TBL

Beam dynamics, instrumentation and measurements

- OUTLOOKS -

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Contents

1) Beam dynamics of the TBL

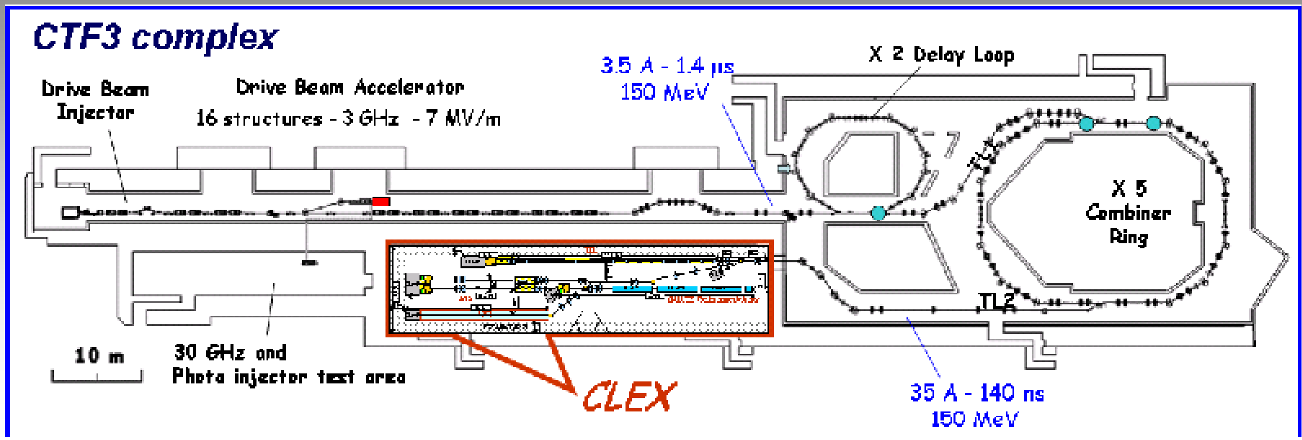
- Comparison with CLIC

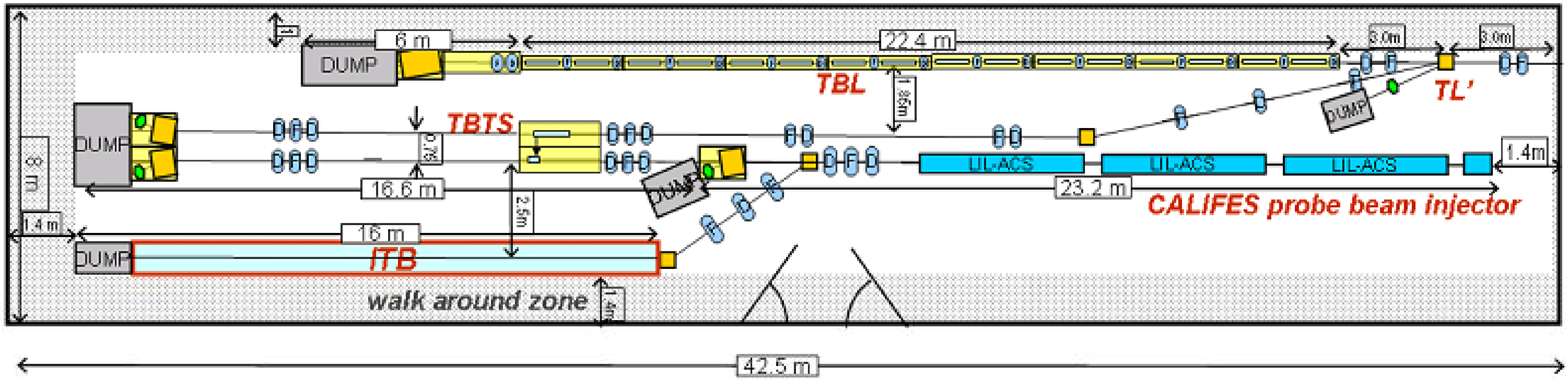
2) Outlooks: TBL measurements and instrumentation

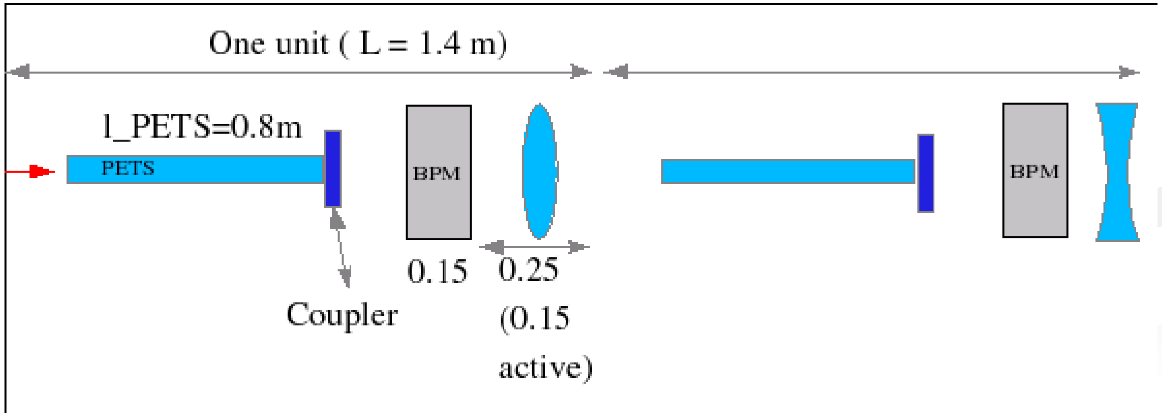
- What could we learn from TBL?
- How can we measure it?
- Short-term outlooks

Focus is **Beam Dynamics**: how the PETS and the TBL **affects the beam** (not how to beam produces RF)

TBL







TBL lattice:

16 units of one of each:

- **PETS w/ coupler**
- **Quad**
- **BPM**

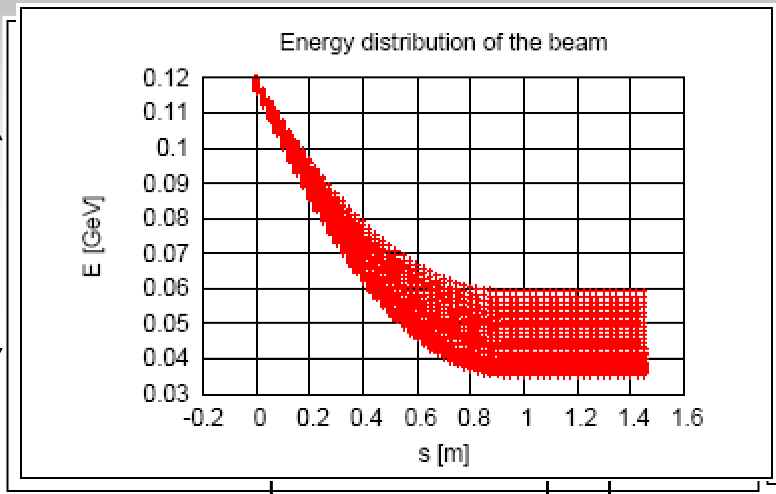
Part 1

Beam dynamics of the TBL

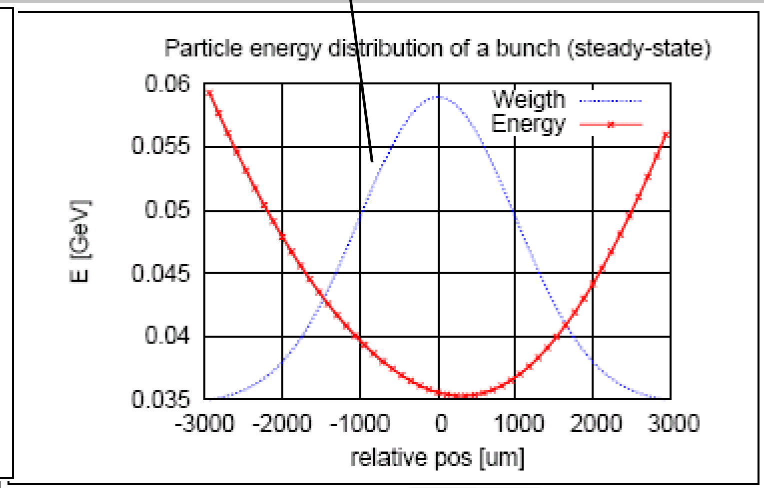
(focusing on items that need to be taken into consideration in the 2nd part)

The effect of deceleration – in one slide

$S=(E-\check{E})/E$
$= 70\%$



$\lambda(z)$



$\check{E} = E(1-S)$
$= E - N_{PETS}\Delta\hat{E} = 35$ MeV

$t_b = 83$ps

$\sigma_z = 1$mm

$t_{fill} = (L_{PETS}/v_g)(1-\beta_g)\ _g = 3$ns

Power extracted from beam (ss)

$P \approx (1/4)\ I^2 L_{pets}{}^2 F(\sigma)^2 (R'/Q)\ \omega_b / v_g = 139$ MW

Power extraction efficiency (ss)

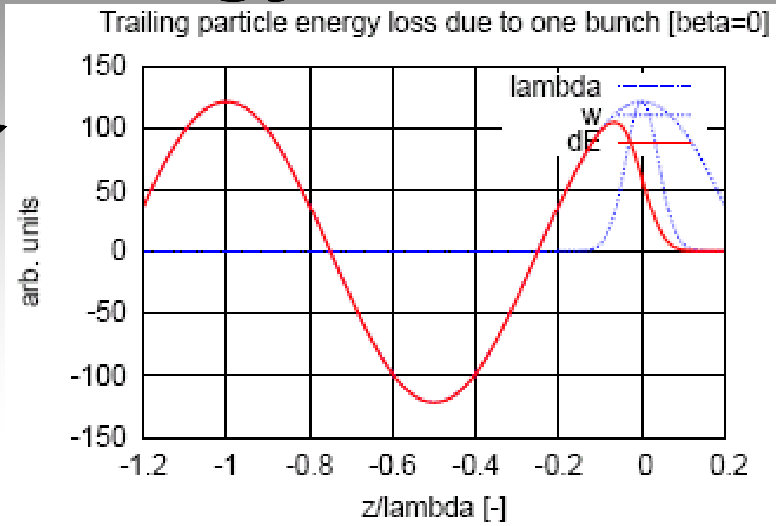
$\eta = E_{in}/E_{ext} = PN_{PETS} / IE/e = 67\%$

PETS energy extraction

Single particle energy loss:

$$\Delta E(z) = Ne^2 \int_z^{\infty} dz' \lambda(z') w_L(z'-z)$$

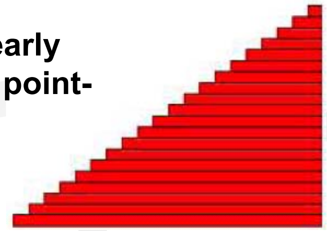
example for Gaussian bunch



PETS longitudinal d-wake, including group velocity:

$$w_L(z) = \omega_L \frac{R'}{Q} \frac{1}{1-\beta_L} \cos(\omega_L \frac{z}{c})(L - z\frac{\beta_L}{1-\beta_L})$$

field builds up linearly (and stepwise, for point-like bunches)



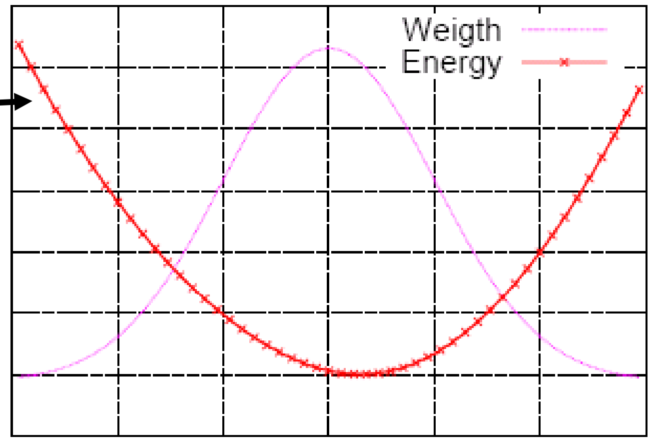
Energy loss from leading bunches + single bunch component:

$$\Delta E(z) = \Delta E_{sb}(z) + \Delta E_{mb}(z)$$

Approx: sb component equal to mb, and linear field increase:

$$\Delta E(z) \approx \frac{n_{ss}}{2} L_{PETS} A N e^2 F(\lambda) \cos kz$$

if mb assumption is good, wake function is recognized for particle energy loss of z



