Review of Beam Dynamics Issues in MW Class Ion Linacs

Romuald Duperrier

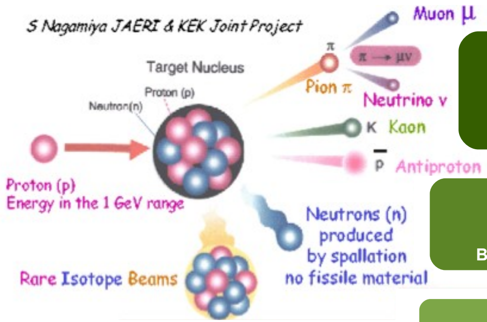
CEA/Saclay

IPAC 2010 - Kyoto

Outline

Outline

Applications of MW class ion linacs



Particle physics

Muons colliders
Neutrinos factories

Condensed Matter

Neutron probe
Biology, Magnetism, Polymers

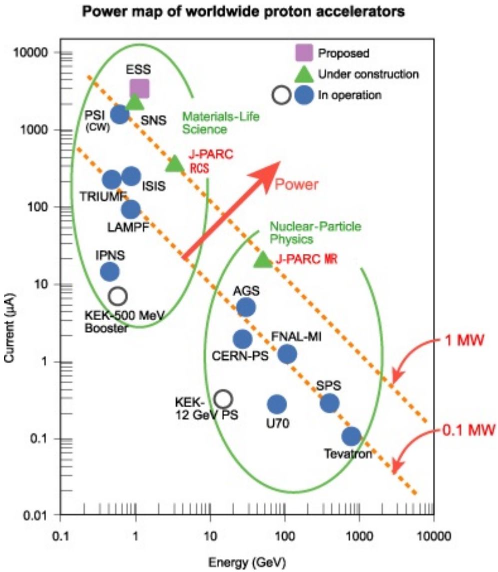
Transmutation
of long-lived radioactive wastes

Nuclear physics
Beams of short-lived elements
Super heavy elements

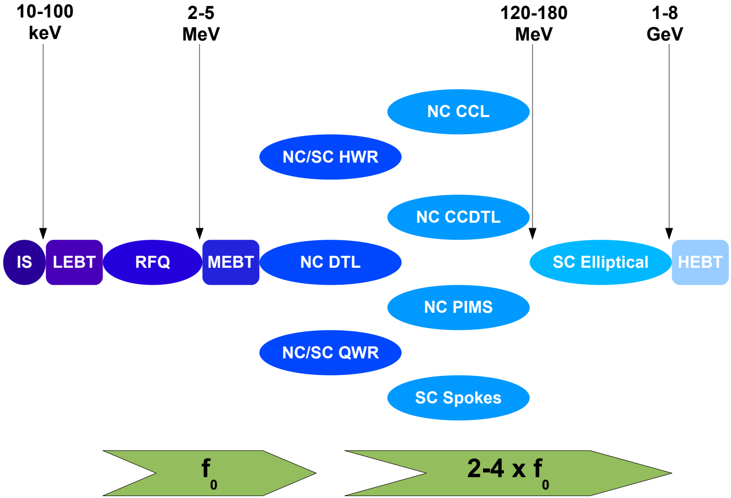
Technical Irradiation Tool
Tests of material (fusion, ...)

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}.



Layouts for MW class ion linacs



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:

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

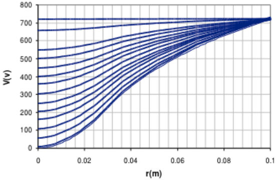
$$\overrightarrow{\nabla} \times \overrightarrow{B} = \mu_0 \overrightarrow{J} + \partial_t \overrightarrow{E} / c^2 \qquad \overrightarrow{\nabla} \cdot \overrightarrow{B} = 0$$

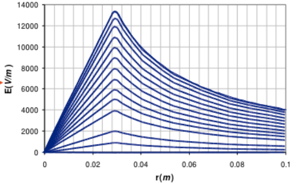
- If the electric part is vanished by adding charge with opposite polarity, the magnetic field would remain.
- This is the reason why "self fields" is more appropriate than "space charge", but both expressions will be used in this talk.

