Review of Instability Mechanisms in Ion Linacs

Romuald Duperrier

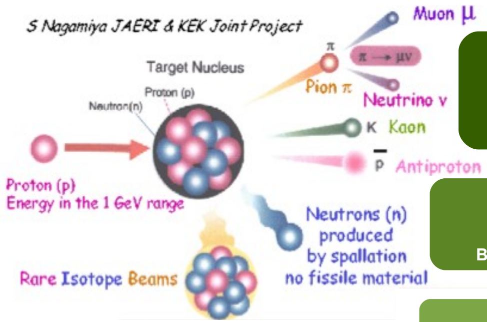
CEA/Saclay

HB 2010
Morschach

Outline

Outline

Applications of MW class ion linacs



Particle physics

Muons colliders
Neutrinos factories

Condensed Matter

Neutron probe
Biology, Magnetism, Polymers

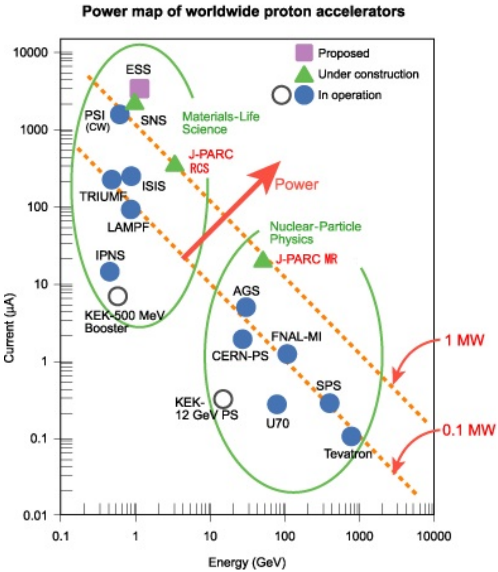
Transmutation
of long-lived radioactive wastes

Nuclear physics
Beams of short-lived elements
Super heavy elements

Technical Irradiation Tool
Tests of material (fusion, ...)

Beam loss in MW class ion linacs

- All these applications aim to use so high flux of secondary particles that the power of the primary ion beam must reach one or several MW.
- Because a acceptable hands on maintenance would mean beam loss of a few W/m, The loosed fraction has to be kept below 10^{-4} down to 10^{-7}.



Outline

Space charge or self fields

- This new generation of accelerators requires peak current in the range of a few mA up to a one hundred of mA.
- For this class of current, the beam as a source term in Maxwell equations can't be neglected anymore:

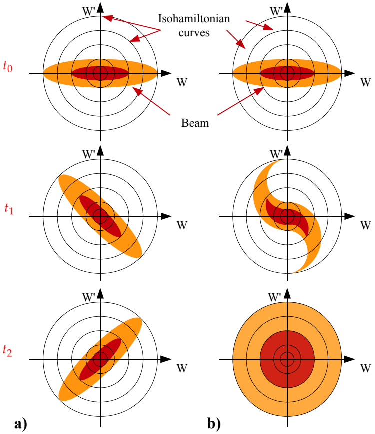
$$\partial_t \overrightarrow{B} = -\overrightarrow{\nabla} \times \overrightarrow{E} \qquad \overrightarrow{\nabla} \cdot \overrightarrow{E} = \rho / \varepsilon_0$$

$$\overrightarrow{\nabla} \times \overrightarrow{B} = \mu_0 \overrightarrow{J} + \partial_t \overrightarrow{E} / c^2 \qquad \overrightarrow{\nabla} \cdot \overrightarrow{B} = 0$$

- If the electric part is vanished by adding charge with opposite polarity, the magnetic field would remain.
- This is the reason why "self fields" is more appropriate than "space charge", but both expressions will be used in this talk.

The non linear nature of self fields

- By essence, the non linear nature of space charge induces a spread of the tune.
- The consequence is that if the beam doesn't match with the isohamiltonian curves in phase space, an emittance growth will occur.
- This process is not an instability (exponential like behavior) but still one of the major source of emittance blow up.

