# Investigation of beam dynamics with not-ideal electron beam on ALICE ERL


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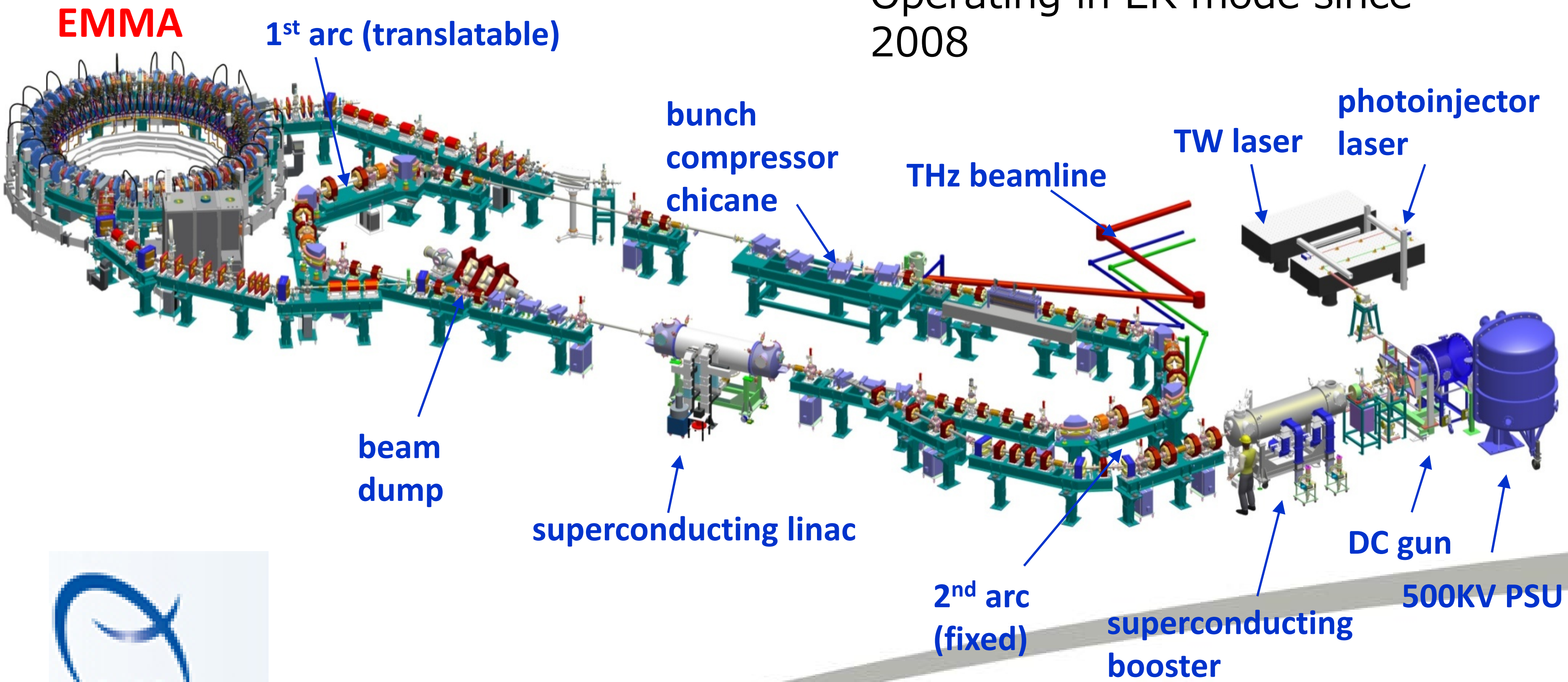
# The ALICE Facility @ Daresbury Laboratory

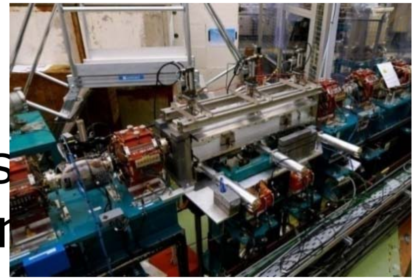
Accelerators and Lasers In Combined Experiments

An accelerator facility based on a superconducting ERL-prototype
Operating in ER mode since 2008

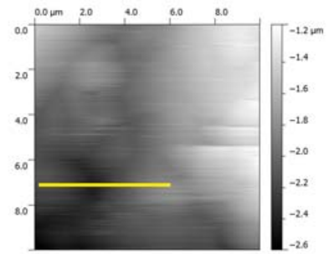


# ALICE: multifunctional facility

## ER modes of operation



- **IR FEL** (5.7-8um; 10-30W ; ~3MW peak power)
  27.5MeV; 60-100pC; 16.25MHz; 10Hz; 100us
- **THz source** (15-20nJ per pulse; >10kW peak power
  26.0MeV ; 60pC; 40.63MHz; 10Hz; 100us

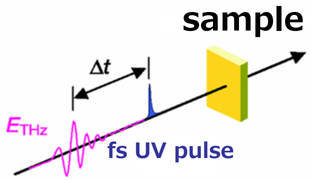


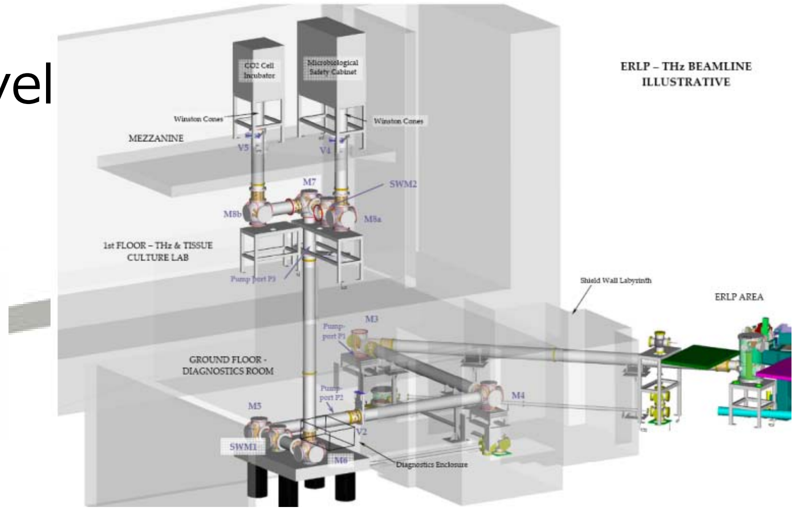
- **FELIS** : Free Electron Laser Integration with
  Scanning Near-field Optical Microscope
  25.0-27.5MeV; 60pC; 16.25MHz; 10Hz; 100u

- **THz for biological exps**. in Tissue Culture Lab.

- **THz for quantum dots** studies for novel
  solar cells

- **Digital LLRF** development

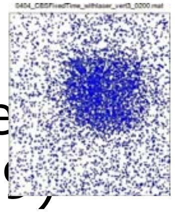


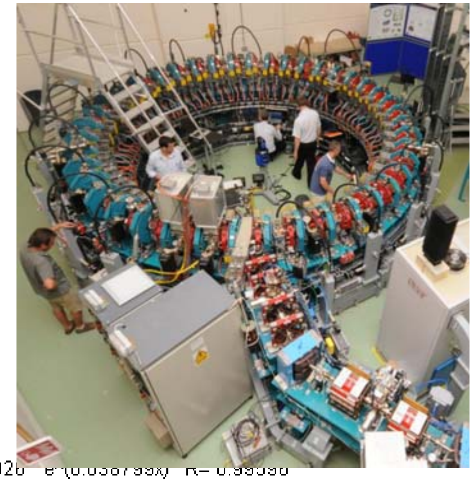



# ALICE: multifunctional facility

## Non-ER modes of operation (single bunch )

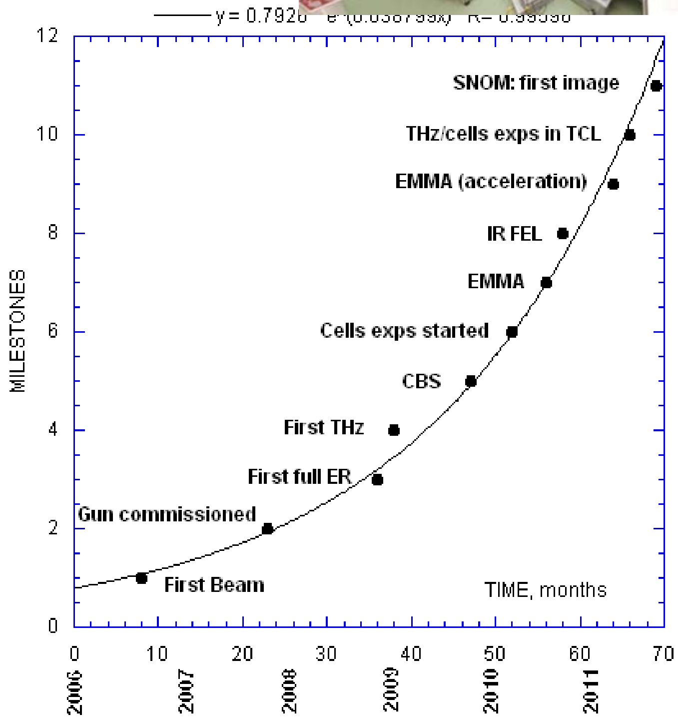
- **EMMA** : First NS FFAG demonstration
  12MeV; 40pC; single bunch
- **CBS** : Compton back Scattering Experime
  30MeV; <100pC (completed in 200 )





- **Electron beam / EM radiation** interaction exps.
  22.5MeV; 20pC
- **Electron beam tomography**
- **Timing and synchronisation** exps.
  (fibre-ring-laser-based system)

ALICE operates in a variety of modes differing in requirements for
- beam energies,
- bunch lengths,
- bunch charges,
- beam loading,
- energy spread etc.

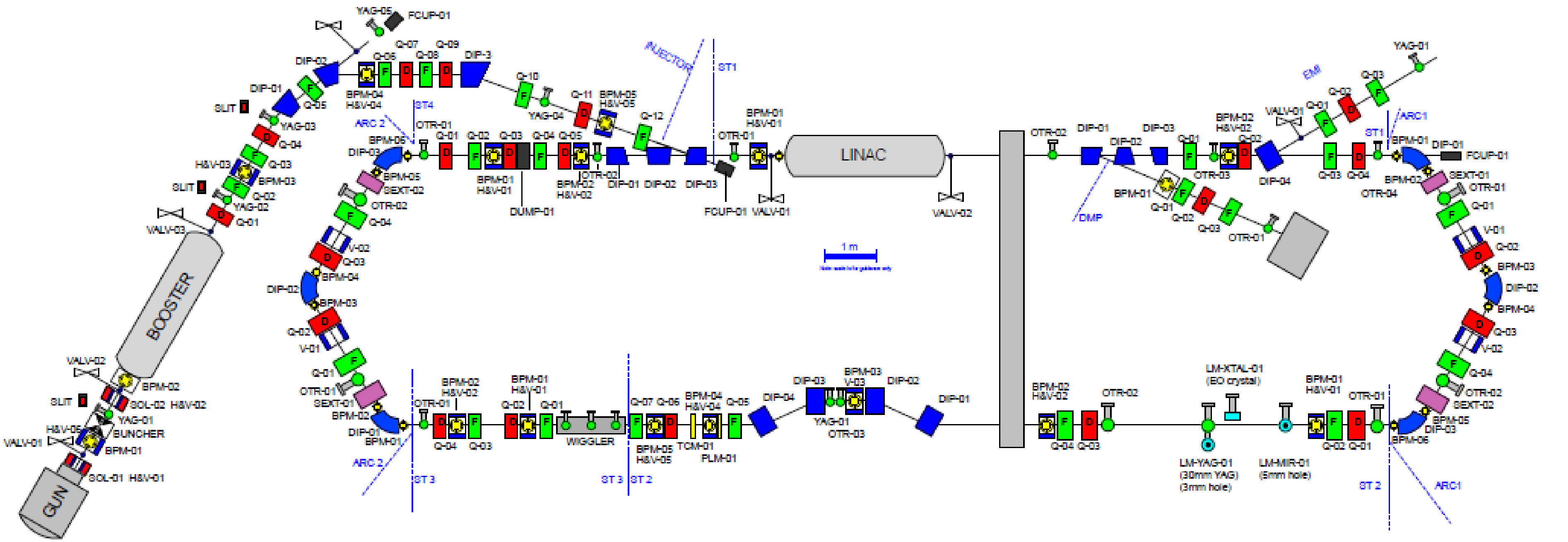


# ALICE

**RF System**
Superconducting booster + linac
9-cell cavities. 1.3 GHz, ~10 MV/m.
Pulsed up to 10 Hz, 100 μS bunch trains

