EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA
Preparatory Phase

Stable beam-driven wakefield in structured plasmas

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Contents

- High transformer ratio acceleration:
  - Sequences of short driver bunches
  - Triangular drivers
- Structured plasma channels (rather crazy)
- External structures (SWFA or DWA) and plasma guiding (crazy)
- Efficient THz coupling (low hanging fruit)

Funded by the European Union

Transformer ratio

- Let us assume, we have a driver with current profile
$$j(\xi) = j_0 f(\xi, \mu, \sigma), \qquad \xi = \omega_p(x - ct)$$
where μ is the bunch centre position, σ is the bunch length

- We define the (unloaded) transformer ratio as

$$R_W = \frac{\max(E_{acc}(\xi))}{\max(E_W(\xi))}$$

where $E_W(\xi) = E(\xi) f(\xi, \mu, \sigma)$ is a weighted field acting on the driver

Transformer ratio

- The wake field is $E(\xi) = \int_{-\infty}^{\xi} j(\xi')\cos(\xi - \xi')\, d\xi'$ (driven oscillator)

- For a short driver, the transformer ratio is limited

$$R_W \leq 2$$

R. D. Ruth, A. W. Chao, P. L. Morton, and P. B. Wilson, Part. Accel. **17**, 171 (1985)

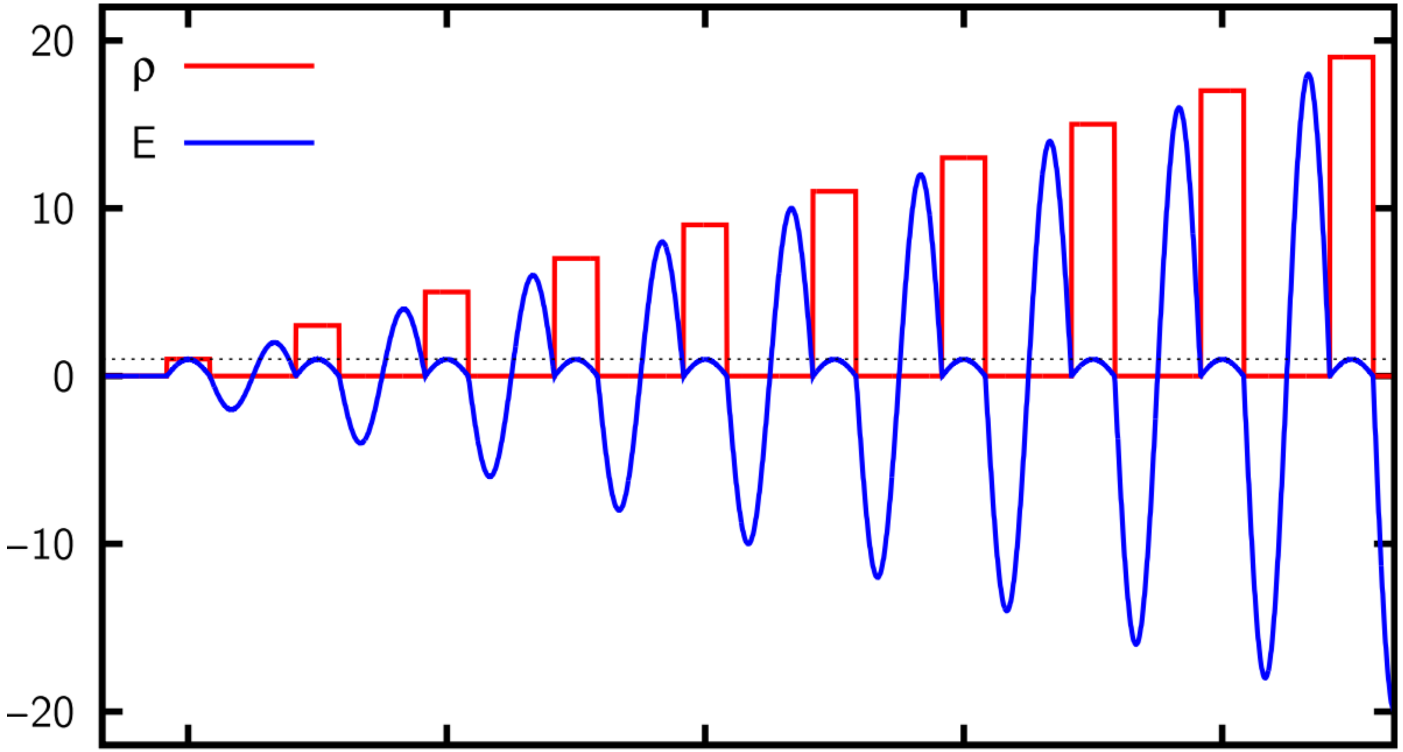
- This implies **many** acceleration stages, when charged particle drivers are used

  Or use highly energetic hadron drivers to accelerate leptons (see **AWAKE**)

Transformer ratio square bunches

- Increase the transformer ratio using pulse trains

- Works pretty well for square bunches:



Choosing a sequence of N bunches with

$$j_n = (2n - 1)j_1$$

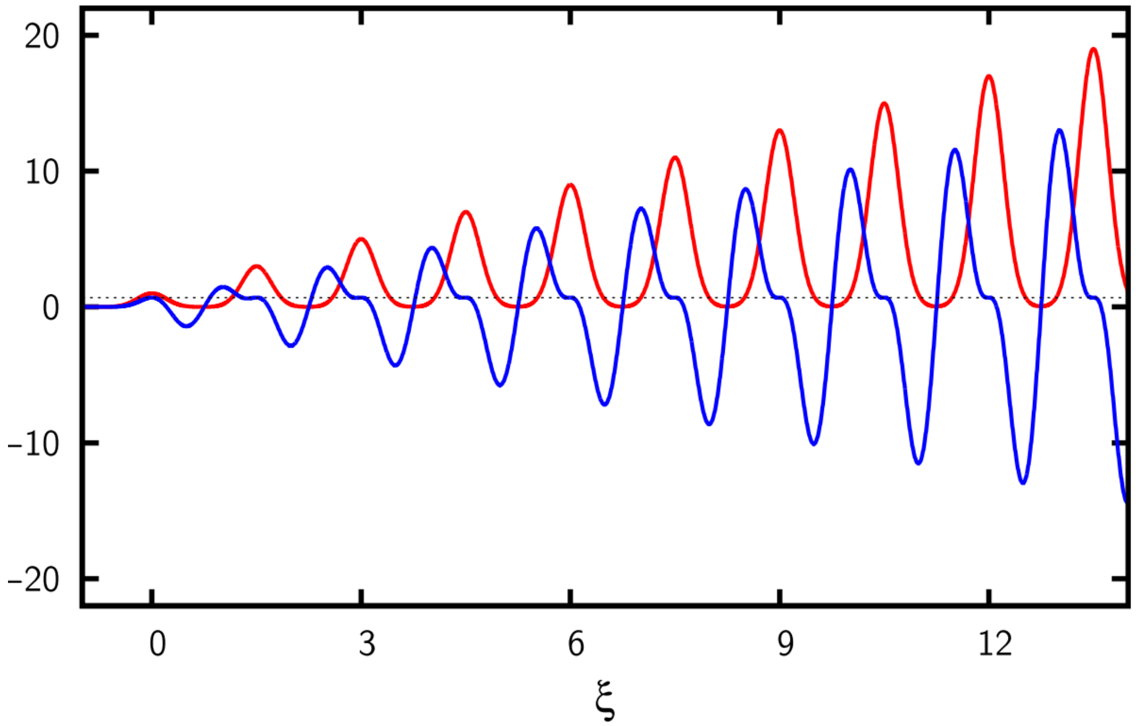
One achieves

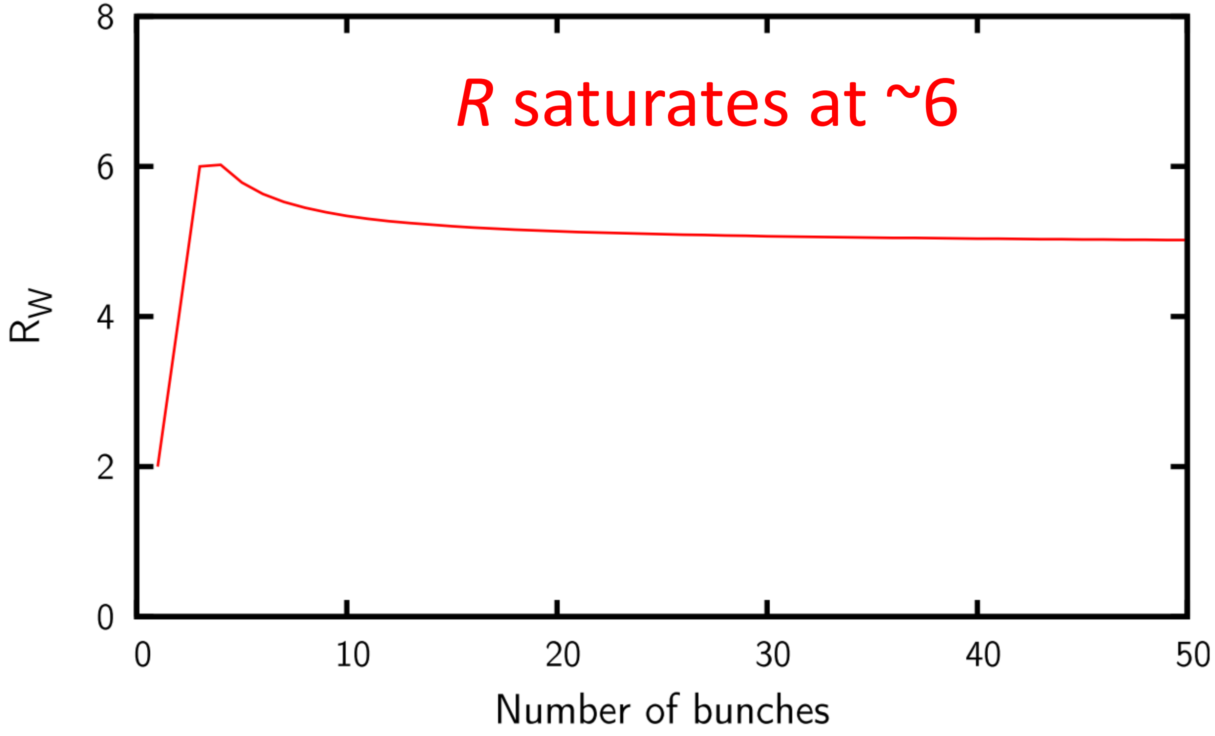
$$R = 2N$$

Farmer et al. Phys Plas **22**, 123113 (2015)

Transformer ratio Gaussian bunches

- Gaussian bunches do not scale. Transformer ratio is limited





Farmer et al. Phys Plas **22**, 123113 (2015)

Long triangular drivers

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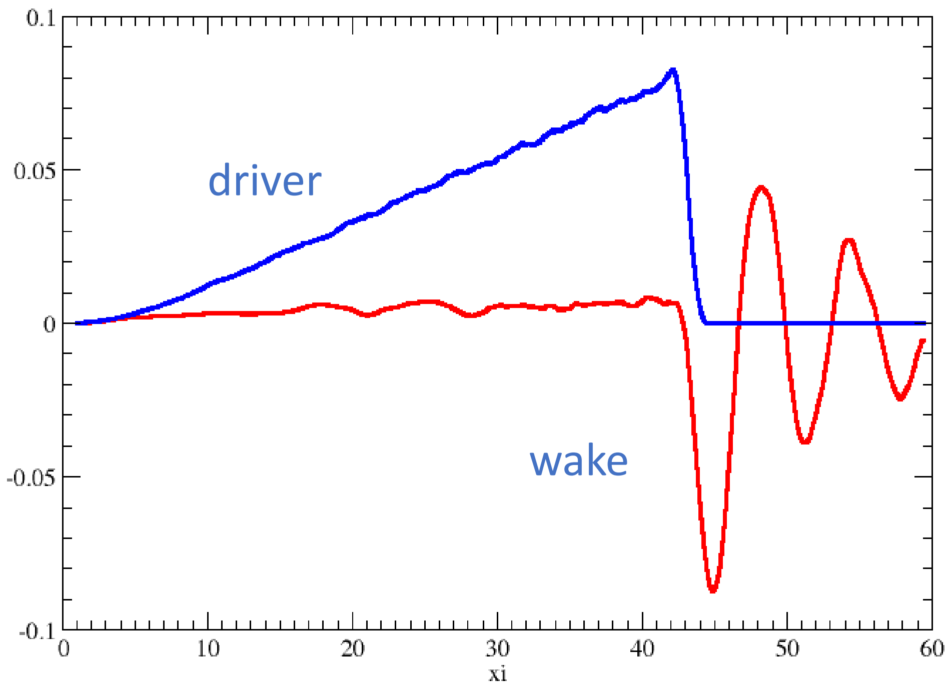
- Wake field: $E(\xi) = \int_0^{\xi} j_0 \frac{\xi'}{\sigma_z} \cos(\xi - \xi')\, d\xi' = j_0 \begin{cases} \frac{1}{\sigma_z}(1 - \cos\xi), & \xi < \sigma_z \\ \sin(\xi - \sigma_z), & \xi > \sigma_z \end{cases}$



Triangular drivers with length $\sigma_z \gg 1/k_p$

can excite wakes
with large transformer ratios

$$R = k_p \sigma_z \gg 1$$

Stability of long triangular drivers?

- Uniform plasma: self-modulation and hosing instabilities
- Hollow plasma channels: asymmetric modes and BBU
- Structures: maximum gradient is limited by external focusing because of Beam Break Up instabilities
- Possible alternative: *structured hollow channels*

Wedge plasma channel

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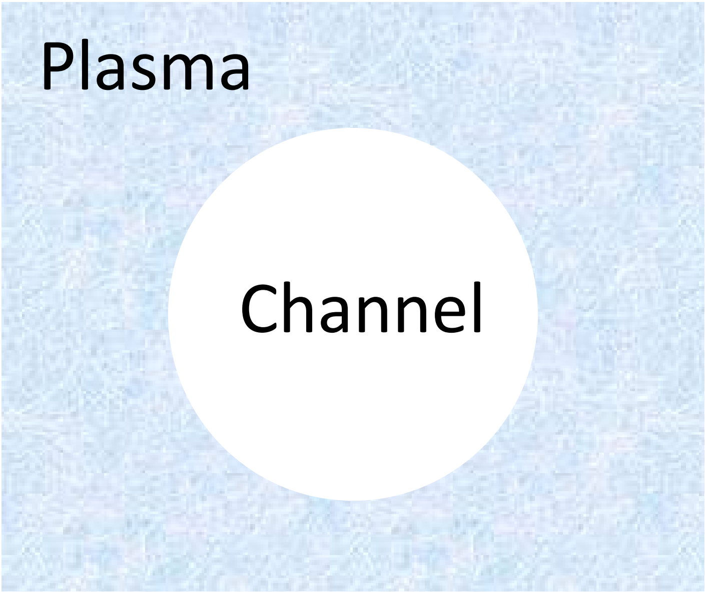
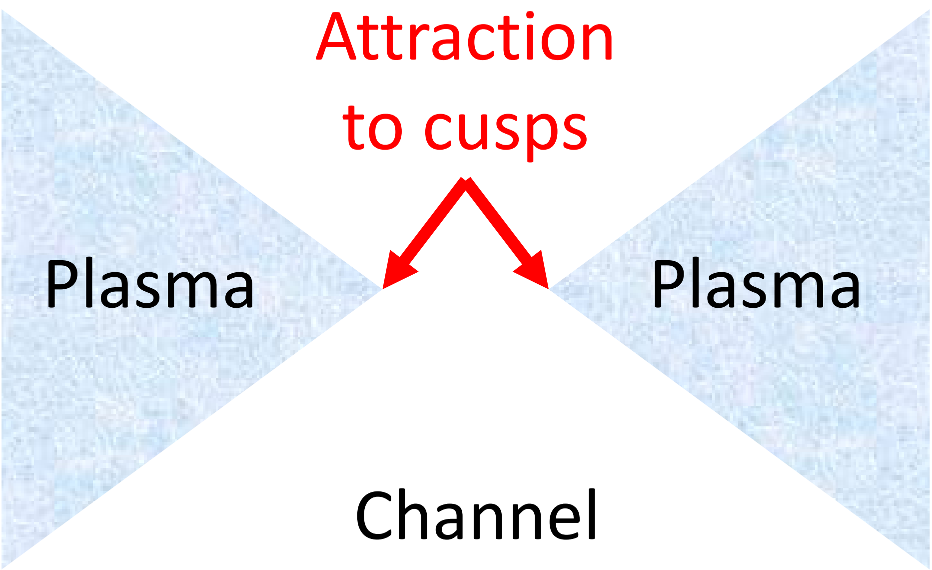
- Round hollow channel