Integrating ΔE over bunch gives second form factor, and times f_b gives extr. power:

$$P \approx \frac{1}{2} I^2 L_{PETS}^2 F^2(\lambda) \frac{R'}{Q} \omega_L \frac{1}{\beta_L c}$$

(x 1/2 for linac-Ohms)

Single particle dynamics

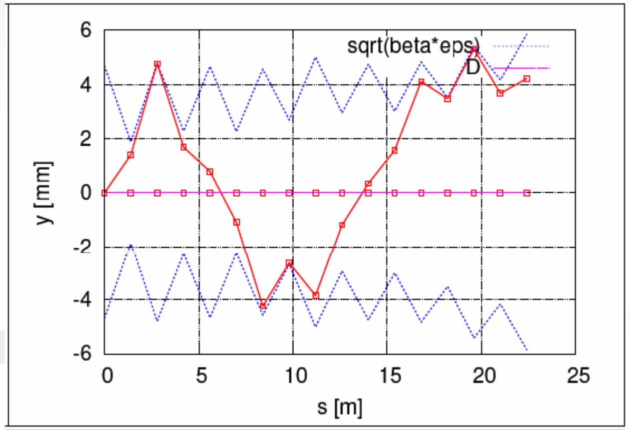
FODO focusing

- Constant FODO phase-advance for the most decelerated particles (linearly decreasing T/m)

- **Least decelerated particles** will have a larger phase-advance, and beta (but still be focused)

$$\sin \phi/2 = L/2f \Rightarrow \sin \phi/2 \propto 1/p$$

$$\Rightarrow \frac{\sin 90/2}{\sin \breve{\phi}/2} = \frac{2.4}{0.24} \Rightarrow \sin \phi/2 = \frac{1}{10}\left(\frac{1}{2}\sqrt{2}\right) \Rightarrow \breve{\phi} = 8^o$$



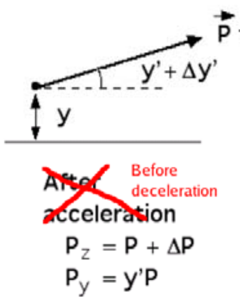
Least decelerated particle, TBL, $\sigma = \sqrt{\beta(s)\varepsilon}$ $(w_T = 0)$

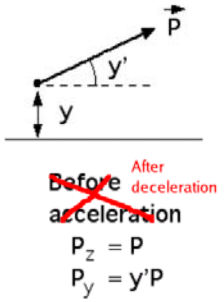
Adiabatic undamping

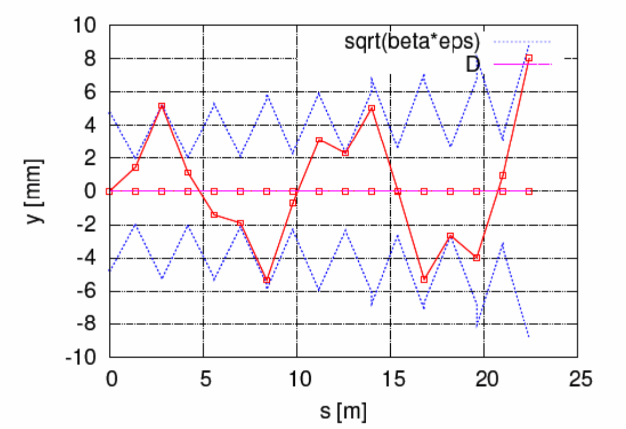
- **Most decelerated particles** will be have emittance growth due to adiabatic undamping

$$y' = y'_0\left(\frac{1}{1+\delta}\right), \delta = -\frac{\Delta \hat{E}}{E}$$

$$\varepsilon_1 = \frac{E_0}{E_1}\varepsilon_0$$







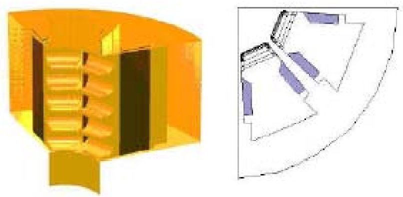
Most decelerated particle, TBL, $\sigma = \sqrt{\beta\varepsilon(s)}$ $(w_T = 0)$

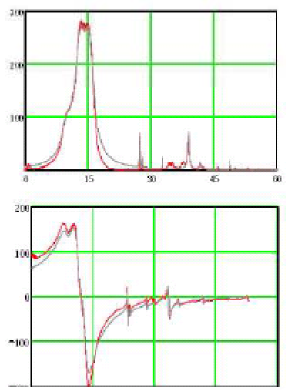
PLACET input: dipole wake function

- A discrete set of significant dipole wake modes are included in the simulations

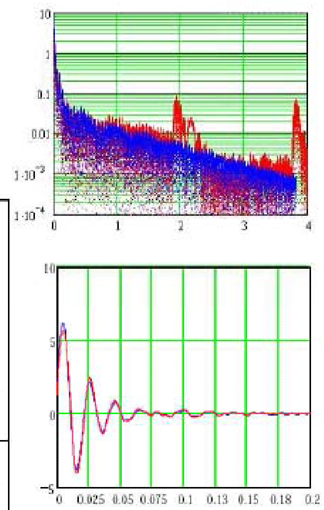
- PETS are modelled with GdfidL (I. Syratchev)

- For a given PETS structure, the transverse δ-wake / impedance is calculated





W_T	Q	F
0.045	300	27.44
0.019	180	28.05
0.017	290	32.912
0.2	85	39.12
0.03	120	41.83
0.015	380	48.91
0.85	3.7	10.0
4.82	3.8	13.4
2.63	6.2	15.46

