Free electron wire for measurement of longitudinal charge distribution of relativistic beams

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Outline

- Introduction
  - Few words about me,
  - and why the problems discussed in the talk are important
- Brief overview of existing techniques – advantages and limitations
- Novel approach
- Discussion

Introduction

- Former PITZ member responsible for transverse phase space characterization
  - Numerical optimization
    - Diagnostic components
    - Beam dynamics
  - Heavy shift participation
- Since:
  - Freelance consultant
  - Postdoc at Advanced Energy Systems

Introduction

- Longitudinal distribution of short electron beams (<<1 ps) is critical for number of applications:
  - accelerator based light sources
  - plasma wake field acceleration
  - high field atomic physics
- The measurement of the longitudinal profile of such a short bunch poses a significant challenge to the existing diagnostic techniques
- Non-destructive and destructive techniques

Overview of existing techniques*

- Spectral Techniques (ST)
  - Coherent transition or difraction radiation (CTR or CDR), surface or apperture
  - Synchrotron radiation (CSR), magnetic field
  - Smith-Purcell radiation (S-P), grating used.
- Electro Optic (EO) techniques
- Electron Bunch Manipulation (EBM) techniques
  - Phase space manipulation
  - Optical replica

* Jamison, S. P. et al., "Femtosecond resolution bunch profile measurements", Proceedings of EPAC'06, TUYPA01, Edinburgh, Scotland, 26-30 June 2006.

Overview of existing techniques*

- Most of the ST and all the EO techniques are cheap, compact, non-destructive with a good resolution.
  - The components involved in the interaction with the bunch field should be close to the beam due to
    - the $1/r^2$ nature of the field,
    - EM field has an opening angle $\alpha \sim 2/\gamma$

      $\gamma \sim$ 1000 distance smaller **2 mm** for resolution of **10 fs**
    - can not be used in high average current machines
  - difficulties transporting and detecting the full spectral range of the emitted radiation for ST techniques.

* Jamison, S. P. et al., "Femtosecond resolution bunch profile measurements", Proceedings of EPAC'06, TUYPA01, Edinburgh, Scotland, 26-30 June 2006.

Overview of existing techniques*

- EBM techniques are intrinsically destructive,
  - inappropriate for use in user-operation conditions,
  - on the other hand are expensive,
  - and bulky
  - the most precise measurement method
  - quite versatile as experimental possibilities

* Jamison, S. P. et al., ”Femtosecond resolution bunch profile measurements”, Proceedings of EPAC’06, TUYPA01, Edinburgh, Scotland, 26-30 June 2006.

Novel approach

- Use another electron beam (PB) wich interacts with the Coulomb field of the relativistic bunch (RB)*
- apply EBM on the PB
  - cheaper than conventional EBM
  - Resolution?

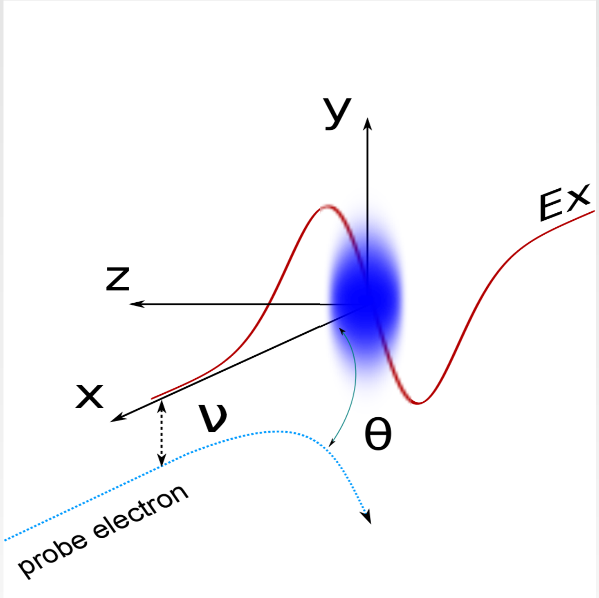
* Pasour, J. A. et al., ”Nonperturbing electron beam probe to diagnose charged-particle beams”, Rev. Sci. Instrum., 63(5), May 1992.

Logatchov, P. V. et al., ”Non-destructive Singlepass Monitor of Longitudinal Charge Distribution in an Ultrarelativistic Electron Bunch”, Proceedings of PAC’99, New York, 1999.

Logachev, P. V. et al., ”Application of a Low-Energy Electron Beam as a Tool of Nondestructive Diagnostics of Intense Charged-Particle Beams”, Instruments and Experimental Techniques., 51(1), 2008.

Novel approach

- Deflecting experiment in ”Mission Research”
  - very thin very low energy (keV) beam
  - deflection θ proportional to distance v and intensity of RB
  - prior knowledge of RB distro
  - down to 300 ps
  - PB intensity main limitation



