Simulations for the 4 MeV OBLA test stand

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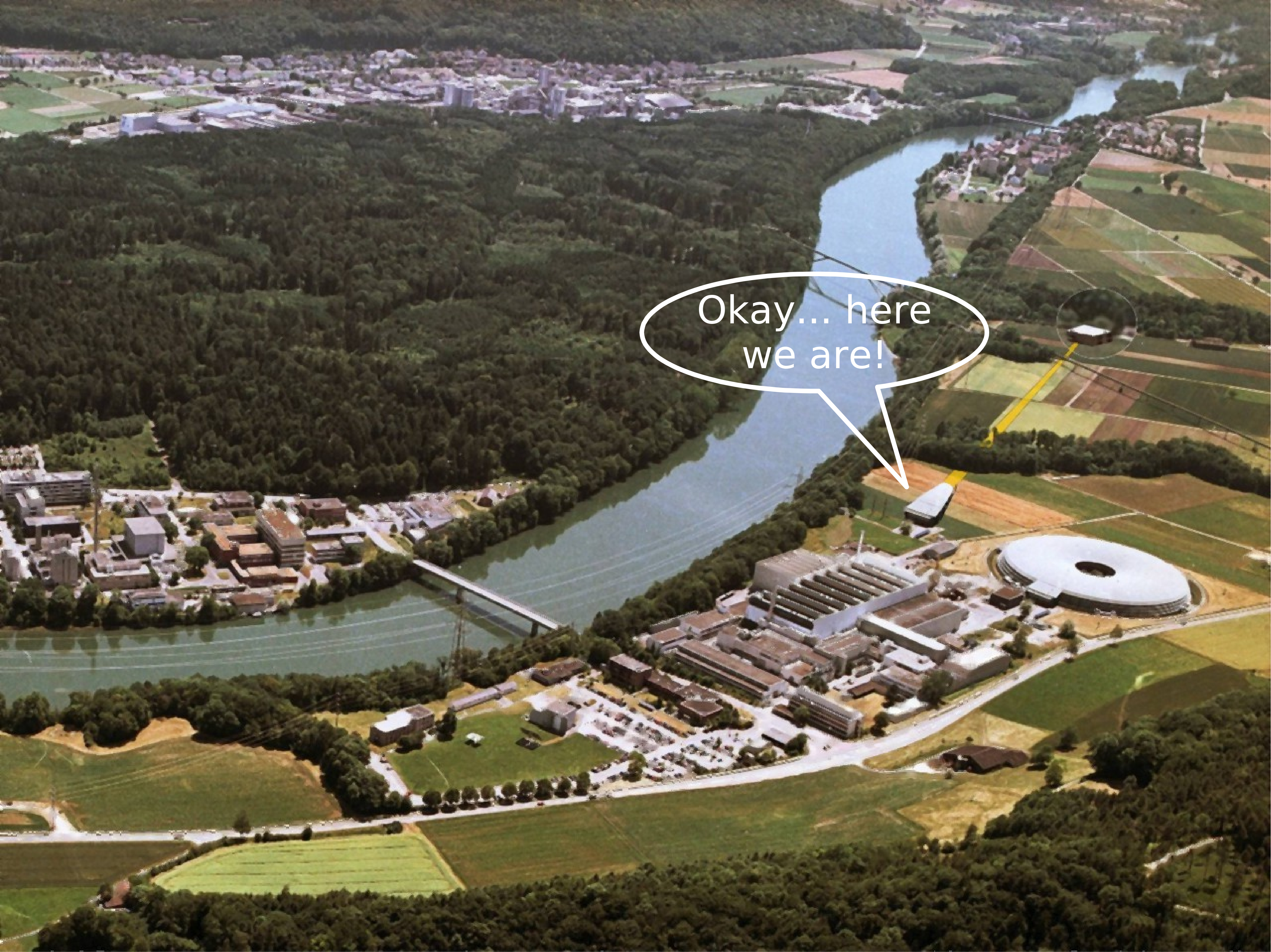
A compact X-FEL for Switzerland

We all know our ultimate goal:

an X-ray laser beam from
a compact source...

A compact X-FEL for Switzerland

Nope...


Okay... here we are!

Low emittance electron gun

$$\varepsilon = \frac{\varepsilon^{(n)}}{\beta\gamma} < \frac{\lambda}{4\pi}$$

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

- High energy, low emittance beams deliver short wavelength laser output → only low emittance is compatible with a compact facility

Design parameters for a low emittance electron gun:

- E : 3.5 MeV
- ε_s : 0.1 mm mrad
- Q : 220 pC
- I : 30 A
- Linear longitudinal phase space

Target parameters:

for the electron beam at the undulator:

- E : 6 GeV
- ε_s : 0.1 mm mrad
- Q : 220 pC
- I : 1.5 kA

→
- accelerator length : 435 m
- undulator length : 80 m
- other sections : 265 m
- **total length : < 800 m**

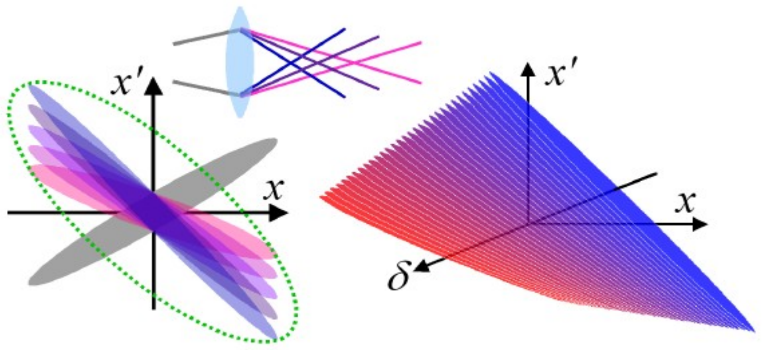
results in an output laser light of:

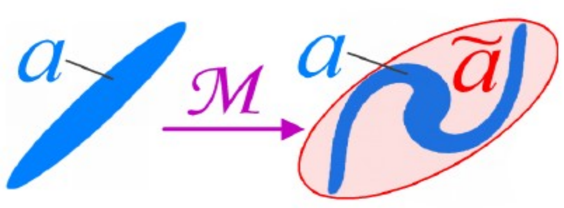
- λ : 1–100 Å
- B : 0.01–1 × 10^{33} [U]
- f : 10–100 Hz

Sources for emittance growth

- The phase space is an even-dimemsional manifold naturally endowed with a symplectic structure (i.e. volume 2-form)
- The evolution of any vector in phase space is generated by a Hamiltonian vector field
  → canonical flux
- A conanical flux preserves the symplectic structure
  → volume preserved
- Dynamics is described by symplectic maps

- The emittance is the mean area in phase space and is not necessarily preserved
- Projected emittance: projection is not a symplectic map
  → emittance increase
- Slice emittance: nonlinear forces (space charge, external fields) lead to filamentation of the phase space
  → emittance increase

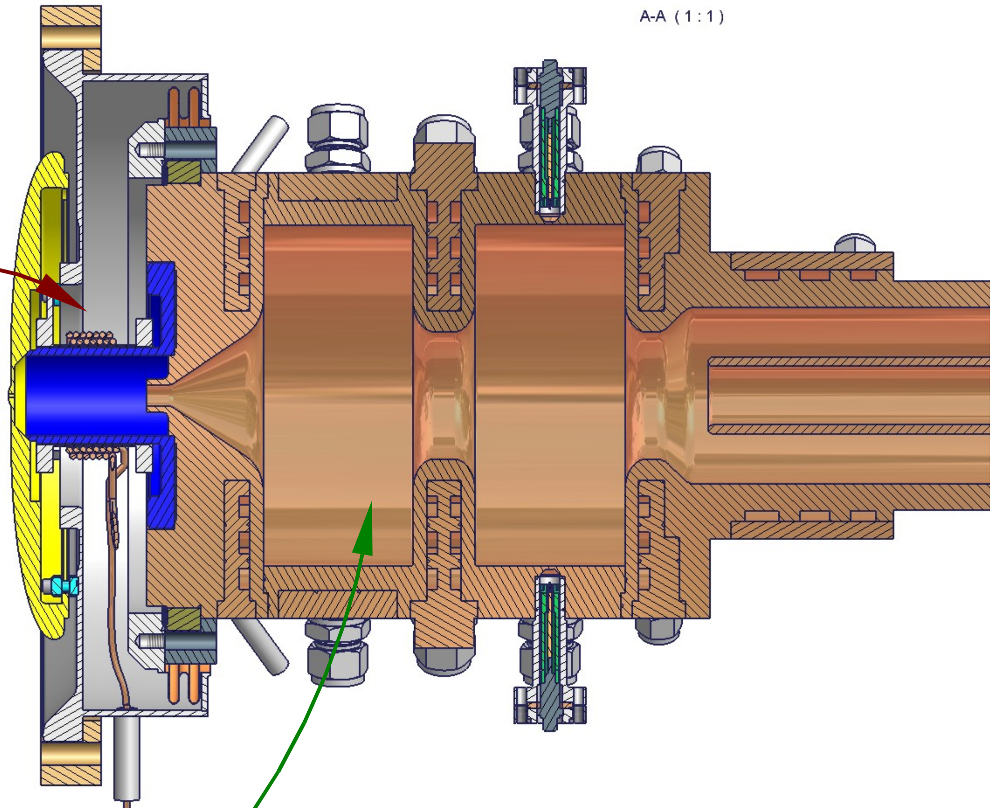




Images courtesy of A. Streun: pempp

Design of a low emittance gun

- Space charge induced emittance dilution dominated by perveance:
  → combine low current with high gradient
- Emittance dilution from external fields dominated by ratio of the diameter so the beam and of the surrounding cavity boundaries
  → minimise beam diameter by adequate matching scheme

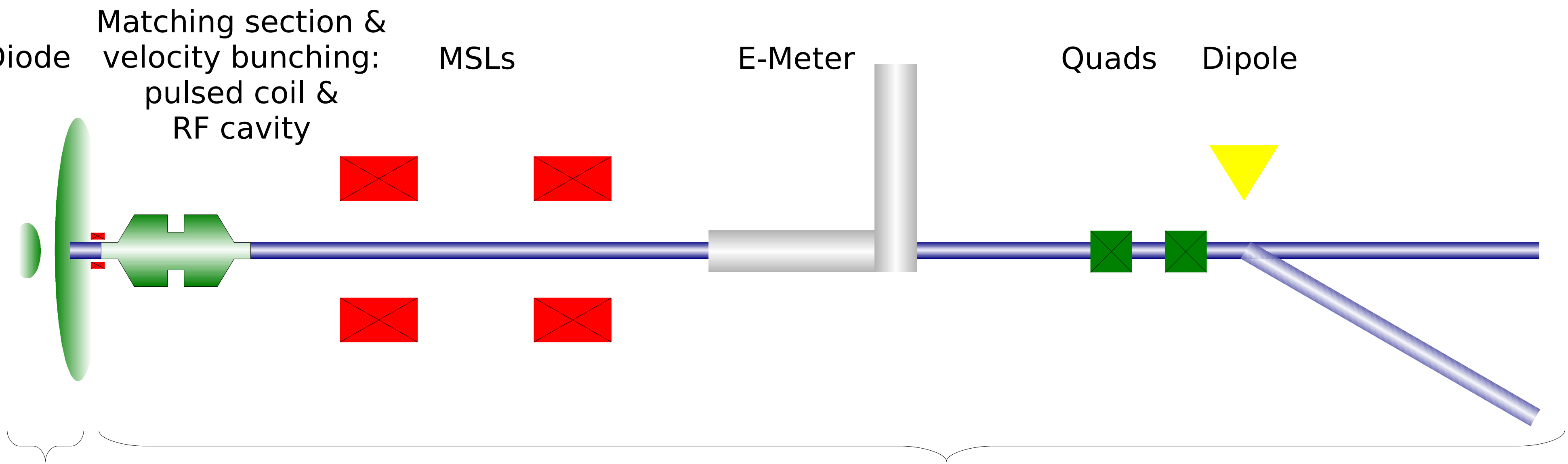


- Low current prevents lasing in the undulator and reduces brightness of photon beam
  → need to increase low current by aggressive bunch compression
  → velocity bunching in the RF cavity
- Bunch profile must not be changes at this early stage to enable further handling of the beam
  → linearisation of the longitudinal phase space
  → superposition of third harmonic mode in the RF cavity