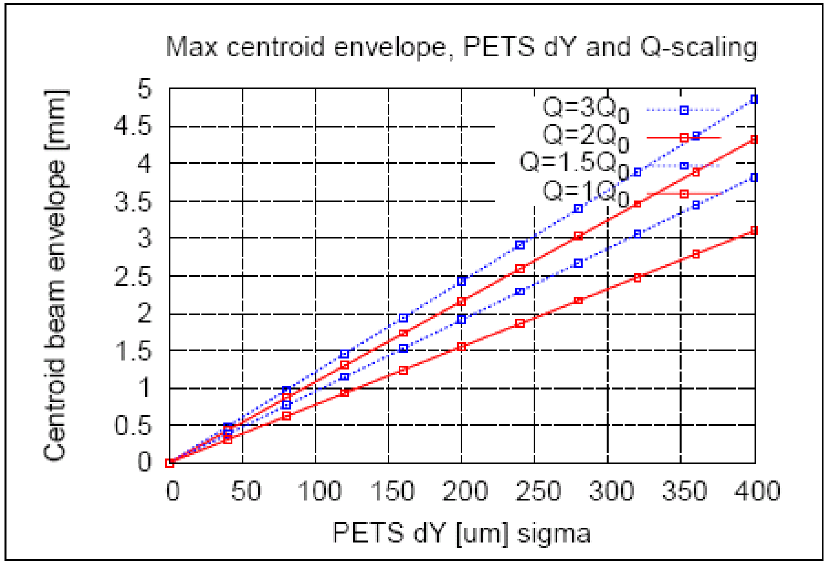


Slide: I. Syratchev

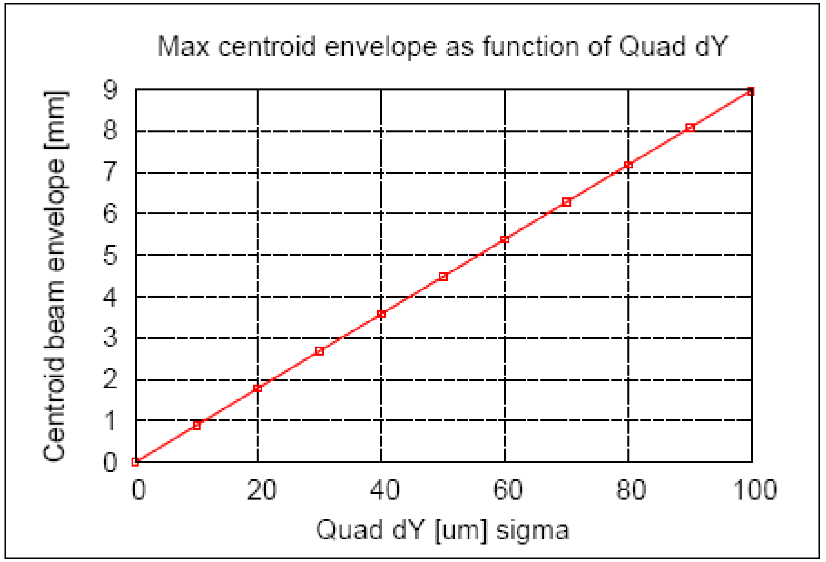
Effect of PETS and quadrupole misalignments

- Lattice element misalignment might drive beam-size → requirements for pre-alignment .

(parameters not up to date)



$\sigma_{PETS} = \{40...400\}\mu m,\ Q = \{1..3\}$



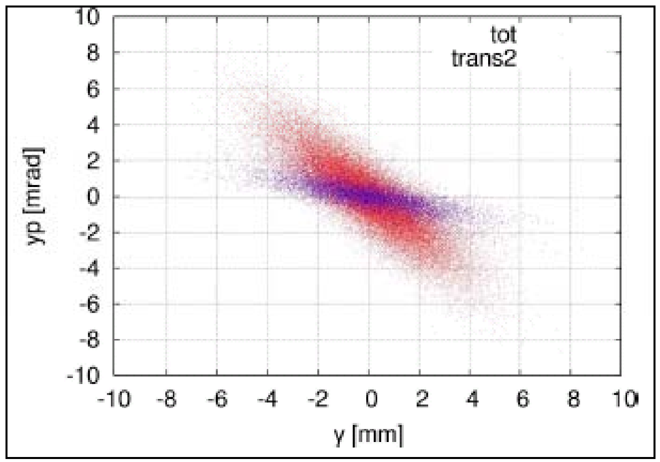
$\sigma_q = \{0...100\}\mu m$

→ σ_{PETS} pre-alignment ~ 100 µm

→ Quads: need for **Beam-Based Alignment**

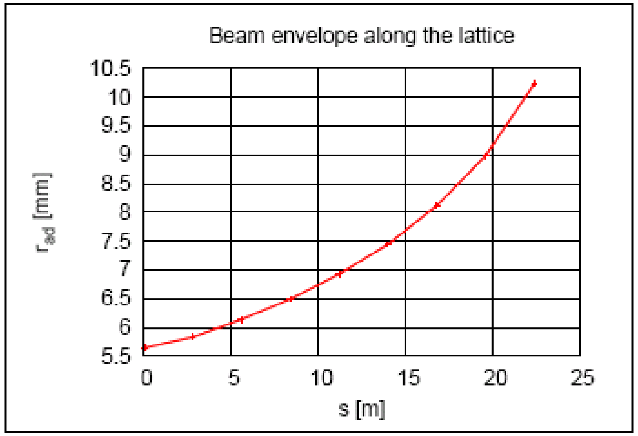
Emittance and beam envelope

- Sources of **emittance** growth in the TBL
  - PETS
    - Adiabatic undamping (also normalized emittance grows due to chromaticity)
    - Beam transverse offsets
    - PETS misalignments
    - PETS RF-kicks (small)
  - Quadrupole misalignment: $\alpha\ \sigma^2_{quad}$



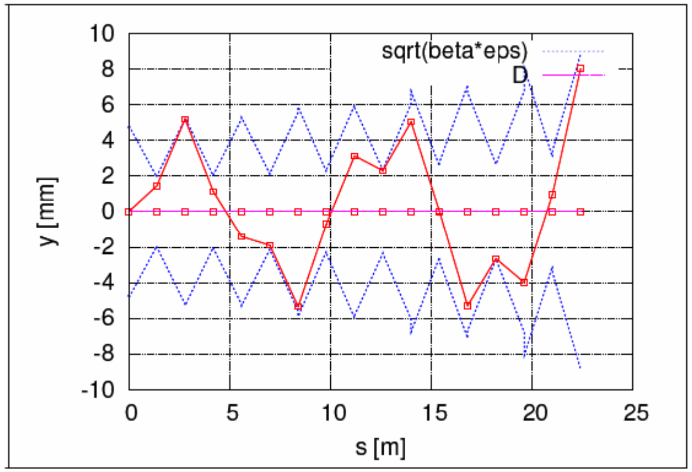
Phase-space after deceleration
(short-train)

