Progress in Laser Plasma Acceleration and the BELLA Project at LBNL

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Lawrence Berkeley National Laboratory

AAC 2010
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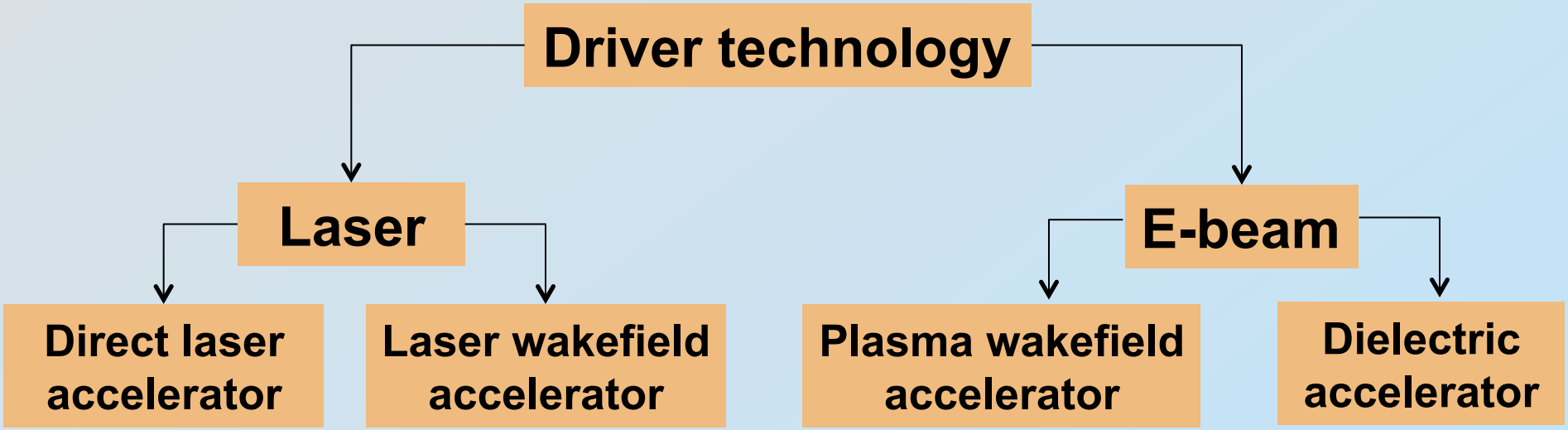
http://loasis.lbl.gov/

Motivation and overview

- Collider size set by maximum particle energy and maximum achievable gradient limited by breakdown
- Motivates R&D for ultra-high gradient technology

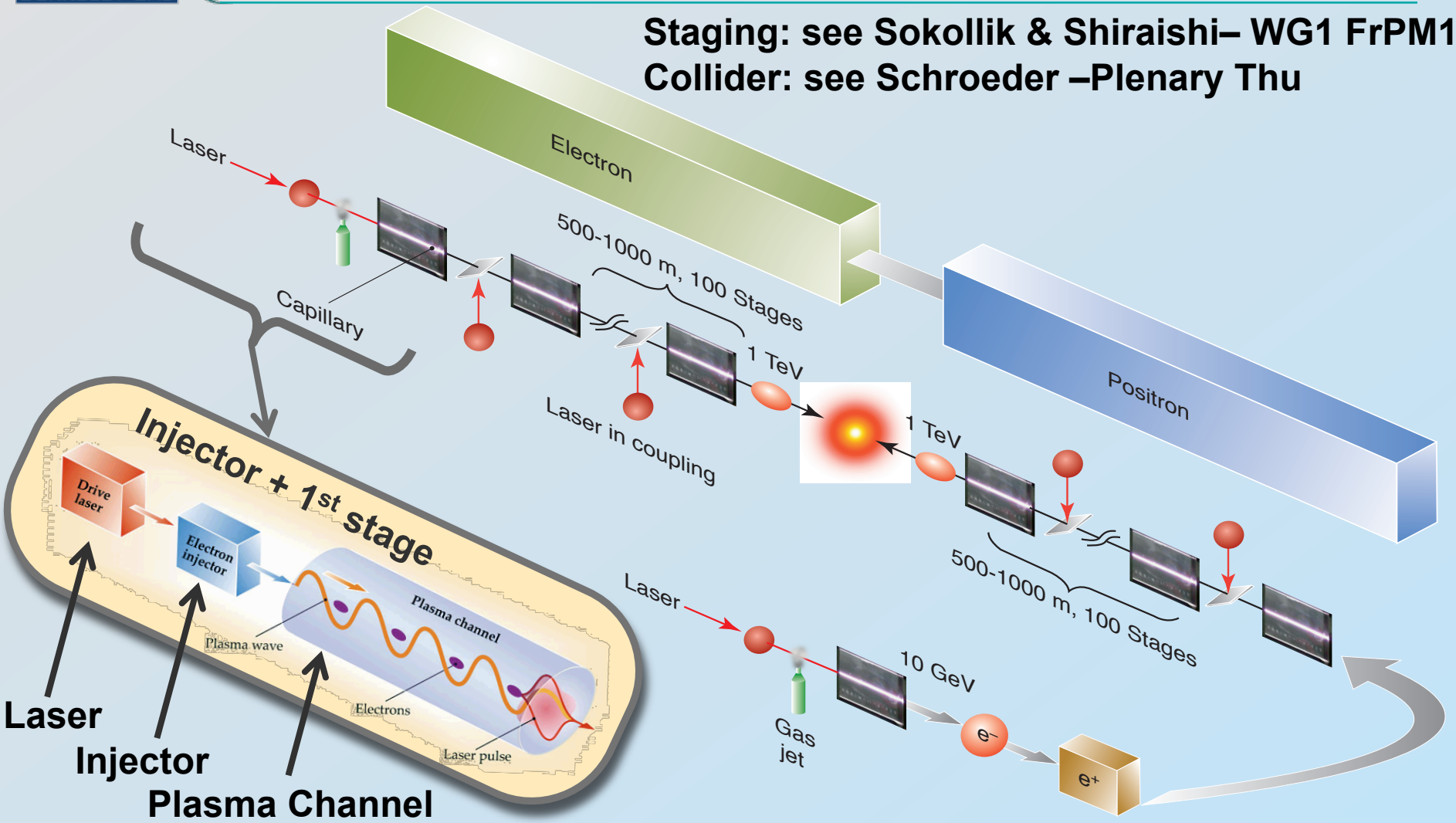


BELLA BERKELEY LAB LASER ACCELERATOR

FACET

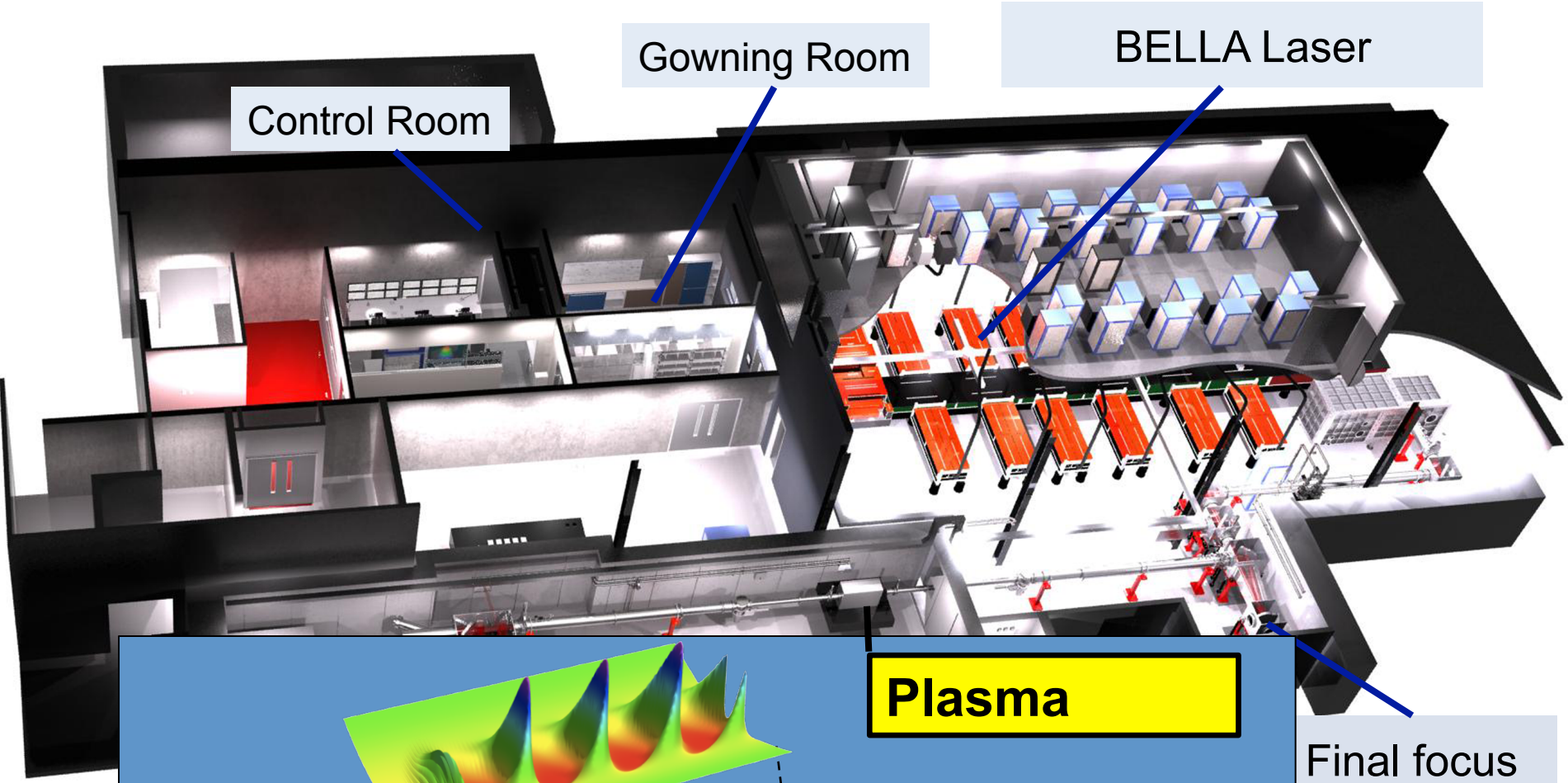
Strawman design of a TeV LPA Collider

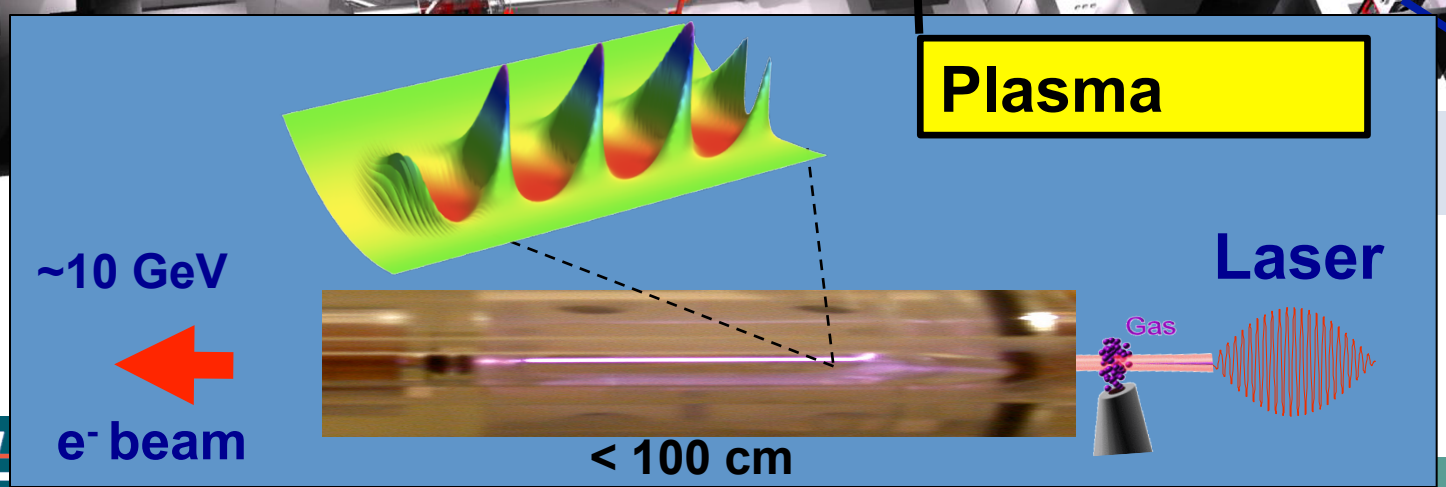
Staging: see Sokollik & Shiraishi– WG1 FrPM1
Collider: see Schroeder –Plenary Thu



Leemans & Esarey, Physics Today, March 2009

BELLA Project: state-of-the-art PW-facility for laser accelerator science





BELLA Laser: 40 J in 30 fs, 1 Hz

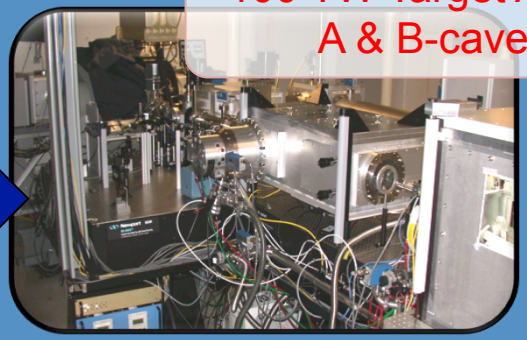
- Laser power and energy requirement:
  - Simple energy balance:
    - 400 pC at 10 GeV = 4 J
    - Assume laser -> beam efficiency = 10 %

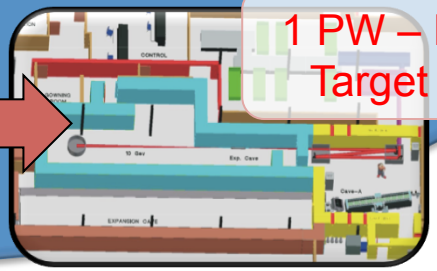
    } **40 J**
  - Point design
    - 40 J, 30 fs laser provides wide parameter range
      - Highly non-linear regime a>> 1
      - Mildly non-linear regime a ~ 1

- 1 Hz repetition rate:
  - Fast enough to do:
    - Rapid parameter scans: science with error bars
  - Slow enough that:
    - Thermal loading of optics remains low
    - Radiation yield remains < 5 mR/hr outside shielding

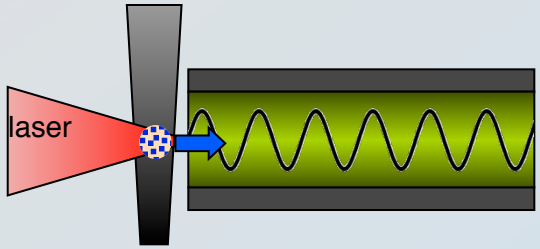
BELLA Laser significantly expands scientific reach

Construction	
1995-1999	Godzilla & Chihuahua ~ 10-15 TW
2002-2005	TREX ~ 50-60 TW
2009-2013	BELLA > 1 PW

