Halo Formation in High-Intensity Beams

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Motivation for halo studies

The increasing interest of high-intensity beams:

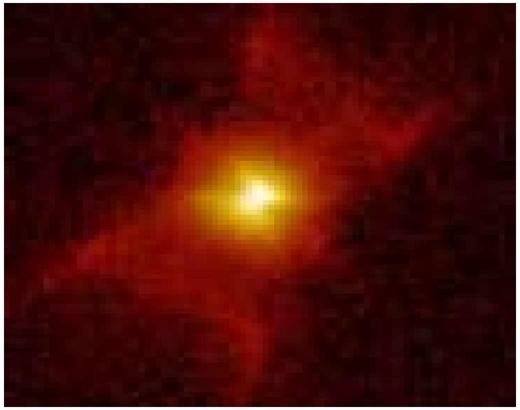
- Proton and light-ion linear accelerators (for nuclear waste management, production of tritium, spallation-neutron sources, etc.)
- Heavy-ion linear accelerators
- low energy protons rings (spallation-neutron sources, etc.)
- electron linacs (ERL, high-power FEL)

led scientific community to study beam losses which originate in the low-density halo which can extend far from the beam core

Definition of beam halo

Beam losses associated with a small fraction of particles surrounding a dense beam core – beam halo.

There were many attempts to come up with the definition of beam halo.



Some definitions attempt to distinguish between “halo” and “tails’. Other – assume that the halo is formed due to a specific mechanism and thus the definition includes the knowledge about the structure of the halo.

The usefulness of such “definitions” is not clear.

For beam loss – there is no difference between “tails” or “halo”.

There are many mechanisms which lead to halo – trying to make a definition based only on one of them may cause difficulties in understanding of a realistic complex behavior.

Definition (continued)

Realizing that "a precise definition" of halo may lead to confusions rather than being helpful we had the following conclusions:

(ICFA Workshop "Halo and Scraping", Wisconsin 1999):

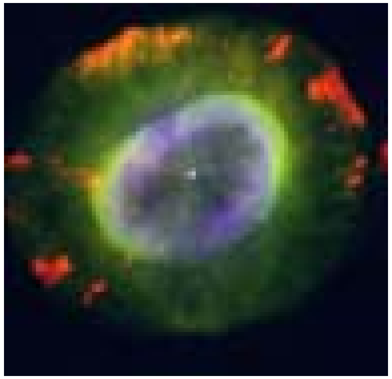
1. Definition of beam halo is not critical.
2. What important are the mechanisms of halo formation – this allows its understanding and possible prevention, as well as provides guidelines for halo observation.
3. It is sufficient to consider "halo" as it appears to experimentalists - direct link to its observations.

(ICFA Workshop "HALO'03", Montauk, Long Island 2003):

Definition of halo mechanism either by "geometrical characteristic" or by "nature of mechanism". The latter appeared to be the more unambiguous choice. However, sometimes it is useful to bring into discussion "geometrical features".

Halo

- Halo – a collection of particles of any origin and behavior which lies in the low density region of the beam distribution far away from the core.
- "Far" stands for "nσ" where "n" maybe = 3, 4 - depends on the distribution and halo mechanism
- density is rather low at that specific "n" - because density is so low it is difficult to measure it
- that is why "halo" is so mysterious – just not easy to observe.
- in most cases such "halo" represents a part of the distribution with density much below the 1% level.



Partial list of halo mechanisms

High-current hadron linear accelerators:

1. Anything from RFQ to various sources of machine nonlinearities and misalignments with unavoidable filamentation and halo growth ("bad design" issues)

2. Rms mismatch

3. Space-charge coupling resonances

4. Space-charge induced structure resonances (90^0 phase advance, etc.)

5. Single and multi-particle scattering

6. Gas scattering

7. Collective instabilities

List of halo mechanisms (continued)

High-current circular accelerators:

8. Additional design contributions – injection, extraction, rf noise, etc.
9. Machine nonlinearities
10. Rms mismatch
11. Space-charge coupling resonances
12. Space-charge induced structure resonances
13. Imperfection lattice resonances
14. Gas scattering
15. Collective instabilities
16. E-cloud effects
17. Project-specific effects – like “banana-shape” driven halo in the SNS Ring

List (continued)

Including short bunches:

18. Transverse-longitudinal coupling

19. Effects from synchrotron motion

Including high-energy accelerators:

20. IBS

21. Instabilities relevant for high-energy

Including colliding beams:

22. Beam-beam driven halo

High-current electron linacs, ERL's:

23. Photoinjector: extreme space-charge regimes – density redistribution, non-linear space charge, partial space-charge compensation, time-dependent rf, plasma waves, etc.