Contents

Codes

“Numerical regions”



MAFIA:

- space charge dominated region
  → space charge model crucial
- no approximations for space charge forces: exacts solutions of Maxwell's equations → Lienard-Wiechert potentials with user defined boundaries

GPT:

- space charge forces suppressed
  → space charge model less crucial
- space charge forces solved on a grid in the rest frame → Poisson equation → after Lorentz transformation: exacts solutions of Maxwell's equations with retardation, but:
  - with identical velocity for all particles
  - without radiation terms

Additional codes

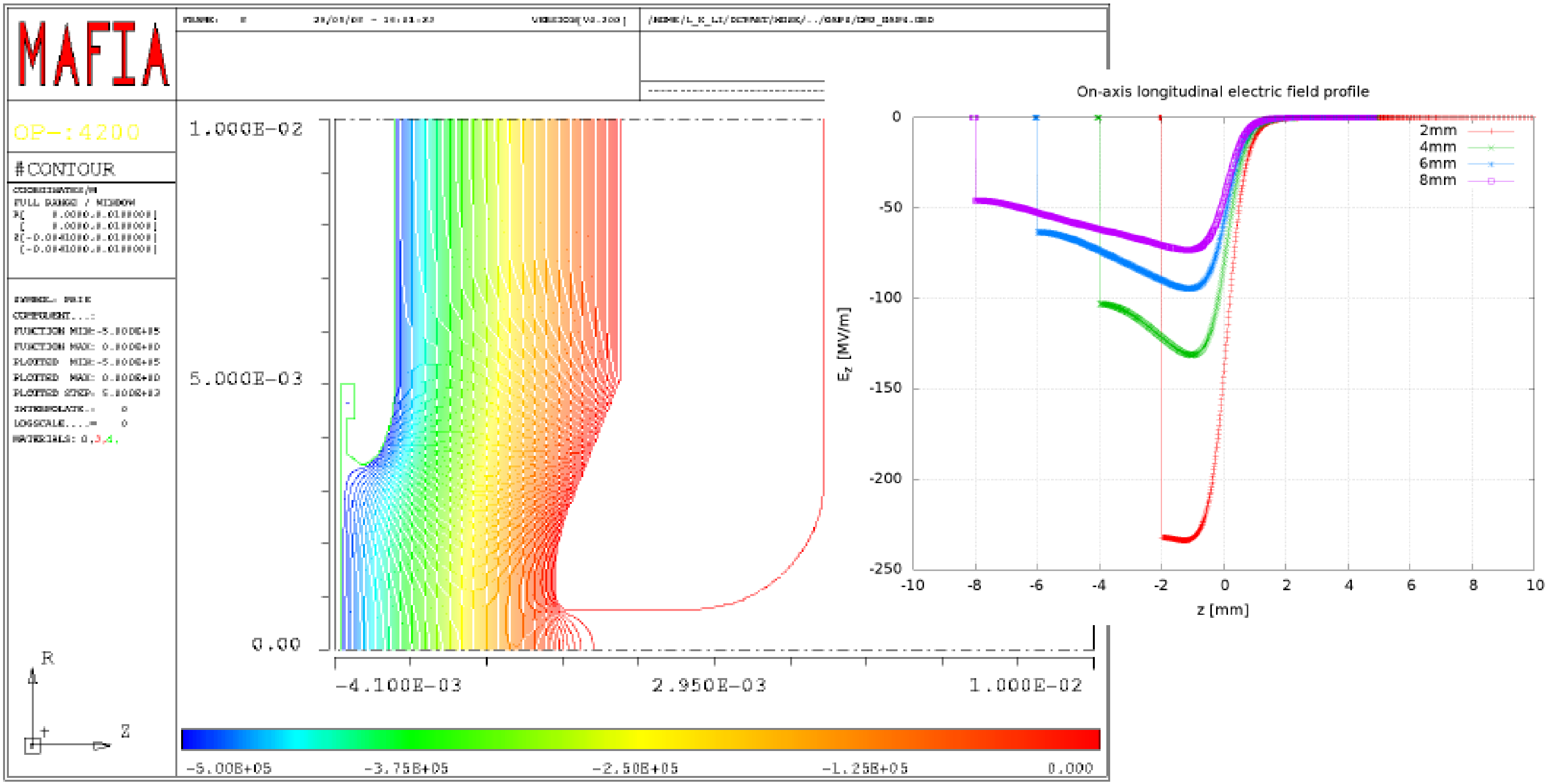
- HOMDYN: Beam envelope tracker
  - space charge calculated in rest frame with subsequent Lorentz transformation
    → retardation but no radiation terms
  - each slice reduced to a single point in phase space
    → all transverse effects are linearised
    → very fast tracking

Raistlin and Caramon (Twins from Dragonlance® Chronicles and Legends novels)

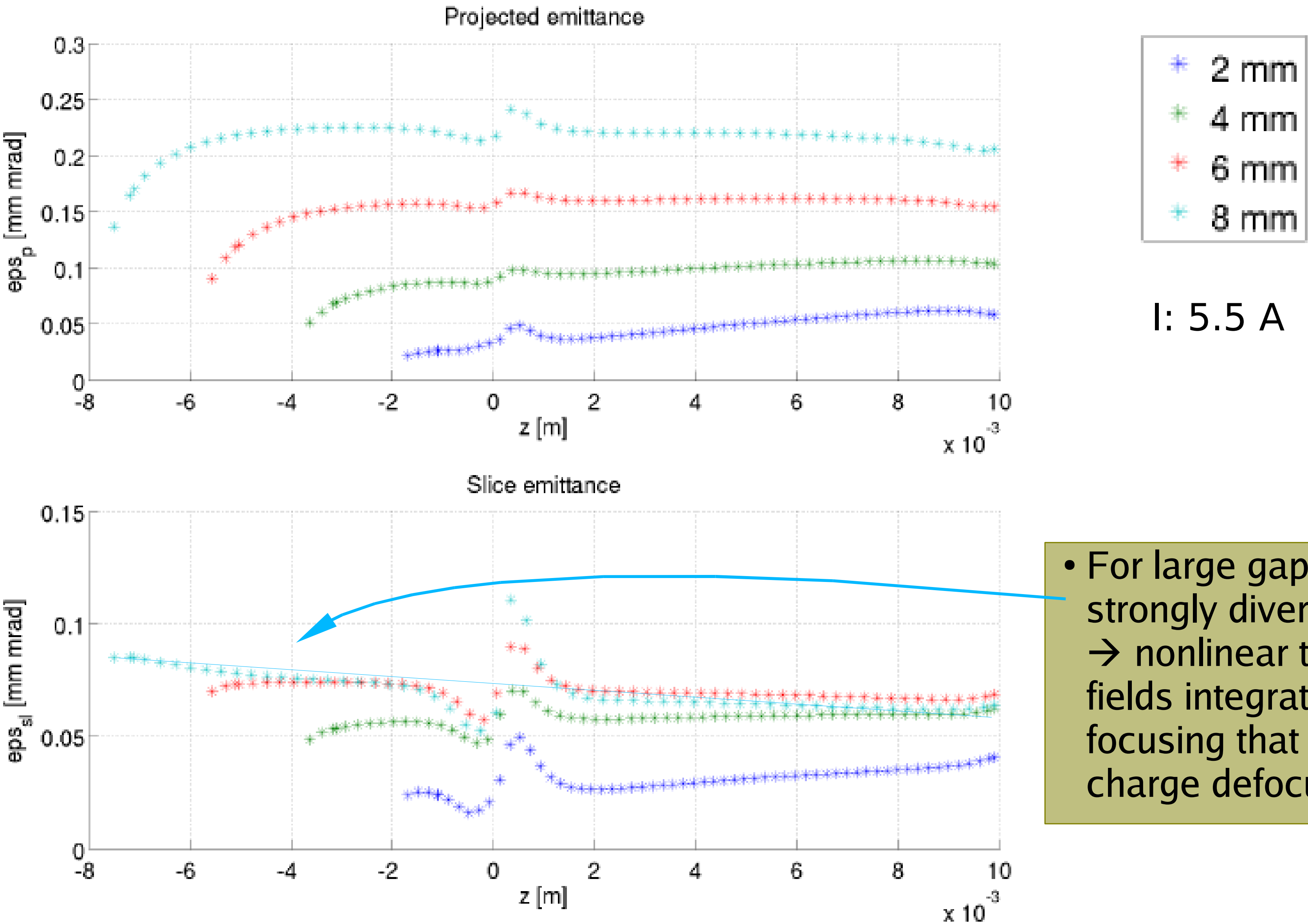
- RAISTLIN (RAdial field Integration by Slice Tracking with LINear space charge)
  - written in C++
  - tracks a single slice → fast
  - space charge forces linear, external fields from SUPERFISH T7 maps
    → evaluates contribution from nonlinear external fields to slice emittance increase
- CARAMON (Charged Axisymmetric Radiofrequency Accelerated Macroparticles ON-axis)
  - written in GNU Octave
  - tracks single macroparticle beamlet on-axis → fast (for multi-dimensional parameter space scans for velocity bunching)
  - RF fields given analytically by the user
    → independent on field maps
    → synchronisation can be investigated by quick evaluation of different RF configurations (varying cell length, distance of peaks)