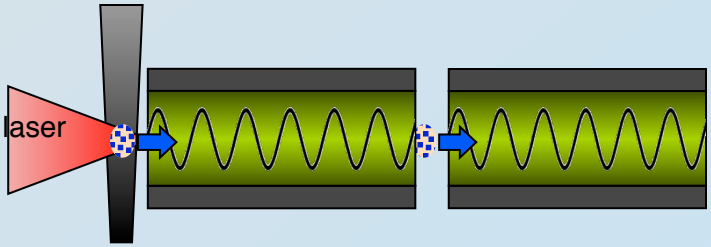




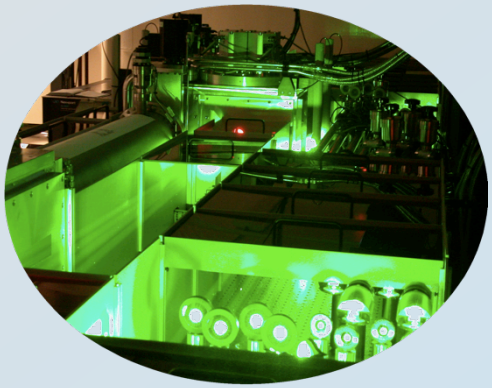
Technical challenges in next decade



High quality beams

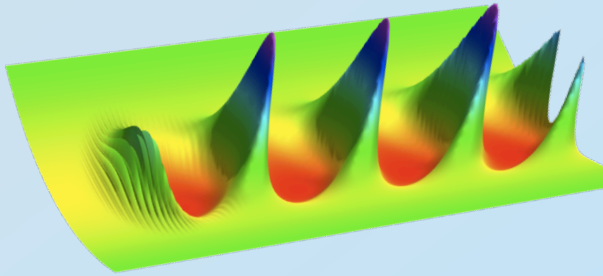


Staging, optimized structures



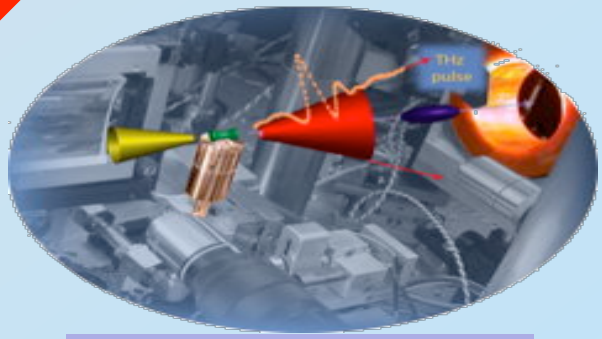
Lasers: high average power

BELLA



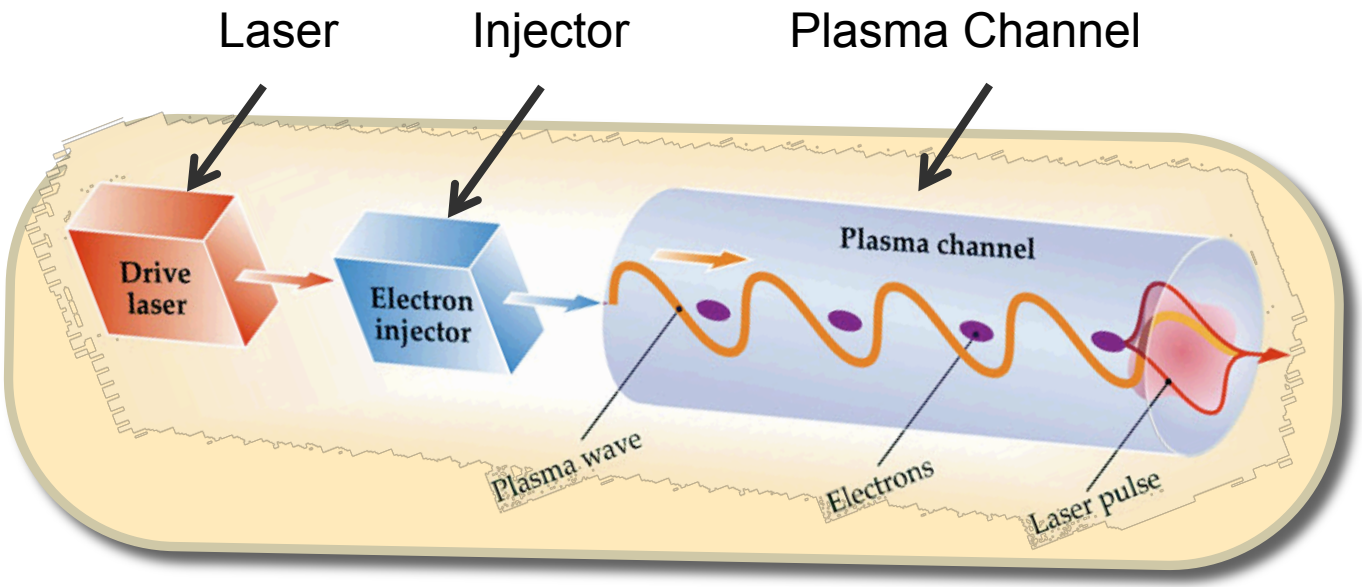
Modeling

Multi-GeV beams



Diagnostics

Building a Laser Plasma Accelerator Using Conventional Accelerator Paradigm



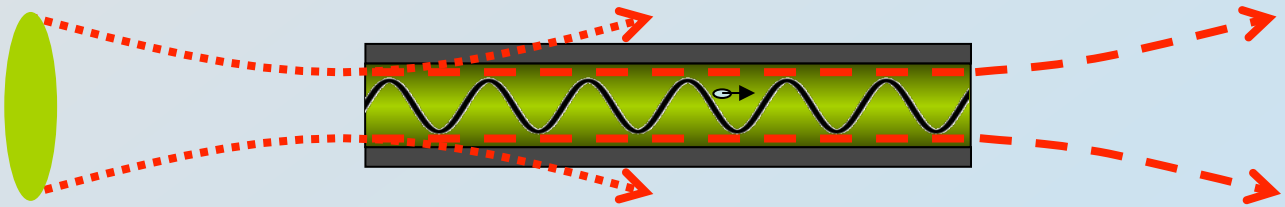
- Drive laser: Ti-sapphire (chirped pulse amplification based)
- Structure: plasma fiber
- Injection: self-trapped, triggered

W.P. Leemans et al., IEEE Trans. Plasma Science (1996); Phys. Plasmas (1998)
W. Leemans and E. Esarey, Physics Today, March 2009
Esarey, Schroeder and Leemans, Rev. Mod. Phys (2009)

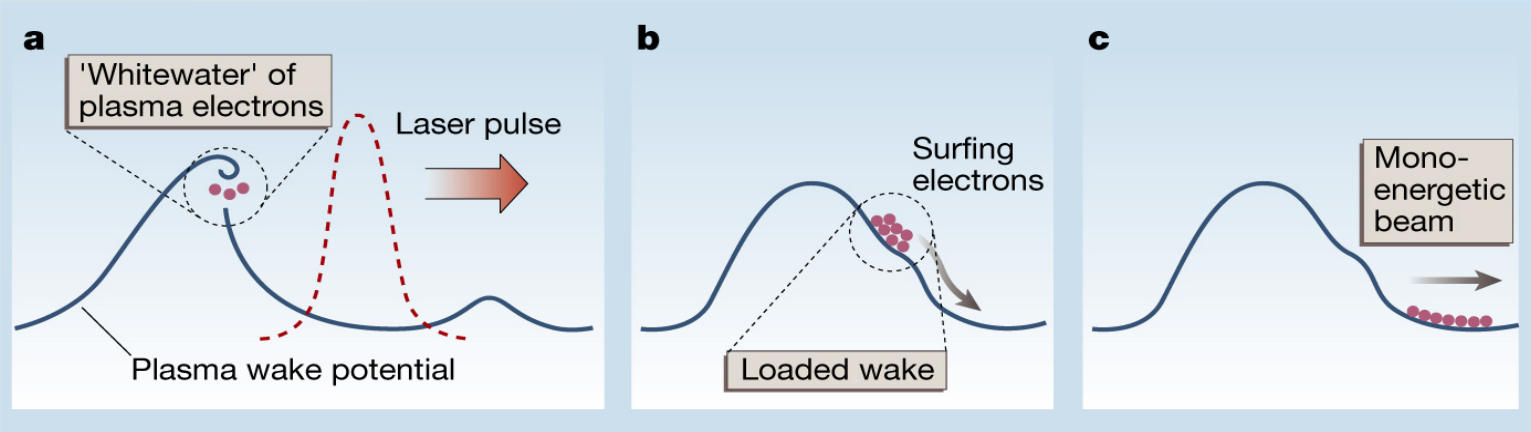
Limits to the accelerator length

"The 3D's of laser accelerators"

- Diffraction of the laser pulse



- Dephasing of the particle with wave



Graphic: T. Katsouleas, Nature 2004

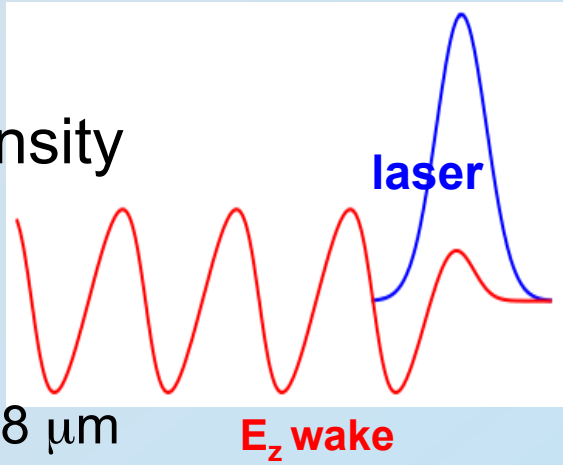
- Depletion of the laser power: cascading of modules

Basic design of a plasma accelerator: single-stage limited by laser energy

- Laser pulse length and plasma density
  - $k_p \sigma_z \leq 1$, $\sigma_z \sim \lambda_p \sim n^{-1/2}$
- Wakefield regime determined by laser intensity
  - Linear (a_0<1) or blowout (a_0>1)

$$a_0^2 \simeq 7.3 \times 10^{-19} [\lambda(\mu\mathrm{m})]^2 I_0(\mathrm{W/cm^2}),$$

  - Ex: $a_0 = 1$ for $I_0 = 2\times10^{18}$ W/cm^2 and $\lambda_0 = 0.8\ \mu$m

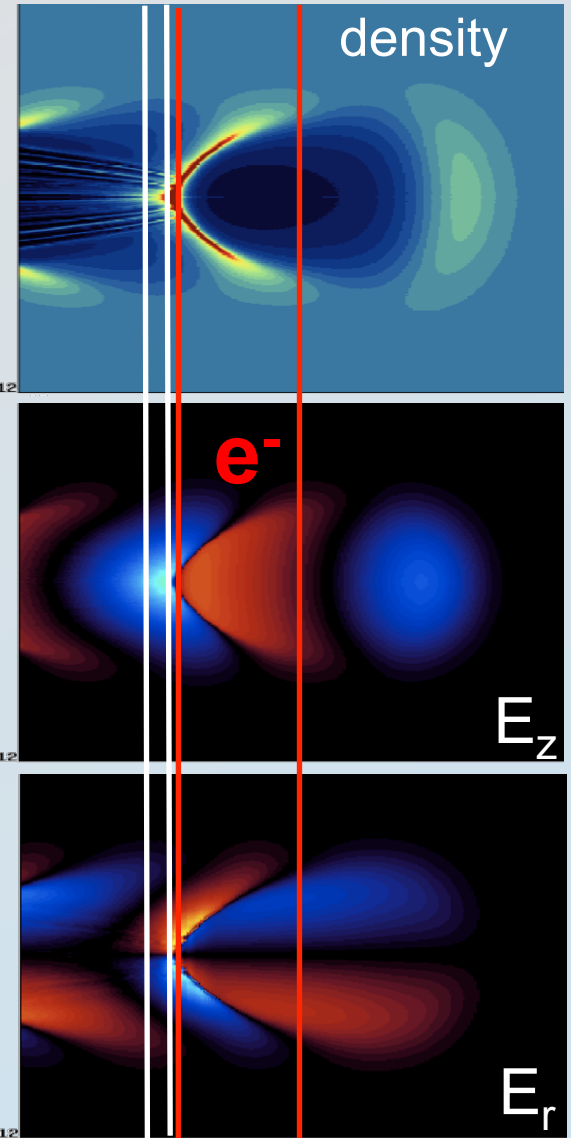


- Accelerating field determined by density and laser intensity
  - $E_z \sim (a_0^2/4)(1+a_0^2/2)^{-1/2}\, n^{1/2} \sim 10$ GV/m
- Energy gain determined by laser energy via depletion*
  - Laser: Present CPA technology 10's J/pulse
  - Bunch parameters also determined via beam loading

*Shadwick, Schroeder, Esarey, Phys. Plasmas (2009)

BELLA optimized stage design: Quasi-linear vs. bubble regime

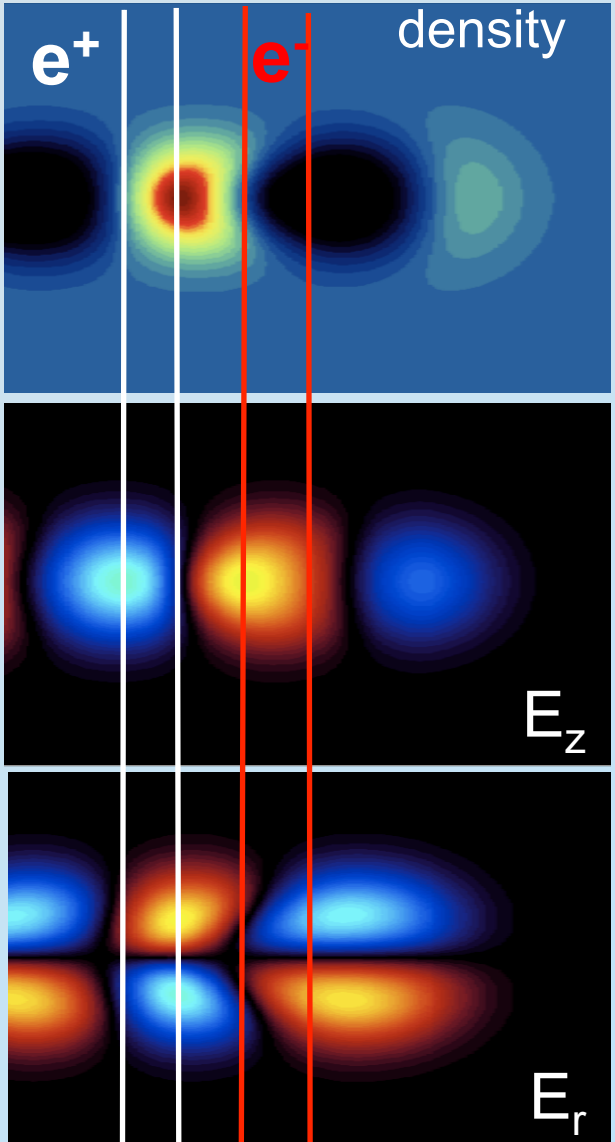
Bubble/blow-out



- Blowout regime
  - a >> 1
  - high field
  - very asymmetric
    - focuses e-
    - defocuses e+
  - self-trapping
  - no guiding
- Quasilinear
  - a ~ 1
  - symmetric e+/e-
  - dark current free
  - channel required
  - tailoring of E_r via laser profile

Benedetti – WG2, TuAM

Quasi-linear

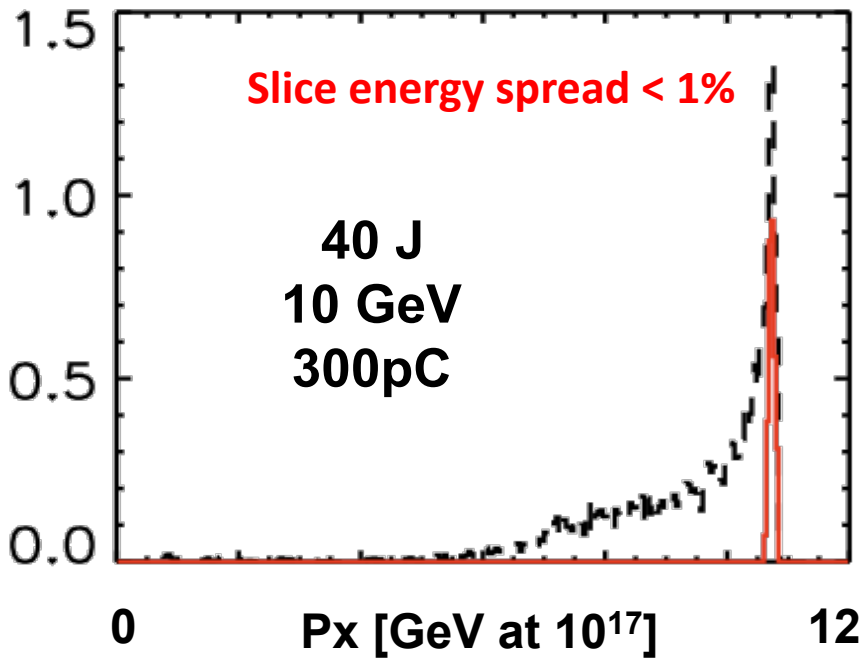


BELLA laser allows access to quasi-linear and non-linear regimes

Example design

ne (1/cm^3)	1.0E+17
a0	1.4
lambda_p(um)	108
kp*L_laser	1
tau (fs)	57
w0 (μm)	90
kp*w0	5.3
P(TW)	563
P/Pc	1.8

BELLA Laser: 40 J in 30 fs – 1 ps



k_pL=1 stage: 300pC scaled to 10^{17}

* Cormier-Michel et al, AAC2008, Geddes et al PAC 2009.

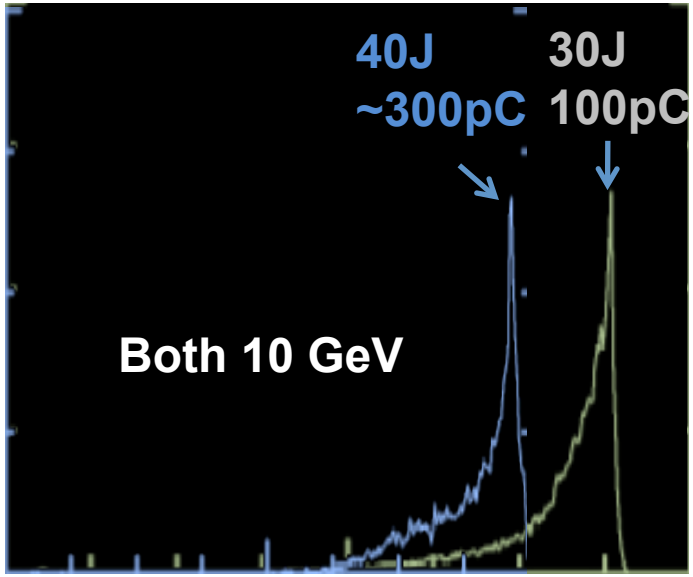
NOTE : Nonlinear** stages accessible with same laser

- **40 J laser focused to 41μm^3 (a_0=2) at n_e = 1.3e17 -> 10 GeV, 200pC**

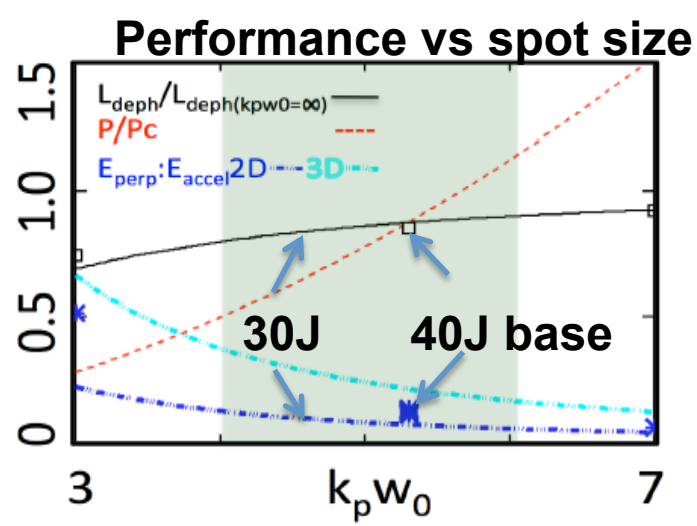
** Lu et al, PRL 96, 0165002 (2006).