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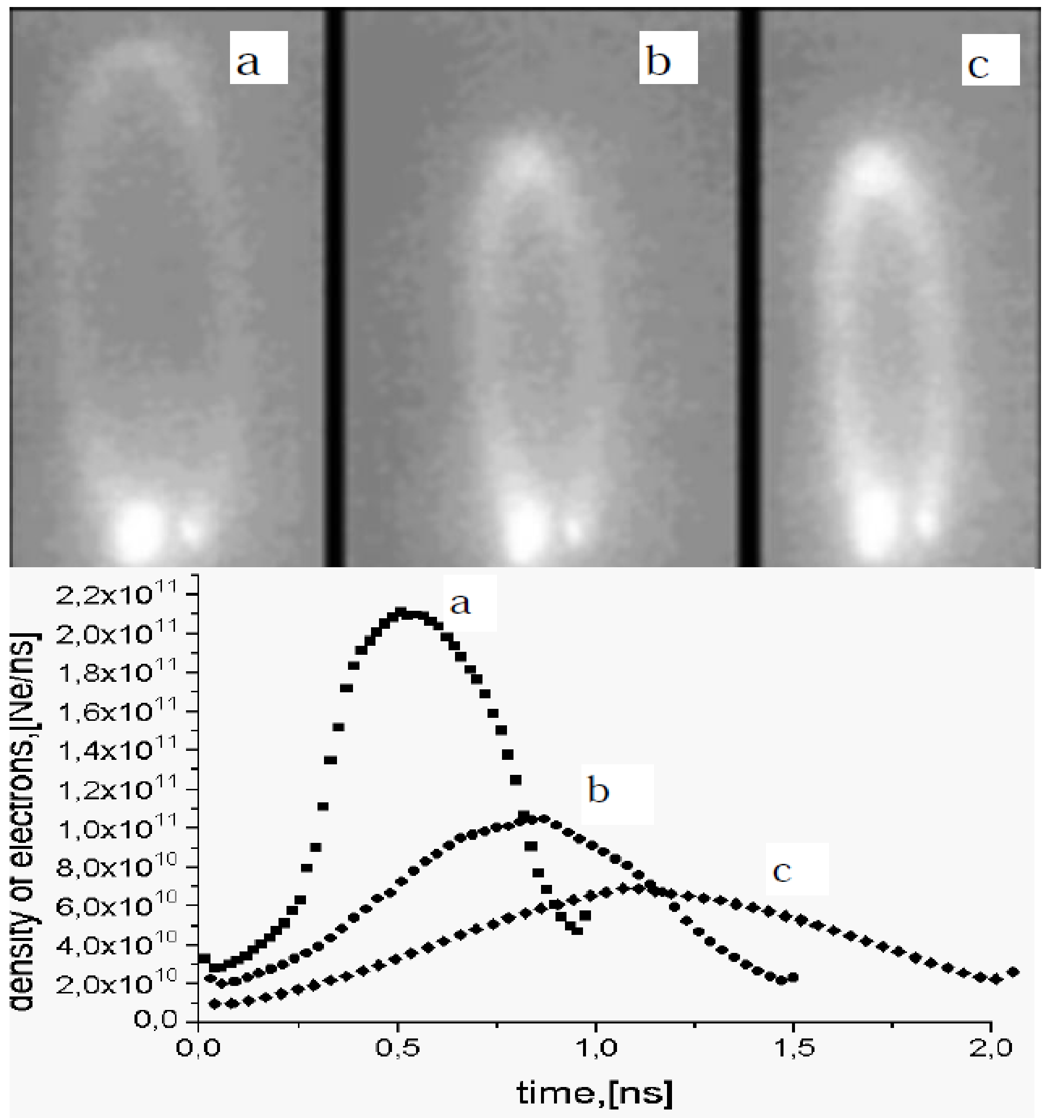
Novel approach

- Deflecting experiment in Novosibirsk
  - complex analysis of PB trajectory
  - prior knowledge of RB distro
  - resolution better than 300 ps



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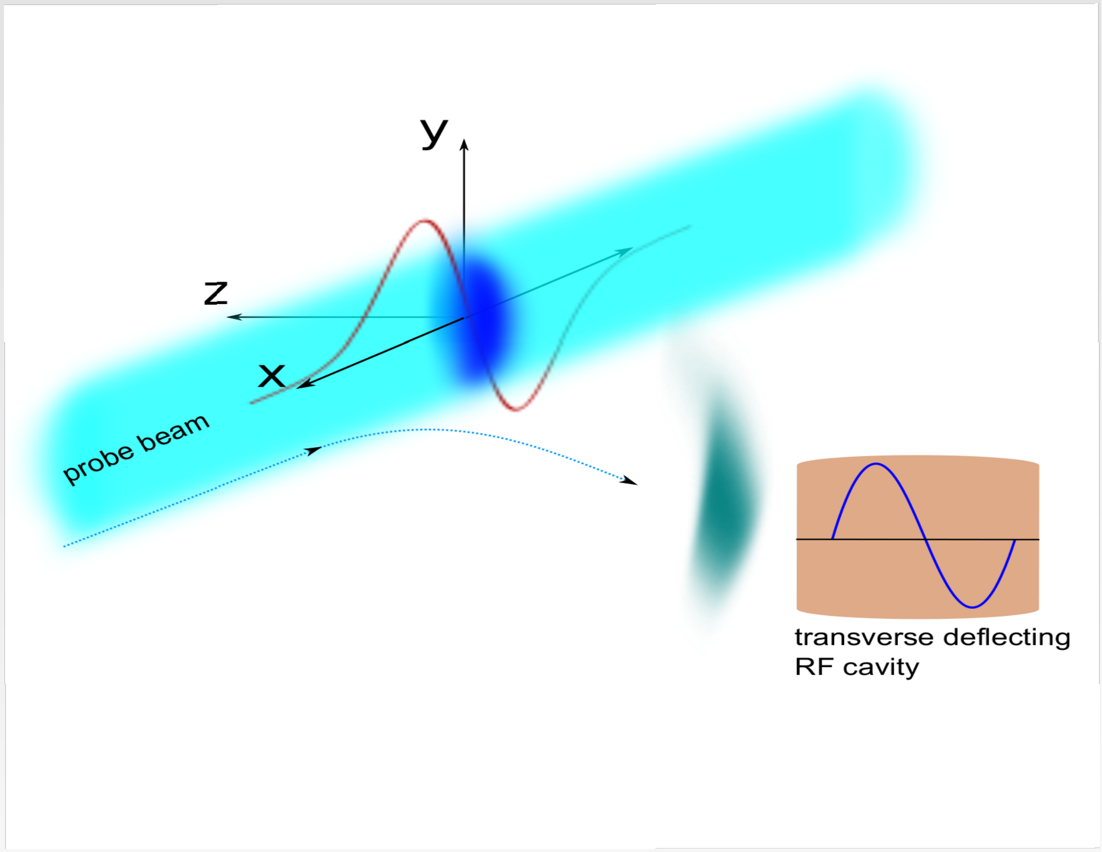
Initial approach

- Use more intense PB and apply EBM
  - interacts directly with RB
  - wider PB x-section
  - cheaper than conventional EBM

$$x' \approx 2\pi eV / (\lambda \cdot E_k)$$



- Find optimal PB parameters using numerical simulations
  - VORPAL for the beam-bunch interaction
  - ASTRA for the rest

