Intrabeam Stripping

Valeri Lebedev
Fermilab

Project X technical meeting

March 2, 2010

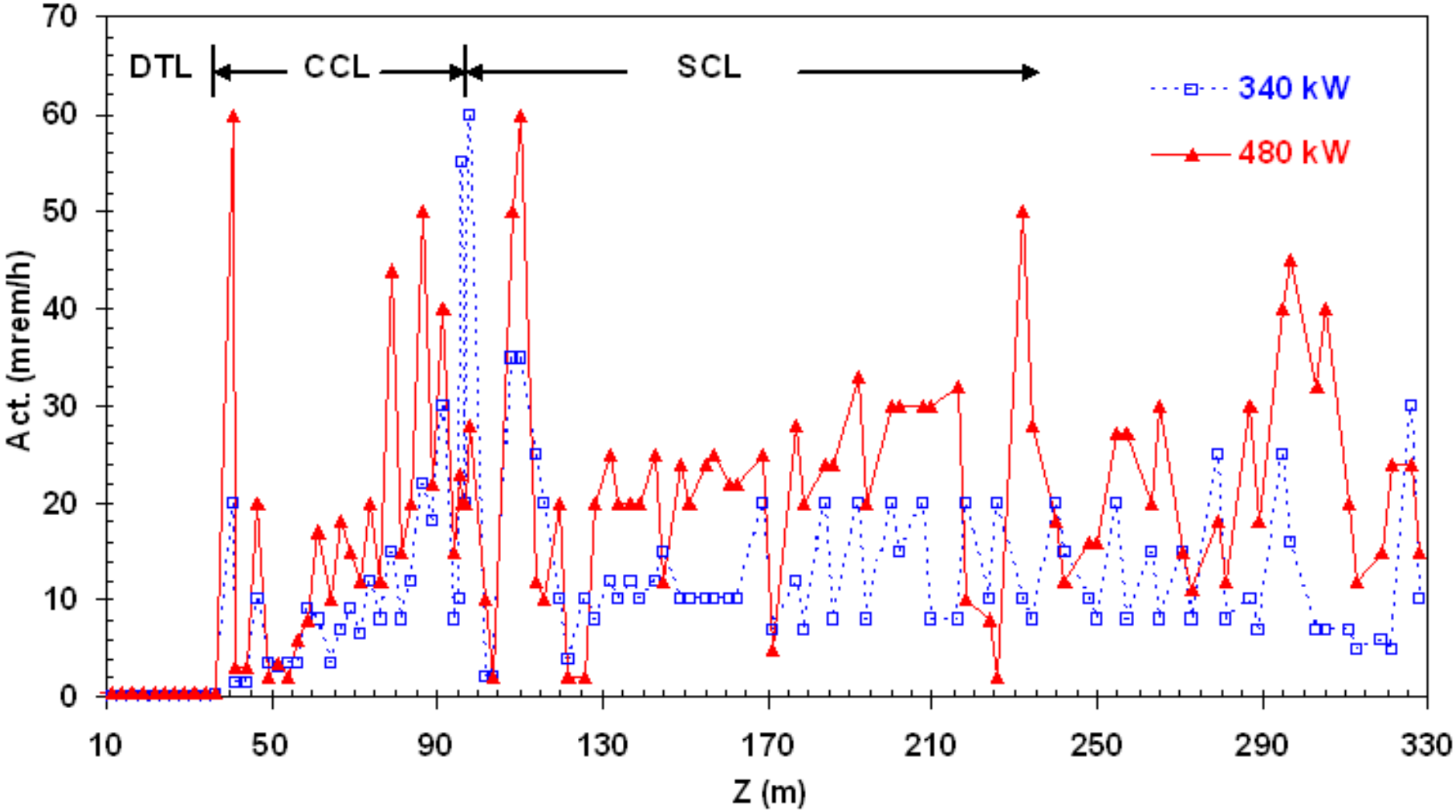
Introduction

- SNS has beam loss in the SC linac which has not been predicted in simulations
  - The loss level estimate results in ~1e-5
    - Residual radiation in quads ~30 mrem/hour @ 30 cm
  - Loss is comparatively uniform along the linac
  - Loss is very weakly affected by scraping at a low energy
  - Loss reduction in the high energy part was achieved by decrease of betatron phase advance (increased beam size)
- It is not big deal for SNS because it is mainly intercepted by warm quads limiting the linac aperture
- It is expected to be much worse in the Project X if there are no warm quads/scrapers
- This loss generated a mistrust to the beam dynamics simulations and software which did not predict it
- Intellectual challenge for SNS folks
- High priority item for Project X
  - It can severely affect the design choices

