Experimental Studies on High-brightness Electron Beam Production and Preservation

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Introduction

- **One of the technological challenges to build X-ray FELs and Linear Colliders is to produce and preserve a high-brightness electron beam from a photo-cathode RF gun.**

- **For the beam production:** We require both longitudinal and transverse laser distributions to be uniform. Question: What is the beam performance when the transverse laser profiles are distorted?

  ⇒ **Emittance vs non-uniform lasers**

  Contributors: M.Babzien, I.Ben-Zvi, X.Y.Chang, A.Doyuran, R.Malone, X.J.Wang, V.Yakimenko

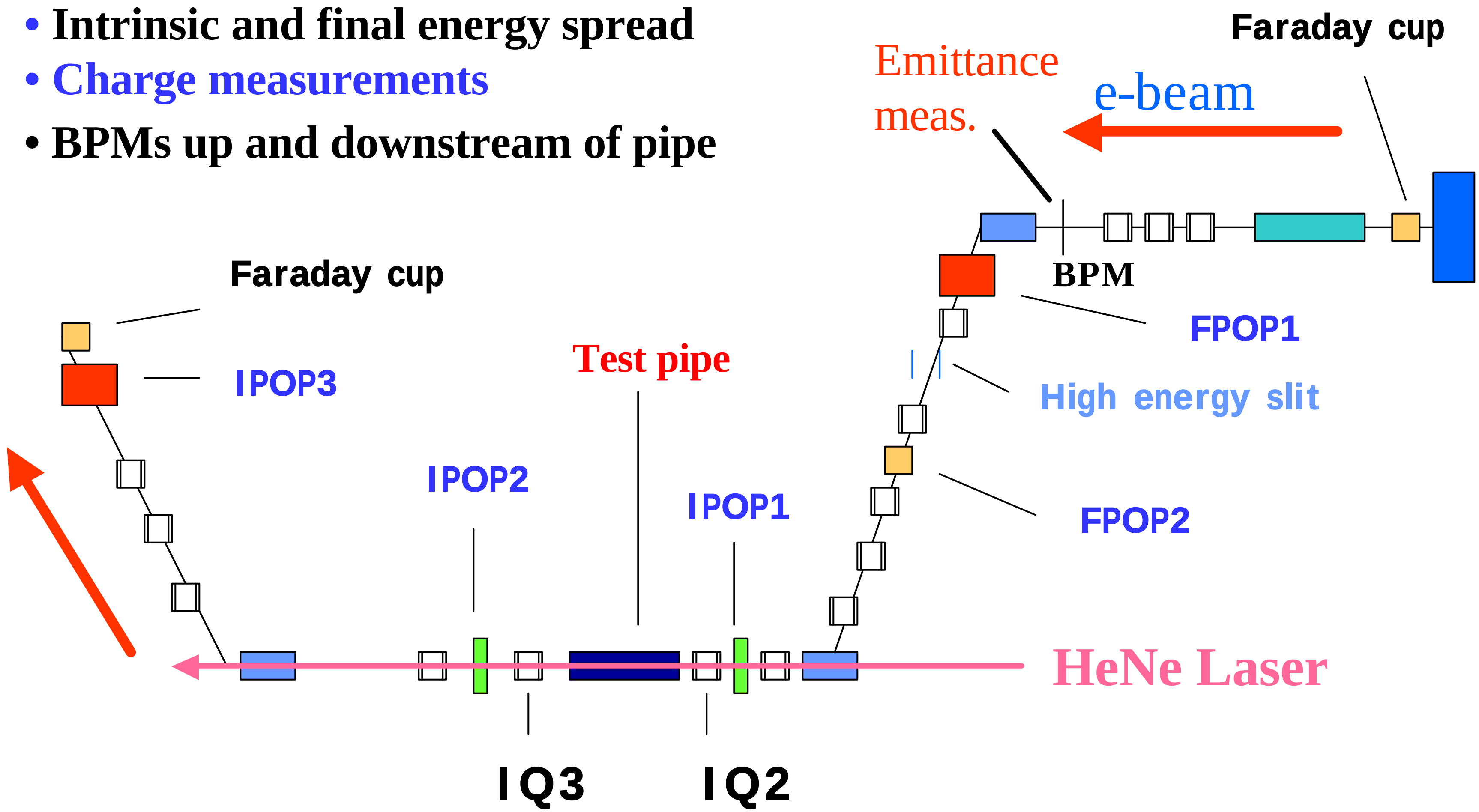
- **For the beam preservation:** Surface roughness wakefield is significant source to beam performance deterioration. Many theoretical models have been developed to predict the effects. However, they lack experimental confirmation.

  Þ **Surface roughness wakefield measurement**

  Contributors: M.Babzien, I.Ben-Zvi, M.Woodle, J.Murphy, X.J.Wang, J.H.Wu, V.Yakimenko

Schematic layout

- Pulse length measurements
- Intrinsic and final energy spread
- Charge measurements
- BPMs up and downstream of pipe



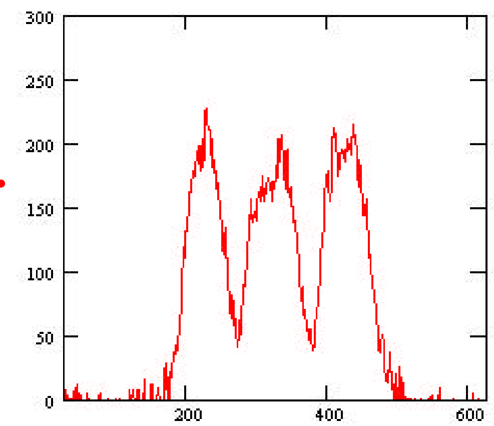
Emittance with non-uniform lasers
- theoretical basis

