Ultra-high Gradient Compact Accelerator Development

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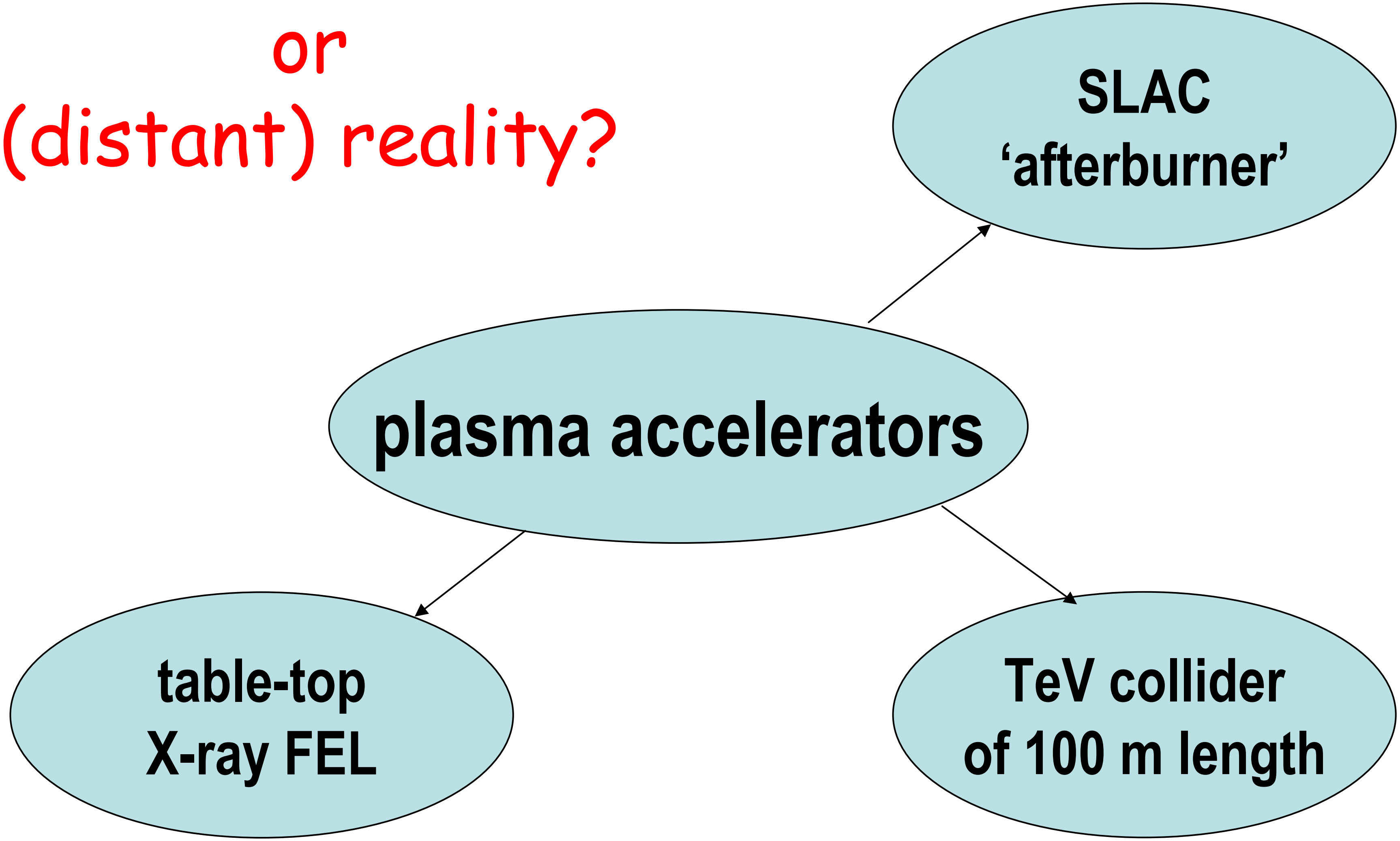
Content

1- plasma accelerators (GV-TV/m ; > 100 MeV)

2- compact, high-gradient injectors (< 10 MeV)

Dreams
or
(distant) reality?



Beyond RF- technology : towards GV - TV/m

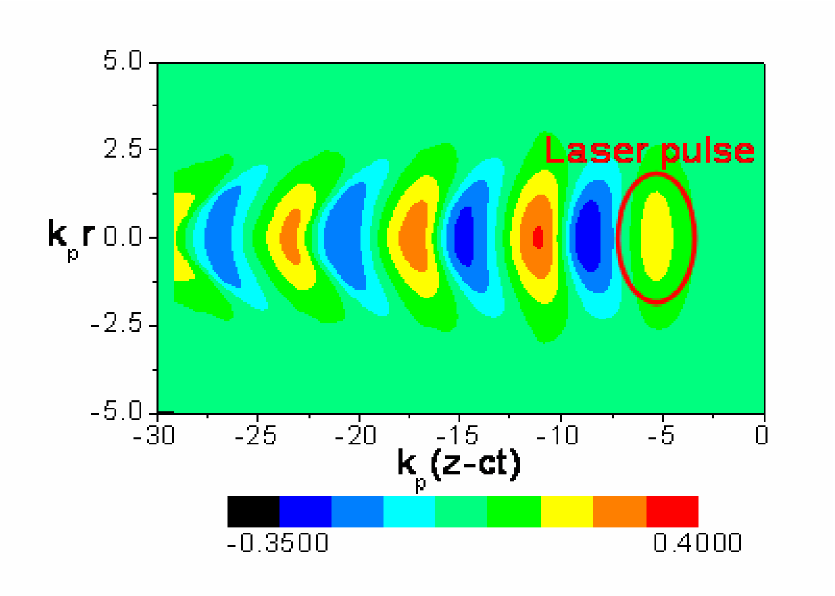
Options: - electron-driven plasma waves (SLAC ‘afterburner’)

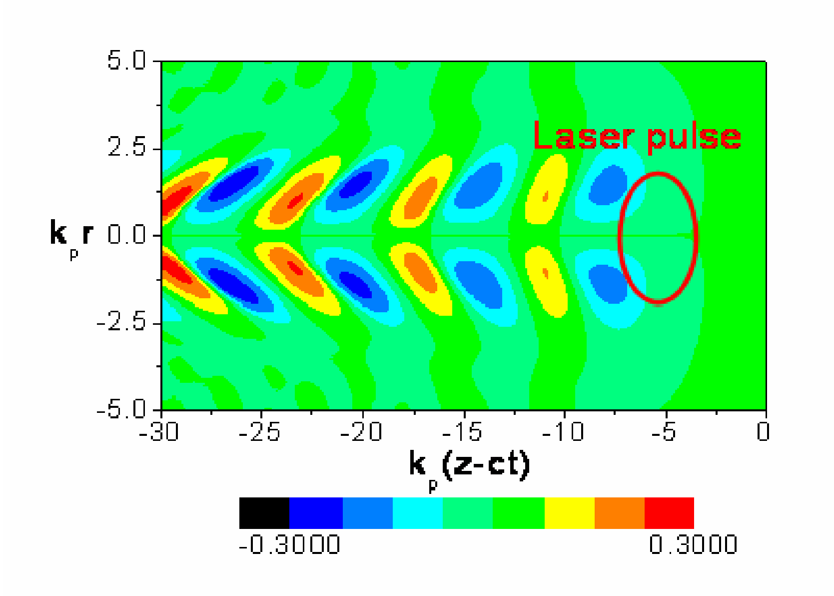
- laser-driven plasma waves

- laser in vacuum

- pulsed-DC

Laser-driven wakefield plasma wave: principle





Longitudinal wake-field:

blue – accelerating,

red – decelerating.

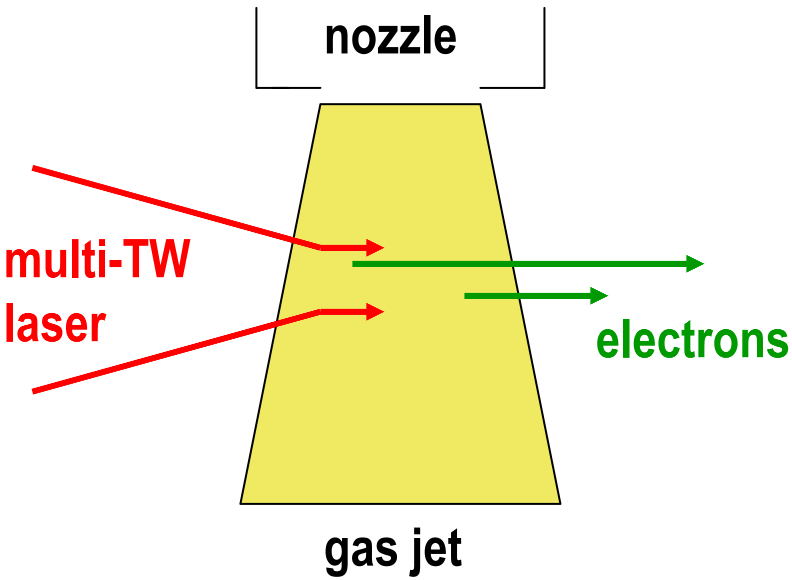
Transverse wake-field:

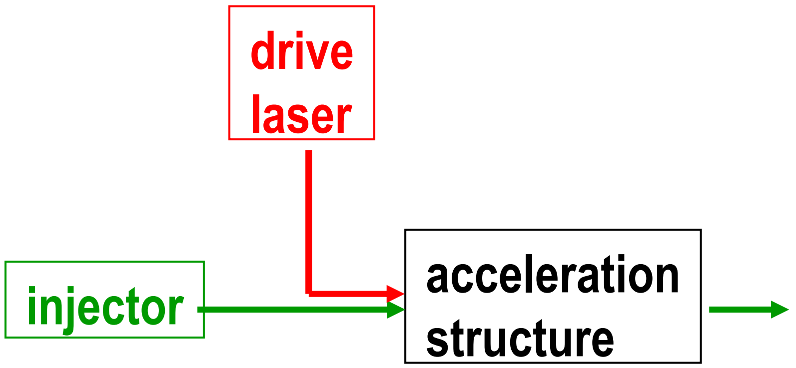
blue – focusing,

red – defocusing.

