Ultra-high-Gradient Compact Accelerator Development

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Beyond RF- technology : towards GV - TV/m

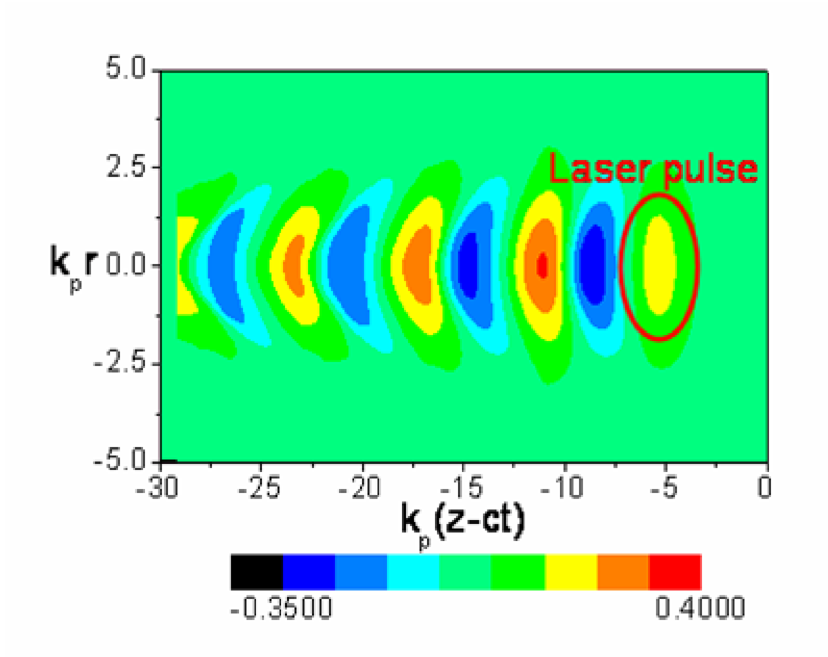
Options: - electron-driven plasma waves (SLAC ‘afterburner’)

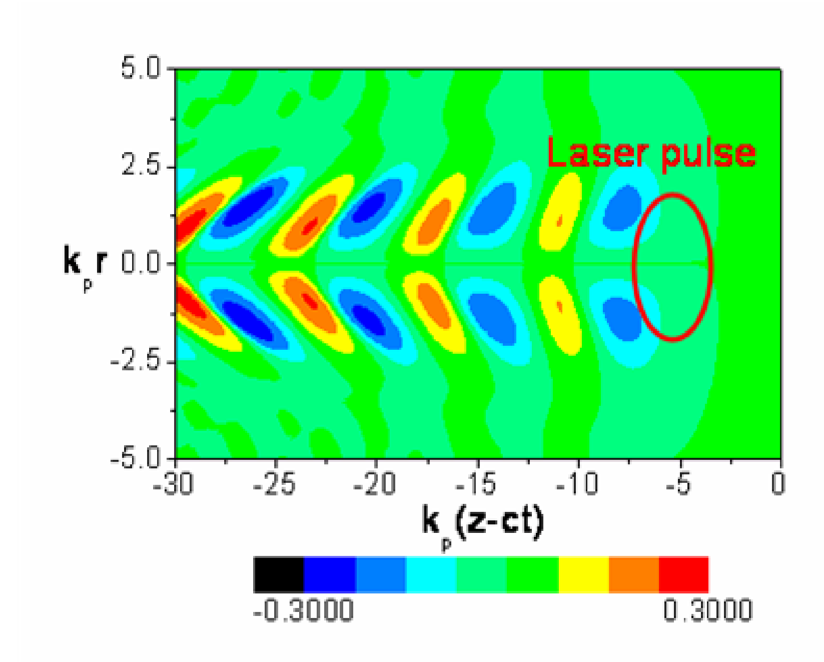
- laser-driven plasma waves

- laser in vacuum

- pulsed-DC

Laser-driven plasma waves: principle





Longitudinal wake-field:

blue – accelerating,

red – decelerating.

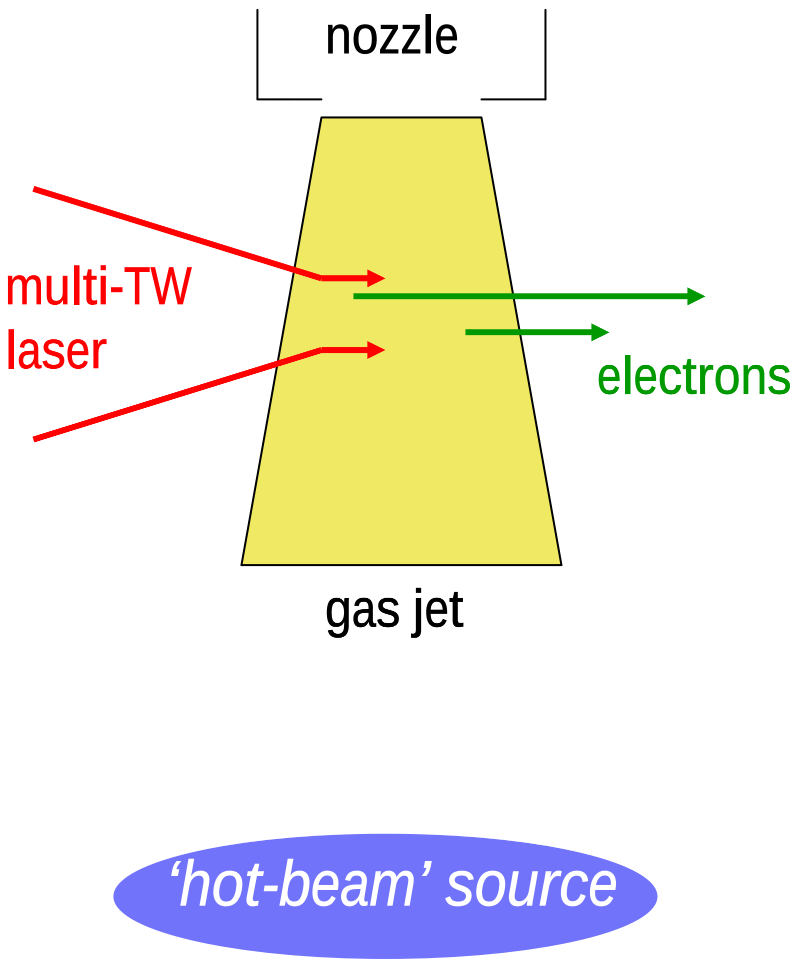
Transverse wake-field:

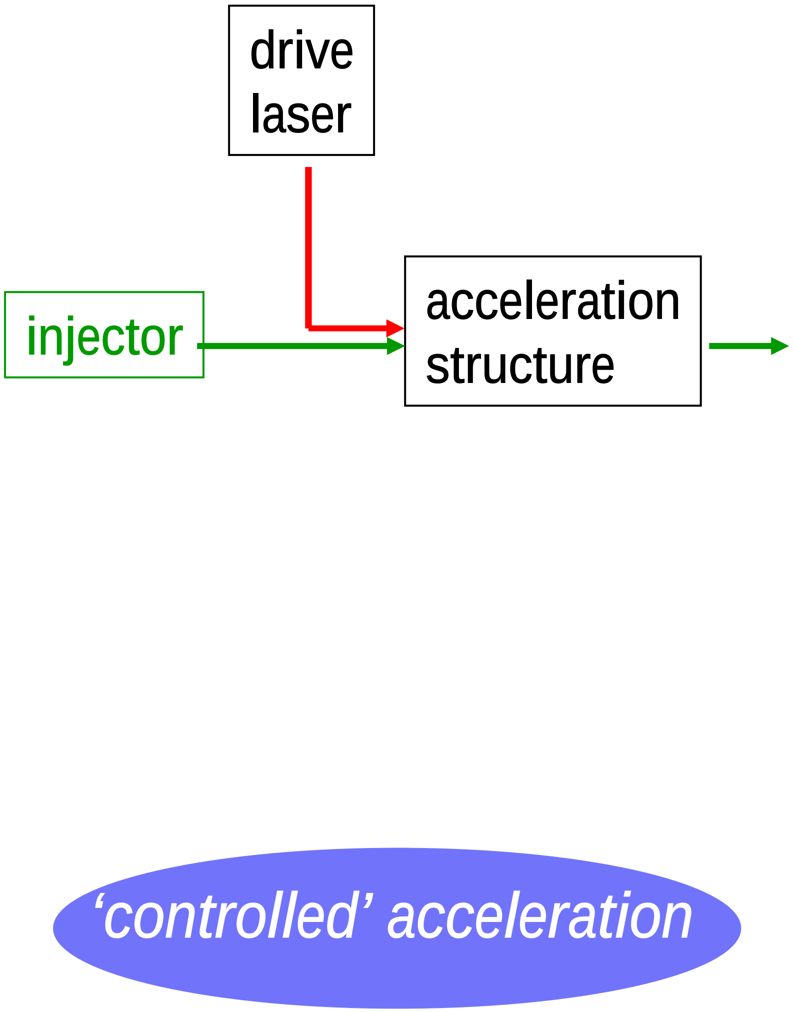
blue – focusing,

red – defocusing.

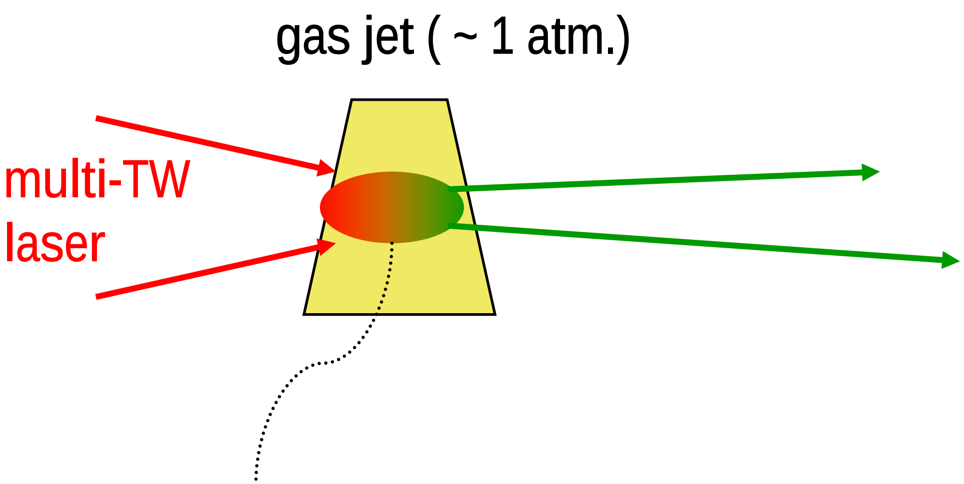
λ_{plasma} = 10 µm – 1 mm ; gradient 1 GV/m – 1 TV/m, limited by wave breaking

Laser-driven plasma waves : Options





Hot-beam 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

electron beam:

- charge per pulse several nC
- short pulse (~ 100 fs)
- norm. emittance few µm

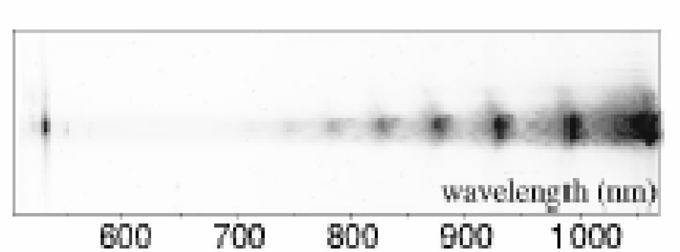
but

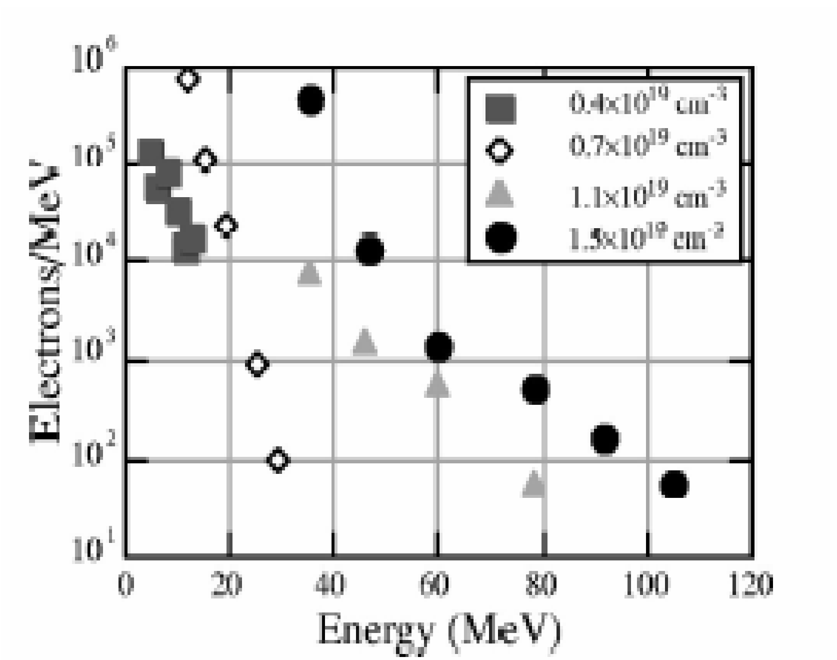
- MeV-'temperature' beam
- shot-to-shot intensity variations of factor 3-10

Hot-beam Source: Experiments

self-modulated regime:

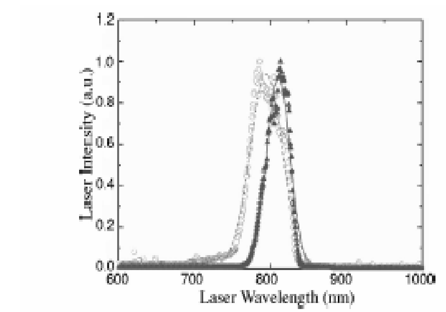
$\tau_{laser} \geq \omega_{plasma}$

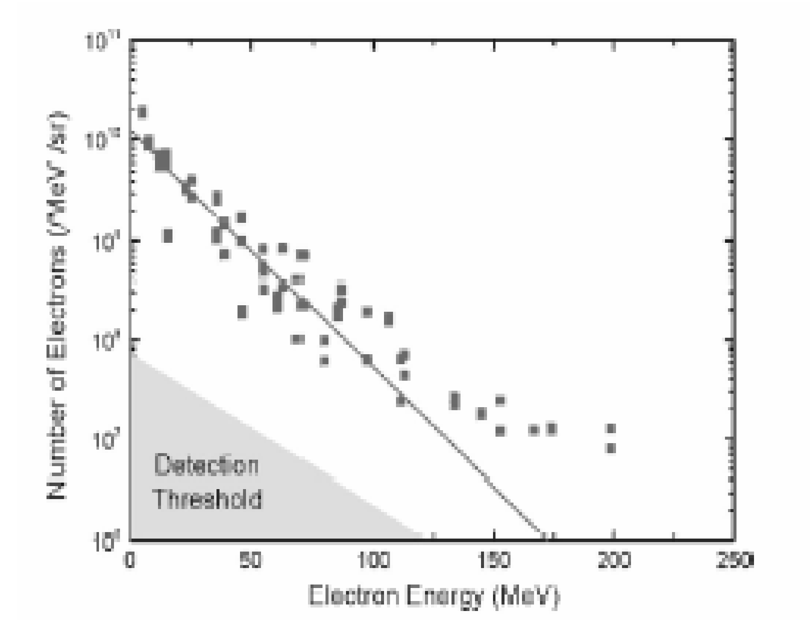




forced wakefield regime:

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





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

Hot-beam Source: possible applications

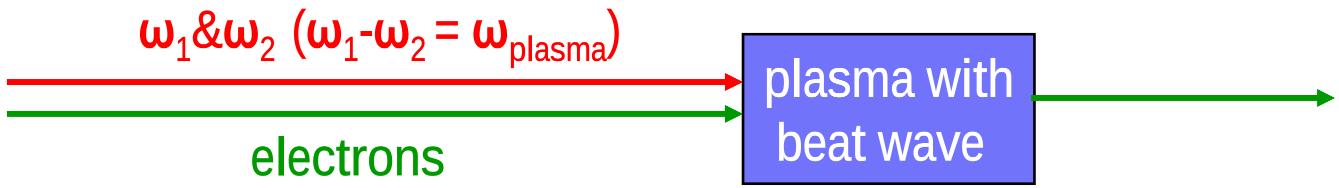
- pulsed radiolysis / electron-photon pump probe

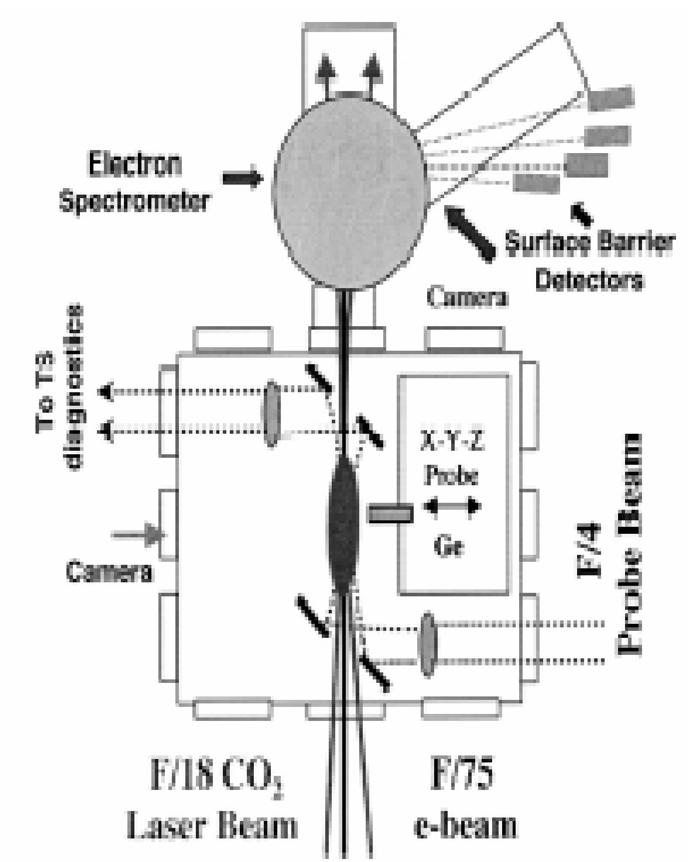
- X- and γ-ray source

- use energy slice for injection into 2nd stage wakefield accelerator

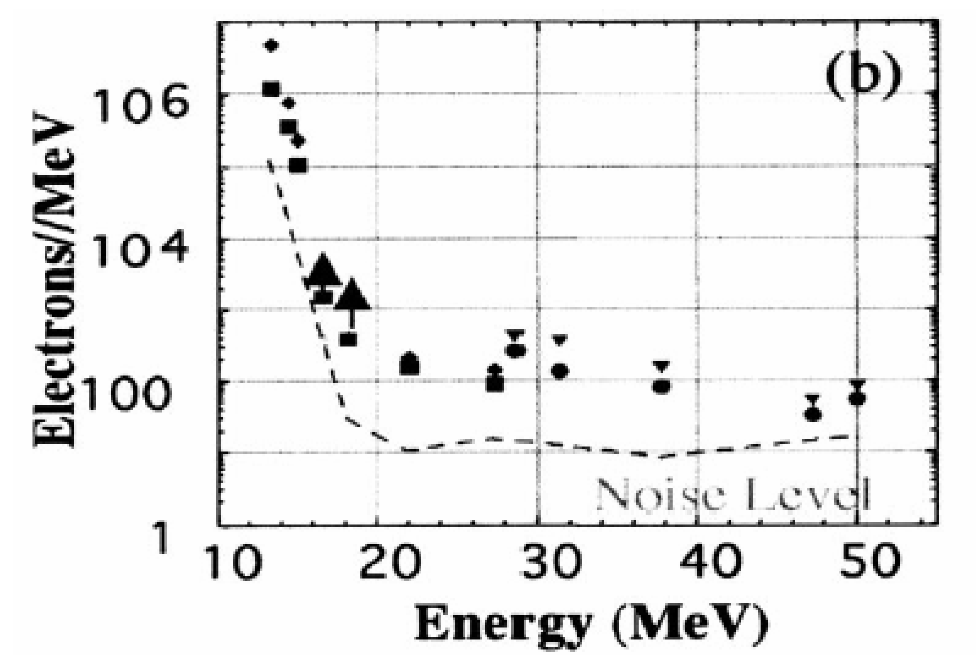
- proton beams $\leq$ 10 MeV (from foil) for radio-isotope production

