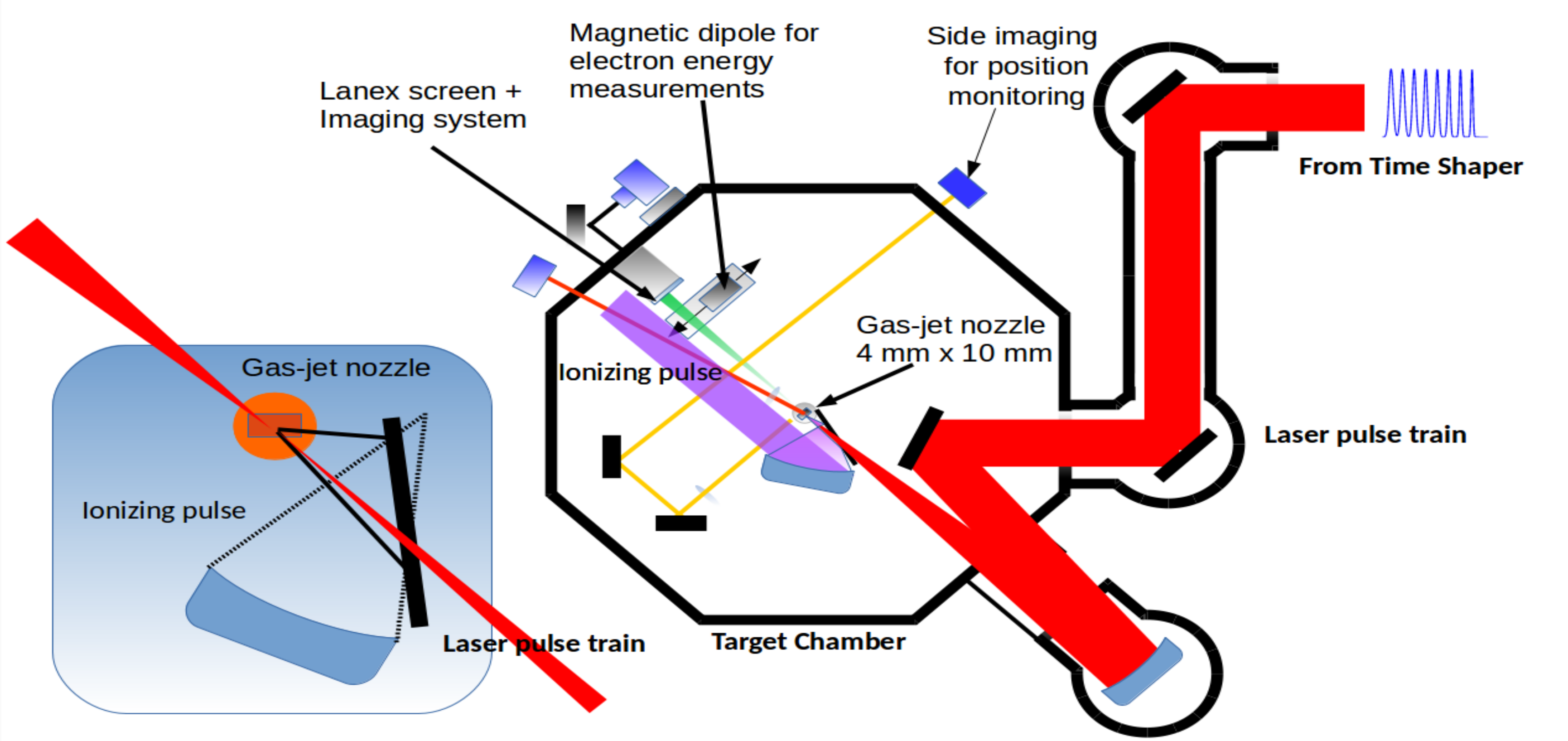
FEL preliminary results

	A	B	C
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]	0.086	1.38	0.702
saturation power [MW]	2602	323	861
saturation length [m]	2.3	33	17.7
coherence length [μm]	0.25	0.04	0.05
sat. power with slippage [MW]	1130	252	826