From "BEAM STUDIES AT THE SNS LINAC"

by *Yan Zhang* On behalf of the SNS team

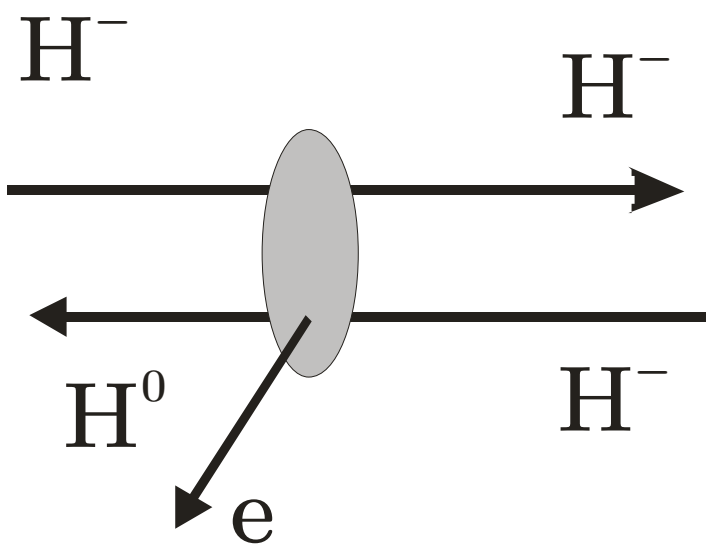
"42-nd ICFA, HB2008, Nashville, USA, August 25-29, 2008"



Linac residual activations after neutron productions

Intrabeam Stripping

- Experimental observations rather point to the intrabeam scattering than to the tail generation due to non linear fields
- Preliminary analysis shows that the intrabeam stripping has to be the major offender
  - Beam loss due to intrabeam scattering is smaller by 3-to-4 orders of magnitude
  - Additional experimental tests are planned to be carried out at the SNS before the end of March



Stripping Crossection

- 3 regions of energy
  - High
    - Born approximation works; a weak dependence of crossection on the charge sign of stripping particle
  - Medium
    - only numerical quantum mechanics simulations can result in a reasonable accuracy
  - Low
    - energy is so small that H- cannot approach each other and stripping does not happen

      $\Rightarrow$ Note that if one H^- is replaced for a proton the particles are attracted to each other and the interaction is amplified

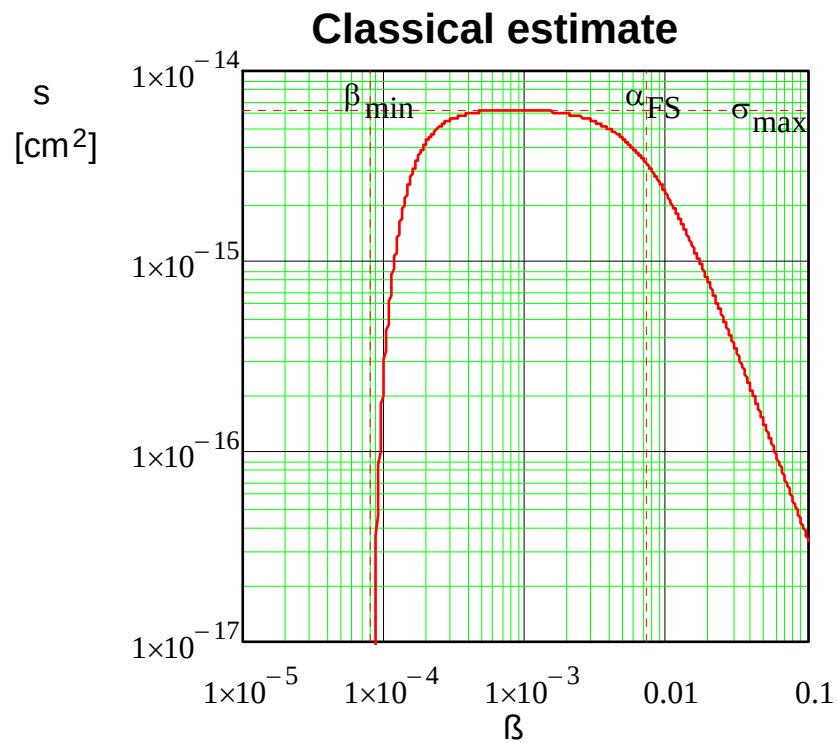
Simple Classical Estimate of the Crossection

$$\left.\begin{aligned} \Delta p = F\,\Delta t = \frac{2e^2}{r^2}\frac{r}{\mathrm{v}} = \frac{2e^2}{r\mathrm{v}} \\ I = \frac{\Delta p^2}{2m_e} \end{aligned}\right\} \Rightarrow \sigma_{strip} = \frac{2\pi e^4}{m_e c^2 I}\frac{1}{\beta^2}$$

I = 0.754 eV

- This estimate stops to work at velocities which are smaller than the electron velocity in the atom: $\beta \approx \alpha_{FS} \approx 1/137$
- That results in: $\sigma_{max} \approx 6.4 \cdot 10^{-15}$ cm^2
- Repulsion stops stripping for velocities below

$$\beta_{\min} = \sqrt{\frac{2r_p}{\sqrt{\sigma_{\max}/\pi}}} \approx 8 \cdot 10^{-5}$$