Beat-wave Acceleration



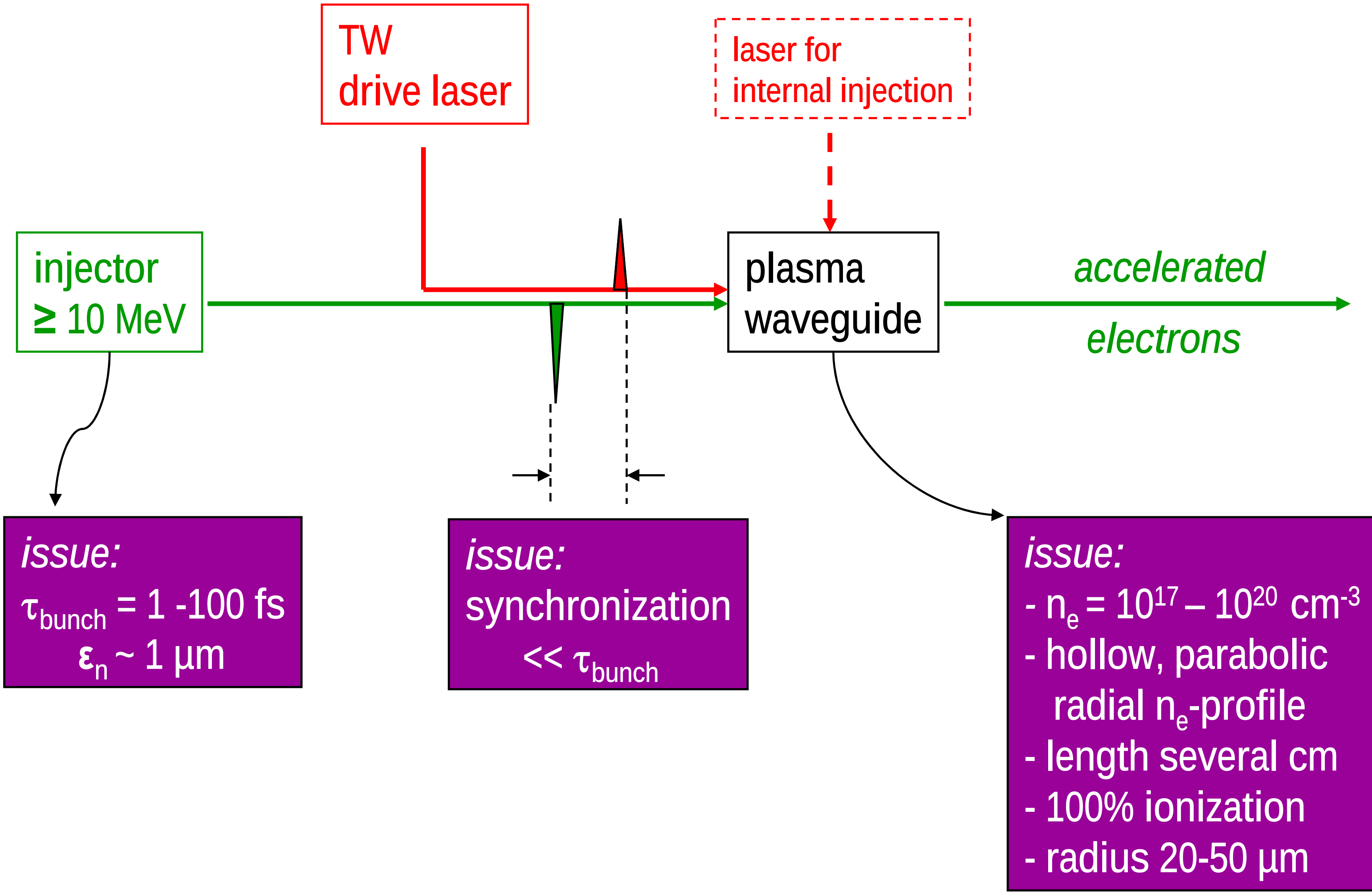


injection: 12 MeV, 10 ps
λ_{plasma} = 300 μm
gradient=1.3 GV/m



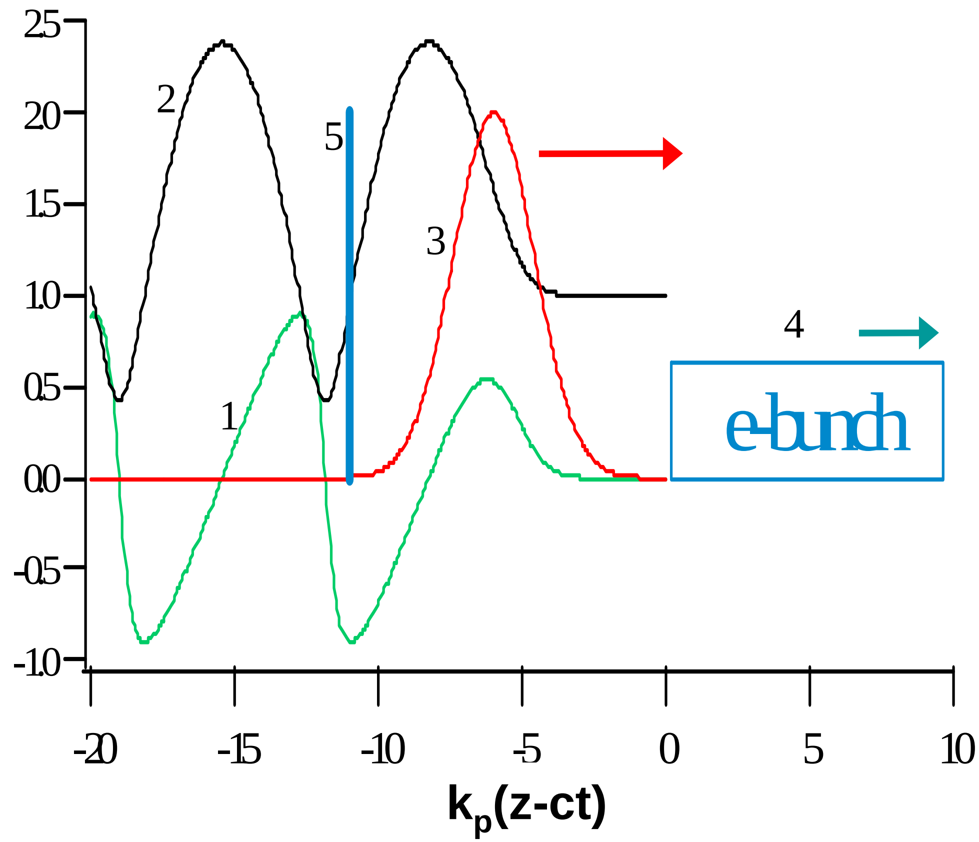
Clayton, Joshi, Rosenzweig et al., Phys. Plasmas 11, 2875 (2004)

Controlled Wakefield Acceleration: Lay-out & Issues



Alternative for injection / compression / acceleration

1: accelerating field
2: wake-field potential
3: laser pulse
4: initial electron bunch
5: trapped e-bunch



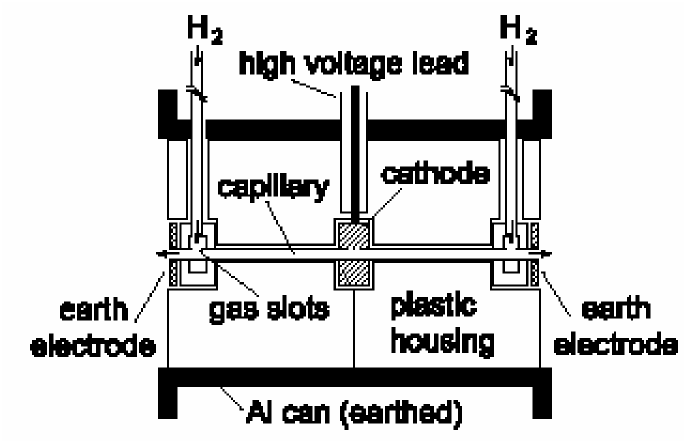
Khachatryan, Van Goor, Boller, Proceedings PAC'03, 1900 (2003).