10 GeV reachable with BELLA laser at 30 – 40 J

- 10 GeV design scalable with density
  - $E_{bunch} \sim n^{-1}$, $E_{laser} \sim n^{-3/2}$, $Q \sim n^{-1/2}$
- Baseline laser performance: 40 J in 30 fs
  - At 10^{17}/cc → 10 GeV 300pC*,**
- For 30 J: increase density and lower charge
  - At 1.2×10^{17}/cc → 10 GeV for ~ 100pC
- Alternative: reduce spot size 15% at 10^{17}/cc
  - Performance vs. spot size characterized**
  - Should allow ~ 200pC at 10 GeV w/ 30J



0 Scale gain [GeV at 1e17] 16
0 Scale gain [GeV at 1.2e17] 13



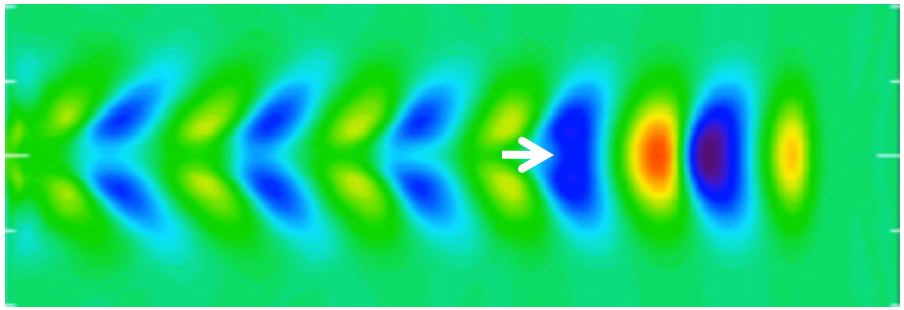
*Cormier-Michel et al, AAC 2008, ** Geddes et al, PAC 2009. & SciDAC Review 2009

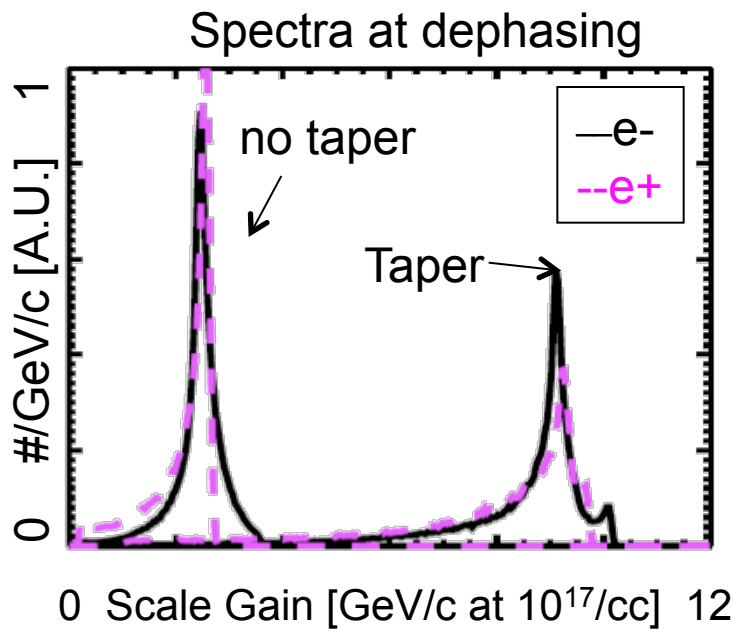
What can we do to enhance efficiency of laser to particle beam?

Can we control emittance?

Axial density taper locks bunch phase

Improves energy gain and reduces ΔE for e^+,e^-



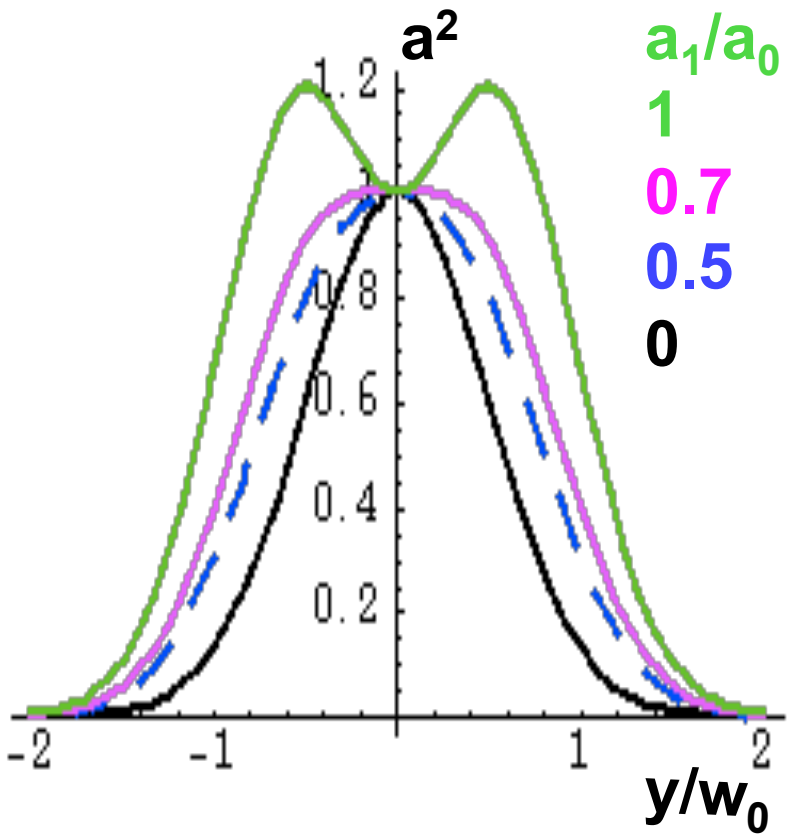


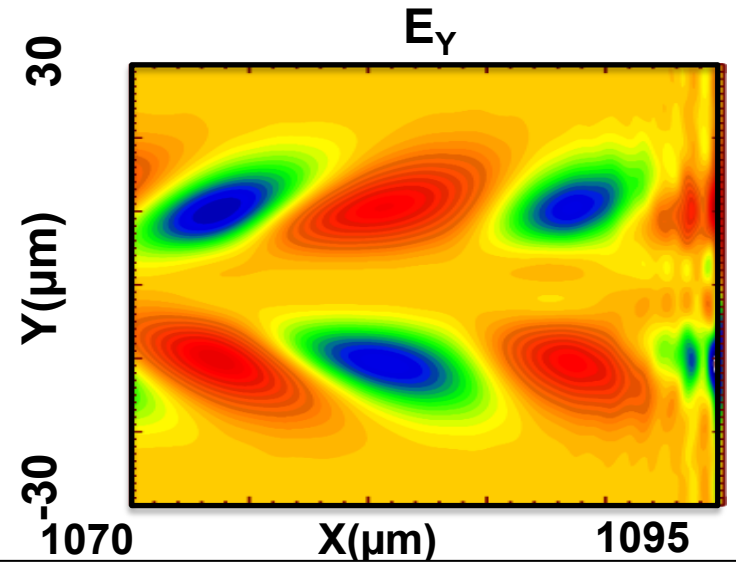
- Compensate dephasing*:
  - Change $\lambda_p \sim n^{1/2}$
- Linear taper at k_pL=2 produces 4x gain
- Positron acceleration ~symmetric
- Ongoing:
  - optimize taper, emittance matching
  - initial k_pL=1 results : 50% depletion, 10 GeV gain for 300pC, 2.5%FWHM
  - 10% of laser energy into electrons

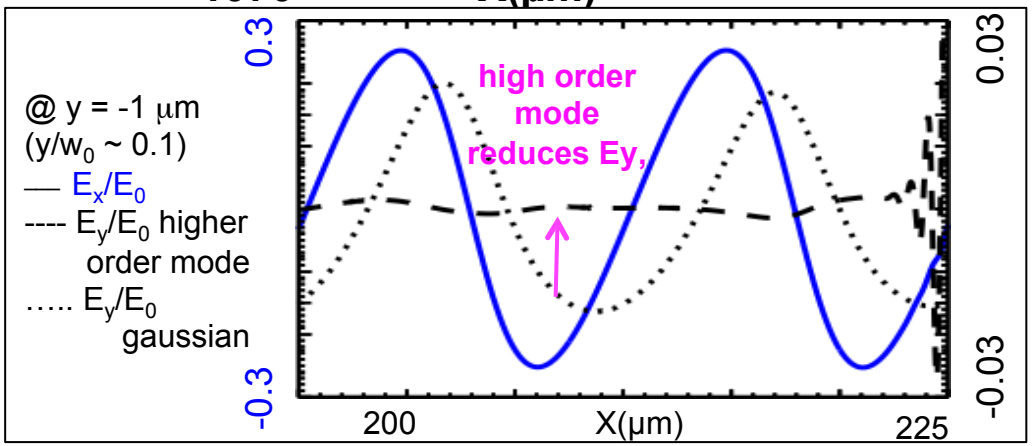
*** Katsouleas (1987); Sprangle (2001); Rittershoffer et al., PoP 2010**

Quasi-linear regime: laser mode controls focusing

Idea: Reduce transverse field gradient to increase matched beam radius



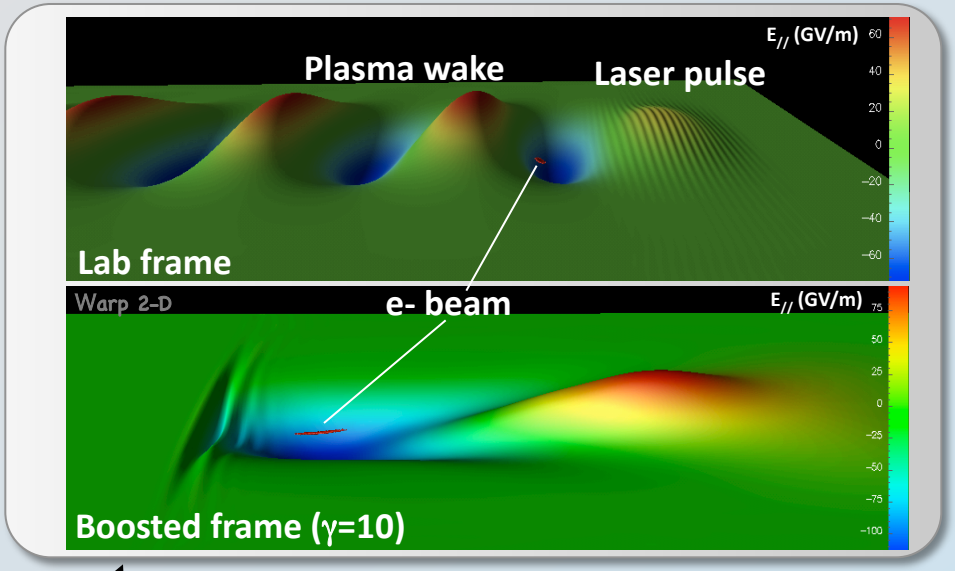




Geddes – WG1&2 – Fr AM

E. Cormier-Michel et al., submitted to PRSTAB

Lorentz boosted simulations of 10 GeV stage for full-scale depletion & stage physics

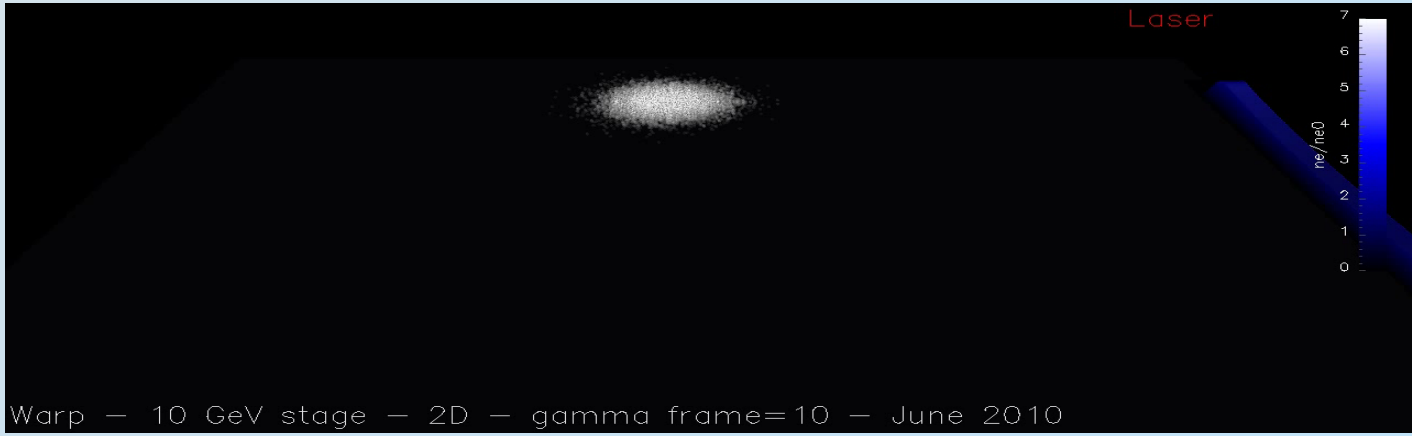


- Calculation in boosted frame
- Minimizes difference of scale from

  λ_{laser} to λ_{wake} to $L_{acceleration}$
- Speedup of >10,000 for 10 GeV
- Directly simulates 10 GeV stages w/ strong depletion
- Noise control techniques developed

Scaled (10^{19} cc)
Run time:
Sec. in 2D
Min. in 3D

Full scale (10^{17} cc)
Run time:
Min. in 2D
Hours in 3D



***Courtesy J.L. Vay – PRL 2007, talk WG2 TuAM**
Similar work by Bruhwiler et al (Tech X, talk WG2 TuAM), Martins et al (UCLA/IST, talk TuPlenary)

Other 10 GeV sims: enveloped model Cowan et al., WG2 TuAM

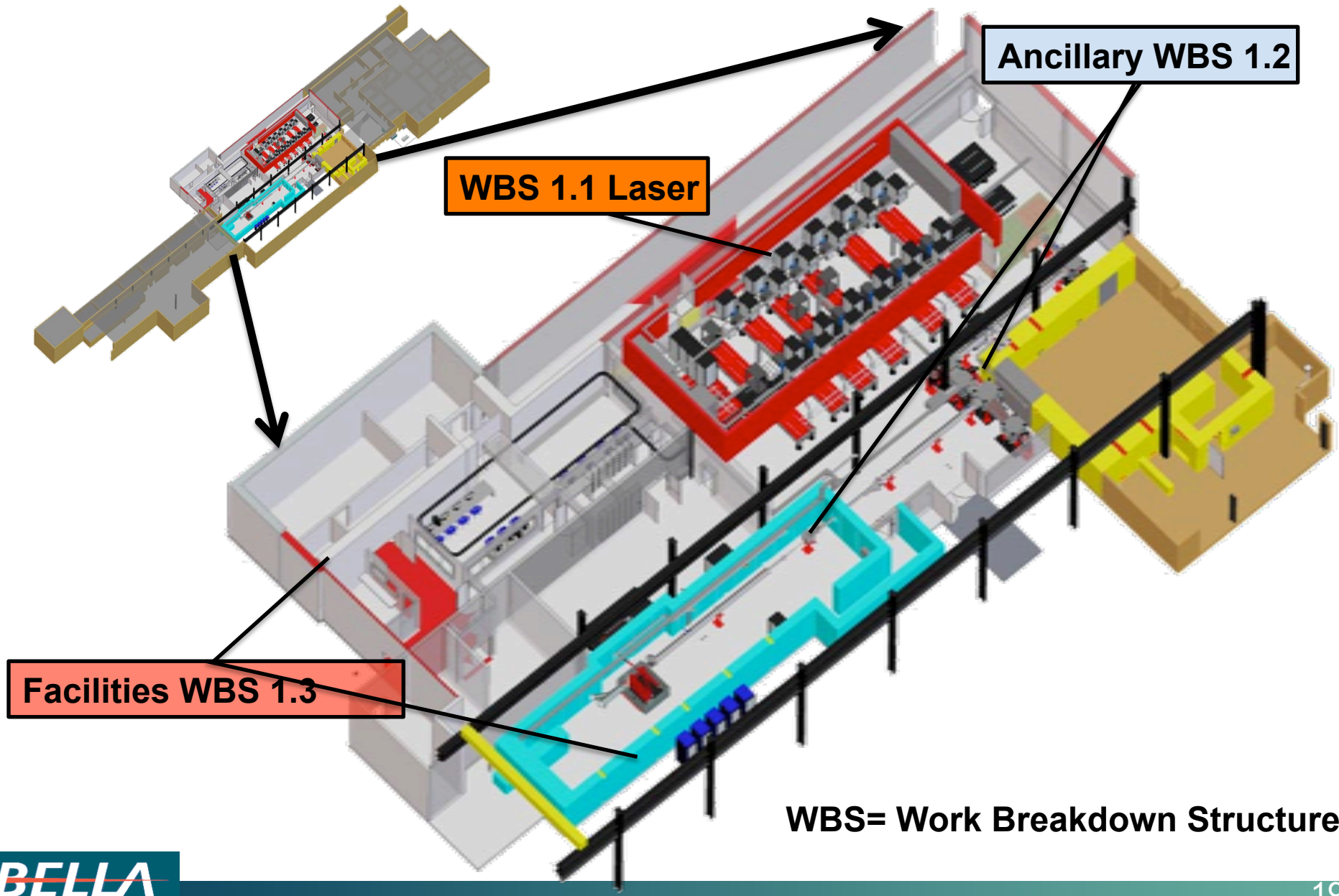
Nominal BELLA 10 GeV experimental parameters

- Operation in quasi-linear regime
  - Integrated injection and acceleration with channel guiding
  - 10 GeV, 100-300 pC charge (beam loading)
- 30-40 J laser pulse in 30 - 150 fs at 1 Hz
  - Analytic calculations
  - Fluid and scaled simulations **See also C. Schroeder – Thu Plenary**
  - Lorentz boosted from full scale sims
- Meter scale plasma channel
  - 10^{17} -10^{18} cm^{-3}
  - May taper to mitigate dephasing and increase efficiency

