Electron Sourcery

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Course objective

- **Lecture 2:** Generation of electron beams: physics of photocathodes, photoinjectors, alternative sources using ultra-cold gases or plasmas, fundamental limits on beams phase space density.

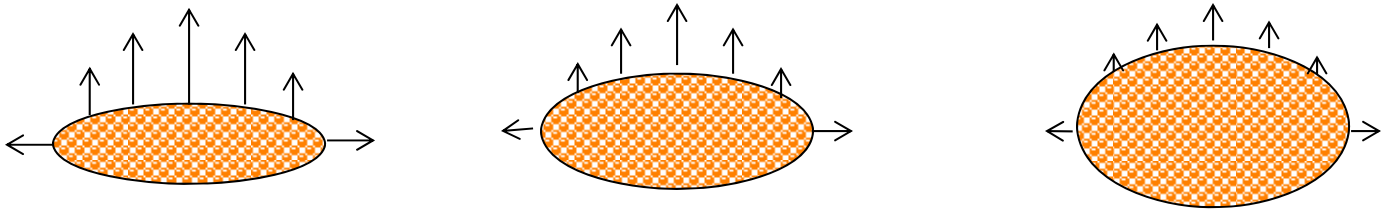
- Disclaimer. Extremely wide topic. Hard to cover exhaustively in a full semester class. Impossible in 3 hours.
- The declared goal of the class is to increase breadth more than depth
- So concepts, figures, tables and references are preferred over equations and derivations

Outline/Syllabus

- Electron source applications
- Electron source figures of merit
- Cathode physics
  - Photoemission. Thermal emittance and quantum efficiency
  - Child-Lamguir law and space charge limits
  - Maximum achievable brightness
- Photoinjector gun types
- Beam Dynamics in RF guns
  - Longitudinal equation of motion
  - Transverse RF effects: rf focusing and emittance.
- Space charge effects
  - Cylindrical beams
  - Emittance oscillations
  - Scaling laws
  - Blow-out regime, pancakes and cigars
- Magneto Optical Trap-based ultracold sources
- Nanotips based e-sources

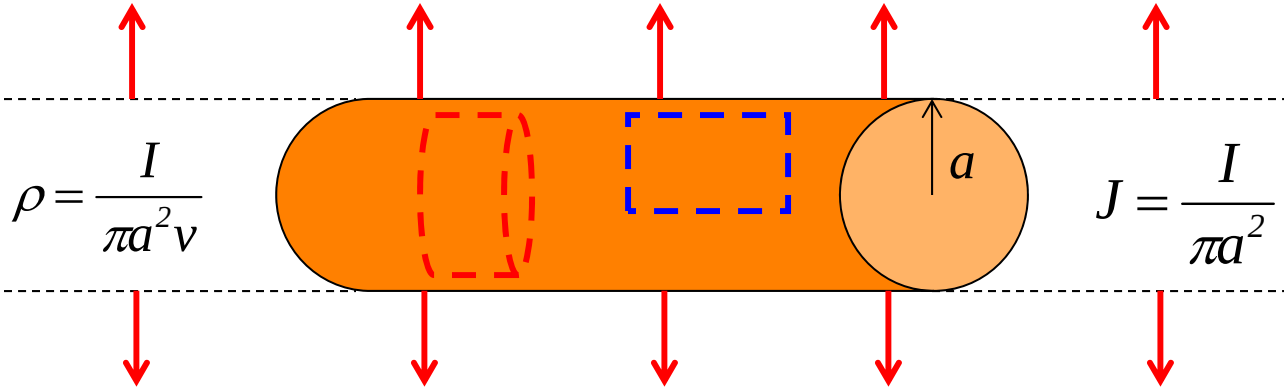
Space Charge effects

Space Charge Regime ==> The interaction beween particles is dominated by the **self field** produced by the particle distribution, which varies appreciably only over large distances compare to the average separation of the particles ==> **Collective Effects**



- If collisions can be neglected the Liouville's theorem holds in the 6-D phase space (**r**,**p**). This is possible because the smoothed space-charge forces acting on a particle can be treated like an applied force. Thus the 6-D phase space volume occupied by the particles remains constant during acceleration.
- In addition if all forces are linear functions of the particle displacement from the beam center and there is no coupling between degrees of freedom, the normalized emittance associated with each plane (2-D phase space) remains a constant of the motion.

Continuous Uniform Cylindrical Beam Model



Gauss's law

$$\int \varepsilon_o E \cdot dS = \int \rho dV$$

$$2\pi r l \varepsilon_o E_r = \rho 2\pi r^2 l$$

$$E_r = \frac{\rho r}{2\varepsilon_o} = \frac{Ir}{2\pi\varepsilon_o a^2 v} \quad \textbf{for} \quad \boldsymbol{r \le a}$$

Linear with r

Ampere's law

$$\int B \cdot dl = \mu_o \int J \cdot dS$$

$$2lB_\vartheta = \mu_o J l r$$

$$B_\vartheta = \frac{\mu_o J r}{2} = \mu_o \frac{Ir}{2\pi a^2} \quad \textbf{for} \quad \boldsymbol{r \le a}$$

$$B_\vartheta = \frac{\beta}{c} E_r$$

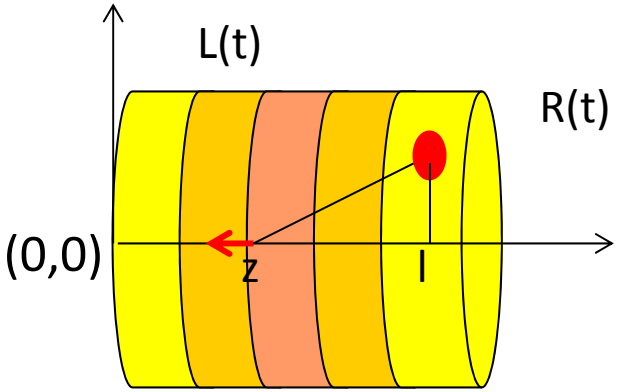
Relativistic suppression of space charge forces

$$F_r = e\left(E_r - \beta c B_\vartheta\right) = e\left(1-\beta^2\right)E_r = \frac{eE_r}{\gamma^2}$$

- The Lorentz force has only **radial** component and is a **linear** function of the transverse coordinate
- The attractive magnetic force , which becomes significant at high velocities, tends to compensate for the repulsive electric force. Therefore, space charge defocusing is primarily a non-relativistic effect, decreasing as the beam energy increases.
- Suppression works also in *z* direction due to longitudinal relativistic mass increase (obviously not applies to infinitely long beams) → Relativistic UEM and UED !
- The space charge force provide a defocusing term (linear at first order) in the paraxial radial equation.

$$\frac{d^2 r}{dz^2} = \frac{eI}{2\pi m\gamma^3 \varepsilon_o a^2 v^3} r = \frac{K}{a^2} r$$

Bunched Uniform Cylindrical Beam Model



$$v_z = \beta c$$

First compute the Longitudinal Space Charge field in the bunch comoving frame:

$$\tilde{\rho} = \frac{Q}{\pi R^2 \tilde{L}} \qquad E_z(\tilde{z}, r=0) = \frac{\tilde{\rho}}{4\pi\varepsilon_o} \int_0^R \int_0^{2\pi} \int_0^{\tilde{L}} \frac{(\tilde{l}-\tilde{z})}{\left[(\tilde{l}-\tilde{z})^2 + r^2\right]^{3/2}} \, r\,dr\,d\varphi\,d\tilde{l}$$

$$E_z(\tilde{z}, r=0) = \frac{\tilde{\rho}}{2\varepsilon_0}\left[\sqrt{R^2 + (\tilde{L}-\tilde{z})^2} - \sqrt{R^2 + \tilde{z}^2} + (2\tilde{z} - \tilde{L})\right]$$

Most of the particle tracking codes used to simulate photoinjectors (Parmela, T-step, GPT, ASTRA) use same approach and solve for electrostatic field in *bunch reference frame*.

Then we can obtain the radial Space Charge field in the bunch moving frame

by series representation of axisymmetric field:

Poisson equation + divergence operator in cylindrical coordinates

$$E_r(r,\tilde{z}) \cong \left[\frac{\tilde{\rho}}{\varepsilon_0} - \frac{\partial}{\partial\tilde{z}} E_z(\tilde{z},0)\right]\frac{r}{2} + [\cdots]\frac{r^3}{16} +$$

$$E_r(r,\tilde{z}) = \frac{\tilde{\rho}}{2\varepsilon_0}\left[\frac{(\tilde{L}-\tilde{z})}{\sqrt{R^2+(\tilde{L}-\tilde{z})^2}} + \frac{\tilde{z}}{\sqrt{R^2+\tilde{z}^2}}\right]\frac{r}{2}$$

Finally we can transform back using Lorentz Transformation to the Lab frame

$$L = \frac{\tilde{L}}{\gamma} \quad \Rightarrow \quad \rho = \gamma\tilde{\rho} \qquad E_r = \gamma\tilde{E}_r$$

$$A = \frac{R}{\gamma L}$$

$$E_z(z) = \frac{\rho L}{2\varepsilon_0}\left[\sqrt{A+(1-\zeta)^2} - \sqrt{A+\zeta^2} + (2\zeta - 1)\right]$$

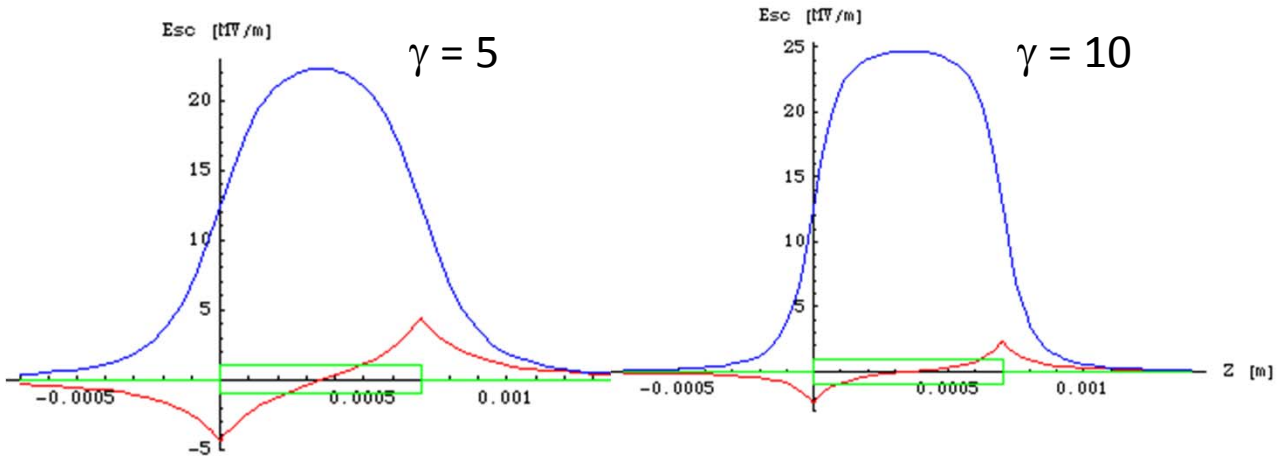
Beam Aspect Ratio in lab frame

$$E_r(r,z) = \frac{\rho}{2\varepsilon_0}\left[\frac{(1-\zeta)}{\sqrt{A^2+(1-\zeta)^2}} + \frac{\zeta}{\sqrt{A^2+\zeta^2}}\right]\frac{r}{2}$$

$$\zeta = \frac{z}{L}$$

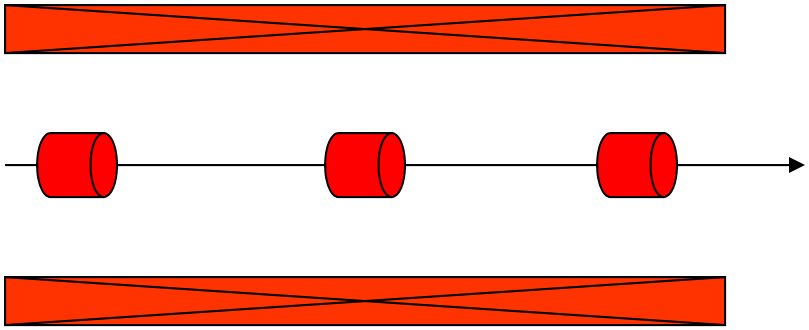
$$= \frac{Ir}{4\pi\varepsilon_0 R^2 \nu} g(\zeta)$$

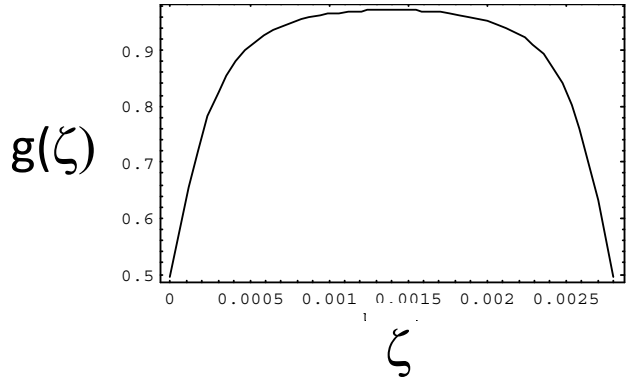
It is still a linear field with r but with a longitudinal correlation ζ

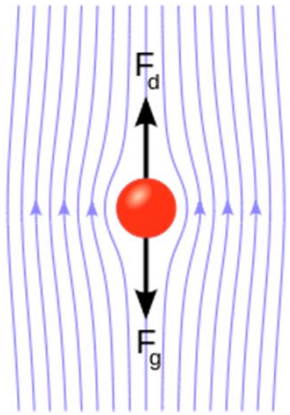


Transport of laminar beam in a long solenoid

Laminarity: Preserve correlation between particles position along the beam and their starting position. We assume laminarity here both in longitudinal and transverse directions.







$$k_s = \frac{qB}{2mc\beta\gamma}$$

$$K(\zeta) = \frac{2Ig(\zeta)}{I_o(\beta\gamma)^3}$$

$$R'' + k_s^2 R = \frac{K(\zeta)}{R}$$

Paraxial equation for particles at beam edge including space charge.

$$R'' = 0$$

==> Equilibrium solution ? ==>

$$R_{eq}(\zeta) = \frac{\sqrt{K(\zeta)}}{k_s}$$

Brillouin Flow

Small perturbations around the equilibrium solution

$$R'' + k_s^2 R = \frac{K(\zeta)}{R}$$

$$R(\zeta) = R_{eq}(\zeta) + \delta r(\zeta)$$

$$\delta r'' + k_s^2 \left(R_{eq} + \delta r\right) = \frac{K(\zeta)}{\left(R_{eq} + \delta r\right)}$$

$$\delta r'' + k_s^2 \left(R_{eq} + \delta r\right) = \frac{K(\zeta)}{R_{eq}\left(1 + \frac{\delta r}{R_{eq}}\right)} = \frac{K(\zeta)}{R_{eq}}\left(1 - \frac{\delta r}{R_{eq}}\right)$$

$$\delta r''(\zeta) + 2k_s^2 \delta r(\zeta) = 0$$

Perturbed trajectories oscillate around the equilibrium with the same frequency but with different amplitudes.