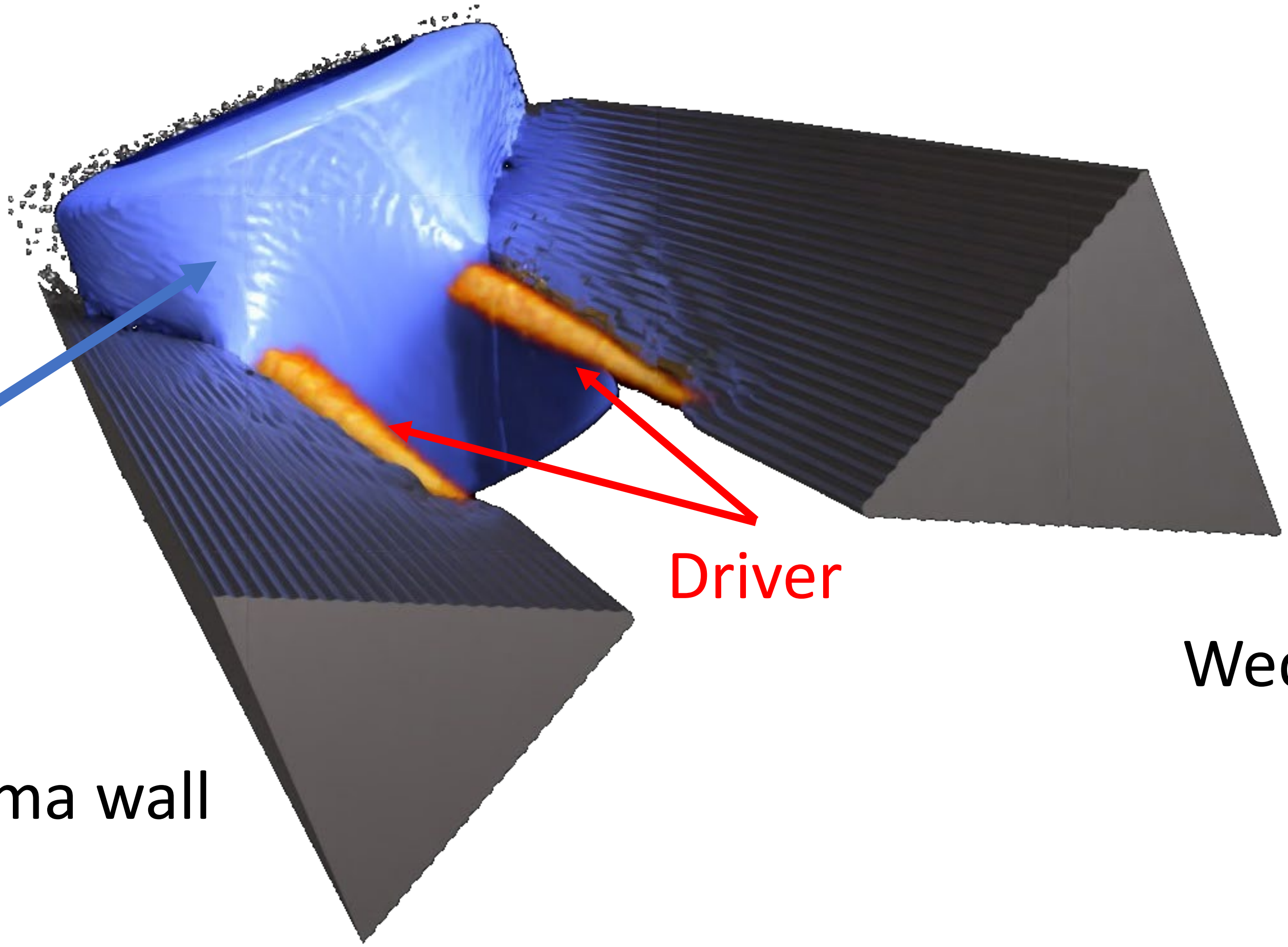
Wedge plasma



arXiv:2403.09427 (2024)

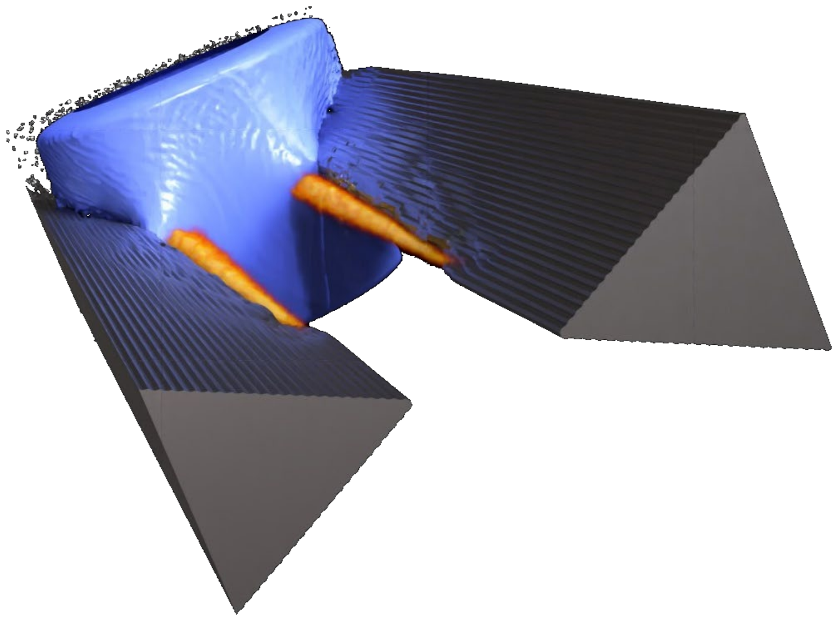
Wedge plasma channel

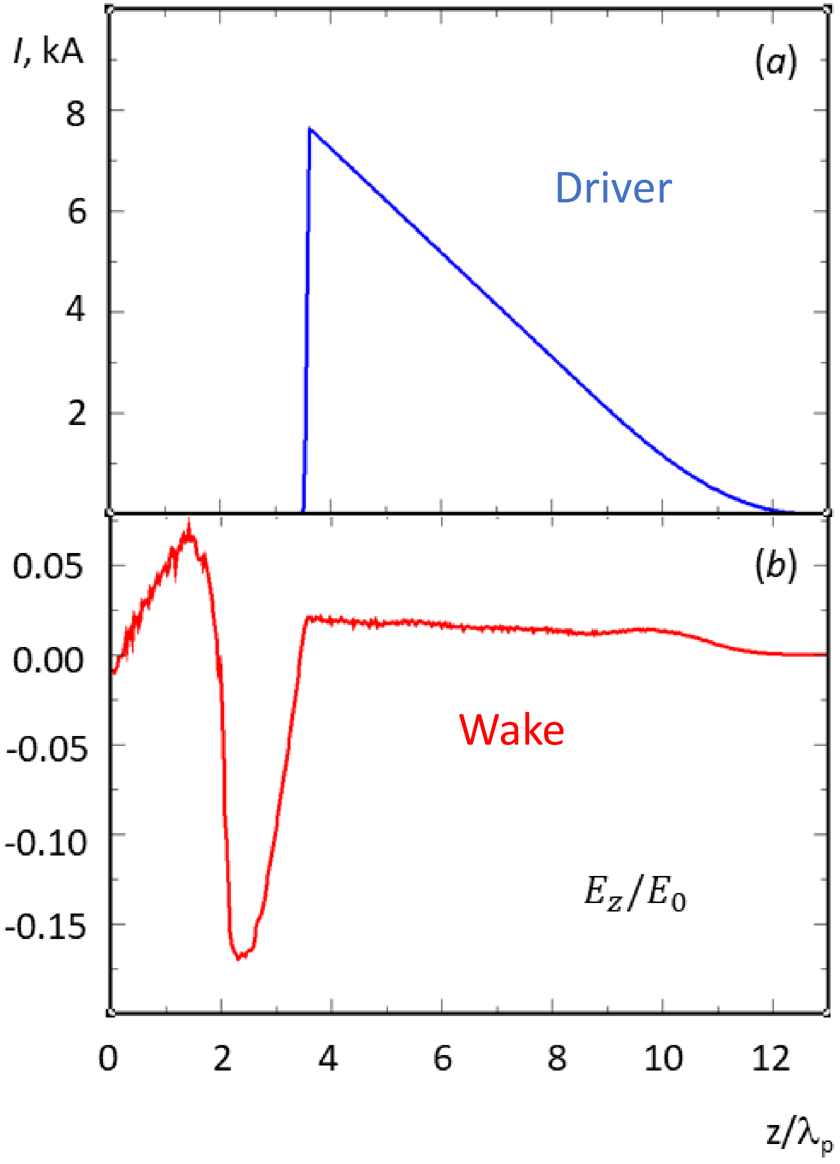
- **3D view**



arXiv:2403.09427 (2024)

