EXHILP 2021
Virtual Meeting
13-17th of Sept.

Strong Field (SF) QED Capabilities at BELLA PW: Second Beamline Overview *

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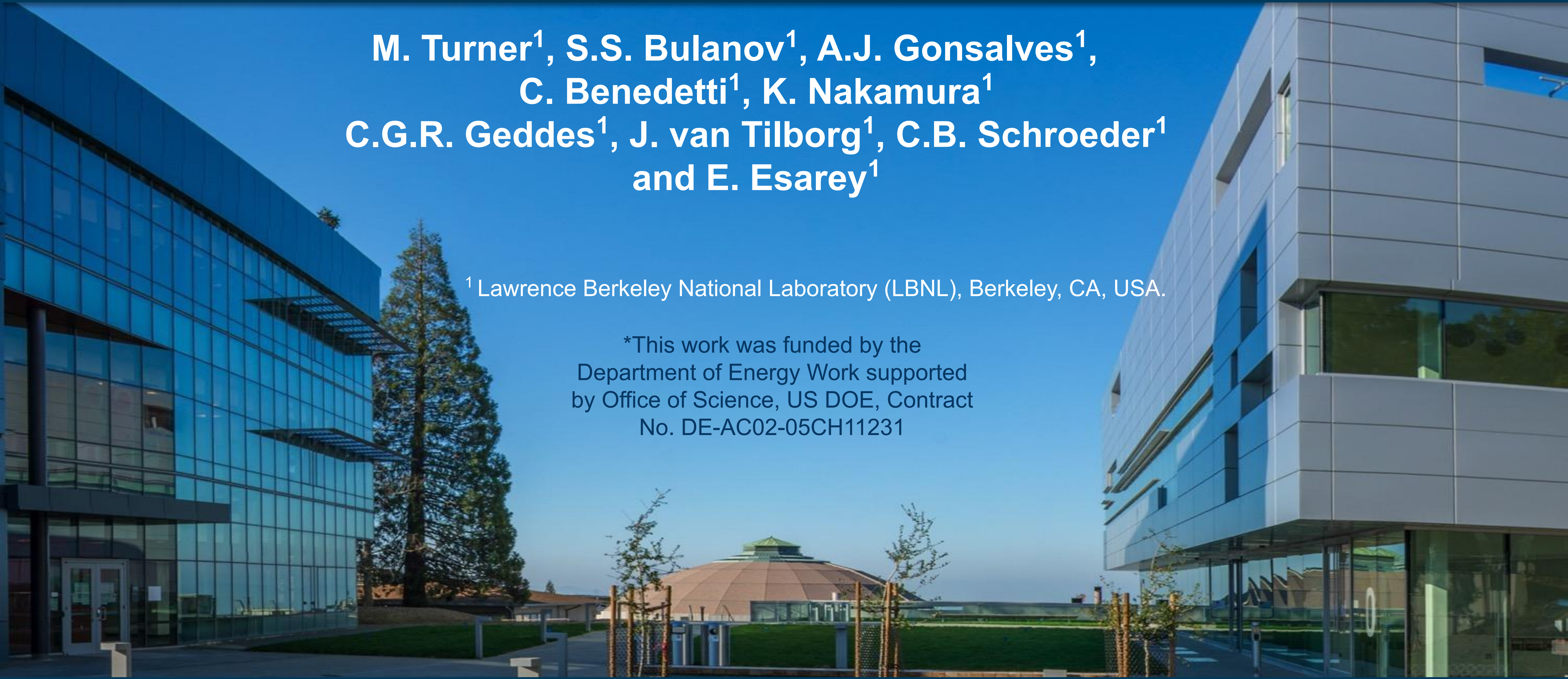
*This work was funded by the Department of Energy Work supported by Office of Science, US DOE, Contract No. DE-AC02-05CH11231



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Outline

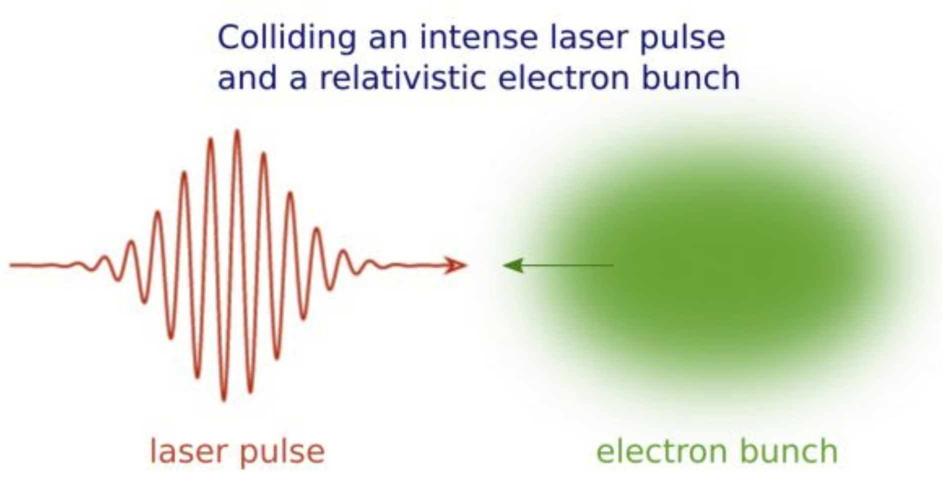
→ Introduction

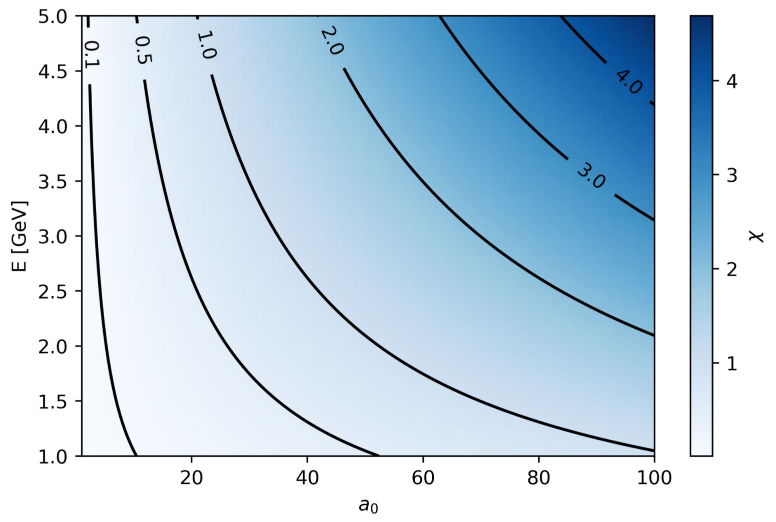
→ BELLA PW Facility and its New 2nd Beamline

→ SF QED Capabilities at BELLA PW

→ Outlook & Conclusions

Reaching the SF QED Parameter Regime



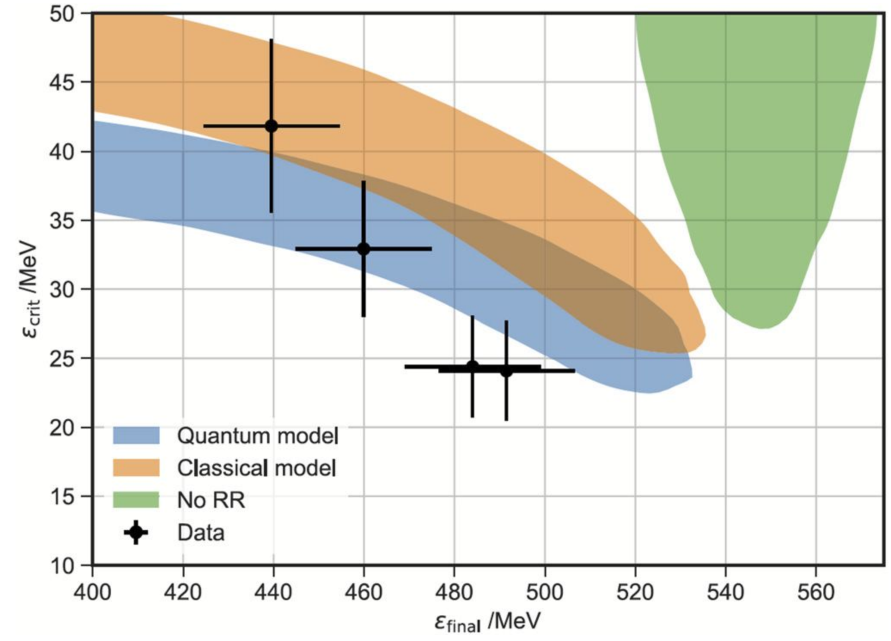


Experimental environment:

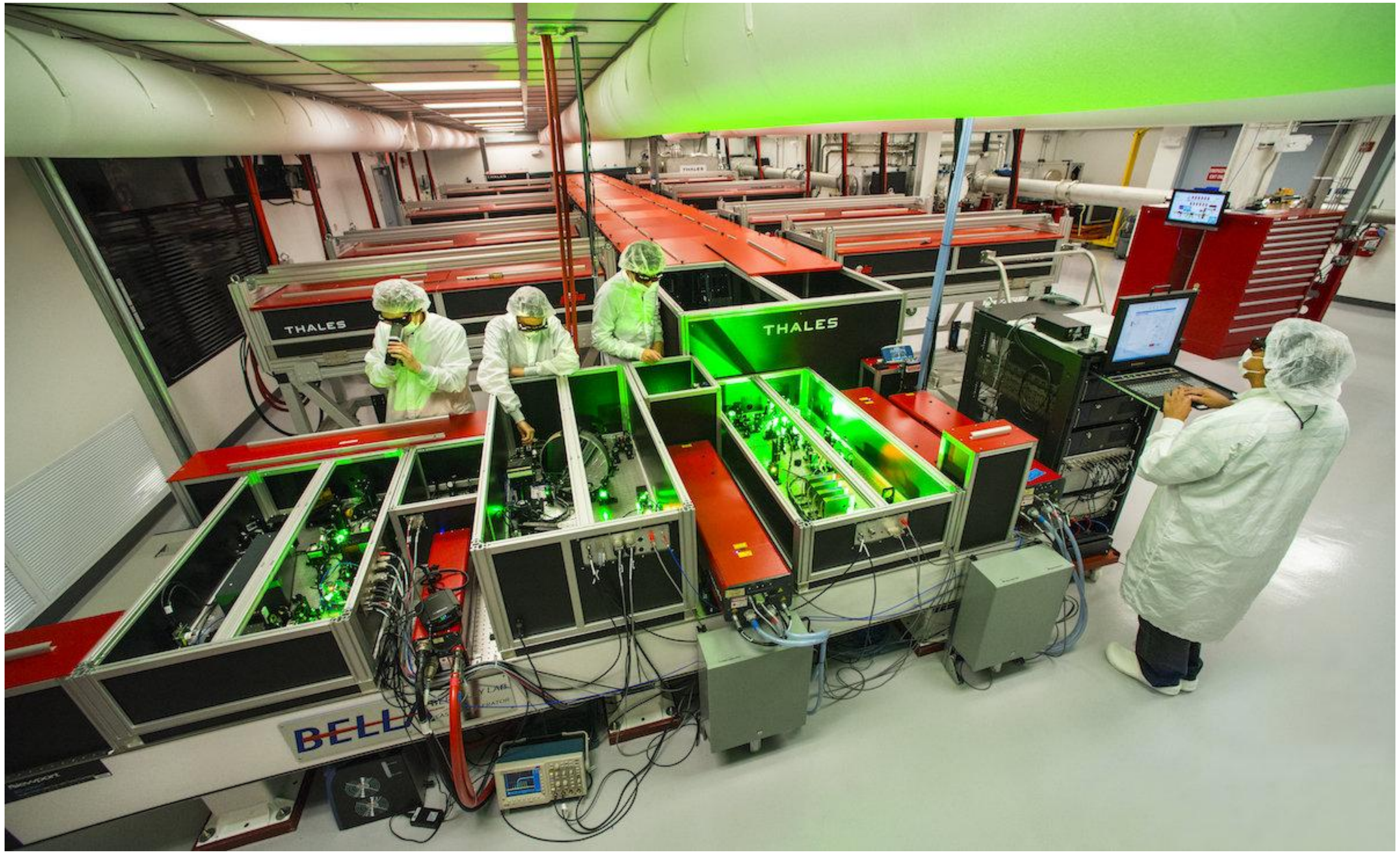
reach the nonlinear quantum parameter χ > 1, where

