Advanced methods & concepts
for very high intensity beams

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Advanced Beam Dynamics
Workshop on High-Intensity,
High Brightness and
High Power Hadron Beams

What is HIGH intensity ?

Only in the sense of comparison:

Beam A intensity is higher than Beam B intensity

Only makes sense if

higher intensity → higher issues to face

Issues to be analyzed are twofold:

High intensity

High power $P = \frac{I_{av}E}{n_q}$

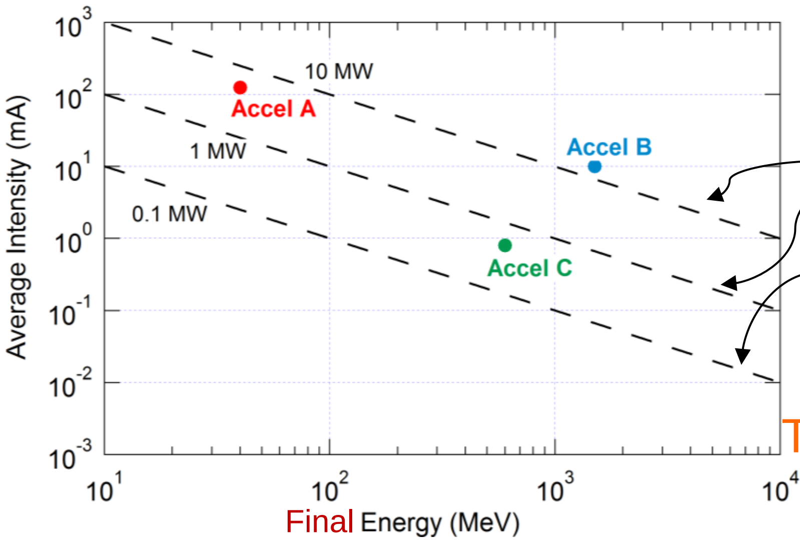
- even tiny losses are harmful
- ….

$K = \frac{qI_p}{2\pi\varepsilon_0 m(\beta\gamma c)^3}$ **Strong space charge**

- strong nonlinear repulsive forces
- …

Combination of the two issues → particularly critical situation

Classically: assimilation to high power



Example of three accelerators:

Average, peak intensity; starting→final energy

- Accel A: 125 mA, 125 mA; 0.1 → 40 MeV
- Accel B: 8 mA, 10 mA; 0.05 →1500 MeV
- Accel C: 40 mA, 0.8 mA; 0.03 → 600 MeV

The most challenging : Accel B, then A, then C ???

This graph is highly reductive:

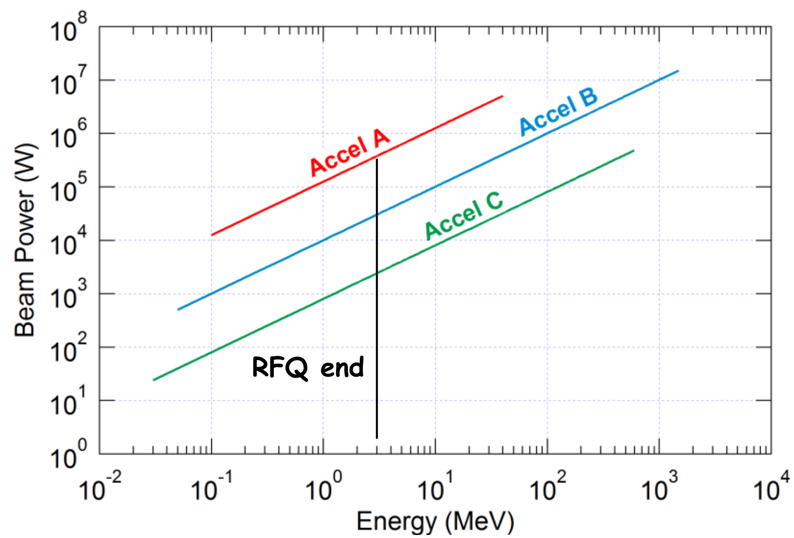
● Only last section, no upstream sections

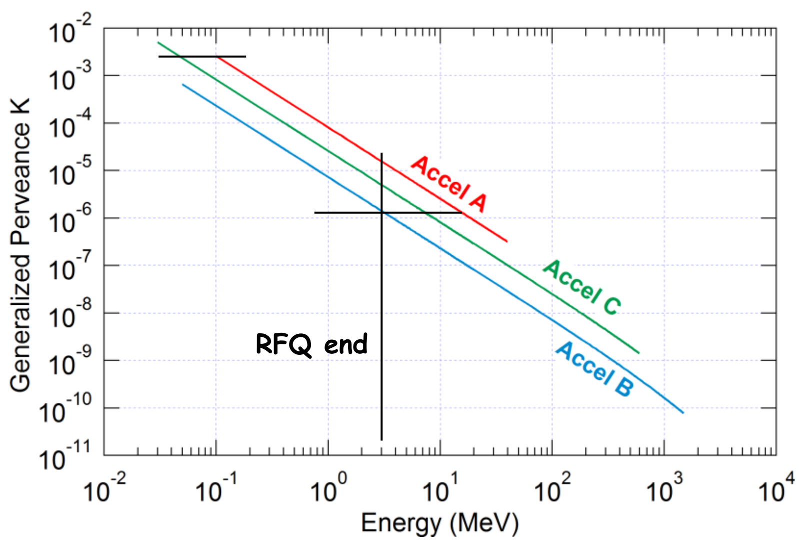
- Each energy range ↔ specific acceleration-focussing technologies
  Source, LEBT, RFQ, DTL, CCL, SC-HWR, Spoke cav, Elliptical cav
- Challenges are not comparable at very different energies
- Challenging last section doesn't mean challenging upstream sections

● No space charge

- need of strong focusing
- non-linearities
- emittance growth
- halo creation
- sudden losses

Beam analysis (2)





Advanced analysis:

Beam power & Space charge along the accelerator

(average & peak intensity, start & final energy)

