BEAM INSTRUMENTATION FOR HIGH-INTENSITY, MULTI-GeV SUPERCONDUCTING LINACS*

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Abstract

A number of high-intensity, multi-GeV superconducting RF (SRF) proton or H$^-$ linacs are being developed or proposed throughout the world. The intensity frontier, having been identified as one leg of the future of particle physics, can be addressed by the development of such a linac. All these accelerators will place strict demands on the required beam diagnostics, especially in the development of none or minimum invasive monitors such as beam profile and halo monitors.

An H$^-$ / proton beam test facility is currently under construction and commissioning at Fermilab. It serves as a test bed for the development of critical beam manipulation and diagnostics components for the anticipated Project X, Fermilab's SRF multi-MW, multi-GeV linac. The paper will discuss the beam diagnostic needs for these high-intensity linacs in particular the role of the Project X test facility for development and testing of these beam instrumentation systems.

INTRODUCTION

Table 1: High Power SRF Linacs

	SNS	SPL	ESS	Myrrha	PX
E [GeV]	1,3	5	2.5	0.6	3
P [MW]	3	4	5	2.4	3
I_{pulse} [mA]	42	40	50	n/a	n/a
I_{ave} [mA]	2.5	0.8	2	4	1
duty fact. [%]	6	2	4	CW	CW
pulse len. [ms]	1	0.4	2	n/a	n/a
rep. freq. [Hz]	60	50	20	n/a	n/a

Table 1 gives an (incomplete) overview of existing (SNS) and planned high power SRF linacs for protons or H$^-$. Some of the high level parameters presented are anticipated after upgrades or improvements. All facilities have a multi-MW beam power at high kinetic energies and therefore operate beams with high risk potential to damage or destroy accelerator components, if miss-steered or of insufficient quality. Already small beam losses can cause major trouble in close proximity of SRF accelerating structures. As a rule of thumb the maximum beam loss along the SRF linac should not exceed an equivalent of 1 W/m.

A precise control and high stability of the guide fields is mandatory, and has to be verified by a set of reliable beam diagnostics, distributed along the linac. Essential are the measurement of

- Beam trajectory – BPMs
- Beam phase, TOF – BPMs, WCM, EO-methods
- Beam intensity – toroids, WCM
- Beam losses – BLM / TLM (e.g. ion chamber)
- Beam profile / emittance and halo – SEM, wire scanner, *Allison* scanner, slits, laser diagnostics, e-beam scanner, IPM, vibrating wire, etc.
- Bunch profile and tails – *Feschenko* monitor, laser diagnostics

Most beam parameters can be diagnosed with non-invasive, i.e. electromagnetic methods, or by detecting particle showers outside the vacuum system. The non-invasive measurement of transverse and/or longitudinal profiles however, remains challenging, particular if photo detachment methods (laser diagnostics) cannot be applied, i.e. monitoring of proton beams. The cryogenic environment of a SRF linac gives additional challenges for the beam instrumentation hardware, thus the segmentation and warm diagnostics sections along the linac are crucial. Except for simple BPM pickups and BLM detectors outside the beam vacuum system, no beam diagnostic detectors are foreseen in the cryogenic parts of the planned SRF linacs. Even if located in warm sections, but still nearby SRF structures, invasive diagnostics may produce too much unwanted spill of dissociated material, and can contaminate the niobium surface of the cavities. And finally, invasive diagnostics are of very limited use in the final, high beam power sections of the accelerator, just because of too high residual losses, even a single wire interacting with <0.1 % on a multi-MW beam produces kW beam losses.

PROJECT X

Fermilab's anticipated high intensity accelerator future is called "Project X" [1]. Major goals are the support of high energy physics (HEP) at the intensity frontier to study rare processes (kaon and muon physics), research in nuclear physics and energy, as well as a staged path towards science at the energy frontier, i.e. utilize Project X as a source for a neutrino factory and/or muon collider.

Central element of the Project X accelerator complex will be a 3 GeV SRF CW linac, accelerating H- to 3 MW beam power (see Figure 1). A system of magnetic and RF beam splitters feeds various experiments simultaneously, as well as a pulsed SRF linear accelerator extension – in favour to a RCS – to accumulate H$^-$ particles using foil or laser stripping at 8 GeV into the existing Recycler / Main Injector ring accelerators.