Initial approach

- PIC simulations using VORPAL
  - simulation volume 0.01x0.03x0.013 m
  - grid 50x100x1000
  - 30 kparticles for RB and 3 Mparticles for the PB
  - RB parameters:
    - duration 100 fs RMS (FT and Gaussian)
    - 15 MeV and 2 GeV
    - Emittance 1 mm.mrad
    - 0.2-0.5 mm X-section at IP

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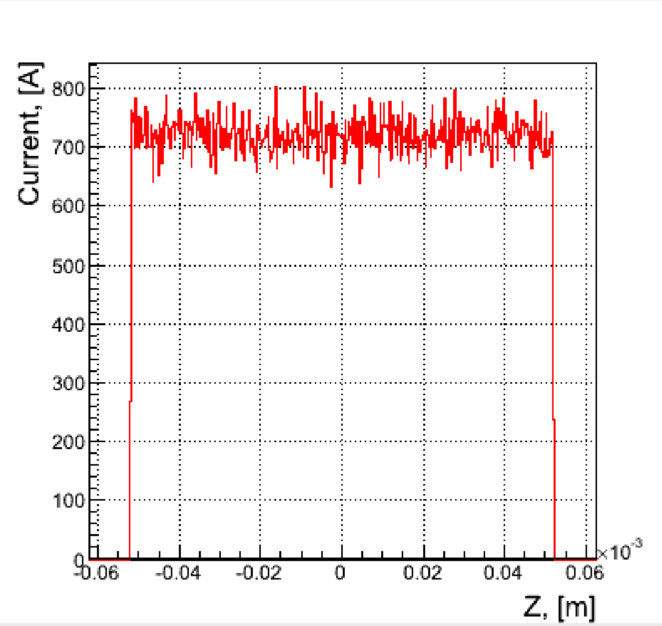
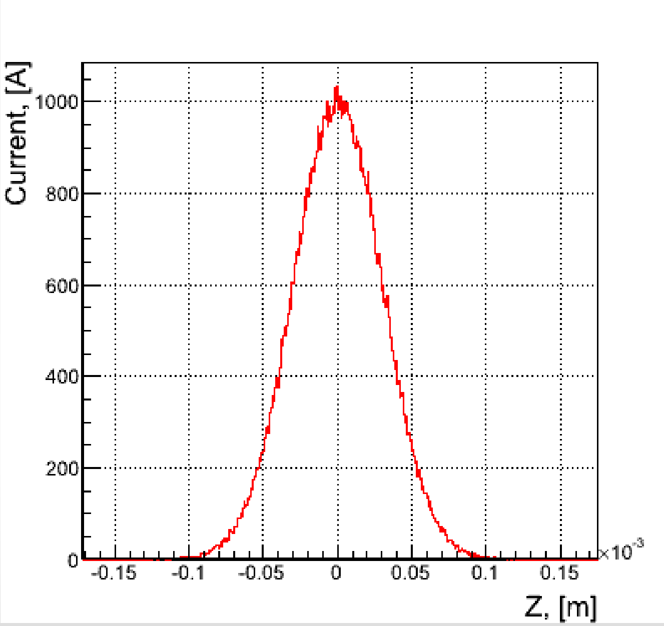
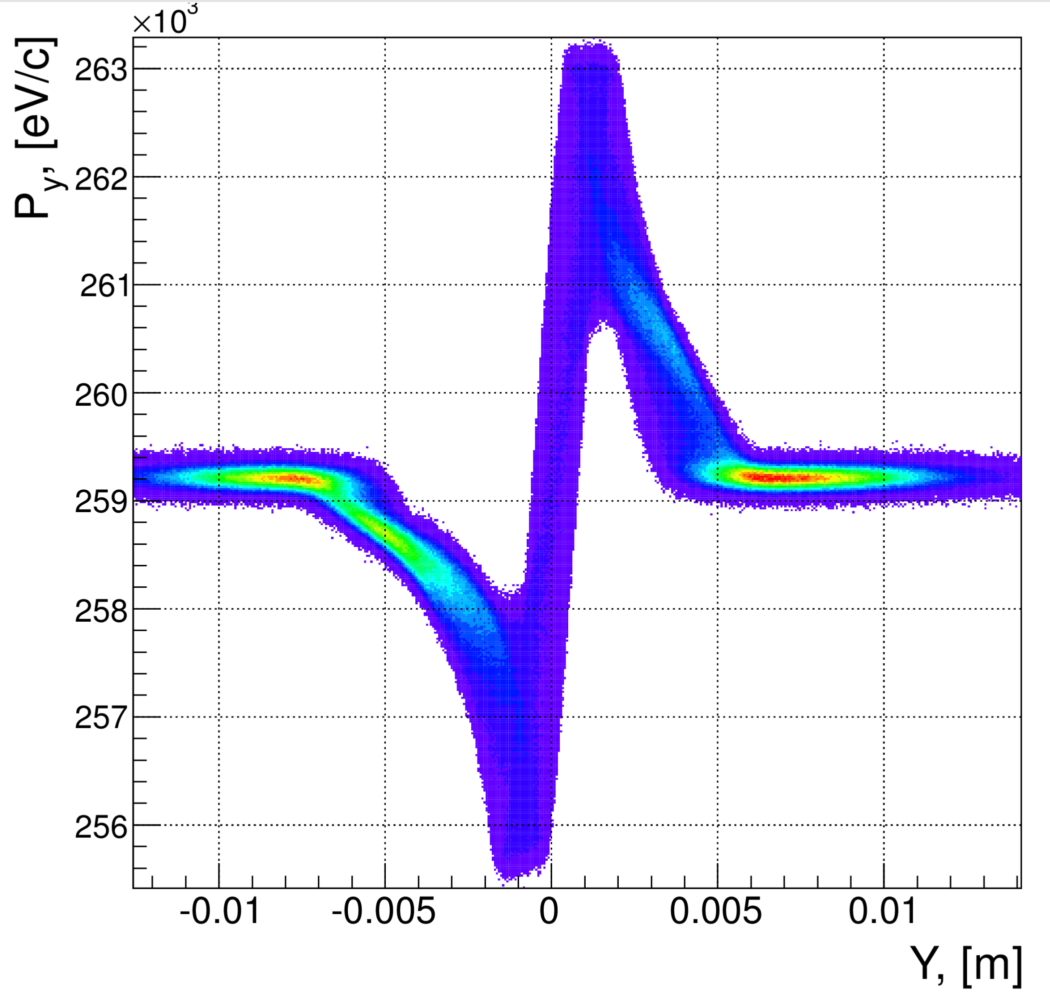
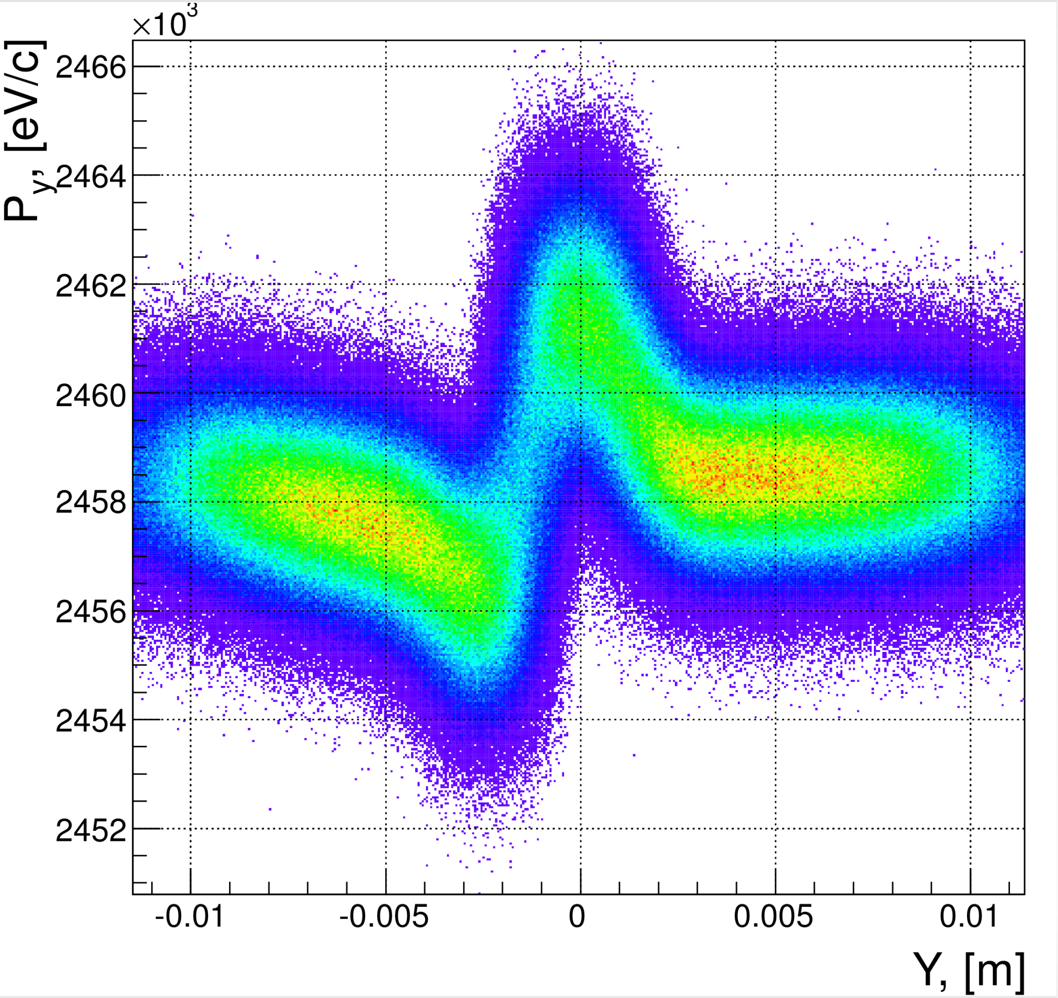