**IR FEL**
Oscillator type FEL.
Variable gap

**Beam transport system.**
Triple bend achromatic arcs.
First arc isochronous
Bunch compression chicane $R_{56}$ = 28 cm



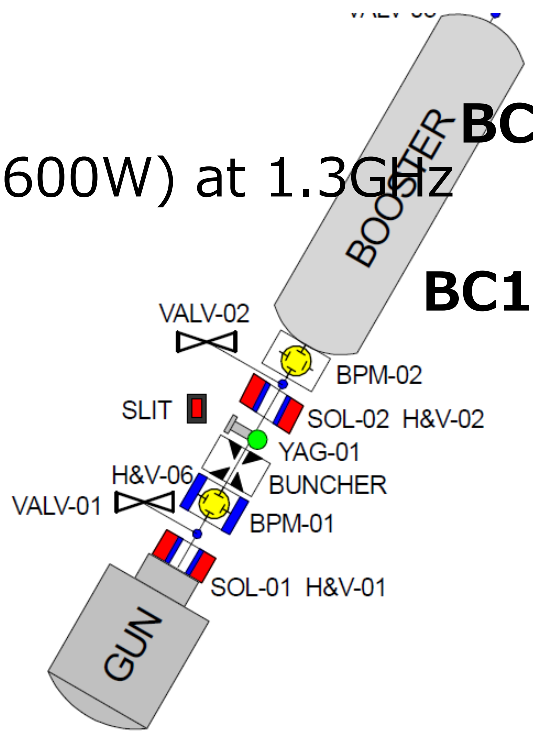

**DC Gun + Photo Injector Laser**
230 kV ; GaAs cathode
Up to 100 pC bunch charge
Up to 81.25 MHz rep rate

**TW laser**
For Compton Backscattering and EO
~70 fS duration, 10 Hz
Ti Sapphire

**Diagnostics**
YAG/OTR screens + stripline BPMs
<u>Electro-optic bunch profile monitor</u>

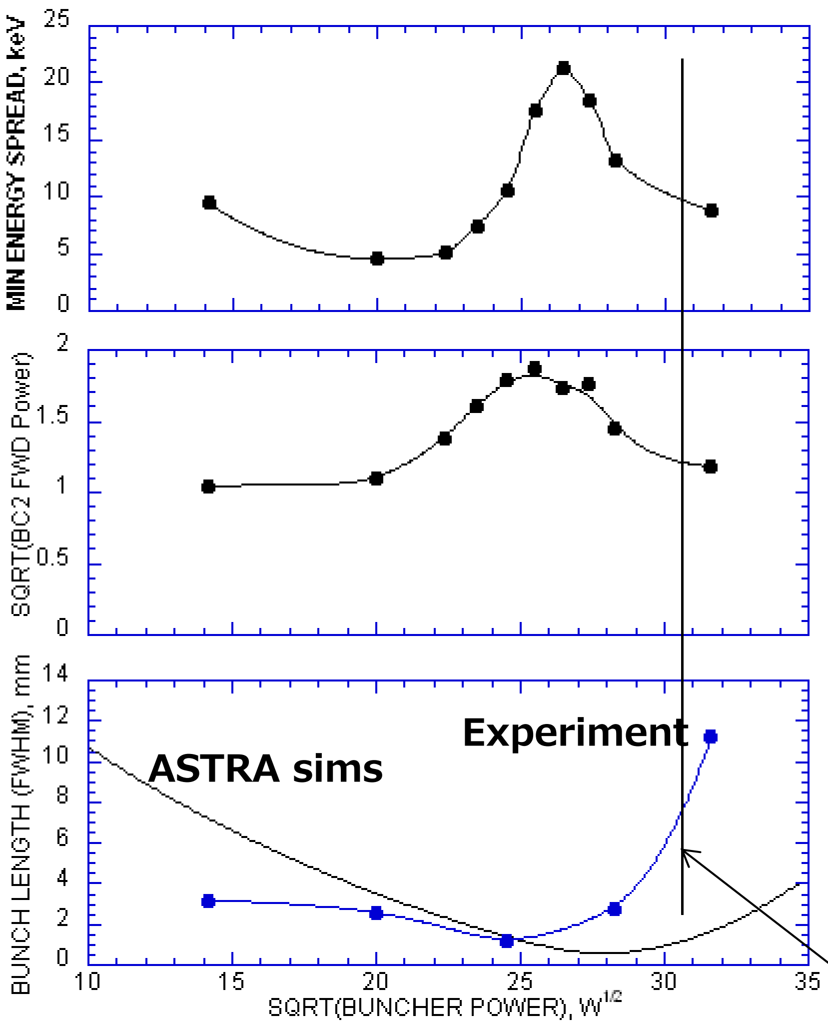
# ALICE optics and bunch formation: Injector

Bunch charge = 60pC (nominal)
Gun voltage = 230kV
Buncher peak voltage = 30-40kV (400-600W) at 1.3GHz




**BC2**

**BC1**




**Longitudinal phase-space "quality factor"**

**Energy chirp from BC1**

**Bunch length**

Longitudinal cross-over threshold (ASTRA)

**Longitudinal phase-space**
**v**
**buncher power**
**Q=40pC; BC1 phase = -10deg**

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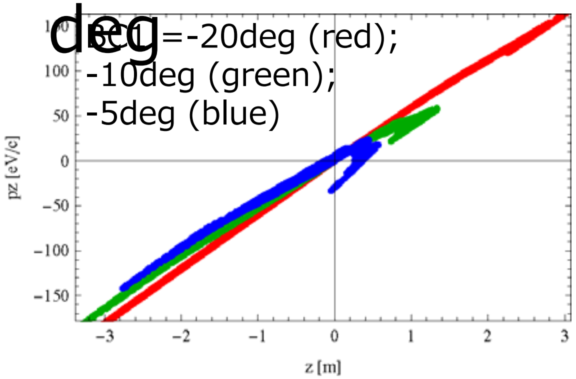
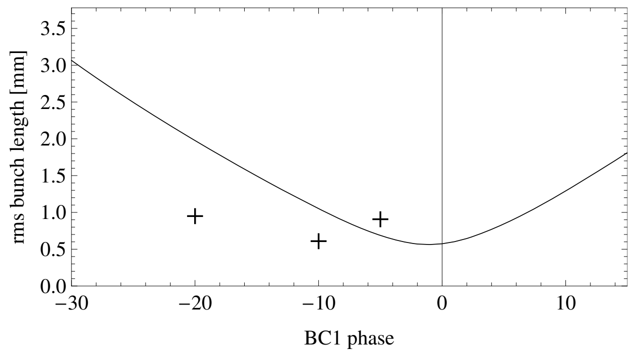
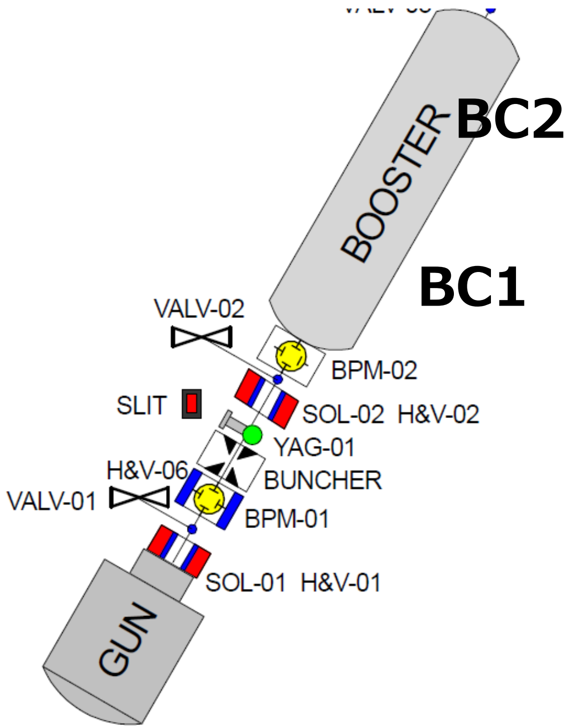
# ALICE optics and bunch formation: Injector

## BC1 off-crest phase : = (-10 to -20 deg

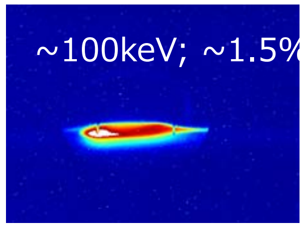


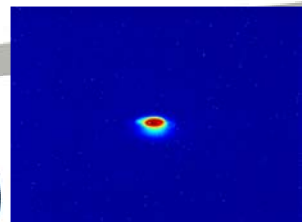

Generally: smaller bunch lengths but worse the "shape" of the longitudinal phase-space

## BC2 off-crest phase : = (+10 to +40) deg




For bunch compression setups:
   tend to leave some positive energy chirp from BC2

Otherwise:
   ~ minimal energy chirp from BC2



**Beam energy**: 4.0MeV (from BC1); 6.5MeV (from BC2)

# ALICE optics and bunch formation: Linac

## Linac phase:

- for R56=28cm, would need +10deg

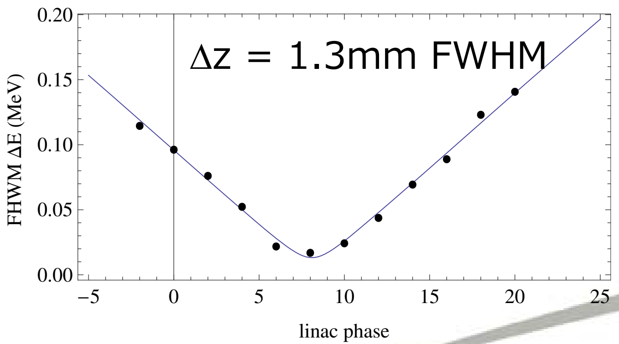
- but … need to compensate energy chirp in the bunch coming from inj
  from 0 to +5 deg

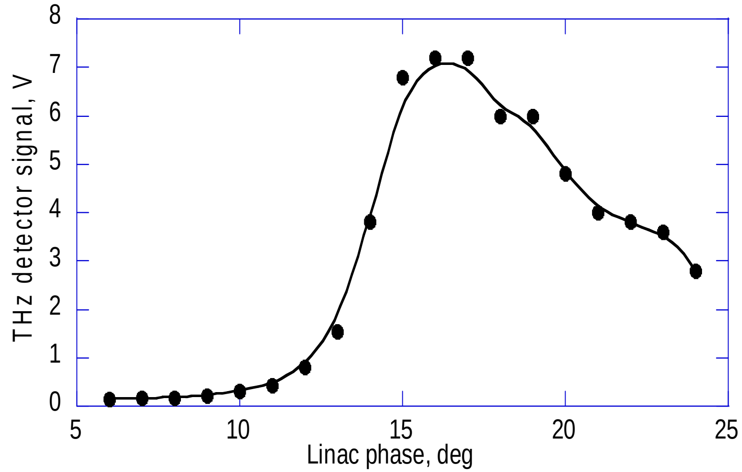
- hence overall off-crest phase (for bunch compression) ; +15 / +16de

Linac phase scan for bunch length evaluation

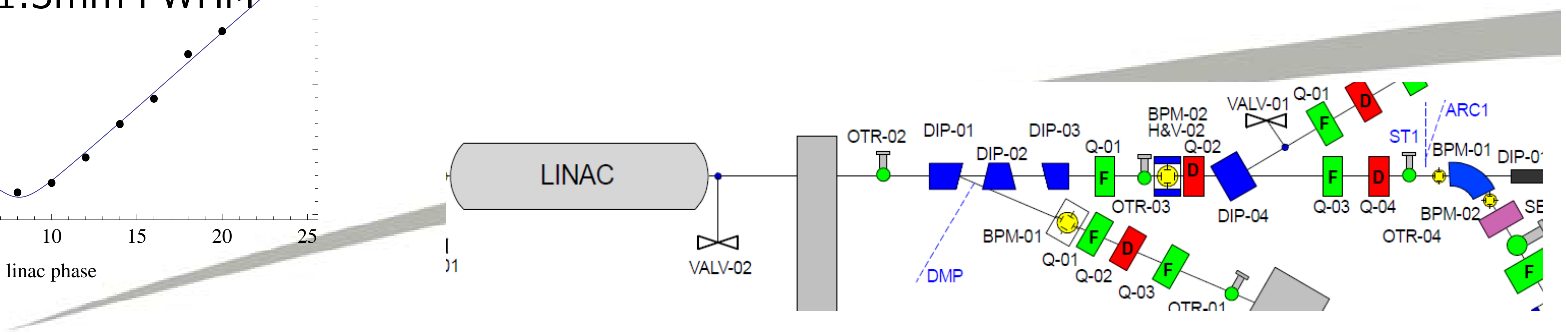
$$\Delta E = \sqrt{\Delta E_0^2 + h^2 \Delta z^2}$$

