Advanced methods & concepts for very high intensity beams

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

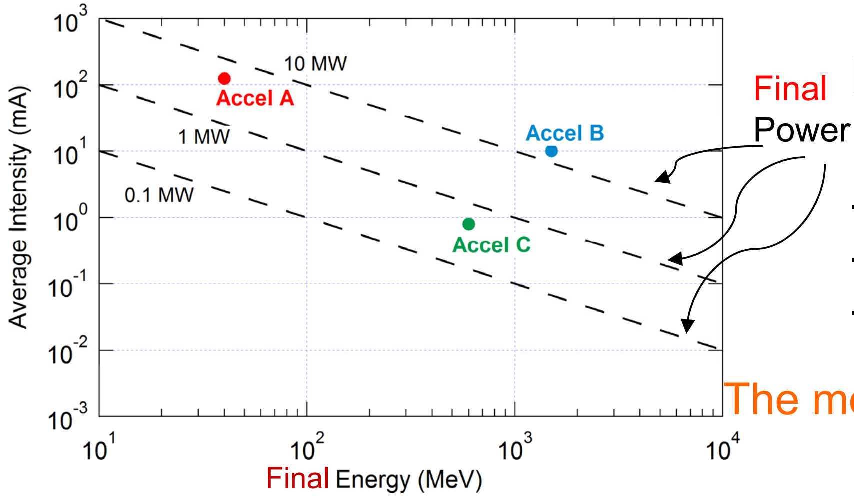
- even tiny losses are harmful
- ….

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

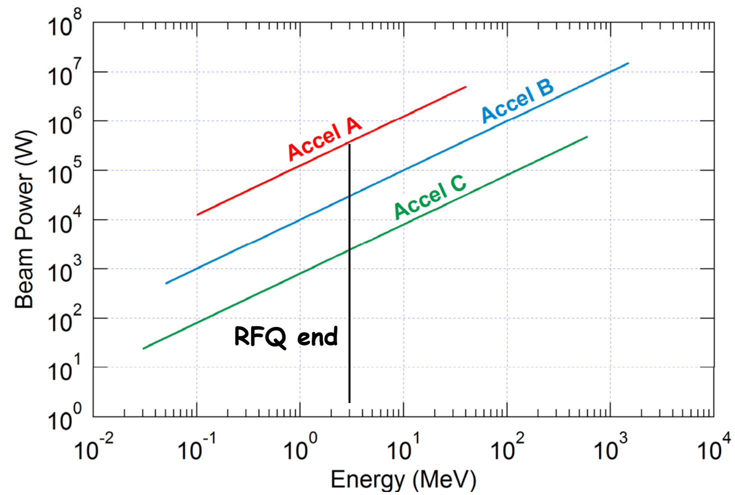
For a given section: A, B, C

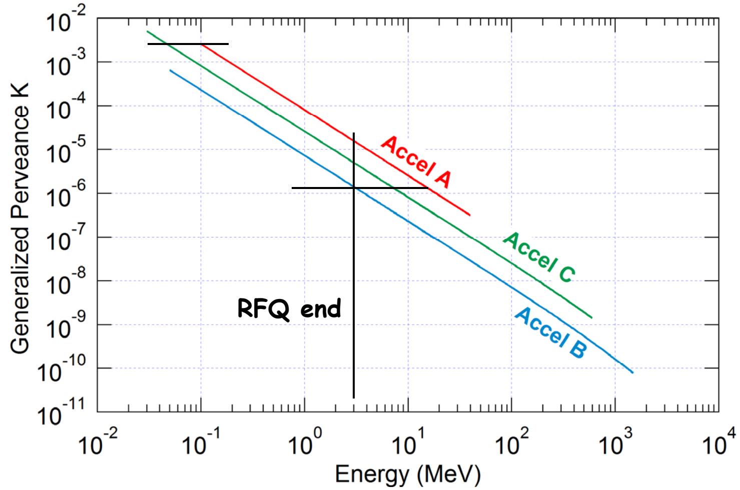
- Space charge issues

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

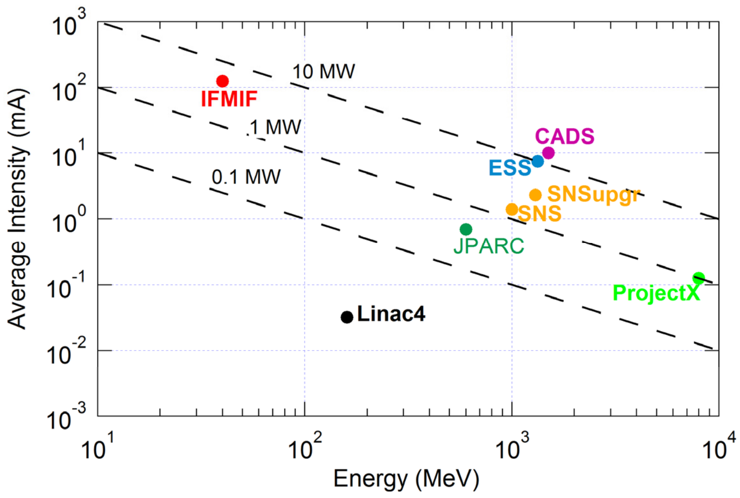




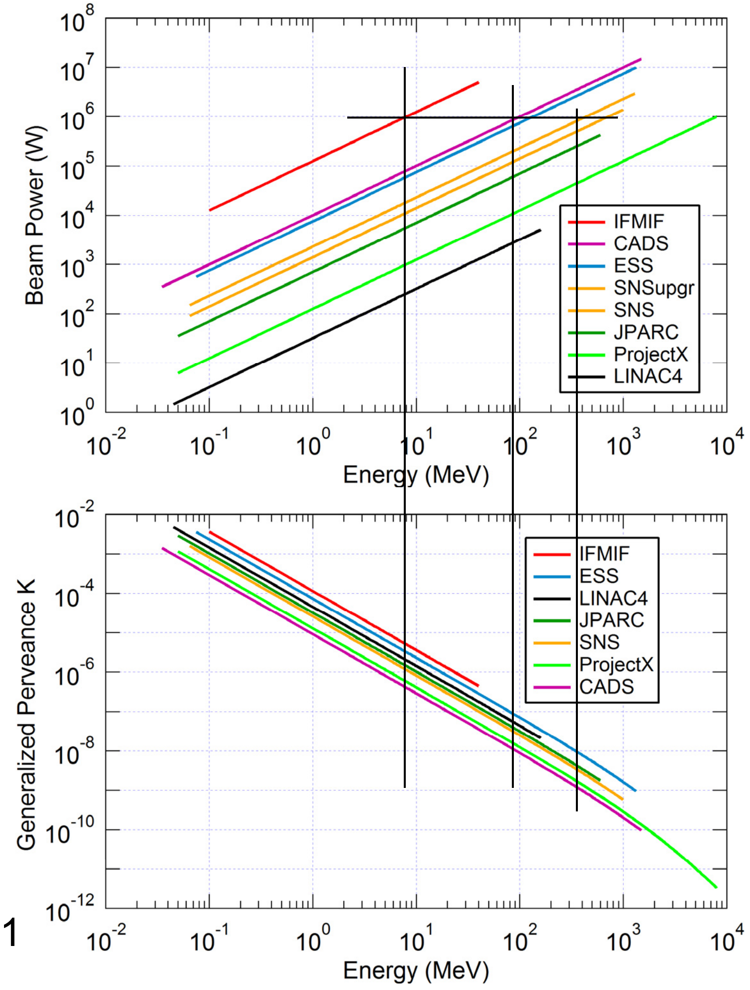
Beam analysis (3)

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
4. New strategy for: Beam measurement
5. New concept for: Beam characterization

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

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%.