Initial approach

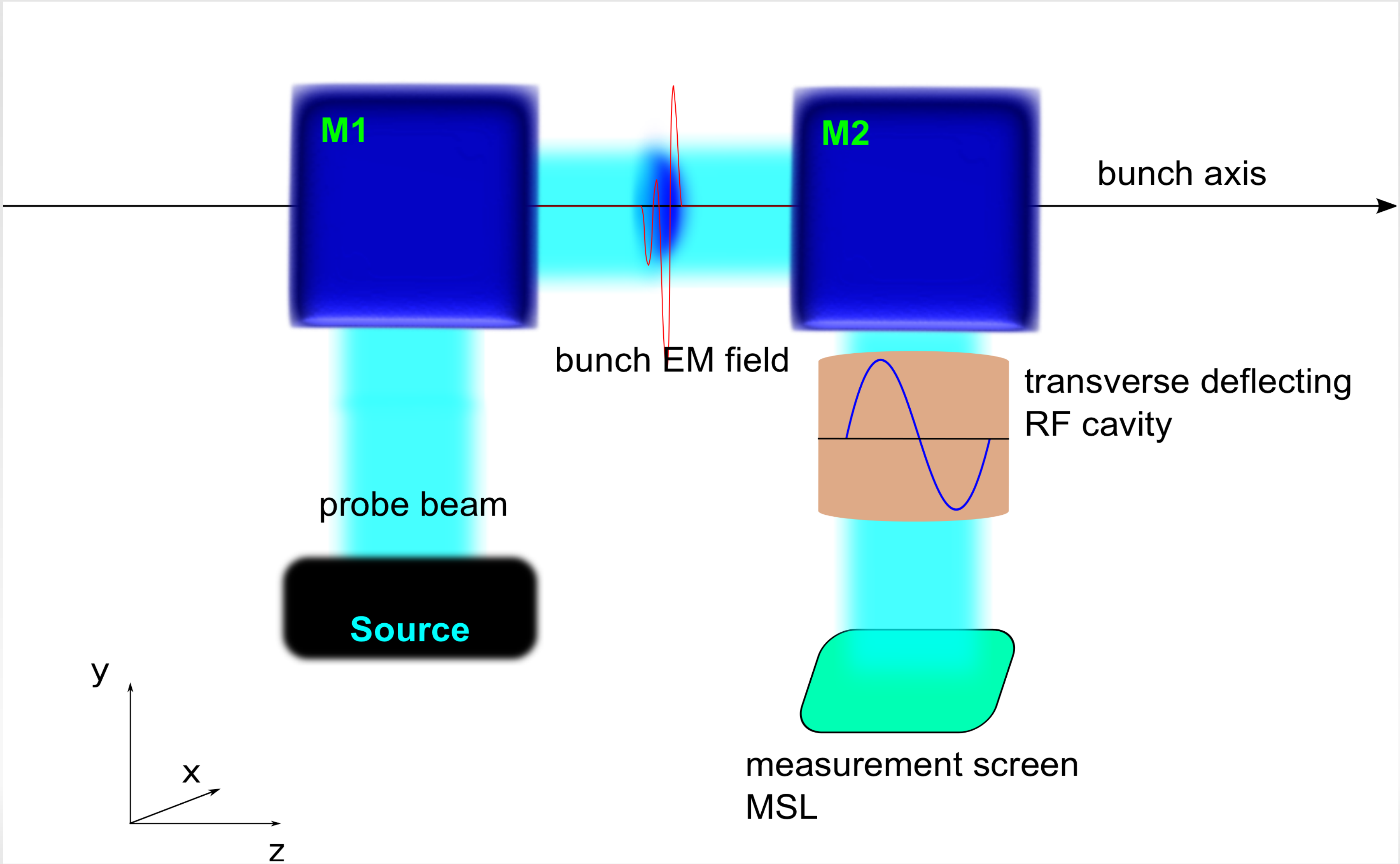
- Ek=60 keV
- Ek=2 MeV





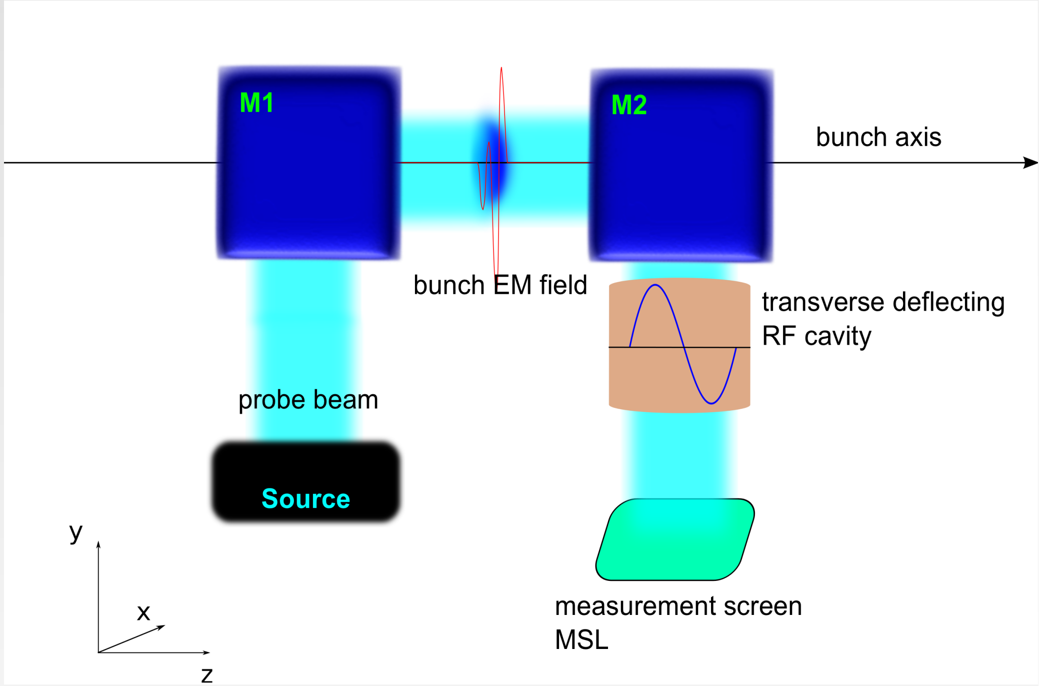
Novel approach

- PB co-propagates with the bunch



Novel approach

- Optimize:
  - source parameters
  - magnet configuration
  - deflecting cavity



Novel approach

- Slippage factor, gap 0.0116 m

PB energy, MeV	bunch@2GeV	bunch@15MeV
0.5	1.58 mm	1.49 mm
2.0	0.26 mm	0.25 mm
3.5	0.09 mm	0.08 mm

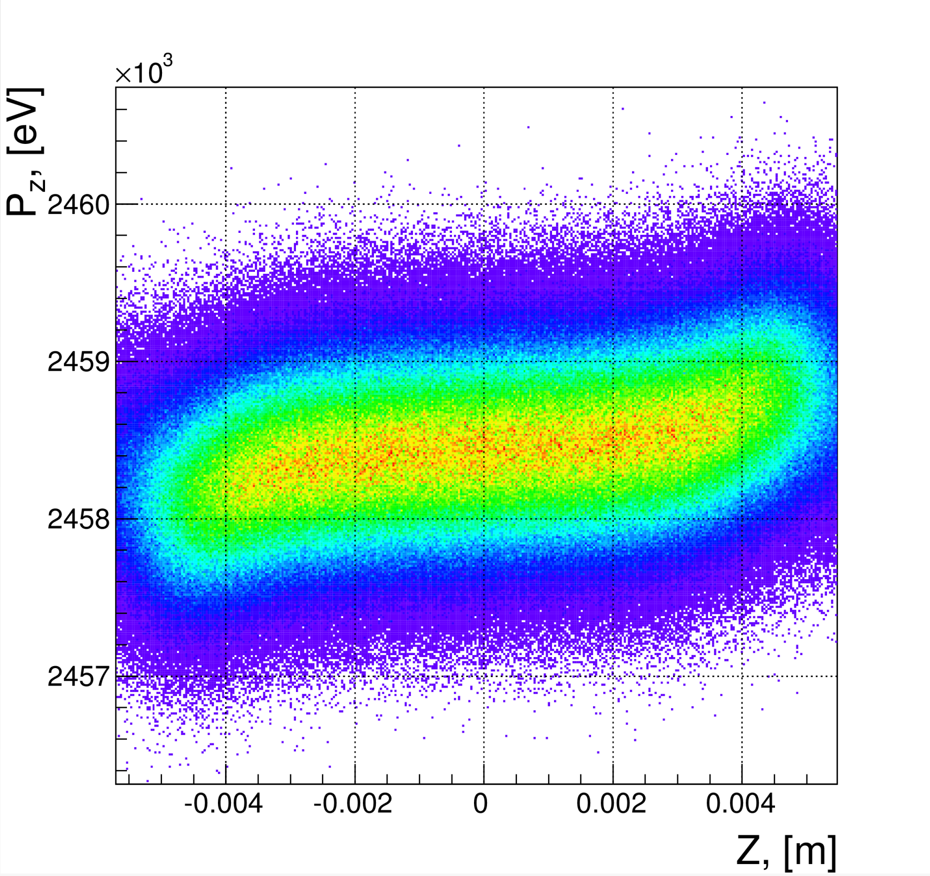
- The higher the PB energy the better
  - this put tough requirements for the source – RF gun
  - 2 MeV choosen as a compromise
  - PB duration ten(s) ps
  - PB peak current max 1 A .