The space charge neutralization

(100 mA proton beam, 100 keV)

Potential well





Electric field

- Considering a residual gas (ex.: H_2) in the vacuum chamber, pairs of e^- and ions (H_2^+) will be produced by ionization:

$$p + H_2 \rightarrow p + e^- + H_2^+$$

It is assumed that the beam density $\ll$ gas density.

- This neutralization is mandatory for peak current higher than 50 mA when electrostatic system are limited.

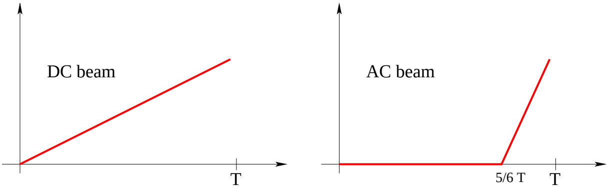
The rise time

- In a first and good approximation, the rise time for a DC beam can be computed with the following classical expression:

$$\tau_n = \frac{1}{\sigma N_{gas} \beta c}$$

with σ is the ionization cross section, $N_{gas} = P/kT_{room}$ and β the reduced beam velocity (to be compared to pulse length).

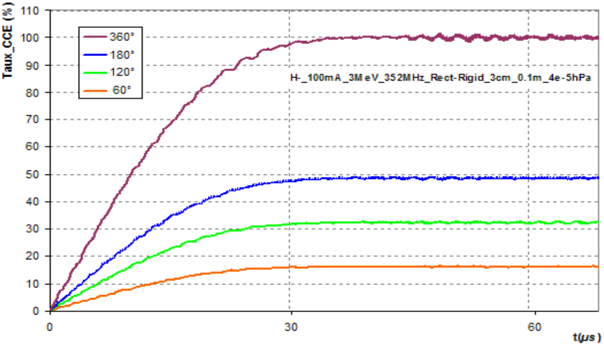
- If we plot the neutralizing charge provided in a drift by a DC and an AC beam ($T/6$) during one period T:



- After one period, the same number of neutralizing charge has been provided to the system.

Neutralization level for bunched beam

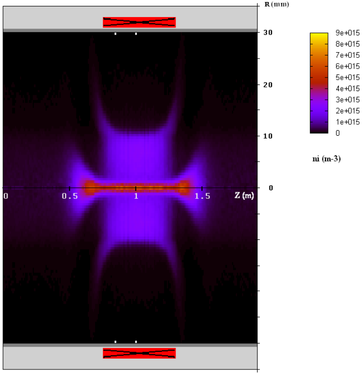
- Because the beam bunch density is greater than the neutralizing particle density, the neutralization can't exceed the ratio bunch length / distance between bunches ($\beta\lambda$).



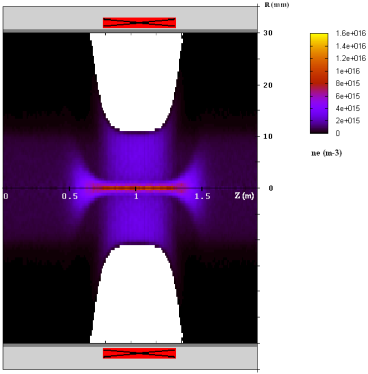
[A. Ben Ismail, PhD thesis, 2005]

Simulation with a PIC code: impact of a solenoid

(H^+, 100 mA, 100 keV case)



H_2^+

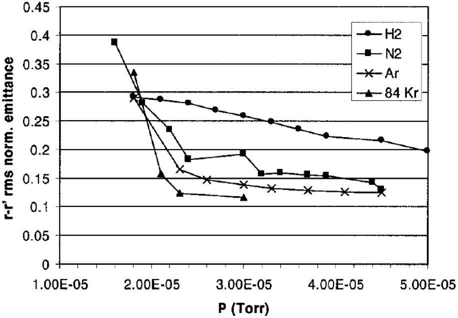


electrons

- Magnetic mirror at the edges.
- Transverse drift inside.

Emittance enhancement

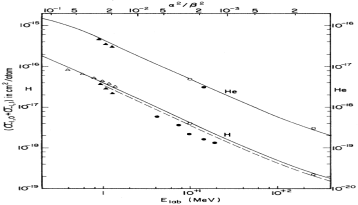
[Gobin et al, Rev. Sci. Instr.,99]

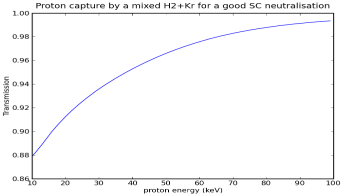


- Emittance enhancement with an increasing of the pairs production rate (pressure and/or cross section).
- The enhancement with the heavy gas is due to a cross section which is multiplied by a factor 5 and a greater mass.

