A plasma source for laser-plasma accelerators

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Outline

- Laser-plasma accelerators introduction
- Scaling laws for electron accelerators
- Initial work at plasma channeling (IST and UCLA)
- Discharges on structured gas cell as a plasma source for e^- acc.
- DC discharge for plasma smoothing
- 8 cm plasma channel status
- e^- beam injection on plasma channels
- Conclusions

Where is the mark on the LPA roadmap ?

- 2004 - mono-energetic e^- beams demo
  - S.P.D. Mangles et al., Nature 431, 535 (2004), C.G.R. Geddes et al., Nature 431, 538 (2004), J. Faure et al., Nature 431, 541 (2004)
- 2006 - 1 GeV mono-energetic beam demo
  - W. P. Leemans et al., Nature Phys. 2, 696 (2006)
- 2006 - some injection control
  - J. Faure, et al., Nature 444, 737 (2006)
- 2007 - scaling laws for LPA's
  - W. Lu, et al., Phys. Rev. ST Accel. Beams 10, 061301 (2007)
- 2006 - some applications
  - electron radiography, S. P. D. Mangles, et al., Laser and Particle Beams, 24 (1), pp. 185 (2006)
  - visible light by periodic B, H. P. Schlenvoigt, et al., Nature Physics 4, 130 (2008)
  - UV light by periodic B, M. Fucks, et al., Nature Physics 5, 226 (2009)
  - ...

Scaling laws for laser-plasma accelerators *

Three main regimes

Bubble

- electrons move faster than laser
- for $n_e=10^{19}$ cm^{-3} requires $a_0=20$ or $I=2\times10^{21}$ W cm^{-2}

$$a_0 \geq \sqrt{2\frac{n_c}{n_p}}$$

for circ. pol. laser,
for lin. pol laser is 1.4 times higher

$$\Delta E\,[GeV] \simeq 0.018\frac{P\,[TW]}{a_0}$$

Blowout - self-guiding

- intensity enough for relativistic guiding $P > P_c$
- matched beam spot size condition $k_p R = k_p w_0 = 2\,(a_0)^{0.5}$
- requires $a_0 > 3$-4 for injection

$$a_0 \simeq \left(\frac{P}{P_c}\right)^{1/3}$$

$$\Delta E\,[GeV] \simeq 0.16\frac{P\,[TW]}{a_0^2}$$

Blowout - external-guiding

- intensity enough for electron cavitation
- requires preformed plasma channel
- requires an external injection mechanism

$$a_0 = 2$$

* W. Lu, et al., Phys. Rev. ST Accel. Beams 10, 061301 (2007)

Example: scaling for ELI

		Laser energy on target	100 mJ 1kHz	1.5J 100 Hz	45 J 10 Hz
Blowout	Self guiding	τ [fs]	9.8	24.2	65.8
		W_0 [μm]	4.4	10.9	29.6
		n_e [10^{19} cm^{-3}]	23.2	3.83	0.63
		L [mm]	0.2	3.3	54.6
		ΔE [GeV]	0.1	0.62	4.59
		Q [nC]	0.13	0.31	1.04
	External guiding	τ [fs]	15.6	38.4	119.2
		W_0 [μm]	7.0	17.3	53.7
		n_e [10^{19} cm^{-3}]	4.62	0.76	0.08
		L [mm]	1.8	26.4	793.1
		ΔE [GeV]	0.26	1.56	15.06
		Q [nC]	0.1	0.25	0.78
Bubble		τ [fs]	6.6	12.2	26.8
		W_0 [μm]	2.0	3.7	8.1
		n_e [10^{19} cm^{-3}]	57.3	24.92	8.74
		L [mm]	0.03	0.2	1.8
		ΔE [GeV]	0.03	0.18	1.5
		Q [nC]	0.55	1.54	5.71

Medium-long term e- beam development

- Laser
  - 20 fs < τ < 120 fs, 1 J < E < 50 J, high stability, (current tech solution: diode pumped Ti: saphire CPA chain)
- Plasma channel
  - 10^{17} cm^{-3} < $n_{e\ axis}$ <5x10^{18} cm^{-3}, 1 cm < L < 1 m
- Injection (beam loading)
  - self injection or colliding beams (dE/E <1%)
  - double stage or other scheme

for application needing...

- short pulses and high currents: Free-Electron-Lasers (seeding required)
- electron beams synch. w/ laser: pump probe experiments
- compact broadband x and gamma-rays: betatron, compton scattering, ...

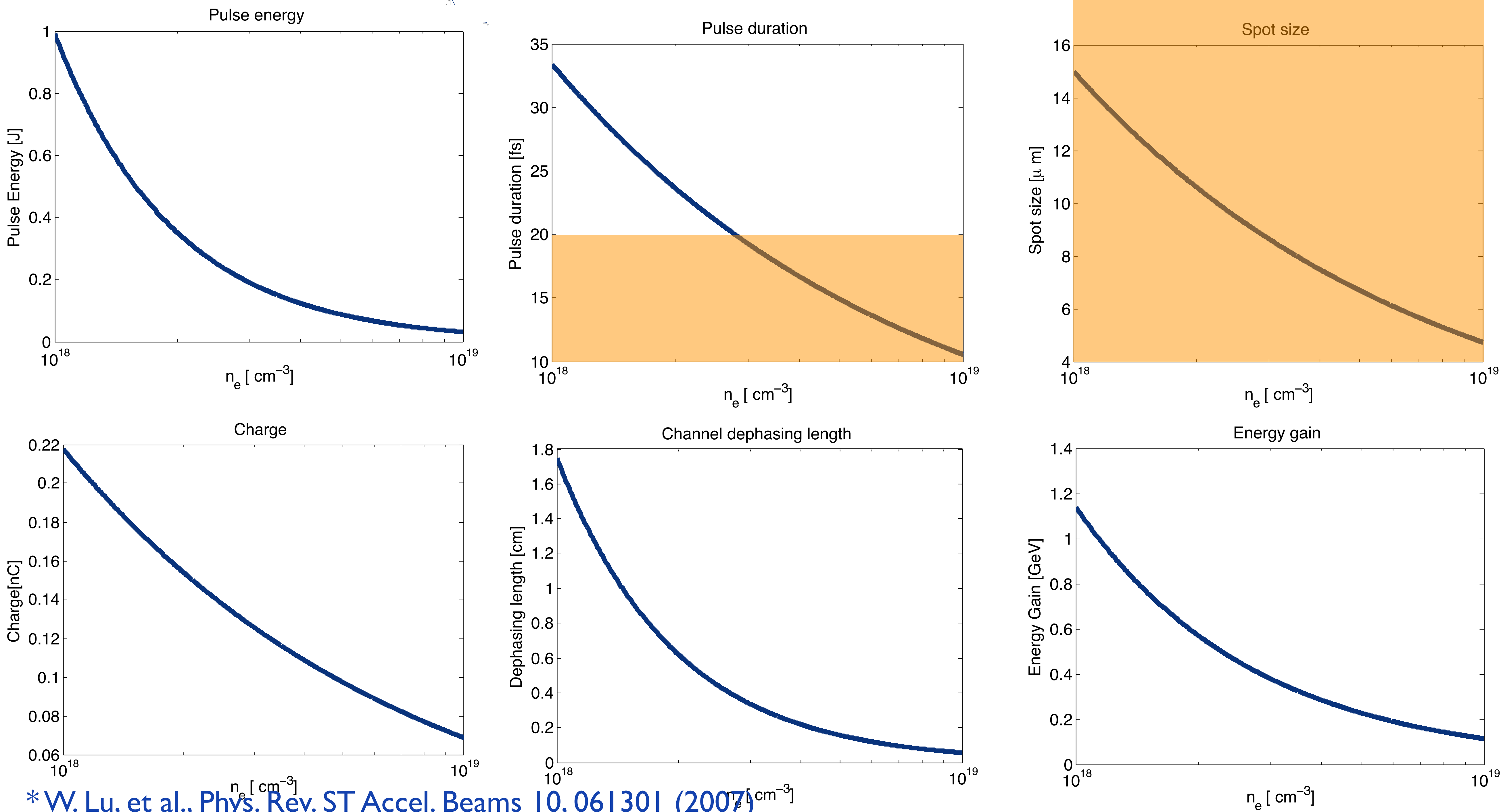
or tolerating...

- few percent dE/E
- beam Coulombian explosion (for high charge & low energy)
- non reproducible E and low rep. rate

Scaling laws for external guided high density LPA*

assumes

- matched propagation external guiding
- a_0=2 for electron blowout
- an external injection mechanism

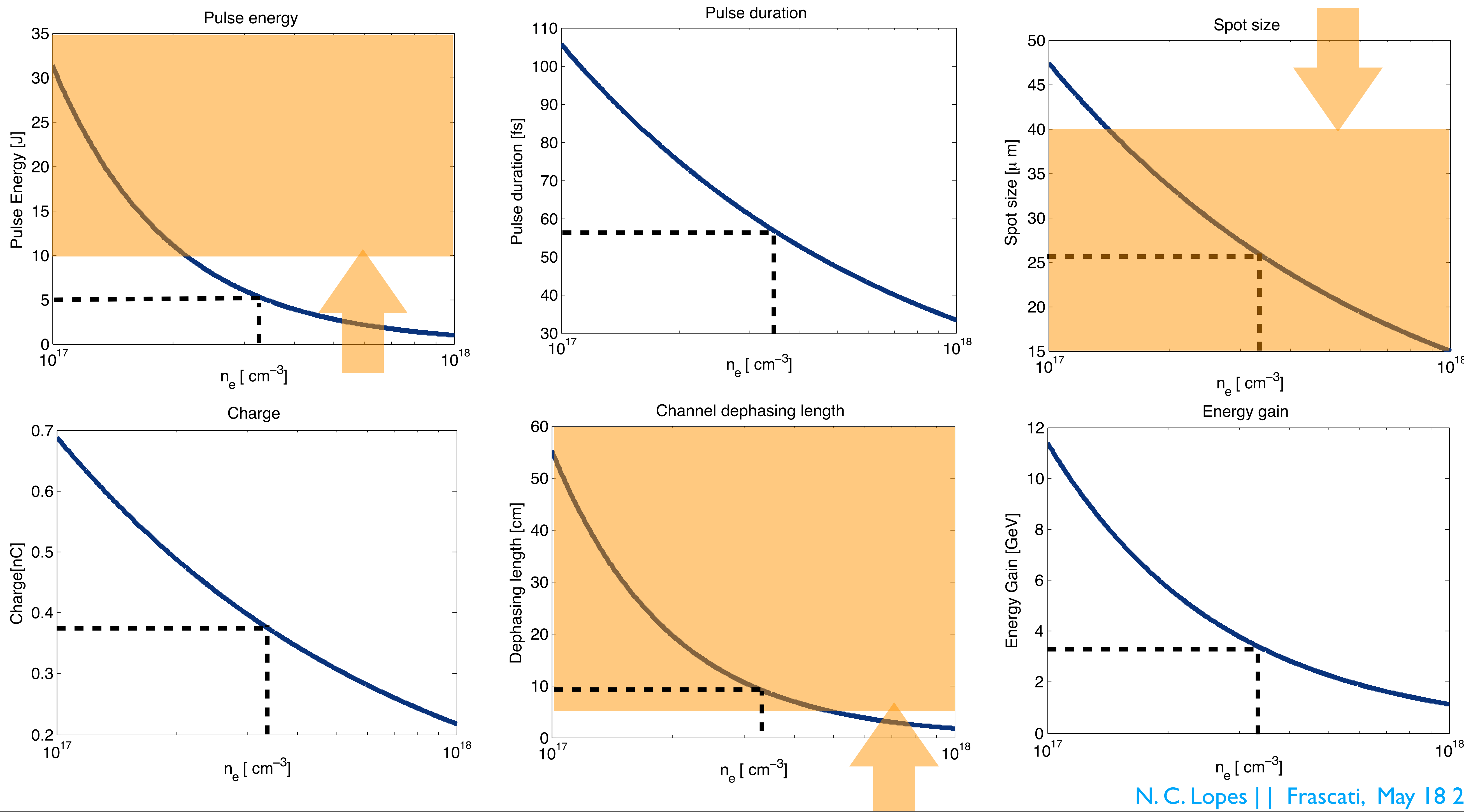


* W. Lu, et al., Phys. Rev. ST Accel. Beams 10, 061301 (2007)

Scaling laws for external guided low density LPA

assumes

- matched propagation external guiding
- $a_0=2$ for electron blowout
- an external injection mechanism



IST experimental program on guiding plasmas

Plasma channels development started at IST in 2001

Why?

Initial motivation

- Decrease laser power for SM-LWFA
- Research line not critically dependent of laser
- Long term research program leading to proprietary technology (and economic return)
- have an electron beam at IST (this was before the monoenergetic beams)