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

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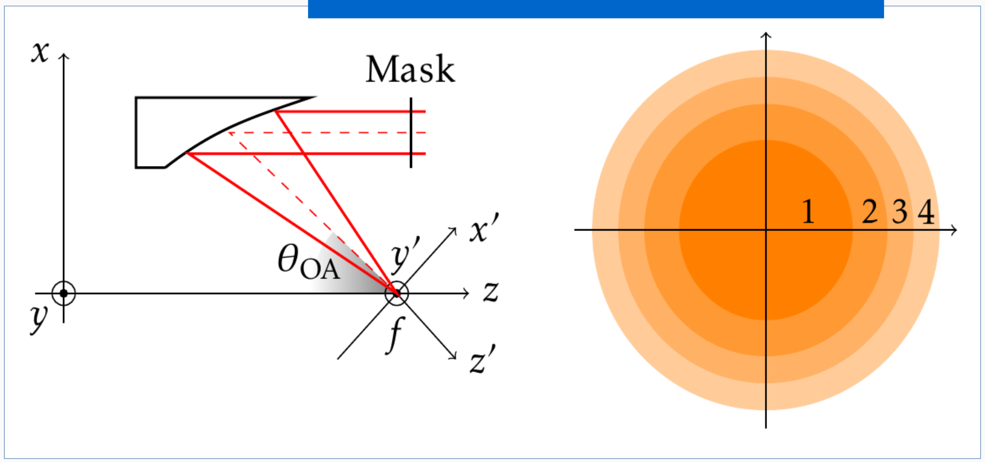
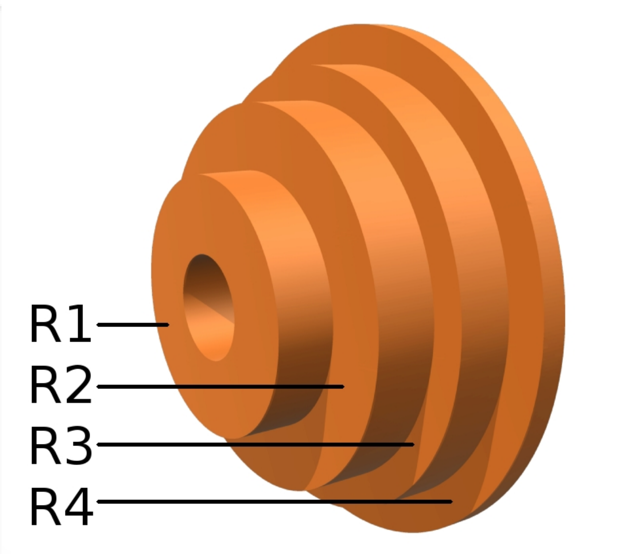
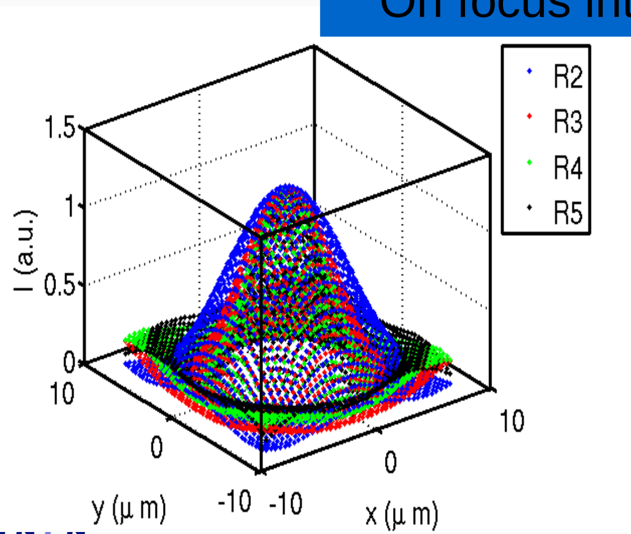
Delay masks with tuned thickness and radii

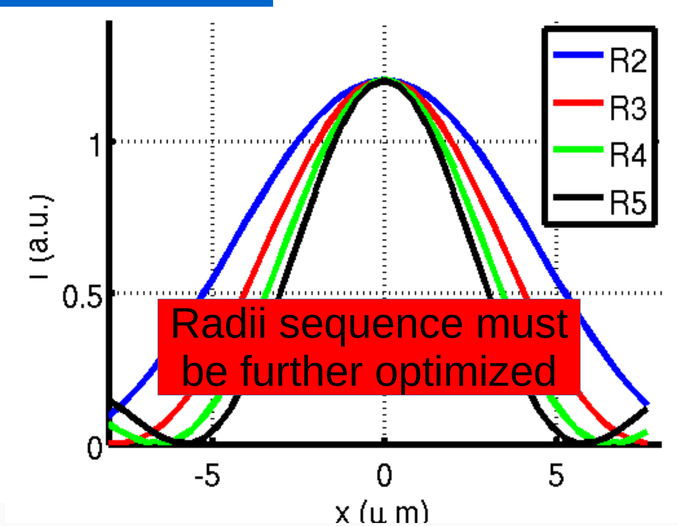




SIDE VIEW

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

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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!