[Chou, Director's review, Fermilab, 2005]

- Energy dependence of total electron loss cross section for H^- incident on atoms.
- Transmission dependence for protons in 2 m LEBT.





Cross section decreases fastly with energy and the pressure is very low at high energy (SC): mainly a LEBT issue.

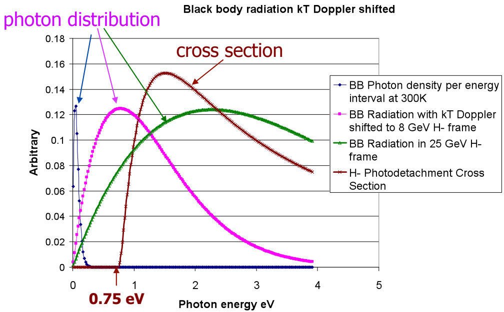
Magnetic stripping

- When an H^- moves in a magnetic field B, a force bends its trajectory and tends to break it up since the protons and electrons are bent in opposite directions.
- In the H^- frame, E[MV/cm] = 3.197 p[GeV/c] B[T] where p is the ion momentum in the lab.
- This phenomena will then be more important in the high energy part of the machine. The effect is negligible if low magnet field are used.

Black Body Radiation

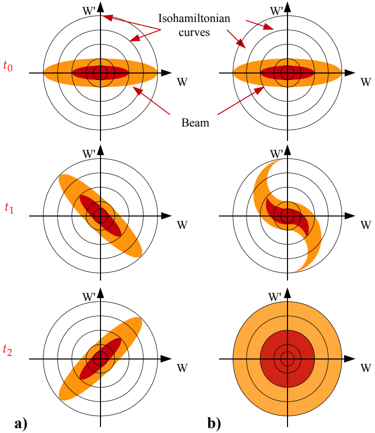
[Chou, Director's review, Fermilab, 2005]

- H^- has two electrons, one tightly bound (13.6 eV), another loosely bound (0.75 eV).
- BBR is a newly discovered loss mechanism, dominant for 8 GeV H^-. For a multi MW beam, the loss rate is a few W/m.
- Cooling the vacuum pipe could solve the problem .



The non linear nature of self fields

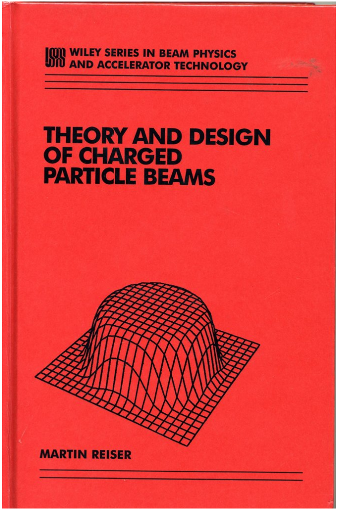
- Linear self fields correspond to an uniform density but this case is only valuable for theoretical investigations.
- By essence, this non linear nature induces a spread of the tune.
- The consequence is that if the beam doesn't match with the isohamiltonian curves in phase space, an emittance growth will occur (a few focusing cells are necessary to relax).



Minimize the number of transitions in your linac!

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 and 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°.



