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Mapping plasma lenses

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Motivation

> Plasma accelerators create sub-μm emittance beams

> Intrinsic energy spread σ_E of percent level

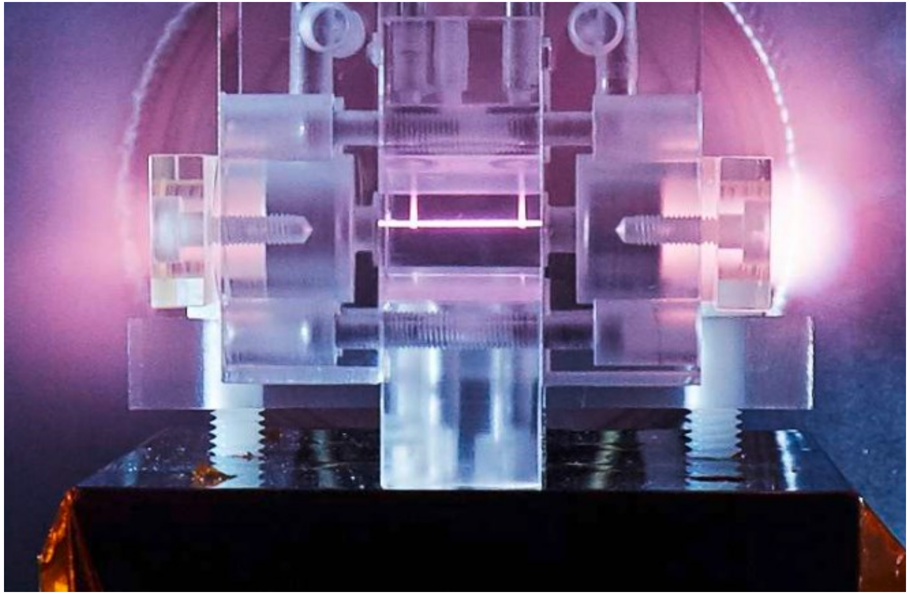
> Divergence $\sigma_{x'}$ typically mrad

> Emittance growth during drift → $\epsilon_n \sim \sigma_E \cdot {\sigma_{x'}}^2 \cdot s$

> Compact and strong capturing needed

> APLs provide short focal length

> Radially symmetric focusing



First experiments: Forsyth et al., *IEEE Trans. on Nucl. Sc.* 12.3 (1965): 872-876.

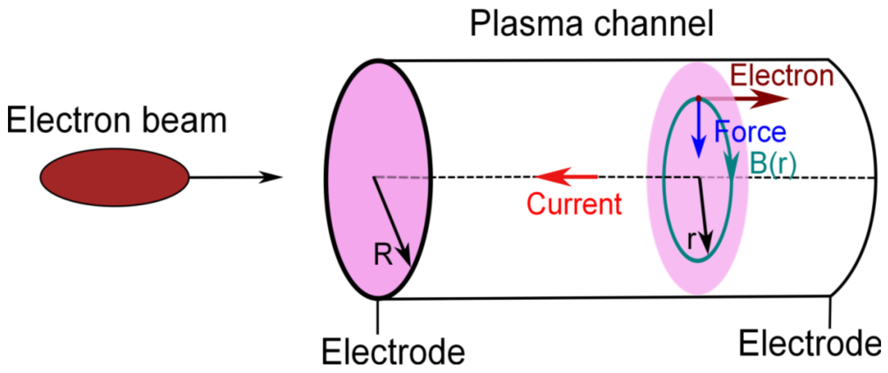
Target concept: Butleret al., *Phys. Rev. Let.* 89.18 (2002): 185003.

First capillary lens: Van Tilborg, et al., *Phys. Rev. Let.* 115.18 (2015): 184802.

Used in staging: Steinke et al., *Nature* 530.7589 (2016): 190.

Active plasma lens principle

- Beam passes high current region
- Radially symmetric magnetic field
- Gradients of ~3kT/m achieved[1]
- High voltage discharge ignites plasma
- Gas volume required
- Wakefields should be avoided



$$B_\varphi(r) = \frac{\mu_0 I_0}{2\pi} \cdot \frac{r}{R^2} \longrightarrow \frac{\partial B_\varphi}{\partial r} = 0.2\ \frac{\mathrm{I[A]}}{\mathrm{R[mm]^2}}\ \frac{\mathrm{T}}{\mathrm{m}}$$

[1]Van Tilborg, et al., *Phys. Rev. Let.* 115.18 (2015): 184802.

