Production of ultra-short, high-brightness waterbag bunches

<u>Bas van der Geer</u>

Marieke de Loos

Jom Luiten

Marnix van der Wiel

Eindhoven University of Technology

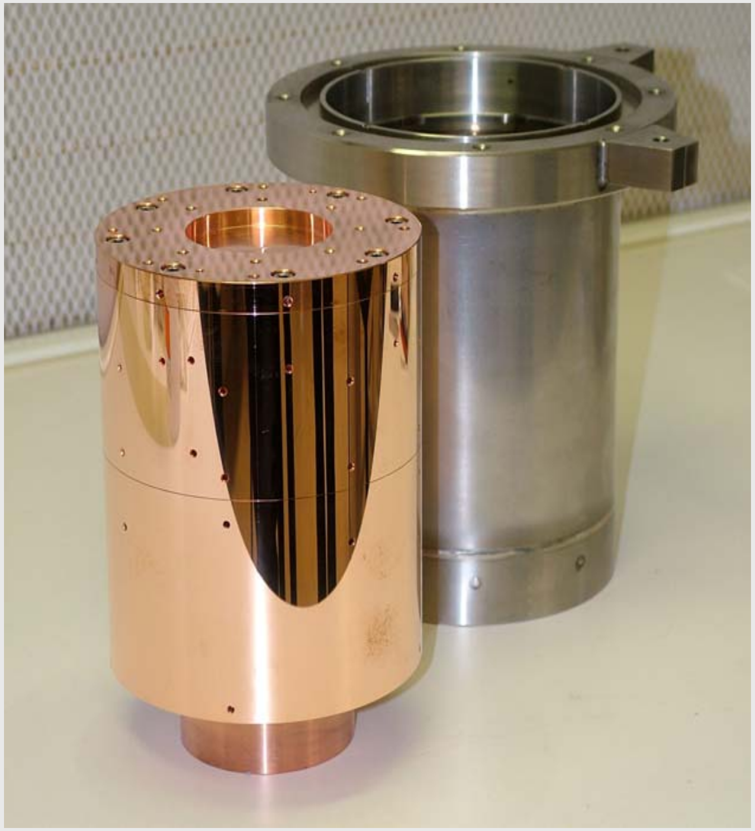
FOM

CPS
CENTRUM
VOOR PLASMAFYSICA EN
STRALINGSTECHNOLOGIE

Overview

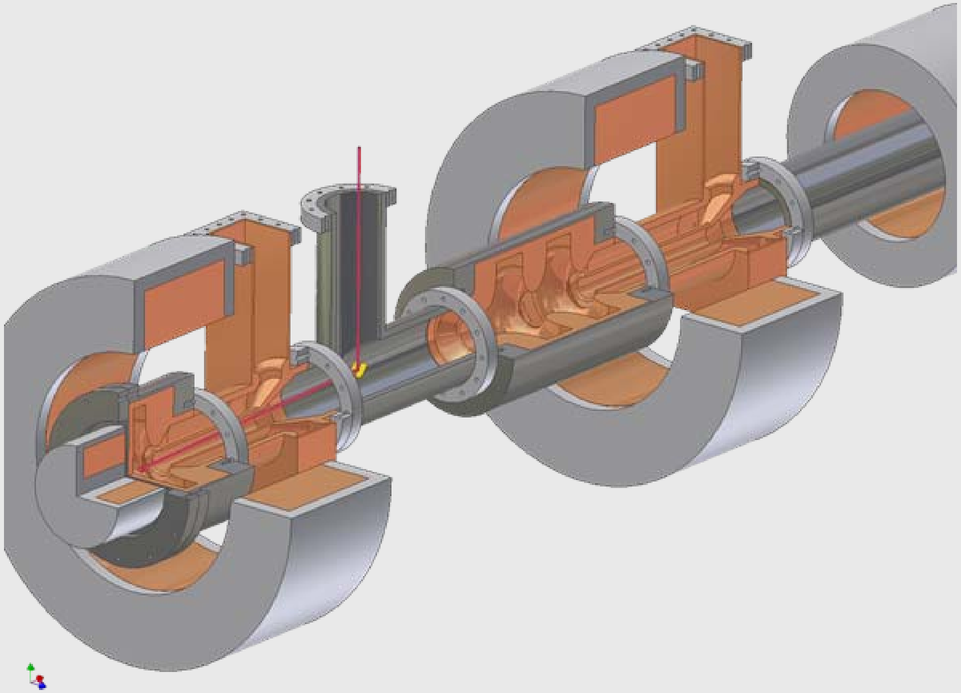
Present status

- 1.5 cell THz
- 2.6 cell Laser wakefield
- 1.6 cell Pulsed radiolysis



Future plans

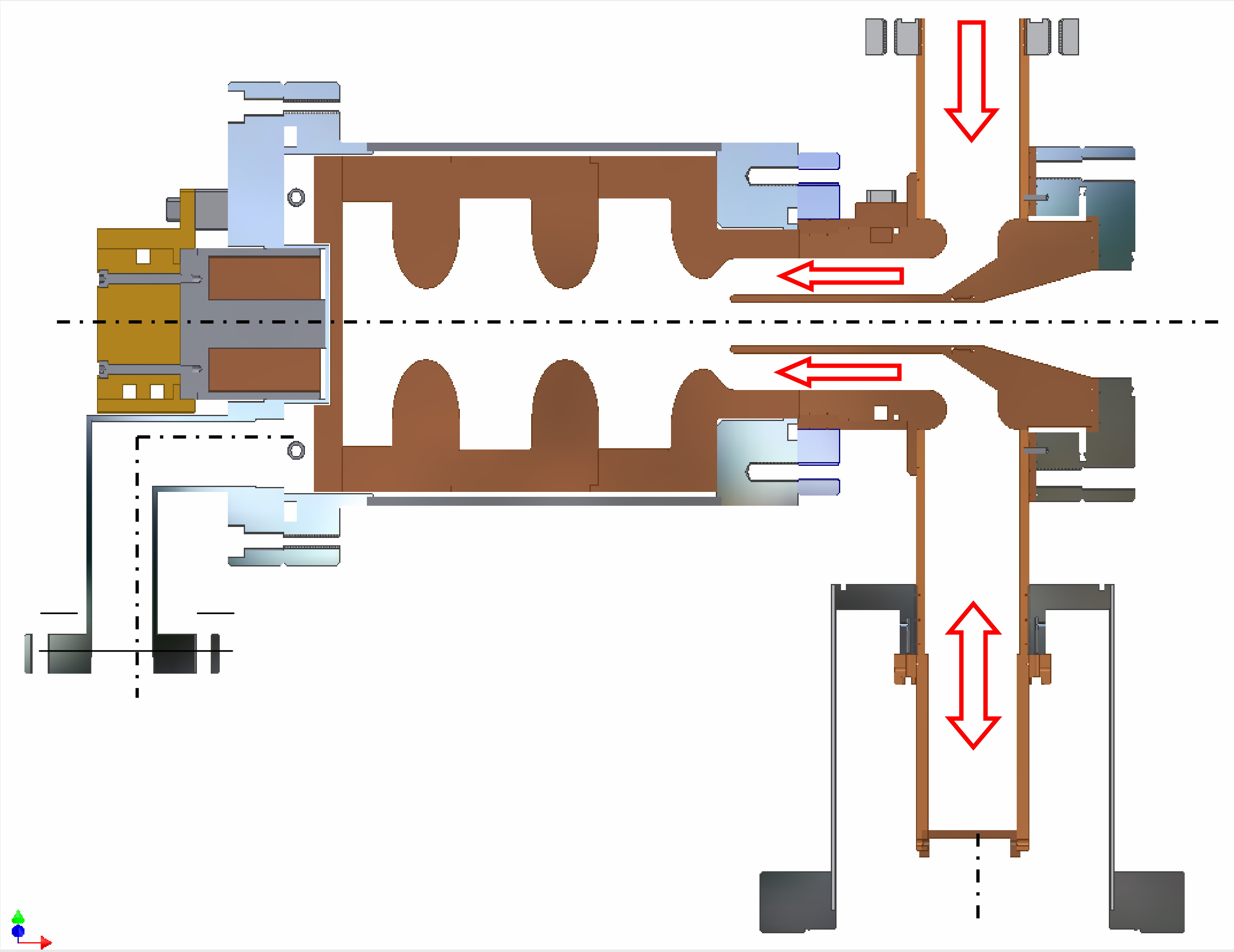
- Creation of ellipsoidal bunches
- Transverse compression
- Longitudinal compression



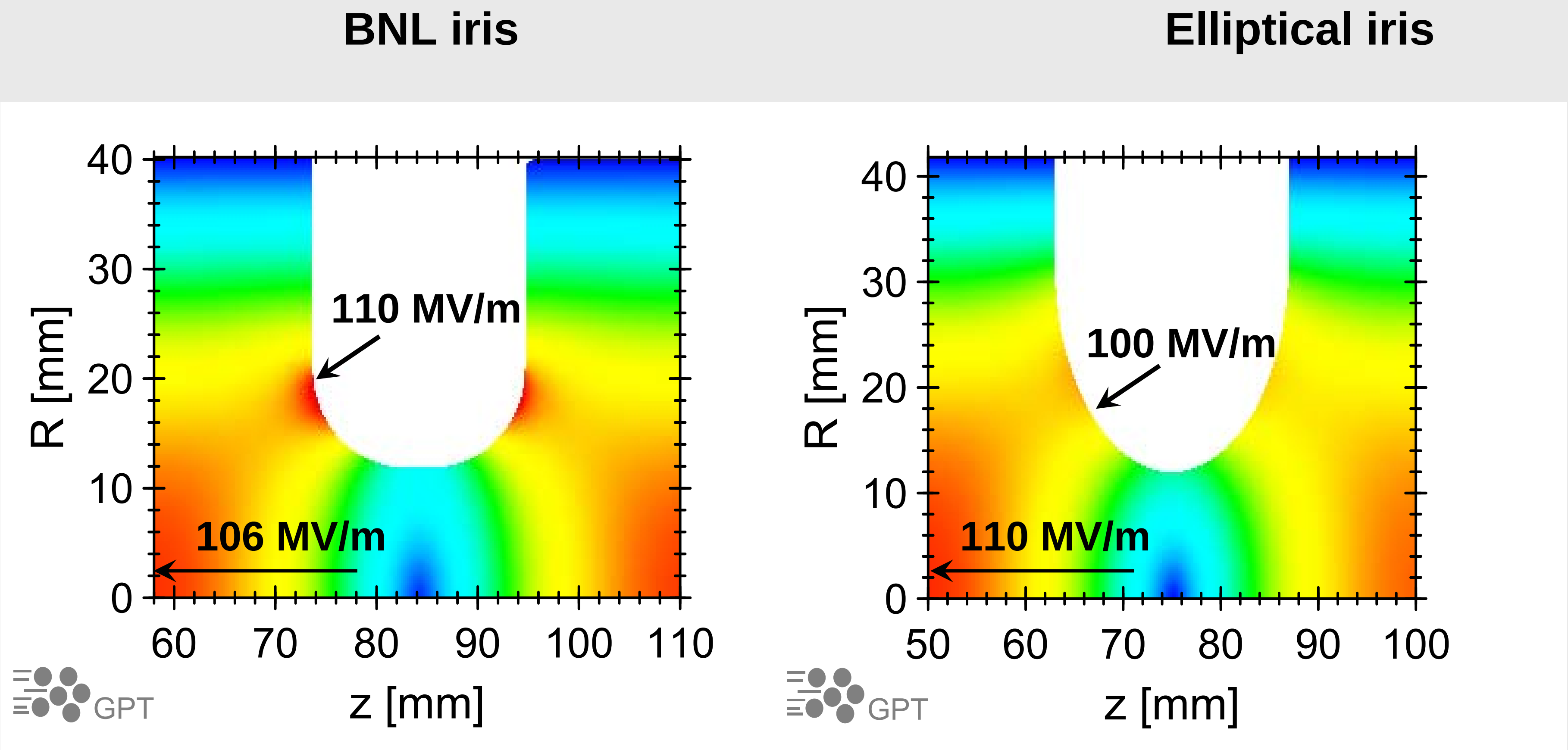
‘Our’ rf-photoguns

- Micrometer precise design and manufacture
- Axial incoupling
  - Modified design from DESY
- Elliptical irises
  - Old idea, dimension from ‘Pulsar/Strathclyde’ collaboration
- Separated cells are clamped, not brazed
  - Not fully tested at high-power so far
- Inside stainless steel vacuum vessel

