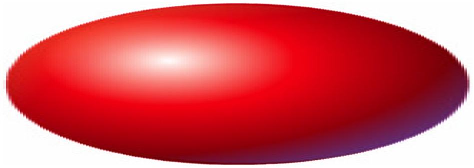
Ultracold waterbags for high-brightness beams



Jom Luiten, Edgar Vredenbregt – project leaders
Thijs van Oudheusden, Willem op 't Root – waterbags
Bert Claessens, Gabriel Taban, Merijn Reijnders – ultracold plasma
Bas van der Geer – GPT
Herman Beijerinck, Marnix van der Wiel – group leaders

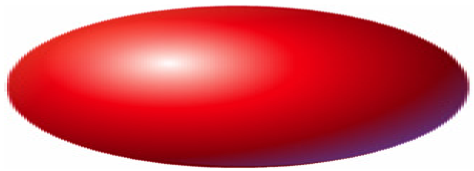
TU/e technische universiteit eindhoven

CPS CENTRUM VOOR PLASMAFYSICA EN STRALINGSTECHNOLOGIE

FOM

AAC '06, 10 July 2006

The ideal electron bunch,
an ultra-cold waterbag,
can be realized in practice.



Brightness limitations

- Nonlinear space charge forces

- Thermal emittance

$$B_{\perp} = \frac{I}{(2\pi)^2 \varepsilon_{n,x} \varepsilon_{n,y}} \leq \frac{mc^2 J}{\pi kT}$$

Nonlinear space charge forces

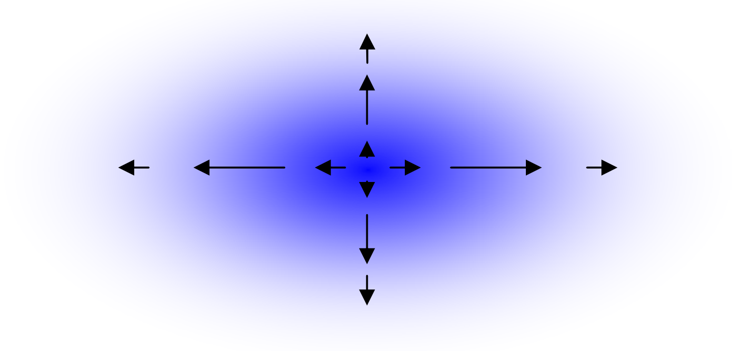
Gaussian bunch

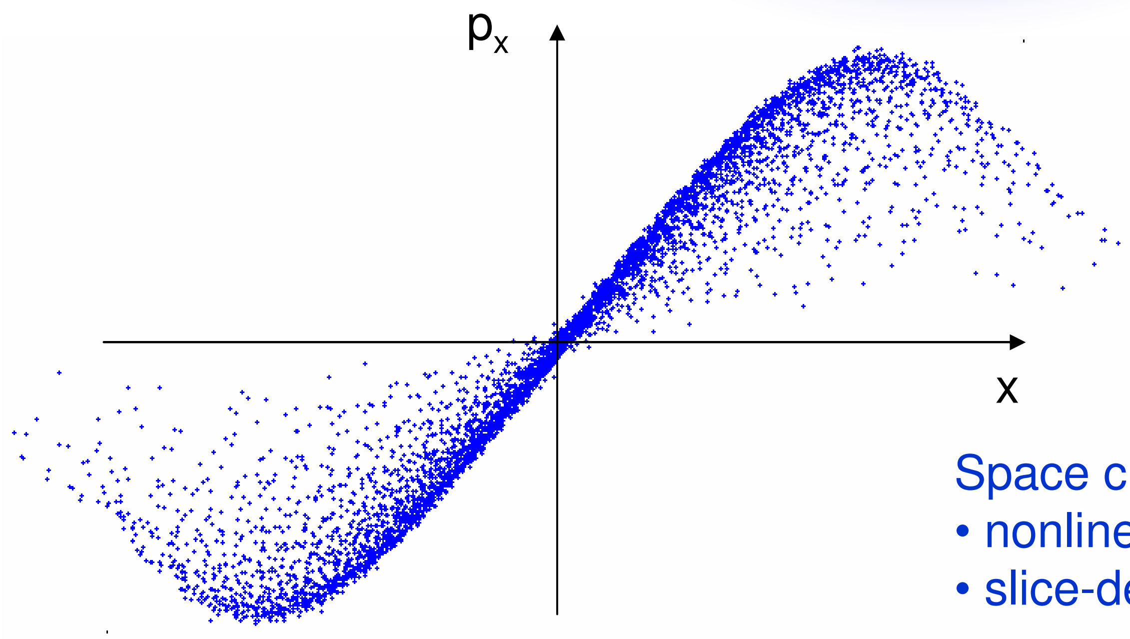
The problem is not the high space charge **density** ...

Nonlinear space charge forces

... the real problem is the space charge density **distribution**.

Gaussian bunch



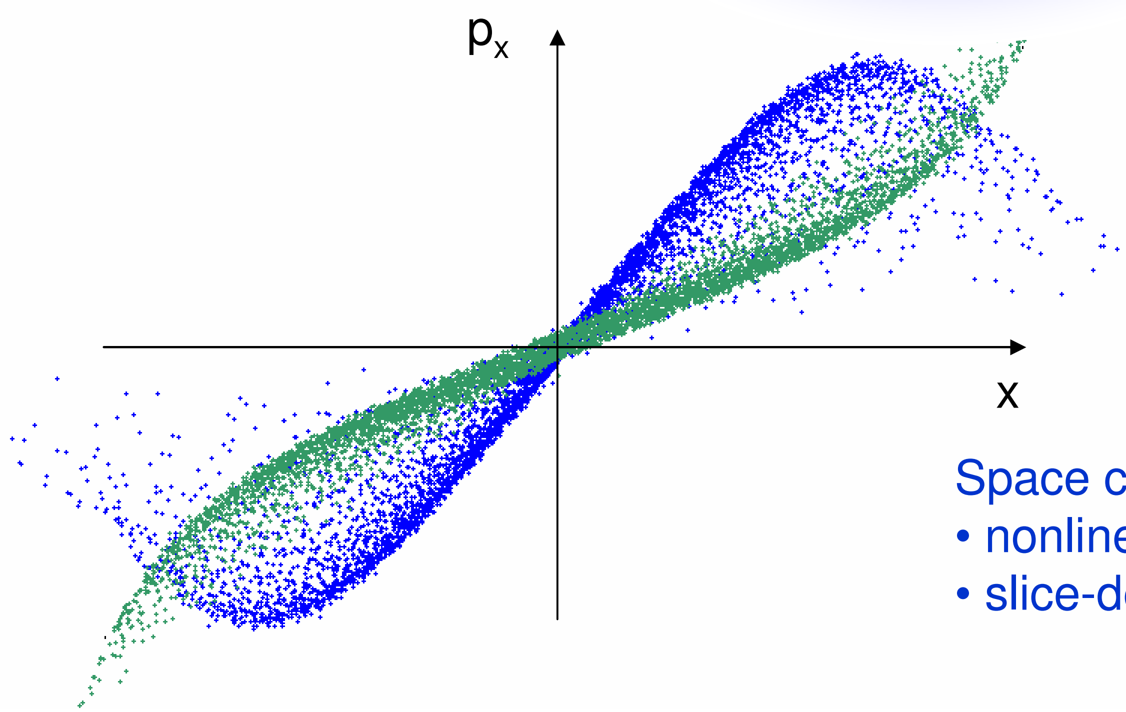


Space charge forces:
- nonlinear
- slice-dependent

Nonlinear space charge forces

Fighting the symptoms:
- Emittance compensation (B. Carlsten)
- Truncated gaussian profile (L. Serafini)
- Uniform temporal & radial profile (DESY,..
- ...

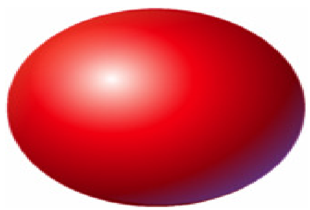
Gaussian bunch



Space charge forces:
- nonlinear
- slice-dependent

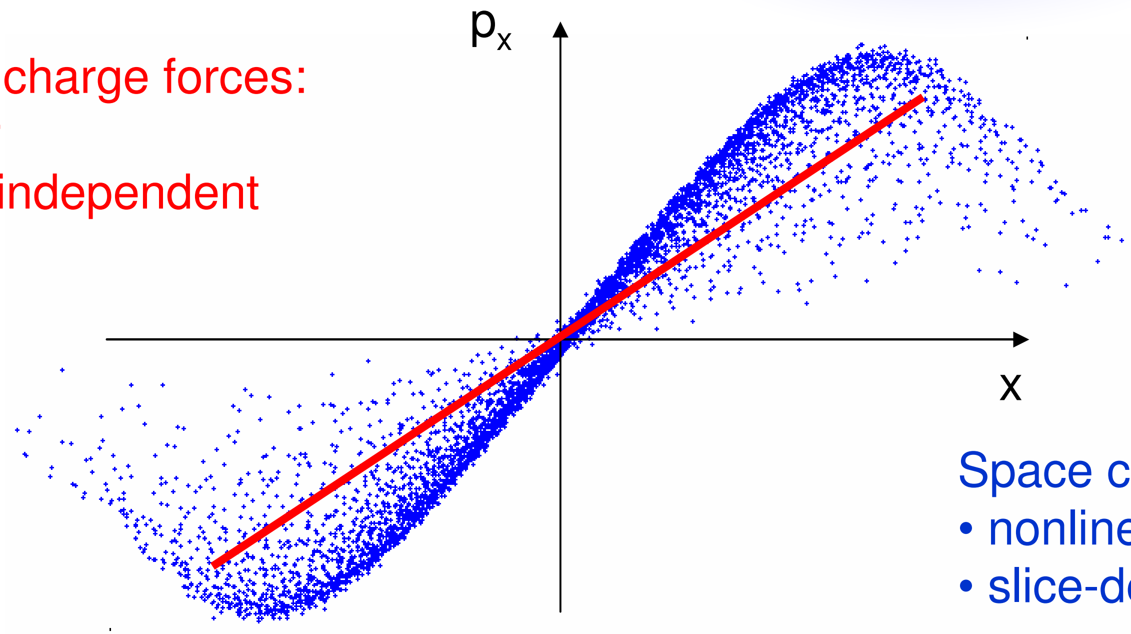
Fundamental solution:

Waterbag bunch



Gaussian bunch

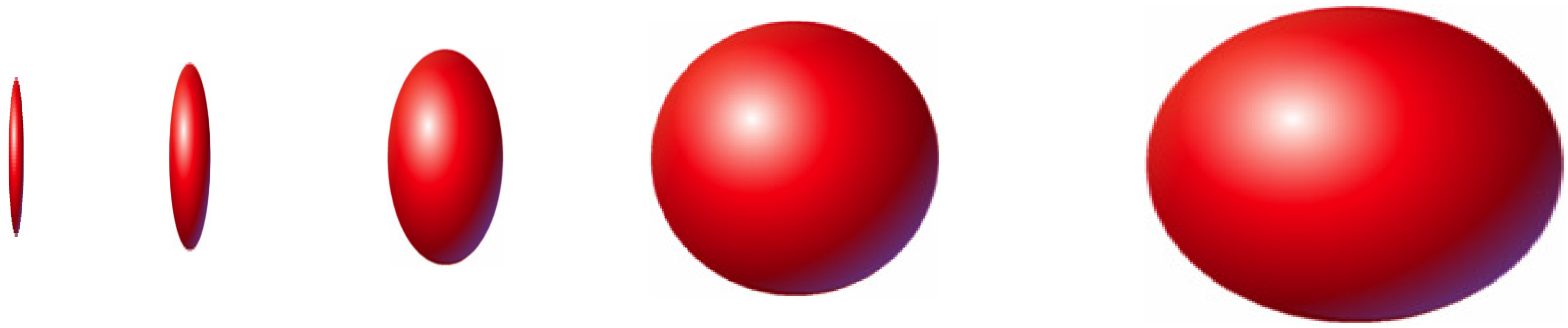
Space charge forces:
- linear
- slice-independent



Space charge forces:
- nonlinear
- slice-dependent

Thermal-emittance-limited beam!