Low power matched guiding in plasma channels*

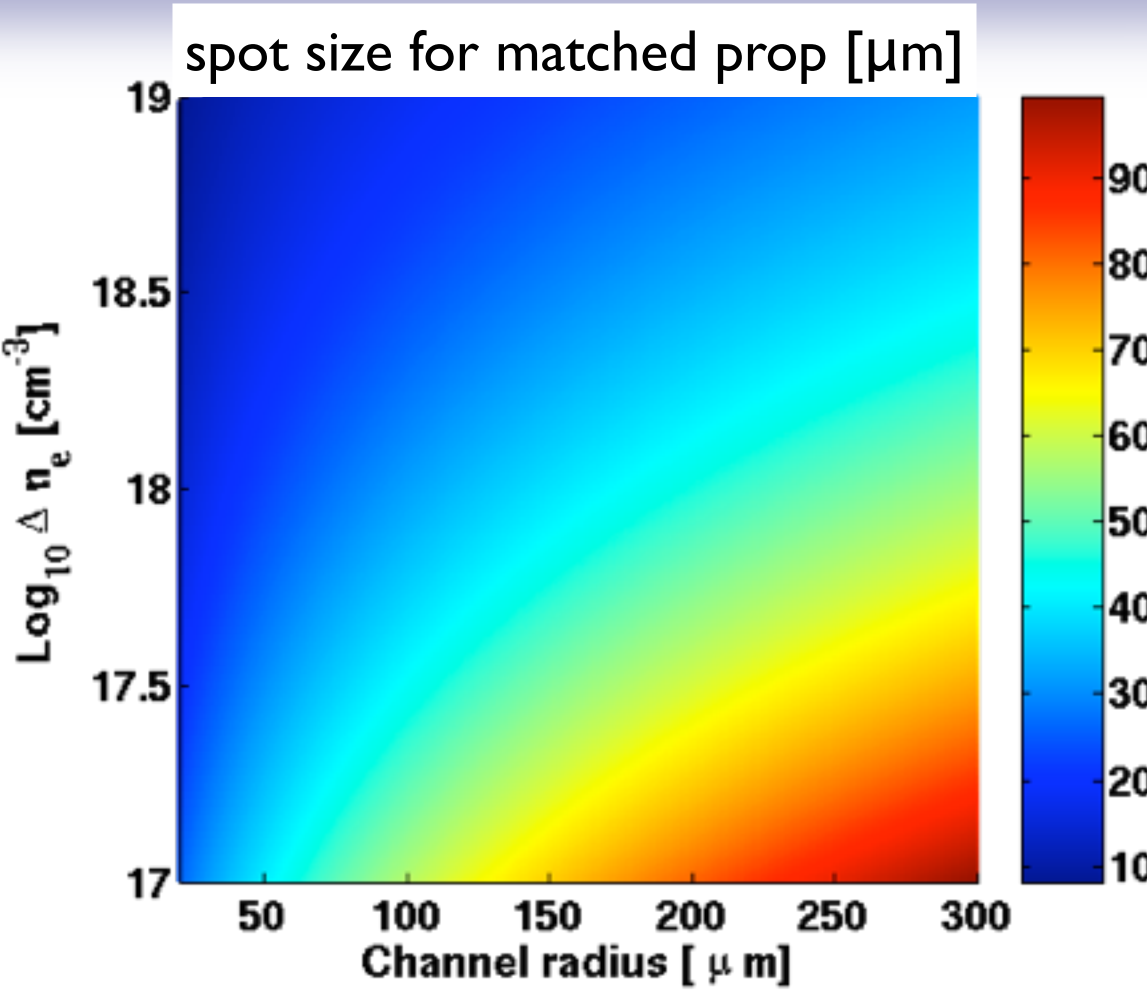
assumes

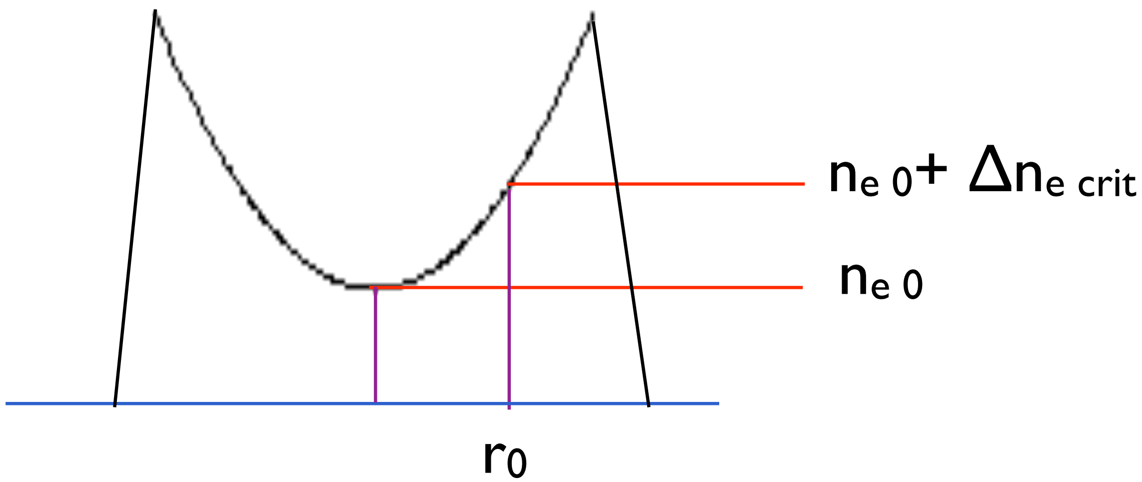
- Gaussian beam
- Low power (a_0<1)
- parabolic profile
- paraxial approximation

$$n_e(r) = n_{e0} + Ar^2$$

$$A = \Delta n_{ecrit} / r_0^{\ 2}$$

$$\Delta n_{ecrit} = 1.1 \times 10^{20} / r_0^{\ 2} [\mu m]$$





* E. Esarey, et al., IEEE Trans. Plasma Sci. 24, 252 (1996)

Early 2000's work on laser channeling (some)

- J. Roca's, U. Colorado - work on x-ray lasers in capillary discharges
- H. Milchberg, U. Maryland - plasma channels created in gases by focusing a a laser w/ a conical lens (a)
- Y, Ehrkich, Jerusalem U. - plasma channels by ablation of plastic capillaries using HV discharges (b)
- Gaul, Texas U. - plasma channels by heating a plasma created by laser w/ conic lens
- S. Hooker, Oxford U. - plasma channels by a discharge in a capillary filled with H2 (c)

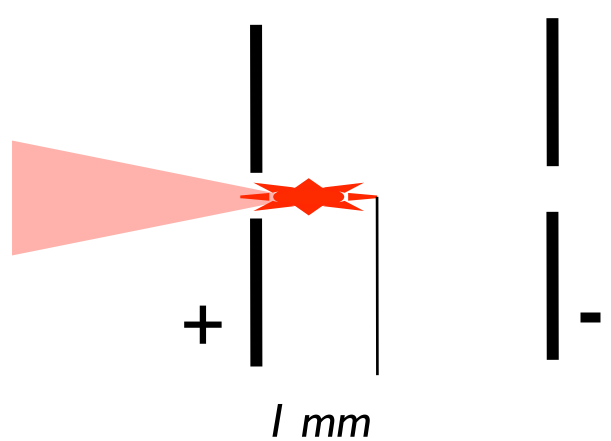
New method: free expansion plasma channels*

Helium ionization

- Gap ≈ 1 cm
- helium working pressure ≈ 100 - 500 mbar ≈ 5 x 10^{18} cm^{-3}
- Voltage = 20 kV
- Electron mean energy ≈ 15 eV
- helium ionization potentials U1=24.6 eV, U2=54.4 ev

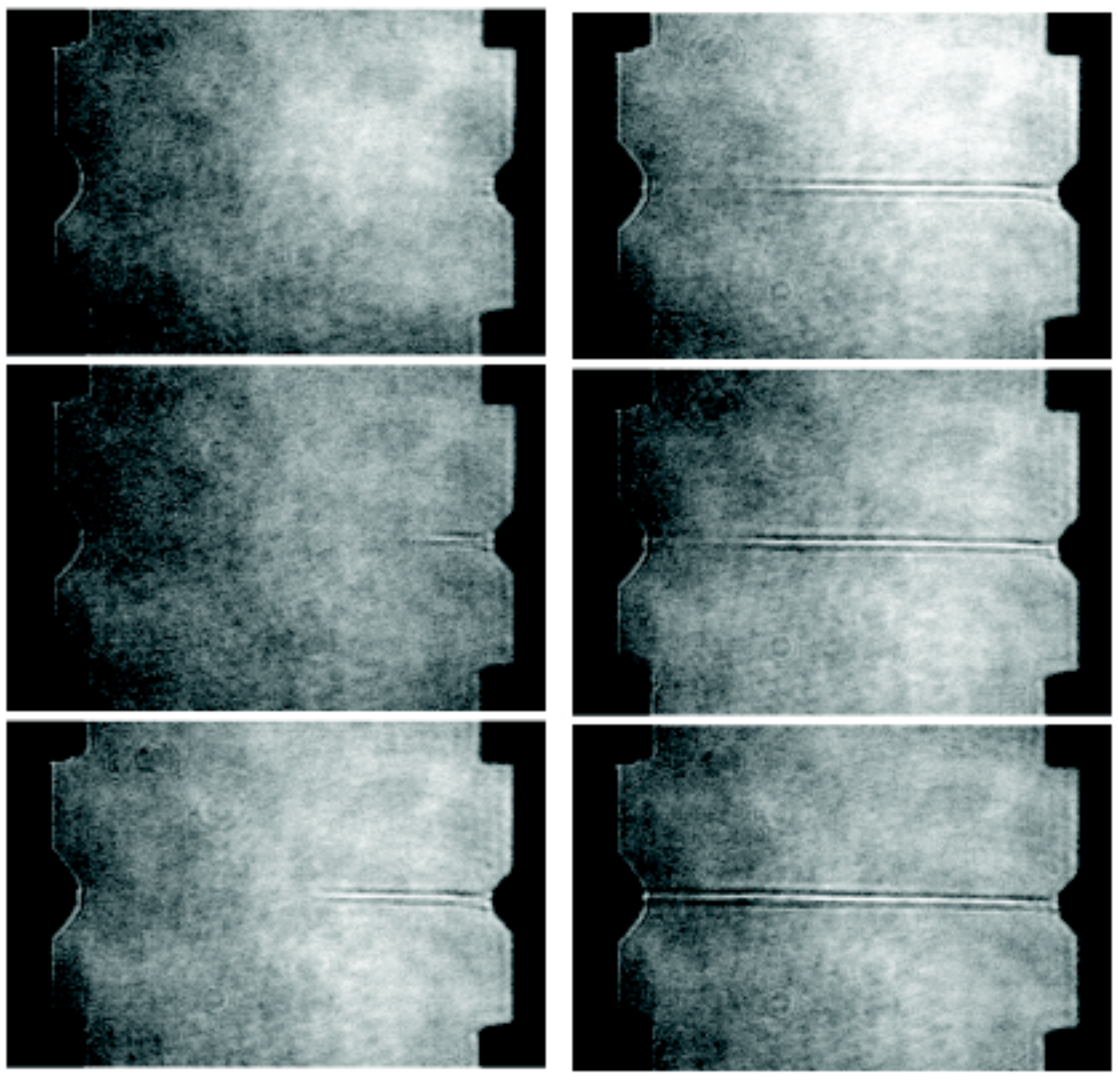
Intense laser triggering

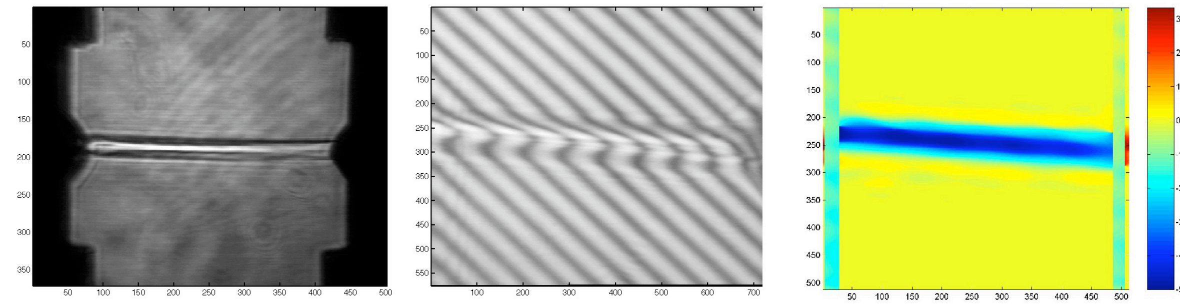
- Laser creates about 1 mm of fully ionized plasma
- Electric field accelerates electrons to > 1keV
- Laser triggering allows
  - Fast ionization
  - Straight plasmas
  - No jitter



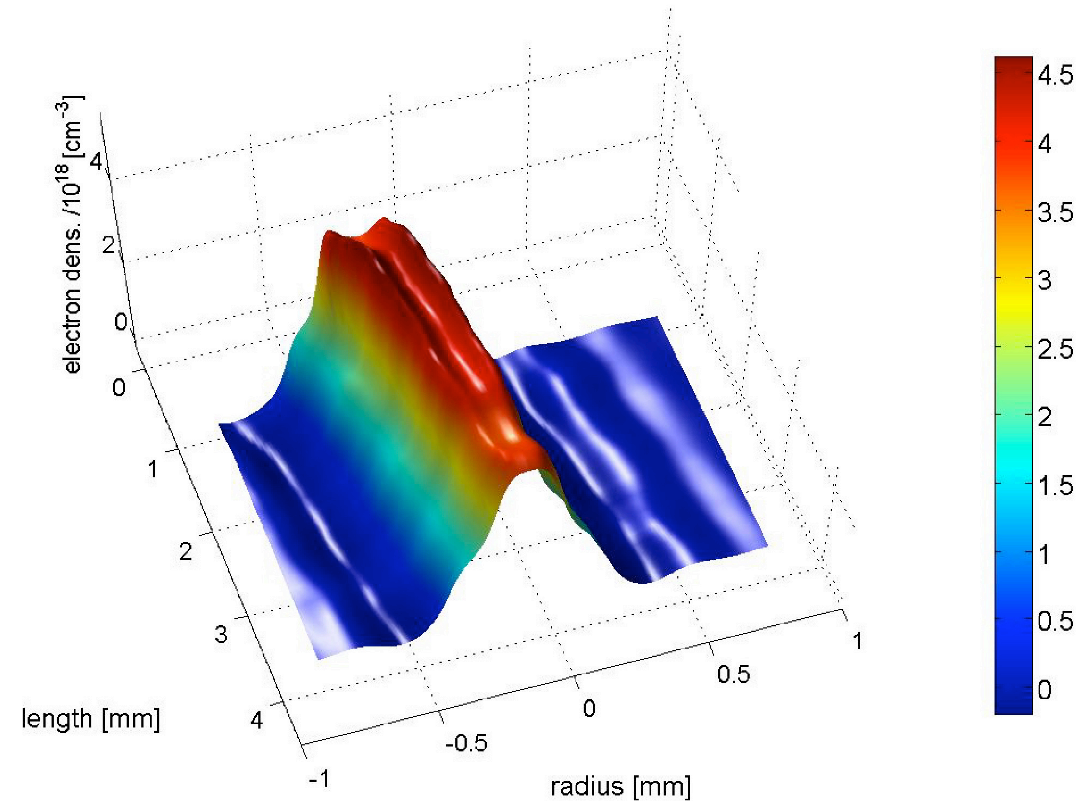
* "Plasma channels produced by a laser-triggered high-voltage discharge", N. C. Lopes et al., Phys. Rev. E. 68, 035402 (2003)

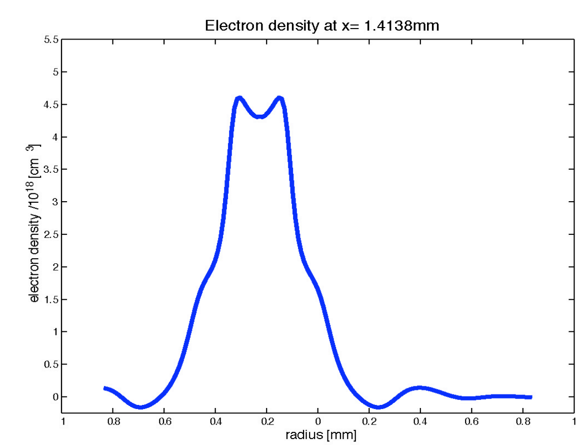
Demonstration of channeling formation





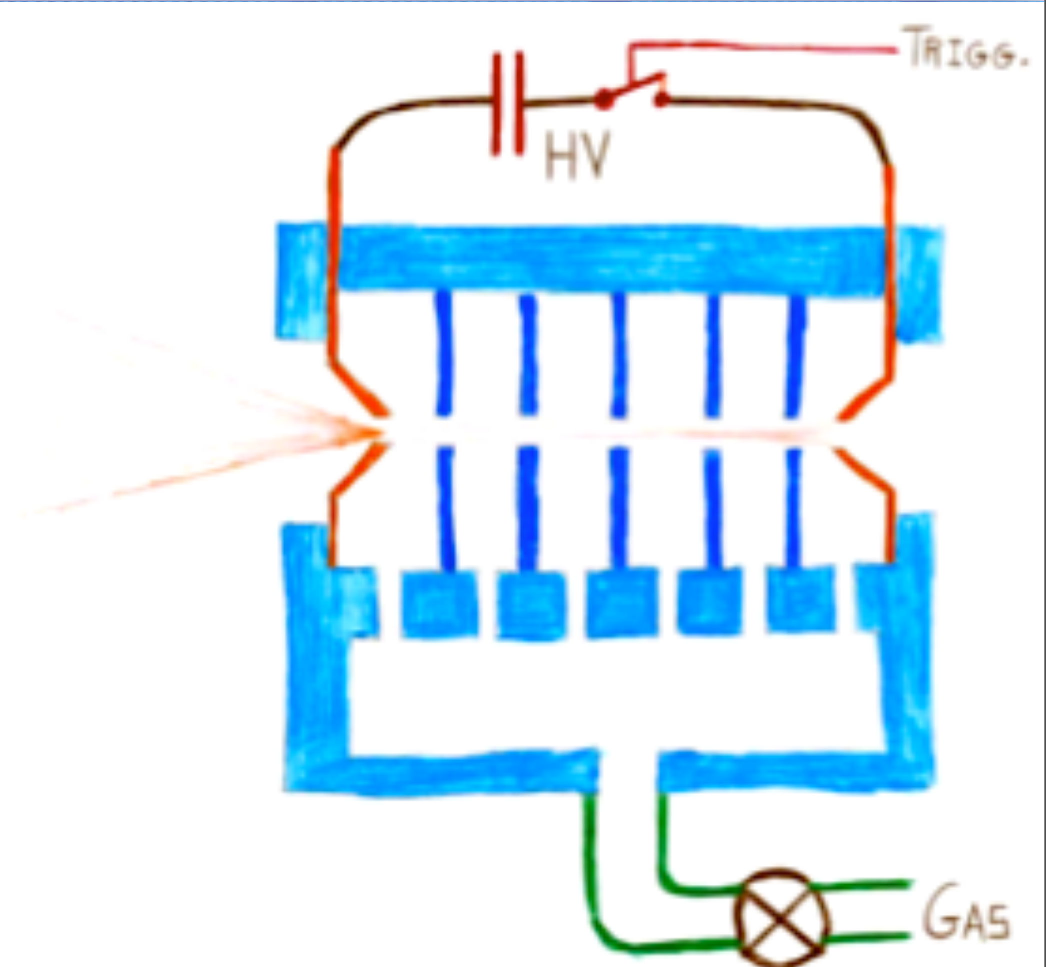
Electron density





- Reproducible reproduction of straight plasma lines ϕ=150 μm
- Development of high density (>$5X10^{18}$ cm^{-3}) parabolic plasma channels
- Experiment to difficult, scheme ok for lab with two lasers
- Free expansion seems to work well

