Beam Dynamics & Beam Diagnostics

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4th DITANET Topical Workshop on High Intensity Proton Beam Diagnostics

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a (LONG) Love Story

Between Beam Dynamics & Beam Diagnostics

QUESTIONS

Do we need BDiag ?

What kind of BDiag ?

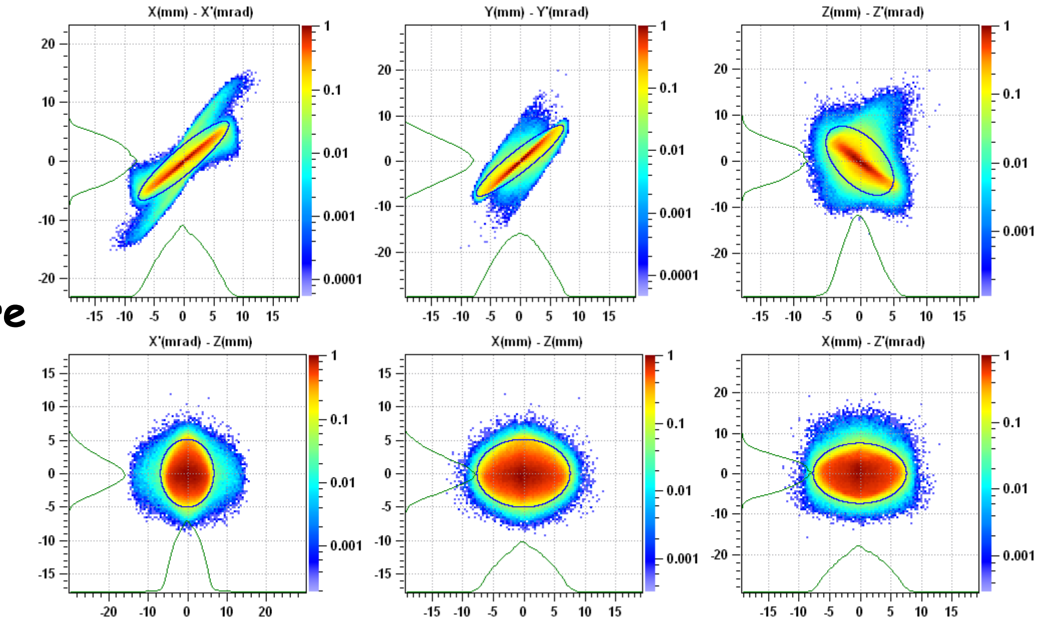
How many BDiag ?

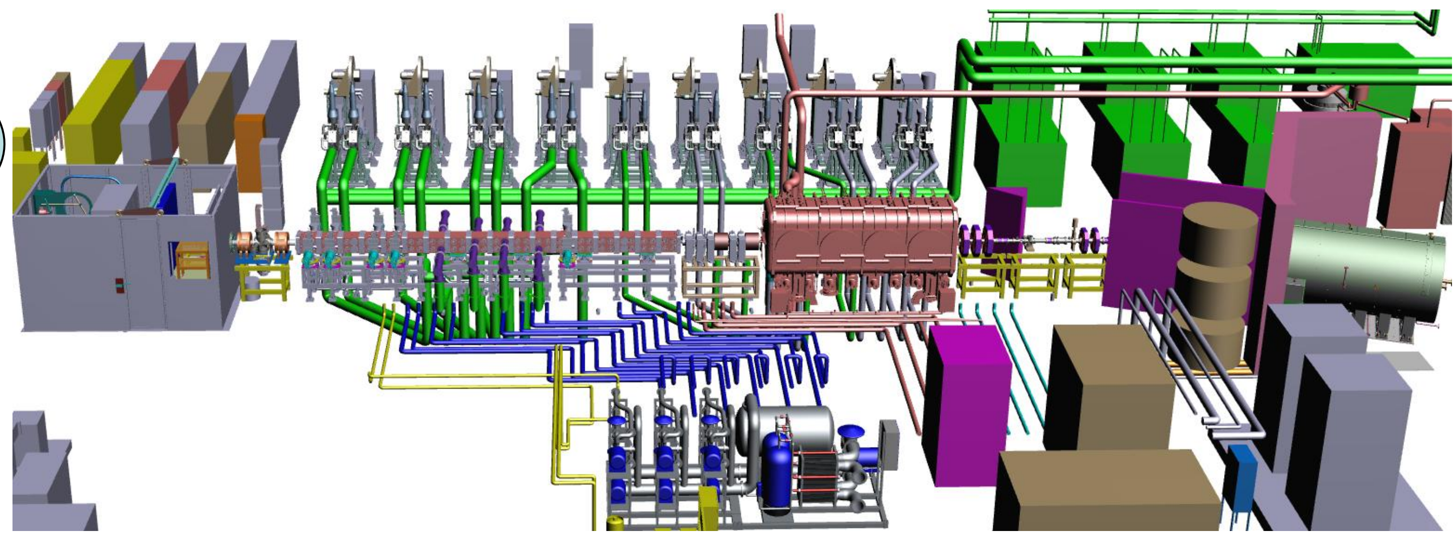
Where to install BDiag ?