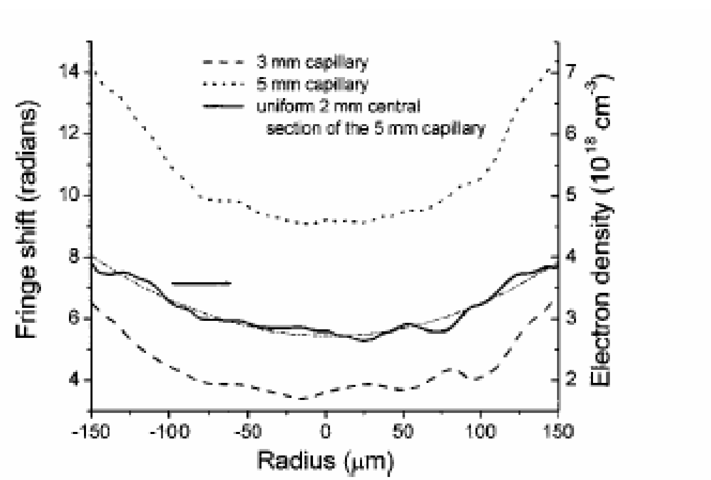
Issue 1: Plasma Waveguiding of TW Laser Pulses

Option	Process	Remarks
• self-focussing	local change of refract. index due to relativ. mass correction of oscillating electrons	instability
• gas-filled capillary	internal reflection; laser ionizes gas	single shot
• 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

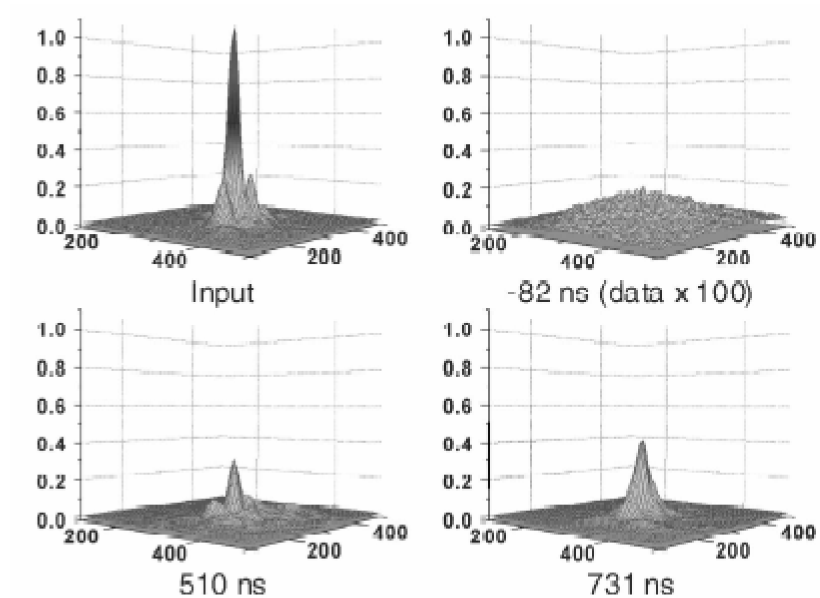
Capillary discharge plasma channel

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



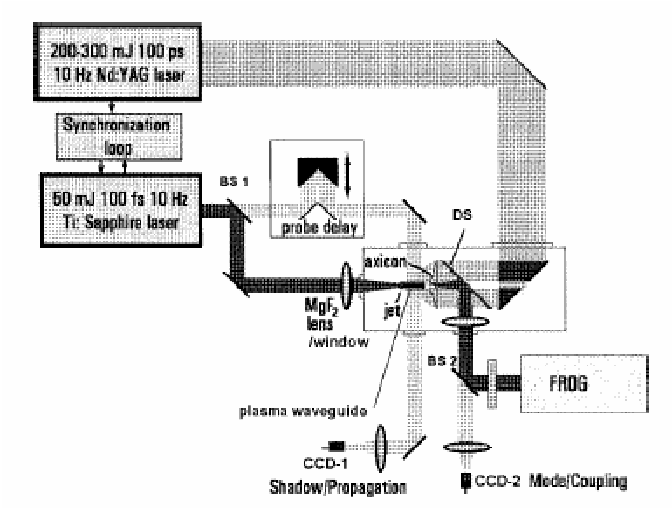


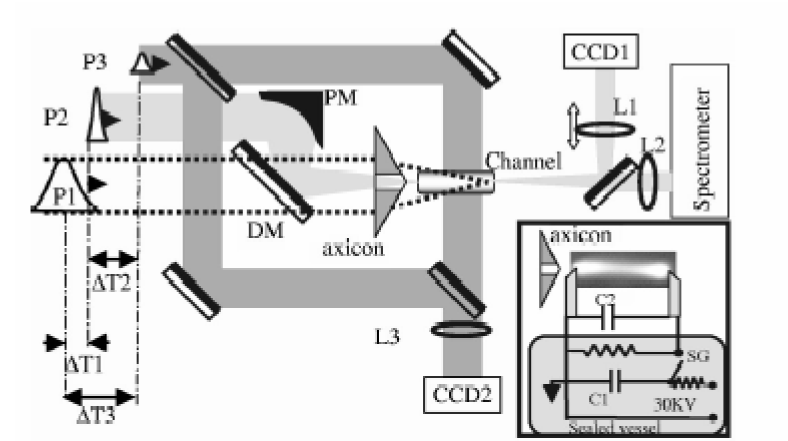
$1.0 = 10^{17}$ W/cm^2

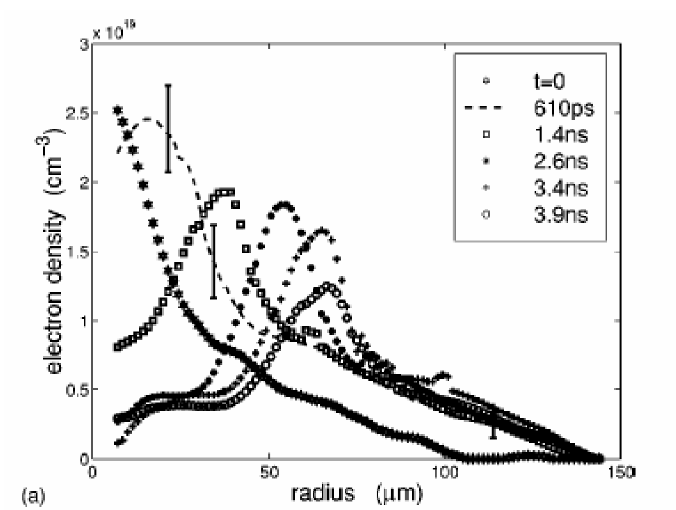


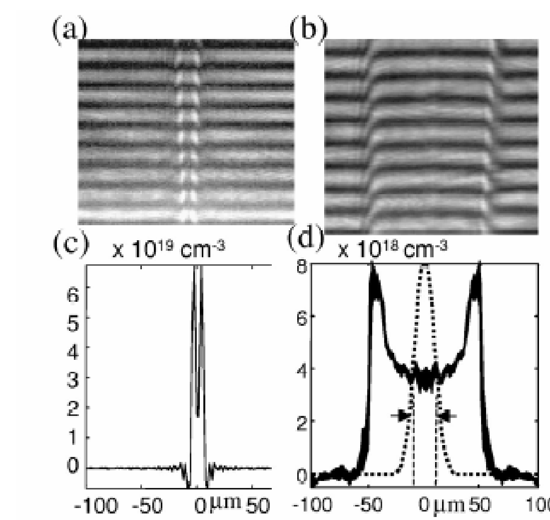
Status: - simple and cheap
- good transmission of TW pulses
- further work needed for pressures ≤ 10^{18} cm^{-3} (λ_{plasma} ≥ 300 μm)