- λ_{plasma} = 1 mm – 10 μm, depending on gas pressure
- max. gradient 1 GV/m – 1 TV/m, limited by wave breaking

Laser-driven plasma waves : Options



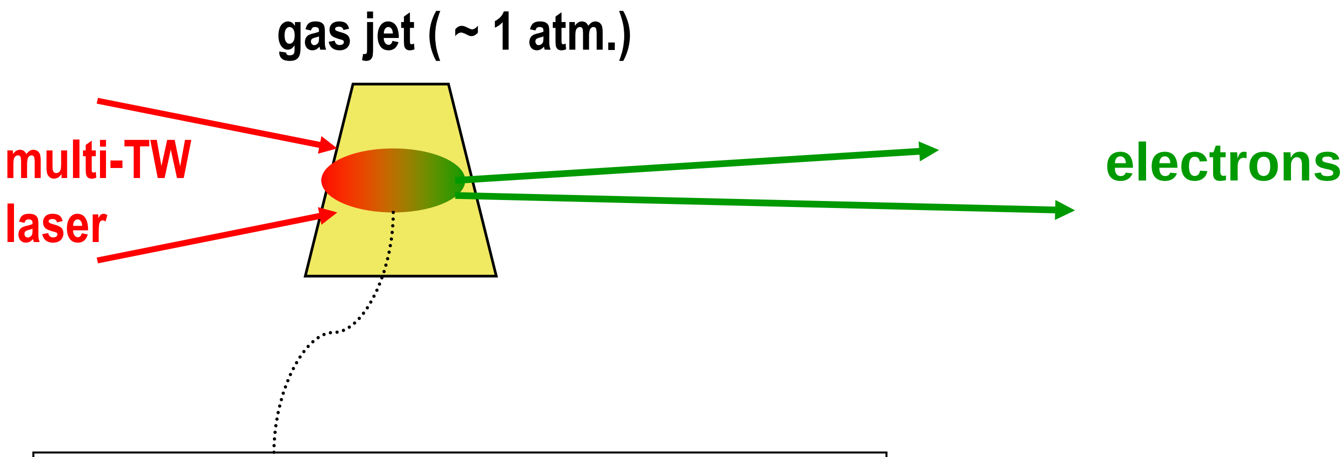


~~‘hot-beam’ source~~

(quasi)monoenergetic beam source

‘controlled’ acceleration

Laser / gas-jet source



in 10^{-4} mm^3, a 5-step process occurs:

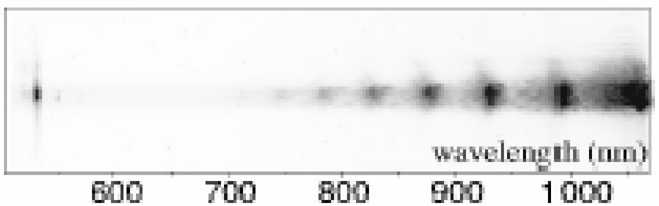
1- laser ionizes gas for 100% in few fs
2- self-focussing *
3- creation of wakefield wave
4- electron trapping by wave breaking *
5- acceleration in wakefield

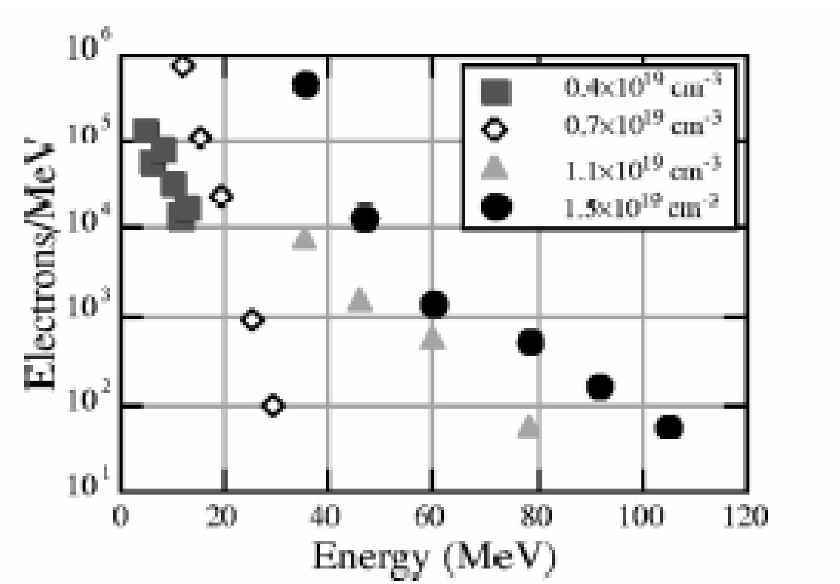
*= instability

Hot-beam Source: Experiments

self-modulated regime:

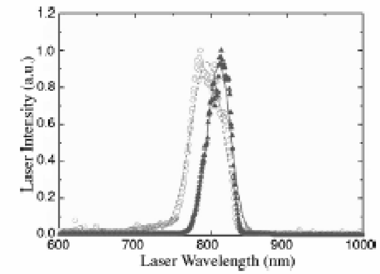
$\tau_{laser} \geq \omega_{plasma}$

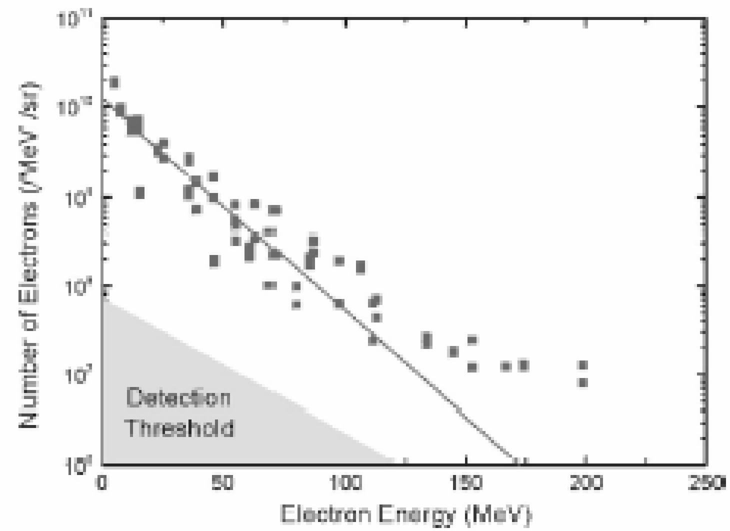




forced wakefield regime:

$\tau_{laser} \leq \omega_{plasma}$

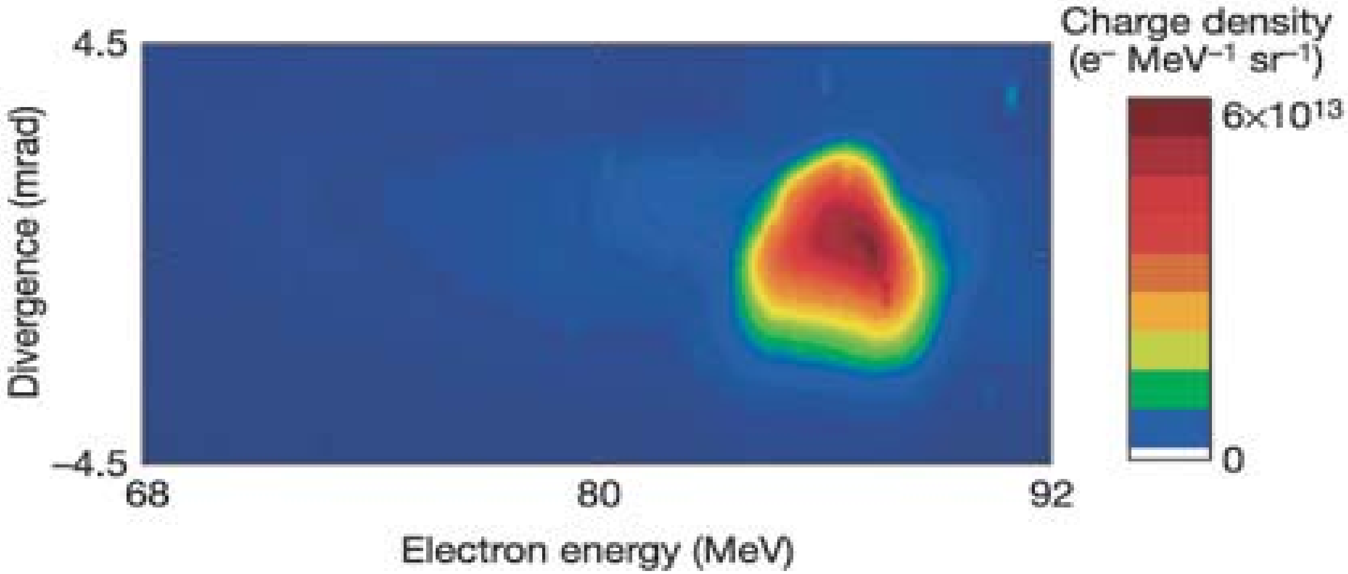




Najmudin et al., Phys. Plasmas 10, 2071 (2003) nature September 2004

High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding

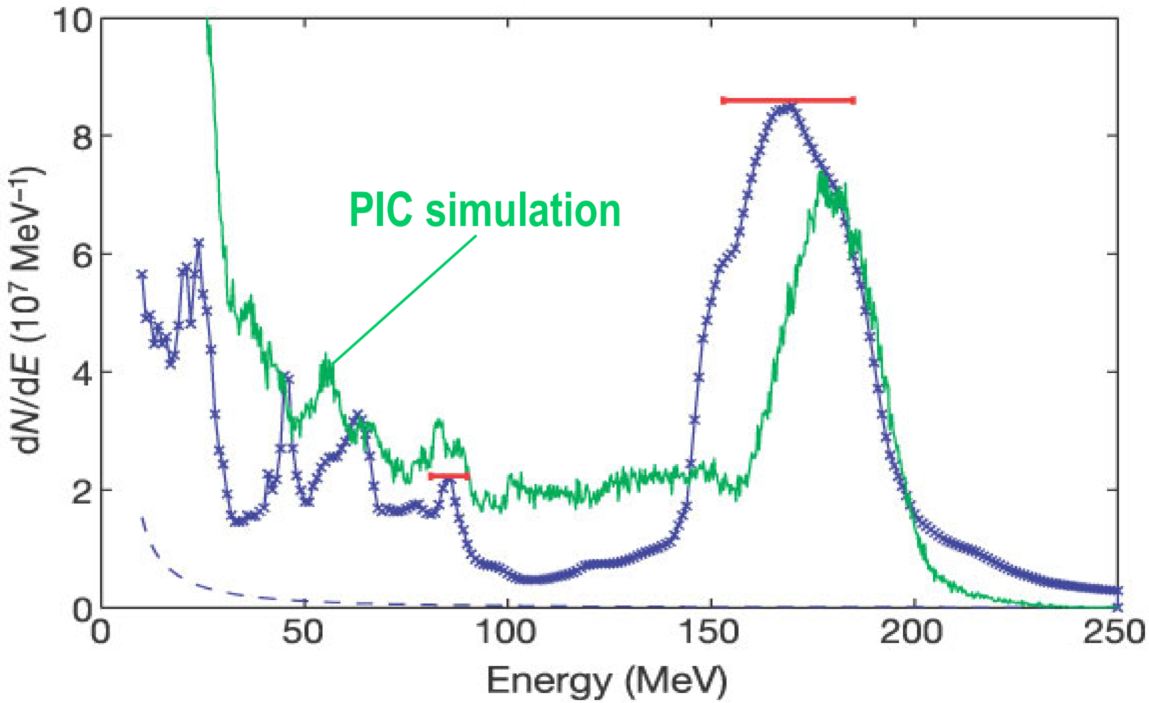
C. G. R. GEDDES, CS. TOTH, J. VAN TILBORG, E. ESAREY, C. B. SCHROEDER,
D. BRUHWILER, C. NIETER, J. CARY & W. P. LEEMANS