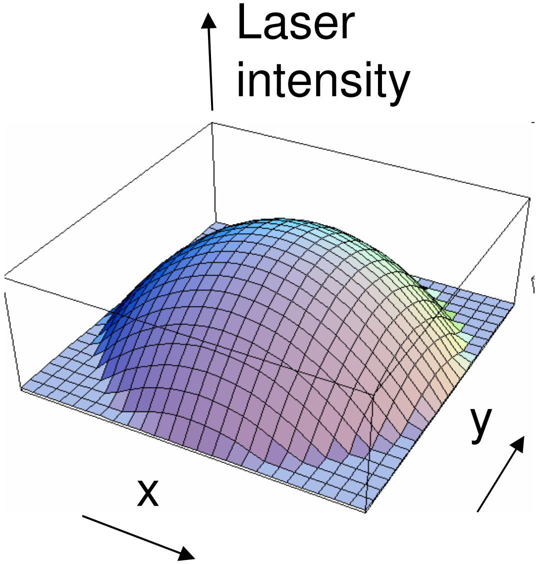
Once a waterbag, always a waterbag!



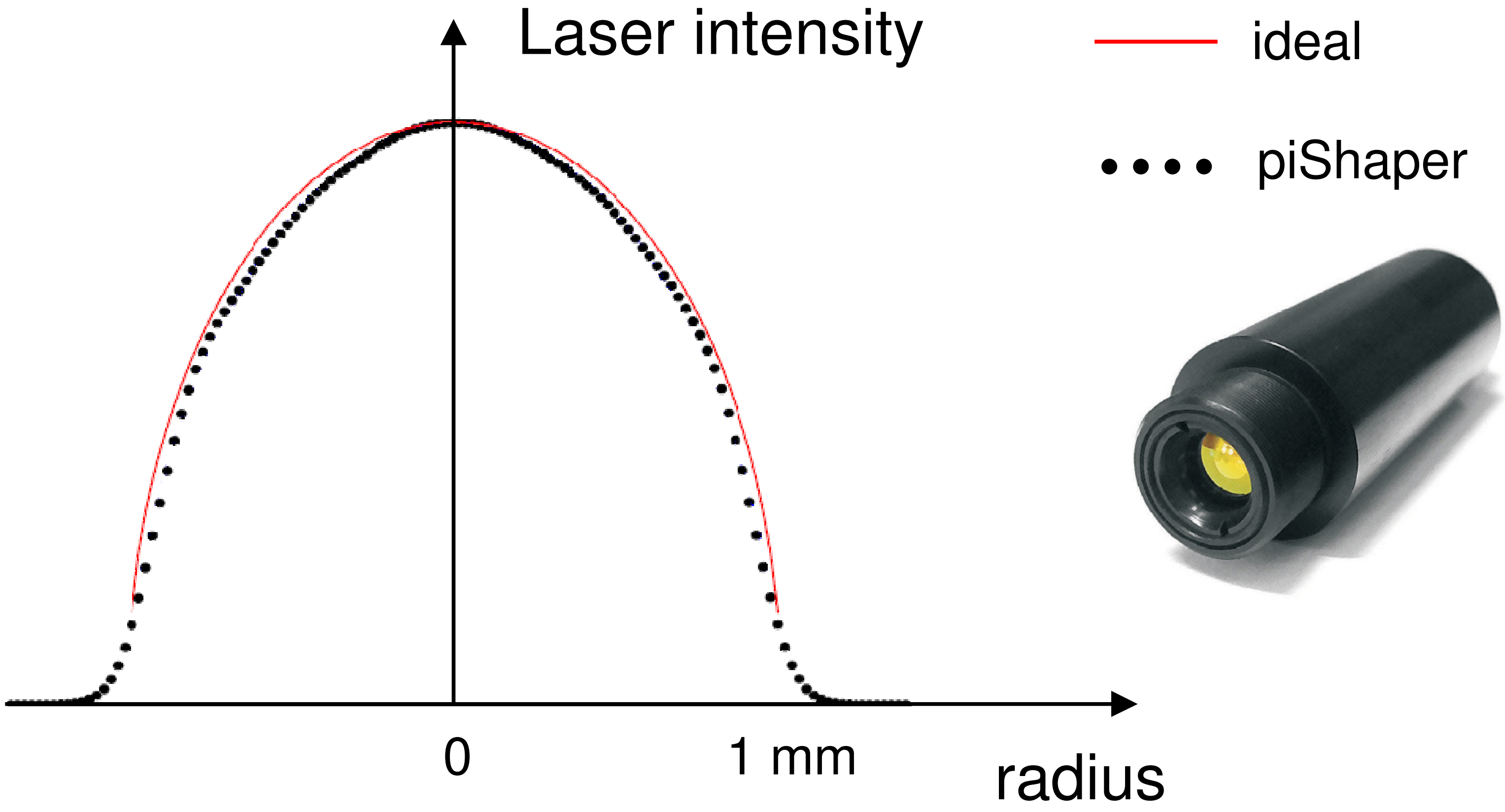
Waterbag recipe:

- *femtosecond* photoexcitation of *pancake* bunch
- *'half-sphere'* laser intensity profile;
- $E_{acc} >> E_{self}$;
- **evolution into 3-D, uniform ellipsoid.**

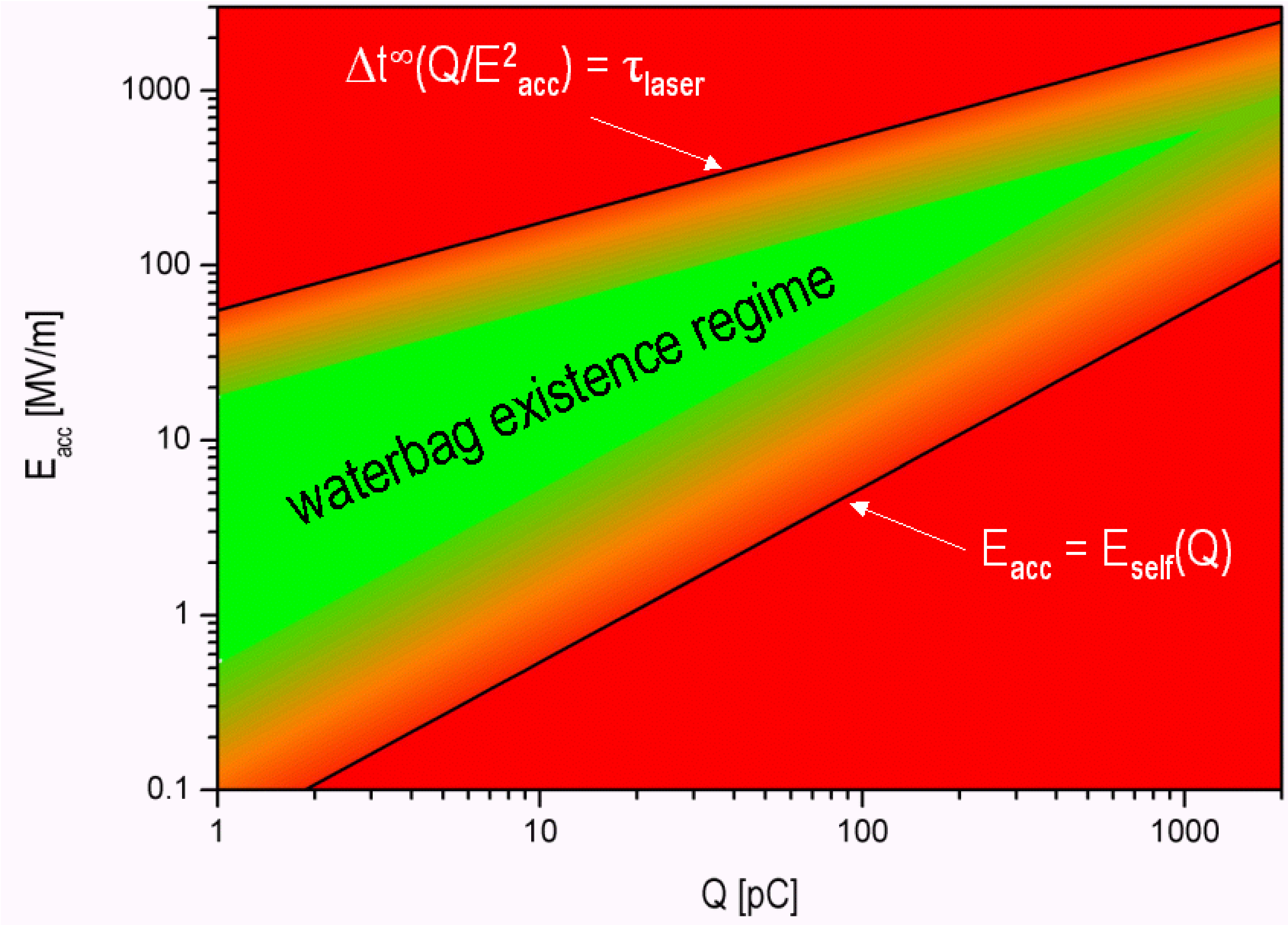
Luiten et al., PRL **93**, 094802 (2004)



Experimental realization ‘half-sphere’ laser intensity profile:



Beam radius = 1 mm, laser pulse length = 30 fs



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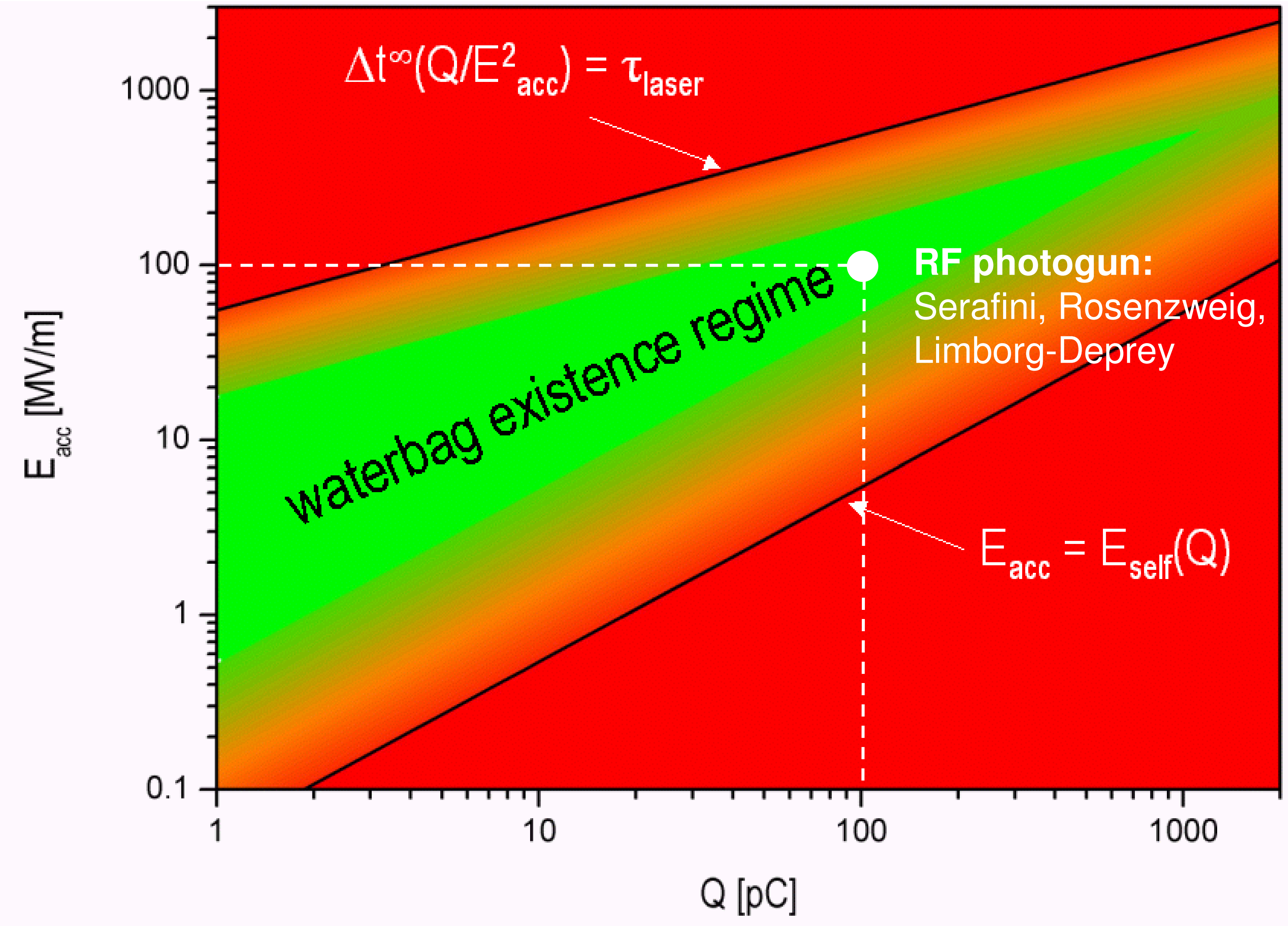

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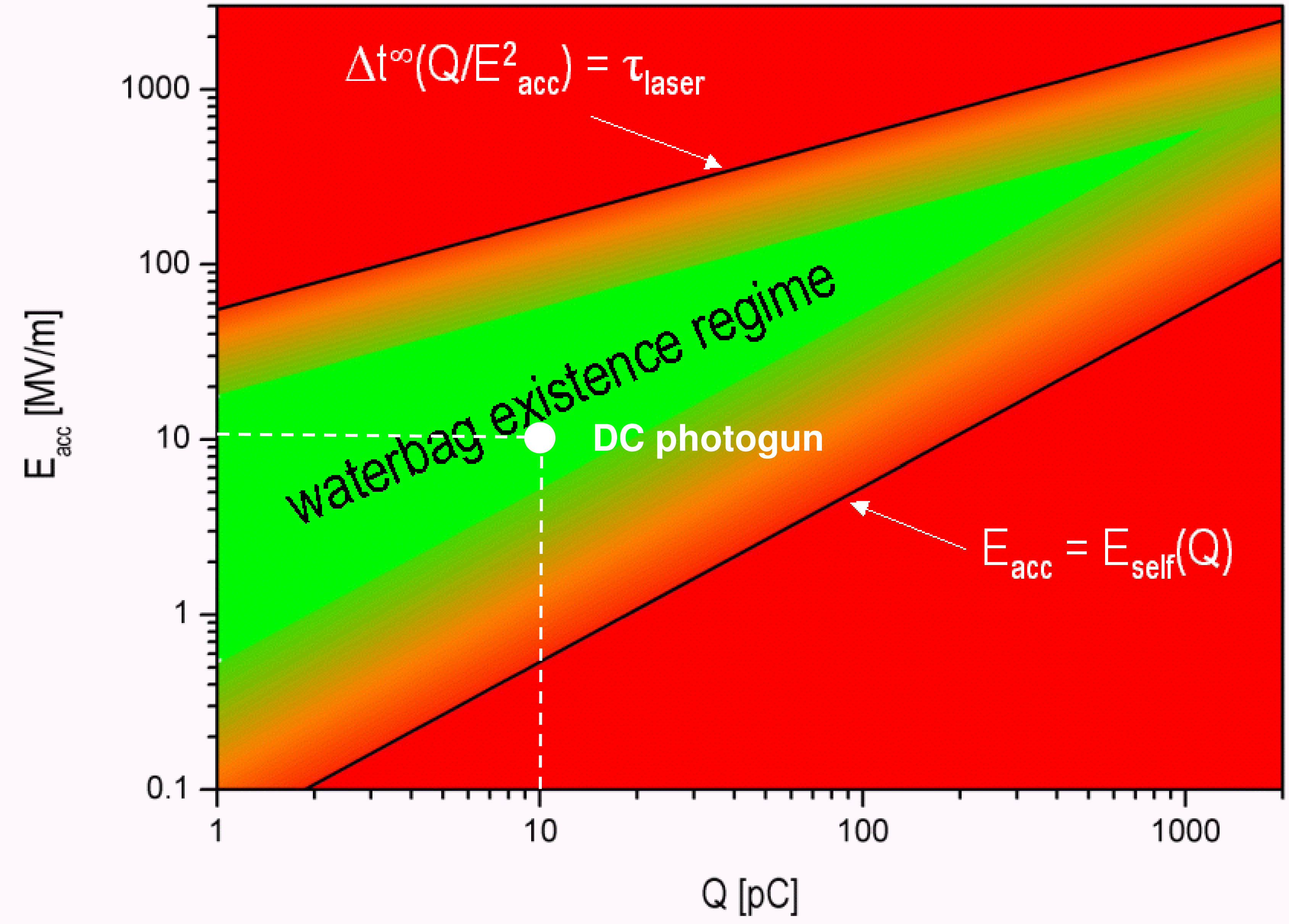
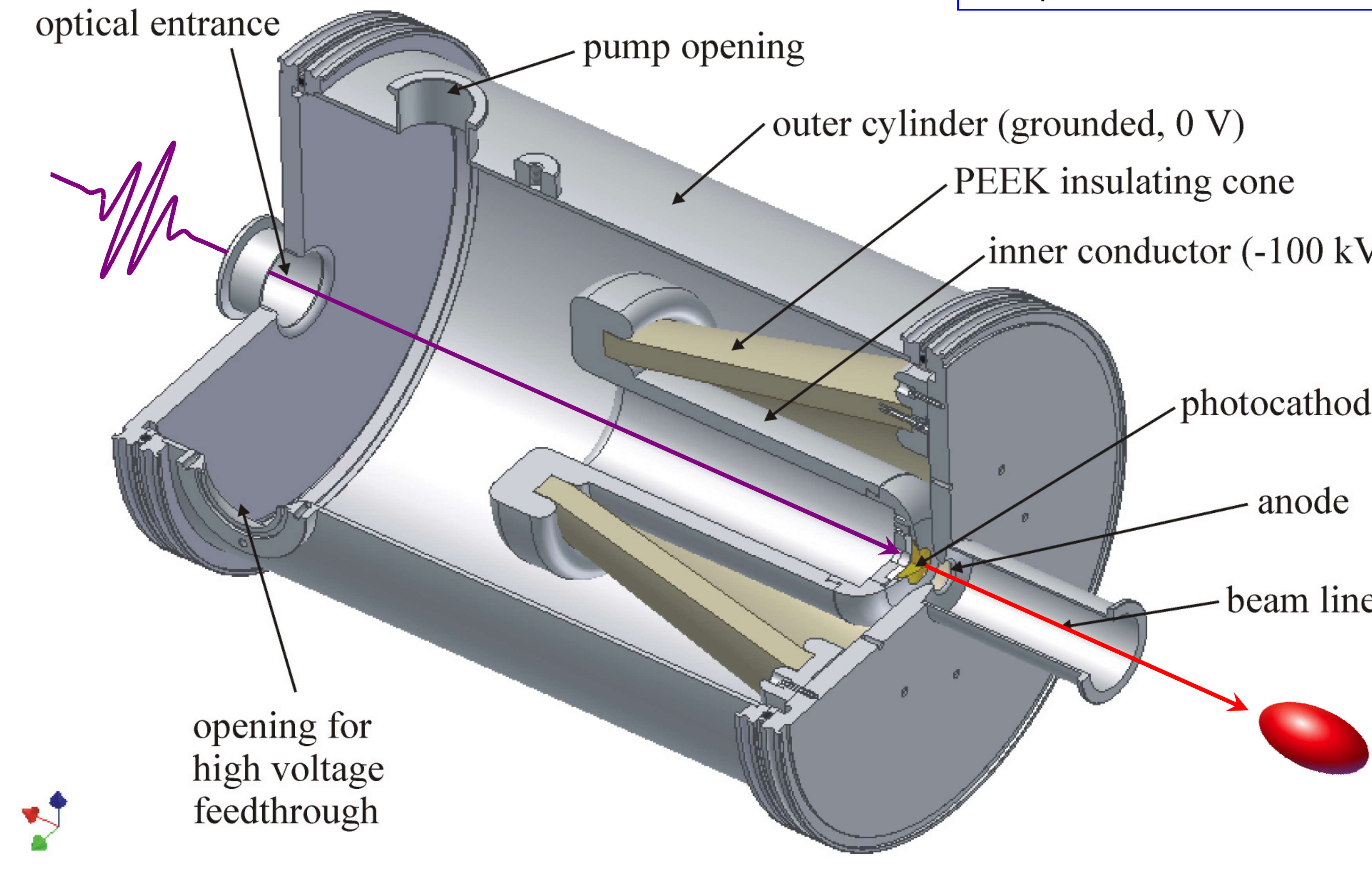