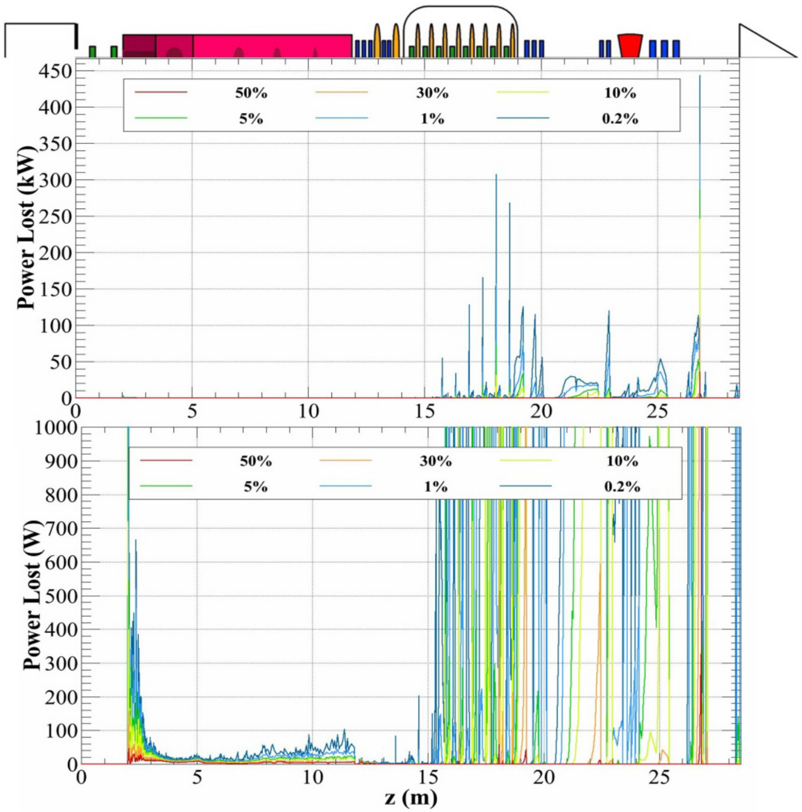
→ CATALOGUE of LOSSES:

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

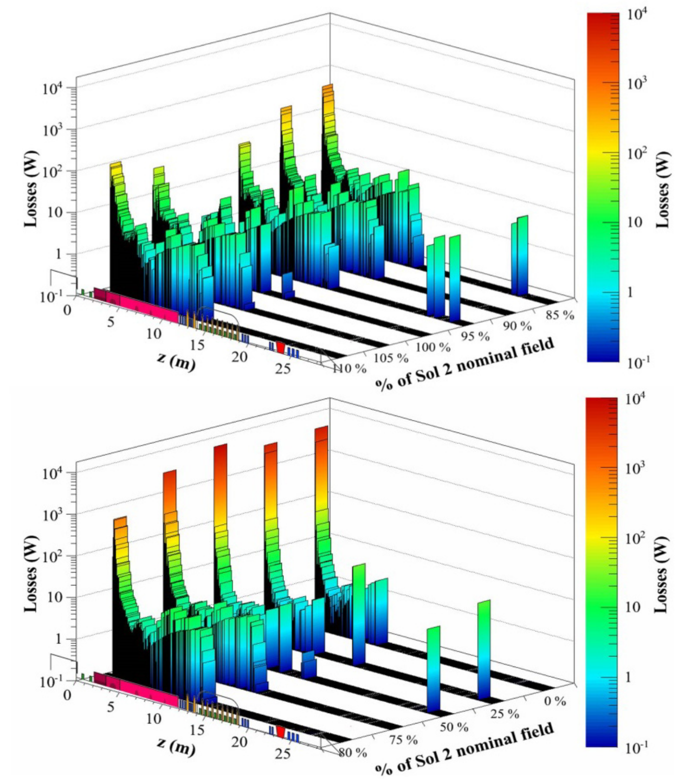
Beam loss prediction (3)

Example: CATALOGUE of LOSSES for the IFMIF Prototype accelerator

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

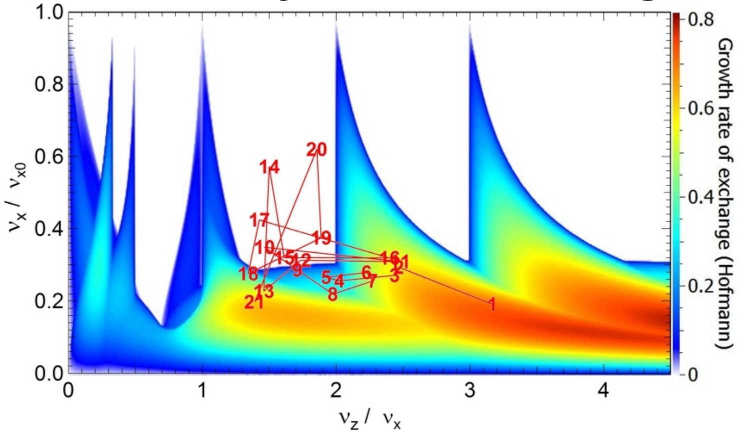
Halo: figure of merit

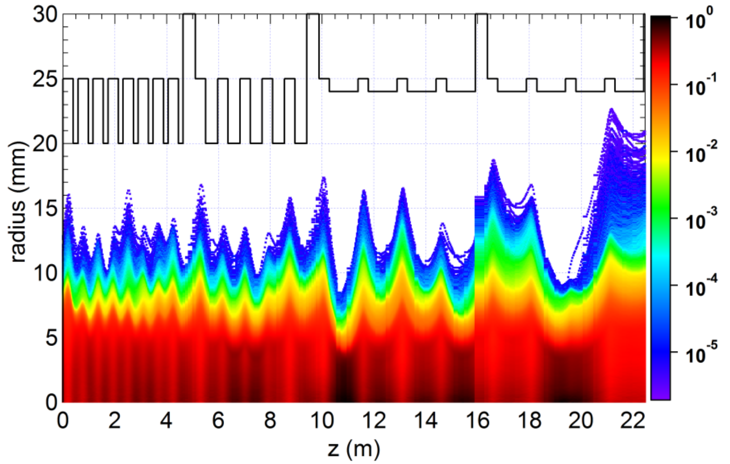
Results:
comfortable margin between
beam external border
and beam pipe wall

Beam Optimization (2)

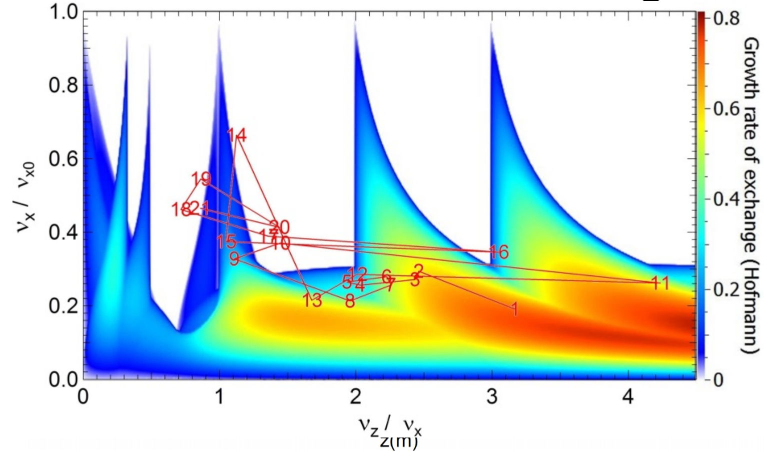
Example: IFMIF SRF Linac (Laser Part. Beams 32, 10-118, 2014)