- Beam power issues

Only last section: B, A, C

For a given section: A, B, C

- Space charge issues

Only first section: C, A, B

For a given section: A, C, B

Direct comparison between accelerators for a same acceleration component

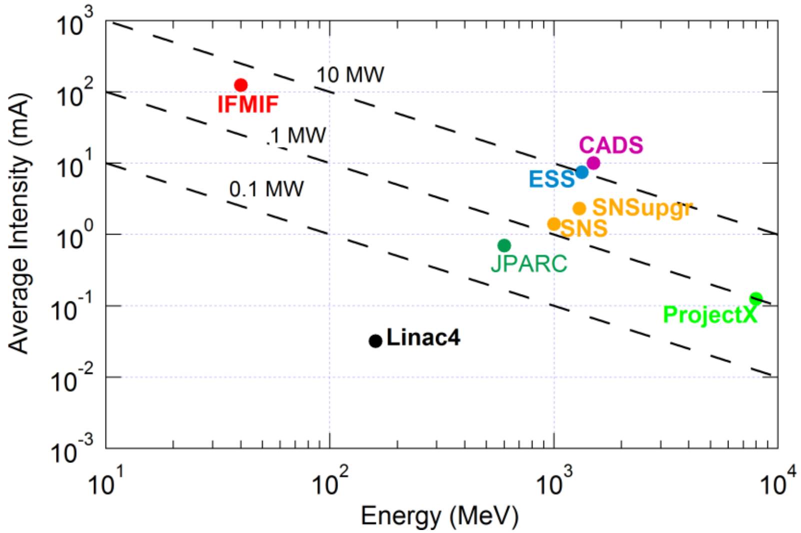
⇒ challenging or not

⇒ adjust section start/end could help

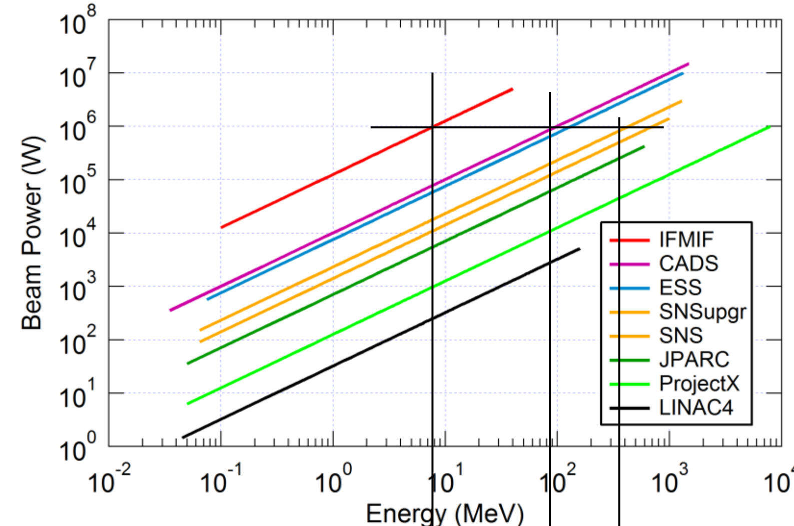
⇒ see effects of combination of high power & space charge

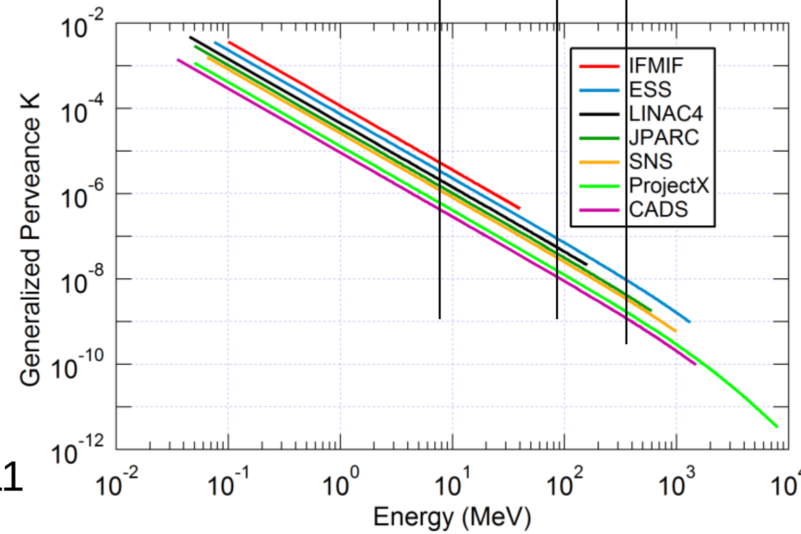
Examples of accelerators achieved or under construction or planned

Classically



Advanced





Nucl. Instru. Meth. Phys. Res. A 654, 63–71, 2011

Advanced methods and concepts

1. New idea for: Beam analysis
2. New protocol for: Beam loss prediction
3. New method for: Beam optimization
4. New strategy for: Beam measurement
5. New concept for: Beam characterization

1. New idea for: Beam analysis
2. **New protocol for: Beam loss prediction**
3. New method for: Beam optimization
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Beam loss prediction (1)

High power → even a tiny part of the beam, when lost, can take away a significant power

- **Accidental loss → brutal heat deposition → damage equipment**
- **Permanent loss → activate materials → harmful radiations for personnel**
  → cryogenic systems must be able to cool down
  Hands-on maintenance requirement: Losses << 1W/m
  MW beam → well less than 1 particle lost over 10^6 is tolerated !!
  → microlosses

High intensity → High power on almost the whole accelerator
→ Carreful and exhaustive prediction of losses all along the accelerator is needed

Beam loss prediction (2)

Double issue:

- **Define exhaustively all the loss situations in the accelerator lifetime**
- **Define the protocols to simulate and estimate them**

Loss situations and protocols:

A. Ideal machine: nominal theoretical conditions, without any error
B. Starting from scratch: errors as tolerances, not corrected, tunable param.±10%
C. Commissioning, tuning, exploration: same as above but errors corrected
D. Routine operation: errors corrected, tunable param. nominal
E. Sudden failure: individual or combination of sudden trips of tunable param. from 100% up to 110%, or down to 0%.

→ CATALOGUE of LOSSES:

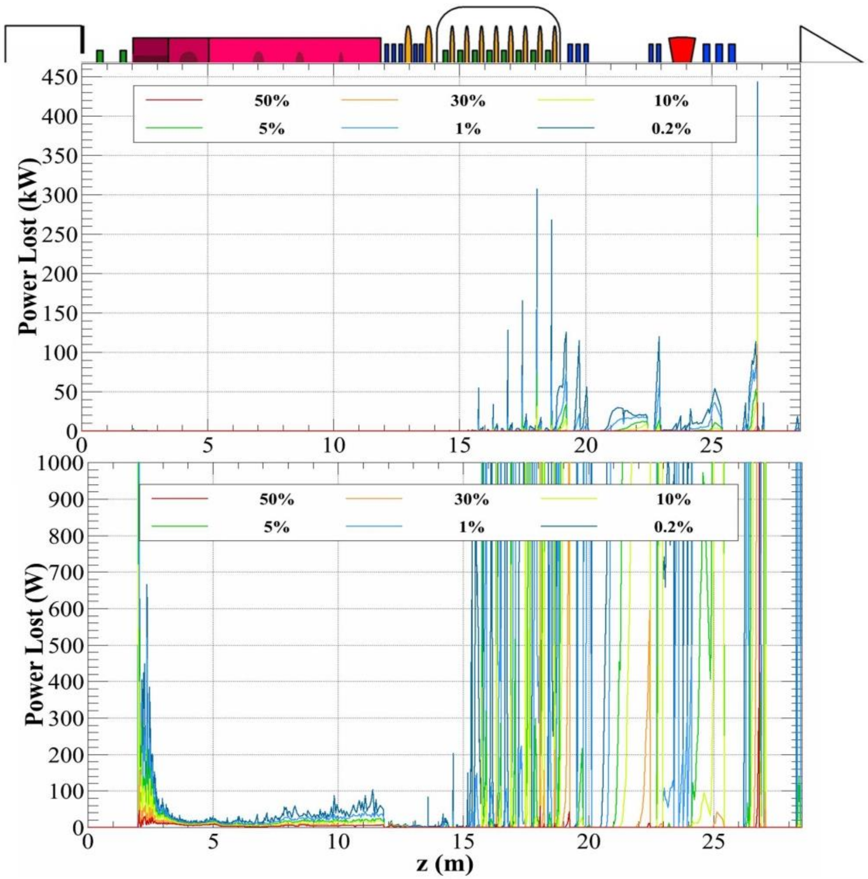
affects all the subsystems: hot points, beam stop system velocity, limitations for control system, maximum beam power for operation, dynamic range of diagnostics, etc.