Discharges on strutured gas cells - IST 2006

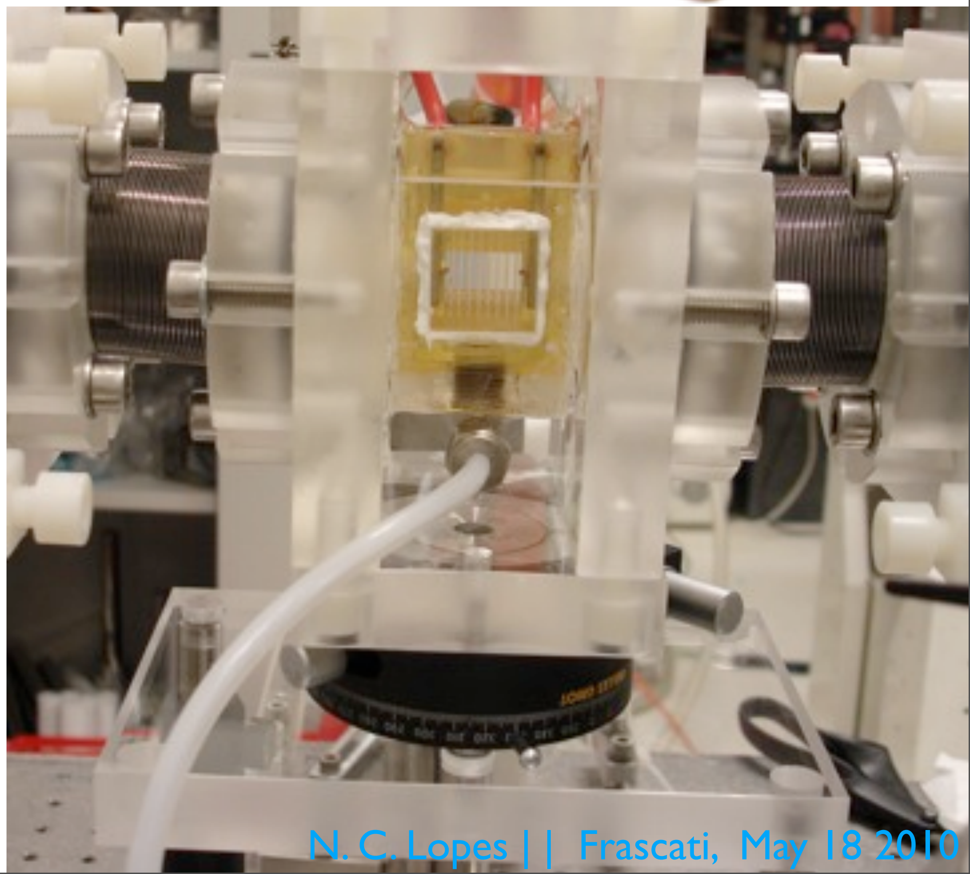


Why

- (almost) free radial expansion
- no laser triggering of discharge
- fast gas filling (reduced leak compared with capillary)
- different zones of pressure/gas composition

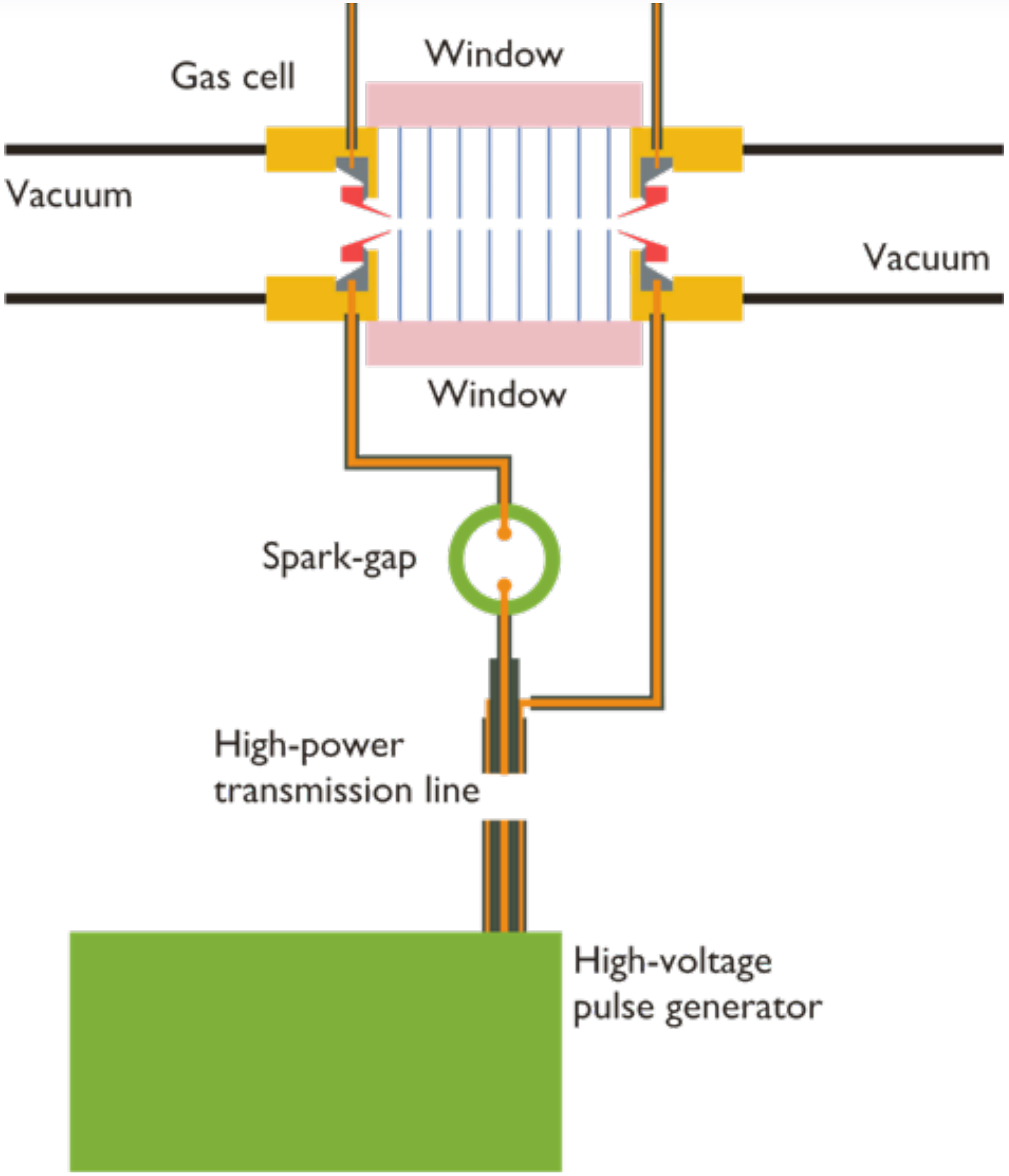
How

- hollow conic electrodes + sequence of dielectric apertures
- use a short rise-time high-voltage and current pulse
- use H2



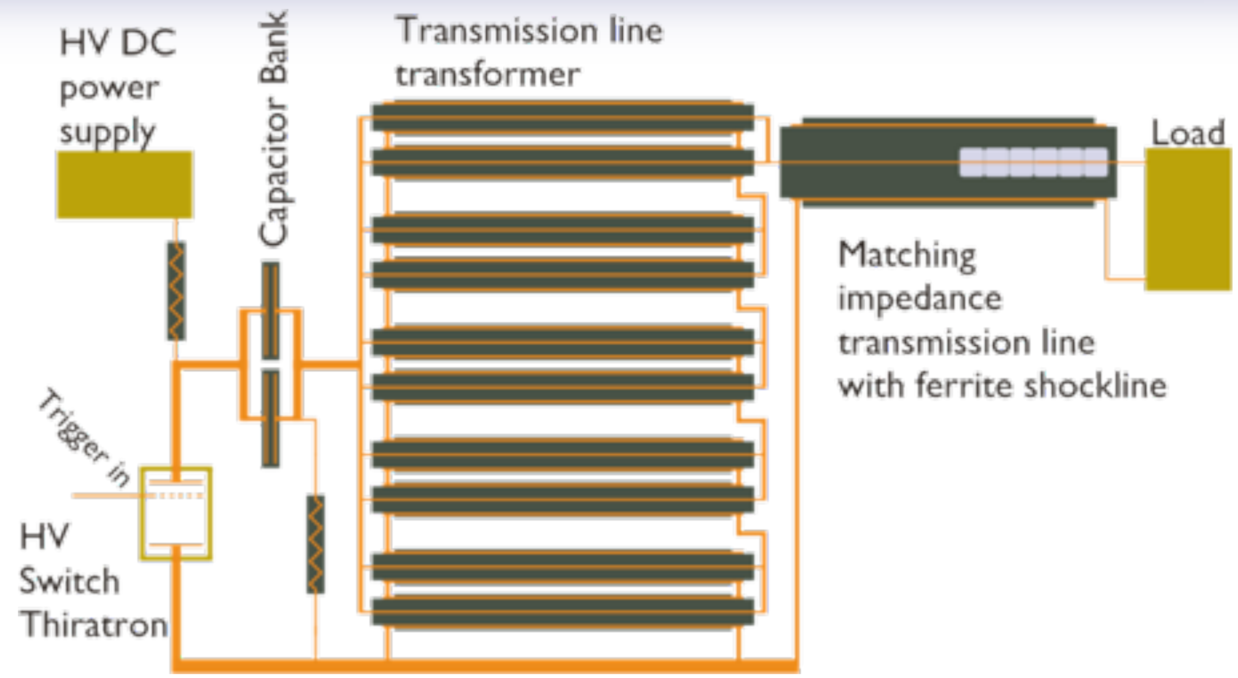
Discharges on strutured gas cells - IST 2006

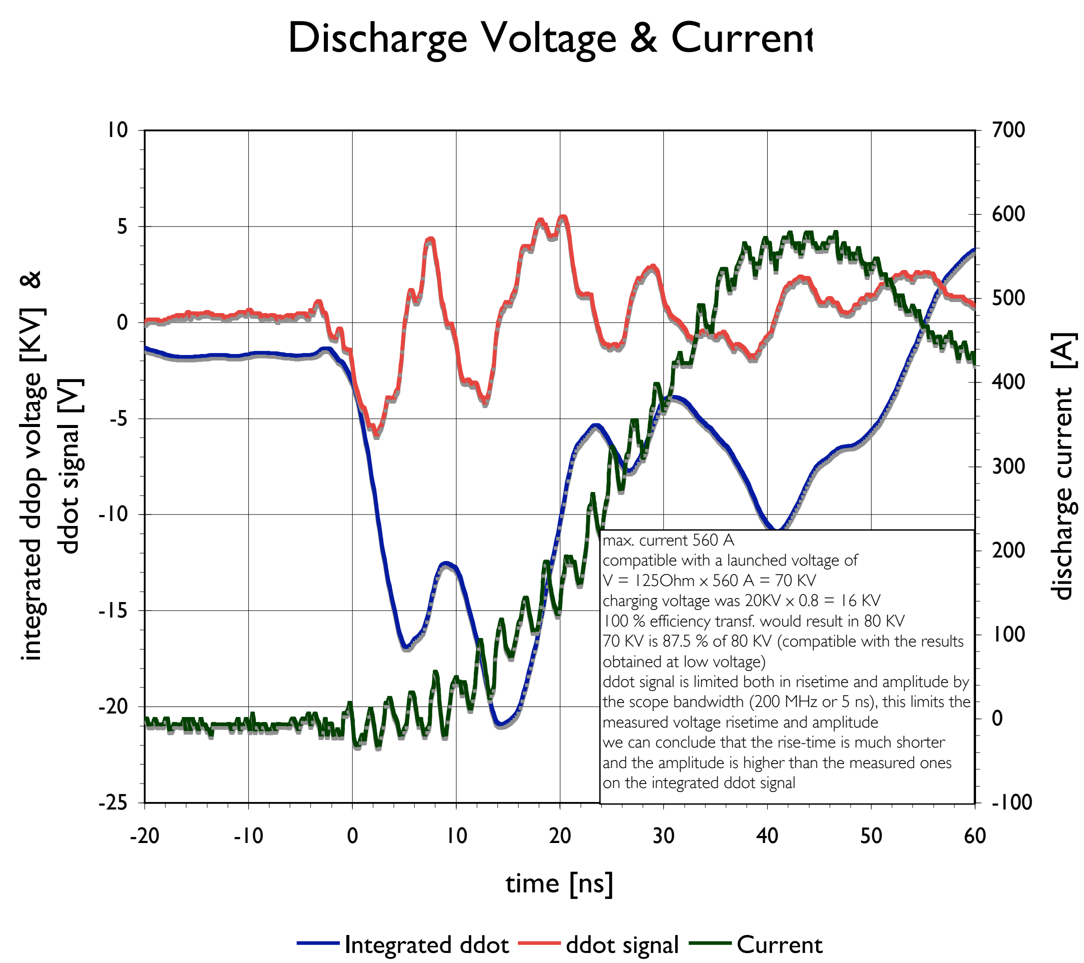
- Gas cell
  - 2 cm long, 9 sub-cells
  - copper electrodes
  - dielectric apertures to fix initial plasma size and position
  - aperture diameters 100 - 300 μm
  - no laser triggering and radial plasma expansion
  - possibility of different density regions
  - gas injection up to 500 mBar in 10 ms
  - vacuum up to 10-3 mbar between shots
  - optical access for diagnostics
  - scalable to multi-GeV energies