Cross section photogun + input coupler



Elliptical irises

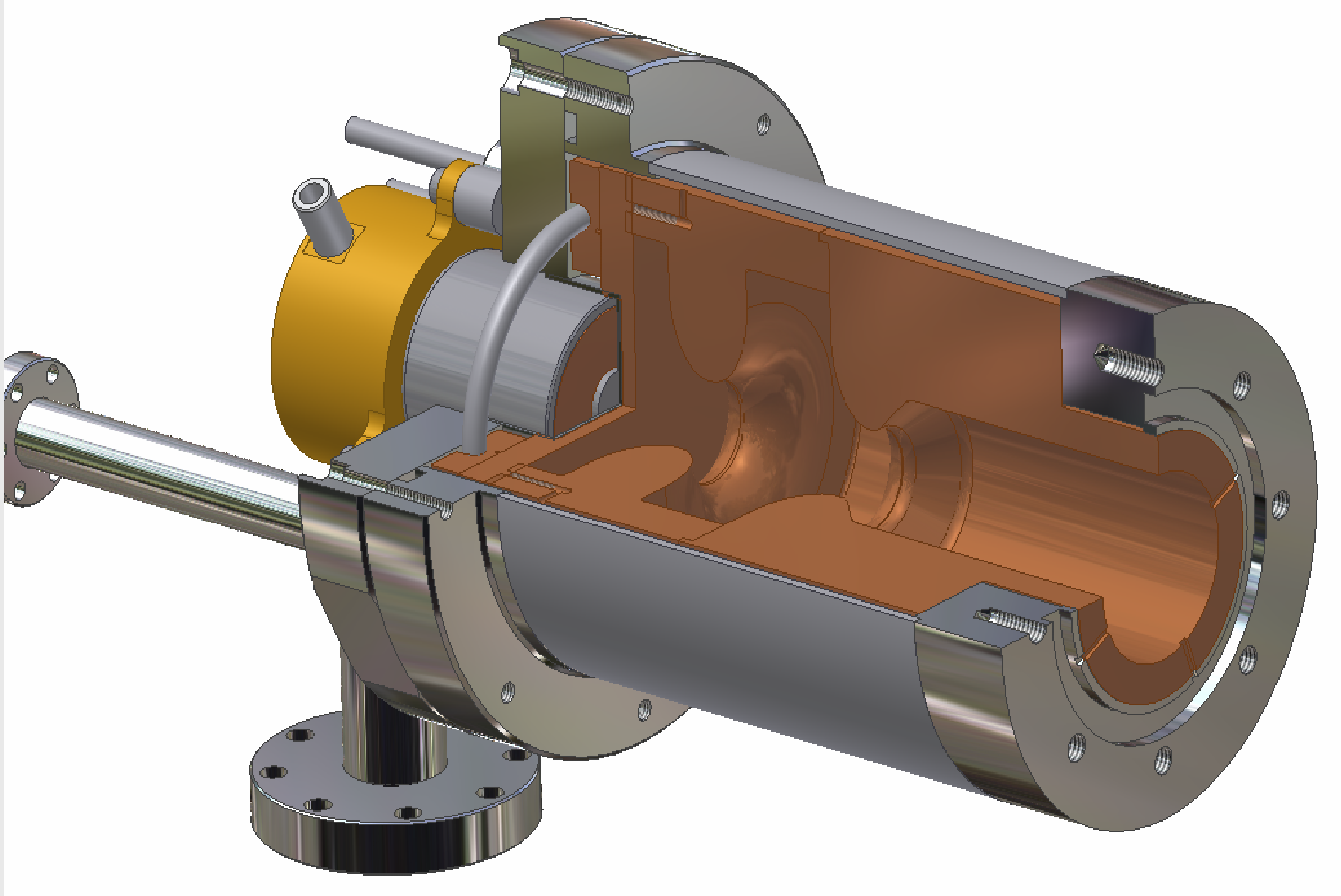


Lower field strength on irises, better ratio between field on iris and field on-axis but lower Q-factor; 10% more RF power needed to get same electron energy

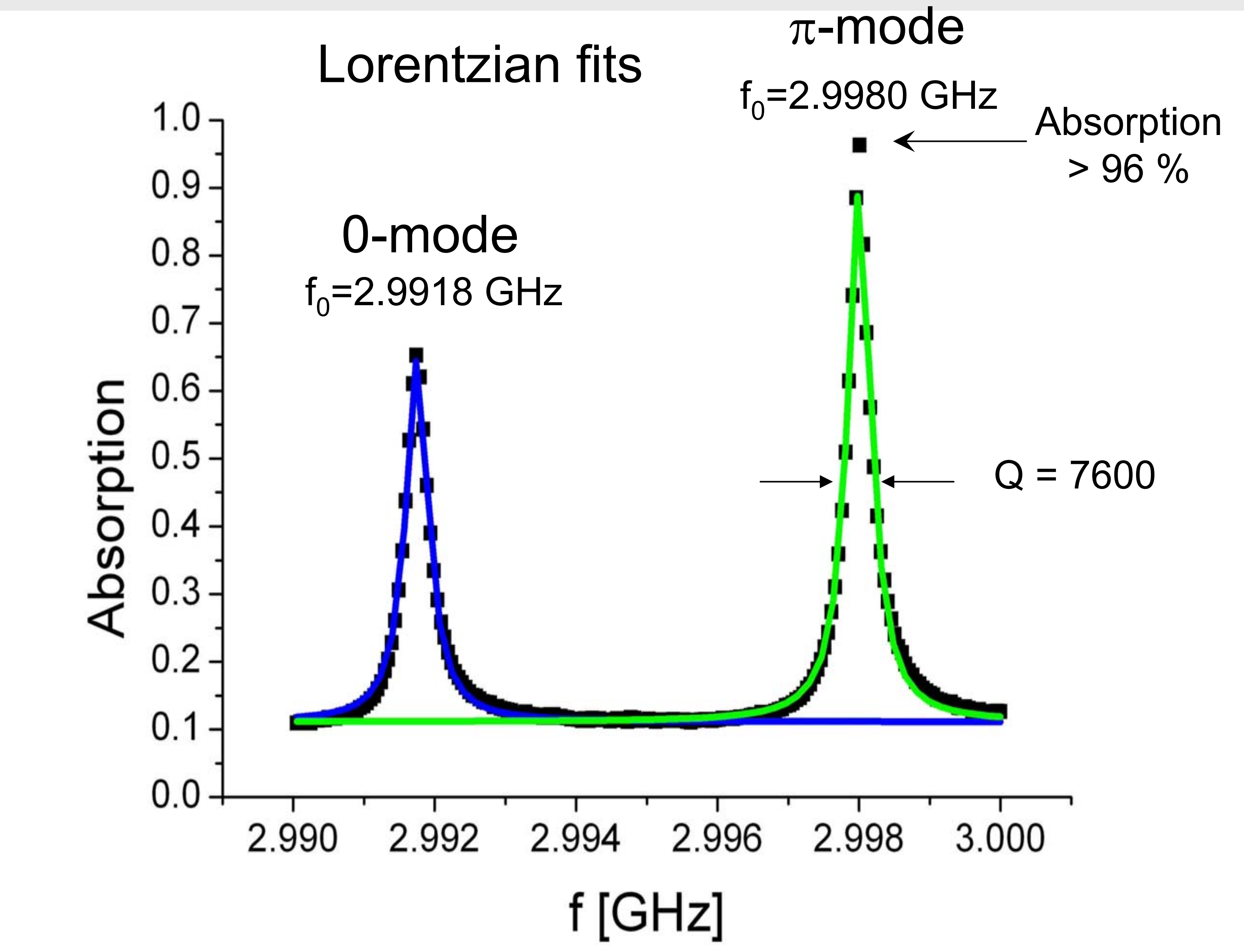
Comparison

Cavity	1.5	1.6	2.6	cells
• Maximum output energy	4.4	4.8	**6.7**	MeV
• Repetition frequency	10	**100**	10	Hz
• Cathode field at max energy	**95**	73	65	MV/m
• Launch phase for max. energy	–30°	–50°	–50°	
• RF input power	8.5	8.2	10	MW
• Maximum field at cathode	110	110	100	MV/m
• Maximum field on irises	100	100	90	MV/m