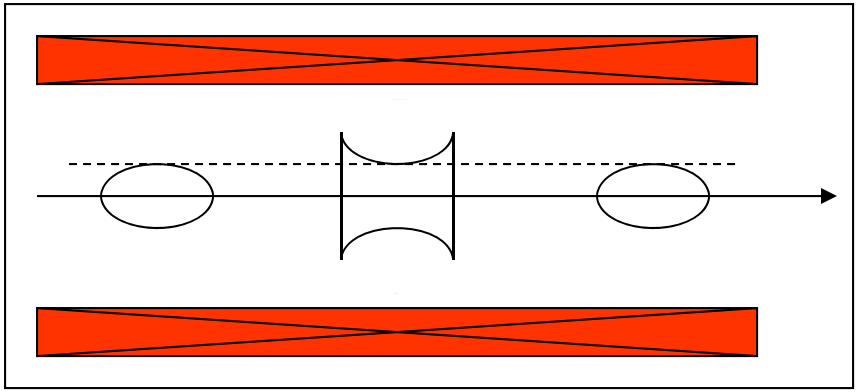
$$\delta r''(\zeta) + 2k_s^2 \delta r(\zeta) = 0$$

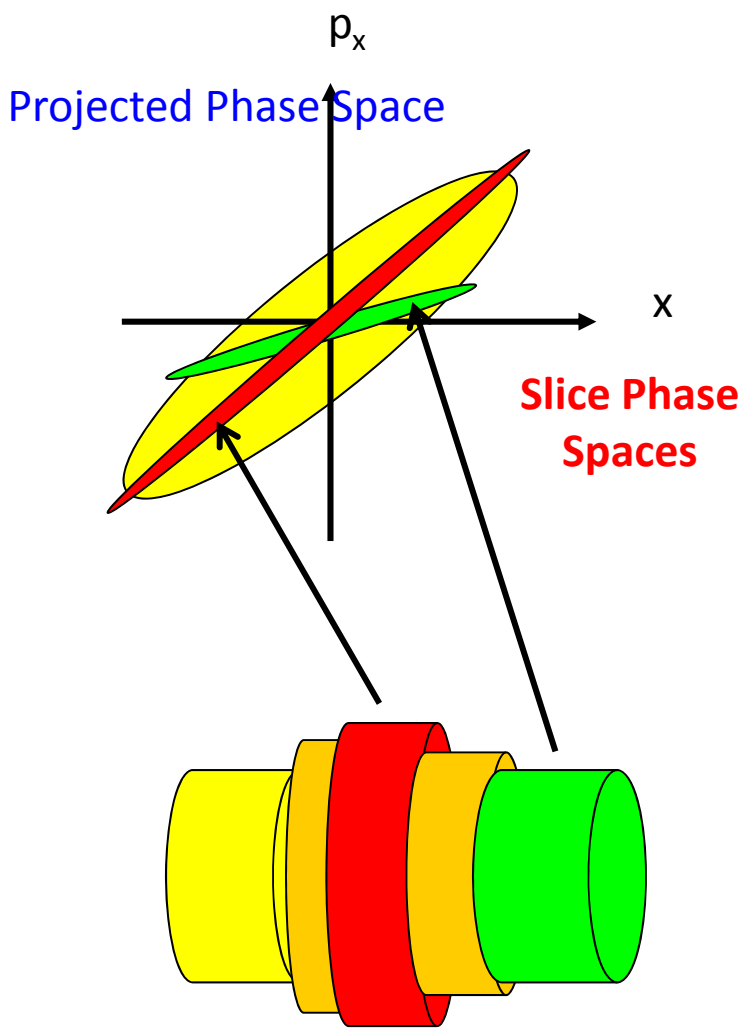
$$R(\zeta) = R_{eq}(\zeta) + \delta r(\zeta)\cos\left(\sqrt{2}k_s z\right)$$

$$R'(\zeta) = -\delta r(\zeta)\sin\left(\sqrt{2}k_s z\right)$$

$$k_p = \sqrt{2}k_s$$

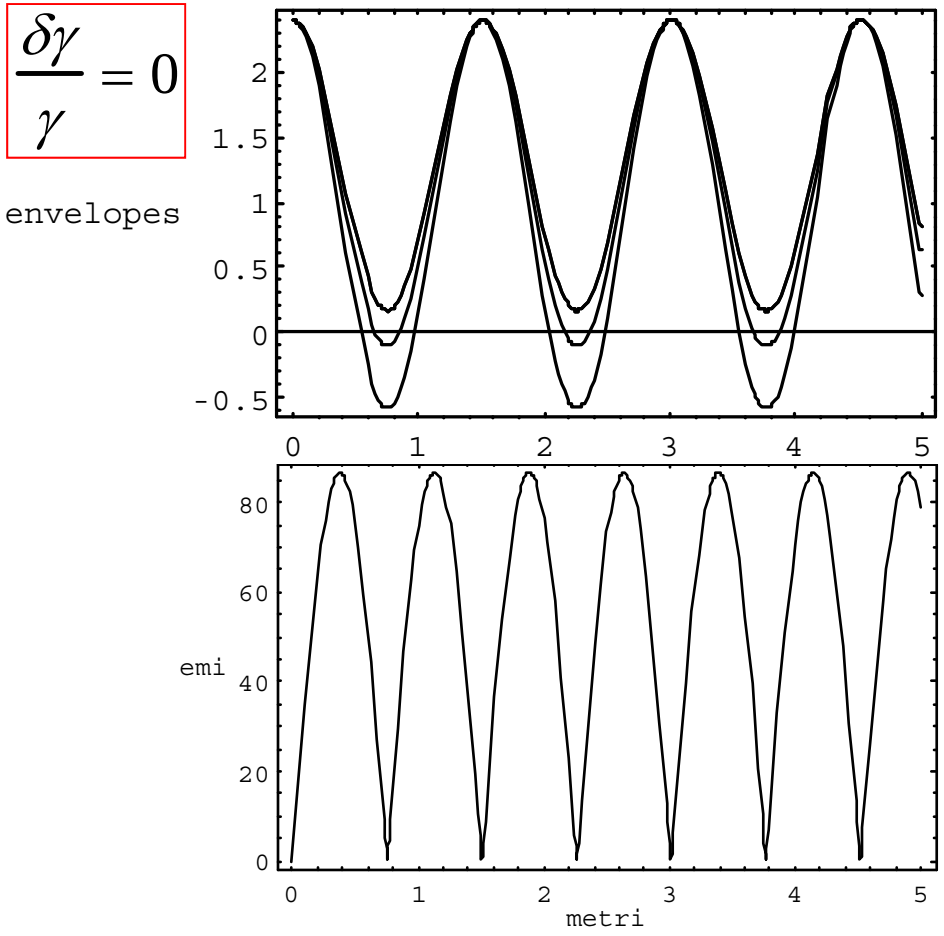
Plasma frequency





Envelope oscillations drive emittance oscillations

$$\frac{\delta\gamma}{\gamma} = 0$$



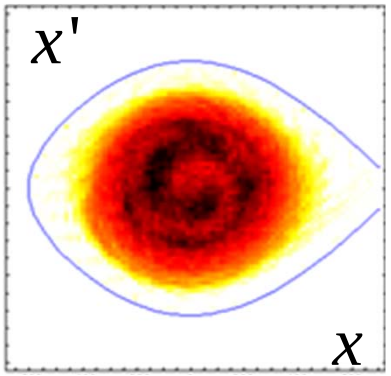
In reality oscillations *will eventually decohere:*

- small dependencies of plasma frequency from oscillation amplitude (pendulum, non linear oscillations)
- Energy dependency of solenoid strength (chromaticity)

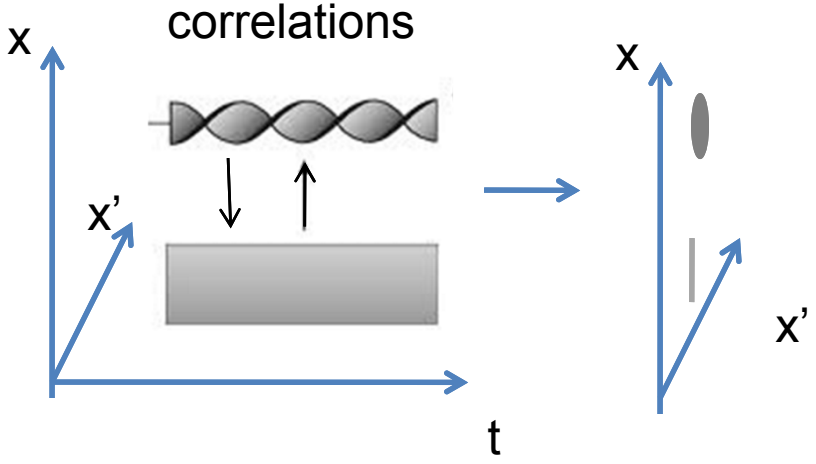
$$\varepsilon(z) = \sqrt{\langle R^2 \rangle \langle R'^2 \rangle - \langle RR' \rangle^2} \div \left| \sin\left(\sqrt{2} k_s z\right) \right|$$

Emittance compensation

non linear forces



correlations

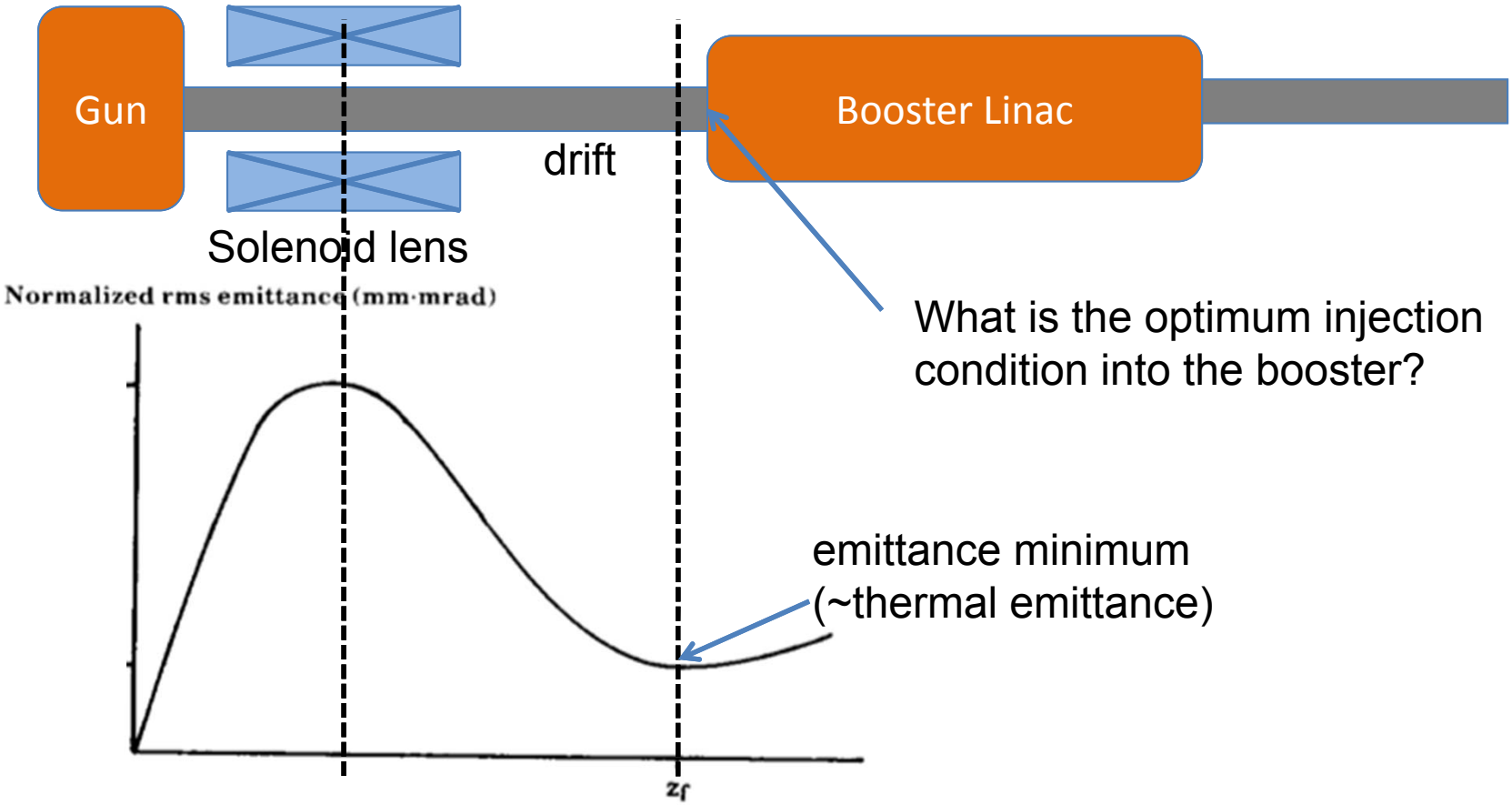


Area occupied by particles is still conserved (Liouville) rms emittance increases

emittance compensation**: un-twisting the ribbon**

Emittance compensation, then, is the process of undoing the effect of space-charge on the phase space angles of the slices by ***careful use of external focusing to line the slices back up****, reducing the overall projected emittance.*

Matching into the Linac: the invariant envelope



We have showed that the emittance increase is correlated and it can be, at least to its linear part, compensated.

Now the question is: how can be keep the low emittance obtained, preventing the oscillations to start again with a consequent emittance growth? How can we freeze the oscillations exactly in the point we want? The answer is: ***by acceleration.***

Is there an optimum injection condition? Yes, it is called the ***invariant envelope.***

The invariant envelope

We now need to consider the acceleration into the envelope equation

$$\sigma_r'' + \sigma_r' \frac{\gamma'}{\beta^2\gamma} + \left(\frac{\eta + 2b^2}{8}\right)\left(\frac{\gamma'}{\gamma}\right)^2 \sigma_r - \frac{K(\zeta)}{\sigma_r} = 0$$

$$\bar{F}_r = \frac{(qE_0)^2}{8\gamma m_0 c^2} r \sum_{n=1}^{\infty} b_n^2 + b_{-n}^2 + 2b_n b_{-n} \cos(2\Delta\phi)$$

$$\equiv \eta(\Delta\phi) \frac{(qE_0)^2}{8\gamma m_0 c^2} r \ ,$$

$$b = \frac{cB_z}{E_0}$$

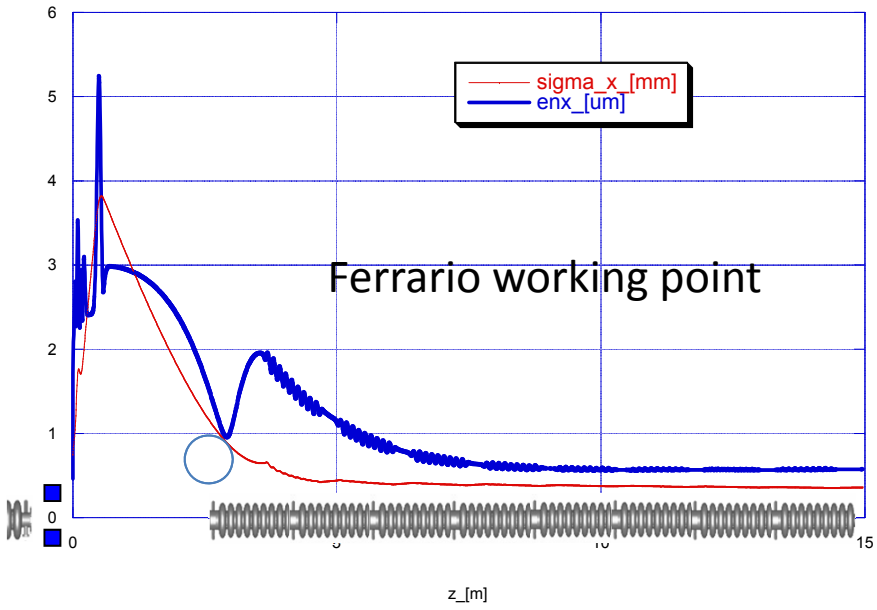
η takes into account spatial harmonics of rf cavities. ~1 for pure π SW; 0 for pure TW

It has been shown shown the existence of a particular solution called the ***invariant envelope***:

$$\sigma_{inv}(\zeta, z) = \frac{2}{\gamma'} \sqrt{\frac{r_e \lambda(\zeta)}{(2+\eta)\gamma(z)}}$$

J. B. Rosenzweig and L. Serafini, Phys. Rev. E 49, 1599,1994;

L. Serafini and J.B. Rosenzweig, Physical review E, Vol. 55, number 6, June 1997

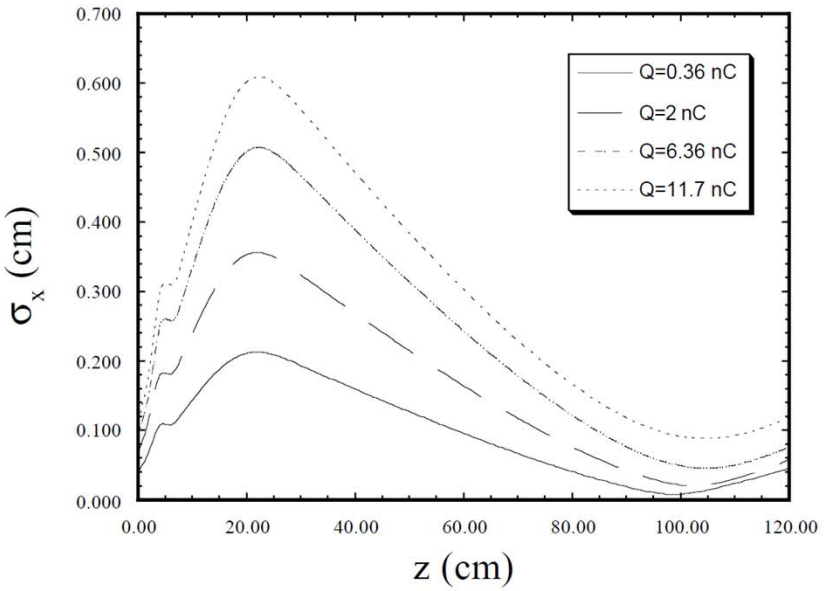


Scaling laws for RF photoinjectors

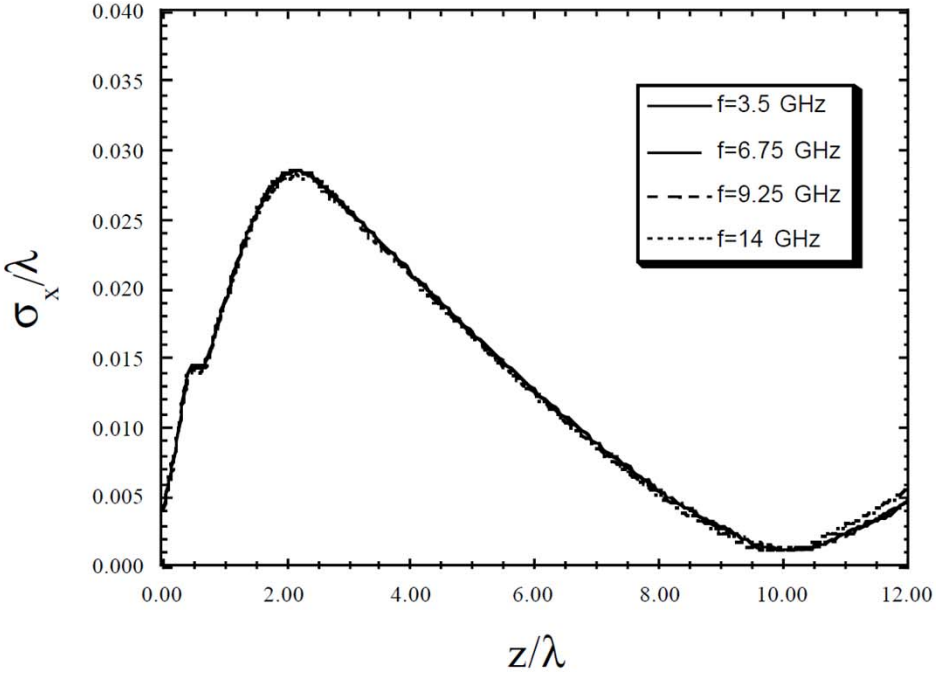
Once we find a solution for the beam dynamics how do we know what happens when we change some of the parameters