Stripping Cross-section in the Born approximation

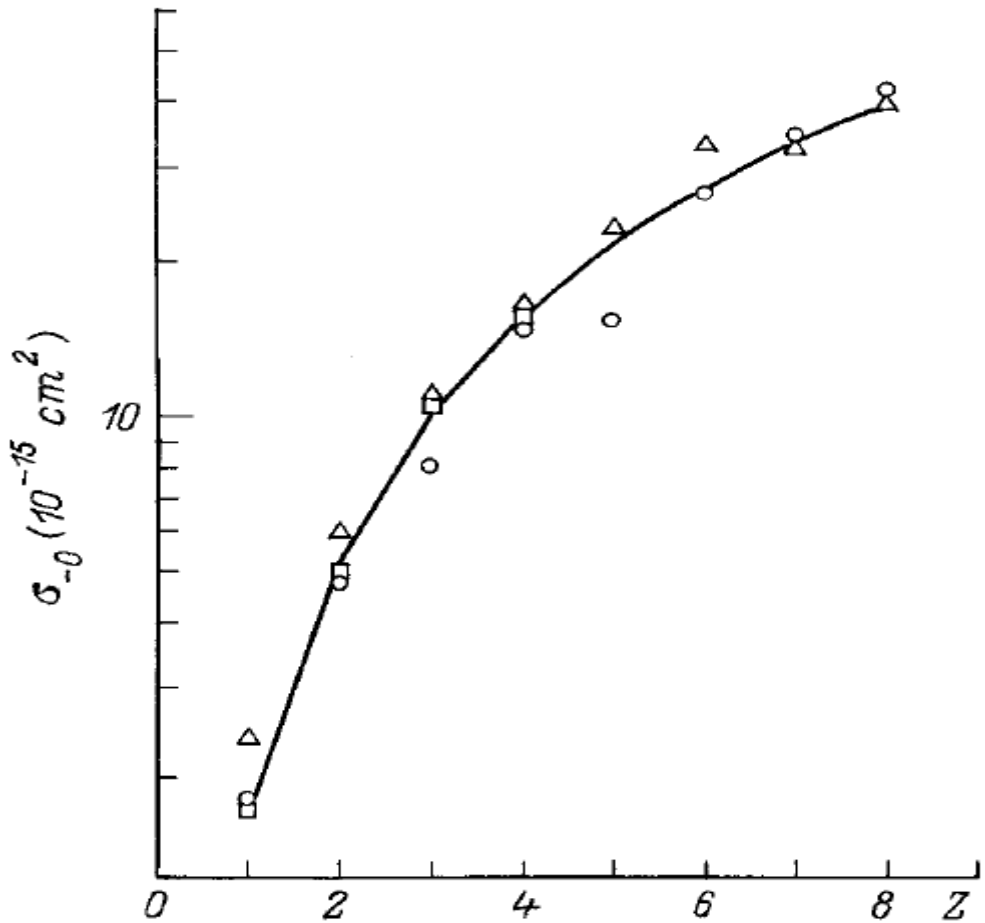
$$\sigma_{strip} = 152.2 a_0^{\,2} Z^2 \left(\frac{\alpha_{FS}}{\beta}\right)^2 \ln\left(\frac{3.2}{Z}\left(\frac{\beta}{\alpha_{FS}}\right)^2\right) \quad ,$$

$$\beta << \alpha_{FS}$$

where $a_0 \approx 5 \cdot 10^{-8}$ – Bohr radius

Russian Physics Journal, Vol. 42, No.l, 1999
NEGATIVE HYDROGEN-ION NEUTRALIZATION IN COLLISIONS WITH FASTHIGHLY CHARGED IONS
A. B. Voitkiv, N. Griin, and W. Scheid

The neutralization of negative hydrogen ions is considered for collisions with fast multicharged ions (including relativistic collision velocities) by means of an approach that gives a simple analytic expression for the neutralization cross section in the parameter region where the Born approximation is inapplicable.



H⁻ stripping with multicharged ions: theory versus experiments, E_{cm}=200 keV

Numeric Solution of Quantum Mechanics Problem

PHYSICAL REVIEW A VOLUME 33, NUMBER 3 MARCH 1986

Stripping of H^- in low-energy collisions with antiprotons: Classical-trajectory Monte Carlo calculation

James S. Cohen
Theoretical Division, Los Alamos National Laboratory, University of California, Los Alamos, New Mexico 87545

Giovanni Fiorentini
Sezione di Pisa, Istituto Nazionale di Fisica Nucleare, I-56100 Pisa, Italy
and Istituto di Fisica, Universita di Pisa, I-56100 Pisa, Italy
(Received 4 November 1985)

The classical-trajectory Monte Carlo method has been used to determine the cross section for stripping of H^- in collisions with $\bar{p}$. The calculations were done for relative velocities from $0.015\alpha c$ to $1.0\alpha c$. A maximum cross section of about 40 $Å^2$ is found, somewhat smaller than previous estimates.