Results

Diode: 2D design

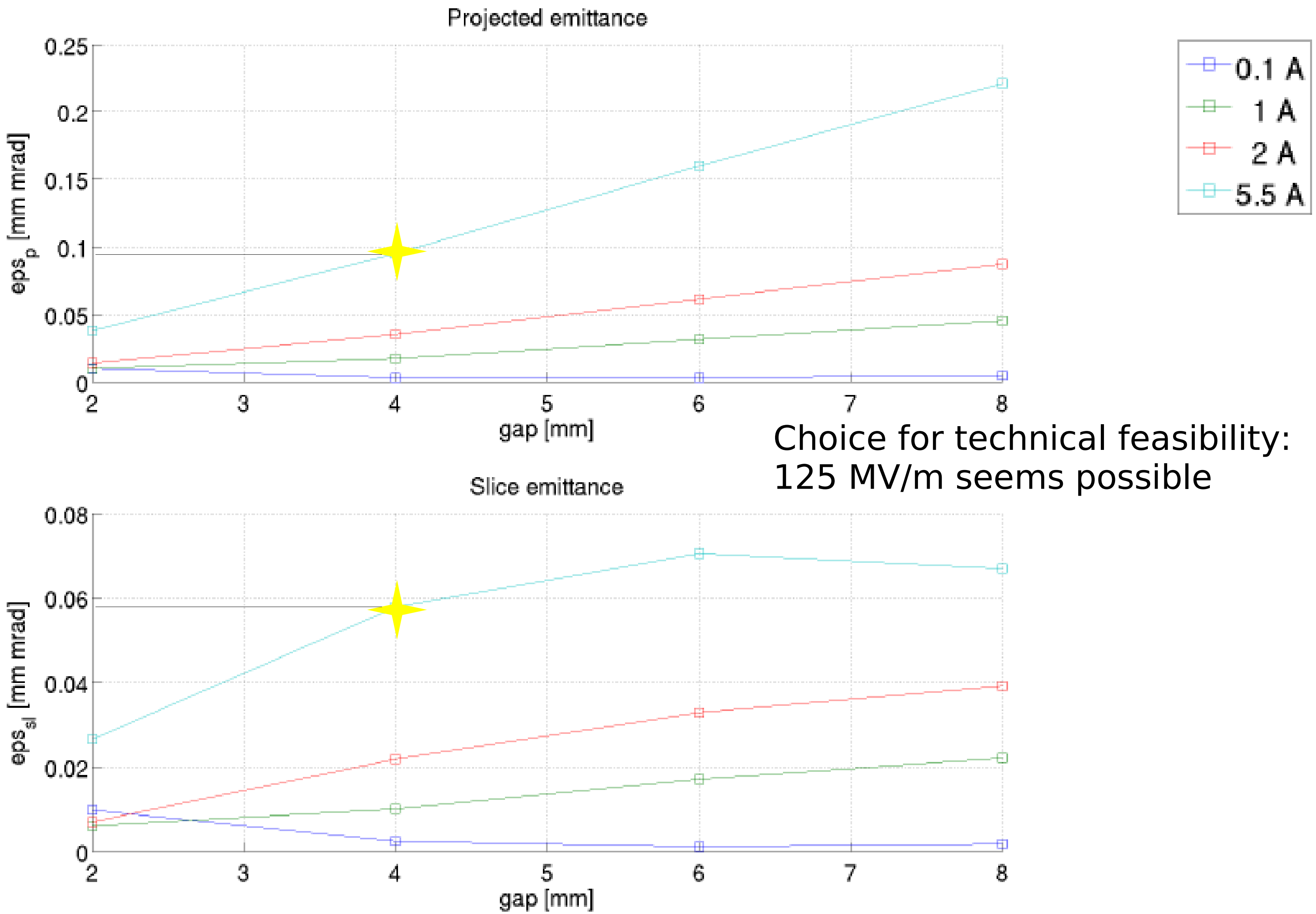


Diode: 2D design (500 kV also have 1 MV)



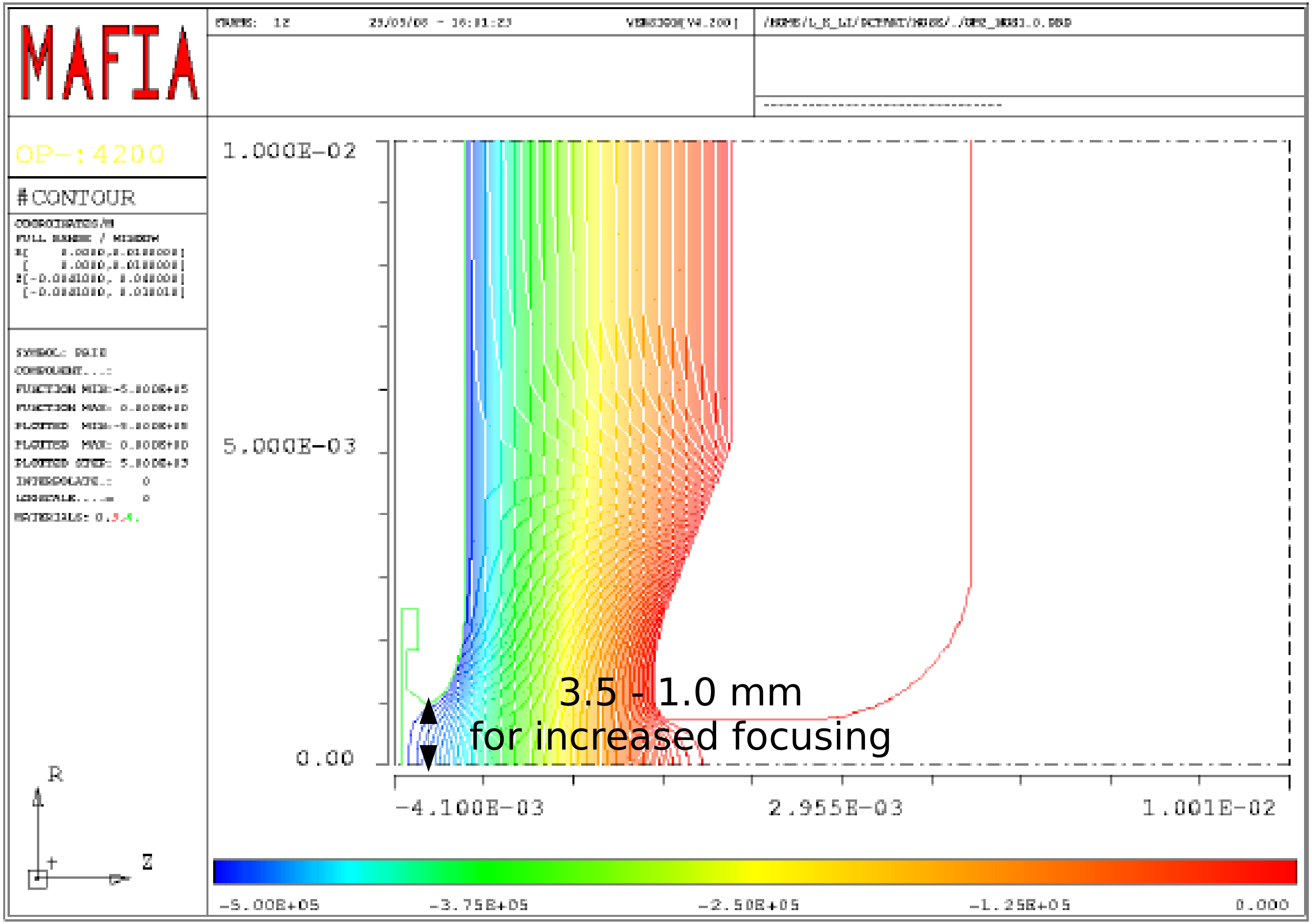
- For large gaps: strongly diverging beam → nonlinear transverse diode fields integrate to yield a net focusing that counteract space charge defocusing

Diode: 2D design (500 kV)

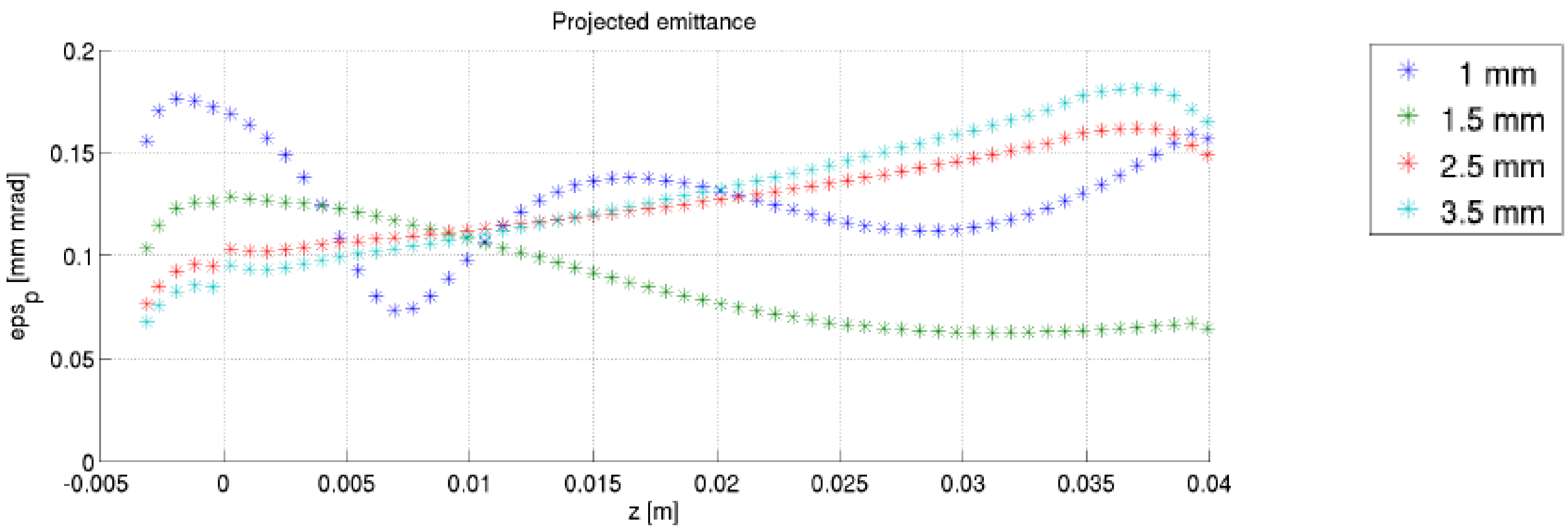


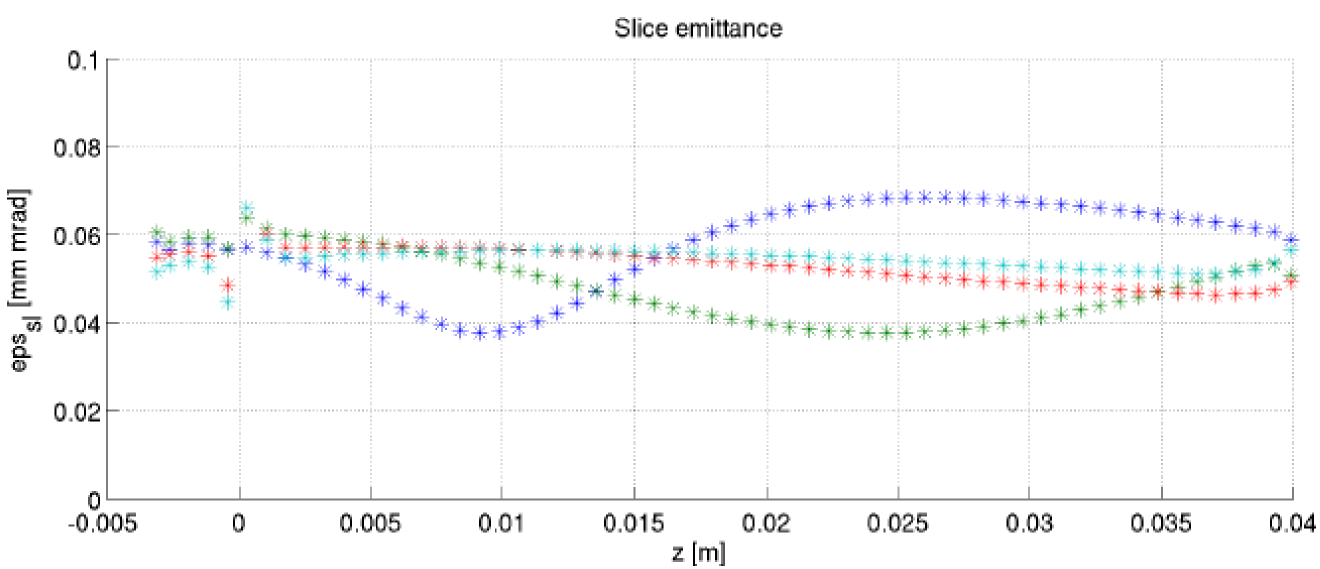
Choice for technical feasibility:
125 MV/m seems possible