Wake in wedge plasma channel





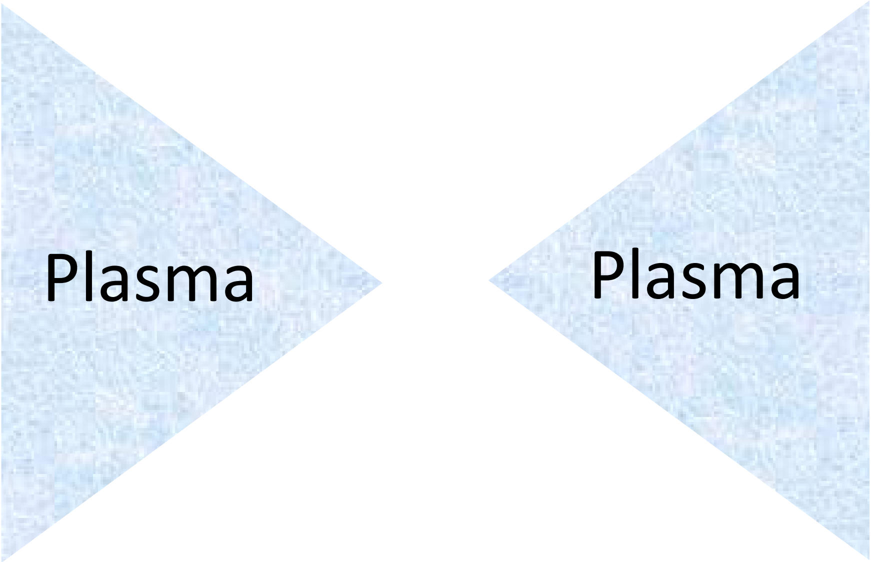
Triangular
10 GeV driver

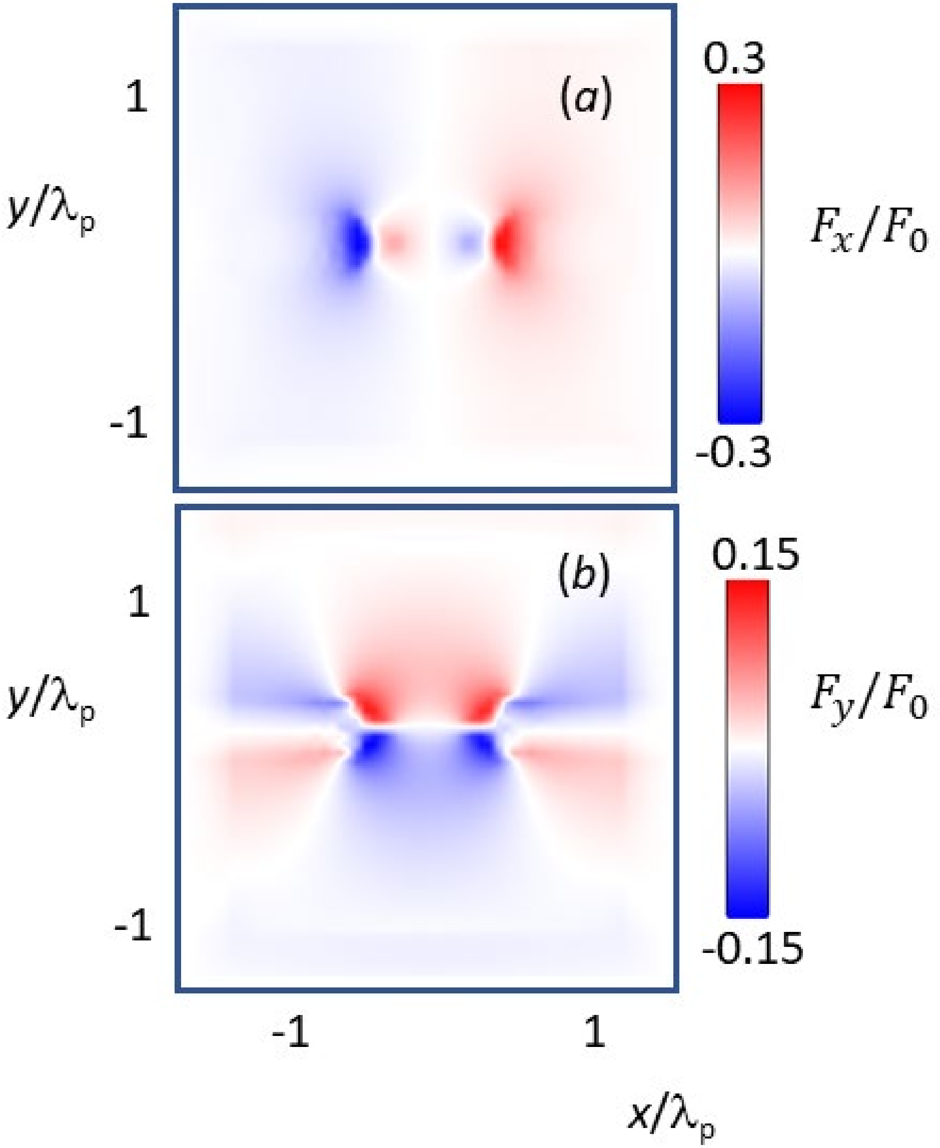
Transformer ratio

$$R \approx 7$$

arXiv:2403.09427 (2024)

Focusing in wedge plasma channel



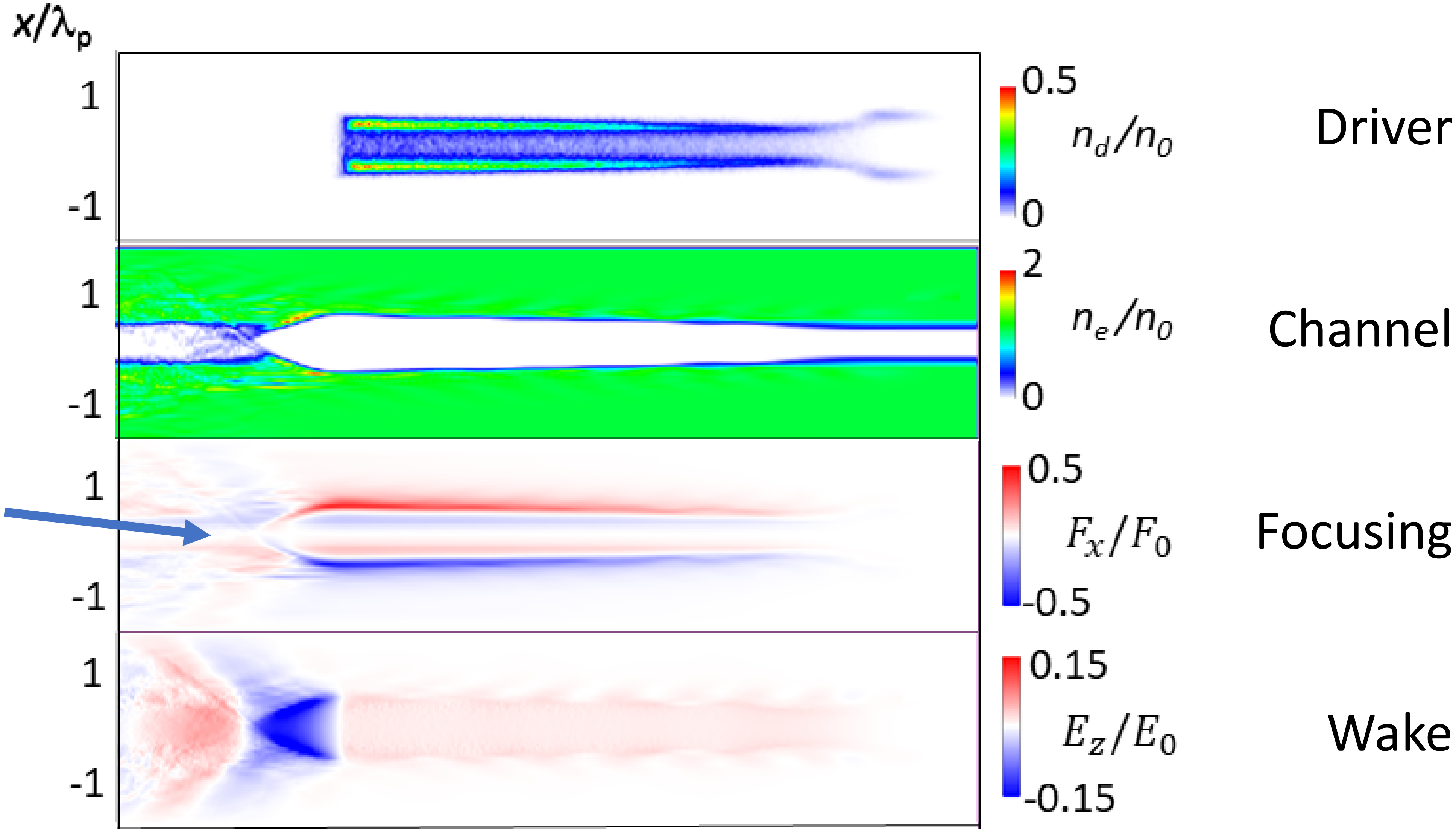


Focusing to the cusps in the both transverse dimensions

arXiv:2403.09427 (2024)