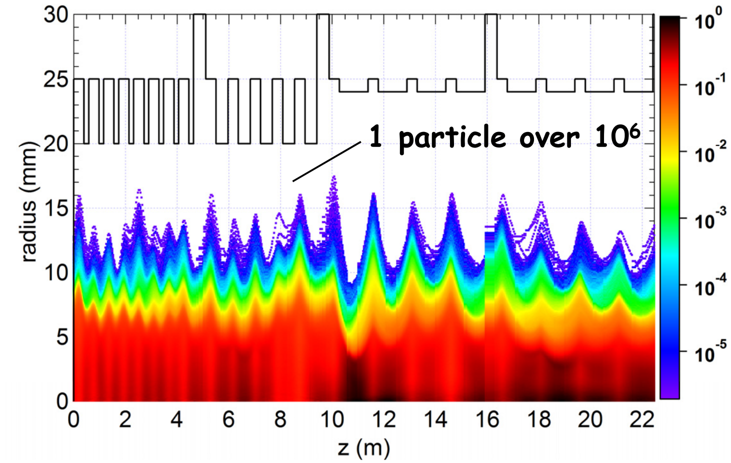
Classically: Emitt. matching





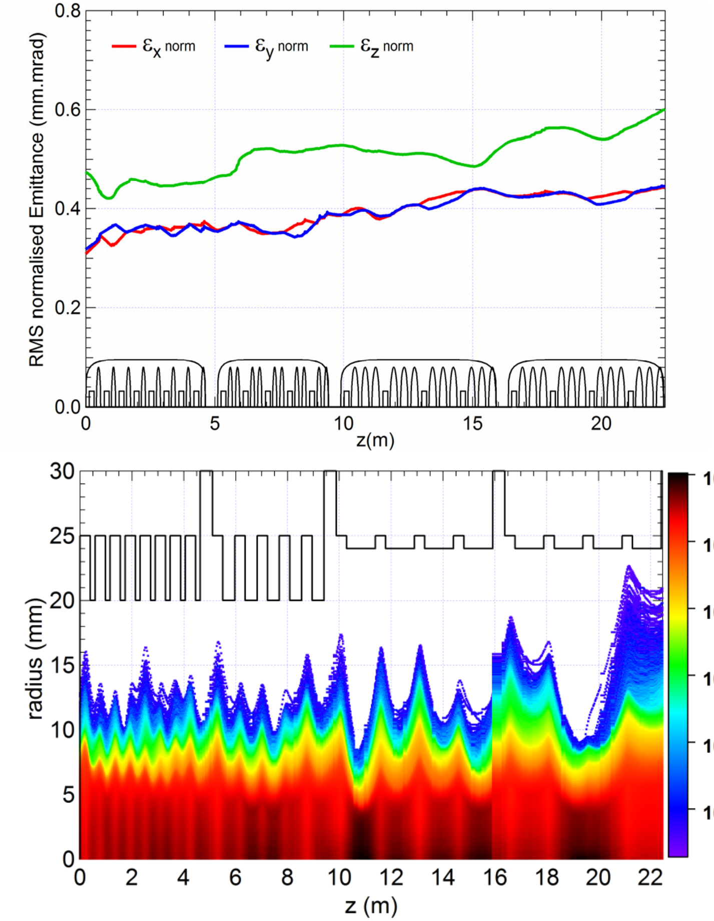
Advanced: Halo matching



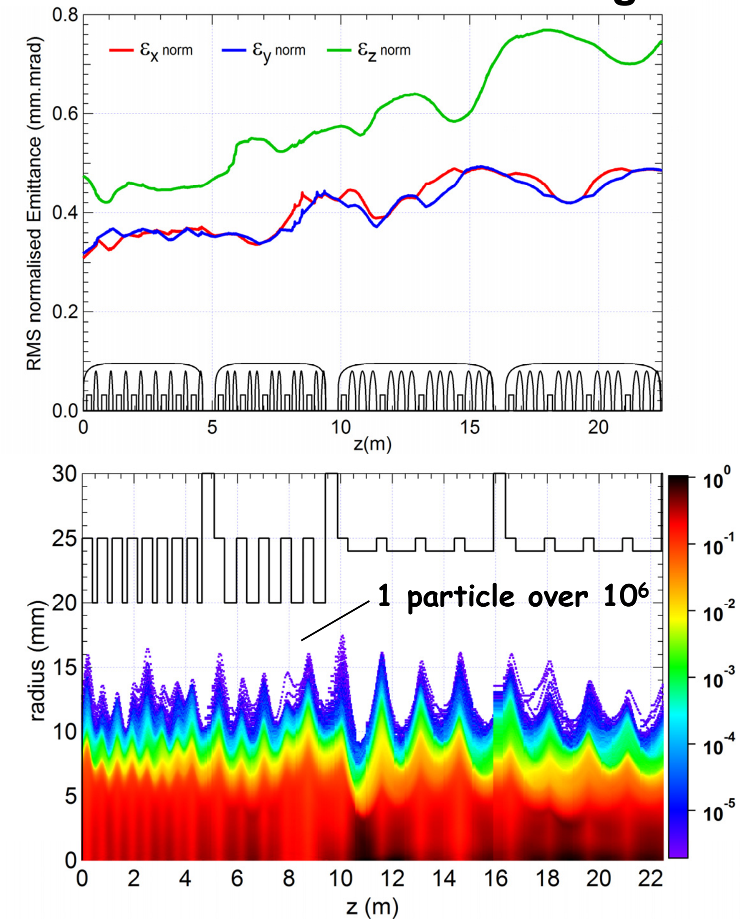


Example: IFMIF SRF Linac (Laser Part. Beams 32, 10-118, 2014)

Classically: Emitt. matching



Advanced: Halo matching



Beam Optimization (4)