nature **September 2004**

A laser–plasma accelerator producing monoenergetic electron beams

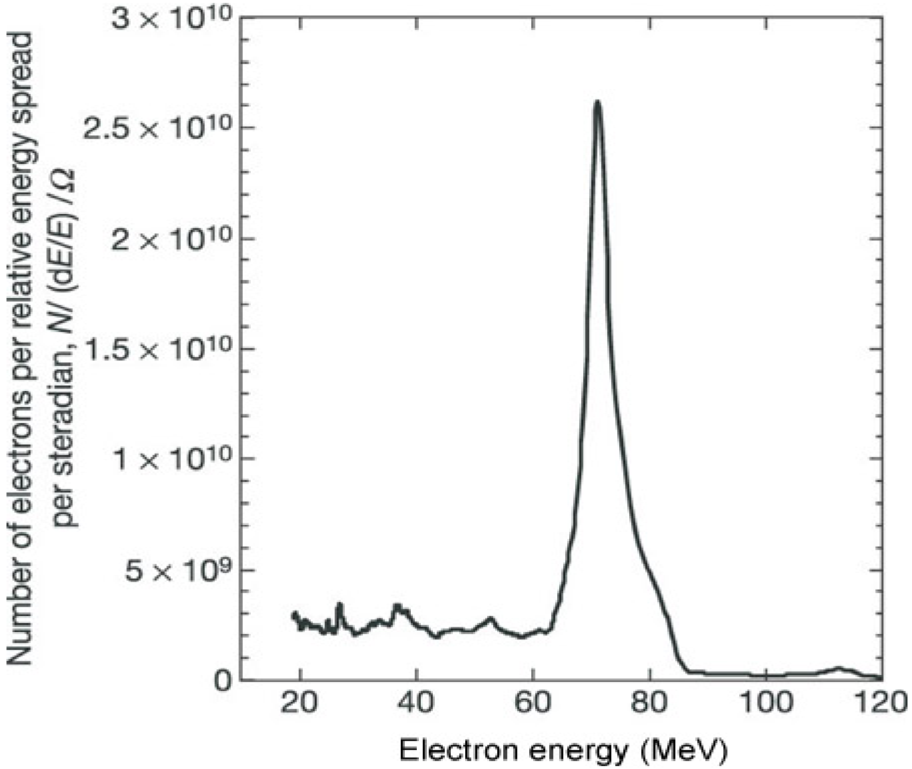
J. FAURE, Y. GLINEC, A. PUKHOV, S. KISELEV, S. GORDIENKO, E. LEFEBVRE, J.-P. ROUSSEAU, F. BURGY & V. MALKA

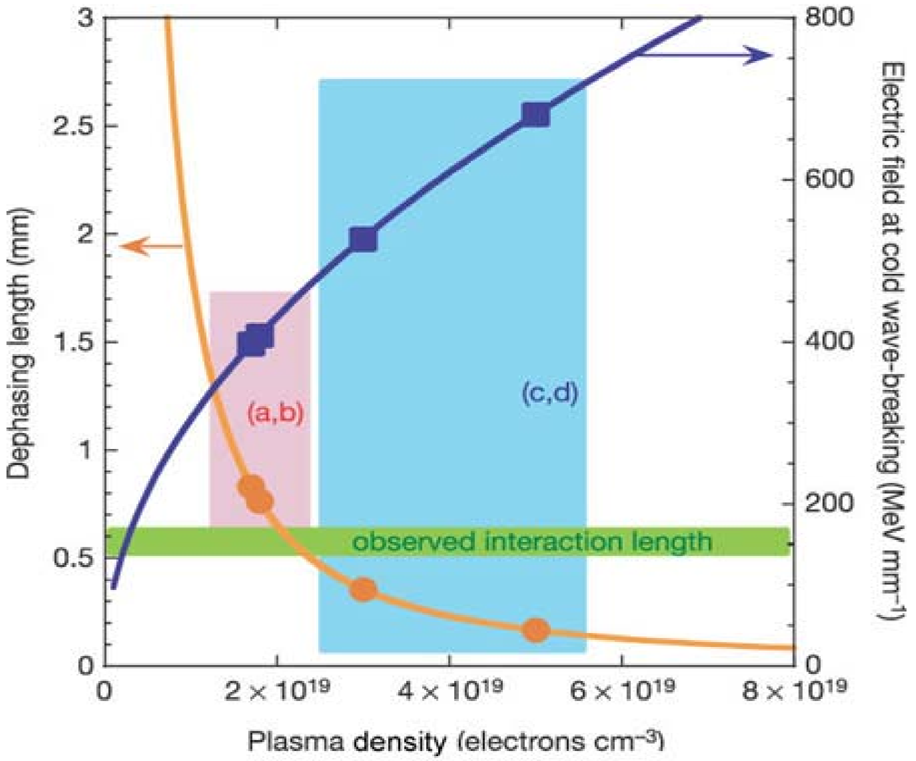


nature **September 2004**

Monoenergetic beams of relativistic electrons from intense laser–plasma interactions

S. P. D. MANGLES, C. D. MURPHY, Z. NAJMUDIN, A. G. R. THOMAS, J. L. COLLIER, A. E. DANGOR, E. J. DIVALL, P. S. FOSTER, J. G. GALLACHER, C. J. HOOKER, D. A. JAROSZYNSKI, A. J. LANGLEY, W. B. MORI, P. A. NORREYS, F. S. TSUNG, R. VISKUP, B. R. WALTON & K. KRUSHELNICK





Characteristics of 'laser / gas-jet' experiments

- impressive specs:

  - charge per bunch $\lesssim$ 0.5 nC

  - normalized emittance $\sim$ 1 μm

  - peak current $\lesssim$ 10 kA (simulated)

- works only in small part of parameter space:

  laser power, -pulse duration and gas pressure

- relies on 'local / partial wave breaking' for internal injection:

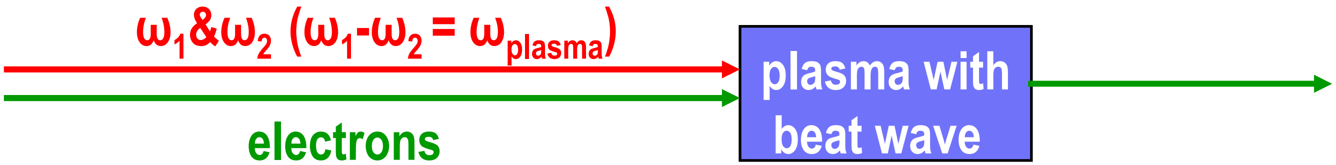
  $\rightarrow$ instability

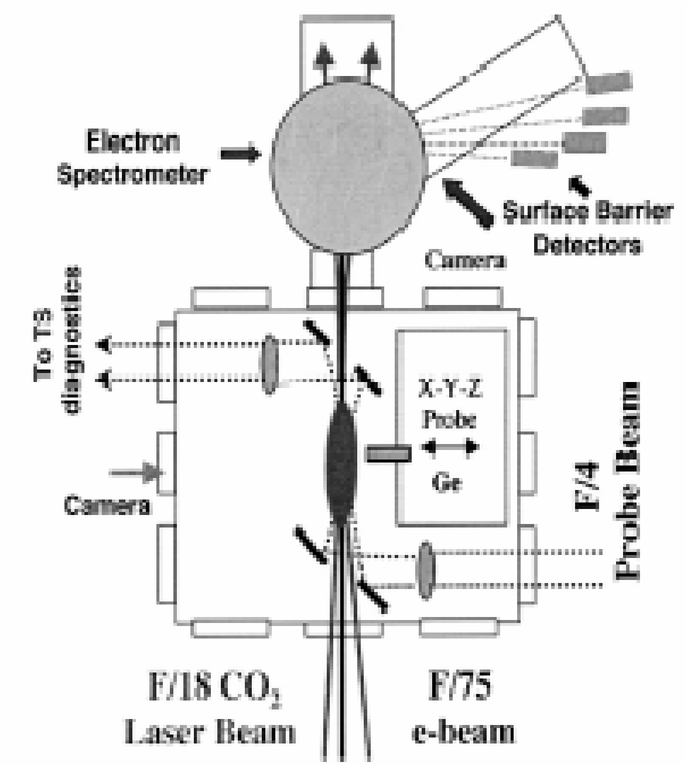
  $\rightarrow$ non-linear dependence on details of laser profile(r,t)

  $\rightarrow$ shot-to-shot variations in charge and energy

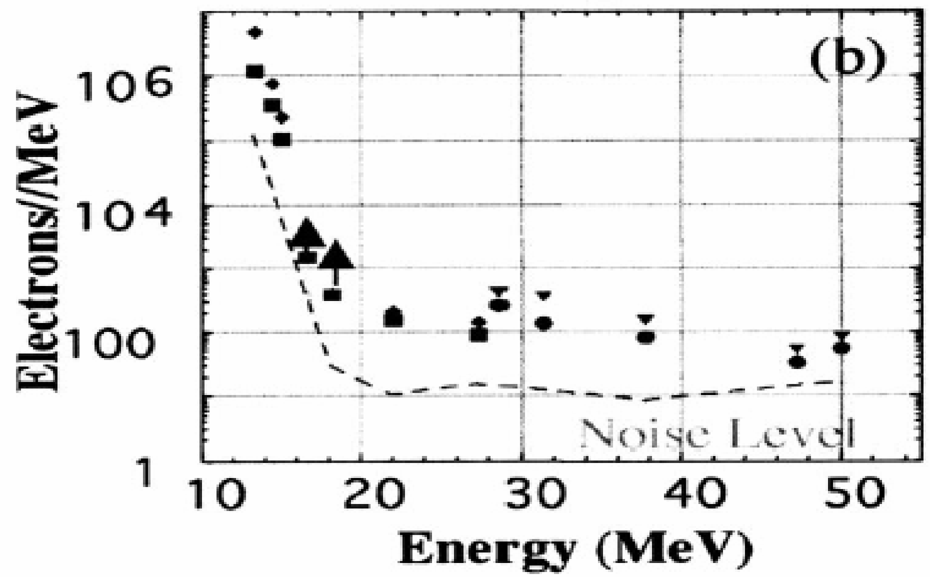
'Controlled' acceleration worth pursuing!