Back-illuminated 100 kV DC photogun

E_{acc} = 8.6 MV/m

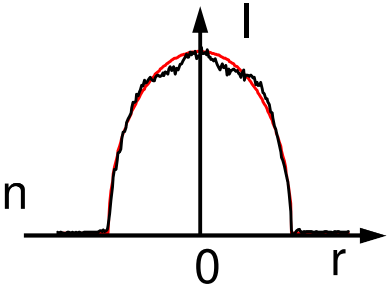
0.6 pC @ 800 nm back

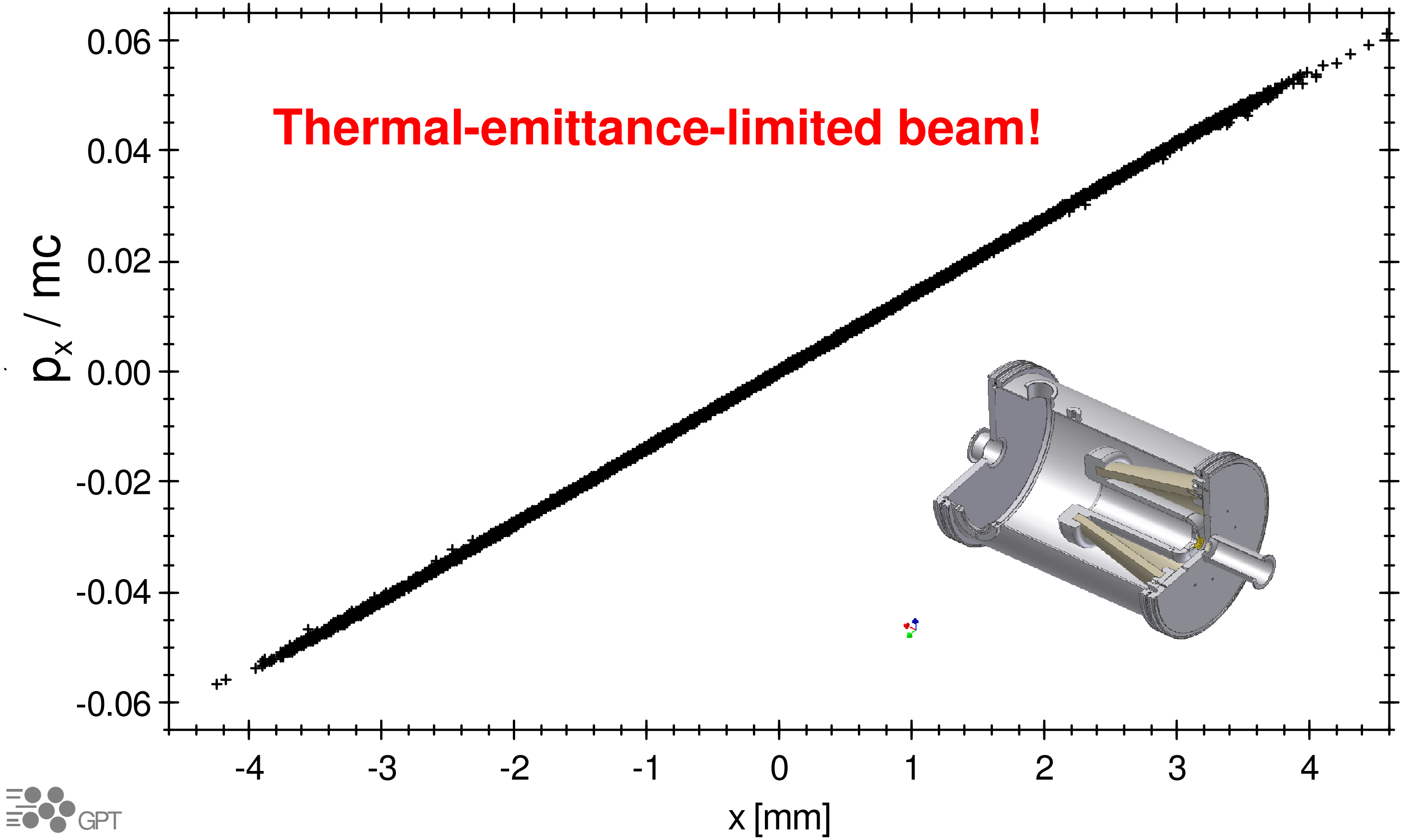
>10 pC @ 266 nm front



GPT Simulations:

- Q = 10 pC, $R_{initial}$ = 1 mm
- Measured HeNe beam profile
- Realistic field 100 kV DC photogun

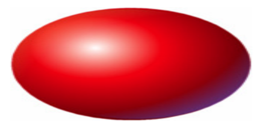




GPT

Brightness limitations

☑ Nonlinear space charge forces

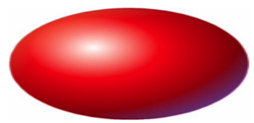


☐ Thermal emittance

$$B_{\perp} = \frac{I}{(2\pi)^2 \varepsilon_{n,x} \varepsilon_{n,y}} = \frac{mc^2 J}{\pi kT}$$

Brightness limitations

☑ Nonlinear space charge forces

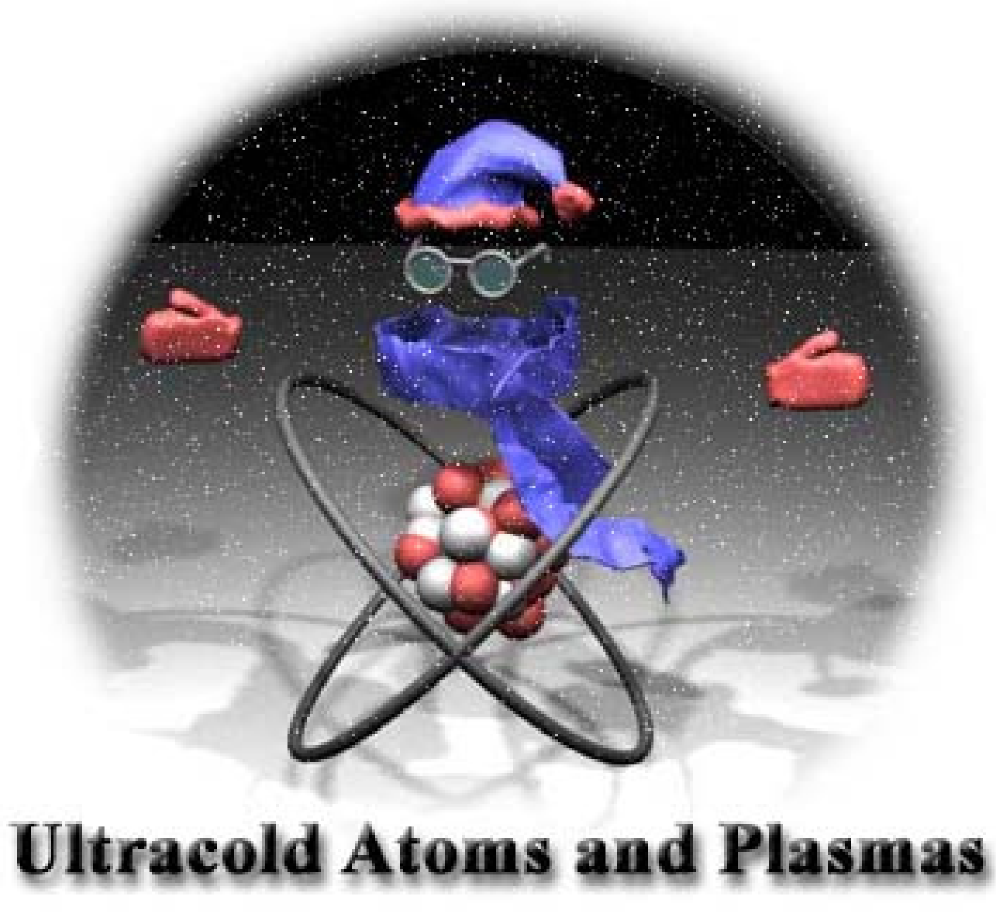


☐ Thermal emittance

$$B_{\perp} = \frac{I}{(2\pi)^2 \varepsilon_{n,x} \varepsilon_{n,y}} = \frac{mc^2 J}{\pi kT}$$

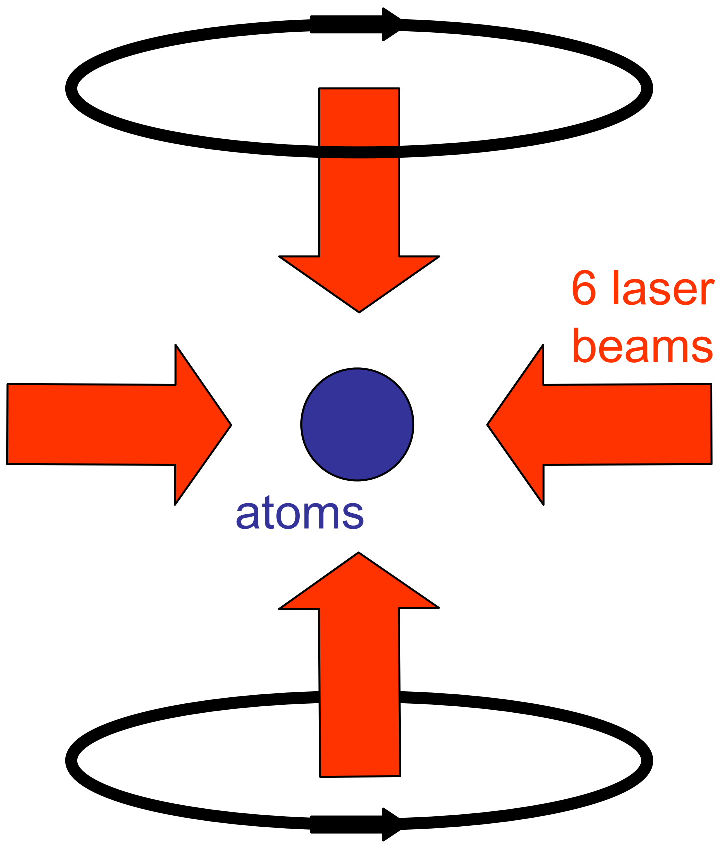
1 eV → $<$ 0.001 eV

10^4 K → $<$ 10 K



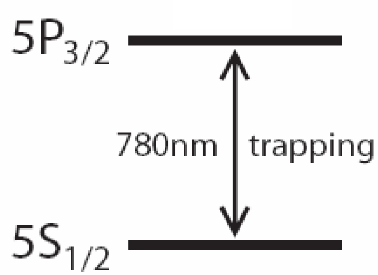
Killian et al., PRL **88**, 065003 (1999)

Ultra Cold Plasma (**UCP**)

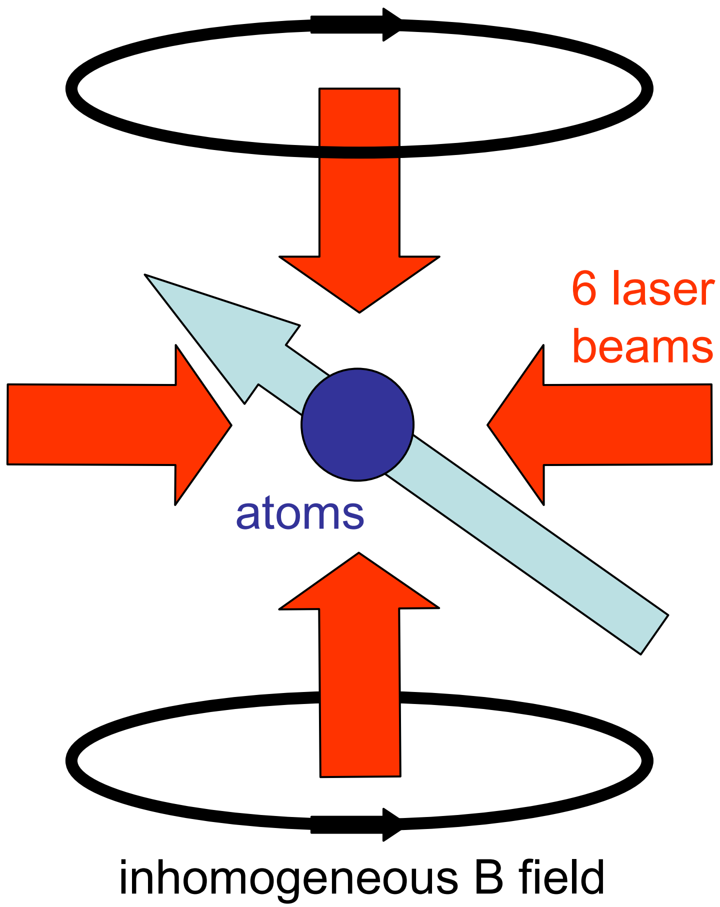


collect **atoms** from beam/vapor

- Laser cooling
- Magneto-Optical Trap (MOT)
- N > 10^9 atoms, R = 1 mm
- T_{atom} < 0.001 K