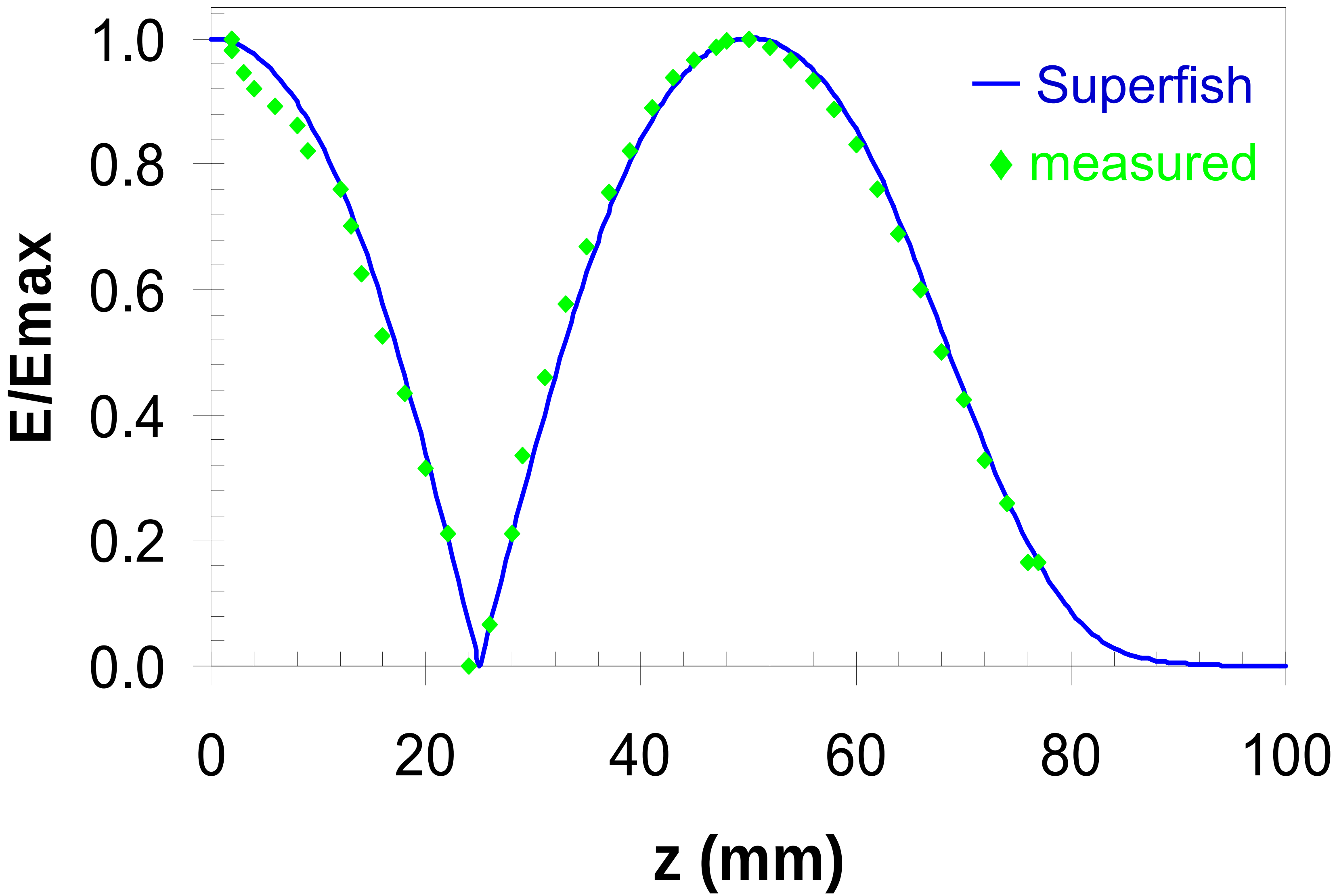
1.5 cell cavity



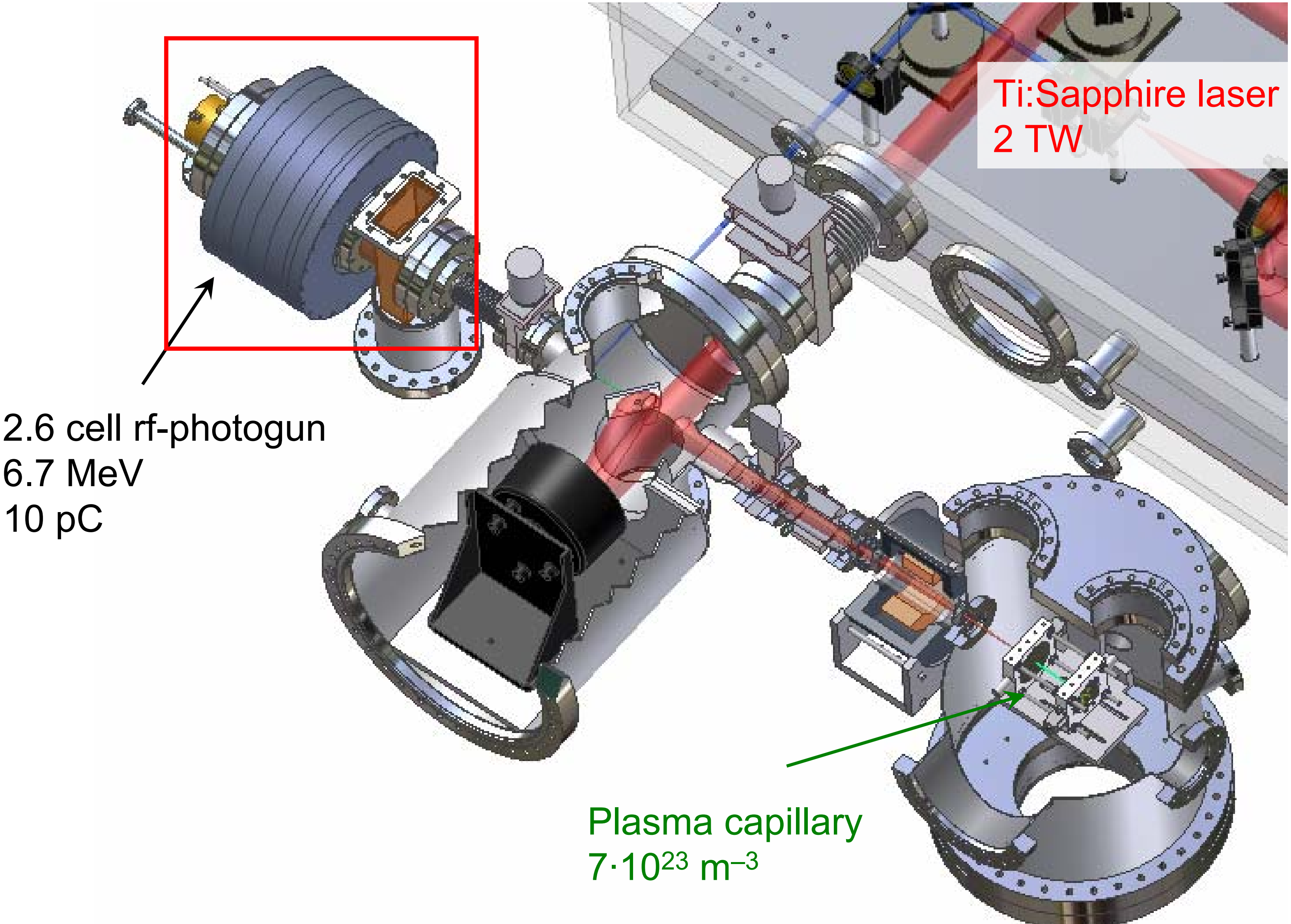
1.5 cell cavity: measured resonances



1.5 cell cavity: field profile π-mode



2.6 cell cavity: Laser wakefield acceleration



Graphics: Wim Urbanus

Precision

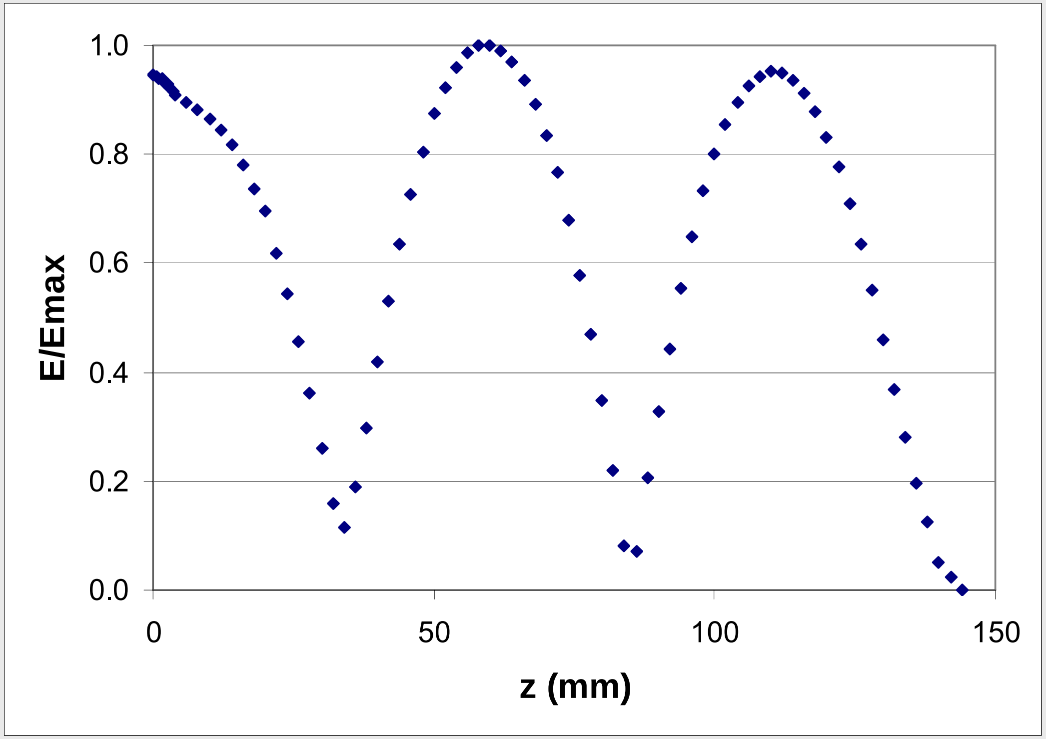
Diameter	Design	Measured	Error
• Cell 1	81.730	81.7314	~1 µm
• Cell 2	83.442	83.4415	–
• Cell 3	83.386	83.3857	–

Length	Design	Measured	Error
• Cell 1	17.994	17.9920	~2 µm
• Cell 2	25.991	25.9923	~1 µm
• Cell 3	25.991	25.9909	–

2.6 cell cavity

Results:

- Field imbalance < 10%
- Frequency: 2998.0 MHz
- Usable



However:

- 20% power reflection

  Fields reduced by 10%

Most likely cause:

- Mismatch between calculated and experimental antenna position
- Under investigation…

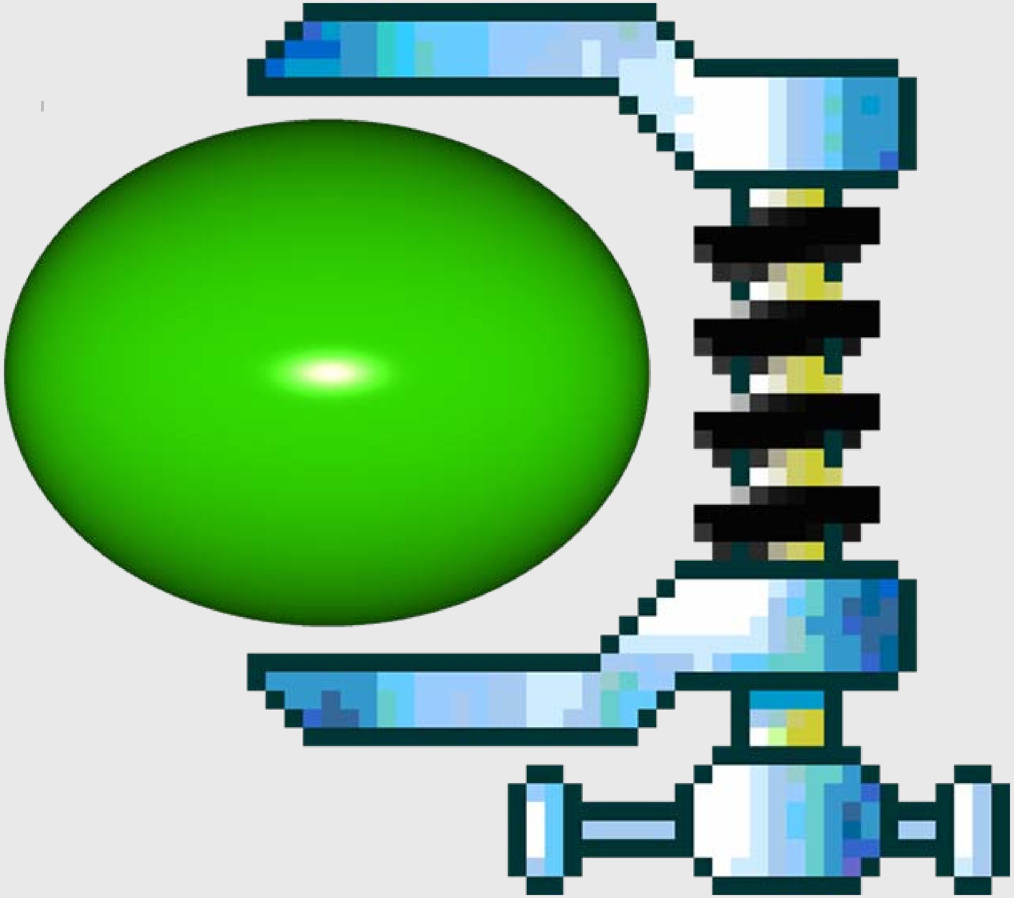
1.6 cell cavity (under construction)

Special feature:

- **100 Hz** operation possible
- Requires additional cooling channel

Commissioned and partially constructed by Delft university of technology
Application: Pulsed radiolysis

Compression of ellipsoidal bunches

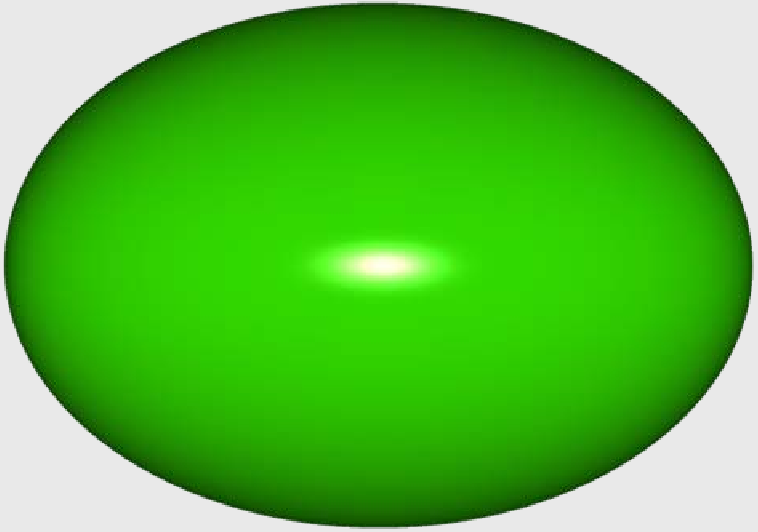


Graphics: Winzip + pulsar

Waterbags

- Transverse phase-space
  - No space-charge induced emittance degradation
  - No ‘slice’ dependence
  - O.J. Luiten, S.B. van der Geer et al, PRL 094802, (2004).
  - Confirmed by J. Rosenzweig and C. Limborg in NIM-A 557 (2006)

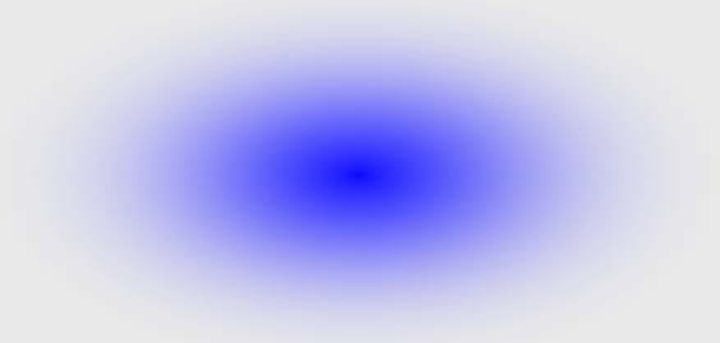
- Longitudinal phase-space
  - Ideal for linear compression
  - Manipulation possible at low energy
  - Energy spread can be recovered
  - S.B. van der Geer *et al*,
    PRST-AB, 9, 044203 (2006)



Brightness degradation

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

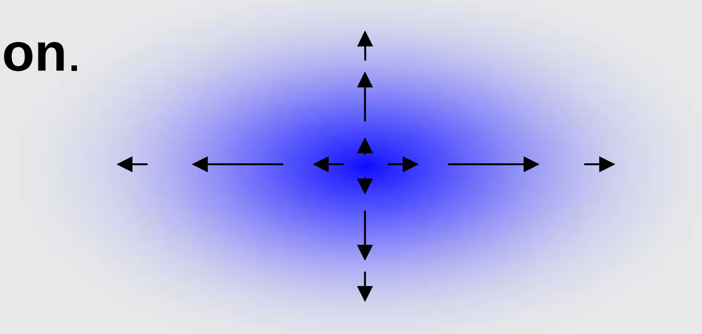
Gaussian bunch

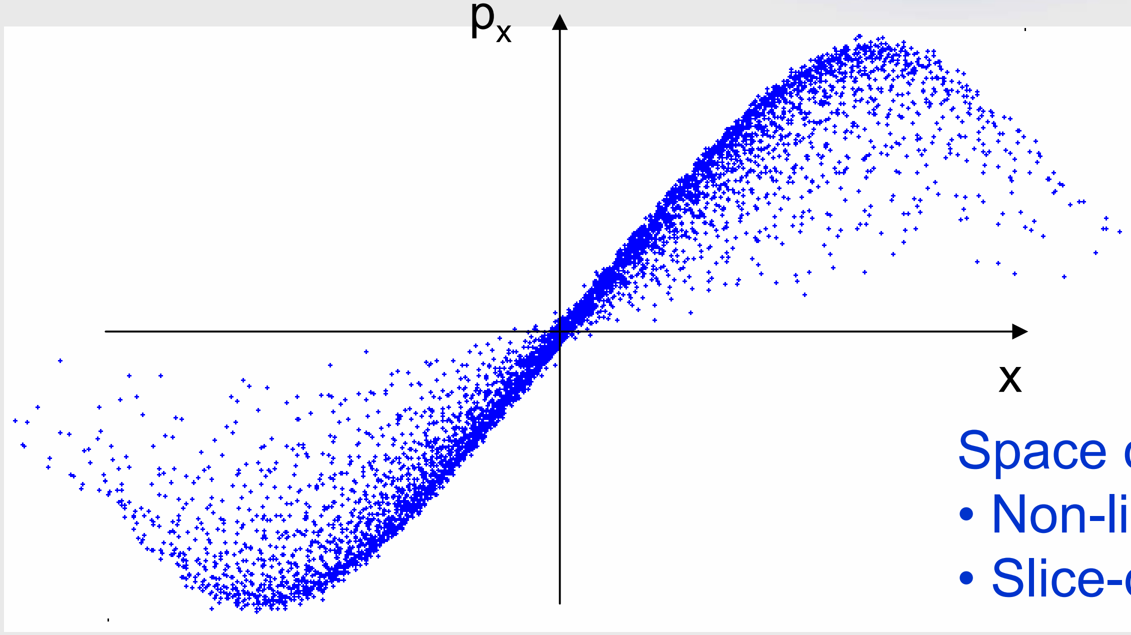


Brightness degradation

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

Gaussian bunch





Space charge forces:

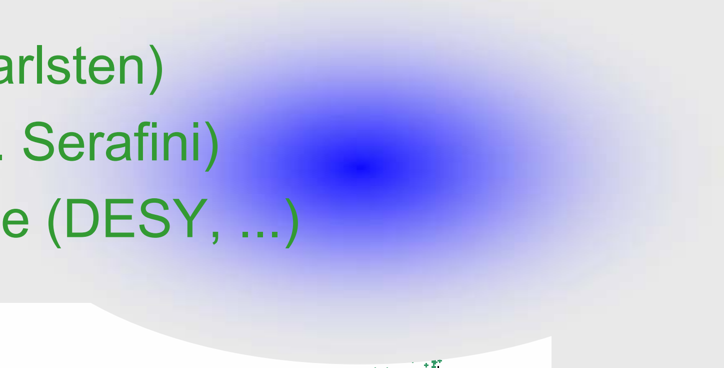
- Non-linear
- Slice-dependent

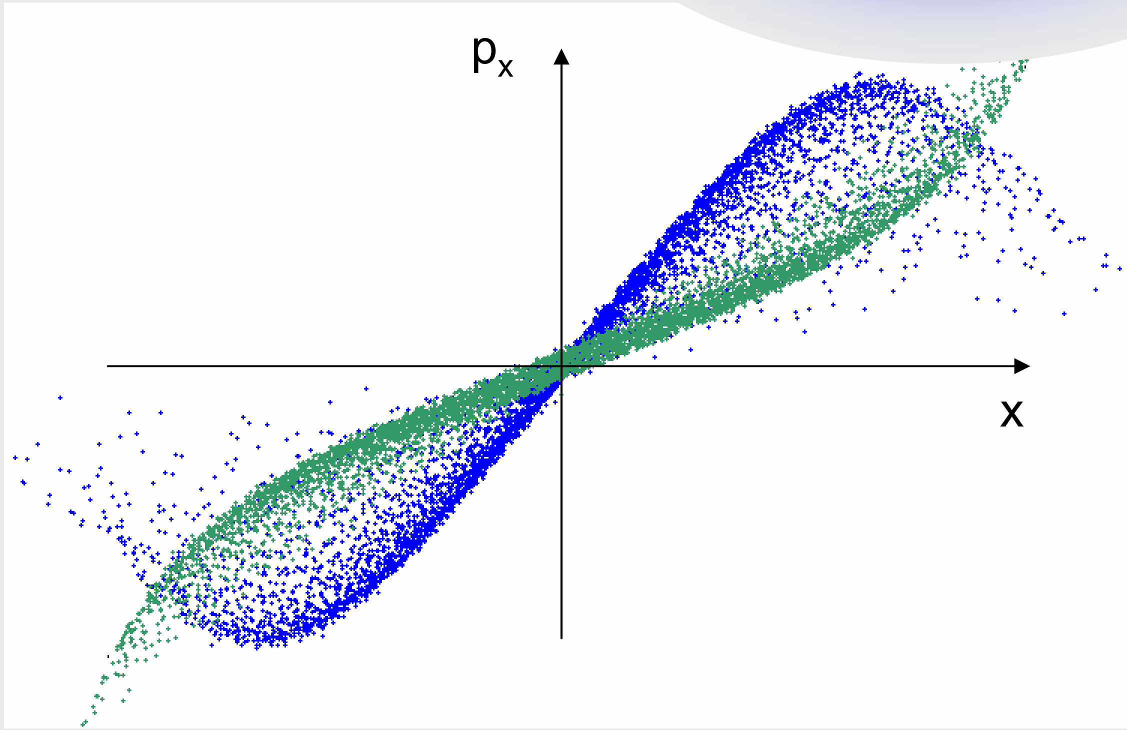
1989 - 2003

Fighting the symptoms:

- Emittance compensation (B. Carlsten)
- Optimized transverse profile (L. Serafini)
- Uniform temporal & radial profile (DESY, ...)
- ...

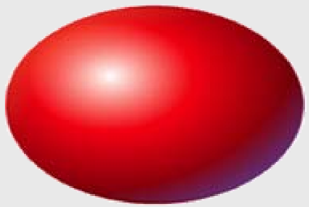
Gaussian bunch



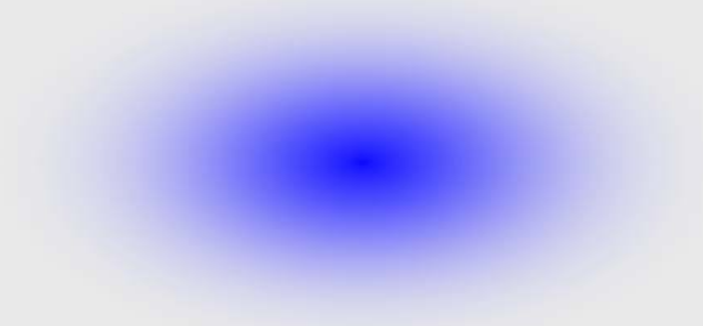


2004: Fundamental solution

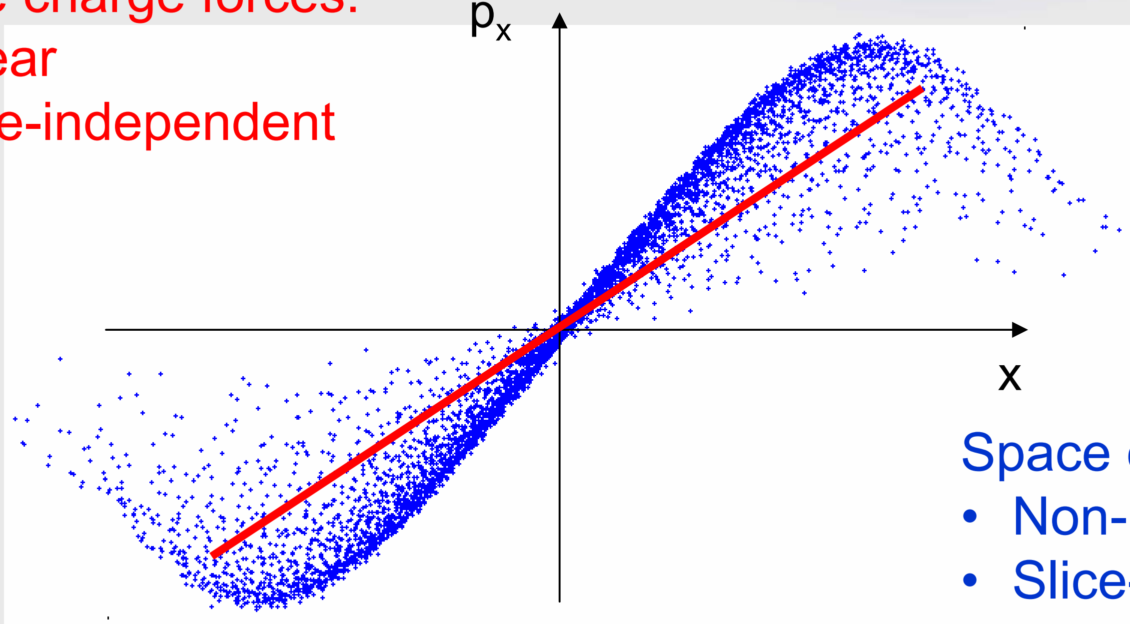
Waterbag bunch



Gaussian bunch



Space charge forces:
- Linear
- Slice-independent



Space charge forces:
- Non-linear
- Slice-dependent

Thermal-emittance-limited beam!

History of uniformly charged ellipsoids

1929 Have linear fields in all three coordinates

O. D. Kellogg, *Foundations of Potential Theory* (Springer-Verlag, **1929**).

1965 Ellipsoids with uniform mass collapse into a disk (astrophysics)

C.C. Lin et al., Astrophys. J. 142, 1431 (**1965**).

Decades of use as idealized beams

…

1997 Pancakes evolve into approximate waterbags

L. Serafini, AIP Conf. Proc. 413, 321 (**1997**)

2004 Fundamental solution and practical recipe

O.J. Luiten, S.B. van der Geer et al, PRL 094802, (**2004**).

O.J. Luiten, S.B. van der Geer et al, EPAC (**2004**).

History of uniformly charged ellipsoids

1929 Have linear fields in all three coordinates

O. D. Kellogg, *Foundations of Potential Theory* (Springer-Verlag, **1929**).

1965 Ellipsoids with uniform mass collapse into a disk (astrophysics)

C.C. Lin et al., Astrophys. J. 142, 1431 (**1965**).

Decades of use as idealized beams

…

1997 Pancakes evolve into approximate waterbags

L. Serafini, AIP Conf. Proc. 413, 321 (**1997**)

2004 Fundamental solution and practical recipe

O.J. Luiten, S.B. van der Geer et al, PRL 094802, (**2004**).

O.J. Luiten, S.B. van der Geer et al, EPAC (**2004**).

2006 Well received in the accelerator community

J.B. Rosenzweig et al., NIM-A 557 (**2006**), *Emittance compensation …*

C. Limborg et al., NIM-A 557 (**2006**), *Optimum electron distributions …*

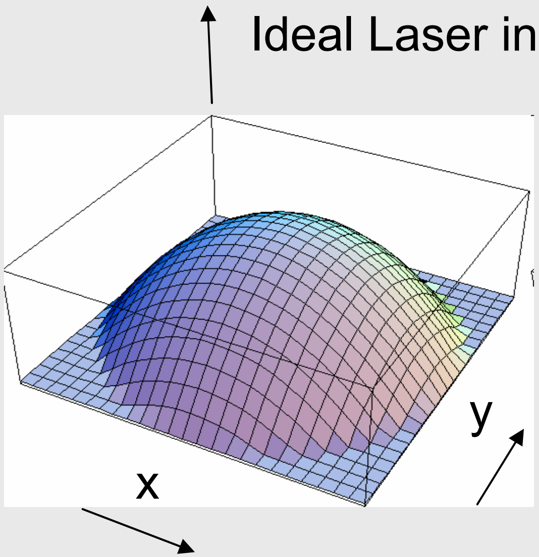
S.B. van der Geer et al, PRST-AB, 9, 044203 (2006), *Longitudinal …*