Charge scaling $\sigma_i \sim Q^{\frac{1}{3}}$

Maintain same density / same aspect ratio



RF wavelength scaling



To preserve capture dynamics

$E_0 \sim \lambda^{-1}$

$\sigma_i \sim \lambda$

$B_{sol} \sim \lambda^{-1}$

J. B. Rosenzweig and E. Colby, Proceedings of 1995 Particle Accelerator Conference

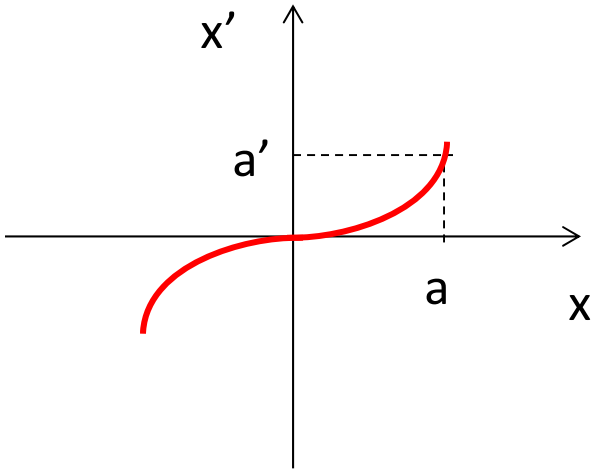
Non linear space charge forces

The presence of nonlinear space charge forces can distort the phase space contours and causes emittance growth

Let us go back to the infinitely long cylindrical beam and assume a transverse profile different than uniform

$$\rho(r) = \frac{I}{\pi a^2 v}\left(1 - \frac{r^2}{a^2}\right)$$

$$E_r = \frac{\rho r}{2\varepsilon_o} = \frac{I}{2\pi\varepsilon_o a^2 v}\left(r - \frac{r^3}{a^2}\right)$$

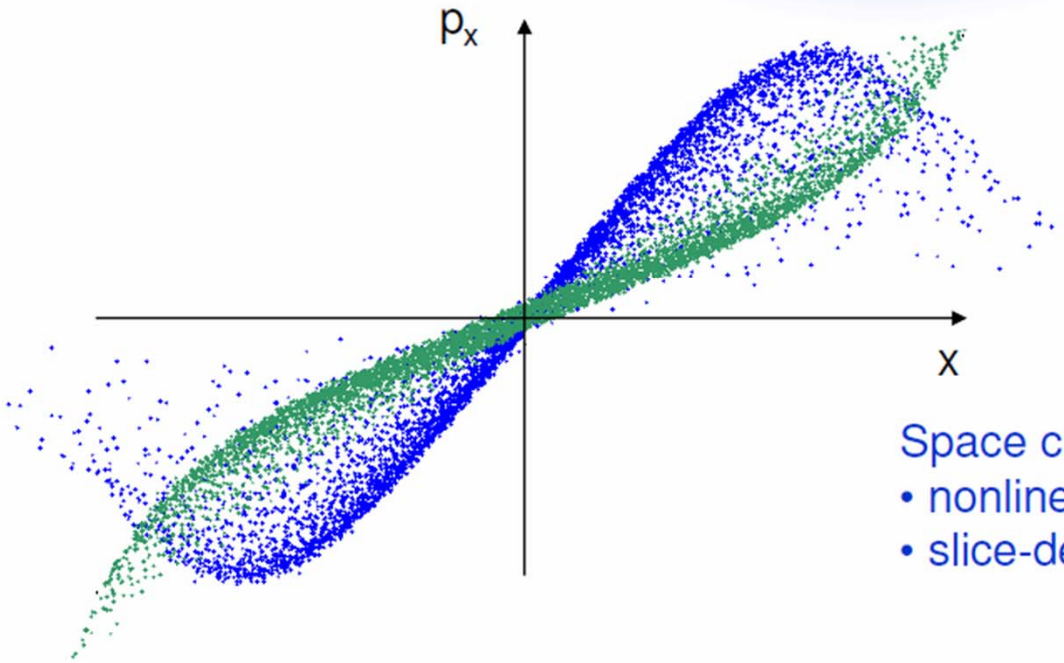


Finite emittance due to non linearities

Nonlinear space charge forces

Gaussian bunch

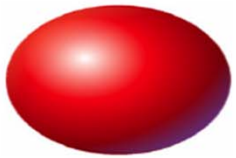
Fighting the symptoms:
- Emittance compensation (B. Carlsten)
- Truncated gaussian profile (L. Serafini)
- Uniform temporal & radial profile (DESY,..
- ...



Space charge forces:
- nonlinear
- slice-dependent

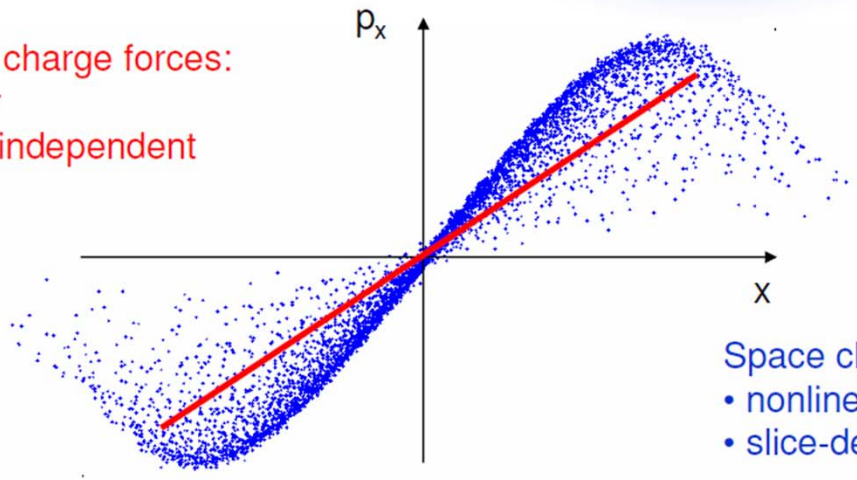
Fundamental solution:

Waterbag bunch



Gaussian bunch

Space charge forces:
- linear
- slice-independent



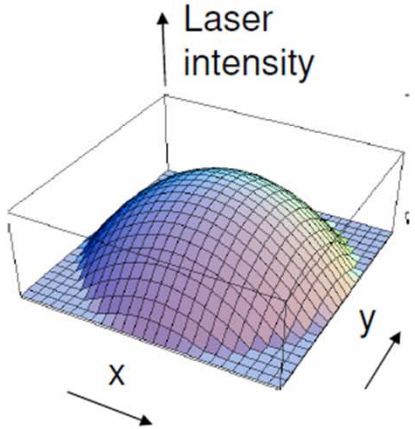
Space charge forces:
- nonlinear
- slice-dependent

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)

Blow-out bunch length calculation

Field at head and tail of the beam is approximated as the field of infinite:

$$\gamma_{\pm} = 1 + \gamma' z \pm \frac{\sigma}{2\varepsilon_0 m_0 c^2} z = 1 + \gamma' \left(1 \pm \frac{\alpha}{2}\right) z$$

$$\gamma' = \frac{eE_0}{m_0 c^2} \qquad \alpha = \frac{\sigma}{\varepsilon_0 E_0}$$

σ is beam surface charge density

Pancake approximation

Then the final bunch length can be calculated by a simple integration

$$c\tau = \int_0^{z_f} \left(\frac{1}{\beta_-} - \frac{1}{\beta_+}\right) dz = \int_0^{z_f} \frac{\Delta\gamma}{\beta^3\gamma^3} dz$$

$$= \int_0^{z_f} \alpha \frac{\gamma - 1}{(\gamma^2 - 1)^{\frac{3}{2}}} dz = \frac{\alpha}{\gamma'} \sqrt{\frac{\gamma_f - 1}{\gamma_f + 1}}$$

where we have used

$$\Delta\gamma = \alpha\gamma' z = \alpha(\gamma - 1)$$

Independent on initial bunch length !

So at the limit (for large γ) we get

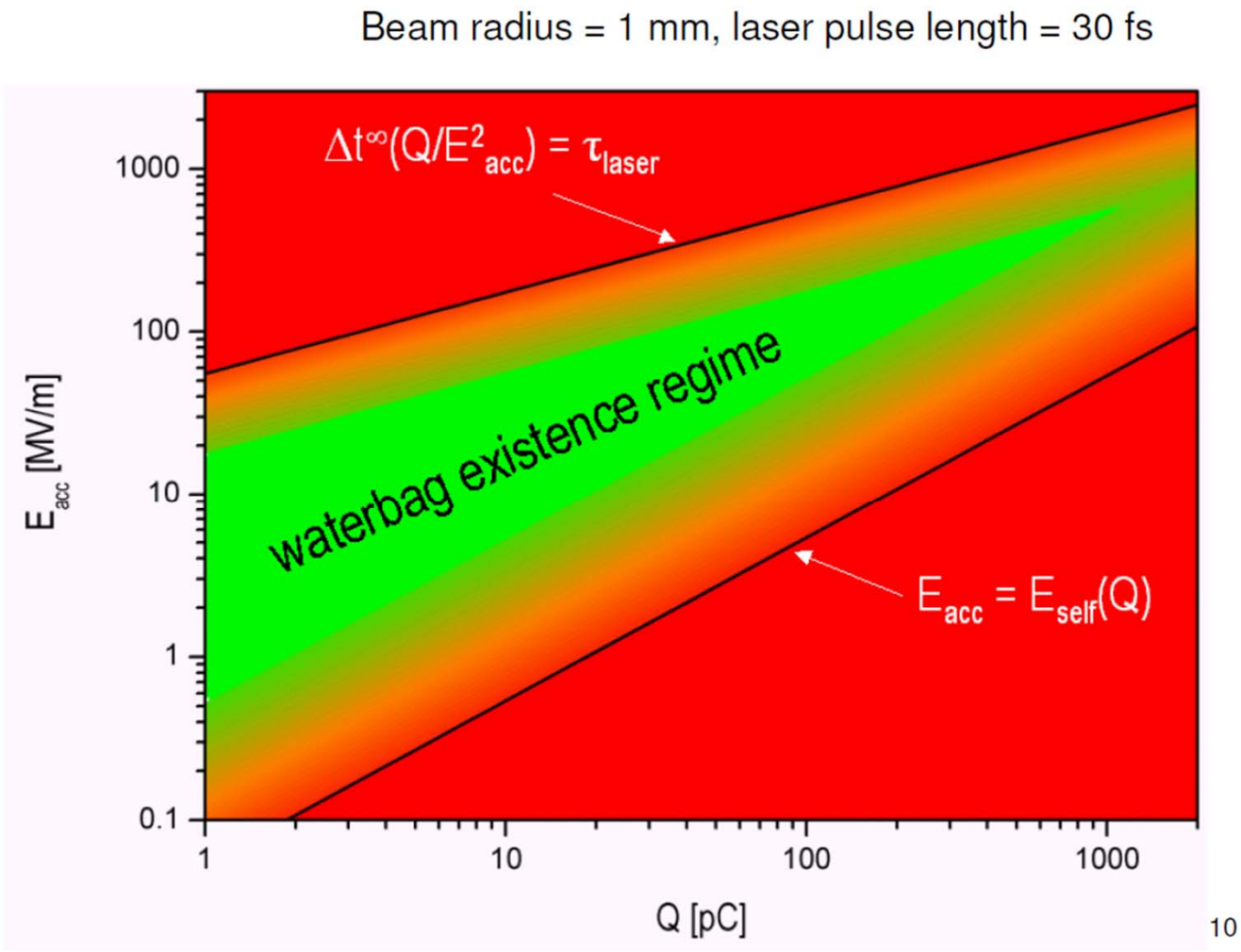
$$c\tau = \frac{\sigma}{\varepsilon_0 E_0} \frac{m_0 c^2}{eE_0}$$

and 5D brightness

$$B = \frac{Q}{{\epsilon_n}^2 \tau} \propto \frac{{E_0}^2}{kT}$$

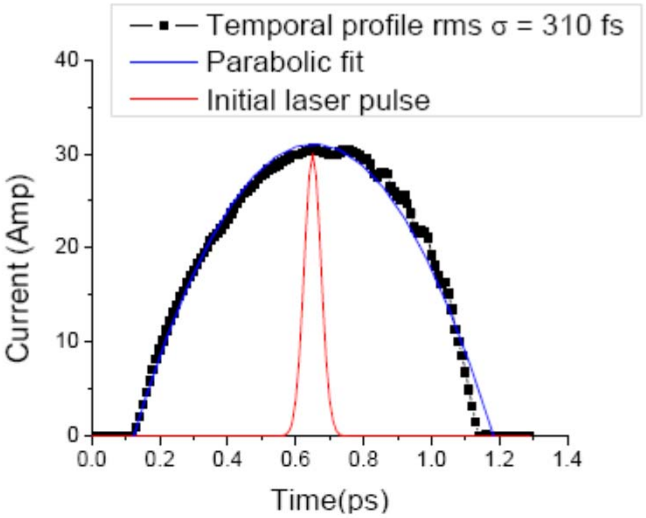
In reality as the beam evolves the pancake approximation is no longer valid.

Condition of existence of blow-out regime

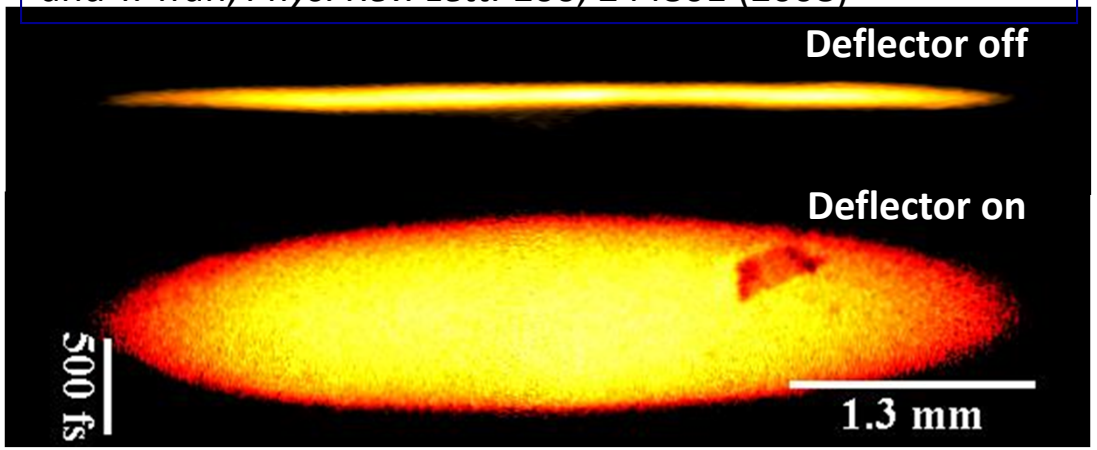


Ellipsoidal beam experimental demonstration At Pegasus

- Charge 20 pC. Laser spot size 400 μm rms (limited by asymmetry due to image charge)
- rms length ~300 fs
- Very sharp ellipsoidal beam boundary due to the ultrashort beam on the cathode.



P. Musumeci, J. T. Moody, R. J. England, J. B. Rosenzweig, and T. Tran, *Phys. Rev. Lett.* **100**, 244801 (2008)

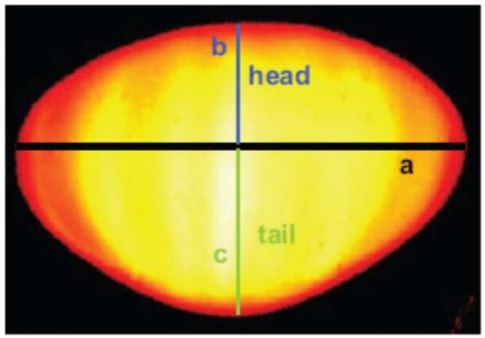


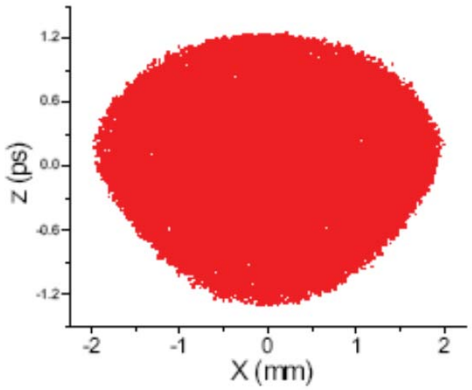
Limits of the Photoinjector Blowout Regime
Head-Tail Asymmetry

- Increasing the charge we observe the development of an asymmetry in the ellipse boundary.

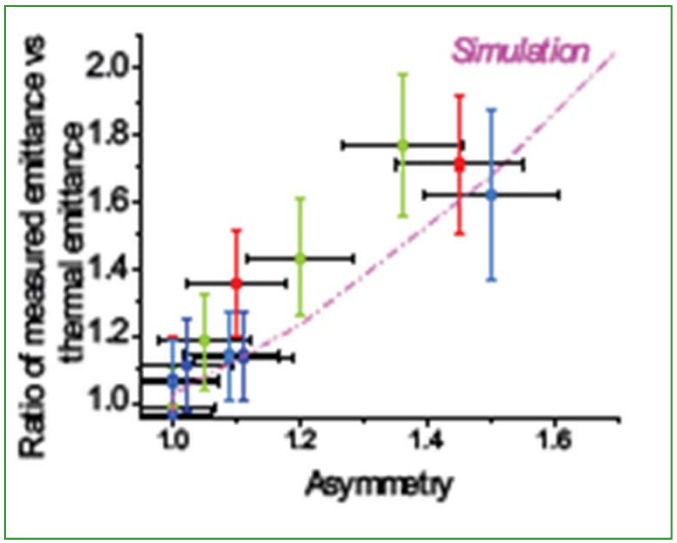
- Simulations predict this effect, which is mainly due to the image charge at the cathode that 'pulls' the beam tail.