Periodic forces and parametric resonances

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

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

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

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

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

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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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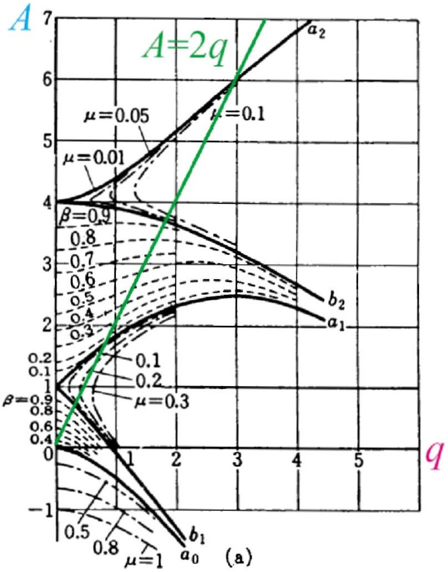
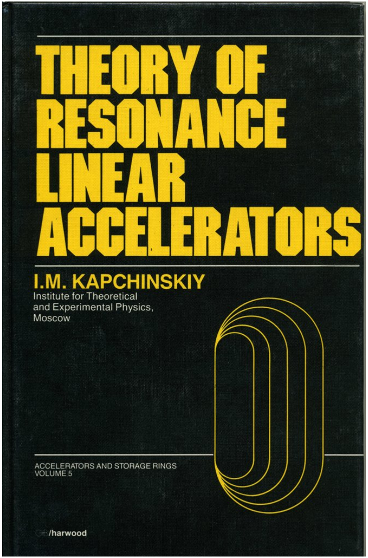


- In Kapchinskiy's book, it is shown how the radial fields couple the transverse and longitudinal planes.
- The transverse motion equation is reduced to the Mathieu equation:
$A = 4\frac{\sigma_t^2}{\sigma_l^2}$ and $q = \Delta\Phi cotg\Phi_s$
- When $q \sim 0$, we have resonance only for $A = n^2$ or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



Resonances with the radial fields in cavities

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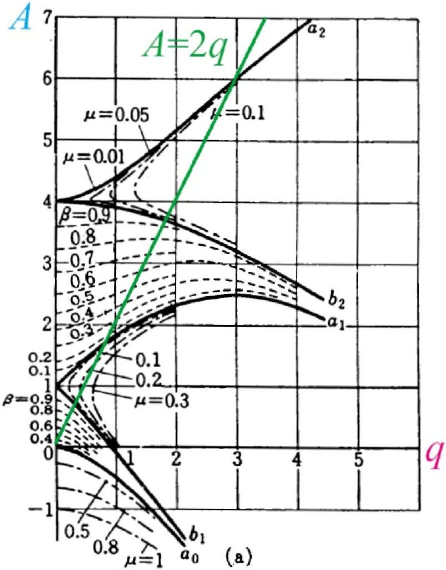


PR with space charge (core-particle)

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

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

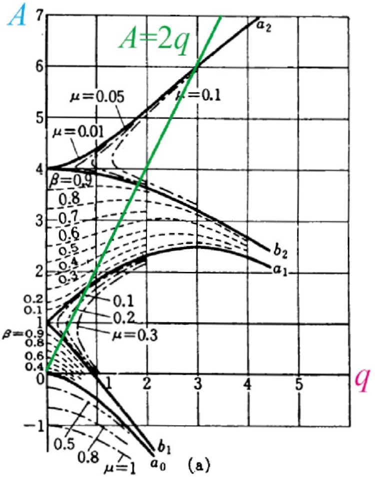
with $\delta = 2M(1/\eta^2 - 1)$.

- 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. But stable solutions may correspond to an amplification of the amplitude.



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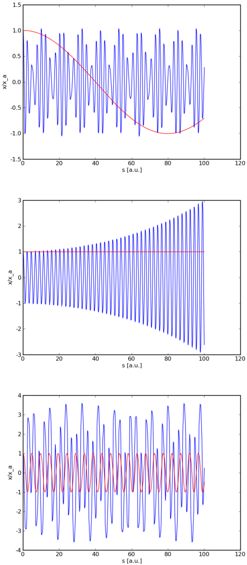
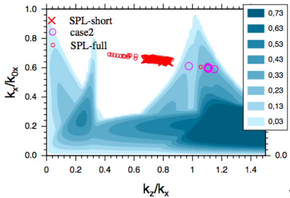
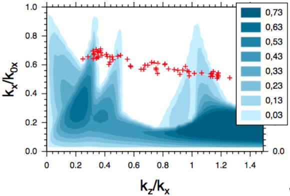


PR with space charge in 3D [Hofmann et al, EPAC'02]

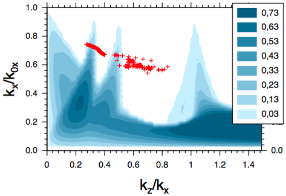
- To investigate the anisotropy effects in ellipsoidal bunches to go beyond this previous simplified halo model, by studying the stability of solutions of linearized Vlasov equation, it has been shown how stop bands can arise in the plane $(\eta, k_z/k_x)$ for different transv./long. emittances ratio.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