$$\chi = 2\gamma_e \frac{a_0}{a_s}$$

to increase the current understanding and validate/test theoretical models by increasing the number of datapoints as wells widen the measurement range.



J. M. Cole, et al., Phys. Rev. X 8, 011020 (2020).



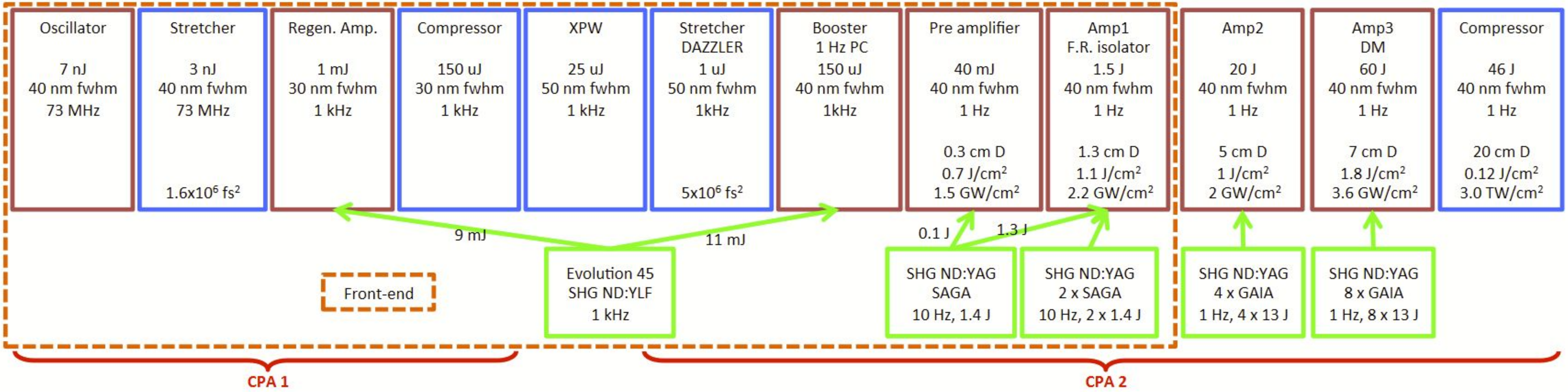
Near Term Experimental Platform: BELLA 2nd Beamline

The BELLA Petawatt Laser

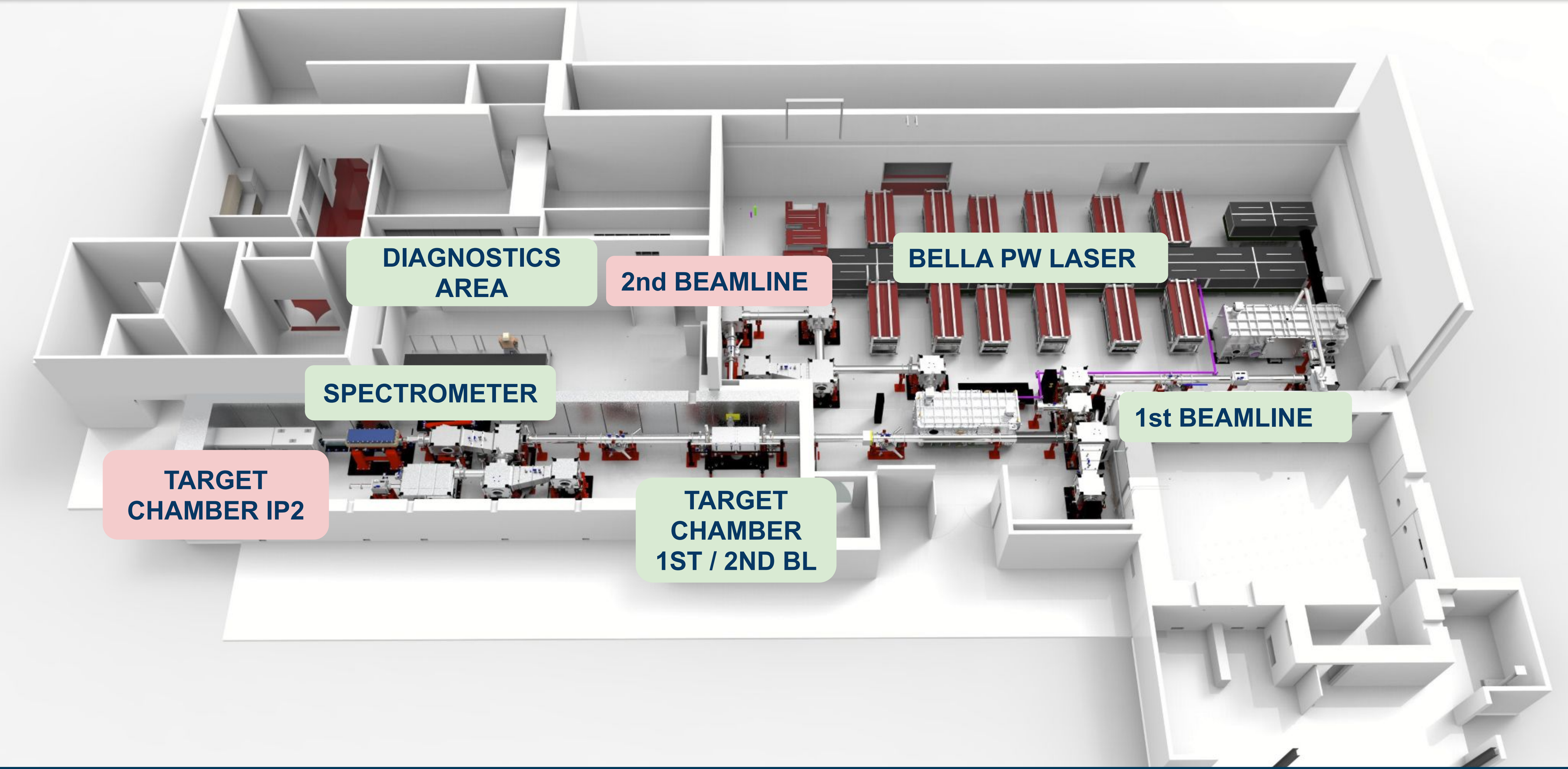
- BELLA: **BE**rkeley **L**ab **L**aser **A**ccelerator
- Ti:Sapphire Laser system
- Pulse energy on target: ~40J, Pulse length down to ~30 fs
- Pulse repetition rate: 1 Hz

New: Two independently tunable high intensity laser pulses

K. Nakamura *et al*., "Diagnostics, Control and Performance Parameters for the BELLA High Repetition Rate Petawatt Class Laser," in *IEEE Journal of Quantum Electronics*, vol. 53, no. 4, pp. 1-21, Aug. 2017.



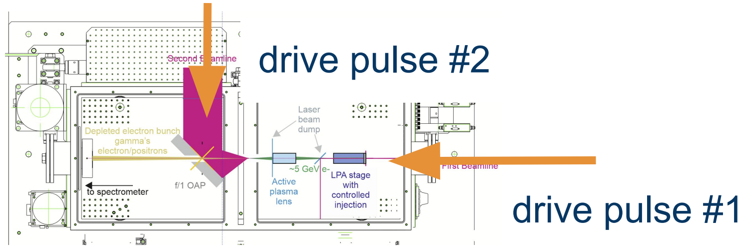
The BELLA PW Laser Facility



BELLA PW Facility Upgrade

2nd Beamline Project

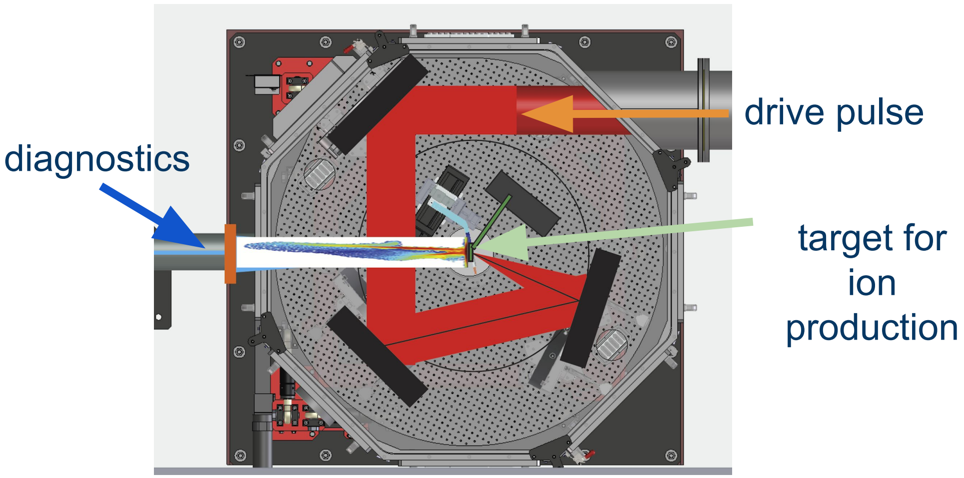
- Provides a new second independent high power laser inside the target chamber thanks to a new pulse transport line.
- 2nd BL has a separate pulse compressor that enables independent pulse length control and pulse delays.
- Long focal length focusing providing laser pulse focal spot sizes on the order of 10s of micron. Currently installed OAP with 13.1m focal length providing a spot size of 53 um.
- Goals include: Staging of two Laser Plasma Wakefield Acceleration Stages, Single Plasma Stage Development,...