It is much more trustable than a classical estimate but is still approximate computation

Results of numerical calculations are presented in the table

TABLE I. CTMC results for $H^- + \bar{p}$ stripping obtained utilizing the vector-polarizable H core.[a]

$E_{c.m.}$ (eV)	$v_{rel}(\alpha c)$	$b^{ion}_{max}(a_0)$[b]	$b_{max}(a_0)$[b]	N_{tot}	N_{ion}	$\sigma_{ion}(10^{-16}\ cm^2)$[c]
2.81	0.015	2.22	6.124	75	1	0.4±0.4
5.00	0.02	5.68	9.798	75	18	20.3±4.2
11.25	0.03	7.27	9.798	150	59	33.2±2.8
31.24	0.05	8.09	11.314	200	71	40.0±3.8
125.0	0.1	9.29	11.314	200	67	37.7±3.8
499.9	0.2	9.56	11.314	200	61	34.3±3.7
1999.7	0.4	9.19	11.314	200	60	33.8±3.6
4499.3	0.6	10.62	12.649	500	94	26.5±2.5
12 498.0	1.0	8.02	11.314	400	68	19.1±2.1

Fitting Formula for Stripping Crossection

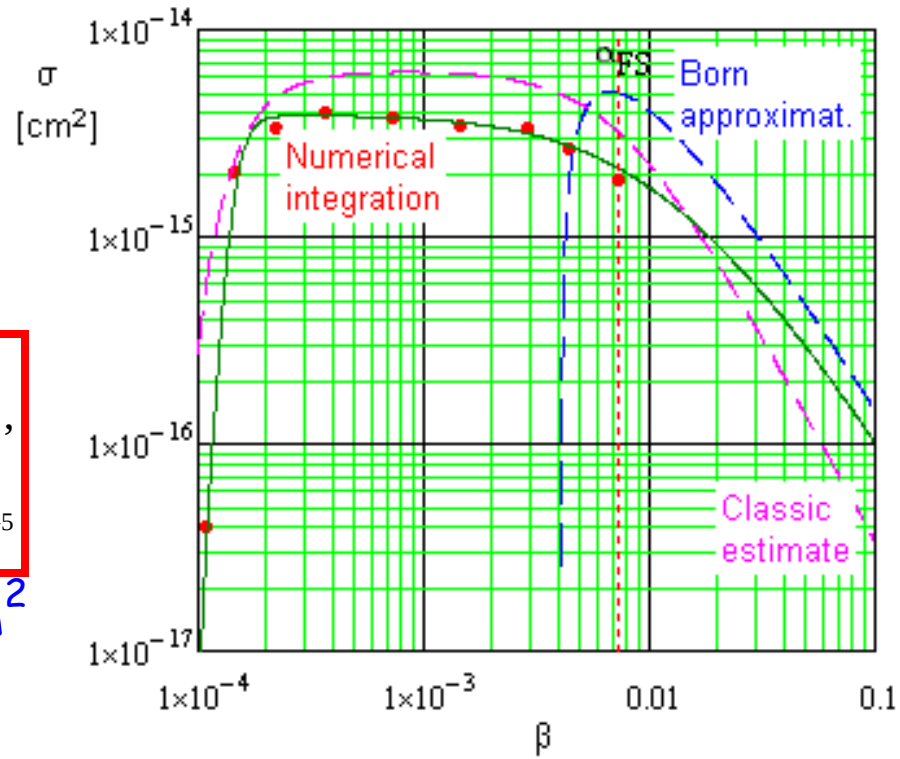
- There is the experimental result from LEAR ("Measurements and surprises with H- ions" CERN/PS 88-06)

*Table 1: Stripping Cross – Section at v = 0.0004*c*

Model	σ (10^{-15} cm^2)
This Measurement	3.6 ± 1.0
Four – body pH$^-$ CTMC ([9])	3.24 ± 0.32
Three – body pH$^-$ CTMC ([10])	3.32 ± 0.28
Single particle approximation ([11])	18

- All these results are consistent with decent accuracy
- Uniting them we obtain the fitting formula

$$\sigma_{strip} = 120 a_0^{\,2} \left(\frac{\alpha_{FS}}{\beta + \alpha_{FS}} \right)^2 \frac{(\beta - \beta_m)^6}{(\beta - \beta_m)^6 + \beta_m^{\,6}} \ln\left(3.2 \left(\frac{\beta + \alpha_{FS}}{\alpha_{FS}} \right)^2 \right), \quad \beta \geq \beta_m = 7.5 \cdot 10^{-5}$$



- Crossection has a plateau at $4 \cdot 10^{-15}$ cm^2 in the velocity range $2 \cdot 10^{-4} < \beta < 4 \cdot 10^{-3}$

What about Stripping with Protons?