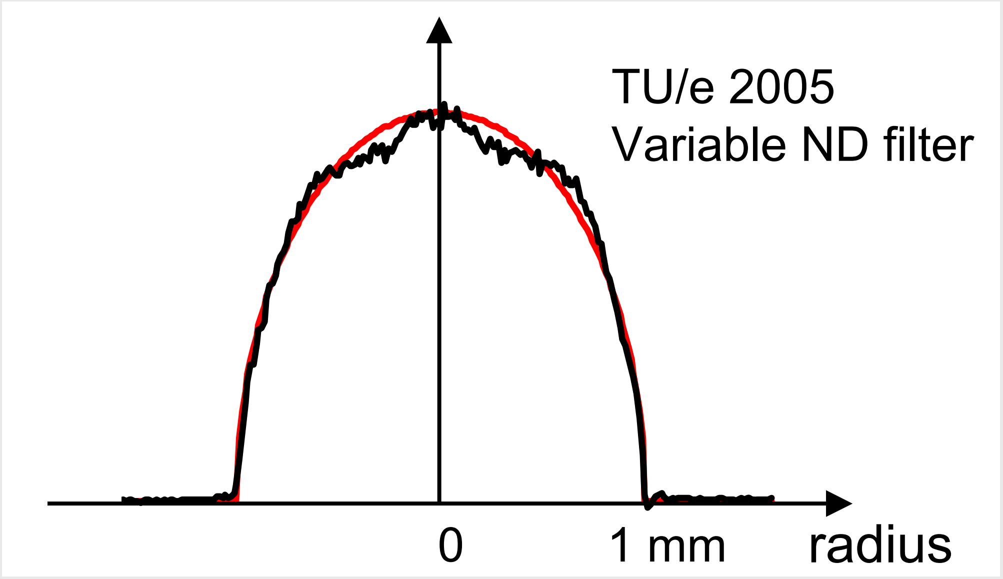
Waterbag bunch recipe

<u>Femtosecond</u> photoexcitation of pancake bunch

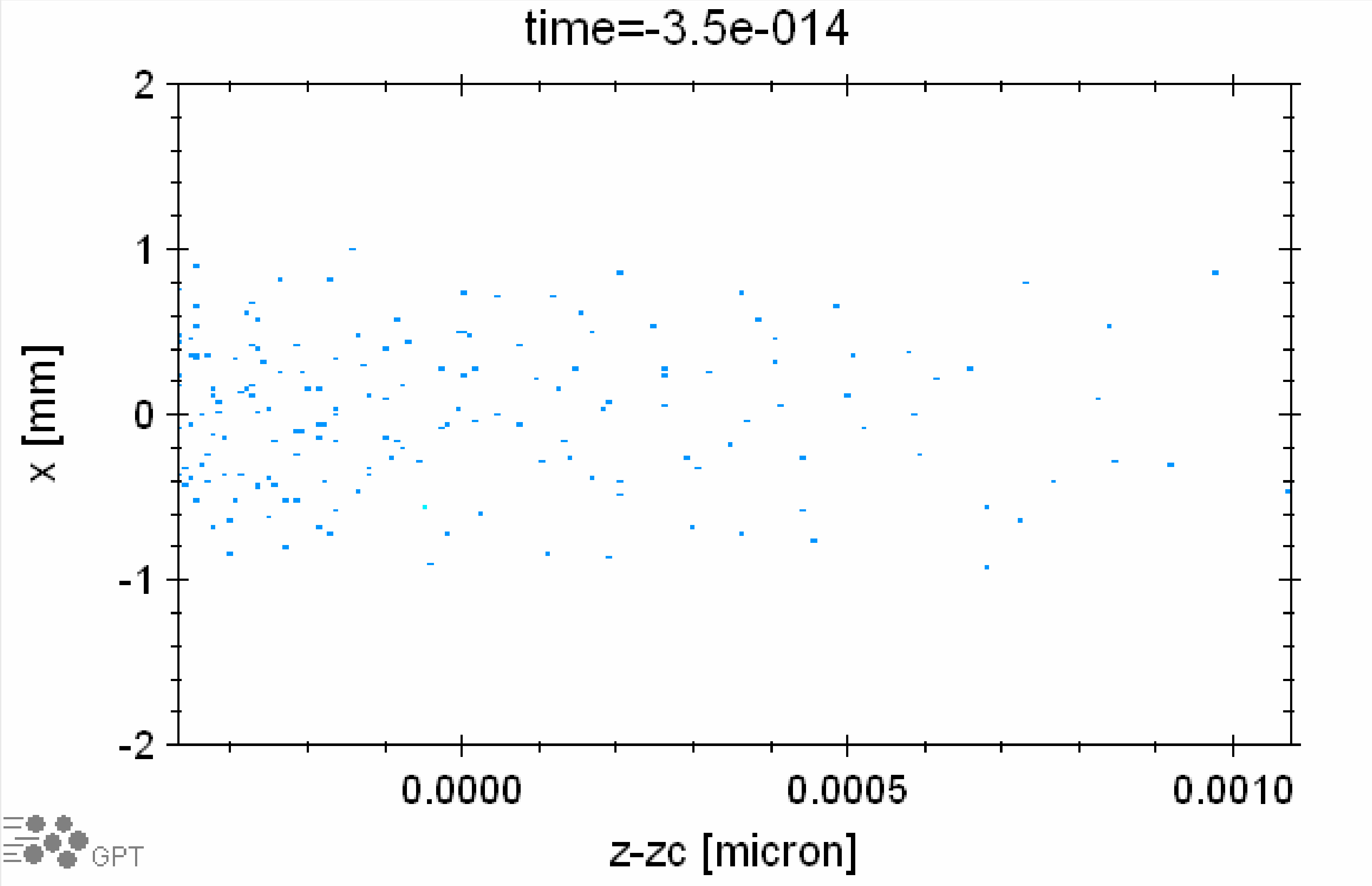
- 'half-sphere' transverse laser intensity profile
- Temporal laser profile is irrelevant

<u>Automatic evolution into 3D, uniform ellipsoid</u>



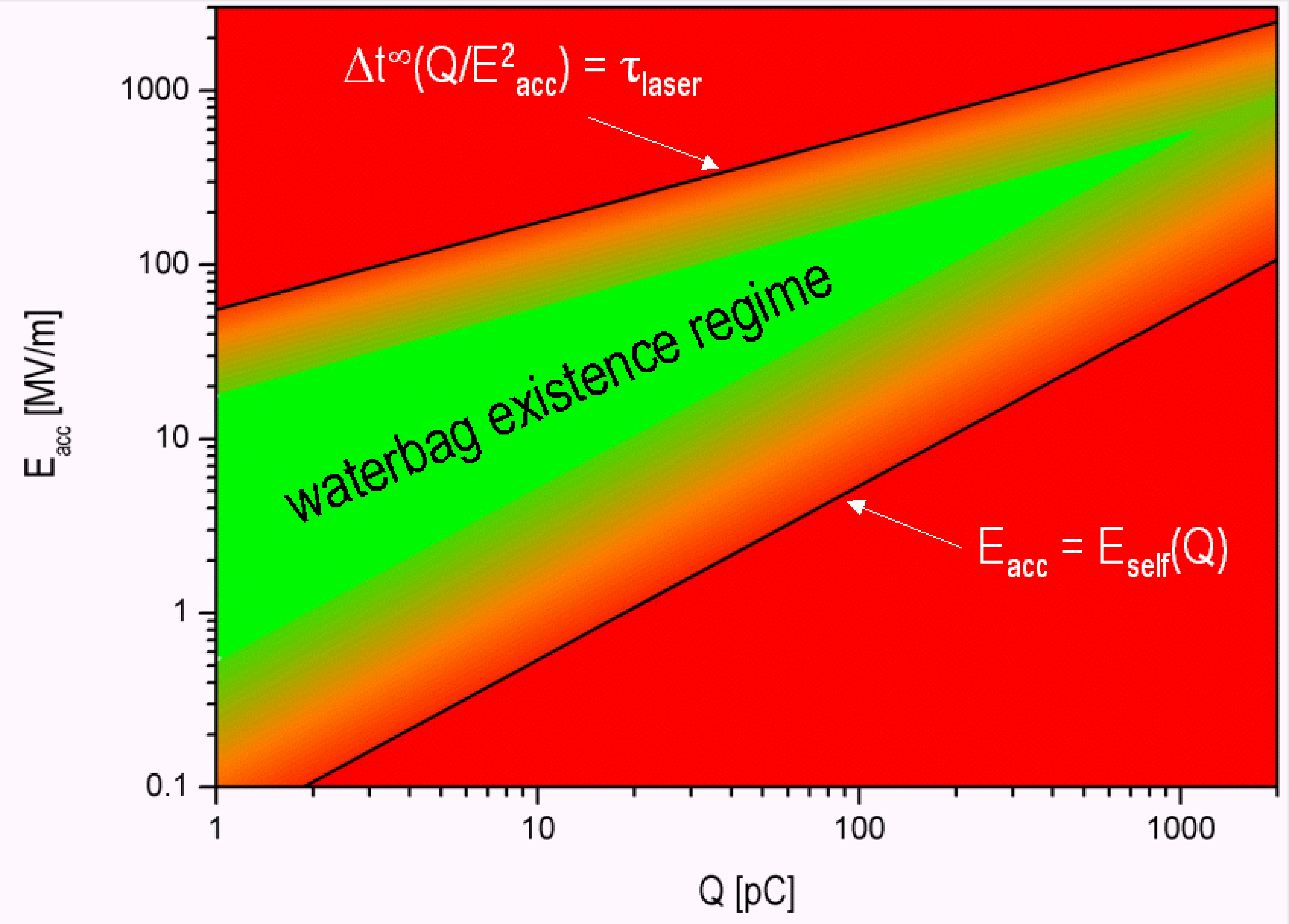


Ellipsoid creation

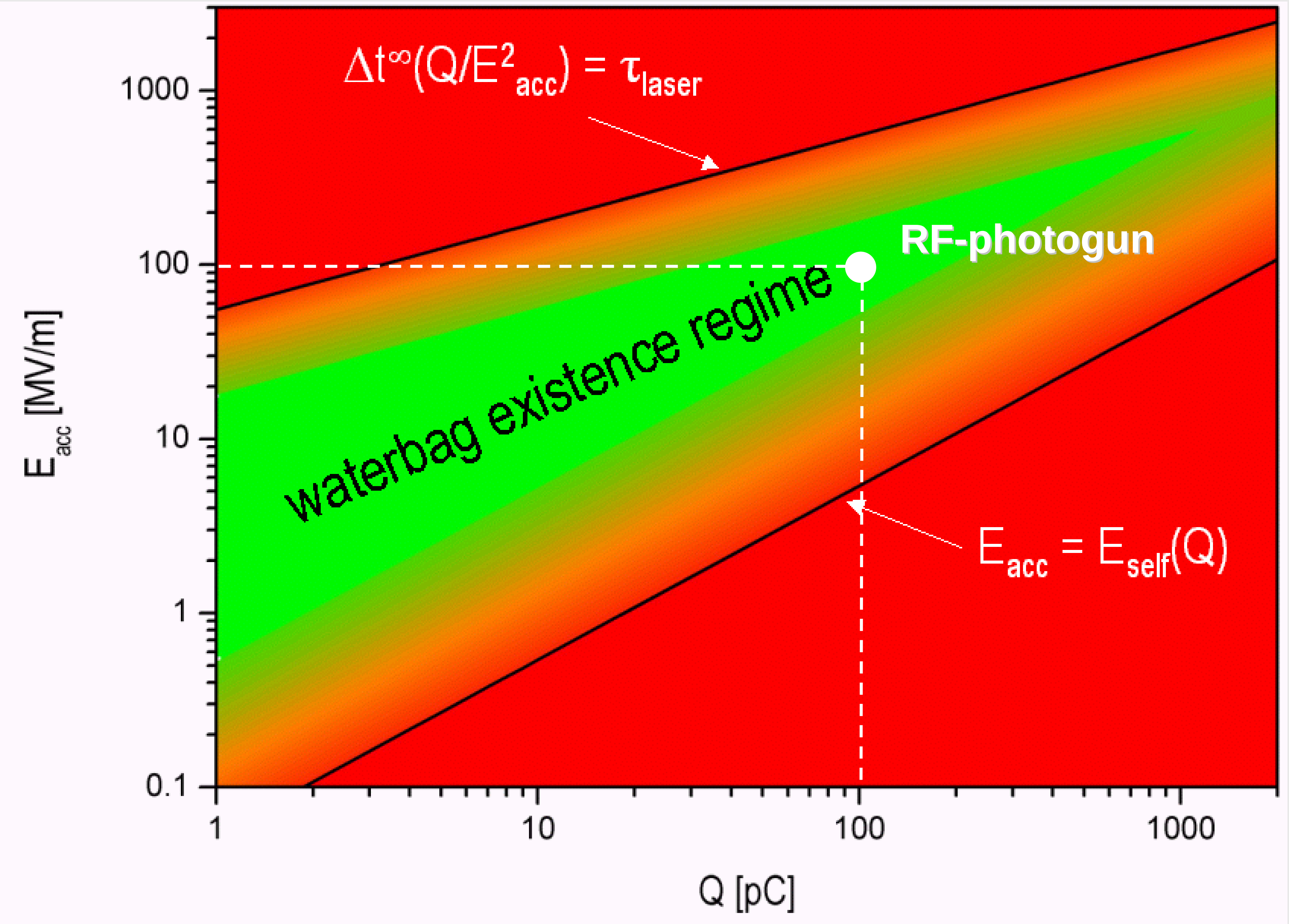


How to Realize Uniform Three-Dimensional Ellipsoidal Electron Bunches
O.J. Luiten, S.B. van der Geer et al, PRL 094802, (**2004**).

Beam radius = 1 mm, laser duration = 30 fs



Beam radius = 1 mm, laser duration = 30 fs



Goal

- Develop compact high-brightness rf-photogun
  - Using waterbag concept
  - Established 100 MV/m S-band technology

- Parameters — Target
  - Peak current: — 1 kA
  - Emittance: — 1 μm

Parameters	Target
Peak current:	1 kA
Emittance:	1 μm
	1 kA/μm^2

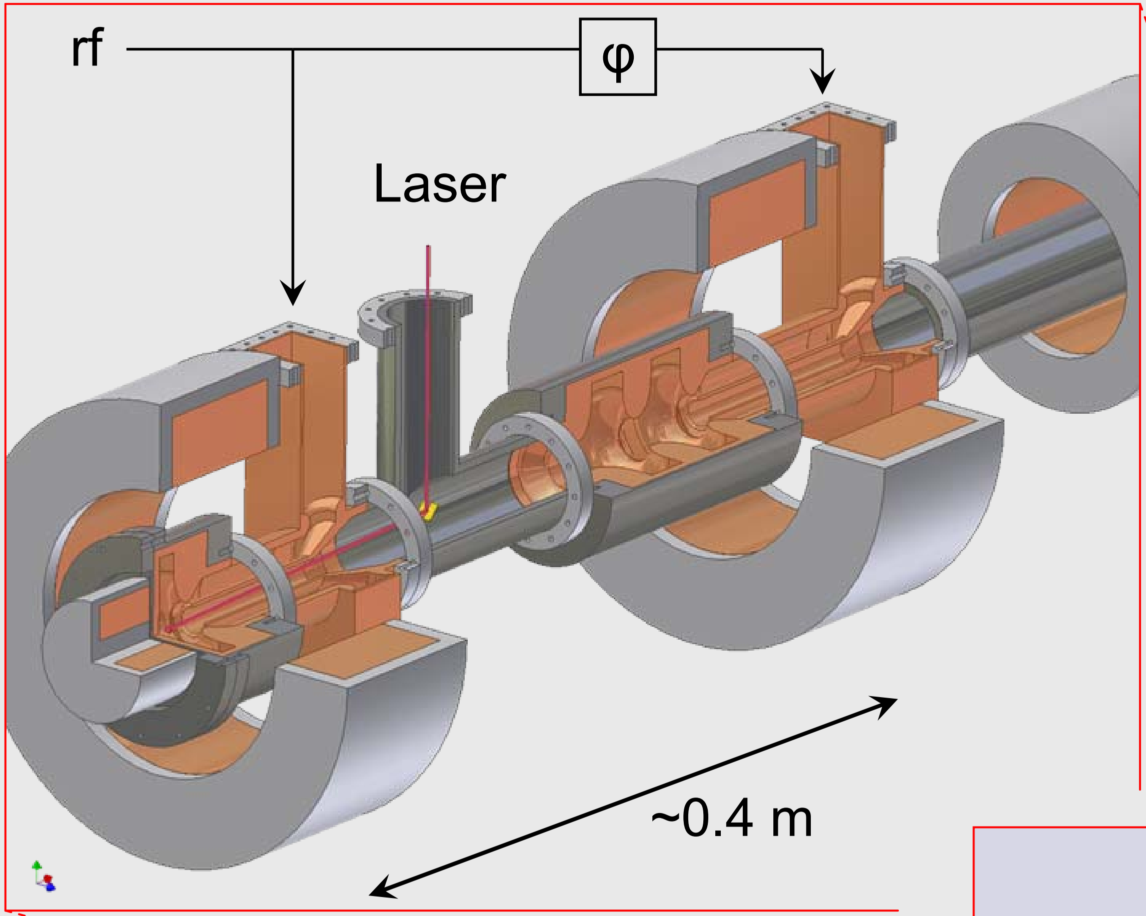
Goal

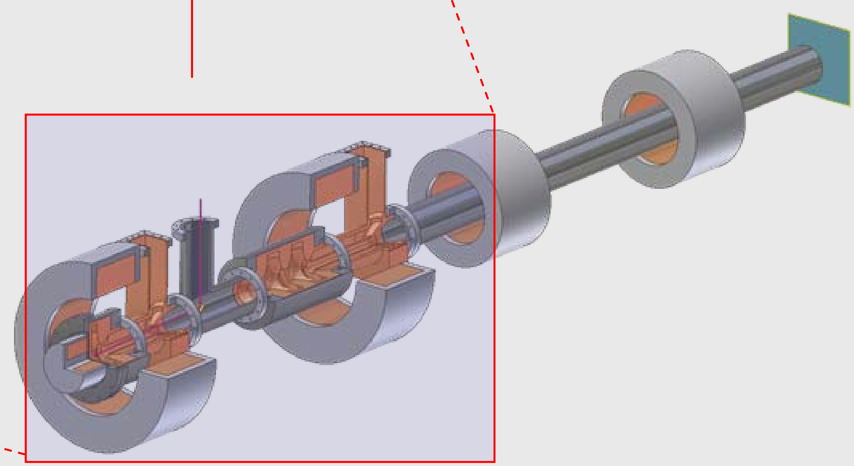
- Develop compact high-brightness rf-photogun
  - Using waterbag concept
  - Established 100 MV/m S-band technology