Beam loss prediction (3)

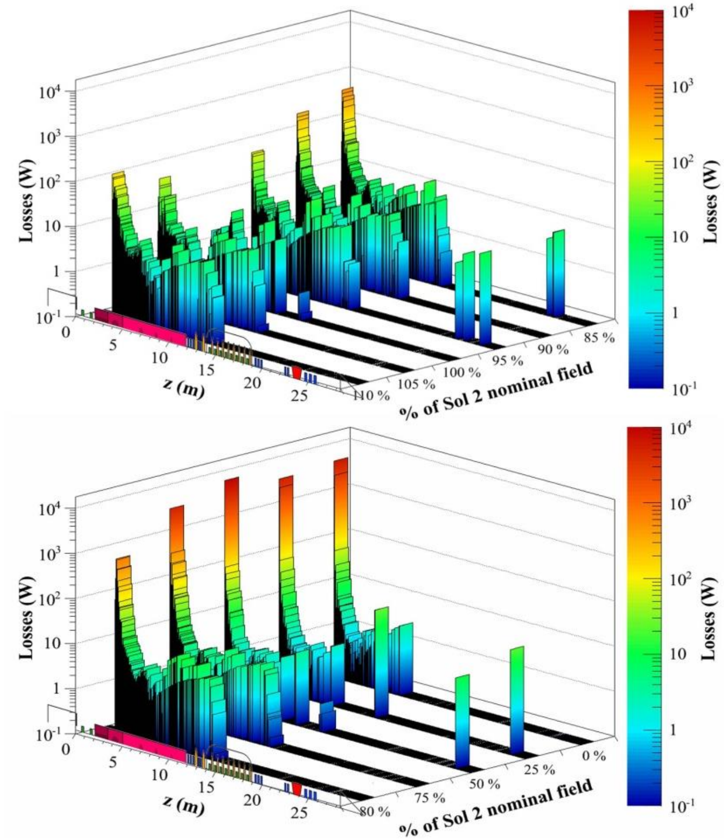
Example: CATALOGUE of LOSSES for the IFMIF Prototype accelerator

Talk of N. Chauvin et al. Thursday morning

Laser Part. Beams (2014), 32, 461-469



Beam loss power probabilities when starting from scratch for a full power beam



Beam loss power in case of sudden failure of the second LEBT solenoid

1. New idea for: Beam analysis
2. New protocol for: Beam loss prediction
3. **New method for: Beam optimization**
4. New strategy for: Beam measurement
5. New concept for: Beam characterization

Beam Optimization (1)

What are the parameters to be optimized ?

Classically:

Global parameter: rms Emittance
Minimize emittance growth
Emittance matching
Halo may be indirectly minimized

Emittance : figure of merit

But: MW beam→ microlosses
10^{-6} of the beam must be avoided
→ very external part
→ halo

Advanced:

Extension of the outermost particles
Minimize directly the halo
Halo matching
Maximize margin between beam border and pipe wall

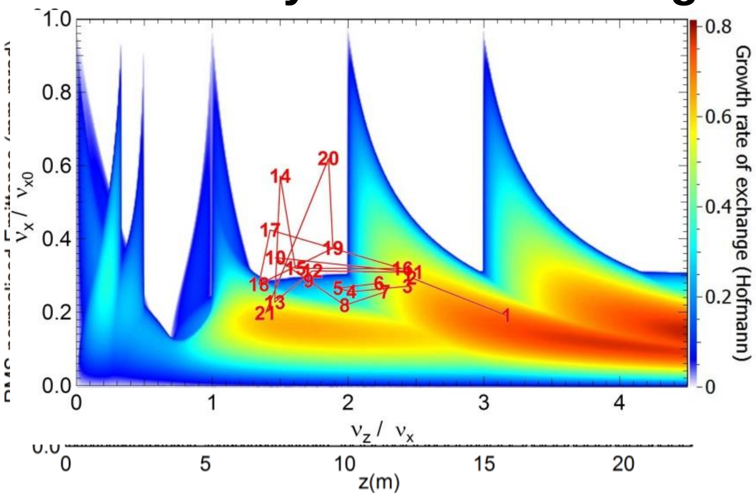
Halo: figure of merit

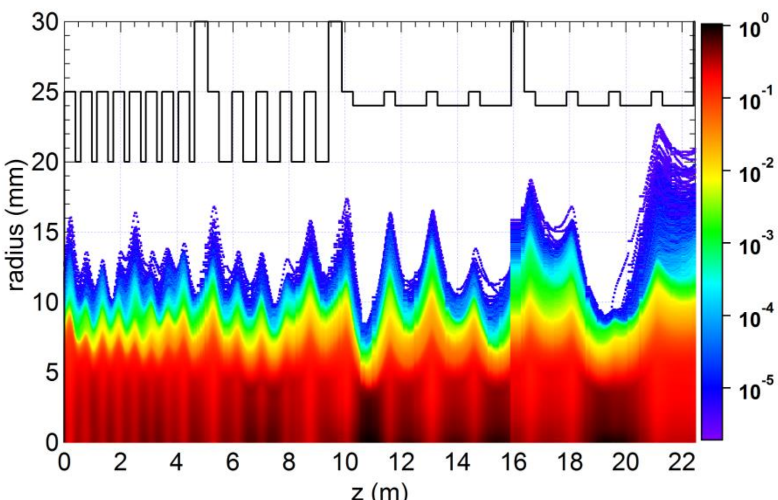
Results:
comfortable margin between
beam external border
and beam pipe wall

Beam Optimization (2)

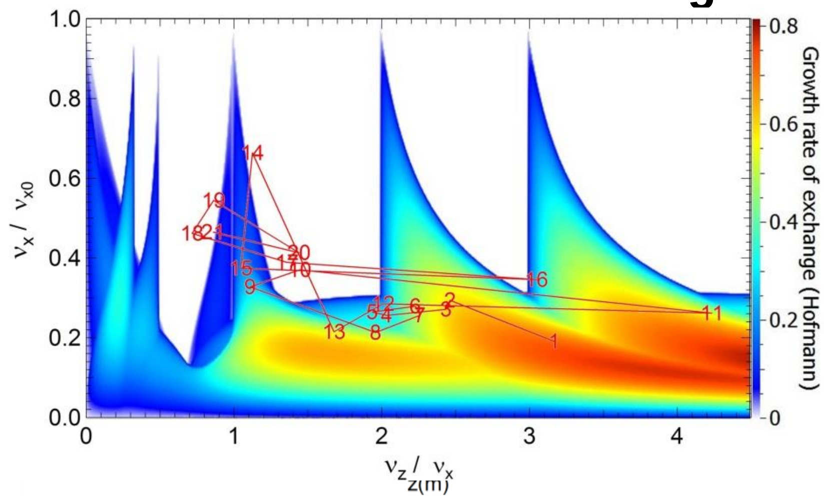
Example: IFMIF SRF Linac (Laser Part. Beams 32, 10-118, 2014)
(Talk of N. Chauvin et al. Tuesday morning)

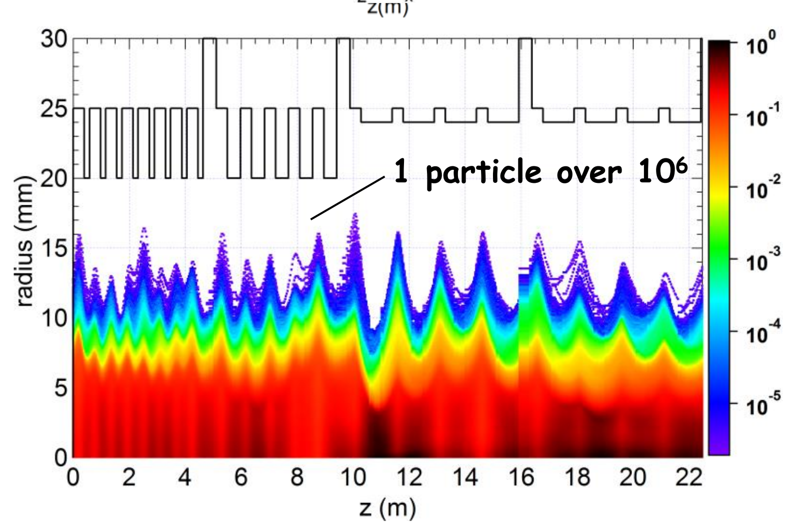
Classically: Emitt. matching





Advanced: Halo matching





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(Laser Part. Beams 32, 10-118, 2014)