- As simulation metric, we usually use the **beam envelope,** driven be the “worst” particle (3σ)
  - Rationale: need to avoid losses

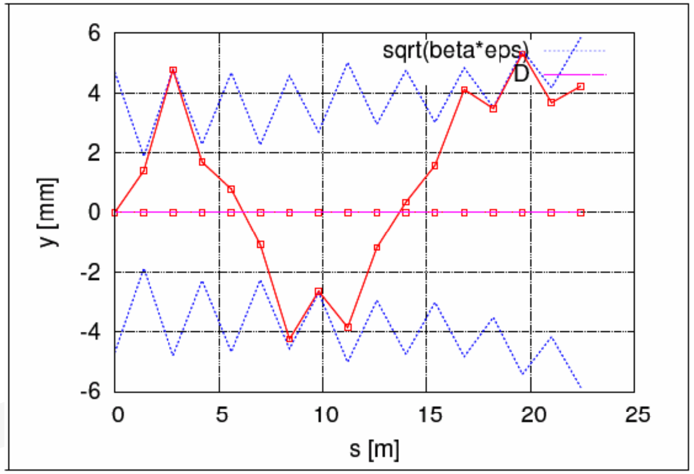


Effect of adiabatic undamping alone
(perfect-machine)

- Currently planned 16 PETS, or 8 FODO cells
- Relevant scale for wake studies: # of betatron oscillations
  - 16 PETS: with $\mu_{FODO} \approx 90^o$ E=Ě particles will undergo ~2 betatron oscillations, while $E=E_0$ particles will undergo < 1.5
- This scale: important for study of effects of transverse wakes
- Gives indication that we are in the right area (but difficult to say precisely whether e.g. 14 PETS would be much worse or 18 is much better)



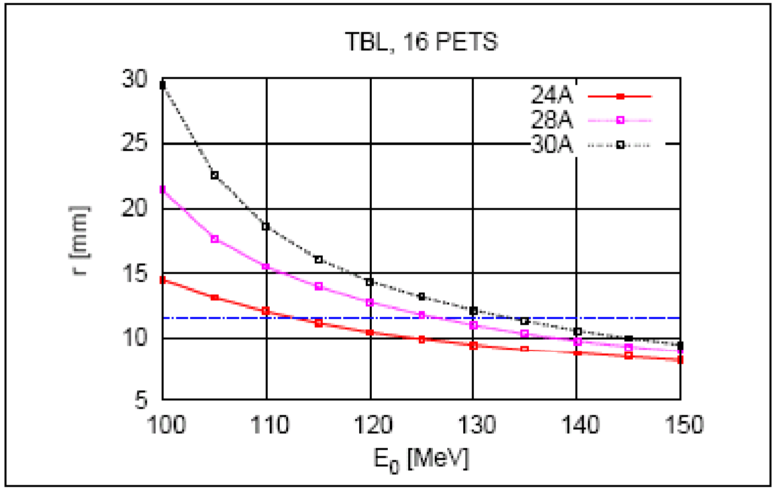
Most decelerated particle, TBL, $\sigma = \sqrt{\beta\varepsilon(s)}$ $(w_T = 0)$



Least decelerated particle, TBL, $\sigma = \sqrt{\beta(s)\varepsilon}$ $(w_T = 0)$

Some similarities and differences TBL and CLIC

- Current of ~28A should produce requested PETS power (P >135MW)
- Initial energy, E, will determine extraction efficiency, η, and beam size r (losses)
  - For current CTF3-options, efficiency will be lower than CLIC, beam size larger



TBL beam envelope for different current and energies

$\eta \propto 1/E, \quad r_{ad} \propto 1/\mathrm{sqrt}(E)$

24A: P = 102 MW
28A: P = 139 MW
30A: P = 160 MW

- **Wake-amplification ∝ E**
  - TBL: O.M. less rigid than CLIC
- **Average beam-size**
  - TBL: close to aperture -> HOMs!
- **Length**
  - TBL: O.M. shorter than CLIC

Apart from the shorter length: all parameters indicates getting the beam fully through the TBL will be more demanding than for CLIC!

TBL simulation reference set-up

- Reference case: E=120 MeV, I=28A
- Beam:
  - $\varepsilon_{N,x,y}$ = 150 μm, $\Delta p/p$ = 1%
  - centroid jitter: 0.5 * sigma ≈ 1 mm, distributed over PETS transverse mode frequencies
  - (equiv. to) τ_{train} = 140 ns
- Power and efficiency:
  - P=139MW, η=67%, Ě = 35 MeV
- Lattice:
  - PETS misaligned with $\sigma_{PETS,x,y}$ = 200 μm
  - Quadrupole misaligned with $\sigma_{quad,x,y}$ = 20 μm
    - (NB: value corresponds to AFTER correction)
  - PETS (energy extr. and ad. undamping, transverse modes and edge-kicks)
- Simulation tool: PLACET (D. Schulte)

Part 2

TBL measurements and instrumentation
(Outlooks)

Requirements TBL

- Driver: requirements for the CLIC decelerator

  Producing the **correct power for accelerating structures**, **timely and uniformly** along the decelerator, while achieving a **high extraction efficiency**

  Uniform power production implies that the beam must be transported to the end with **very small losses**

- Translation into requirements for the TBL :
  - show correct power production *and extraction*, uniform in time and space, high η
  - strive towards, and show, minimal losses in TBL
- In addition: potential benchmarking of PETS model and simulations :
  - uniform drain-out of single monopole mode
  - discrete sets of dipole modes
  - higher order modes negligible
- Other requirements
  - Requirements from Beam-Based alignment

Possible TBL observables

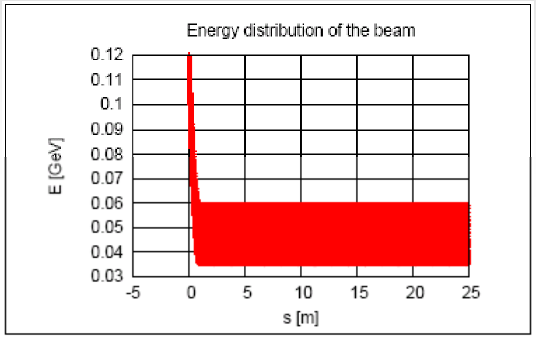
- a) RF (not discussed further here)
- b) energy extraction and transient, σ_z, $F(\lambda)$
- c) current / losses
- d) transverse beam size, emittance and halo
- e) others