- Parameters

Parameters	Simulations	Target
– Peak current:	700 A	1 kA
– Emittance:	0.7 μm	1 μm
	1.4 kA/μm^2	1 kA/μm^2
– Energy:	3.5 MeV	
– Pulse length:	120 fs rms	
– Spot size:	140 μm rms	
– Energy spread:	40 keV rms	

Set-up

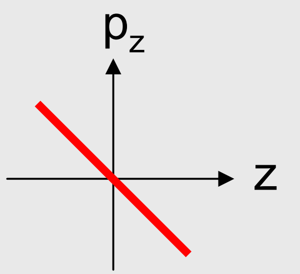




S.B. van der Geer et al, PRST-AB, 9, 044203 (2006),

Ballistic bunching

- Time compression
  - Velocity differences can compress a bunch
  - Requires <u>negative</u> slope in z-p_z space



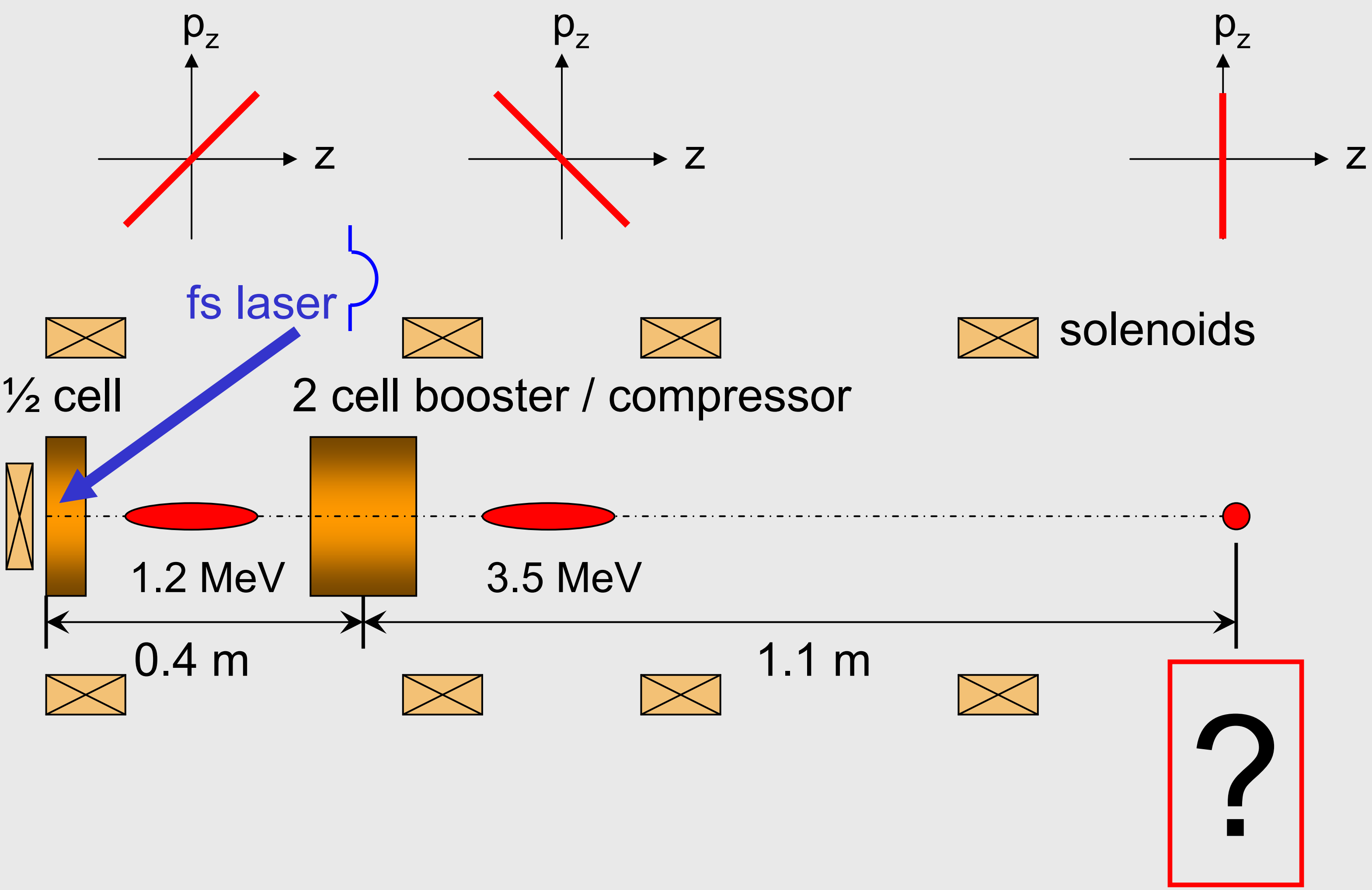
$$\begin{cases} \gamma = \dfrac{1}{\sqrt{1-v^2/c^2}} \\ E_{kin} = (\gamma - 1)\, m\, c^2 \end{cases} \Rightarrow \Delta v = \frac{1}{v\,\gamma^3}\frac{\Delta E}{m}$$

