Active plasma lenses at 10 GeV

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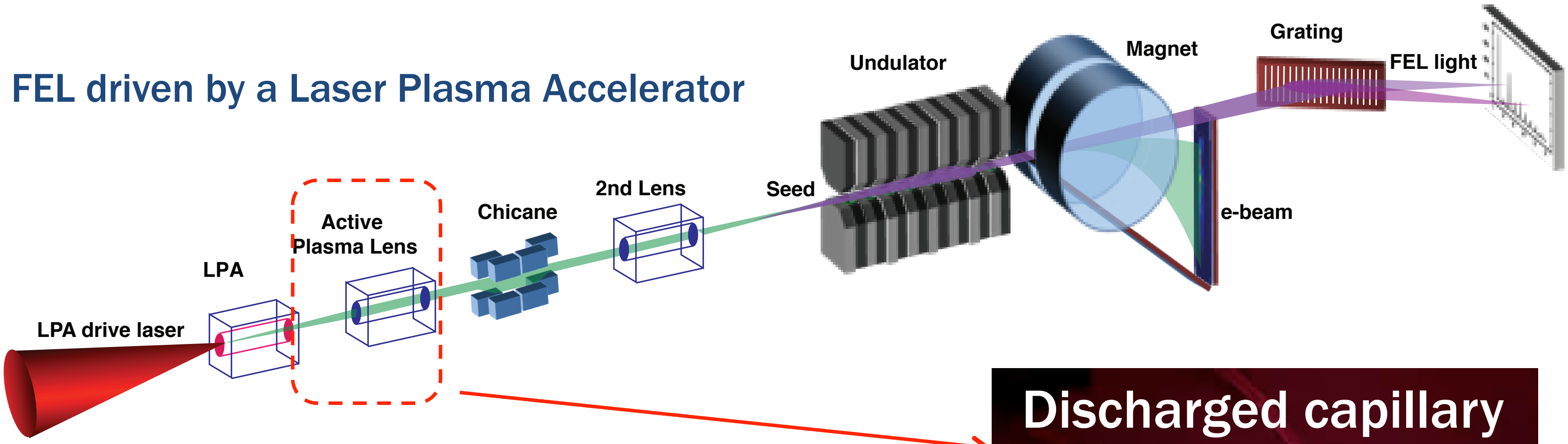
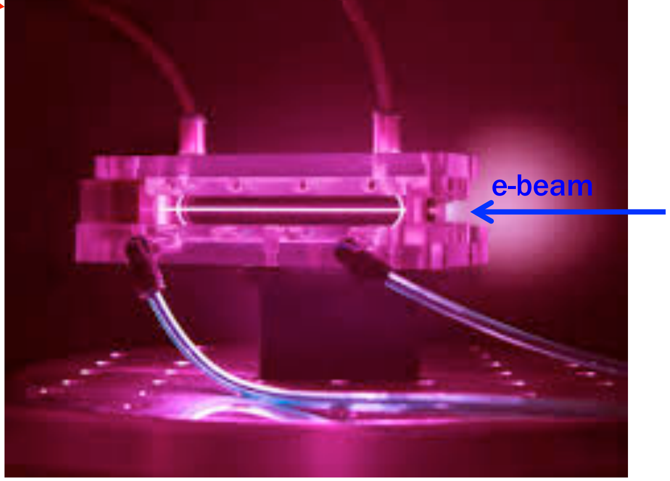
National Nuclear Security Administration

Magnetic lenses play a critical role in accelerator applications. Strength & tunability desirable.

FEL driven by a Laser Plasma Accelerator



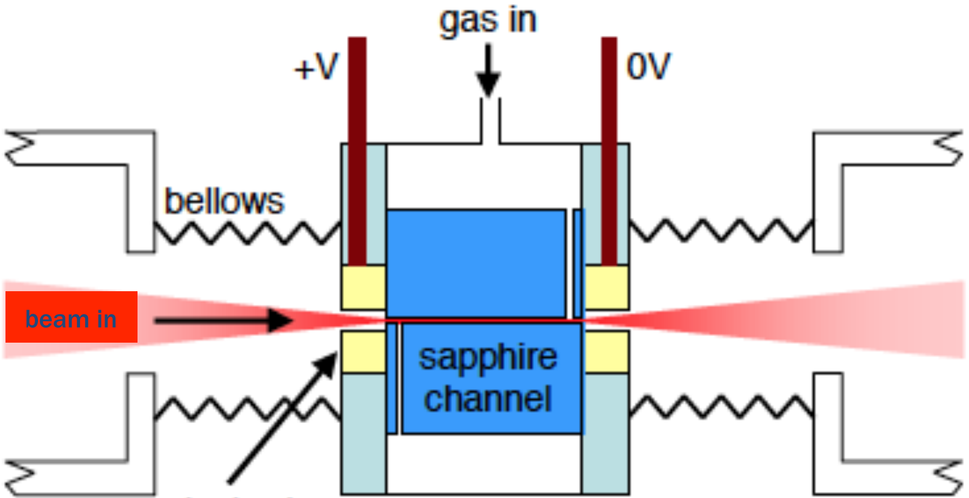
Discharged capillary



Accelerator applications → transport line

- Magnetic lens for collimation, focusing
- Focal length ~ gamma / (dB/dr)
- High gradient → compact applications
- High gradient → high energy applications
- Ideal: tunable, radially symmetric
- Active Plasma Lens meets these criteria

Discharge current flowing through a capillary: linear B-gradient for uniform current distribution



courtesy of A. J. Gonsalves

Ampere's law

$$2\pi r B(r) = \mu_0 \int_0^r 2\pi r' J(r') dr'$$

$$\int_0^R 2\pi r J(r) dr = I_0$$

Uniform current

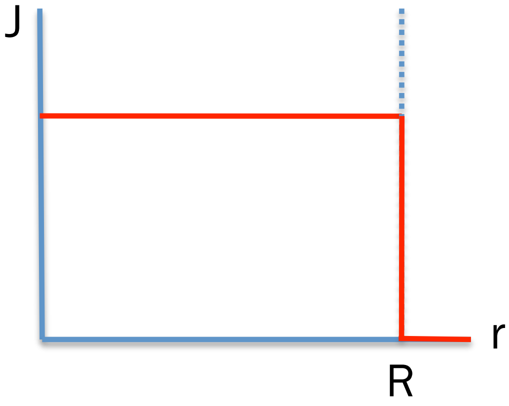
$$J(r) = J_0$$

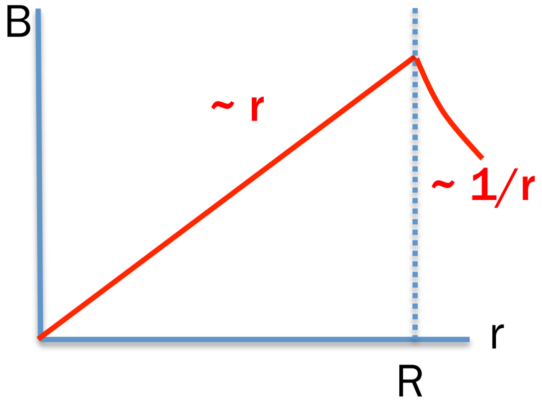
$$J_0 = I_0 / \pi R^2$$

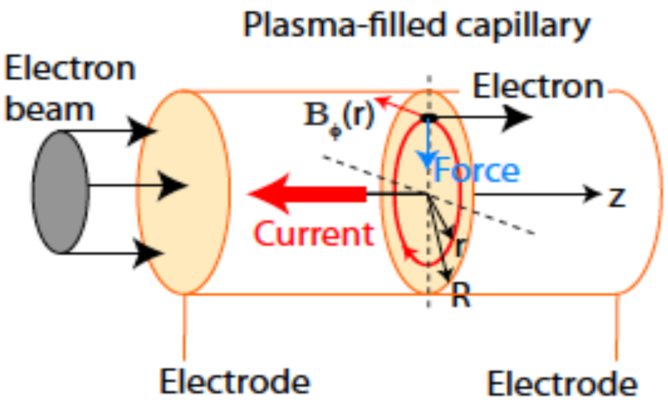
→

$$B(r) = \frac{\mu_0 I_0}{2\pi R^2} r$$

$$\frac{\partial B}{\partial r} = \frac{\mu_0 I_0}{2\pi R^2}$$







Active plasma lens an "old" concept for ion beams. Attractive due tunability, symmetry, and strength

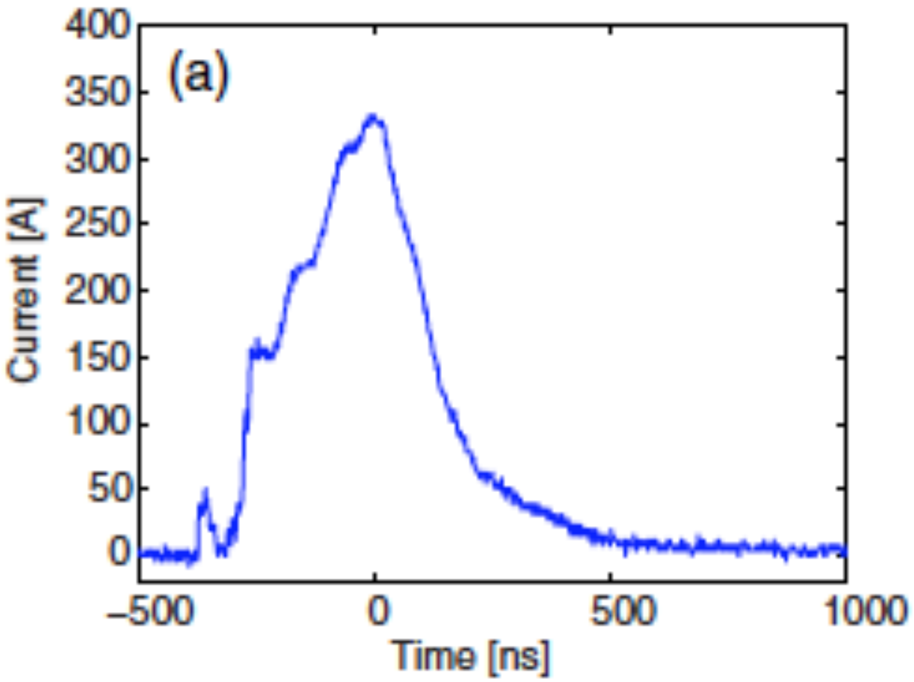
Active Plasma Lens

- Introduced 1950s (ion beams) Panofski *et al*. RSI 1950
- Radial symmetric focusing
- Tunable, up to ~1 kA ("active")
- Gradients >3000 T/m