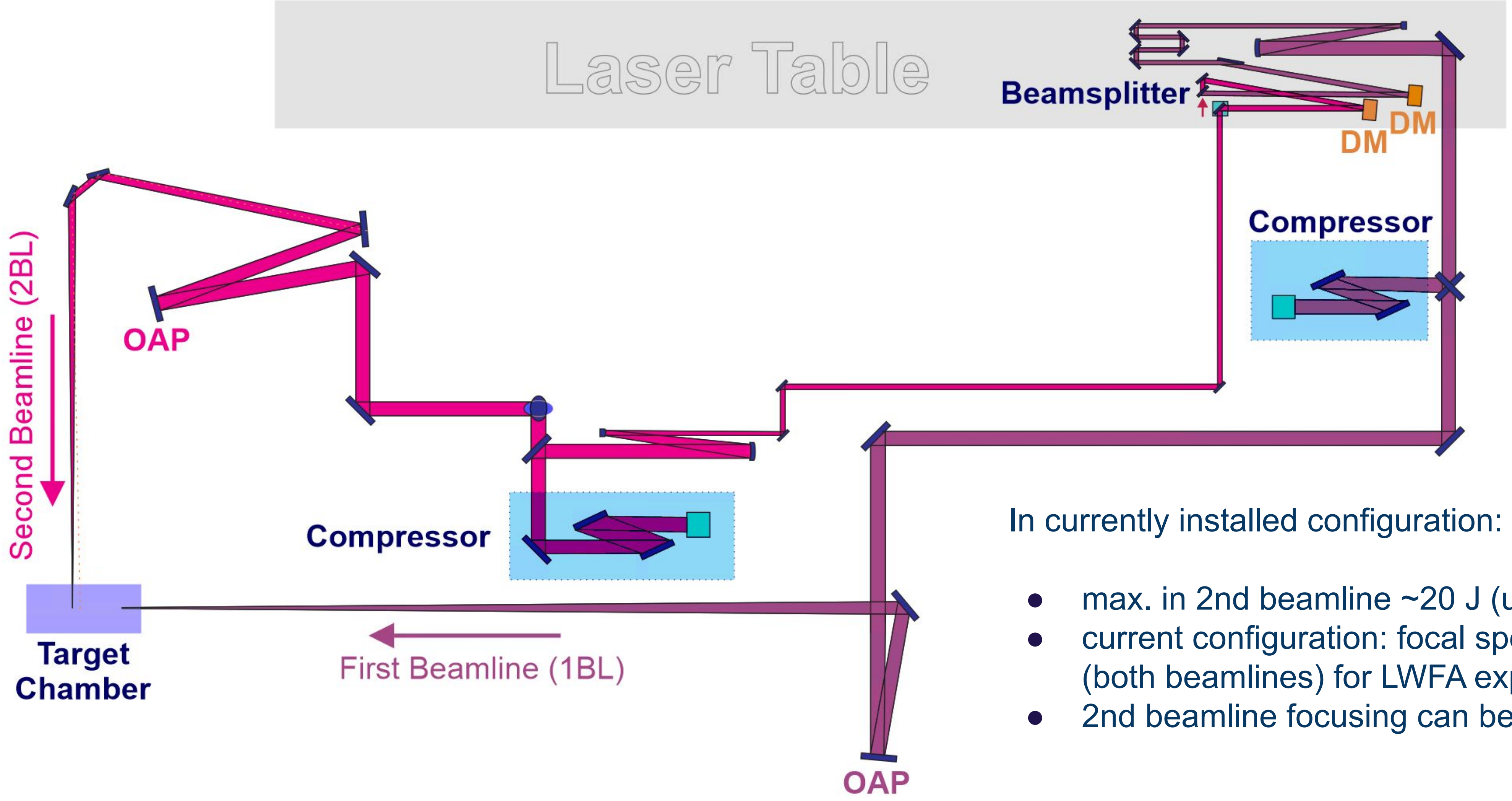
IP2 Project

- New, separate target chamber for one high intensity laser pulse using the first BELLA PW beamline with a pulse energy up to 40 J.
- Short focal length OAP f/2.5 to produce 2.5 um focal spot size and a pulse intensity of $6x10^{21}$ W/cm^2.
- Goals: produce ~100 MeV protons for applications, high energy density science experiments.

IP 2 target chamber layout



Overview of the BELLA Petawatt Beamlines



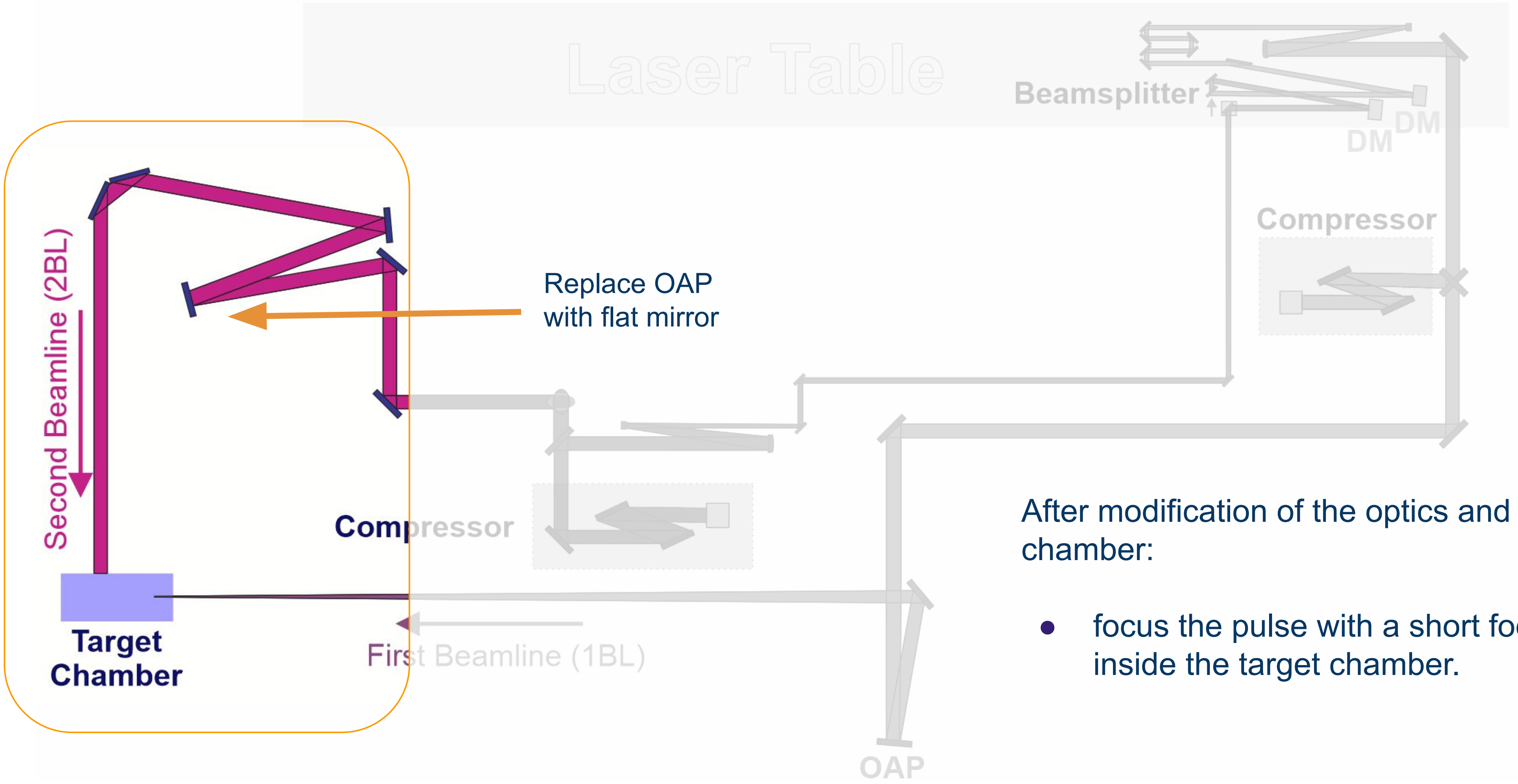
Laser pulse beam-splitter installed on the laser table:

- Reflectivity of the beam-splitter determines how much energy is transported in the 2nd Beamline.

In currently installed configuration:

- max. in 2nd beamline ~20 J (upgrade possible).
- current configuration: focal spot sizes of ~53 um (both beamlines) for LWFA experiments.
- 2nd beamline focusing can be adjusted.

2nd Beamline OAP could be Replaced by Flat Mirror to Transport Full Beam Size to the Target Chamber



After modification of the optics and the target chamber:

- focus the pulse with a short focal length OAP inside the target chamber.

BELLA PW Target Layout for SF QED Experiments

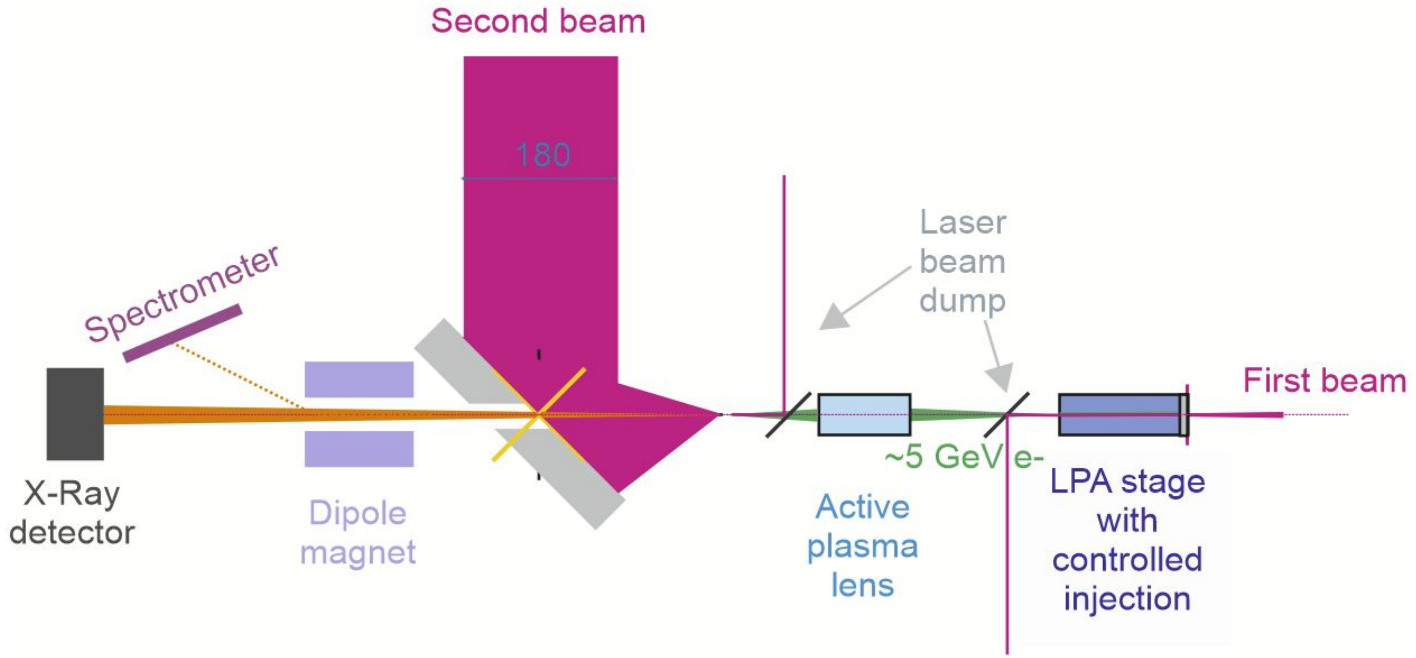
BELLA PW 1st beamline:

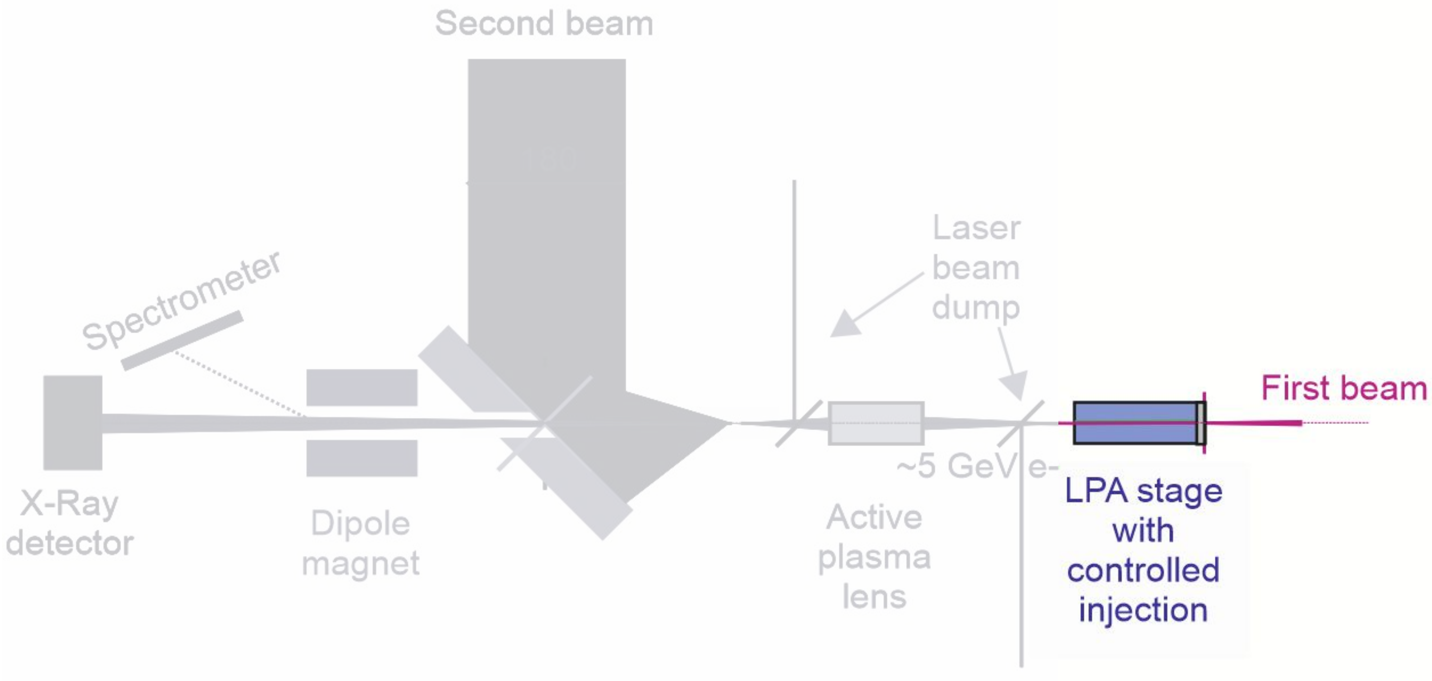
- ~20 J laser pulse energy to produce LWFA electron with energies ~5 GeV

BELLA PW 2nd beamline:

- ~20 J pulse energy together with a short focal length OAP to reach $a_0 > 10$

Idea: collide the laser pulse with the LWFA electron beam



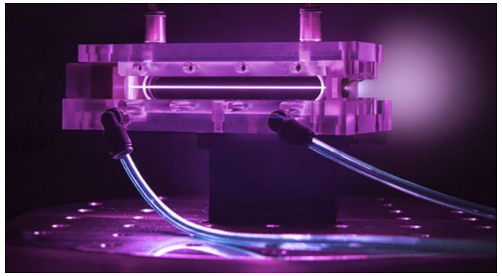


1st Laser-Pulse to Produce and Accelerate an Electron Beam

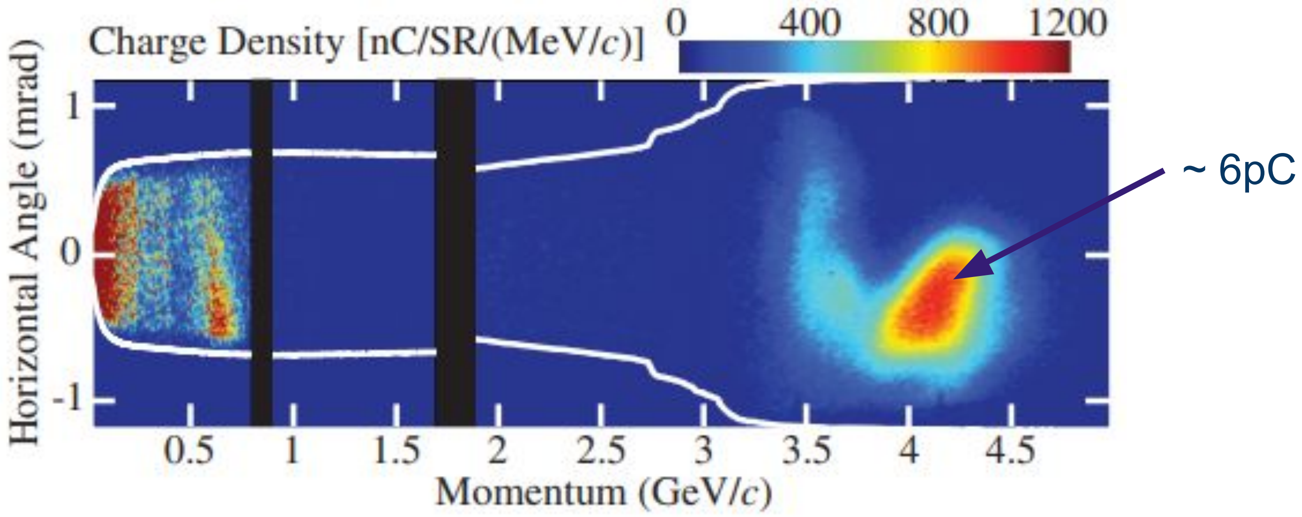
using a Laser Plasma Wakefield Acceleration Stage

20 J Laser Pulse Energy Sufficient to Accelerate Electrons to ~5 GeV

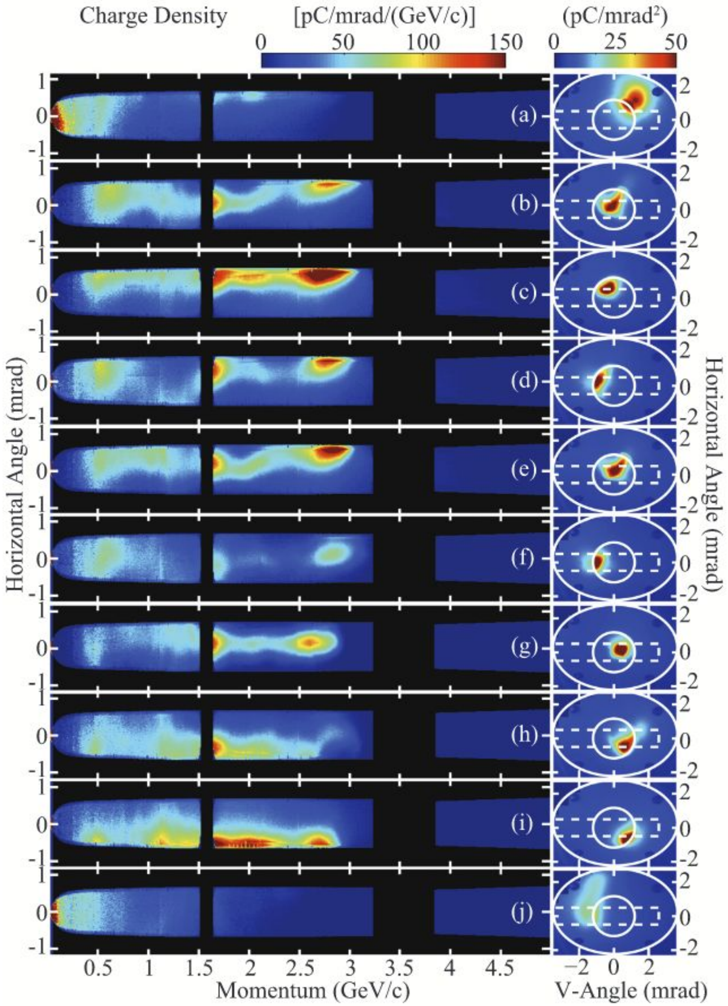
Experimental Results:
accelerated electrons up to 4.2 GeV.



- 9 cm long capillary plasma waveguide,
- 16 J of pulse energy to drive wakefields.