Laser system

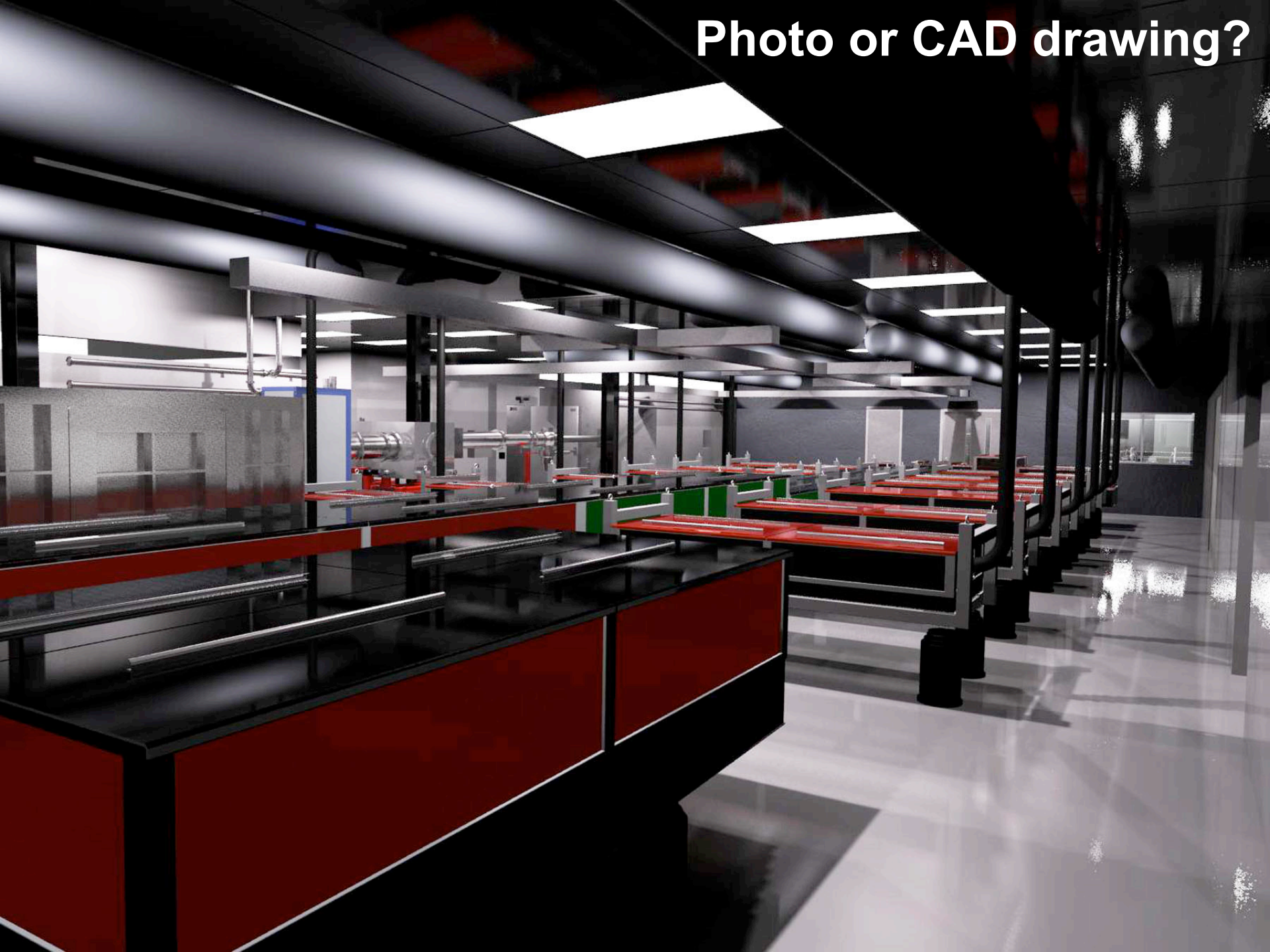
- Commercial system from THALES
- Expected delivery by early 2012

BELLA Project: to be completed in FY13



WBS= Work Breakdown Structure

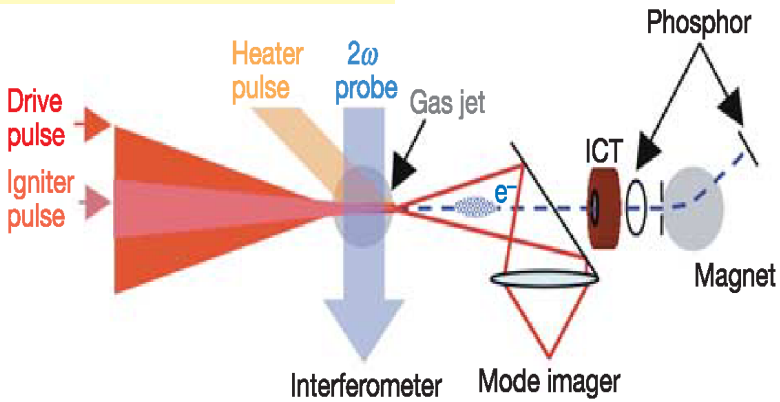
Photo or CAD drawing?



Plasma source:
- Channel
- Integrated injector

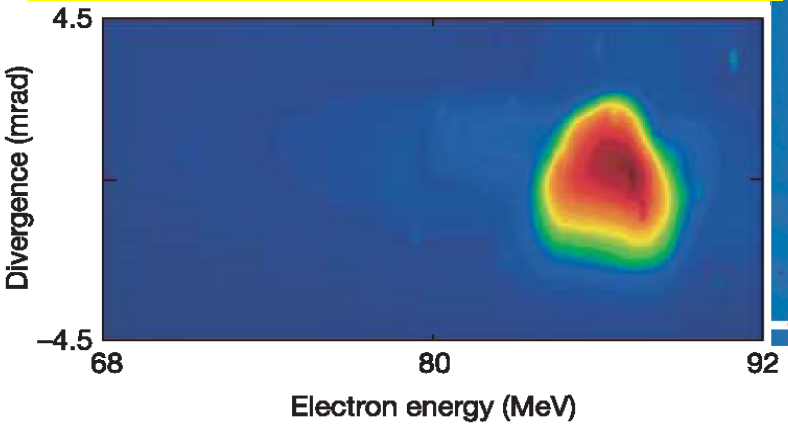
Channel Guided Laser Plasma Accelerators

2004 Result

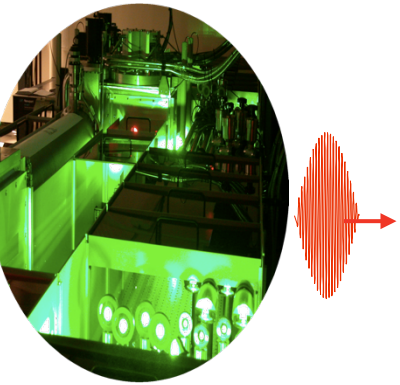


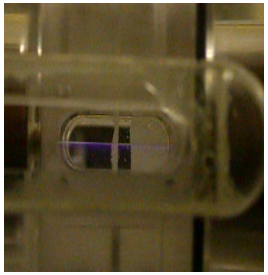
C. G. R. Geddes et al, Nature,431, p538 (2004)

10 TW laser => 100 MeV e-beam



2006 Result

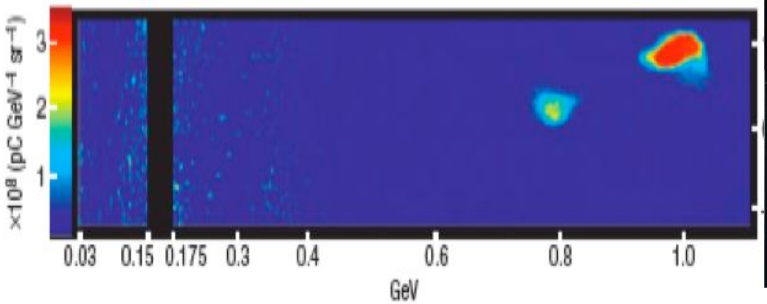


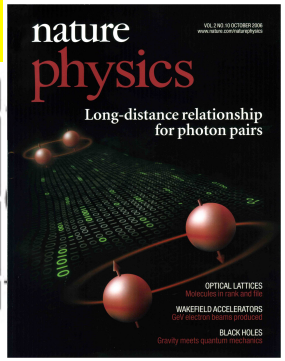


1 GeV

e⁻

40 TW laser => 1 GeV e-beam





W.P. Leemans et. al, *Nature Physics* 2, p696 (2006)

Capillary discharge technology and diagnostics will be refined for 10 GeV module

- Integrated injector+cap
- Capillary discharge:
  - Longer capillary discharges
  - Radial density shaping
    - Deep, shallow or hollow channels
  - Longitudinally tapered channels
  - Wall ablation issues: magnetic confinement

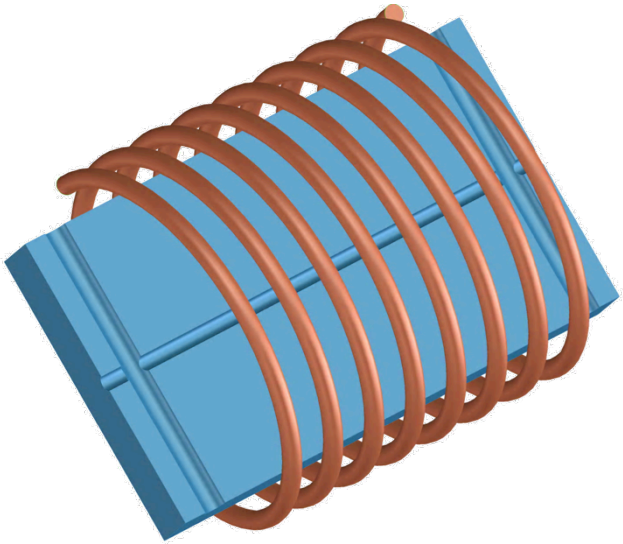
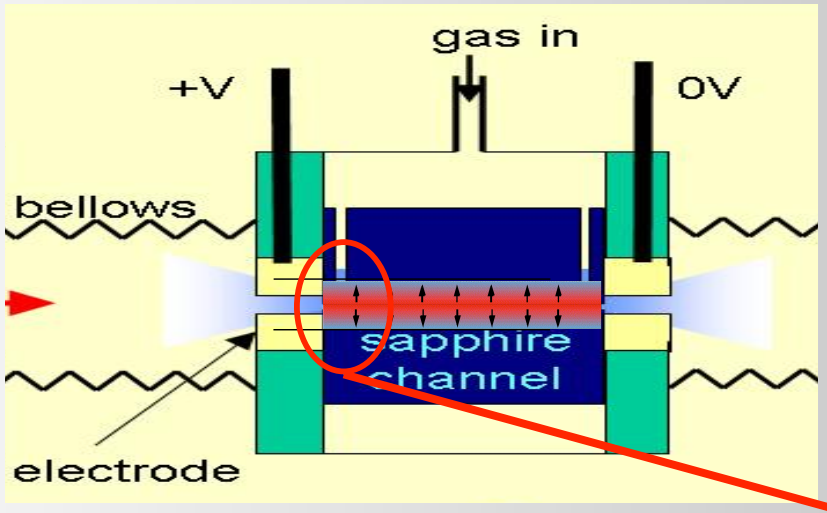


Figure: courtesy W. Kimura

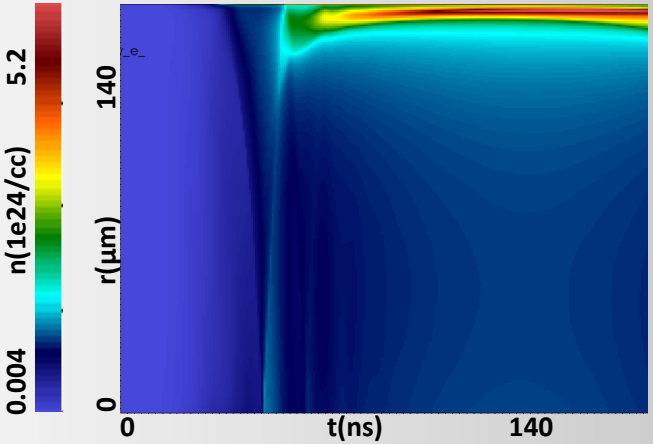
STI OPTRONICS

Capillary simulations designing BELLA channels and evaluating 3D structure

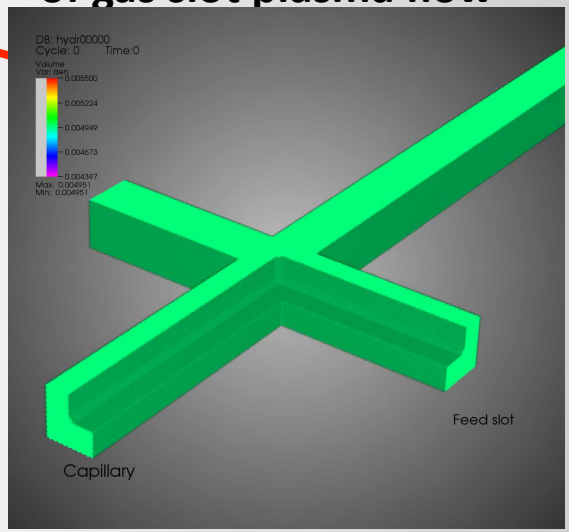
Discharge capillary
Density profile via heat conduction



1d simulations show guide formation



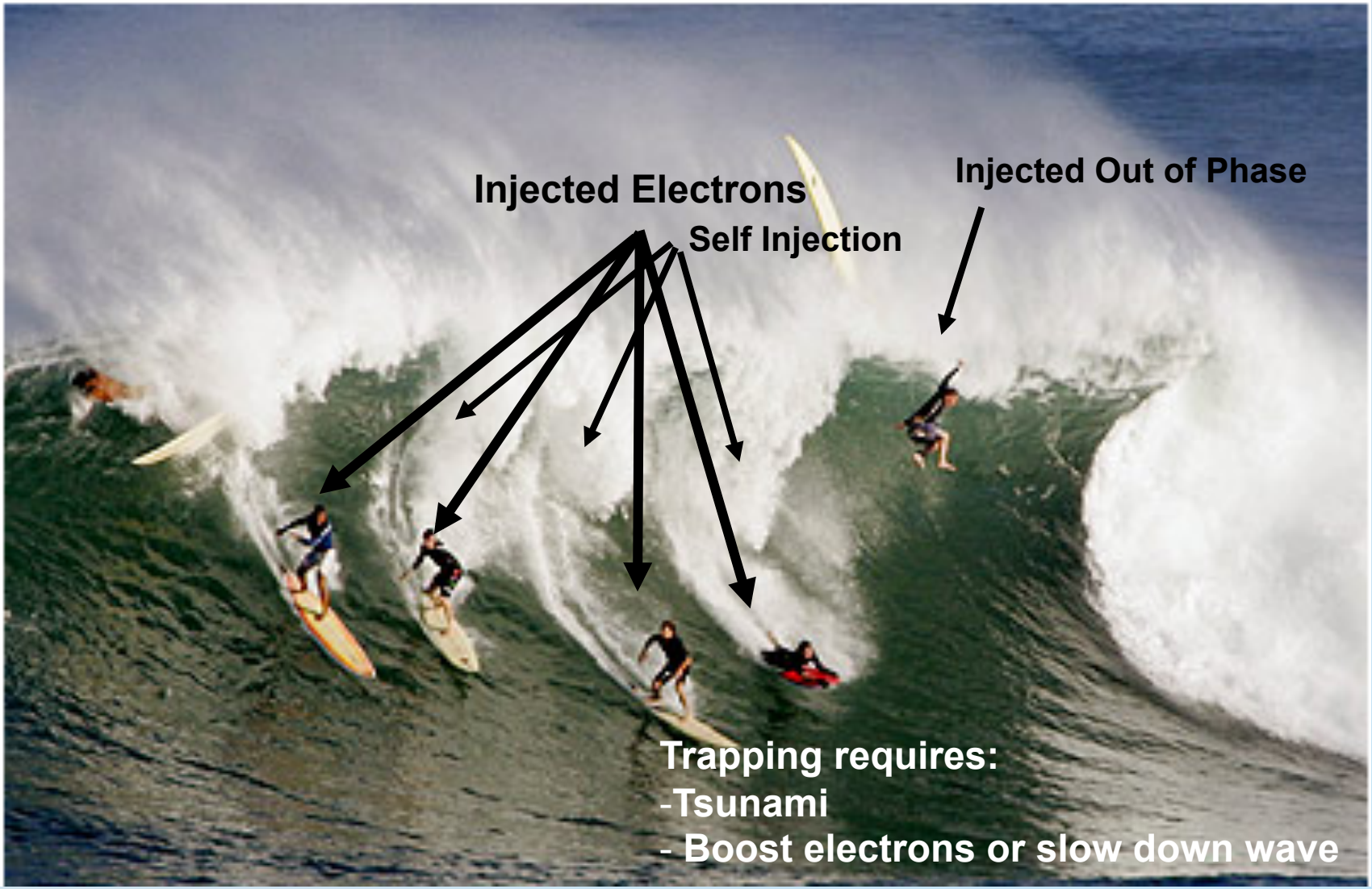
3d Hydra simulations of gas slot plasma flow



- Capillary guides of ~1m to be used for 10 GeV
- 1D 2 temp, multi-species cylindrical model (LBL)
  - Discharge, heat conduction, magnetic field
  - In progress: diffusion & multi-dimensional
- HYDRA 3D hydrodynamics code (LLNL)
  - 3D geometry, external circuits, guide 3D development
- Complimentary effort starting at Tech-X under SBIR