Field gradient $\frac{\partial B}{\partial r} = \frac{\mu_0 I}{2\pi R^2}$

Strength parameter $k = \frac{q}{m_0 \gamma c} \frac{\partial B}{\partial r}$

Focal length $F = 1/(kL)$

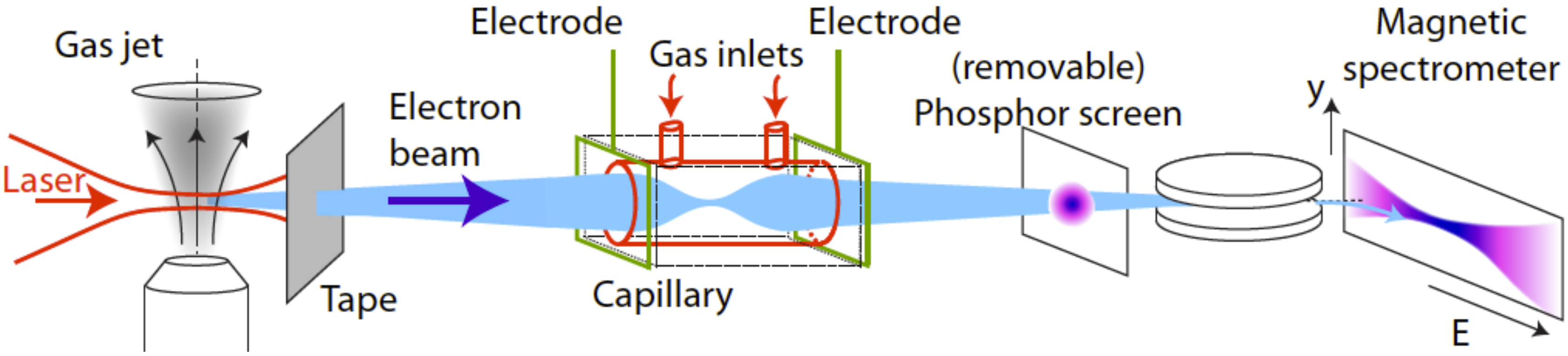


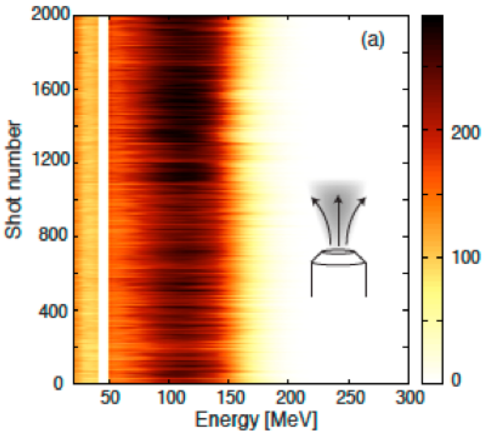
Example
D=0.5mm, L=6cm
F=2cm @ 500 MeV
I=430 A (1400 T/m)

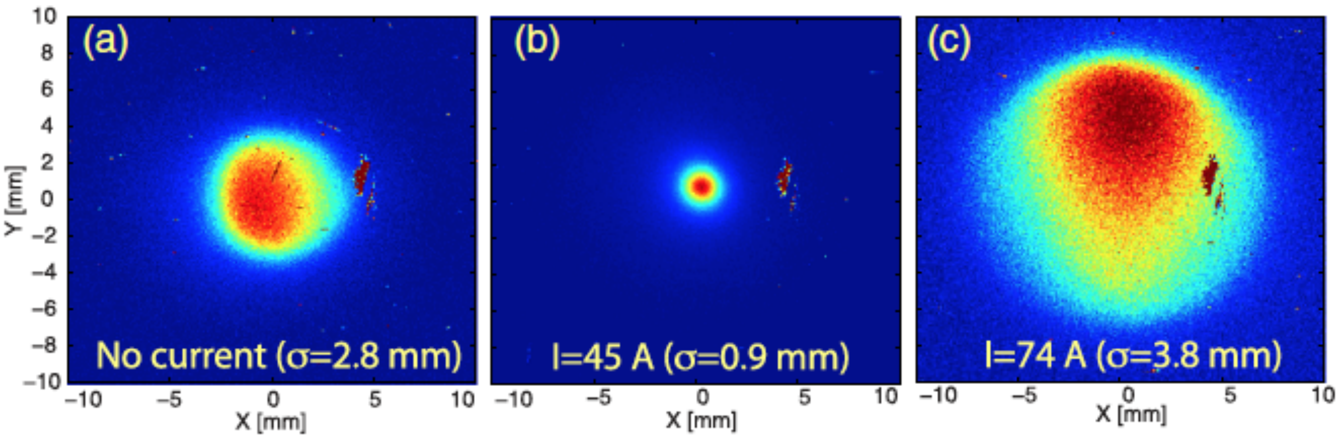
Example
D=0.5mm, L=6cm
F=25cm @ 10 GeV
I=695 A (2200 T/m)

1 mrad & 25cm → σ=250 μm

Experimental demonstration on Laser-Plasma Accelerated electron beams in 2015

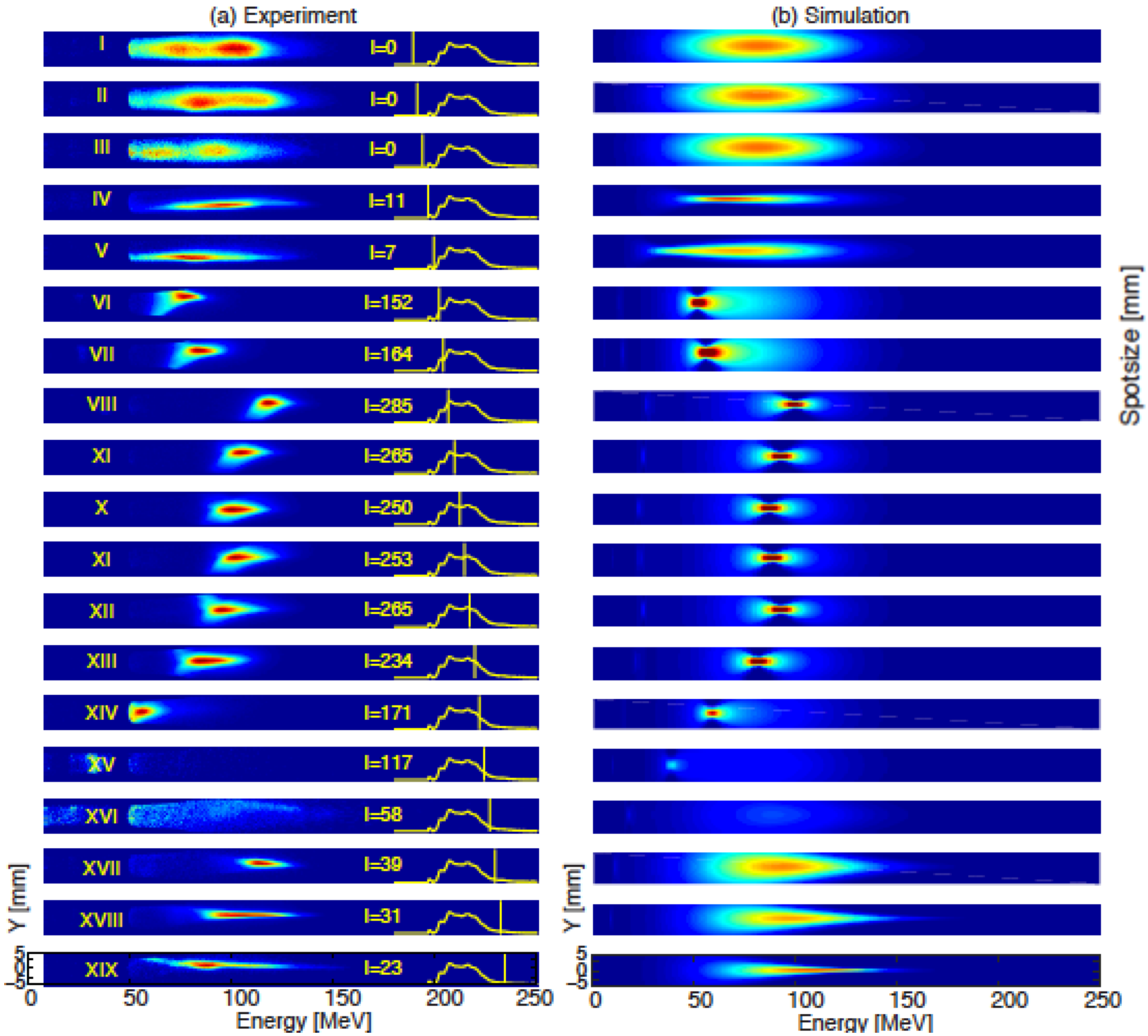


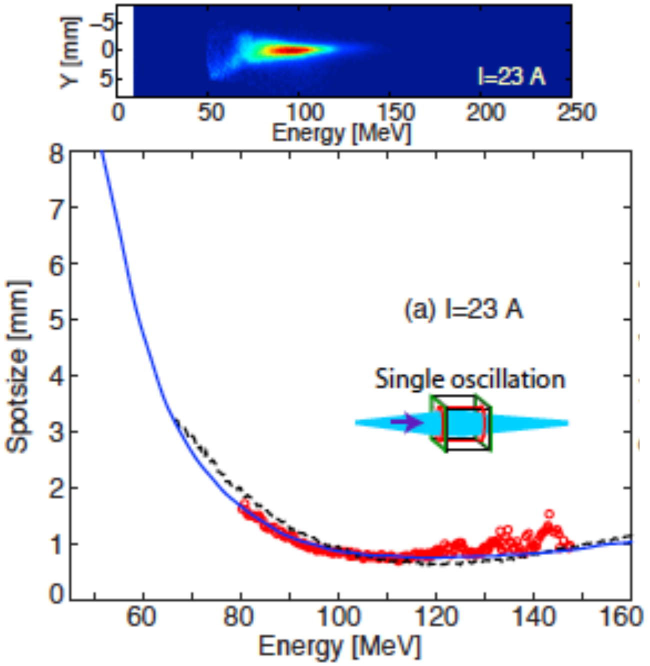




van Tilborg *et al*. PRL 115, 184802 (2015)