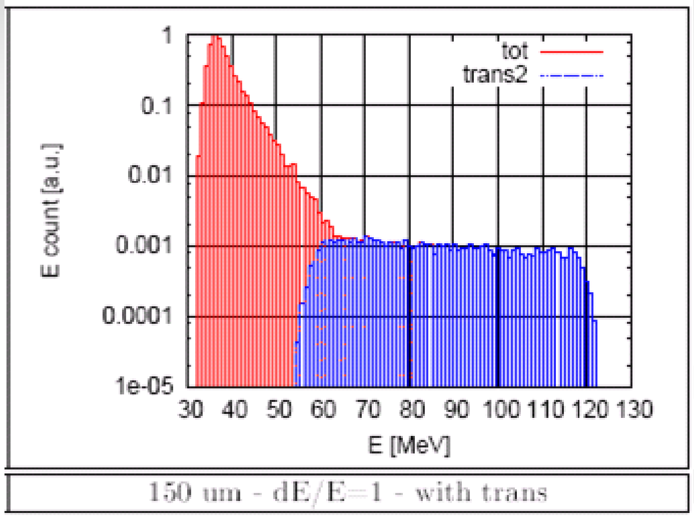
Important to keep in mind for all the above: The CTF3 beam might be far from Gaussian when entering the TBL

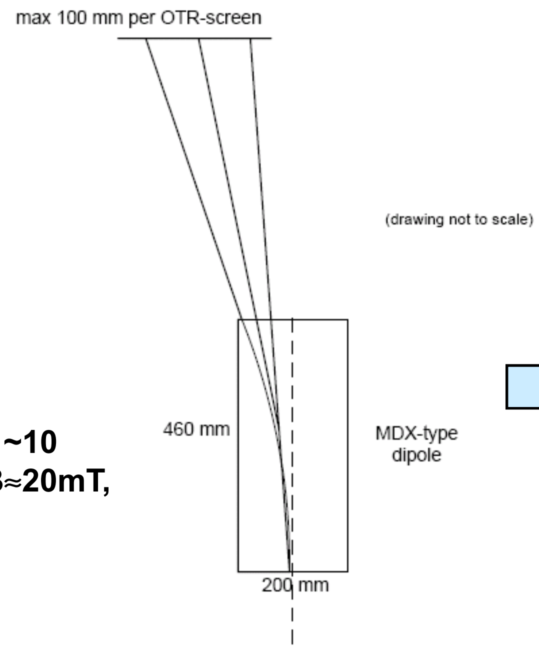
$\rightarrow$ Measurement after the TBL should, to the extent possible, be compared with measurement before the TBL (in TL2‘)

b) Energy extraction

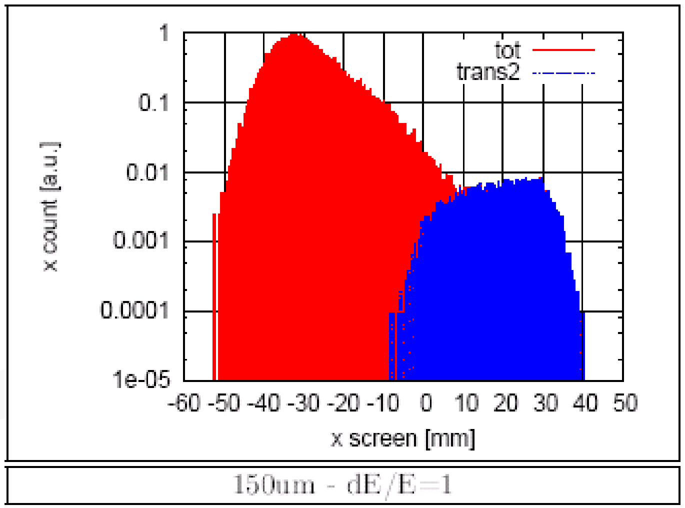
- **Objectives**: precision measurements, compare with analytical predictions, compare with RF power, check parameter dependence



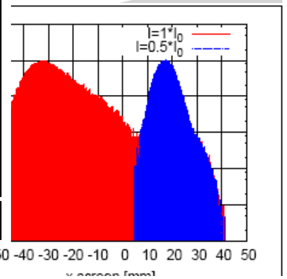




(**MDX adjusted for ~10 cm screen image: B≈20mT, θ_{min}~1°, θ_{max}~5°**)



(dE(I))

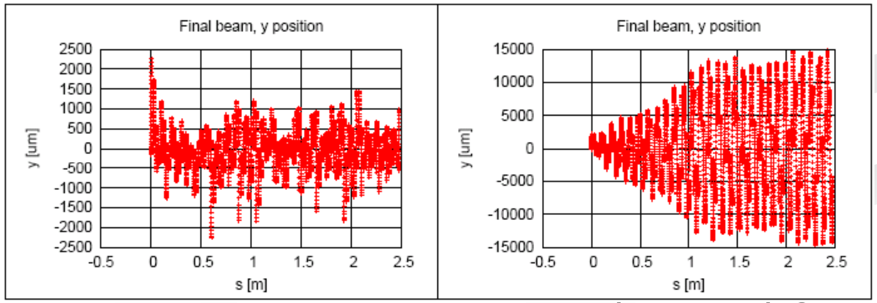


Transient

- **Objective:** verify size (in charge) and length (in time) of transient
  - will give indications of drain-out dynamics and group velocity
  - In order to distinguish transient in time,

  a time resolution of <= 1 ns would be needed

- **Objective:** verify time-resolved steady-state part
  - show whether we really have reached a good beam steady state condition
  - if not, how and where are the perturbations? (e.g. beam growth? losses due to unknown weakly damped modes?)