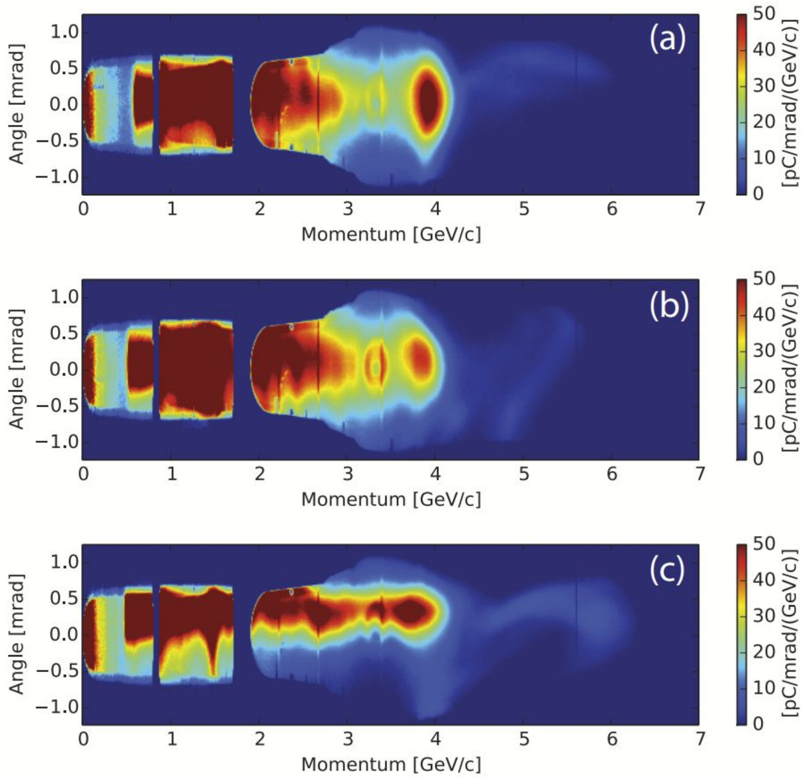
W. P. Leemans, et al., Phys. Rev. Lett. 113, 245002 (2014)



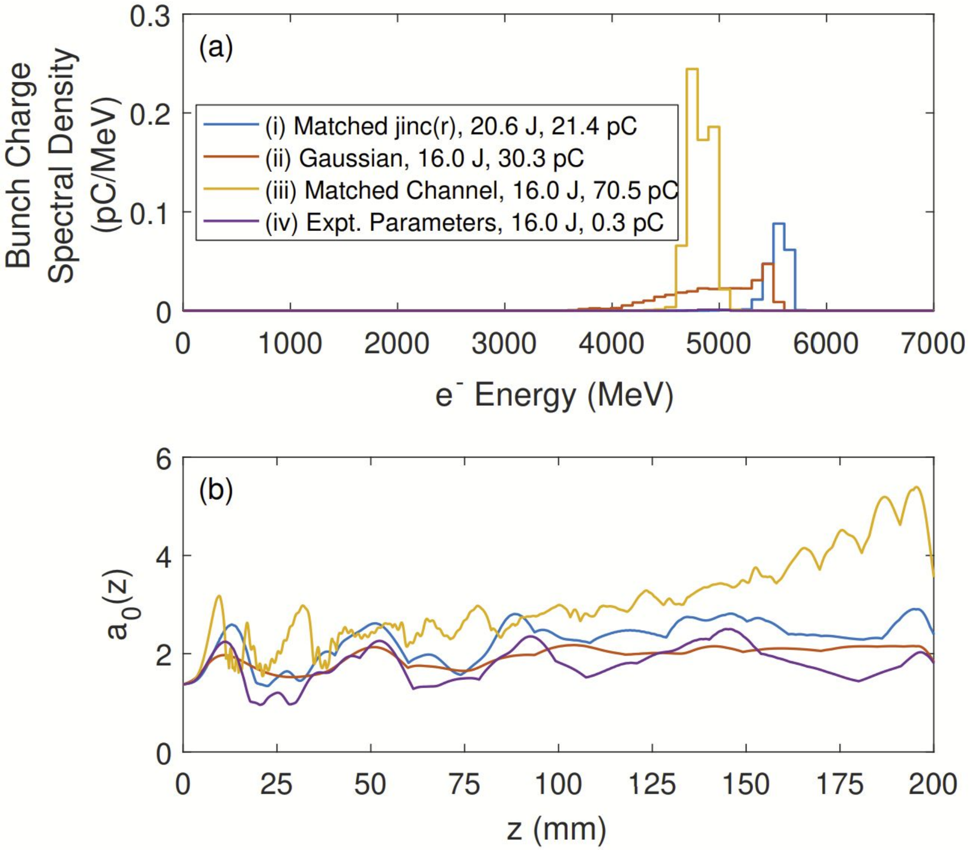
Gonsalves et al., Phys. Plasmas 22, 056703 (2015)

20 J Laser Pulse Energy Sufficient to Accelerate Electrons to ~5 GeV

20 cm long capillary plasma waveguide and induced electron injection.



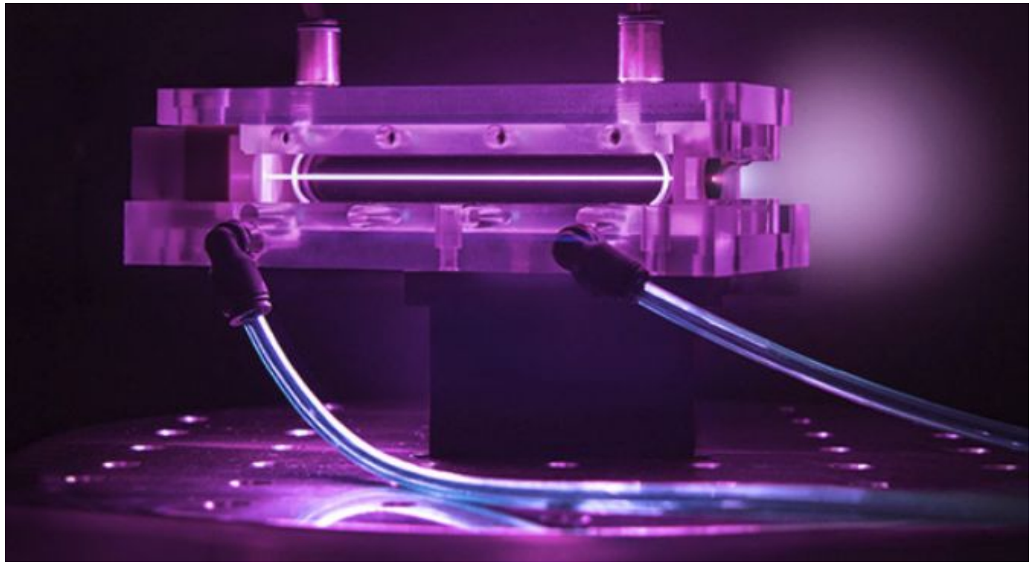
- 16 J pulse energy,
- H/N mixture,
- Total charge registered on the magnetic spectrometer ~200 pC and 2-5pC above 4.5 GeV.
- Simulation study suggest that different waveguide parameters are the path to higher charge at higher energies.

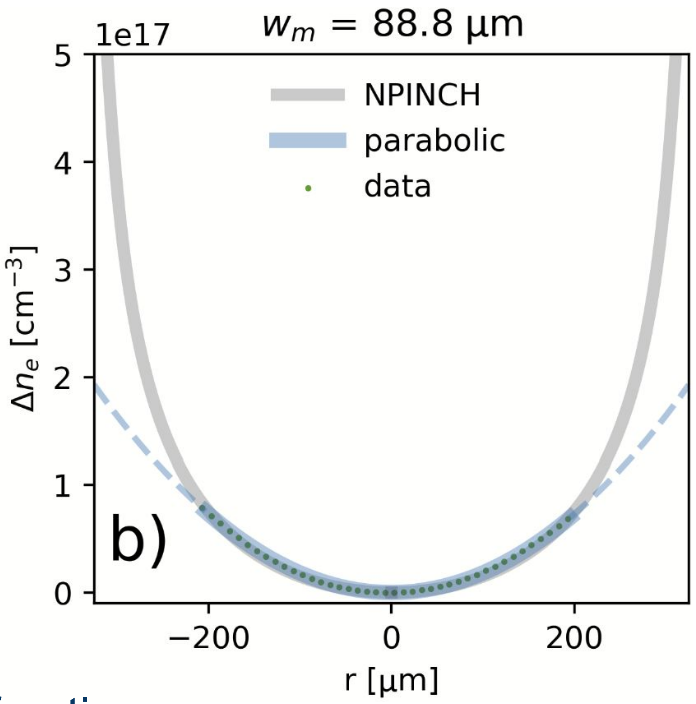


C. V. Pieronek et al., Controlled injection and dark-current suppression in a 20-cm-long channel-guided laser-plasma accelerator, in preparation.

Pulse Guiding to Extent Acceleration Distance

Plasma waveguides counteract pulse diffraction and can be used to keep the laser pulse intensity high over an extended distance (>> z_R = 1.1 cm).





M. Turner, et al., Radial density profile and stability of capillary discharge plasma waveguides of lengths up to 40 cm. *High Power Laser Science and Engineering*, *9*, E17 (2021)

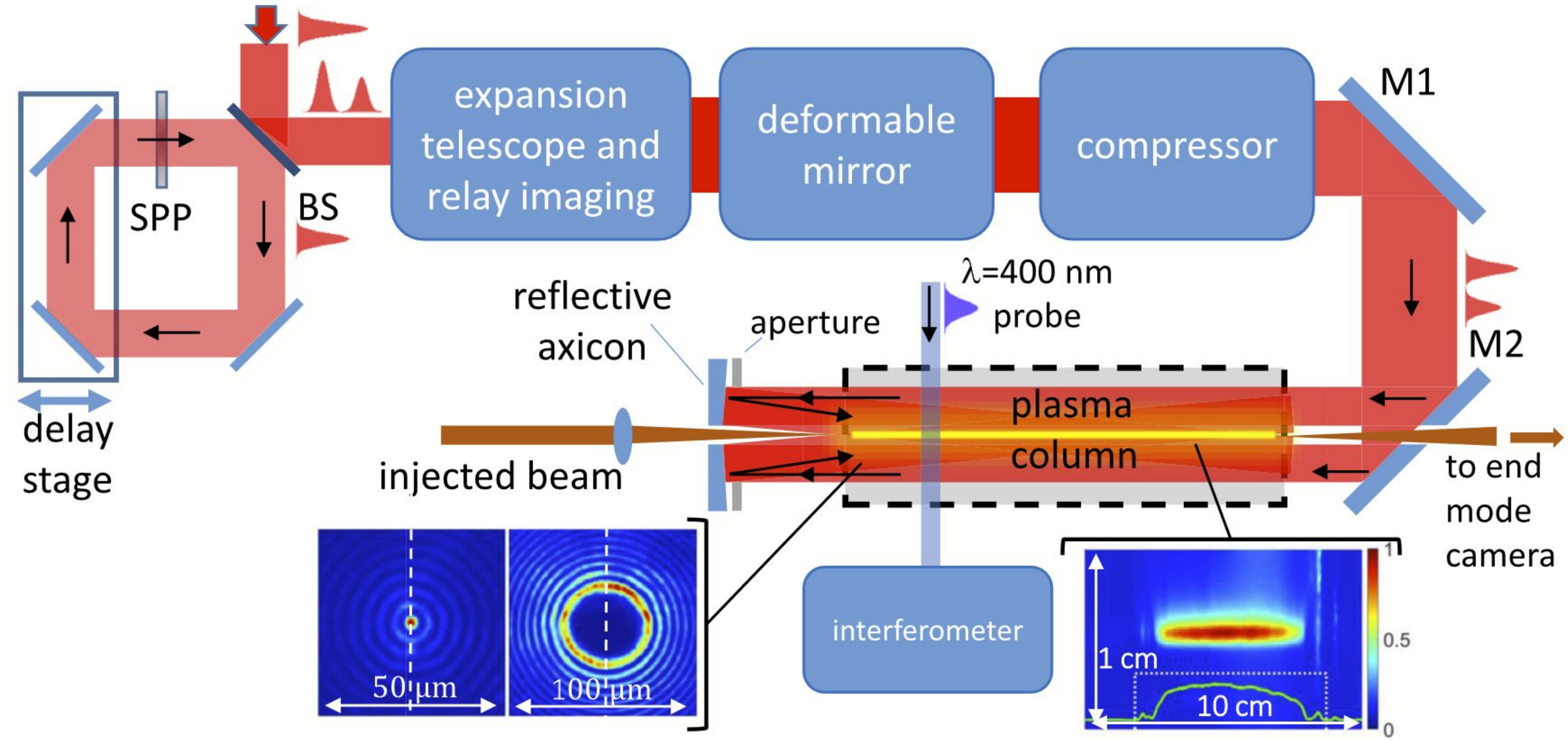
radially increasing density provides a radially decreasing refractive index
⇒
provides pulse focusing

Ideally: focusing of the channel compensates pulse diffraction.