What performances for BDiag ?

Do we need BDiag ?

Beam is known everywhere
in 6D phase space
(15 projections onto 2D)





When do we need BDiag ?

When there is a risk of discrepancy between
Theory ⇄ Reality
BDynamics calculations ⇄ Real on-line beam

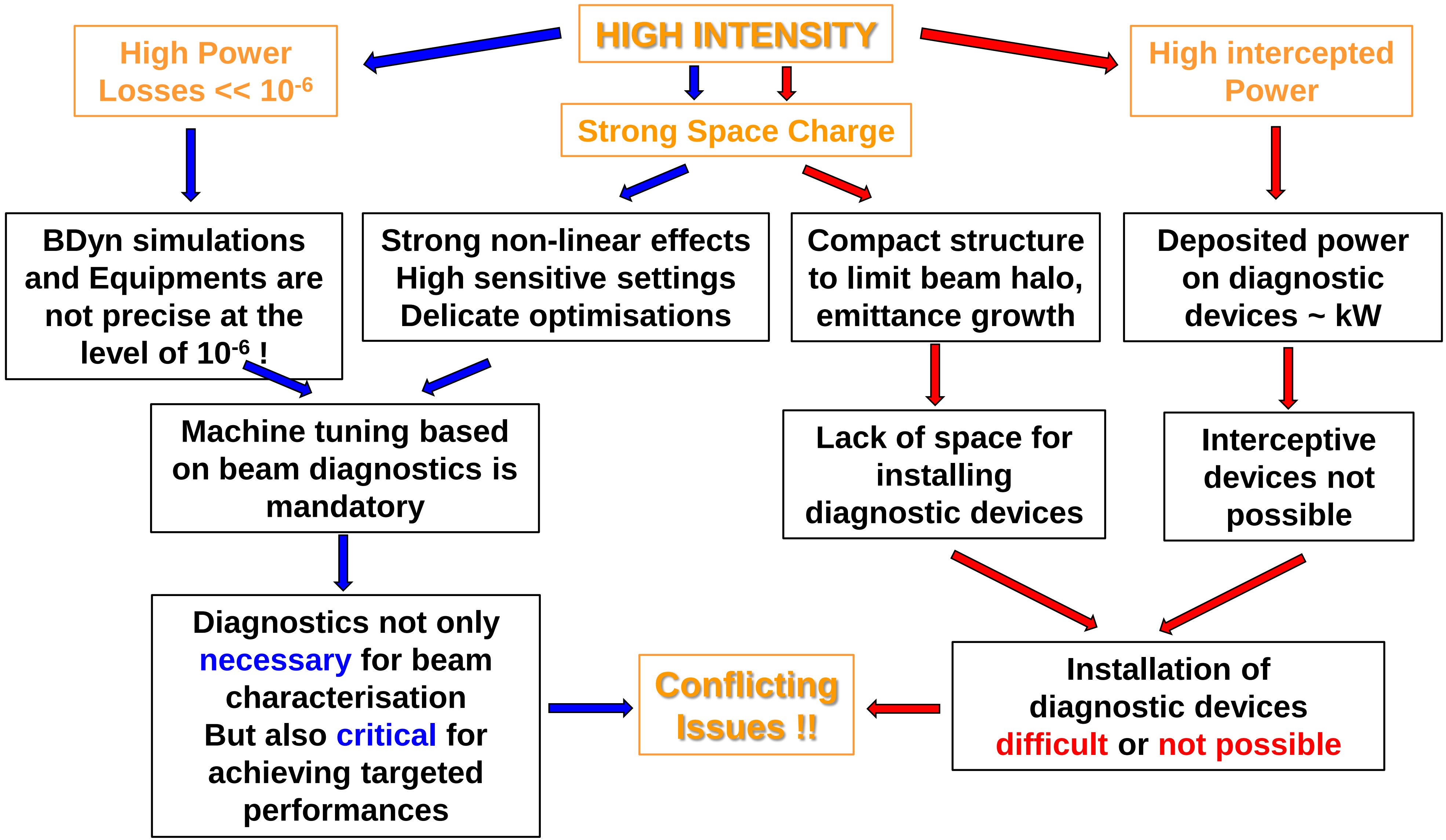
Due to theory imperfections or equipment imperfections