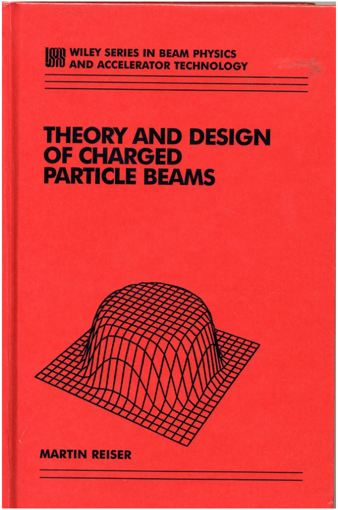


It is worth noting that when an instability occurs, the instability itself kills the instability conditions.

Outline

Instability for mismatched envelops

- More than a filamentation, a mismatched beam can be unstable if the channel working point is not properly set.
- By linearization of the X/Y envelop equations for small mismatched, Struckmeier and Reiser have shown that the two mismatched modes (low and high frequency) can exhibit an instability when the phase advance without space charge per focusing period is greater than 90° and the tune depression is low.



Review of Instability Mechanisms in Ion Linacs

R. Duperrier

MW ion linacs

Space Charge

Parametric Resonances

HOMs

Resonant Build Up and Errors

Resonances and experimental highlights

Conclusions

Periodic forces and parametric resonances

- Particles in an accelerator are oscillators driven by a periodic force (Hill):

$$x'' + \omega^2(s)x = 0$$

- When the two first harmonics are dominant, Hill's equation may be reduced to the Mathieu equation:

$$\frac{d^2x}{d\tau^2} + \pi^2\left[A + 2q sin(2\pi\tau)\right]x = 0$$

- Depending on q and A, the solution is stable or unstable. Stop-band can be determined with the Mathieu diagram.

PURES ET APPLIQUÉES. 137

MÉMOIRE

SUR

LE MOUVEMENT VIBRATOIRE

D'UNE MEMBRANE DE FORME ELLIPTIQUE;

PAR M. ÉMILE MATHIEU [*].

Imaginons une membrane tendue également dans tous les sens, et dont le contour, fixé invariablement, est une ellipse. Notre but, dans ce Mémoire, est de déterminer par l'analyse toutes les circonstances de son mouvement vibratoire; nous y calculons la forme et la position des lignes nodales et le son correspondant. Mais ces mouvements sont assujettis à certaines lois générales qui peuvent être définies sans le secours de l'analyse.

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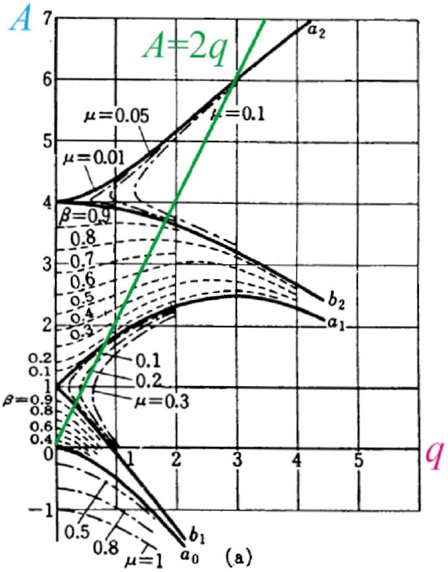
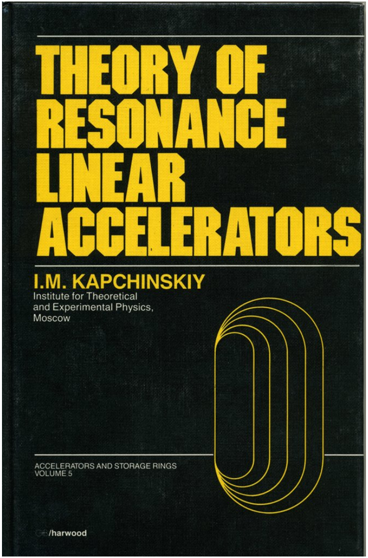


- In Kapchinskiy's book, it is shown how the radial fields couple the transverse and longitudinal planes.
- The transverse motion equation may be reduced to the Mathieu equation:
  $A = 4\frac{\sigma_t^2}{\sigma_l^2}$ and $q = \Delta\Phi cotg\Phi_s$
- When $q \sim 0$, we have resonance only for $A = n^2$ or $\sigma_t = \frac{n}{2}\sigma_l$.
- This is the reason why $\sigma_t > \sigma_l$ is preferred.