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

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

… 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

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

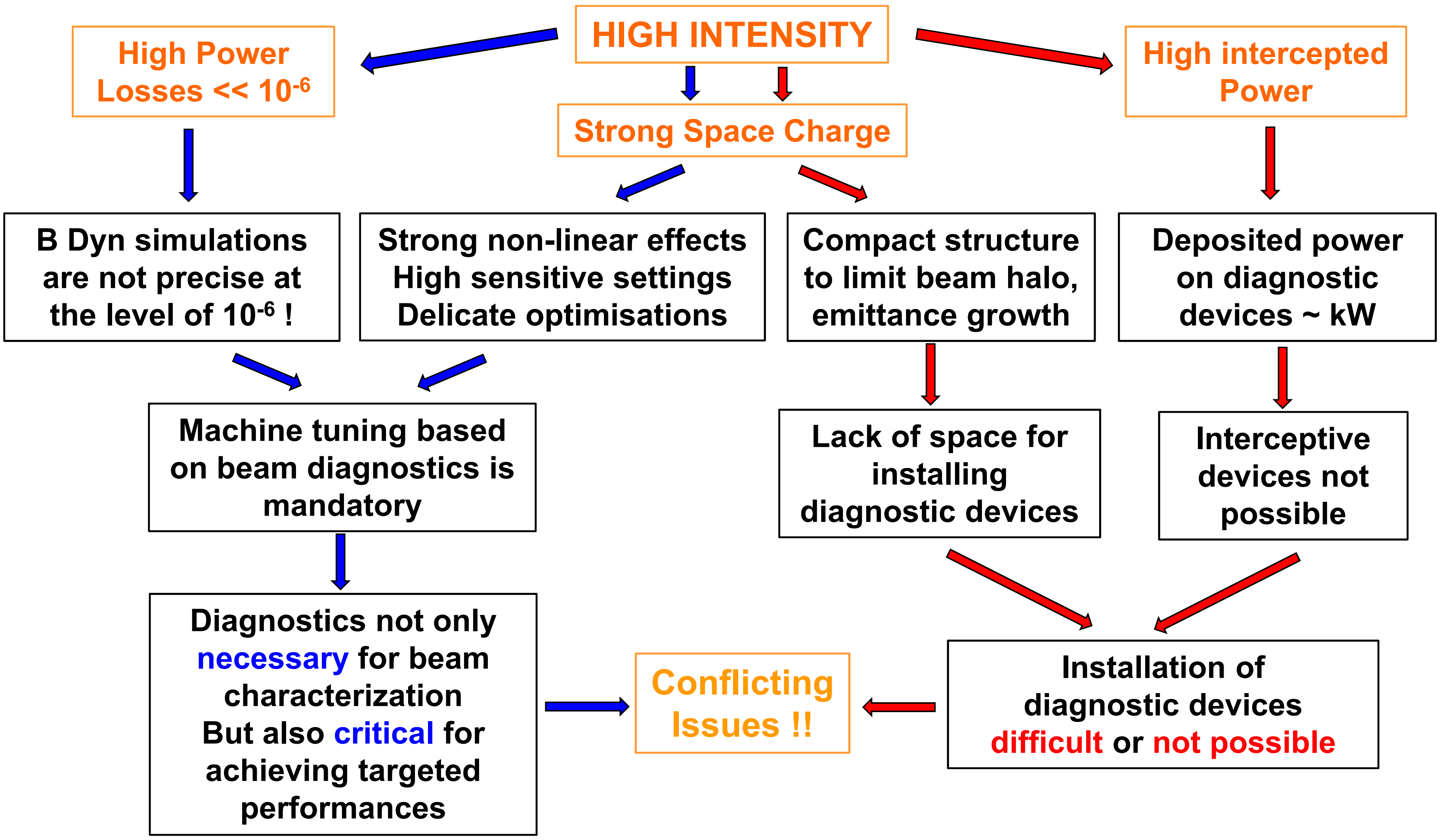
Enough independent diagnostics:

at least the same number as that of available tuneable parameters

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

Beam Measurement (1)



Beam Measurement (2)

Classically: A lot of measurements, no need of sorting, classification

Advanced: clearly distinguish between

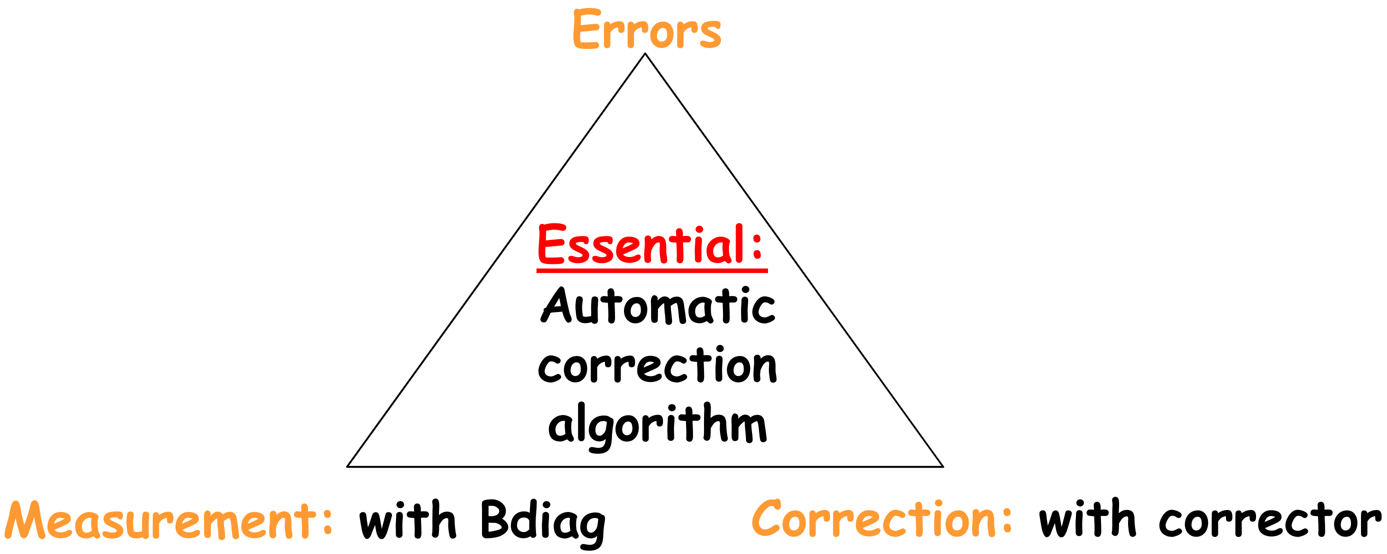
ESSENTIAL measurements

- 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)

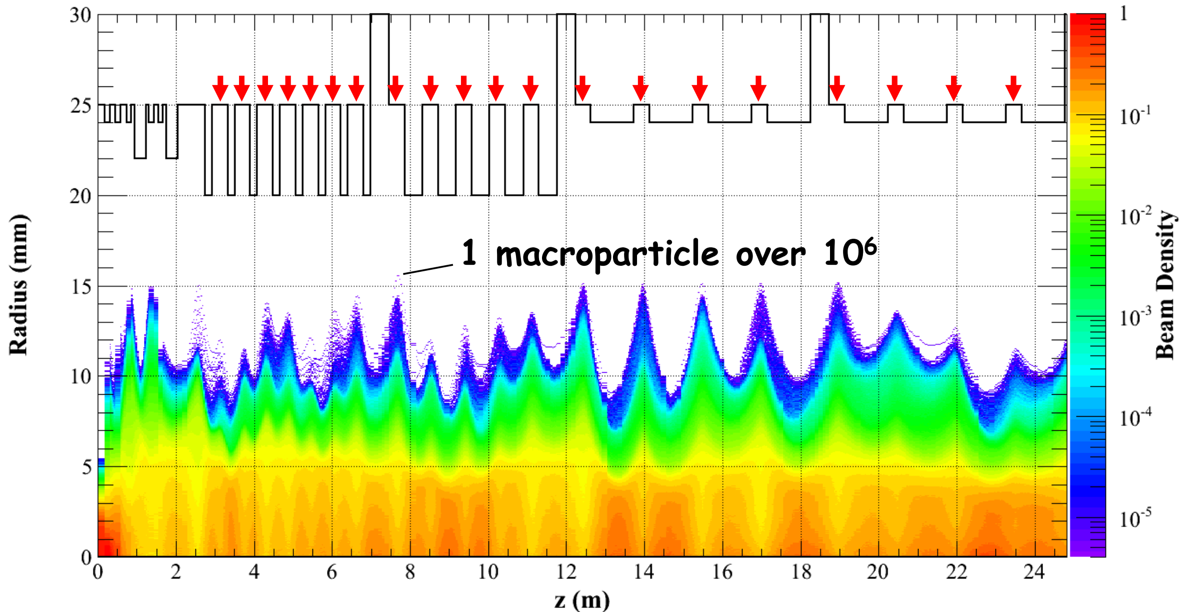


Characterization: Knowledge, Understanding, Surveillance

➡ **Definition of the complete beam diagnostic system**

Example of essential diag: Microloss monitors for IFMIF

Best μLM: CVD diamond (Proc. of DIPAC11, Hamburg, Germany)
Best correction: PSO (Part. Swarm Opt.) algorithm (Proc. of PAC09, Vancouver, Canada)
⇒ 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

