Staging Experiments at BELLA

Carlo Benedetti

BELLA Center, LBNL

ALEGRO WORKSHOP, CERN
March 26-29, 2019

Work supported by Office of Science, US DOE, Contract No. DE-AC02-05CH11231

BERKELEY LAB

ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION ATAP

U.S. DEPARTMENT OF ENERGY | Office of Science

Acknowledgements

Lawrence Berkeley National Laboratory

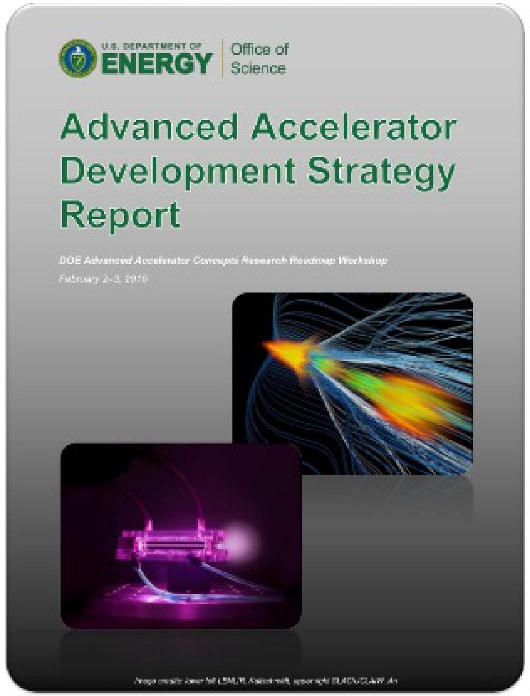
~BELLA~

C. B. Schroeder, T. Mehrling, S. S. Bulanov, A. J. Gonsalves, S. Steinke, K. Nakamura, J. Daniels, , K. Swanson, L. Fan-Chiang, J. H. Bin, Cs. Tóth, J. van Tilborg, C. G. R. Geddes, C. Pieronek, W. P. Leemans (DESY), and E. Esarey

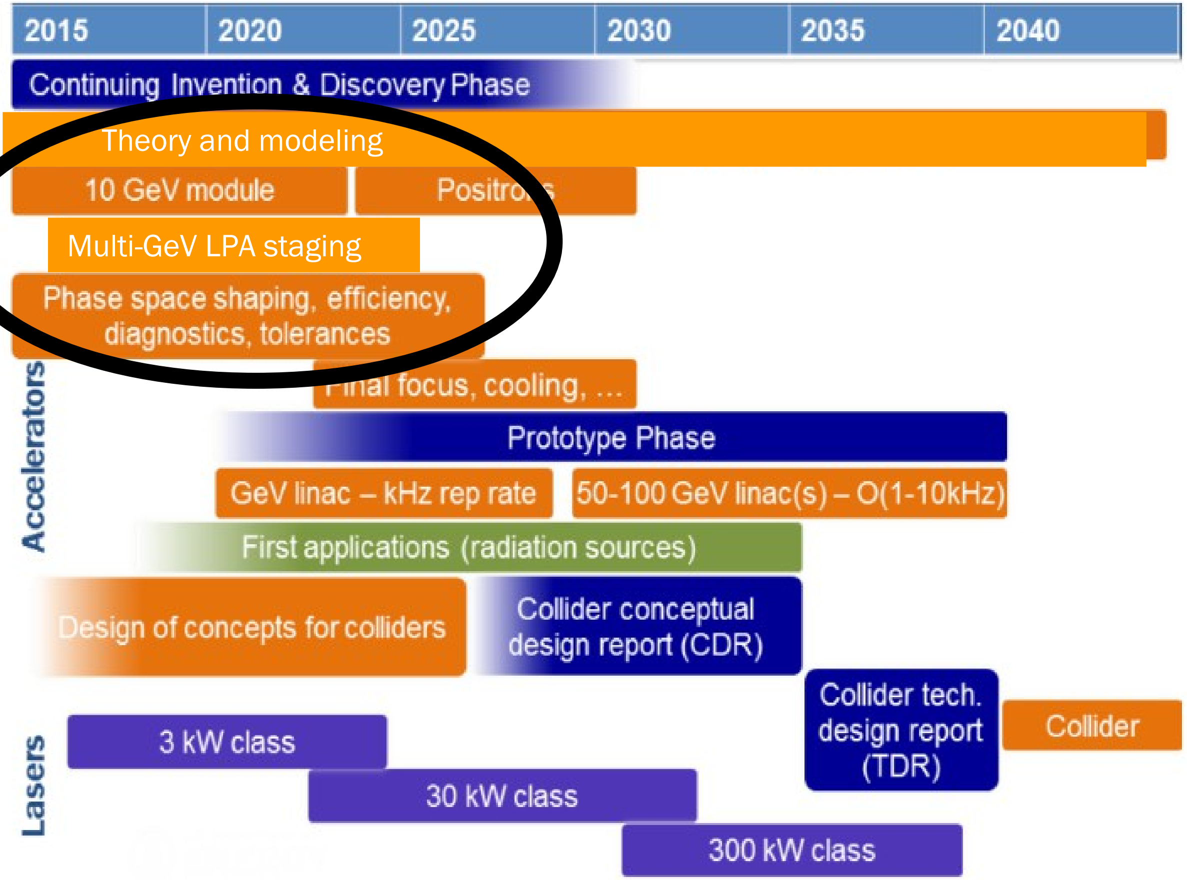
~AMP~

M. Thevenet, R. Lehe, J.-L. Vay

The BELLA activities aim at executing elements of the 2016 U.S. National Advanced Accelerator Development Strategy



→ sets roadmap for development of technology for an LPA-based TeV collider by 2040-2050



*"**The ten-year R&D goal is to accelerate 100 pC of charge to 10 GeV in a single LPA stage**. **Accomplishing this requires development of techniques for matched guiding of the laser pulse in the plasma**. […] With the completion of a 10 GeV electron LPA stage, the 10 GeV beam may be employed for electron-positron pair creation and subsequent positron beam capture"*

*"Critical to the collider application is demonstration of **multi-GeV LPA staging** with independent, equal energy, drive beams."*

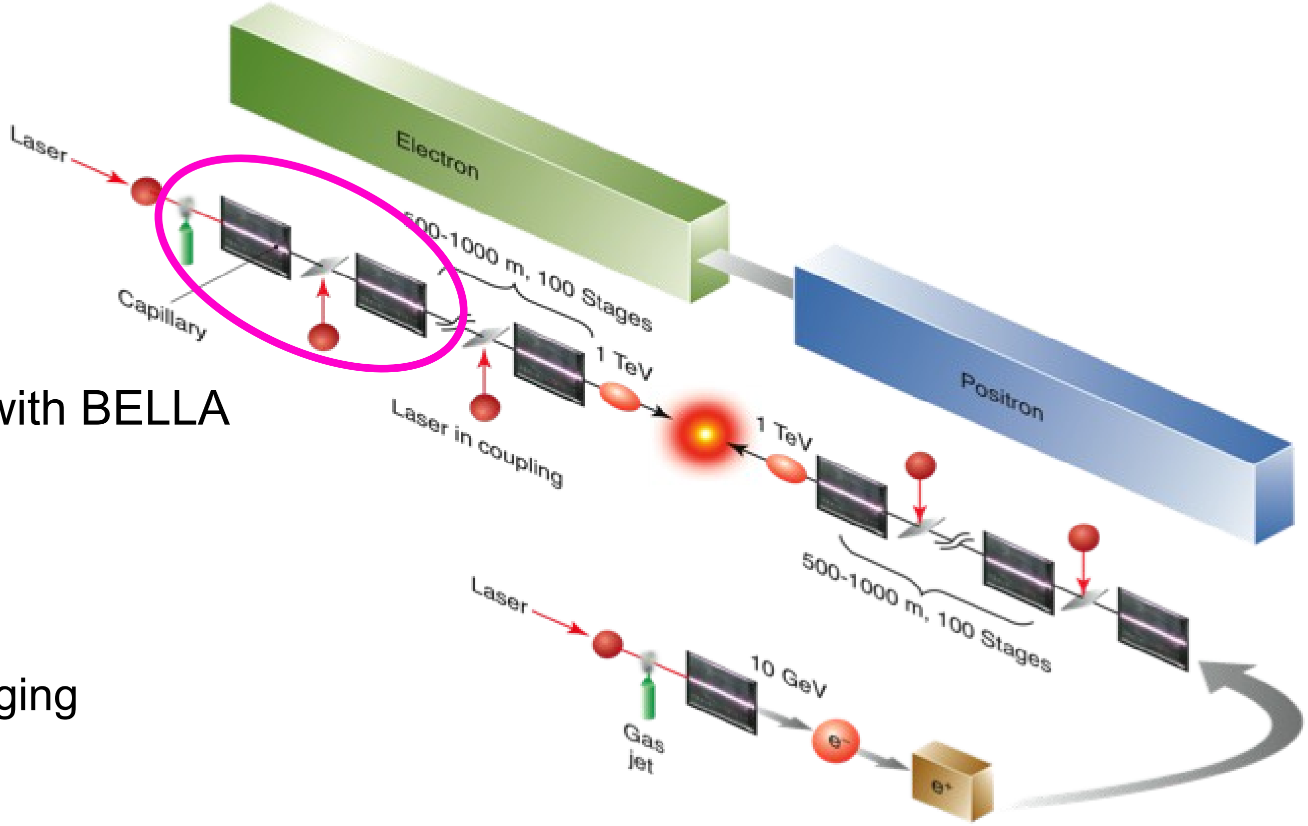
Overview of the presentation

- Review of 100 MeV staging experiments
  → Challenges and results

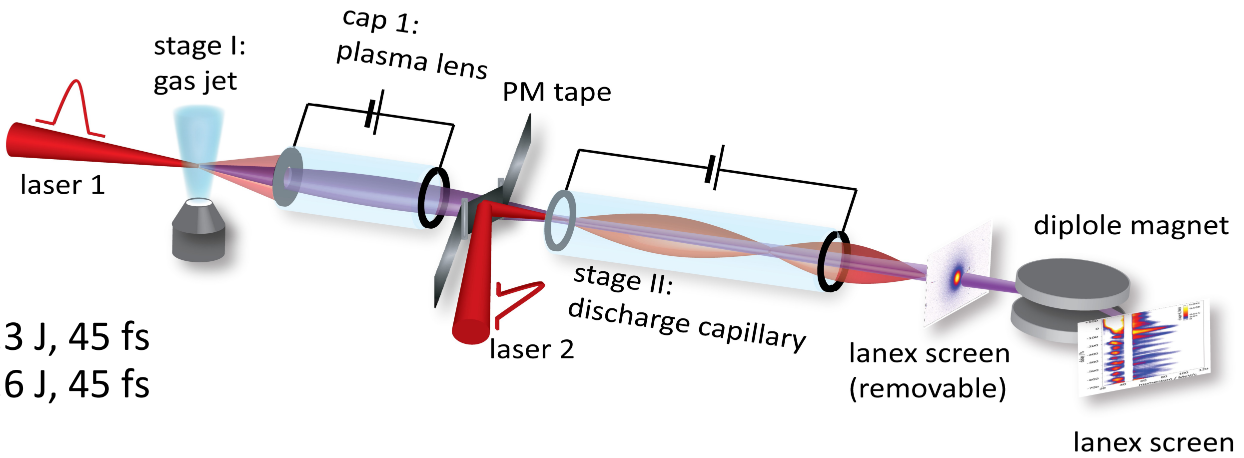
- Design and optimization of multi-GeV staging with BELLA (with realistic laser-plasma parameters)
→ optimization of LPA stages
→ e-beam transport