24. Space charge and dispersion in arcs

25. CSR

26. Longitudinal space charge and instabilities

27. Many "design-related" – like laser-beam transport in rf photoinjectors, like misalignments in in linear transport, etc.

28. etc.

AND, yes, both transverse and longitudinal halo

Observation of beam halo

Standard (from WWW) way to observe halo:

Stretch out your arm and spread your fingers wide. Cover the bright core with the thumb and the halo will be near the tip of the small finger.

Well, we have to do better than this …

wire scanners, scrapers, hole-drilled screens, filters, etc. – challenge to observe beam profiles to 4 or 5 decades – several dedicated experiments on beam halo were performed in both proton and electron beams.

Examples of Dominant mechanisms

Halos due to "design issues/non-perfect transport" are very important and require optimization, for example, RFQ in proton linacs or photoinjector in electron linacs.

Halos which results as a result of multi-particle beam dynamics typically requires a lot of study – to come up with a proper solutions to avoid halos.

↓

Few examples of some basic effects common to both linacs and rings and differences in their application to linear and circular accelerators.

Useful parameter:

Radius of charged particle beam is determined by external focusing (wave number k_0), space charge (perveance κ) and beam emittance ε.

Tune depression η is defined as k/k_0 where k is the wave number depressed by the space charge (also σ/σ_o in terms of phase advance per period, also ν/ν_o in terms of tunes)

$\eta > 0.7$ – emittance dominated regime

$\eta < 0.7$ – space-charge dominated regime

- Typical circular machine – emittance dominated regime
- High-current proton linacs – space-charge dominated regime
- High-current heavy ion linacs – extreme space-charge dominated regime
- High-current electron linacs :

1) Photoinjectors: extreme space-charge regime (plasma limit)

2) Very quick transition into emittance-dominated regime due to acceleration to high γ.

BUT emittance dominated regime does not mean that effects from space-charge regime are not there….

1. Space-charge incoherent resonances
Halo due to rms mistmatch

- The oscillating space-charge force can lead to a class of resonances where the individual particles inside the beam interact with an oscillating beam modes.
- Such resonances are referred to as “intrinsic” or “incoherent” parametric resonances (Wangler, Gluckstern, et al. - 50+ people 1990-1999, and many papers before ’90s, where “emittance growth” was used instead of “halo”):

$$x'' + \nu_0^2 x = F_{sc}$$

$$x'' + \nu^2 x = \mu \frac{\kappa}{a^2} x \cos \Omega s$$

ν– depressed tune
μ – mismatch parameter
κ - space-charge perveance
a – beam radius
Ω– frequency of beam oscillations