Focusing in wedge plasma channel

Focusing
and acceleration
for positrons

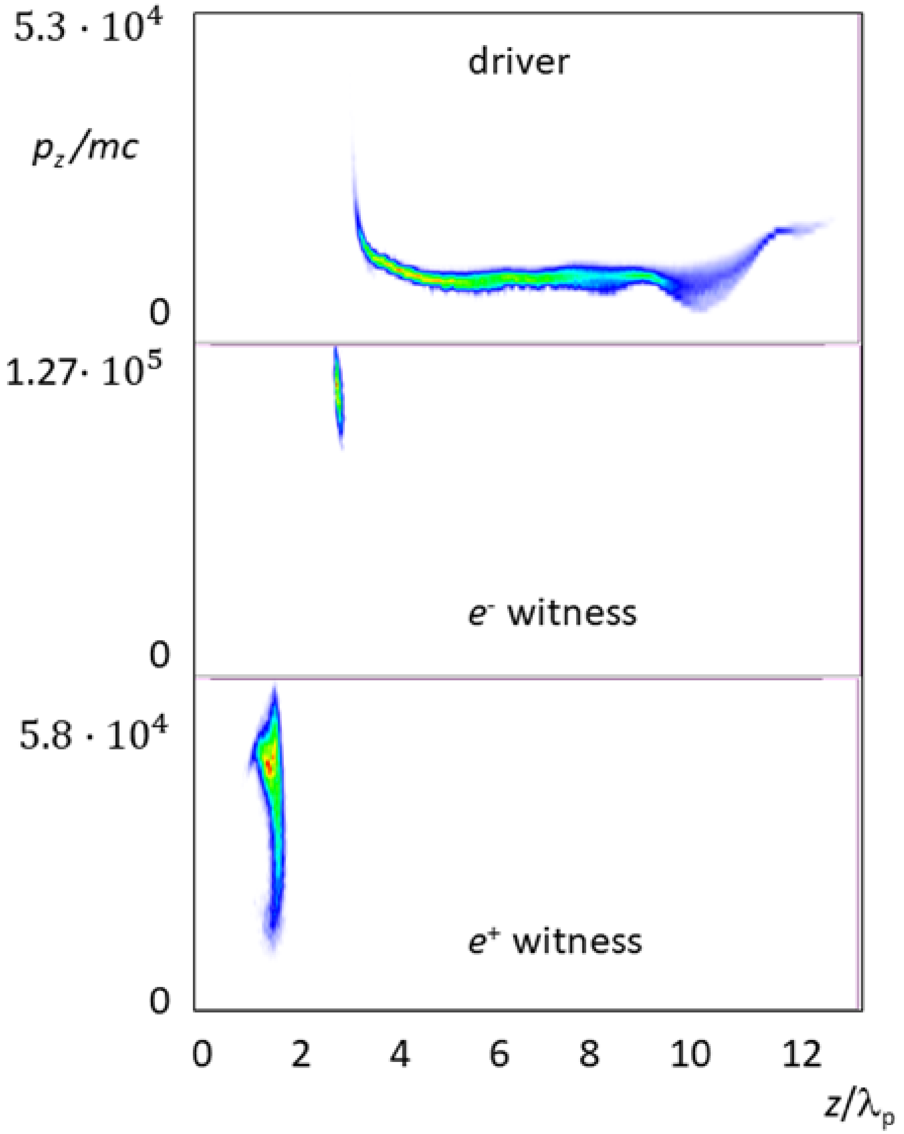


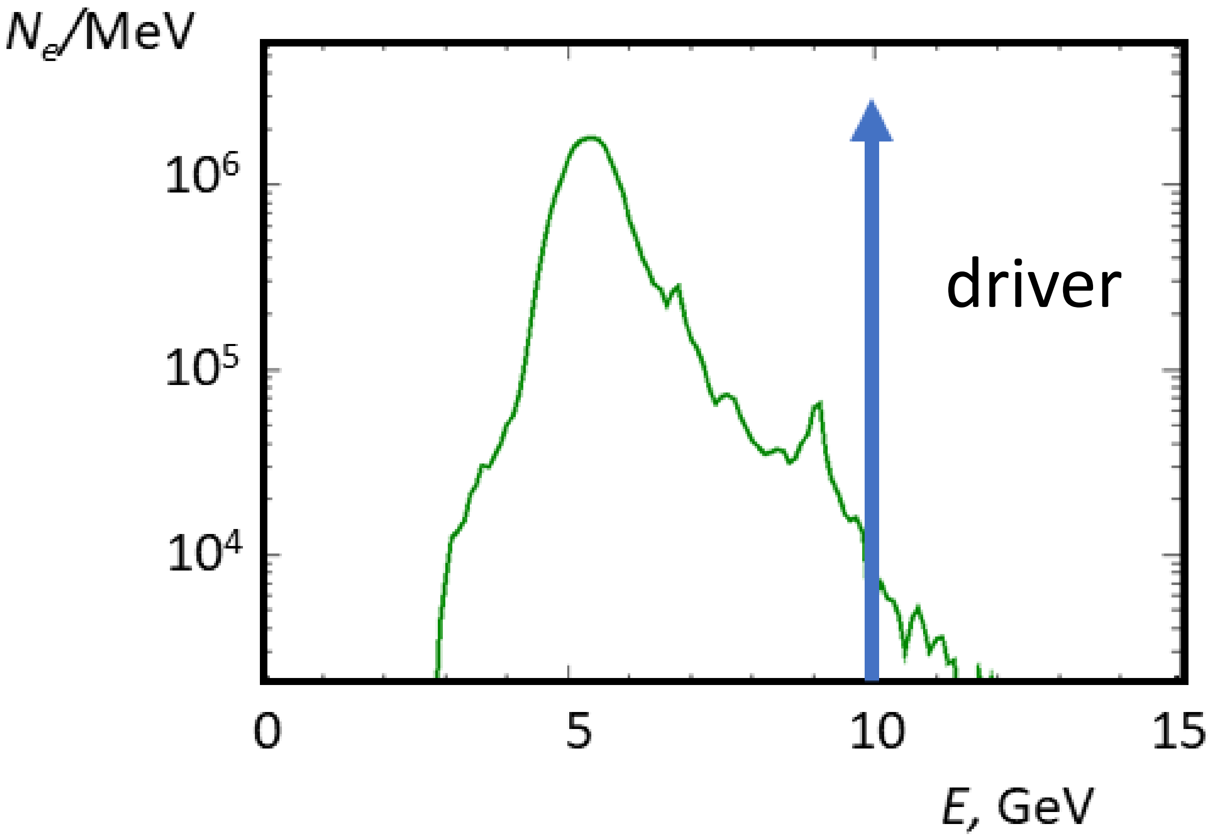
Acceleration in wedge plasma channel

Funded by the European Union

Acceleration in wedge plasma channel

Funded by the European Union



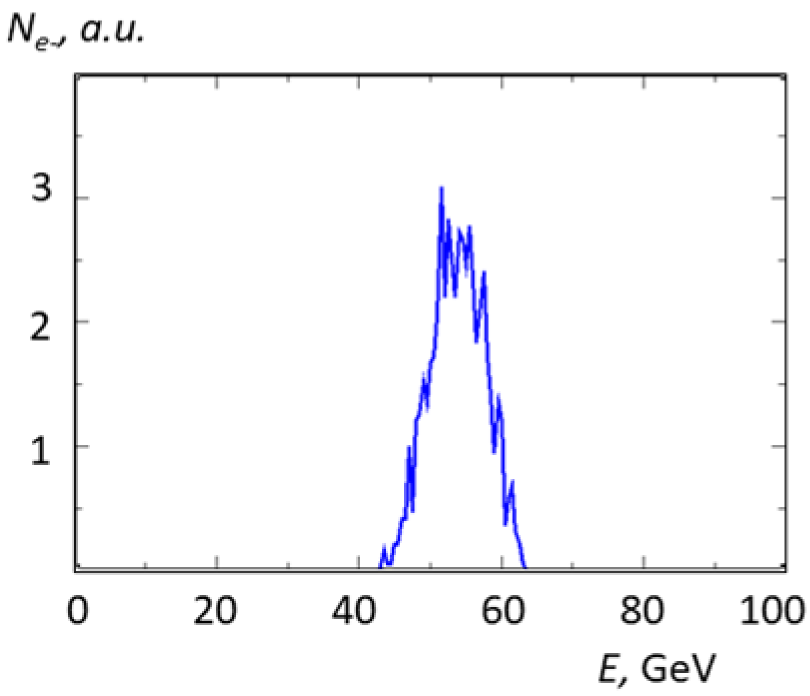


Driver has lost about half of its energy

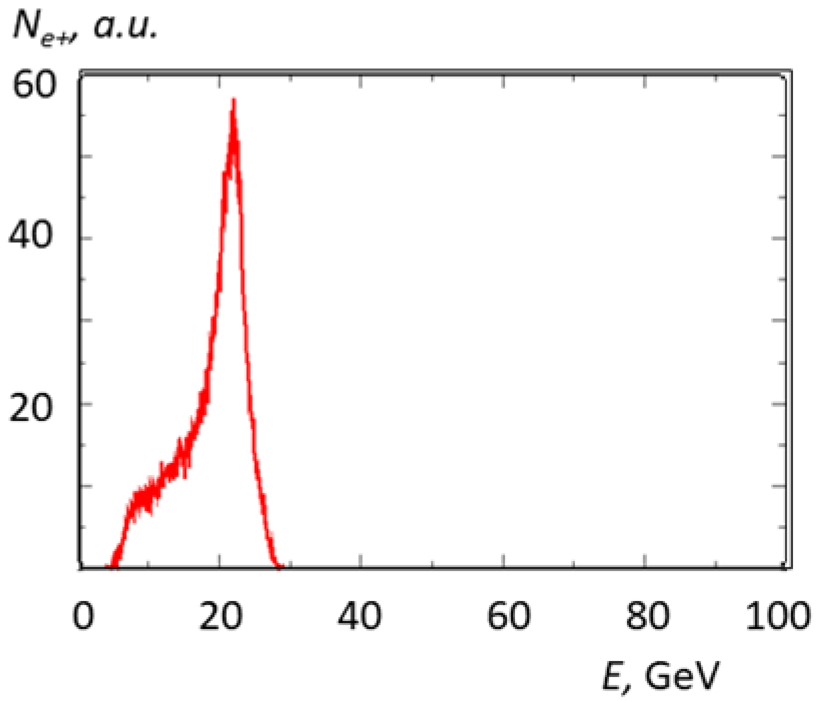
arXiv:2403.09427 (2024)

Electron and positron spectra

Funded by the European Union



Electrons



Positrons

arXiv:2403.09427 (2024)

Wedge plasma channel