- Development of key technology for multi-GeV staging

- Summary

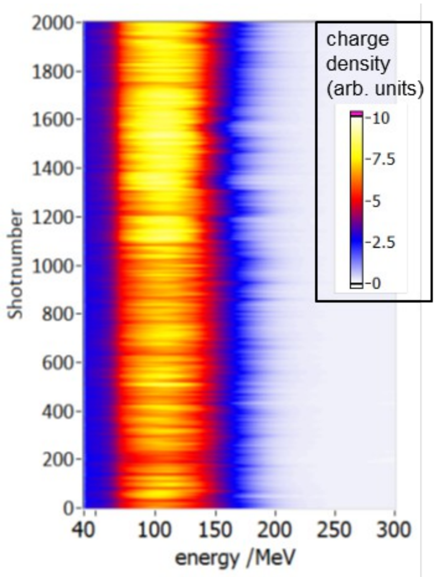


Multistage coupling of two independent LPAs successfully demonstrated with 30 TW laser (TREX laser)



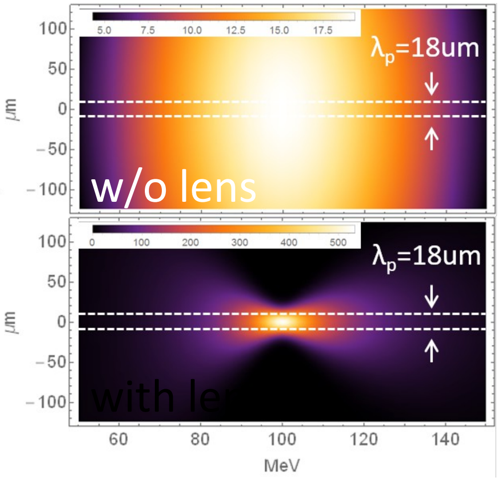
TREX:
laser 1: 1.3 J, 45 fs
laser 2: 0.6 J, 45 fs

Stable Injector



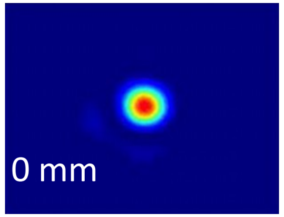
Plasma Lens Transport

Beam at stage 2 entrance:

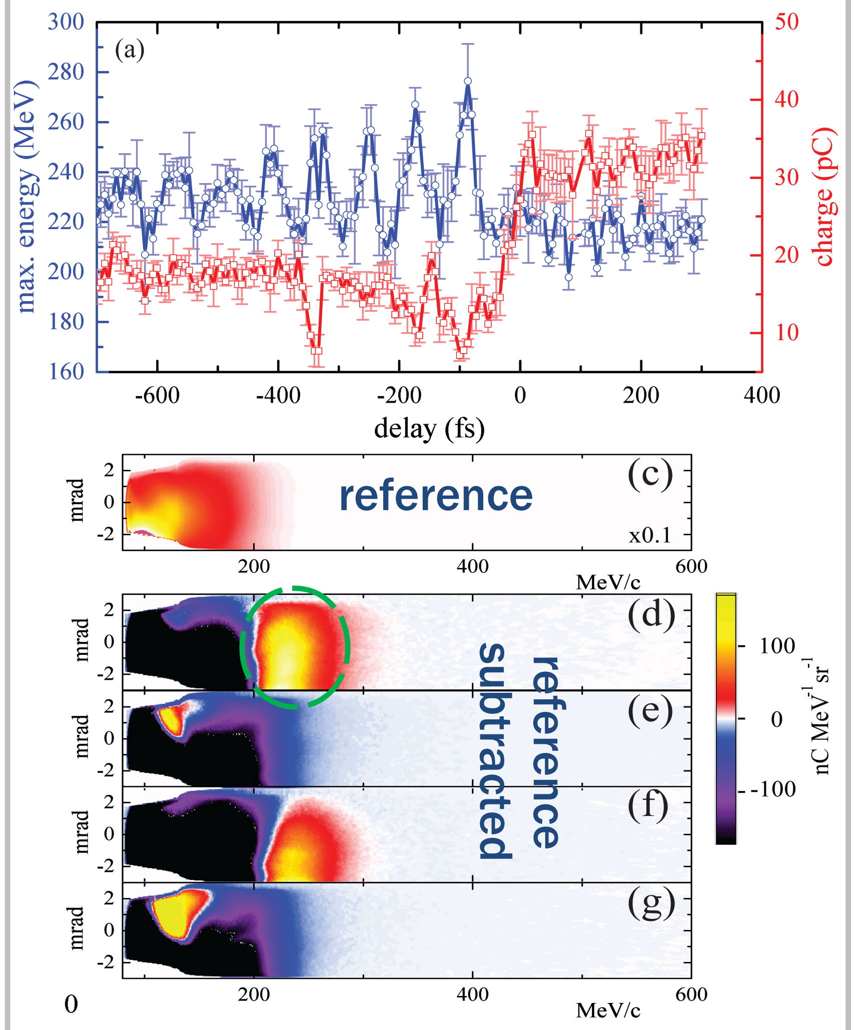


Plasma Mirror Tape

- Reflectivity <80%
- Strehl ratio >0.8
- Small pointing fluctuation
- Hours of runtime



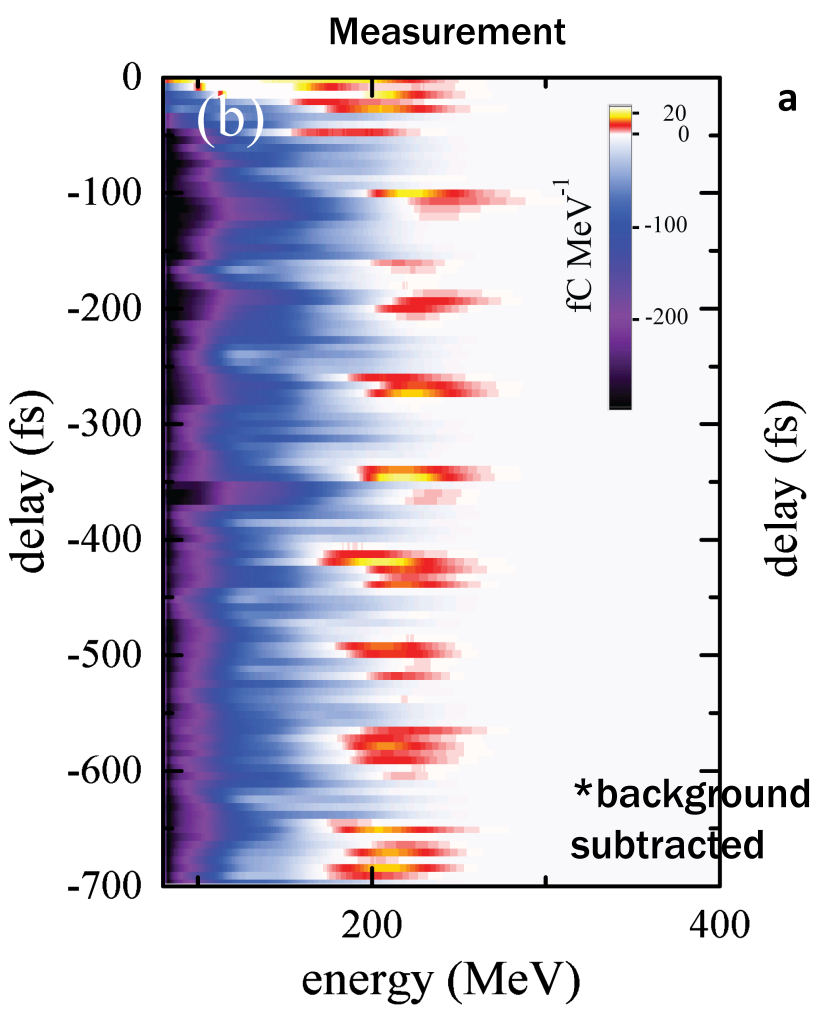
Staging Result

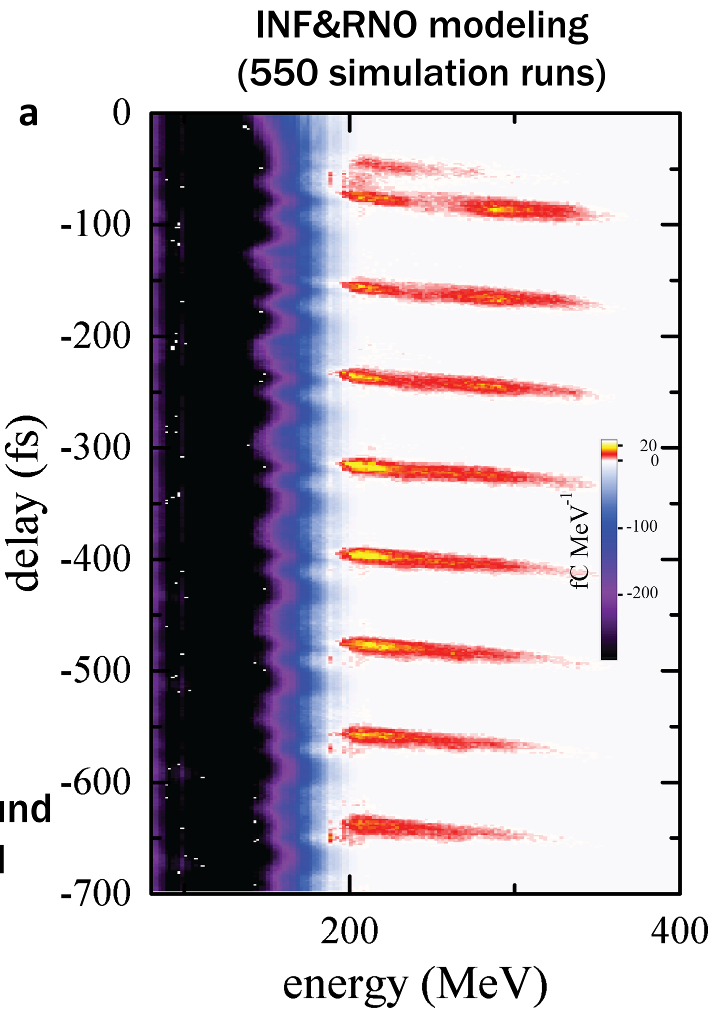


S. Steinke PoP 23, 056705 (2016); B. H. Shaw, PoP 23, 063117 (2016); J. van Tilborg, PRL **115**, 184802 (2015); S. Steinke, Nature **530**, 190 (2016)