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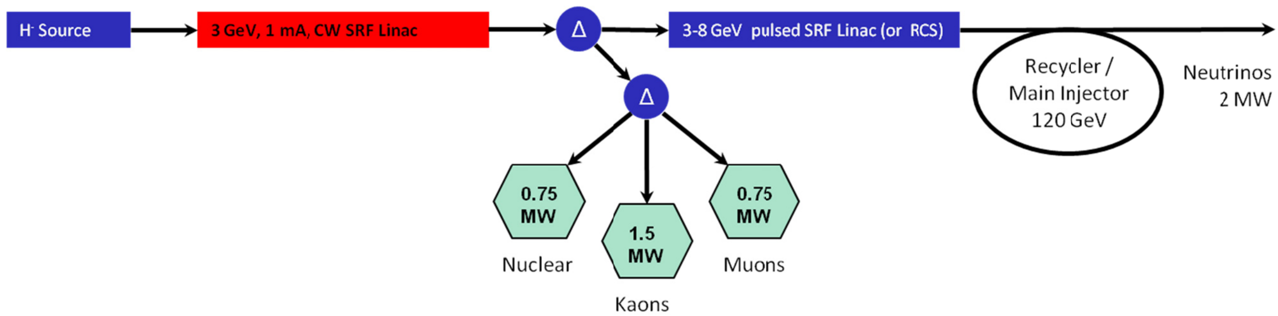

Figure 1: Conceptual layout of Project X, with a 3 GeV, 3 MW SRF H- linac as central accelerator element.

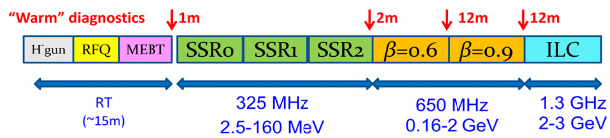

Figure 2: Project X CW linac baseline RF configuration.

Starting at 2.5 MeV beam energy, after the RFQ and MEBT, SRF acceleration technology will be used. Figure 2 shows the preferred layout, based on *n x* 325 MHz. A total of 109 focusing elements, solenoids in the 325 MHz spoke resonator sections, and quadrupoles in the 650 / 1300 MHz elliptical cavities, are integrated in the cryomodules. The same quantity of beam position monitor (BPM) pickups is required, and has to be assembled in close proximity to these magnets, thus also compatible to operate at 1.8 K temperatures inside the cryomodule.

As the layout suggests, the cryo-string will be sectioned in three or more parts, allowing dedicated warm diagnostic insertions for the measurement of beam intensity, profile, and other parameters. Beam phase and time-of-flight however, can be evaluated at each BPM utilizing the phase detection in the digital I-Q signal processing with respect to the RF derived precision clock. Also in the warm insertions we prefer non-invasive beam diagnostics, i.e. photo detachment methods based on lasers for the beam profile measurement.

BEAM TEST FACILITIES

Beam studies on mission critical components and technical systems are mandatory for the success of the projects. This includes beam diagnostics, from a technical aspect, as well as for verification of beam dynamics and simulations. Two test accelerators are currently under construction and commissioning:

ILC Test Accelerator

The ILC test accelerator (ILCTA) is located at the Fermilab *New Muon Lab (NML)* building [2]. An electron beam, delivered by a RF photoinjector, will be used to test a complete RF unit, i.e. a string of three ILC/TESLA/XFEL style cryomodules, each equipped with eight 9-cell 1.3 GHz β=1 cavities. The cryomodule also holds a superconducting quadrupole/correction magnet package, and flanged to this a BPM pickup. Beside this "cold" BPM and a BLM detector operating inside the cryomodule, most of the installed beam diagnostics at ILCTA is dedicated to electron beams.

Project X Test Accelerator

Most of the "interesting" beam dynamics in a hadron linac is space charge originated and takes place in the low energy areas of the accelerator, at the source, LEBT, RFQ, and MEBT. The MEBT of Project X is particular challenging, as it has to include an ultra-broadband beam chopper and collimator to format various bunch structures for the different end-users (experiments), i.e. to chop individual 325 MHz bunches.

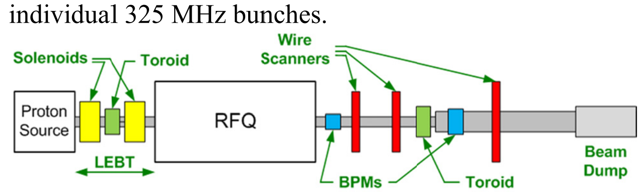

Figure 3: Initial configuration of the Project X Test Accelerator (movable beam slits not shown).