- Non-linear process
  - $E \approx \frac{1}{2} m v^2$
  - Relativistic effects

- Works most efficient at relatively low energies

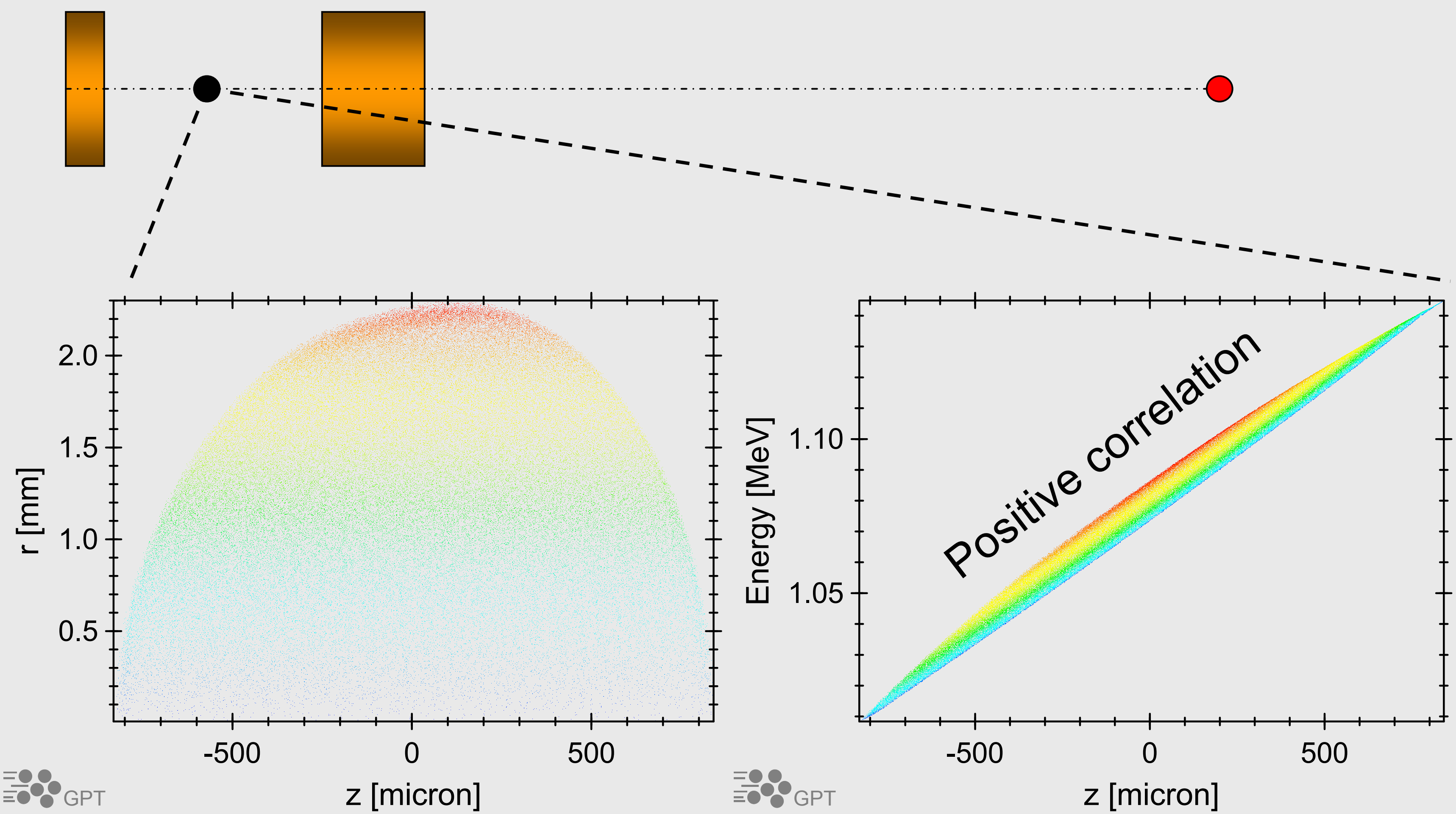
Split rf-photoinjector

Waterbag bunches, 100 MV/m, 3 GHz, 10 MW



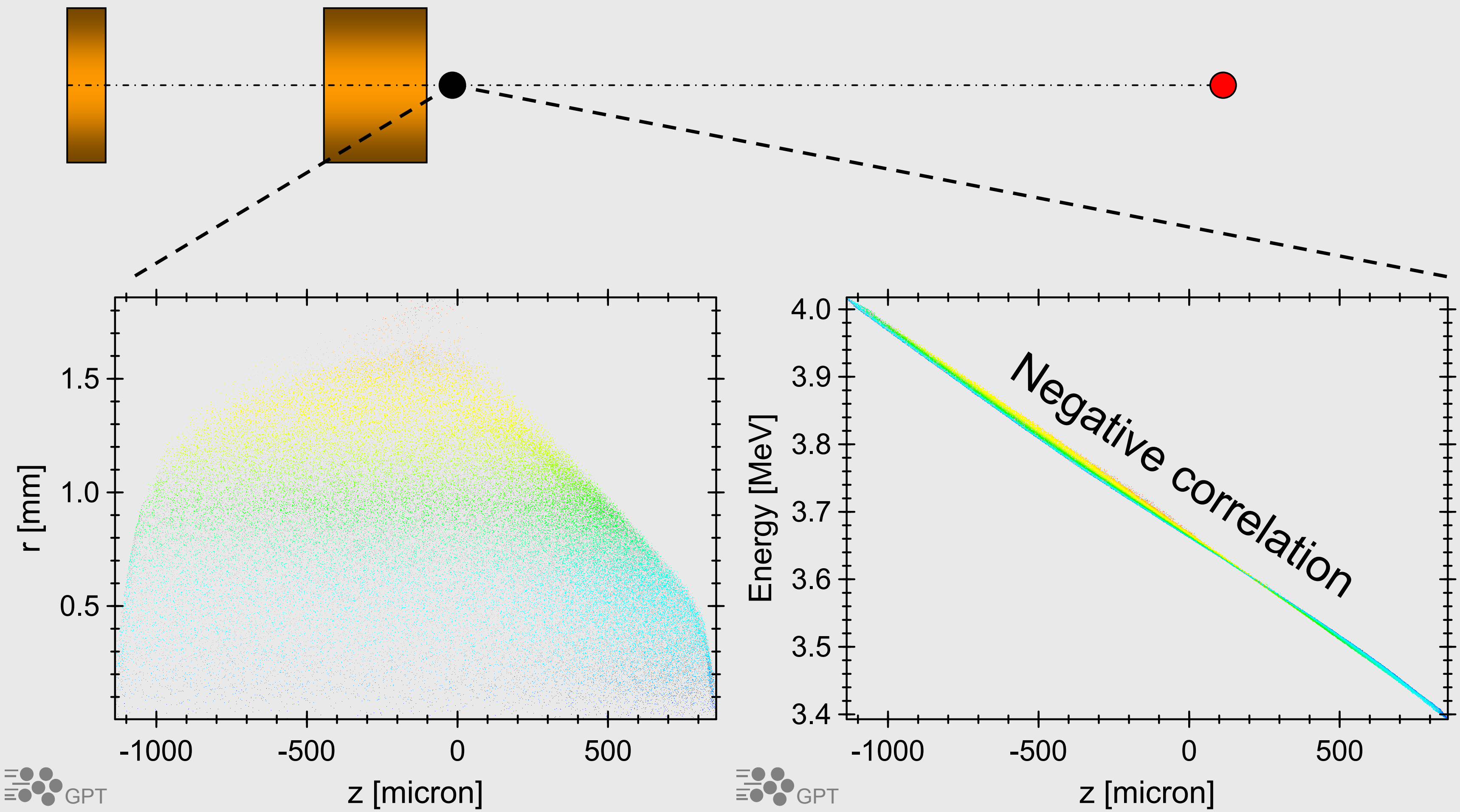
0.2 m

Bunch expands longitudinally, remains ellipsoid



0.5 m

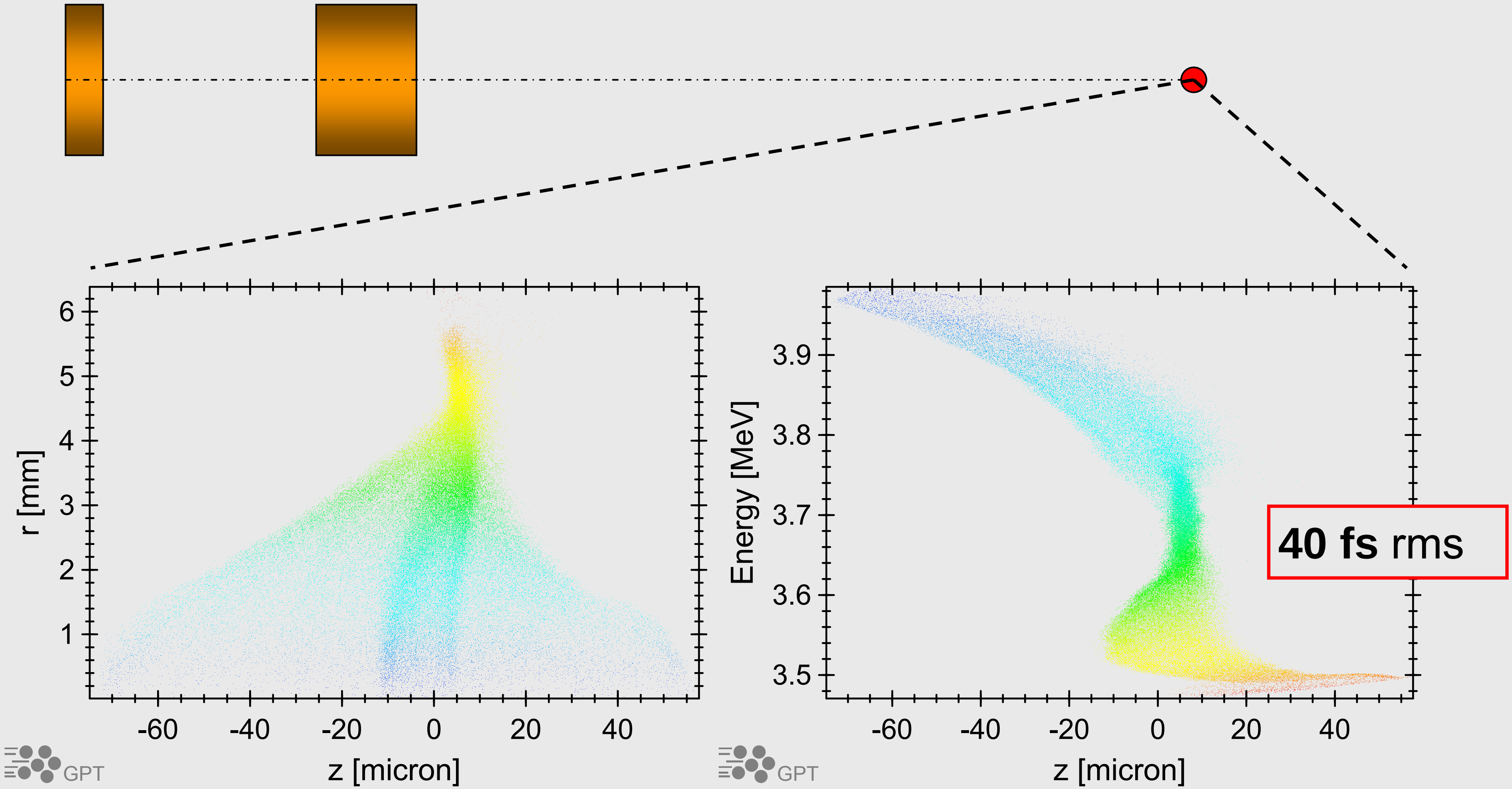
Energy-position correlation reversed



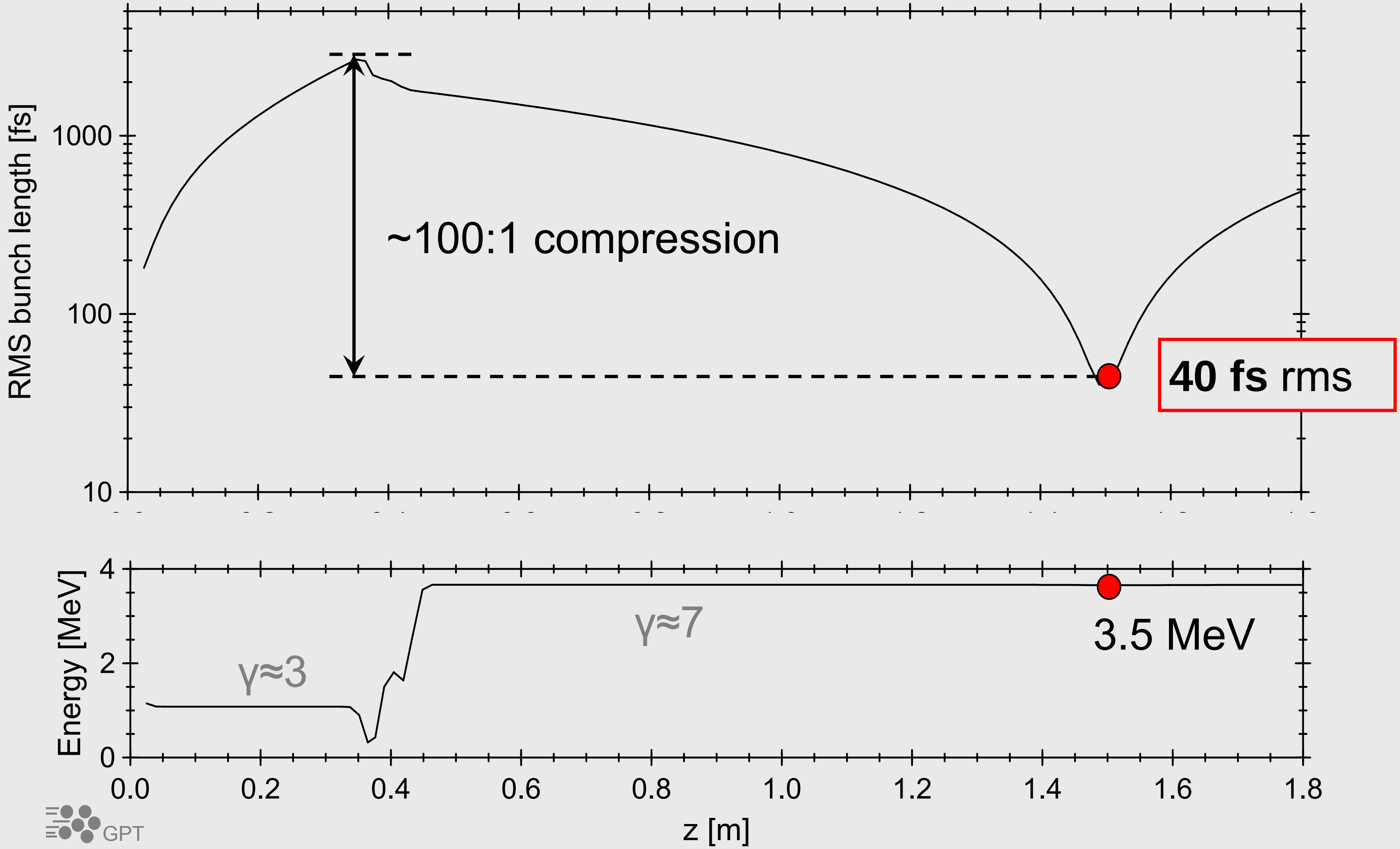
Longitudinal focus

In longitudinal focus:

- Dominated by an accumulation of non-linear effects

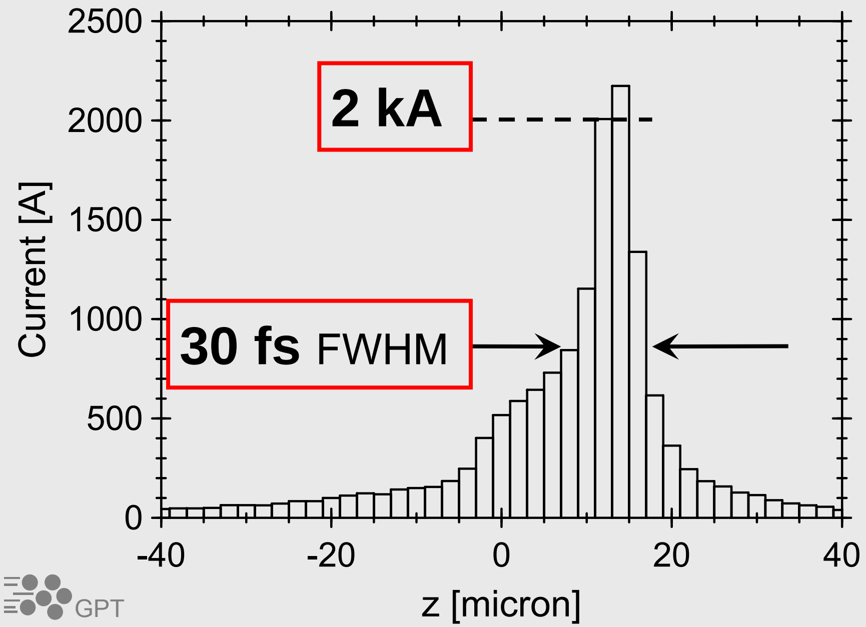


Evolution of bunch length and energy

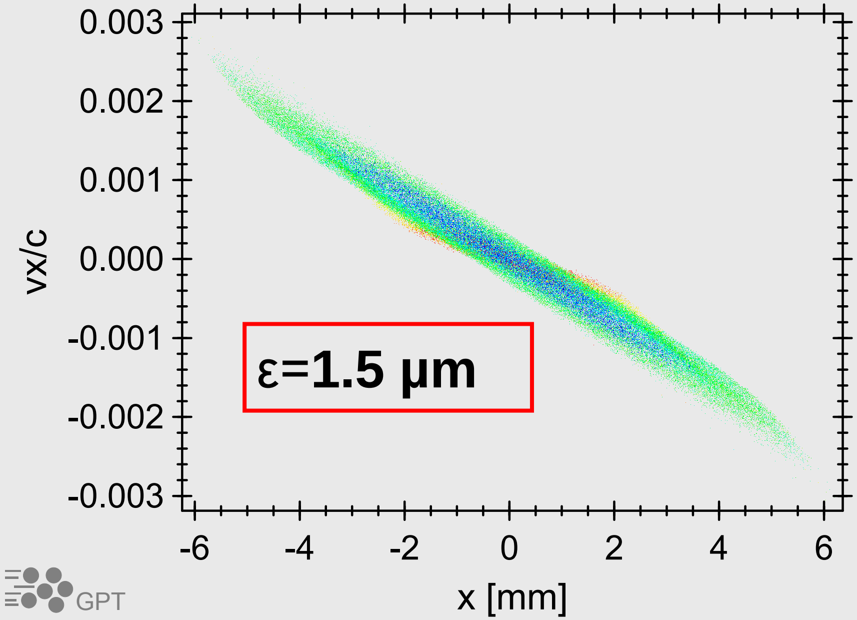


Longitudinal focus

Current profile

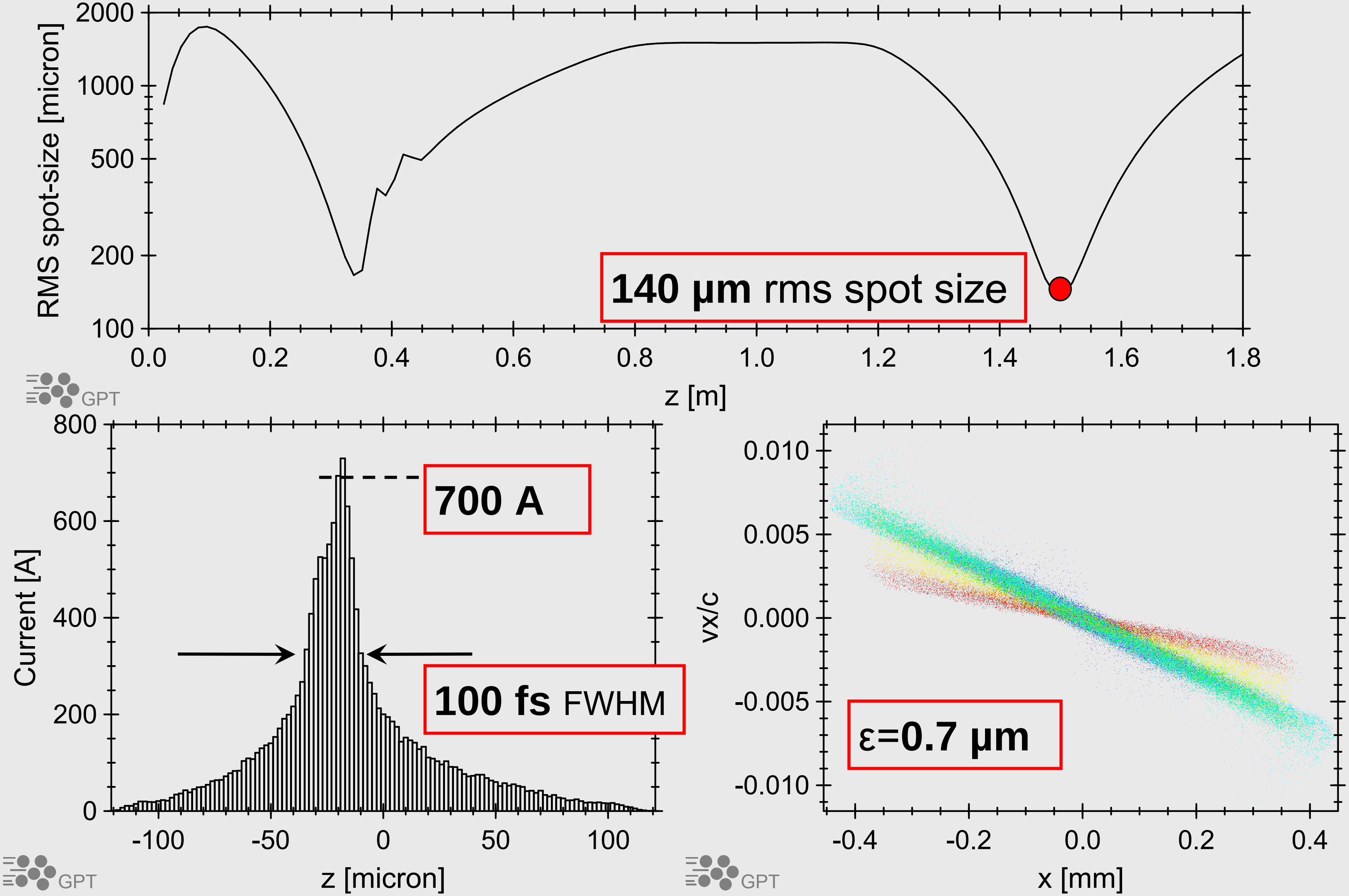


Transverse phase-space



Short bunch, extremely high peak current, reasonable emittance

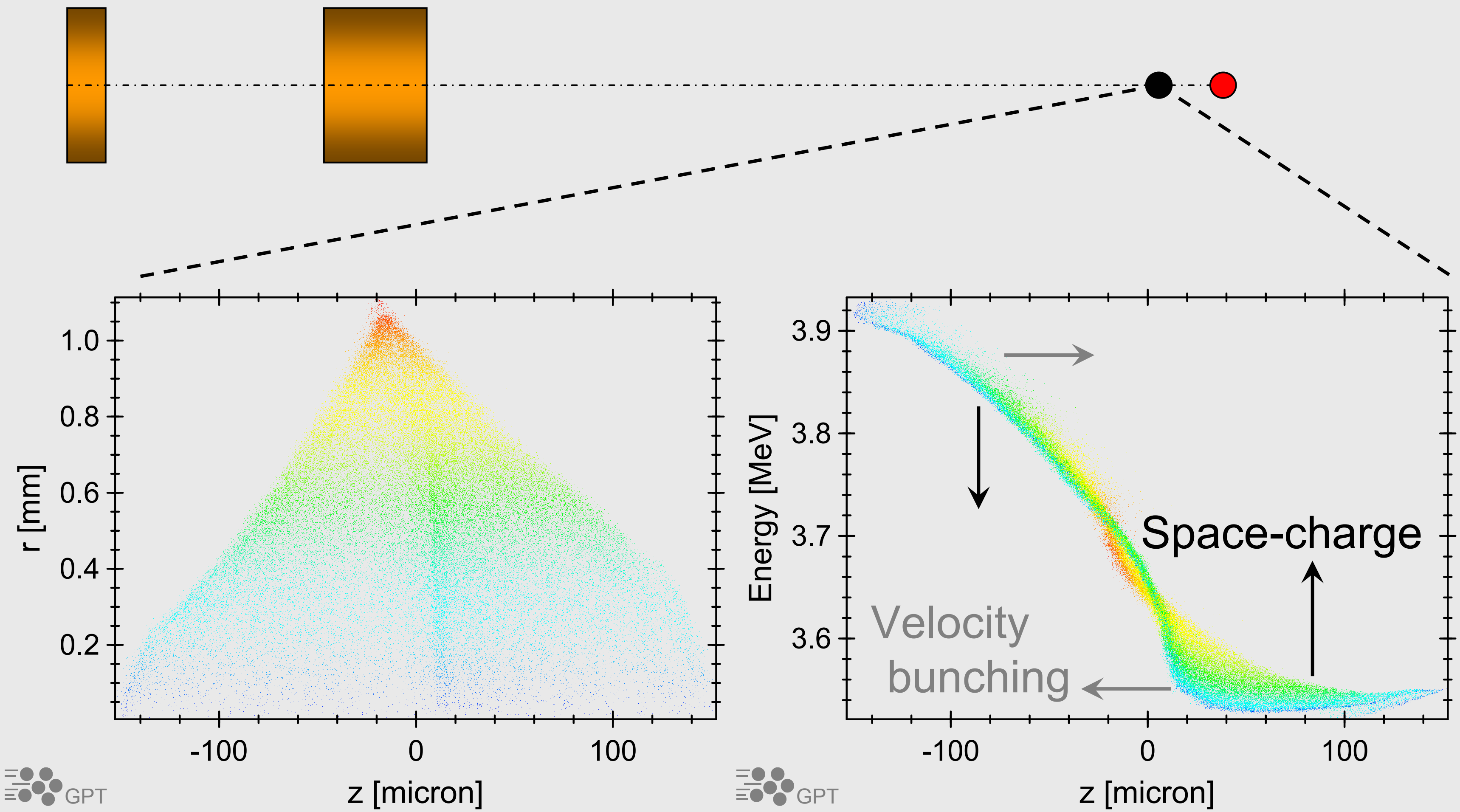
Optimize for 6D brightness



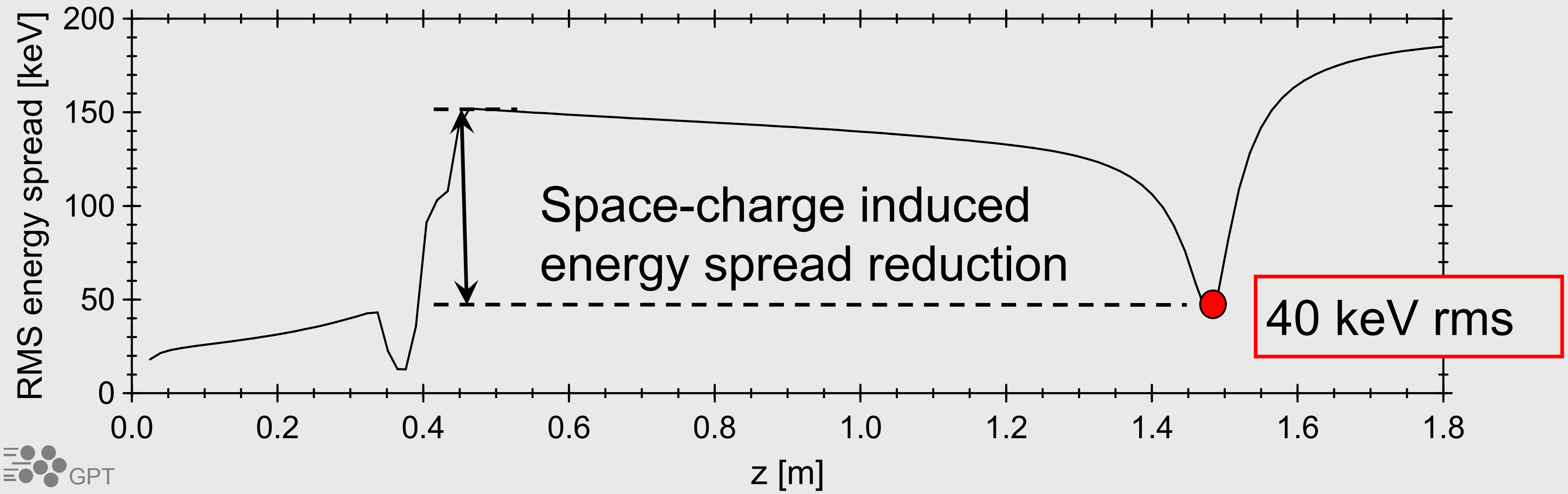
1.4 m

10 cm before 3D focus

- Not ellipsoid



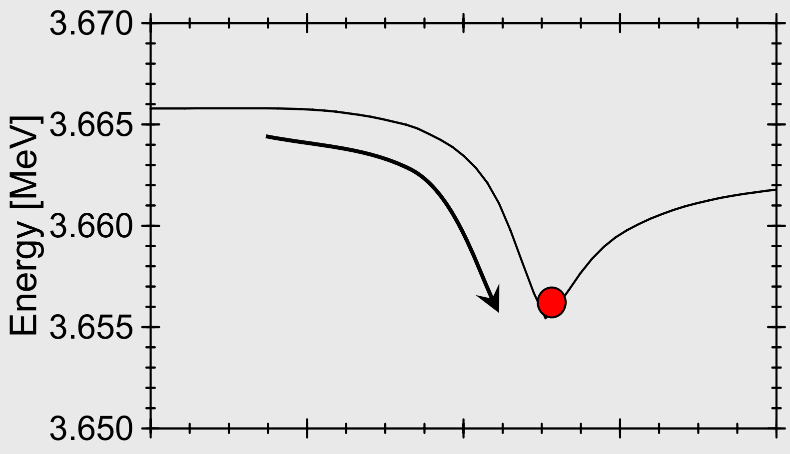
Energy spread reduction



- Transverse focusing
  - Increases SC forces
  - Kinetic → potential energy
  - Reduces energy spread

100 fs FWHM	**ε=0.7 μm**
700 A	**40 keV** rms

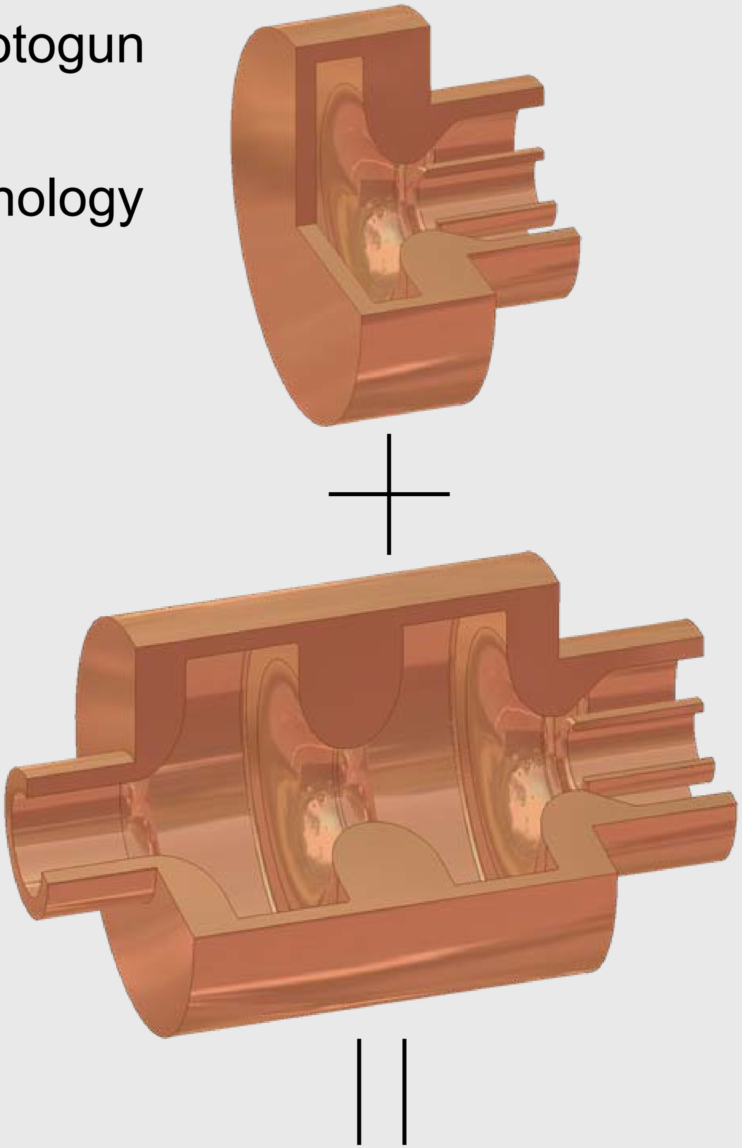
Bunch average kinetic energy



Conclusion: Reached our goal

- Develop compact high-brightness rf-photogun
  - Using waterbag concept
  - Established 100 MV/m S-band technology

Parameters	Simulation
– Peak current:	700 A
– Emittance:	0.7 µm
	1.4 kA/µm^2
– Energy:	3.5 MeV
– Pulse length:	120 fs rms
– Spot size:	140 µm rms
– Energy spread:	40 keV rms



Coherent Transition Radiation (CTR)

100 pC, 100 fs, 100 µm, 5 MeV

- Energy per pulse: ~10 µJ
- Electrical fields: ~ 1 GV/m