INF&RNO simulation reproduce staging signatures at correct magnitude

Electron beam spectra after LPA2 as a function of laser delay (waterfall plot)

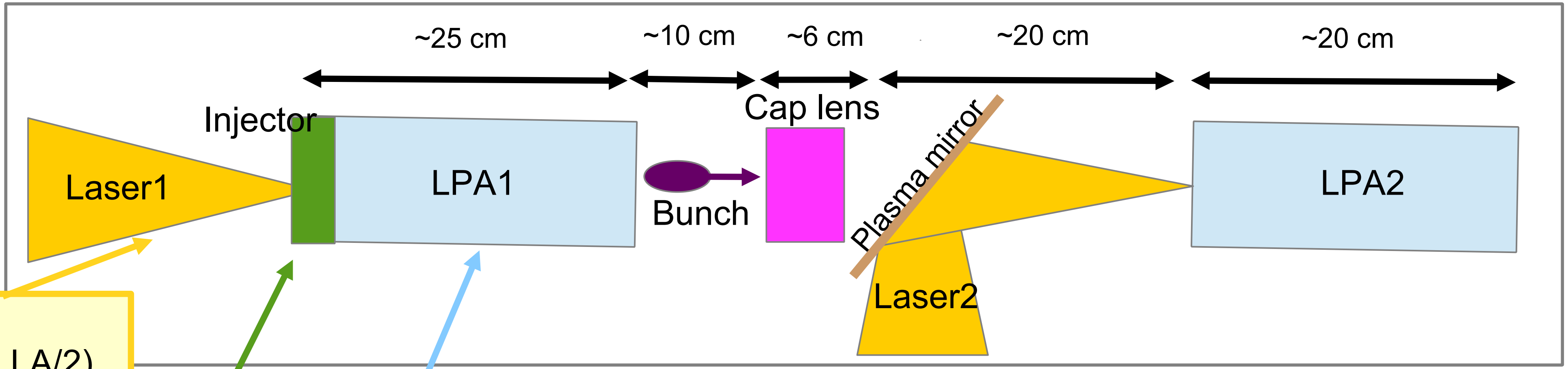




- Recurring post acceleration (~100 MeV) at the plasma frequency
- ~1 pC of charge at energies >200 MeV
- Quasi-linear wakefield
- Bunch length < $\lambda_p/4$ ~ 6 um
- Analysis of simulation results unravels details of the acceleration/ deceleration processes

S. Steinke et al., Nature **530**, 190 (2016); C. Benedetti et al., AAC Proc. (2016)

Schematic and parameters for multi-GeV staging experiments with BELLA (from scaling laws and preliminary INF&RNO simulations)

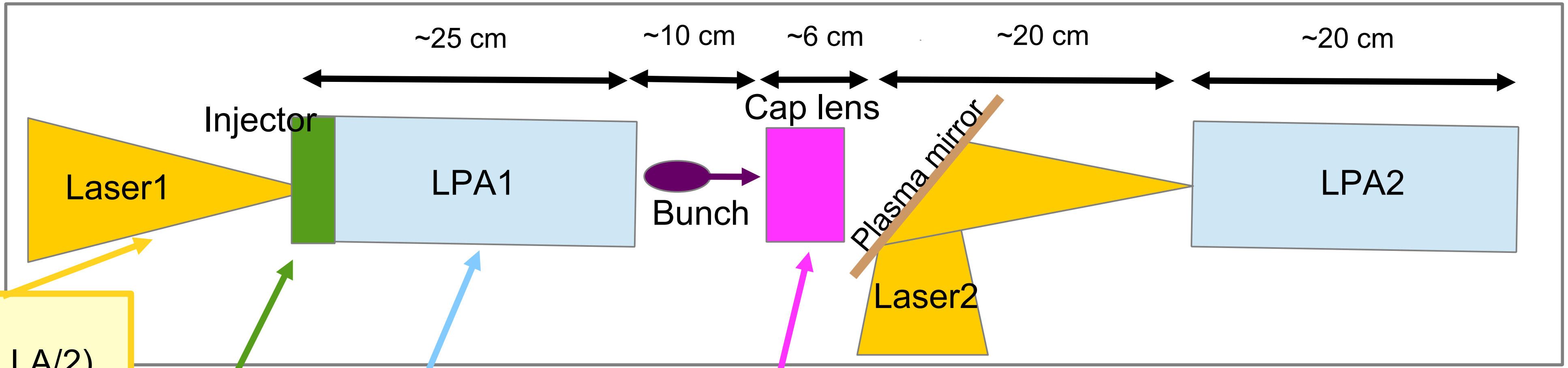


Laser1
U_{01}=20 J (≈BELLA/2)
T_{01}=80 fs (FWHM)
w_{01}= 53 um (jinc)

Injector
Ionization injection:
~1% N_2 / ~99% H_2
Length ≈ 1 cm

LPA1
Cap discharge
(R_{LPA1}= 250 um)
n_{LPA1}=3x$10^{17}$$cm^{-3}$
R_{LPA1}=90 um (no heater)
R_{LPA1}=70 um (w/ heater)
L_{LPA1}=24 cm

Schematic and parameters for multi-GeV staging experiments with BELLA (from scaling laws and preliminary INF&RNO simulations)



Laser1
U_{01}=20 J (≈BELLA/2)
T_{01}=80 fs (FWHM)
w_{01}= 53 um (jinc)

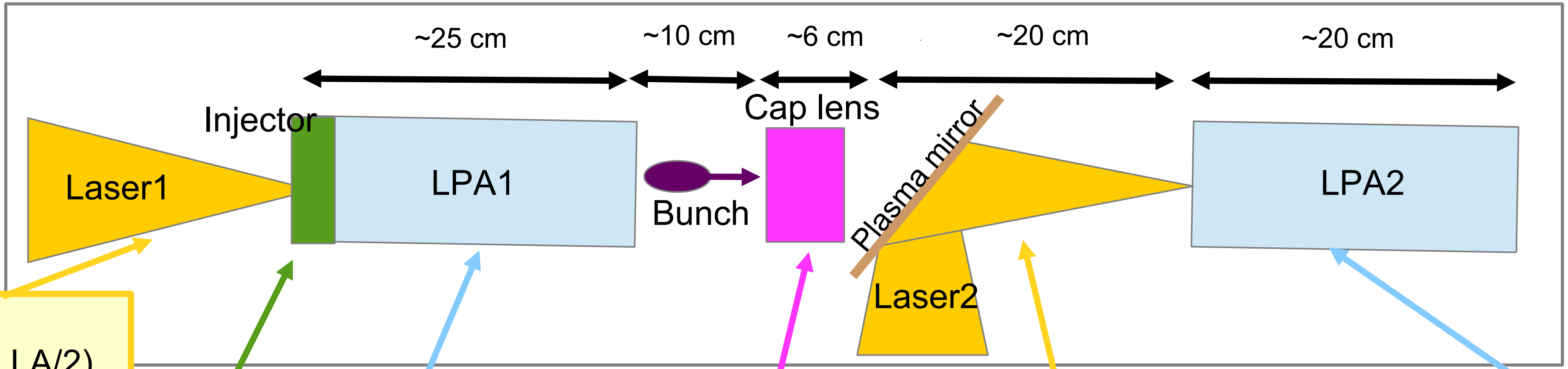
Injector
Ionization injection:
~1% N_2 / ~99% H_2
Length ≈ 1 cm

LPA1
Cap discharge
(R_{LPA1}= 250 um)
n_{LPA1}=3x10^{17}cm^{-3}
R_{LPA1}=90 um (no heater)
R_{LPA1}=70 um (w/ heater)
L_{LPA1}=24 cm

Focusing
Active plasma lens
R_{cap}= 250 um
I_{cap}= 800 A
L_{cap}=6 cm

→ Plasma mirror realized with liquid crystal film (small thickness, negligible impact on bunch emittance) [collab. with OSU]

Schematic and parameters for multi-GeV staging experiments with BELLA (from scaling laws and preliminary INF&RNO simulations)



Laser1
U_{01}=20 J (≈BELLA/2)
T_{01}=80 fs (FWHM)
w_{01}= 53 um (jinc)

Injector
Ionization injection:
~1% N_2 / ~99% H_2
Length ≈ 1 cm

LPA1
Cap discharge
(R_{LPA1}= 250 um)
n_{LPA1}=3x10^{17}cm^{-3}
R_{LPA1}=90 um (no heater)
R_{LPA1}=70 um (w/ heater)
L_{LPA1}=24 cm

Focusing
Active plasma lens
R_{cap}= 250 um
I_{cap}= 800 A
L_{cap}=6 cm

Laser2
U_{02}=18 J (≈ BELLA/2)
T_{02}=80 fs (FWHM)
w_{02}= 71 um (jinc)
*new beamline

LPA2
Cap discharge
(R_{LPA2}= 250 um)
n_{LPA2}=3.5x10^{17}cm^{-3}
R_{LPA2}=85 um (no heater)
L_{LPA2}=21 cm
→ **must operate in quasi-linear regime!**