Diode: 2D alternative



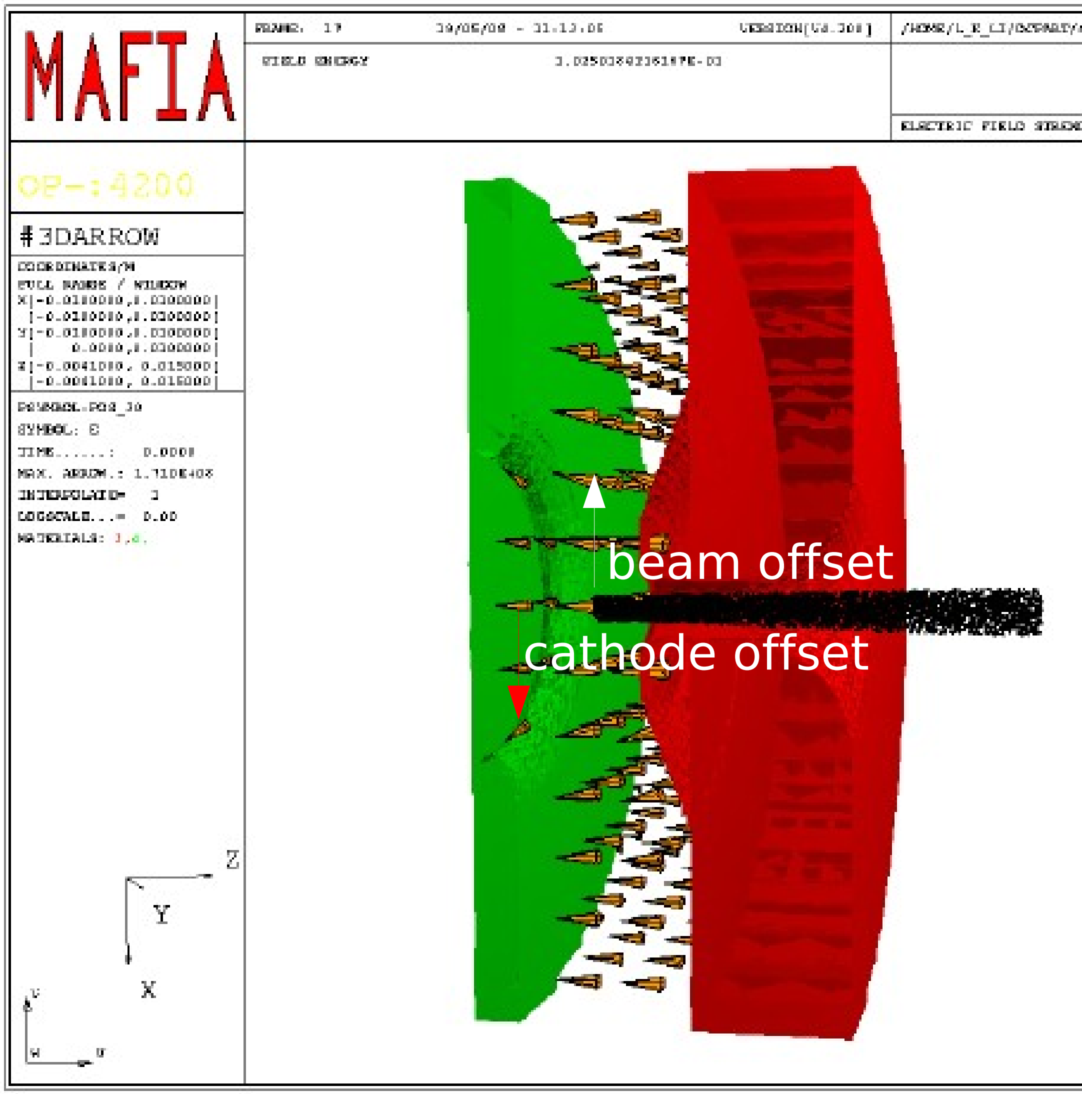
Diode: 2D alternative

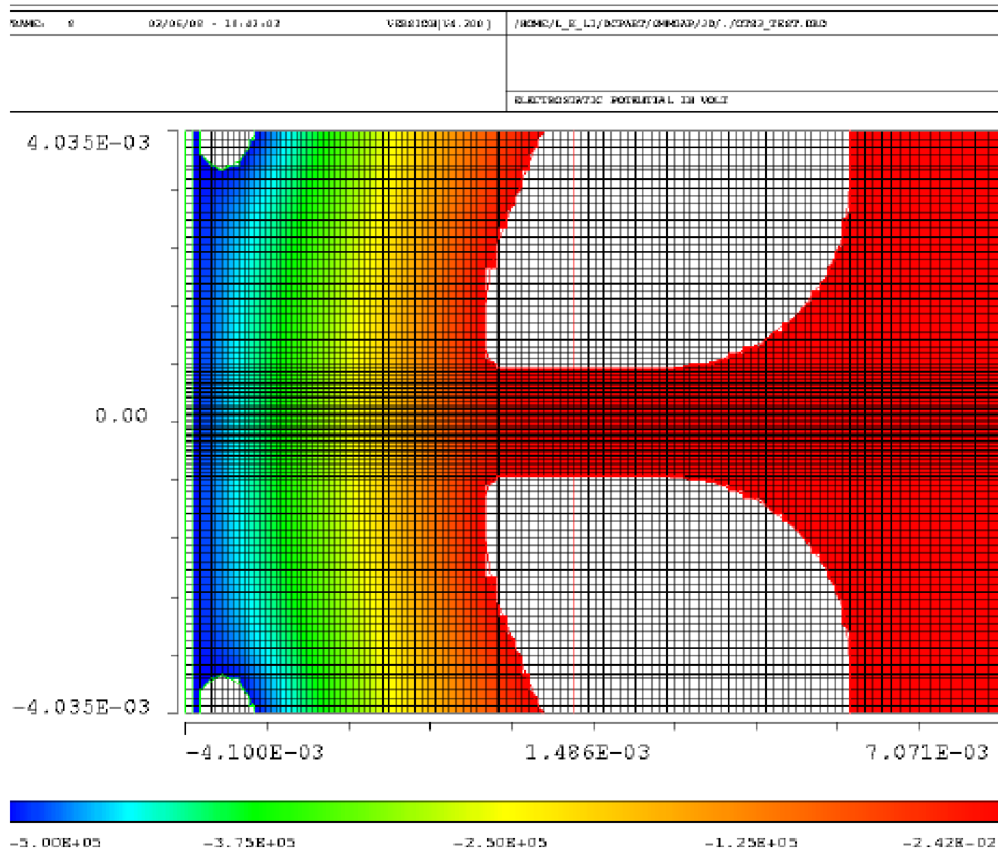




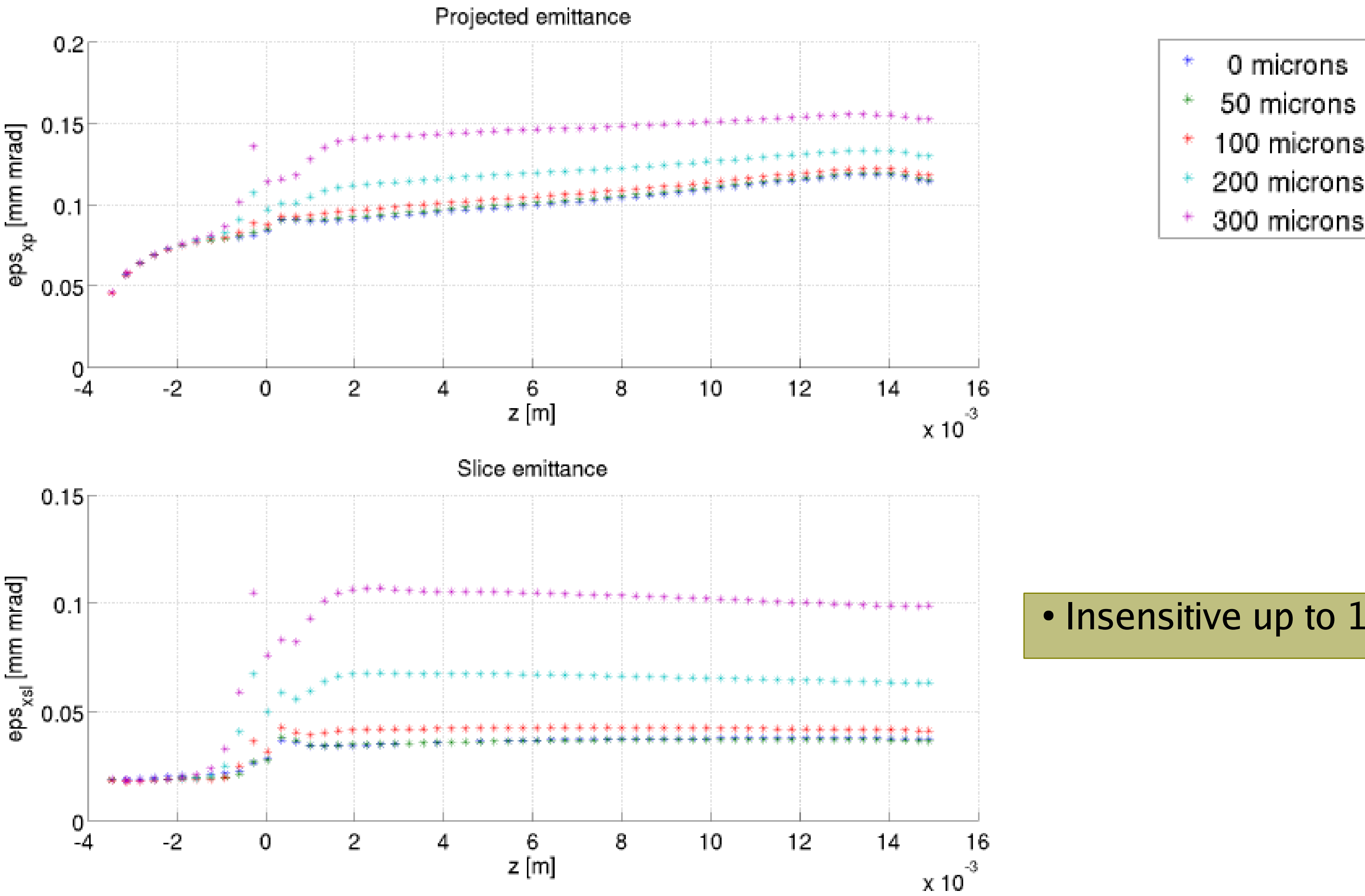
- Emittance compensation at an early stage improves emittance:
  - projected by factor 3
  - slice by factor 1.5

