Overview of Methods

- LASER PULSE SHAPING (for photocathodes)
  → ATF @ BNL / UCLA (Zhou, Ben-Zvi, Babzien, Chang, Doyuran, Malone, Wang, Yakimenko)
  → Sumitomo Heavy Industries Ltd. / Femtosecond Technology Research Association
- SOLENOIDS
  → TTF @ DESY (Zhang)
  → PITZ @ DESY / TU Darmstadt (Cee, Krassilnikov, Setzer, Weiland)
- NON-LINEAR ELECTROSTATIC FIELDS
  → Eindhoven University of Technology / Pulsar Physics (van der Geer, de Loos, Botman, Luiten, van der Wiel)

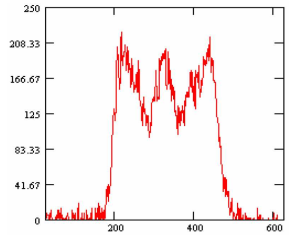
Laser Pulse Shaping (1)

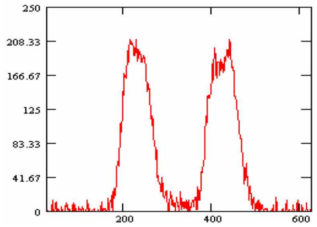
- Simulation code: PARMELA
- Laser beam non-uniformity:
  $\Longrightarrow$ Non-linear space charge forces
  $\Longrightarrow$ Emittance growth
- Investigate spatial and temporal shaping!

Laser Pulse Shaping (2)

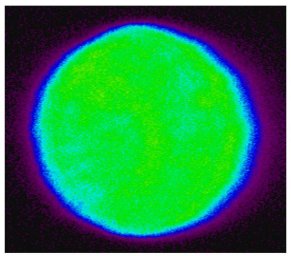
Spatial shaping:

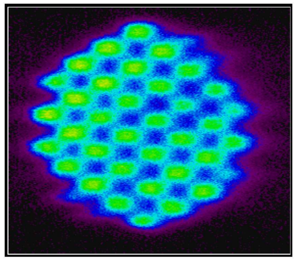
- Cylindrical symmetry: 30% – 40% emittance growth for peak-to-peak variations (40% – 70%); “hollow beam” leads to 100% increase!





- Non-cylindrical symmetry: Masks (90% – 50% transmission efficiency) show an increase of emittance between 30% – 100%

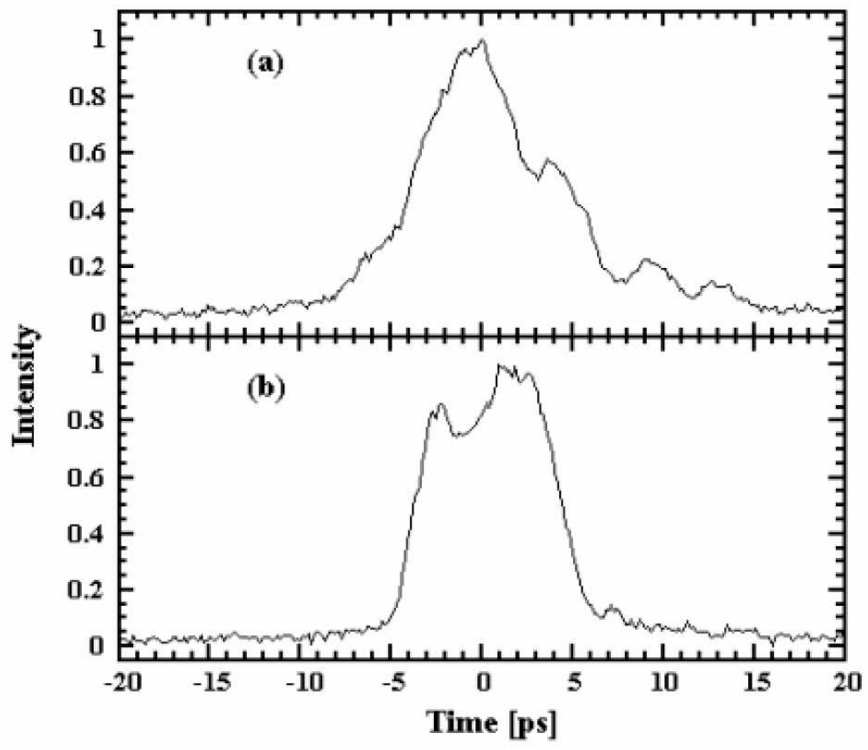




Laser Pulse Shaping (3)