In capillary plasma waveguides, the focusing strength is tied to the capillary geometry and the plasma electron density.

New Channel Technology without Solid Structures

Plasma channel created by optical field ionisation of one or two short laser pulses.



B. Miao, et al., Phys. Rev. Lett. 125, 074801 (2020).

Advantages:

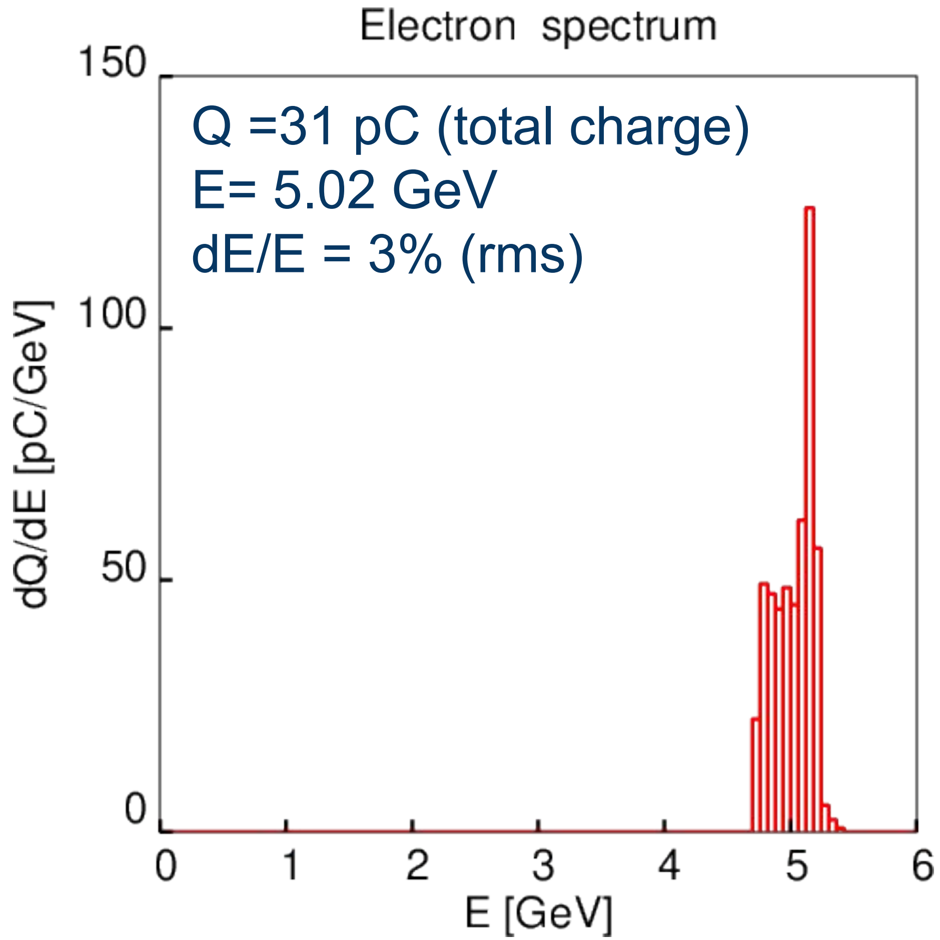
- no solid walls or structures,
- choose and tune channel parameters for optimal guiding,
- channel lengths up to 30 cm have been demonstrated,
- potential to accelerate electrons to ~10 GeV in a single stage.

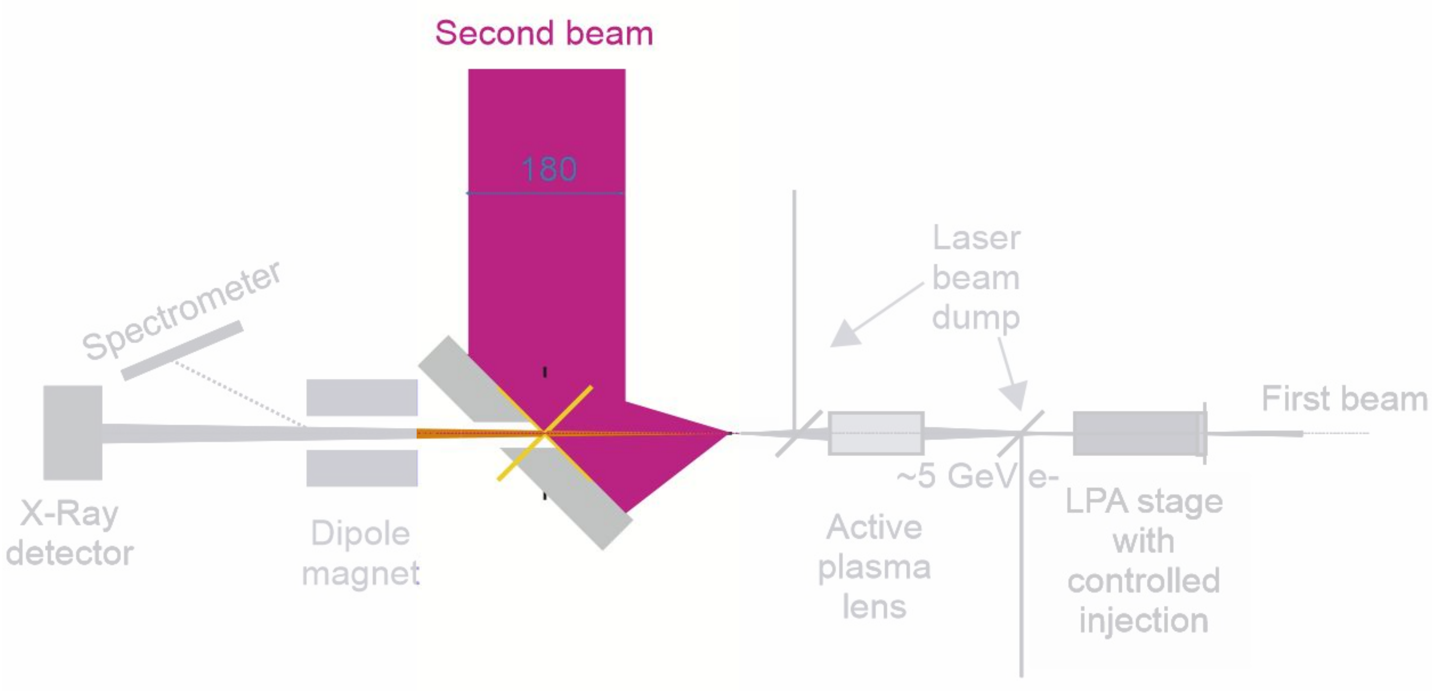
20 J Laser Pulse Energy Sufficient to Accelerate Electrons to ~5 GeV

Simulations performed by C. Benedetti, using the INF&RNO code.

INF&RNO simulation results

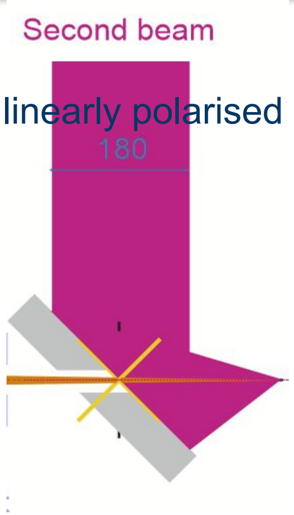
- Drive pulse energy of 16 J,
- Focal spot size of w0=52 um using a jinc profile,
- Plasma electron density of 2.2x10^{17} cm^{-3},
- Ionisation injection: ~ 0.5 cm long mixed gas region (H2/N2) at the plasma entrance,
- Plasma channel with 20 cm length and a channel matched spot size of 50 um.

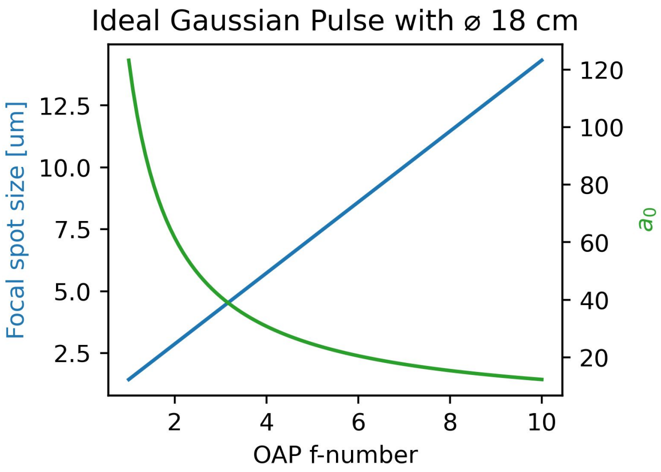


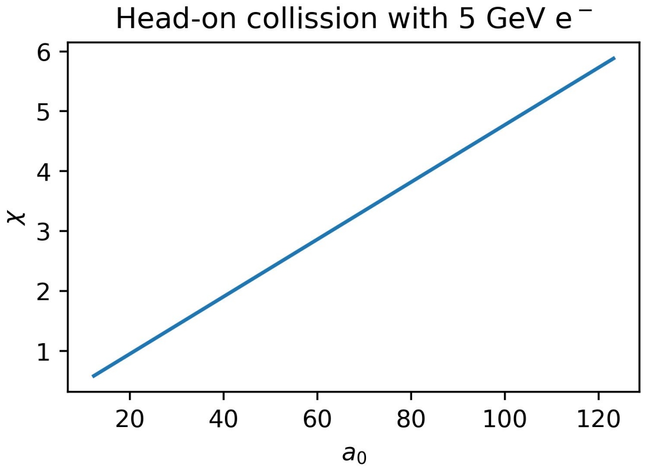


High-Intensity Scatter Laser Pulse

Vary χ by Varying Pulse Energy







Estimates, based on ideal Gaussian beams.

Change χ by varying the laser pulse energy.