The Project X Test Accelerator at the Fermilab *Meson Detector Building (MDB)* – formally known as *High Intensity Neutrino Source (HINS)* – addresses the need of hardware R&D and hands-on beam dynamics studies at low energies [3]. Figure 3 shows the initial configuration utilizing a pulsed proton source, a LEBT with two solenoids, and a 2.5 MeV 325 MHz RFQ, followed by a simple diagnostics section and beam dump. An H^- source and other beam-line configurations will follow, to test the vector modulator concept, an ultra-broadband bunch chopping system, and various other beam diagnostics.

FIRST BEAM MEASUREMENTS

Some preliminary beam measurements have been performed on the initial configuration of the MDB Project X Test Accelerator (Figure 3) [4].

Beam Current

Figure 4 compares the beam currents in the LEBT (upper trace) and in the diagnostics beam line (lower trace). Because of cooling issues of the RFQ the beam pulse is reduced to 50 μsec, while the LEBT transports beam for 500 μsec. The drop in the current from 18 mA (LEBT) to 4 mA (diagnostic beam-line) hints for different charge states transported in the LEBT. The RFQ acts as a filter and the remaining 4 mA at its output are of H^+ charge state (protons).

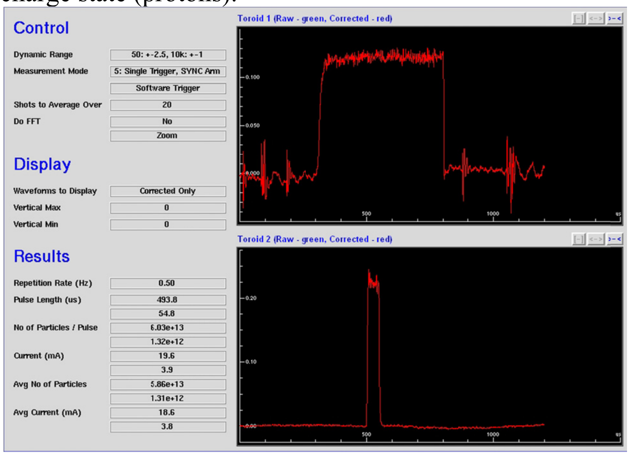

Figure 4: Beam currents in the LEBT (upper trace) and in the diagnostics beam-line (lower trace).

The bunching efficiency of the RFQ is shown in Figure 5. In this graph the toroid signal level and the level of the 325 MHz spectral component of a button-style BPM are compared versus RFQ RF power. The particles are captured at RFQ power levels >300 kW.

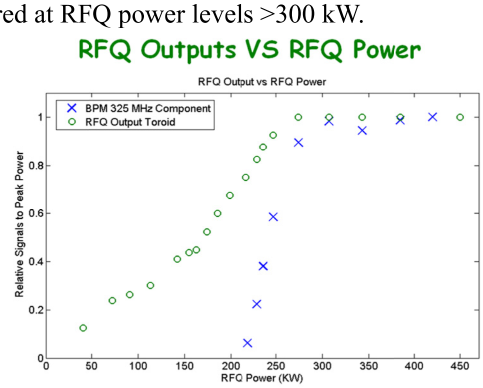

Figure 5: RFQ bunching efficiency.

Transverse Beam Profile

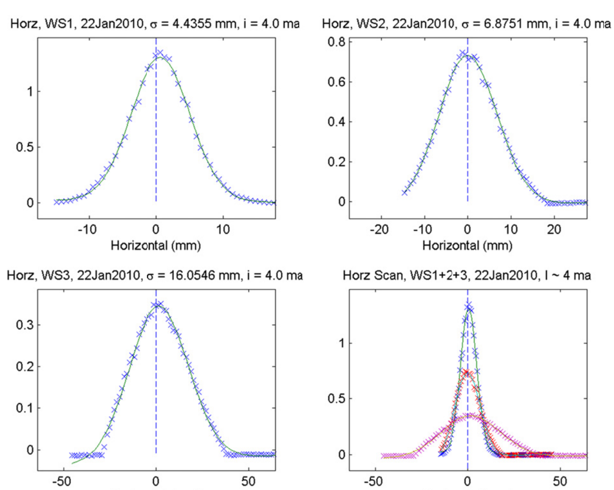

Figure 6: Transverse beam profiles along the MEBT.