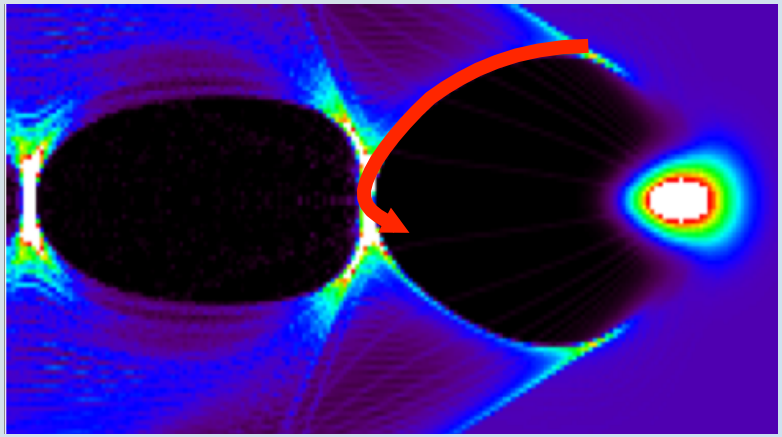
Electron injection in BELLA

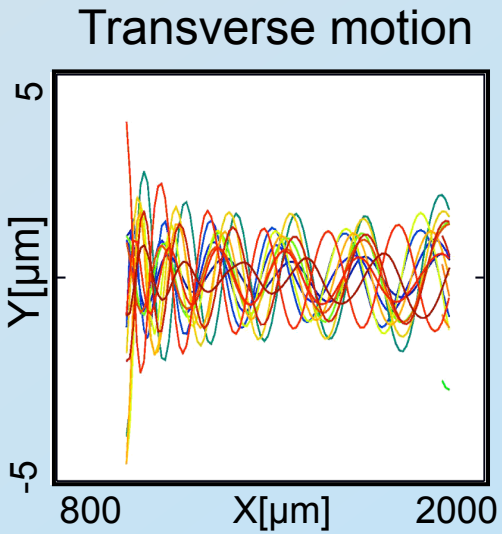
“Electrons” accelerating on a wave: controlled injection



Reducing energy spread and emittance requires controlled injection

- Self-injection experiments have been in bubble regime:
  - Cannot tune injection and acceleration separately
  - Emittance degraded due to off-axis injection and high transverse fields.
  - Energy spread degraded due to lack of control over trapping



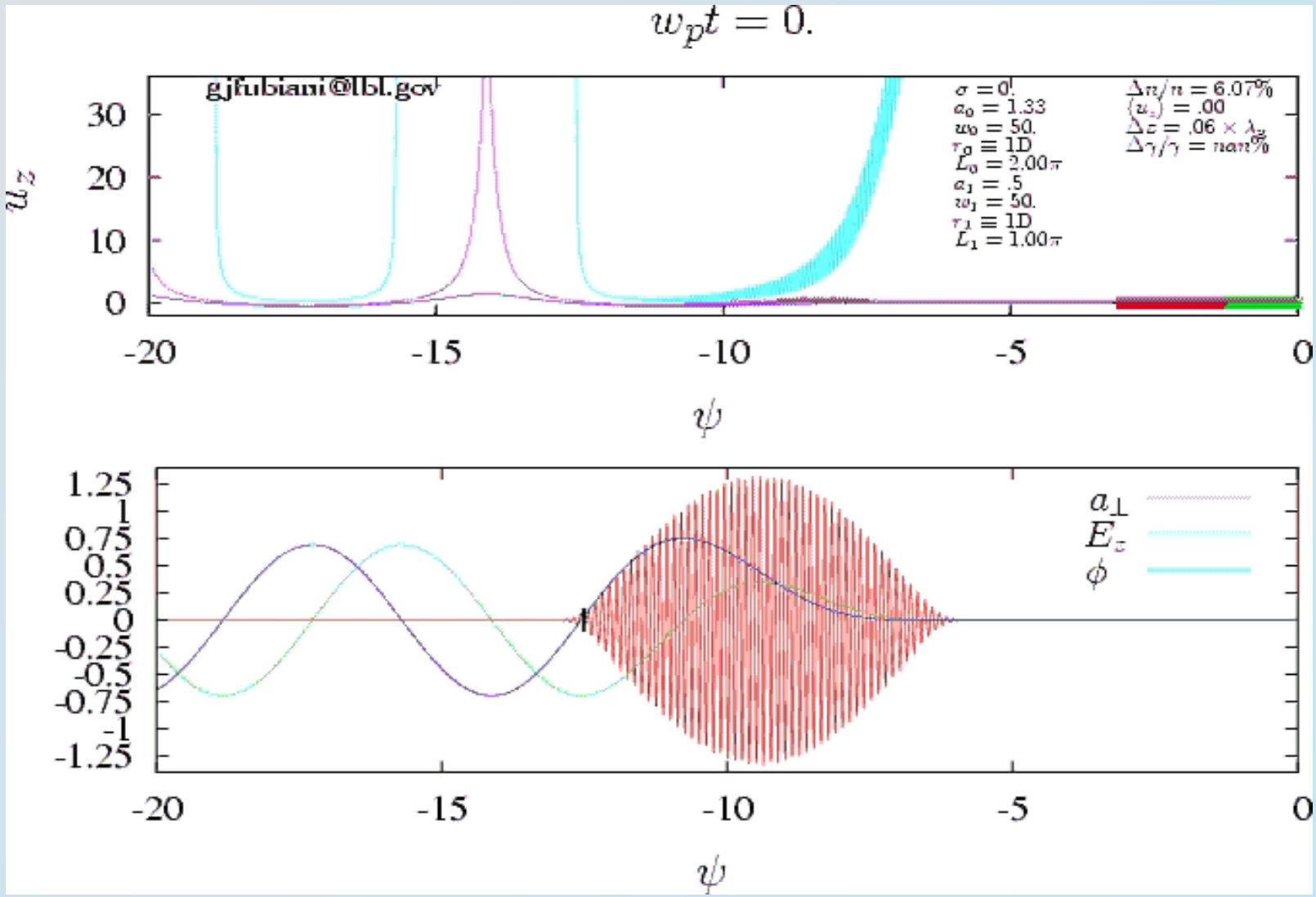


⇒ Use injector based on controlled trapping at lower wake amplitude and separately tunable acceleration stage to reduce emittance and energy spread

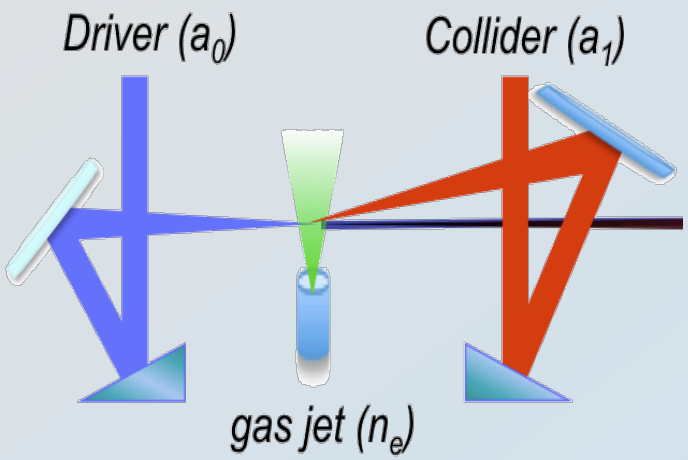
Colliding laser pulses allows control of injection of beam into plasma wave

Colliding pulse [*Esarey et al. PRL (1997), Schroeder et al., PRE (1999)*]: **TEST PARTICLES**

Self-consistent sims: E. Cormier-Michel – FR AM

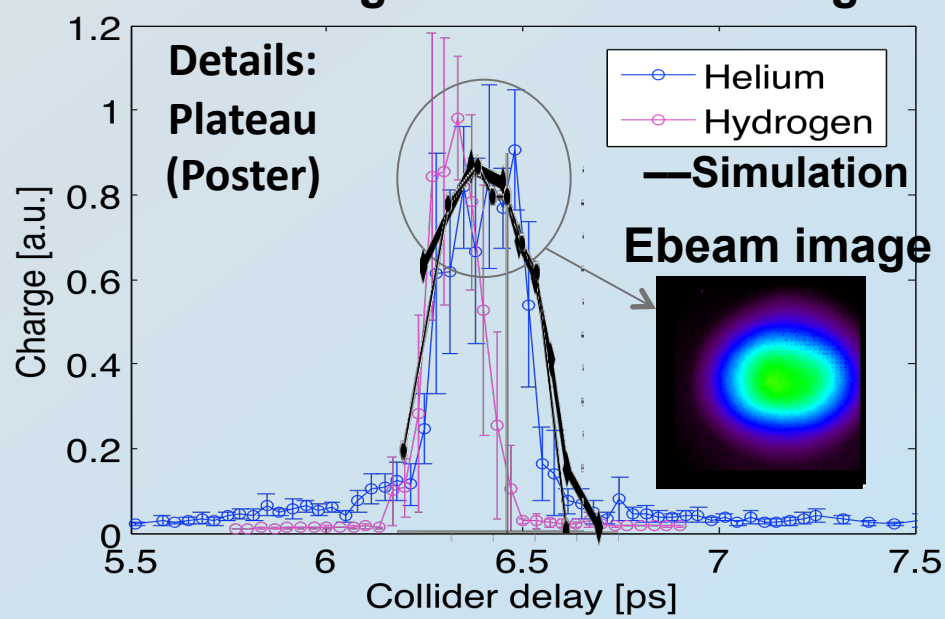


Colliding pulse experiments demonstrate repeatable injector

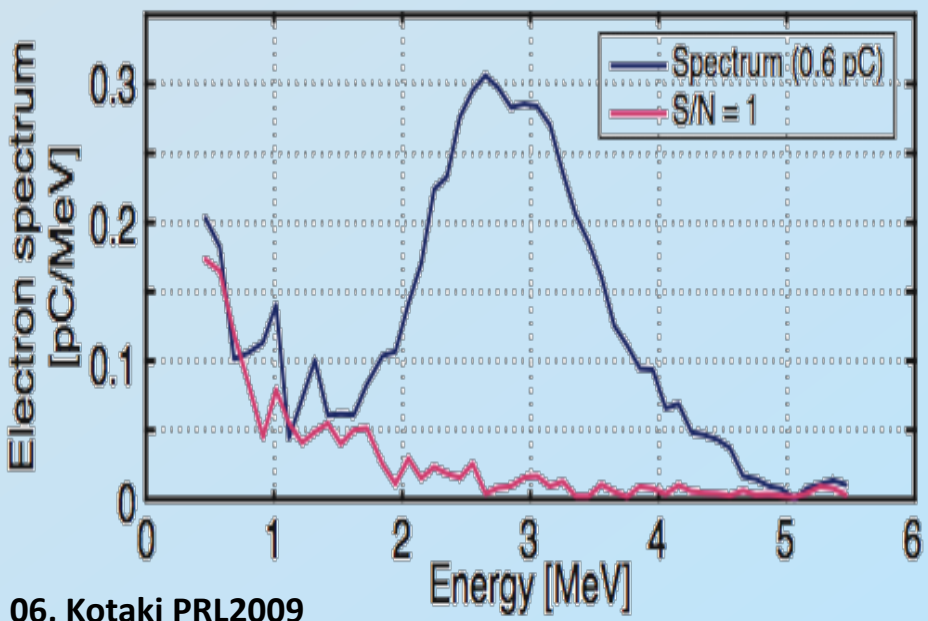


- a_0=2-4 nonlinear, 19° colliding pulse, 10 TW
- Reproducible over hours – automated controls
- Stable charge, divergence, pointing
- Guiding implemented to increase energy – simulations show >200 MeV accessible

Charge vs. collision timing

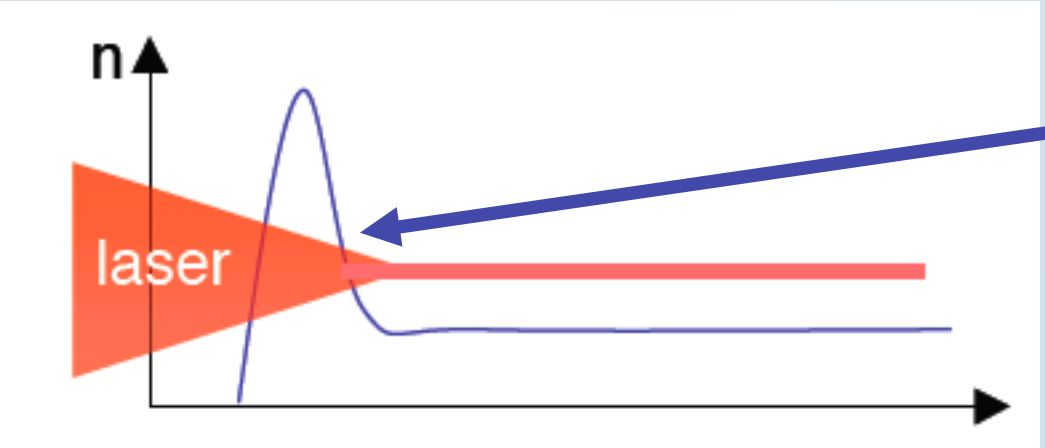


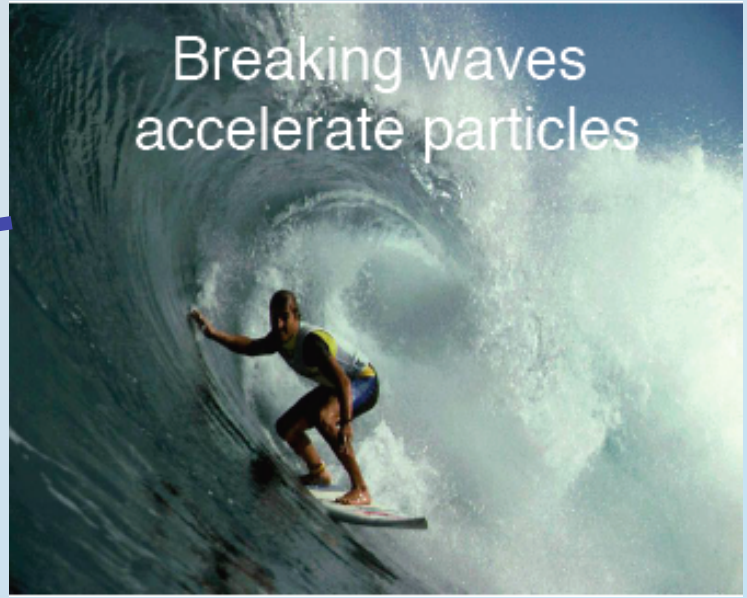
Energy spectrum @ $L_{accel} \leq Z_r$



Concept: Esarey PRL 97; Fubiani PRE04; Related : Faure Nature 06, Kotaki PRL2009

Longitudinal density tailoring allows trapping control





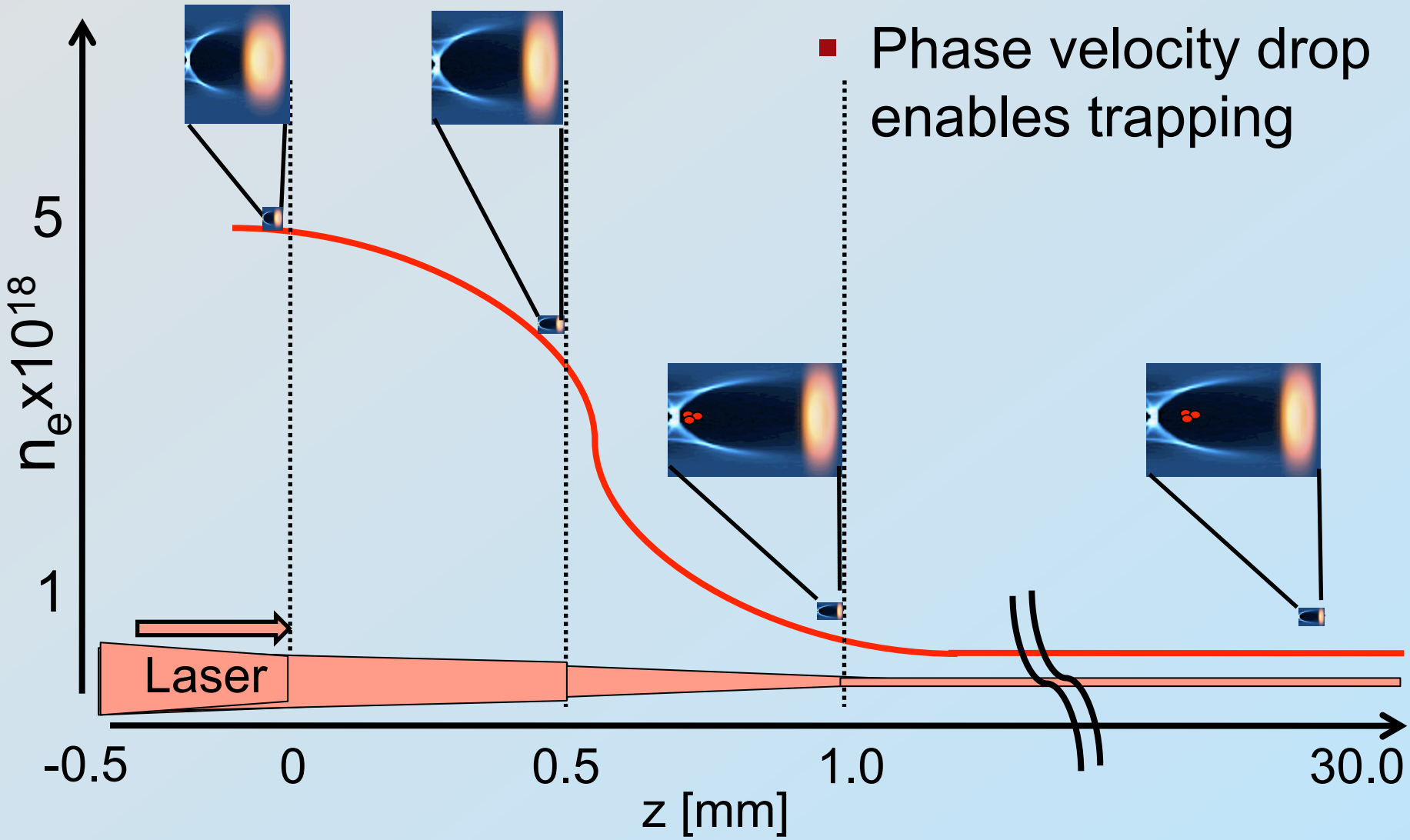
- As laser propagates through down-ramp
  - Plasma wavelength increases so wave period and laser period match

  leading to
    - Efficient wave generation
    - Slower phase velocity that enables trapping