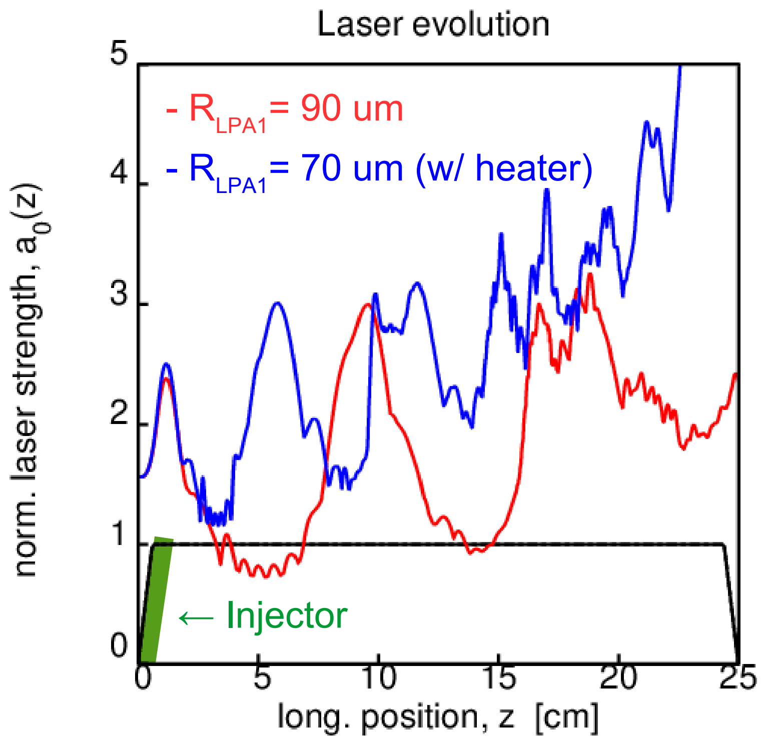
→ Plasma mirror realized with liquid crystal film (small thickness, negligible impact on bunch emittance) [collab. with OSU]
→ Second beamline funded but under design right now

LPA1 with triggered injection produces quasi-monoenergetic, multi-GeV beams with a charge of up to a few 10s of pC

Laser1
U_{01}=20 J (≈ BELLA/2)
T_{01}=80 fs (FWHM)
w_{01}= 53 um (jinc)

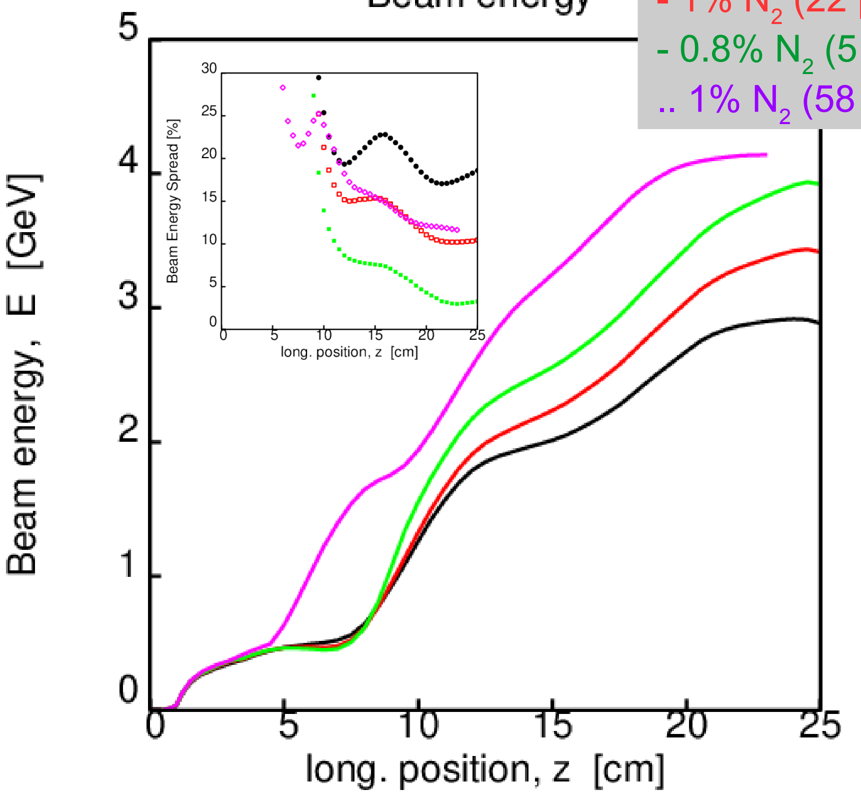
LPA1 (cap discharge R_{cap}= 250 um)
n_{LPA1}= 3x10^{17}cm^{-3}
R_{LPA1}= 90 um / 70 um (w/ heater)
L_{LPA1}= 24 cm

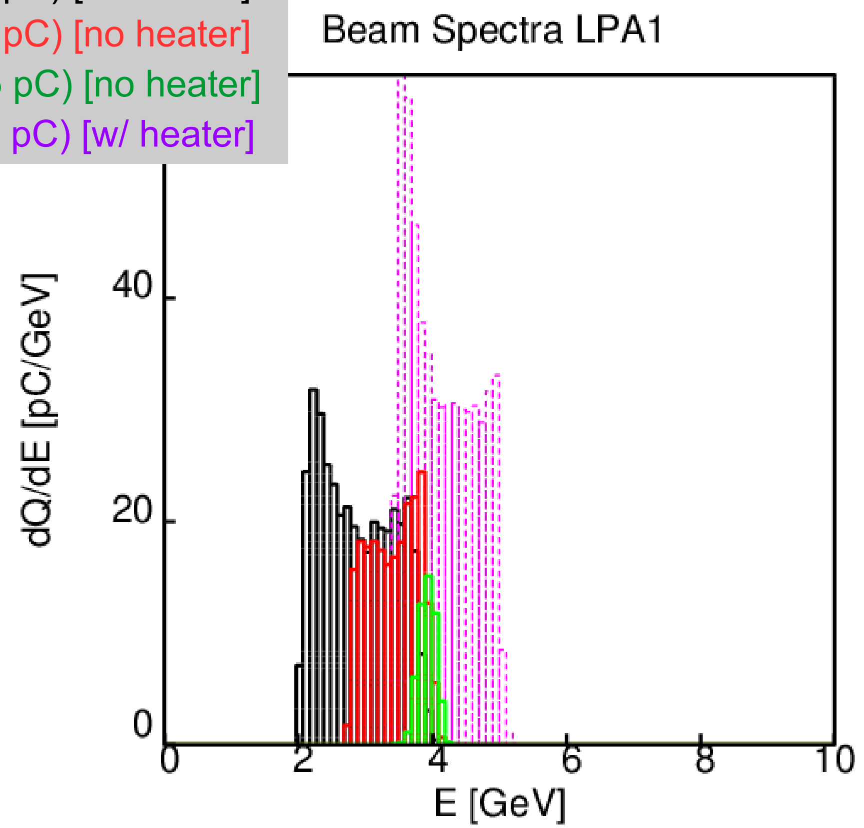
Injector (ionization injection, H_2/N_2 mixed gas, 1 cm)
N_2 dopant concentration: 2%, 1%, 0.8%
→ **Further optimization of the injector performance is underway!**



→ dark current free for R_{LPA1}= 90 um
→ low energy particle tail might be present in the heated case

- 2% N_2 (39 pC) [no heater]
- 1% N_2 (22 pC) [no heater]
- 0.8% N_2 (5 pC) [no heater]
.. 1% N_2 (58 pC) [w/ heater]