Diode: 3D design



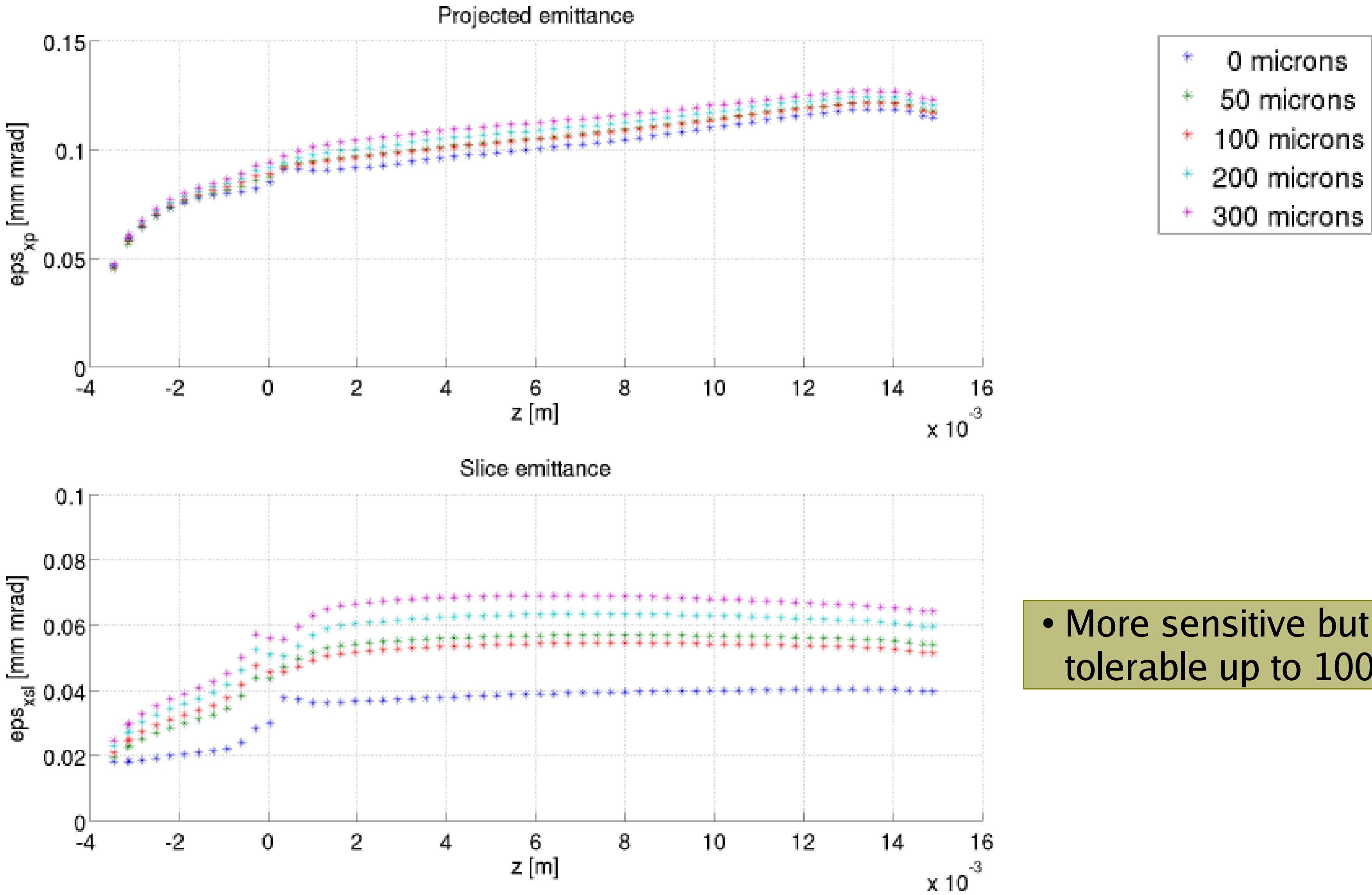


Diode: 3D beam offset



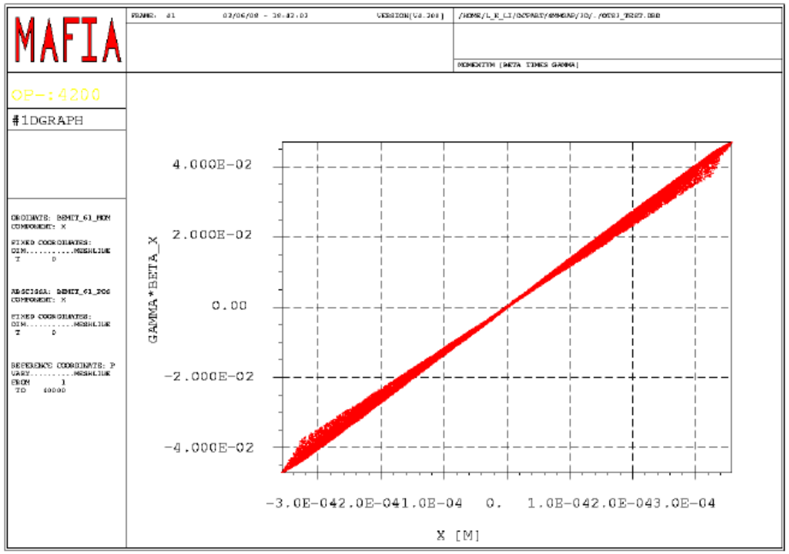
- Insensitive up to 100 microns

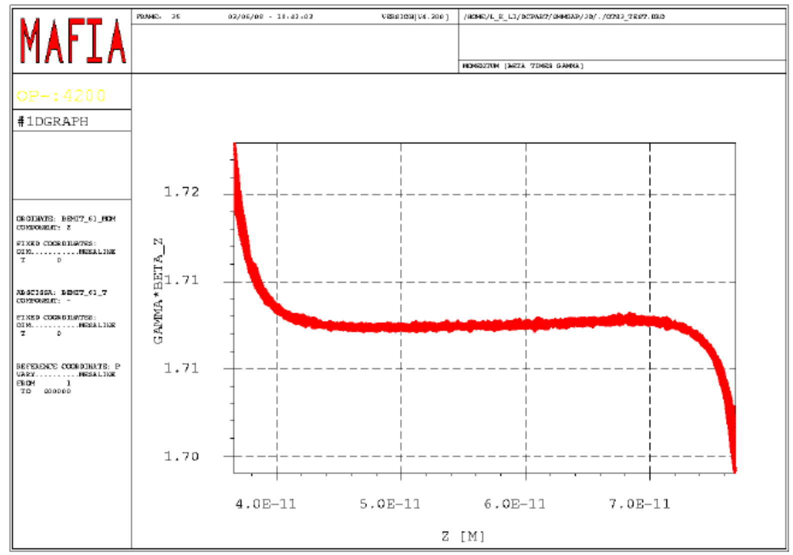
Diode: 3D cathode offset

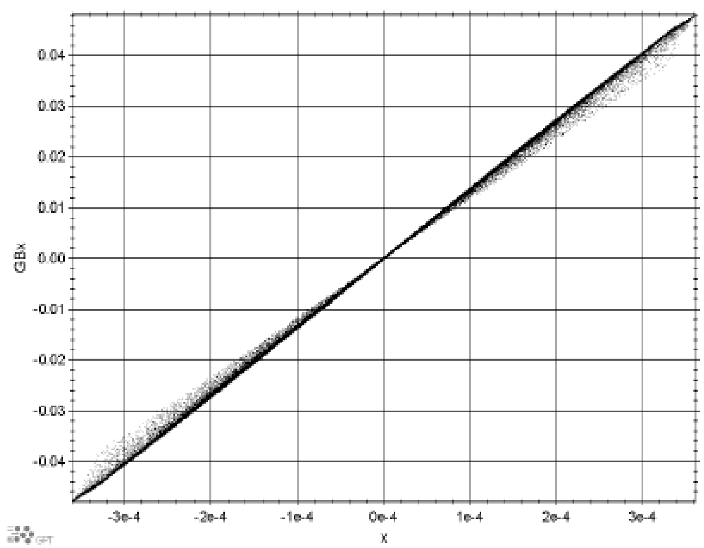


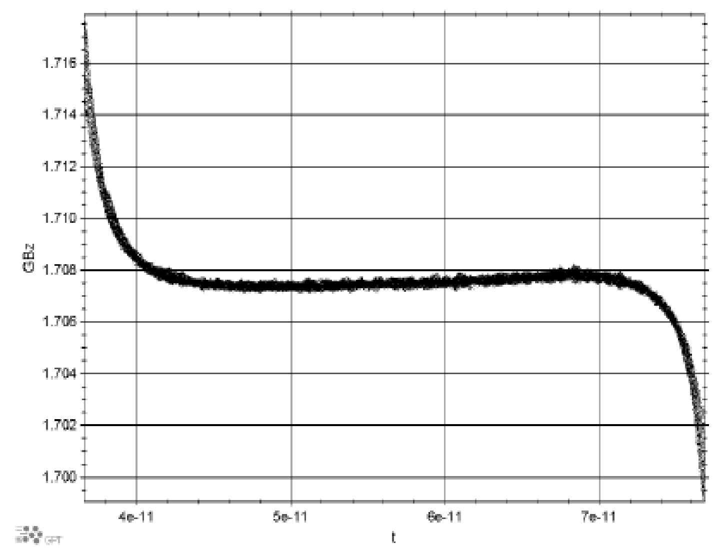
- More sensitive but still tolerable up to 100 microns