- In the equilibrium state, the electron beam can be described by "MB" distribution, which tends to be uniform.
- Any deviation from the uniform profile will cause emittance growth, which can be represented by the energy difference between a non-stationary and the stationary beam:

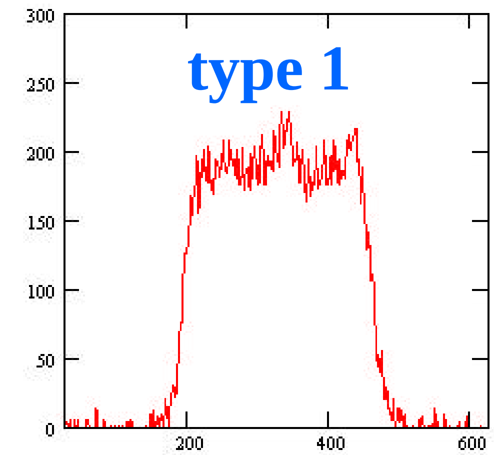
$$\frac{e_{nf}}{e_{ni}} = \left[1 + \frac{N r_c \tilde{x}}{15\sqrt{5}\, g_0 e_{ni}^{\ 2}} \frac{U}{w_0}\right]^{1/2}$$

One profile as an example:

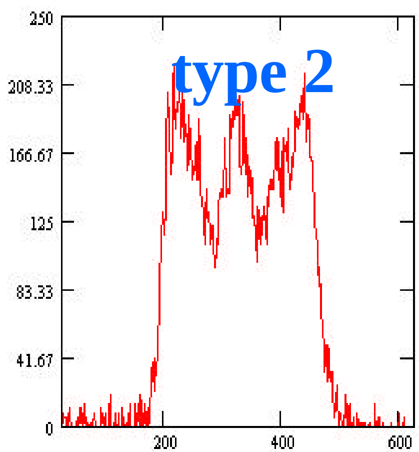
at 0.5 nC, the emittance growth is 83%, which agrees with both measurements and simulations.

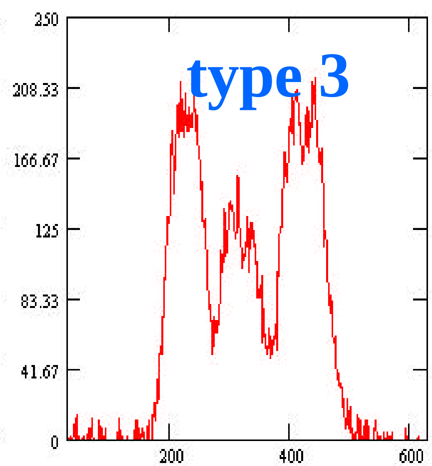


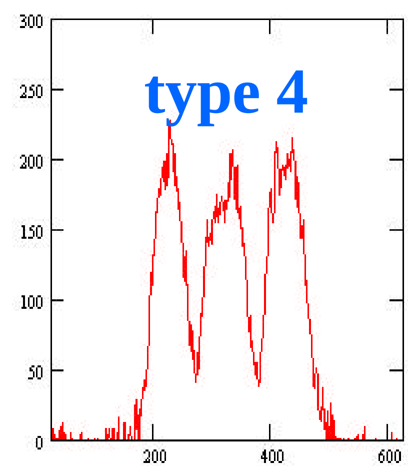
Transverse laser profiles (cylindrical symmetry)

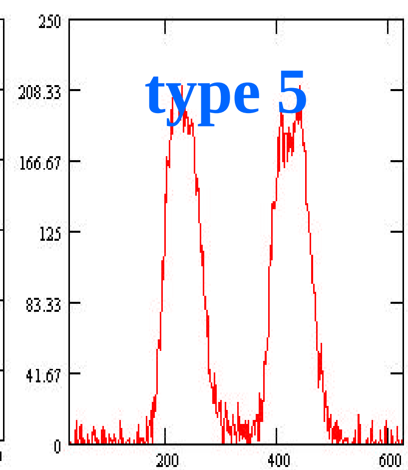


The ATF's photocathode's YAG laser has important qualities: ***stability and transverse uniformity ,*** *which provides a good opportunity to do this experiment.*