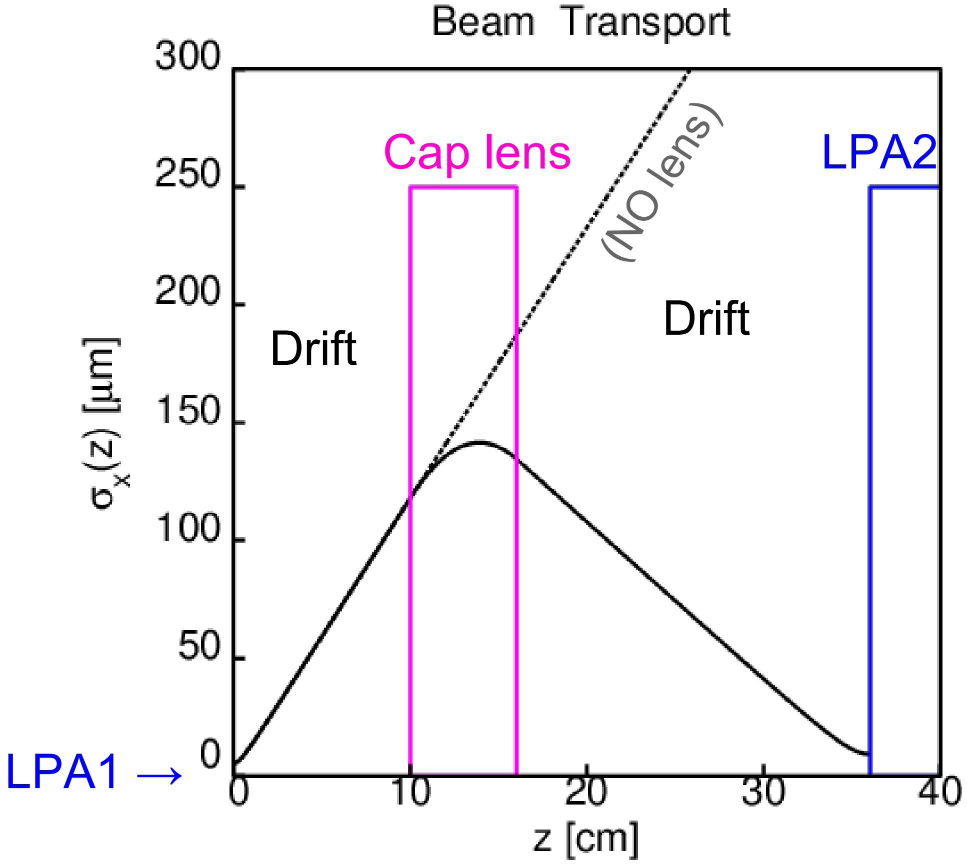


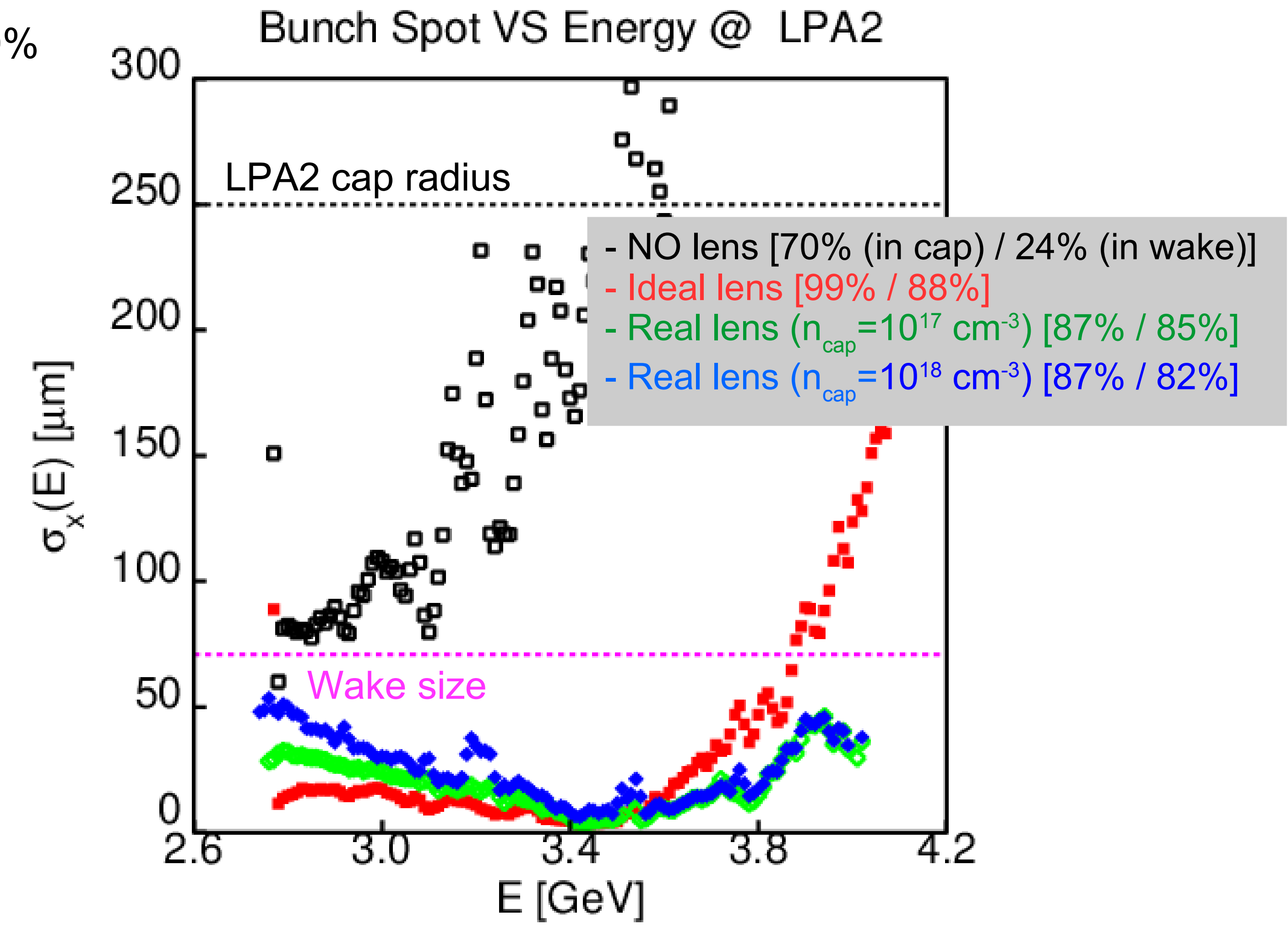
→ heater helps increasing bunch charge and energy

Cap lens required to maximize beam charge injected in LPA2

Bunch [1%, NO heater]: Q=22 pC, E=3.5 GeV, dE/E =10%

Focusing: active plasma lens
R_{cap}= 250 um, I_{cap}= 800 A, L_{cap}=6 cm





→ with no lens most of bunch is out of the wake
→ finite radius of real cap lens main cause of particle loss
→ aberration from bunch-induced wake in cap lens not too important
→ nonlinear B-field in cap lens not considered

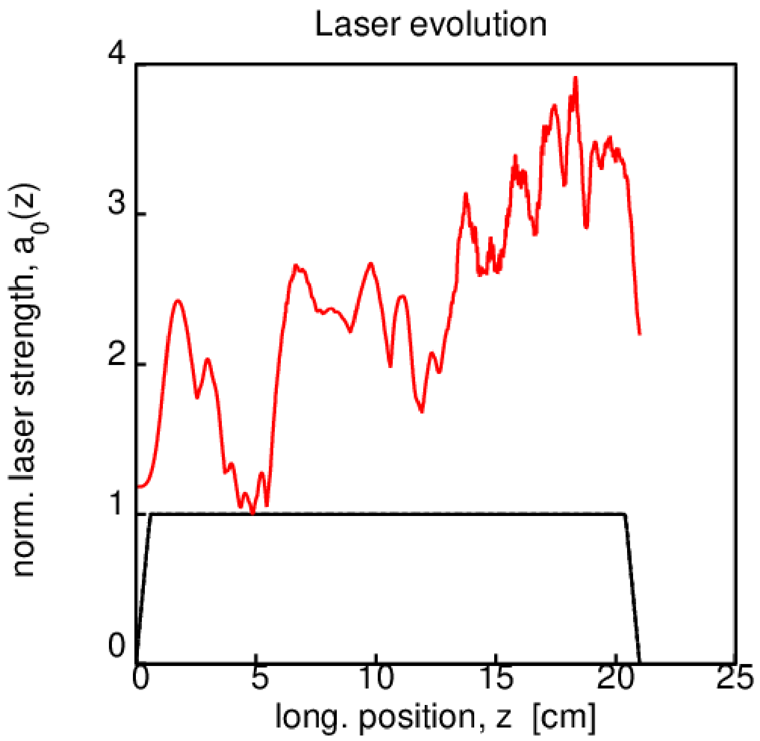
van Tilborg, et al., PRL (2105);
van Tilborg, et al., POP (2018); Lindstrom et al.,, PRL (2018)

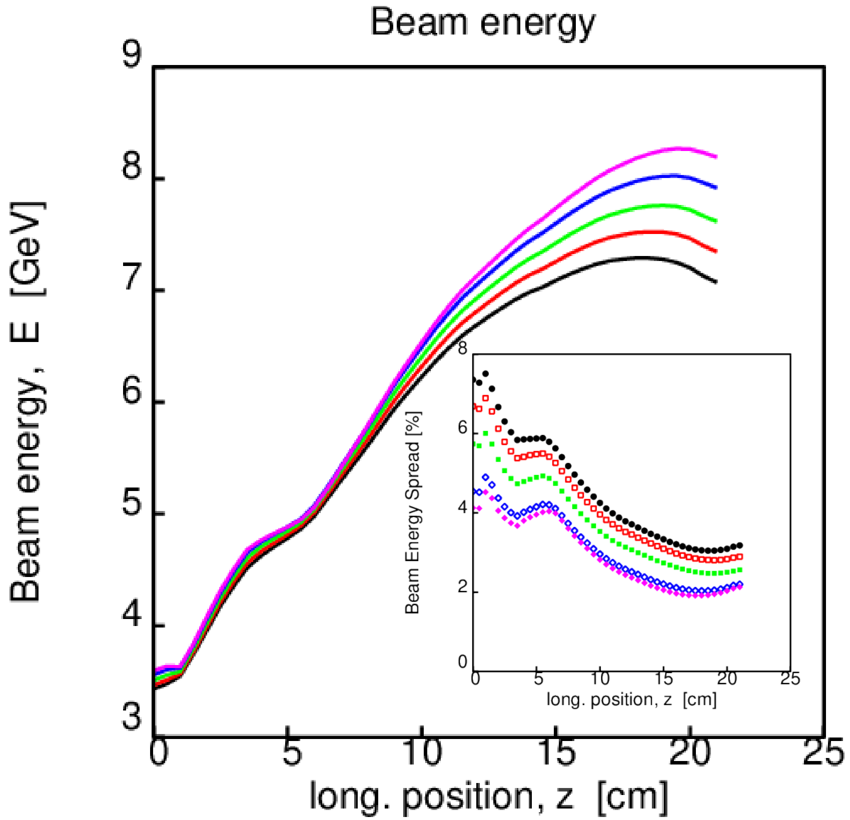
For optimal delays LPA2 provides > 4 GeV energy gain with > 50% charge capturing efficiency

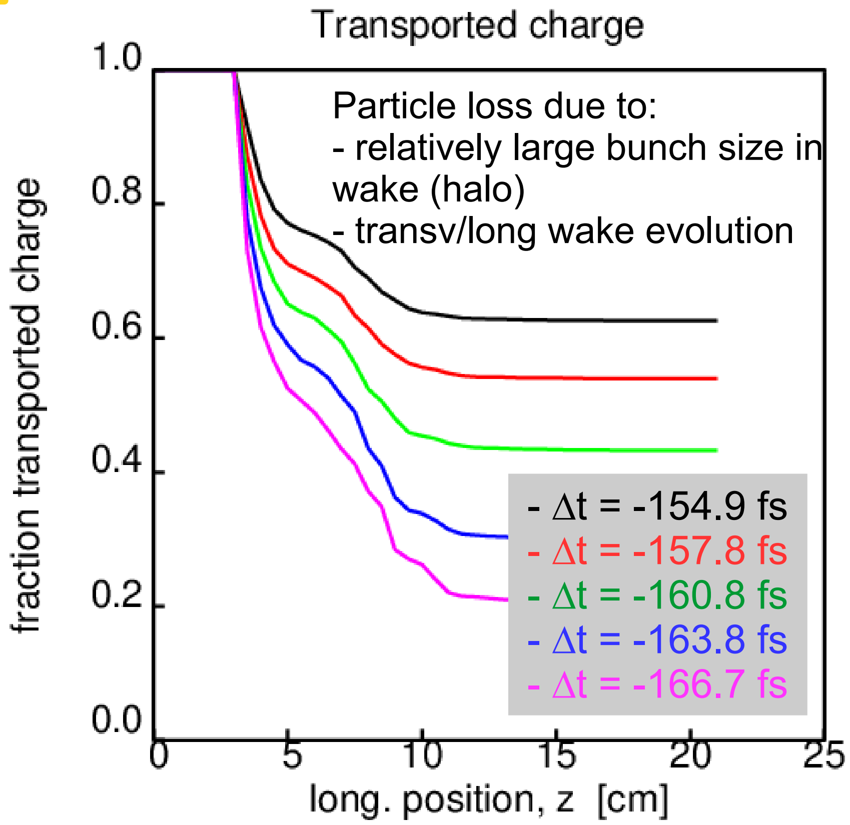
Bunch [1%, NO heater]: Q=22 pC, E=3.5 GeV, dE/E =10% +
Real lens (R_{cap}= 250 um, I_{cap}= 800 A, L_{cap}=6 cm, n_{cap}=10^{17} cm^{-3})