Ultra Cold Plasma (**UCP**)



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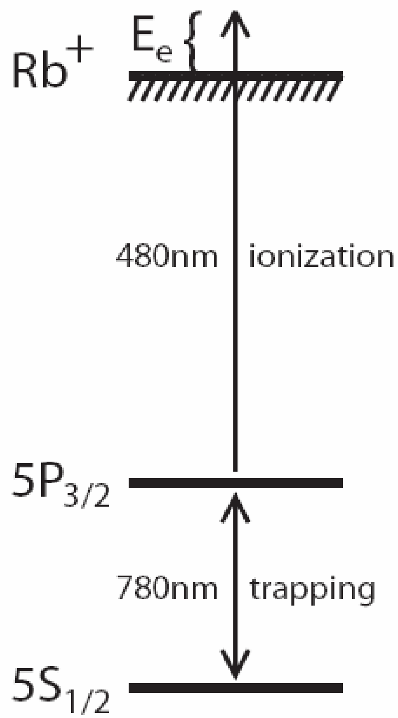
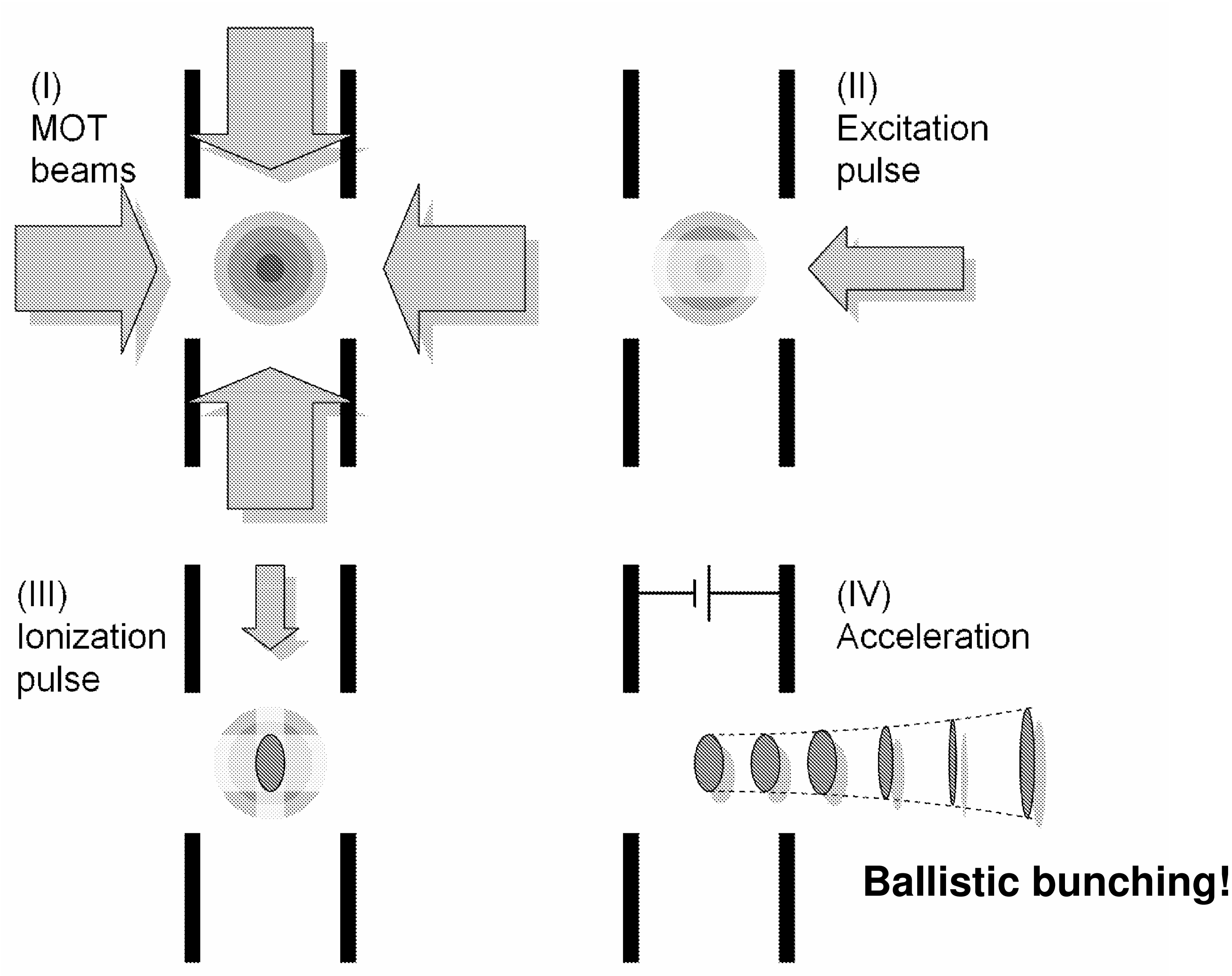


Ionize with **pulsed laser** ($\tau_{pulse} > 1$ ns)

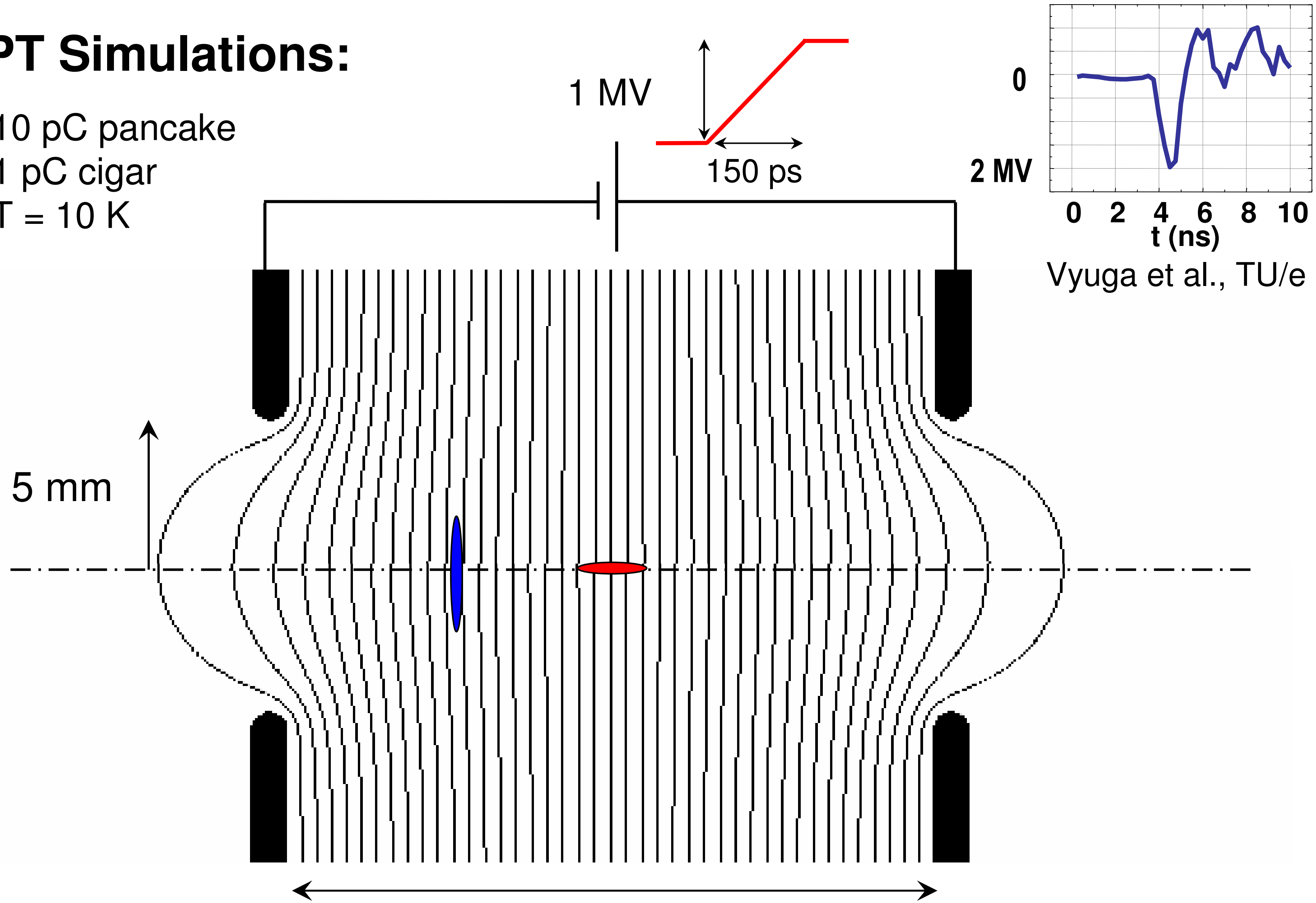
$T_{electron} = 10$ K

kT=0.001 eV

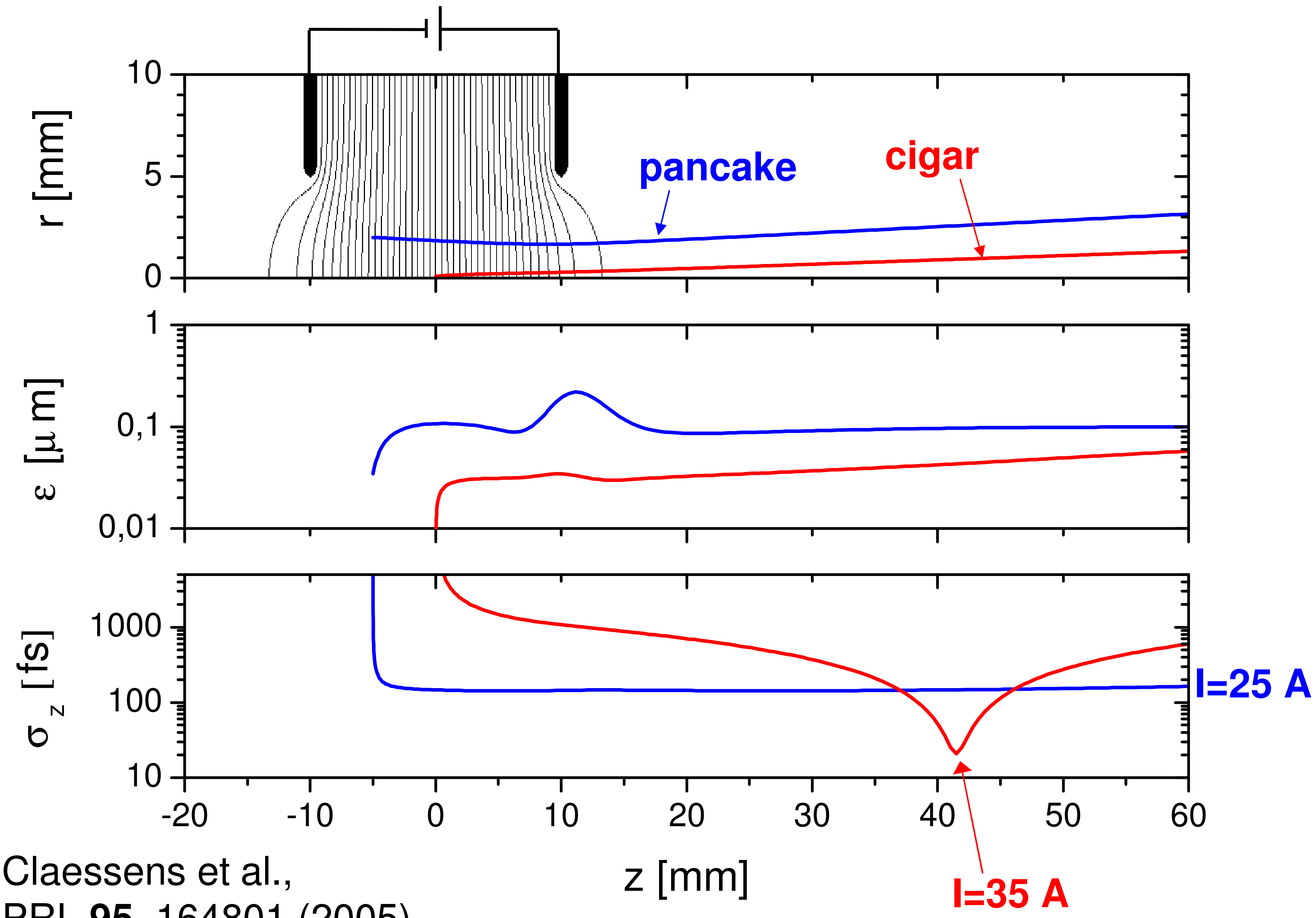

(I)
MOT
beams
(II)
Excitation
pulse
(III)
Ionization
pulse
(IV)
Acceleration
Ballistic bunching!