When discrepancy could be > required tolerances
BDiag are needed for tuning the beam on-line in order to meet requirements
→ Direct improvements of accelerator performances

When BDynamics results are uncertain
BDiag are needed for verifying
and understanding the beam behavior
→ Indirect improvements of accelerator performances

Diagnostics: to measure is NOT the ultimate goal
to measure for TUNING, CORRECTING, IMPROVING …

ISSUES for High Intensity Beam



STRATEGY - BDyn

SELF-RULE

Perform only Beam Dynamics optimisations that could be reproduced in-situ on the real machine with the appropriate Beam Diagnostics

In other words:

Each BDyn tuning procedure MUST have its on-line Avatar on the machine

STRATEGY – Bdiag (1)

Clearly distinguish between:

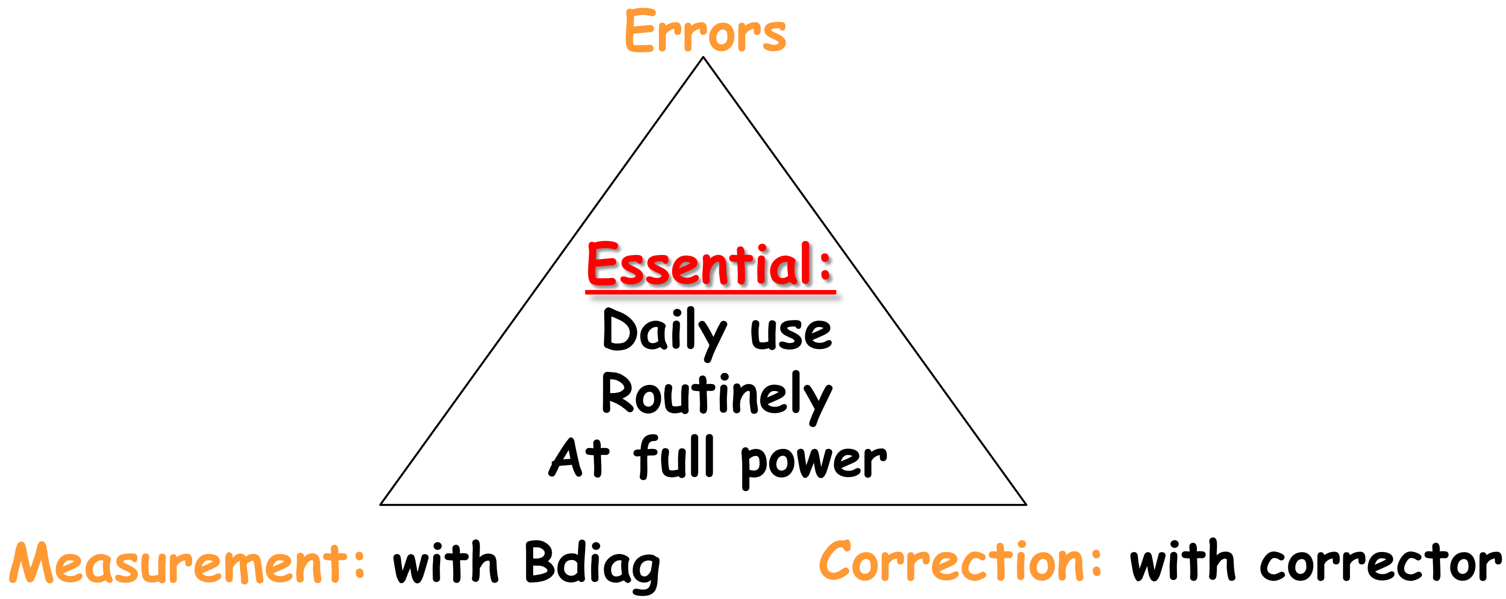
ESSENTIAL measurements

- for commissioning & tuning & operating the accelerator
- in order to meet required specifications of current and losses
- direct impact on the achievement of accelerator specifications
- available for everyday beam tuning at full power, non interceptive
- beam position, beam phase, current, losses, micro-losses

CHARACTERISATION measurements

- for beam commissioning or beam study or beam dynamics understanding
- could be measurements during beam commissioning only, if lack of room
- could be interceptive devices for low duty cycle, if pb of power deposition
- transverse profile, emittance, halo, energy spread,
- mean energy, bunch length