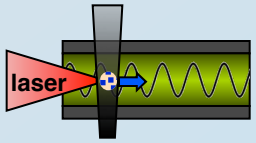
Geddes et al., PRL V 100, 215004 (2008); S.V. Bulanov et al., *PRL* 78, (1997)

Basic physics of downramp injection

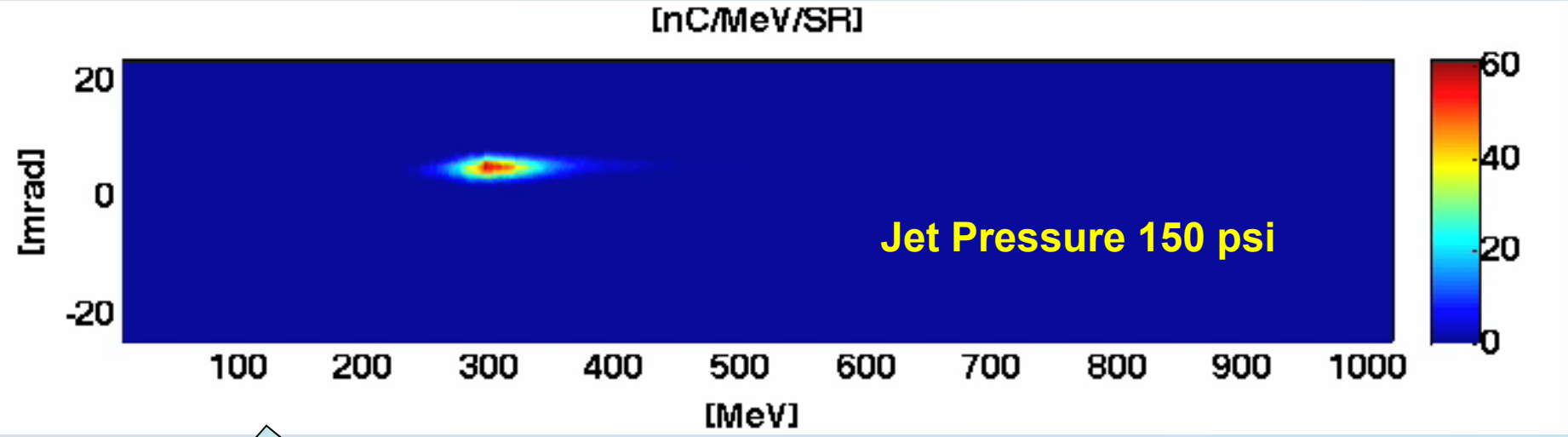
- Bucket length ~ $1/\sqrt{n}$
- Phase velocity drop enables trapping

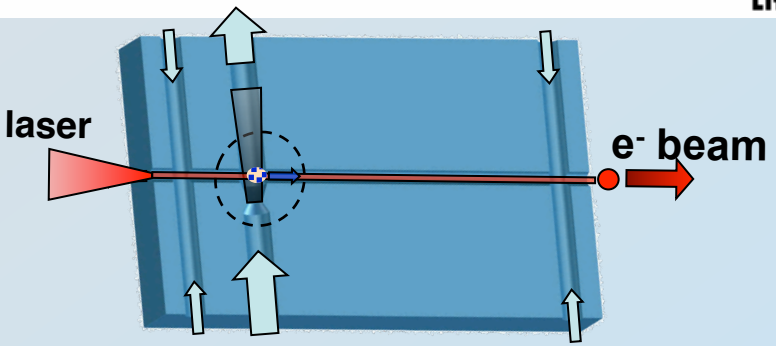


Gas jet triggered injections provides for enhanced stability & tuning

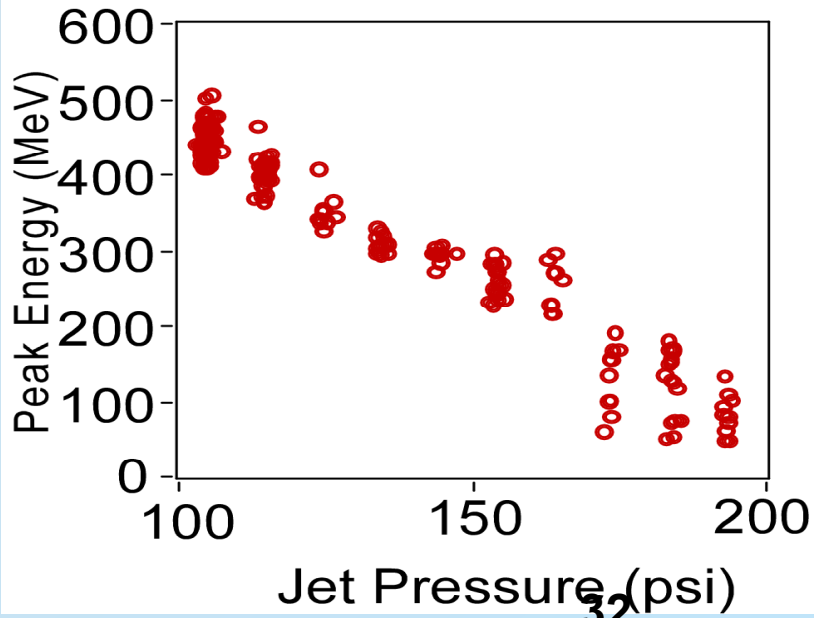


Input Parameters: $N_e \approx 2 \times 10^{18}$ cm^{-3}, $a_0 \approx 1$ (25TW), Laser pulse length ≈ 45 fs

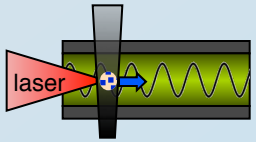




- Pointing ± 0.8 mrad
- Divergence <3mrad
- Peak energy 300MeV ± 7MeV

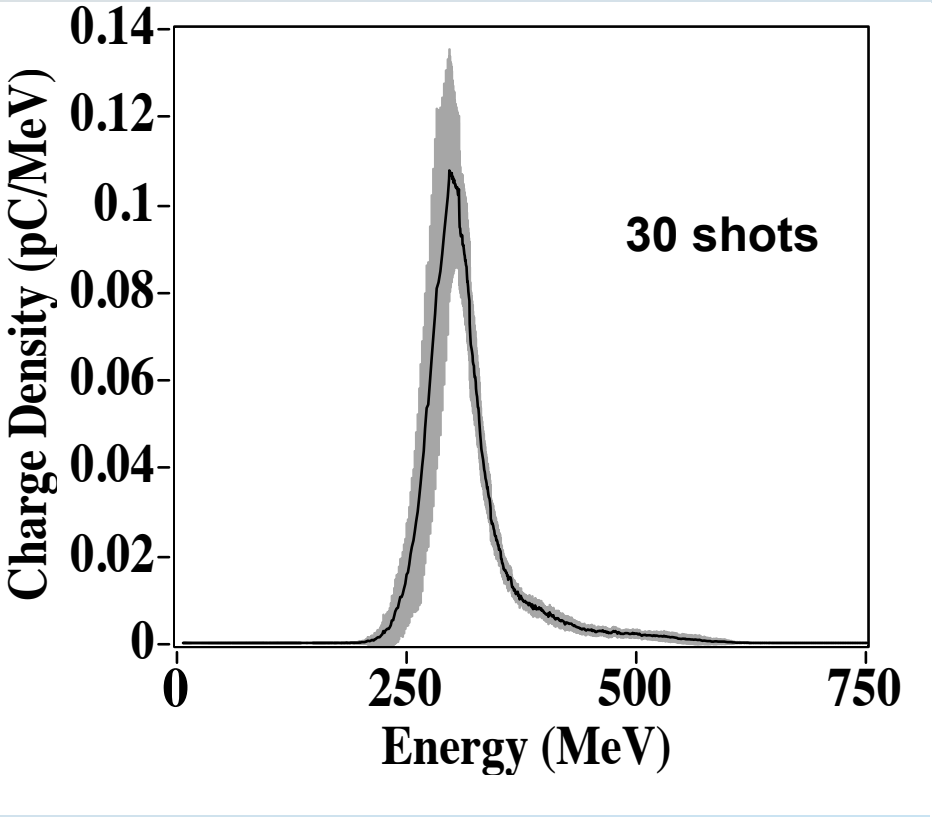


Jet Improves Beam Stability

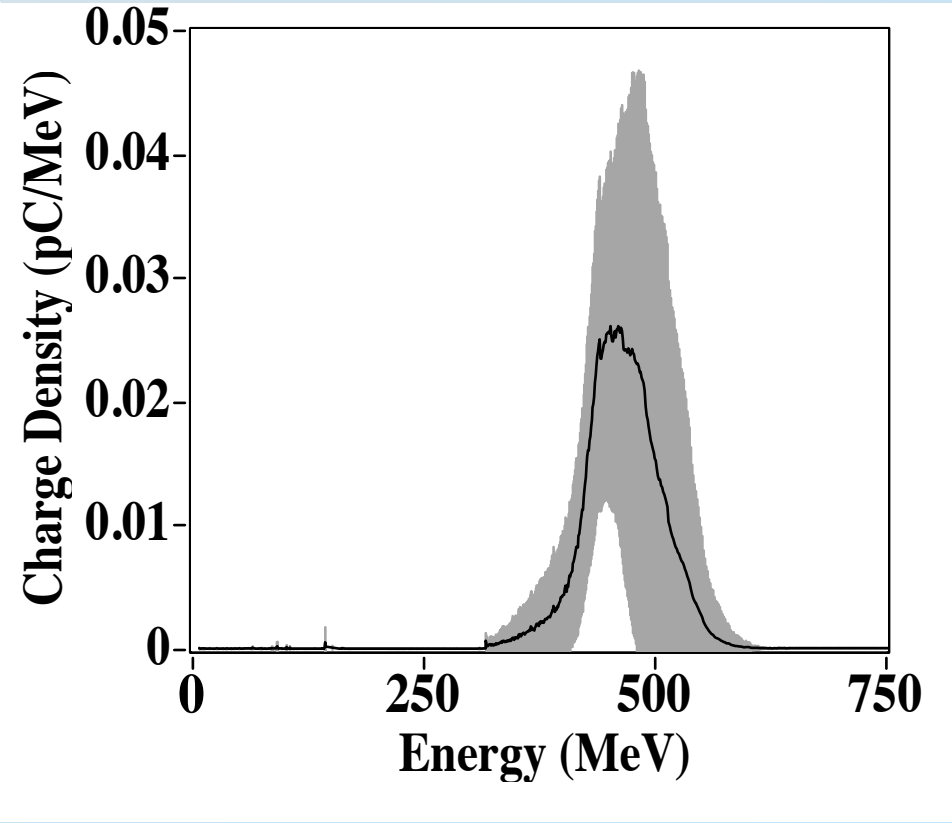


- Central energy fluctuation improved from 20 % to 2 %
- Pointing improved to less than mrad
- Charge correlated with shot-to-shot laser energy fluctuation

Stability with jet



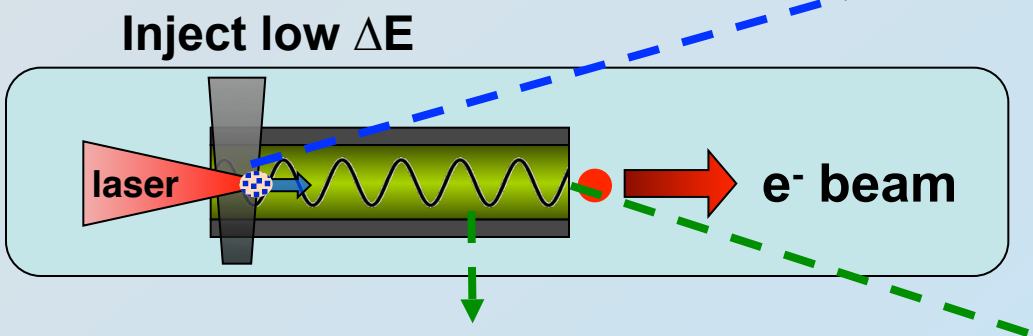
Best stability without jet

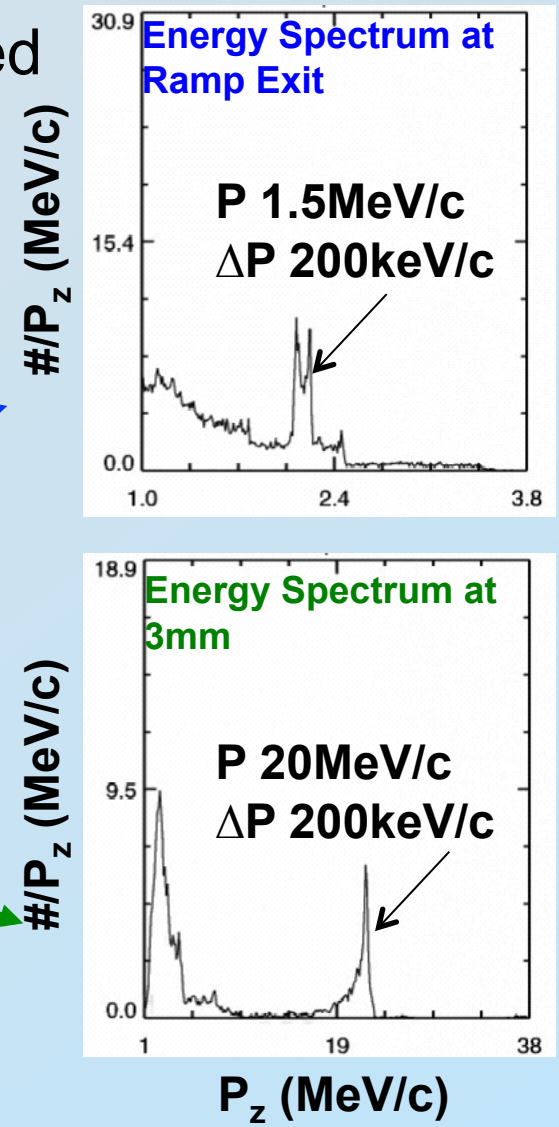


Laser pointing: Gonsalves –WG1, TuPM2; Ionization Injection: Chen – WG1, ThPM1

Optimization of capillary and gas jet is underway, guided by simulations

- Simulations indicate <0.25 % can be reached
  - 2D simulation done in VORPAL* of injector + accelerator up to 3mm
  - Injector peak density $2x10^{19}$ cm^{-3}, FWHM 900μm
  - Accelerator density $3x10^{17}$ cm^{-3}

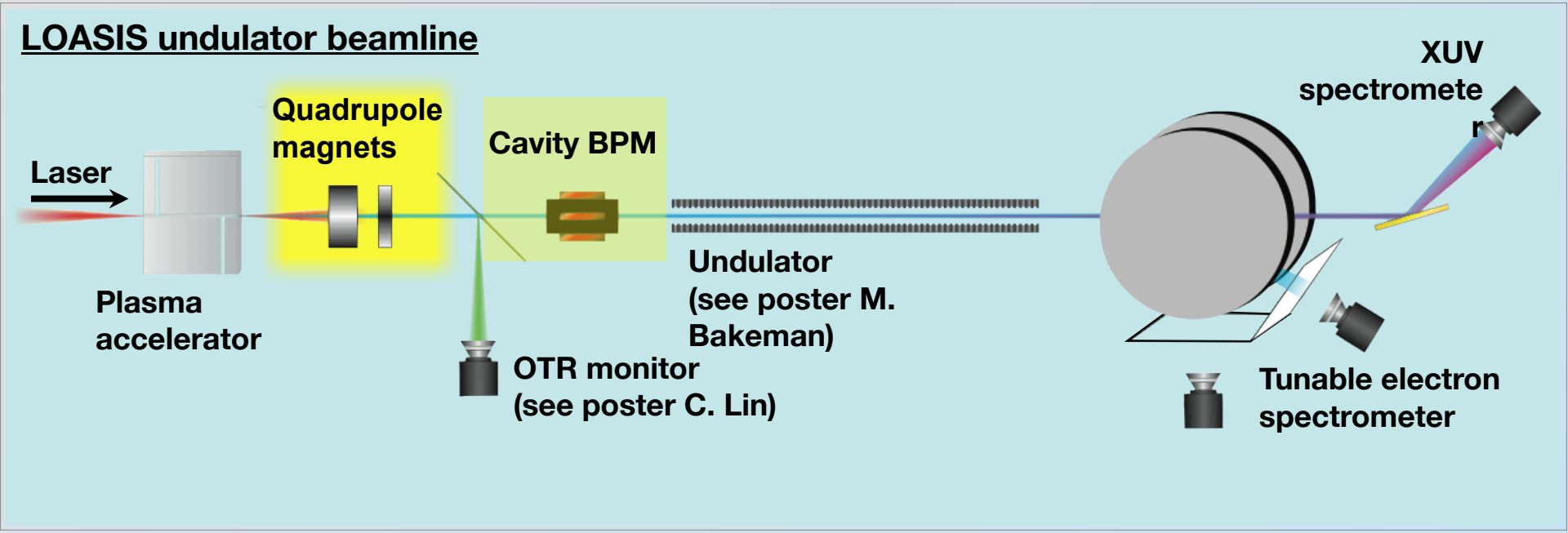




Geddes et al., PRL V 100, 215004 (2008) *Nieter et al., JCP 2004

e-beam transport and diagnostics

Electron beam transport essential for controlled accelerator operation

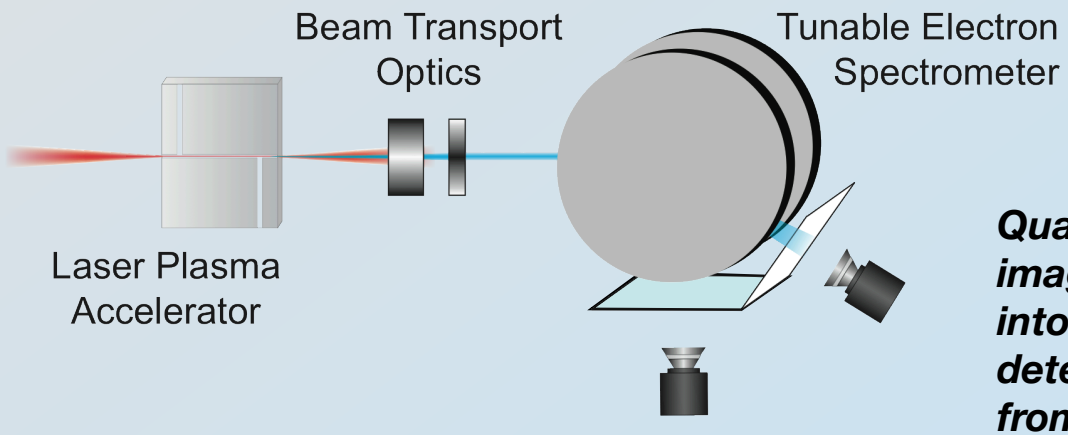


- Observed coherent OTR at 4 m from LPA exit
  - Femtosecond structure maintained over long range -- **Chen LIN poster**
- Testing small permanent magnets – **Jens OSTERHOFF talk**
- Testing cavity (from SLAC) and button based BPMs – **Jens' talk**
- Developing single shot energy spread and emittance diagnostic based on undulator – **Mike BAKEMAN poster**