MAFIA - GPT



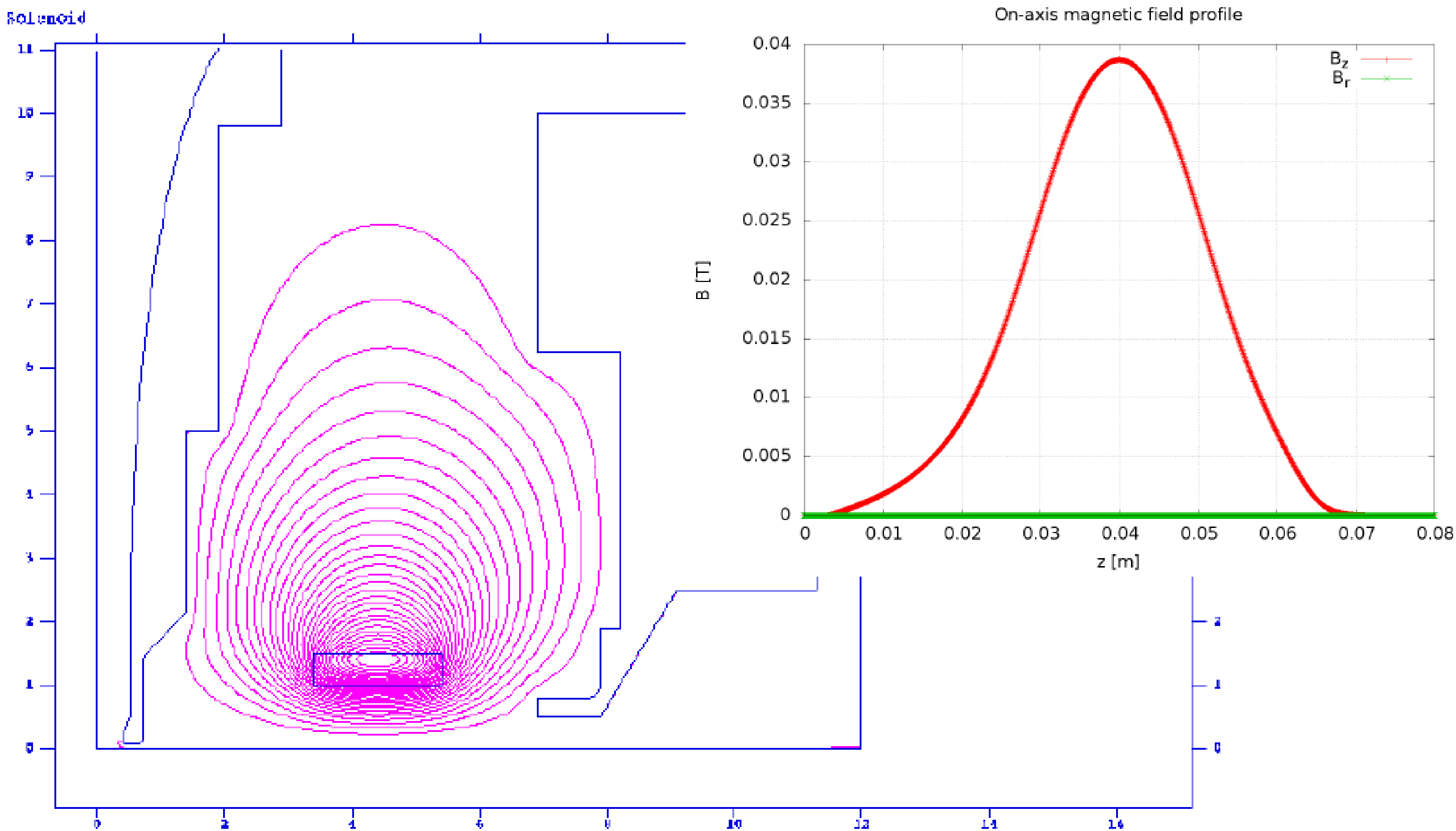




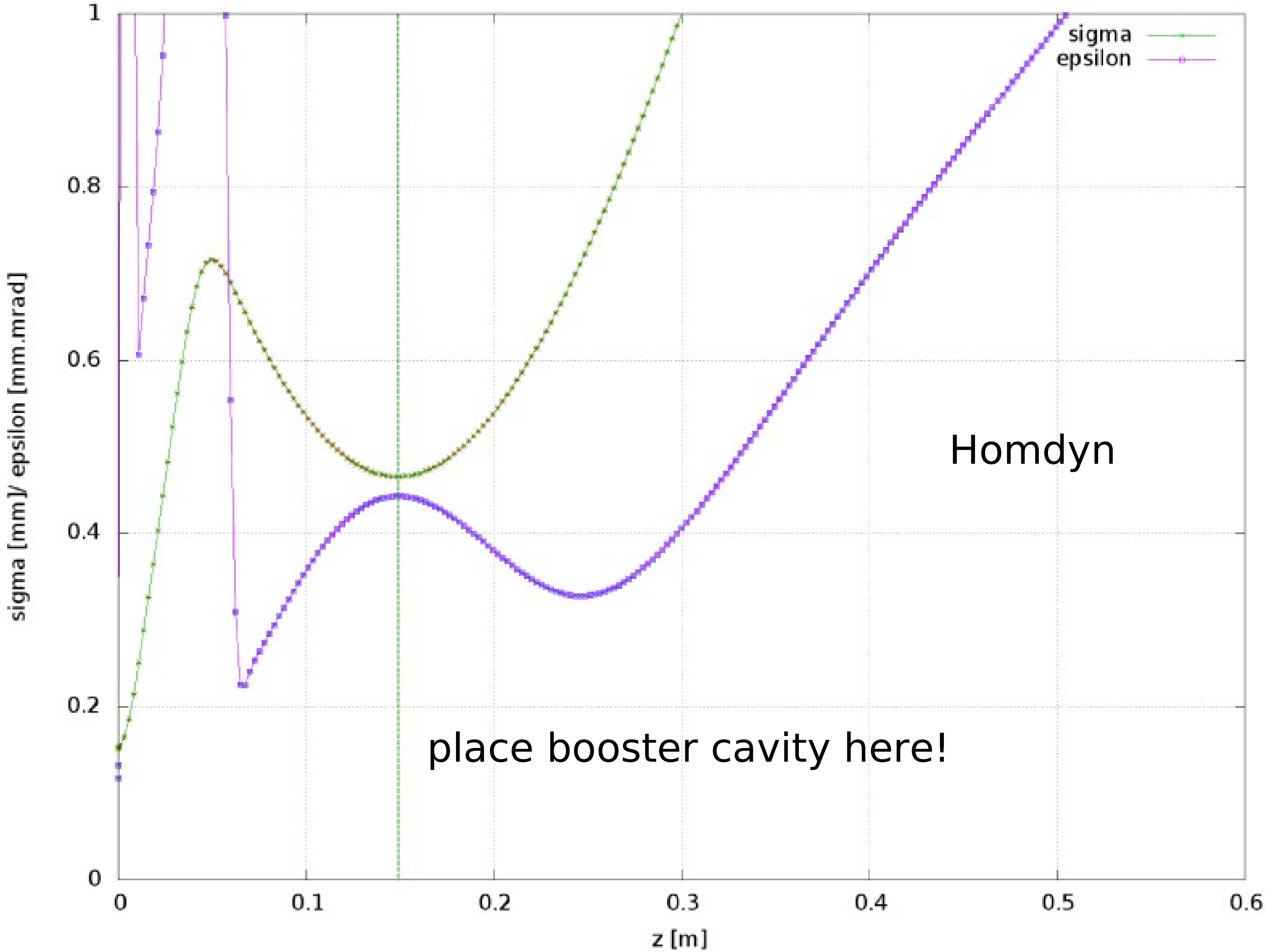


Dump at 2 mm

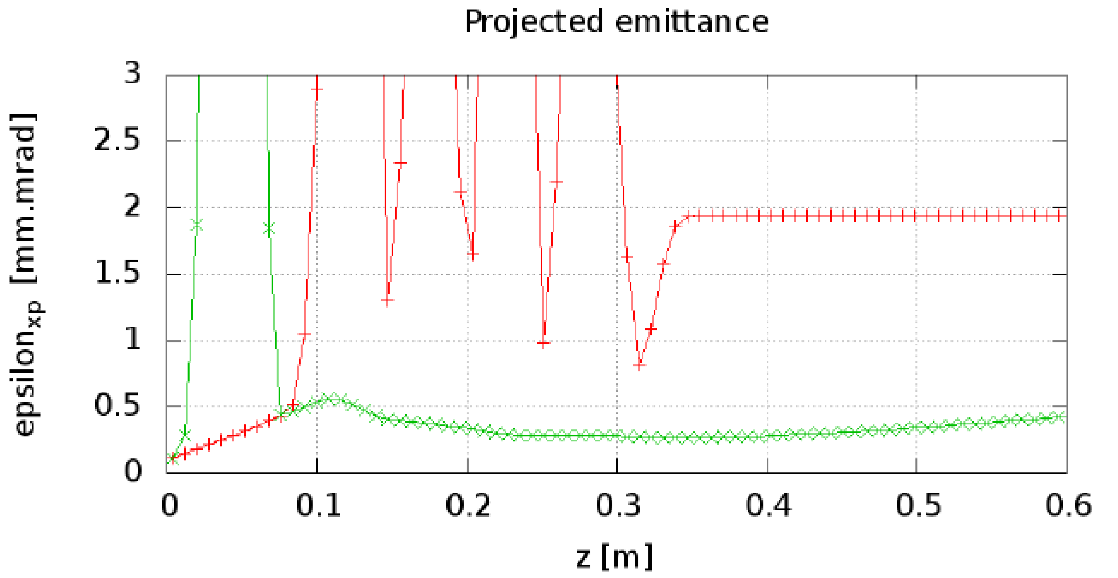
Pulsed coil design

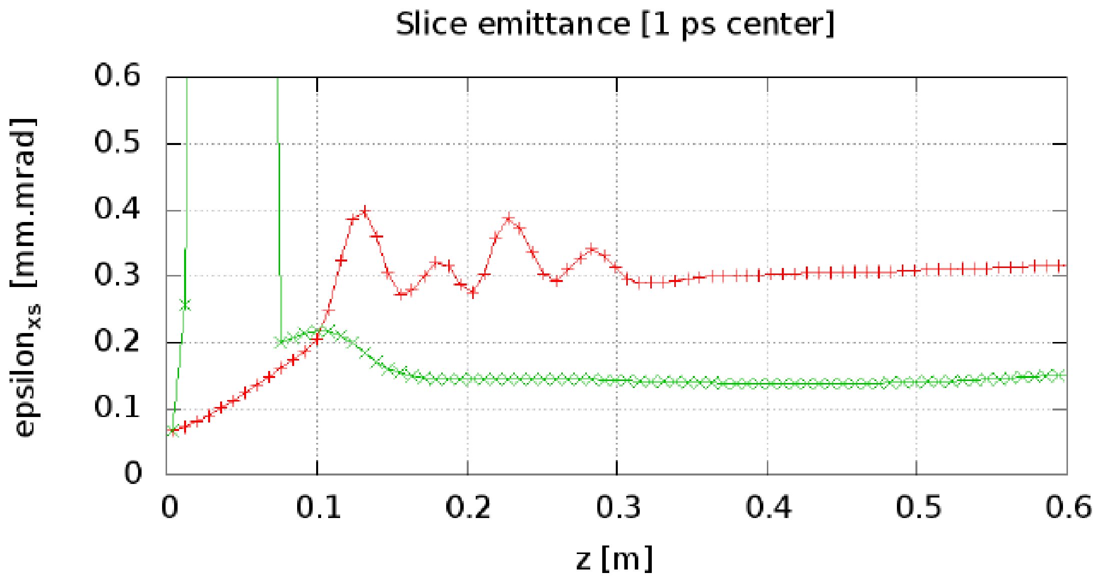


Pulsed coil: emittance oscillation



Coil with cavity: beam matching

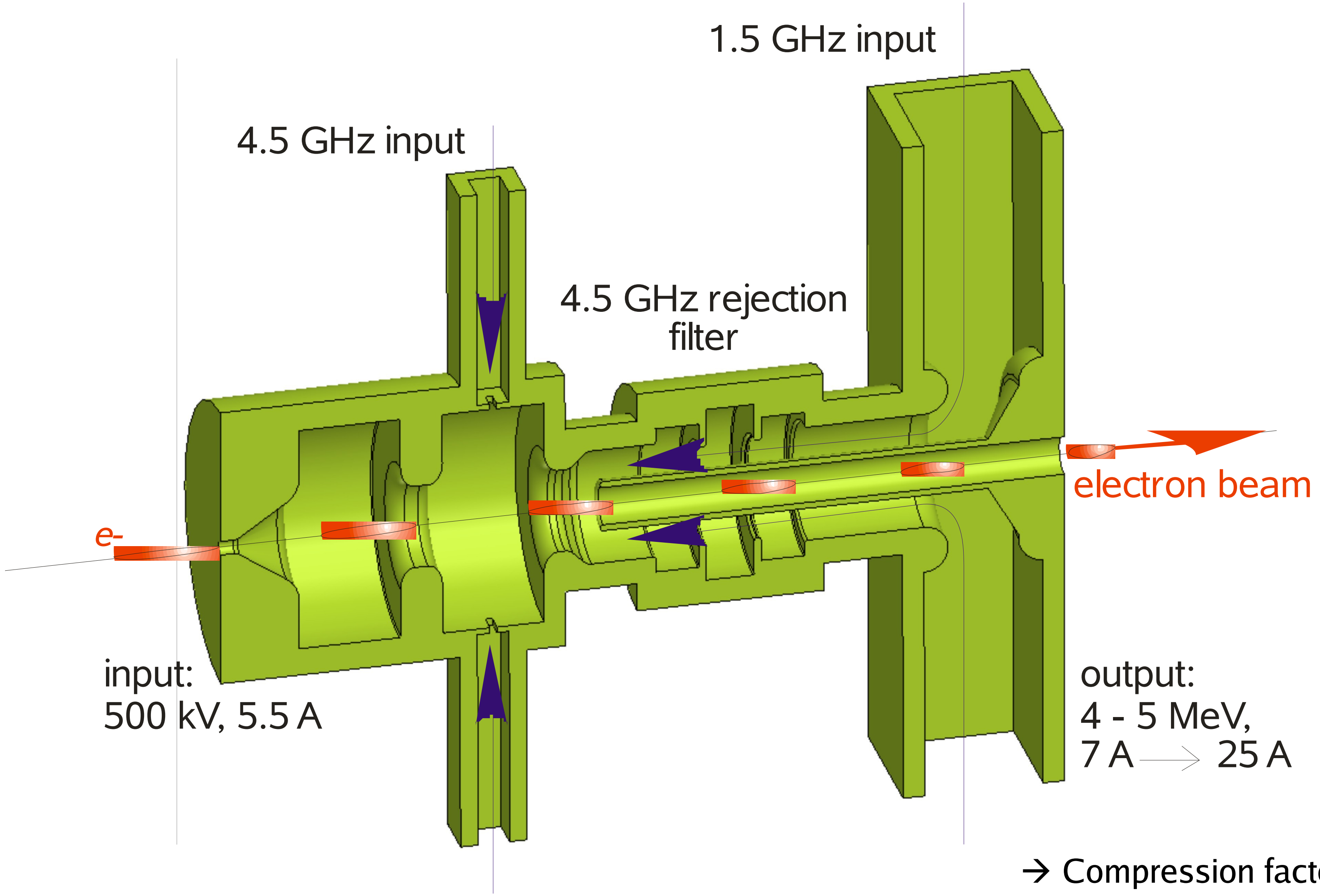




$$\hat{\sigma}_{\mathrm{inv}} = \sqrt{\frac{K}{K_r}}$$

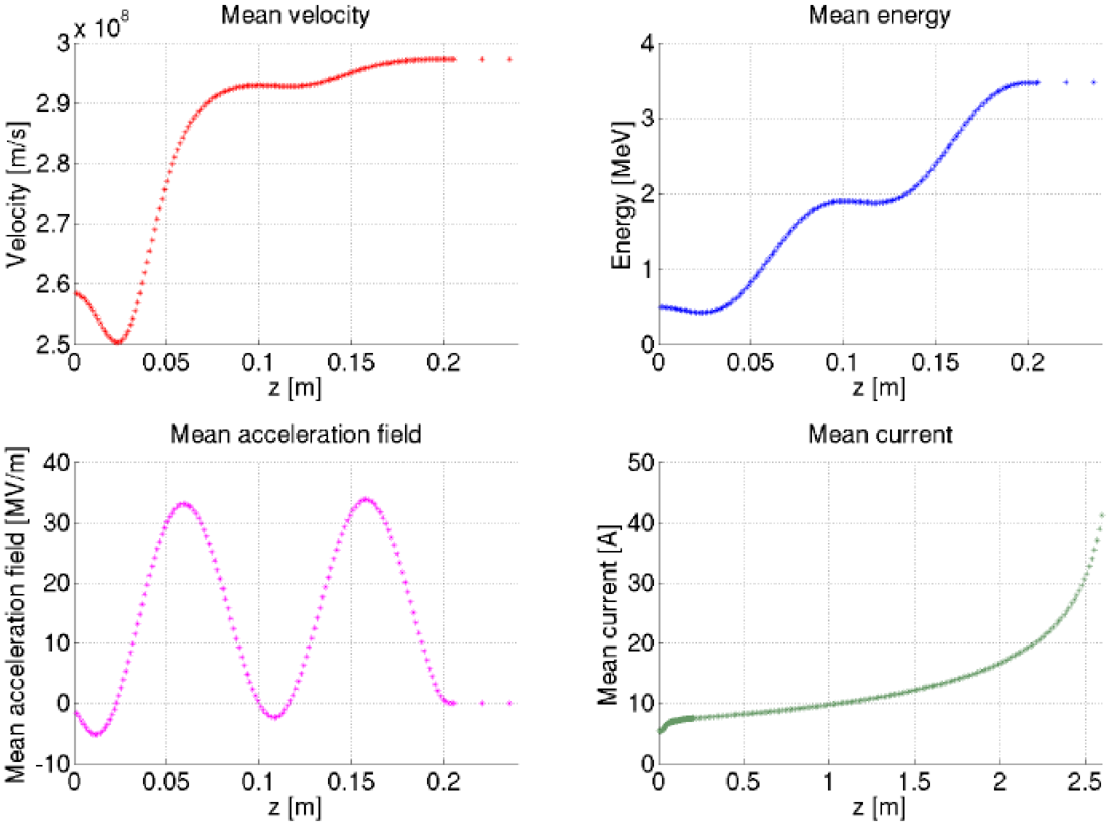
- good matching obtained for