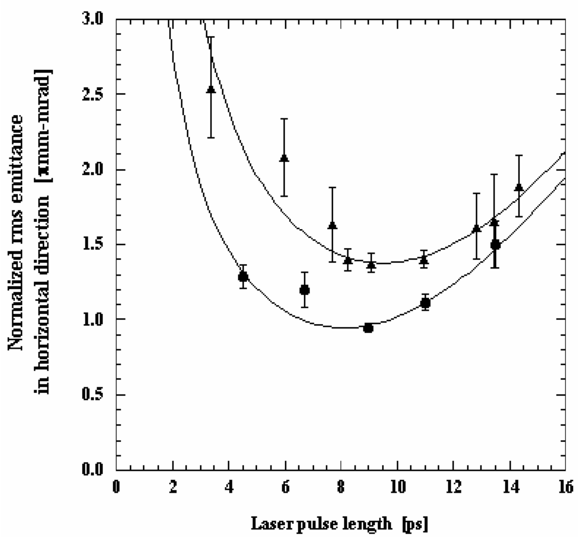
Temporal shaping:

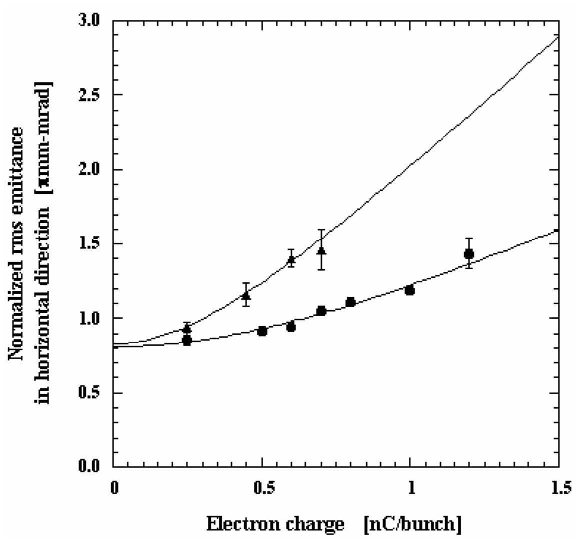
- Compare emittance growth between Gaussian and square pulses



Laser Pulse Shaping (4)

- Compare these shapes for different pulse length and different bunch current (for small pulse length emittance is dominated by space-charge, for long pulse length it is dominated by RF)





$\Longrightarrow$ Emittance reduced by 44% for square pulse shape (8 – 10 ps)

$\Longrightarrow$ Emittance reduced by 50% for square pulse shape ($Q_b = 0.6$ nC)

$\Longrightarrow$ $\epsilon_n^{RMS} = 1.2\pi$ mm·mrad for 1 nC current and 9 ps FWHM laser pulse

Solenoids(1)

- Simulation code: MAFIA
- Key Idea: Solenoid confines beam to forming Brillouin flow and transfers particles' angular momentum to a focusing force at its exit
  $\Longrightarrow$ Focusing Force = Space Charge Repulsion
  $\Longrightarrow$ Thereafter further acceleration to $\gamma \gg 1$
- $\epsilon_x = \sqrt{\overline{x^2}\ \overline{p_x^2} - \overline{xp_x}^2}$ $\quad\rightarrow$ linear forces don't alter ϵ_{RMS}
- Busch's Theorem: $rP_\phi + \frac{q}{2\pi}\psi = const$ $\quad$ ($\psi = \oint B\ d\sigma$ is the flux)

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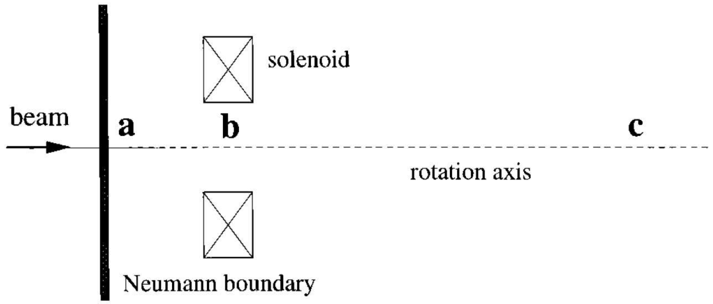
Solenoids(2)