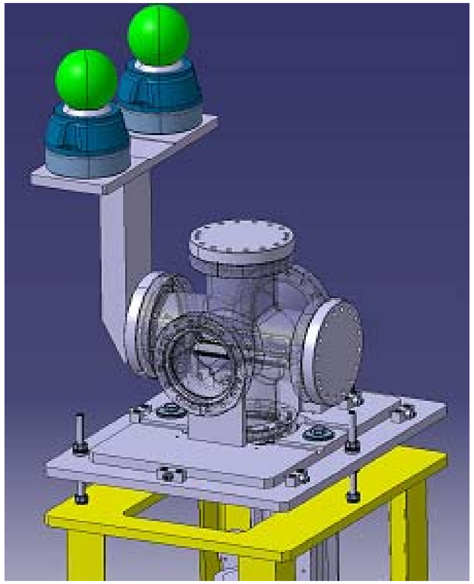


Nominal params **High (extreme) Q**

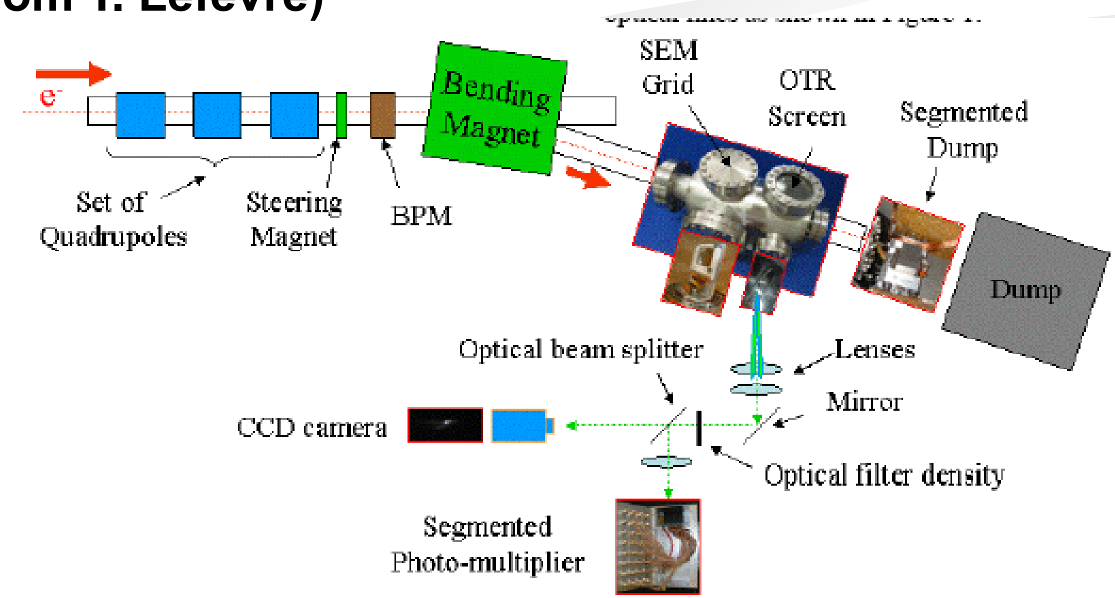
Spectrometer line: potential solutions

- Spectrometer line, time-resolved OTR (seg dump or multi-anode photo-multiplier?)
  - REQ: Spatial resolution (200 μm) → adequate
  - REQ: Dynamic range must be > 3 OM → should be feasible
  - REQ: Time resolution of <= 1ns → should be feasible

    (however, resolving intra-bunch profile: need <= 1ps resolution)



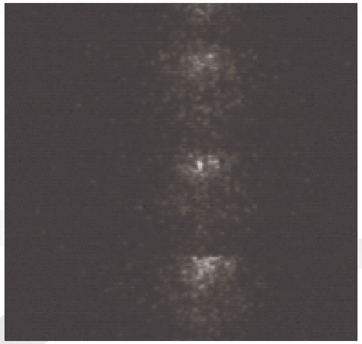
(From T. Lefevre)



- **Objective: verify bunch charge profile/ f.f.**

  * Streak-camera (triggered)

  - Available with current equipment: 2-3 ps resolution ~ $\sigma_z \rightarrow$ not adequate
  - REQ: <= 1 ps $\leftrightarrow$ 1/3 σ_z already much better



(T. Lefevre)

  * RF-deflectors?

  - Available: 1.5/3GHz
  - But nominal bunch spacing is 12 GHz $\rightarrow$ still aq. res.?

- **Objective: verify bunch energy profile**

  * RF-deflector combined with spectrometer?

Under study!

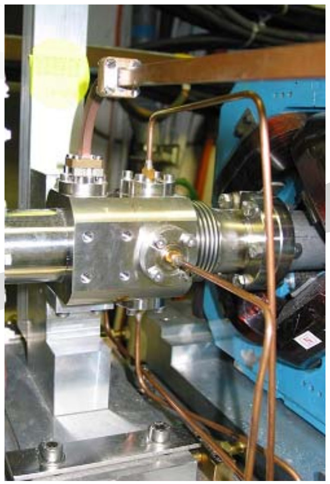
Bunch-length / form-factor

- Power extraction depends on current and form factor :

$$P \approx (1/4)\, I^2\, L_{pets}^2\, F(\sigma)^2\, (R'/Q)\, \omega_b / v_g$$

- Objective: Form factor
  - Given by eventual time-resolved charge-distribution (prev.slide)
  - As complement, continuous monitoring of form-factor, or at least bunch length:
    - RF-pickup w/ length measurement?
- Objective: current
  - BPM should be of types that provides continuous current measurement

(A. Dabrowski)



c) loss measurement

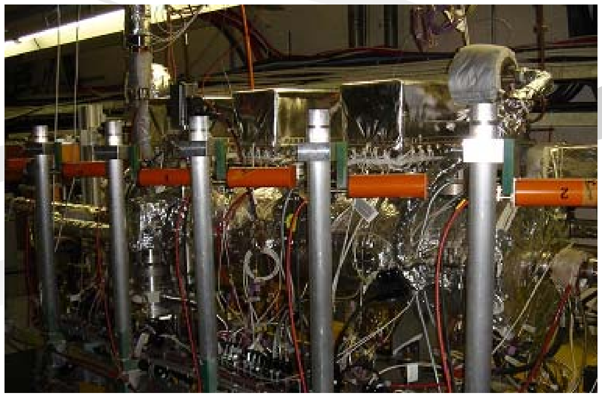
Objective: track losses

- the CLIC decelerator beam will traverse 1400 PETS over ~1km distance without significant losses. To show feasibility it would help if we are able to traverse the TBL with negligible losses
- Possible show-stopper: quality of beam coming into CLEX
  - Collimation before TBL might be considered
- If we have losses it is of interest to know location of the losses
  - in space: where along the TBL? (e.g. is focusing strategy working well?)
  - in time: in transient, or in steady-state part?
- Loss monitors along the whole TBL should