$$h = E_L \frac{2\pi}{\lambda} \sin(\phi - \phi_0)$$

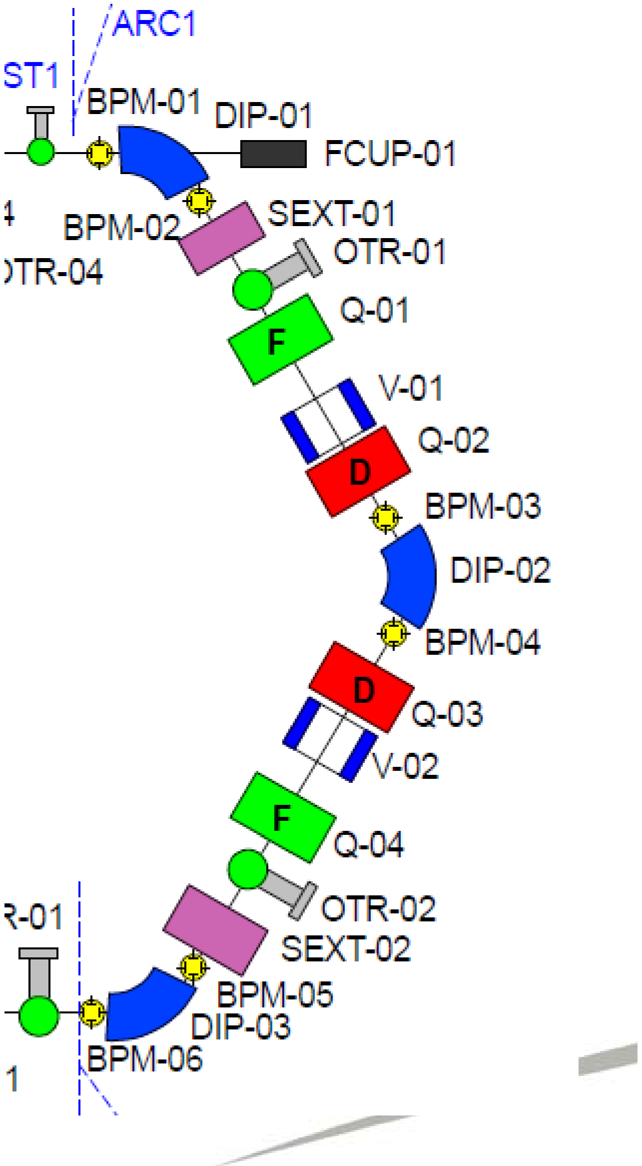


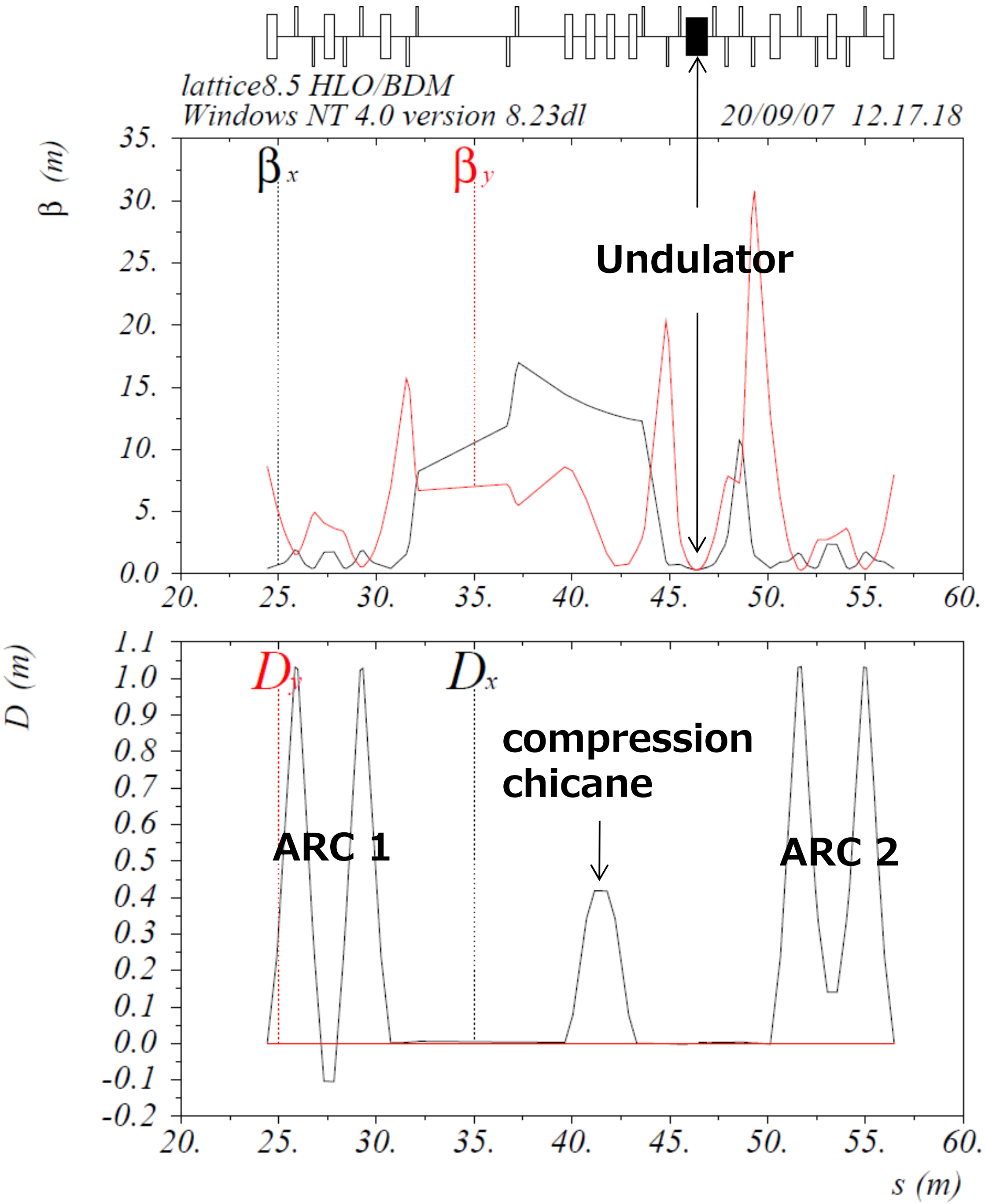




THz signal as function of linac phase



# Beam optics: Arc1-to-Arc2



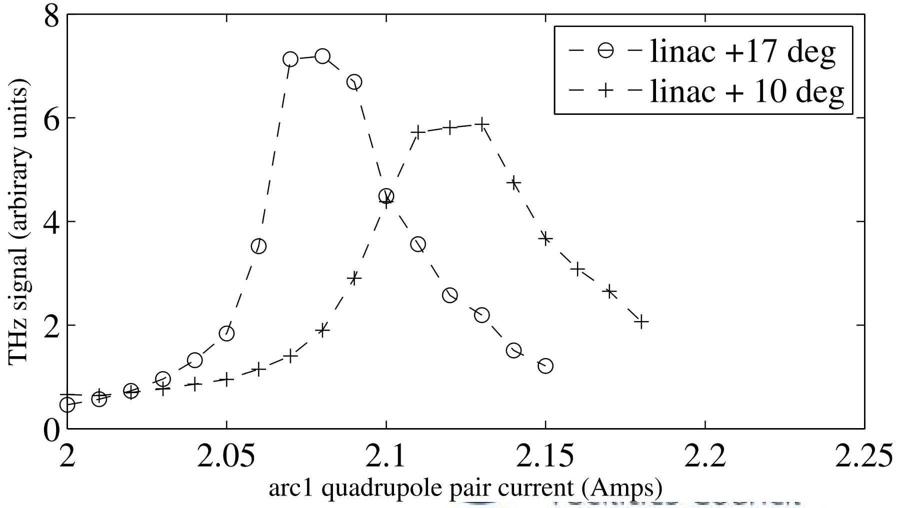



# Beam optics: Arc1-to-Arc2

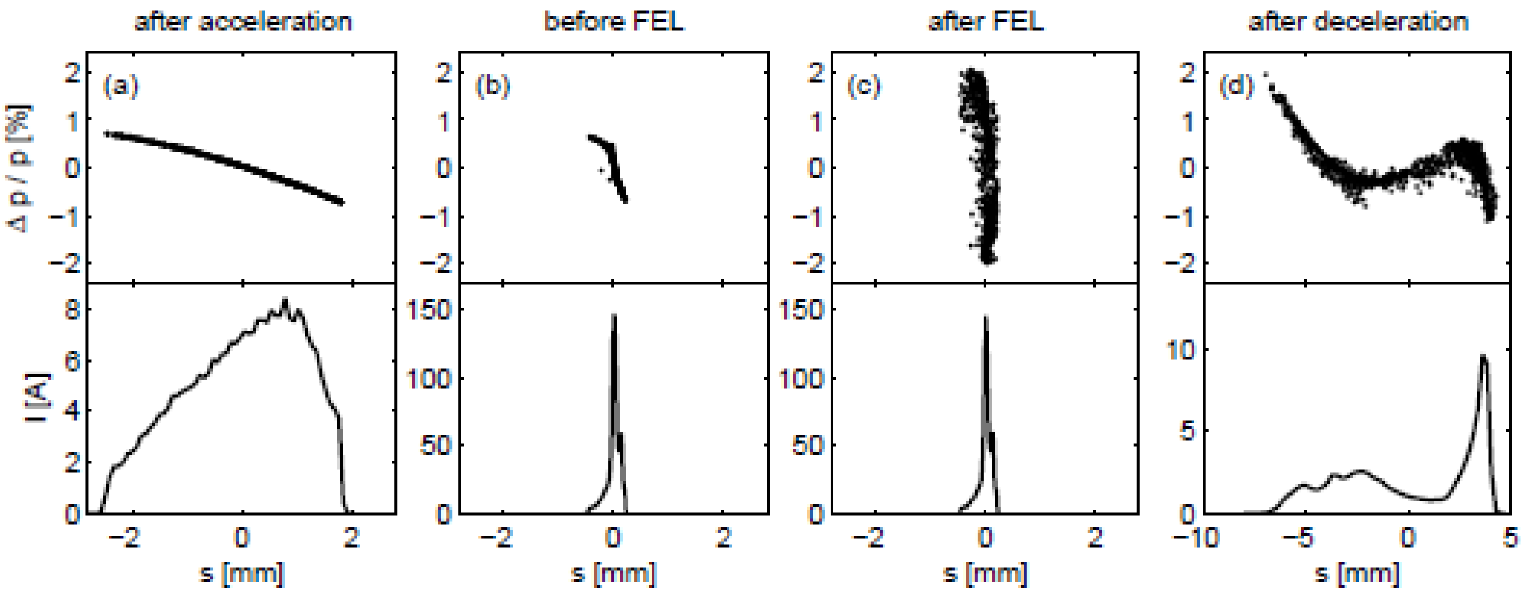
- ARC 1 and ARC 2 – Triple Bend Achromats
- AR1 – isochronous ; $R_{56} = 0$
- Compression chicane : $R_{56} = 0.28m$
- AR2 : $R_{56} = -0.28m$ (equal and opposite to $R_{56}$ of the compression chicane) – decompressing the bunch
- Sextupoles in AR1: linearization of curvature ($T_{566}$)

ARC 1 quadrupoles can also be used to "tune" $R_{56}$ alongside the linac phase

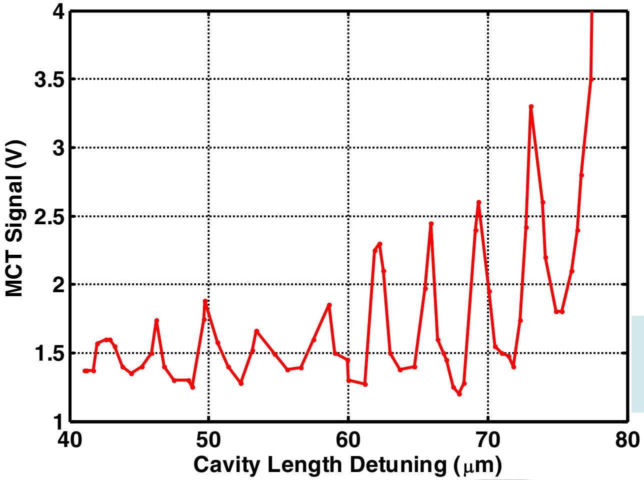
THz signal v ARC1 quadrupoles strength at two linac off-crest phases



# ALICE: bunch compression

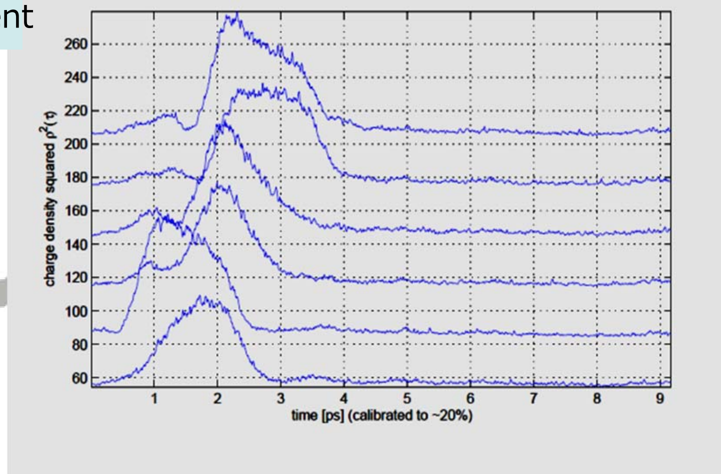



ALICE design model




Spontaneous signal IR FEL Cavity Scan

Electro-optic bunch length measurement



# Transverse optics (example at 20pC)

- Goal: Tune the machine to provide "special" optics.
  - e.g. for energy modulation experiment, need beam waists near centre of long drift in Straight 2, and near the centre of the chicane.