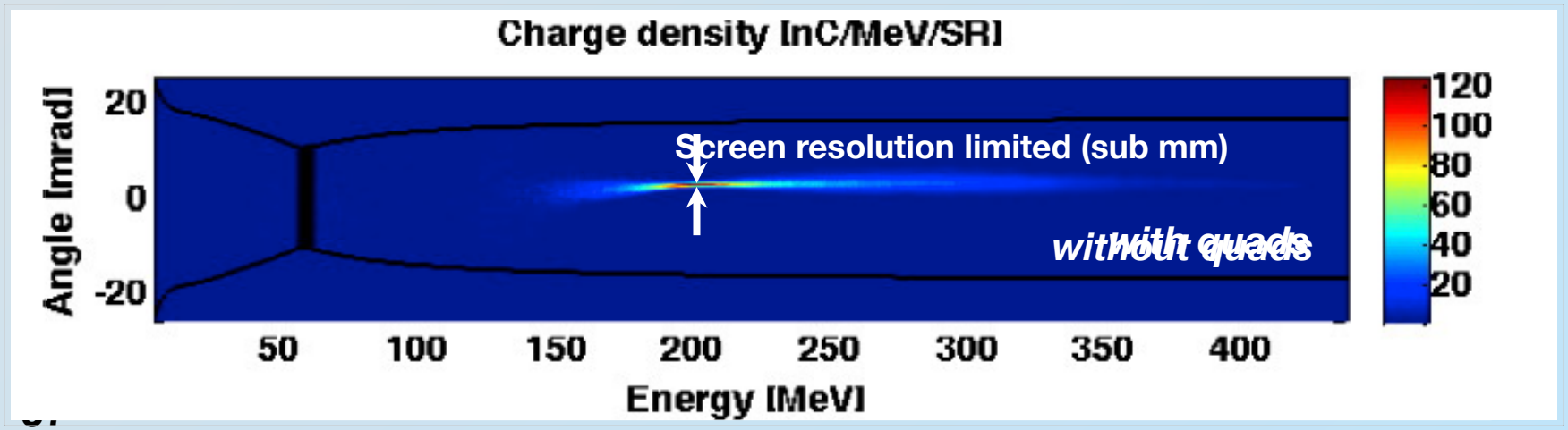
Quads allow for source imaging onto the spectrometer phosphor screen

Supported by DTRA

Experimental setup



Quads positioned to image ~180 MeV electrons into spectrometer detection plane (1.3 m from source)

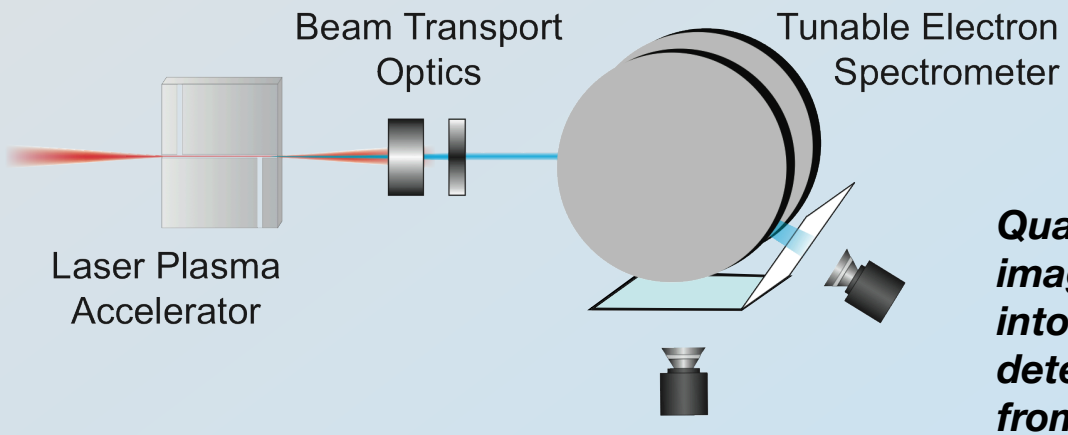


Collaboration with MPQ

Beam stability

Supported by DTRA

Experimental setup



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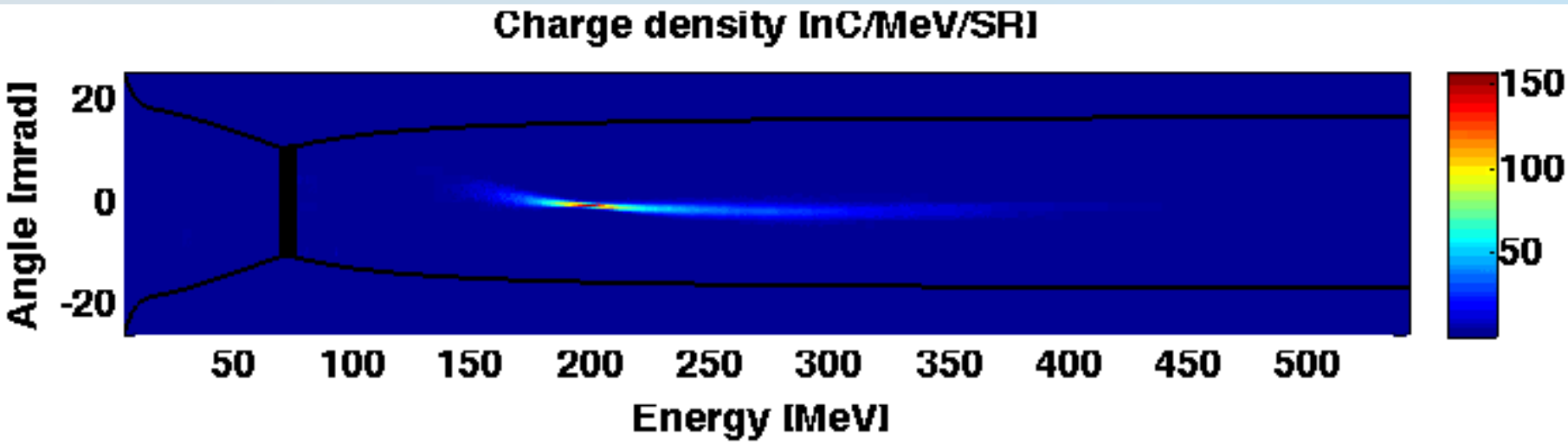


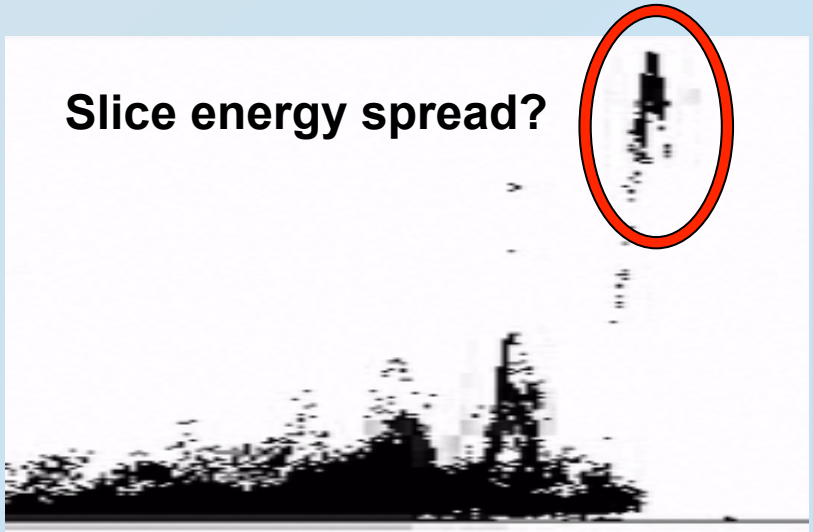
Collaboration with MPQ

Beam brightness studies are underway

- Charge:
  - Phosphor screen calibration vs. ICT at storage ring (up to 1.5 GeV)
  - Activation studies
  - %-level agreement between various diagnostics

K. Nakamura – WG1, FRPM1

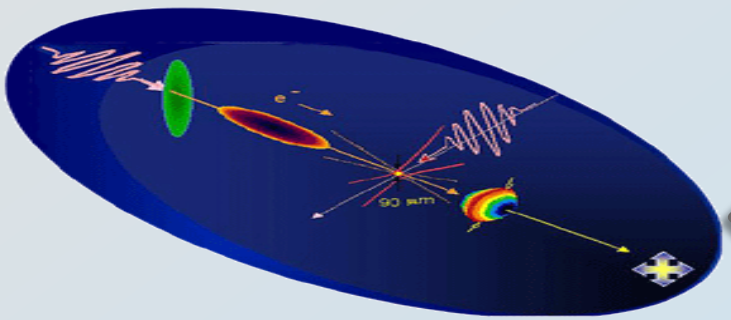
- Emittance & energy spread:
  - Source size and divergence
  - OTR (COTR) experiments
  - Undulator based diagnostic



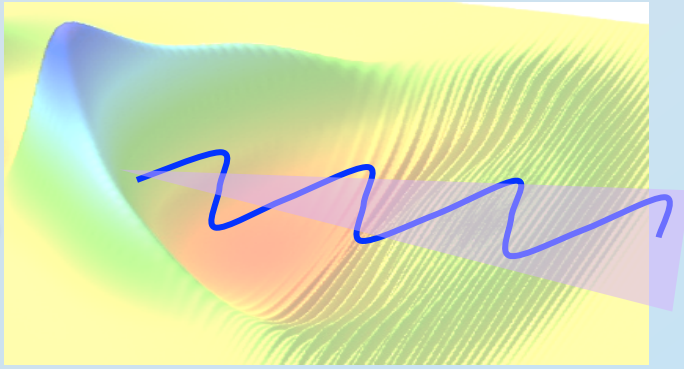
- Bunch duration:
  - Fluctuational interferometry (P. Catravas et al., PRL 1999)
  - THz radiation -- upper bound

Radiation from THz to Gamma Ray – synchronized and ultra-short

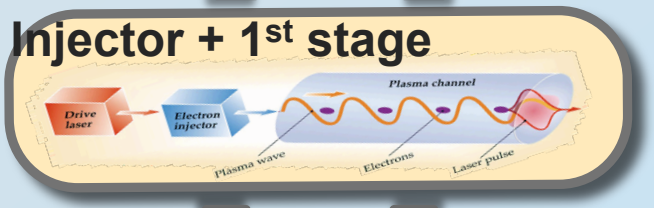
Thomson Scattering – Multi keV/ MeV x-ray/gamma ray



Betatron radiation during acceleration – Multi keV

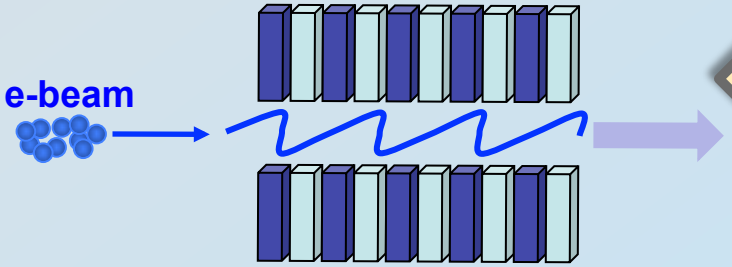


Injector + 1st stage

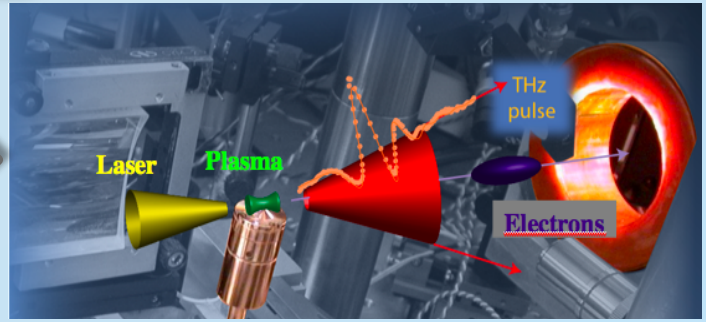


Poster -- Plateau
Talk by Matlis
Talk by Van Tilborg

Poster -- Bakeman

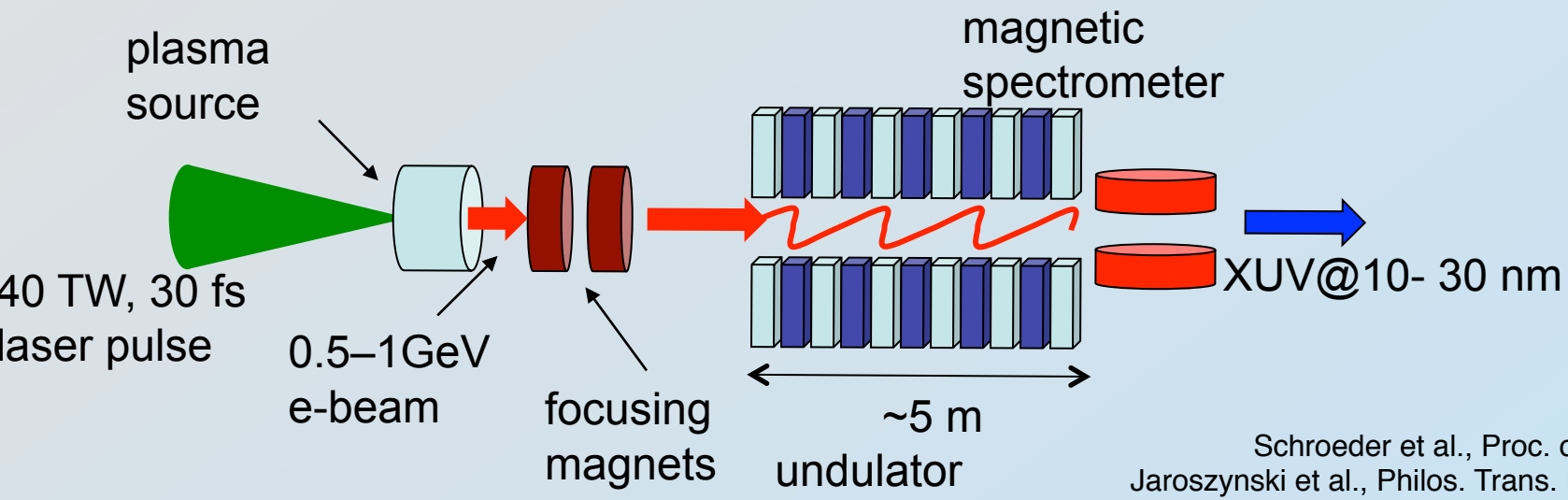


Free Electron Laser-> XUV, x-ray



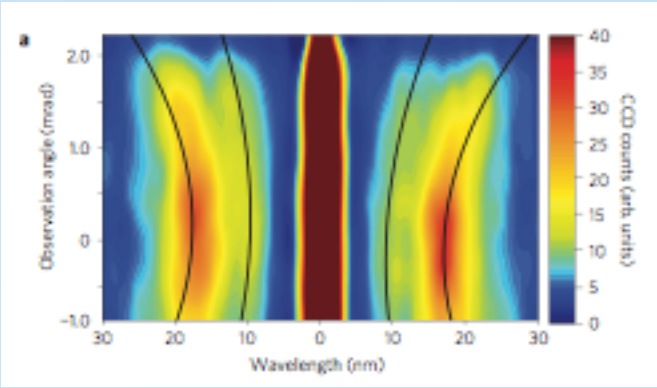
Transition radiation from beam exiting plasma – MV/cm THz

Proof-of-principle experiments of Free Electron Laser driven by LPA-beam underway



Schroeder et al., Proc. of FEL06 (2006)
Jaroszynski et al., Philos. Trans. R. Soc. A (2006)
Grüner, et al., Appl. Phys. B (2007)

Spontaneous emission 17 nm (@ MPQ-Garching)