GPT Simulations:

- 10 pC pancake
- 1 pC cigar
- T = 10 K



Vyuga et al., TU/e



Claessens et al.,
PRL **95,** 164801 (2005)

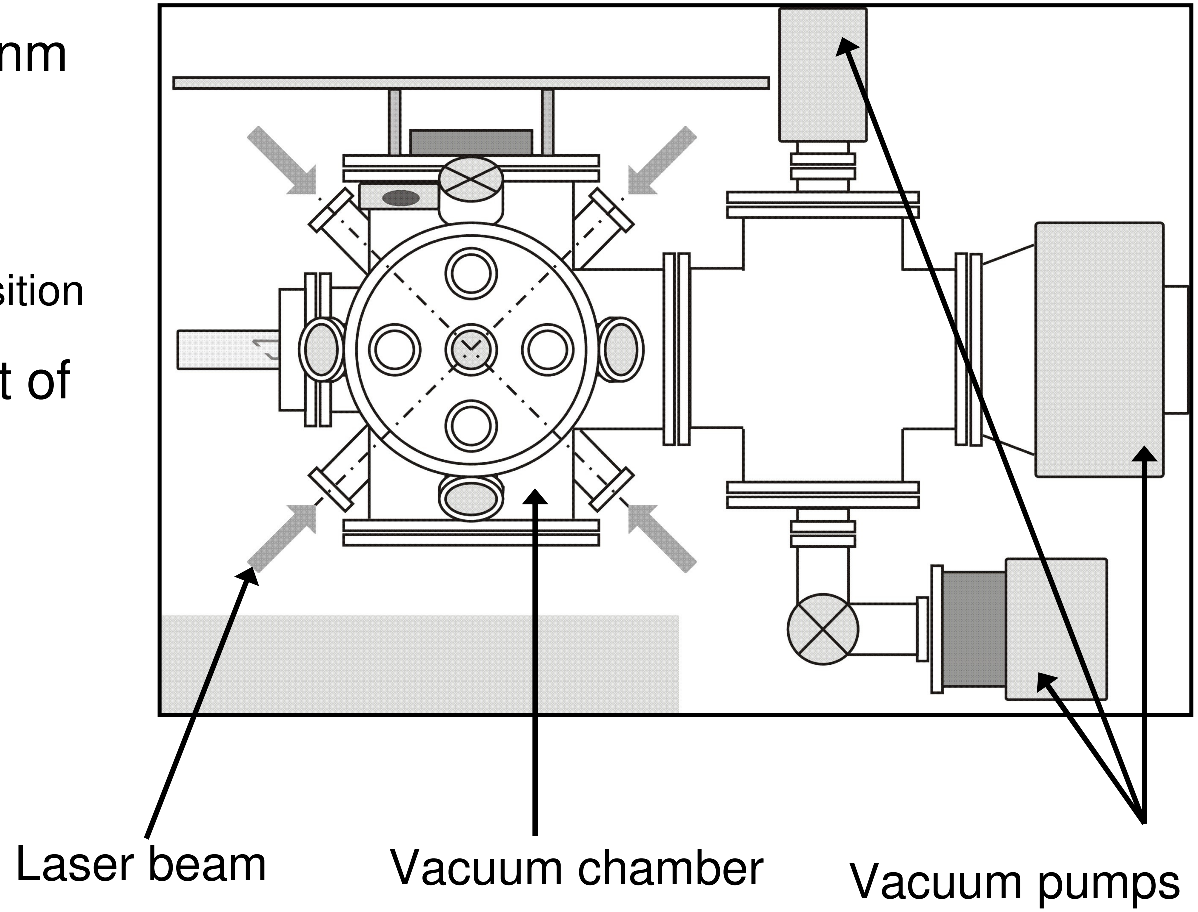
GPT Simulations: resulting beam parameters

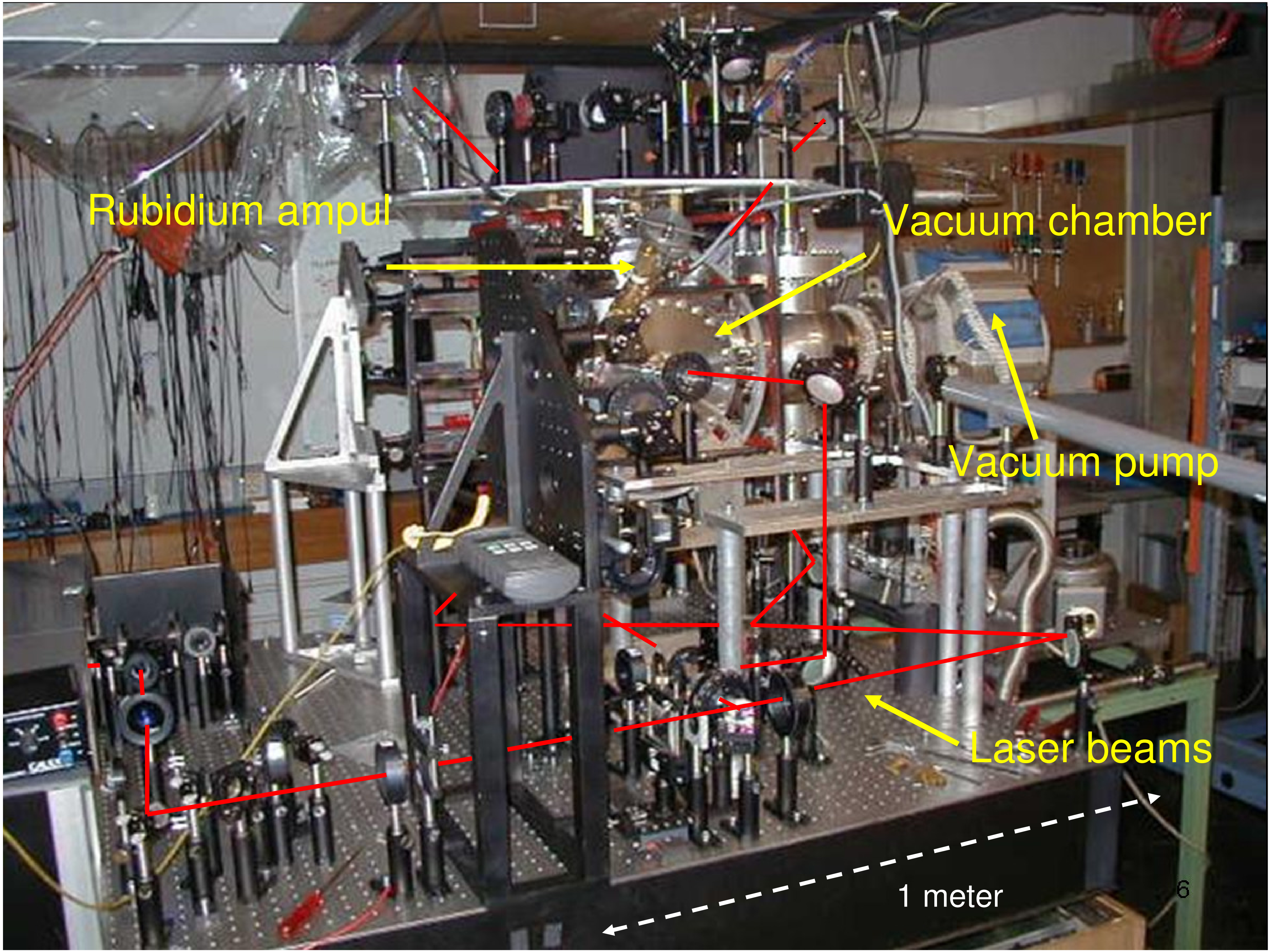
	pancake	cigar
– Peak current:	25 A	35 A
– Emittance:	0.1 µm	0.04 µm
– Charge:	10 pC	1 pC
– Energy:	470 keV	270 keV
– Pulse length:	150 fs rms	20 fs rms
– Energy spread:	0.8 keV rms	7.5 keV
– Current density:	2 A/mm^2	1.7 kA/mm^2

Ultra cold beam experiments

Setup

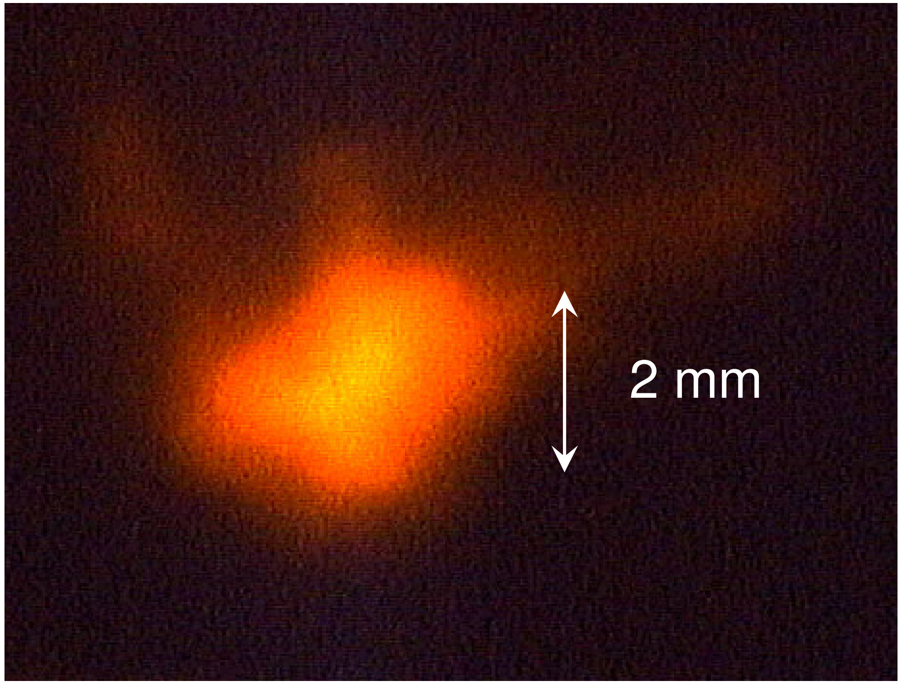
- CW Diode lasers 780 nm
  - 1 W
  - 2 MHz stability
  - Locked on atomic transition
- Magnetic field gradient of 10 G/cm
- 10^{-9} mbar