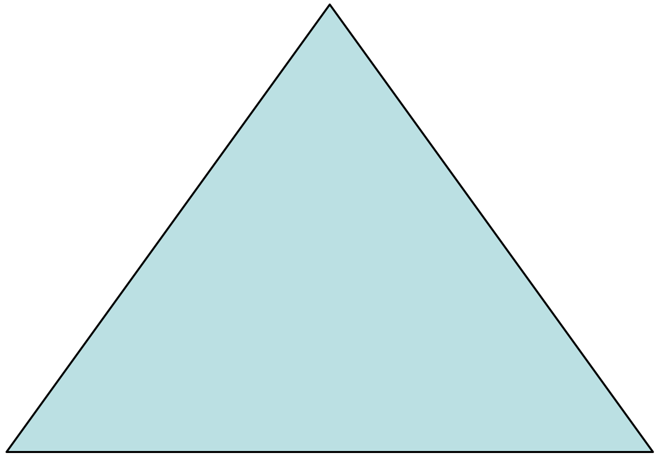
STRATEGY – Bdiag (2)



Characterisation: Knowledge, Understanding, Survey

Beam Position Monitor (1)

Errors: transverse magnetic, electric field
- in magnetic, electric elements
- due to equipment imperfections, misalignments

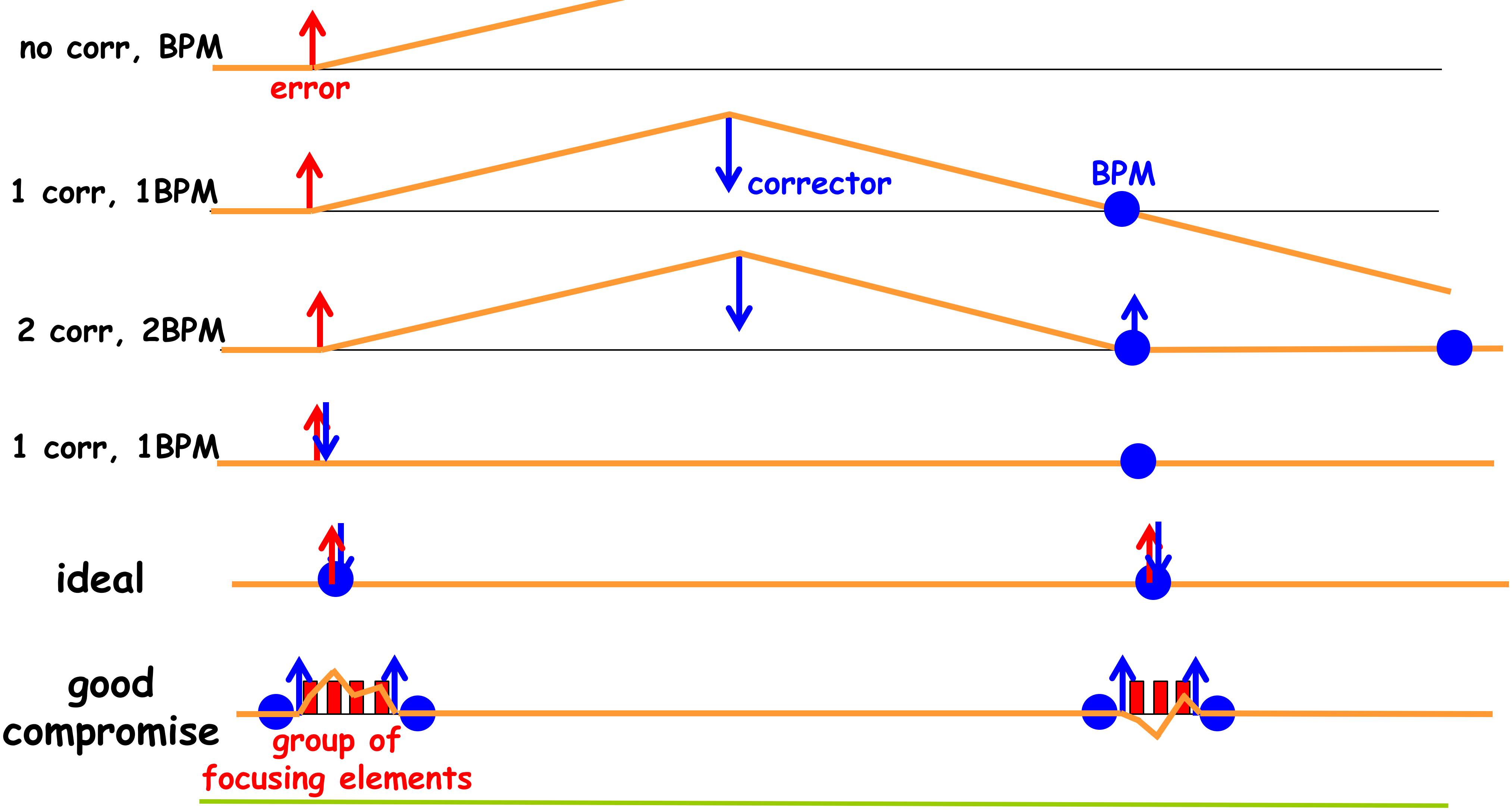


Measurement: with BPM trajectory displacements

Correction: trajectory
Corrector: transverse magnetic field

Best correction: least residual trajectory, least corrector strength
⇒ Locations of Correctors and BPMs:
the closest to errors, ideally where there are errors