Energy-dispersed beam size diagnostic reveals oscillations within plasma lens

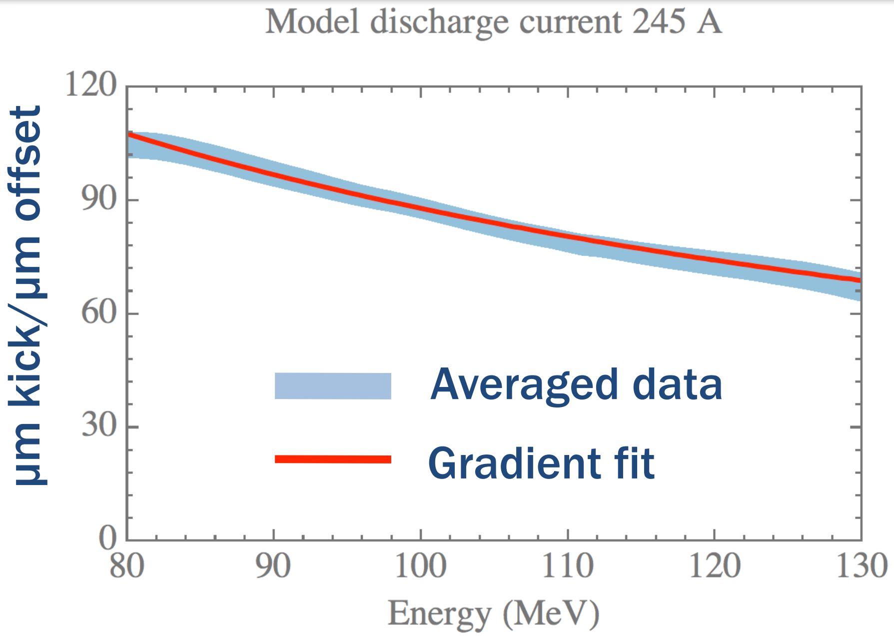




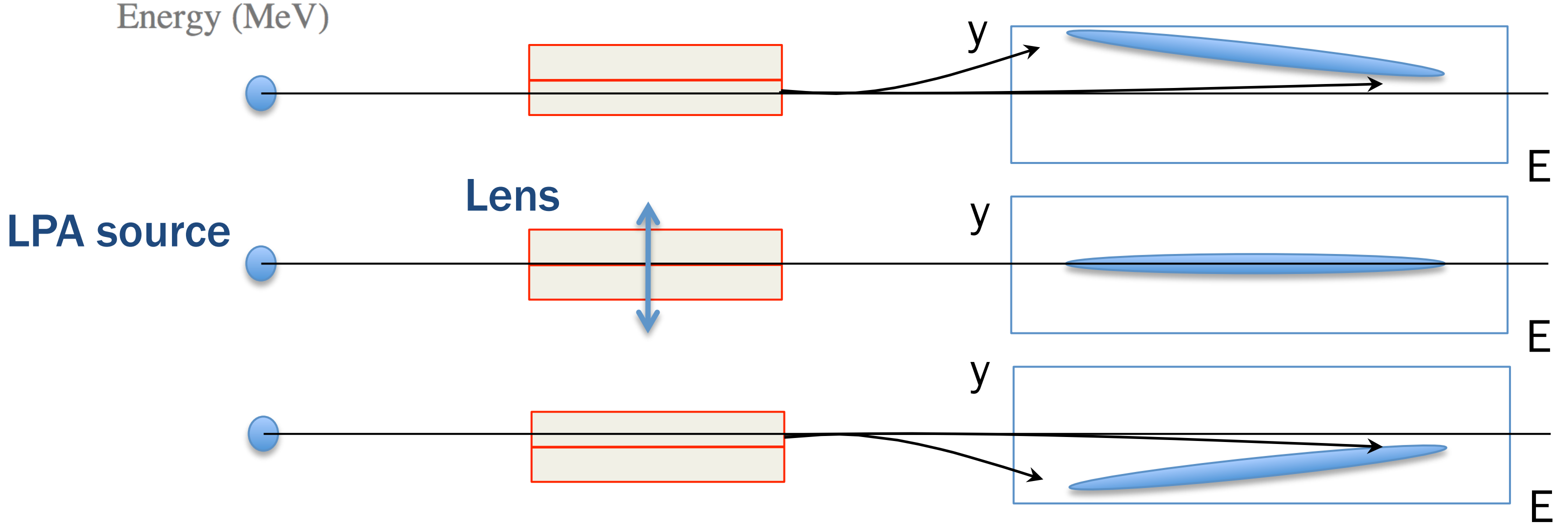
- D 0.25mm capillary, L=33mm, tape protection
- Agreement with simulation
- @300A → 3000 T/m
- 2nd and 3rd oscillation inside lens observed

van Tilborg *et al*. PRL 115, 184802 (2015)

Transverse scan useful to measure focusing gradient


Model discharge current 245 A

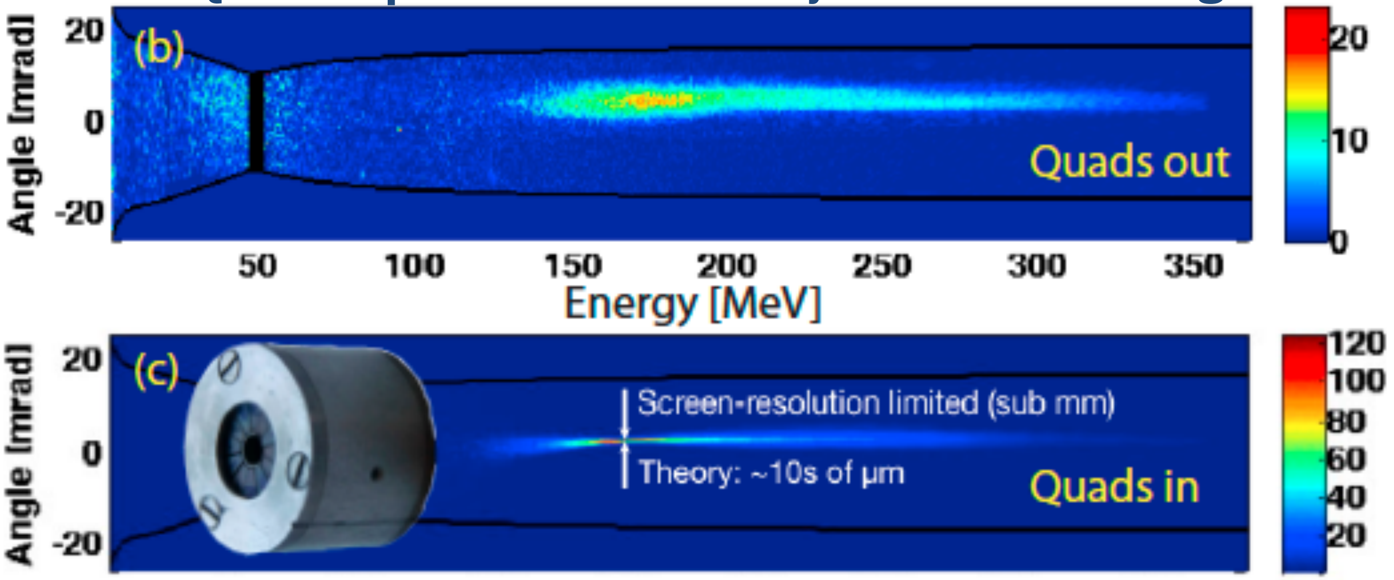
- Good technique regardless of imaging geometry
- D 0.5mm capillary, L=15mm, 30mm drift, no tape protection
- Under investigation: measured current ~360 Amps
- Cap wider (on average) by 21%?