SPL



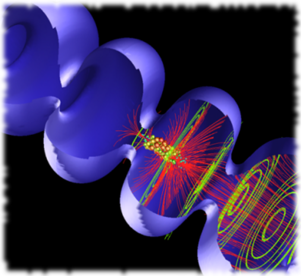
SNS

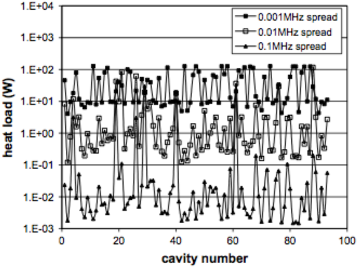


ESS

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.





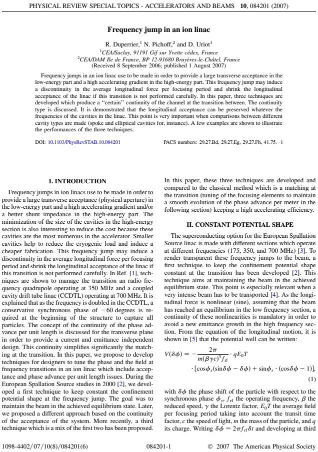
High Order Modes : still a difficult issue

- Recent studies for the SPL mainly show that HOMs are not a concern for this linac too (see Marcel Schuh's poster THPE082).
- "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].
- 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

Frequency jumps

- Different techniques to manage frequency jumps exist.
- They help to reduce the impact of the frequency transition on the brilliance.
- Their drawback is a reduced REG at the transition.
- This reduced accelerating efficiency becomes negligible when the output energy of the linac increases.


PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **10**, 084201 (2007)

Frequency jump in an ion linac

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(Received 8 September 2006; published 1 August 2007)

Frequency jumps in an ion linac use to be made in order to provide a large transverse acceptance in the low-energy part and a high accelerating gradient in the high-energy part. This frequency jump may induce a discontinuity in the average longitudinal force per focusing period and shrink the longitudinal acceptance of the linac if this transition is not performed carefully. In this paper, three techniques are developed which produce a ''certain'' continuity of the channel at the transition between. The continuity type is discussed. It is demonstrated that the longitudinal acceptance can be preserved whatever the frequencies of the cavities in the linac. This point is very important when comparisons between different cavity types are made (spoke and elliptical cavities for, instance). A few examples are shown to illustrate the performances of the three techniques.

DOI: 10.1103/PhysRevSTAB.10.084201 PACS numbers: 29.27.Bd, 29.27.Eg, 29.27.Fh, 41.75.−i

I. INTRODUCTION

Frequency jumps in ion linacs use to be made in order to provide a large transverse acceptance (physical aperture) in the low-energy part and a high accelerating gradient and/or a better shunt impedance in the high-energy part. The minimization of the size of the cavities in the high-energy section is also interesting to reduce the cost because these cavities are the most numerous in the accelerator. Smaller cavities help to reduce the cryogenic load and induce a cheaper fabrication. This frequency jump may induce a discontinuity in the average longitudinal force per focusing period and shrink the longitudinal acceptance of the linac if this transition is not performed carefully. In Ref. [1], techniques are shown to manage the transition an radio frequency quadrupole operating at 350 MHz and a coupled cavity drift tube linac (CCDTL) operating at 700 MHz. It is explained that as the frequency is doubled in the CCDTL, a conservative synchronous phase of −60 degrees is required at the beginning of the structure to capture all particles. The concept of the continuity of the phase advance per unit length is discussed for the transverse plane in order to provide a current and emittance independent design. This continuity simplifies significantly the matching at the transition. In this paper, we propose to develop techniques for designers to tune the phase and the field at frequency transitions in an ion linac which include acceptance and phase advance per unit length issues. During the European Spallation Source studies in 2000 [2], we developed a first technique to keep constant the confinement potential shape at the frequency jump. The goal was to maintain the beam in the achieved equilibrium state. Later, we proposed a different approach based on the continuity of the acceptance of the system. More recently, a third technique which is a mix of the first two has been proposed.