Beam Position Monitor (2)



Beam Position Monitor (3)

PERFORMANCES

Errors: Tolerances

Measurement: BPM precision

Correction: Corrector strength

Error Tolerances ↗ $\Rightarrow$ Corr. Strength ↗

BPM precision ↘ $\Rightarrow$ Corr. Strength ↗

Compromise among this trio

Beam Position Monitor (4)

PERFORMANCES

- If BPM precision too bad ⇒ no sense

  Not to correct is better than … to correct

  Corrector strength is used to … deteriorate the trajectory

Typically: required BPM precision is defined so that

corrector strength for correcting tolerated errors +BPM imperfection

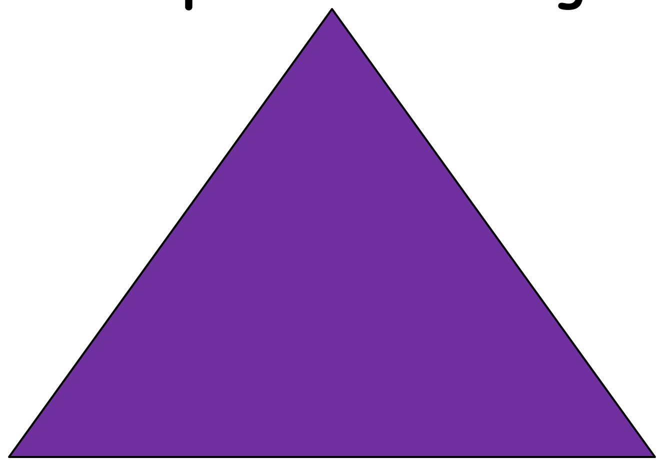
not very ≠ corrector strength for correcting tolerated errors +perfect BPM

- This presicion is only needed near the center

  Far from the center, less BPM precision is needed

μ-Loss Monitor (1)

Errors: Theory precision
Machine reproducibility
Input beam changes



Measurement: with μLM
Losses 10^{-5} - 10^{-7} beam

Correction: minimise μlosses
Corrector: focusing strength

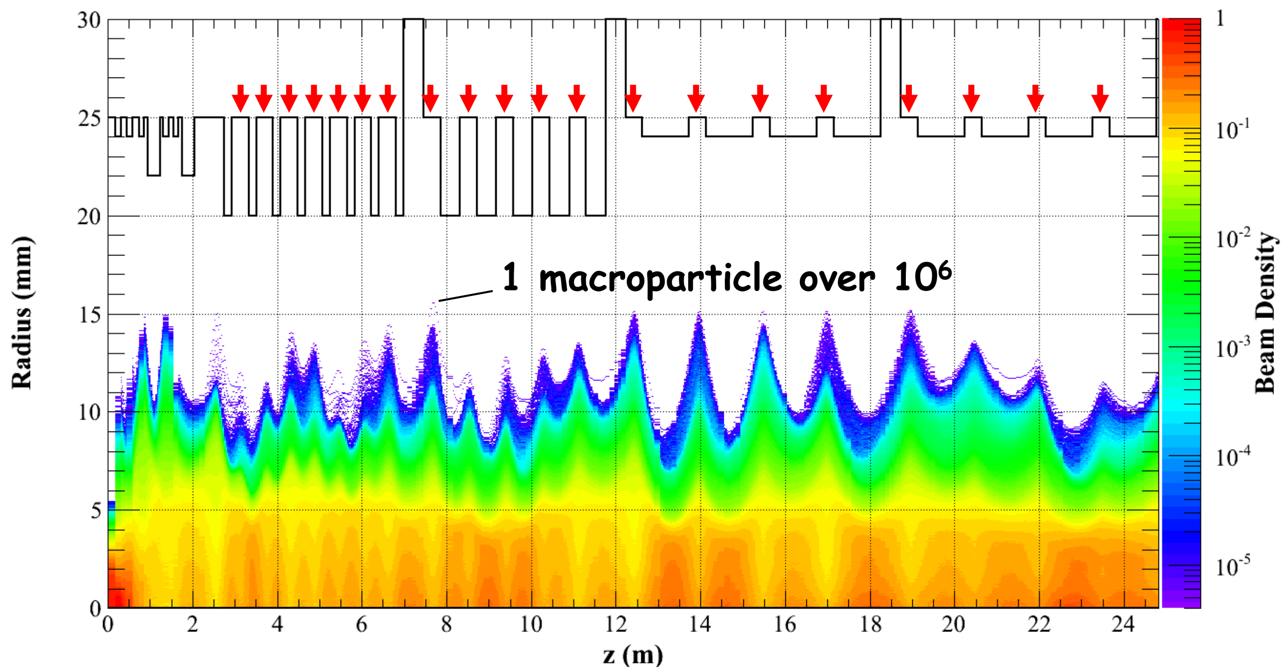
This correction would to be done daily,
like for Trajectory correction with BPM