  - σ_r = 0.500 mm
  - E_{max} = 33.0 MV/m
  - B = 0.250 T
- transverse RF effects invisible

Compression: Two-frequency cavity

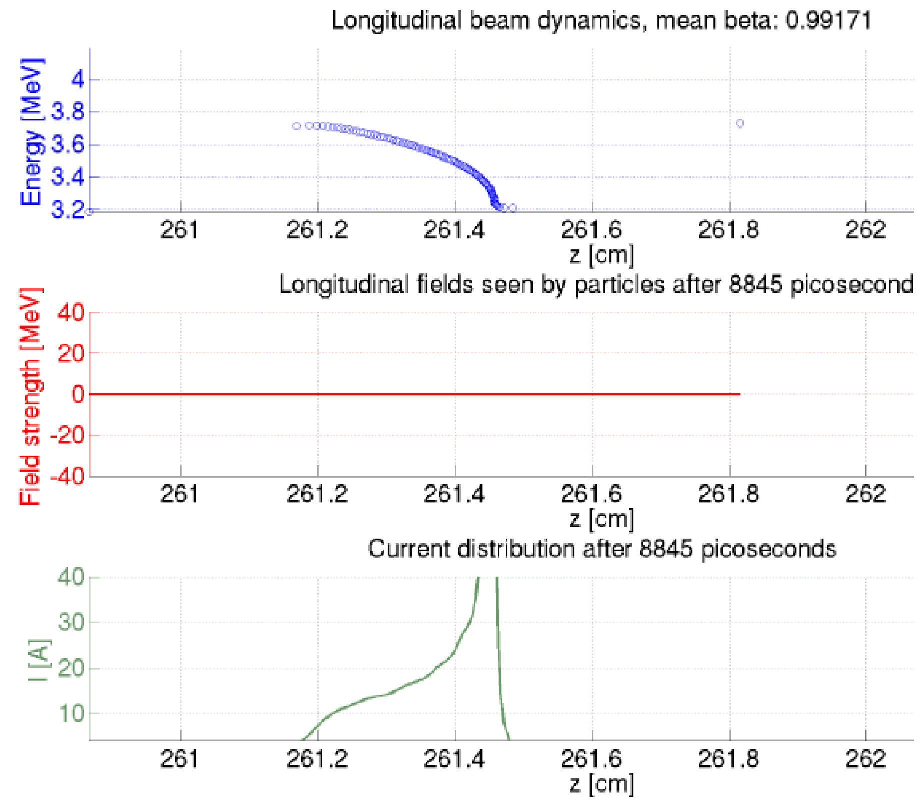


→ Compression factor ~ 5

Compression: Two-frequency cavity

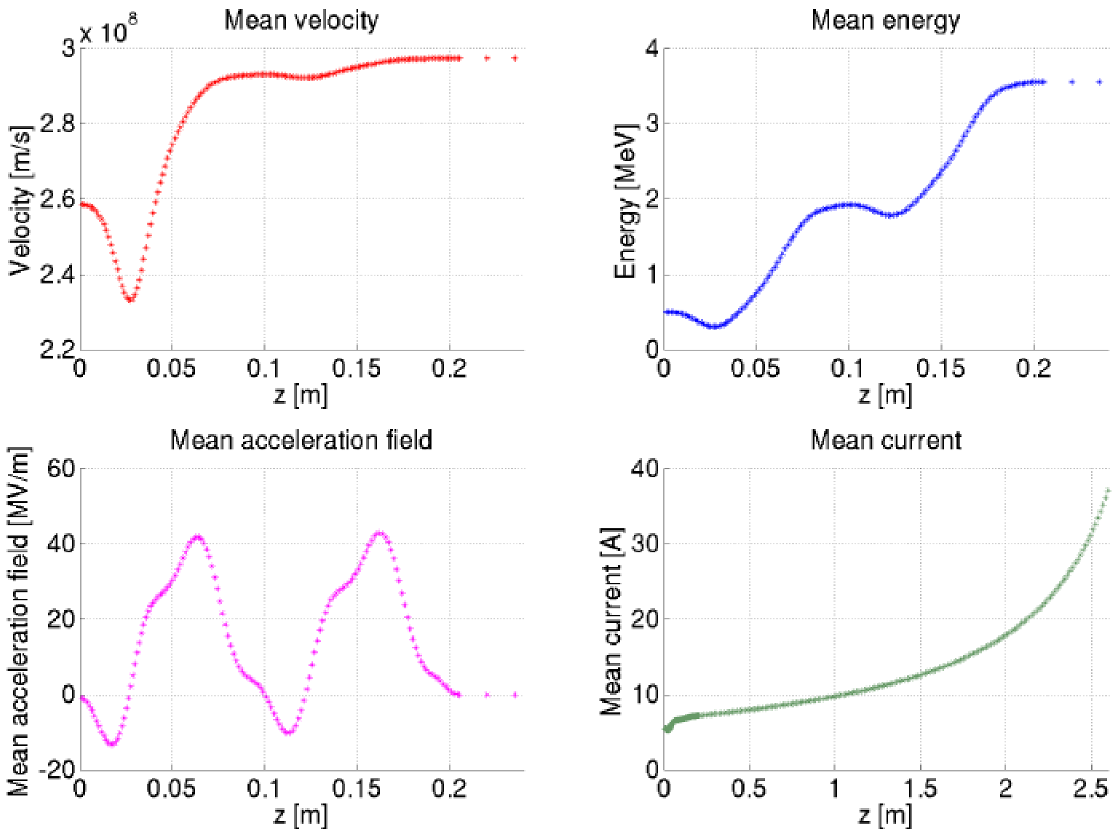


Caramon

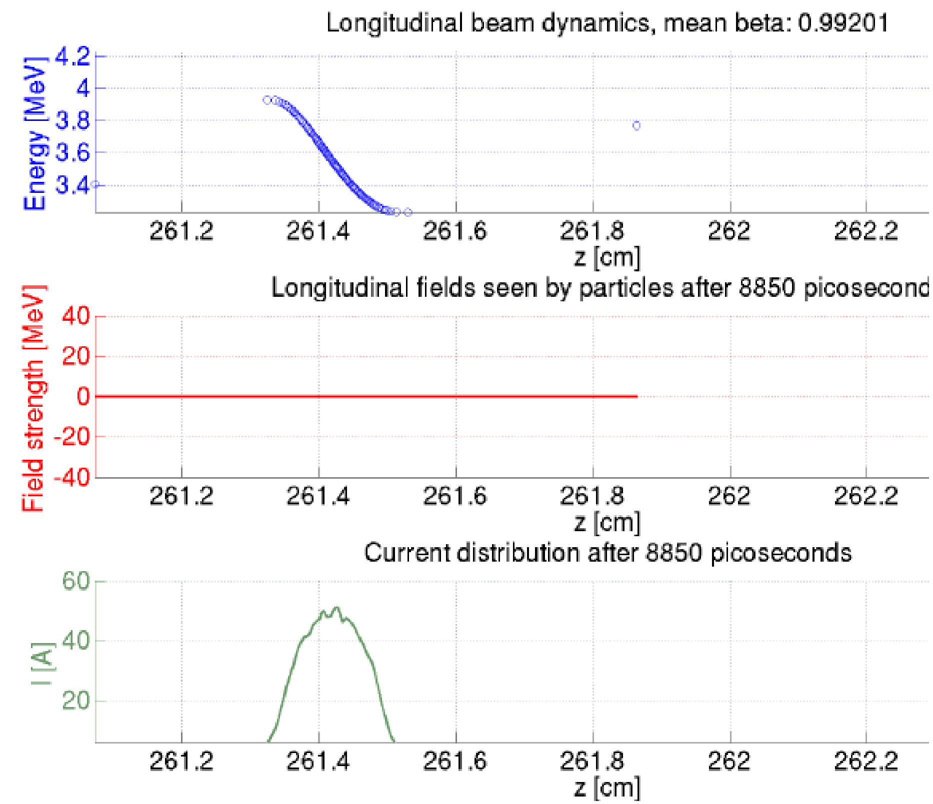


- fundamental: 36 MV/m, -39 degrees
- all particles concentrated in head
  → makes further beam handling very hard