The three wire scanners in the 2.5 MeV diagnostics section (Figure 3) allow studies of the transverse beam profile and emittance. Unfortunately the beam diverges rapidly after the RFQ output, and evidently scrapes the beam pipe before reaching the wirescanner WS3 location (Figure 6, lower left plot). Therefore we feel not comfortable to estimate the transverse emittance. The overlay of all three profiles in Figure 6 (lower right plot) demonstrates the rapid, space charge driven beam blow-up in absence of further focusing elements.

Beam Energy

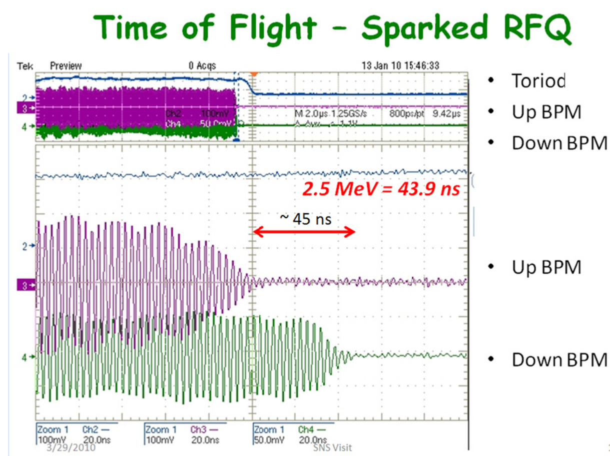

Figure 7: Time-of-flight based beam energy estimation.

The absence of a spectrometer beam-line at the initial setup of the Project X test accelerator make the measurement of the beam energy challenging. The nominal beam energy of 2.5 MeV is equivalent to β=0.073 or 45.8 nsec/m, which we try to verify by a time-of-flight (TOF) measurement between two 0.96 m spaced button-style BPMs downstream of the RFQ. As it is impossible to identify or mark an individual bunch out of the BPM signal, we tried to spark shock the RFQ for an abrupt stop of the beam transport; still it takes 10-15 nsec to kill the beam. However, Figure 7 indicates the nominal 2.5 MeV beam energy.

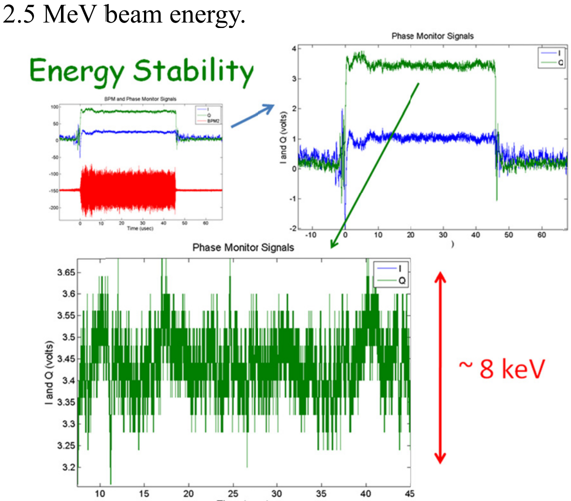

Figure 8: Stability of the beam energy.

Feeding an analog I-Q phase detector with the BPM beam and the RFQ RF signals allows the measurement of the energy stability throughout the beam pulse. Blue and green traces in Figure 8 are the in-phase (I), respectively quadrature-phase (Q) signal components versus beam time. Modifying the phases of the input signals such that the Q-signal is adjusted to 0^0, it returns a pure beam phase, or time signal, demonstrating a stability of <8 keV or 0.3 % of the beam energy.

BEAM INSTRUMENTATION R&D

A variety of beam diagnostics is currently under development to characterize proton, as well as H^- beams of 2.5 MeV energy at the Project X test accelerator [5]. A proposed, more advanced diagnostics beam-line includes a quadrupole triplet to enable transverse focusing for an energy spread measurement in the spectrometer arm. As longitudinal focusing will be unavailable, the bunch shape monitor and the fast *Faraday* cup are located in the upstream area, somehow close to RFQ and triplet. A wire scanner and a beam halo monitor are located before the spectrometer dipole, a laser wire will be installed once the proton source is replaced by a H^- source. Both beam-line arms downstream the spectrometer magnet are equipped with transverse diagnostics, wire scanners, BPMs, at a later stage an SEM multiwire, and of course toroids for beam intensity measurements.