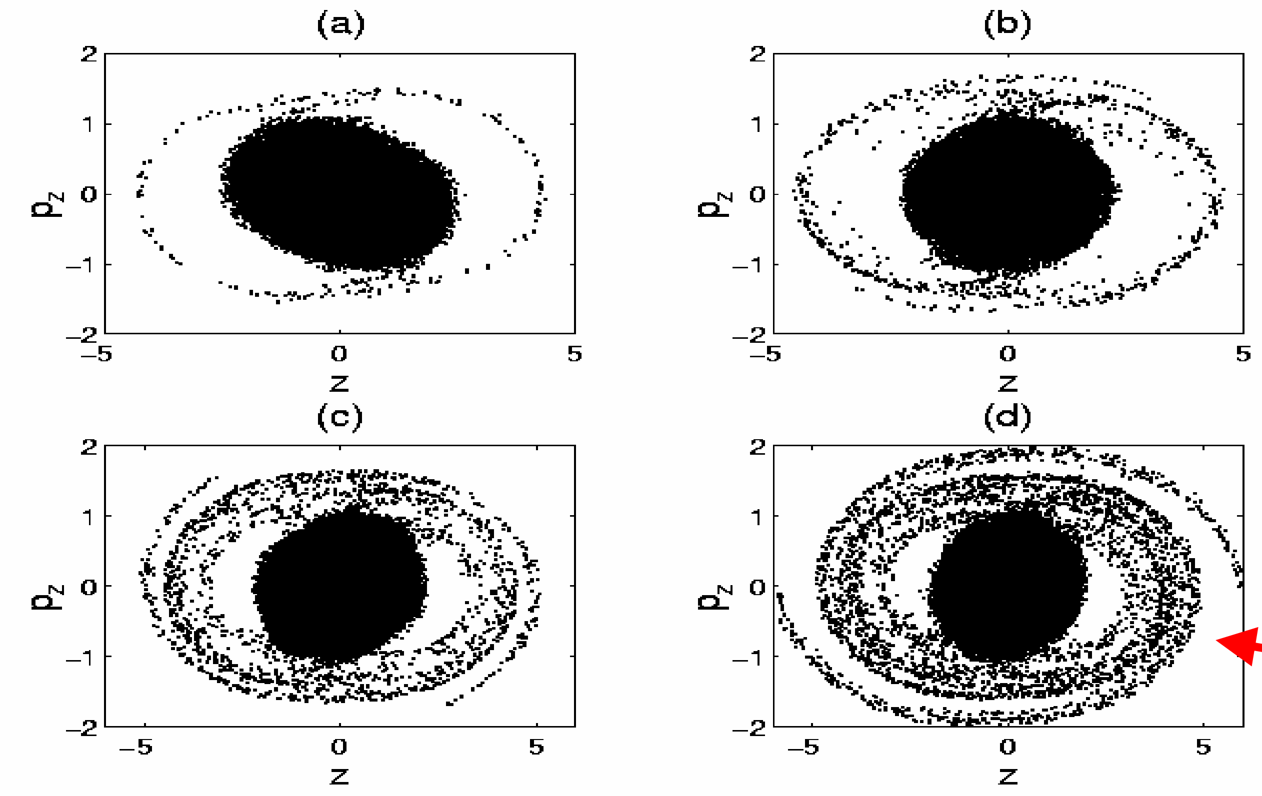
mechanism: parametric resonance

primary resonance (1:2) - **Ω=2ν**

“parametric halo “

Intrinsic incoherent resonances

weak tune depression – mismatch dependence

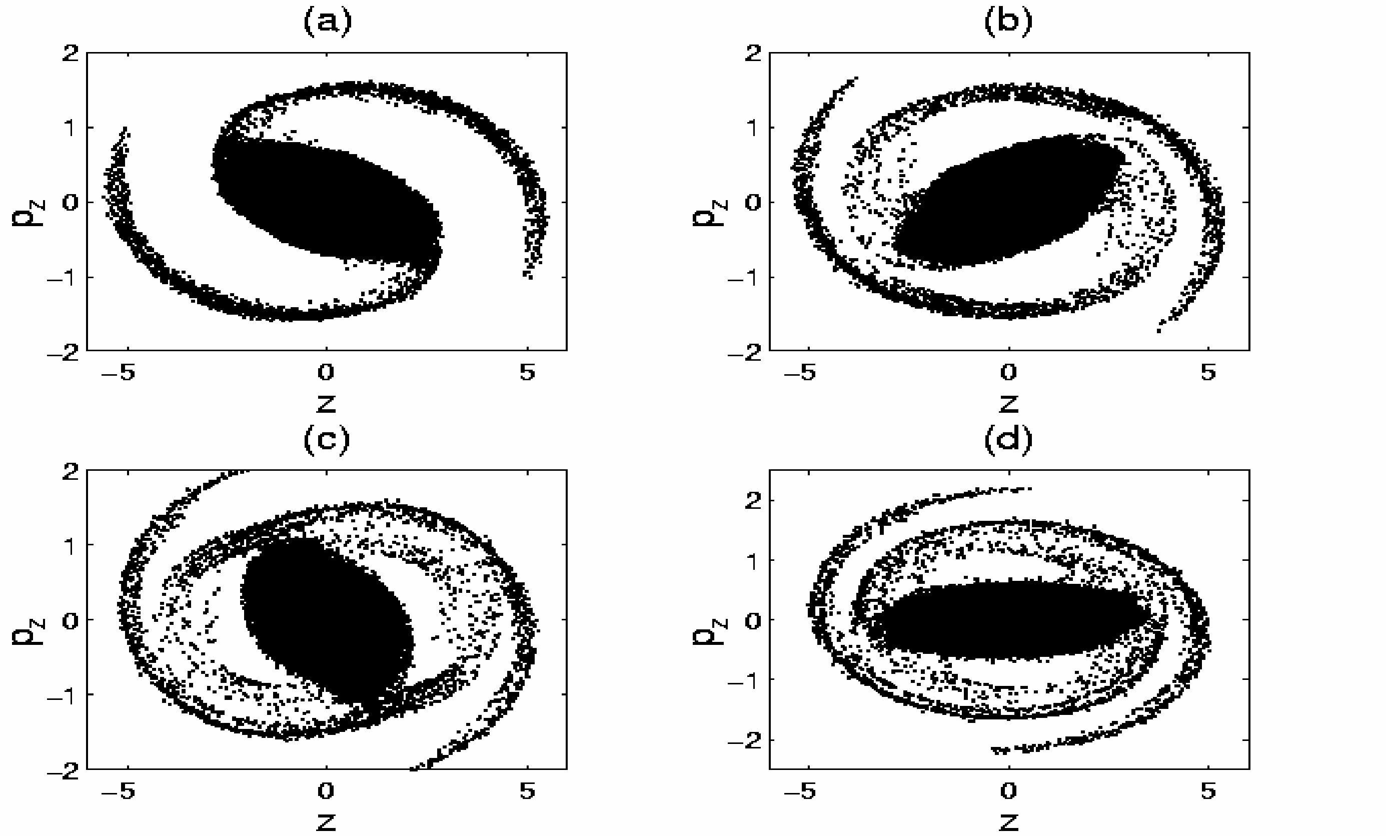