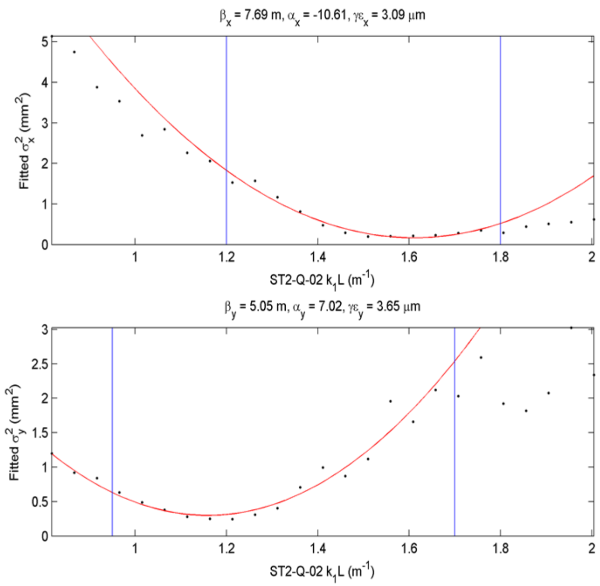
- Procedure:
  1. Determine Twiss parameters (and emittances) at entrance of Straight 2 from quad scan.
  2. Determine initial values in Straight 1 by propagating Twiss parameters back, using known magnet settings.
  3. Rematch optics, using known initial values

**Step 1**

Find $\alpha$, $\beta$ and $\varepsilon$ by fitting a parabola to plot of $\sigma^2$ *vs* $k_1L$.

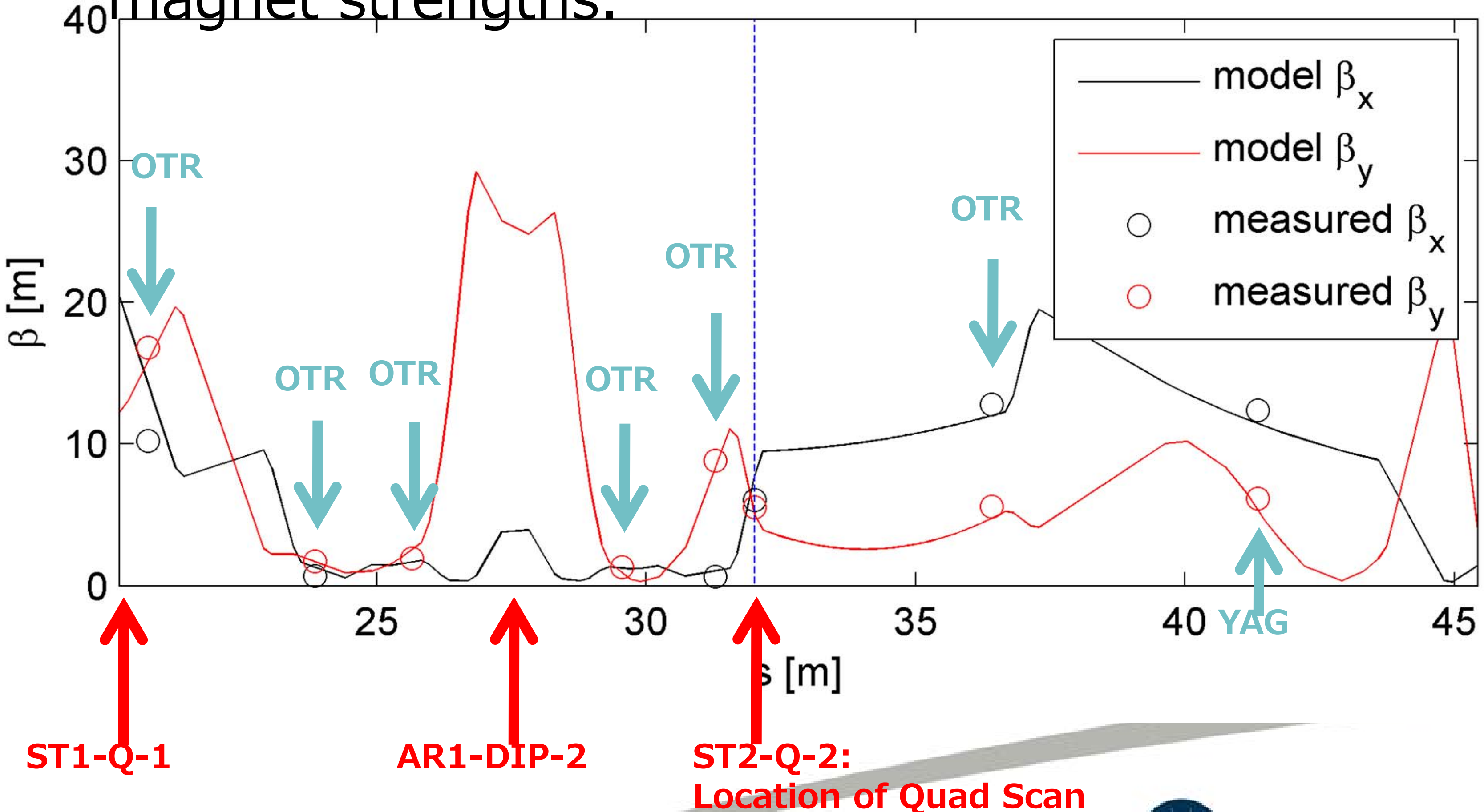
In practice, the best results are obtained if the beam aspect ratio is not too large.

The ability to perform reliable quad scans is an optics design issue.



# Step 2

Obtain $\beta$ functions in a lattice model by propagating from quad scan, using known magnet strengths.

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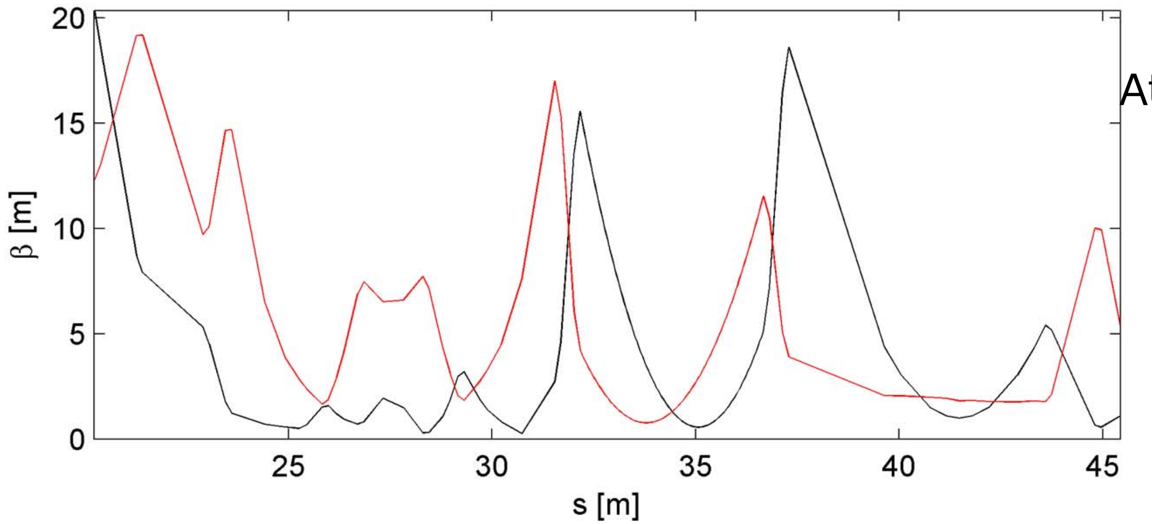
# Step 3: Match new quad strengths




At centre of chicane, aim for:

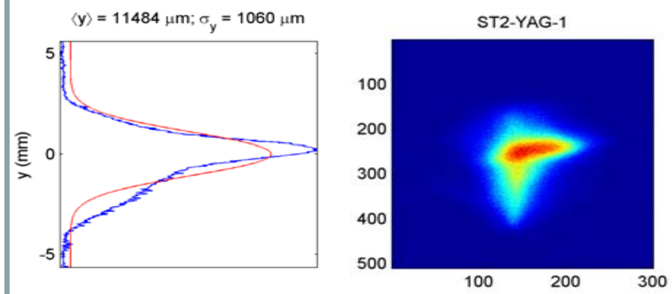
$\sigma_x = 460\ \mu$m

$\sigma_y = 400\ \mu$m

Optics tuning results:

reduced beam size achieved

Beam : 22.5MeV 20pC

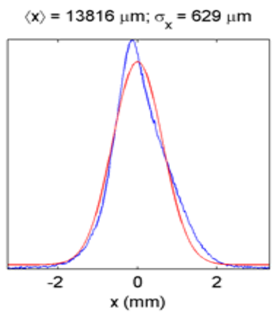


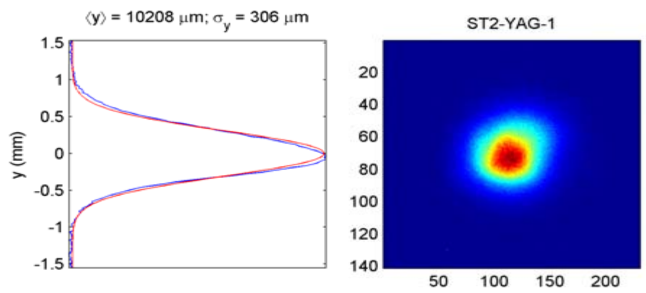

**Standard optics:**

$\sigma_x$ = 629 $\mu$m

$\sigma_y$ = 1060 $\mu$m

(at chicane centre)



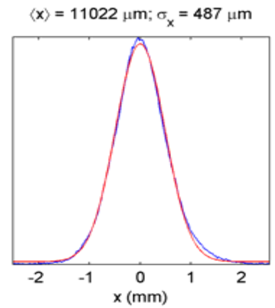




**"Tuned" optics:**

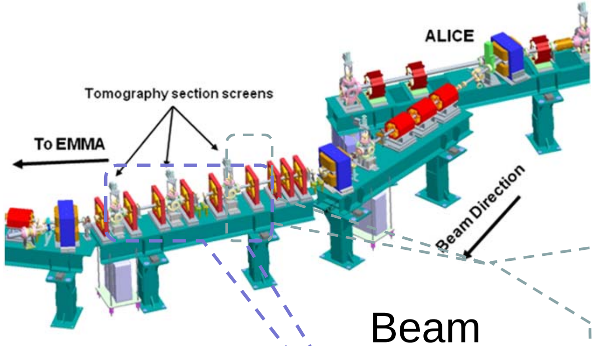
$\sigma_x$ = 487 $\mu$m

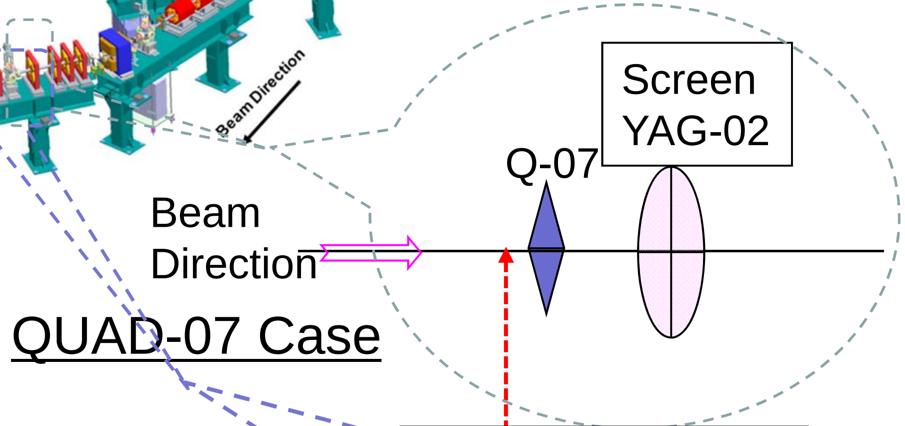
$\sigma_y$ = 306 $\mu$m

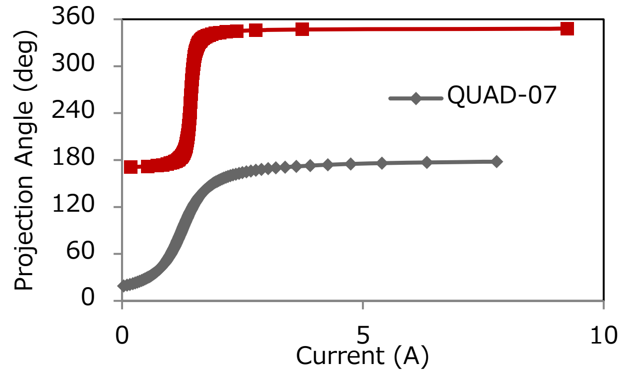
(at chicane centre, $\eta_x \approx$ 40 cm, $\sigma_\delta \approx 10^{-3}$:
$\sigma_x$ dispersion dominated.)