Controlled Acceleration in Beat Wave



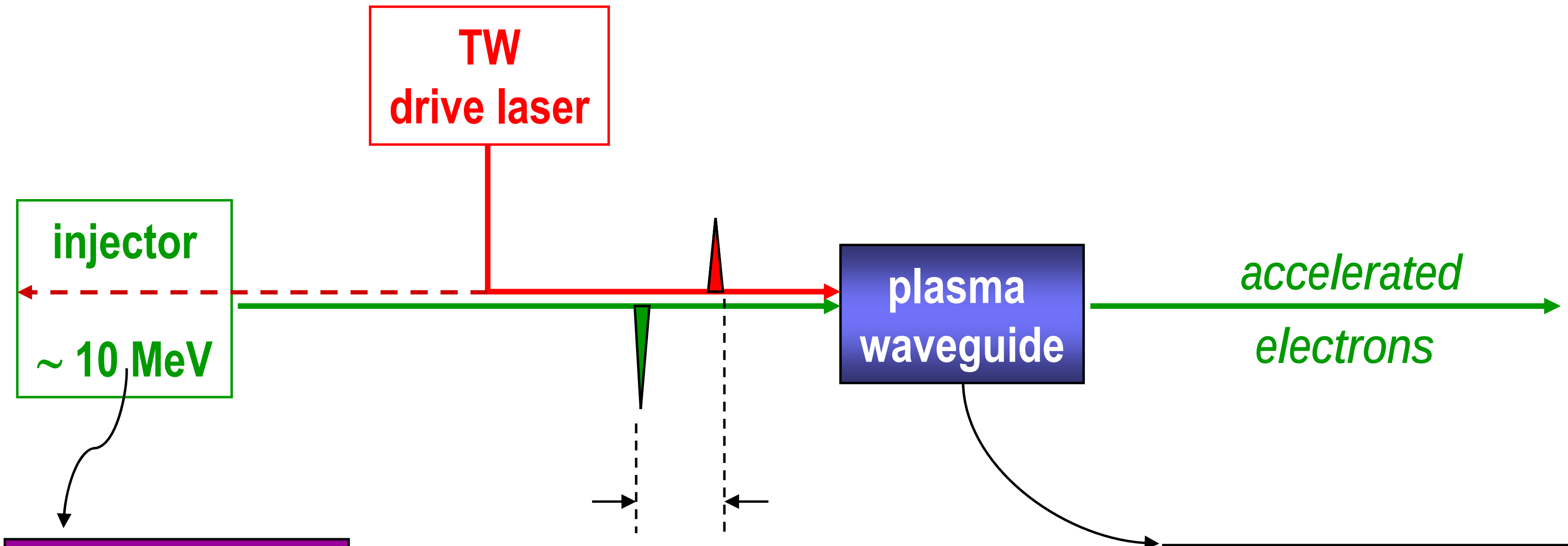


injection: 12 MeV, 10 ps
λ_{plasma} = 300 μm
gradient=1.3 GV/m



Clayton, Joshi, Rosenzweig et al., Phys. Plasmas 11, 2875 (2004)

Controlled Wakefield Acceleration: Lay-out & Issues

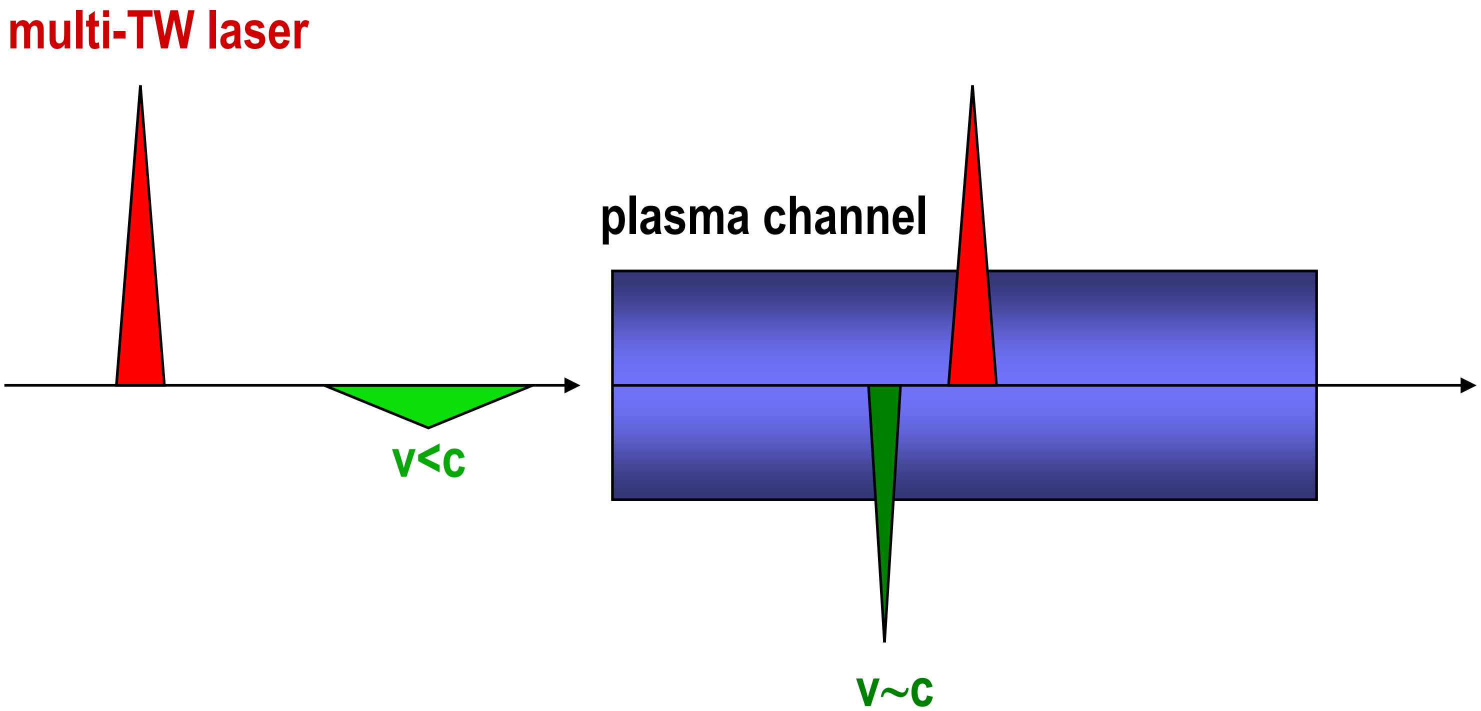


issue:
τ_{bunch} = 1 -100 fs
$\varepsilon_n \sim 1\ \mu m$

issue:
synchronization
<< τ_{bunch}

issue:
- $n_e = 10^{17} – 10^{19}\ cm^{-3}$
- hollow, parabolic radial n_e- profile
- 100% ionization
- radius 20-50 μm
- length several cm

Alternative for injection / compression / acceleration



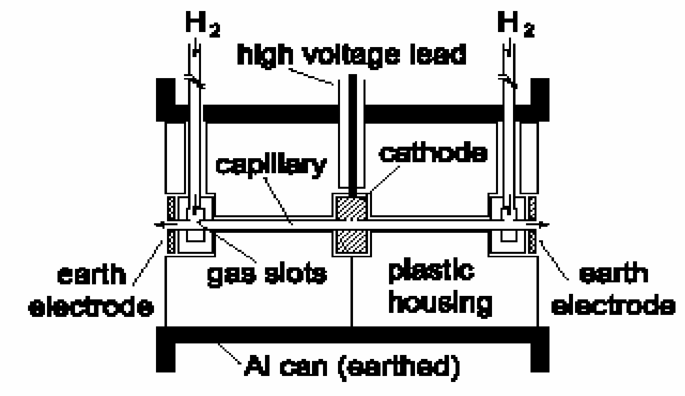
Khachatryan, Van Goor, Boller, Proceedings PAC’03, 1900 (2003).

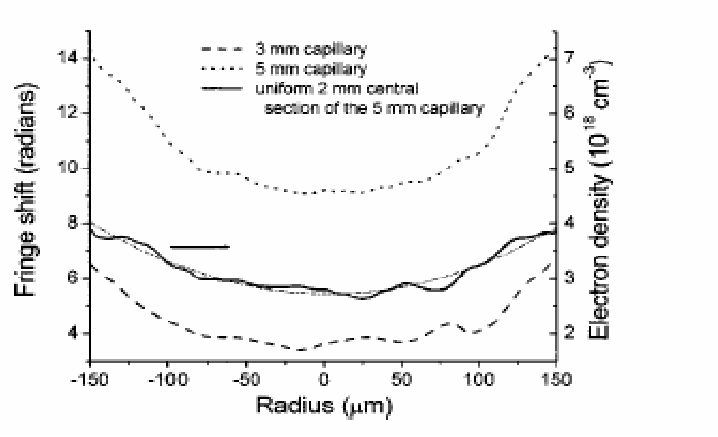
Issue 1: Plasma Waveguiding of TW Laser Pulses

Option	Process	Remarks
• self-focussing	local change of refract. index due to relativ. mass correction of oscillating electrons	instability
• pulsed discharge in capillary	plasma cooling at capillary wall; radially expanding shock wave creates hollow density profile	simple, durable, > 90% transmission
• laser ionization	ionization and heating creates shockwave and hollow profile	optically complex; works down to radii of 5 μm

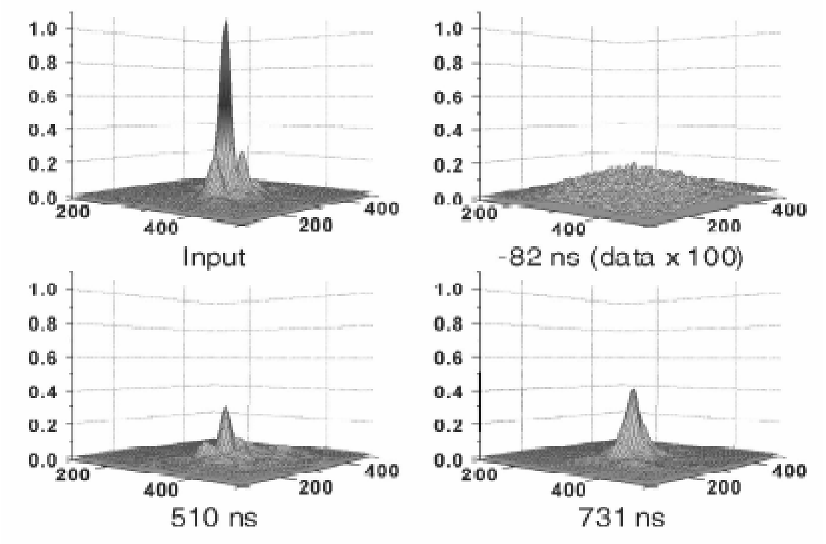
Capillary discharge plasma channel

Butler, Spence, Hooker, PRL 89,185003 (2002)