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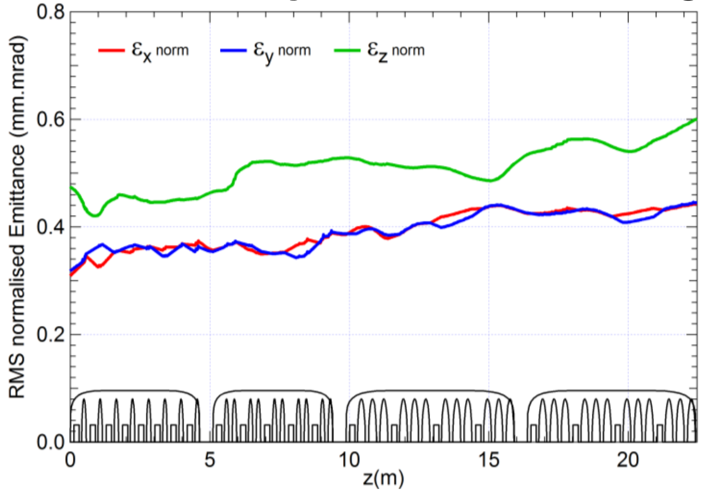

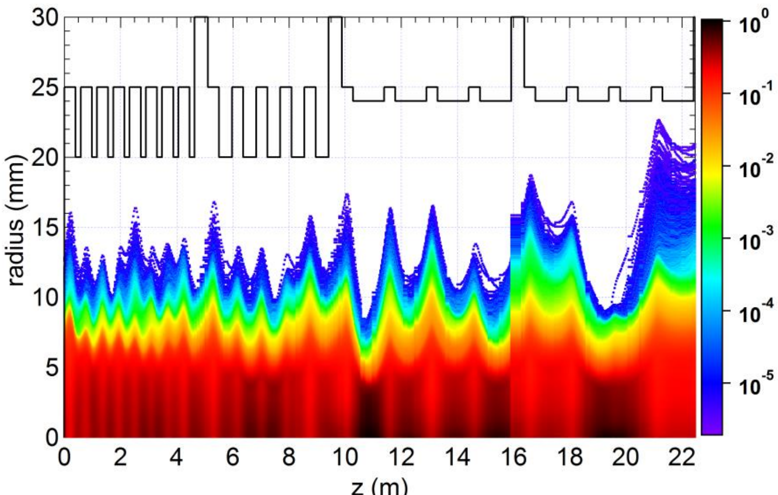

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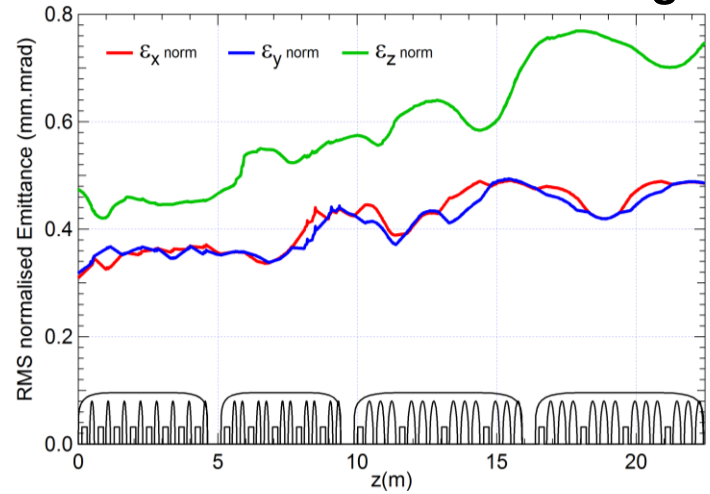
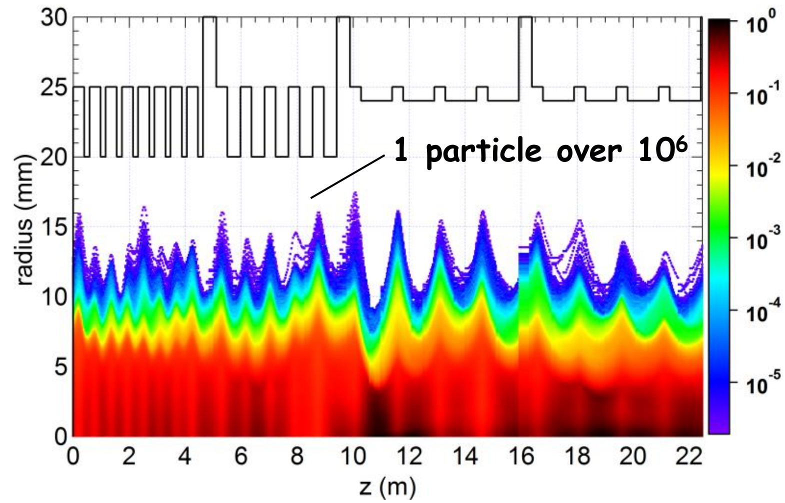




Beam Optimization (4)

Issue: The beam must be optimised to an accuracy of 10^{-6}
But simulations are not reliable to that accuracy
accelerator components are not reproducible to that accuracy
→ Frequent in-situ fine tuning are mandatory

STRATEGY: SELF-RULE

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

In other words:

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

Beam Optimization (5)

Examples of beam matching …

… to the RFQ

Optimization

Not to fulfill theor.Twiss param.
But to maximize RFQ transmission

⇕

Diagnostic

Current measurements at
RFQ entrance and exit

… to the SRF Linac

Optimization

Not to minimize RMS envelope, emittance
But to minimize micro-losses

⇕

Diagnostic

Micro-loss measurements
the closest to solenoid vacuum chamber

Enough independent diagnostics:
at least the same number as that of available tuneable parameters

Rev. Sci. Instru. 83, 02B320, 2012

Proc. of PAC. Vancouver, BC, Canada, 2009

1. New idea for: Beam analysis
2. New protocol for: Beam loss prediction
3. New method for: Beam optimization
4. **New strategy for: Beam measurement**
5. New concept for: Beam characterization

Beam Measurement (1)

HIGH INTENSITY

High Power Losses << 10^{-6}

Strong Space Charge

High intercepted Power

B Dyn simulations are not precise at the level of 10^{-6} !

Strong non-linear effects
High sensitive settings
Delicate optimisations

Compact structure to limit beam halo, emittance growth

Deposited power on diagnostic devices ~ kW

Machine tuning based on beam diagnostics is mandatory

Lack of space for installing diagnostic devices

Interceptive devices not possible

Diagnostics not only necessary for beam characterization
But also critical for achieving targeted performances

Conflicting Issues !!

Installation of diagnostic devices difficult or not possible

Beam Measurement (2)

<u>Classically</u>: A lot of measurements, no need of sorting, classification

<u>Advanced</u>: 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

CHARACTERIZATION 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

Beam Measurement (3)