Very large mismatch

Strong redistribution

(η=0.93) mismatch parameter μ=1.2, μ=1.3, μ=1.4, μ=1.6

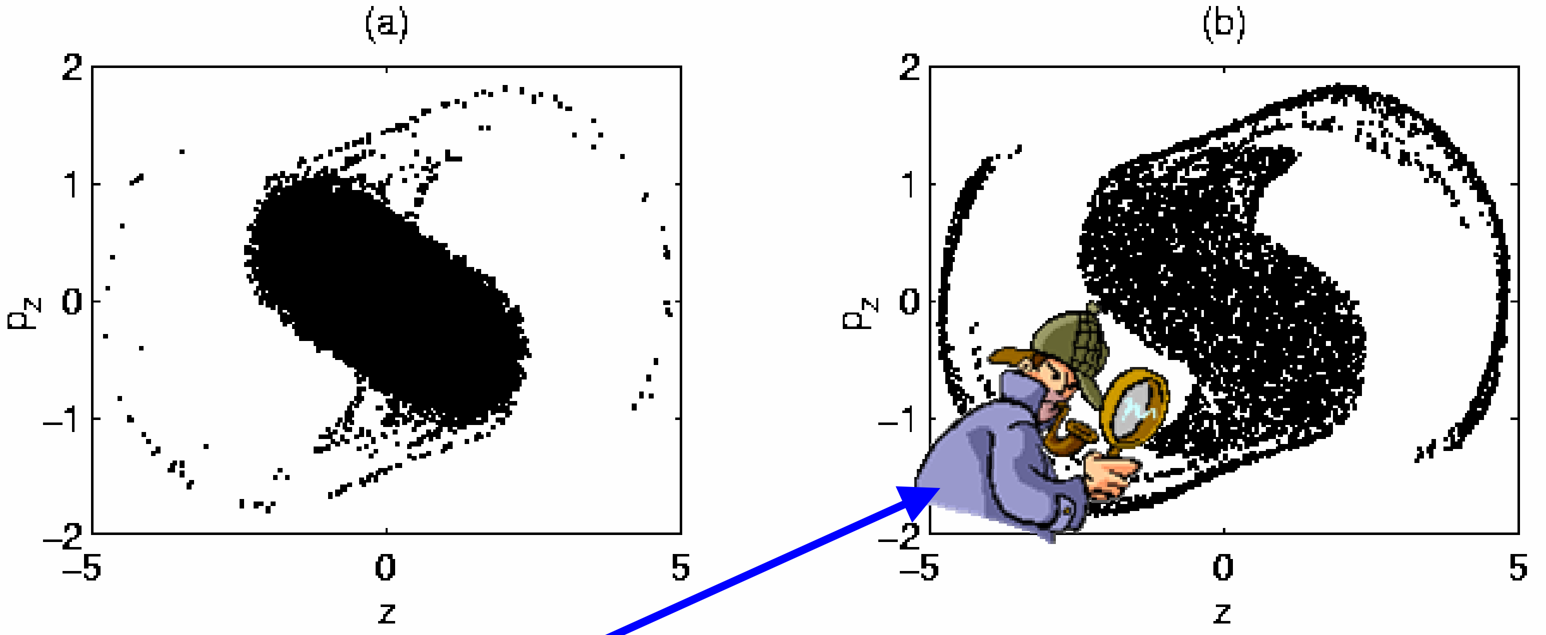
Time evolution of parametric halo with violent mismatch - filamentation