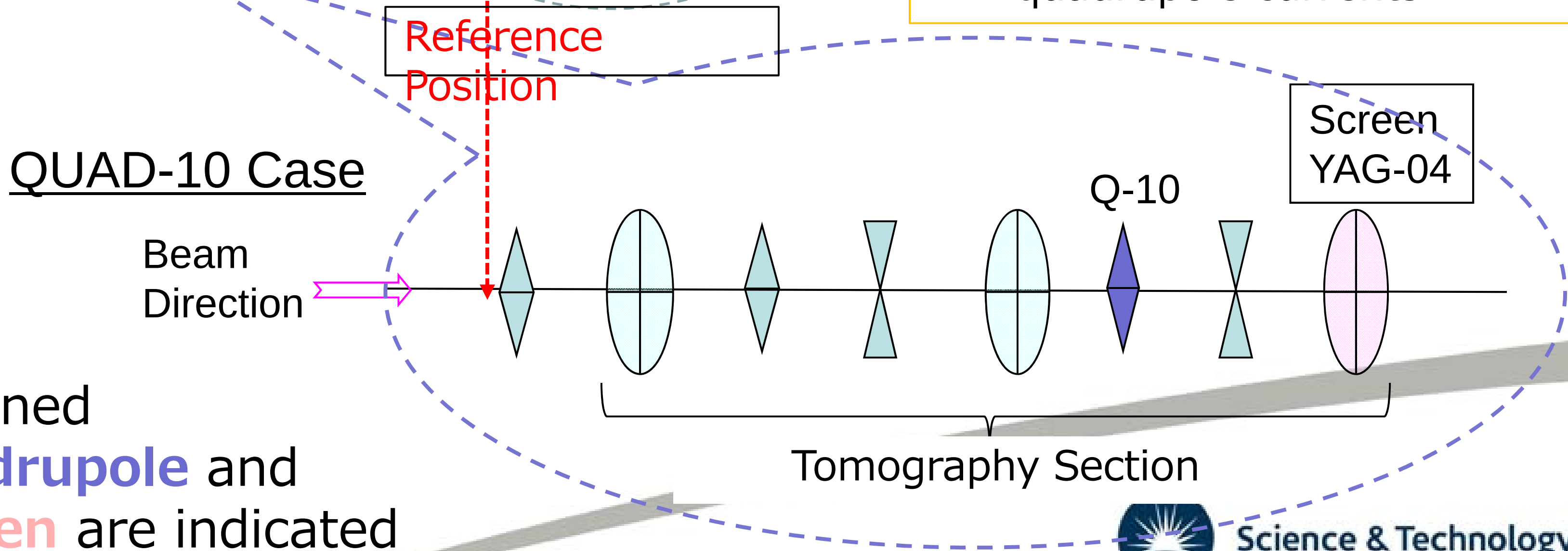
# Tomography Experiment: ALICE Elements used for Space-Charge Studies




Projection angles versus quadrupole currents




Scanned **quadrupole** and **screen** are indicated for each case

Thanks to M. Ibison

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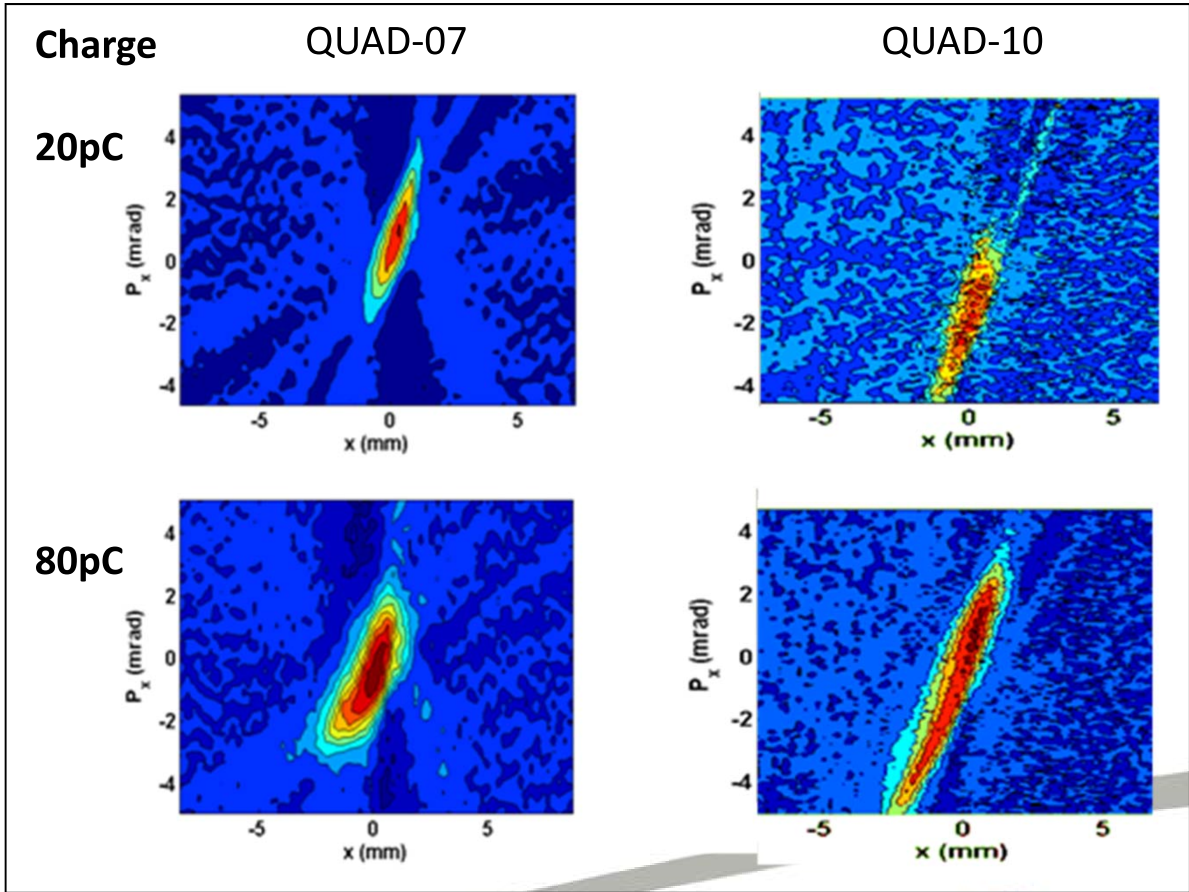
# Phase-Space Tomography Results - ALICE/EMMA Experiments on Space-Charge Effects

Reconstructed phase-space at the entrance to QUAD-07

(from QUAD-07 and QUAD-10 scans)

Beam Energy = 12MeV




Thanks to M. Ibison

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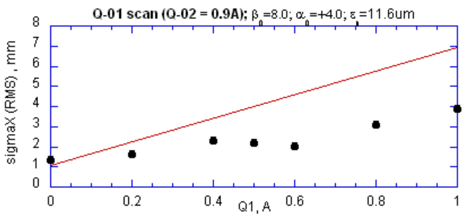
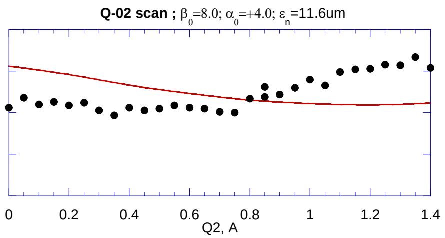
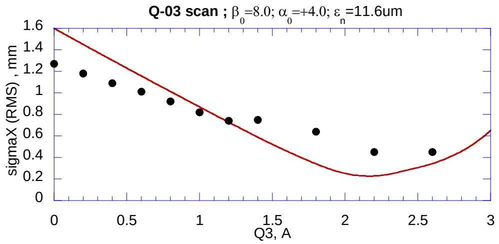
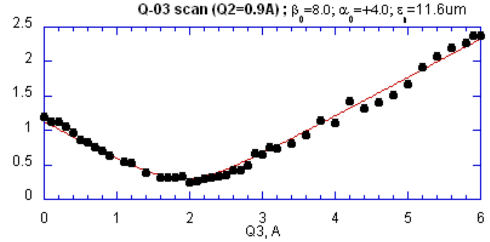
# Twiss measurements in ST1

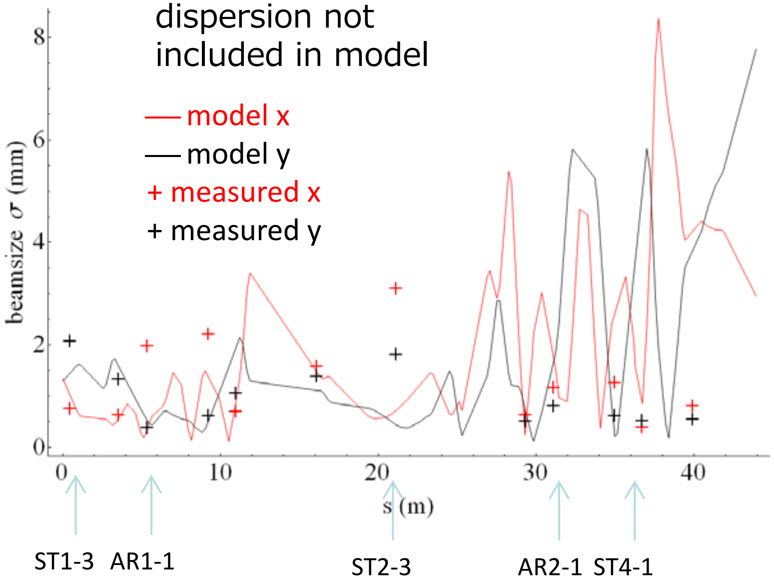
Twiss parameters measured from Q-02/03 scans; then propagated back to Q-01 position; then  propagated forward around the machine

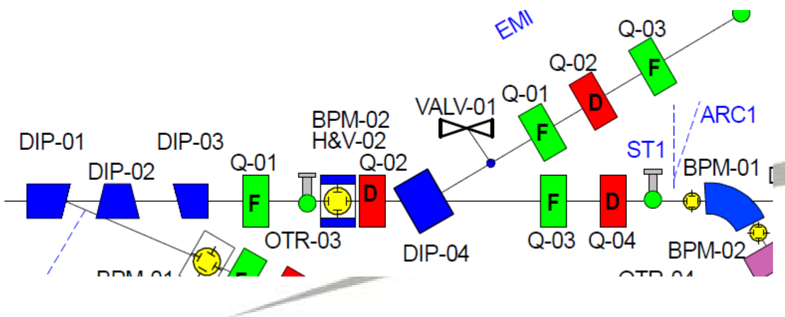


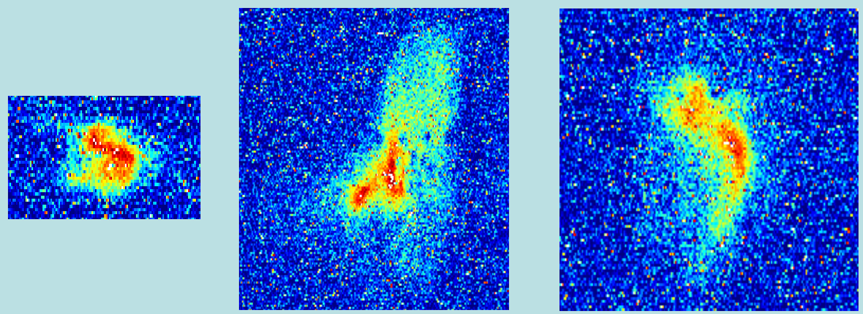



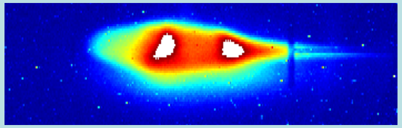



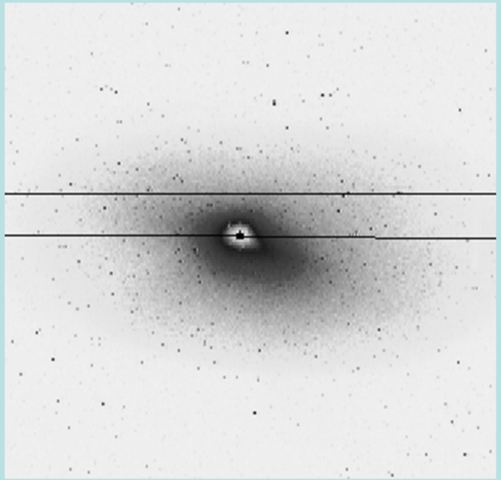

Agreement between measurements and the model is not good …
… could it be due to “funny” beam shape
… two beams seen ?
… remnant fields a factor ?
… and the model itself ?