Laser2
U_0=18 J (≈ BELLA/2)
T_0=80 fs (FWHM)
w_0= 71 um (jinc)

LPA2 (cap discharge R_{LPA2}= 250 um)
n_{LPA2}= 3.5x$10^{17}$$cm^{-3}$, R_{LPA2}= 85 um, L_{LPA2}= 21 cm



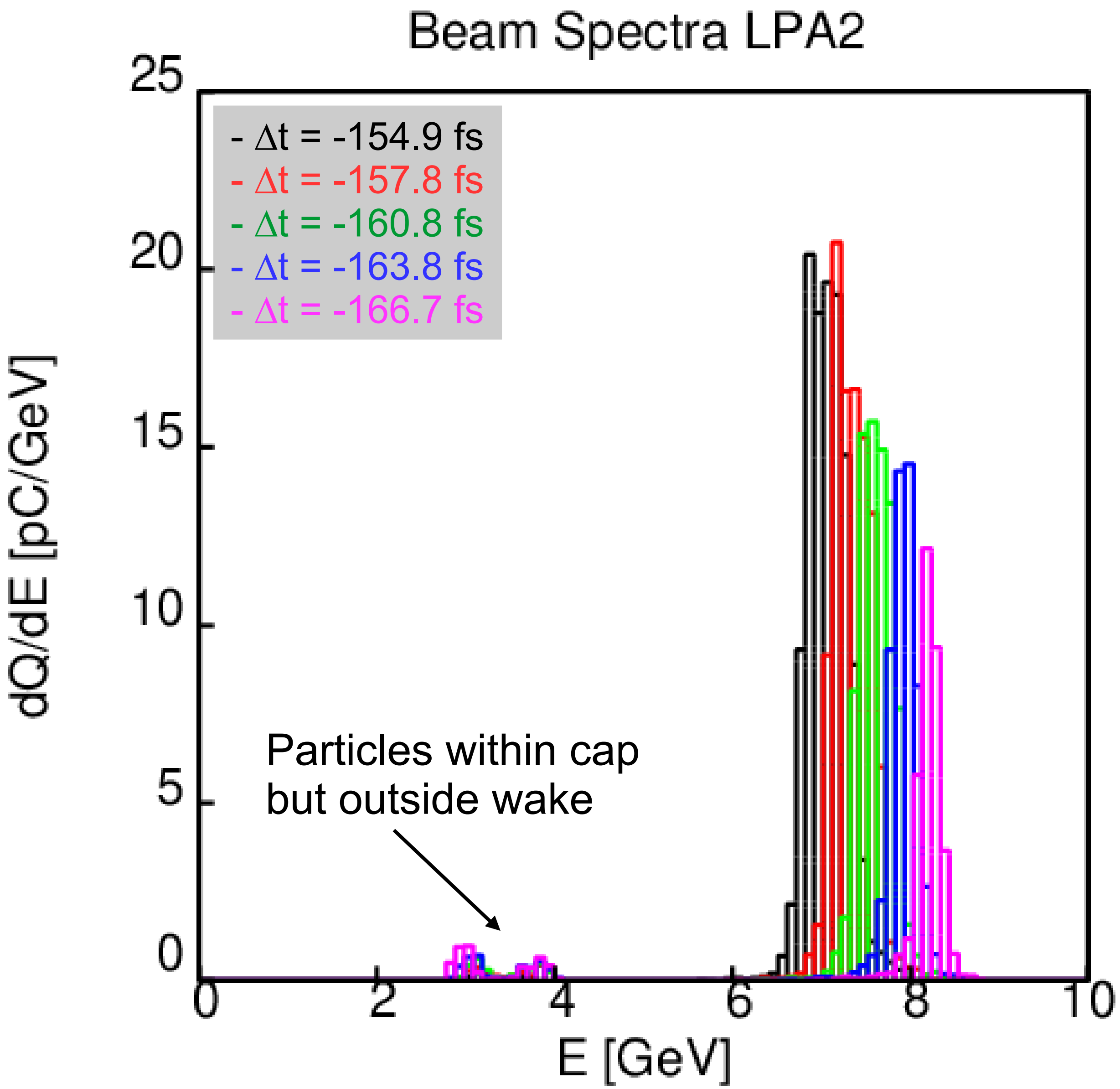


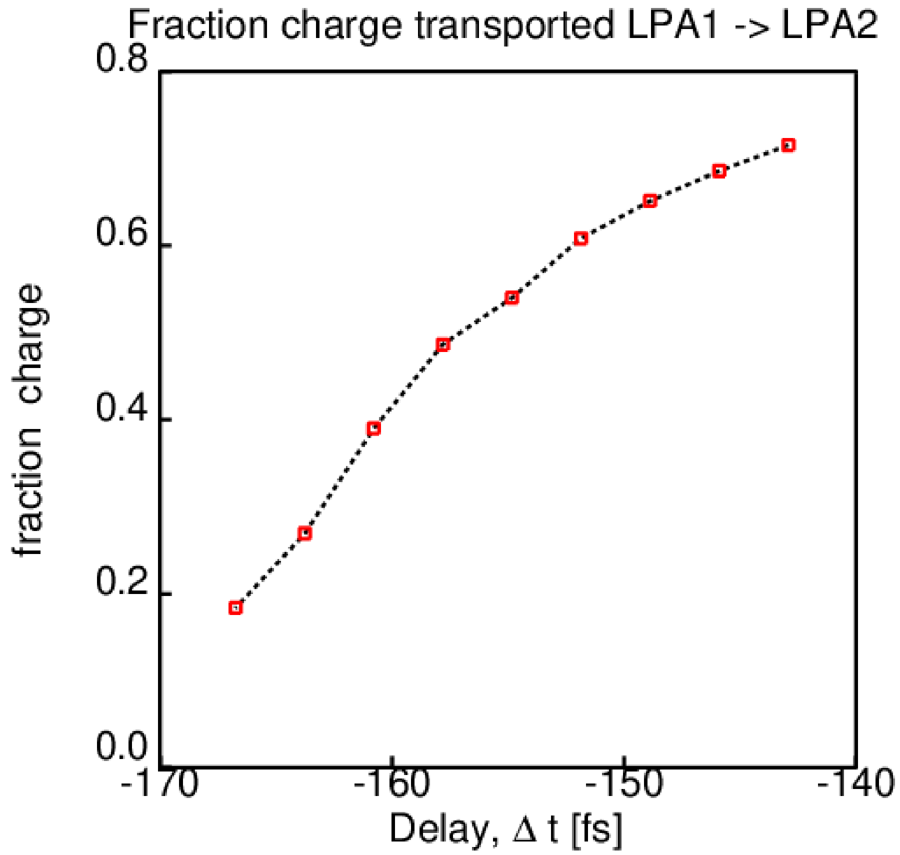


→ LPA2 is dark current free
(verified in full PIC simulation)

Better transport efficiency requires
→ improving injector (reduce energy spread)
→ optimization of bunch and laser in-coupling / matching

Electron spectra and fraction of transmitted charge after LPA2 as a function of the delay between bunch and Laser2

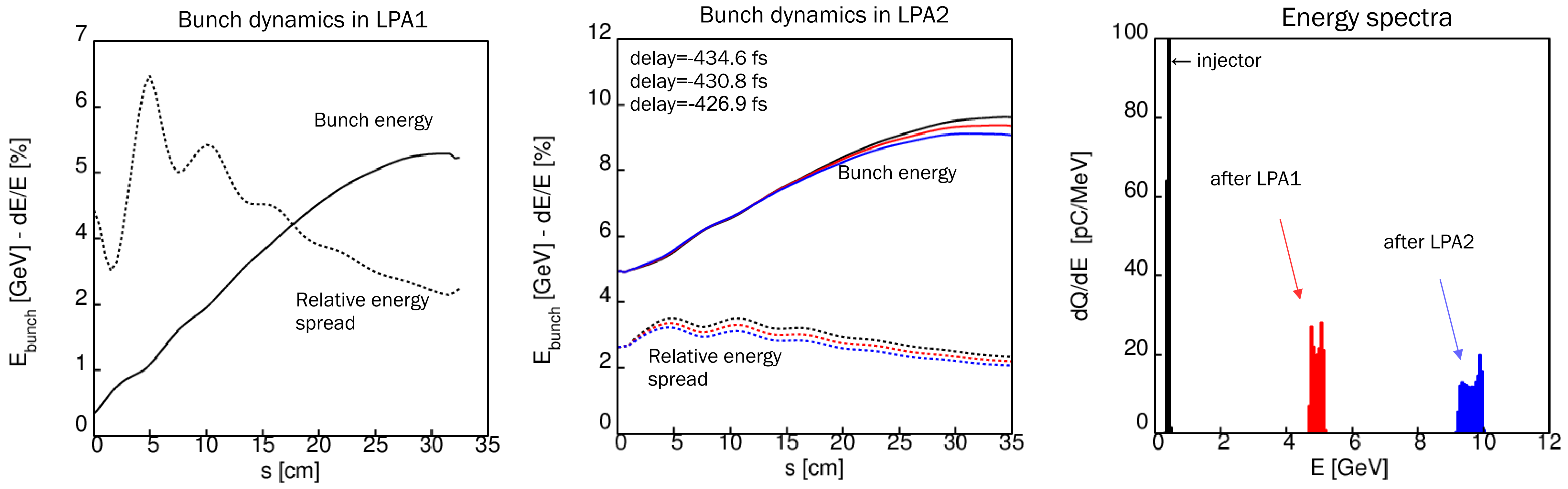




Staging design with optimized injector and guiding parameters shows 100% bunch capture and acceleration

→ Assuming better laser matching (heater) in LPA1 and LPA2 and operating in a more linear regime (i.e., less wake evolution)