- **When the space charge field at the cathode reaches approximately 10 % of the accelerating field, a strong asymmetry develops in the formation of the ellipsoid quickly degrading the beam quality.**



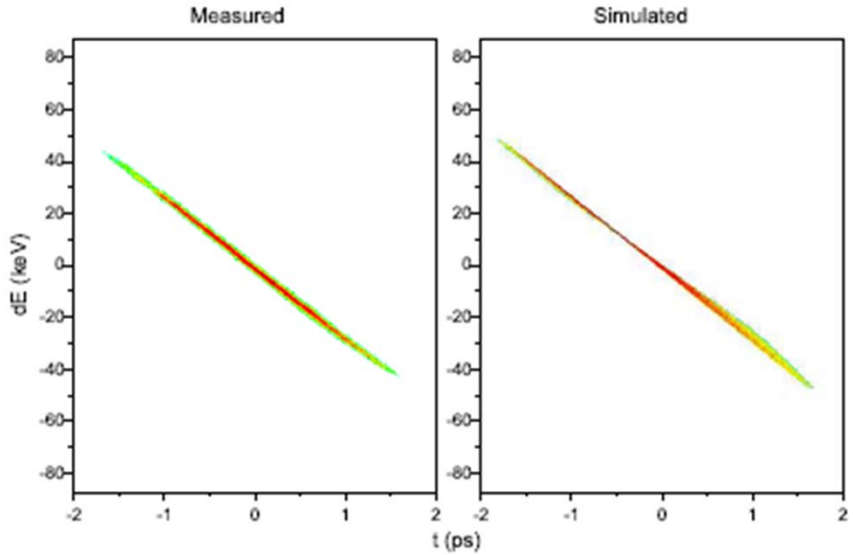


GPT simulation with Pegasus photoinjector parameters



Longitudinal phase space

- Use vertically deflecting cavity in conjunction with horizontally dispersing dipole
- Control the induced energy spread from the cavity as predicted by Panofsky-Wenzel theorem
- Record resolution in time (50 fs) and energy (1 keV).
  - Advantages of measurement on low energy beams.



Very linear phase space

High 6D beam brightness

Ultralow longitudinal emittance (<0.5 um)

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **12**, 070704 (2009)

Longitudinal phase space characterization of the blow-out regime of rf photoinjector operation

J. T. Moody, P. Musumeci,* M. S. Gutierrez, J. B. Rosenzweig, and C. M. Scoby
Department of Physics and Astronomy, University of California at Los Angeles, Los Angeles, California 90095, USA
(Received 27 April 2009; published 29 July 2009)

Ultralow charge nm-emittance beams.

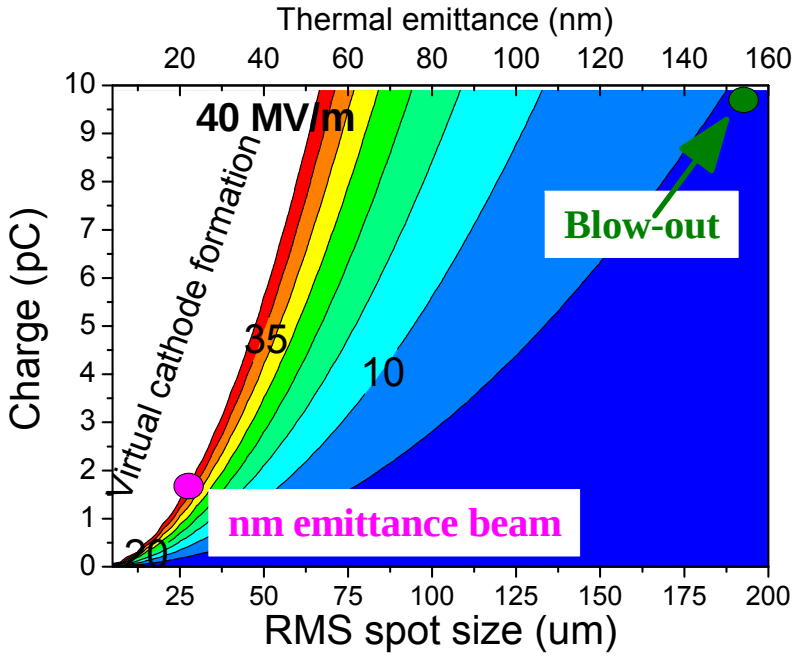
- Electron sources in new low charge regime. 0.1 pC – 1 pC.
  - ✓ UED
  - ✓ FELs
  - ✓ laser-based Advanced Accelerators

$$\left.\frac{\mathcal{B}_n}{f}\right|_{\max} = \frac{mc^2\epsilon_0 E_{\text{cath}}}{2\pi kT}.$$

Bazarov's limit for 4D brightness

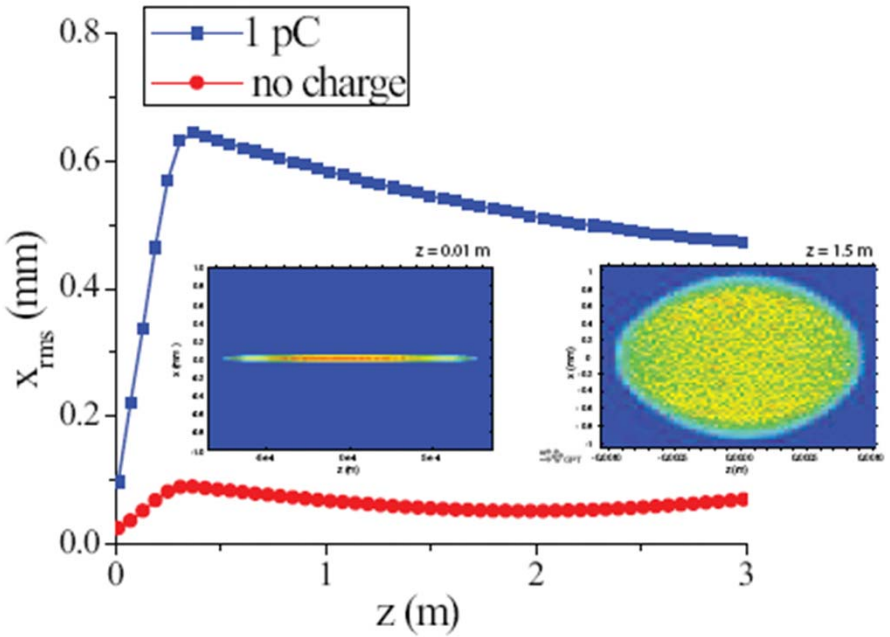
- What can we get in terms of emittance, beam brightness?

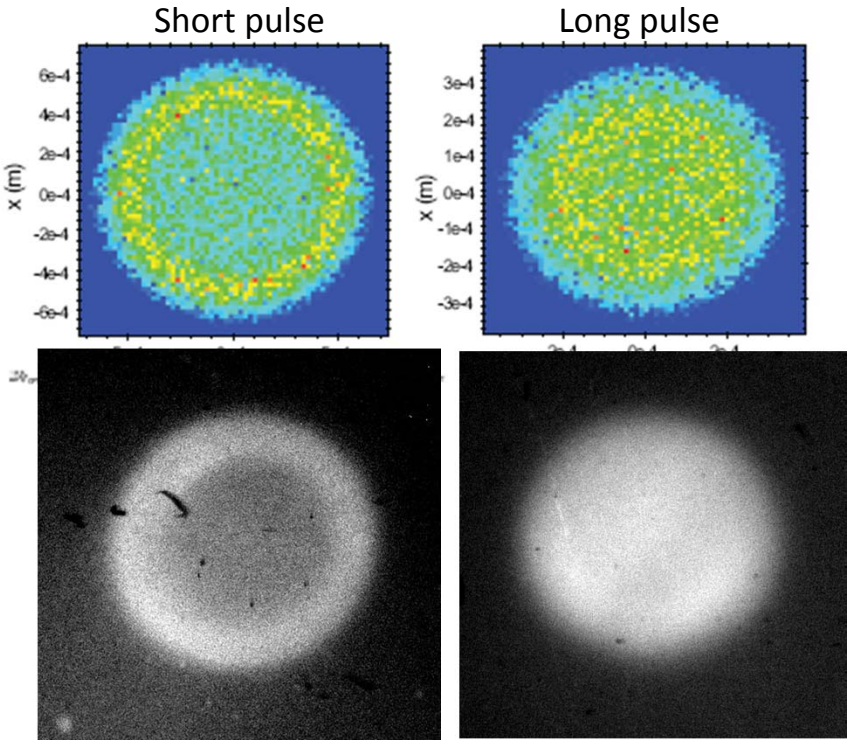
- Focus the laser tight (< 20 um rms) on the cathode.
  - Avoid space charge limited emission
  - Laser Damage threshold (Cu ~ 100 GW/cm^2)



Cigar beams

- Can’t use blow-out regime with small laser spot. But...
- Stretch laser pulse and use long parabolic temporal profile.
- Transverse space charge expansion creates ellipsoidal beam (again!) preserving emittance (same as blow-out).
- Normalized emittance 20 nm





Outline/Syllabus

- Electron source applications
- Electron source figures of merit
- Cathode physics
  - Photoemission. Thermal emittance and quantum efficiency
  - Child-Lamguir law and space charge limits
  - Maximum achievable brightness
- Photoinjector gun types
- Beam Dynamics in RF guns
  - Longitudinal equation of motion
  - Transverse RF effects: rf focusing and emittance.
- Space charge effects
  - Cylindrical beams
  - Emittance oscillations
  - Scaling laws
  - Blow-out regime, pancakes and cigars
- Magneto Optical Trap-based ultracold sources
- Nanotips based e-sources

Brightness limitations

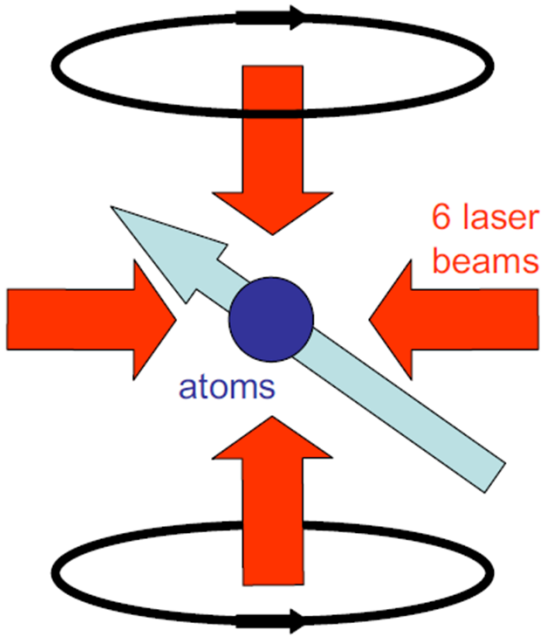
☑ Nonlinear space charge forces

☐ Thermal emittance

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

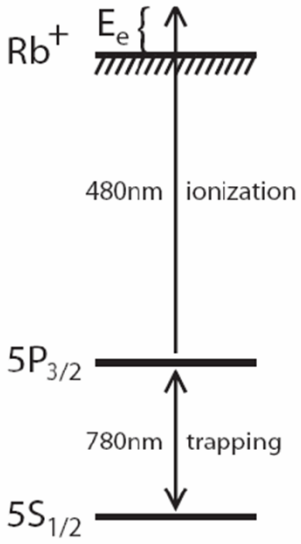
1 eV → < 0.001 eV
10^4 K → < 10 K

Ultra Cold Plasma (**UCP**)



collect **atoms** from beam/vapor

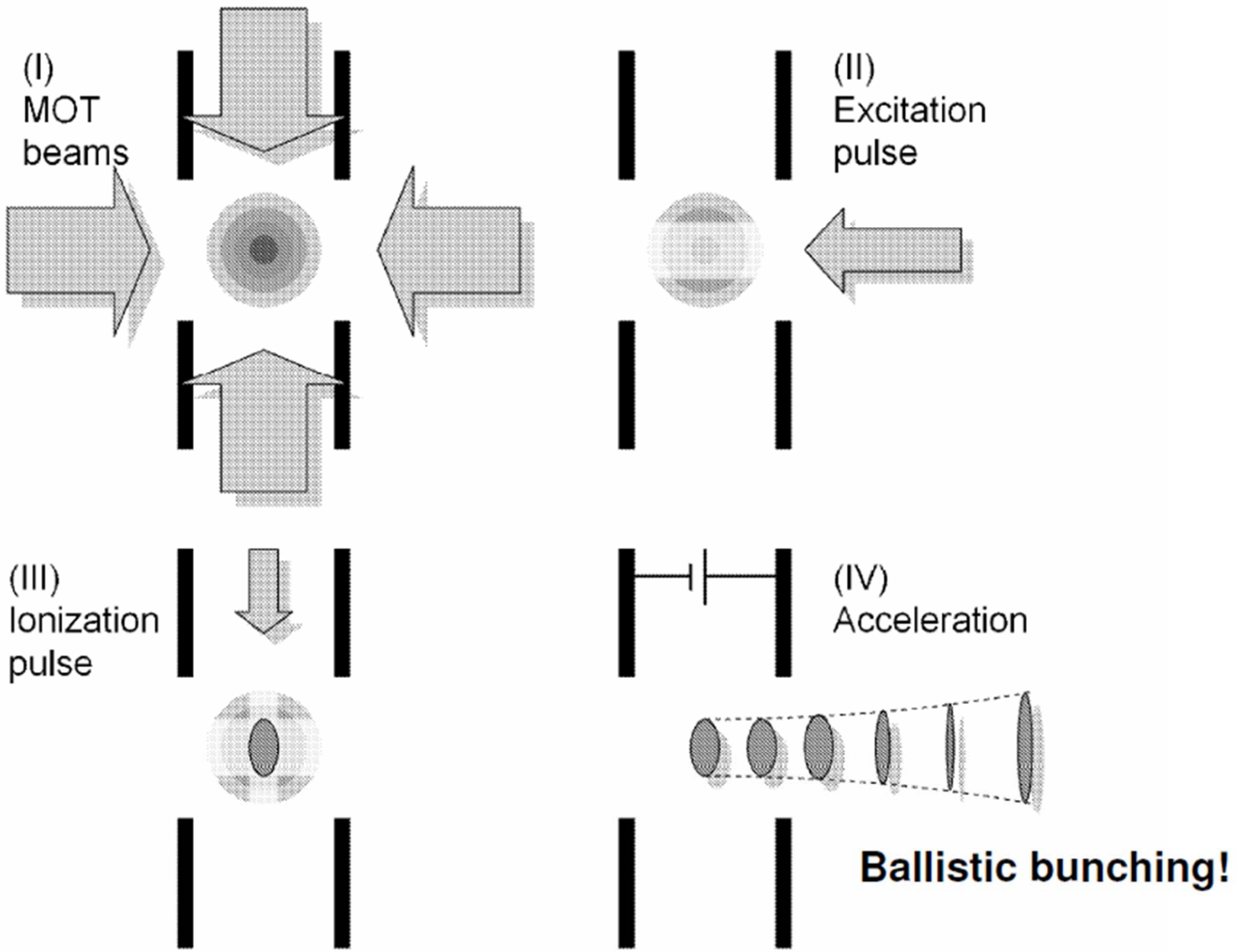
- Laser cooling
- Magneto-Optical Trap (MOT)
- $N > 10^9$ atoms, $R = 1$ mm
- $T_{atom} < 0.001$ K



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

$T_{electron} = 10$ K

kT=0.001 eV

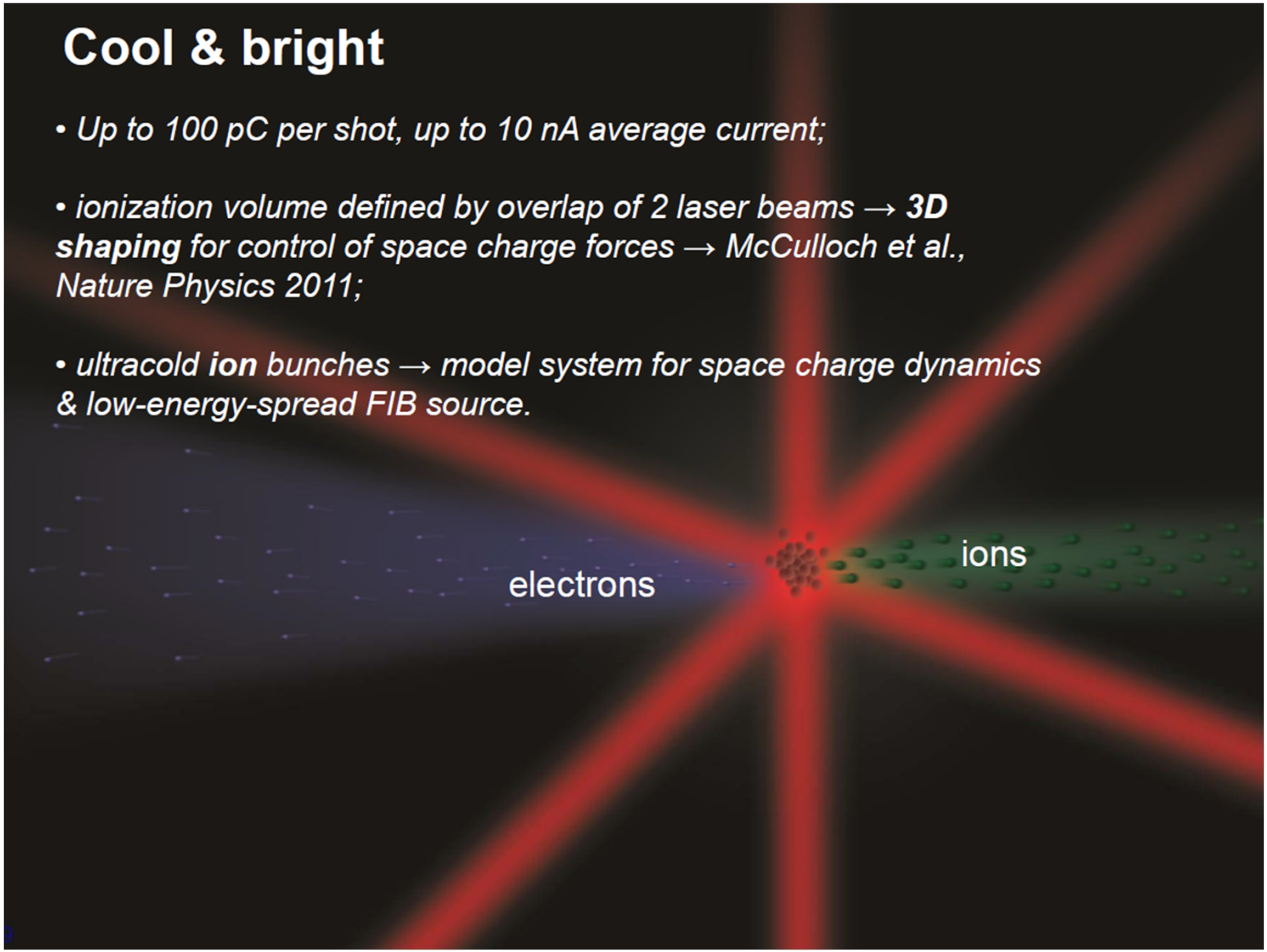

(I)
MOT
beams
(II)
Excitation
pulse
(III)
Ionization
pulse
(IV)
Acceleration
Ballistic bunching!