Errors

Essential:
Daily use
Routinely
At full power

Measurement: with Bdiag   Correction: with corrector

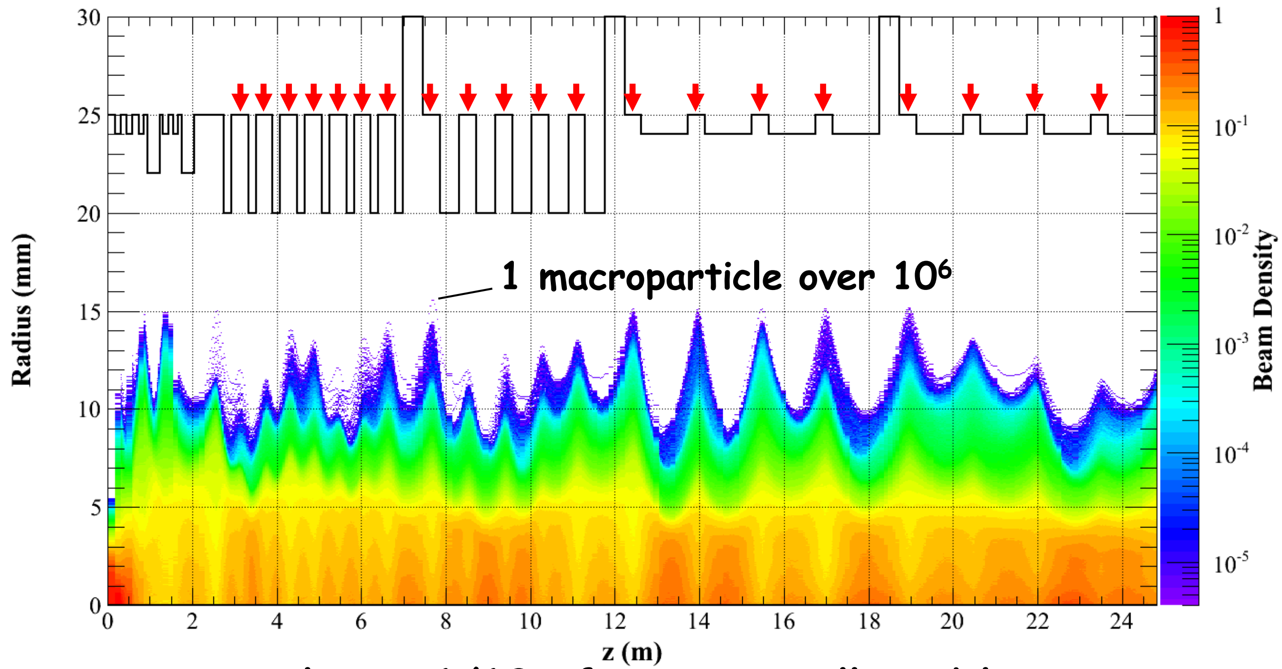
Characterization: Knowledge, Understanding, Surveillance

⇒ Definition of the complete beam diagnostic system

Example of Microloss "correction" for IFMIF

Proc. of DIPAC11, Hamburg, Germany, 2011
Talk of N. Chauvin et al. Tuesday

Best μLM: CVD diamond
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

Advanced methods and concepts

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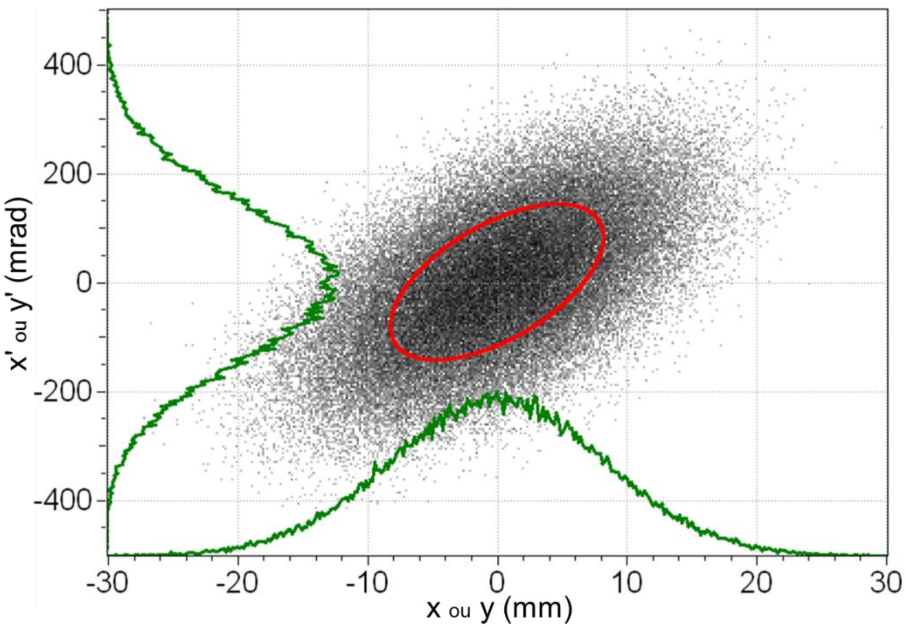
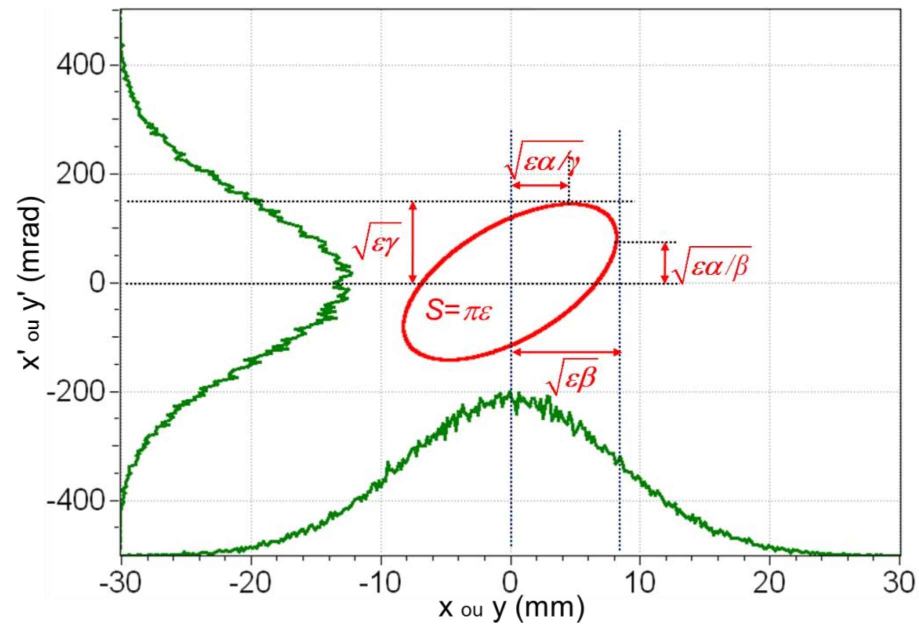
Beam Characterization (1)

Classically





10^6 particles in 6D phase space
→ 6 10^6 parameters
→ huge
→ numerical simulations

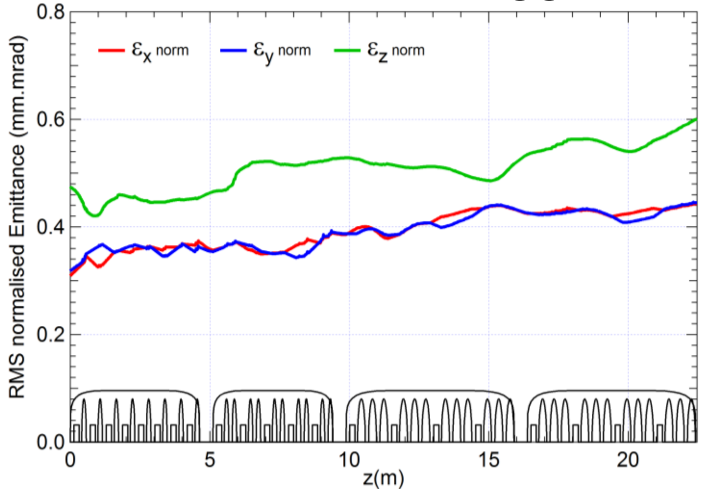
Concentration ellipse

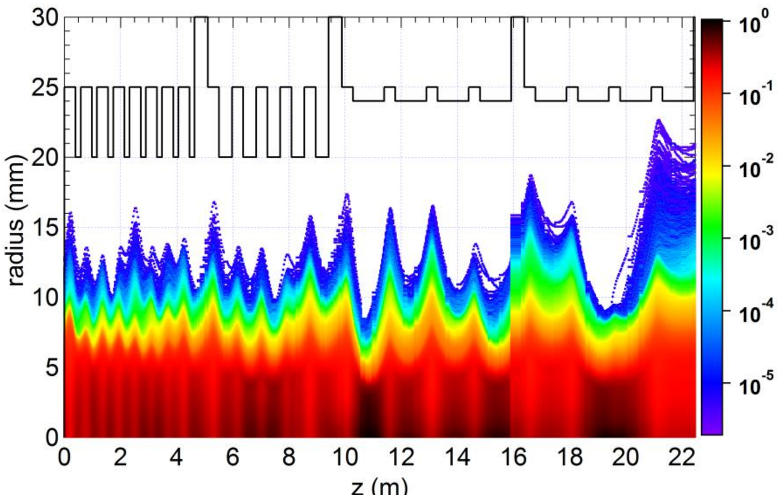
Emittance ε
Twiss parameters α, β (,γ)
→ 3 global parameters