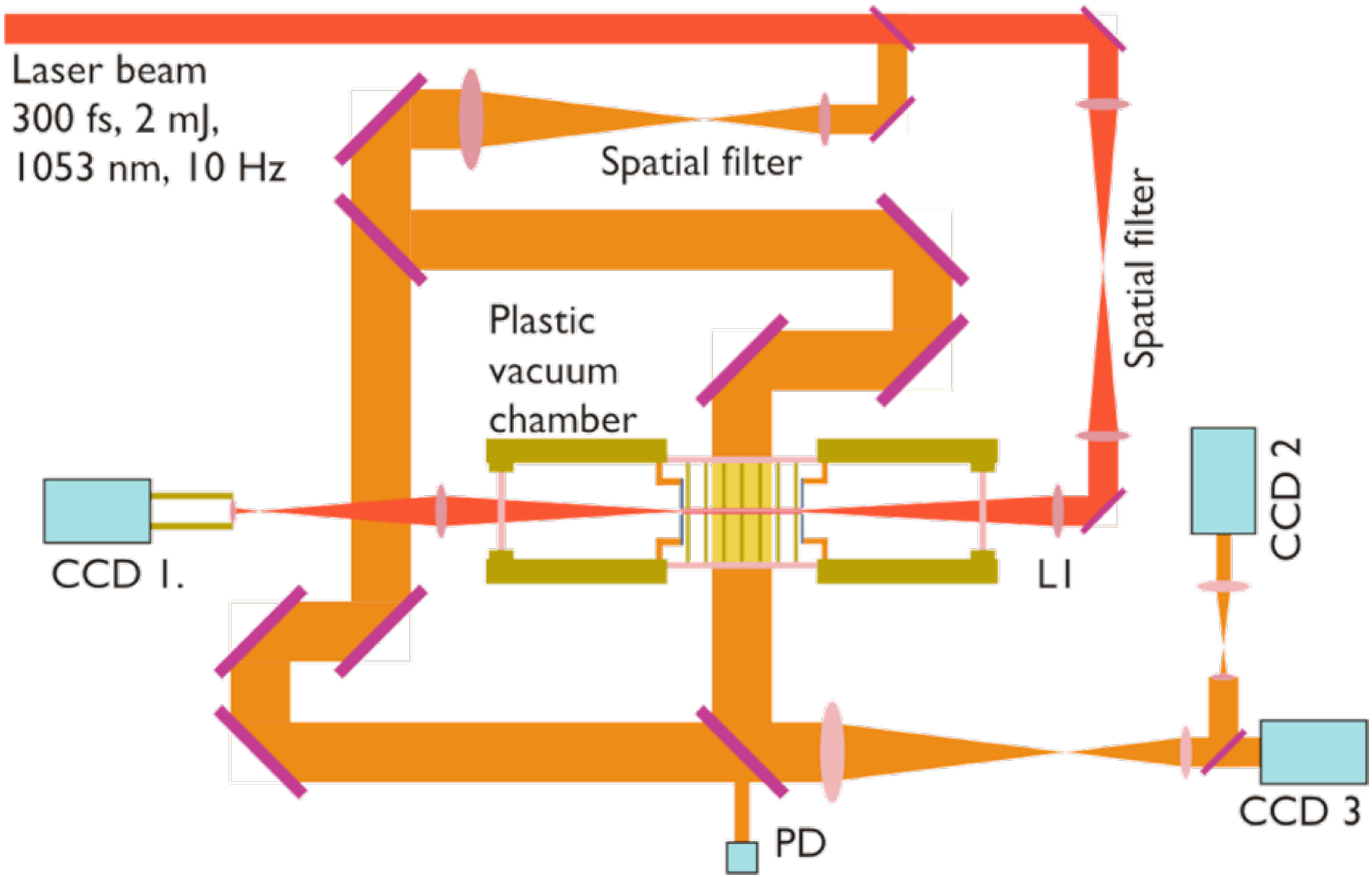
Structured gas cell: HV pulse generator

- High-voltage pulse generator
  - capacitor discharge (20 kV)
  - pulse transformer (5 x)
  - 125 Ohm output impedance
  - up to 100 kV /125 Ω/ 1kA pulse
    rise time: ~ 20 ns
    duration: ~ 200 ns
  - may use magnetic pulse compression for rise time: < 5 ns
  - synchronization with laser
    (1 ns jitter)



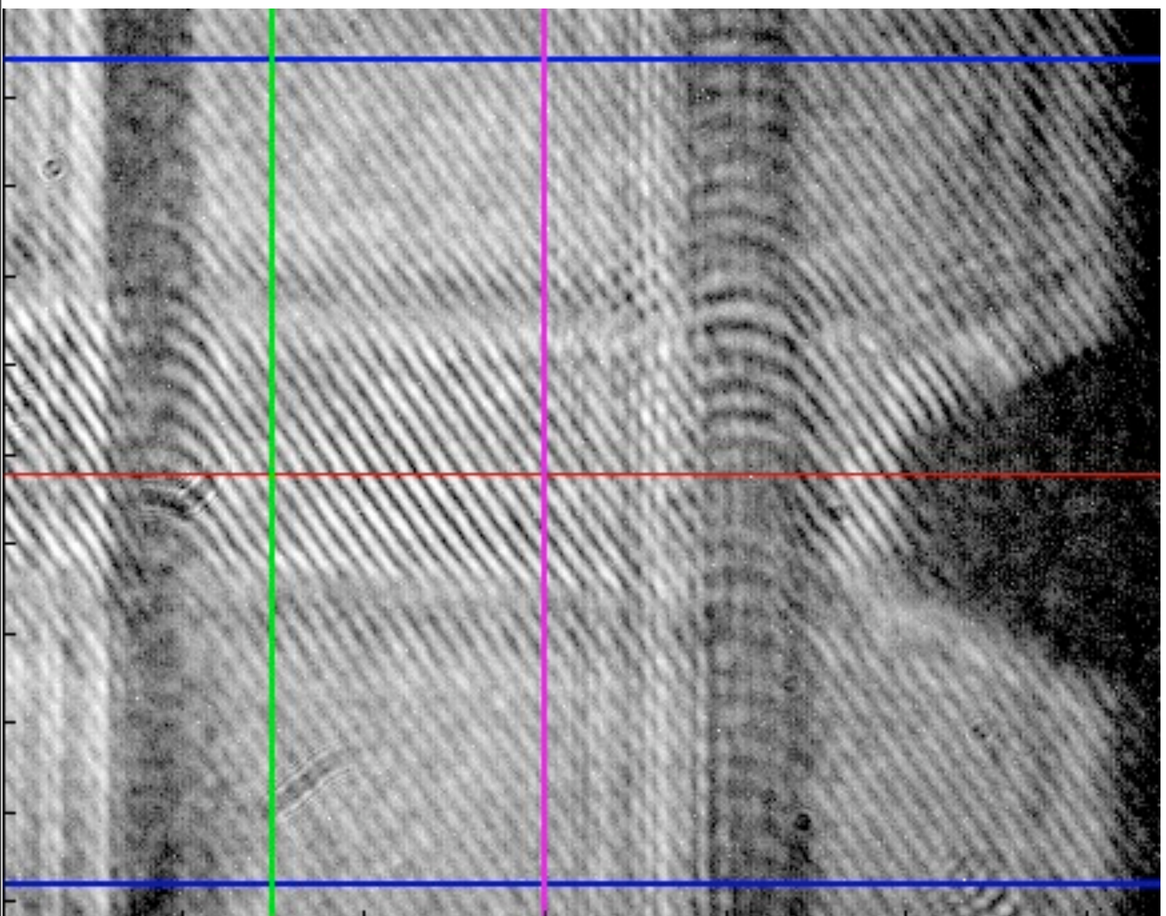


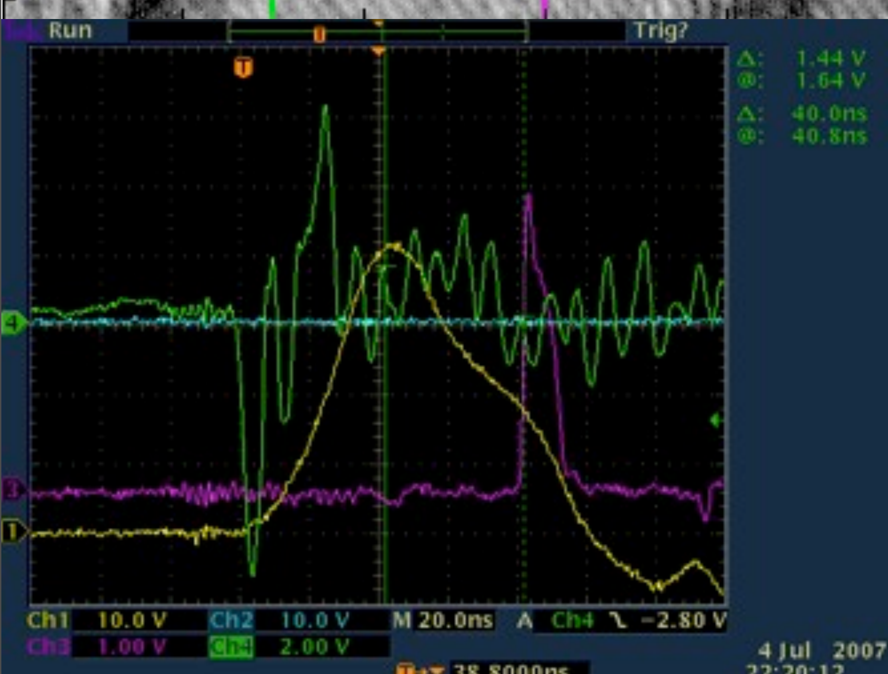
Schematic of the channel test facility at L2I