Cool & bright

- *Up to 100 pC per shot, up to 10 nA average current;*

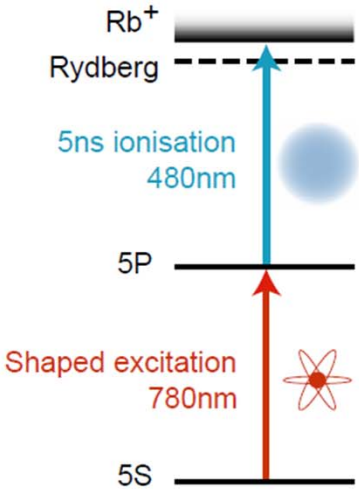
- *ionization volume defined by overlap of 2 laser beams → **3D shaping** for control of space charge forces → McCulloch et al., Nature Physics 2011;*

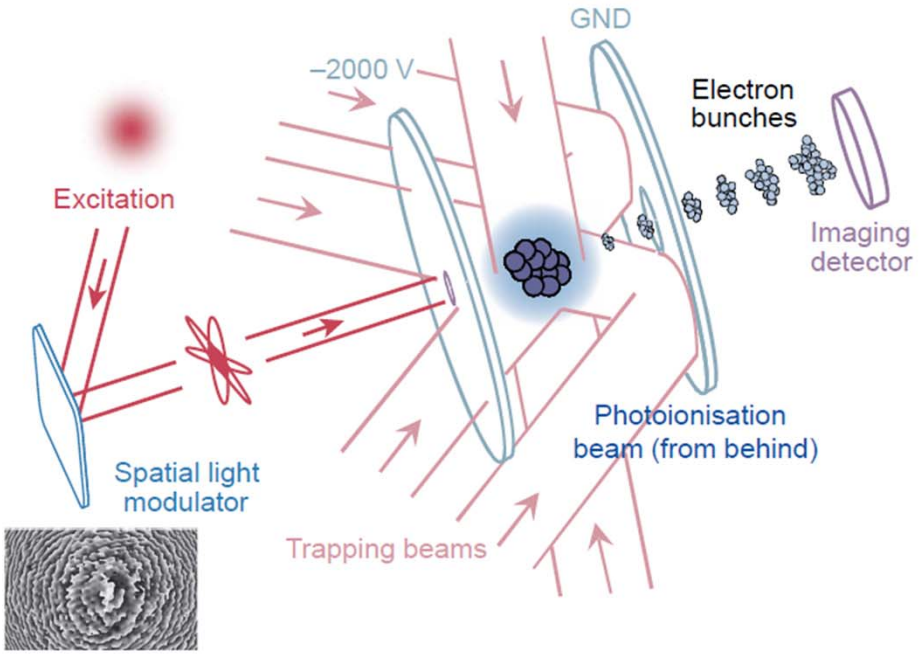
- *ultracold **ion** bunches → model system for space charge dynamics & low-energy-spread FIB source.*



Bunch shaping

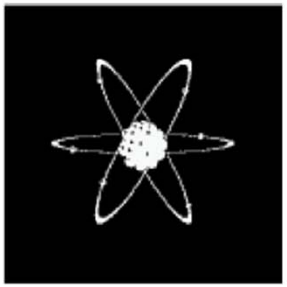
Cold atom electron source allows spatial control



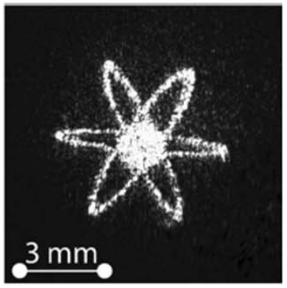


Arbitrary bunch shaping

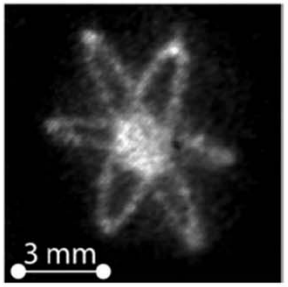
Desired

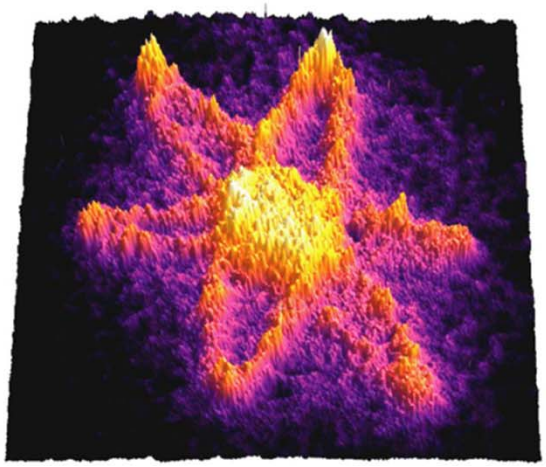


Excitation laser beam profile



Electron density





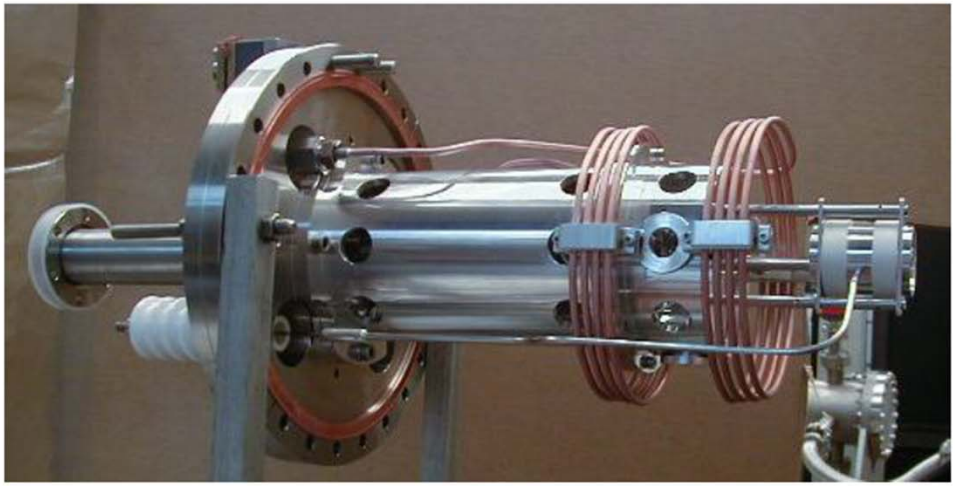
Propagation distance 24cm
Time of flight 14ns

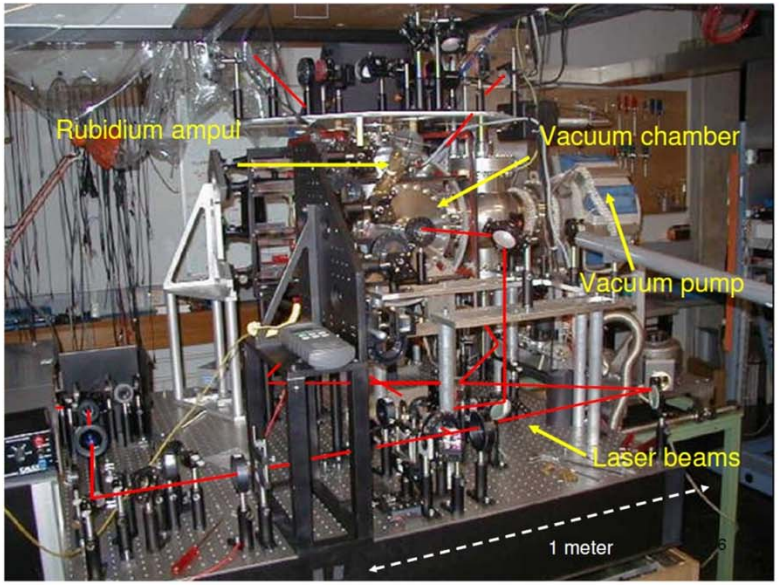
Electron mass is *small*
10K = <1 meV, v = 17 km/s

Andy McCulloch et al, Nature Physics **7** p785 (2011)

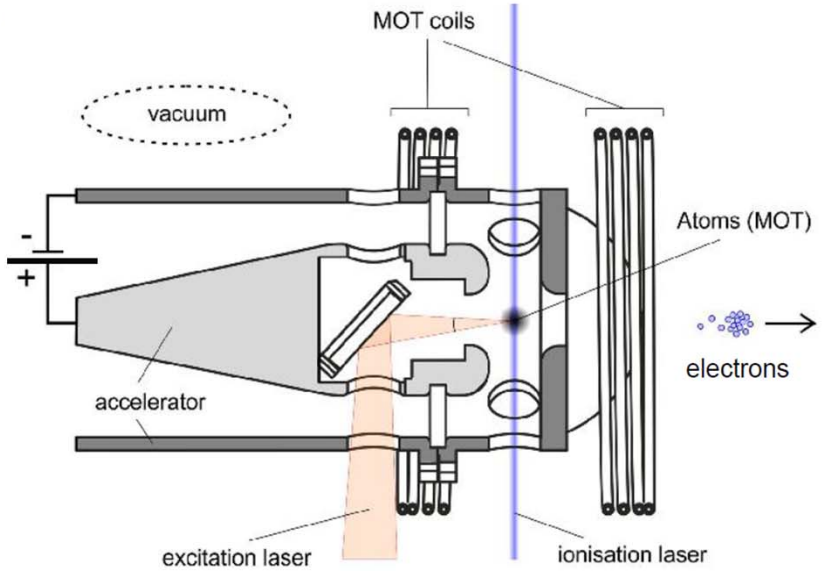
Cold electron gun

TU/e Technische Universiteit Eindhoven University of Technology



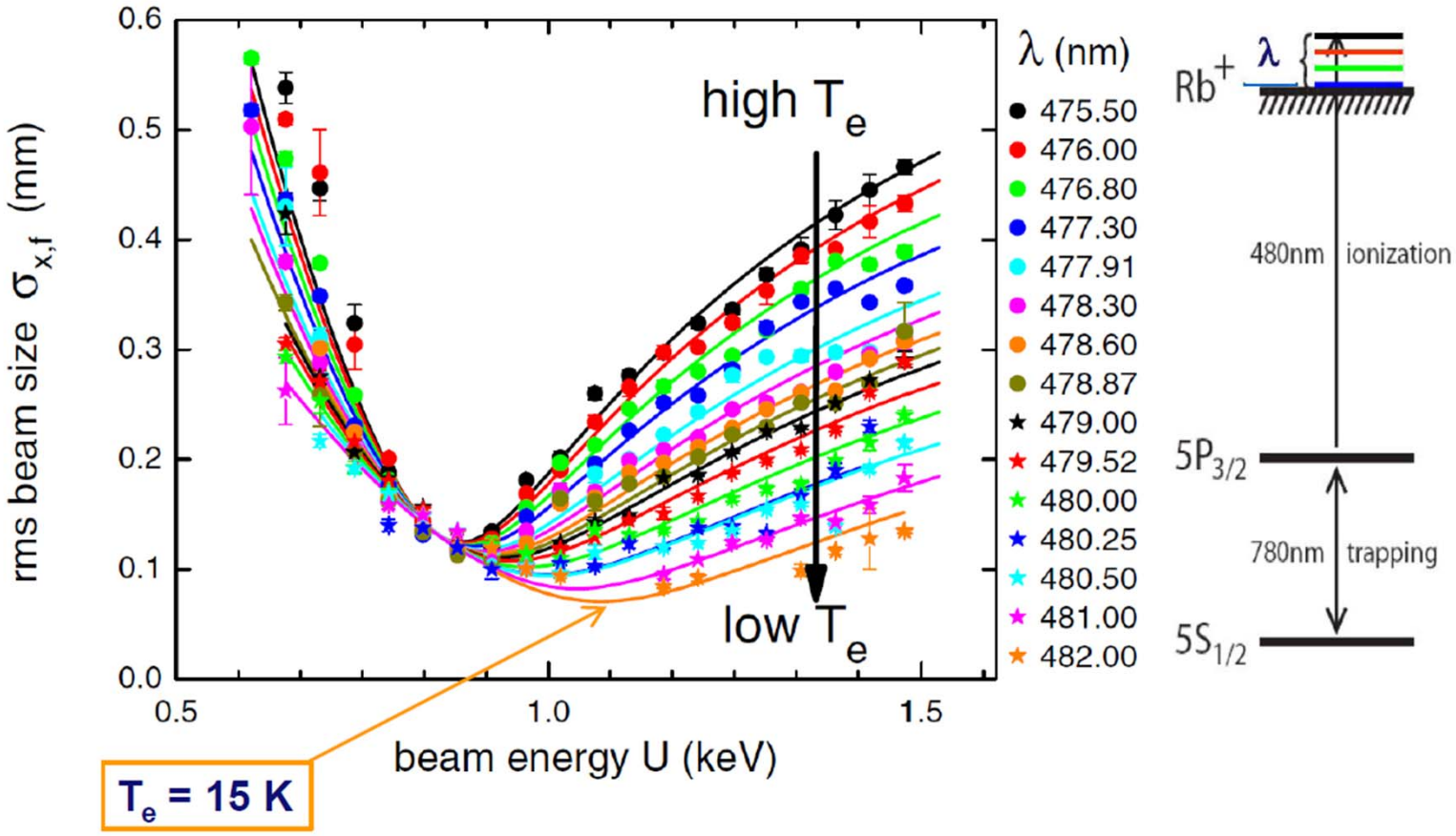


Atom trap inside coaxial accelerator



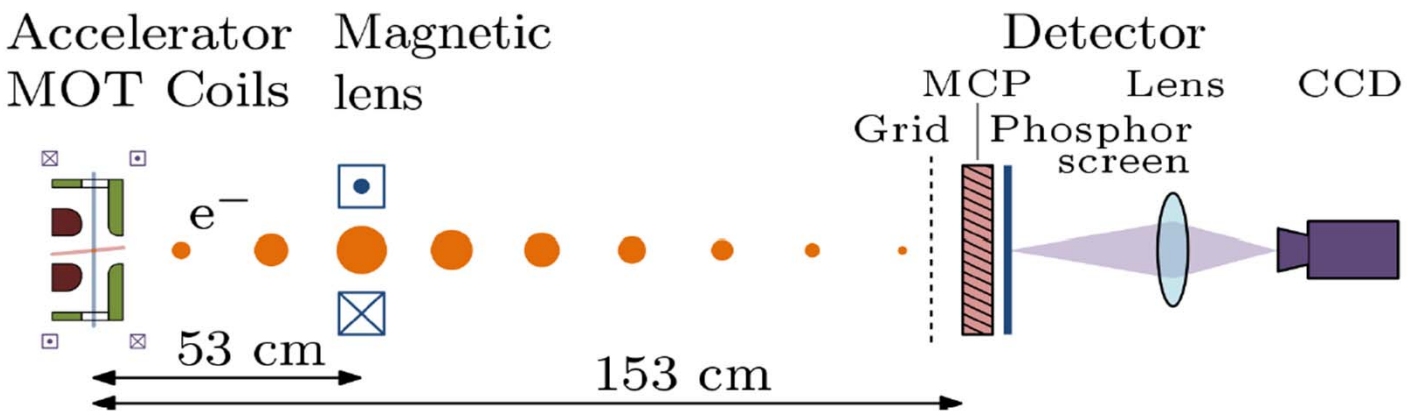
Claessens et al., PRL **95,** 164801 (2005)
Claessens et al., Phys. Plasmas **14**, 093101 2007
Taban et al., PRSTAB **11**, 050102 (2008)
Reijnders et al., PRL **102**, 034802 (2009)
Taban et al., EPL**91**, 46004 (2010)
Reijnders et al., PRL **105**, 034802, (2010)
Reijnders et al. JAP **109**, 033302 (2011)
Debernardi et al., JAP **110**, 024501 (2011)
Vredenbregt & Luiten, Nat. Phys. **7**, 747 (2011)