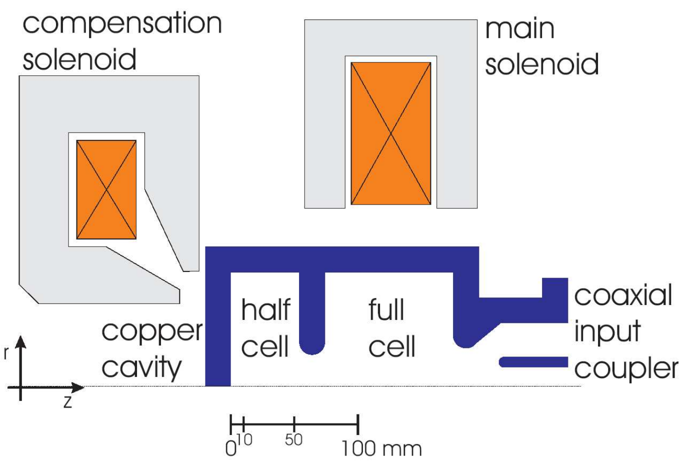
- TTF setup:



  - $B = 0$ at the Neumann boundary; necessary for Busch's Theorem, otherwise beam would become axial-confined flow (each particle rotates around local magnetic flux line instead of global precession around beamline axis)
  - Between a and c Brillouin flow (particles rotate around axis)
  - Solenoid fringe very weak at $c \rightarrow$ rotating momentum turns into focusing momentum

Solenoids(3)

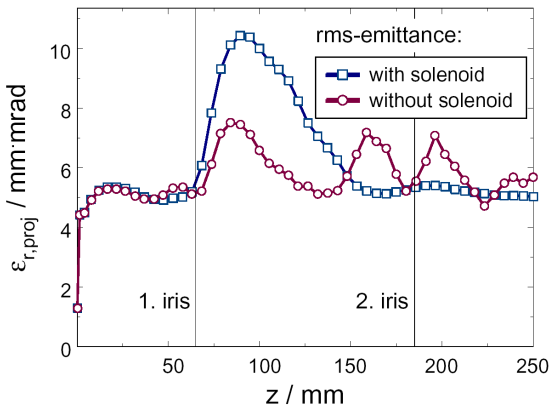
- TU Darmstadt setup:



  - Main solenoid: DC lens → beam focusing and compensation of emittance caused by space charge effects
  - Compensation solenoid: $B = 0$ at cathode → electrons have no azimuthal momentum at gun exit

Solenoids(4)

- MAFIA results:



  - $z \ll 1$: Strong emittance growth due to nonlinear radial space charge forces to about ≈ 5 mm·mrad
  - $z \gg 1$: Emittance determined by RF effects and iris fringe fields

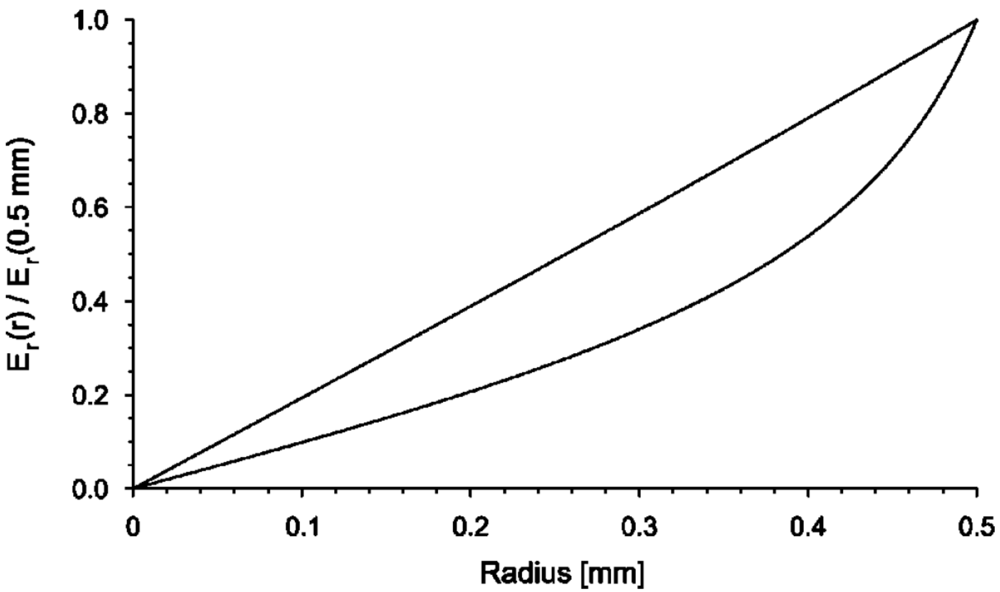
$\Longrightarrow$ Emittance with and without solenoid field similar, but different slope of phase space ellipse (with solenoid: converges, without solenoid: beam exits gun in divergent state)

Non-linear Electrostatic Emittance Compensation (1)

- Simulation code: GPT (General Particle Tracer) and POISSON
- Requirements:
  - kA disk-shaped electron bunches
  - Accelerate to 2 MeV in a 1 GV/m field (keep non-relativistic part of trajectory short!)
  - No magnetic compression (avoid radiative collective effects) $\Longrightarrow$ instead photo-emission from metal cathode by 1 fs laser