- As expected the crossection is much larger at low velocities
- This paper presents only fraction of the crossection $H^- + H^+ \rightarrow H_2^+ + e$
- Other contribution comes from the direct stripping: $H^- + H^+ \rightarrow H^0 + H^+ + e$

J. Phys. B: Atom. Molec. Phys., Vol. 11, No. 21, 1978. Printed in Great Britain

LETTER TO THE EDITOR

H_2^+ formation in low energy H^+–H^- collisions

G Poulaert, F Brouillard, W Claeys, J W McGowan† and G Van Wassenhove

Institut de Physique Corpusculaire, Université Catholique de Louvain, Sciences 1, Chemin du Cyclotron 2, B-1348, Louvain-la-Neuve, Belgium

Received 11 August 1978, in final form 11 September 1978

Abstract. $H^+ + H^-$ associative ionisation cross sections over the relative energy interval 0·001–3 eV have been measured in a merged beam experiment. The energy dependence below 1 eV is found to be $E^{-0.9}$ while the cross section at 0·003 eV is 1.5×10^{-14} cm^2.

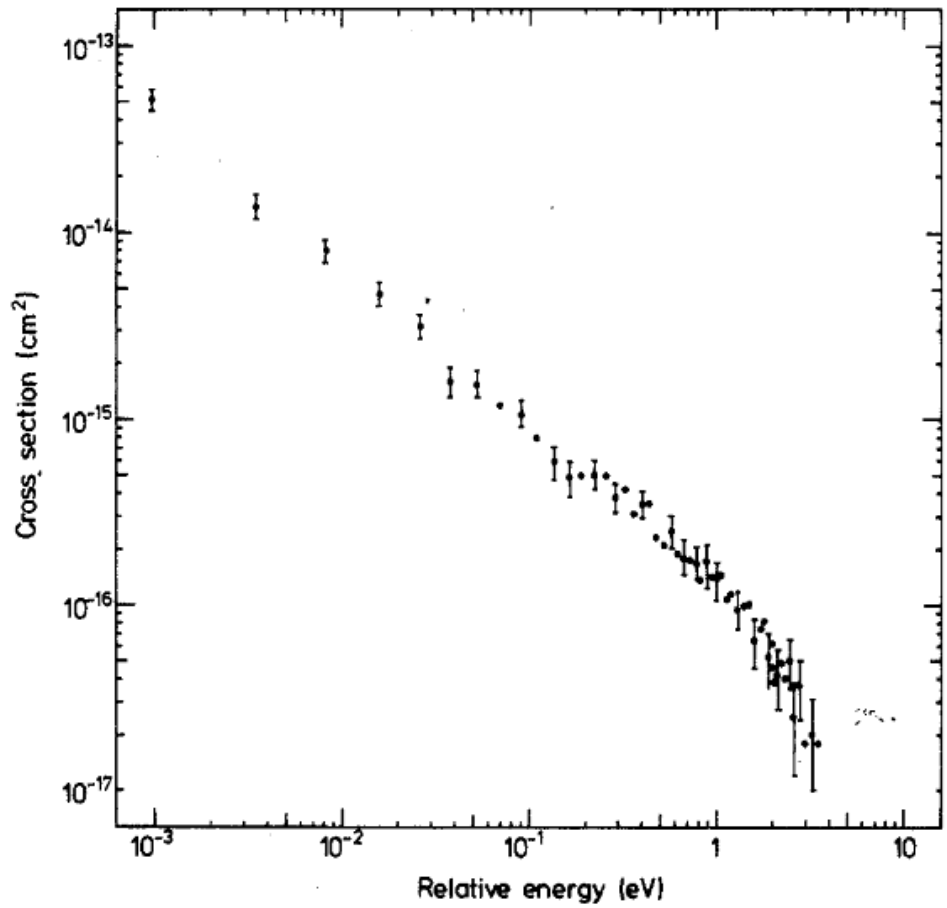
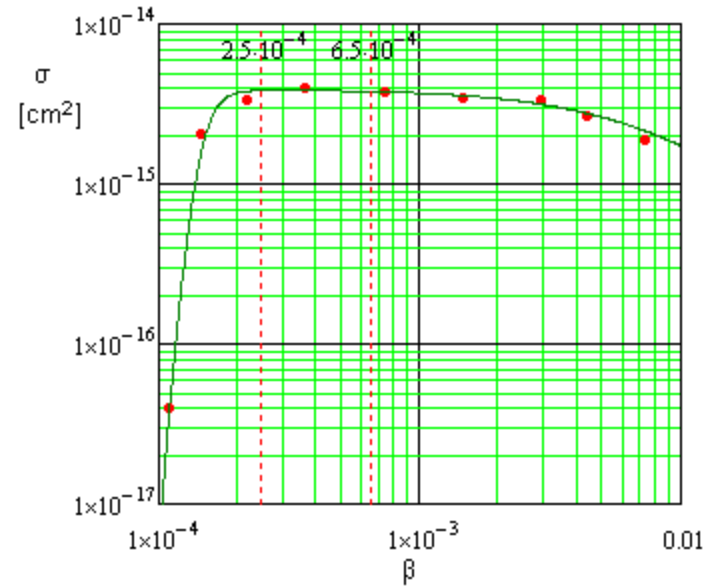


Figure 2. Cross section for the associative ionisation: $H^+ + H^- \rightarrow H_2^+ + e$.