Resonances with the radial fields in cavities

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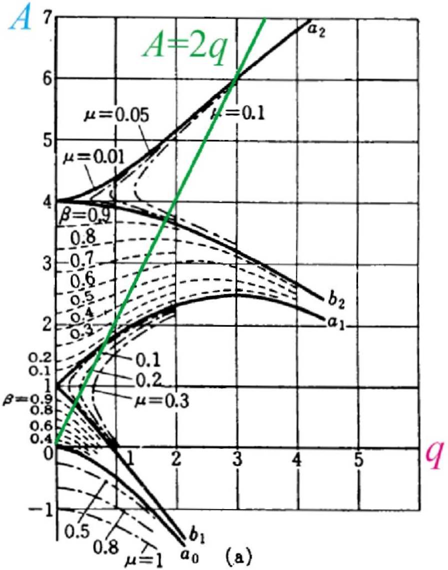


Review of Instability Mechanisms in Ion Linacs

R. Duperrier

- For a mismatched cylindrical beam with uniform density, the particle motion can be solved by:

  $x'' + k_r^2\,(1+\delta cos(k_{rm}s))\,x = 0$

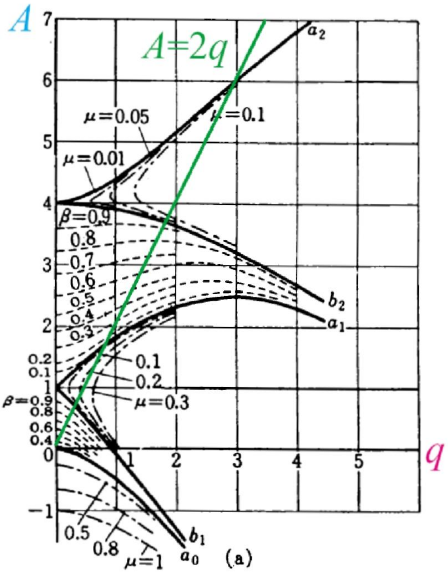
  with $\delta = 2M(1/\eta^2 - 1)$.

- One can find out :

  $A = 2\eta^2/(1+\eta^2)$ and

  $q = 2M(1-\eta^2)/(1+\eta^2)$

- Instabilities require high mismatch factors M and low tune depressions, η.



PR with space charge (core-particle)

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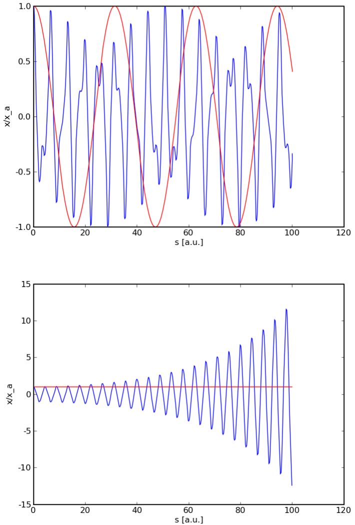
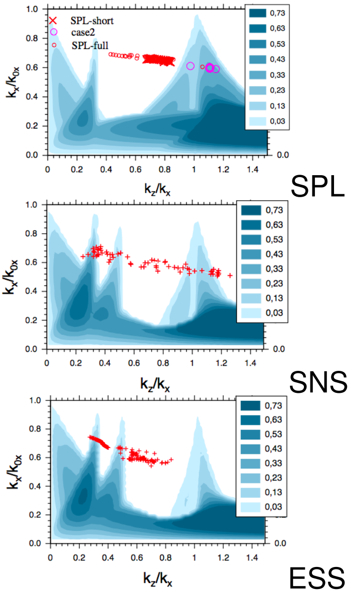


PR with space charge in 3D [Hofmann et al, EPAC'02]