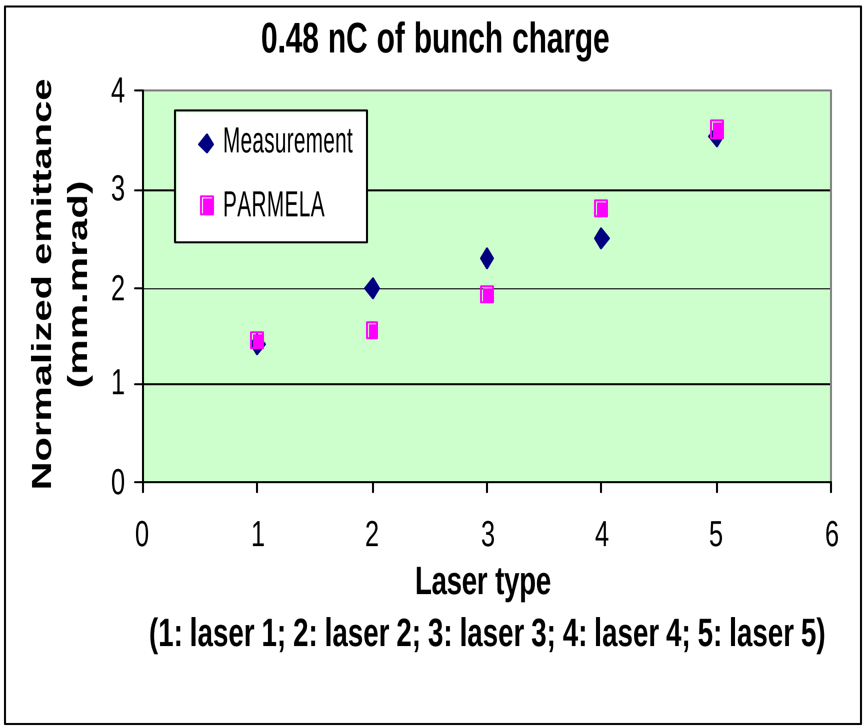


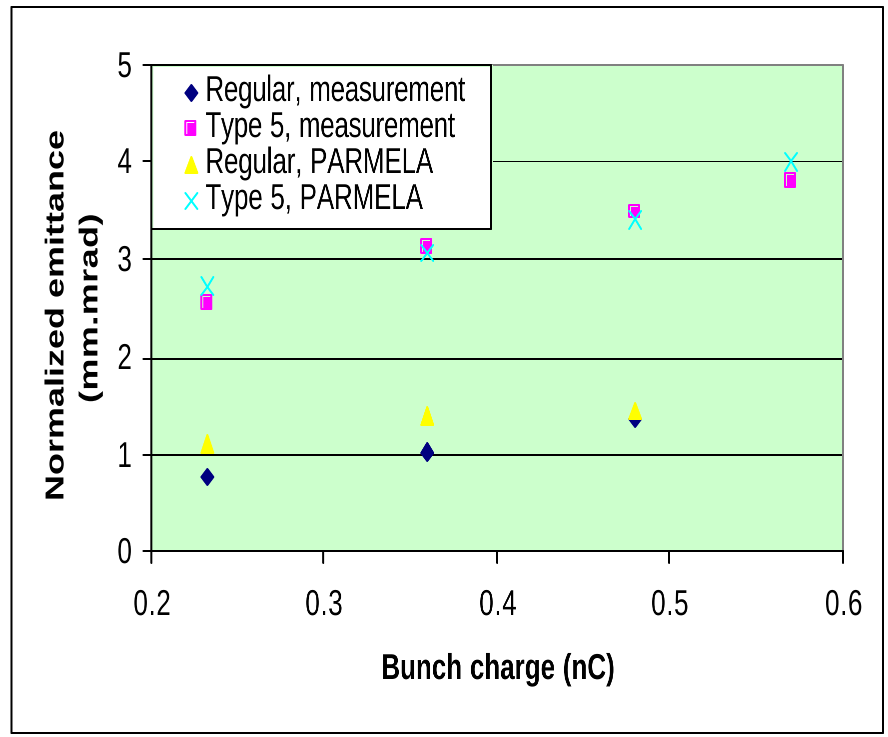




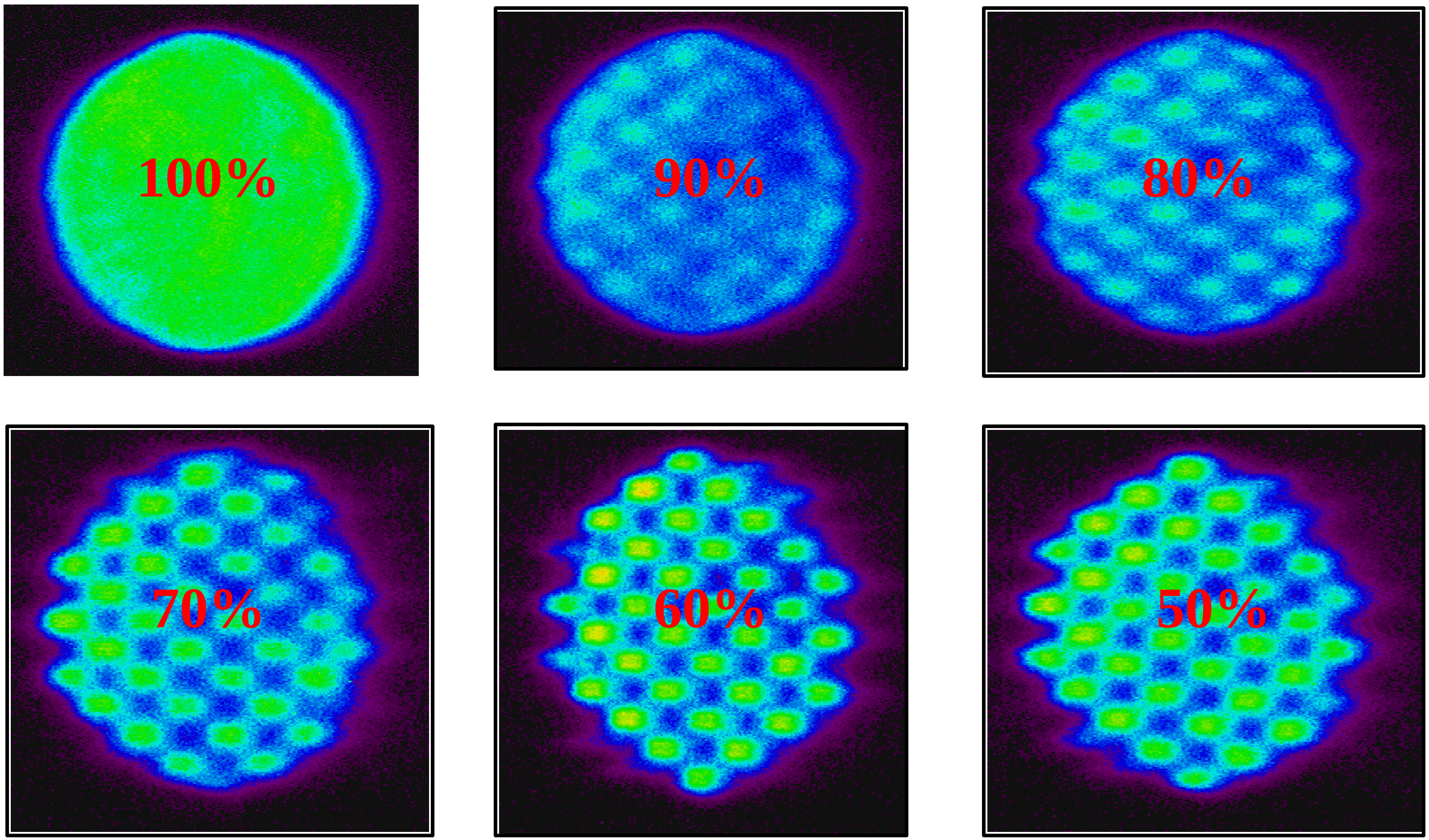
Emittance measurements

Emittance is measured at a Beam Profile Monitor (just after the linac, at >40 MeV) by scanning one upstream Quadrupole at the ATF's H-line. (Qiu, Batchelor, Ben-Zvi and Wang, PRL, 1996)

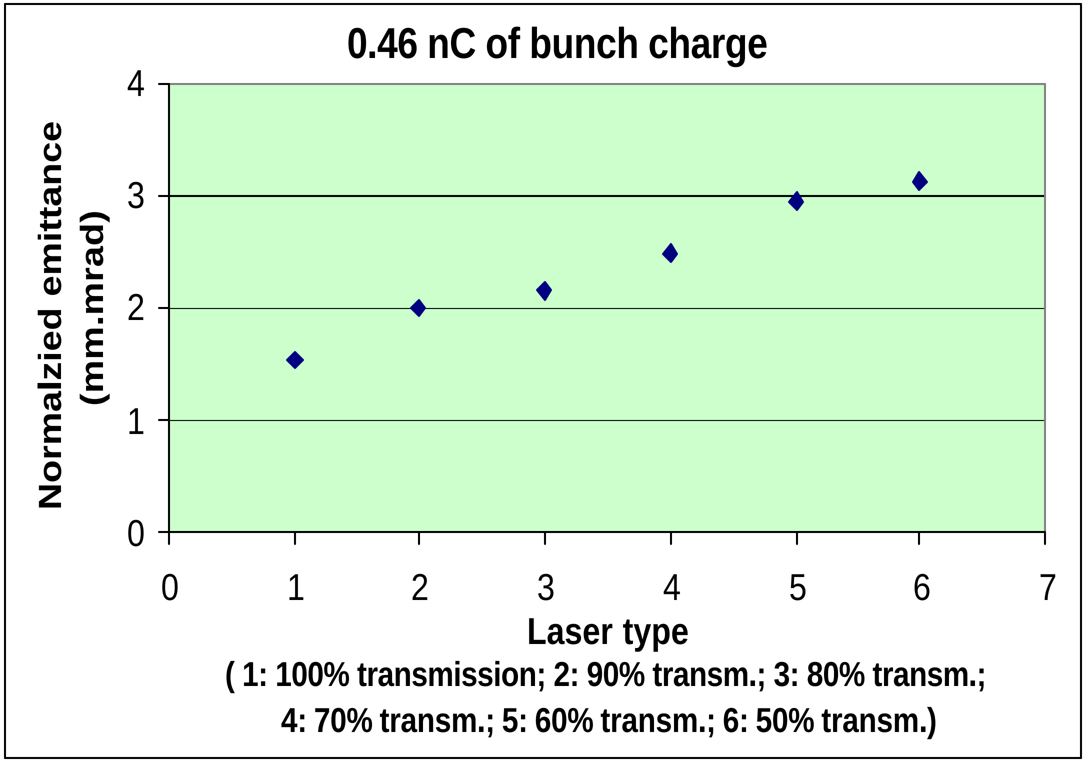




Transverse laser profiles (non-cylindrical symmetry)



Emittance measurements



Summary for emittance vs uniformity

- **For cylindrical symmetry non-uniform beams:**

- Emittance growth is about 30% when a ~40% laser P-P fluctuation is created relative to the flat-top. The emittance grows by a factor of more than 2 when the middle part of laser is blocked.

- In both regular and non-uniform lasers, the dependance of the emittance on the bunch charge is similar, linear with charge.

- Experimental results agree well with both the analytical estimate and PARMELA simulations.

- **For non-cylindrical symmetry non-uniform beams**

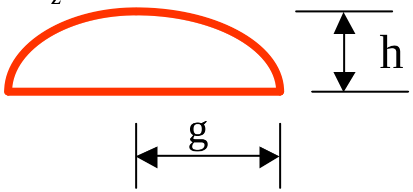
Emittance is linear with the laser transmission through the laser masks. The emittance growth is about 100% when the laser transmission through mask is only 50%.