Compression: Two-frequency cavity

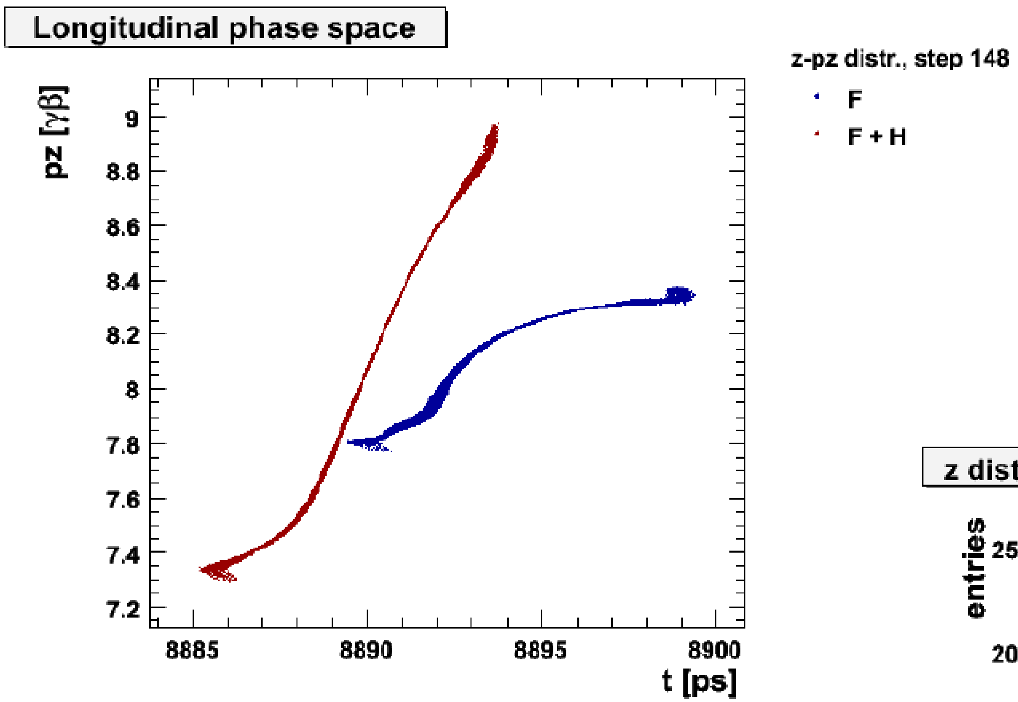


Caramon

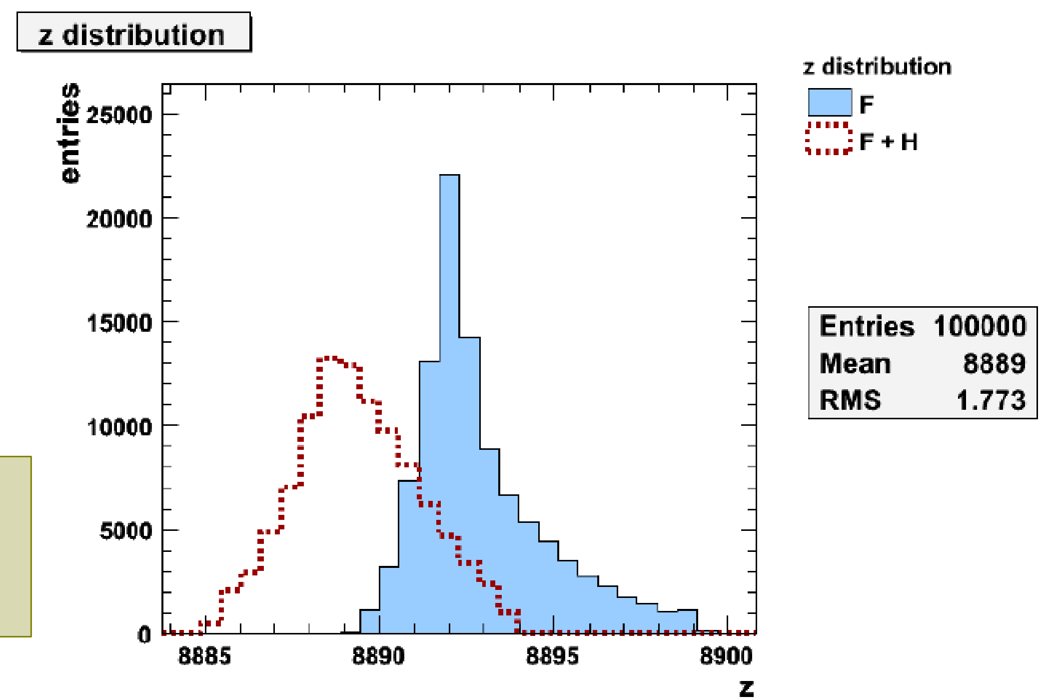


- fundamental: 47 MV/m, - 40 degrees
- harmonic: 10 MV/m, + 154 degrees
- bunch profile symmetric

Compression: Two-frequency cavity



GPT



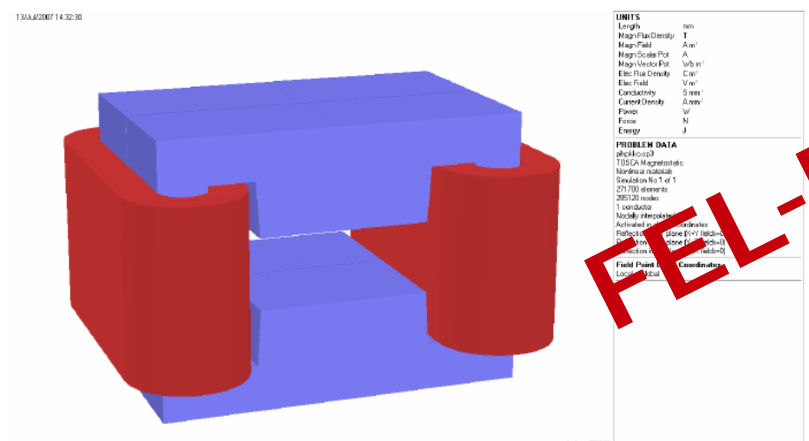
- fundamental: 48 MV/m, - 36 degrees
- harmonic: 14 MV/m, + 148 degrees
- bunch profile symmetric

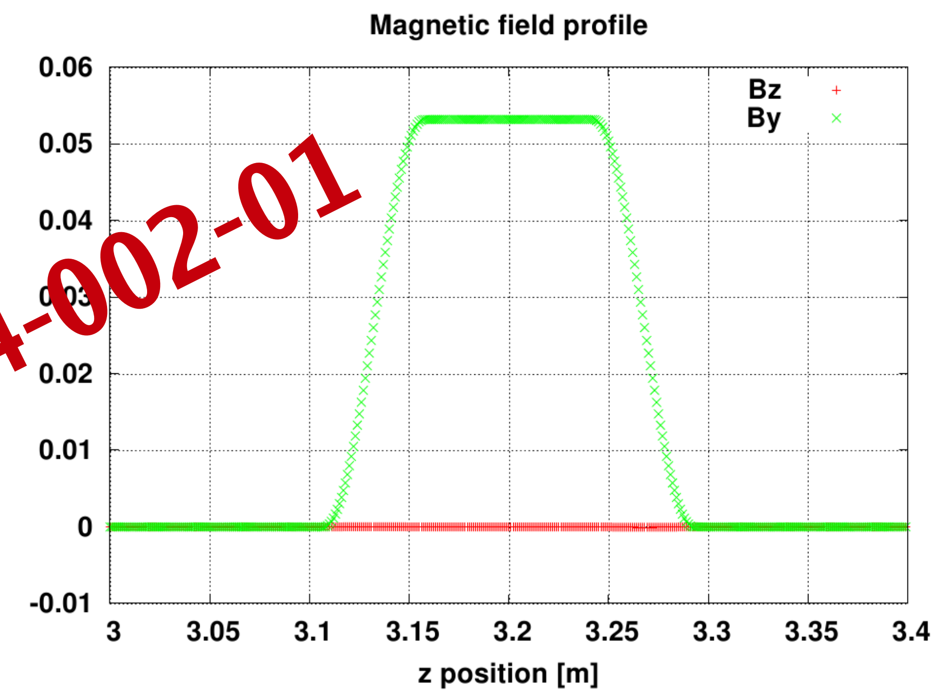
Momentum measurements

Möglicher 30° Magnet für 4 MeV
(Marco Negrazus 13.7.07)

Jochlänge: 130 mm
Magnetische (Effektiv) Länge: 185.3 mm
Polbreite: 100 mm
Int B ds bei (I = 10A): 14.2 Tmm (Für 30° Ablenkung bei 4 MeV braucht man 7.8 Tmm)
Ich habe noch keine Feldoptimierung gemacht!

Imax: 10 A
Gap: 40 mm





Measured	δx_β	$[1 \cdot 10^{-4}]$ m	3.52	2.21	2.72	2.36	1.12
Deduced	δp_β	$[10^{-4}]$	3.477	2.937	4.743	5.286	6.847
Measured	δx_m	$[10^{-4}]$ m	57.96	43.55	33.09	25.81	9.790
Deduced	δp_m	$[10^{-4}]$	57.25	57.87	57.70	57.81	59.85
Simulation	δp	$[10^{-4}]$	50.18	50.33	50.37	50.56	52.59
$\delta_i = \frac{(\delta p_i)}{(\delta p_m)}$	$\delta_{\text{res},m}$		6%	5%	8%	9%	11%
	δ_{res}		7%	6%	9%	10%	13%

Conclusions

A) Physics

i. Design done

B) Codes

i. Codes implemented, prepared and ready to use

ii. Additional codes added

C) Results

i. Usable set of parameters evaluated for achieving the target beam