Beam Optimization (3)

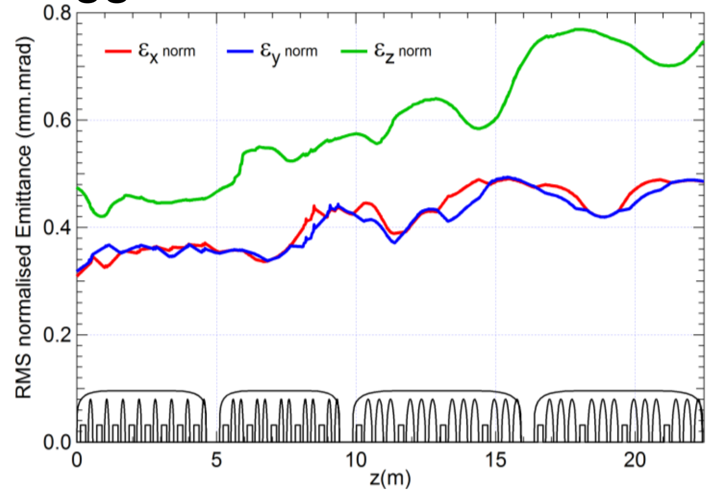
Example: IFMIF SRF Linac (Laser Part. Beams 32, 10-118, 2014)

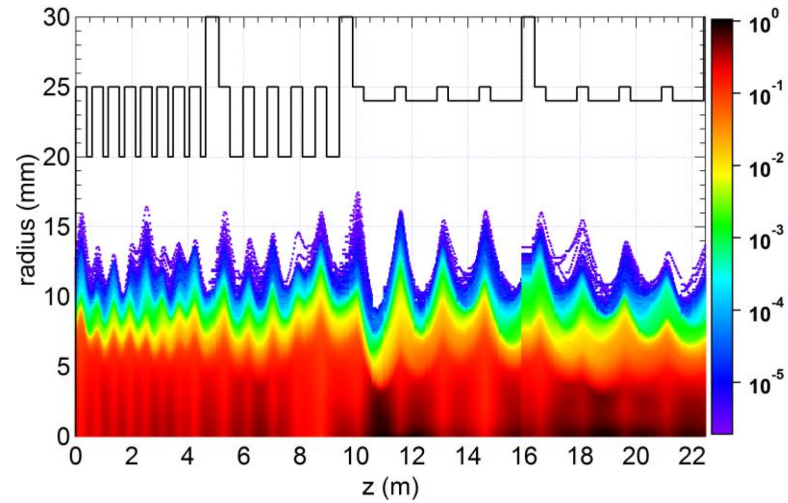
Smaller emittance: Bigger size



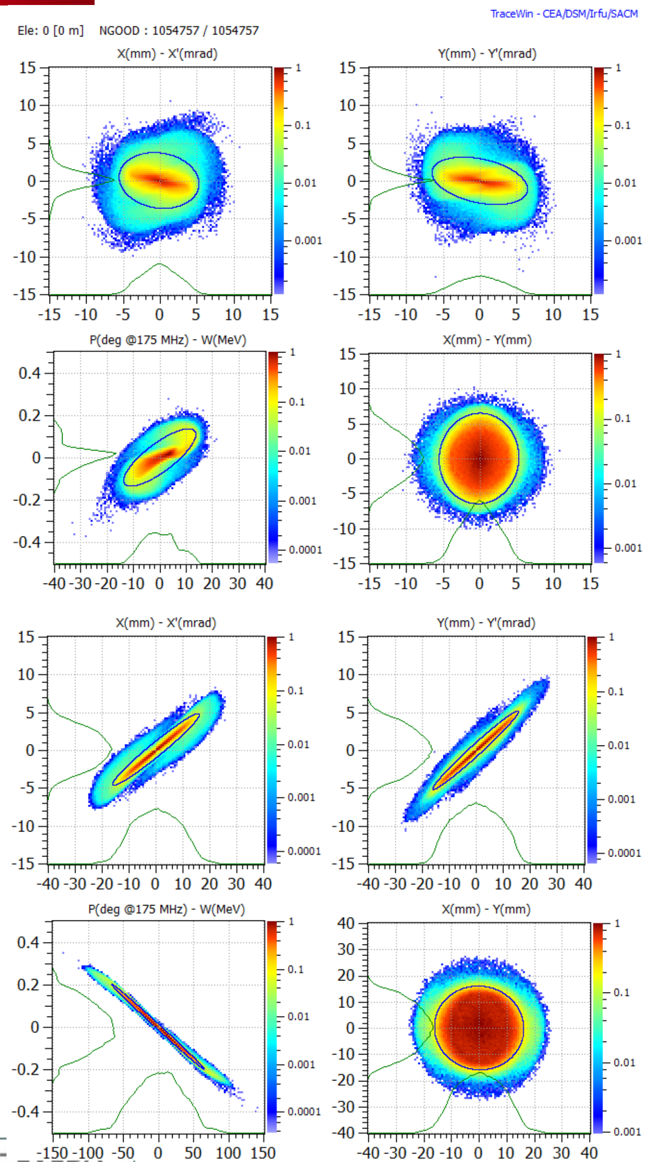


Bigger emittance: Smaller size





Beam Characterization (2)

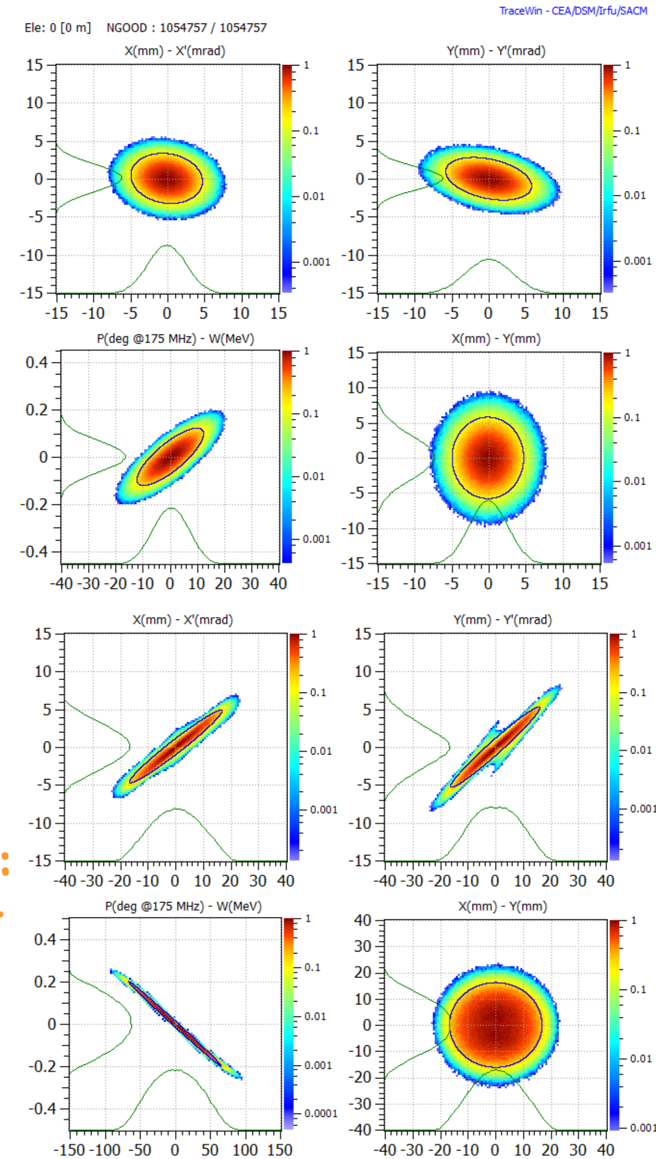


"Nominal" distribution

HEBT entrance exactly same
α,β,γ,ε

3.5 m downstream through 3 quadrupoles: significantly different beam outputs
α,β,γ,ε