In this paper, these three techniques are developed and compared to the classical method which is a matching at the transition (tuning of the focusing elements to maintain a smooth evolution of the phase advance per meter in the following section) keeping a high accelerating efficiency.

II. CONSTANT POTENTIAL SHAPE

The superconducting option for the European Spallation Source linac is made with different sections which operate at different frequencies (175, 350, and 700 MHz) [3]. To render transparent these frequency jumps to the beam, a first technique to keep the confinement potential shape constant at the transition has been developed [2]. This technique aims at maintaining the beam in the achieved equilibrium state. This point is especially relevant when a very intense beam has to be transported [4]. As the longitudinal force is nonlinear (sine), assuming that the beam has reached an equilibrium in the low frequency section, a continuity of these nonlinearities is mandatory in order to avoid a new emittance growth in the high frequency section. From the equation of the longitudinal motion, it is shown in [5] that the potential well can be written:

$$V(\delta\phi) = -\frac{2\pi}{m(\beta\gamma c)^3 f_{\mathrm{rf}}} \cdot qE_0T \cdot [\cos\phi_s(\sin\delta\phi - \delta\phi) + \sin\phi_s \cdot (\cos\delta\phi - 1)], \qquad (1)$$

with $\delta\phi$ the phase shift of the particle with respect to the synchronous phase ϕ_s, f_{rf} the operating frequency, β the reduced speed, γ the Lorentz factor, E_0T the average field per focusing period taking into account the transit time factor, c the speed of light, m the mass of the particle, and q its charge. Writing $\delta\phi = 2\pi f_{\mathrm{rf}}\delta t$ and developing at third

1098-4402/07/10(8)/084201(6) 084201-1

[Duperrier, Pichoff & Uriot, PRSTAB 2007]

Frequency jumps

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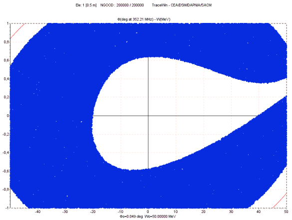

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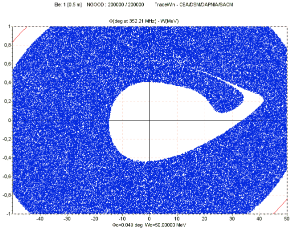

2 f0, constant Φ_s

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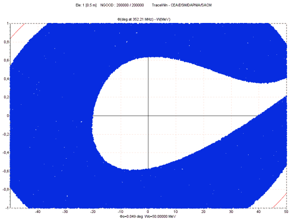

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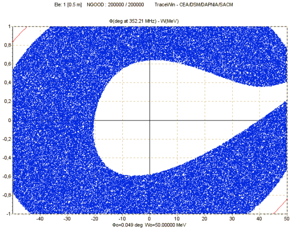
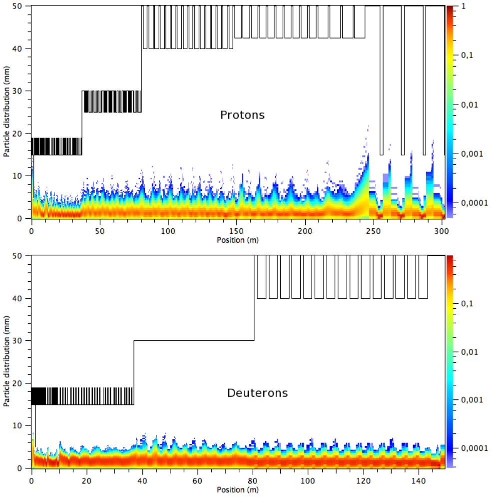


2 f0, matched Φ_s

Outline

Start to end simulation

- Once the reference design has been set up, it is necessary to evaluate the collective effects in presence of perfect or imperfect elements.
- To tend to “realistic” simulation, it is needed to perform start-to-end transport for estimating the impact of halo produced at low energy in the high energy part.