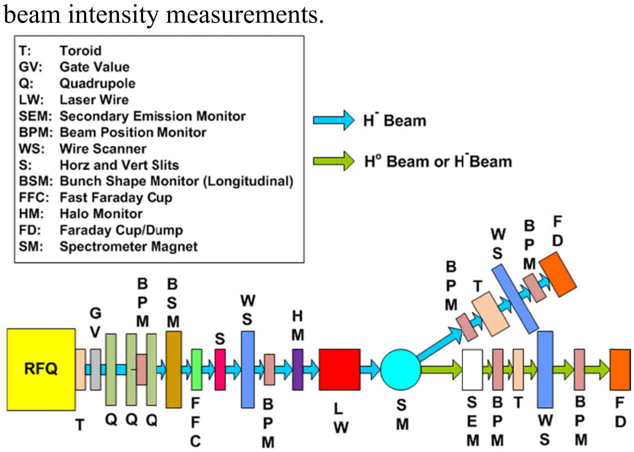

Figure 9: Beam instrumentation R&D at the MDB Project X test accelerator.

Bunch Shape Monitor

The bunch shape monitor is of *Feschenko* style, and minimum invasive to the beam [6]. A thin wire, set to a 10 kV potential, samples a part of the hadron bunch, and generates secondary electrons. A fraction of these electrons, imprinted with the longitudinal distribution of the proton / H^- bunch, are accelerated through a slit. An RF deflector, tuned to 650 MHz rotates the electron bunch, i.e. exchanges the longitudinal with a transverse coordinate, which are sampled by an EMT located behind a stationary slit. The RF deflector cavity phase is shifted to transport different electrons through the slit, and thus determine the longitudinal hadron bunch profile (Figure 10).

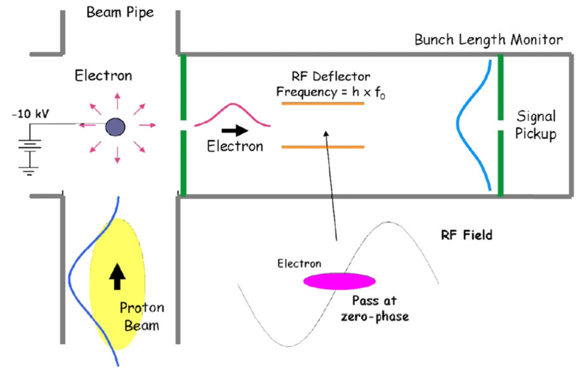

Figure 10: Principle of the *Feschenko* bunch shape monitor.

Fast Faraday Cup

The fast *Faraday* cup (Figure 11) is an invasive element, i.e. total dump of the entire beam. The longitudinal bunch shape is determined by sampling the part of the beam that passes through a 1 mm hole in the ground plane, hitting a mircrowave stripline structure. The signal of the induced charges travel to the stripline ports, and further to a broadband oscilloscope for read-out, represents a copy of the longitudinal particle distribution. The prototype fast *Faraday* cup is developed in collaboration with SNS/ ORNL, and provides >10 GHz bandwidth, however dispersion effects on the external cabling will reduce the usable bandwidth.

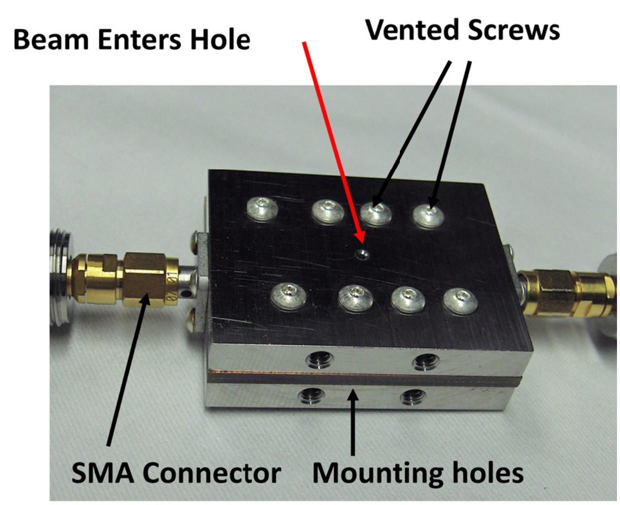

Figure 11: Fast *Faraday* Cup (courtesy C. Deibele / SNS).

The prototype in Figure 11 cannot handle the full, up to ~500 W beam power of the Project X test accelerator. In collaboration with SNS a water cooled, high power unit is under development.