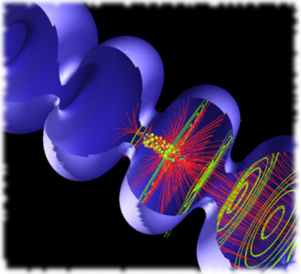
- To investigate the anisotropy effects in ellipsoidal bunches to go beyond this previous simplified halo model, by studying the stability of solutions of linearized Vlasov equation, it has been shown how stop bands can arise in the plane $(\eta, k_z/k_x)$ for different transv./long. emittances ratio.
- If working points are properly selected in passband regions, “equipartition” is not necessary, this condition being inaccessible for most of the practical cases.

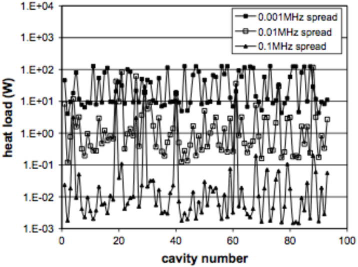


Outline

High Order Modes *[Jeon et al, NIM A 495 (2002)]*

- A beam passing through a cavity deposits a fraction of its energy and can excite modes.
- Numerical simulation indicates that cumulative transverse beam breakup instabilities are not a concern for the SNS (mass).
- As little as ± 0.1 MHz HOM frequency spread stabilizes all the instabilities from both transverse and longitudinal HOMs.





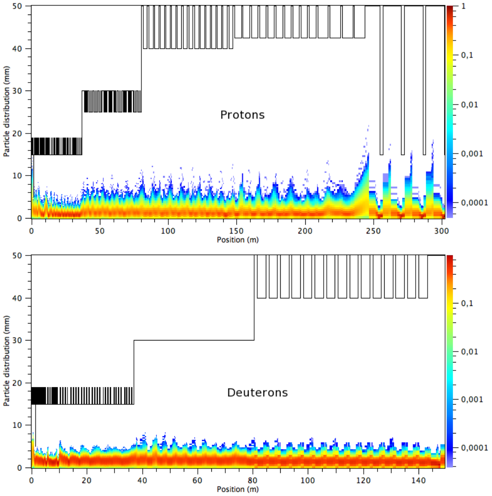
High Order Modes : still a debate

- Recent studies for the SPL mainly show that HOMs are not a concern for this linac too [M. Schuh, IPAC 2010].
- “Mainly” because machine lines may always correspond to a HOM.
- Recently, Tuckmantel shown that one order of magnitude for the current or the HOM frequency spread is sufficient to induce an instability “from the noise” whatever the considered mode frequency [Tuckmantel , BE-Note-2009-009 RF].
- Fermilab for Project X proposes to retune fundamental mode in order to shift HOM frequencies in case one or several modes are resonant [Solyak et al, IPAC 2010].
- For the decision about the necessity to equip the linac with HOM dampers, a part of the answer is more a risk management issue than a scientific issue.

Outline

Resonant Build Up and Errors

- In presence of imperfect elements, the particle motion may know a resonant amplitude build up.
- To tend to “realistic” simulation and investigate such extreme scenarios, it is needed to perform start-to-end (S2E) transport for estimating the impact of halo produced at low energy in the high energy part.



[Duperrier, EURISOL TM 2009]

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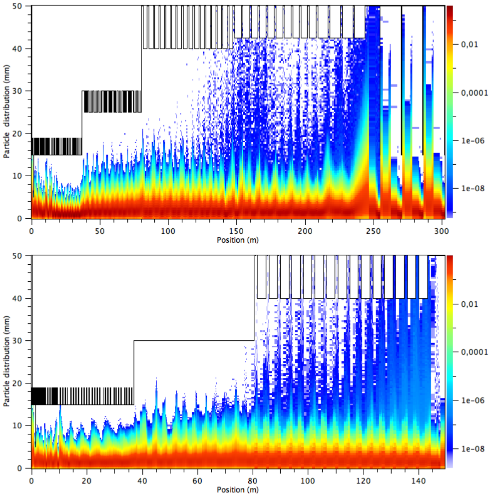
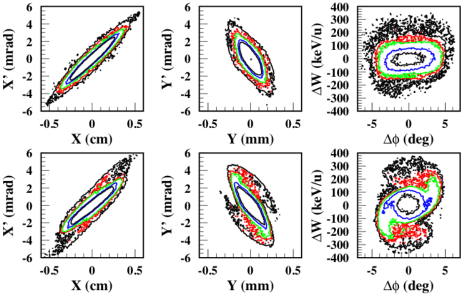