Non-linear Electrostatic Emittance Compensation (2)

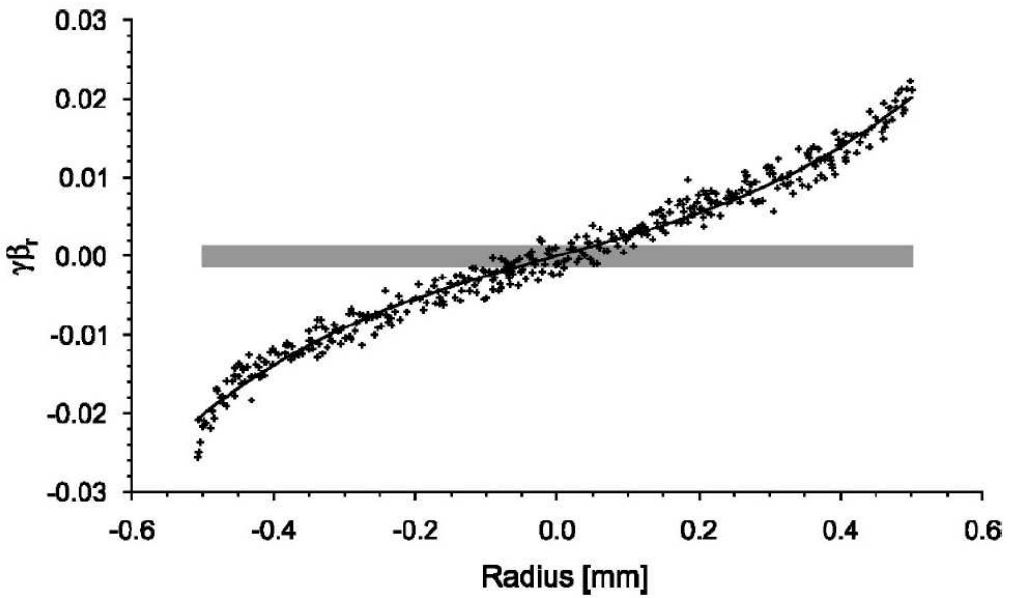
- Problems:
  - Non-linearity of radial space charge is much larger in a flat disk-shaped bunch than in a cigar-shaped bunch



Radial component of the electric self-field in the median plane of a short and long bunch with 1 mm diameter and identical density profiles

Non-linear Electrostatic Emittance Compensation (3)

- Problems:
  - Small iris of the 1 GV/m accelerating diode gives rise to highly non-linear radial field component

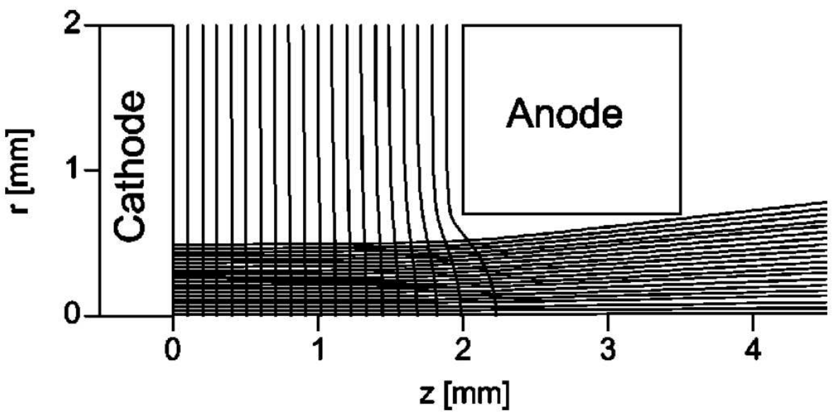


$r - p_r$ transverse phase space at $z = 0$ mm and $z = 0.85$ mm from cathode surface

Non-linear Electrostatic Emittance Compensation (4)