Laser-produced plasma channels







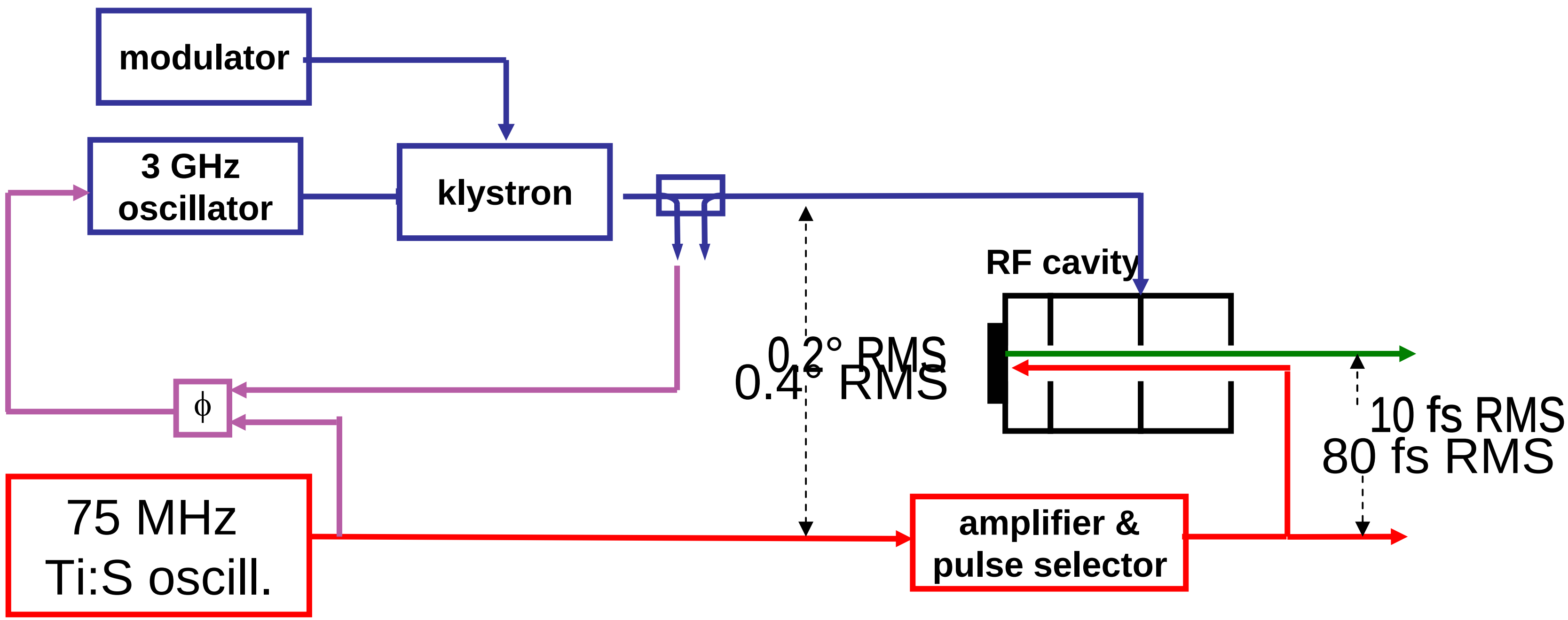


Nikitin et al, Phys Rev E 59,3839 (1999)

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

Issue 2: Synchronisation of RF and laser

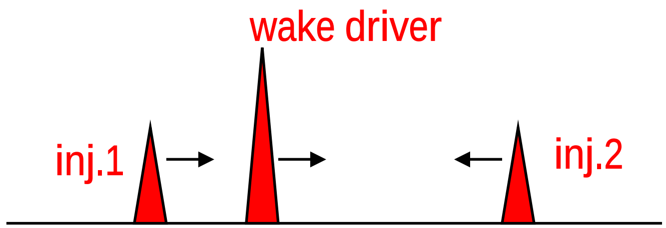
- State-of-the-art for case of RF master / laser slave: ~ 1 ps
- Recent progress at TU- Eindhoven by choosing laser master / RF slave: 80 fs
  (Kiewiet et al., NIM-A, A484, 619, 2002)



- Easy route towards 10 fs: - klystron power stability 0.1% → 0.05%
  - RF cavity 2.6 cell → 2.5 cell