Measuring emittance varying beam energy



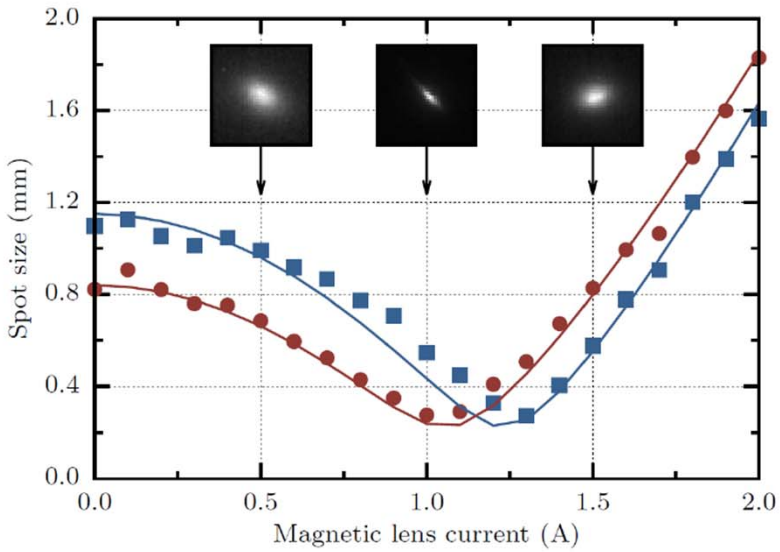
Why is it so high? Ionization induced disorder. Initial temperature much lower, but random particle position increase beam temperature to 10 K

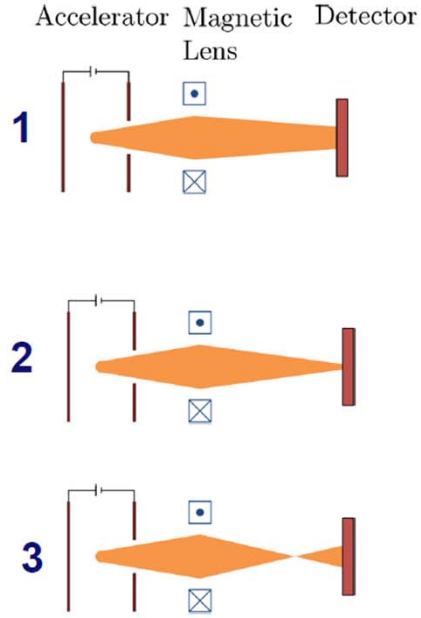
Emittance measurement using lens scan



$F = 2.2$ kV/cm

λ=489 nm



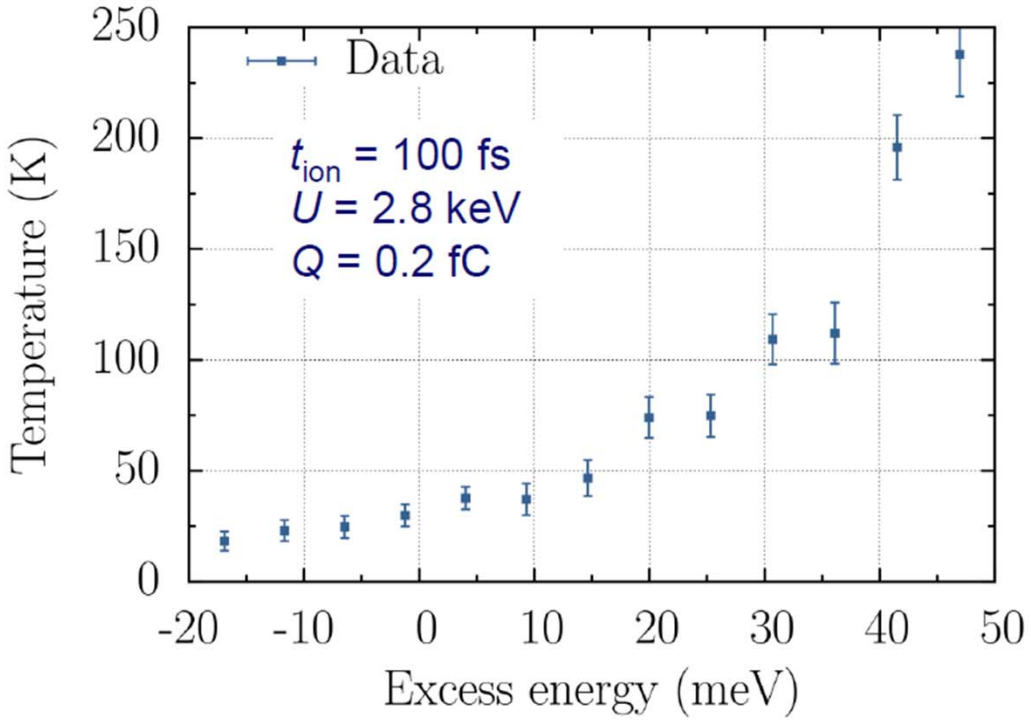


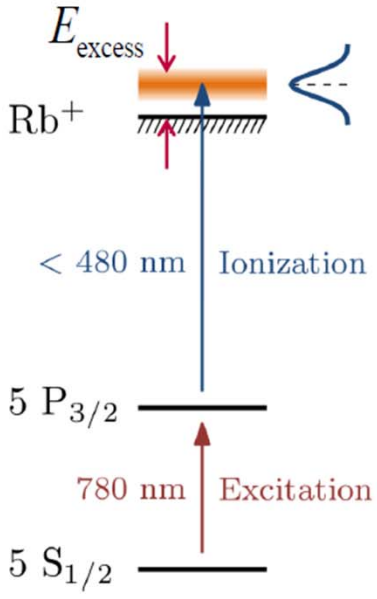
normalized emittance: $\varepsilon_n = 1.4$ nm·rad

$\sigma_{\text{source}} = 25\ \mu\text{m} \Rightarrow T_{\text{source}} = 18$ K

TU/e Technische Universiteit Eindhoven University of Technology

Ultrafast laser: unexpected results ?





Expected:

$\sigma_\lambda = 4$ nm $\rightarrow T_{source} \geq 200$ K

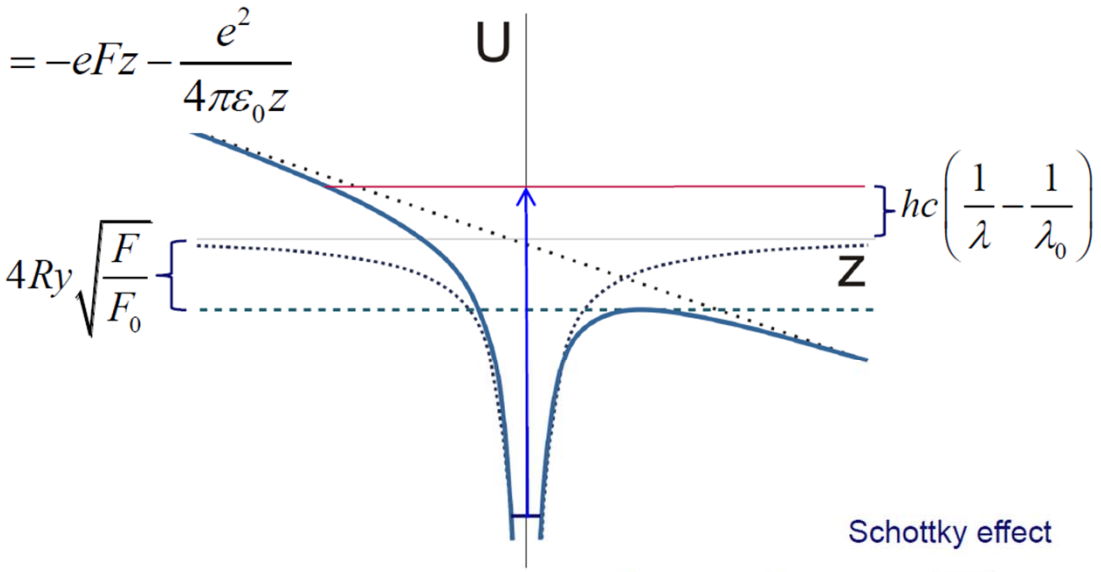
?

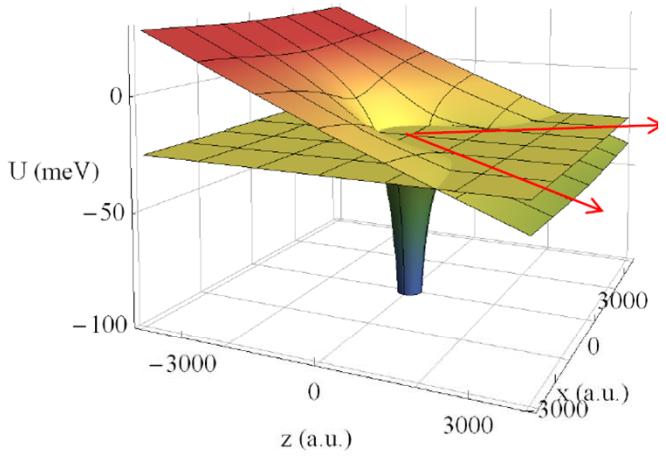
Engelen et al.,
Nat. Commun. (2013)

TU/e Technische Universiteit Eindhoven University of Technology

Semiclassical model to calculate trajectories

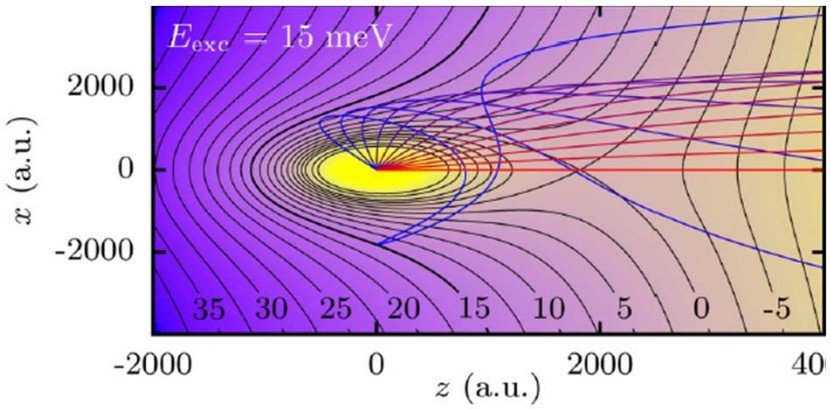
$$U = -eFz - \frac{e^2}{4\pi\varepsilon_0 z}$$

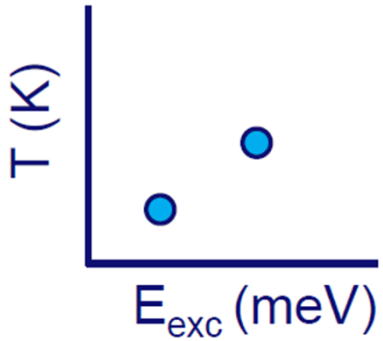




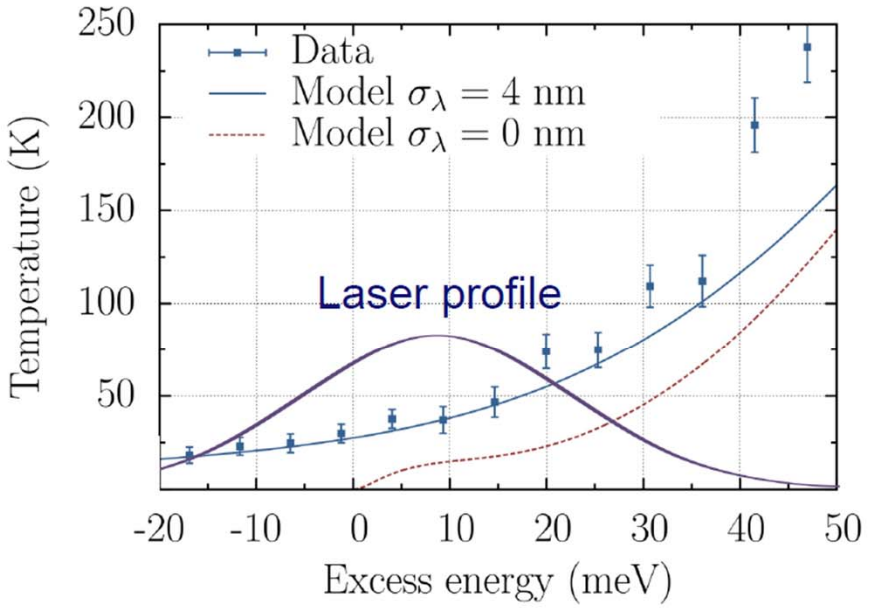
Schottky effect

Excess energy $E_{exc} = hc\left(\frac{1}{\lambda}-\frac{1}{\lambda_0}\right) + 4Ry\sqrt{\frac{F}{F_0}}$



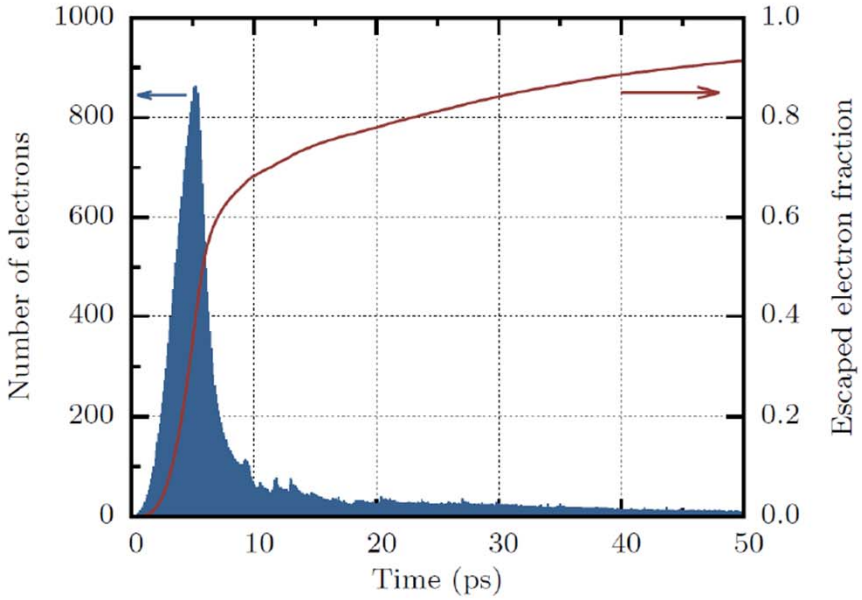


Model results



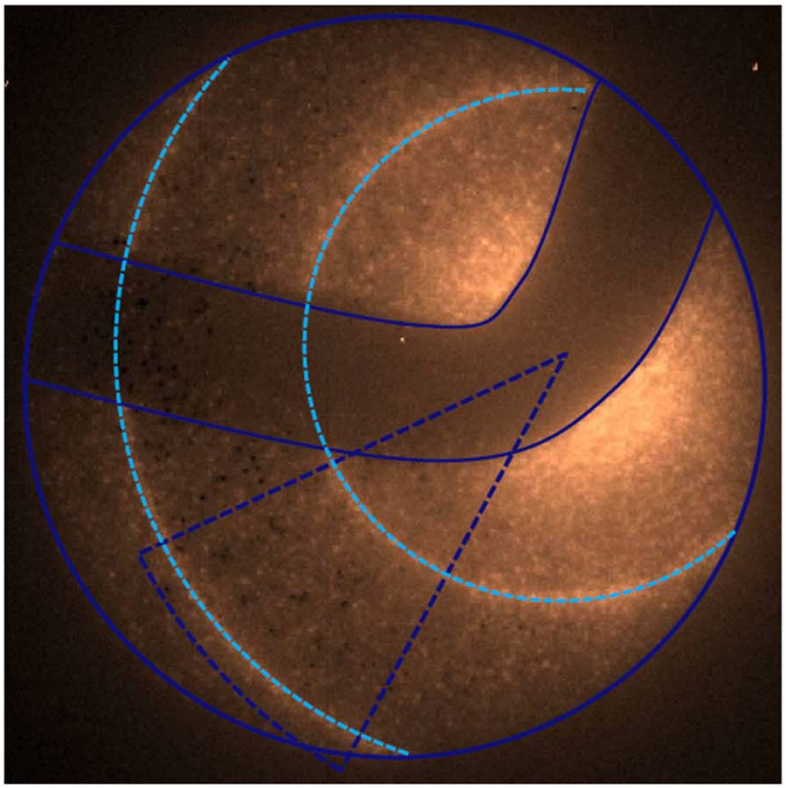
- **Analytical model explains femtosecond data;**
- ***few 10 K electron source with fs laser!***

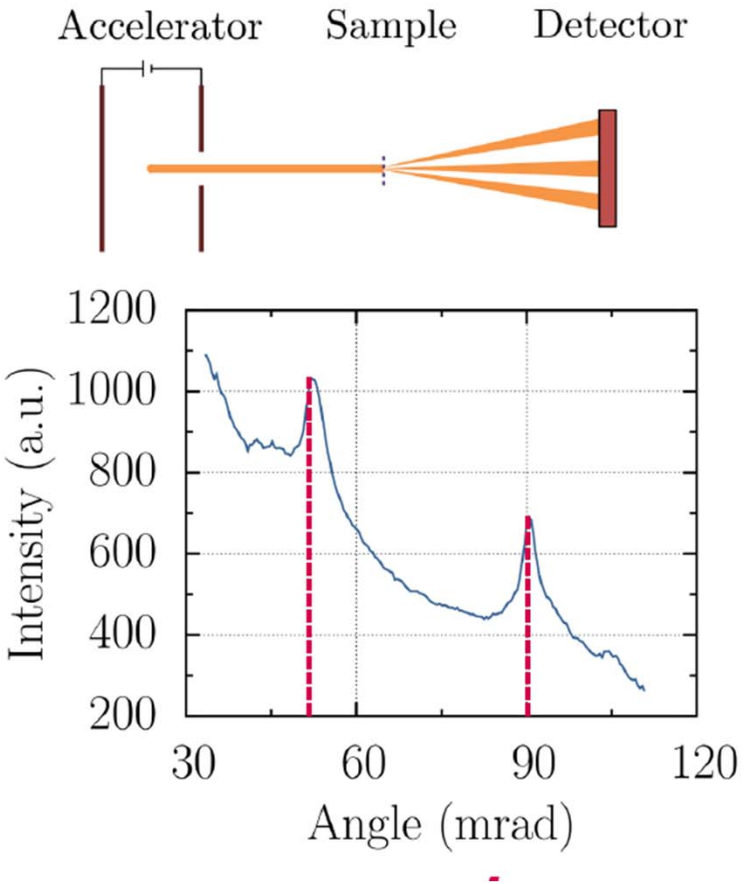
After convolution with spectral bandwidth fs ionization laser:

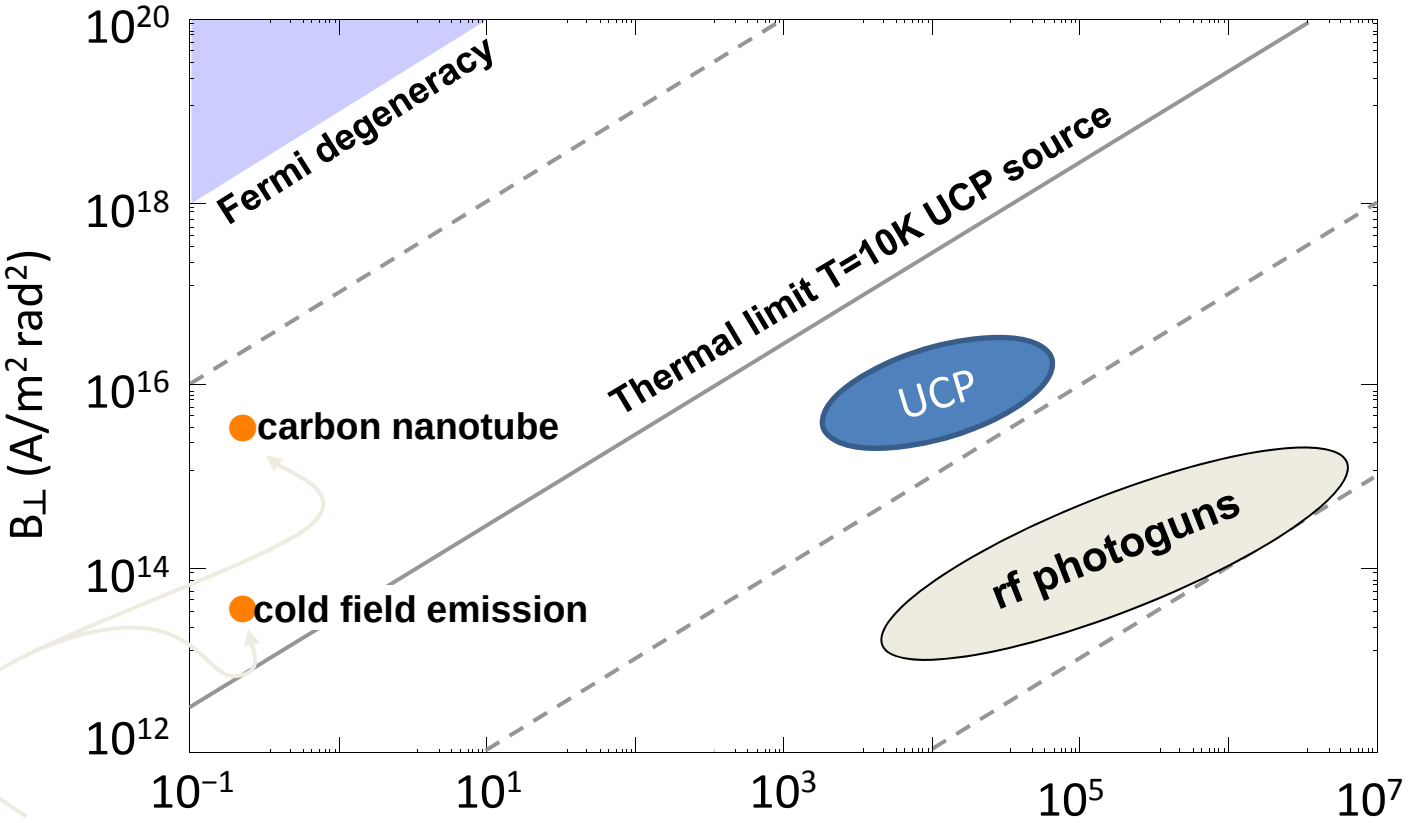


few-ps bunch length

UCP source diffraction pattern







High brightness but insufficient current.

Outline/Syllabus

- Electron source applications
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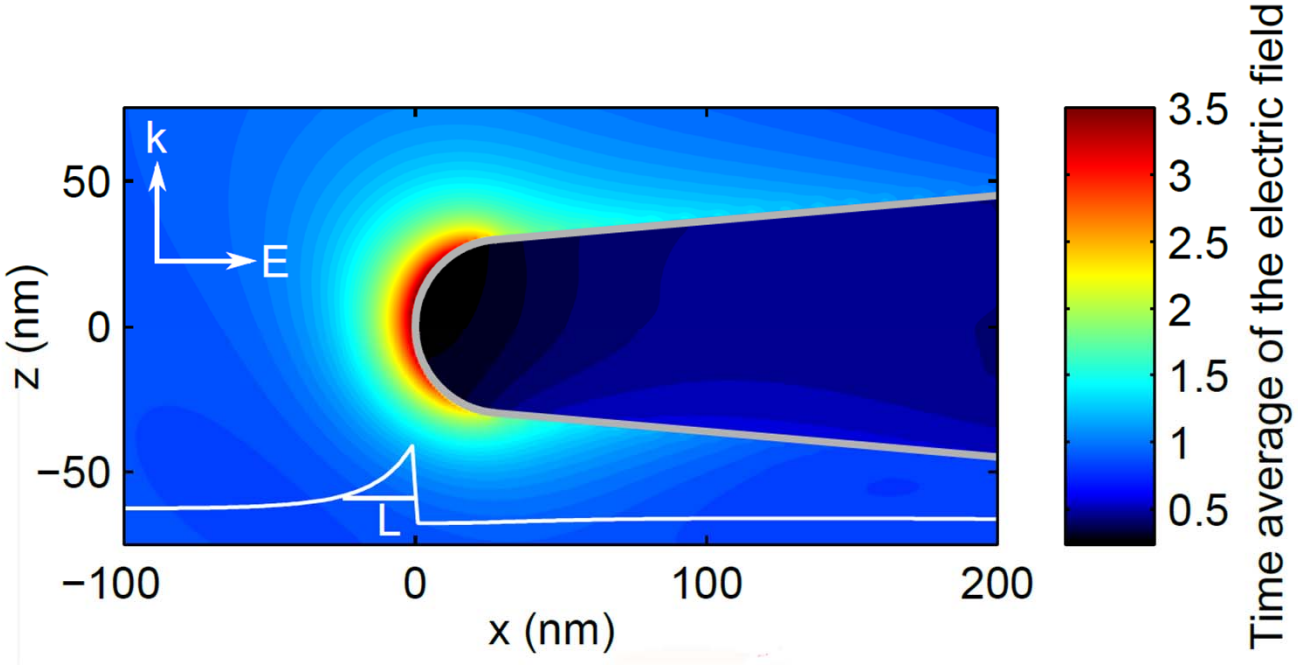
  - Scaling laws
  - Blow-out regime, pancakes and cigars
- Magneto Optical Trap-based ultracold sources
- Nanotips based and other kind of advanced e-sources

Different approach to increasing beam brightness

- Shrink the source size !
- Cigar beam regime is in similar direction, but due to laser hard to make < 1 um spot sizes
- Nanofabrication and nano-optics can reduce two more orders of magnitude the source size.

Nano-optics or near-field optics

"Plasmonics" is closely related



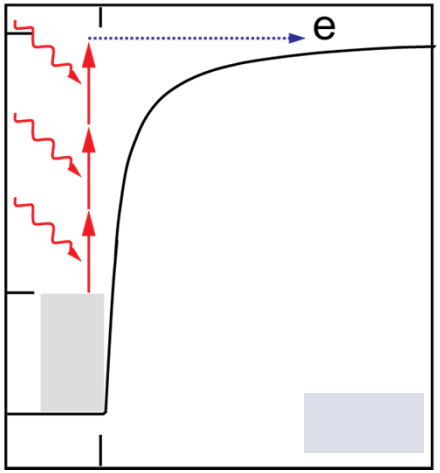
800 nm laser wavelength
focused on 30nm radius tip

Nano-optics & field enhancement overviews (small selection of recent literature):

Novotny, Hecht, Principles of nano-optics, Cambridge Univ. Press
Hartschuh, Tip-enhanced near-field optical microscopy, Ang. Chem. 2008
Novotny, van Hulst, Antennas for light, Nat. Phot. 2011
S. Thomas et al., arxiv:1209.5195.

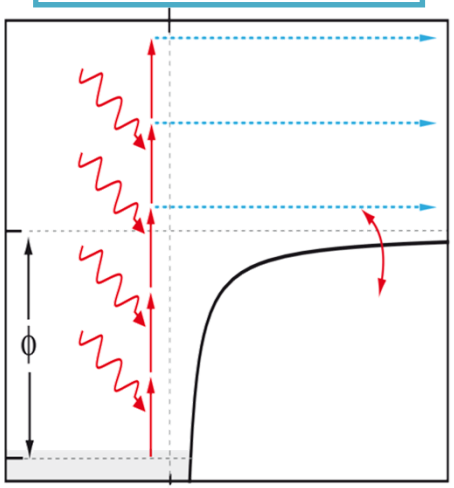
Photoemission from a metals in strong optical fields

Multiphoton photoemission



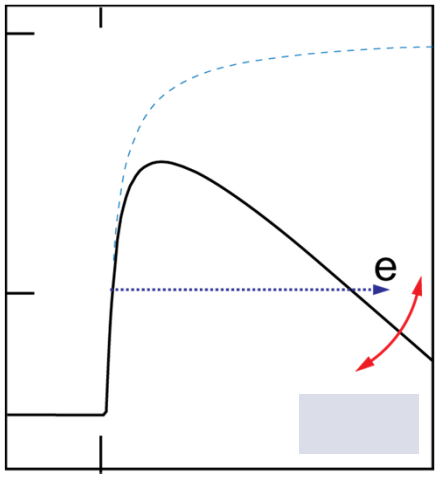
- n-photon-photoelectric effect: $n*E_{ph} > \Phi$
- photocurrent ~ I_{laser}^{n}
- perturbative regime

Above-threshold-photoemission



- n+1 and higher orders of photon absorption

Light-induced direct tunneling



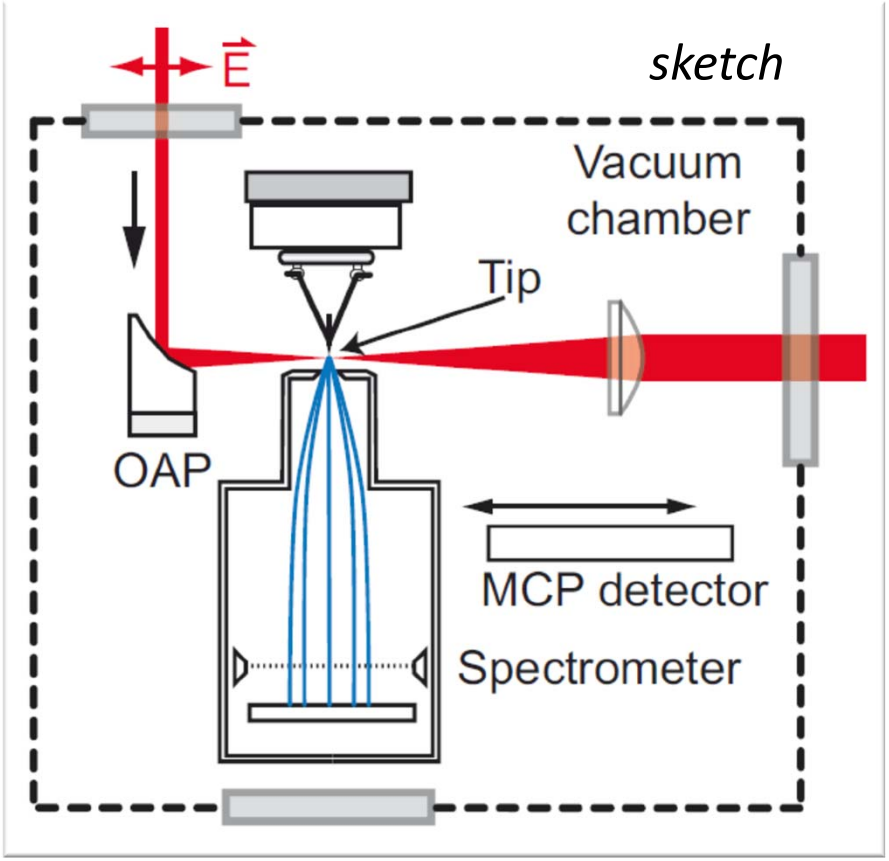
- potential AC-modulated
- quasi-static tunneling
- current resolves field

G. Farkas et al., Opt. Comm. 1983
R. Bormann et al., PRL 2010
P. Dombi et al., Opt. Expr. 2010

Strong-field regime

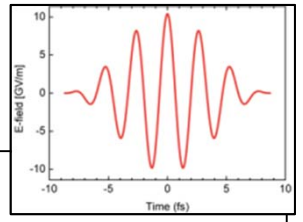
Increasing I_{laser} (beyond perturbative approach)

Experimental setup



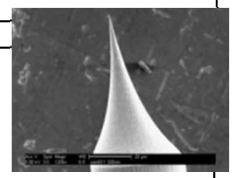
Typical operating parameters:

- up to 0.5nJ, 10^{11}W/cm^2
  Keldysh parameter (incl. FE): $\gamma = 2$
- yield of <1 electron/pulse (several pA)



Ti:sa oscillator

- pulse duration 6.5 fs
- central wavelength 800nm (1.56eV)
- repetition rate 80MHz
- max. output 750mW
- max. pulse energy 9 nJ



Tungsten tip

- etched from single crystal wire in W(310) orientation
- apex radius around 20nm
- clean surface by field evaporation

Focal parameters

- f = 15 mm; w_0=2.2µm
- max. intensity: 10^{12}W/cm^2

Previous work (selection)

P. Hommelhoff, Y. Sortais, et al., PRL **96**, 077401 (2006)
P. Hommelhoff, C. Kealhofer et al., PRL **97**, 247402 (2006)
C. Ropers et al., PRL **98**, 043907 (2007)
B. Barwick et al., NJP **9**, 142 (2007)

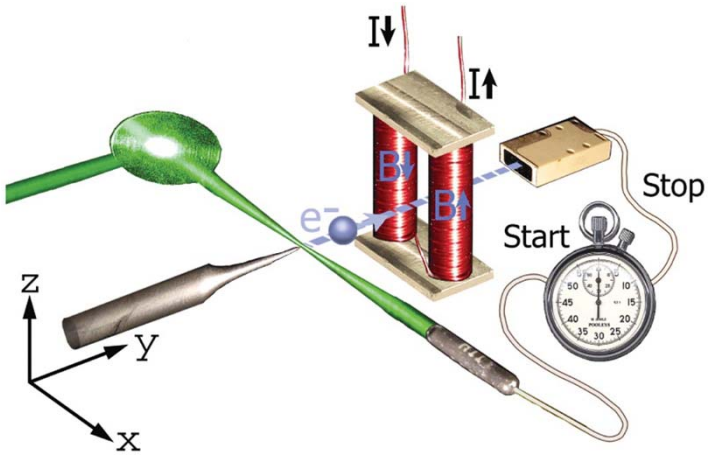
Femtosecond nanometric electron emission: processes etc.