(μ=1.6, η=0.9) at various time periods t=250, t=350, t=450, t=550

Intrinsic incoherent resonances

halo structure



Looking into the halo

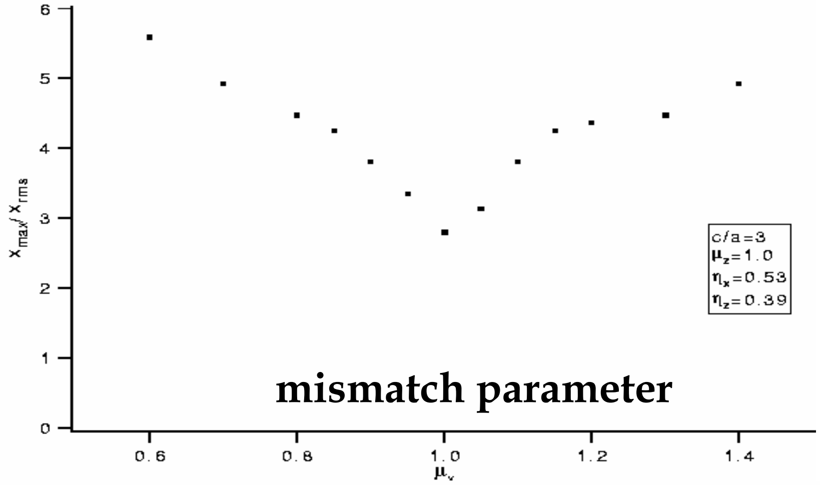
allows to study onset of various order resonances and halo structure

High-order resonances become important for very strong tune depression

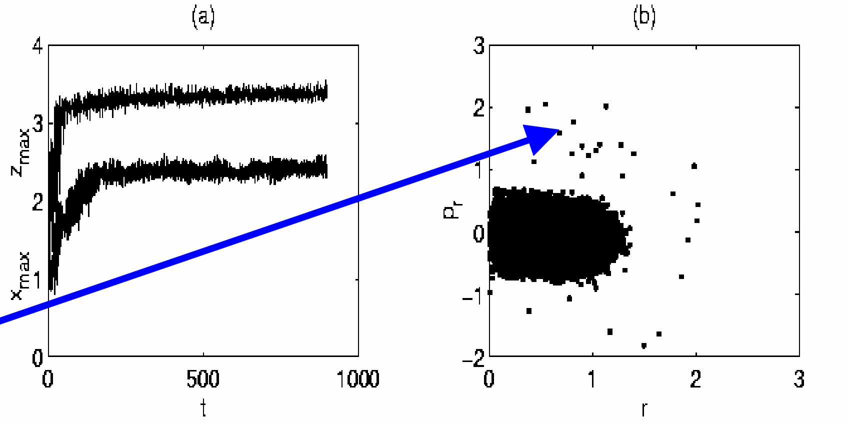
Longitudinal parametric halo and coupling

- Longitudinal halo can have the same mechanism – was studied extensively in linacs ('96-'99).
- For short bunches – halo due to mismatch in one plane can lead to extensive halo in the other due to the coupling ('97-'98).
- Stabilization of longitudinal parametric halo with nonlinear RF in linacs ('98)
- Nonlinear rf and longitudinal halo in rings ('99).

coupling effect – development of transverse halo as a result of longitudinal mismatch