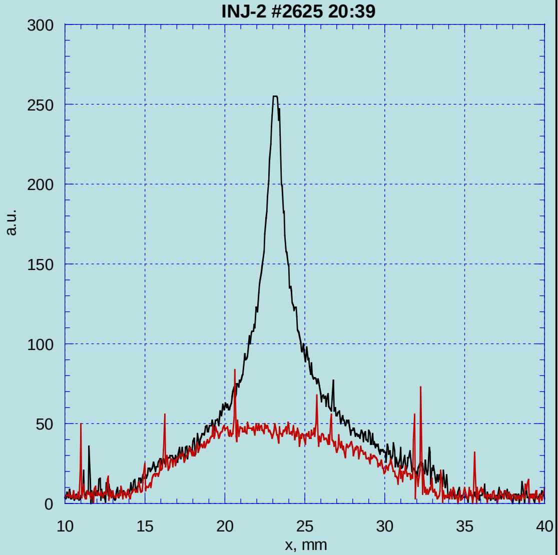


# ALICE “not-ideal” beam

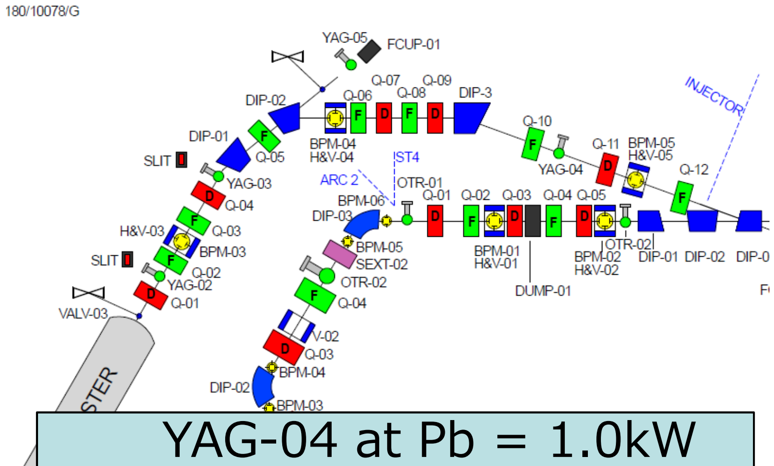


YAG-05 in “THz setup”

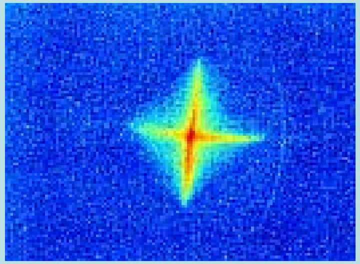




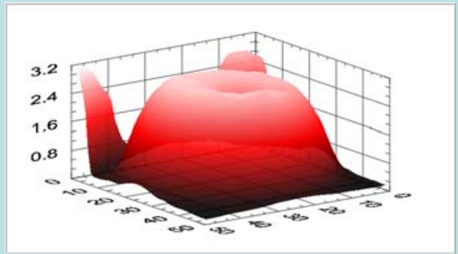

YAG-02 image and single-pixel profiles



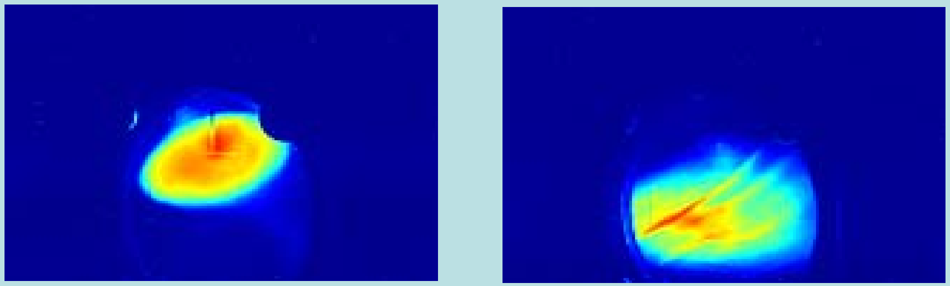

YAG-04 at Pb = 1.0kW



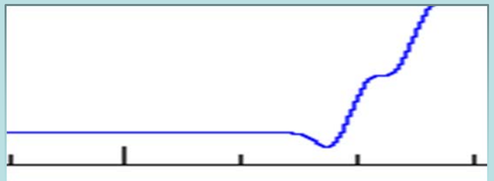
QE map




YAG-01 images at nominal and lower SOL-01 fie



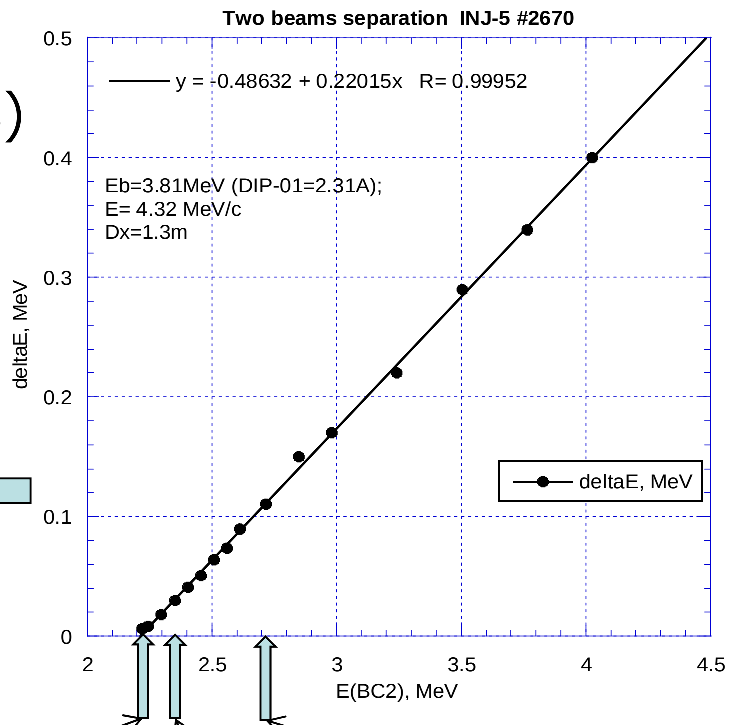
Deceleration in BC1



# “Two beams” separation (60pC; BC1 exit)

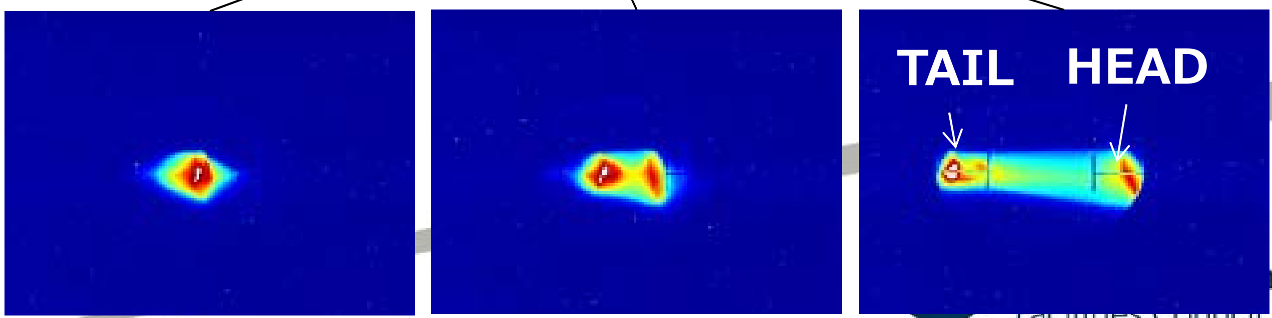
**... to investigate “two beams” structure – make it worse !**

BC1 = -10deg
BC2 = +90deg (zero-cross)
Buncher power = 1.0kW
Beam energy = 3.8MeV



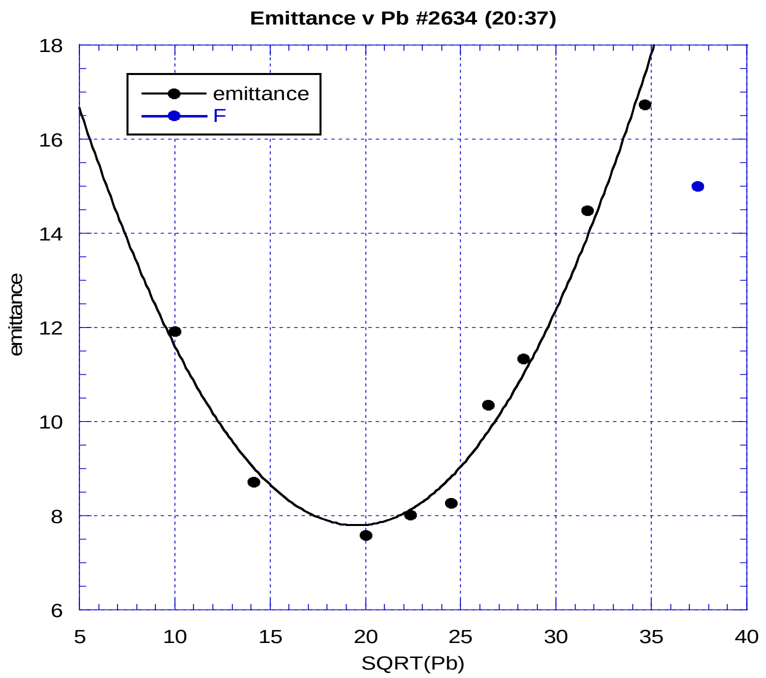

Two beams separated by 27.0ps
at buncher power = 1.0kW

Longitudinal
phase-space
ellipse
flipped over from
positive to
negative chirp

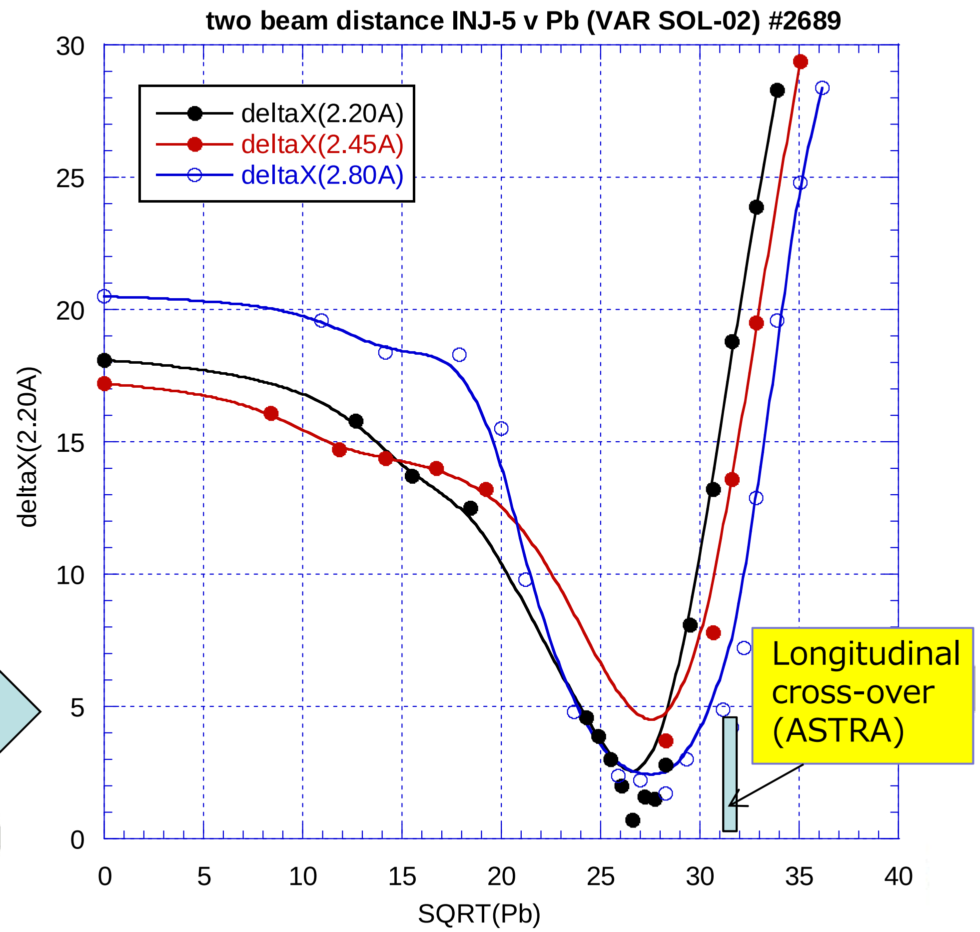


# "Two beams" separation v buncher power (60pC)

Emittance v buncher power




BC = -10 / +40deg
6.5MeV
SOL-02 = 2.20 / 2.45 / 2.80A

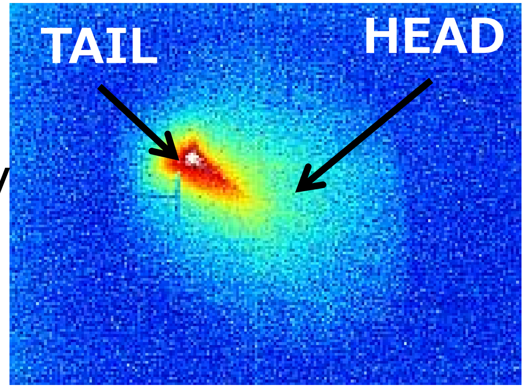



- Beams separation depends on buncher power
- Space charge effects play significant (?) role in two beams separation