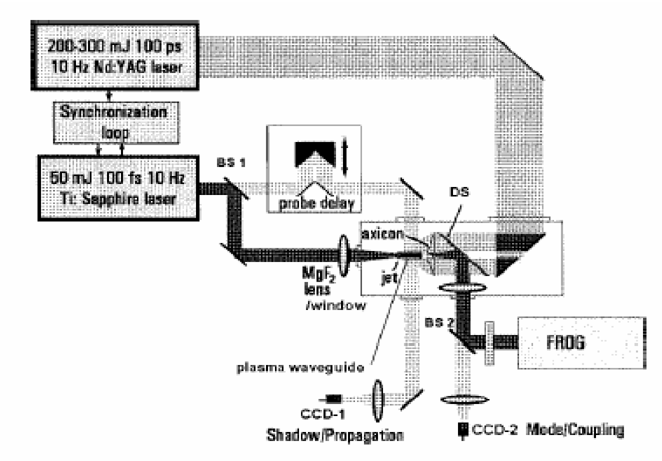


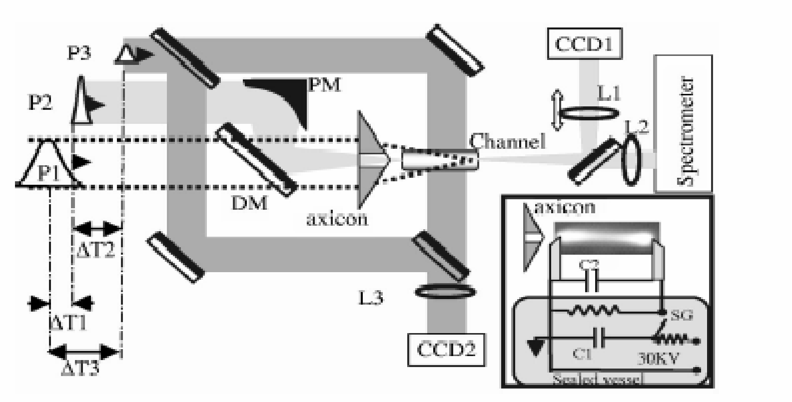
1.0 = 10^{17} W/cm^2

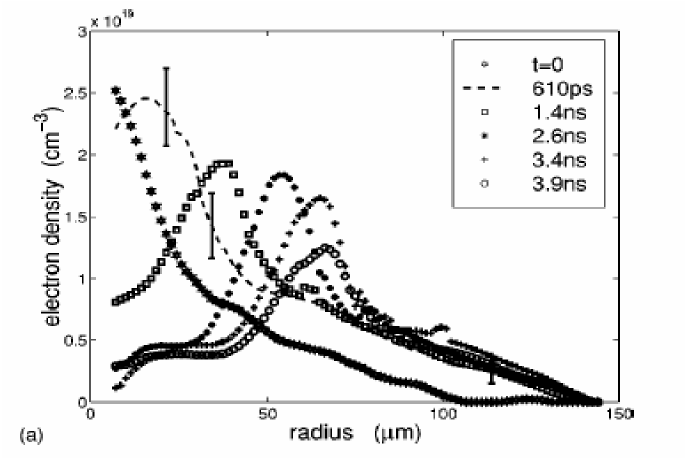


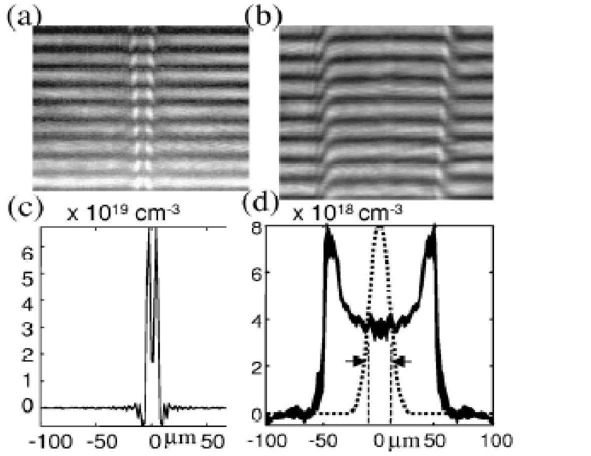
further work needed for pressures ≤ 10^{18} cm^{-3} (λ_{plasma} ≥ 300 μm)

Laser-produced plasma channels









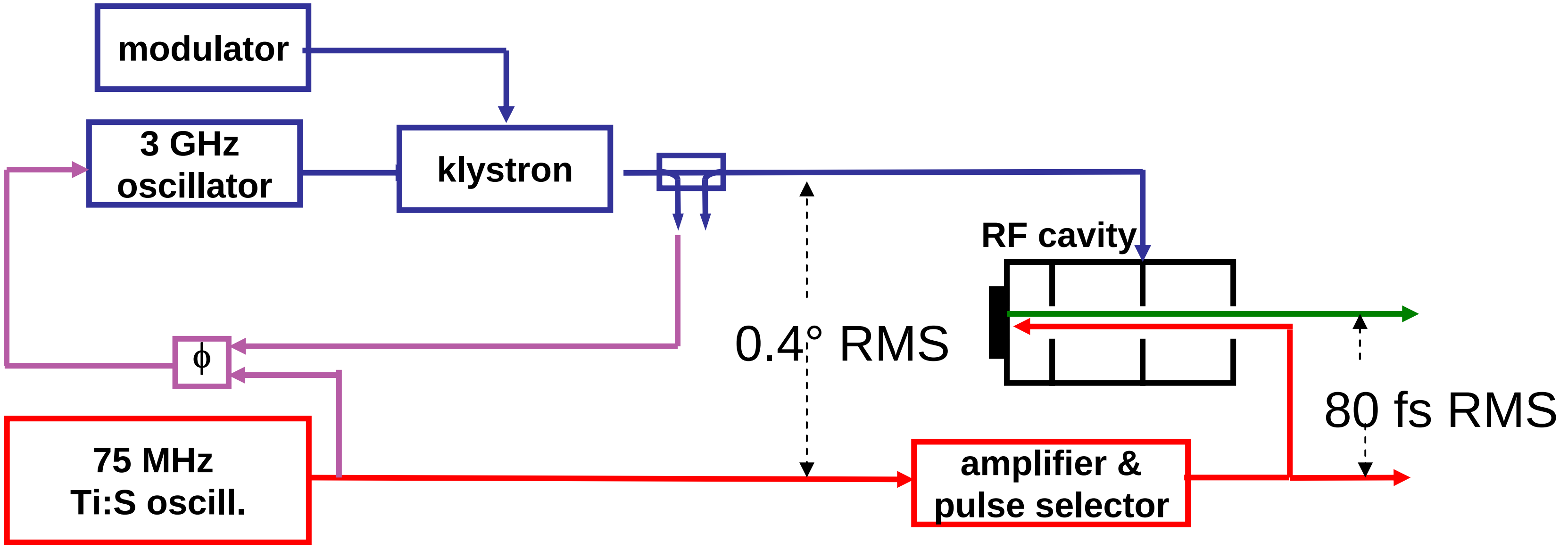
Nikitin et al, Phys Rev E 59,3839 (1999)

Gaul et al, Appl Phys Letters 77,4112 (2000)

Issue 2: Synchronisation of RF and laser

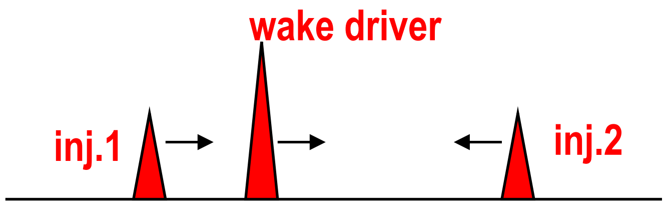
- State-of-the-art for case of RF master / laser slave: ~ 200 fs

- Recent progress at TU- Eindhoven by choosing laser master / RF slave: 80 fs
  (Kiewiet et al., NIM-A, A484, 619, 2002)



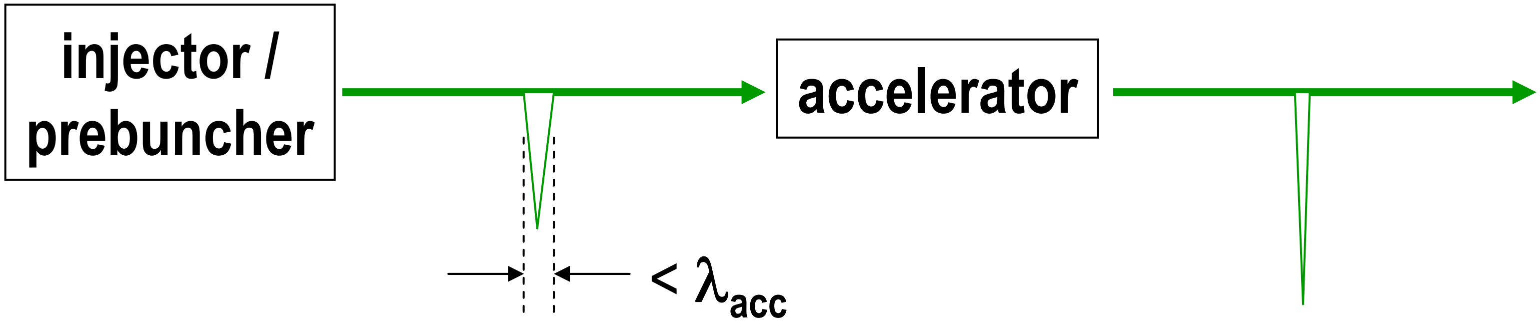
- Easy route towards 10 fs: - klystron power stability 0.1% → 0.05%
  - select optimum phase RF *vs*. laser

Issue 3: Injection

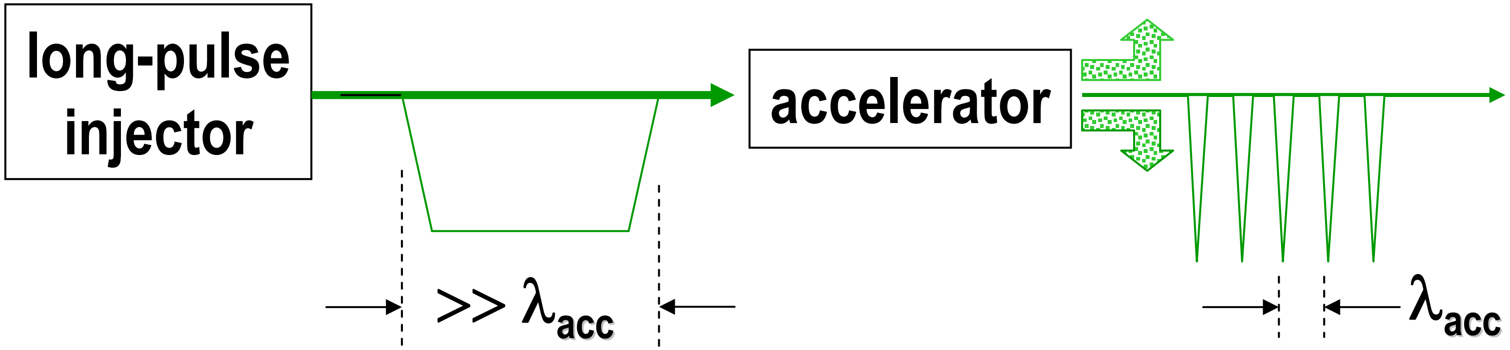
Options	achieved	promised
• *external:*		
- RF photogun & metal cathode	1 ps, 100 pC	200 fs, 10 pC
- idem, with novel approach to ultra-high brightness	--	100 fs, 100pC
• *internal:* optical injection		
	--	1 fs, 1 pC

Generic Injection / Acceleration Schemes

1)