Experimental results - plasma density profile

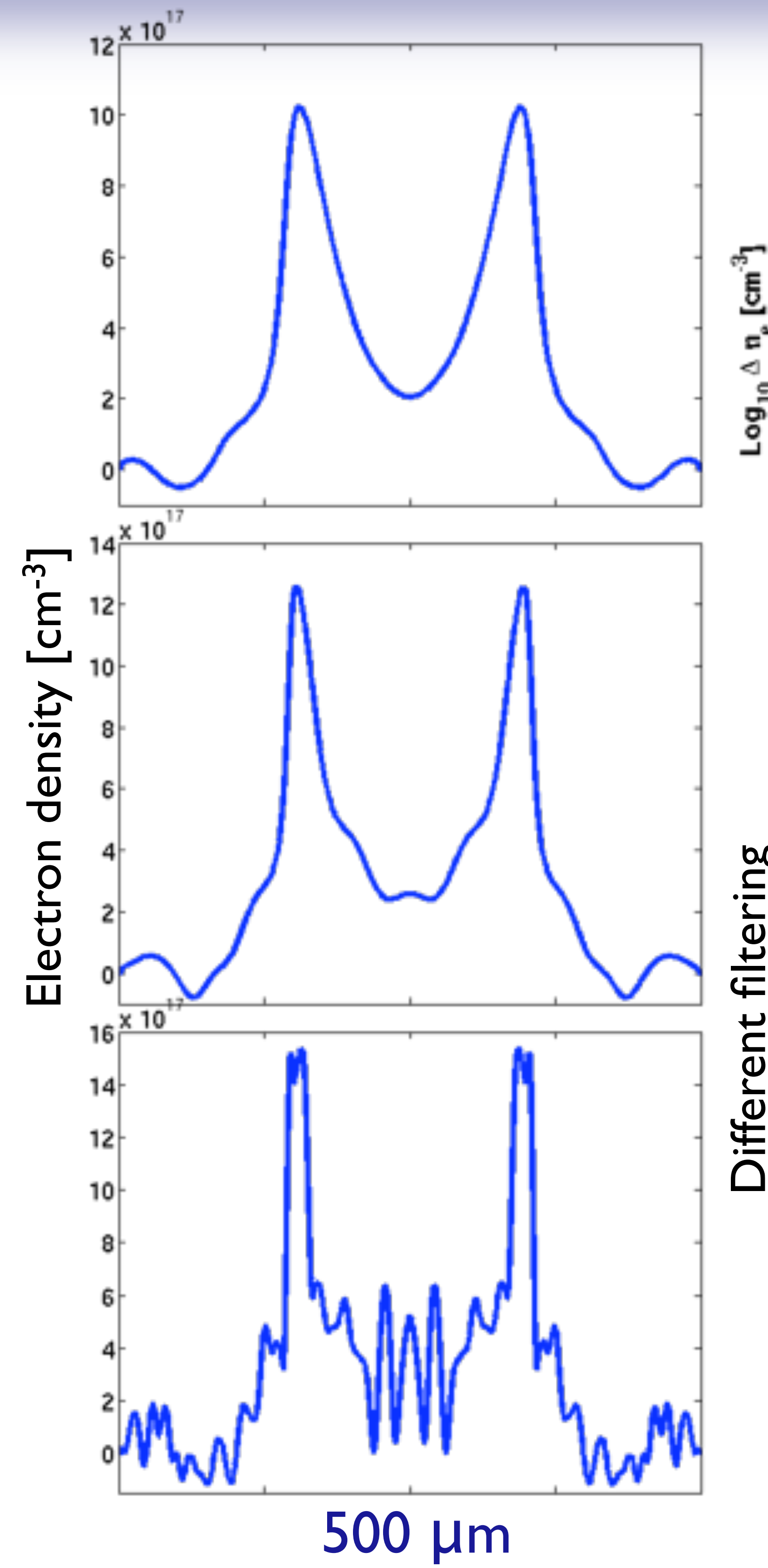
Interferometry

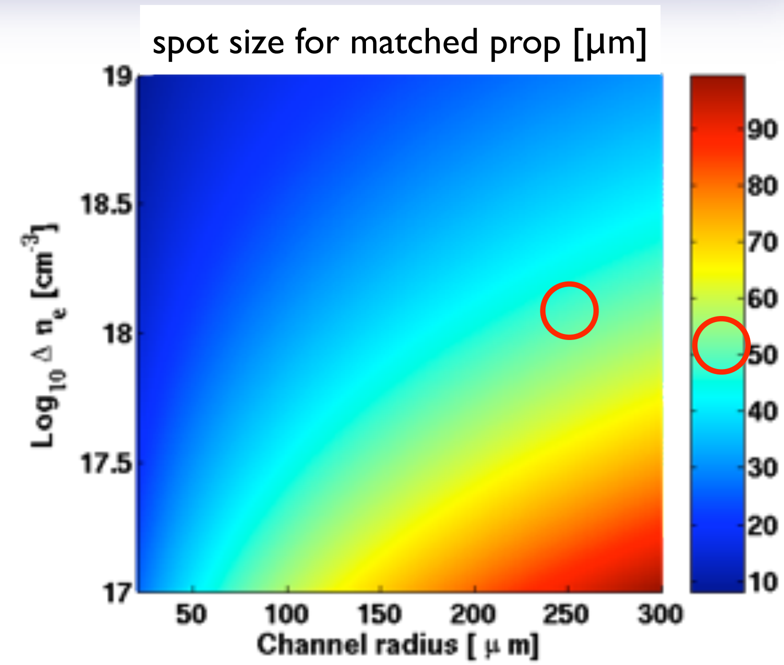




Current

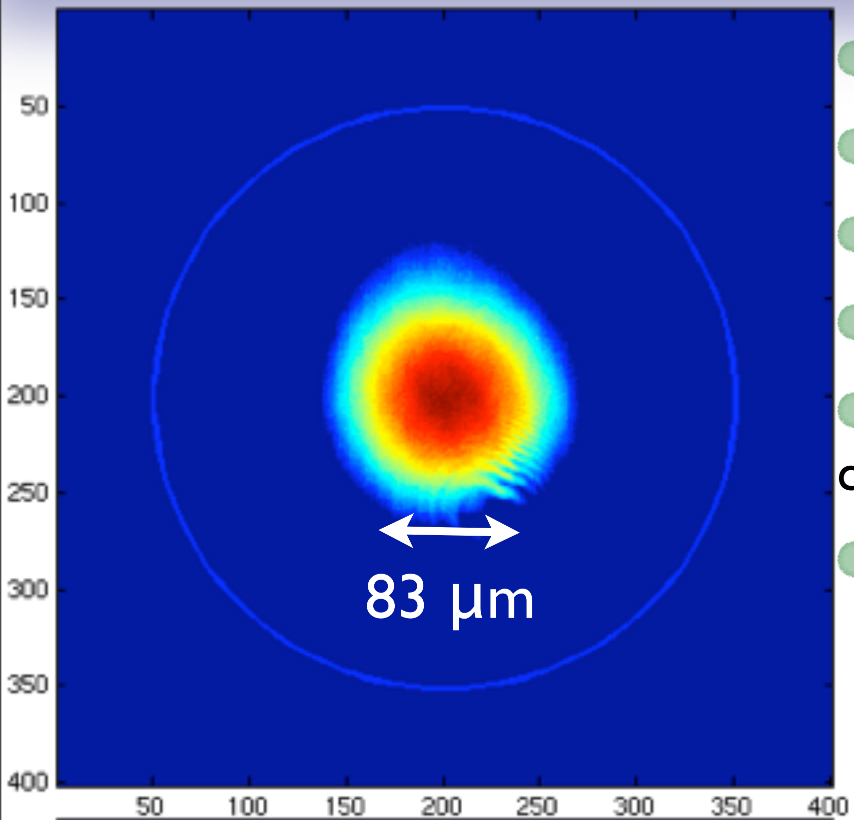
Laser



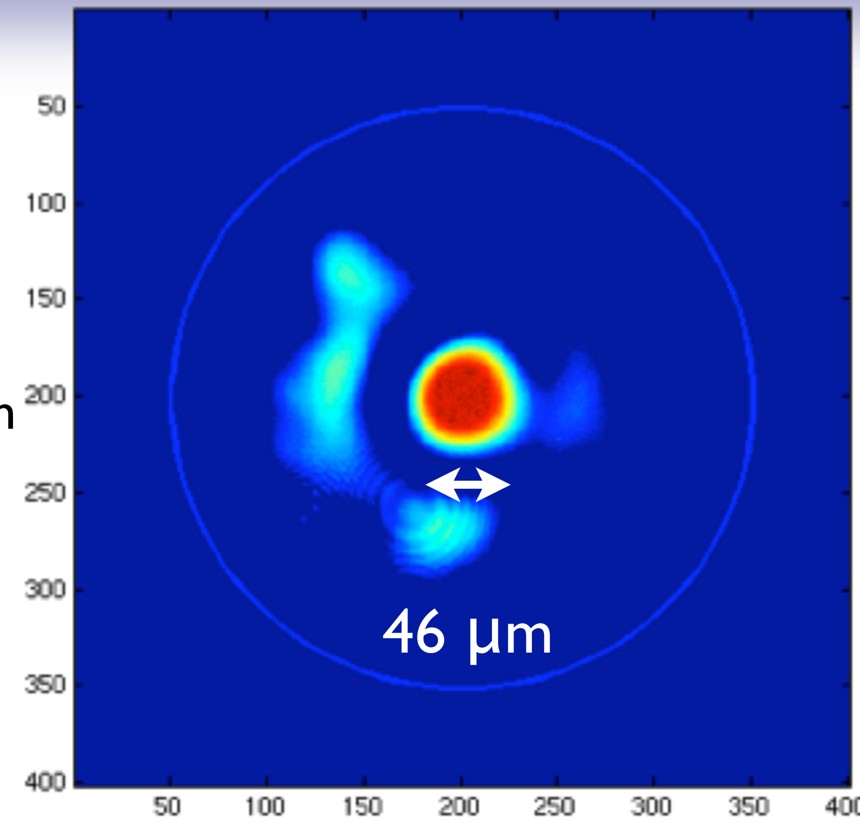


- matched prop. spot radius ≈ 50 µm
- analysis made 2 mm before channel exit
- but channel seems uniform
- density where guiding was obtained

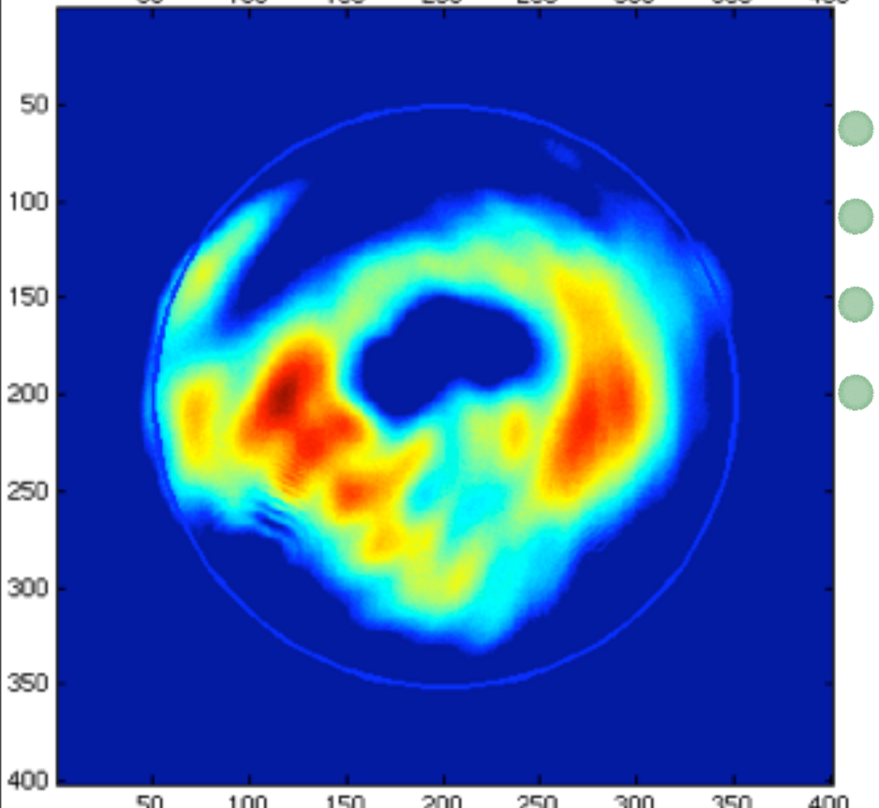
Experimental results - Low power guiding



- focal spot
- channel entrance
- no discharge
- no gas
- image made through cell apertures
- no filter



- channel exit
- discharge
- gas
- ND filter 0.4
- typical shot

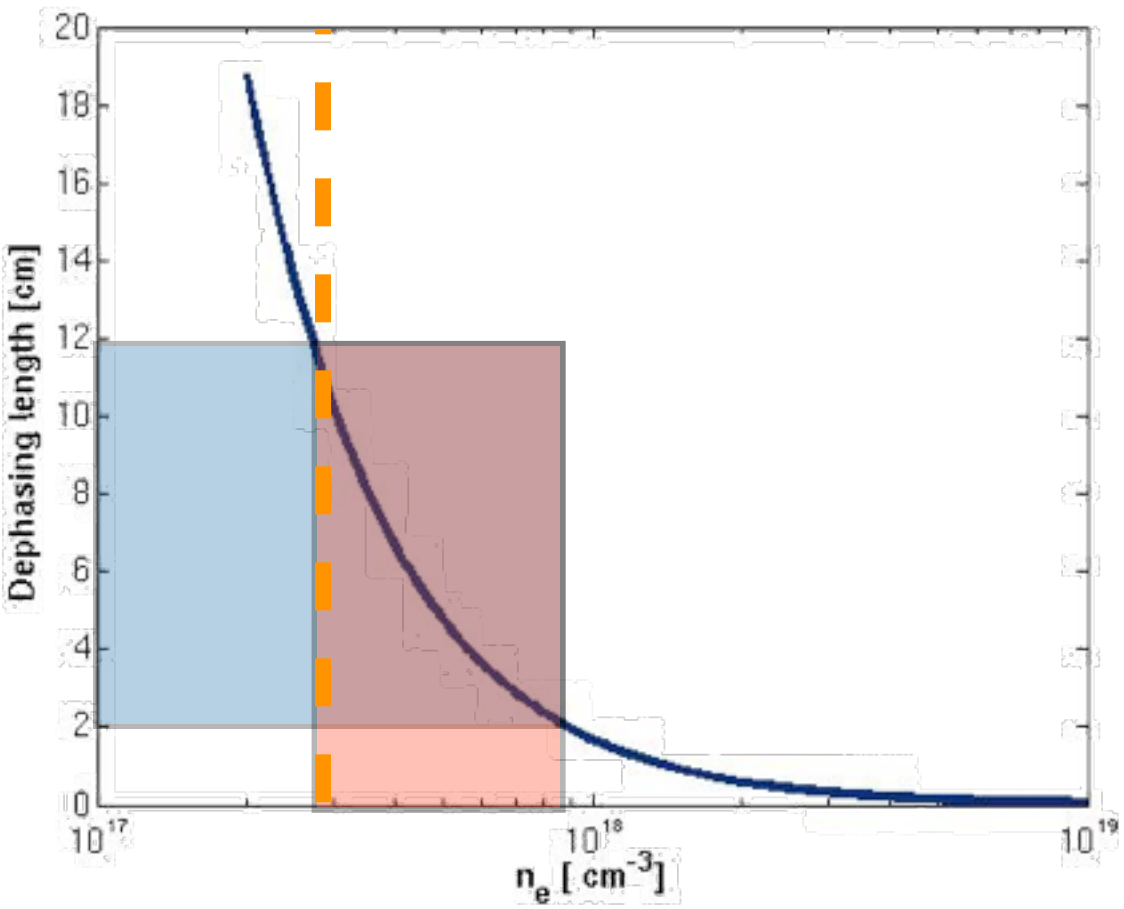


- channel exit
- no discharge
- gas
- no filter

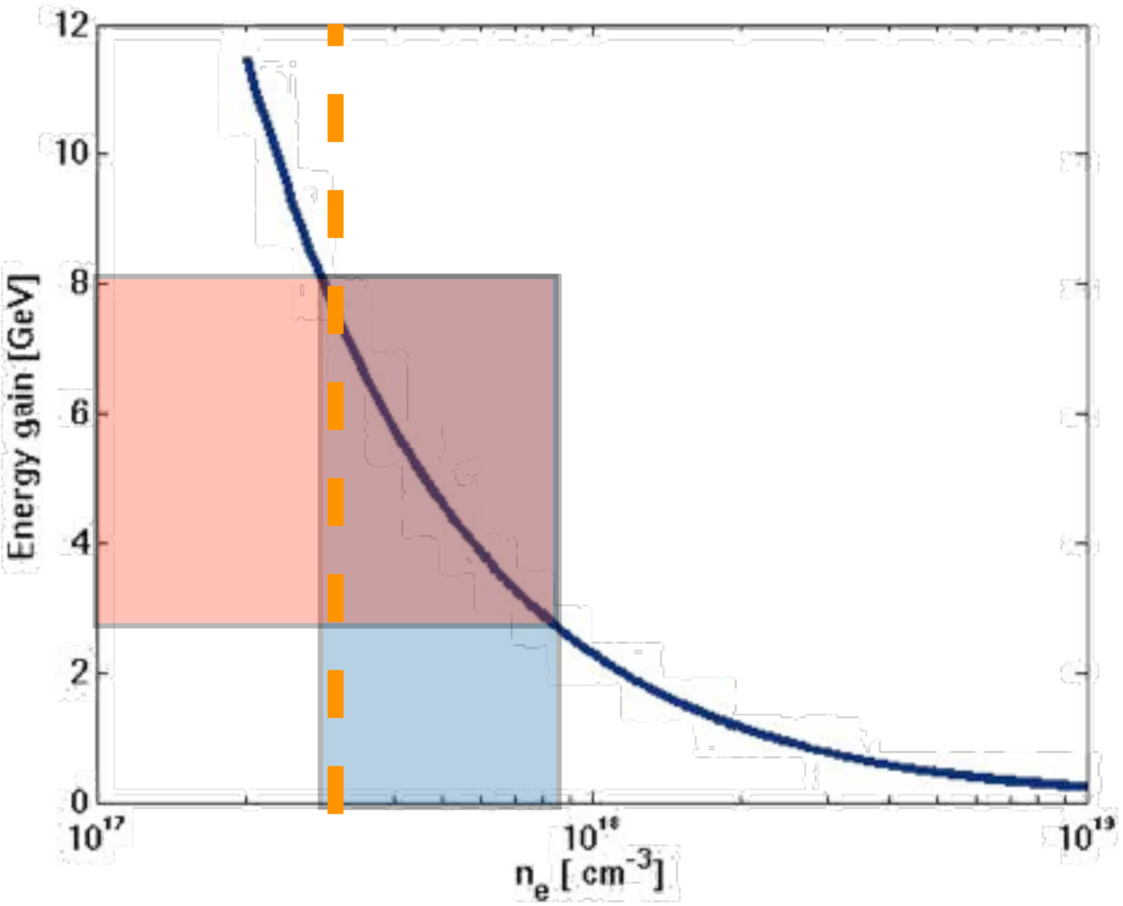
- Beam diam. 30 mm
- F. distance 1 m
- Gauss. spot radius 44 µm
- R. Length 1.5 mm
- Channel length 16 mm

Experimental results - e⁻ acceleration prospects

Channel dephasing length

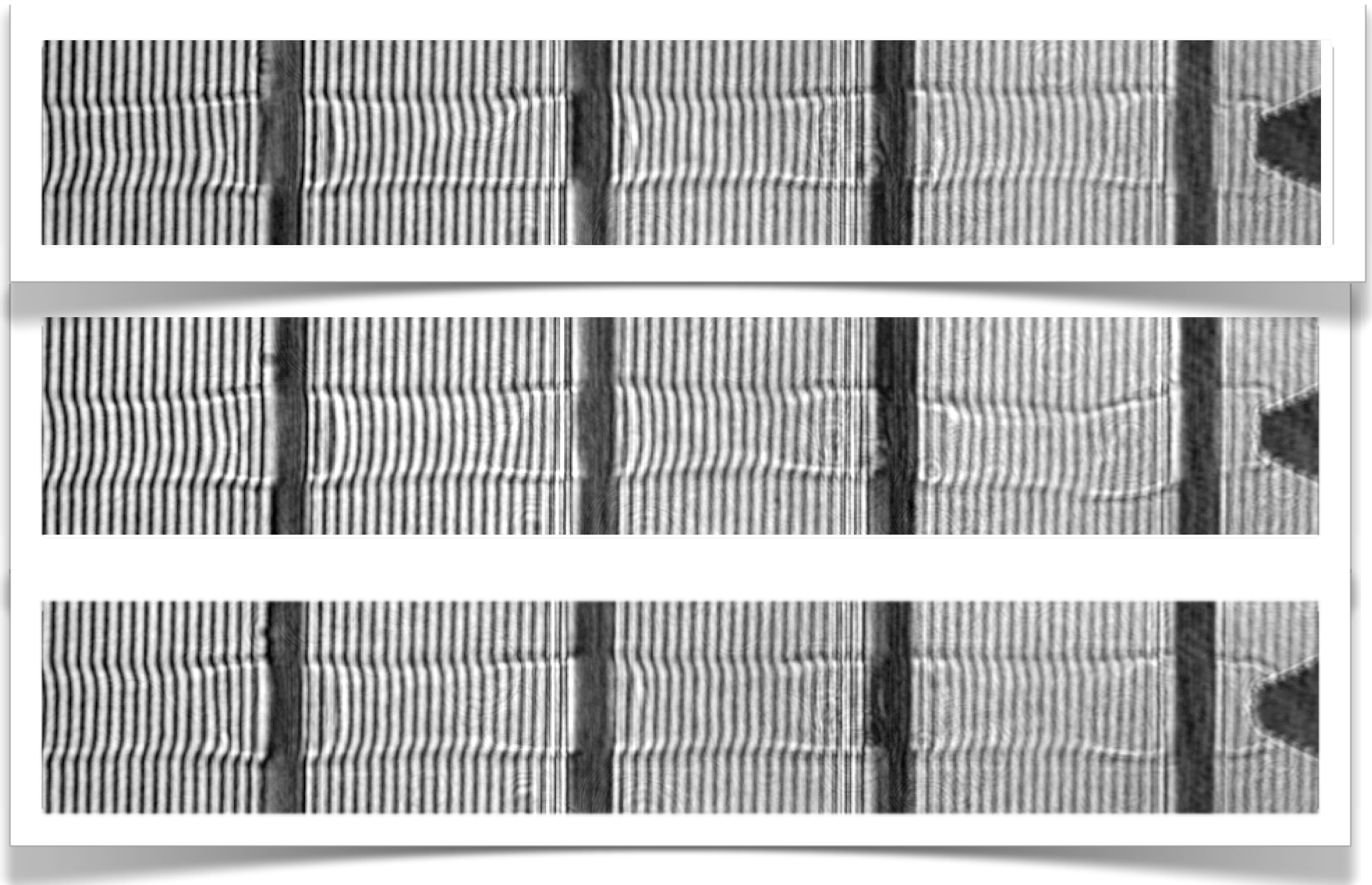


Max. Energy gain



- dephasing length is ~ 11 cm
- max. energy gain (for the deph. length) ~ 8 GeV
- plasma wall Δne ~ 10^{18} cm^{-3}, channel radius ~ 500 µm
- matched prop. spot radius ~ 45 µm
- requires laser pulse with ~ 10 J, 70 fs