Lens

LPA source

Where active plasma lenses can provide unique solutions:
1. Ultra-relativistic e-beams

Quadrupole doublet: Asymmetric focusing



Quads out

Screen-resolution limited (sub mm)

Theory: ~10s of μm

Quads in

For 300 MeV e-beam
Solenoid (2 T, L=20 cm): F=500 cm
Quad doublet (500 T/m, L=3 cm): F=13 cm
Active plasma lens (2000 T/m, L=3 cm): F=1.7 cm

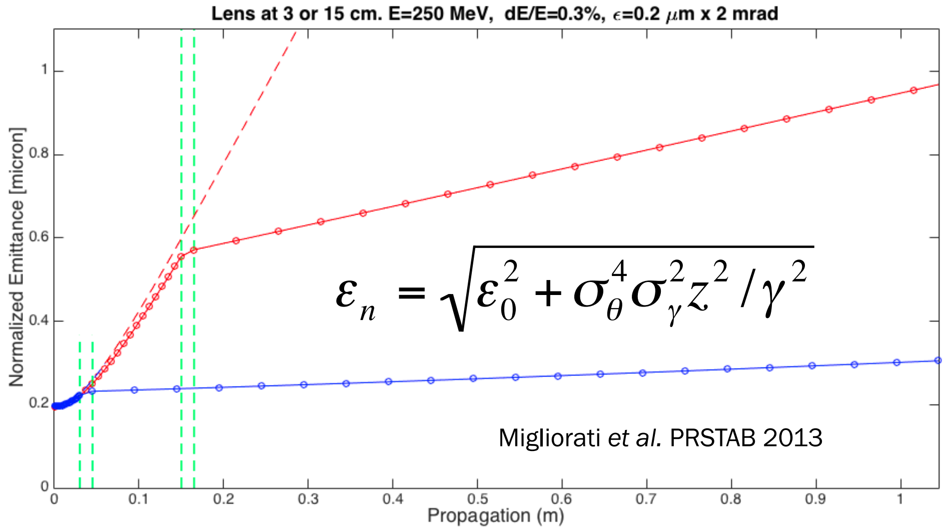
For 10 GeV e-beam
Quad doublet (500 T/m, L=3 cm): F=4.5 m
Active plasma lens (2000 T/m, L=6 cm): F=0.28 m

$$k = \frac{q}{m_0 \gamma c} \frac{\partial B}{\partial r}$$

(also of interest to ion beams)

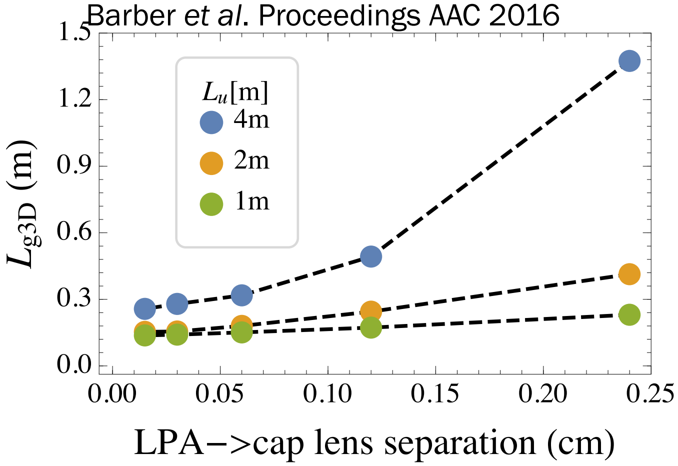
Panofski *et al*. RSI 1950, Boggasch *et al.* Proceedings EPAC ‘92

Where active plasma lenses can provide unique solutions: 2. Rapid capture for compactness, mitigation ε growth



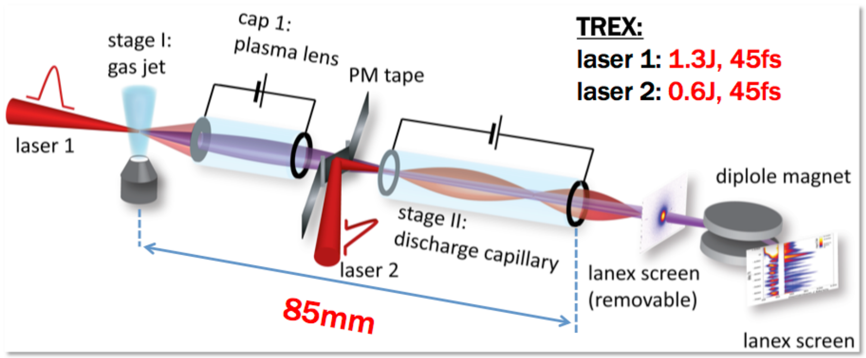
$$\varepsilon_n = \sqrt{\varepsilon_0^2 + \sigma_\theta^4 \sigma_\gamma^2 z^2 / \gamma^2}$$

Migliorati *et al.* PRSTAB 2013



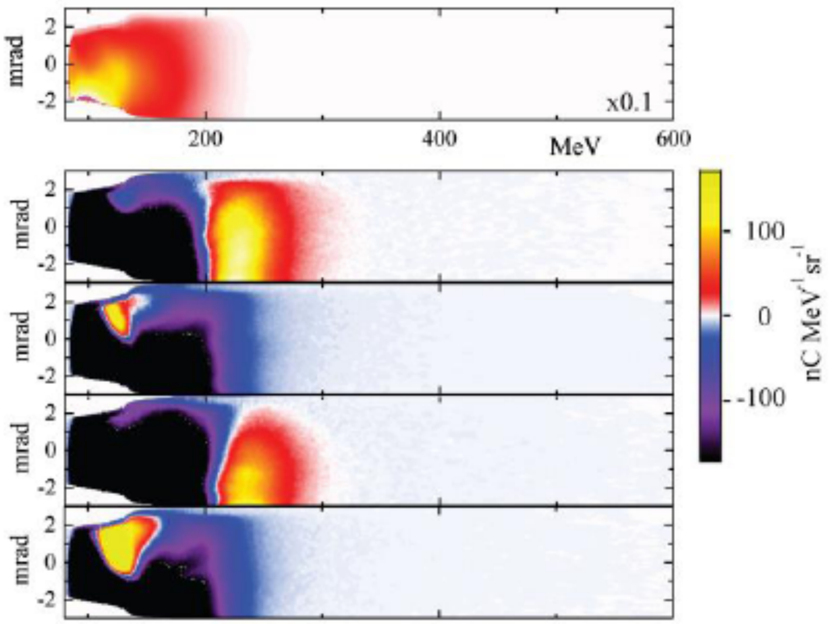
Barber *et al*. Proceedings AAC 2016

- Compact (staging)
- Quick capture → emittance mitigation for Δγ/γ~%
- Quick capture → matching in undulator for larger Δγ/γ



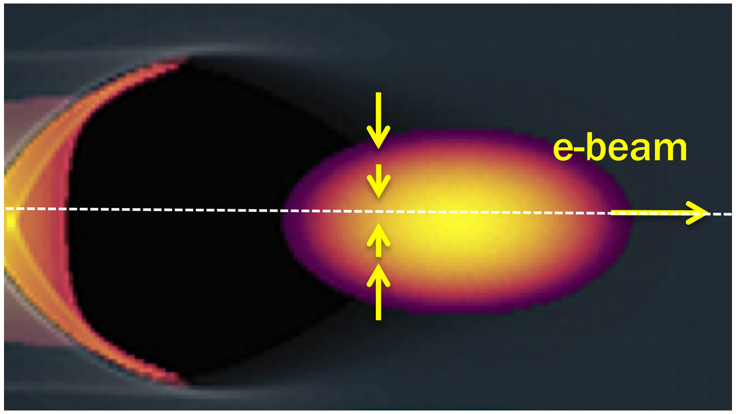
TREX:
laser 1: 1.3J, 45fs
laser 2: 0.6J, 45fs

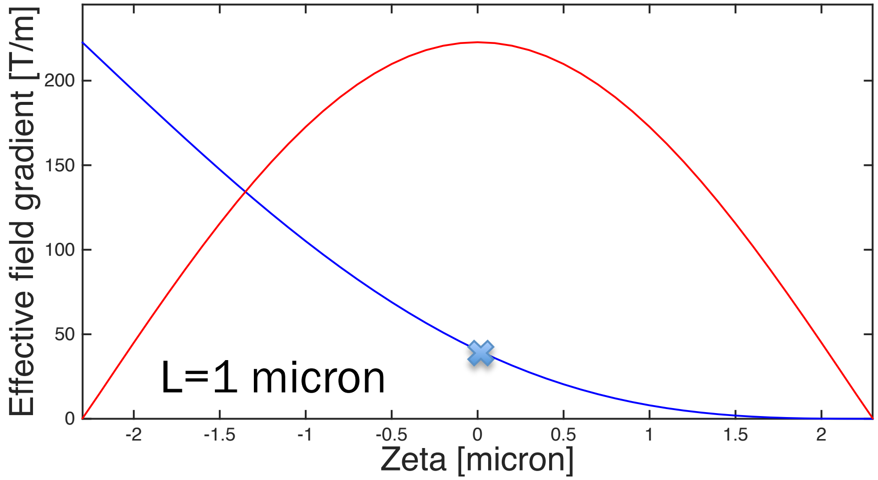
Steinke *et al*. Nature 2016

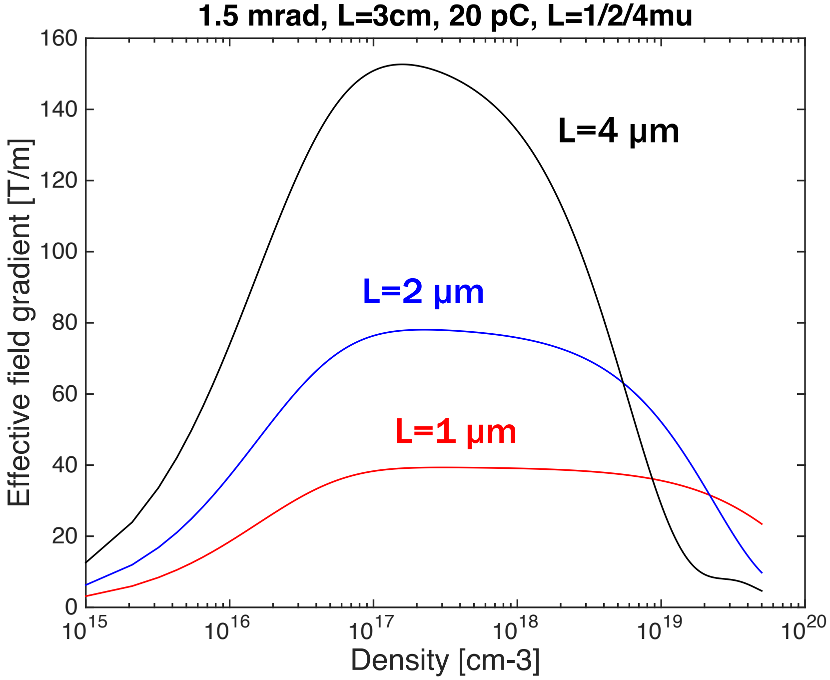


Possible limitation: emittance degradation from beam-driven wakefields for dense e-beams