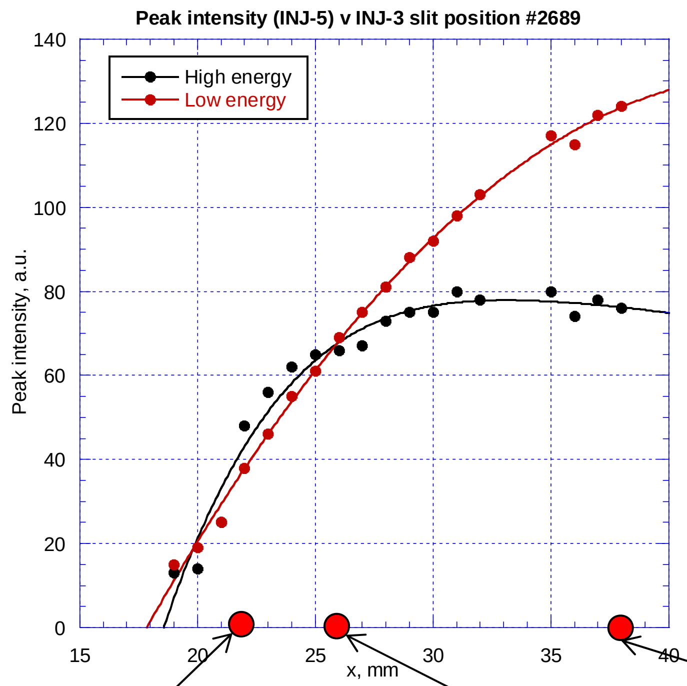
# “Two beams” on INJ-5: blocking with INJ-3

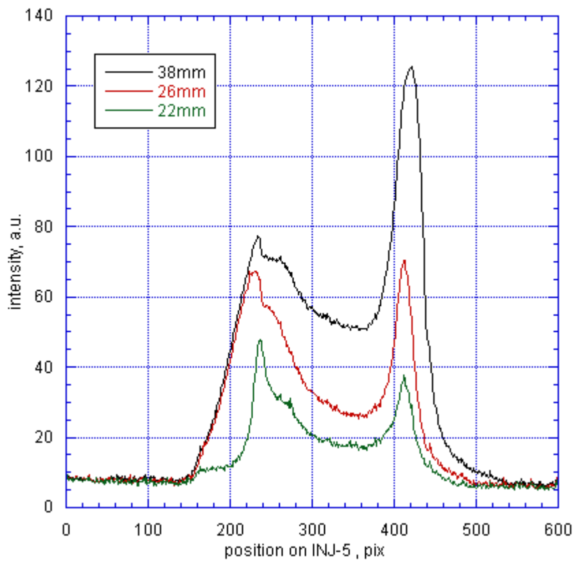
**Beam is progressively blocked by the INJ-3 slit assembly.**

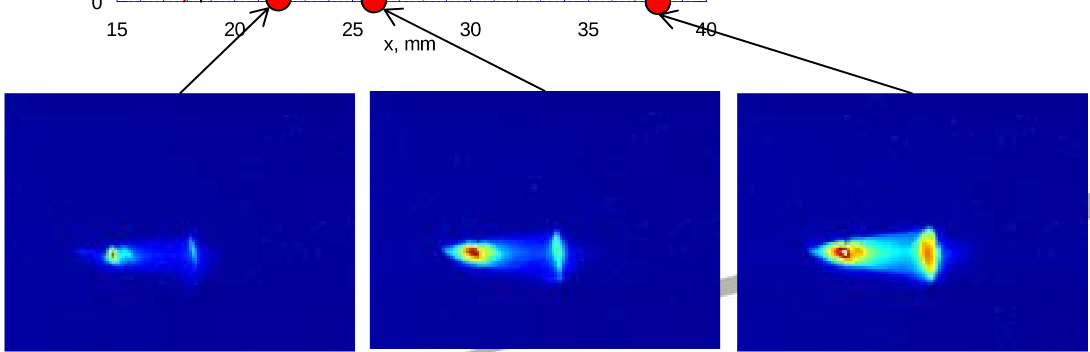
BC1 = -10deg ; BC2 = +90deg (zero-cross)
Buncher power = 1.0kW; Beam energy = 4.0MeV
$E_{BC2}$ =2.5MV

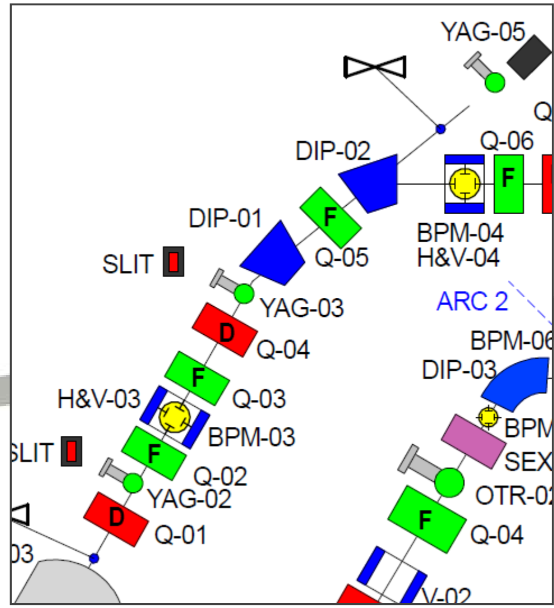



Beam on INJ-3
Block moves from right to left

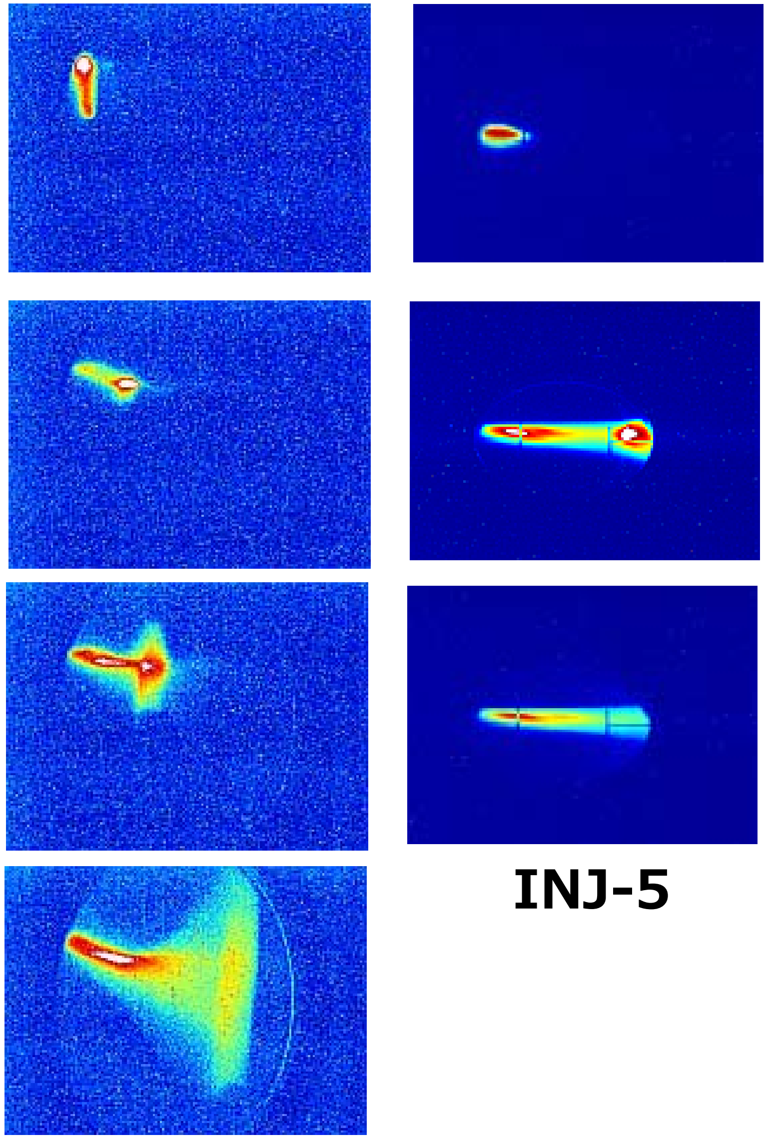




# "Two beams" on INJ-4/5 v BC2 gradient (60pC)



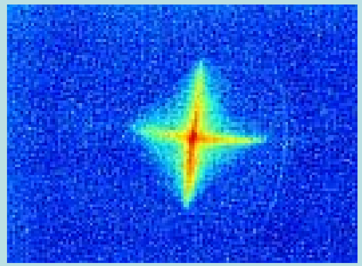
INJ-4

INJ-5

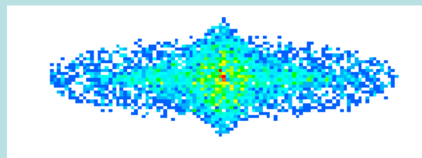
Increasing BC2 gradient

BC1 = -10deg
BC2 = +90deg (zero-cross)
Buncher power = 1.0kW
Beam energy = 4.0MeV

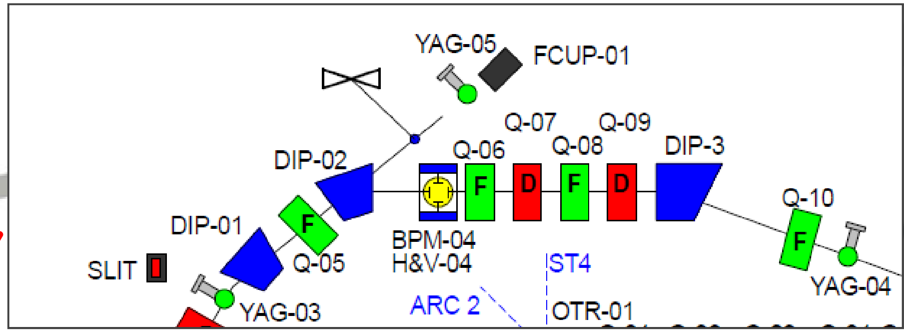
INJ-4 at "nominal" setup
But at buncher power = 1.0kW



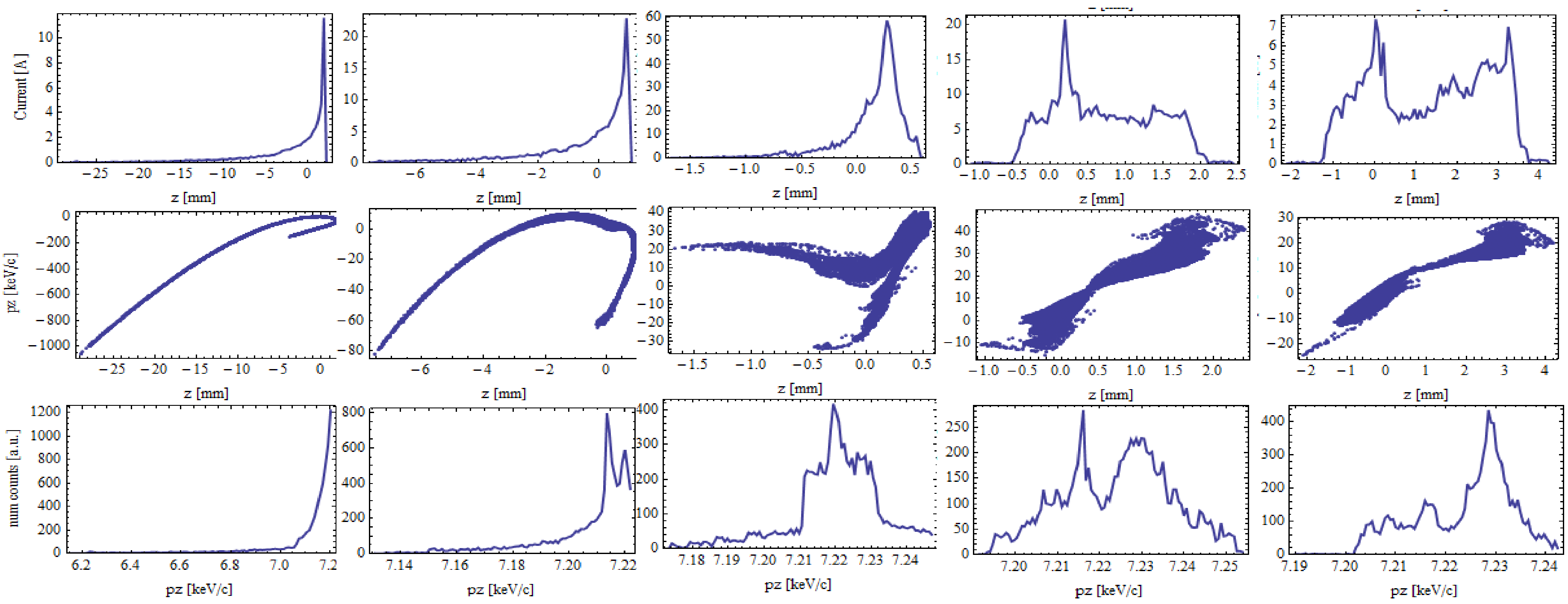
**GPT simulations**



Conclude:
horizontal part of the "cross" : TAIL
Vertical part of the cross : HEAD