Reproducibility/symmetry/uniformity issues



obtained with HV magnetic compression
(<4 ns voltage risetime)

Problem

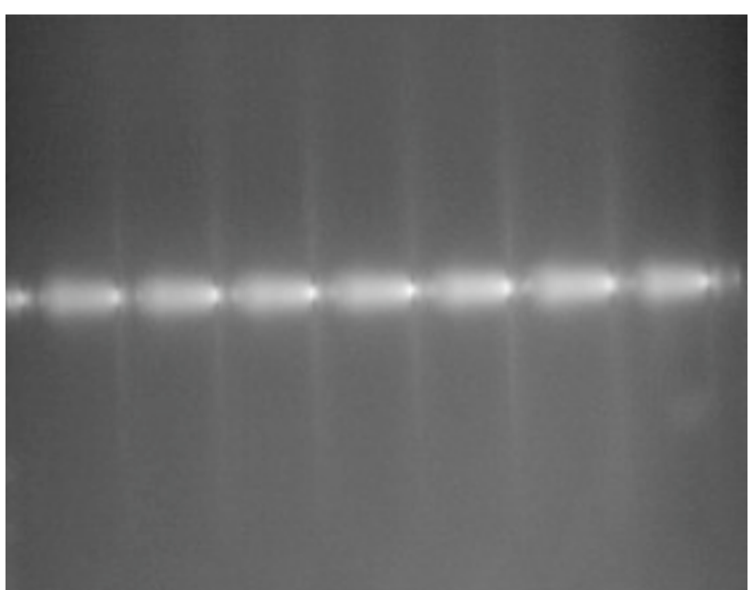
- deeper channels require short HV rise-times and higher currents
- short rise-times strongly increase the probability of hot-spots and non-uniform/non-reproducible plasmas

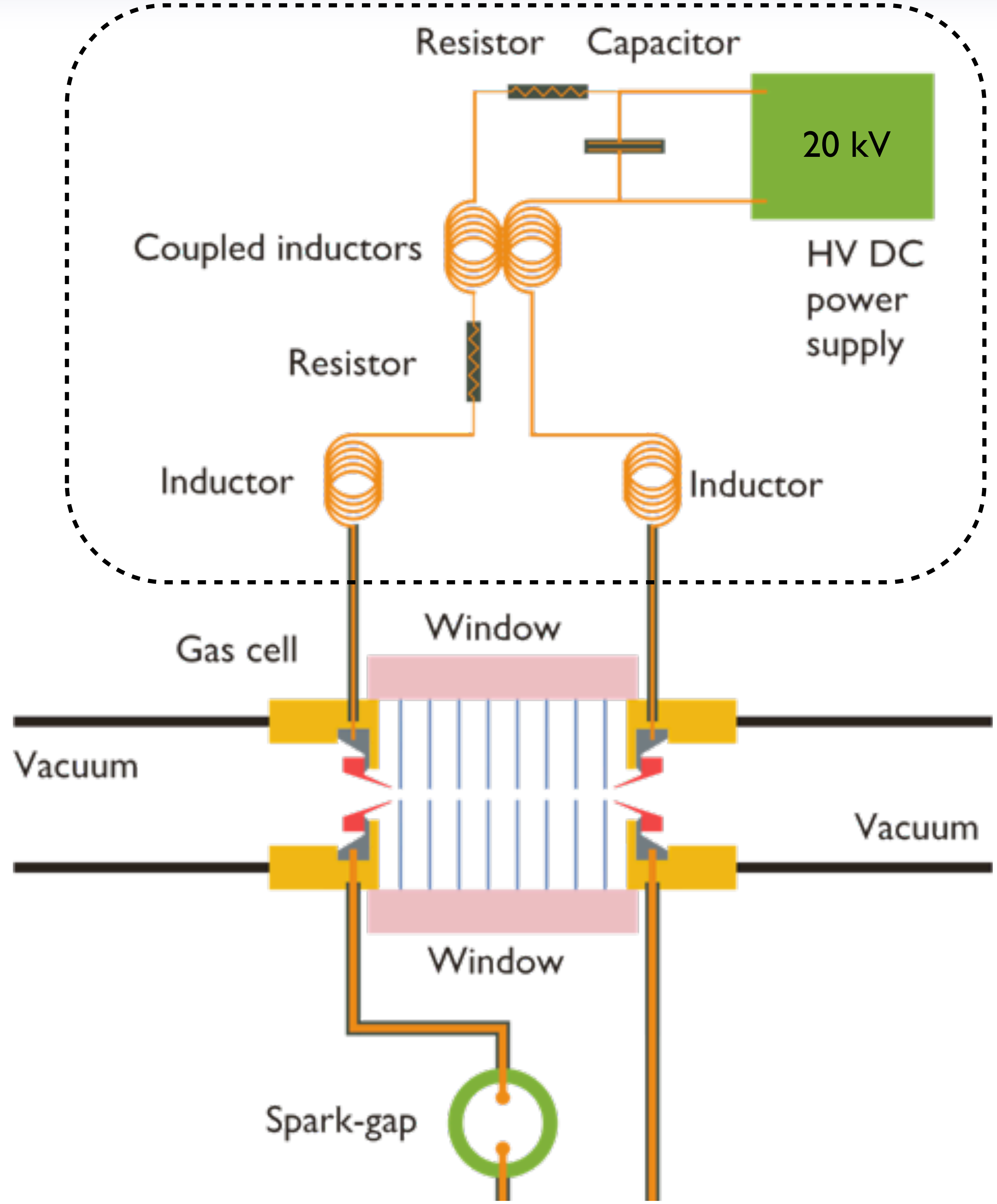
Solution

- produce the main discharge over a partially ionized uniform gas background

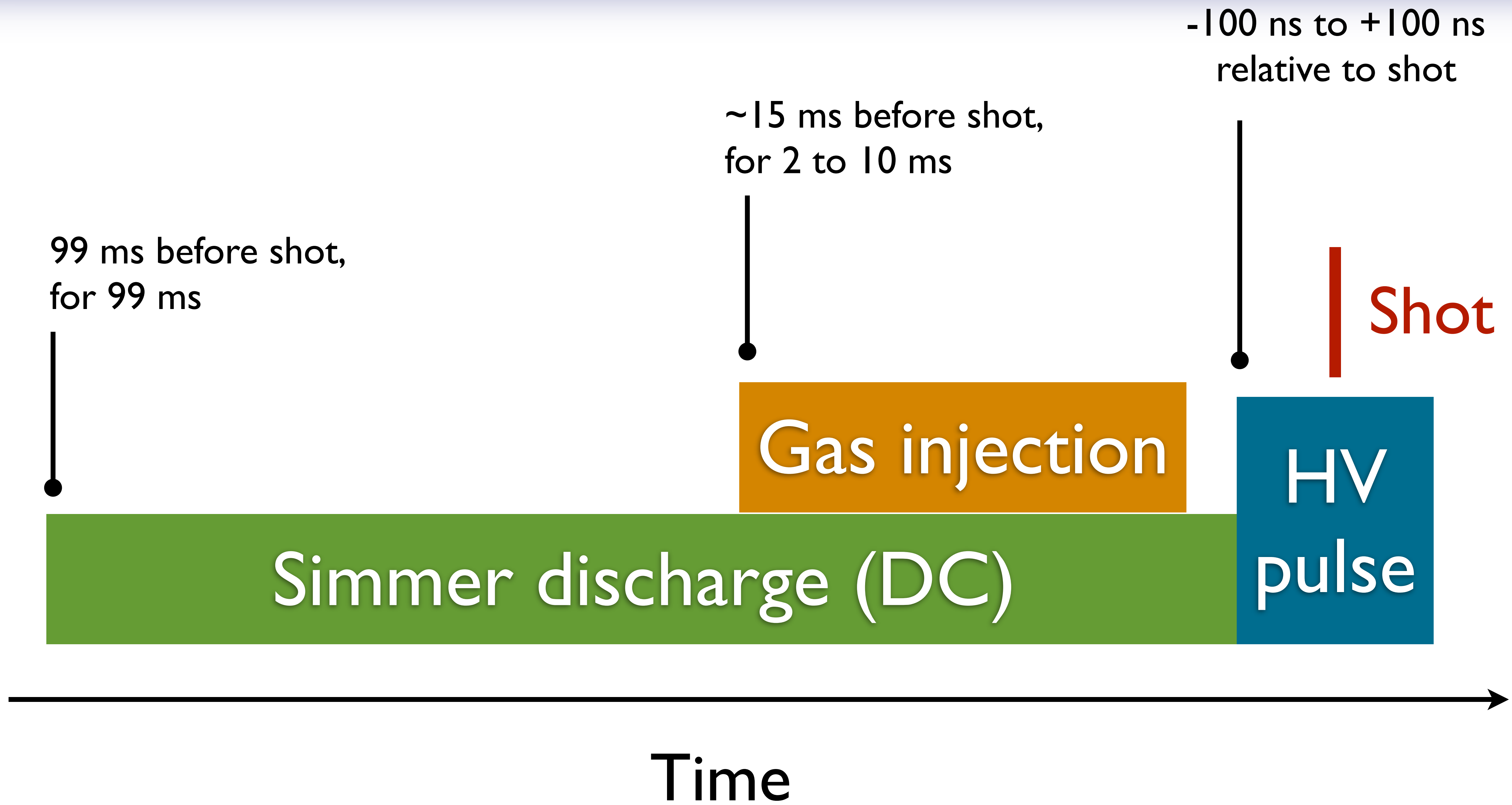
Electric setup for a glow pre-discharge

- Simmer discharge (DC)
  - 20 kV power supply
  - slow rise time (ms)
  - inductors block main HV pulse
  - resistor limits current (R = 20 MΩ) to ~ 1mA