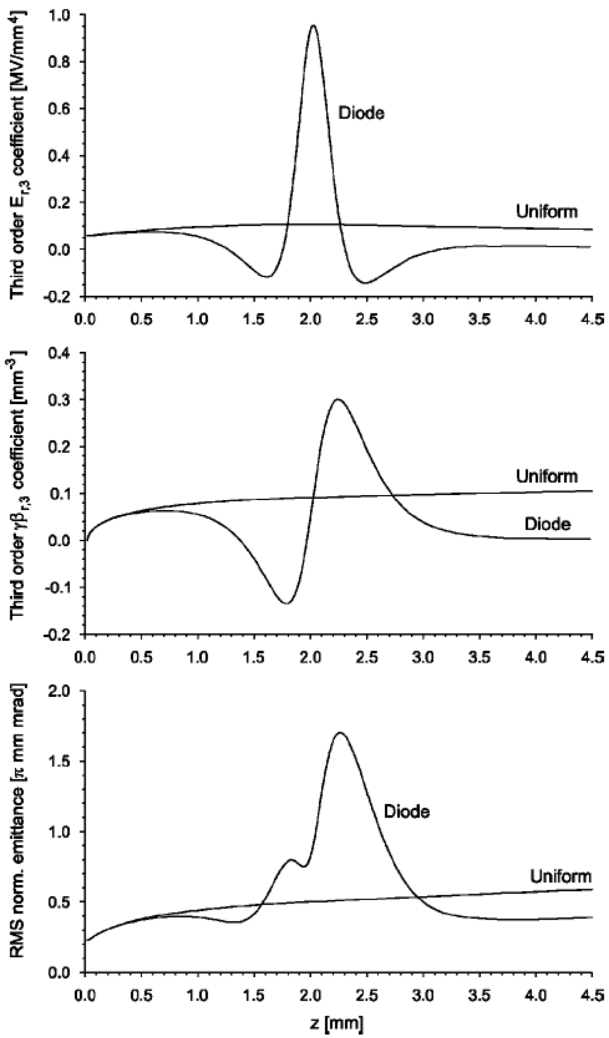
- Solution:
  - Detrimental effects due to these field non-linearities must cancel each other
  - Radial third-order component of the electrostatic accelerating field should minimize transverse RMS emittance

$\Longrightarrow$ Special diode geometry:



Spherical aberration of diode lens: $E_r = E_{r,1}(z)\, r + E_{r,3}(z)\, r^3$

Non-linear Electrostatic Emittance Compensation (5)



- Uniform acceleration: only space charge
- Anode opening is at 2 mm $\longrightarrow$ largest $E_{r,3}$
- For $z \leq 1$ mm and $z \geq 4$ mm acc. field is almost uniform and therefore $E_{r,3}$ similar

- $\gamma\beta_r = p_r/mc$ vs. r is governed by $E_{r,3}$ $\Longrightarrow \gamma\beta_r = \gamma\beta_{r,1}(z)\ r + \gamma\beta_{r,3}(z)\ r^3$
- Special diode geometry: $\gamma\beta_{r,3} = 0$ for $z \geq 3.5$ mm

- $z \leq 1$ mm: roughly uniform field
- $1 \leq z \leq 1.5$ and $2.5 \leq z \leq 3$: compensation due to negative sign of $E_{r,3}$
- Over-compensation at $z \geq 1.5$ mm
- Strong emittance blow-up at $z = 2.3$ mm because of large positive $E_{r,3}$

$\Longrightarrow$ Resulting ϵ_n^{RMS} lower than with uniform acc. field

Non-linear Electrostatic Emittance Compensation (6)

- Results:
  - At the diode exit $\gamma\beta_{r,3} = 0$, i.e. non-linearities have been fully compensated
    $\Longrightarrow$ Minimum RMS emittance achieved!
  - From simulation: 100 pC, 73 fs FWHM pulse $\rightarrow$ 1,2 kA @ 2 MeV with RMS emittance reduced by 34% to 0.4 π mm·mrad at the exit of the diode structure

References

- *Emittance Growth Due to the Laser Non-Uniformity in a Photoinjector*, F. Zhou, I. Ben-Zvi, M. Babzien, X. Y. Chang, A. Doyuran, R. Malone, X. J. Wang, V. Yakimenko, Proceedings of EPAC 2002, Paris, France
- *Experimental Studies of Photocathode RF Gun with Laser Pulse Shaping*, J. Yang, F. Sakai, T. Yanagida, M. Yorozu, Y. Okada, T. Nakajyo, K. Takasago, A. Endo, Proceedings of EPAC 2002, Paris, France
- *Intuitive Description of Emittance Compensation and its Application to Beam Transport Lines*, M. Zhang, Proceedings of APAC 1998, Tsukuba, Japan
- *Beam Dynamics Simulations for the PITZ RF-Gun*, R. Cee, M. Krassilnikov, S. Setzer, T. Weiland, Proceedings of EPAC 2002, Paris, France
- *Nonlinear Electrostatic Emittance Compensation in kA, fs Electron Bunches*, S. B. van der Geer, M. J. de Loos, J. I. M. Botman, O. J. Luiten, M. J. van der Wiel, Physical Review E, Volume 65, 046501

The transparancies of this talk can be found at
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