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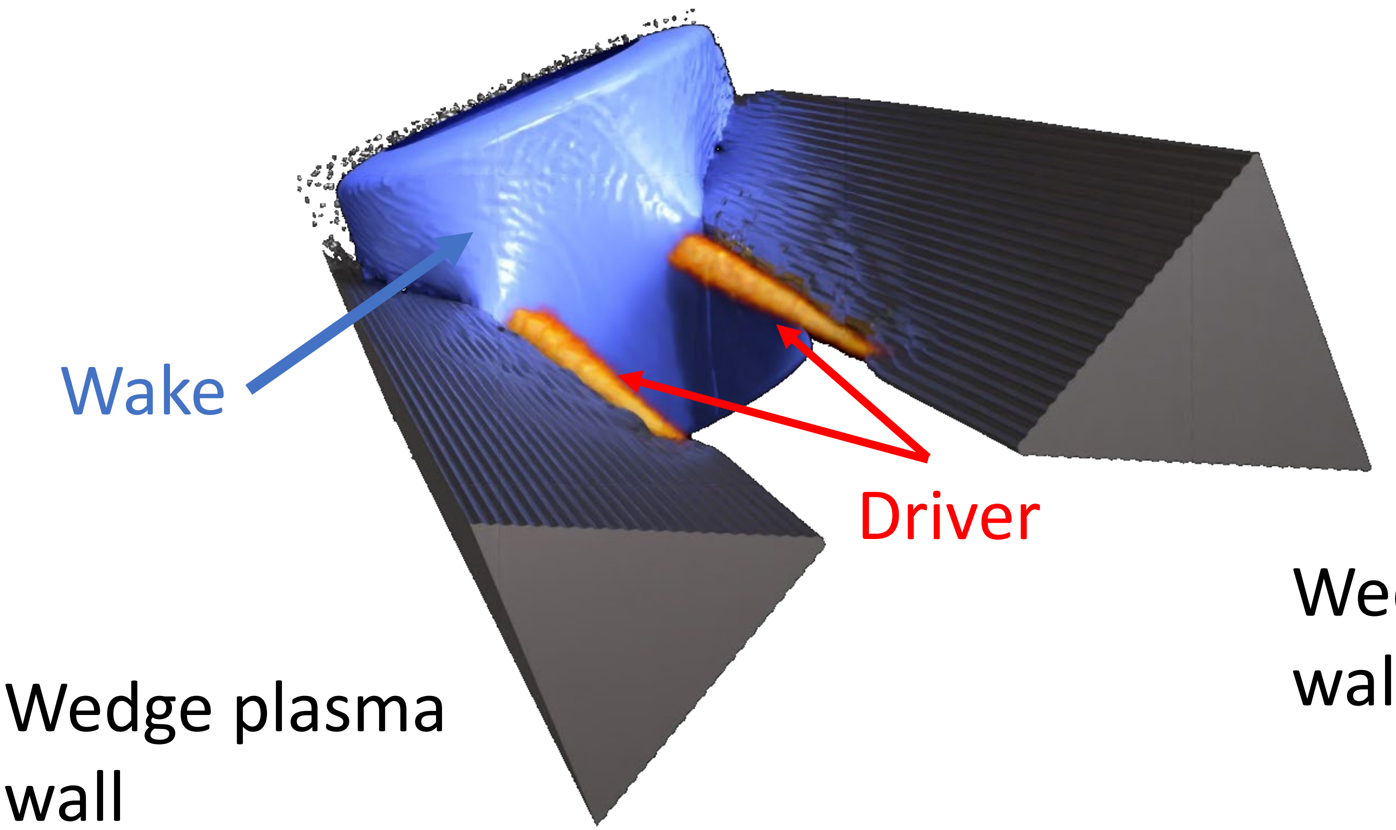
Central question: *how to create such a plasma channel?*

Laser ionization of neutral gas?



arXiv:2403.09427 (2024)

Marry SWFA/DWA with Plasma

Solid state structures are easier to handle

- Acceleration and focusing in plasma are intrinsically coupled

- We can decouple focusing from acceleration:

  - use structures to generate the accelerating fields

  - use plasma to guide and focus the bunches
    (limitation: only negative charges can be accelerated)

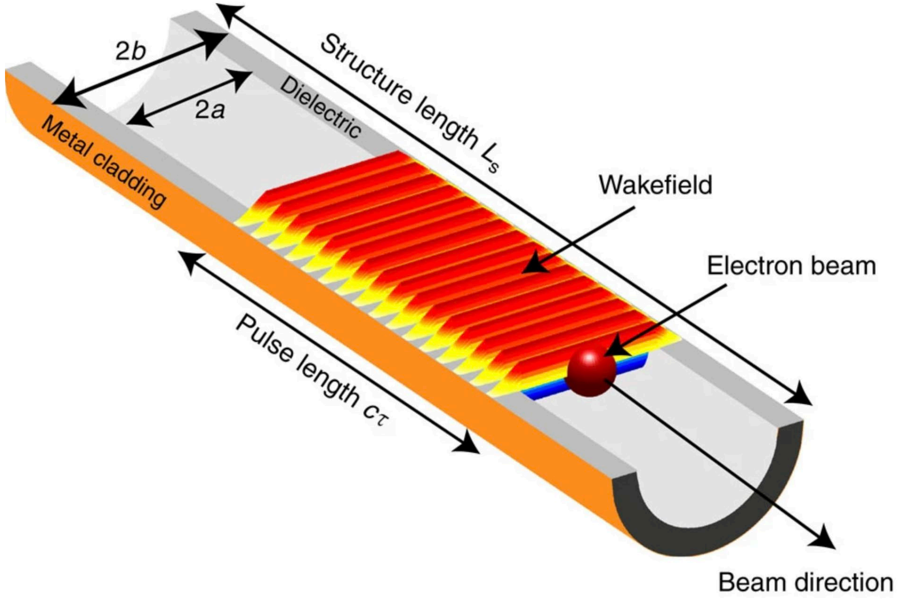
J. Rosenzweig on Wednesday)