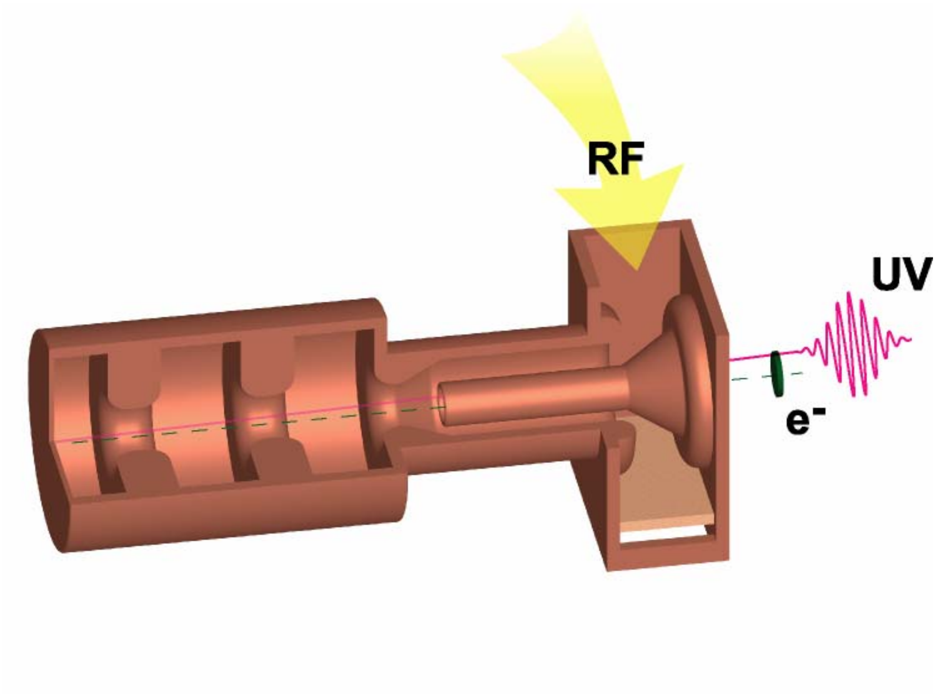


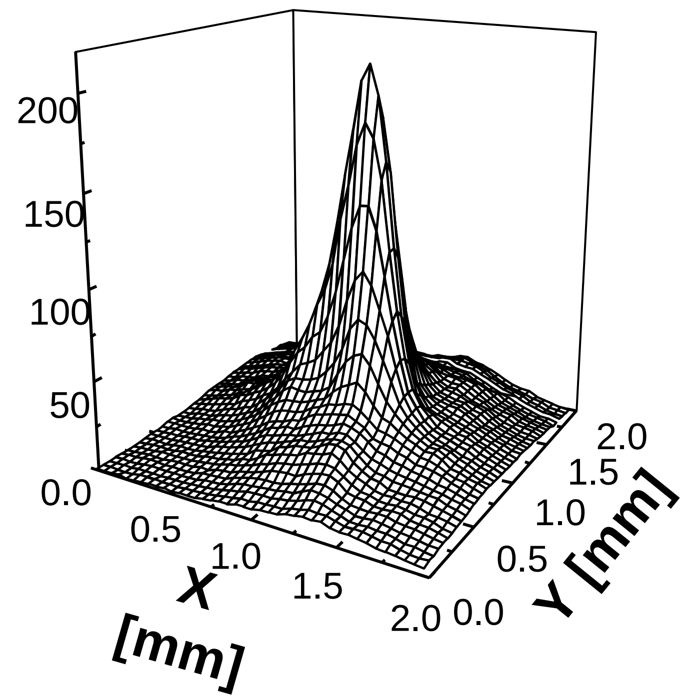
2)



RF photogun

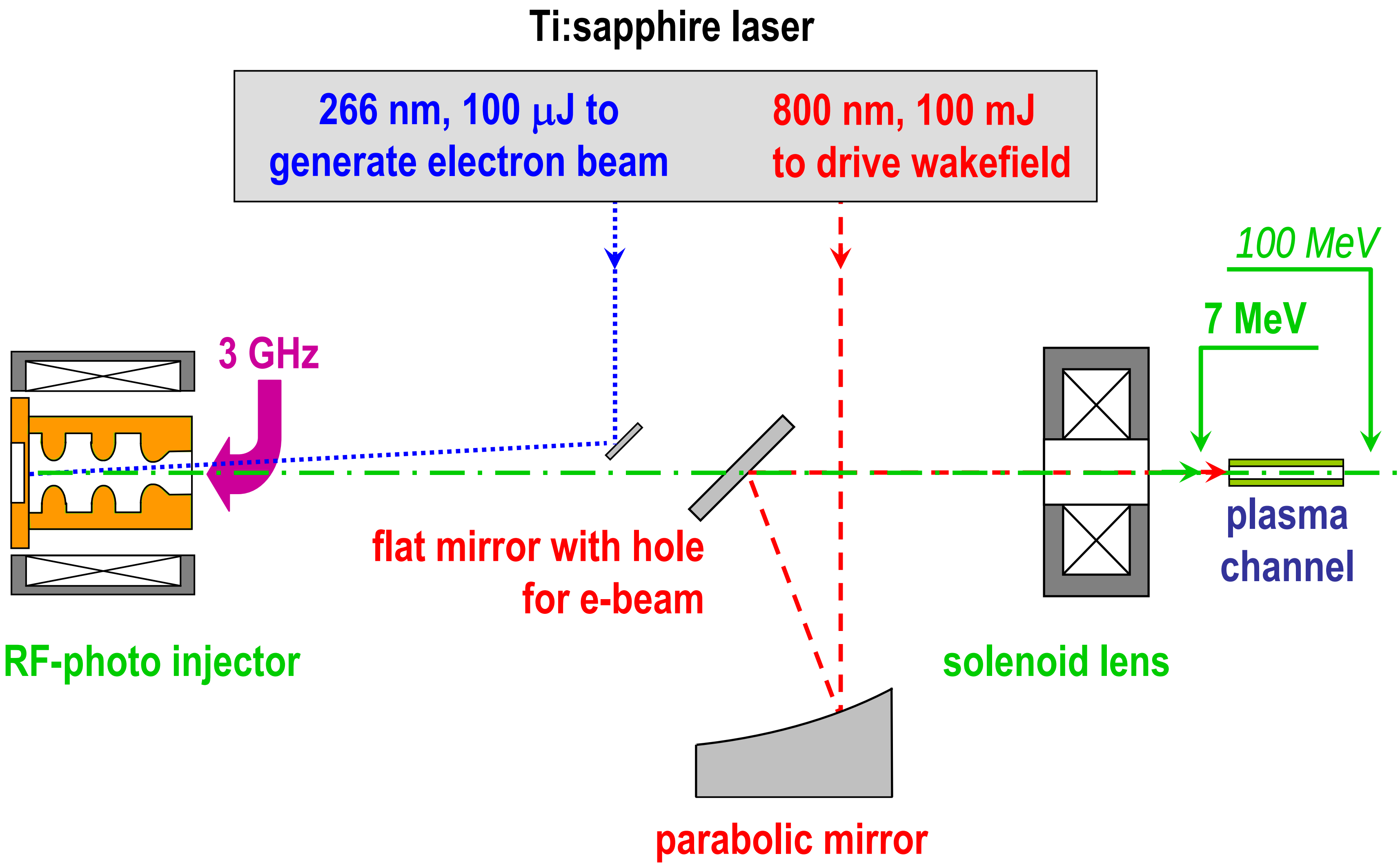
Fred Kiewiet et al. , thesis TU-Eindhoven