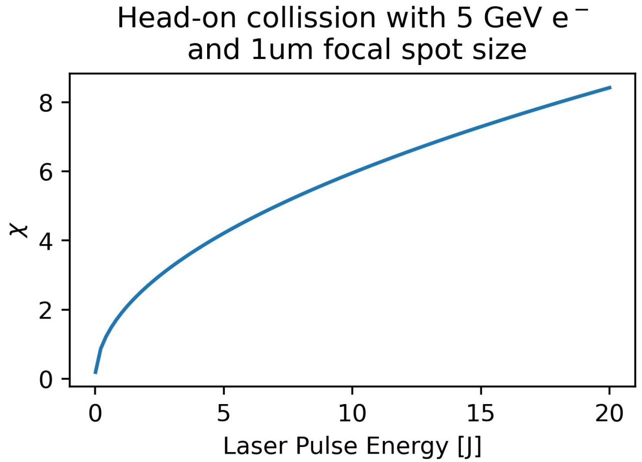
1. Radiation effects become dominant

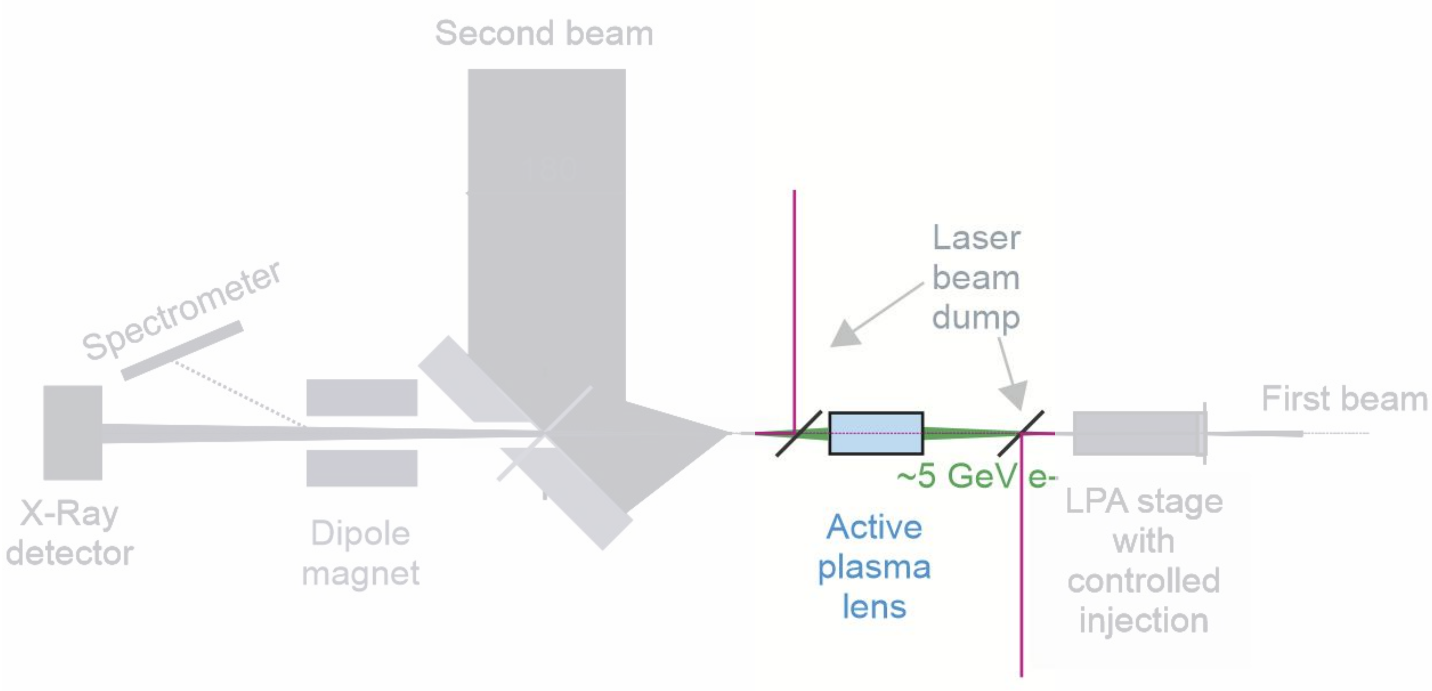
$$a > a_{rad} = (\omega \tau_{laser} \gamma_e \epsilon_{rad})^{-1/2} = \sim 15$$

2. QED effects become dominant

$$a > a_Q = (2\alpha/3)\gamma_e^{-1}\epsilon_{rad}^{-1} = \sim 40$$

from talk of S. Bulanov on Monday





IP: Active Plasma Lenses & Reproducibility

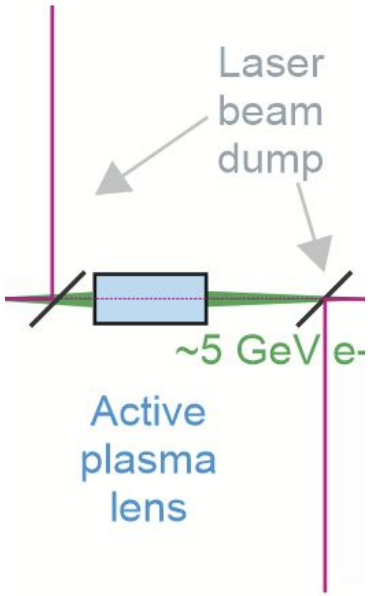
to Select Electron Energy and Refocus the Electron Bunch and Enable a Reproducible Collision.

Active Plasma Lens to Refocus Electron Beam

Active Plasma Lens provides radially symmetric focusing for the electron beam.

Other Advantages:

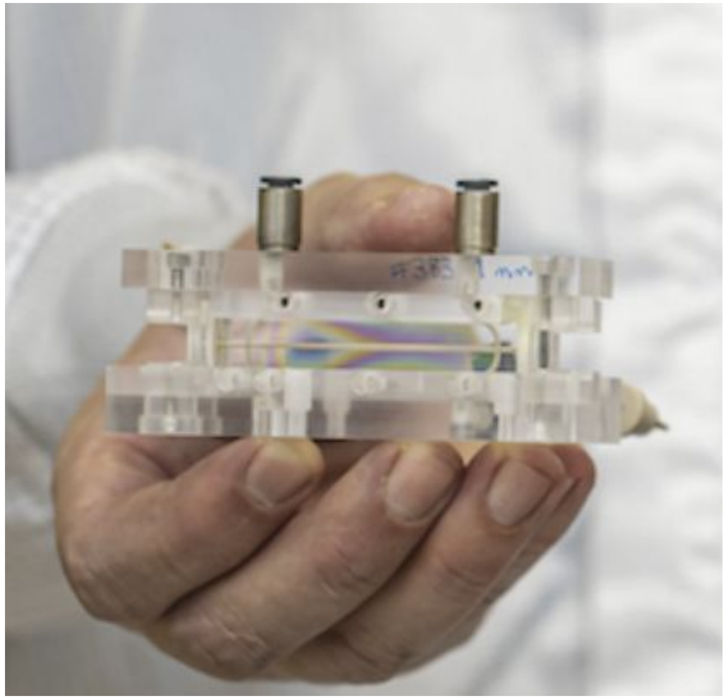
- field gradients up to 3000 T/m providing short focal lengths even at GeV beam energies, $f = (2m_0\gamma c/e)^2/(B^2L)$
- possible to achieve low magnification, $M = \frac{f_0}{d_0 - f_0}$.
- compact.



Possible design:

- transverse electron beam size at plasma exit ~c/ω_{pe} ~ 5 um,
- ~1 um spot size at the IP,
- beam magnification ~0.2,

- ⇒ 3 cm long APL with ~1000 T / m field strength.

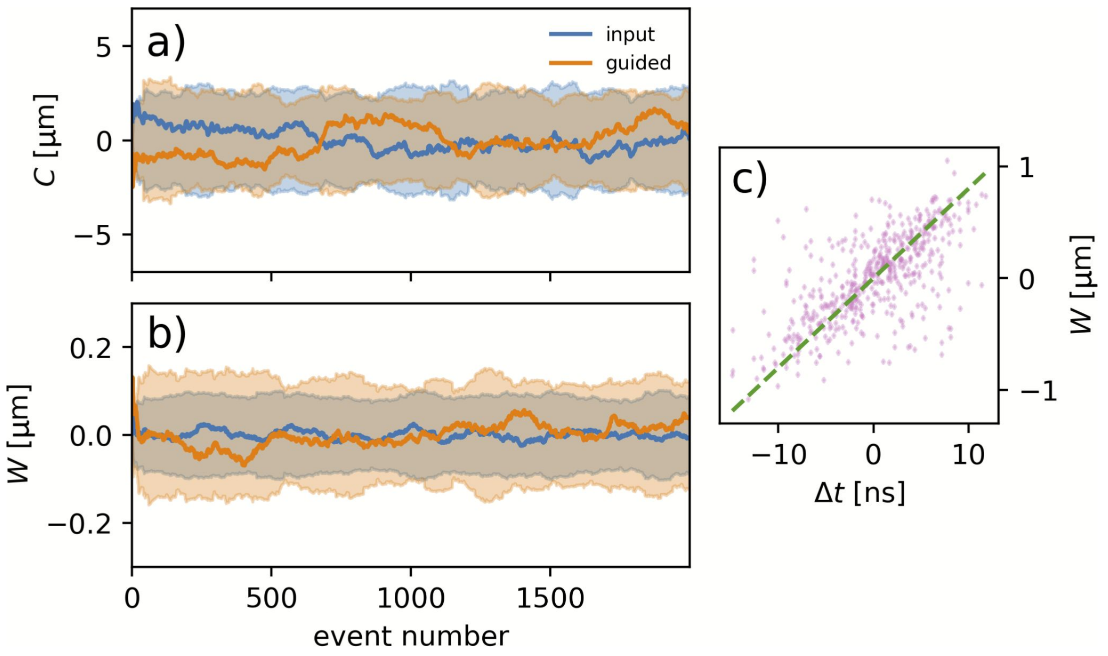


S. K. Barber et al., Appl. Phys. Lett. 116, 234108 (2020);

Plasma Target Reproducibility & LPA Stabilization

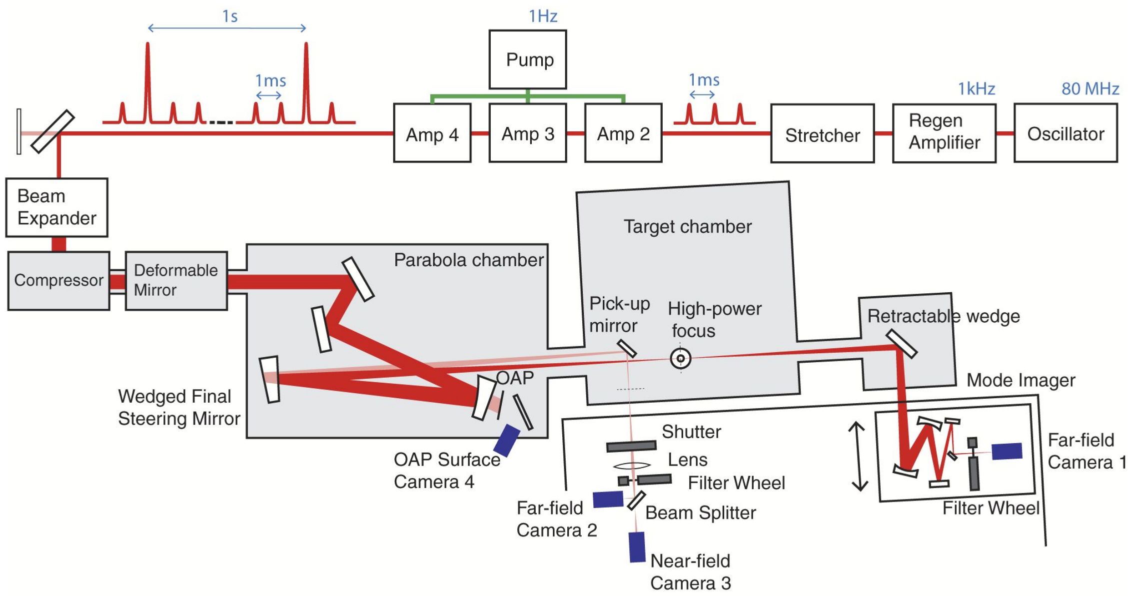
Challenge: Enable stable collision with micron sized beams and pulses.