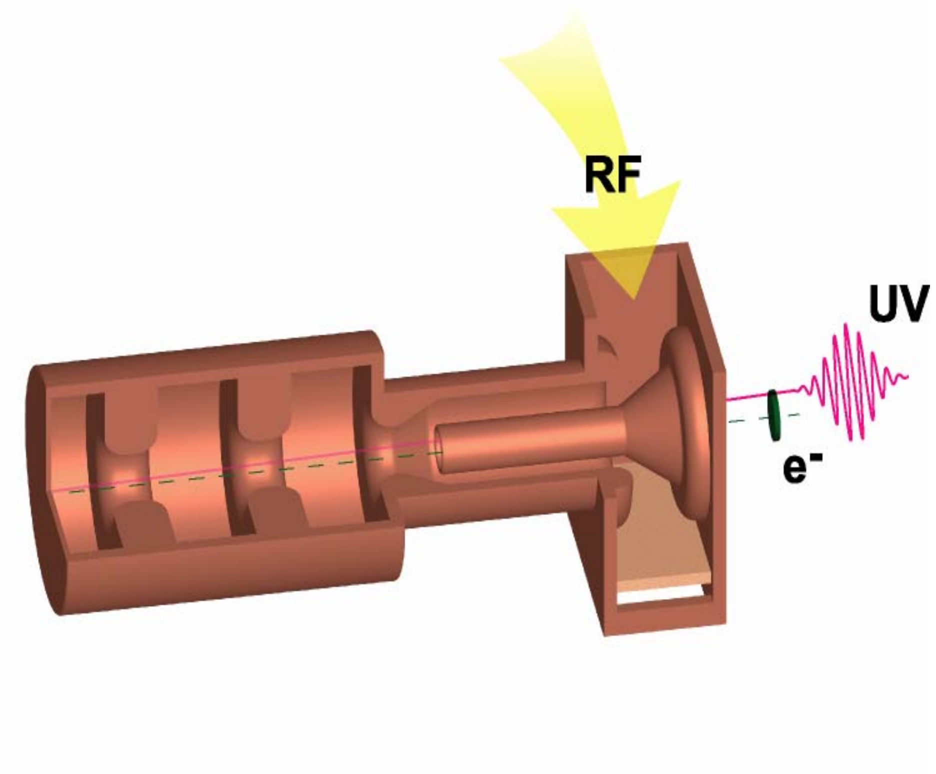
Issue 3: Injection

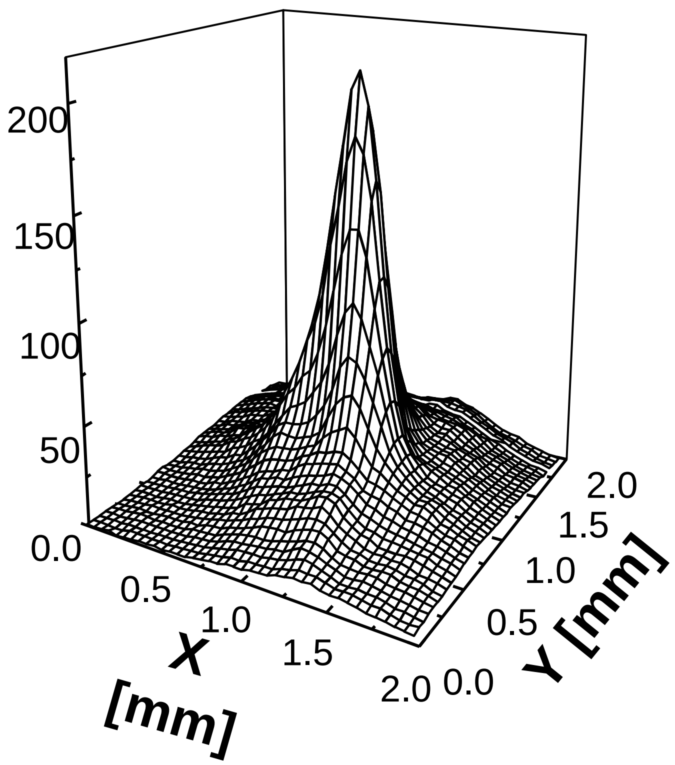
Options for 10-100 fs bunches with reasonable charge (I_{peak}= 100 A –1 kA)	achieved	promised
• *external:*		
- RF photogun & metal cathode	1 ps, 100 pC	100 fs, 10 pC
- pulsed-DC photogun & metal cathode	(1.3 GV / m)	100 fs, 100 pC
- idem, with novel approach to ultra-high brightness	--	10 fs, 50 pC
• *internal:* optical injecton	--	1 fs, 1 pC



RF photogun

Fred Kiewiet et al. , thesis TU-Eindhoven and submitted to Phys.Rev. ST





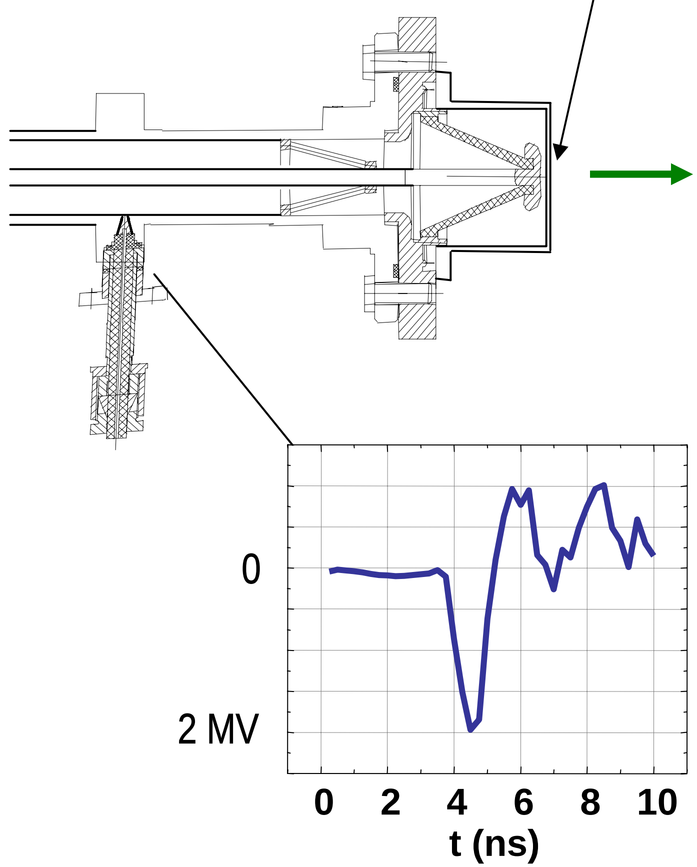
bunch: - 8 MeV
- 100 pC, 1 ps or 10 pC, 100 fs
- $\varepsilon_n \cong 1\ \mu m$

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

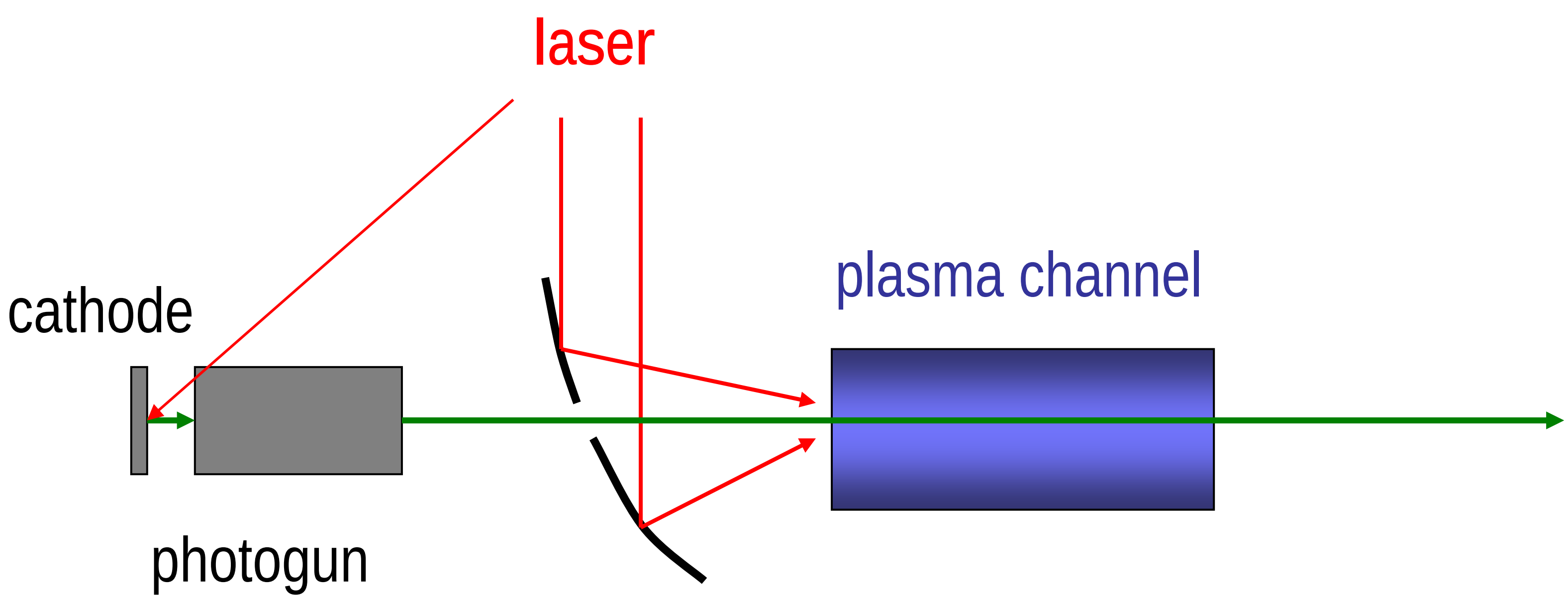
Dmitry Vyuga and Seth Brussaard, TU-Eindhoven