→ Assuming optimized injector parameters:
- E=400 MeV, dE/E= 4% (rms)
- Q=10 pC, Lb=2 um, x' < 1 mrad (rms)



→ Producing and maintaining low energy spread is key element for 100% bunch capture

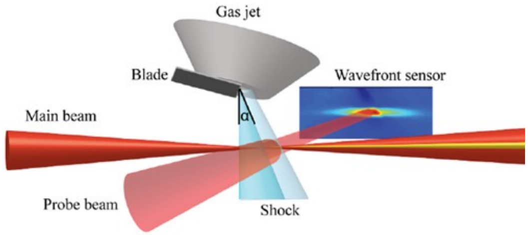
S. Steinke PoP 23, 056705 (2016)

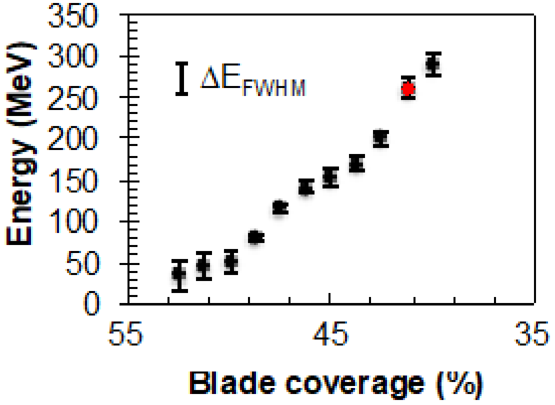
Development of key technologies for multi-GeV staging with BELLA already underway I: injector(s)

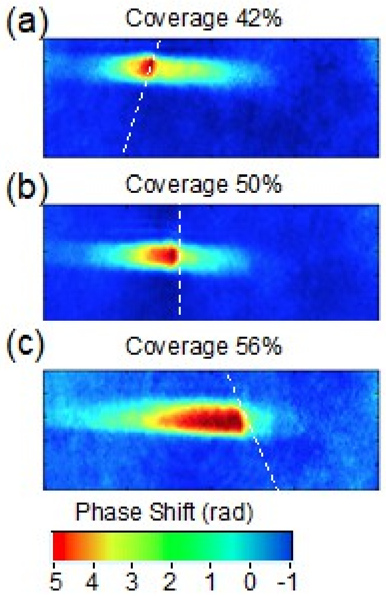
Injector studies with mixed gas

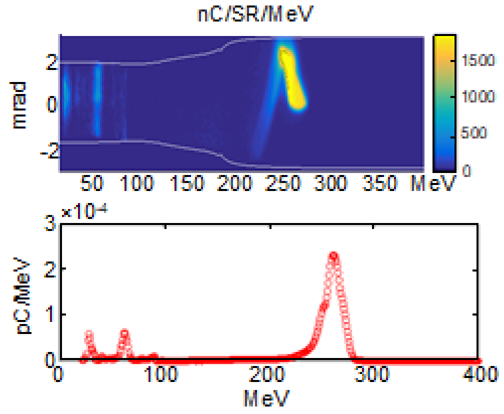
Shock-downramp injection

Experiments at (2 J, TREX):





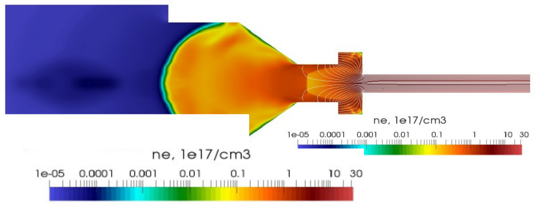




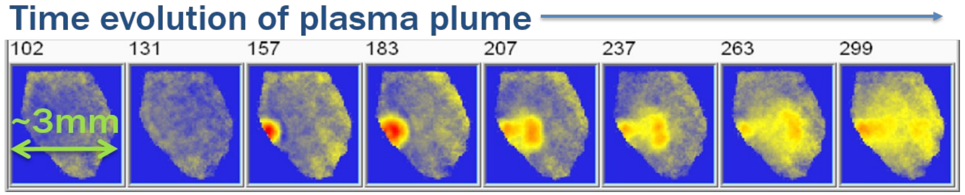
H.-E. Tsai et al., PoP **25**, 043107 (2018)
K. K. Swanson et al., PRAB **20**, 051301 (2017)

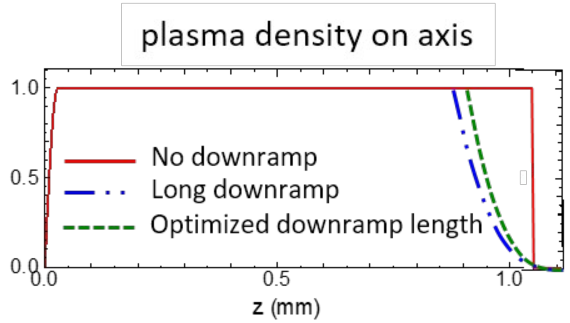
Development of key technologies for multi-GeV staging with BELLA already underway II: study of plasma plumes and focusing of 1.7 GeV beams with an active plasma lens

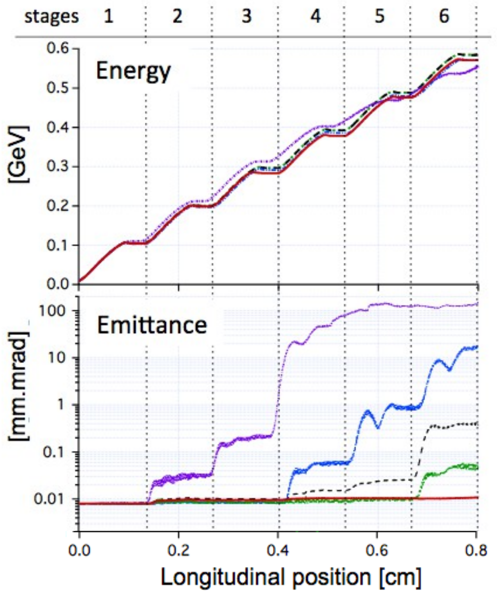
Study of plumes @ cap entrance/exit to optimize laser in-coupling and/or to mitigate emittance degradation



← Preliminary modeling of plasma plumes (MARPLE)