Probing the quality of plasma lenses

- Measure shot-to-shot stability
  - Assess gradient stability
  - Assess discharge stability
  - Stable electron beam needed
- Probe for inhomogeneity
  - Gradient depends on current distribution
  - Inhomogeneity leads to nonlinear focusing
  - Emittance degradation in the plasma lens

$$B_\varphi(r) = \frac{\mu_0}{2}(a_1 + a_4 \cdot r^3)r$$

Magnetohydrodynamics simulation

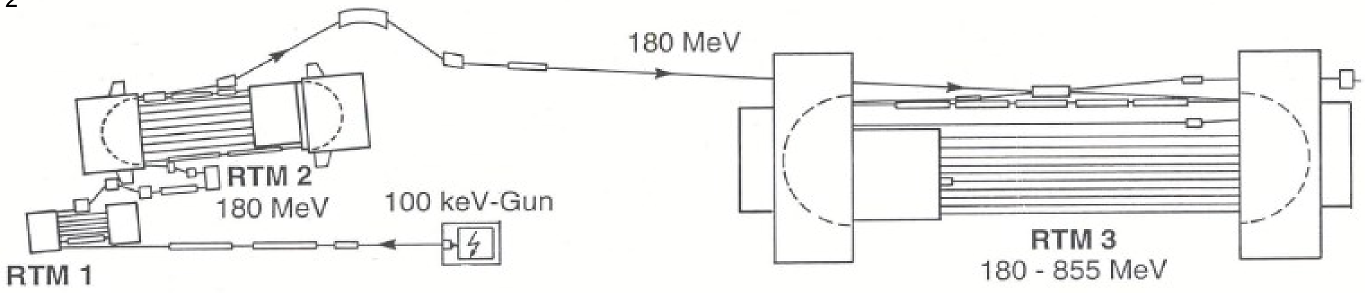
To be published

Courtesy of J. van Tilborg and S. Bulanov

The Mainz Microtron

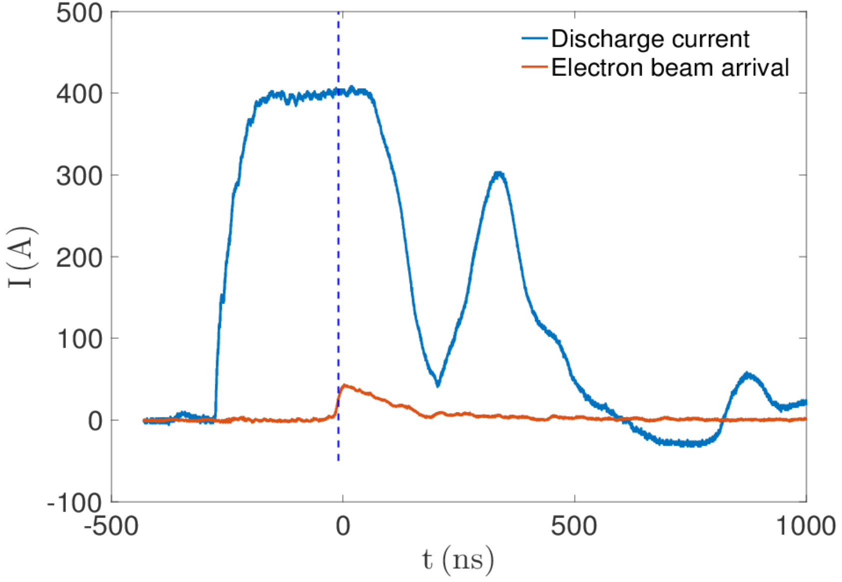
> Racetrack Microtron
  - E = 855 MeV with $\sigma_E = 4 \cdot 10^{-5}$
  - Special operation mode with 10 ns bunch train
  - Current 100 µA – no wakefields
  - Norm. Emittance 1.5 mm mrad
  - Transverse jitter ~20% of beam size