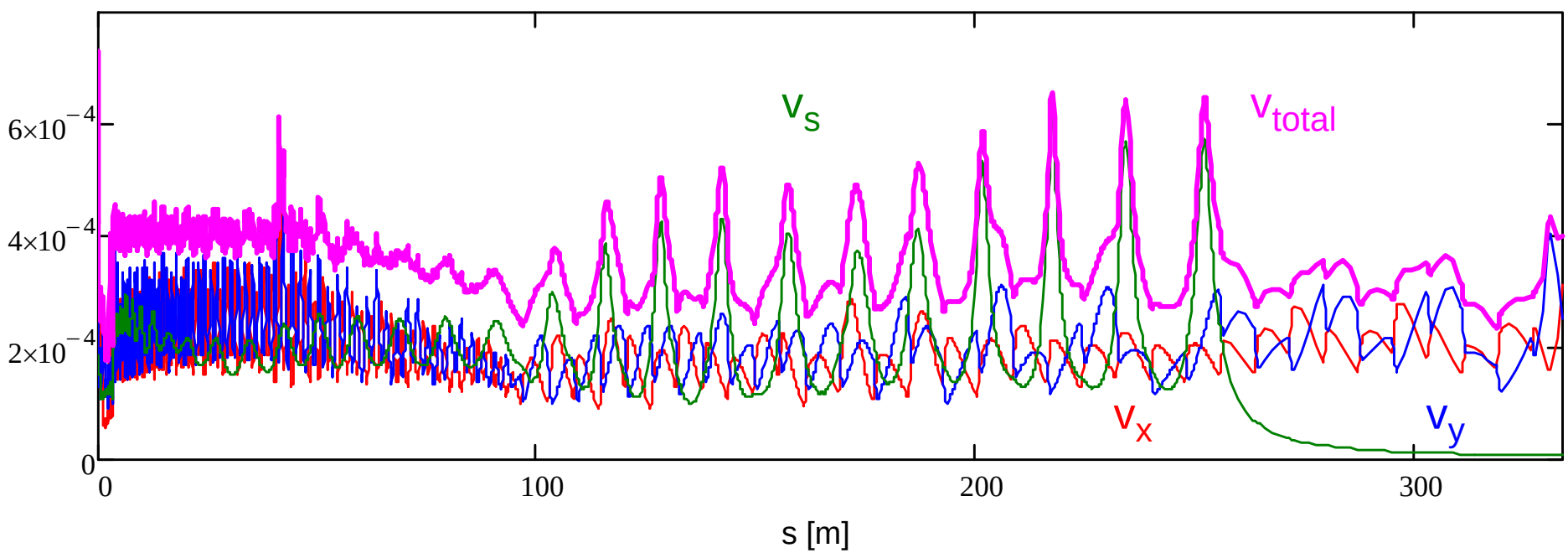
Particle Velocities in the Beam

- In the course of beam motion the rms particle velocities are on the plateau of beam crossection and its variations can be neglected in the averaging over distribution
- For Gaussian distribution

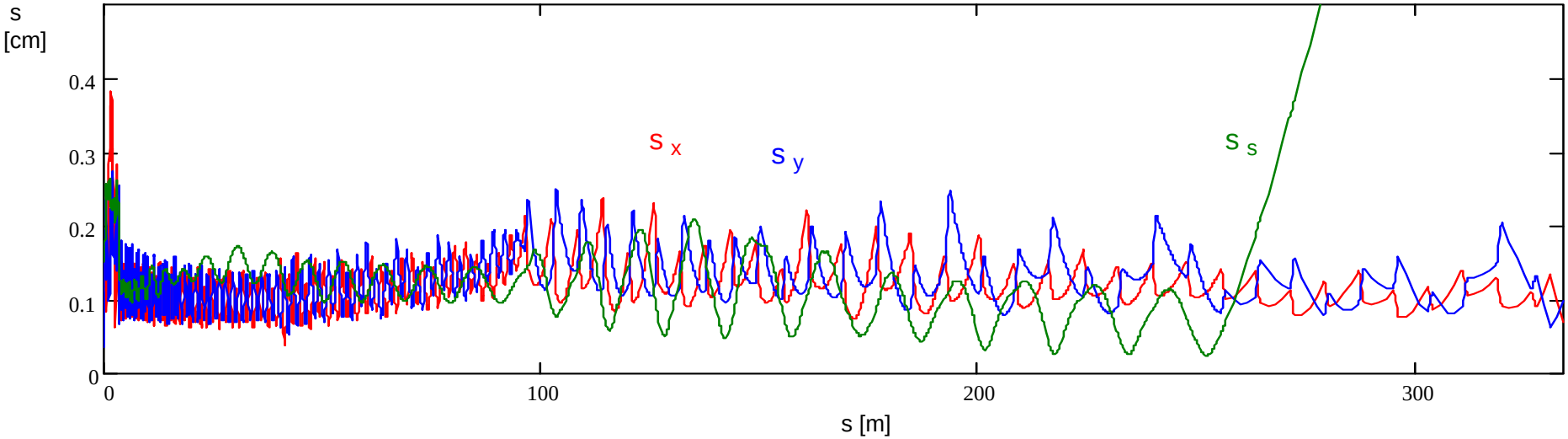
$$\frac{1}{N}\frac{dN}{ds} = \frac{N\sigma_{strip}}{4\pi\sigma_x\sigma_{yx}\sigma_s\gamma^2}\sqrt{\gamma^2\overline{\theta_x^{\,2}} + \gamma^2\overline{\theta_y^{\,2}} + \overline{\theta_{\|}^{\,2}}}$$