[Duperrier, EURISOL TM 2009]

Codes for S2E: Track

- Born in 2001 at Argone, this code has been initially for the non linear transport of several beams for RIA.
- Users: FERMILAB, SOREQ, ESS-B...

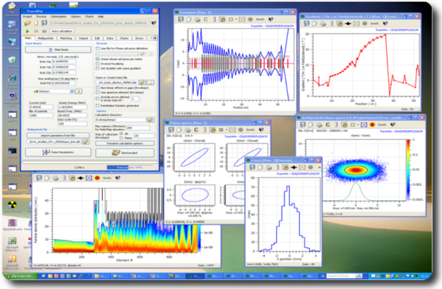


P.N. Ostroumov et al

Main features

- Most of the elements.
- Diagnostics.
- Distributed MC.
- Parallelized.

- Born in 1994 at Saclay, this code is able to simulate in a first order mode or in a PIC mode the beam motion in a linac.
- Users: LANL, J-PARC, LBNL, CERN, GANIL, IAP, INFN, RAL,...



D. Uriot et al

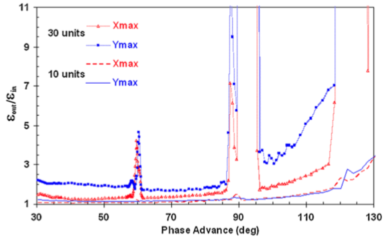
Main features

- Most of the elements.
- Diagnostics.
- Distributed MC.
- Part. parallelized.
- EPICS.

Outline

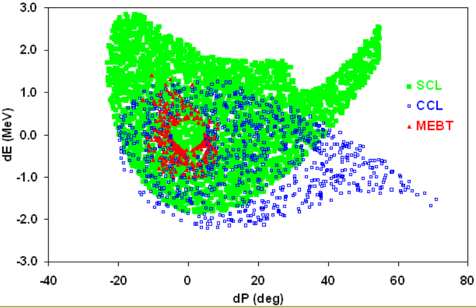
SNS feedback (1/2)

- An important feedback from SNS is the confirmation that HOM dampers wouldn't be necessary for ms pulse machines with peak current of 30 mA at 60 Hz with less than one hundred cavities.



- On the other hand, unexpected beam loss have been measured in the SC section. One possible origin could be the large dodecapole components of the quads [Zhang et al, PRSTAB 2010].

- Simulations show that the instability can be killed when transverse phase advances at zero current is lower than 60°. Lower beam loss are also observed with the linac when the transverse phase advance is decreased.
- Nevertheless, unexpected longitudinal tails have been also observed at the SC linac entrance and by minimizing the quad strenght, the probability to keep low energy particles increases.



SCL Acceptance, MEBT Particles and CCL Particles

90° resonance stop band

- To give rise to space charge induced resonances, a recent experiment has been carried out at GSI.
- Measurements of transverse phase space distributions reveal a resonance stop band above zero current phase advance of 90° per focusing cell. These experimental findings agree very well with results from three different beam dynamics simulation codes.