Esarey *et al*. Rev. Mod. Phys. 2009



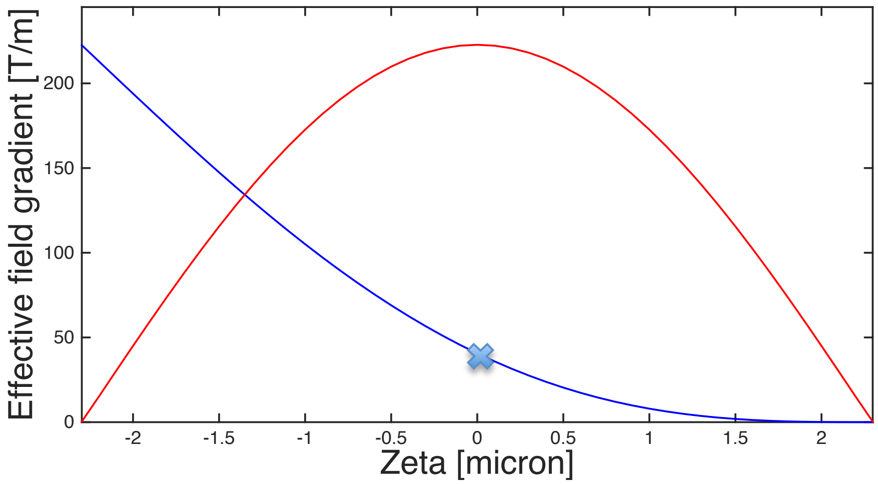




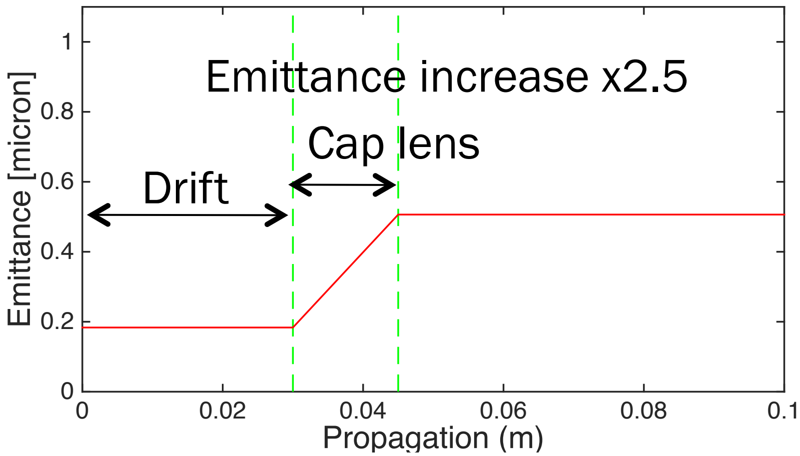
Linear regime:

$$\frac{(E_r - B_\varphi)(r,\zeta)}{E_0} = \frac{\pi(k_p L)}{\pi^2 - k_p^2 L^2}\frac{n_b}{n_0}\left\{\frac{1}{k_p}\sin\left[k_p\left(\zeta-\frac{L}{2}\right)\right]+\frac{L}{\pi}\cos\left[\frac{\pi\zeta}{L}\right]\right\}\times\left[-\frac{2r}{r_b^2}+2k_p I_0'(k_p r)K_2(k_p r_b)\right]$$

Possible limitation: emittance degradation from beam-driven wakefields for dense e-beams



250 MeV, 0.25 micron source, 1.5 mrad
L=2 micron, Lprop=3 cm, σ=45 micron
nbeam=1.3e15 cm-3 (25pC)
Lens=840 + 80 T/m front-end variation



$$\frac{q}{m_0\gamma c}\frac{\partial B}{\partial r} = \frac{q}{m_0\gamma c}\left[\frac{\mu_0 I}{2\pi R^2} + \eta(\zeta - \zeta_s)^2\right]$$

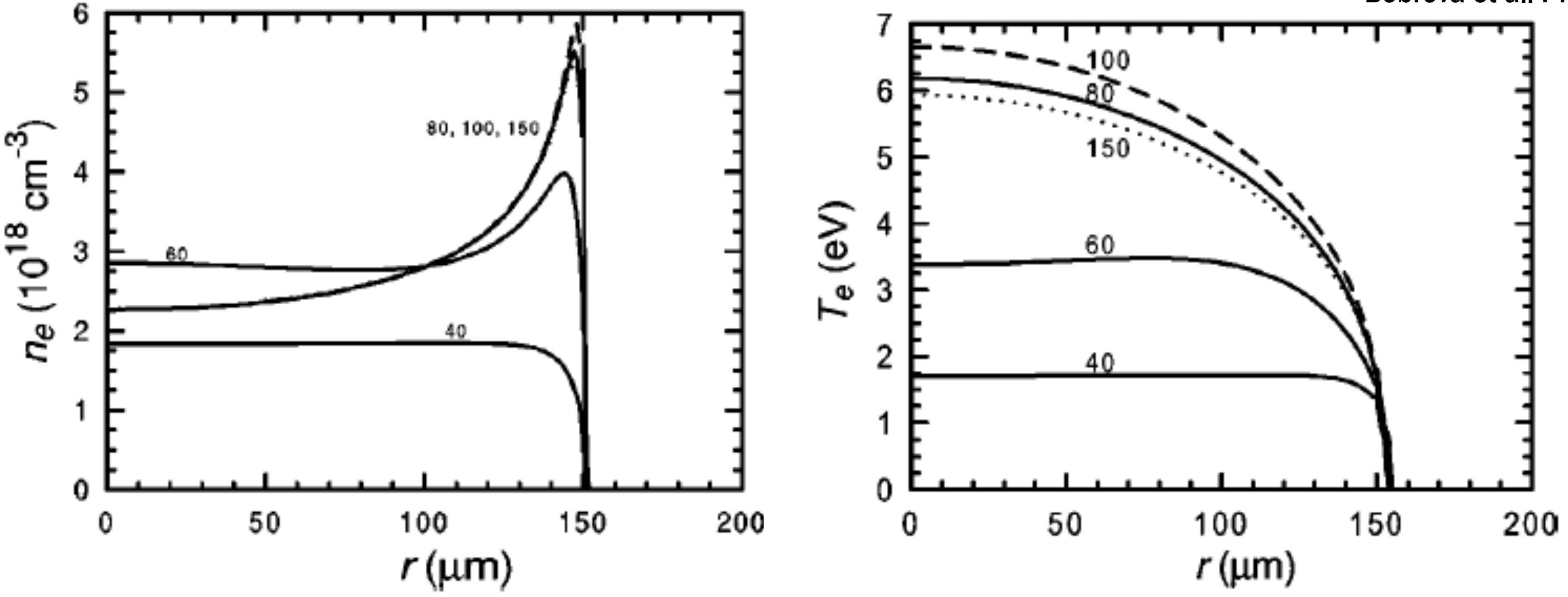
To minimize wakefield effect:

- **Let e-beam divergence more**
- **Operate at highest current (shortest cap)**
  → reduce relative effect
- **Emittance degradation ~1/γ**
- **Away from resonant density (weak effect, low density most practical)**
- **Wakefields play role for “>20pC sub-GeV <100μm” beams**

Possible limitation: emittance degradation from non-uniform current

Radial current distribution dominated by temperature
Towards peak of current pulse: more current on-axis!

Bobrova et al. PRE 2002



classical conductivity
(resistivity: η=1/σ)

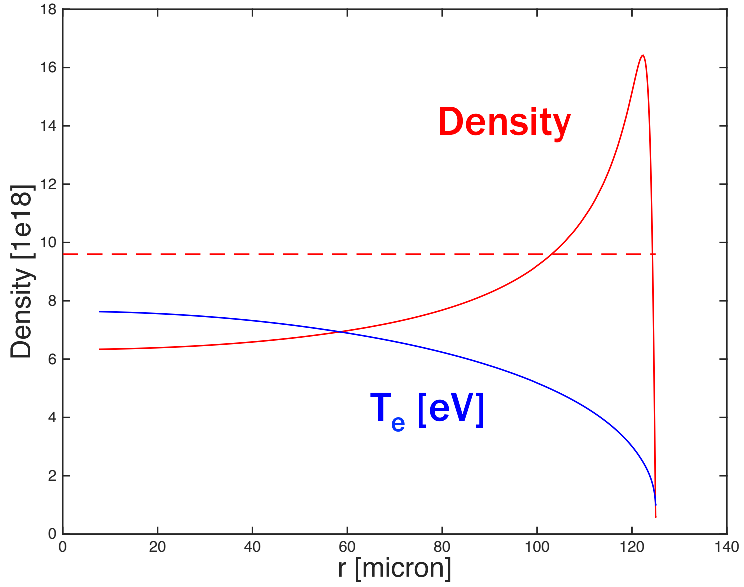
$$\boxed{\eta = \frac{1}{32\pi\varepsilon_0^2}\frac{e^2 m_e^{1/2}}{(k_B T)^{3/2}}\ln\Lambda}$$

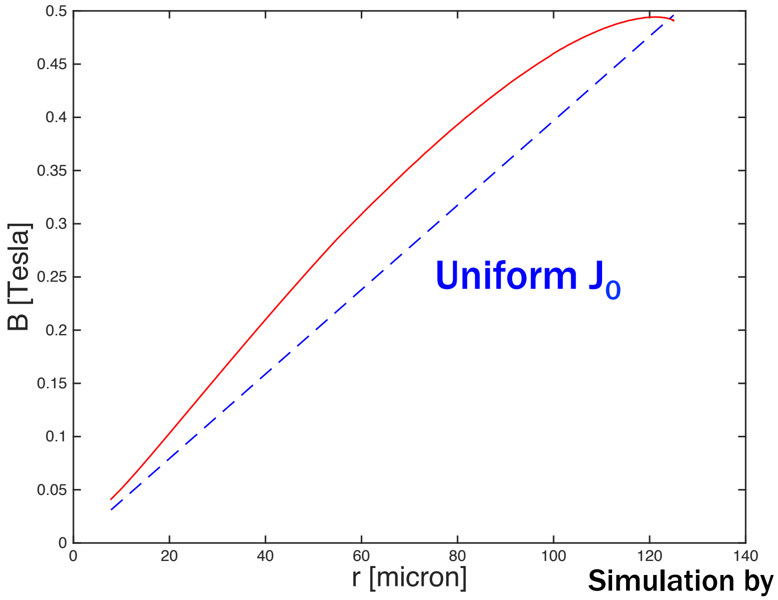
$$\Lambda = n_e\lambda_D^3 = n_e \times \left(\frac{\varepsilon_0 k_B T_e}{n_e e^2}\right)^{3/2}$$

only weak dependence of n_e in $\ln\Lambda$! → $\mathbf{J}$ independent of number of charge carriers