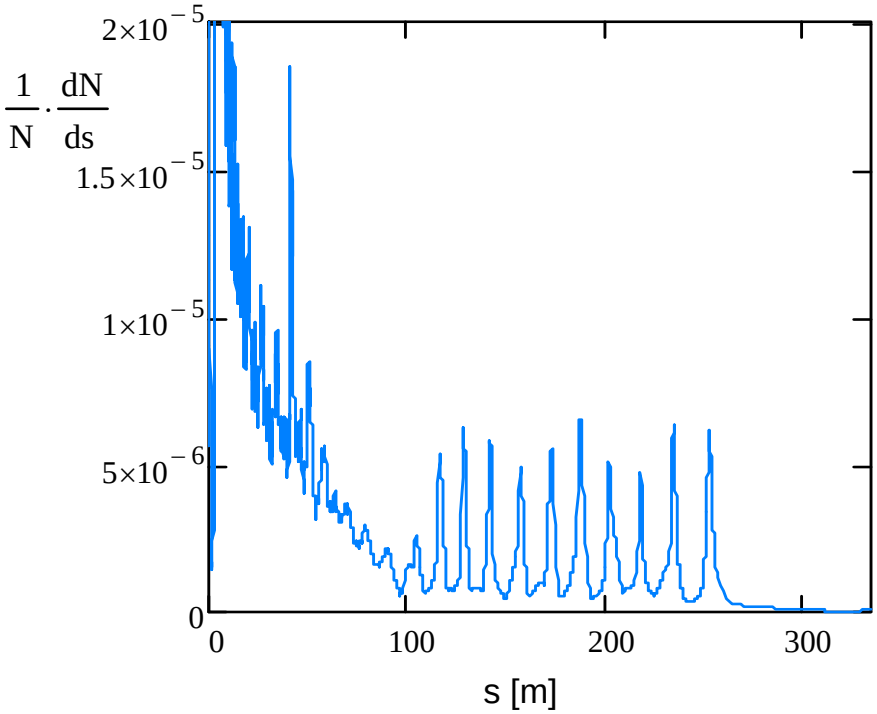
Total, transverse and longitudinal rms velocities in the beam frame for SNS (v/c)



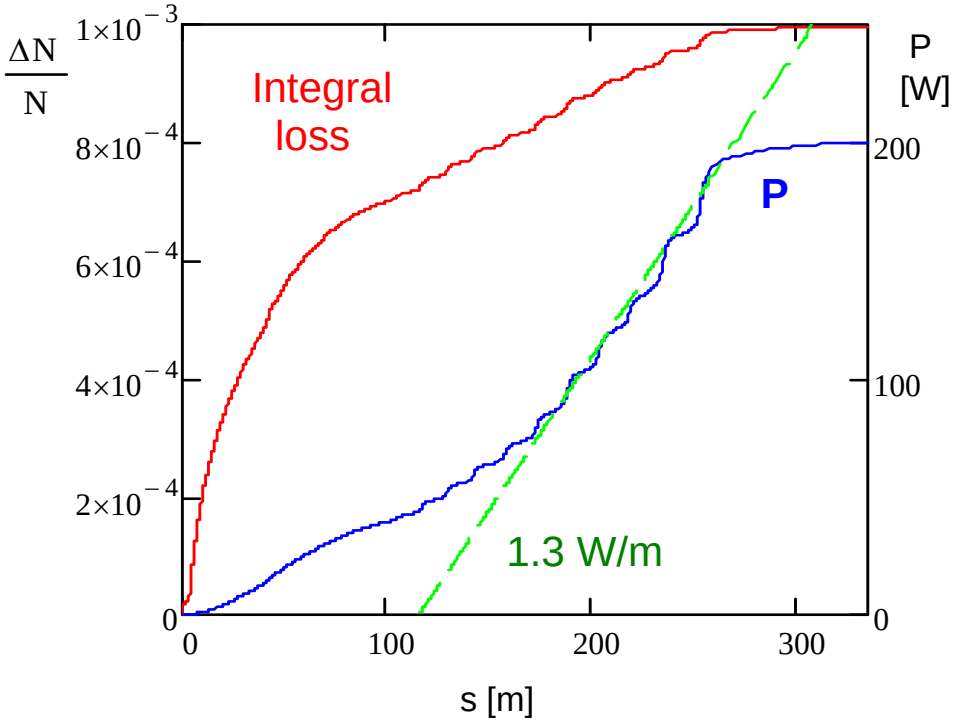
Beam Loss due to Intrabeam Stripping in the SNS