Showed sub-percent level parameter reproducibility for capillary plasma waveguide parameters.



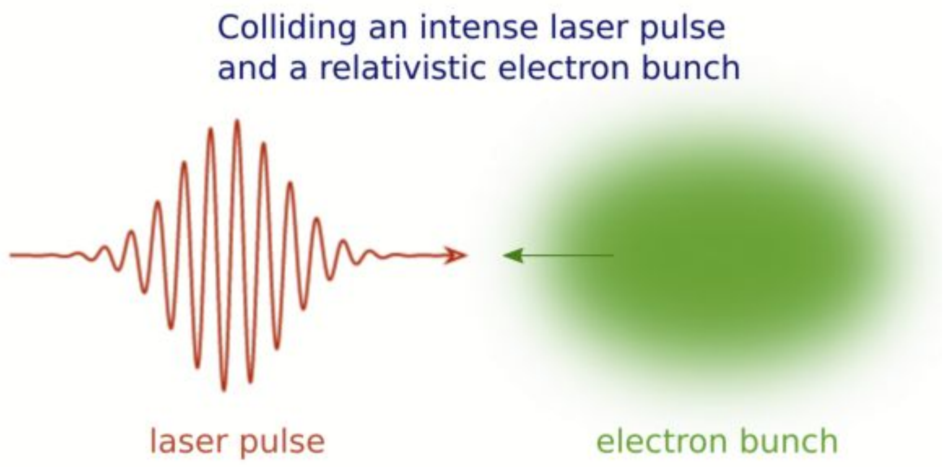
M. Turner, et al., Radial density profile and stability of capillary discharge plasma waveguides of lengths up to 40 cm. *High Power Laser Science and Engineering, 9*, E17 (2021)

The path on on how to stabilize the LPA produced electron beam.



F. Isono,et al., High-power non-perturbative laser delivery diagnostics at the final focus of 100-TW-class laser pulses. *High Power Laser Science and Engineering, 9* (2021)

SF QED Simulation Estimates



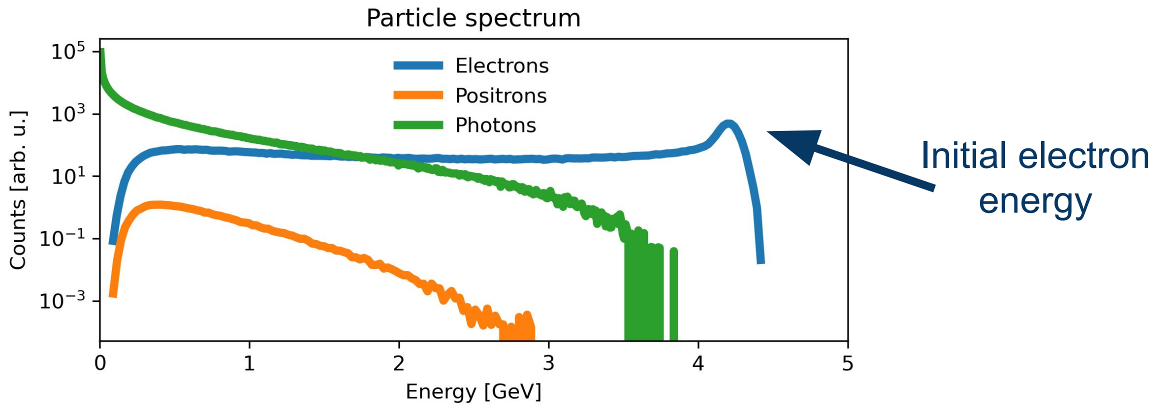
Simulation input:

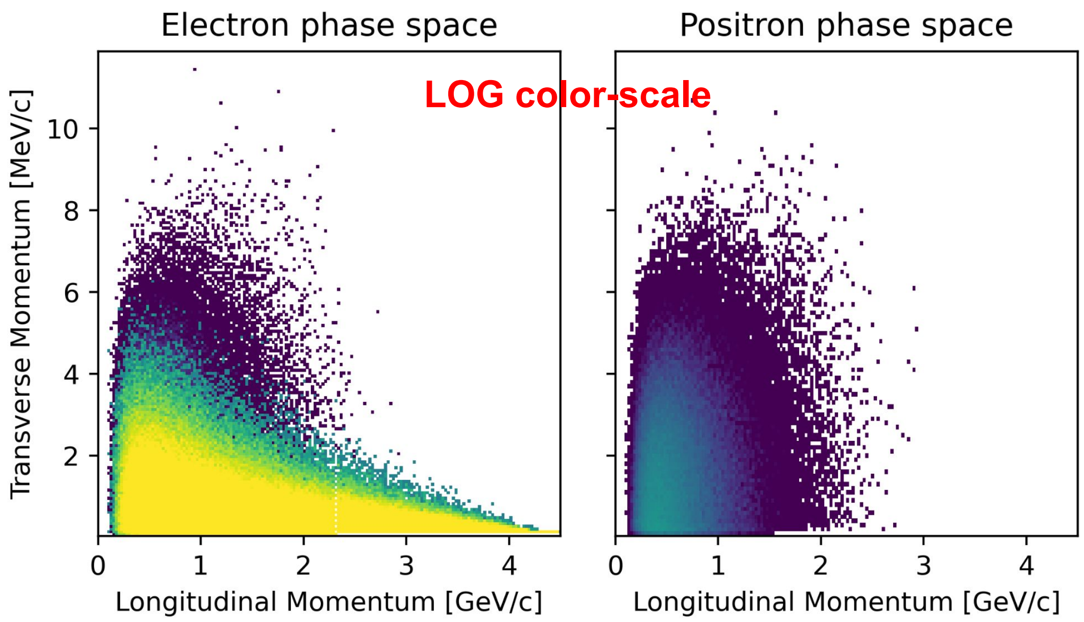
Simulations by S. Bulanov performed using the code **Ptarmigan**, T. G. Blackburn *et al* 2021 *New J. Phys.* 23 085008

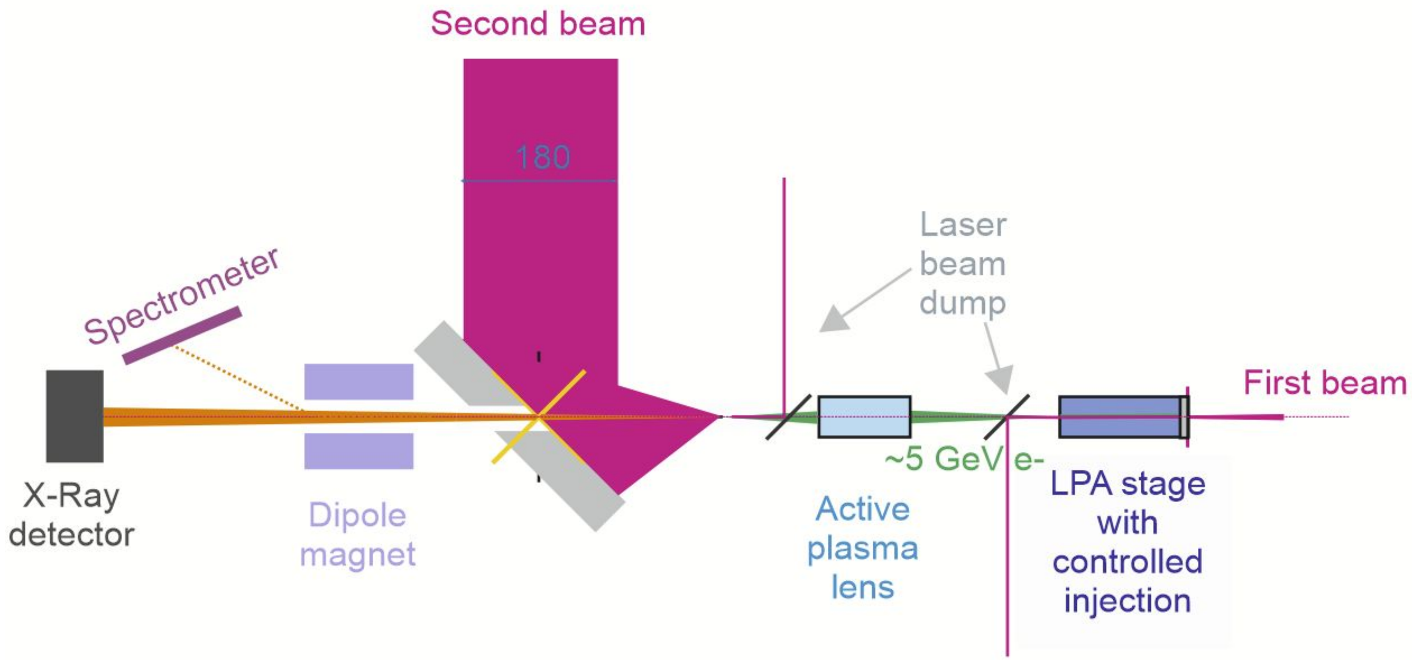
- laser a_0 = 42,
- laser pulse focal spot size w_0 = 2.5 um,
- electron beam energy = 4 GeV,
- electron bunch size = 2.5 um.

Simulation results:

Number of positrons = 5 x 10^{-3} * Number electrons, χ =1.7







Outlook & Conclusions

Outlook

- Continuation of low power commissioning of the BELLA PW 2nd Beamline scheduled for November 2021. All optics are in place and low power beam has already been measured inside the target chamber.

- For SF QED experiments, modifications to the currently installed Beamline are needed to transport the full beam diameter into the Target Chamber. Studies are ongoing.

Summary & Conclusions

- The BELLA PW facility will soon have two independent high intensity laser pulses available for experiments.
- SF QED experiments would require modifications on the existing 2nd beamline and the spectrometer, but are feasible within the current facility.
- Electron energies up to ~5 GeV and laser pulse intensities up to ~10^{22} W/cm^2 could be within reach enabling measurements with $\chi > 1$.