# Beam dynamics v Buncher power (60pC; BC2 exit)




100W (10)

400W (20)

700W (26.5)

950W (30.8)

1100W (33.2)

Single laser pulse 28ps flat top, 60pC

BC = -10/+40deg
6.5MeV

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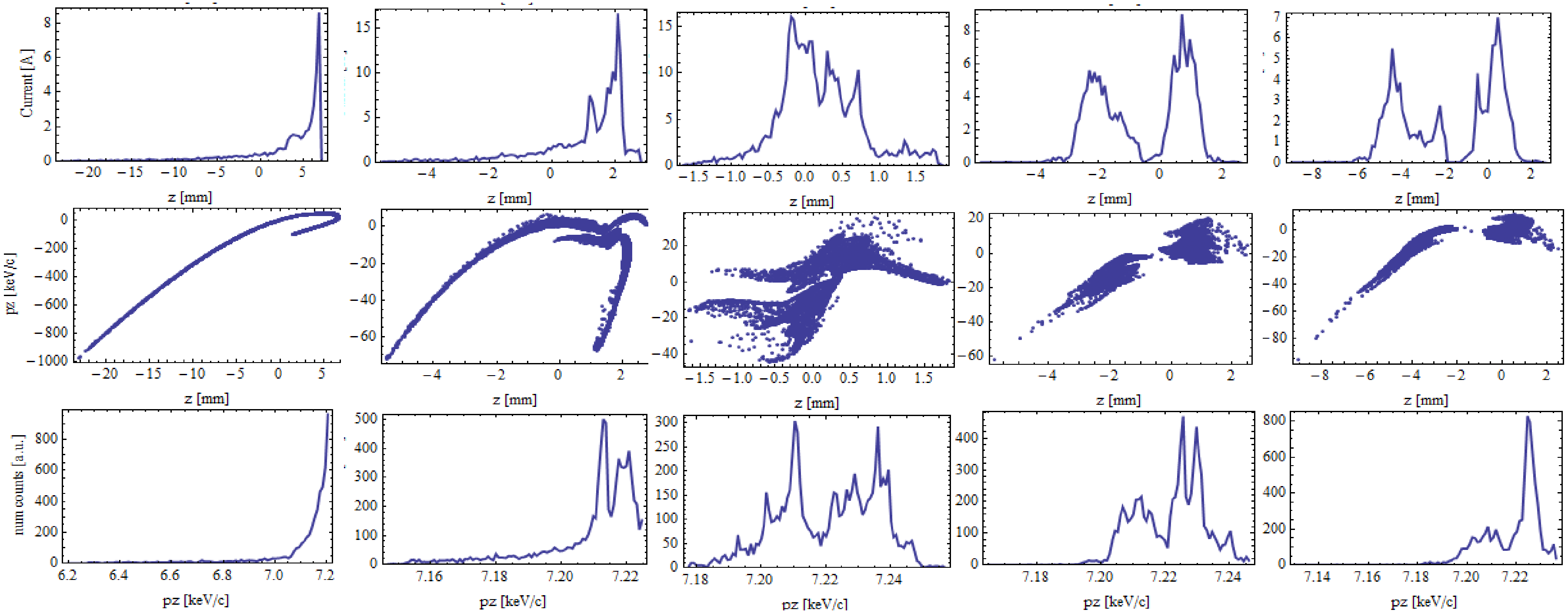
# Beam dynamics v Buncher power (2x30pC) : extreme case

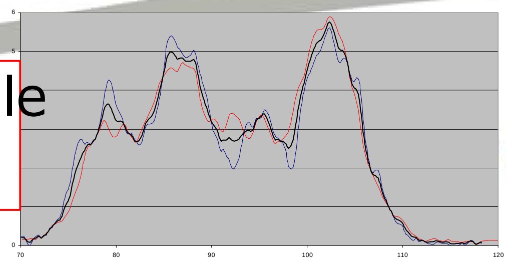



| 100W (10) | 400W (20) | 700W (26.5) | 950W (30.8) | 1100W (33.2) |
|---|---|---|---|---|

Two laser pulses 3ps, 30pC each with 25ps separation

BC = -10/+40deg
6.5MeV

Laser pulse temporal profile
(in 2008)



# Concluding remarks

- ALICE – multifunctional facility
  hence various beam energies, bunch charges, bunch properties, ER & non-ER modes etc
- Machine setups vary accordingly
- Currently, the beam is far from ideal
  (transverse structure, low 230kV gun voltage, non-uniform QE map, "two beam" structure)
- "Two beams" : investigated by "exaggerating" the underlying physics
- Two beams : is it a permanent feature of the beams from photoinjector HV DC guns ? ... even if we do not see them explicitly !
- Two beams cause problems in transverse dynamics investigation
- Ways of improvement :
  - increase gun voltage
  - uniform QE map and "good natured" laser beam on cathode
- ALICE plans:
  - investigate beam without laser pulse stacker (7ps FWHM)
  - install large gun ceramic → 350kV (autumn 2011)

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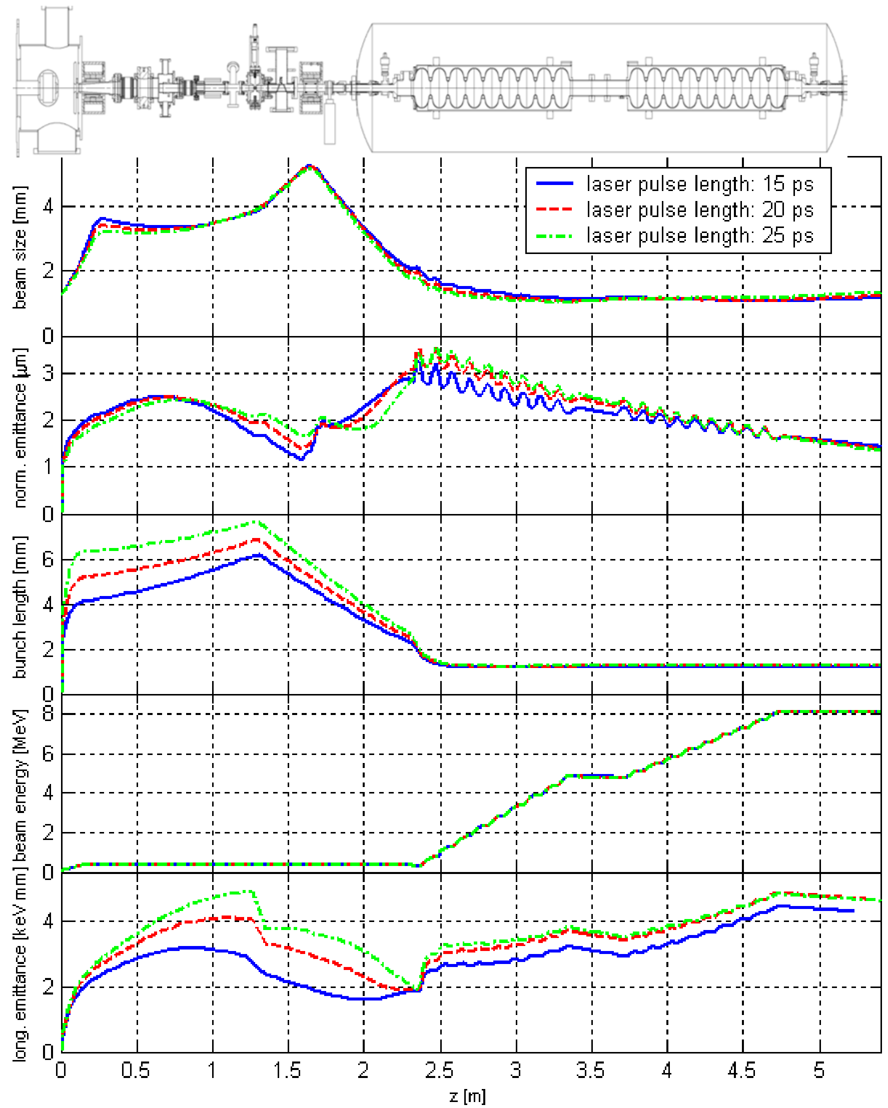
# ADDITIONAL SLIDES

# ALICE

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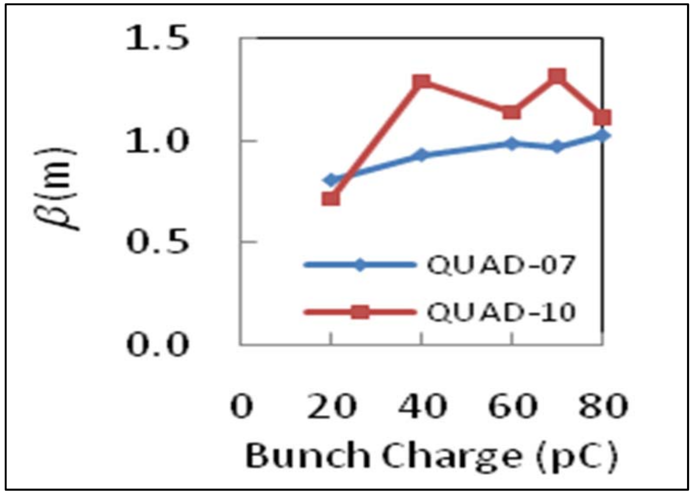
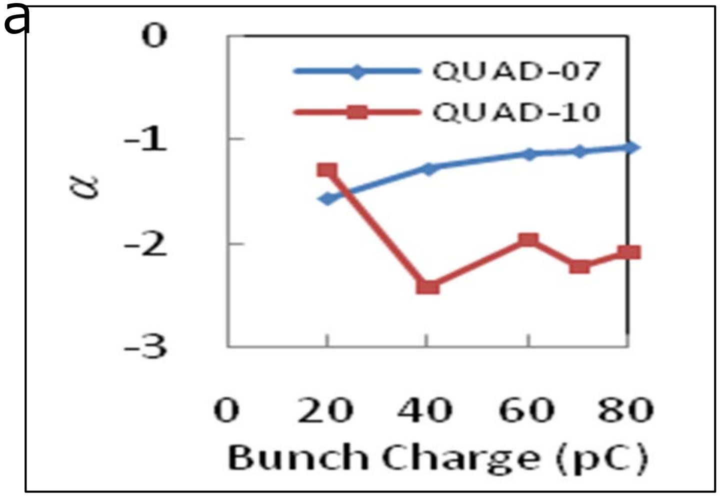
# Tomography: Analysis of Experimental Results

Twiss Parameters:

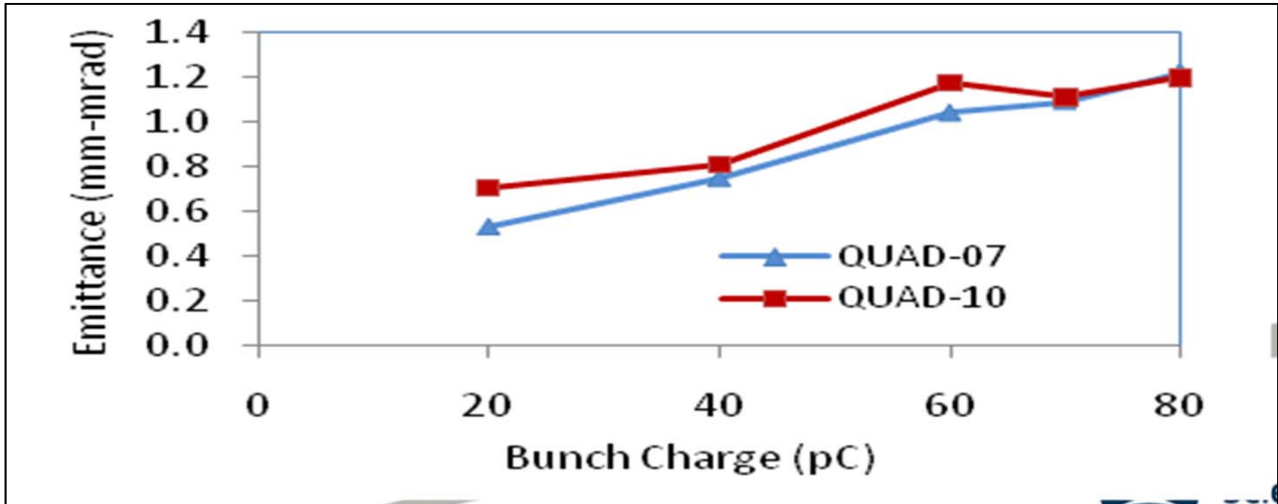
Beta




Alpha




Emittance (horizontal):




Thanks to M. Ibison