> Beamline allowing for H_2 flow



Discharge characteristics

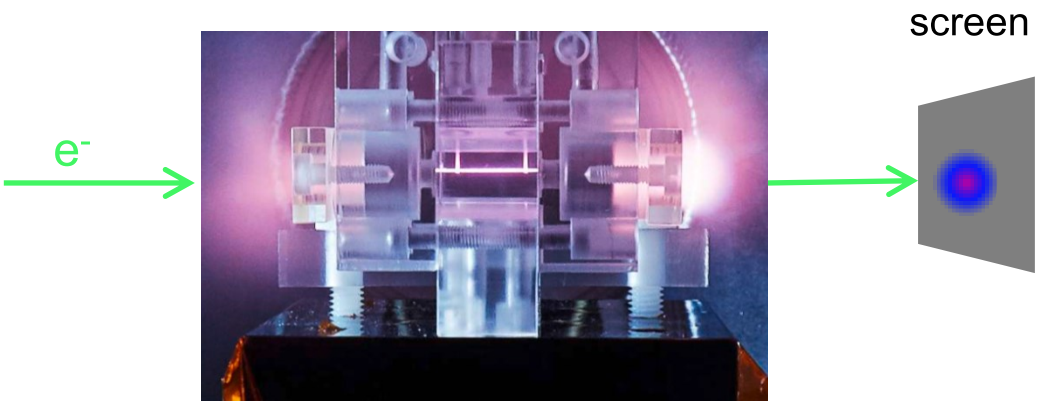
Current profile @20kV



- Amplitude stability of 1.5 A rms
- Plateau region of ~250 ns
- Current plateau tunable up to 1.5 kA
- Stable in timing: ~1 ns rms breakdown jitter
- Electron beam arrival monitored
- Single shot analysis possible

Lens position scan – gradient via dipole kick

- Lens position varied transversally
- Dipole kick introduced
- Beam position on screen changes
- Kick yields field – kicks yield gradient
- Position stability → gradient stability



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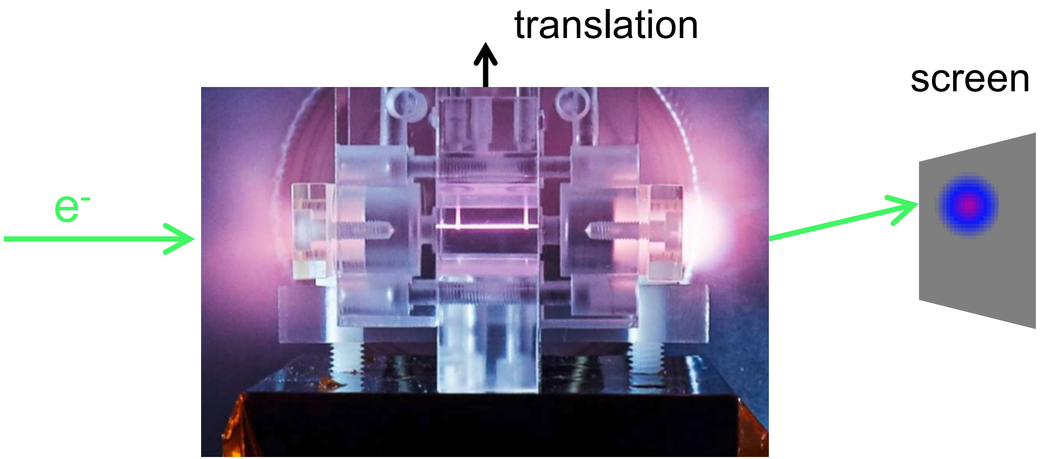


Gradient measurement results

> Scans using 7 mm long APL

> Very low transverse jitter

> Stable discharge and APL

- 100 shots per scan point
- No faulty discharges

> Higher gradients than expected

- 40% - 60% bigger than uniform density

To be published

Current [A]	Uniform [T/m]	Linear [T/m]	Polynomial [T/m]
188	150	246 ± 10	265 ± 35
368	294	437 ± 8	475 ± 30
740	592	823 ± 8	886 ± 38

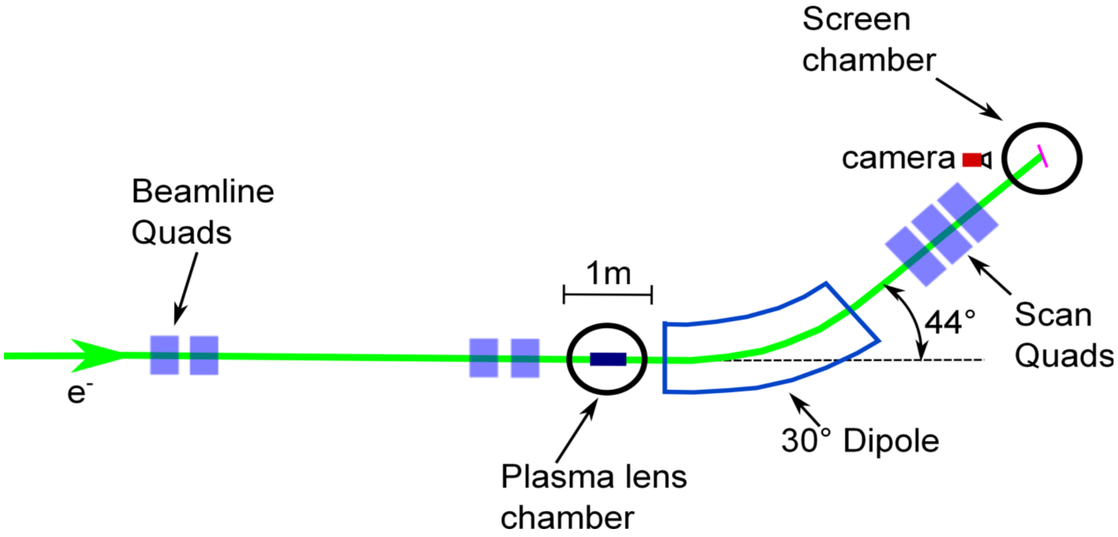
$$I_0 = 2\,\pi \int_0^R J(r) \cdot r dr \longrightarrow B_\varphi(R) = \frac{\mu_0 I_0}{2\pi \mathrm{R}}$$