From Helsinki University online lecture

Possible limitation: emittance degradation from non-uniform current

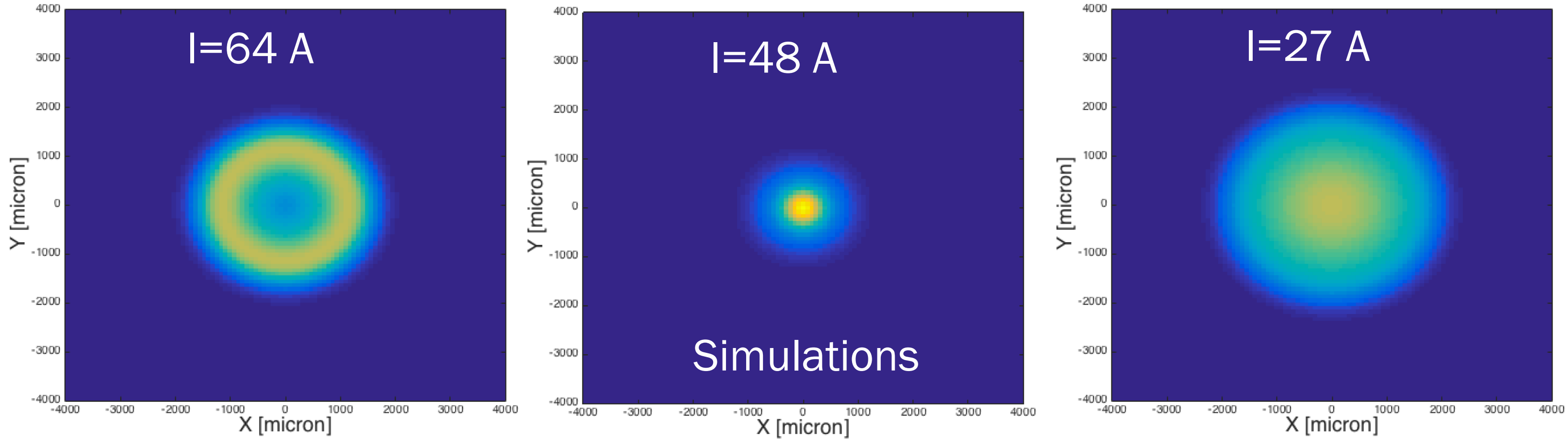


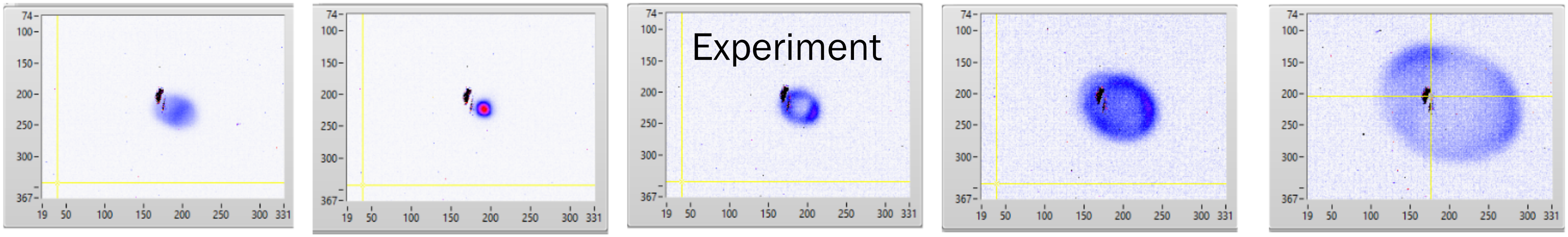


Simulation by Bobrova

- Hotter plasma on-axis
- More current on-axis
- Stronger gradient on-axis (shorter focal length)
- Curved gradient → emittance degradation

On-axis current concentration reveals itself as donut mode when beam is over-focused





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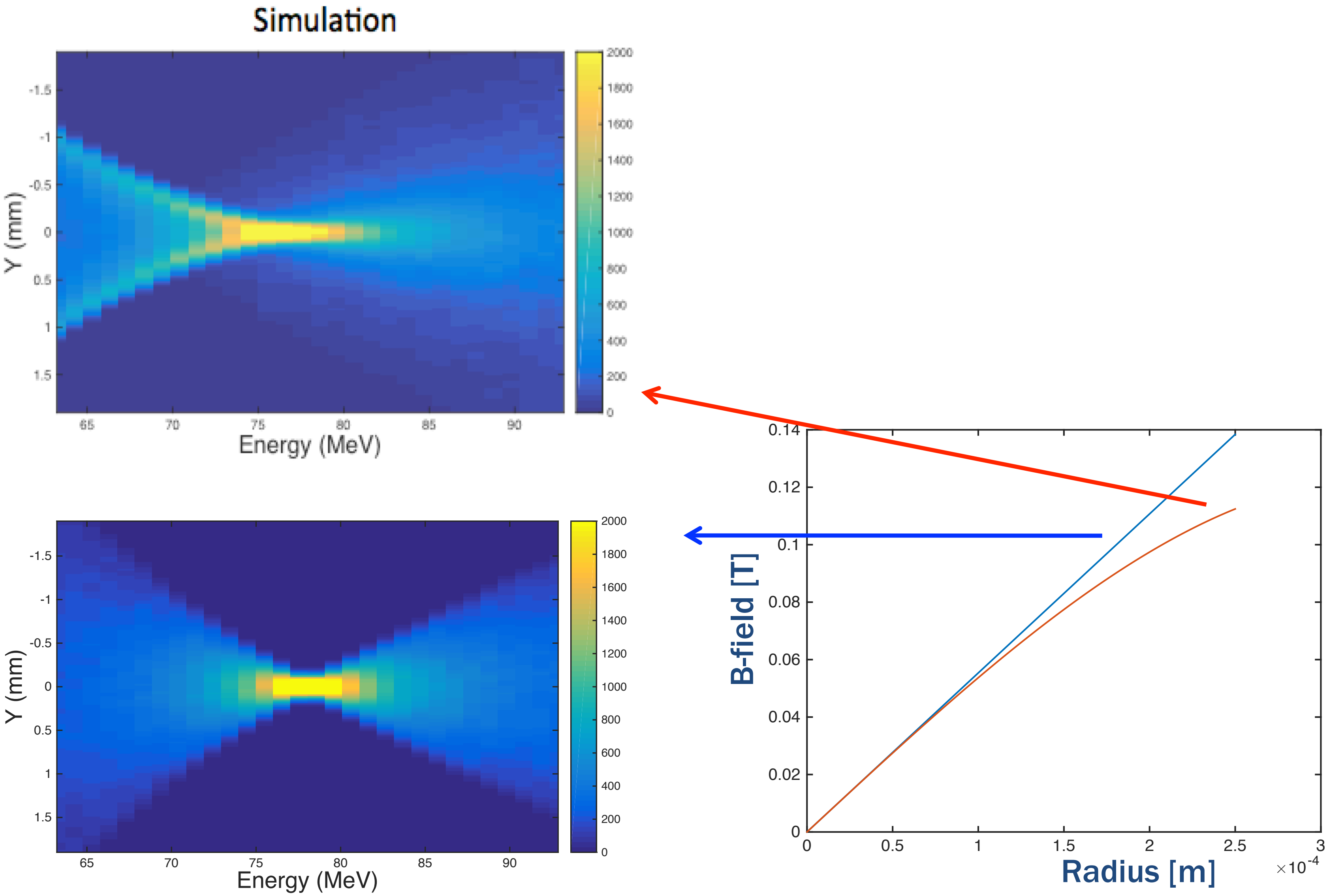
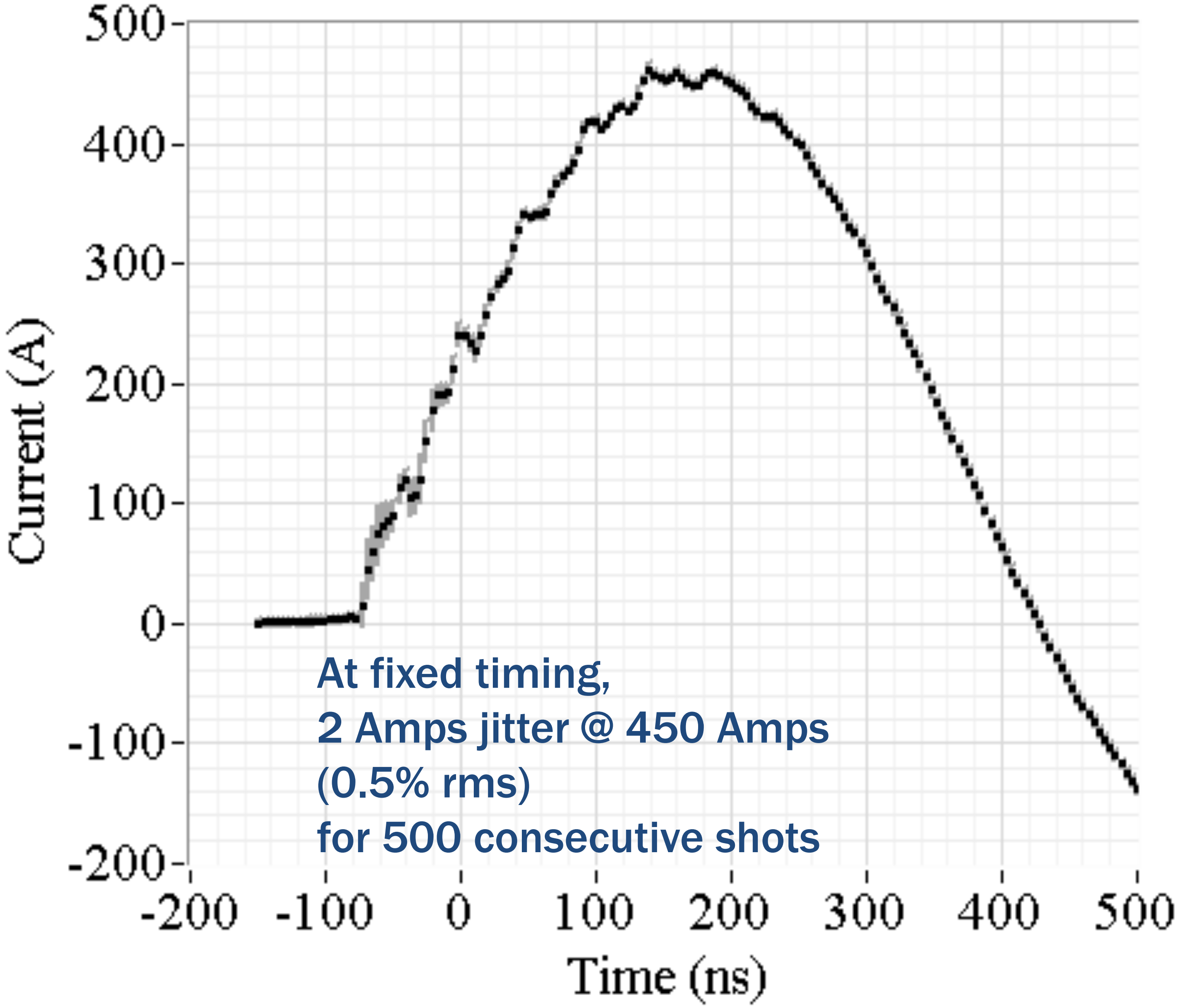
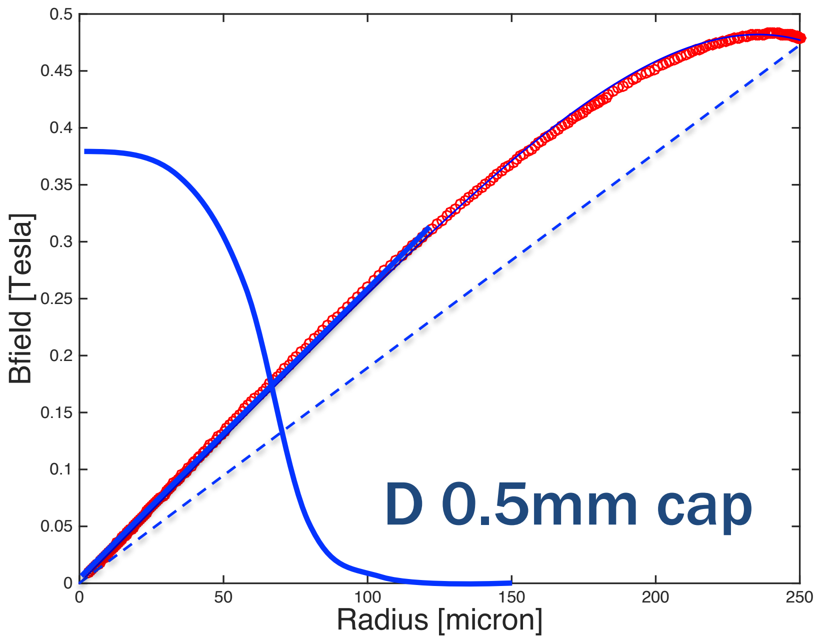