mismatch parameter



Intrinsic incoherent resonances
rate of halo formation

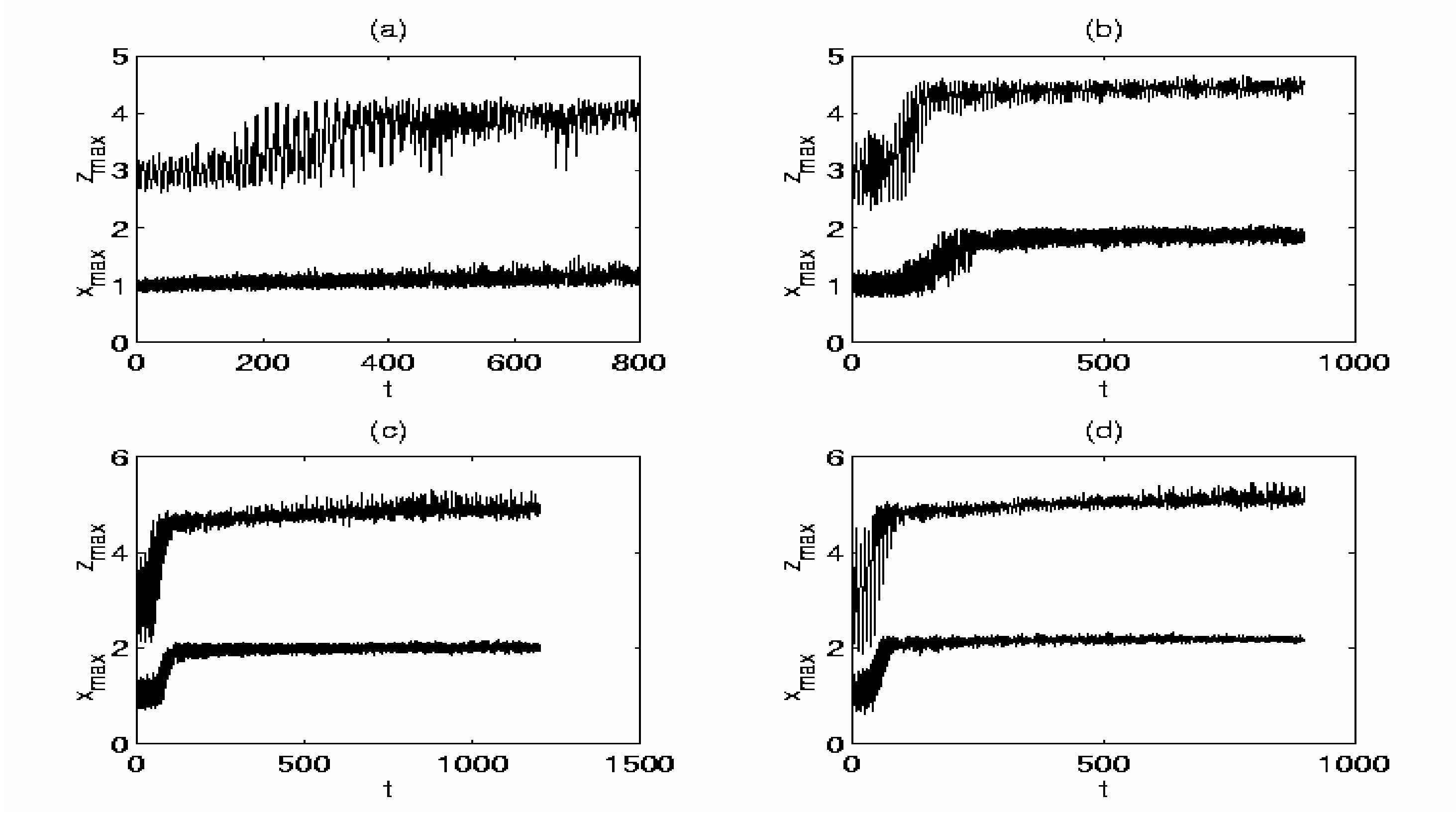
Rate of halo formation - function of tune depression & mismatch parameter

For reasonable mismatches – it takes much more time for particles to be trapped into the 1:2 resonance in emittance dominated regime than in space-charge dominated regime.

More importantly, when applied to real accelerator – need to take into account many other effects which may destroy the resonance condition:

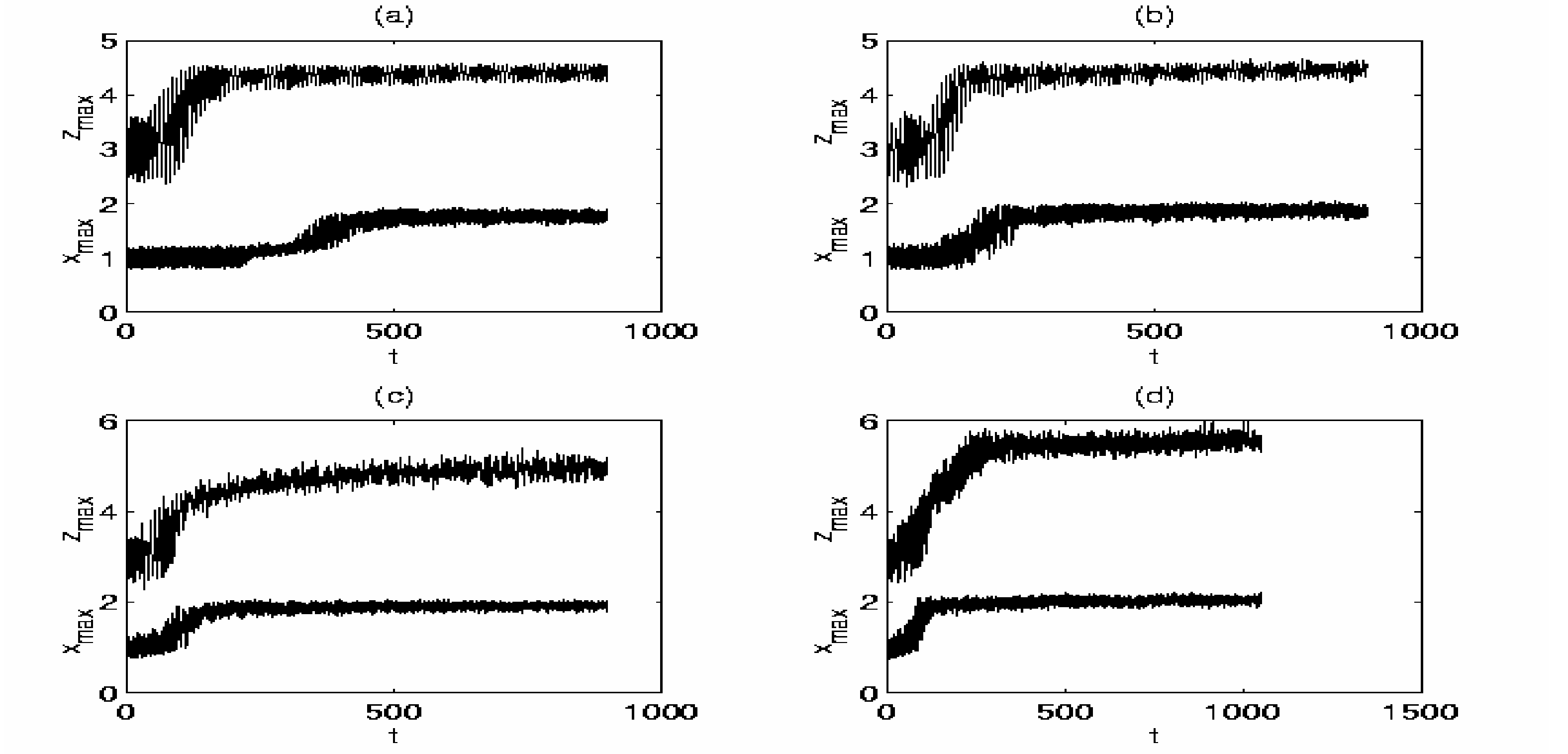
- changing beam density and intensity during accumulation
- phase-mixing during multi-turn injection
- acceleration and rapid change of focusing wave number
- etc.

Dependence of halo onset on mismatch



(c/a=3, η_x=.65, η_z=.49) μ=1.1, μ=1.2, μ=1.3, μ=1.4

Dependence of halo onset on tune depression



(c/a=3, μ=1.2) a) η_x=0.79, η_z=0.65 b) η_x=0.65, η_z=0.49

c) η_x=0.53, η_z=0.39 d) η_x=0.45, η_z=0.32

Intrinsic halo – comparison

- **Linacs** – tune depression is very high – rate of such space-charge driven halo can be very fast - warrants consideration.

- **Rings** – tune depression is very weak (unless we are talking “cooler rings” or specific small scale rings for space-charge studies). In addition, there are such effects as multi-turn injection which lead to phase-mixing of oscillating particles, redistribution due to the painting, etc. - may exist, but in many situations it will have a little chance to develop – negligible.

- **ERL’s** – for typical scenario, fast acceleration leads to emittance dominated regime.

2. Space-charge coupling resonances (both horizontal-vertical and transverse-longitudinal)

Space-charge resonances – driven by the space-charge potential itself

Their importance was first shown by Montague (1968) for the coupling resonance:

$2\nu_x-2\nu_y=0$ - does not require perturbation harmonics

Due to the fact that this resonance is symmetric difference resonance, such a coupling can lead to significant halo only for the beam with unequal emittances.

Analysis of this type of resonances was recently done using a more self-consistent approach of collective beam dynamics (Hofmann, 1998):

$m\nu_x-l\nu_y=0$ (single-particle) $m\nu_x-l\nu_y+\Delta\omega=0$ (collective correction)

Such asymmetric resonances with zero-th harmonic are mainly relevant for linacs where the ratio of the transverse (transverse/longitudinal) focusing constants can be very different (Hofmann's charts)

Space-charge coupling resonances - comparison

- Linacs - any nonlinear resonances due to a possibility of significantly different focusing constants - results in "equipartitioning charts" which suggest to avoid operation near such resonances – important for consideration

- Rings – typically not a big split in tunes – mainly symmetric resonance with the zero-th harmonic – as a result – need to worry only for unequal emittances. Tune depression is weak but long storage times – need to consider in many cases.