Gaussian distribution



Beam Characterization (4)

Classically: beam characterised by its second moments

$$\varepsilon = \sqrt{\langle q_i^2\rangle \langle p_i^2\rangle - \langle q_i p_i\rangle^2} \qquad \alpha = -\langle q_i p_i\rangle/\varepsilon \qquad \beta = \langle q_i^2\rangle/\varepsilon$$

rms values of the particle coordinates and the beam 'envelope': $\sqrt{\langle q_i^2\rangle} = \sqrt{\beta\varepsilon}$

But: not enough for very high intensity beam

Advanced:

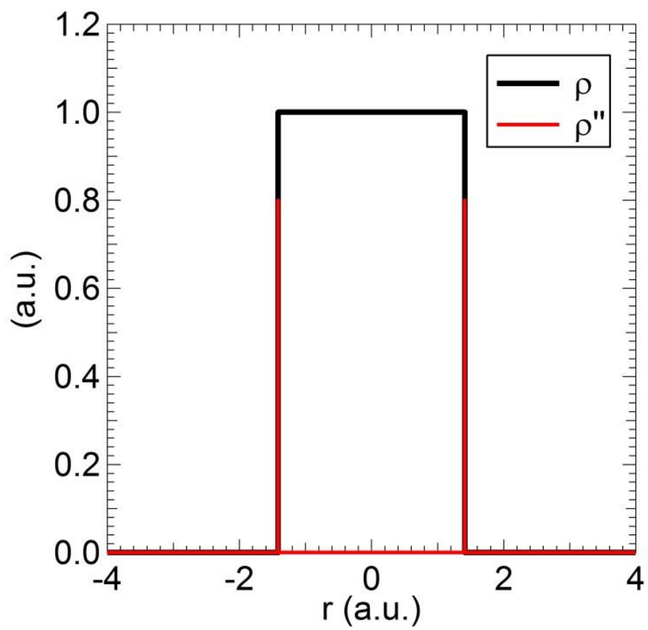
- **Characterise the beam by its core and halo separately**
- **Replace beam 'envelope' by the core-halo limit**

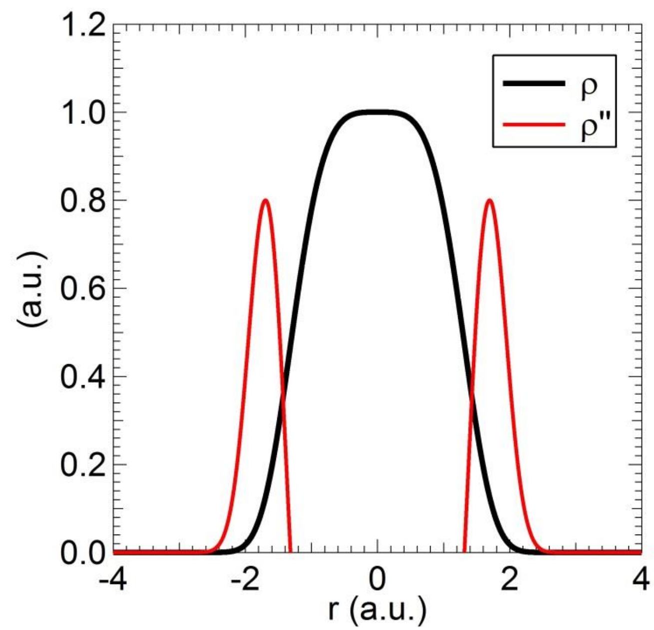
What is the core? What is the halo?

Beam Characterization (5)

<u>Advanced</u>: Core-Halo limit based on the beam internal dynamics

Appl. Phys. Lett. 104, 074109, 2014

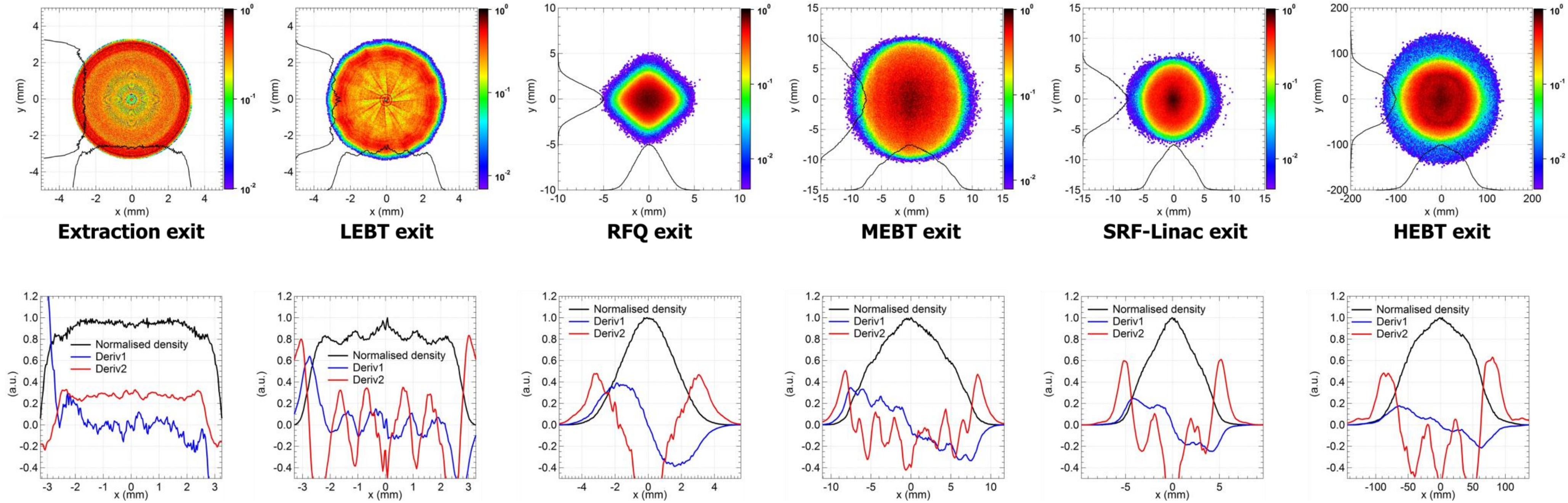




<u>Extreme case:</u>
Core: uniform, sc force strictly linear
Halo: tenuous, sc force nonlinear
→ core-halo limit: very steep (infinite) variation of the slope

<u>General case:</u>
Continuously varying density
Core-Halo limit: steepest variation of the slope → <u>max of 2nd derivative</u>
→ Core & Halo are submitted to two different space charge force regimes