K. Bane and G. Stupakov, NIMA 690, 106 (2012)

SWFA/DWA and Plasma

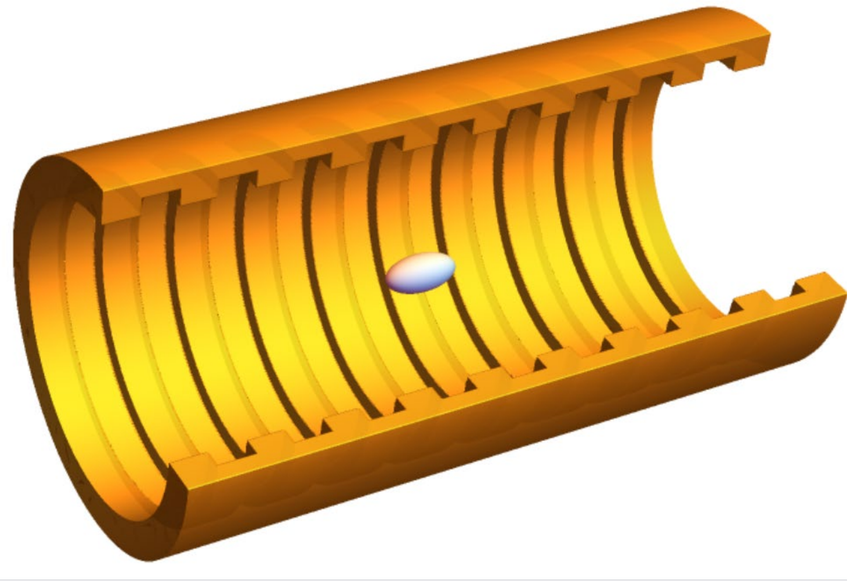
Various structures can be used for acceleration

Dielectric structures



J. Rosenzweig on Wednesday)

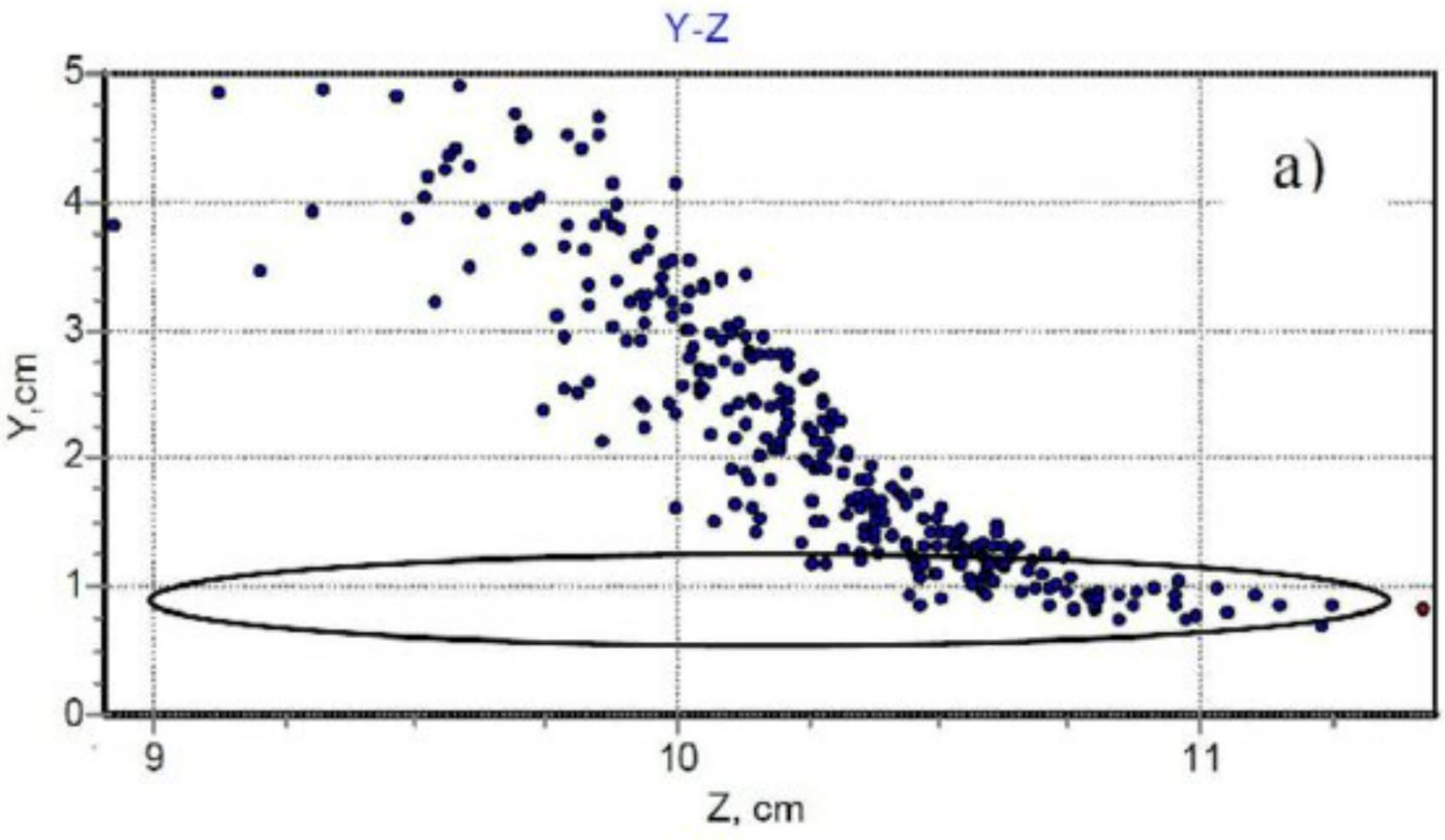
Corrugated metallic pipe



K. Bane and G. Stupakov, NIMA 690, 106 (2012)

SWFA and BBU

The main limit for SWFA: Beam Break Up (BBU)



Tail of the bunch is attracted to the wall

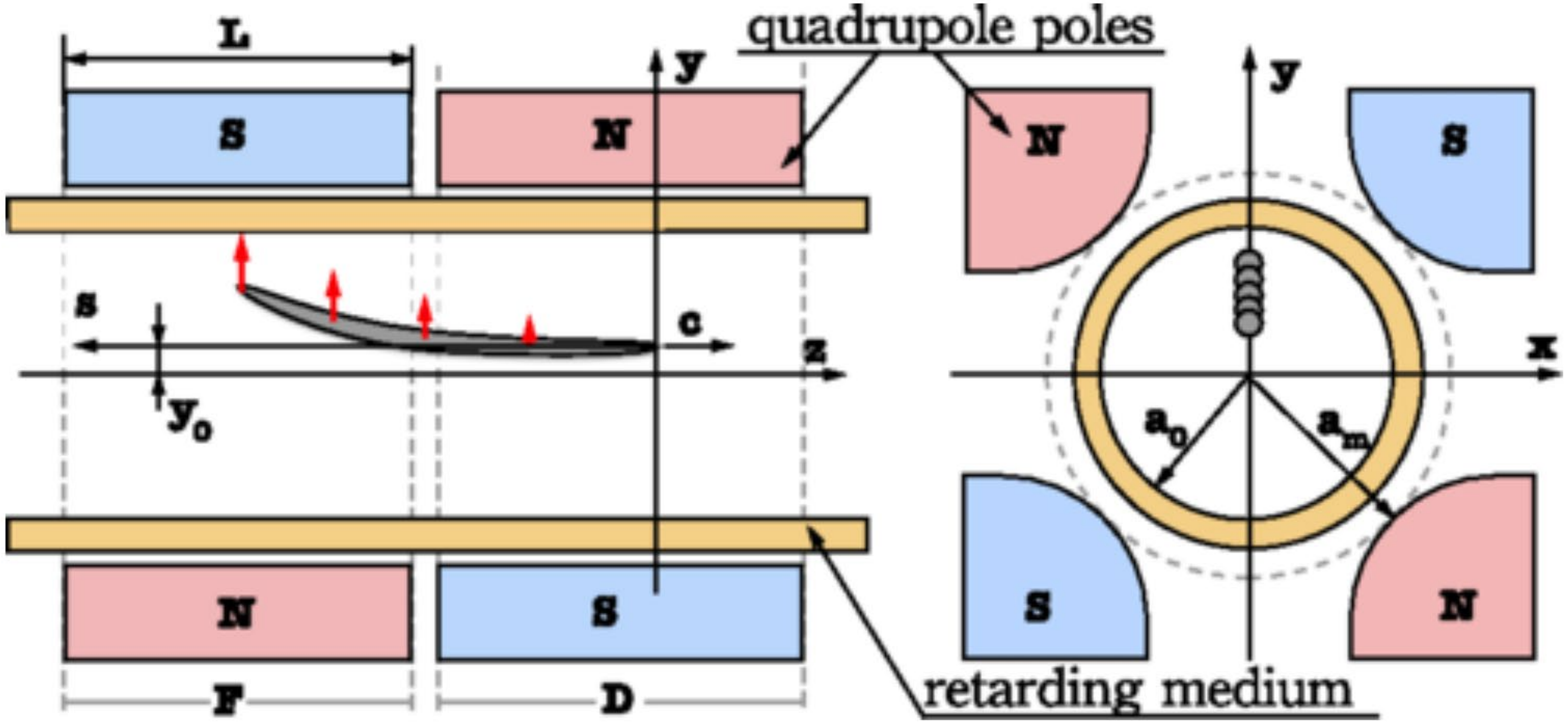
Fig. by Alexandr Moiseevich Altmark

BBU instability in a hollow channel

The main limit for SWFA: Beam Break Up (BBU)

SWFA and BBU

Strong focusing (and chirp) is required to stabilize the BBU



1.5 T quadrupoles can provide (may be) up to 100 MV/m stable accelerating fields

S. S. Baturin and A. Zholents Stability condition for the drive bunch in a collinear wakefield accelerator Phys. Rev. Accel. Beams **21**, 031301 (2018)

SWFA and Plasma

Let us decouple acceleration and focusing
We use the structure to support accelerating wake
while plasma provides focusing only!