Relative particle loss [1/m]



Integral particle and power loss [W]

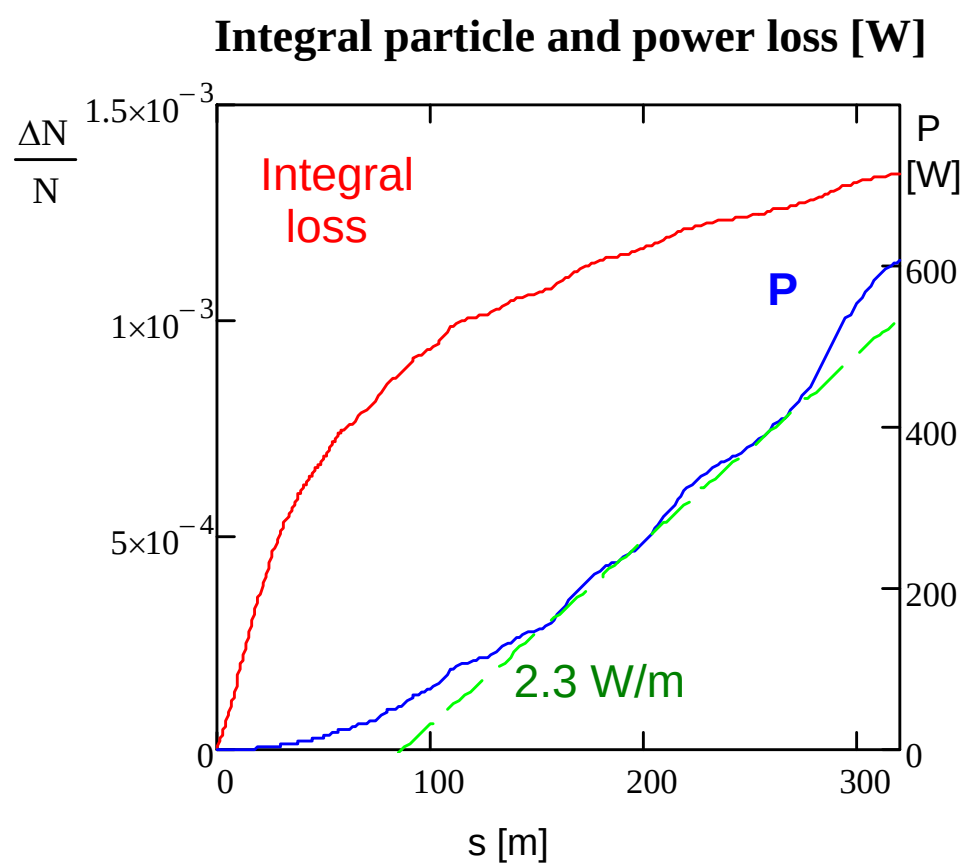


Comments about Calculation of the SNS Intrabeam Stripping Loss

- This calculation overestimates the particle loss
  - The longitudinal beam size is taken from the SNS simulations
  - Measurements show about twice longer beam in the end of SC linac

Intrabeam Stripping for Project X

- Almost twice larger loss than in the SNS
  - Tighter focusing in the SC linac
  - Shorter bunch in the 1.3 GHz linac results an increased loss at the linac end
- Further optimization will reduce the loss
  - Factor of 2 is a reasonable expectation



Integral particle and power losses along the Project X 3 GeV linac; I_{peak}=10 mA, 162.5 MHz RFQ

Conclusions

- Intrabeam striping will make major contribution to the particle loss at the energy above ~0.5 GeV
- It results in an uniform particle loss along the machine
- Its effects have to be taken into account in the machine design
  - Loss interception by warm collimators
  - Increased beam size where it is possible
  - RFQ operating at 162.5 MHz increases particle loss twice relative to the 325 MHz RFQ
- Previous measurements and calculations of the stripping crossection are sufficiently reliable and do not require additional calculations or specialized experiments
- Additional study of intrabeam stripping will be carried out in the SNS