Surface roughness wakefield:
Typical models

• Inductive impedance model

The surface roughness was represented as a collection of bumps distributed over a smooth surface. If the bump dimensions < s_z :

$Z_i = -iw \cdot f(b, g, h)$ then $Z = \sum_i Z_i$



· Synchronous modes

The roughness wakefield is associated with the resonant modes when $V_p \leq c$

- Periodic corrugation

Lowest mode’s frequency: $w_0 = c\sqrt{\dfrac{2p}{hb \cdot 2g}}$ (p: period of bumps)

- Random corrugation

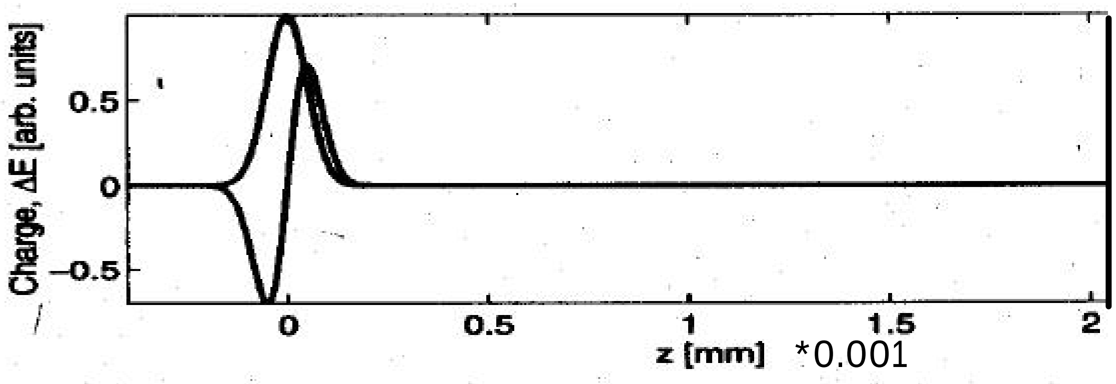
The synchronous mode still exists, but its amplitude decays.

Lowest mode’s frequency:

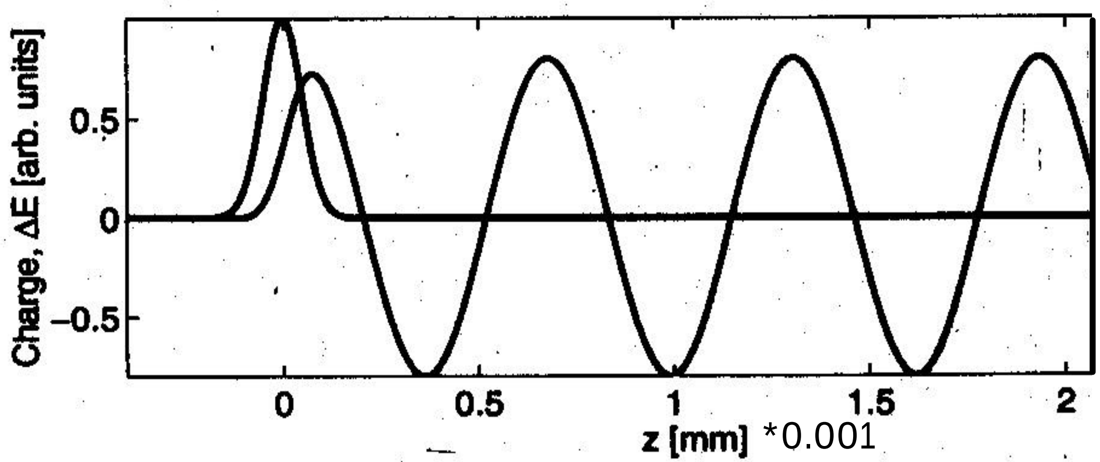
$$k_0 = \sqrt{\frac{2e}{bh(e-1)}}$$

(e is dielectric constant, usually 1.5)

Wakefield comparison



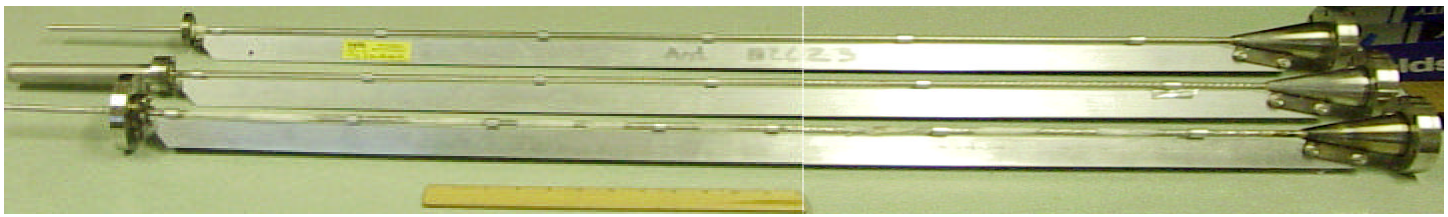
Inductive impedance:
Energy spread: **YES**
Energy loss: **NO**