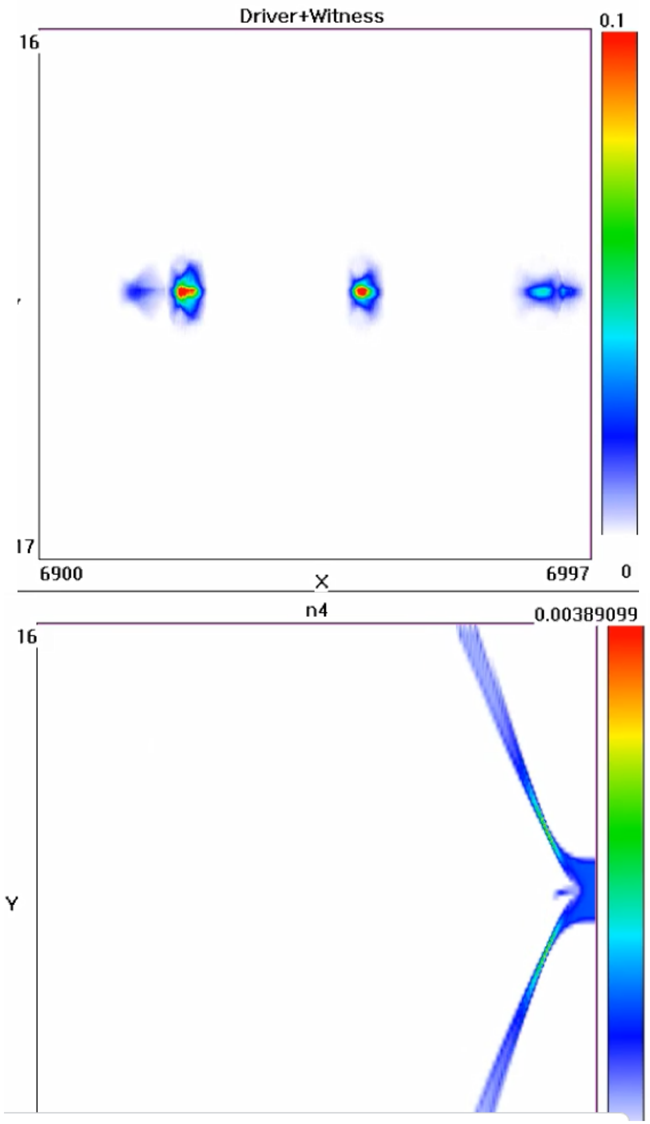
Plasma can provide focusing strength as high as

$$\frac{B}{r}[\mathrm{T/mm}] \approx 6 \cdot 10^4 \sqrt{\frac{n_e[\mathrm{cm}^{-3}]}{10^{15}}}$$

when all electrons are swept away from the plasma channel

Narrow plasma column: Complete stabilization, $R \approx 5$

SWFA and Plasma



bunches

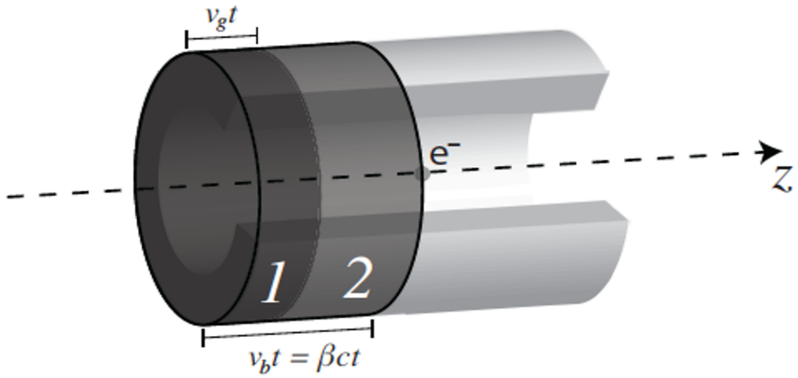
plasma electrons

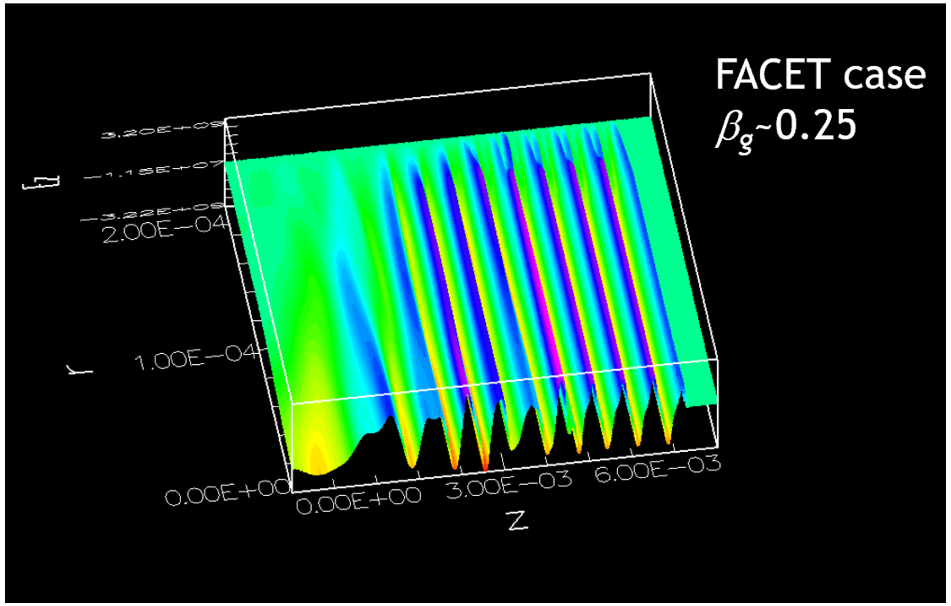
The leading bunch scatters away electrons off the narrow plasma column

The trailing bunches stay stable and tightly focused by the ion column

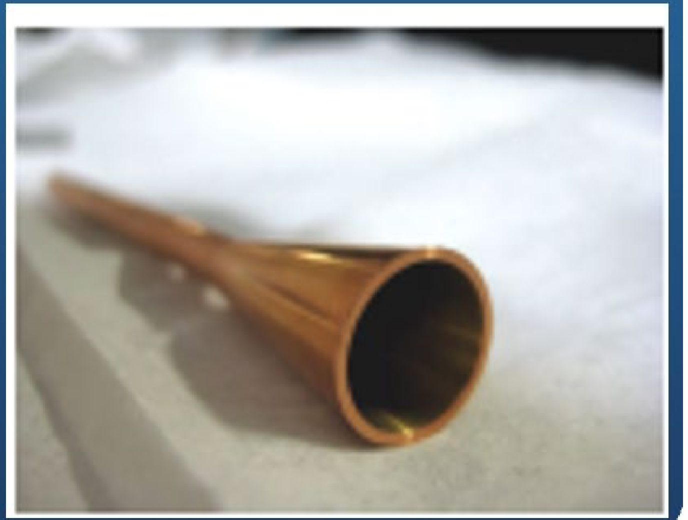
How to create the plasma column?

THz: Narrow band CCR (J. Rosenzweig)





A. Cook, et al., Phys. Rev. Lett. **103**, 095003 (2009)



THz radiation inside corrugated pipe

Very similar to dielectric, but there is a point

THz radiation inside the closed structure

The corrugated metallic pipe
acts *as a dielectric* for *longitudinal* polarization

It works *as a metallic* rod for *radial* polarization

Thus, it supports *Sommerfeld modes* in free space

Removing the metal mantle we let the THz radiation from inside to couple to the Sommerfeld modes outside

Coupling THz radiation to Sommerfeld mode

Sommerfeld mode is released at the end of the structure

Energy conversion into THz up to 100%

Conclusions

Funded by the European Union

- High transformer ratio acceleration:
  the path to reduce the number of stages

- Structured plasma channels:
  stabilization of BBU (rather crazy)

- Plasma in external structures (SWFA or DWA)
  can stabilize the driver and the witness (crazy)

- Efficient THz coupling
  in open corrugated metallic structures (low hanging fruit)