- ERL's – weak tune depression and short times - however, for very high-charge short bunches should be evaluated

3. Space-charge structure resonances (also "envelope instability" in high-current linear transport system)

When collective modes of beam oscillation resonate with the lattice structure (Hofmann et al, 1983, Okamoto et al. 2001):

$$N/2=\Omega_m$$

where N is the structure harmonic and Ω_m is the frequency of oscillation of m-th order collective beam mode.

↓

For m=2 (envelope modes) $N/2=\Omega_m$ - this is known as the "envelope instability" (Struckmeier, Reiser, 1984)

↓

Large halo growth

Space-charge structure resonances - comparison

- Linacs - important since tunes are not limited by imperfection resonances and thus tune depression can be increased until one hits structure stopbands

  -90^0 phase advance

  -60^0 (if 3rd order modes are driven)

- Rings – same problem if emittance growth due to the imperfection resonances can be minimized like in cooler rings with additional external cooling force. Otherwise – intensity is already limited due to the halo driven by the imperfection resonances.

- ERL's- emittance dominated and no structure harmonics

4. Single and multiple scattering

- Linacs – one can get a halo shell surrounding the beam which would look similar to the one due to a mismatch halo – "what do you expect? – it is halo after all".
- However, calculated scattering rates (with space charge) showed that the process is too slow to be important for proton linacs (Gluckstern, Fedotov, 1999, Pichoff, 98-99)

Simple analytic expressions in terms of beam parameters were obtained

$$f(\mathbf{r},\mathbf{v}) = \begin{cases} N(H_0 - H)^n = N[G(r) - mv^2/2]^n, & H < H_0, \\ 0, & H > H_0, \end{cases} \qquad G(r) \equiv H_0 - kr^2/2 - e\Phi_{\mathrm{sc}}(r).$$

$$\frac{dP}{c\,dt} \sim \begin{cases} r_p^2/\epsilon_N^3, & n > 0, \\ (r_p^2/\epsilon_N^3)\ln(\epsilon_N^2/r_p a), & n = 0, \\ (r_p^2/\epsilon_N^3)\,(\epsilon_N^2/r_p a)^{-n}, & 0 < -n < 1 \end{cases}$$

Coulomb scattering – rate in proton linacs

Probability of ions to leave the bunch per unit length

$$\frac{dP}{cdt} \sim \begin{cases} 10^{-15}/\mathrm{km}, & n > 0\,, \\ 10^{-14}/\mathrm{km}, & n = 0\,, \\ 10^{-11}/\mathrm{km}, & n = -0.5\,, \\ 10^{-8}/\mathrm{km}, & n = -0.9\,, \end{cases}$$

For typical beam parameters in a proton linac:

- Relatively singular distribution → 10^{-8}-10^{-11}/km
- Waterbag distribution → 10^{-14}/km
- Gaussian-like distributions → 10^{-15}/km

Linacs - diffusion is too slow to be important.

Caution: simulations can give “numerical” halo.

Rings: - for long storage times IBS is the dominant effect

General comments

- It is important to keep in mind that there are many mechanisms of halo formation.

- Obviously, when several mechanisms are present simultaneously, one gets a complex behavior - typically requires realistic simulation.
- Physics of some mechanisms can be the same in linacs and rings – but application of these mechanisms may be very different.

Halos in ERL

1. RF Photoinjectior related:

a) Linear SC b) Non-linear SC c) Non-linear time independent RF d) linear time dependent RF

a) & b) can be compensated – partial compensation will lead to halo and emittance growth

c) & d) lead to halo and emittance growth

2. Magnetic bunch compression leads to emittance growth: SC and dispersion:
3. CSR in bunch compression
4. Coulomb scattering
5. Amplification of microbunching by CSR
6. Longitudinal SC & instabilities
7. Longitudinal SC and modulations
8. Optics non-linearities in high-energy transport (design-related)
9. Design-related for photoinjector beam transport

Summary

…to be continued in Discussion sessions

In present ERL: halos is already a subject of discussion, mainly "design-related".

In proposed high-intensity ERL: certainly becomes an issue; with good progress in design and primary beam dynamics topics the subject of beam halo also becomes important.

Acknowledgments:

I would like to thank many collaborators with whom I worked on the subject of beam halo in linear and circular accelerators, as well as the Accelerator Physics groups of SNS and RHIC for numerous useful discussions on this subject.