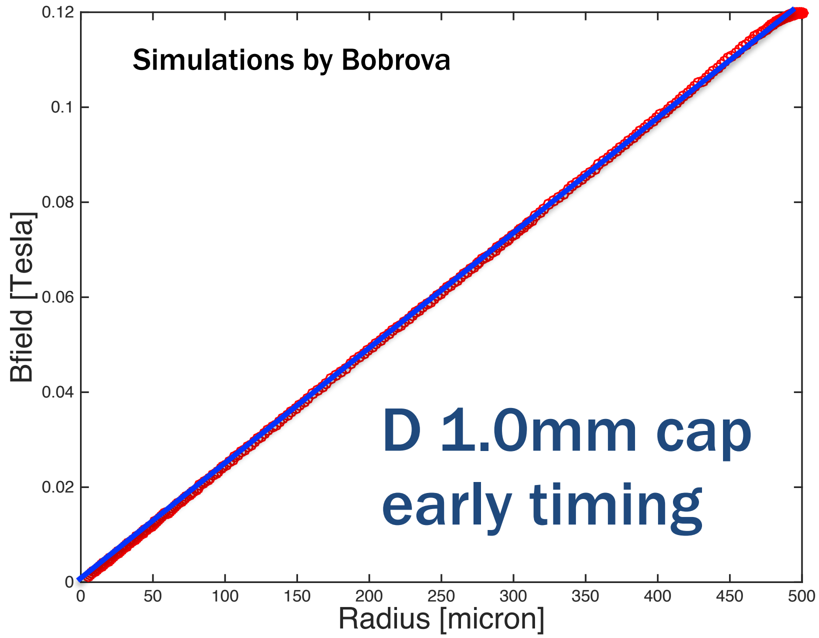
Stability: 0.5% rms jitter in current at e-beam timing

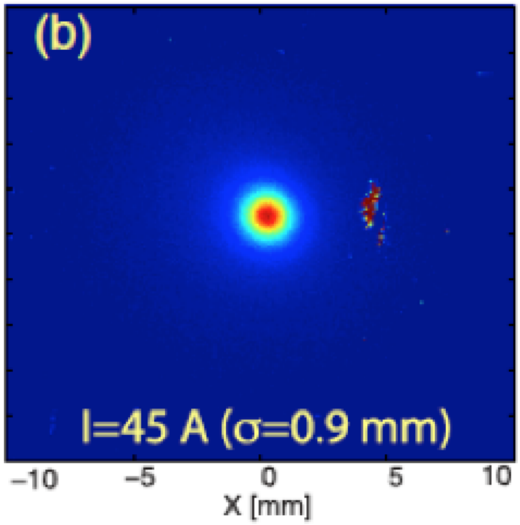


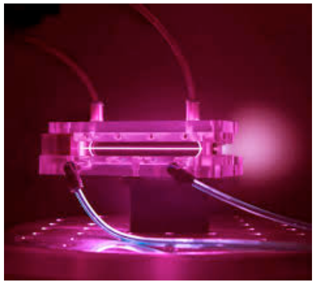
At fixed timing,
2 Amps jitter @ 450 Amps
(0.5% rms)
for 500 consecutive shots

Conclusion





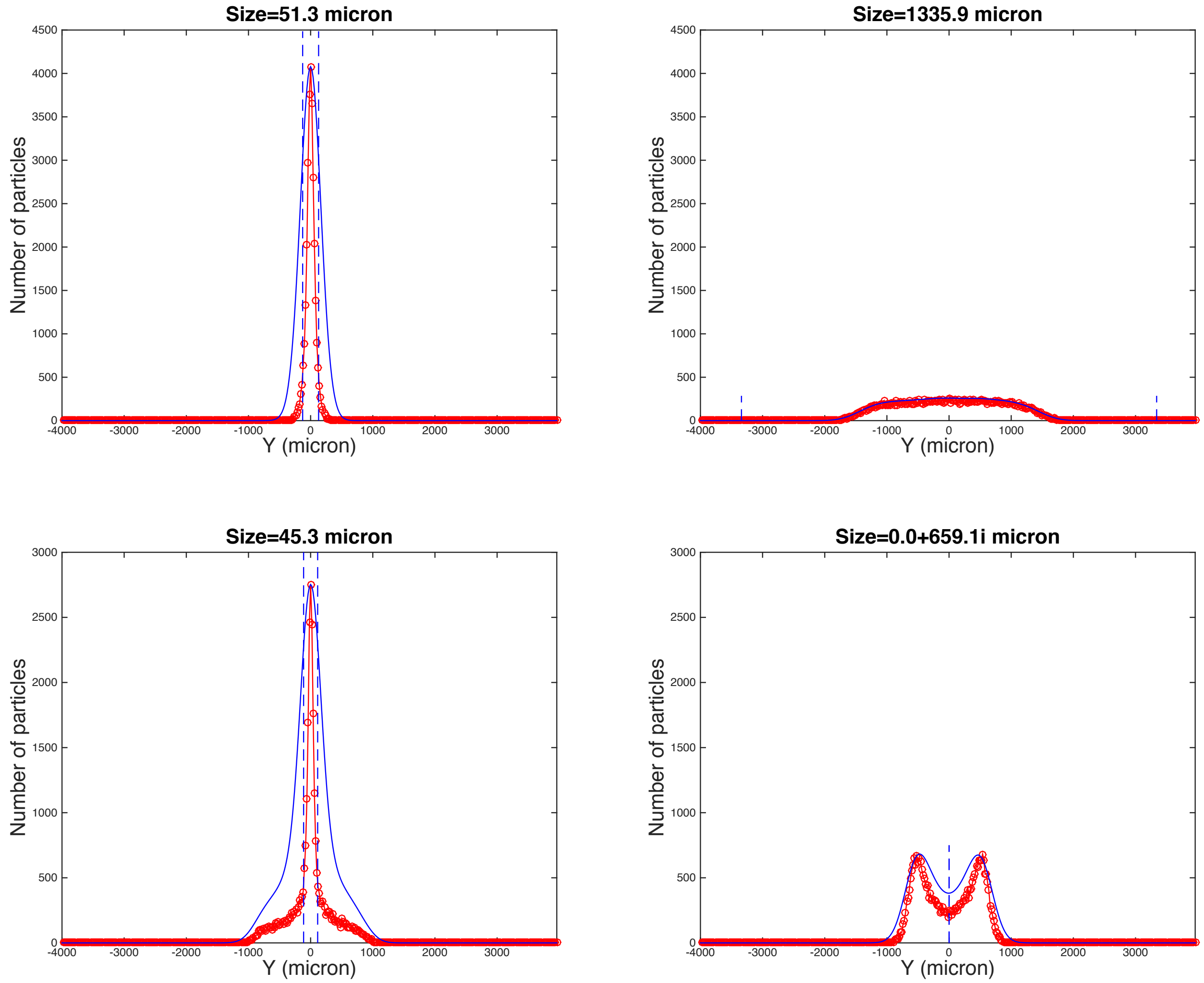




Active Plasma Lens:

- Strong gradients observed
- Ideal for compact & GeV applications
- Understand limits wakefields and non-uniform current
- More uniform for optimized timing, pressure, diameter, beam size
- Nov 2016: DESY collaboration at Mainz accelerator

End



70 Amps, uniform

48 Amps, actual

60 MeV

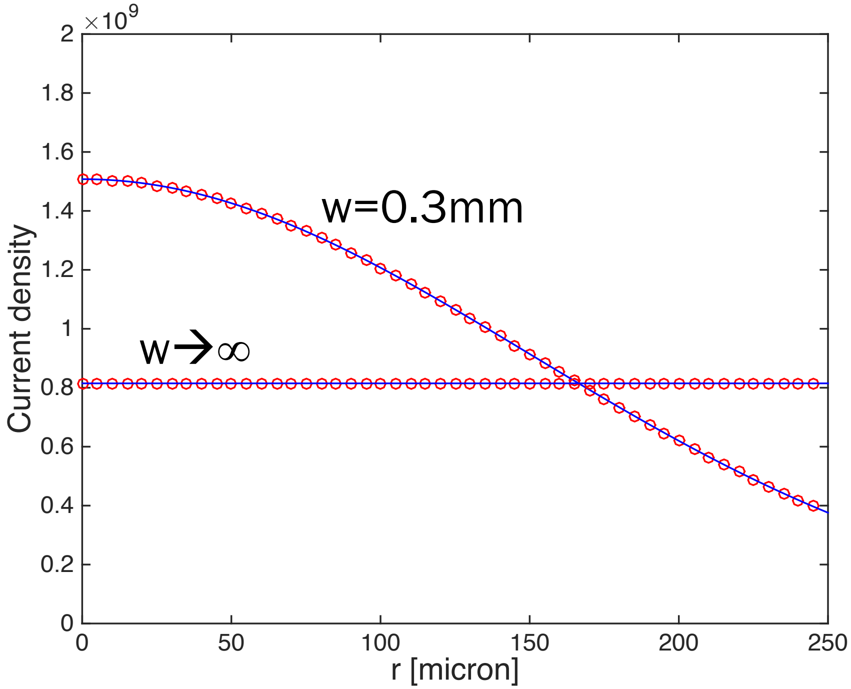
40 MeV

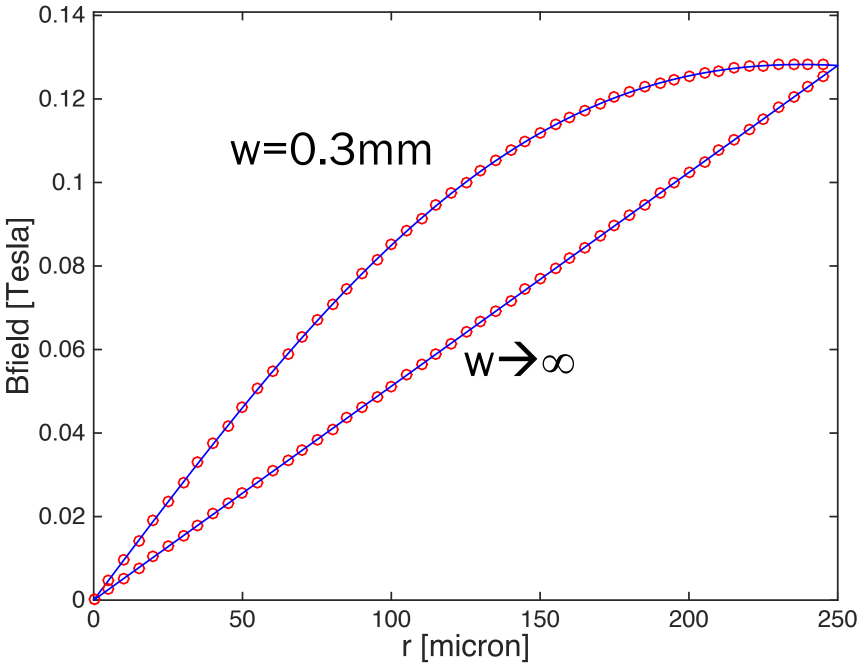
Effect of on-axis current (stronger near-axis B-field gradient)

$$\boxed{J(r) = J_0 \exp\left(-2r^2/w^2\right)}$$

$$\int_0^R 2\pi J(r) r dr = I_0 \Rightarrow \boxed{J_0 = \frac{2I_0}{\pi w^2\left[1-\exp\left(-2R^2/w^2\right)\right]}}$$

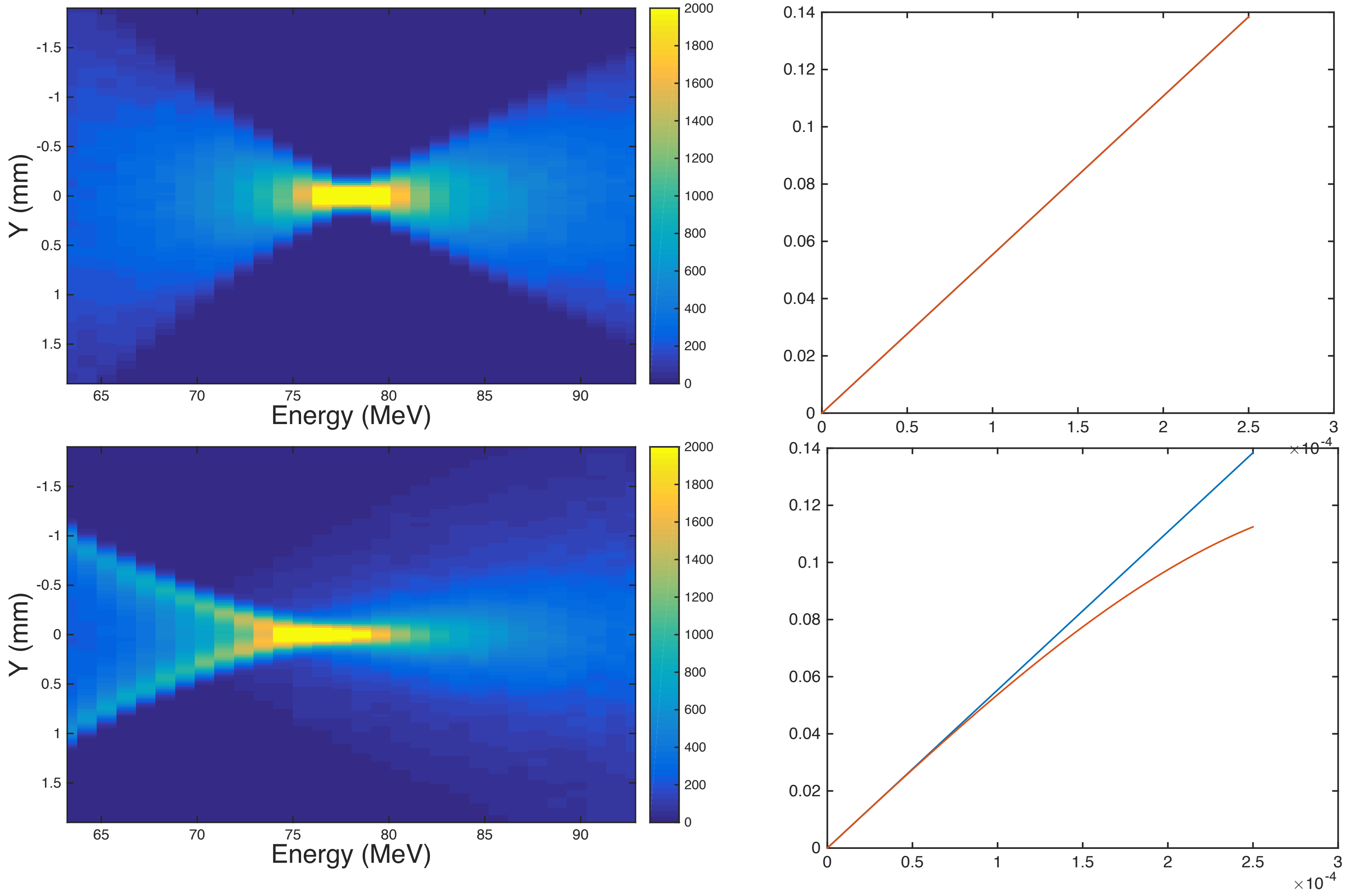
$$2\pi r B(r) = \mu_0 \int_0^r 2\pi J(r') r' dr' \Rightarrow \boxed{B(r) = \frac{\mu_0 J_0 w^2}{4r}\left[1-\exp\left(-2r^2/w^2\right)\right]}$$





Example: R=1mm, I_0=160 Amps

Title



Y (mm)
-1.5
-1
-0.5
0
0.5
1
1.5
65
70
75
80
85
90
Energy (MeV)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.5
1
1.5
2
2.5
3
×10⁻⁴
Y (mm)
Energy (MeV)
×10⁻⁴