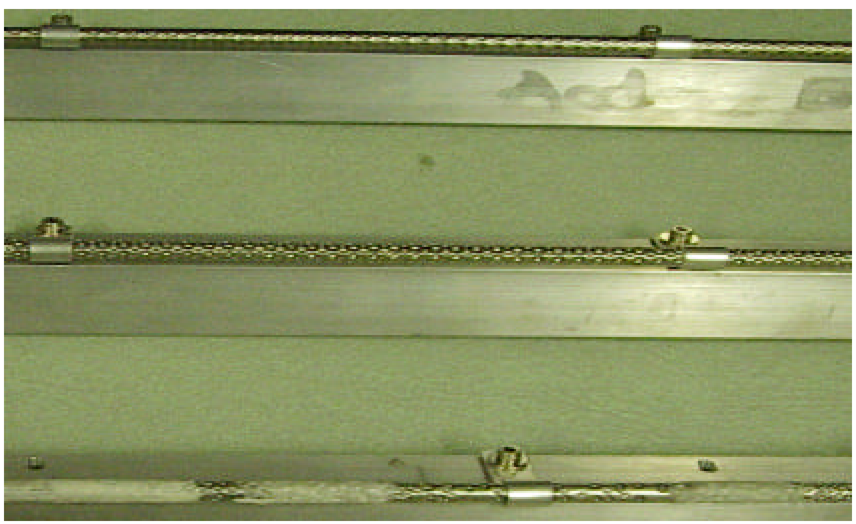


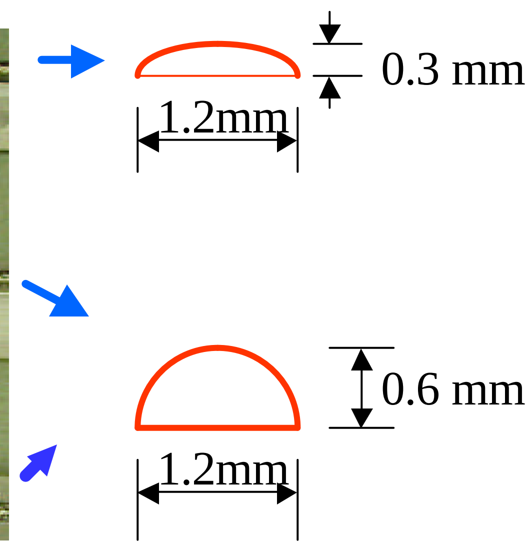
Synchronous mode:
Energy spread: **YES**
Energy loss: **YES**

Beam pipes design

Large-scale bumps are artificially produced to match the shorter beam pipe length (~1 m) and longer pulse length (~ps) at the ATF. The ATF has a ***high quality e-beam with ultra-small emittance and high stability,*** **which provides opportunity to produce small beam through small long pipes** (length: 97 cm, ID:6 mm).







Regular 3200

Regular 3200

Random 2900

Optics and alignment

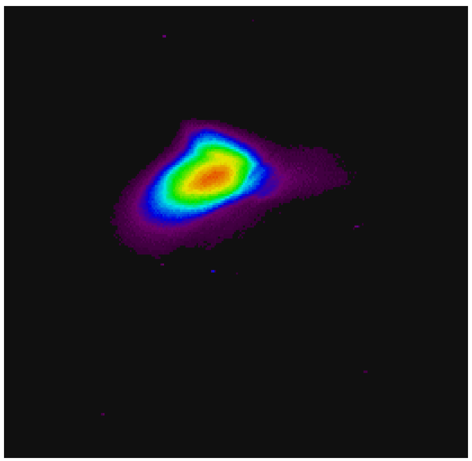
- Energy spread and loss are measured in term of horizontal beam size and central beam position, respectively. The simulated spectrometer resolution is about 0.02%. 40 MeV of beam energy is used.

- In order to suppress the transverse kicks, misalignment of the beam pipe with the beam line and straightness of pipe self is controlled to below 50 μm.

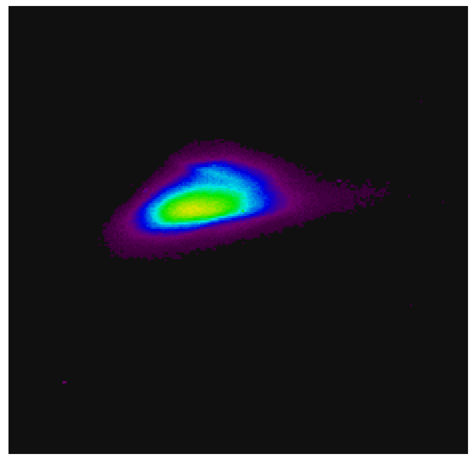
- The HeNe laser alignment is also used to make sure the electron beam overlaps the laser beam at the BPMs upstream and downstream of the test pipe.

Beam images

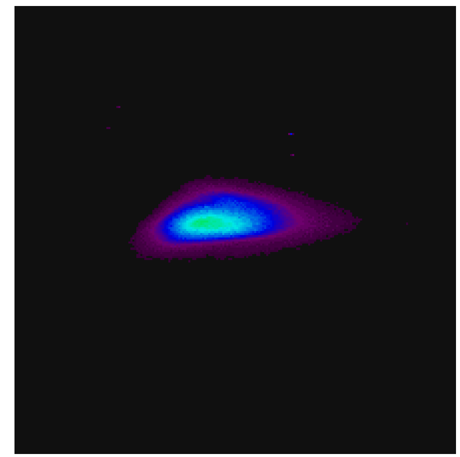
- A regular smooth beam pipe was measured to serve as a reference. The energy spread at the end of the test pipe is at the same level of the intrinsic energy spread, ~0.05%.



16 pixels,
0.32 nC, 6.5 ps



18 pixels,
0.22 nC, 4.5 ps

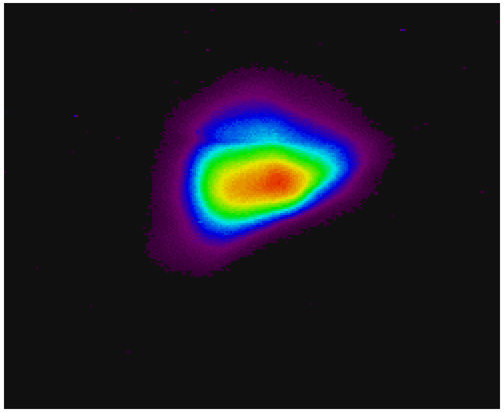


19 pixels,
0.4 nC, 9.33 ps

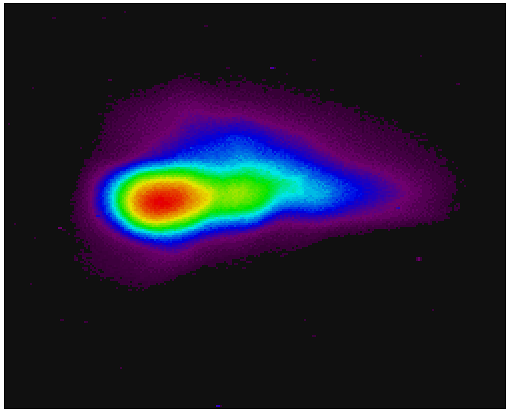
Note: ~30 pixels corresponds to 0.1% energy spread