[Duperrier, EURISOL TM 2009]

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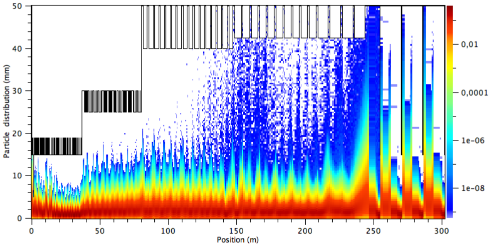
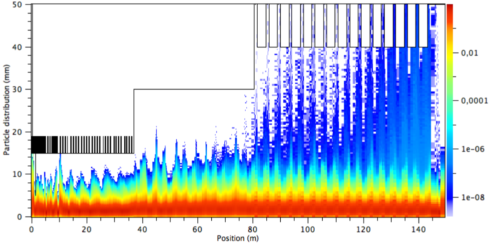
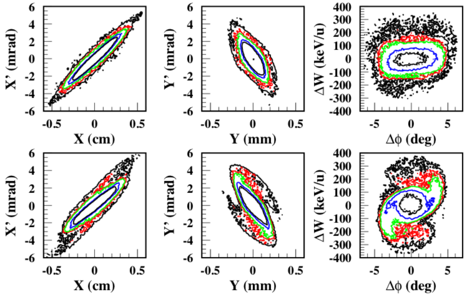




[Duperrier, EURISOL TM 2009]

- 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...

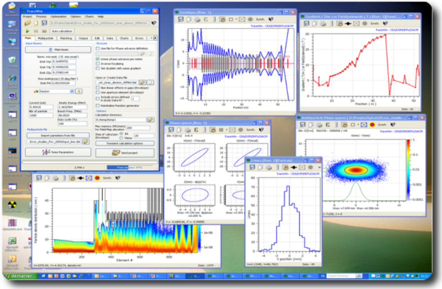


P.N. Ostroumov et al

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) [Zhang, EPAC 2008]

Review of Beam Dynamics Issues in MW Class Ion Linacs

R. Duperrier

MW ion linacs

Beam Physics

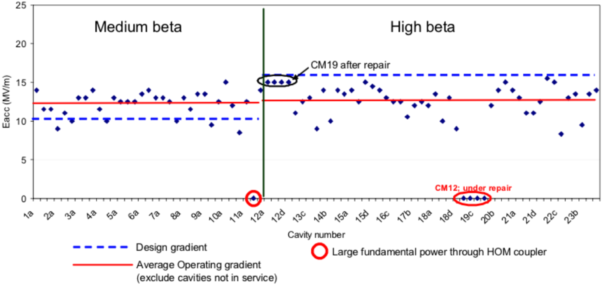
Single particle dynamics

Multiparticle dynamics

Observed issues

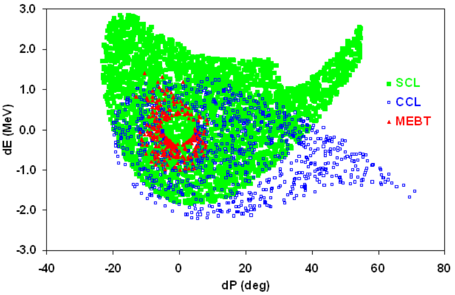
Conclusions

- 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, the operational gradient in the SC part may vary widely from -100 % to +80%.
- Future errors studies for intense linacs will have to include a huge gradient spread in the cavity set.



SNS feedback (2/2) [Zhang, HB 2008]

- Unexpected longitudinal tails have been measured at the entrance of the SC section.
- Is it the sign of the effect of the shrinkage of the acceptance at the frequency jump?
- Reduction of beam loss when the transverse phase advance is decreased would confirm this hypothesis.



SCL Acceptance, MEBT Particles and CCL Particles

SNS feedback (2/2) [Zhang, HB 2008]

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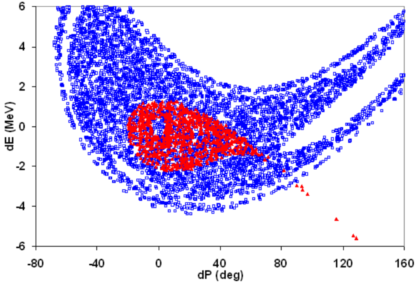

Φ_s = -35°(design: -20°), sacrifices ∼100 MeV output energy

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)

90° resonance stop band

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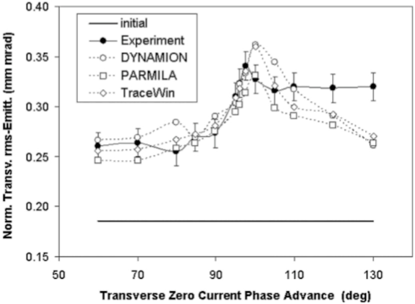


Outline

Conclusions

- Beam dynamics in a high intense ion linac is a very rich field of physics.
- It requires skills in plasma physics as well as in statistical physics.
- Supported by activities of present and future accelerators, this domain progressed during the last decades and allows now very fine simulations based on a more mature knowledge of the beam behavior.
- Learning from SNS and on going studies, future MW linacs with beam loss in the W range are within reach.