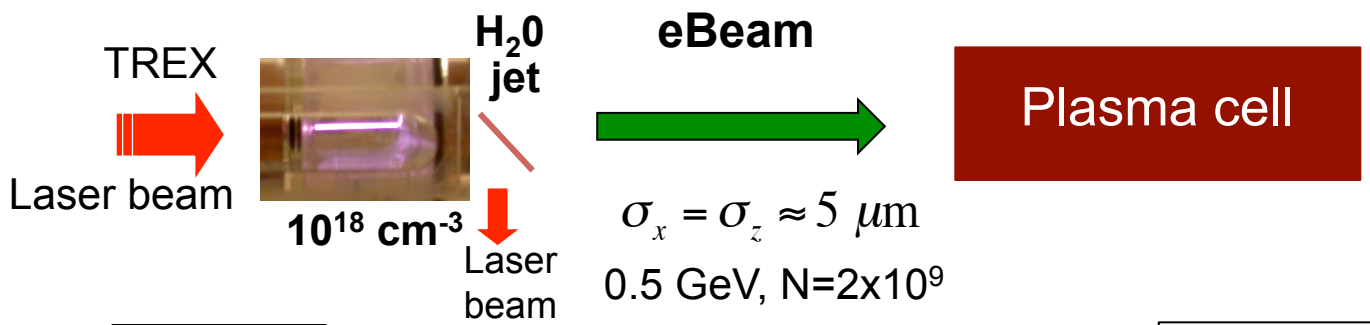
- Uses THUNDER undulator
- Collaboration with MPQ and Oxford University
- Platform for investigating beam diagnostics, transport, focusing etc…

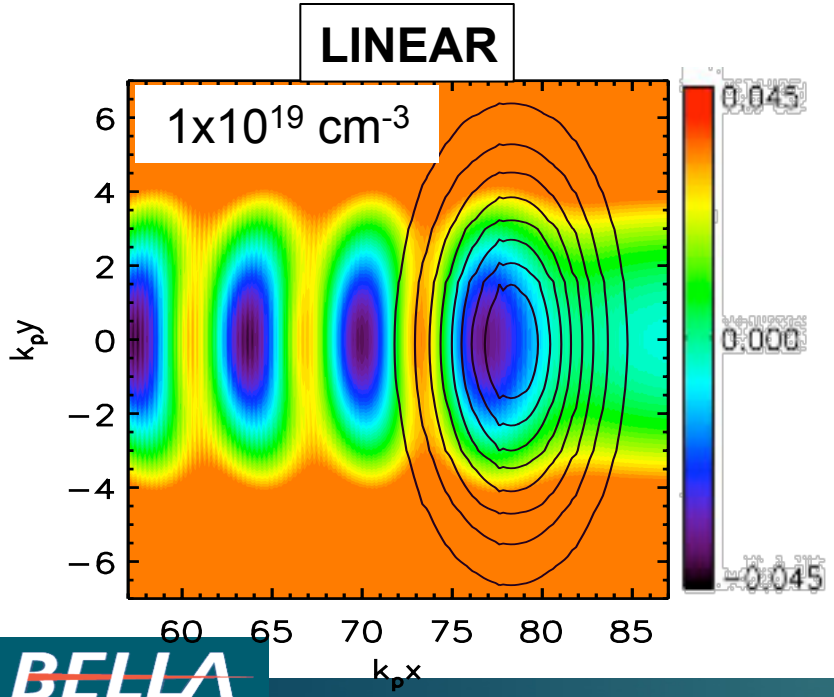
Fuchs et al.,Nature Physics (2009)

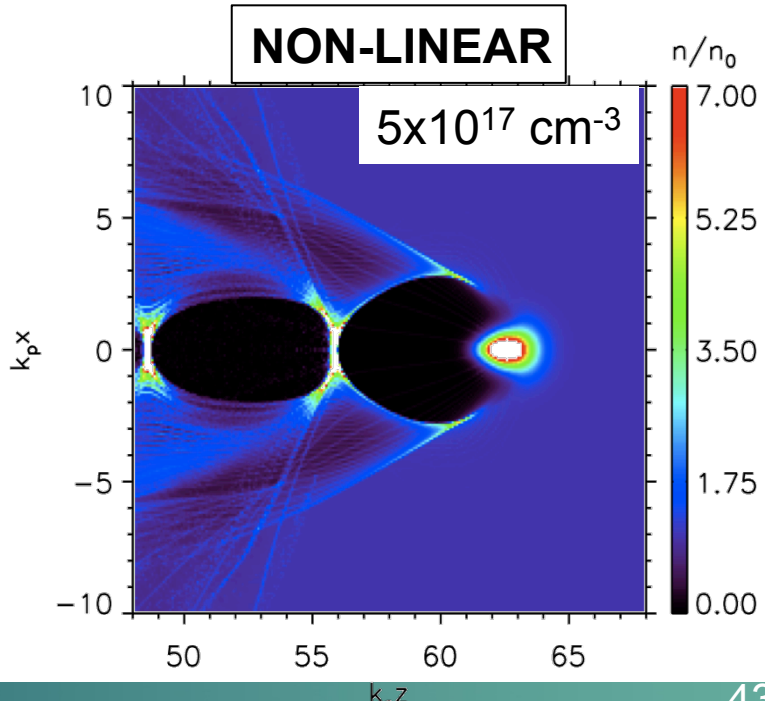
Applications with BELLA

Beam-driven wakefield (PWFA) cell will be tested in non-linear and linear regimes

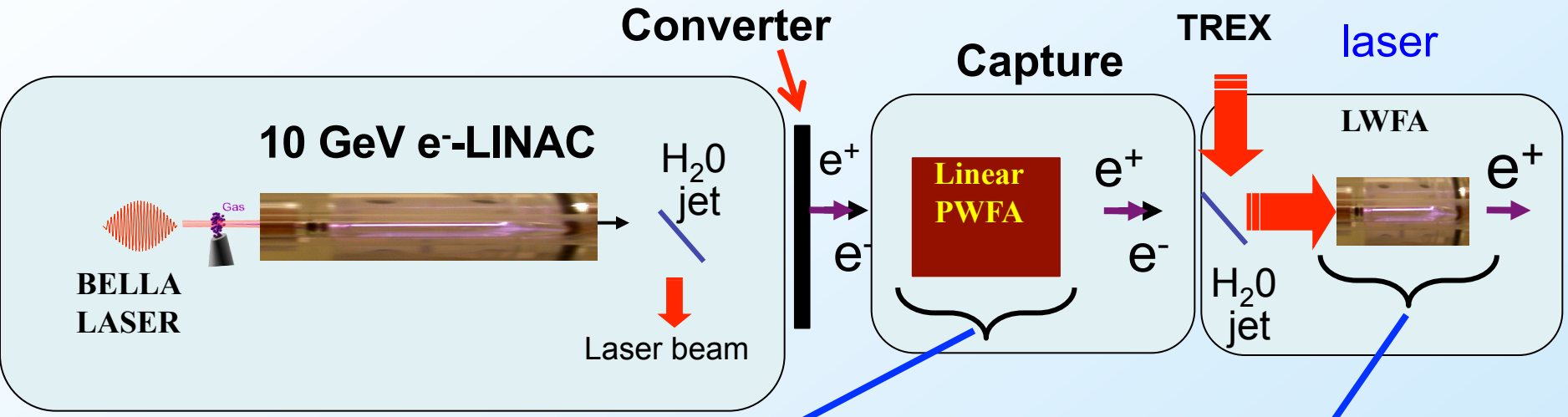
- LWFA beams are ultra-short (<10 micron), high-peak current (~10 kA), ideal for beam-driven wake studies: $E_{acc} \propto \frac{N}{\sigma_z^2}$

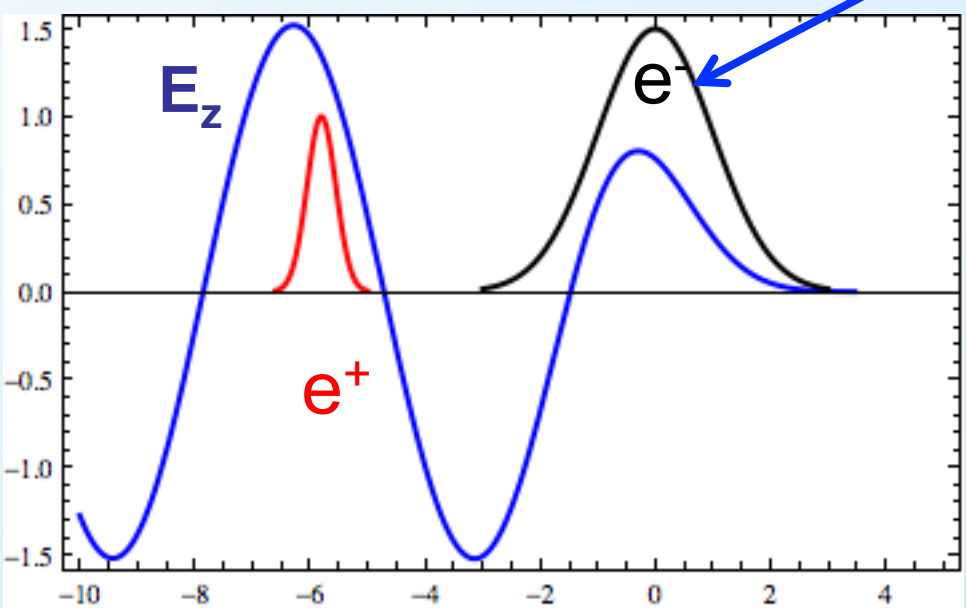






R&D with BELLA: Proof-of-principle positron acceleration experiment



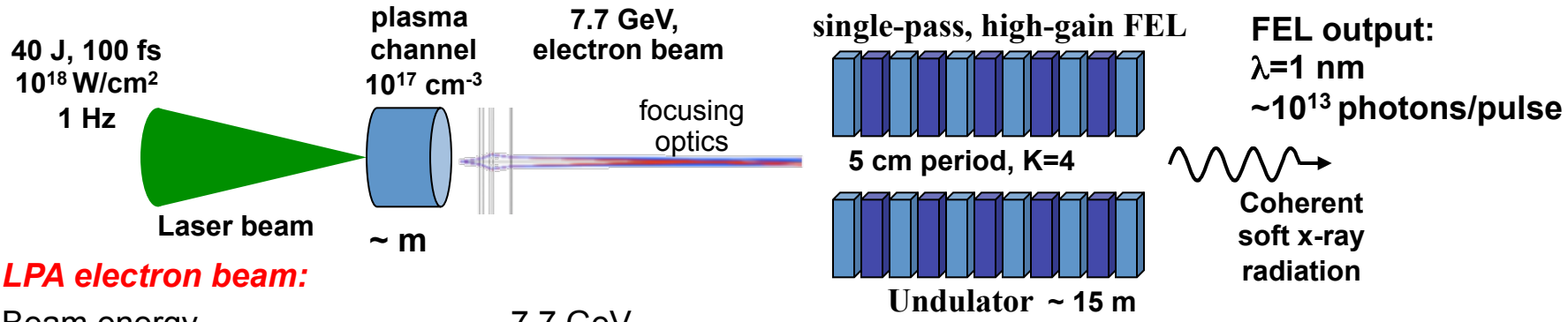


Quasi-linear stage driven by laser

H. Vincenti, MS thesis

BELLA laser will enable basic collider components to be developed

Laser-plasma accelerator driven soft x-ray FEL

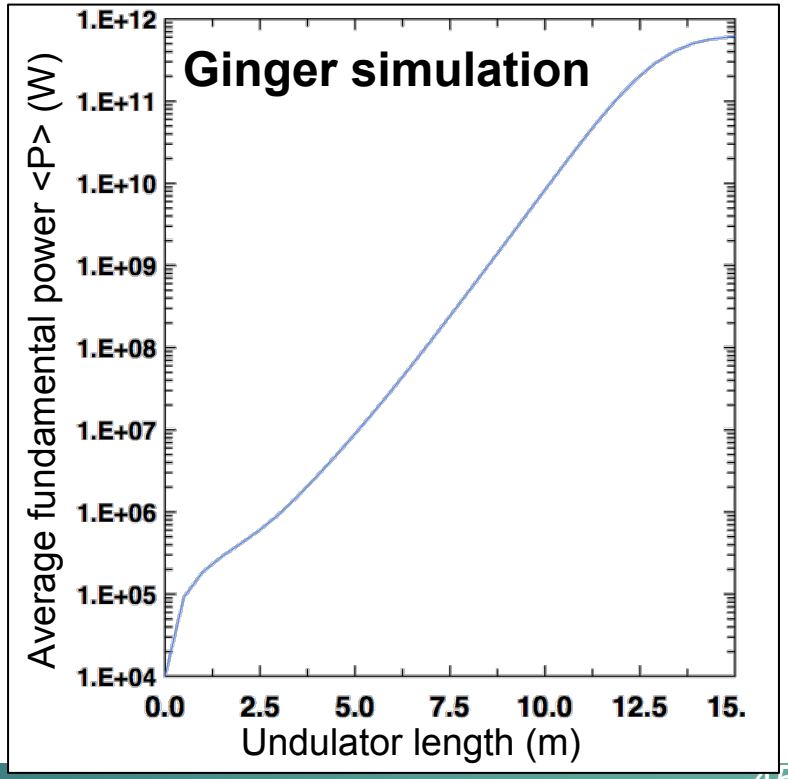


LPA electron beam:

Beam energy	7.7 GeV
Peak current	30 kA
Bunch length	20 fs
Relative energy spread	10^{-3}
Normalized emittance	1 micron

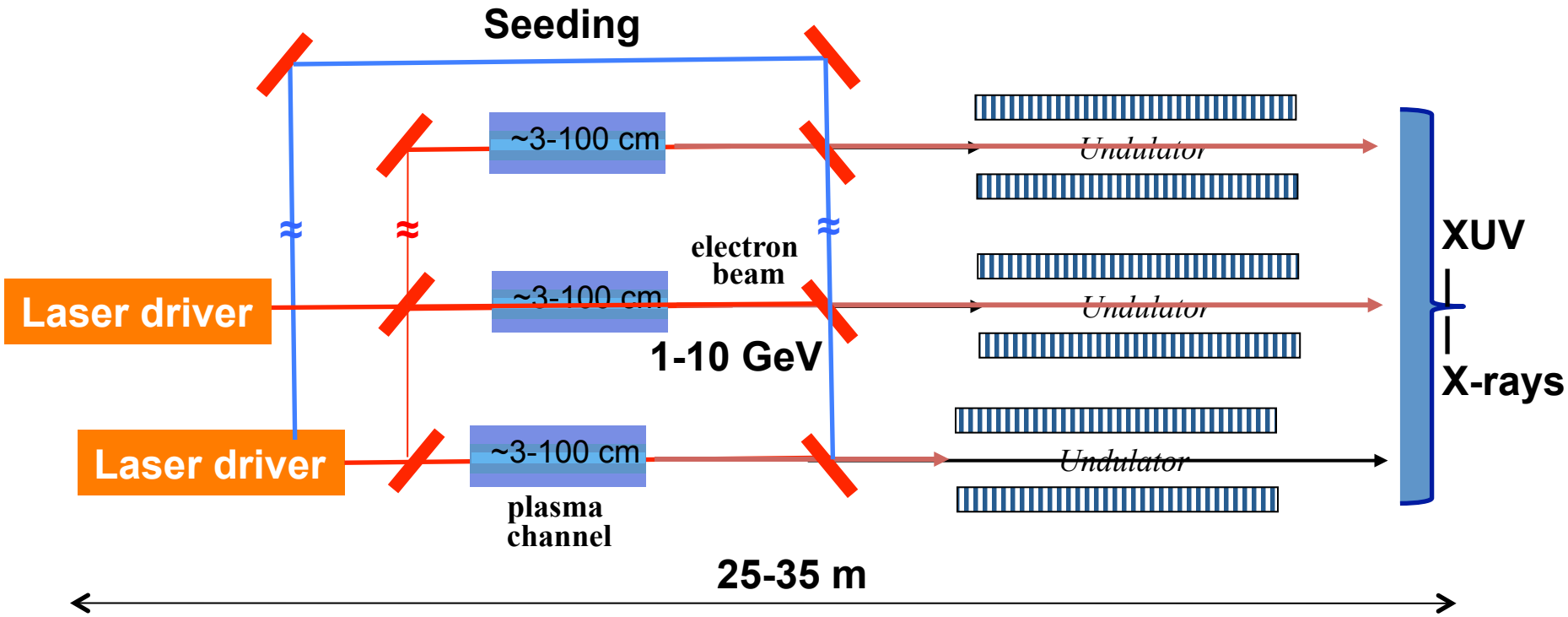
FEL Radiation:

Resonant fundamental wavelength	1 nm
Photon energy	1.2 keV
FEL parameter	5×10^{-3}
1D gain length	0.4 m
3D gain length	0.6 m
Saturation length	13 m
Energy/pulse (fundamental)	8 mJ



Strawman Facility Design

- Linac costs near nothing – build multiple linacs and beam lines driven by single laser or multiple lasers
- With laser cost decreasing and performance increasing: power each beam line with its own laser



Summary

- BELLA Project:
  - Installation and commissioning of 40 J, 30 fs, 1 Hz laser
    - Includes remodeling of facility to house laser system
- Driver for 10 GeV laser plasma accelerator
  - Quasi-linear regime operation
    - Channel guiding
    - Integrated electron injection
- Optimized designs underway:
  - Longitudinal density tailoring for efficiency
  - Laser transverse mode control for emittance
- Demonstration of 10 GeV module:
  - Building block for collider
  - X-ray FEL

LOASIS Team FY2010

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- TechX-Corp: J. Cary, D. Bruhwiler, et al.
- SciDAC team
- Oxford Univ.: S. Hooker et al.
- MPQ: F. Krausz, F. Gruener et al.
- LOA: O. Albert, L. Canova
- GSI: T. Stoehlker, D. Thorn

BELLA Team