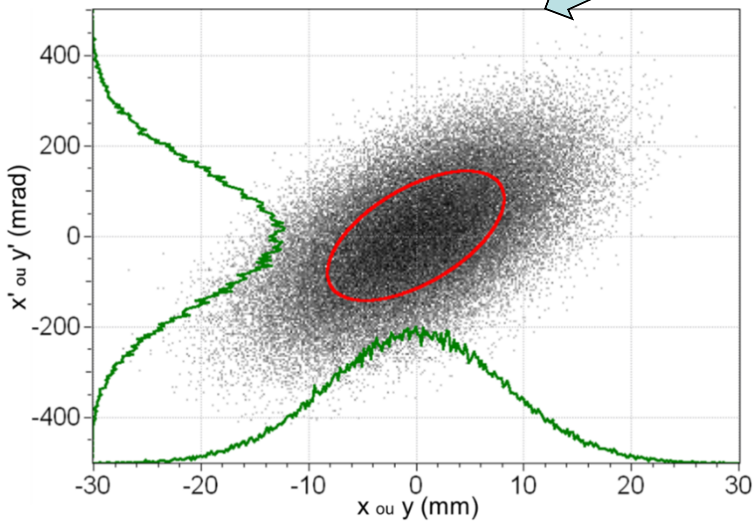


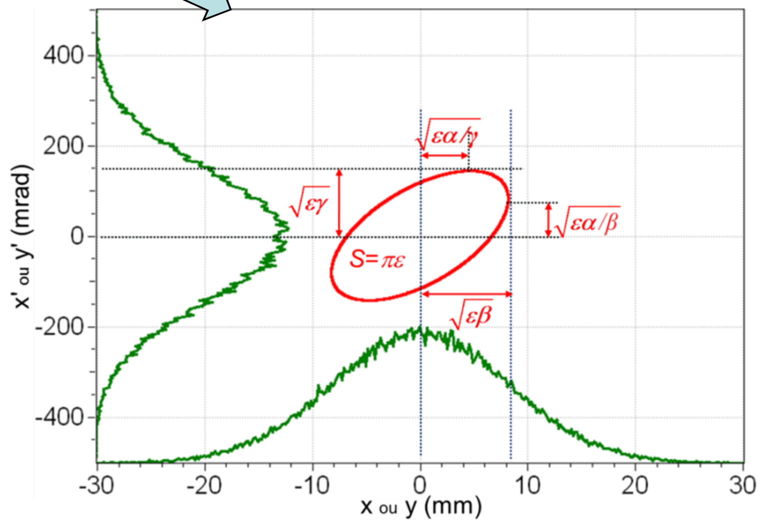
Performances: resolution 1/10 of maximum allowed losses

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 Characterization (1)

Classically





10^6 particles in 6D phase space
→ 6 10^6 parameters
→ very big number → num. simulations

Concentration ellipse
RMS ε, α, β (,γ)
→ 3 global parameters

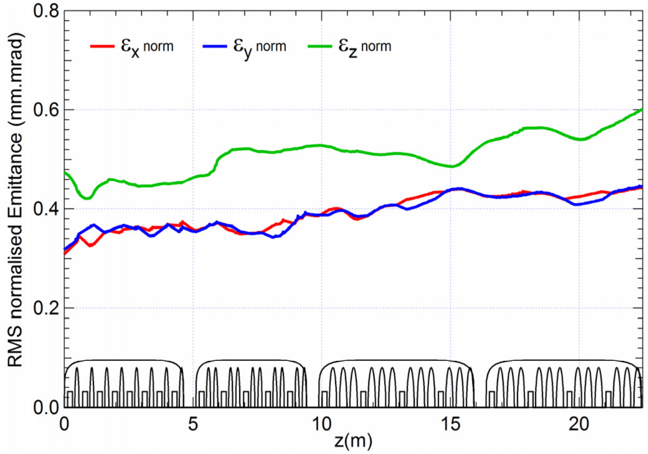
High intensity

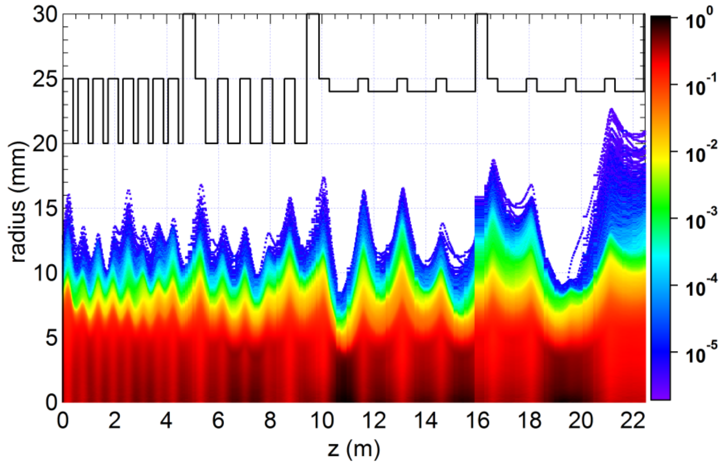
10^9 particles in 6D phase space
→ 6 10^9 parameters
→ huge number

RMS ε, α, β (,γ)
Not enough !!

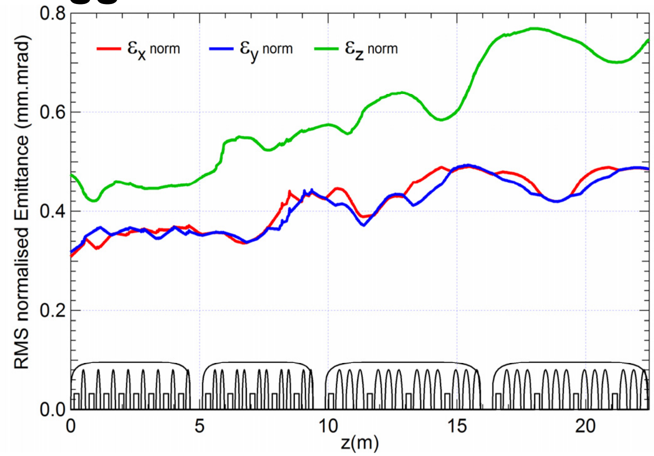
Example: IFMIF SRF Linac (Laser Part. Beams 32, 10-118, 2014)