Vibrating Wire Beam Halo Diagnostics

In cooperation with *Bergoz Instrumentation* a minimum invasive vibrating wire monitor will be used to detect the transverse beam halo [7]. A stretched wire, excited at its resonant frequency, with help of a magnetic feedback loop, is moved into the beam halo by a step-motor controlled translation stage. The interaction with the halo particles will change the wire temperature, thus the elongation and therefore the detectable resonant frequency of the wire. The system proved to be very sensitive, changes of 0.01 Hz of the typically 5 kHz nominal resonant frequency are detectable, equivalent to a sensitivity of a few µW in a linear range of 0-100 W beam power.

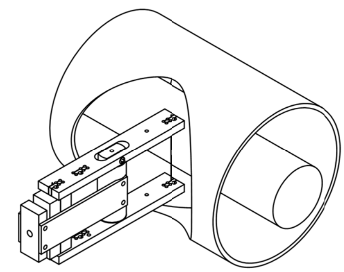

Figure 12: Vibrating wire beam halo monitor (courtesy S.G. Arutunian / J. Bergoz).

Laser Diagnostics

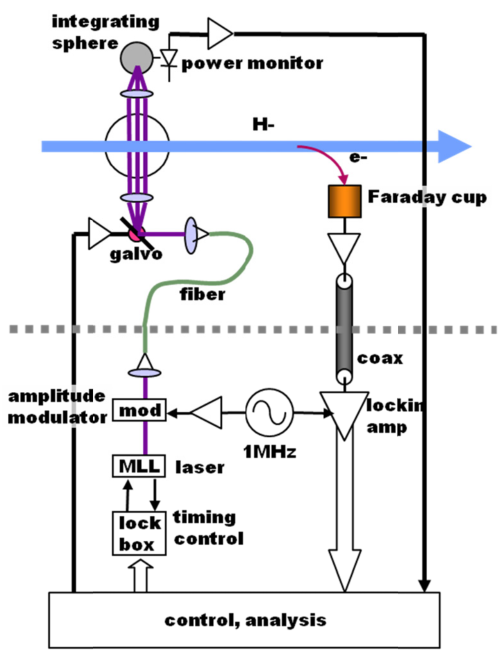

Figure 13: Laser scanner (courtesy R. Wilcox / LBNL).

Non-invasive laser beam diagnostics are applicable as soon as the H^- source becomes operational. In collaboration with LBNL a mode-locked fiber laser system for transverse and longitudinal beam characterization is under development. To avoid expensive, high-power lasers for the photo detachment, we investigate a laser intensity modulation feedback, detectable by a lock-in amplifier, which helps to improve the S/N-ratio and allows the use of commercial, lower power fiber lasers.

Other Monitors

Beam position monitors (BPM), beam loss monitors (BLM) and toroids for beam intensity measurements are used throughout the beam lines at the test accelerators, some also inside the cryostat. Button and stripline style BPMs are under investigation for beam displacement and time-of-flight (beam phase) monitoring, using analog and digital signal processing techniques. The beam phase can be measured by referencing the I-Q data samples to the RF locked clock signal.

Energy Spread Measurement

The beam size includes two terms

$$\sigma = \sqrt{\varepsilon\beta + D^2\left(\frac{\Delta p}{p}\right)^2} \tag{1}$$

The spectrometer dipole (Figure 9) creates horizontal dispersion required to measure the energy spread. Beam optics and wire scanner location have been optimized to maximize D^2_x/β_x. Using a 30^0 sector dipole (ρ = 0.684 m, ℓ_{arc} = 0.358 m) at B = 0.34 T, max $\beta_x = \beta_y < 9$ results in $\sigma^2_{x,p}/\sigma^2_{x,\beta} \approx 8$, and gives an error of ~6 % for the energy spread measurement when the contribution of the betatron part $\varepsilon\beta$ is ignored (Figure 14).

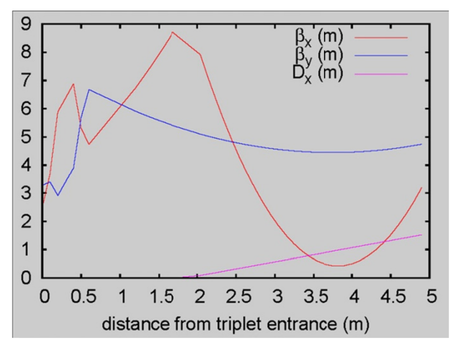

Figure 14: Wire scanner location set to 3.9 m for the energy spread measurement.

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