Novel approach

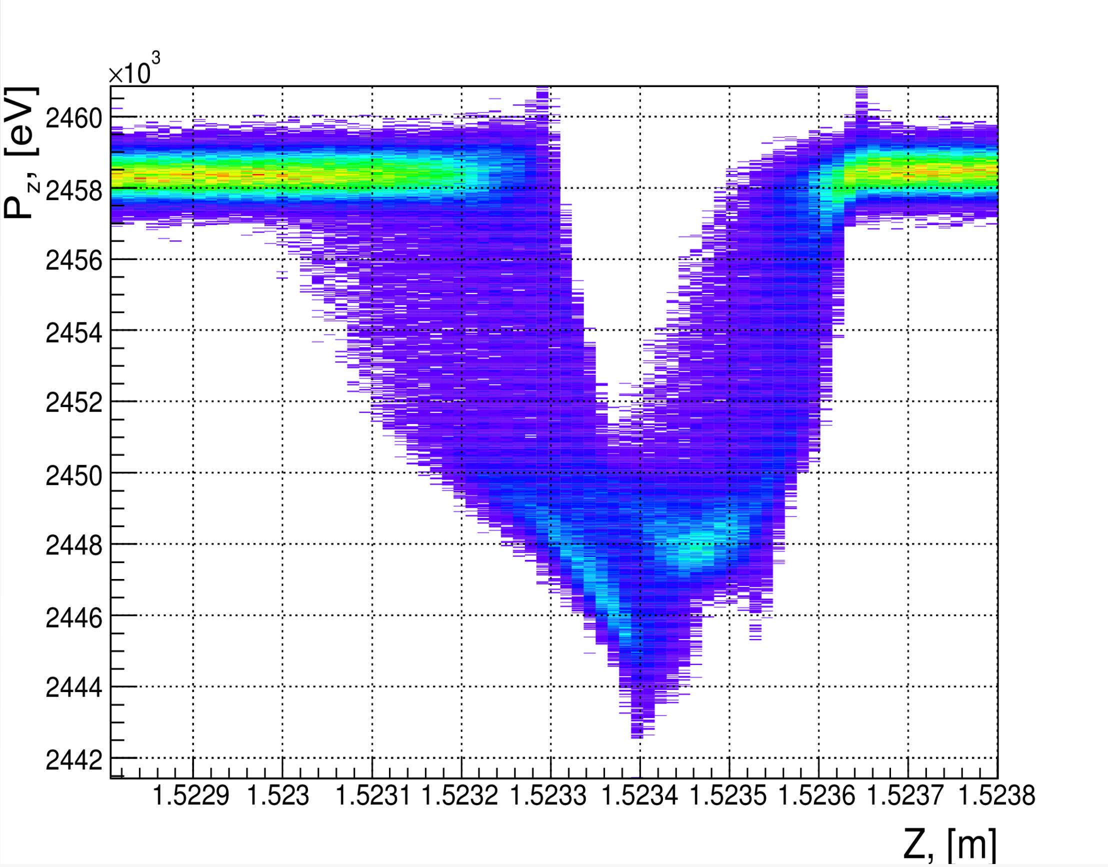
- PIC simulations using VORPAL
  - simulation volume 0.01x0.01x0.0116 m
  - grid 50x50x2000
  - 30 kparticles for RB and 3 Mparticles for the PB
  - RB parameters:
    - duration 100 fs RMS (FT and Gaussian)
    - 15 MeV and 2 GeV
    - Emittance 1 mm.mrad
    - 0.2-0.5 mm X-section at IP