μ-Loss Monitor (2)

Best correction: least residual μlosses

⇒ Ideally as many μLM as foc. elements upstream (one-to-one correspondence)

⇒ Located at foc.elements where loss probability is the highest, and the closest to the beam to allow locating losses



Performances: resolution 1/10 of maximum allowed losses

Other Beam Diagnostics

Current: as only resolution ~10^{-3}
to optimise transmission at low energy parts (RFQ)
and high energy parts for scrapers or for first rough tuning

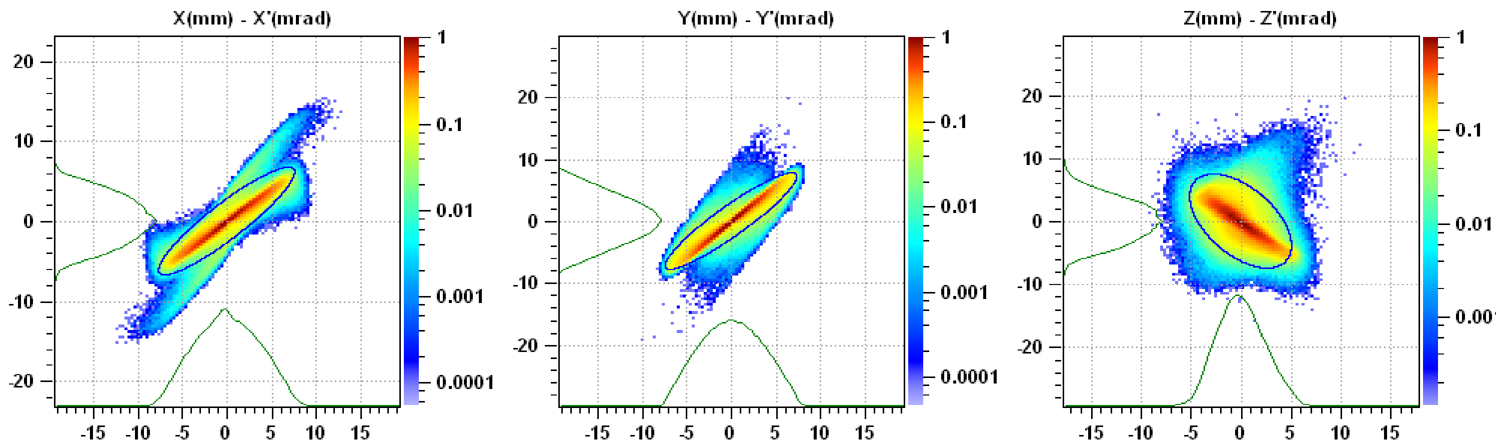
Phase: as many as accelerating cavities, resolution ~ 1/10 phase tolerance

Mean energy, Energy spread: after an accelerating structure, precision and importance depend on the objective of the Linac

Beam distribution: after an accelerating structure, to verify, understand the beam behavior, regarding beam dynamics calculations
Low energy: Ion species, Space Charge Compensation
Any energy: Bunch length, Transverse Profile, Halo, Emittance

Emittance measurement (1)

The beam phase space results from focusing elements:
quadrupoles, solenoids in transverse or electric cavities in longitudinal



The 6D beam phase space (Npartx6 parameters) can be partially represented by projections in different 2D phase spaces (Npartx2 parameters)

A 2D phase space can be partially represented by an ellipse characterised by the 3 parameters α, β, ε ← emittance (surface of the ellipse)

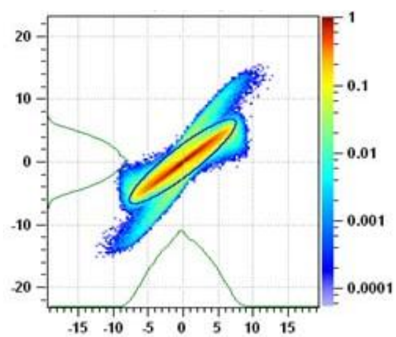
... which is enough to describe a linear beam transport !