Emittance measurement - MaMi-B beamline

> Two chambers
  - First for plasma lens and screen
  - Second for screen

> Large dipole
  - Introduces dispersion
  - Strong edge focusing

> Quadrupole triplet for scan
  - Two independent power supplies
  - Low maximum gradient quads



Emittance scan results

- Scans using 7 mm long APL
- rms beam size calculated for 100 shots
- Resolution of ~0.1 mm mrad
- MaMi-B emittance measured – 1.5 mm mrad
- Emittance increases in APL

Current [A]	Normalized emittance [mm mrad]	
	Measured	Simulated
188	2.6 ± 0.2	3.1 ± 1.3
368	3.6 ± 0.2	4.7 ± 1.1
740	9.5 ± 0.1	7.5 ± 1.1

To be published

Particle tracking simulations

- Results from offset scans fed into simulation
- MaMi-like beam sent through field
- Emittance for different currents and beam sizes
- Core emittance can be preserved
- Small beam size favorable

To be published

Particle tracking simulations

- Results from offset scans fed into simulation
- Low emittance beam sent through field
- Emittance for different currents and beam sizes
- Core emittance can be preserved in small emittance beams

To be published

FACET II considerations

- High current beams may drive wake
- Transversally large beam in APL needed
- Large beam needs large APL for emittane preservation
- Drive beam final focus
- Witness beam capturing

Parameters	Driver	Witness
I_{peak} [kA]	200	15
$\sigma_{x,y}$ [µm]	200	150
n_b [cm^{-3}]	10^{16}	10^{15}
R [mm]	2	2
I_0 [kA]	16	16
g [T/m]	800	800
n_0 [cm^{-3}]	$5 \cdot 10^{16}$	$5 \cdot 10^{16}$
K_{APL}/K_{wake}	10^5	10^6

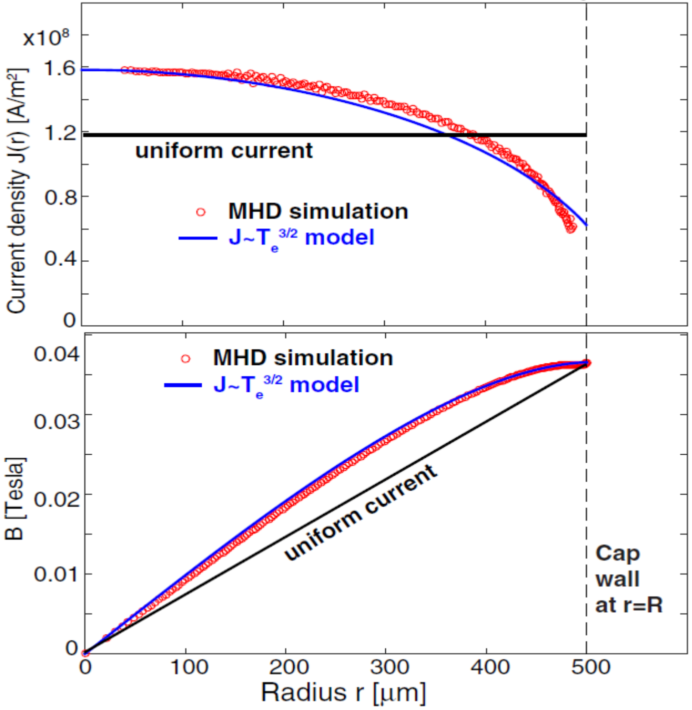
Summary

- First experiment with a plasma lens in a conventional electron accelerator
- Direct magnetic field measurement of a capillary plasma lens – 823 T/m over 350 μm
- Stability of discharge and APL assessed in gradient scans – very stable
- Study of emittance preservation shows degradation – explained by simulations
- Emittance preservation possible for relatively small beams
- Might be a technique worth considering for FACET II program

Thank you for your attention,
please ask away!

APLs – a hot topic

- Recent publication shows heating effects
- Heating causes pinching of current
- Higher focusing field for core part of APL



J. vanTilborg et al., PRAB 20, 032803 (2017)