Novel results

- Non perturbed beam



- Perturbed beam

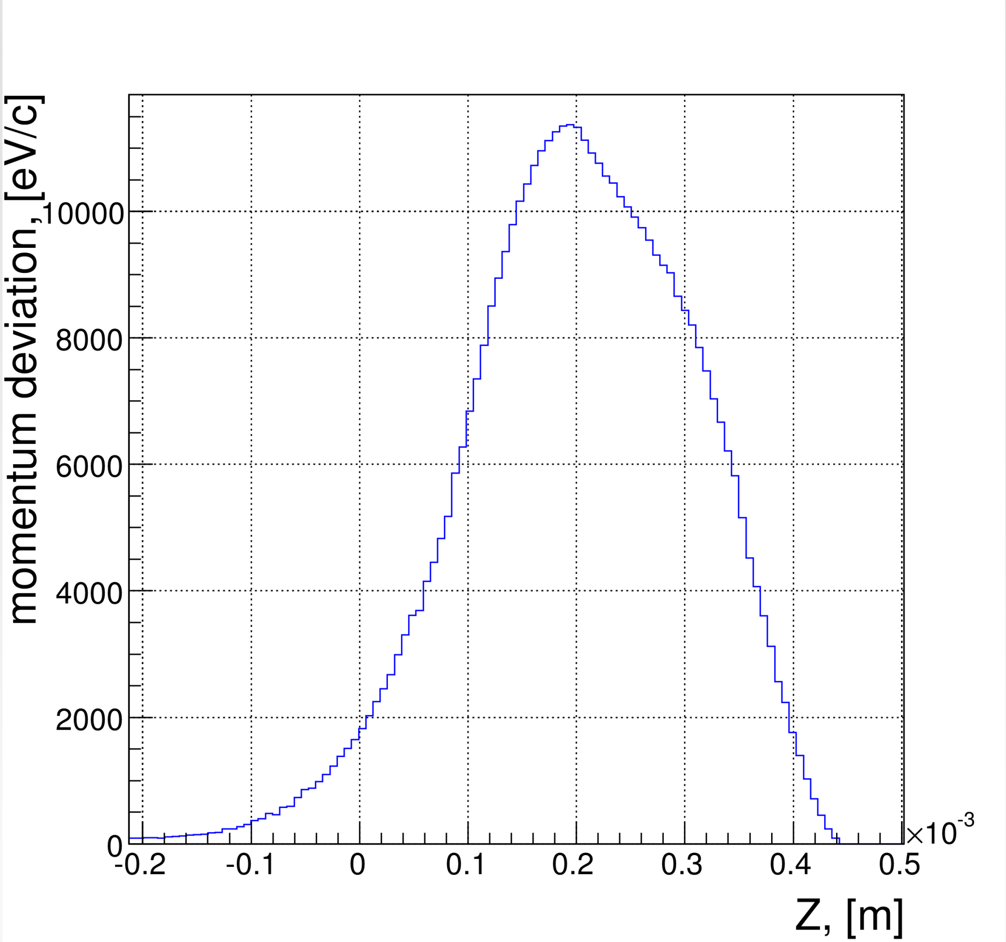


Novel results

- The FWHM and the RMS parameters increased exactly with the slippage factor

	X_{rms}, [mm]	Z_{rms}, [mm]	$Z_{rms,m}$, [mm]	deviation, %
Gaussian	0.5	0.03	0.038	27%
	0.2		0.037	23%
Flat Top	0.5		0.037	23%
	0.2		0.036	20%

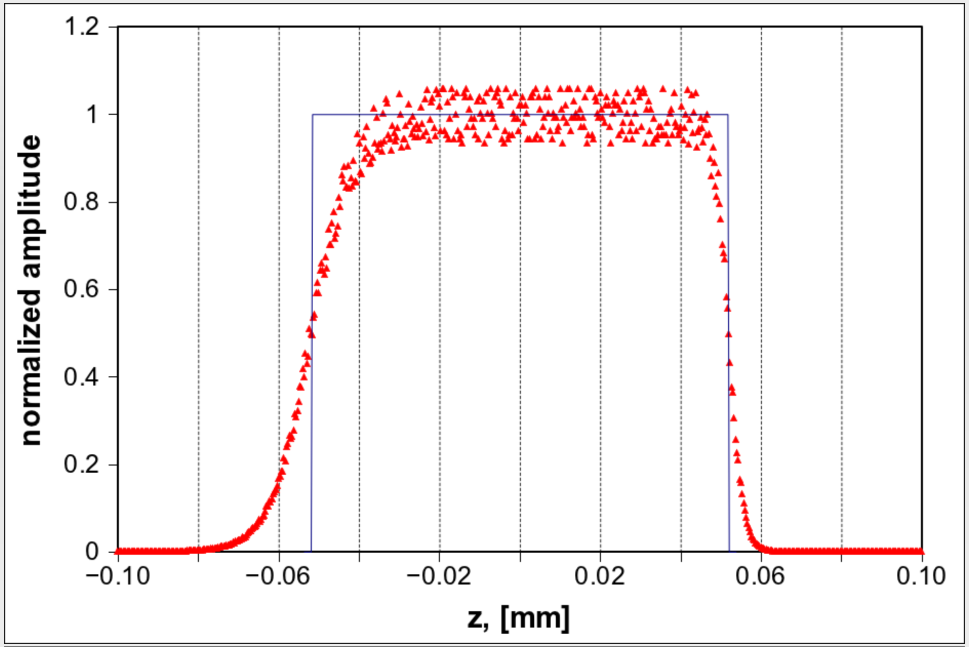
- Additional deconvolution analysis to recover the shape of the distribution

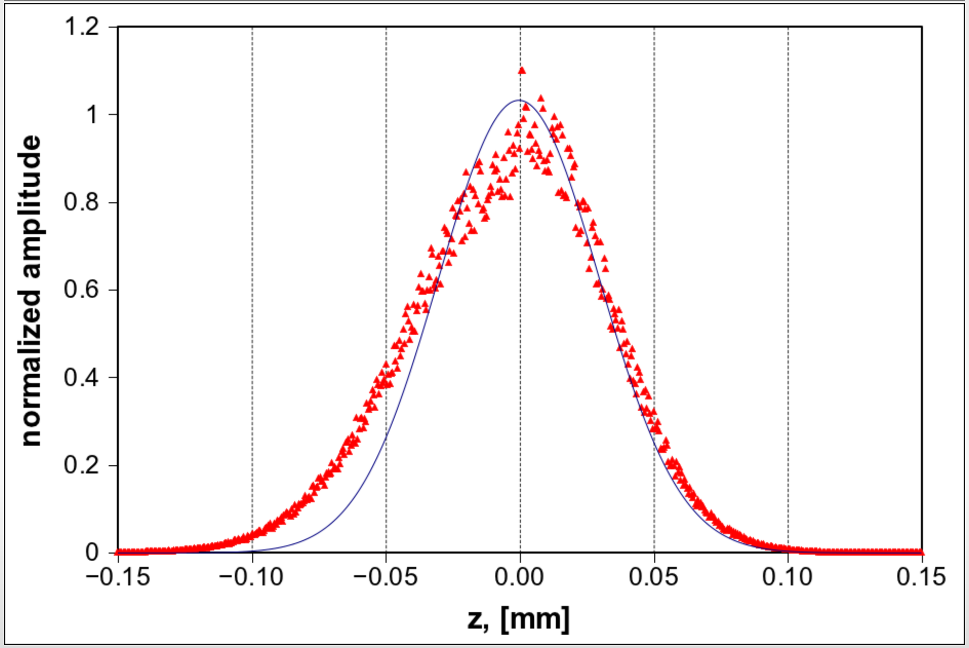


Deconvolution

- Preliminary results, deconvoluting a moving rectangle
  - the distributions were assumed known
  - results are encouraging