Emittance measurement (2)

"Emittance" measurement

Interceptive method:
Pepper pot or Slits + Grid

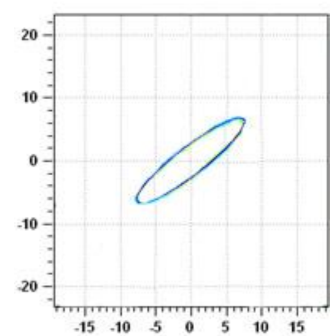
Particle density distribution in a 2D phase space



More information
But no direct use
→Input to beam dynamics calculations

Non-interceptive method:
Quadrupole gradient variation

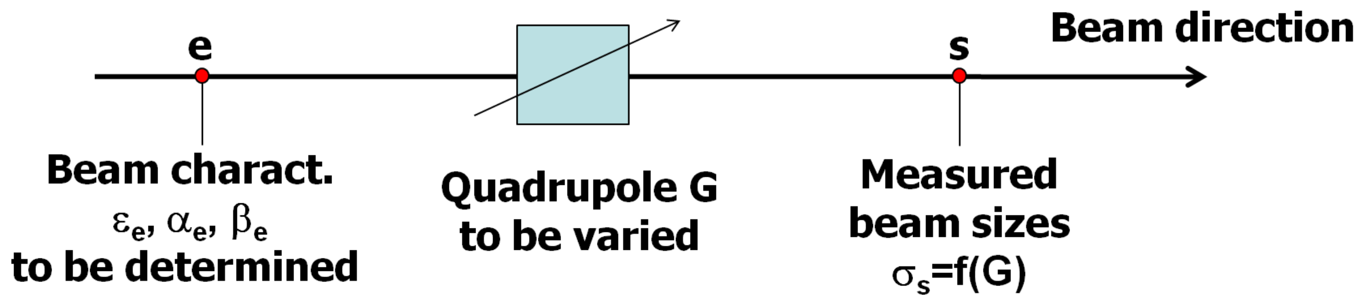
Envelope ellipse $\alpha, \beta, \varepsilon$



Incomplete information
But possibly direct use
In case of linear beam transport

Emittance measurement (3)

Measurement by Quadrupole variation- Linear beam transport



$$[x_s] = [M][x_e]$$

rms beam size →

$$\sigma_s^2 = M_{11}^2(\varepsilon_e\beta_e) - 2M_{11}M_{12}(\varepsilon_e\alpha_e) + M_{12}^2(\varepsilon_e\gamma_e)$$

Measuring σ_s for different [M] (at least three values)
→At least three such equations are obtained,
→from which α, β, ε can be obtained by inversion

Emittance measurement (4)

When the beam is "emittance dominant" (in the RFQ for ex.) instead of "space charge dominant", the beam transport is linear

Simulation results:

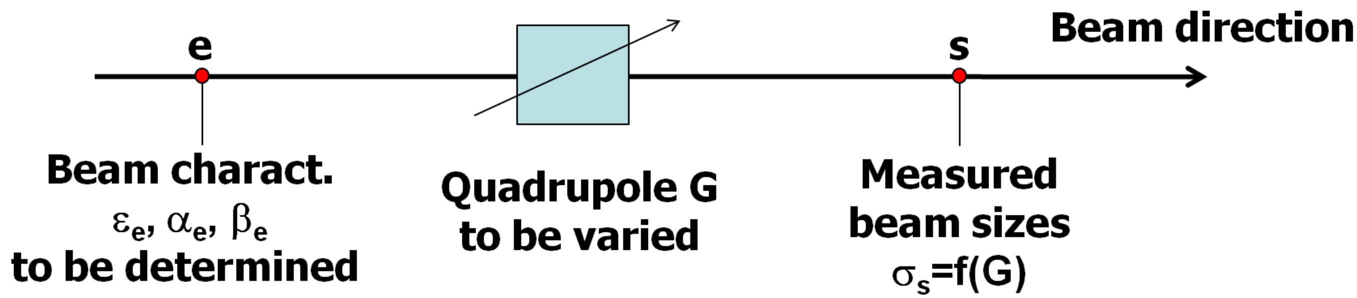
At the RFQ entrance:

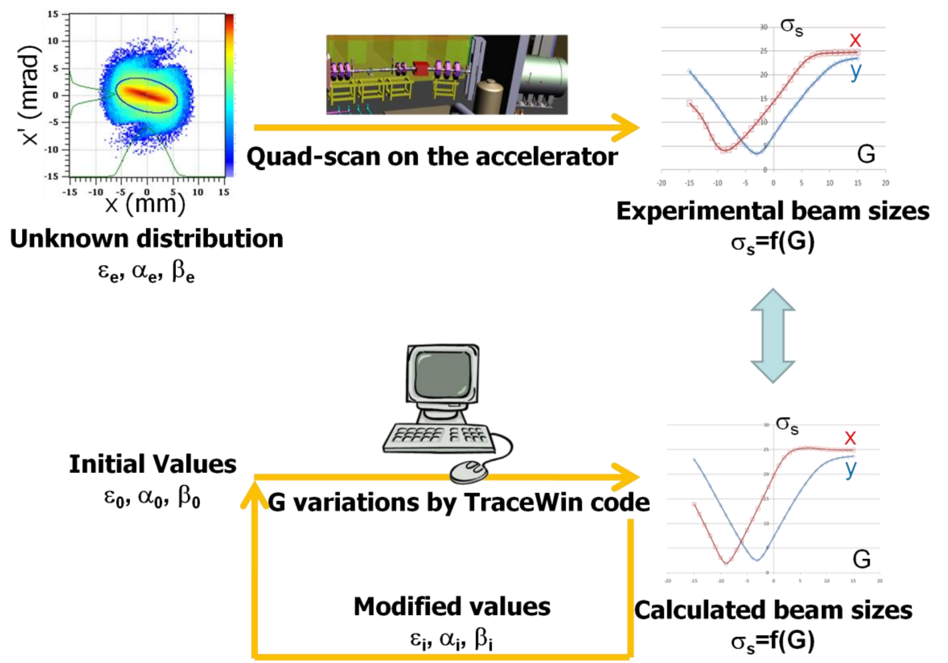
α	β (mm/πmrad)	ε (πmm.mrad)	RFQ transmission
2.8	0.135	0.21	92.5 %
2.2	0.110	0.22	88.5 %

⇨ In principle α, β, ε could be used as a guideline for obtaining the best RFQ transmission

BUT: Are we confident on the measurement precision of α, β, ε ?
Isen't it easier to measure and interpret directly the current (1 value) rather than 3 values ?

Measurement by Quadrupole variation- Nonlinear beam transport

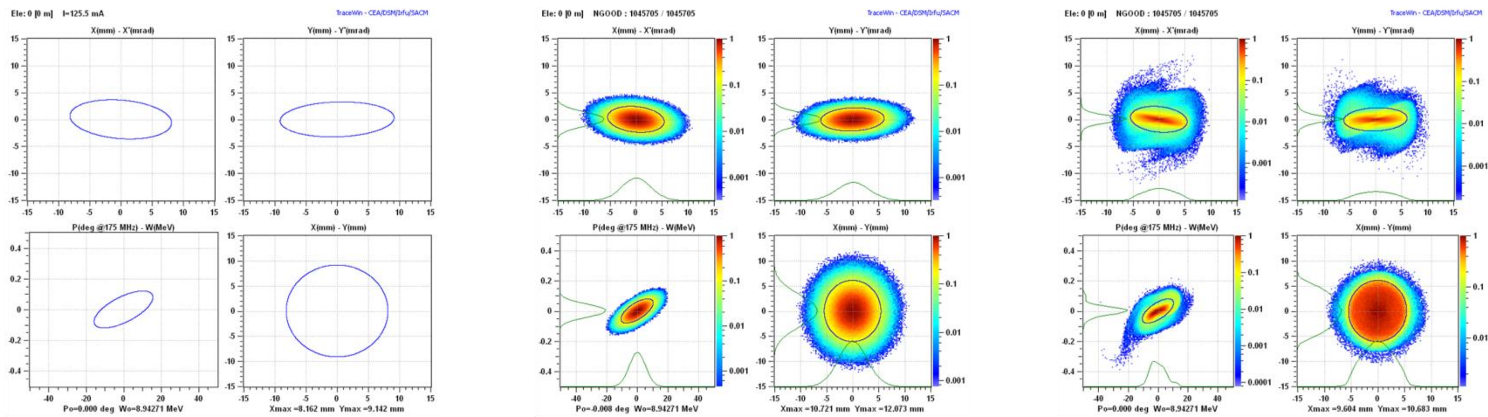




Emittance measurement (6)

Measurement by Quadrupole variation- Nonlinear beam transport

ENVELOPE distribution | **GAUSSIAN distribution** | **'NOMINAL' distribution**



Non-linear space charge forces:
results are strongly distribution dependent

⇨ **Interpretation of the results are not so easy**

Emittance measurement (7)

Measurement of Emittance or Phase Space:

Reachable precision and Delicate interpretation
→is useful for verifying beam dynamics predictions
or as input to beam dynamics calculations of downstream sections
→ hard to be used in routine beam tuning

A few measurements along the accelerator,
At some specific locations (start or end of an acceleration section)
During beam commissioning or beam study

SUMMARY

It is important to distinguish between
essential and characterisation diagnostics

The <u>number</u>, the <u>location</u>, the <u>performances</u>
of diagnostics will directly depend on that distinction

These questions being somewhat clarified, hope that
between Beam Dynamics and Beam Diagnostics

It is a YOUNG love story