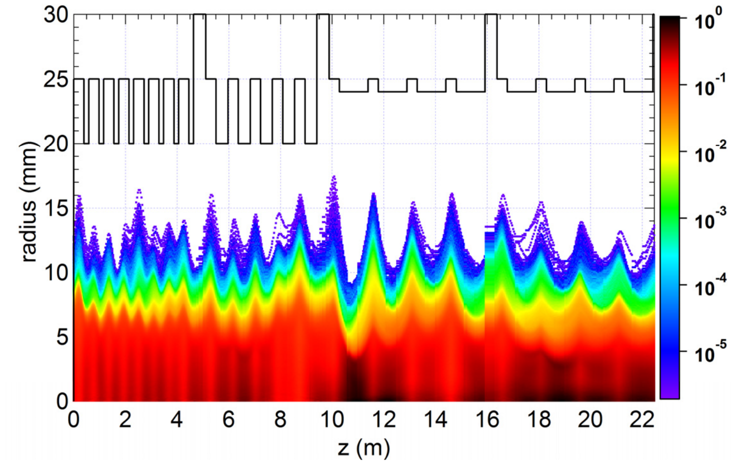
Smaller emittance: Bigger size





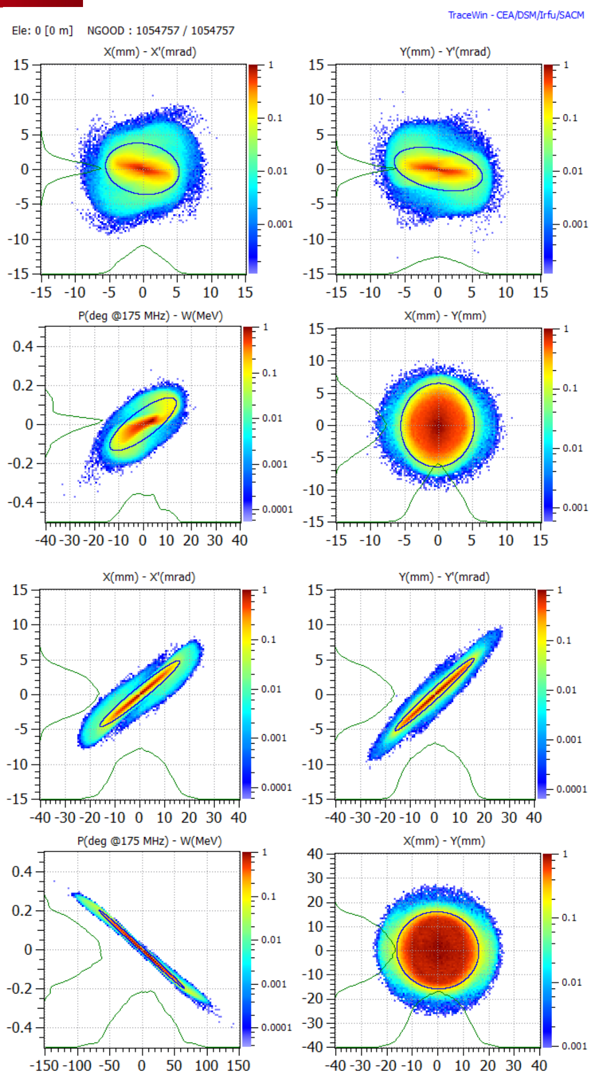
Bigger emittance: Smaller size





Beam Characterization (2)

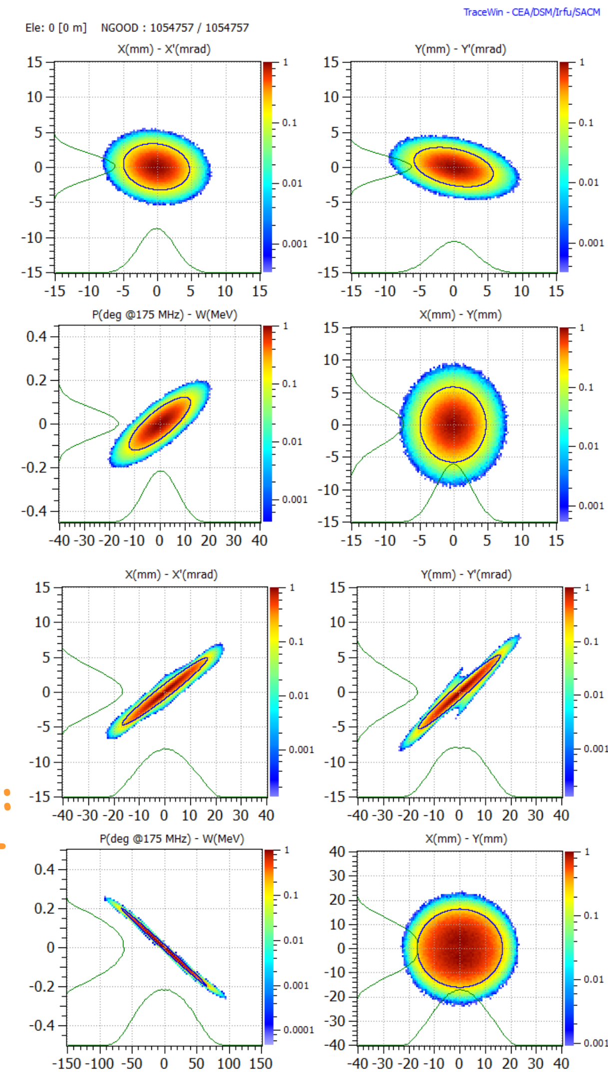
"Nominal" distribution



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



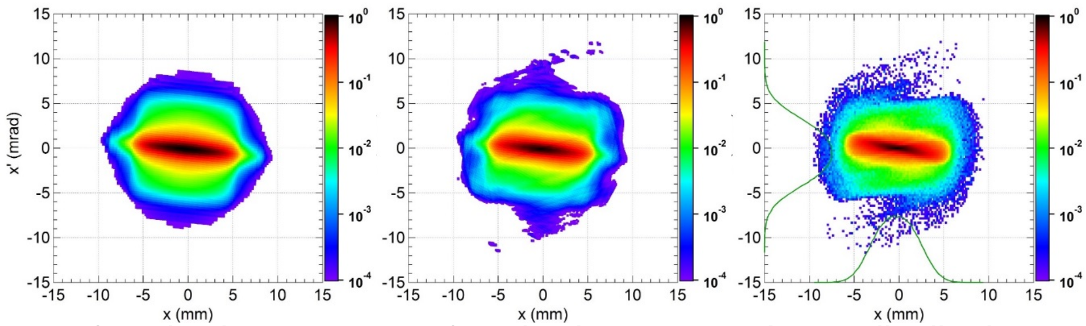
Advanced:

1) Massive simulations with the actual number of particles

5 10^9 particles (125 mA) for IFMIF-LIPAc (WEPOY032, IPAC'16)
→ 175 processors for 25 days
→ confirm losses < 10^{-7}
→ representative statistics of microlosses

2) Characterize the beam by its projections onto a few axes

MENT method: reconstruct a distribution from its projections (MOPOR032, IPAC'16)
Projection axes correctly chosen
→ 2 projections for the core
→ 6 projections for the external parts
→ ~ 10 - 30 parameters for 2D



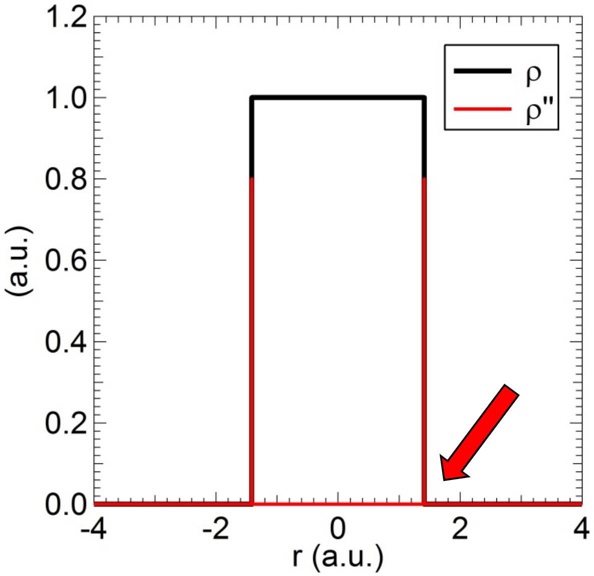
3) Characterize the beam by its core and halo separately