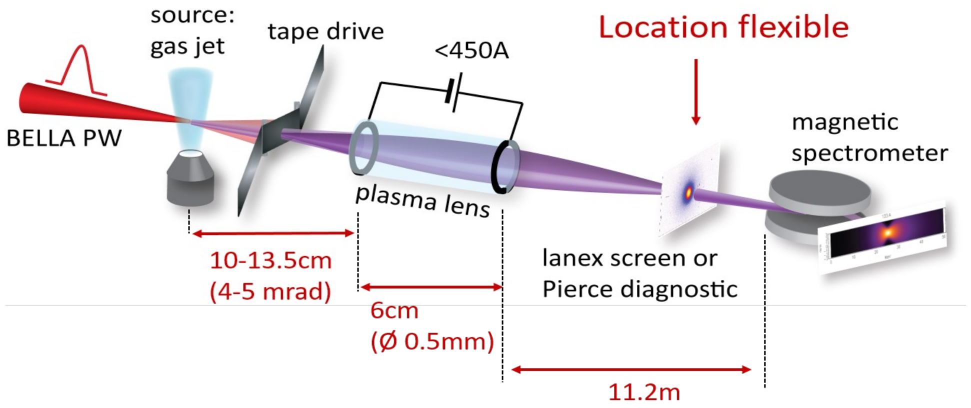


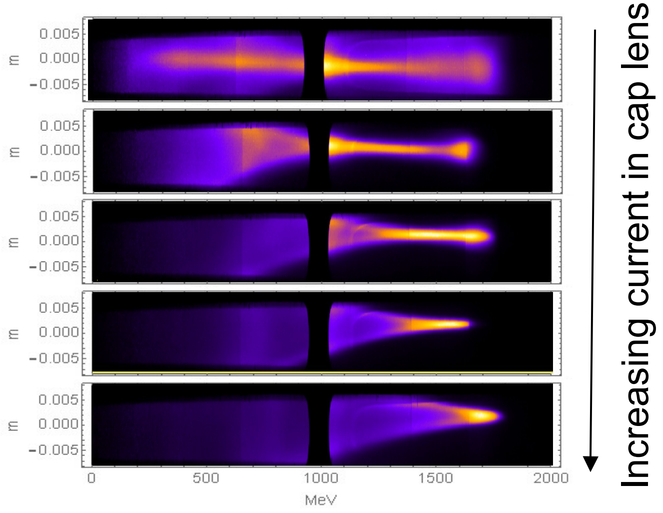




X. Xu et al., PRL (2016)
J.-L. Vay et al., Proc. AAC Proc. (2014)

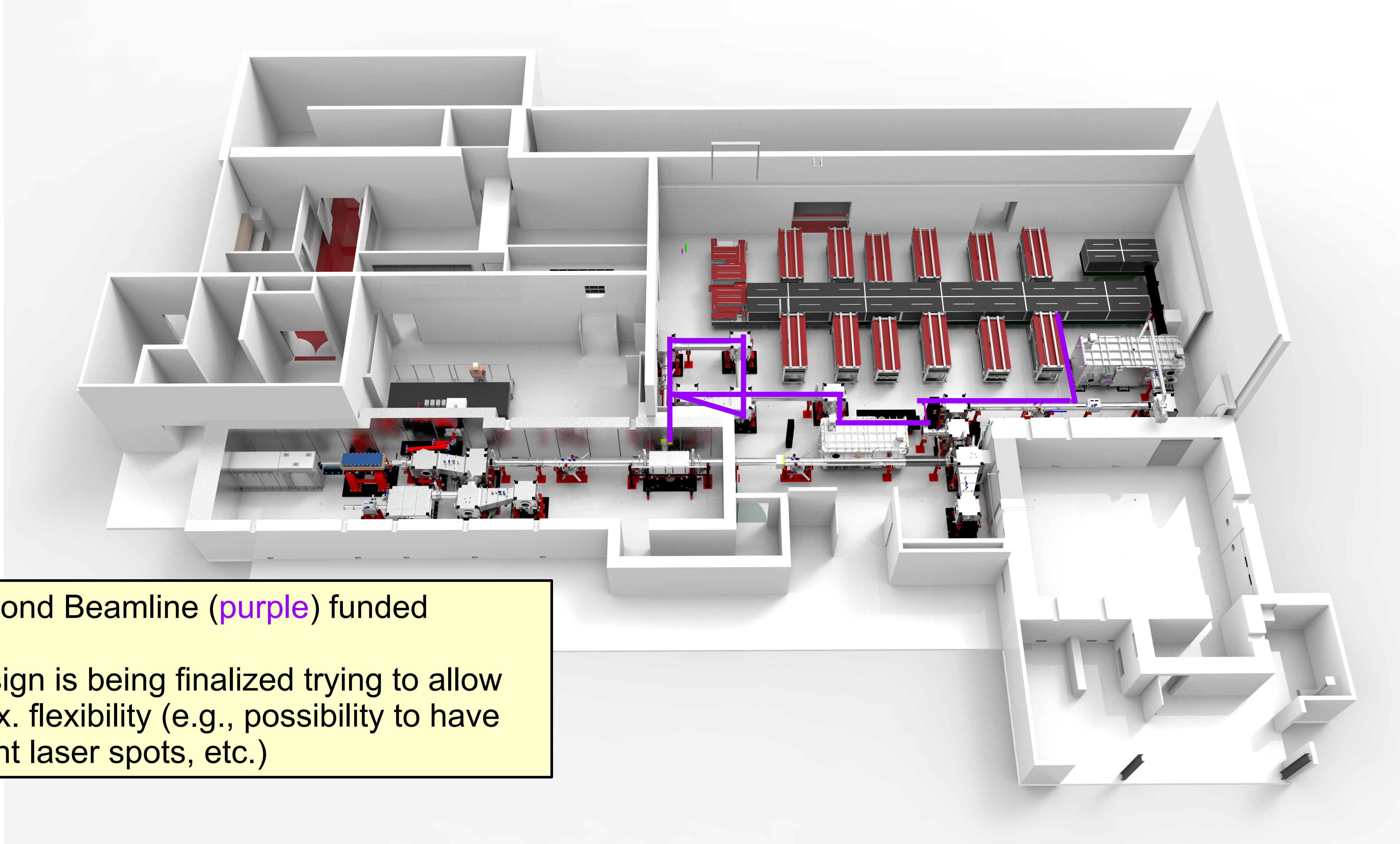
Focusing of 1.7 GeV beams with active plasma lens





← < mm spot size at 11.2 m downstream of target

2nd Beamline Project underway to be completed in 2021



→ Second Beamline (purple) funded

→ Design is being finalized trying to allow for max. flexibility (e.g., possibility to have different laser spots, etc.)

Summary

- Staging demonstrated at the 100 MeV level energy gain (with second stage operating in the linear regime)

- Multi-GeV staging experiment at BELLA planned and project underway (design and optimization of sub-components in progress, realistic description for laser and plasma)
  → LPA1 with triggered injection: quasi-monoenergetic, multi-GeV beams with a charge of up to a few 10s of pC;
  → cap-lens required for high in-coupling efficiency;
  → LPA2 operating in quasi-linear regime provides > 4 GeV energy gain with ~50% capture efficiency;
  → with optimal laser-plasma parameters 5 GeV + 5 GeV with 100% capture efficiency possible.

- Development and testing of key technologies already underway:
  → ionization induced injection + downramp shock injection;
  → study of plasma plumes @ cap ends for laser in-coupling and/or control beam extraction;
  → focusing of GeV beams with active plasma lenses;
  → plasma mirror realized with liquid crystal films (collaboration w/ OSU).

See talk by M. Thevenet about tollerances (Thursday, 10:15am)

Job opportunity

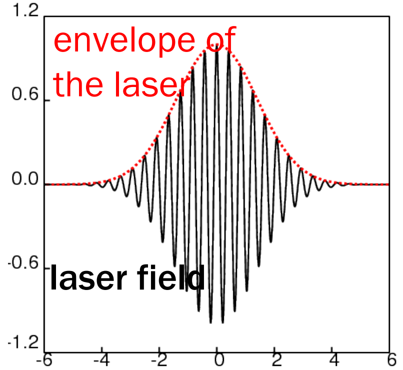
Postdoc position (1 year, renewable) at BELLA to work on theory and modeling of plasma-based acceleration...

Contact me (cbenedetti@lbl.gov) for more info!

INF&RNO* is a reduced code tailored to efficiently model LPAs: several orders of magnitude faster than full 3D PIC codes still retaining physical fidelity

INF&RNO framework

Envelope description for laser



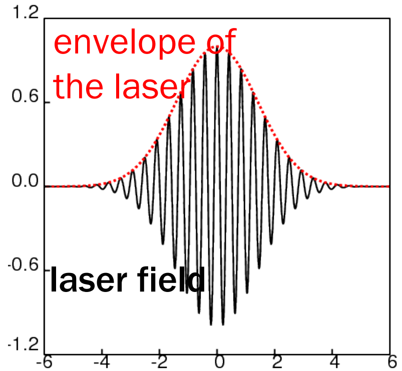
*Benedetti *at al.*, AAC2010, AAC2012, ICAP2012, AAC2016, PPCF (2018)

INF&RNO* is a reduced code tailored to efficiently model LPAs: several orders of magnitude faster than full 3D PIC codes still retaining physical fidelity

INF&RNO framework

Envelope description for laser

laser → plasma force via averaged ponderomotive force (scales @ λ_0 are removed from simulation)



2D-cylindrical geometry: 3D physics at 2D comp. cost

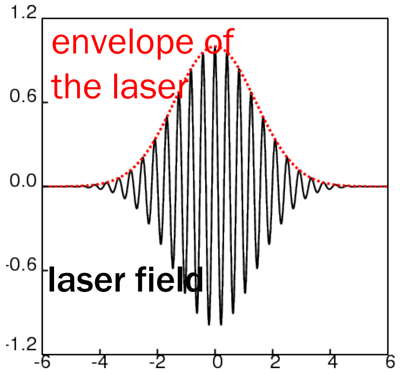
Correct laser physics at low computational cost

*Benedetti *at al.*, AAC2010, AAC2012, ICAP2012, AAC2016, PPCF (2018)

INF&RNO* is a reduced code tailored to efficiently model LPAs: several orders of magnitude faster than full 3D PIC codes still retaining physical fidelity

INF&RNO framework

- **Envelope description for laser**
  - **laser → plasma force via averaged ponderomotive force (scales @ λ_0 are removed from simulation)**
  - **2D-cylindrical geometry: 3D physics at 2D comp. cost**
- **PIC or (cold) fluid description for plasma**



Correct laser physics at low computational cost

*Benedetti *at al.*, AAC2010, AAC2012, ICAP2012, AAC2016, PPCF (2018)

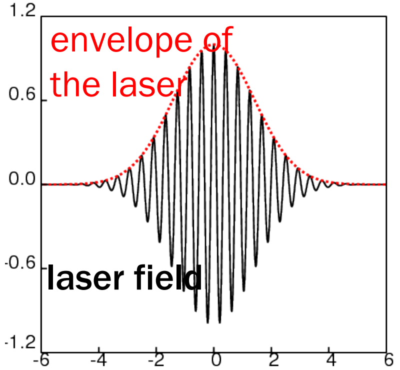
INF&RNO* is a reduced code tailored to efficiently model LPAs: several orders of magnitude faster than full 3D PIC codes still retaining physical fidelity

INF&RNO framework

Envelope description for laser

laser → plasma force via averaged ponderomotive force (scales @ λ_0 are removed from simulation)

2D-cylindrical geometry: 3D physics at 2D comp. cost



Correct laser physics at low computational cost

PIC or (cold) fluid description for plasma

“time-explicit” or quasi-static evolution

Different levels of approximation and completeness of plasma description

*Benedetti *at al.*, AAC2010, AAC2012, ICAP2012, AAC2016, PPCF (2018)

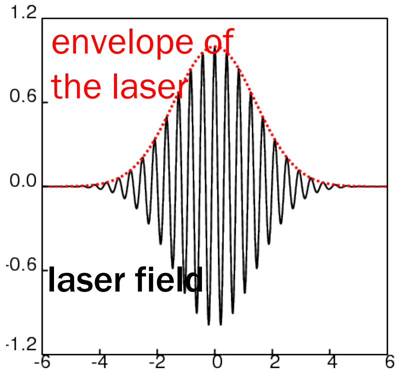
INF&RNO* is a reduced code tailored to efficiently model LPAs: several orders of magnitude faster than full 3D PIC codes still retaining physical fidelity

INF&RNO framework

Envelope description for laser

laser → plasma force via averaged ponderomotive force (scales @ λ_0 are removed from simulation)

2D-cylindrical geometry: 3D physics at 2D comp. cost



Correct laser physics at low computational cost

PIC or (cold) fluid description for plasma

"time-explicit" or quasi-static evolution

Different levels of approximation and completeness of plasma description

Moving window, parallel, independent grid for laser driver and wakefield, tunnel ionization module, ion motion module, etc.

Features to increase the speed-up & additional physics

*Benedetti *at al.*, AAC2010, AAC2012, ICAP2012, AAC2016, PPCF (2018)

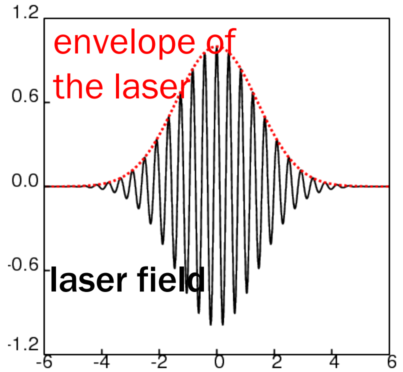
INF&RNO* is a reduced code tailored to efficiently model LPAs: several orders of magnitude faster than full 3D PIC codes still retaining physical fidelity

INF&RNO framework

Envelope description for laser

laser → plasma force via averaged ponderomotive force (scales @ λ_0 are removed from simulation)

2D-cylindrical geometry: 3D physics at 2D comp. cost



Correct laser physics at low computational cost

PIC or (cold) fluid description for plasma

"time-explicit" or quasi-static evolution

Different levels of approximation and completeness of plasma description

Moving window, parallel, independent grid for laser driver and wakefield, tunnel ionization module, ion motion module, etc.

Features to increase the speed-up & additional physics

INF&RNO enables efficient modeling of multi-GeV LPAs in a reasonable time (a few hours/days) and on small computers.

*Benedetti *at al.*, AAC2010, AAC2012, ICAP2012, AAC2016, PPCF (2018)