Rubidium ampul
Vacuum chamber
Vacuum pump
Laser beams
1 meter

Ultra cold beam experiments

Fluorescence image of cold Rb atom cloud

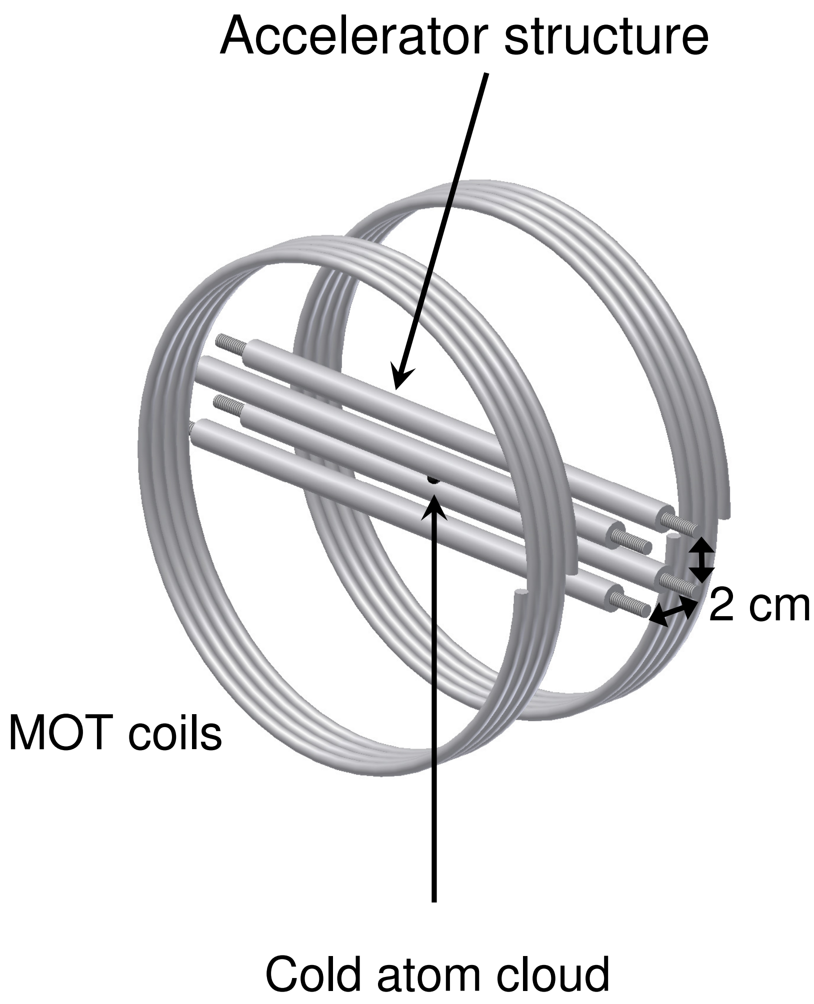


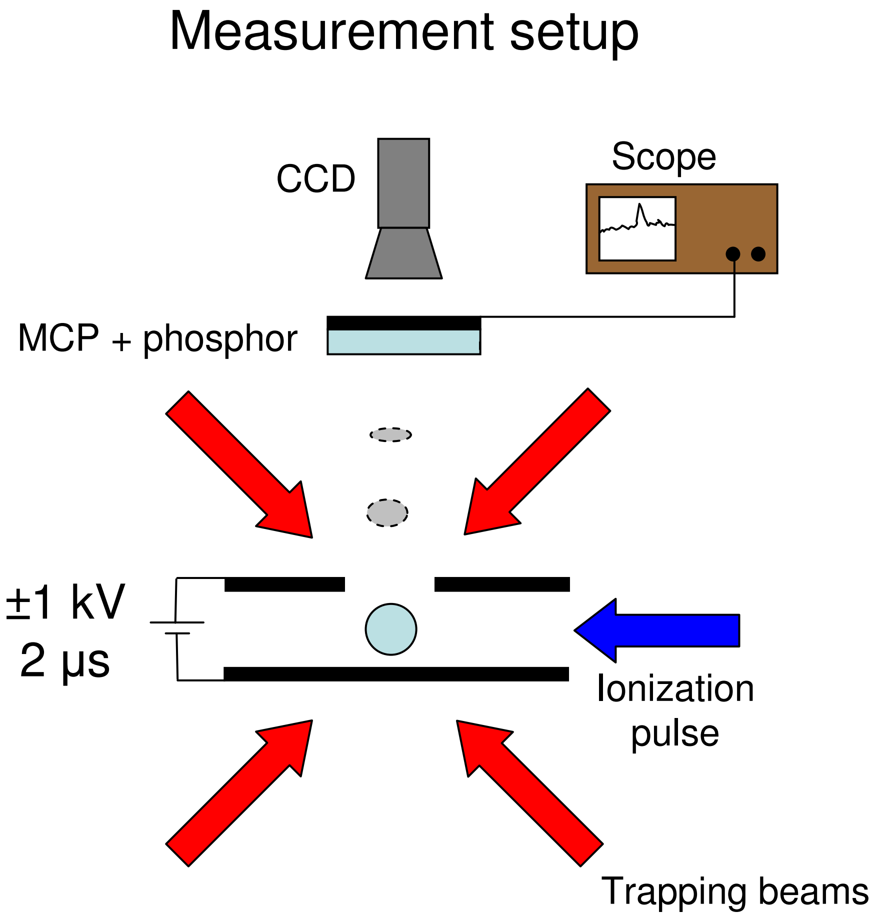
$N = 10^9$ atoms

$n = 10^{11}$ atoms/cm^3

$T = 200 \pm 100$ µK

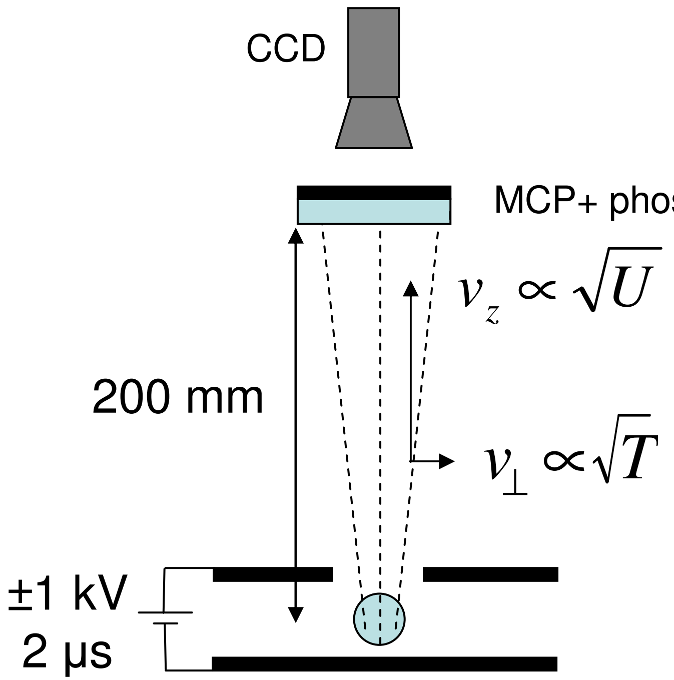
Ultra cold beam experiments



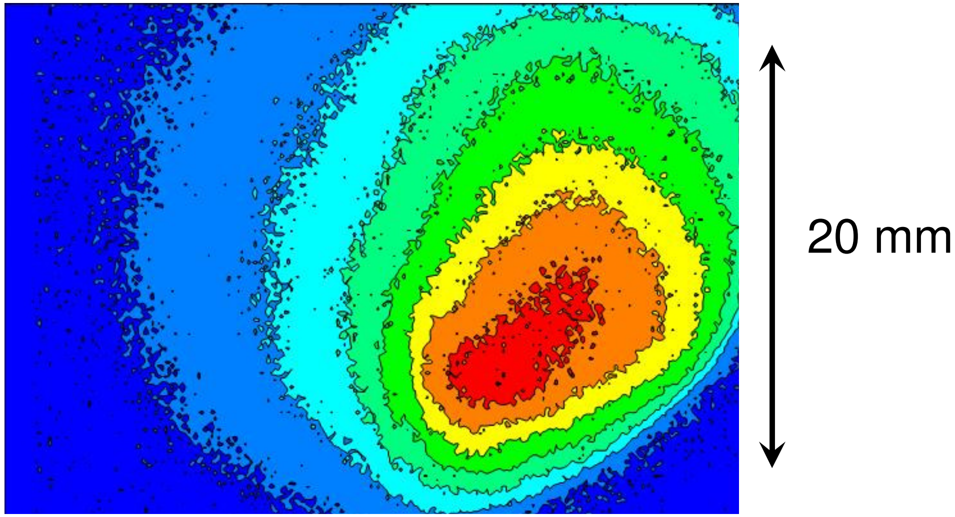


Ultra cold beam experiments

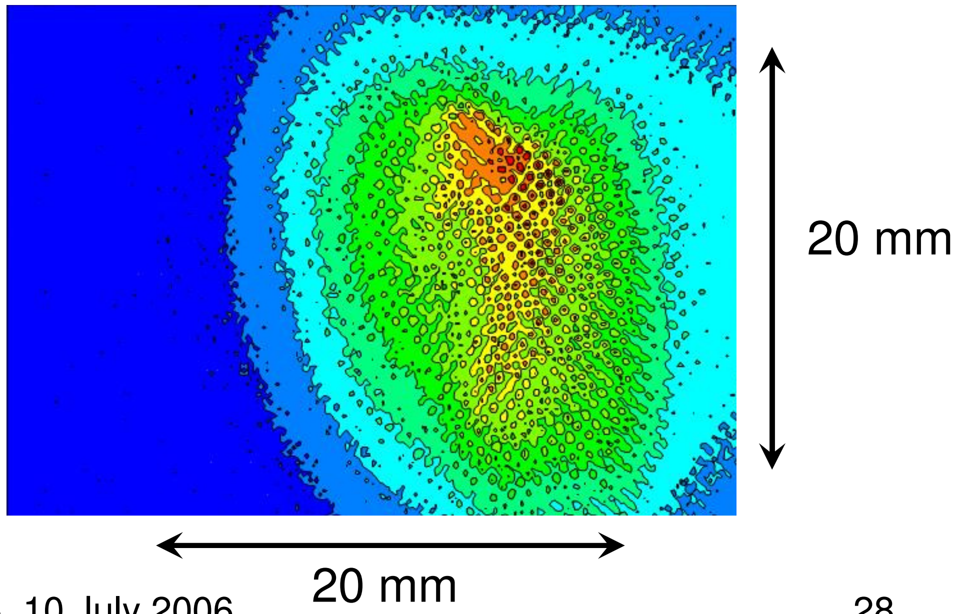
Q ≈ 2 pC



Electrons
U ≈ 10 eV

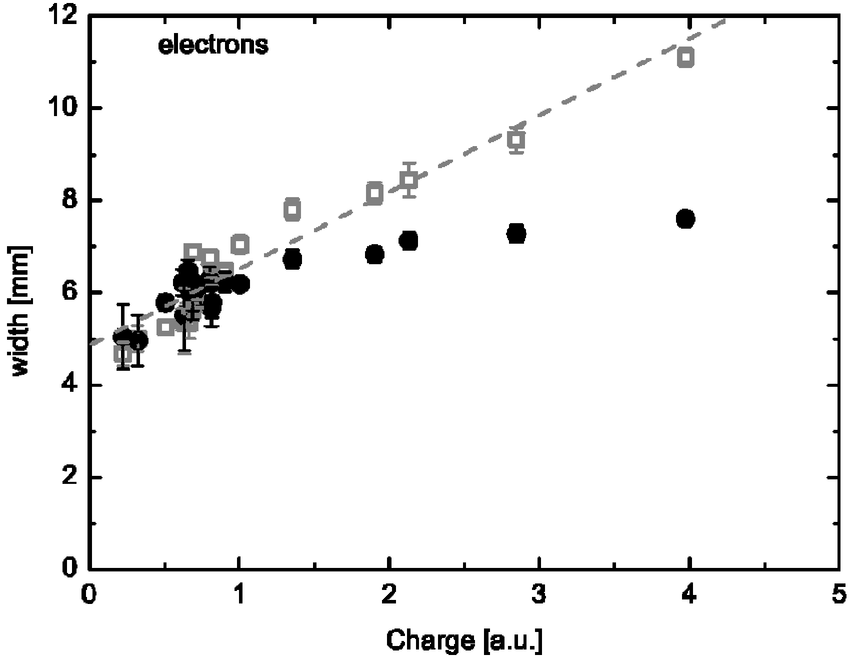


Ions
U ≈ 400 eV

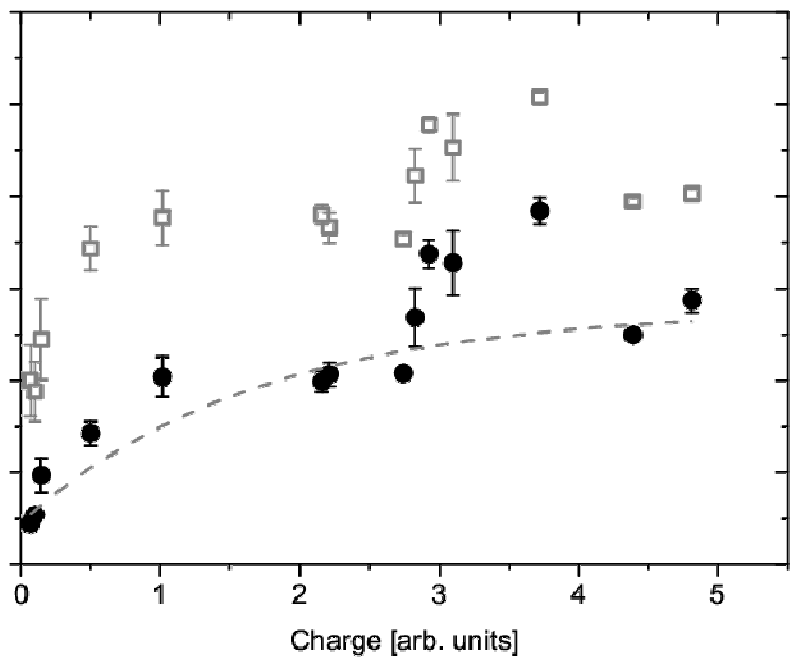