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

controlled field emission
of 4 MeV electrons



Integrated Experiment with *present* components



now:

injected bunch
10 pC, 100fs (30 μm)

0.25 λ_{plasma}
50 μm

accelerated bunch
50 ± 20 MeV

later:

100 pC, 50 fs (15 μm)

250 μm

200 ± 5 MeV

Phase-space control of short bunches with high space charge

Standard approach:

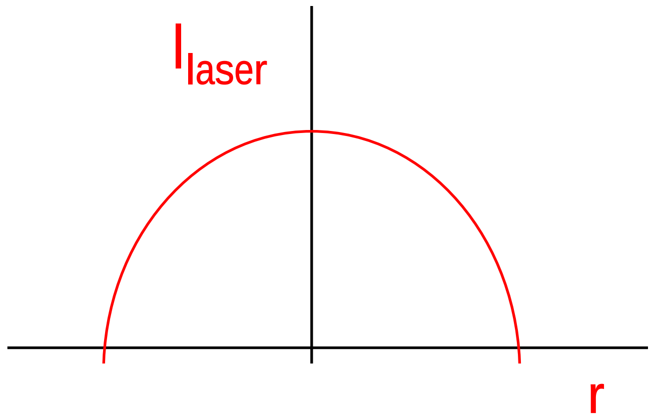
- keep space charge low near cathode
- use ps-laser on (high-efficiency) ps-response cathode
- compress to sub-ps at high energy

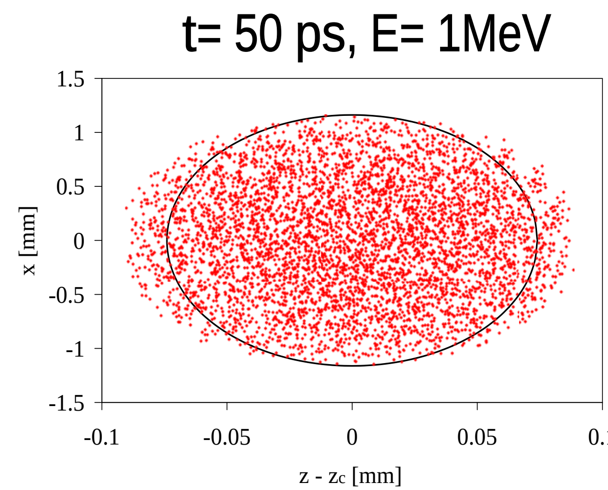
Novel, <u>counter-intuitive</u> approach for compact injector:

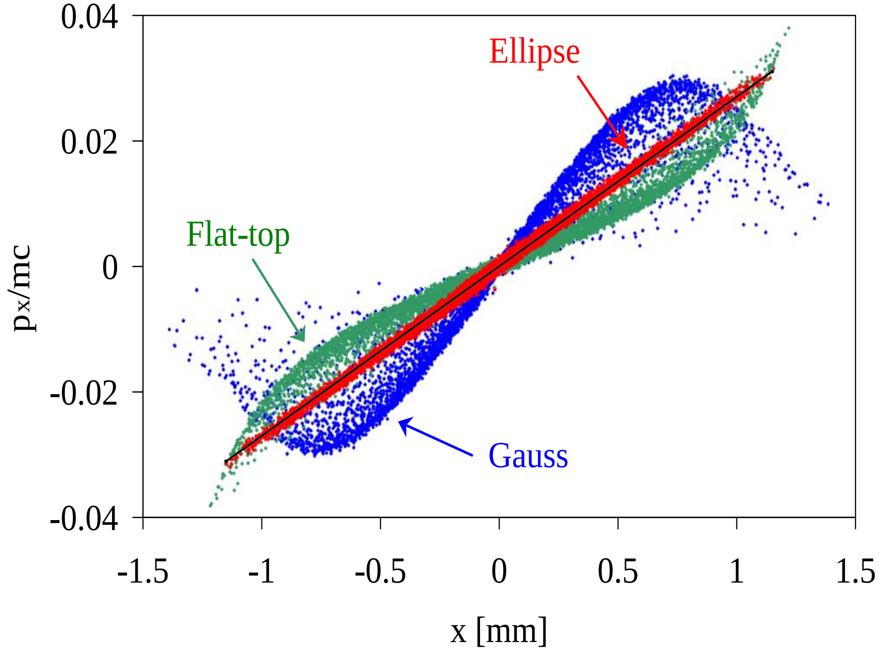
- use fs-laser on (low-efficiency) fs-response cathode
- keep bunch in ‘pancake’ regime up to γ as high as possible
- this <u>reduces</u> emittance dilution due to Coulomb explosion

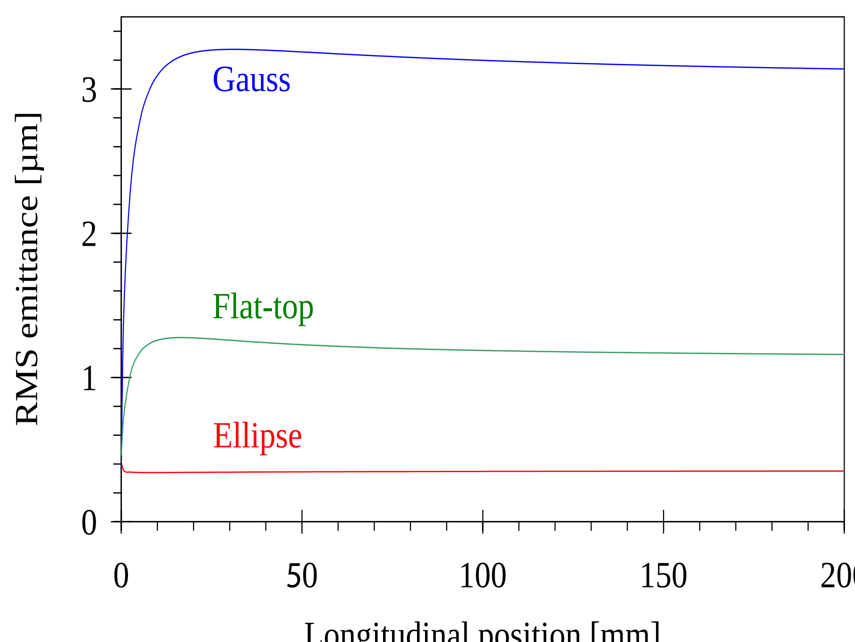
Pancakes evolving into bunches with purely linear self-fields

Luiten, Van der Geer and Van der Wiel, PRL 2004 (accepted)









Conclusion & Outlook: 1

- *'Hot-beam' source:*

  - works; provides energies up to few 100 MeV

  - may find niche applications

  - progress towards mono-energetic beams
    requires all-optical injection of $\sim$1 fs bunches

Conclusion & Outlook : 2

- *Controlled acceleration:*

  - components available for first demo of ‘regular’ acceleration and of novel injection / compression / acceleration scheme

  - integrated experiments being prepared by national consortia in both The Netherlands [1)] and the UK [2)]

  - full demo requires further development
    - on injector: demo of laser radial profile shaping and / or of pulsed-DC photogun
    - on plasma channel: operation at lower pressure / longer plasma waves

1) TU-Eindhoven, FOM-Institute for Plasma Physics, University Twente
2) Univ Strathclyde, RAL, Imperial College, Oxford Univ, Daresbury Lab, St. Andrew’s Univ, Univ Abertay