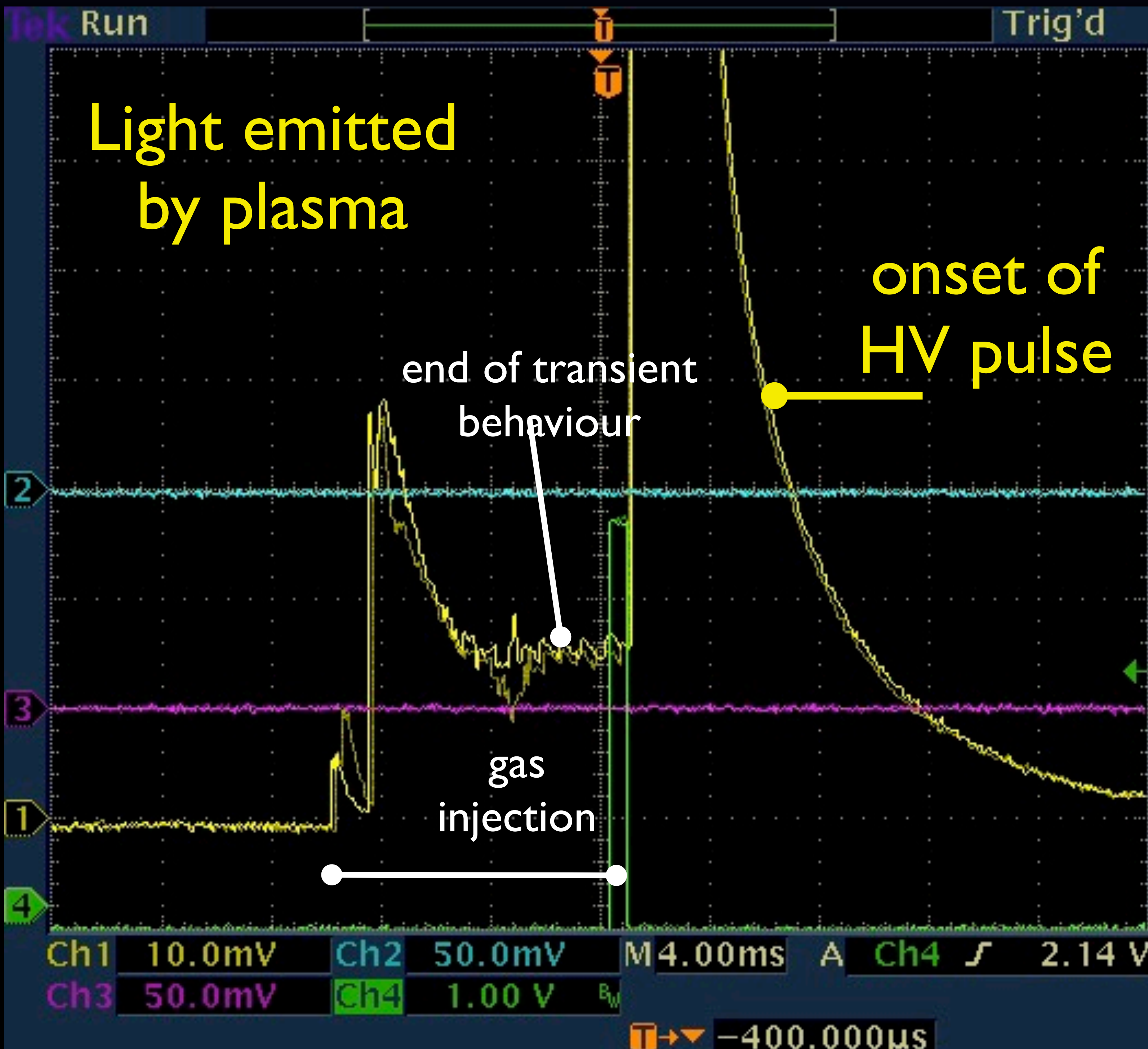


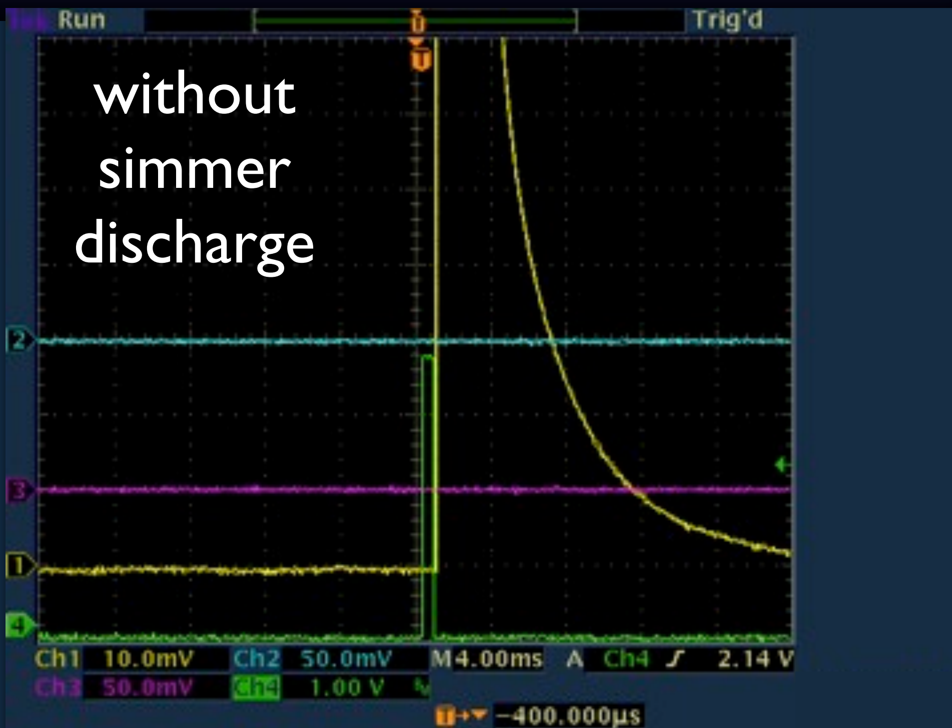


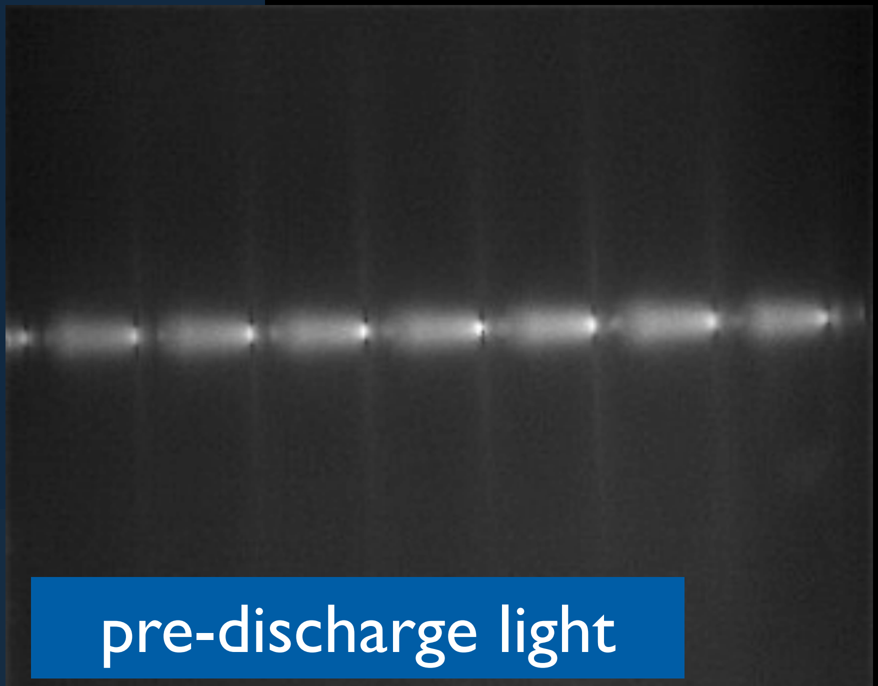
Time sequence with pre-discharge



Pre-discharge signature



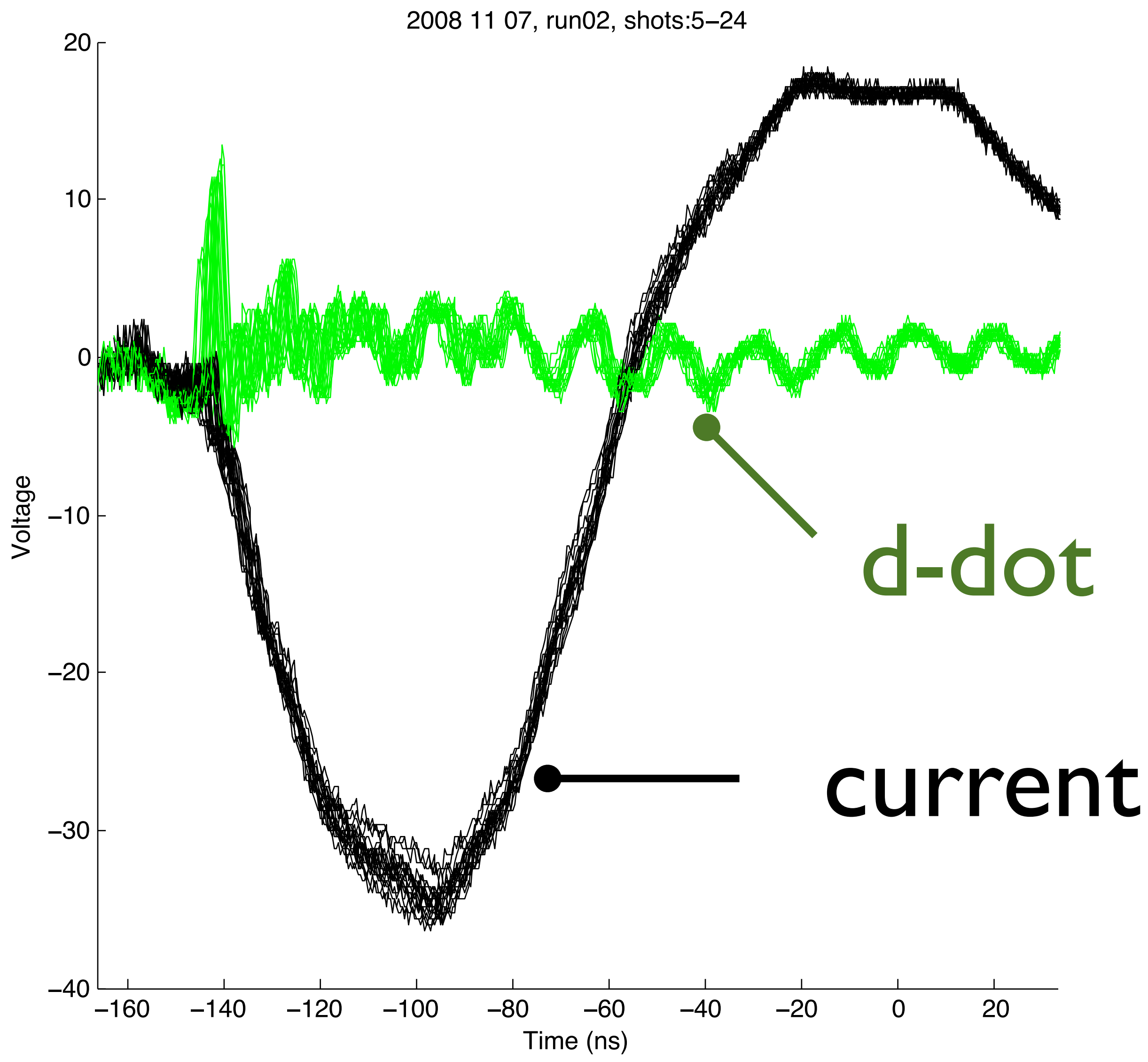




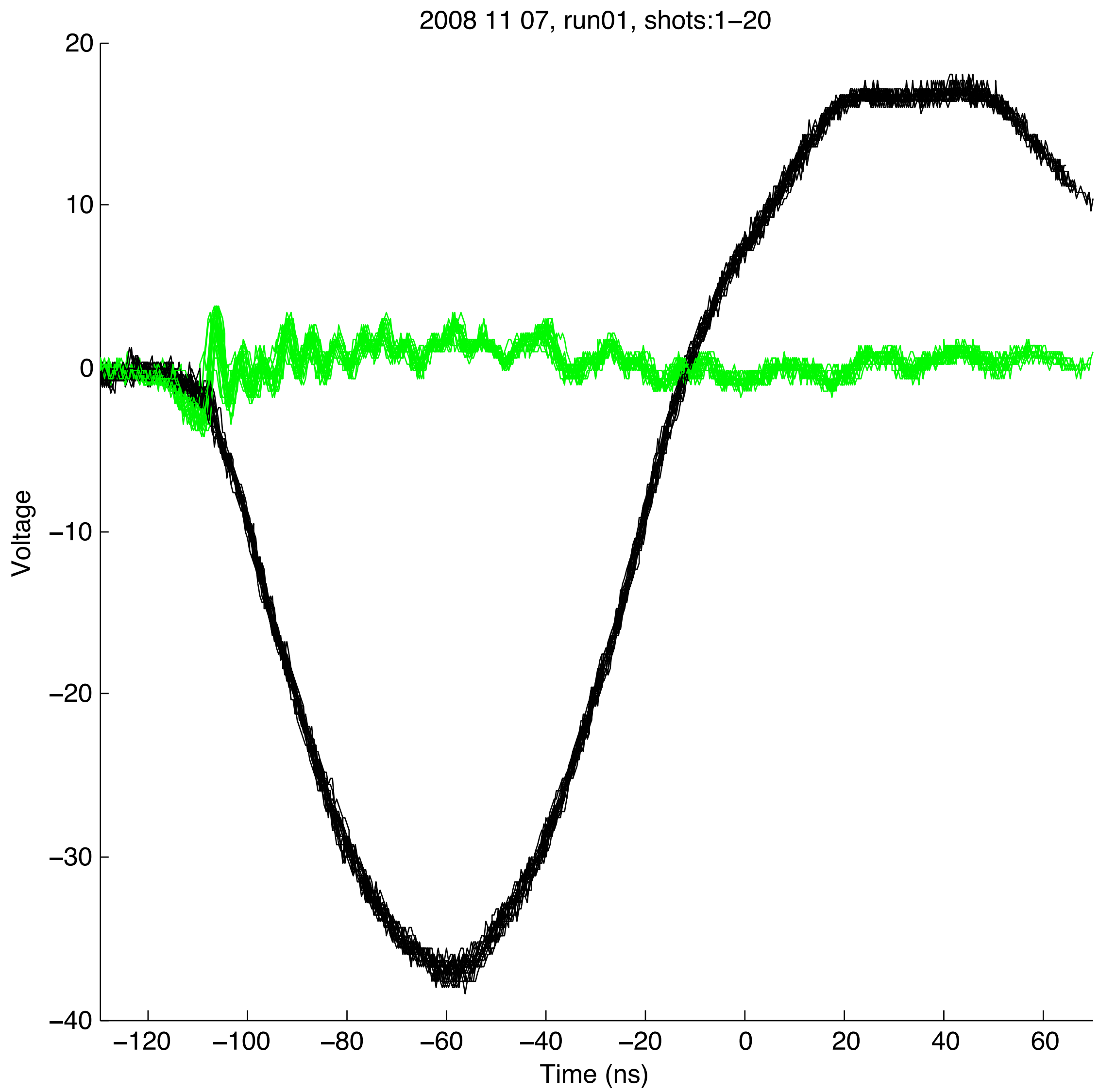
Reproducible and smooth discharges

Overlapping 20 consecutive shots

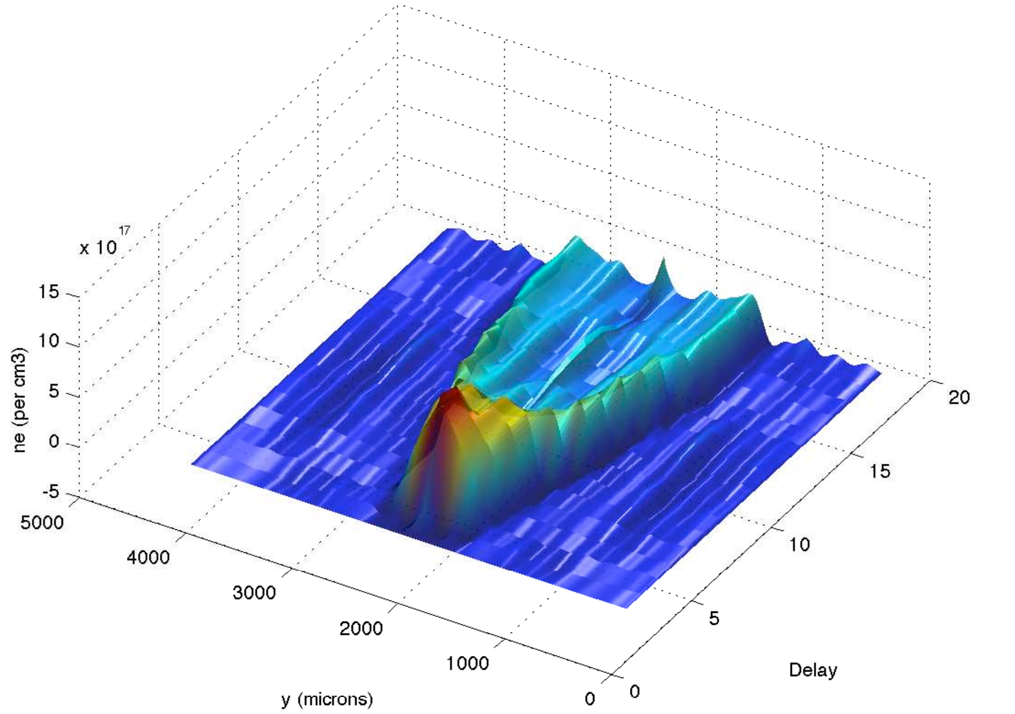
HV pulse only



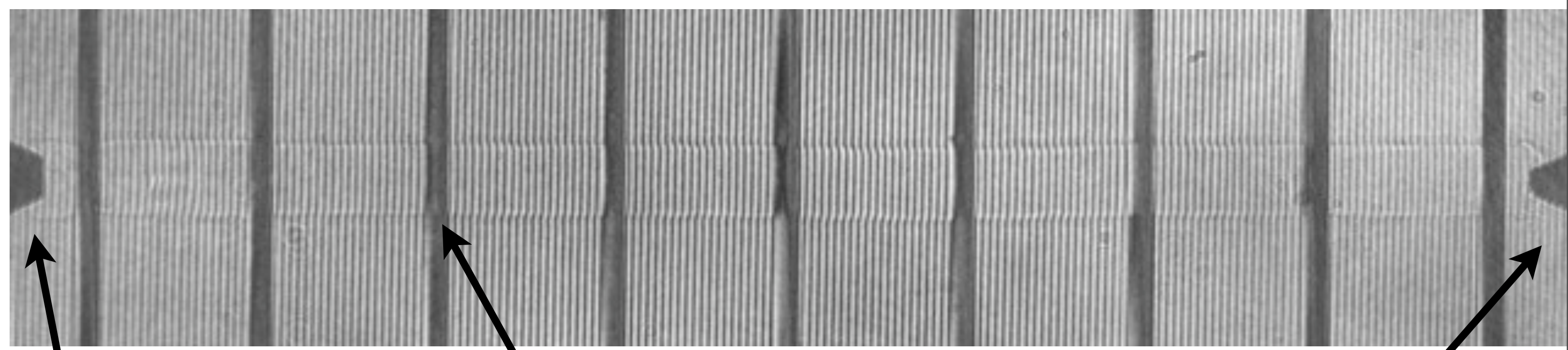
HV + simmer discharge



Reproducible and smooth plasma channels



Expansion rate: ~ 800 m s^{-1}



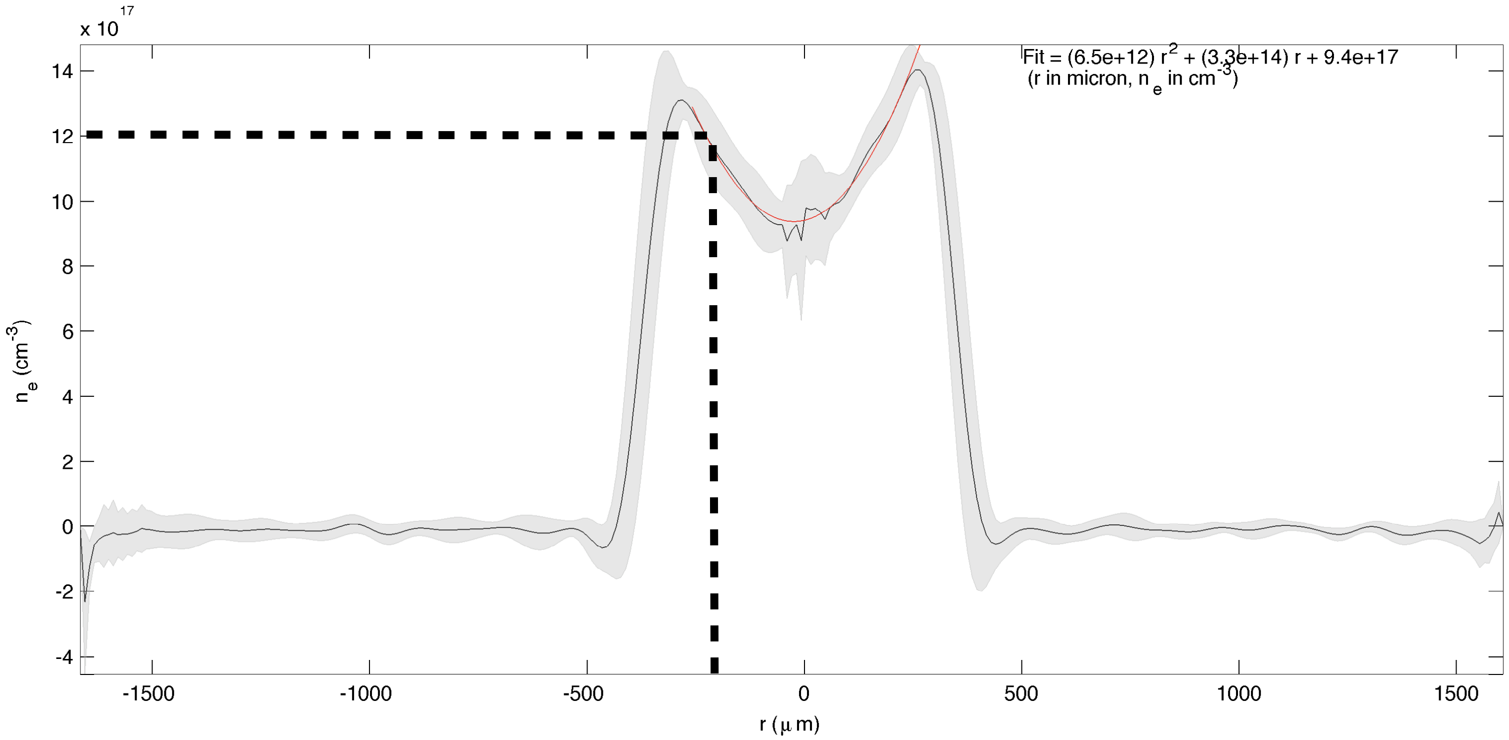
300 µm diameter electrode

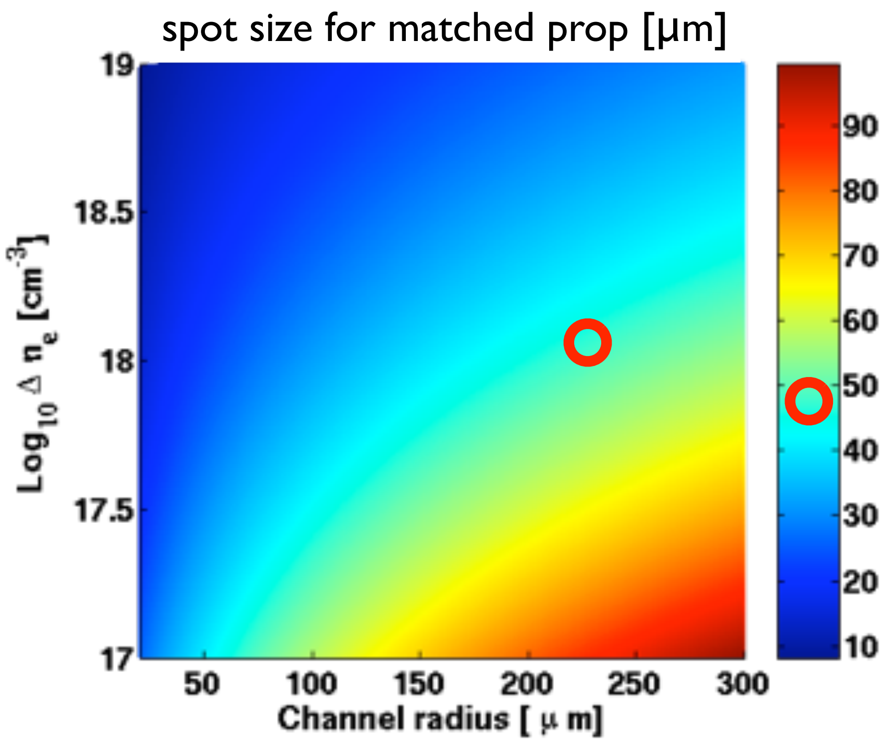
150 µm diameter dielectric apertures

125 µm diameter electrode

- Pre-discharge allow for reproducible and symmetric plasma channels
- Was not possible to make guiding experiments (KA system required)
- Plasma channels seem to be robust enough to try increase the length of the gas cell approaching the dephasing length (~10 cm)

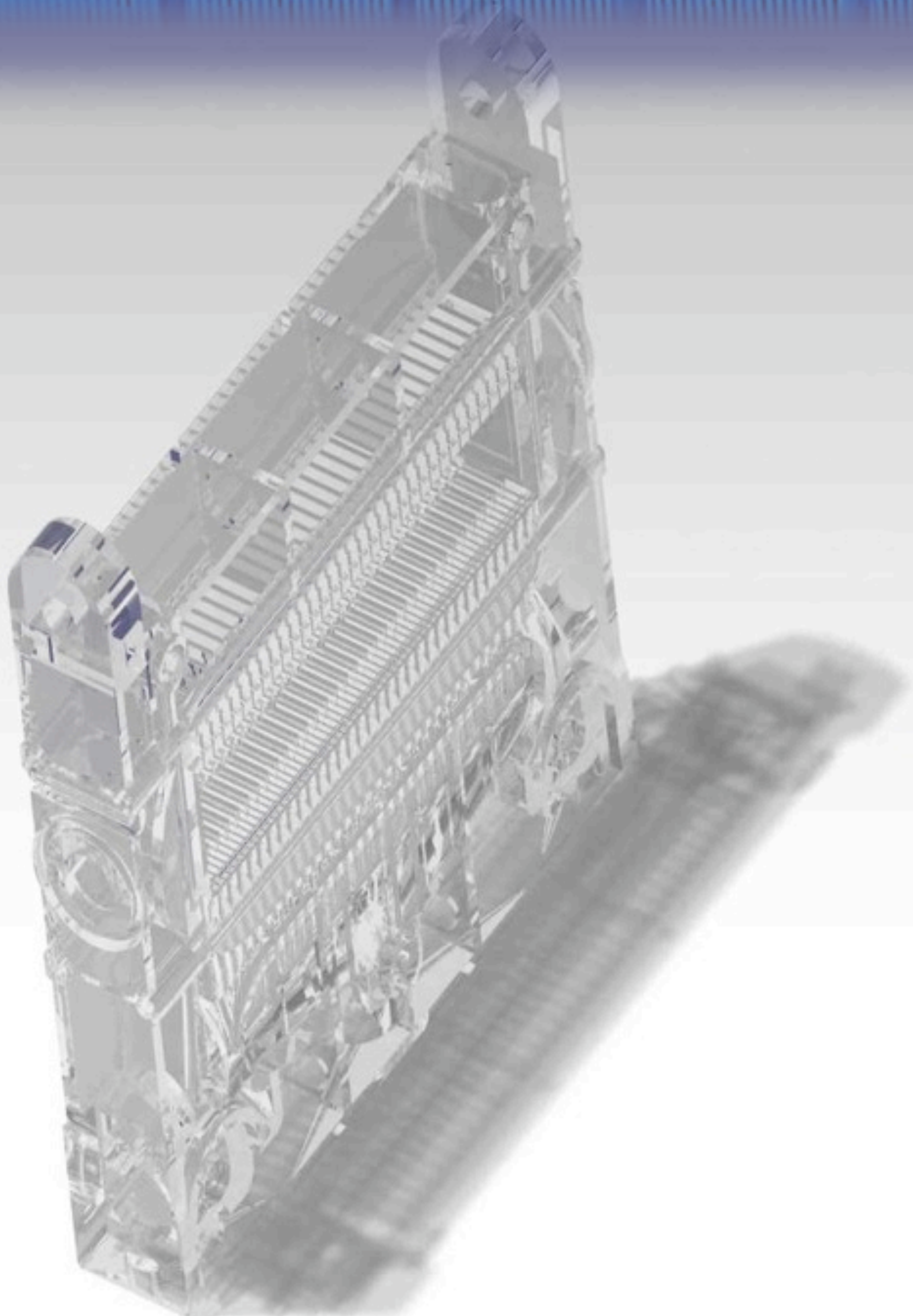
Reproducible and smooth plasma channels





- matched guiding for 40-50 μm spot sizes
- $n_{e0}=10^{18}$ cm^{-3}
- 5J Laser requires
  - $n_{e0}=3.5\times10^{17}$ cm^{-3}
  - spot size 25 μm
  - lenght 10 cm
- Next experiment will try to reach these goals with a new pulser with >2 kA discharge

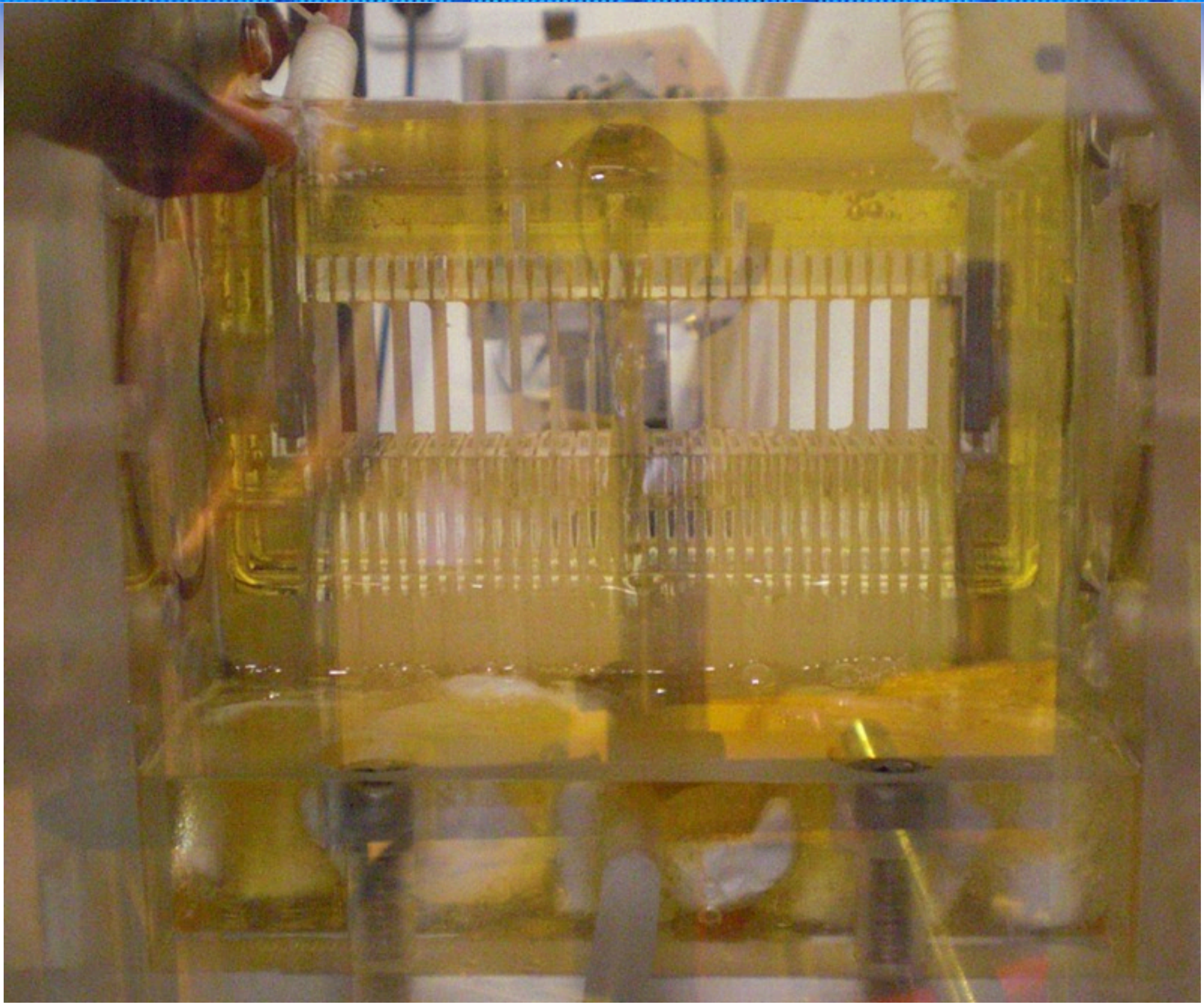
8 cm long structured gas cell



- 8cm: a compromise to between what we now (2 cm) and what we need (12 cm)