Ultra cold beam experiments

electrons



ions



Assuming point source and thermal ballistic expansion:

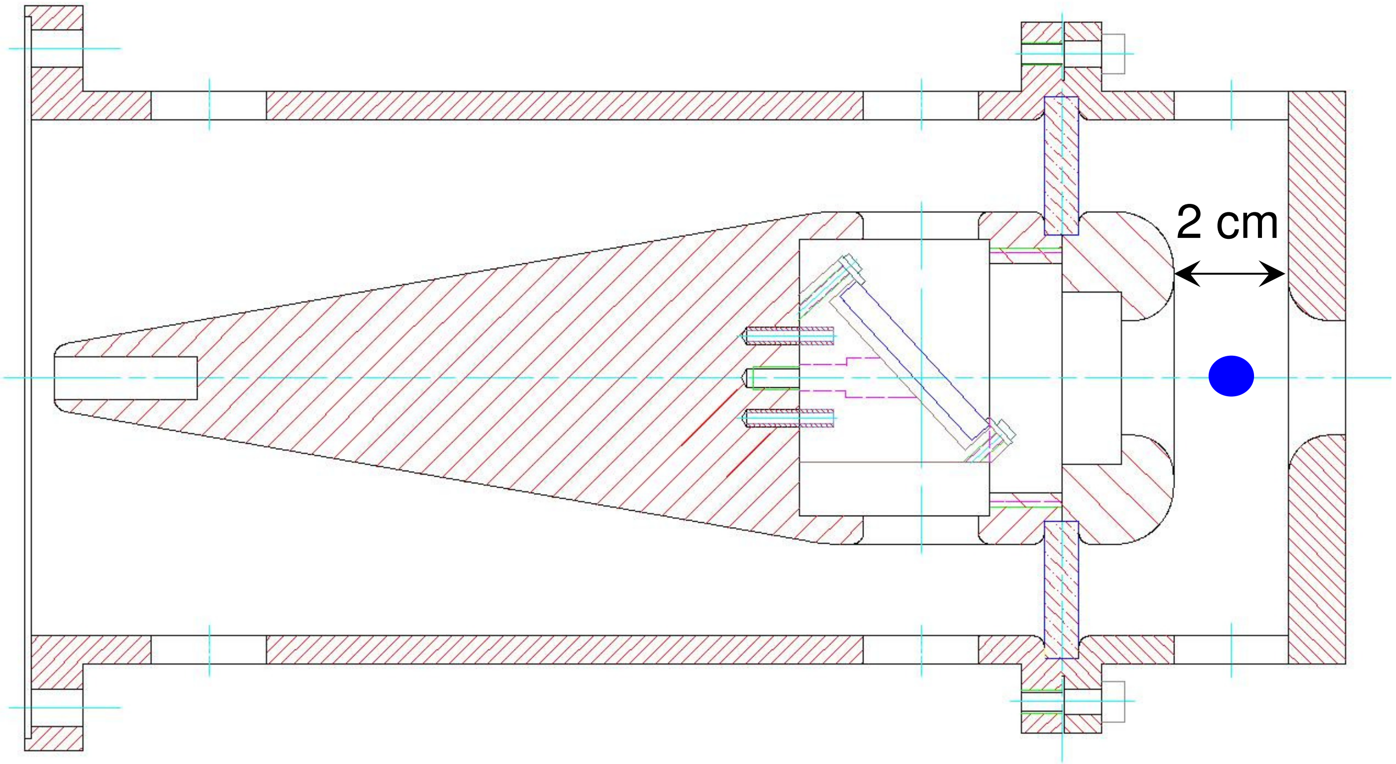
$T_{electron} \approx 50$ K

$T_{ion} \approx 50$ K

Upper limit temperature!

Ultra cold beam experiments

Next: 30 kV, 10 ns risetime coaxial accelerator structure



Ultra cold beam experiments

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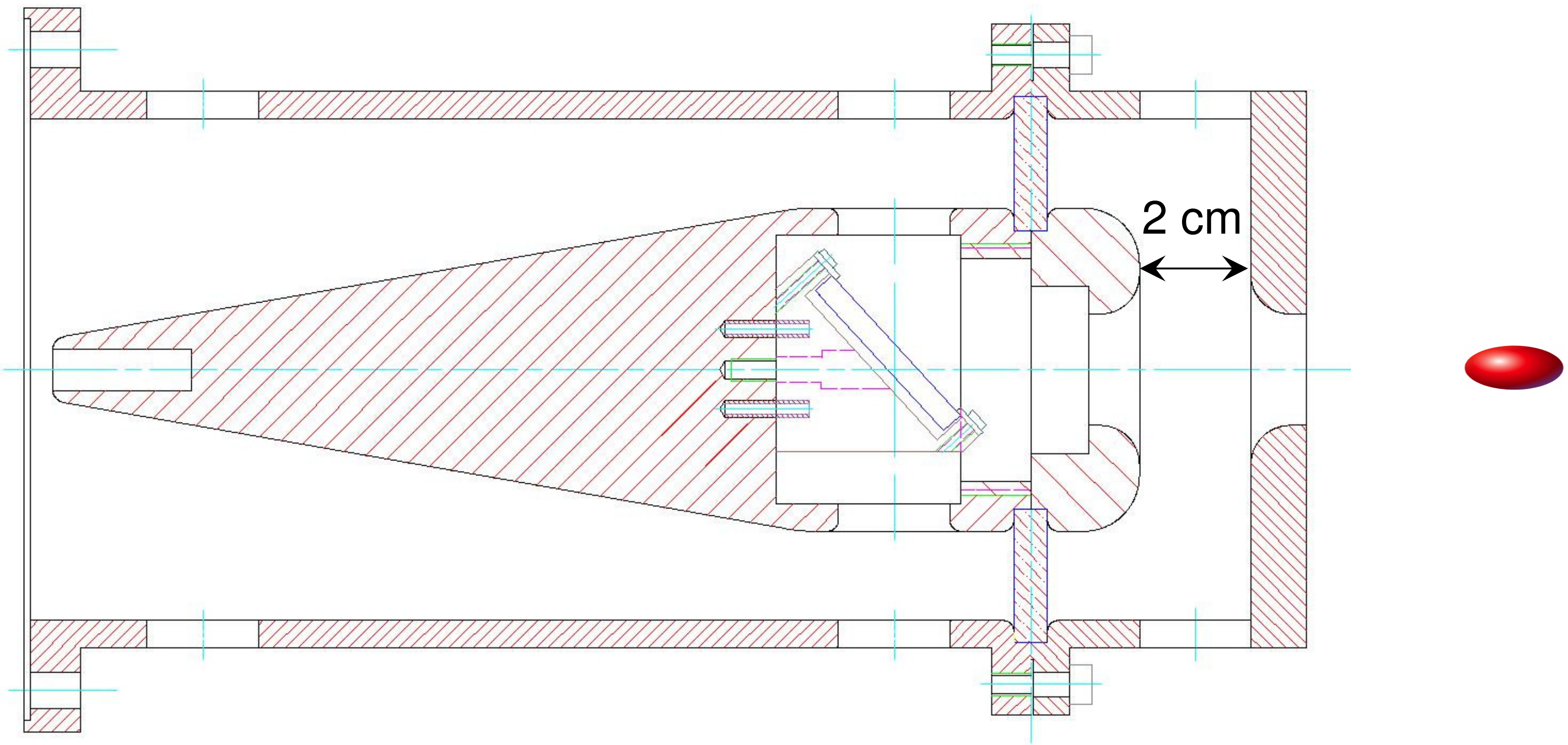
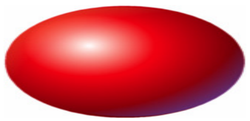
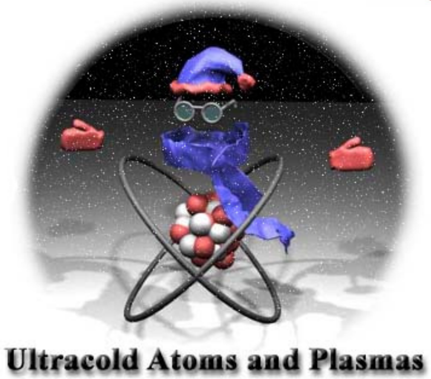


Brightness limitations

☑ Nonlinear space charge forces



☑ Thermal emittance



"Cold wine in new bags"