Neutralization stability for bunched beam

- The beam space charge force for the neutralizing particle acts as a periodic focusing channel in time.
- Baconnier shown that to get a stable motion for this particle, the bunch repetition frequency has to be:

$$f_b > \sqrt{\frac{r_e \cdot c}{2e \cdot m_p} \cdot \frac{I_b}{\beta R^2}}$$

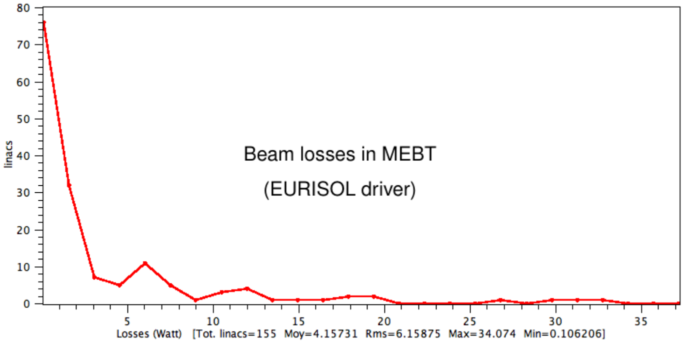
with m_p is the proton mass in a.m.u., r_e the classical radius of the electron, I_b the beam current and R its radius [Baconnier, CERN-PS-PSR-84-24-REV-2].

Design of the architecture based on single particle dynamics

- Phase advances per focusing period for zero current beams must be below 90°.
- Phase advance per meter ($\bar{\beta}$) must change adiabatically along the linac despite of many lattice transitions (different types of focusing and inter-cryostat spaces).
- Choose working points to avoid parametric resonances (space charge and rf defocusing).
- **Beam matching in the lattice transitions is very important to avoid emittance growth and beam halo formation.**
- Short focusing periods in the Front End to maximize acceleration because $\sigma_l < \sigma_t < 90^\circ$ and $\sigma_l \sim E^2 L_p / \beta^{3/2}$.
- To respect these rules, projection of transit time factor can't be used anymore. An optimization based on single particle transports is necessary. The optimum may be found with a space parameter discretization.

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!

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

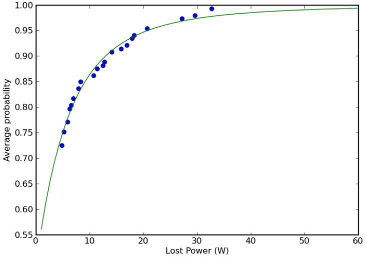
$$H_{\xi\sigma\mu}(p) = exp\left(-\left(1+\xi\frac{p-\mu}{\sigma}\right)^{-\frac{1}{\xi}}\right) \quad (1)$$

  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).

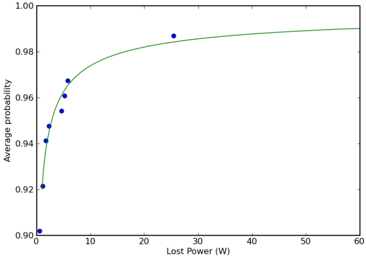
GEV distribution

(EURISOL driver: proton case)

MEBT collimator



HEBT dipole



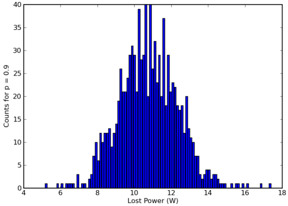
P(losses > 20 W) = 5%

P(losses > 10 W) = 3%

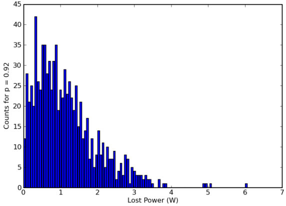
Confidence intervals at $\pm 2\sigma$

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