be considered, preferably with time-resolved output <= 1ns

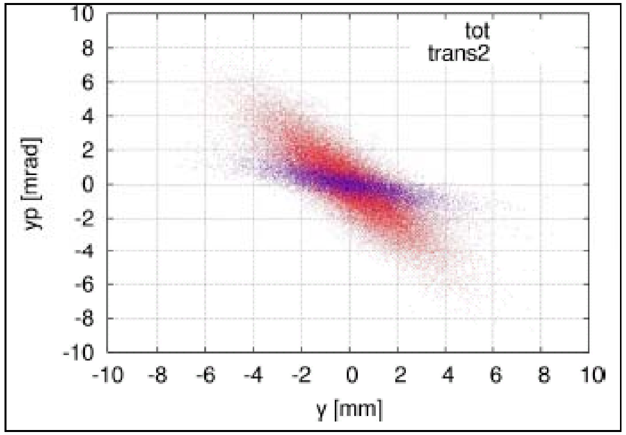
(e.g. Cherenkov type?)

(from T. Lefevre)



d) emittance, beam size and beam halo

Objective:transverse profiles and emittance



- quad scan
  - gives, in principle, phase-space and beam-size, however energy spread leads to some problems

    $\sigma = (\mathbf{X}^T\mathbf{X})^{-1}\mathbf{X}^T\mathbf{R}$, but $\mathbf{X}=\mathbf{X}(p)$ ($\mathbf{M}_{12}=\mathbf{M}_{12}(p)$)

    → leads to wrong estimate of emittance ~10% wrt. to perfect measurement (prelim. est.)
  - still useful (and advantage of being a "standard CTF3-technique")
- core profile
- transverse tails
- halo measurement
  - collimator, possibly movable, might be needed for halo-measurement
  - Needed in order to prove eventual transport of the whole beam (>99.9%)

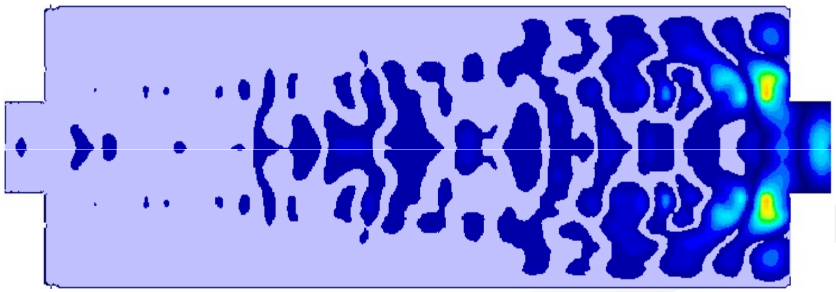
d) Other suggestions

Objective: further study of PETS transverse modes

1) Study of jitter amplification?

- Possibility: to induce jitter at specified frequencies (drive PETS transverse modes), and measure amplification
  - Modes lie at ~10 GHz
- Implementation: no concrete suggestions

2) Direct probe of PETS RF-field?



(From I. Syratchev)

Under study

BPMs

TBL will also be used as test-bed for beam-based alignment. This gives some additional requirement on the BPMs :

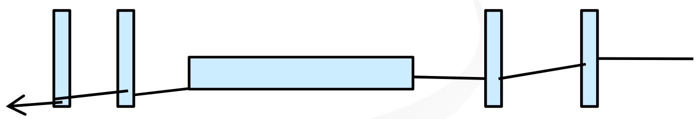
- One BPM per quadrupole
- BPM resolution requirement derived from dispersion-free steering: <= 10 um
- Beam envelope might reach close to PETS aperture limit of 11.5 mm
  - Centroid signal / range of BPM: few millimeters
  - But signal from halo-particles must be taken into account
- Time resolution of ~10ns (resolve parts of the beam)
- Available length for BPMs: < 15 cm

(→ Consistent with the design from IFIC / UPC)

Short-term: effect of 1 PETS

- In order to prepare for TBL we should measure as much as possible already 1 PETS
  - Where? Dedicated instrumentation after TBL 1 PETS? TBTS?
- Examples of 1 PETS beam dynamics measurements:

1) measure dipole mode, scanning of offset beam



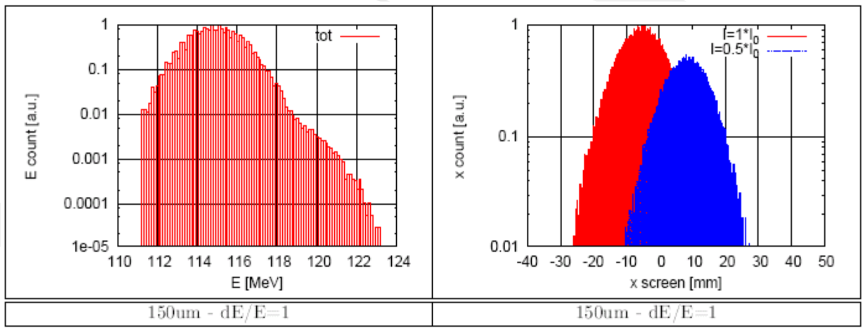
- verify with simulations
- steer to constant offset [0-5 mm]
- in order to give an indication of amplitude of transverse modes (dipole modes + **higher order modes**) (1 mm gives ~0.1mrad – IF models are right)

2) measure extraction dependence of parameters

- Should be possible to resolve even for 1 PETS (and ΔE/E=1%)

3) phase-space

- Verify simulations



Preliminary conclusions

- Many interesting beam observables in the TBL, and it seems feasible to measure most of them
- If we can prove stable TBL operation, without significant losses, it will be a good indication that the CLIC decelerator will work
- Specification of final TBL instrumentation is an on-going work, to be completed this year
- Soon available information from TL2’ and 1-PETS-tests should be used to finalize to the TBL specifications
  - Important to get a fully realistic prediction of TBL measurement possibilites

Many thanks to T. Lefevre and D. Schulte for a lot of useful input