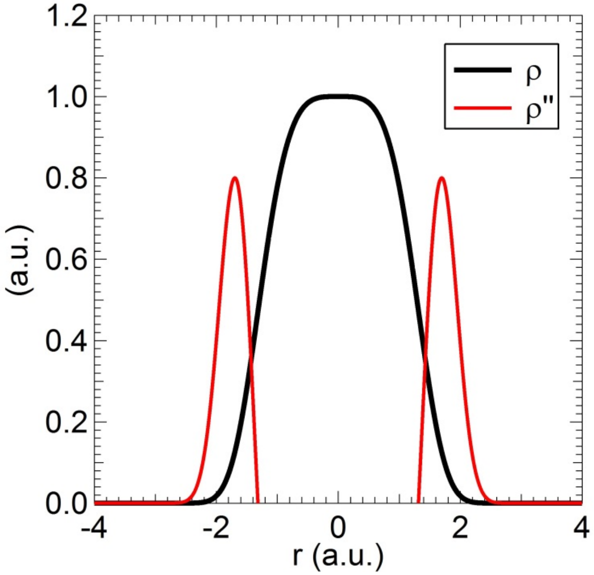
Loose fine details but gain more insight into the physics of the beam

Beam Characterization (5)

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

Appl. Phys. Lett. 104, 074109, 2014



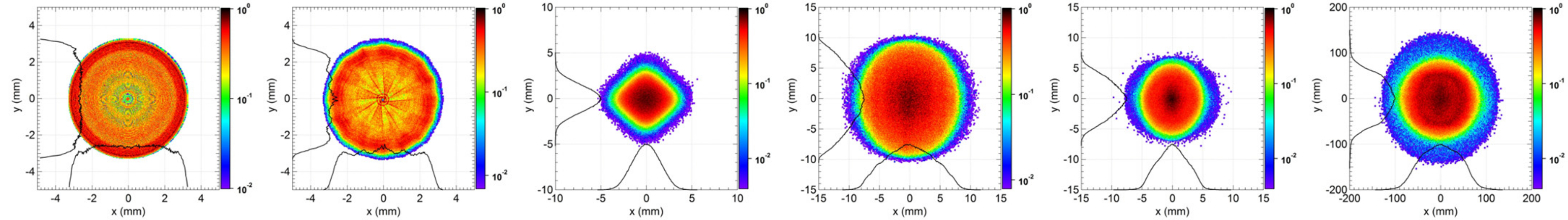


<u>Extreme case:</u>
Core: uniform, sc force strictly linear
Halo: tenuous, sc force nonlinear
→ core-halo limit: very steep (infinite) variation of the slope

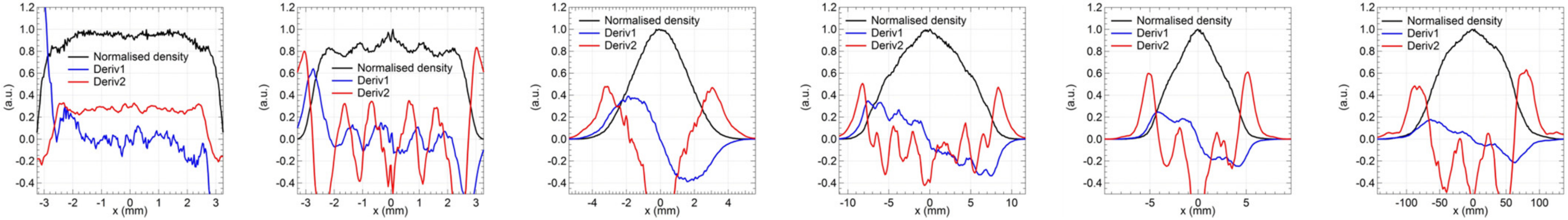
<u>General case:</u>
Continuously varying density
Core-Halo limit: steepest variation of the slope → <u>max of 2nd derivative</u>
→ Core & Halo are submitted to two different space charge force regimes

Phys. Plasmas 22, 083115, 2015: **This core-halo limit ≡ good indicator of beam internal dynamics**