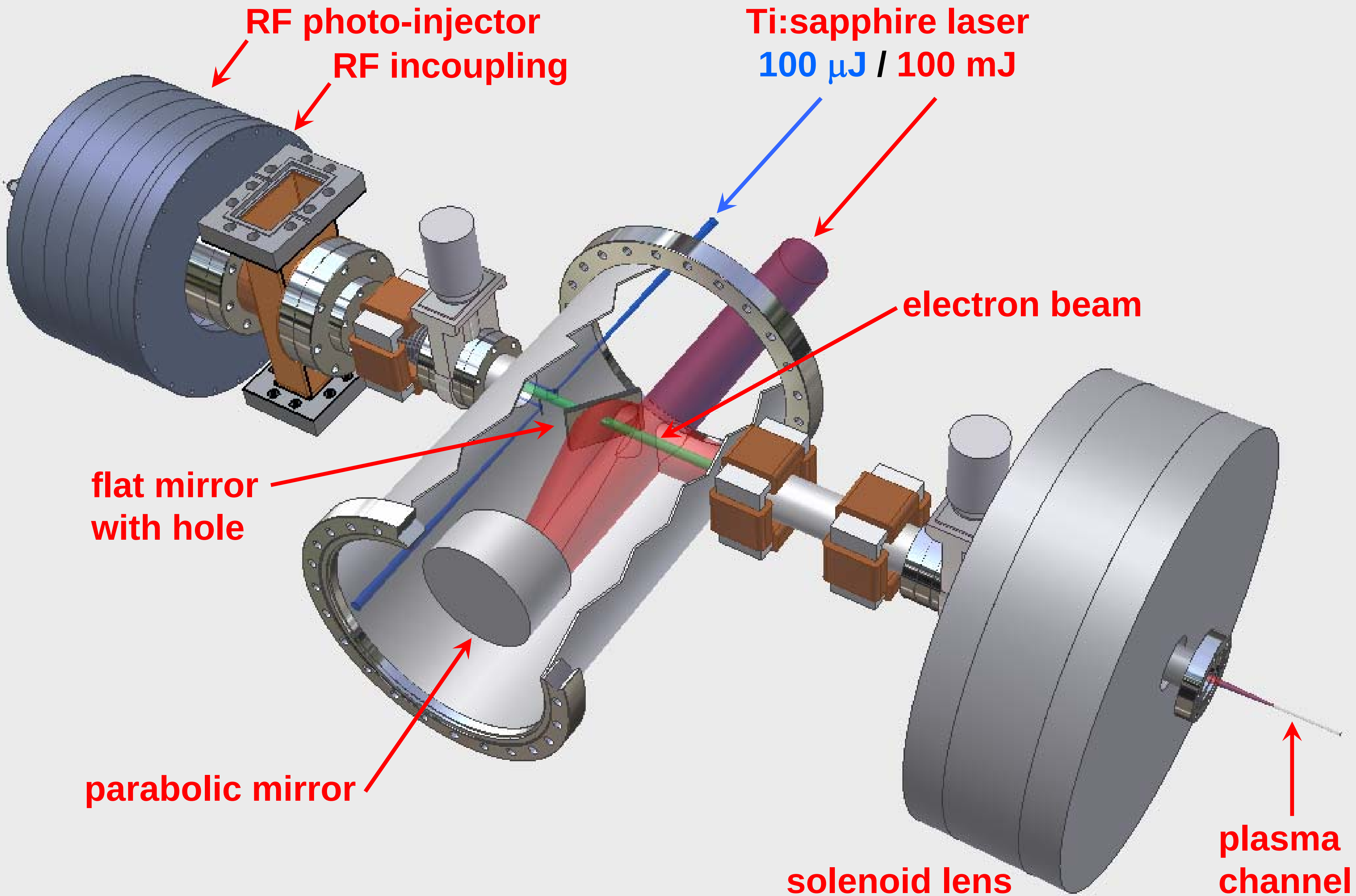


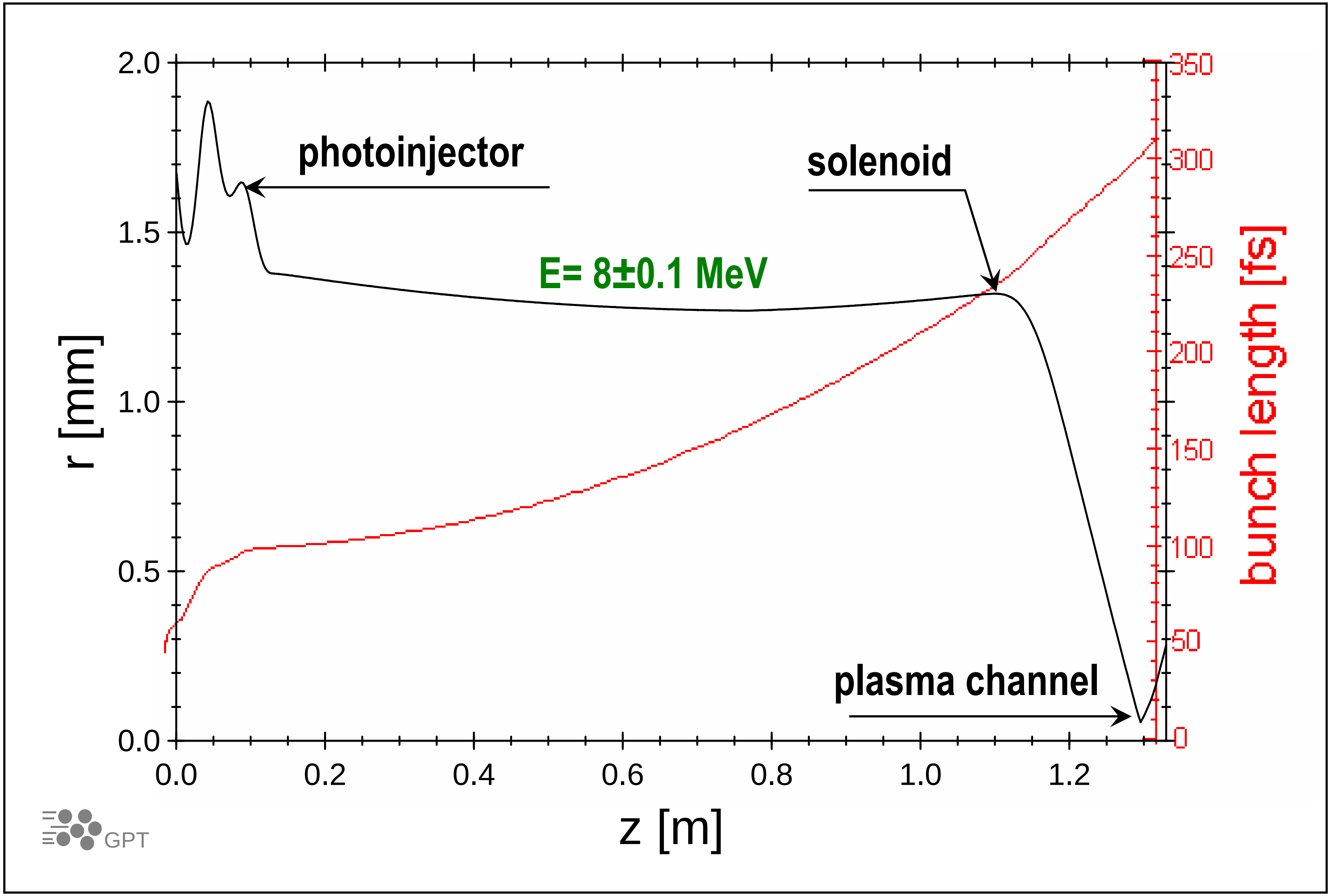


bunch: - 8 MeV
- 100 pC, 1 ps or 10 pC, 200 fs
- $\varepsilon_n \cong 1\ \mu m$

Design of first-demo set-up with presently available components




RF photo-injector
RF incoupling
Ti:sapphire laser
100 μJ / 100 mJ
electron beam
flat mirror
with hole
parabolic mirror
solenoid lens
plasma
channel



photoinjector
solenoid
E= 8±0.1 MeV
plasma channel
r [mm]
2.0
1.5
1.0
0.5
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
z [m]
350
300
250
200
150
100
50
0
bunch length [fs]
GPT

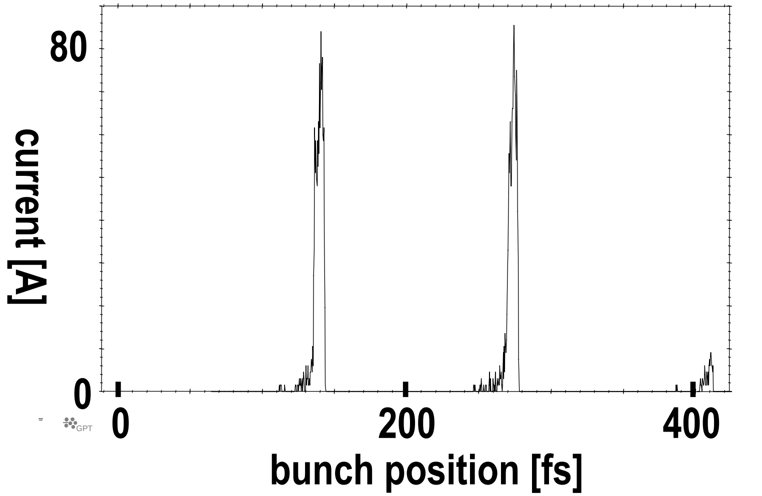
GPT predictions for first demo of controlled LWA

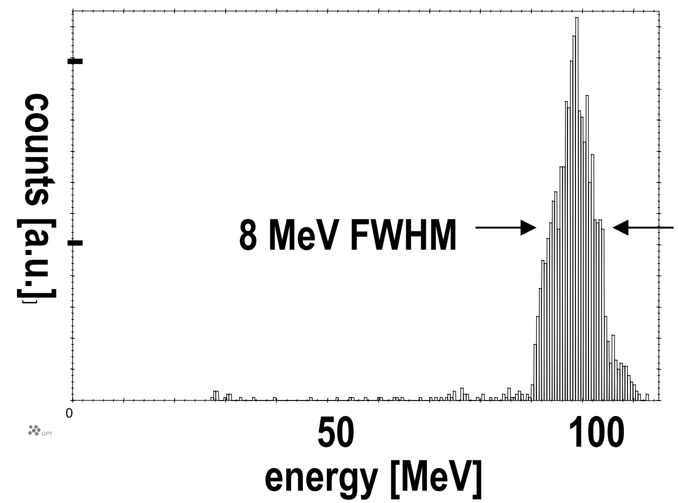
Input

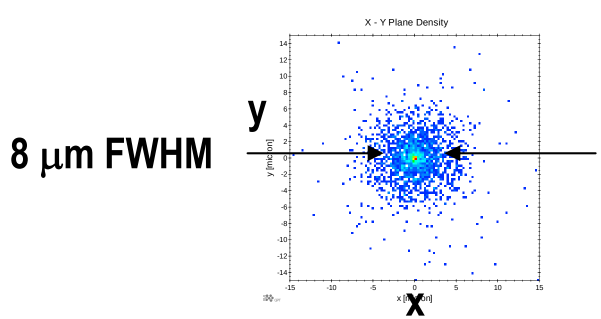
- bunch: 10 pC, 300 fs, 7 MeV
- λ_{plasma} : 40 μm (period 120 fs)
- laser: 0.1 J, 50 fs in 30 μm

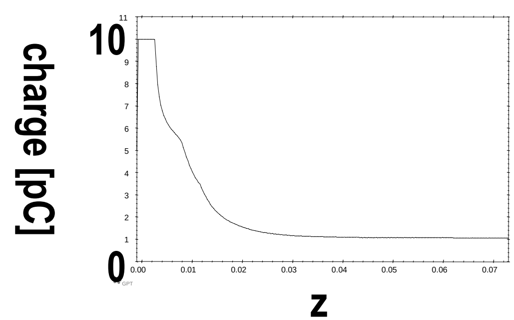
~2 buckets filled

Output









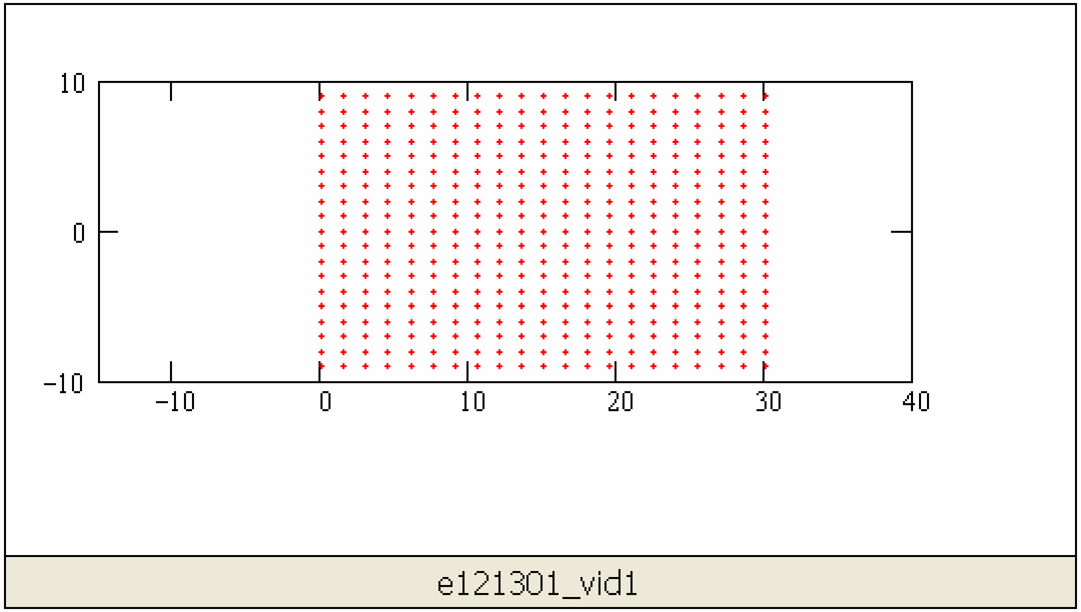
Predictions Khachatryan et al. for U-Twente approach

Input

bunch: 5 λ_{plasma}, 1.1 MeV

laser: a_0=2

Process



Conclusions & Outlook for Part 1: Plasma Acceleration

- recent results in Nature make Laser Wakefield Acceleration a serious business;

  laser / gas-jet approach already interesting for e.g. injection in GeV accelerator

- to suppress shot-to-shot variations in charge/energy, further work needed on:

  - reproducible laser profiles *and /or*
  - internal injection with laser pulses

- first demo of 'controlled' wakefield acceleration possible with present components;

  integrated experiments being prepared by national consortia in NL and UK

- full demo requires further development on:

  - injector
  - plasma channel: operation at lower pressure / longer plasma waves

Part 2.

Compact, high-gradient injector development:

Towards brighter, shorter electron bunches
for improved injection
and a variety of other applications

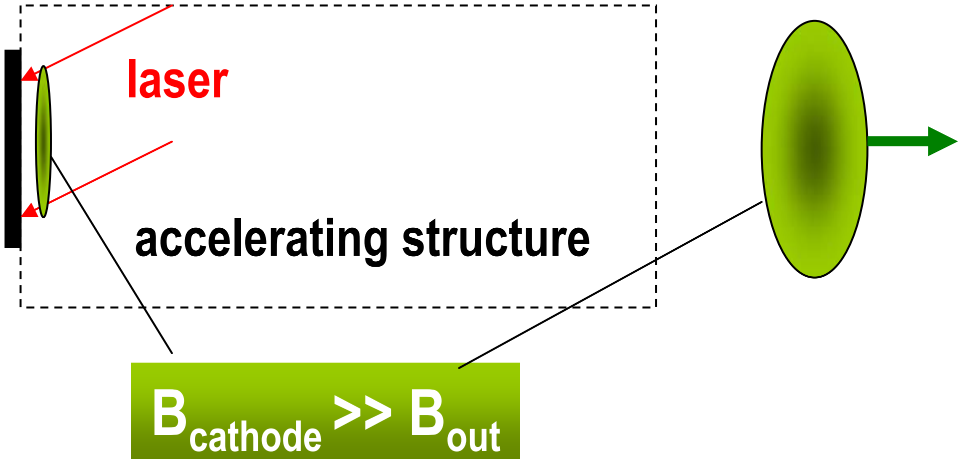
Electron bunches: brighter and shorter!