- 150 micron apertures: decrease the plasma diameter
- duplicate the lenght of the cells 2.5 mm →5mm
- increase the height of the dielectric apertures: reduce parasitic discharges

- Goal: a step forward on a plasma cell we could use w/ advantage in current systems

8 cm long structured gas cell



8 cm long structured gas cell

- Parasitic discharges always present and more important
- Plasma not heated to full ionization
- Expansion not resulting in a plasma channel
- Pashen curves do not apply due to the sequence of small apertures
- 0.25 T longitudinal B field did not change the behavior

Rescue in progress

- to pulse the DC discharge - start on more favorable pressure
- increase the DC voltage from 14 kV to 40 kV
- increase complexity of gas cell (may reduce gas pressure uniformity)
- increase B Field (require embebed coils and high current pulse)
- trigger the plasma w/ a ~100 KeV electron beam (€, long term project)

Conclusions

- convincing demo for 2 cm plasma channels (quality, reproducibility)
- easy path for at least 4 cm channels
- easy (but not inexpensive) path for 10 Hz use
- >40 µm spot size matched propagation (more work needed to reduce it)
- current versions compatible with > GeV e^- beams
- system is working now inside a metalic big vacuum chamber

Thanks to...

- EEA team - GoLP-IPFN-IST
  - Carlos Russo
  - Luis Cardoso
  - Rodolfo Bendoyro
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  - J. Dias
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