Example: Beam along the IFMIF prototype accelerator

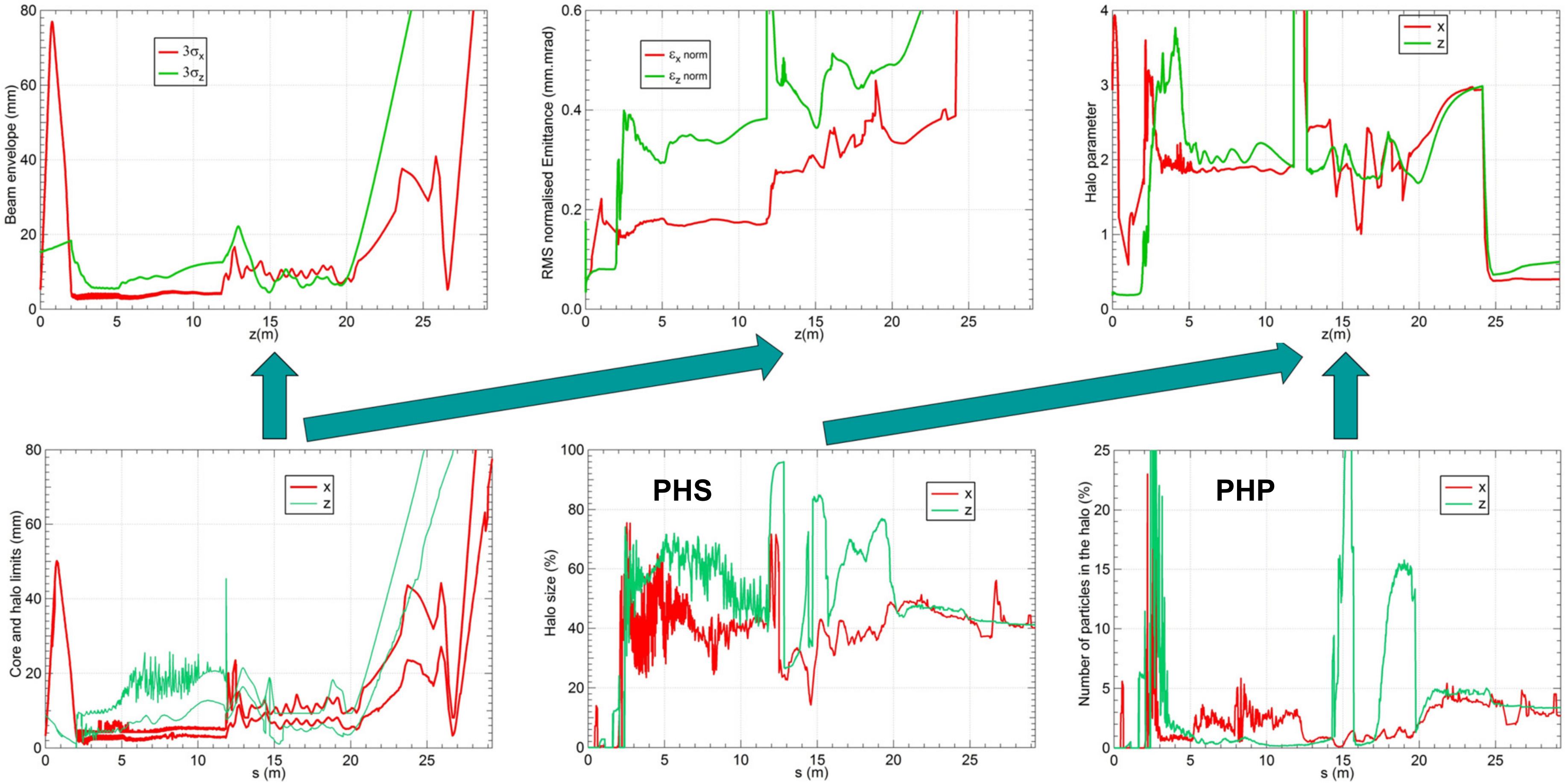


Extraction exit | LEBT exit | RFQ exit | MEBT exit | SRF-Linac exit | HEBT exit



Example: Beam along the IFMIF Prototype accelerator

Classically



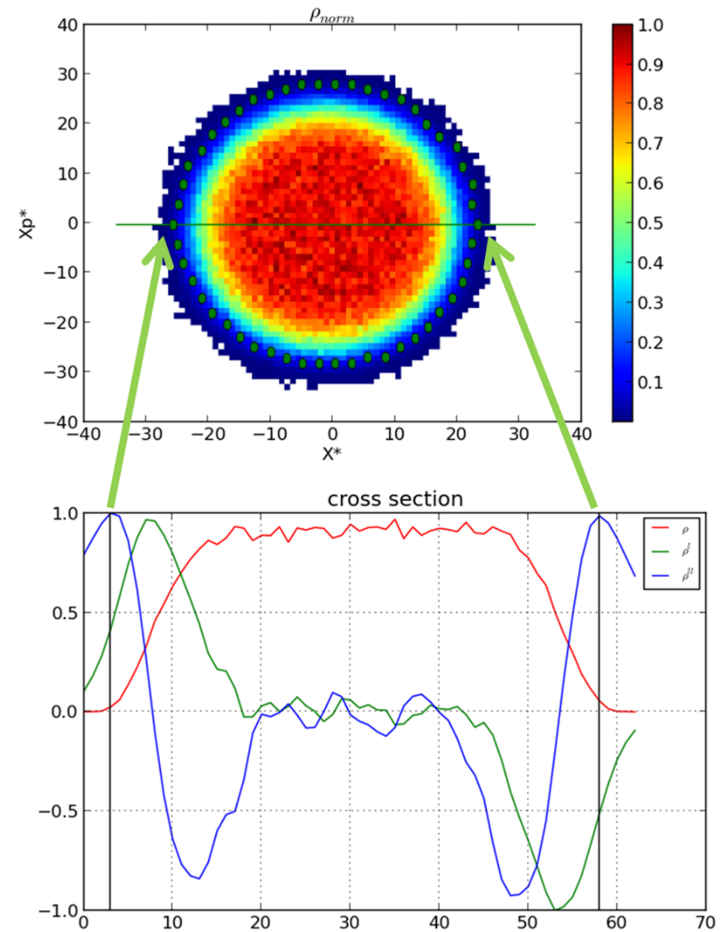
Advanced

Beam Characterization (10)

MOPWA010, IPAC'15: Extension to 2D

"Wheel algorithm": Max of second derivative along many sections

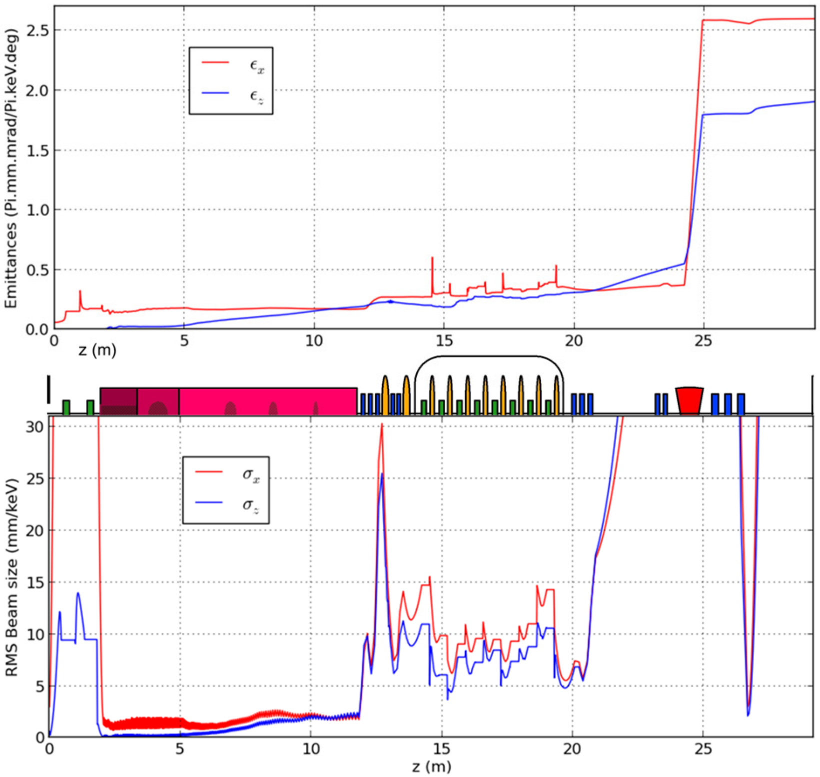
- ⇨ **Core-Halo limit contour**
- ⇨ **PHS, PHP**
- ⇨ **Emittance ε and Twiss parameters α, β, γ of the core and the halo separately**



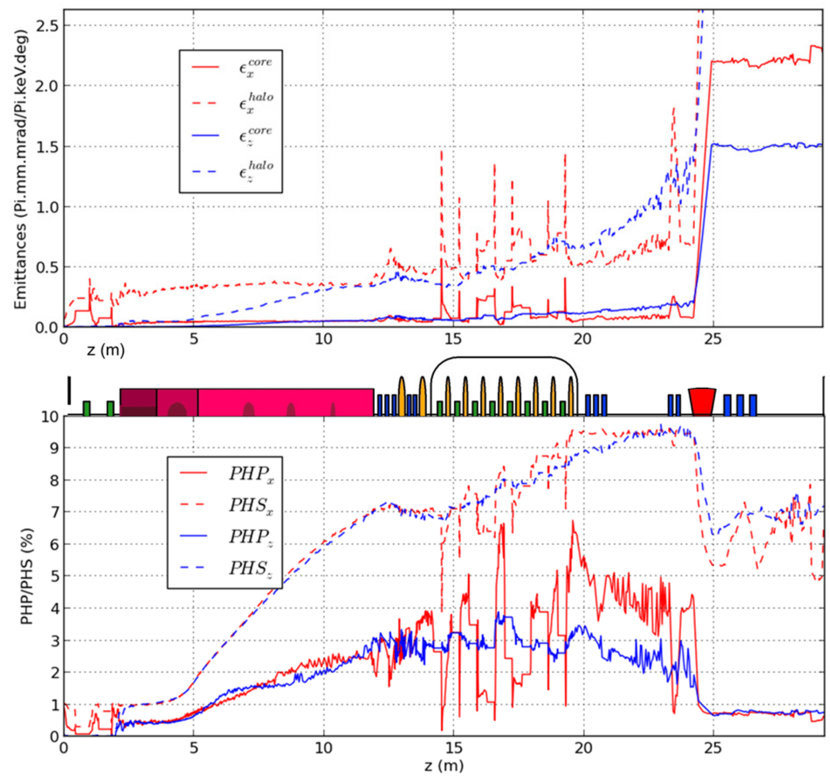
THPMR014, IPAC'16:
This Core-Halo limit contour is <u>consistent</u> with the well-established halo formation dynamics

Beam Characterization (11)

Classically



Advanced



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 32, 639-649, 2014