PRL **102,** 234801 (2009) PHYSICAL REVIEW LETTERS week ending 12 JUNE 2009

Experimental Evidence of the 90° Stop Band in the GSI UNILAC

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(Received 16 March 2009; revised manuscript received 5 June 2009; published 12 June 2009)

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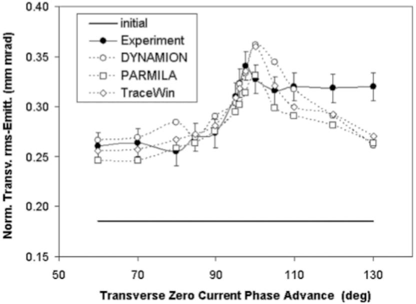


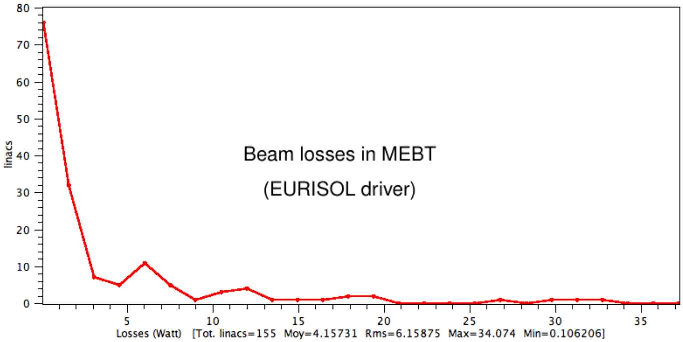
Outline

Conclusions

- To avoid the envelope instability require $\sigma_{t,0}$<90 deg.
- To avoid the rf defocusing instability require $\sigma_{l,0}$<$\sigma_{t,0}$<90 deg.
- To avoid the sixth order instability, minimize the dodecapole component of the quadrupole magnets, or require $\sigma_{t,0}$<60 deg.
- To avoid core-particle instability, minimize mismatches, minimize transitions.
- To prevent emittance transfer avoid $k_z/k_x = 1$ stopband in case of anisotropy.

Statistical analysis

- With a large set of imperfect linacs, Cumulative Density Functions (CDF) can be established for any position.



- But the discrete form of this CDF induces that the probability to loose more than the more extreme recorded loss becomes null!

Extreme Value Theory and Bootstrap technique

- EVT provides a Generalized Extreme Value function that may represent the tail for extreme events:

$$H_{\xi\sigma\mu}(p) = exp\left(-\left(1+\xi\frac{p-\mu}{\sigma}\right)^{-\frac{1}{\xi}}\right) \quad (1)$$

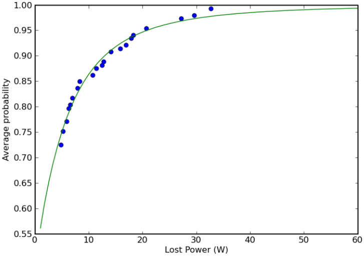
with μ, the location parameter, σ, the scale parameter and ξ a form parameter.

- To construct confidence intervals, one can *resample* with *replacement* from the actual data X to generate B bootstrap samples X^*.
- Properties expected from the replicate real sample are inferred from the bootstrap samples by analysing each bootstrap sample exactly as we first analyzed the real data sample. From the set of results of sample size B, we measure our inference uncertainties (variance).

GEV distribution

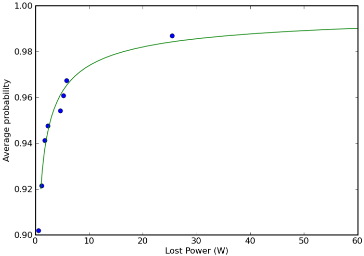
(EURISOL driver: proton case)

MEBT collimator



P(losses > 20 W) = 5%

HEBT dipole



P(losses > 10 W) = 3%

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MW ion linacs

Space Charge

Parametric Resonances

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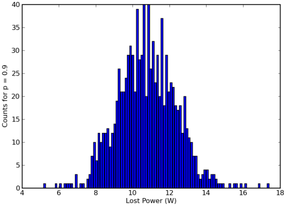
Resonances and experimental highlights

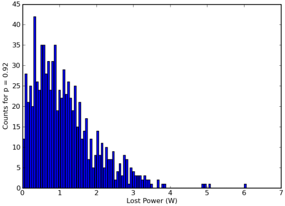
Conclusions

EURISOL driver: proton case
(1000 resampled loss distributions for a fixed probability)

MEBT collimator



HEBT dipole



	CDF	Lower bound	Average value	Upper bound
MEBT collimator	10%	8 W	11 W	14 W
HEBT dipole	8%	0. W	1.15 W	2.82 W