	Measured, [mm]	Deviation, %
Plateau	0.0307	2.6
Gaussian	0.0334	11





RF cavities

- Normal conducting S-band gun 2.856 GHz
  - Spectra-Physics ”Tsunami” laser

- Deflecting cavity, same frequency as gun:
  - voltage 600 kV
  - power 120 kW
  - resolution beter than 50 fs
  - a matching quad will be necessary

$$V = \sqrt{\left(2Z \cdot P_{RF}\right)}$$

$$\sigma_x = \sqrt{\left(\sigma_x^2 + r_{12}^2 \cdot k^2 \cdot \sigma_z^2\right)}$$

$$k = 2\pi \mathrm{eV} / \lambda E_k$$

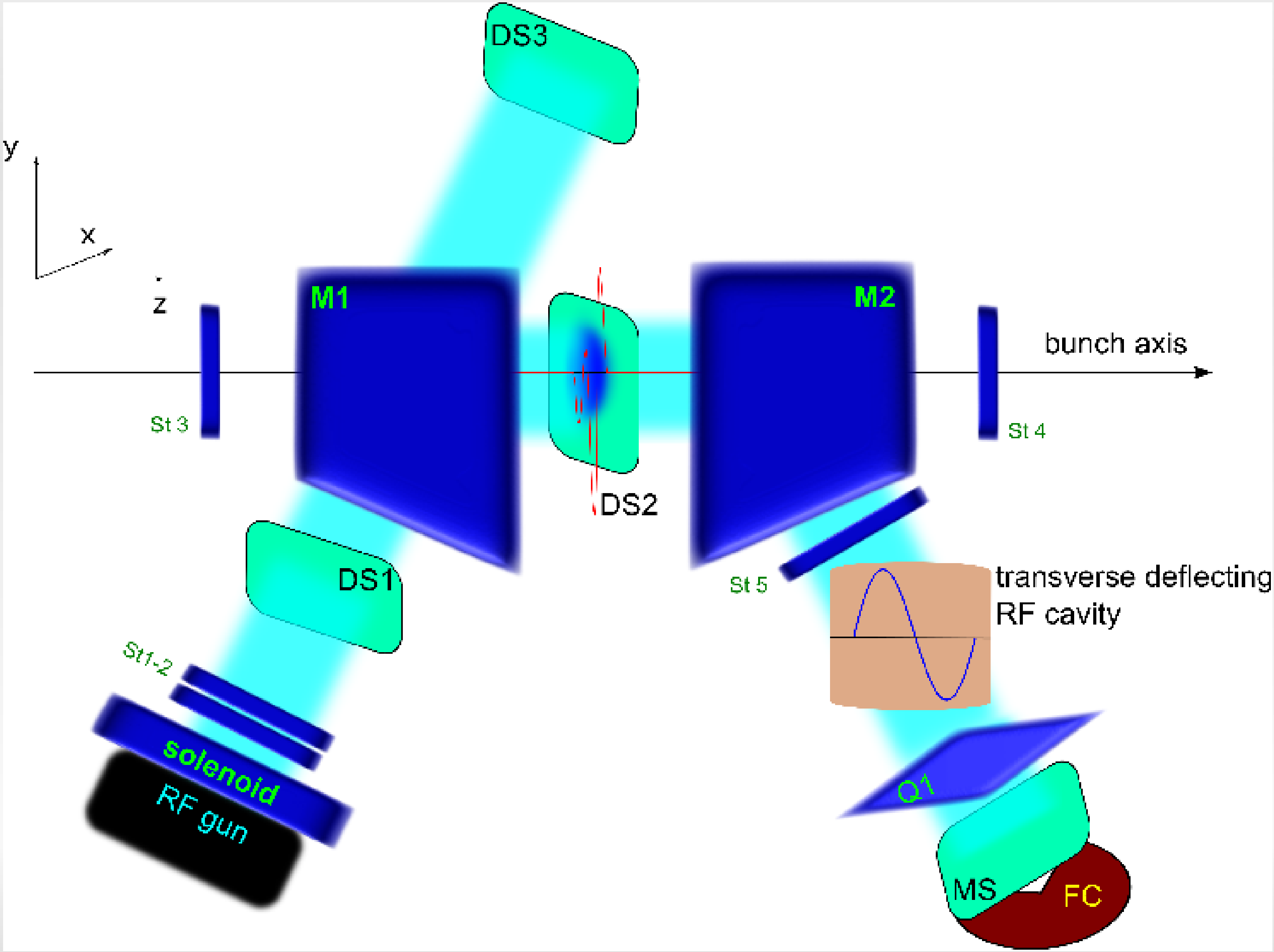
* D. Xiang, "Longitudinal-to-transverse mapping for fomtosecond electron bunch length measurement," SLAC-PUB-14100, 2010.

** S. Jia-Ru, "RF deflecting cavity design for bunch length measurement of photoinjector at Tsinghua University," Chinese Physics C (HEP&NP), vol. 32, no. 10, 2008.

Spectrometer magnets

- Requirments:
  - high resolution
    - 2x90° maximizes resolution and cancels divergence terms
  - smaller radius possible
    - trade off against magnet power consumption
    - if $\rho = 0.2$ m, $\alpha=90°$ then $B=0.06T$, $I \sim 30A$
    - at such peak field the deflection of 2 GeV beam is very small, correctors St3 and St4

Final layout



Discussion

- Benefits
  - non-destructive
  - very good resolution
  - small footprint
  - direct measurement
  - costs still lower than conventional EBM techniques,
- Disadvantages
  - requires RF gun and a laser
  - more expensive than most ST and EO
  - development of complex data analysis