Issues	Current paradigm	Novel concepts at TUE
• space charge	• keep ρ low, use ps laser • accelerate in highest field • compress at large γ	• space charge not the problem!
• space charge distribution	try 'truncated-Gaussian' or 'top-hat' radial laser profile	• create 'pancake' bunch • let evolve into 'waterbag' with linear self-fields
• thermal emittance	still the best there is!	ultra-cold plasma as cathode

	↓ *stagnation!*	↓ *progress!*

Electron bunches from compact injectors:
State-of-the-art

RF photogun



due to: - ~~space charge~~
- space charge <u>distribution</u> giving non-linear self-fields

&

- non-ideal optics
- wakefields

Electron bunches from compact injectors:
1. How to make them brighter?

1- how to create ideal bunches with linear self-fields?

2- how to reduce the thermal emittance at the cathode?

The ideal 'waterbag' bunch: a homogeneously-filled ellipsoid having linear self-fields

Novel concepts and recipe:

1- create half-circular radial intensity profile of a fs-laser

2- create fs 'pancake' of charge out of a fs-response photocathode

3- let evolve in E_{accel} >> E_{self} into waterbag

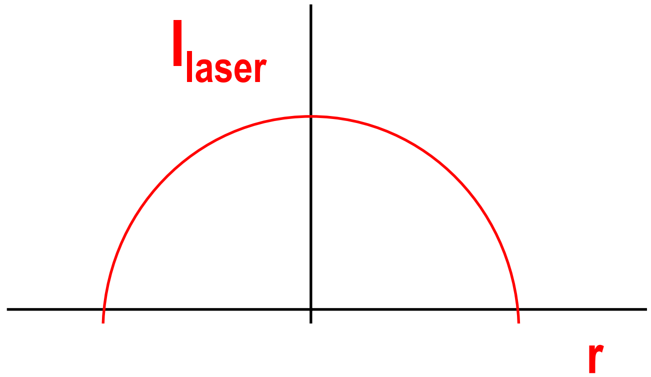
4- conserve ideal bunch properties, even for non-relativistic energy:

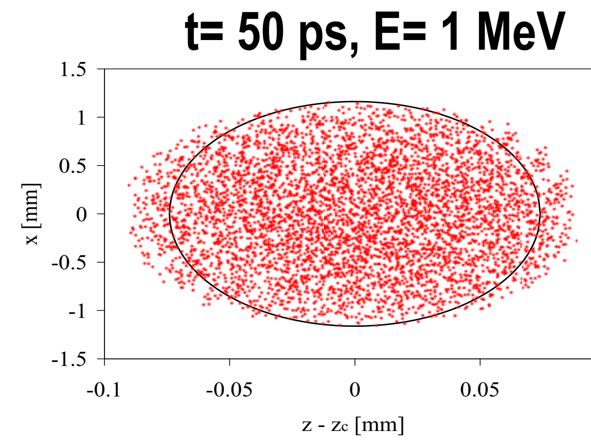
- **→ purely linear self-fields**
- **→ no transverse / longitudinal coupling**
- **→ brightness conserved,**

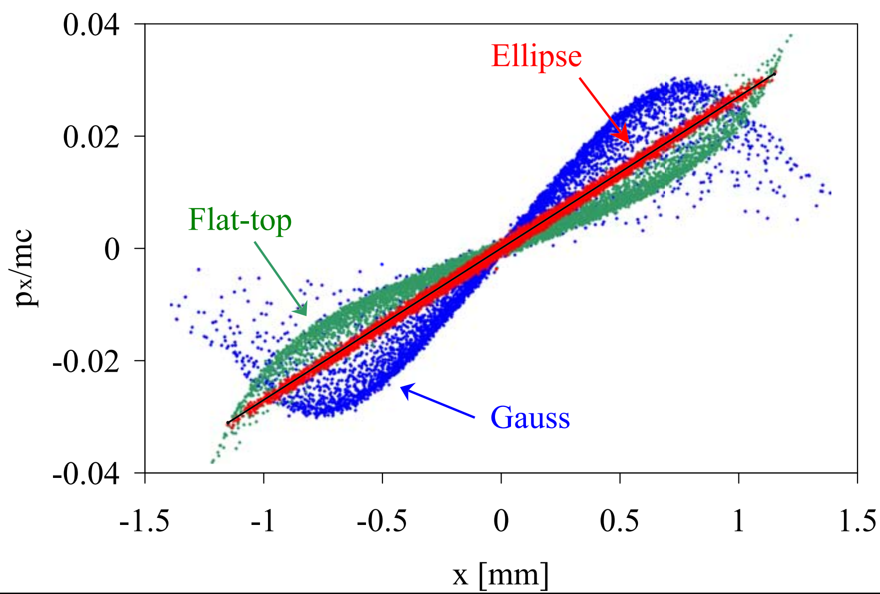
  except for path-length differences and non-ideal optics

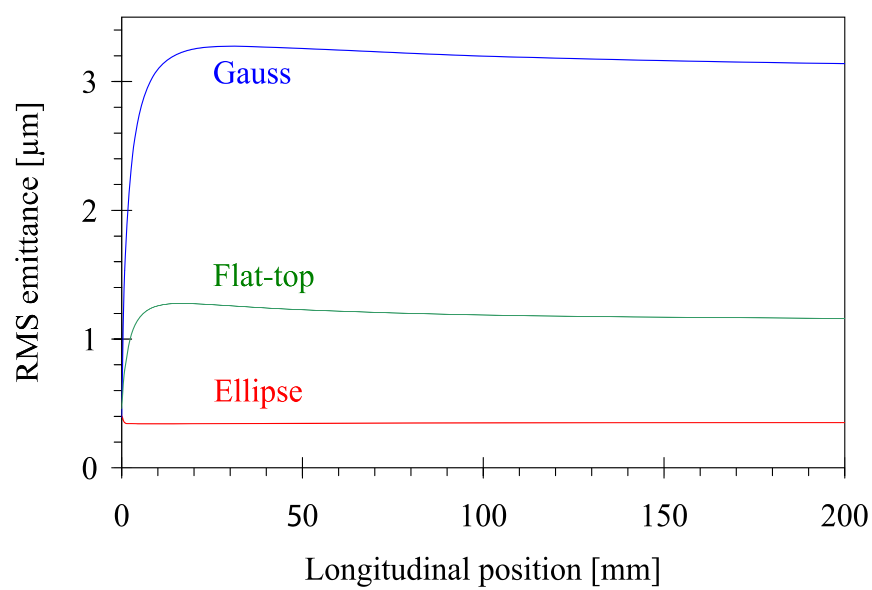
Pancakes evolving into bunches with purely linear self-fields

Luiten, Van der Geer and Van der Wiel, PRL 93,094802-1 (2004)









The thermal emittance at the cathode

Novel concept and recipe:

1- create ultra-cold gas in MOT

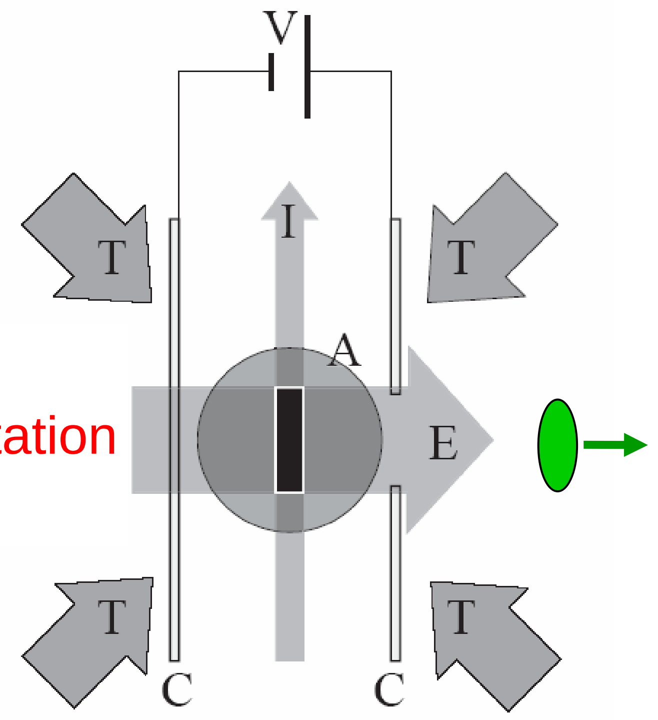
2- photo-ionize a pancake slab

3- extract electrons with $E_{extract} >> E_{self}$

4- end up with ultra-bright waterbag

N.B. : ionization laser is narrow-band,
ns pulses for minimal excess energy

excitation



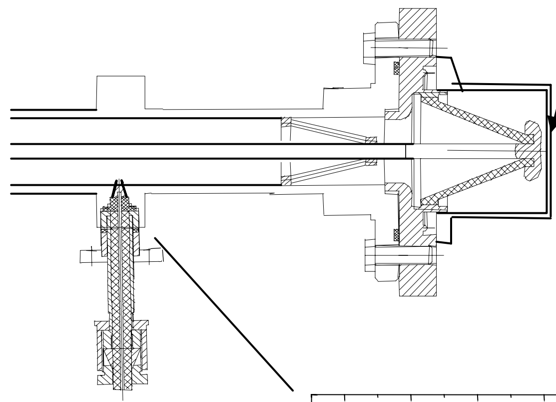
ionization
(10ns pulsed
dye)

Pulsed-DC photogun: ≥ 1GV / m on cathode

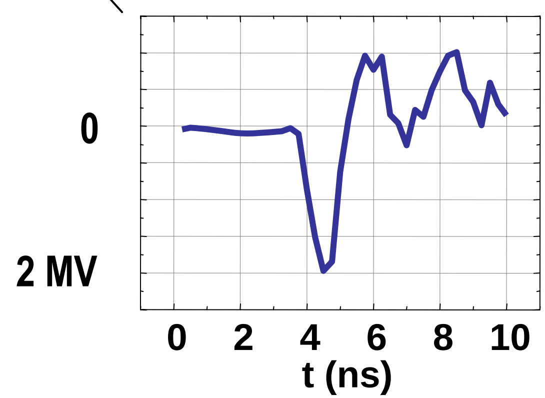
Dmitry Vyuga and Seth Brussaard, TU-Eindhoven

2 MV pulser & pulse shaping transmission line

voltage doubling → 4 MV across 3-mm gap, i.e. 1.3 GV/m



controlled field emission of 4 MeV electrons



Conclusions & Outlook for Part 2: Injectors

- **state-of-the-art injector enables first demo**
- **novel concepts for significant improvement of specs identified**
- **improved injector allows full demo of controlled acceleration with specs comparable to laser / gas-jet approach**
- **novel concepts also lead to stand-alone small accelerators for interesting applications such as:**

  → *ultrabright laboratory THz-source*
  → *fs time-resolved electron microscopy*
  → *fs time-resolved electron diffraction*