S. Tsujino et al., APL **92**, 193501 (2008)
R. Ganter et al., PRL **100**, 064801 (2008)
S. Tsujino et al., APL **94**, 093508 (2009)

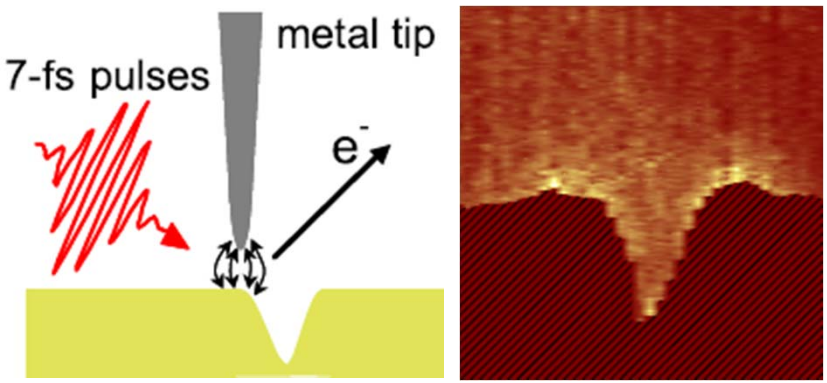
Ultralow emittance electron source applications

H. Yanagisawa et al., PRL **103**, 257603 (2009)
H. Yanagisawa et al., PRB **81**, 115429 (2010)

Surface field effects

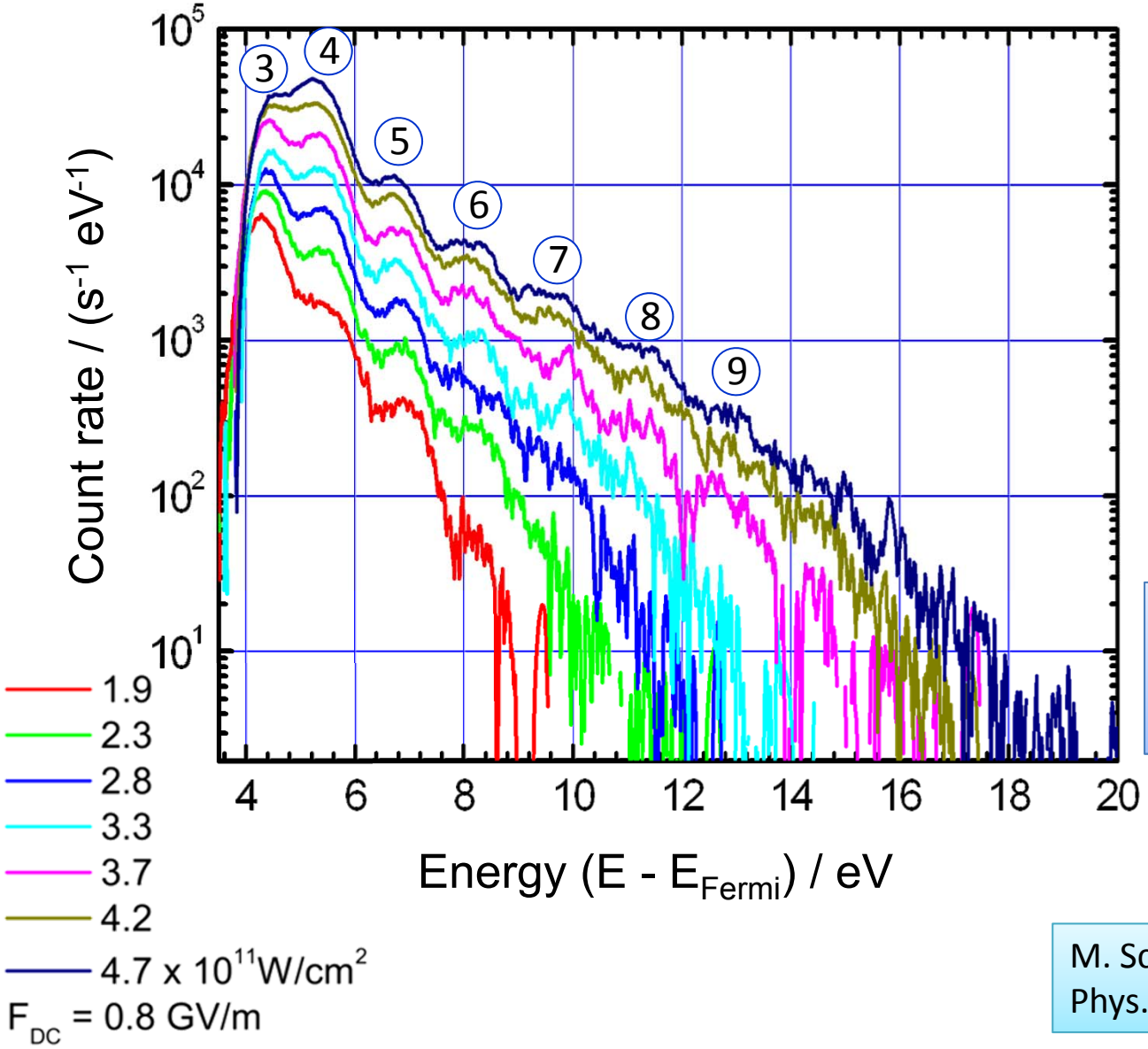


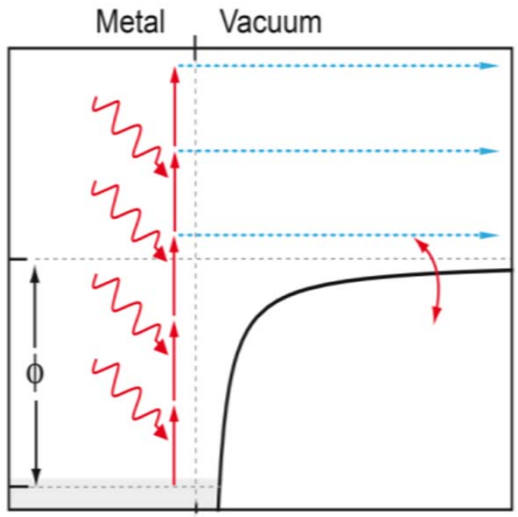
Test of the Aharanov-Bohm effect
Caprez et al., PRL **99**, 210401 (2007)



Nanometric imaging tool
C. Ropers et al., PRL **98**, 043907 (2007)

Above-threshold photoemission

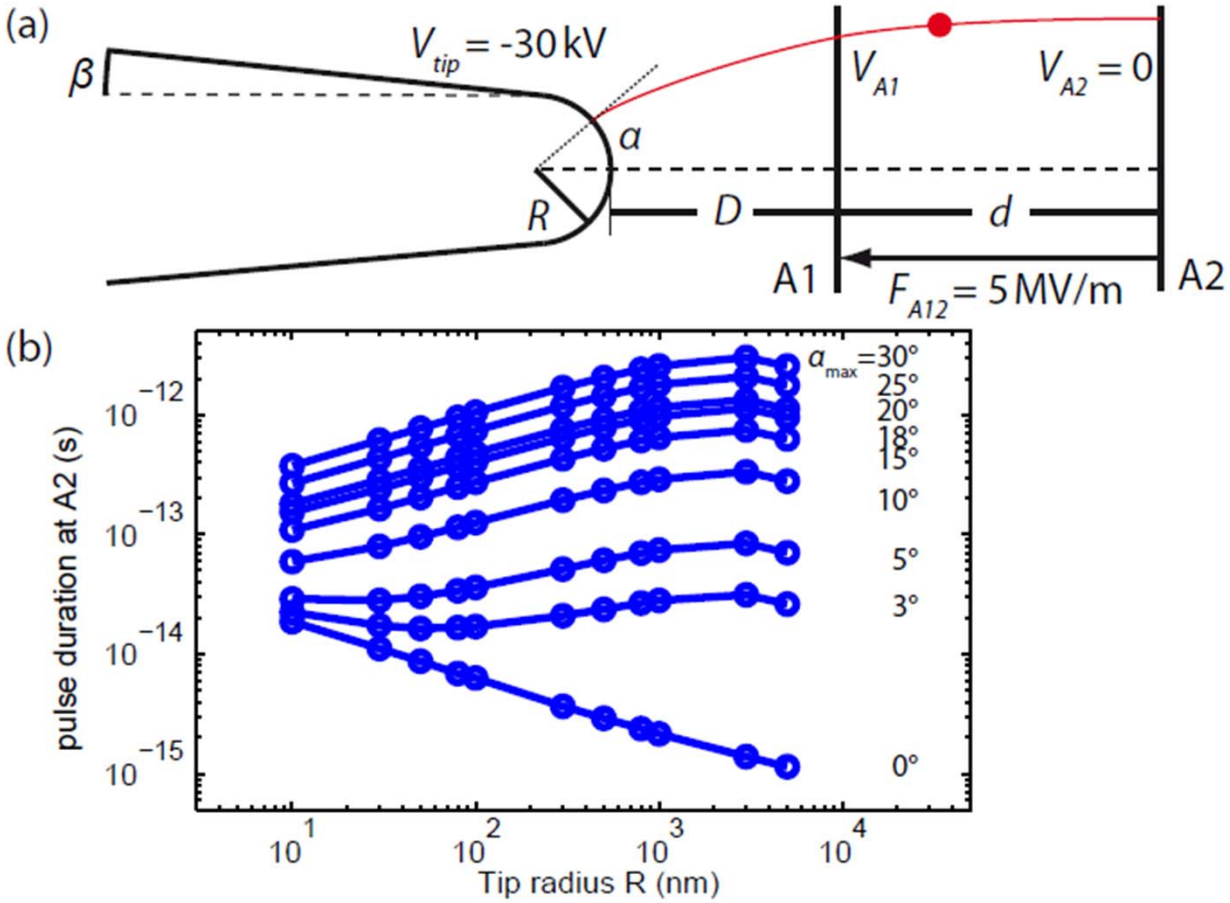




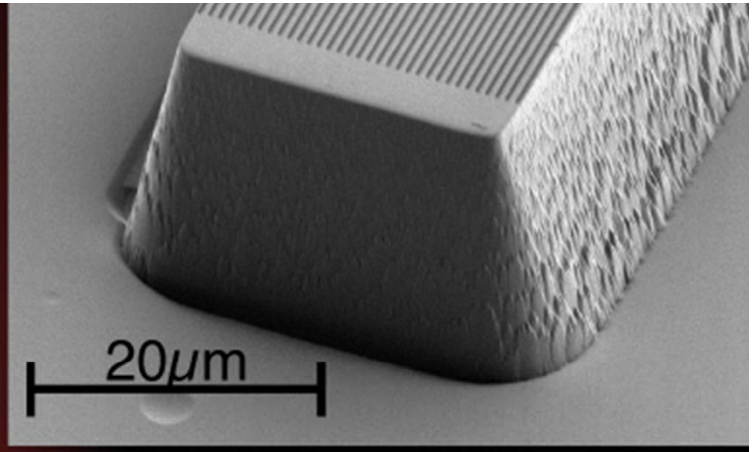
- ATP with 1.46 eV photons
- Clear peaks because of single clean nanoemitter

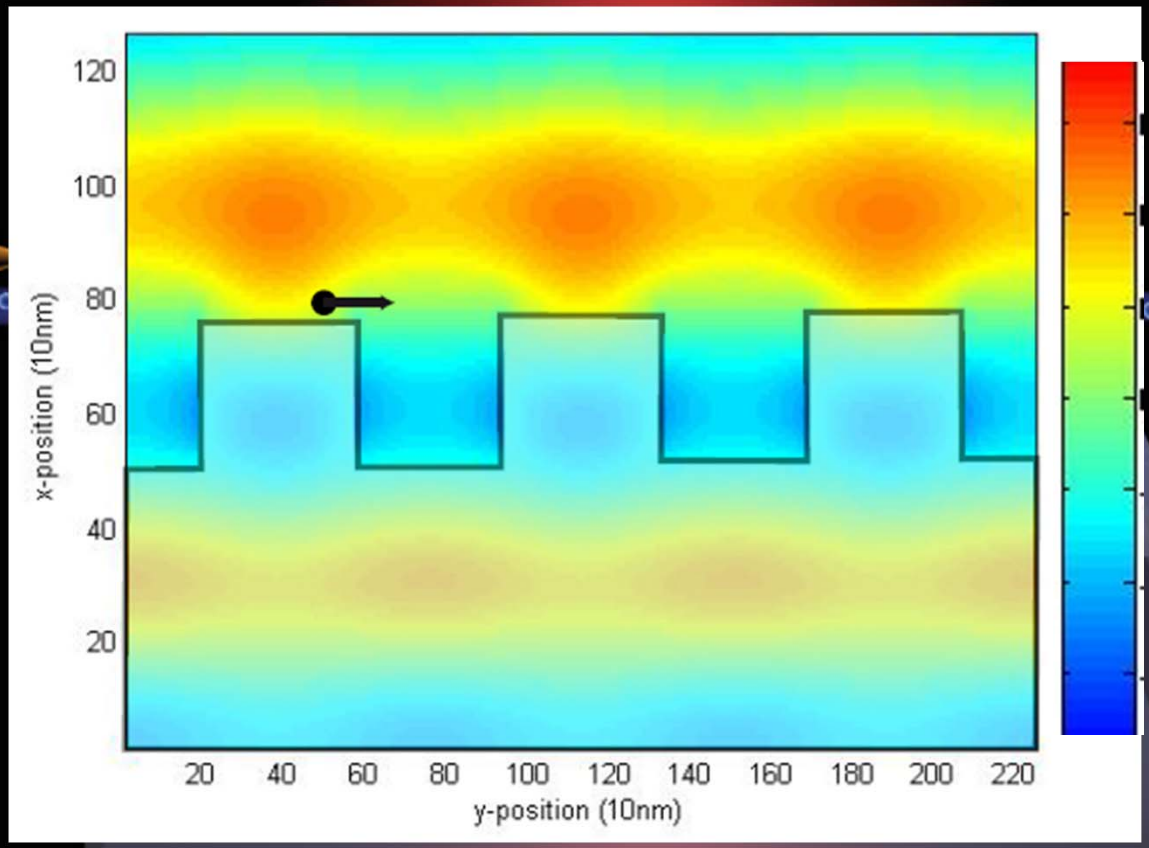
M. Schenk, M. Krüger, P. Hommelhoff, Phys. Rev. Lett. 105, 257601 (2010)

Pulse length: geometrical aberrations



Dielectric laser acceleration of non-relativistic electrons at a photonic structure





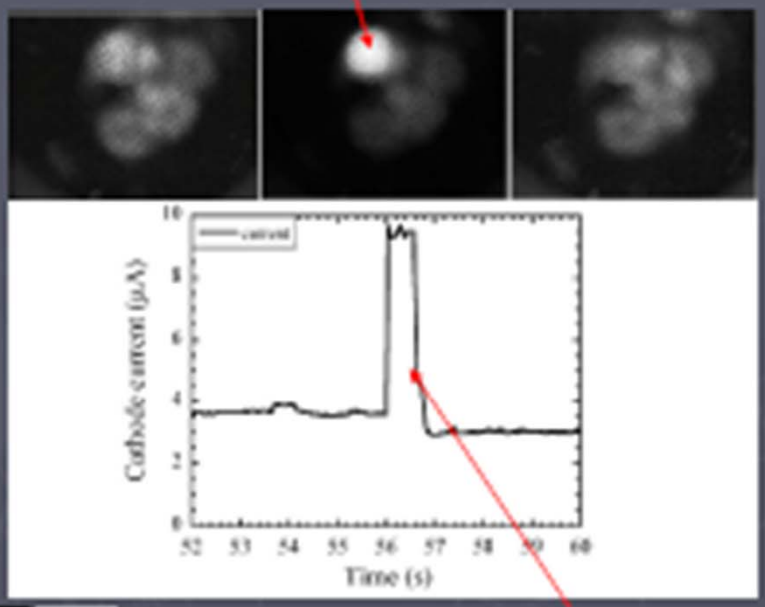
acceleration

deceleration

Field emitting tips

Field emission from atoms adsorbed on CNTs approaches the quantum limit

Emittance of beam from adsorbed atom is near the Heisenberg limit



Current spike due to adsorbate emission

- Field emission from adsorbed atoms forms intense spots
  - Emittance is close to Heisenberg limit
- Background gas atoms are weakly bound, unstable, and desorb at high current
  - Emission is too unstable to measure energy spectrum
- Same thing seen on diamond pyramids

Increase field to increase brightness

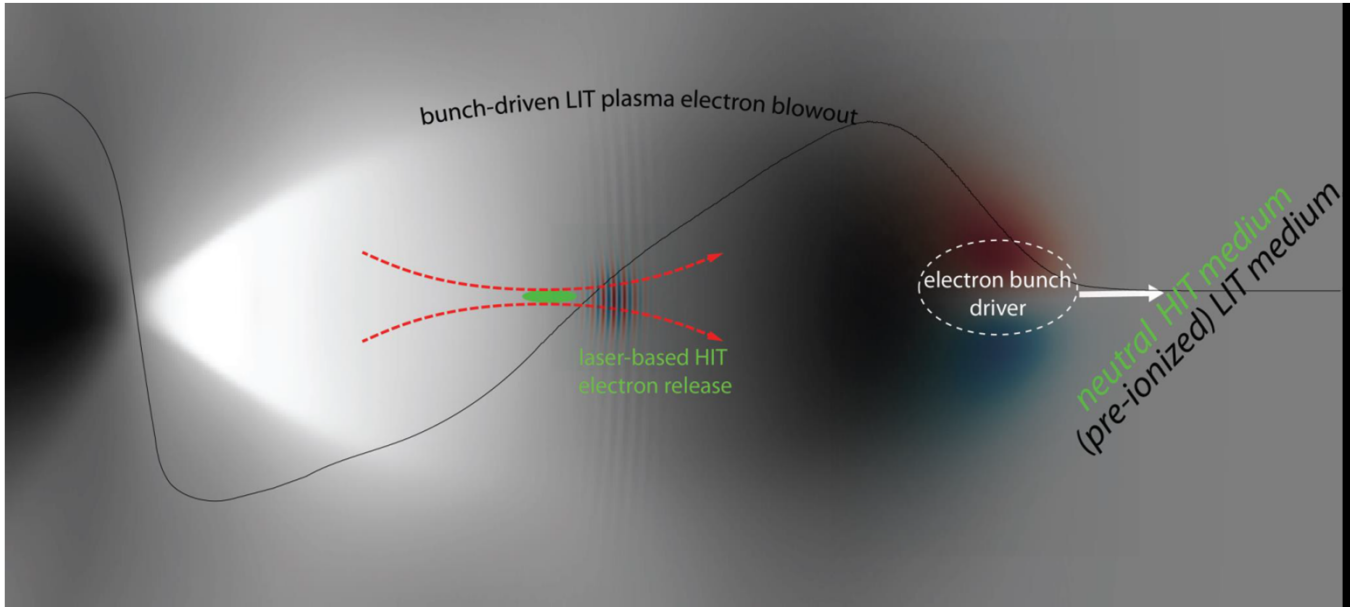
Plasma based sources boast gradients of multi GV/m
Many schemes to inject particles directly in plasma waves

Simulation results

Q	2 pC
I_{peak}	300 A
ε_n	30 nm
B_{5D}	5 10^{17} A/m^2

Focus laser pulse intensity has to be just above the ionization threshold of the HIT medium
~10^{14} -10^{15} W/cm^2

Trojan Horse E-210 experiment.



6D brightness vs. charge