Beam images (Cont')

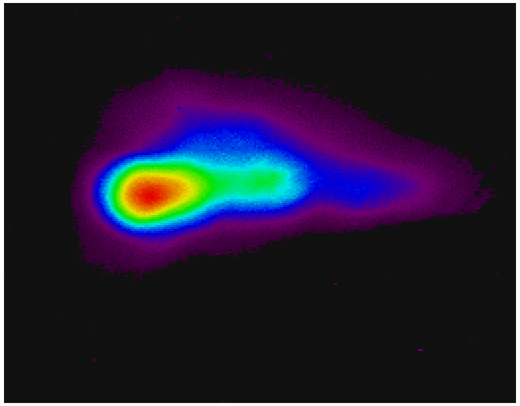
- Small-bumps beam pipe: Wakefield effects are observed.



20 pixels,
0.31 nC, 6.3 ps



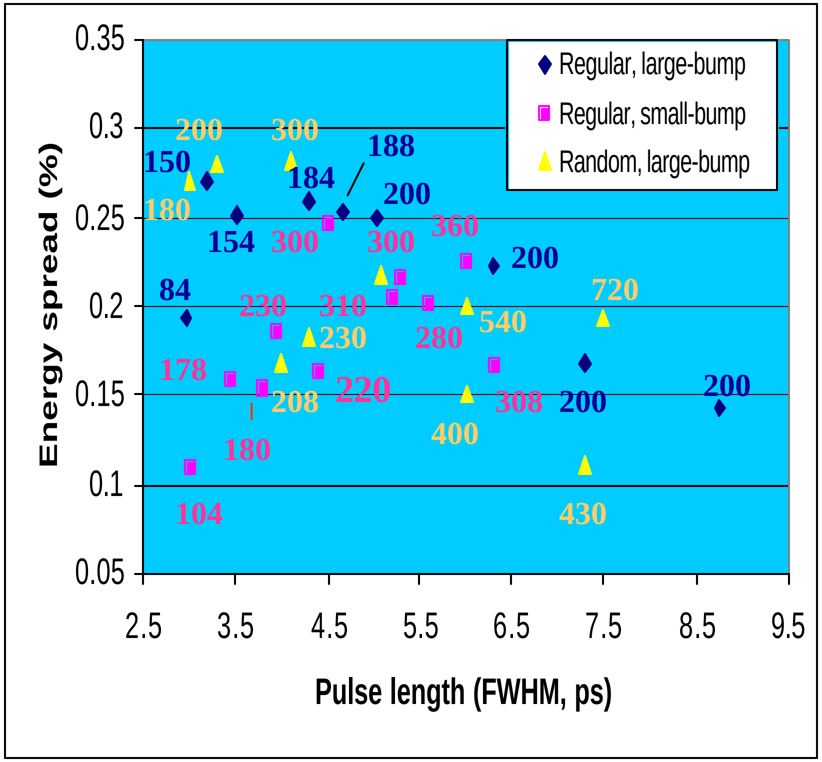
34.7 pixels,
0.3 nC, 4.8 ps



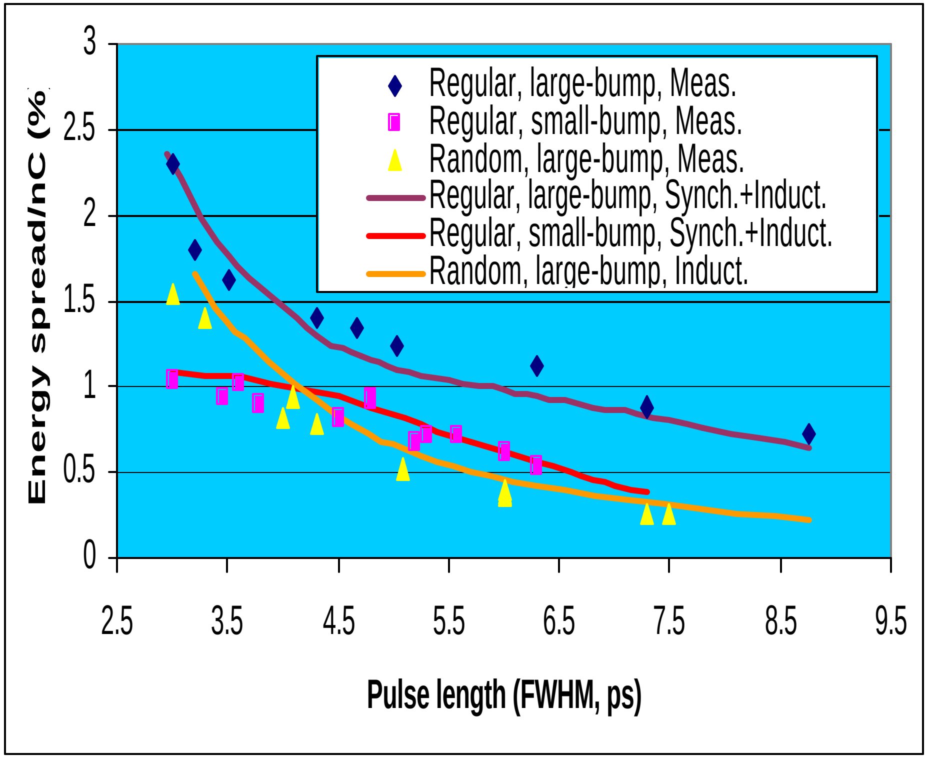
38.4 pixels,
0.29 nC, 3.6 ps

Note that 12 pixels correspond to 0.1% energy spread

Energy spread



raw data at various charges



normalized to 1 nC

Approach for data analysis

- **Inductive impedance**
- **Synchronous modes**

- Modes in cylindrical symmetric iris can be predicted by models.
- In our pipes, the bumps' distribution is interleaved although periodic, and thus the modes can not be predicted with known models.
- A single synchronous mode is used to fit the measurements:

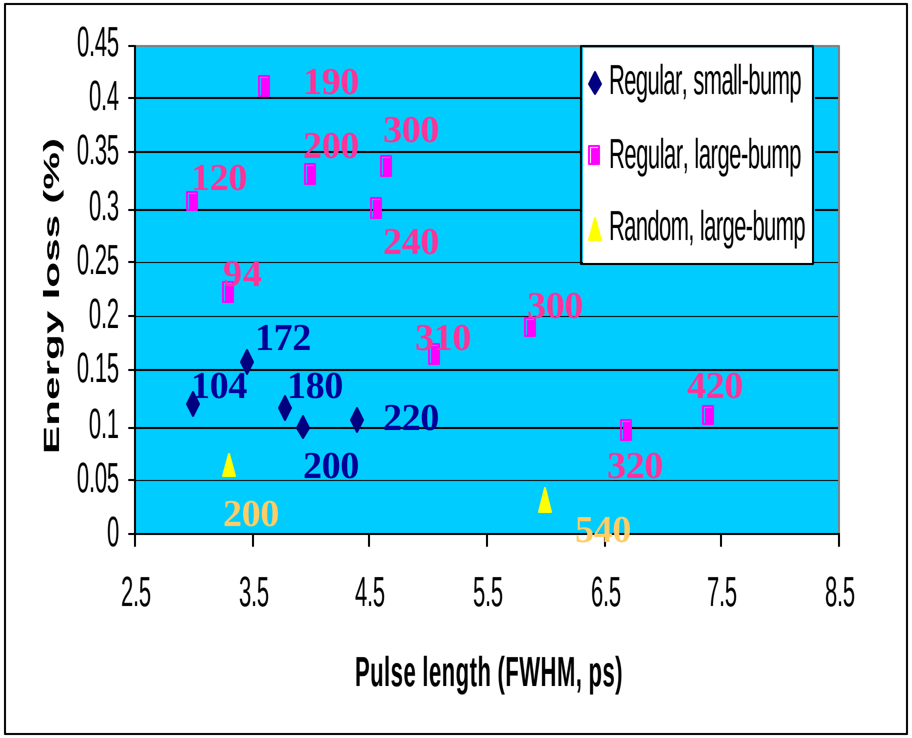
small bumps: $w_0 = 0.76$ THz

large bumps: $w_0 = 0.47$ THz

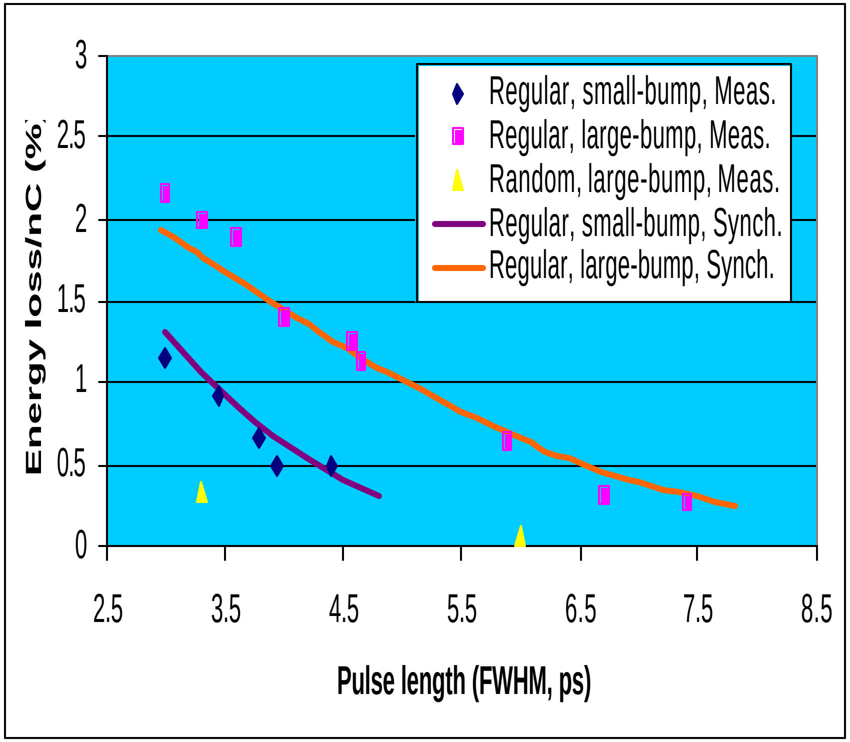
- Dielectric layer constant

small bump: 1.52, large bump: 1.82, which are comparable to 1.5 in the assumption in references.

Energy loss



raw data at various charges



normalized to 1 nC

Summary for surface roughness wakefield experiment

- **For the pipes with periodic bumps**
  - The results can not be explained only by the inductive impedance model
  - In addition to the inductive impedance, a single synchronous mode is used to fit well the measurements for both the additional energy spread and loss.

- **For the pipe with random bumps**
  - Energy loss is significantly reduced
  - Energy spread agrees well with the predictions by the inductive impedance model

- **Real surface roughness is closer to the random corrugations. The synchronous modes could not survive in such pipe.**

Acknowledgments

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