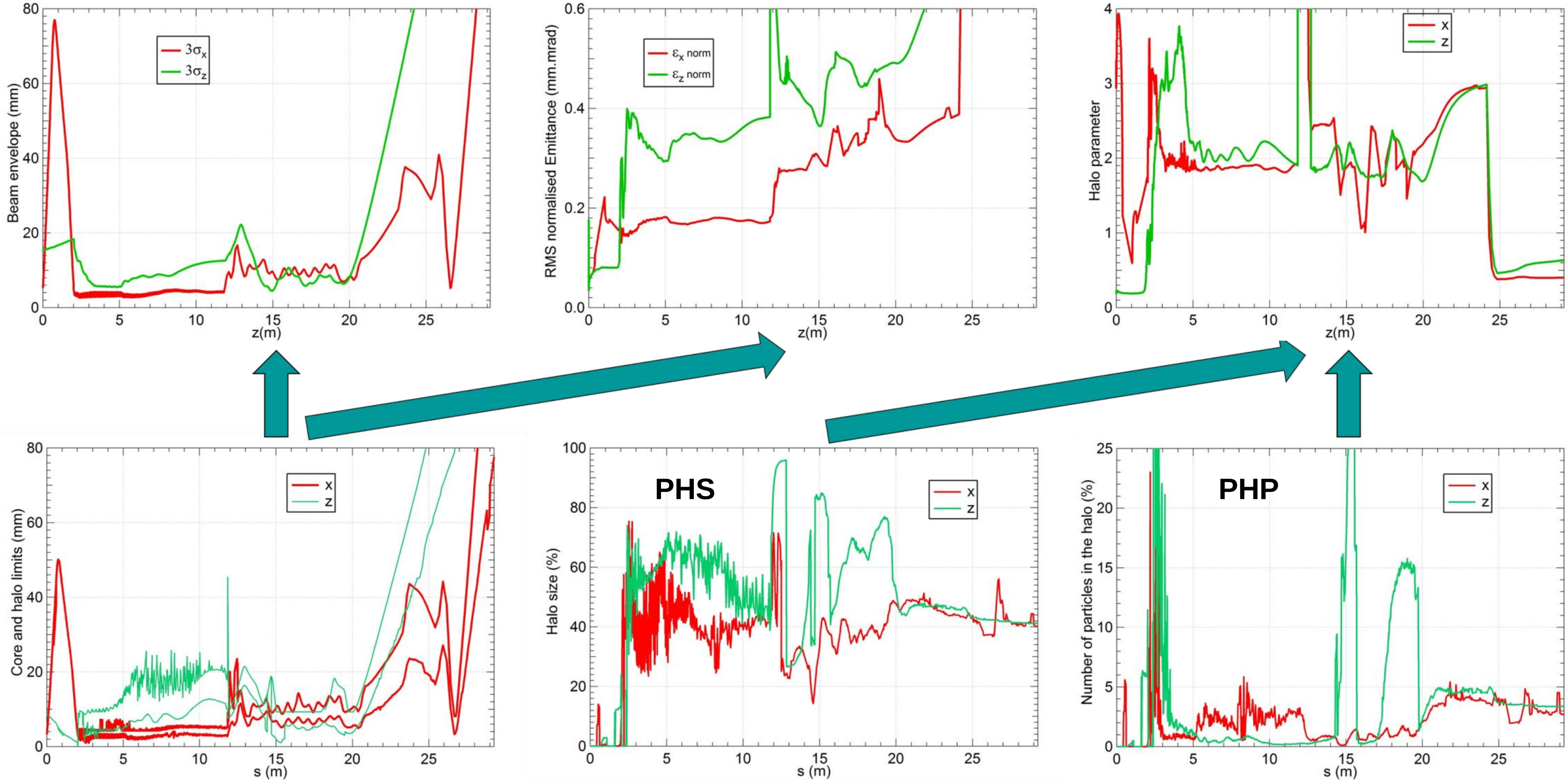
Example: Beam along the IFMIF prototype accelerator



Beam Characterization (8)

Example: Beam along the IFMIF Prototype accelerator

Classically

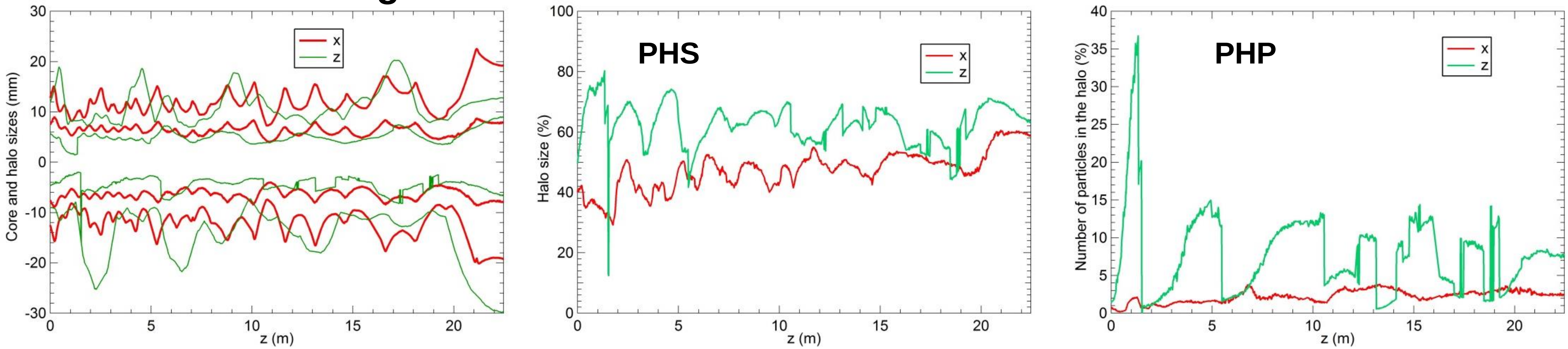


Advanced

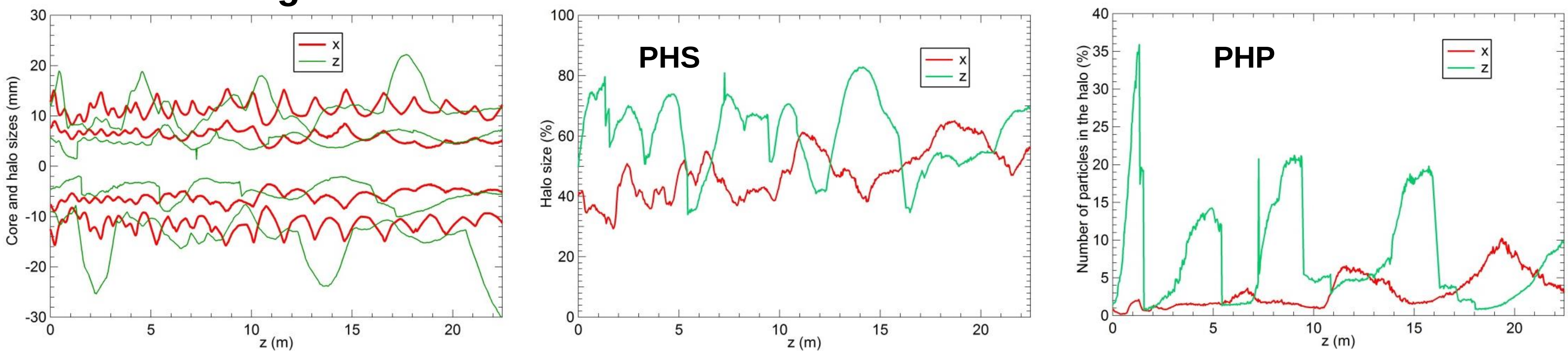
Beam Characterization (9)

Example: Beam along the IFMIF SRF Linac

Emittance matching



Halo matching



Mitigate loss risks: Minimize total size, PHS, PHP

Beam Characterization (10)

Under study:

Generalization to nD phase space

Core-halo limit : maximum of Laplacian of density (Δn)

→ Define Emittance and Twiss parameters for core and halo separately

→ Study mechanisms of core growth, halo growth, core-halo interaction, exchange of particles, etc.

Summary

High intensity

High power | **Strong space charge**

Combination of the two aspects → new and serious issues

Advanced methods and concepts:
Catalogue of Losses, Halo matching, online Avatar of BD optimization, Essential and Characterization diagnostics, Core-Halo limit, PHS, PHP

For the five purposes of:
Beam analysis, beam loss prediction, beam optimization beam diagnostic and beam characterization

Laser Part. Beams 2014, in press