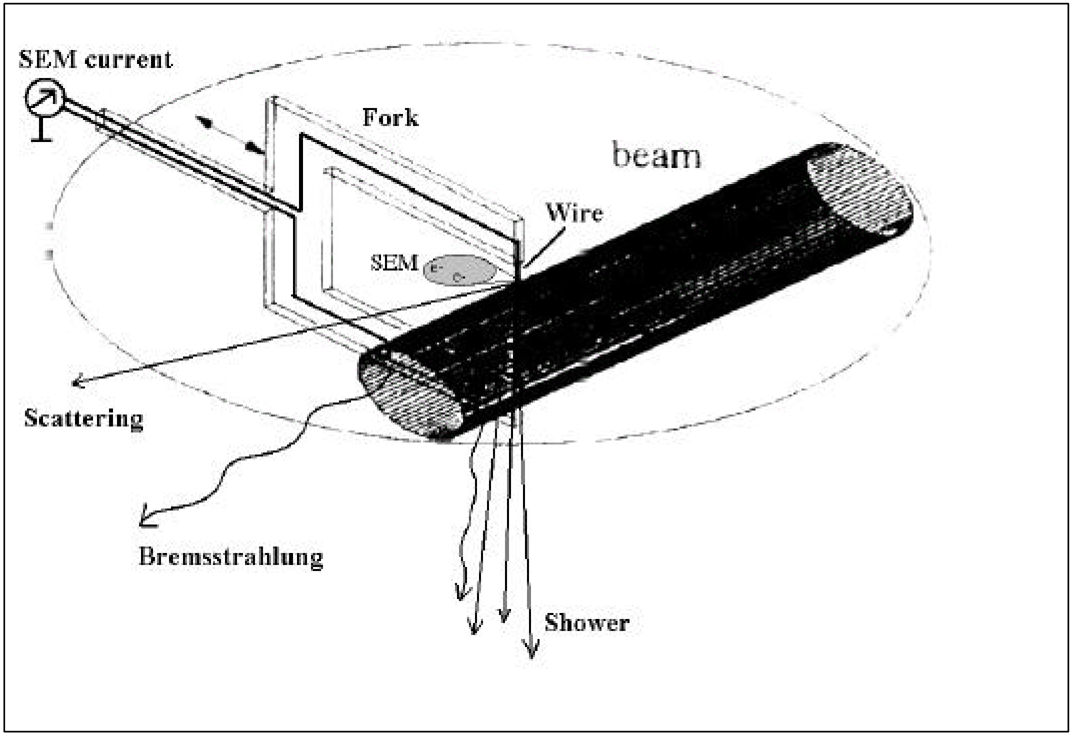
Wire Scanners

Introduction

Conventional wire scanners with thin solid wires (conventional compared with new techniques using, for example, Lasers) are widely used for beam size measurements in particle accelerators.



Their advantages:

1) Resolution of down to 1 μm
2) Trusty, reliable
3) Direct

Their known limitations are:

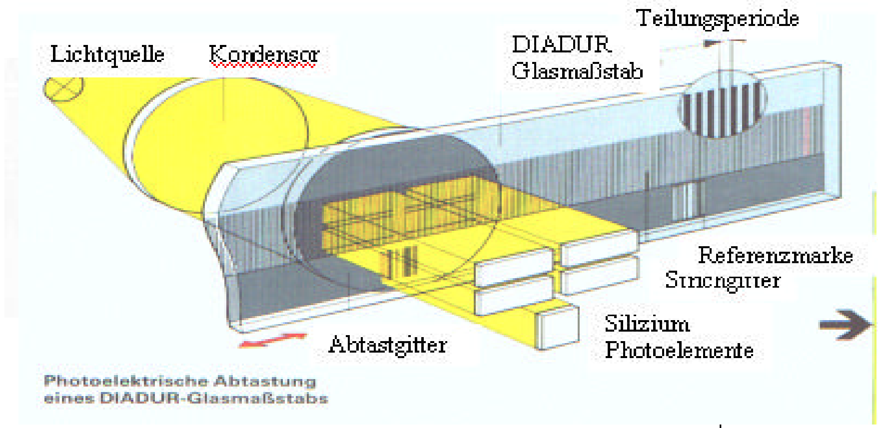
1. The smallest measurable beam size is limited by the finite wire diameter of a few microns,

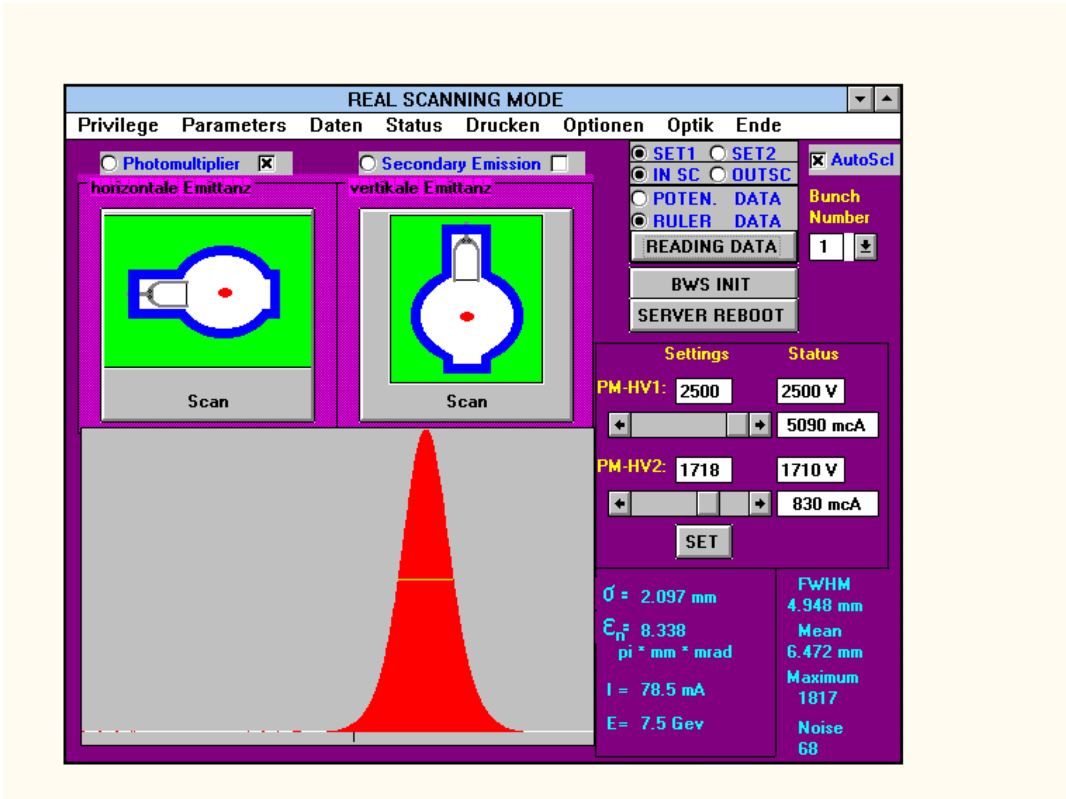
2. Higher Order Modes may couple to conductive wires and can destroy them,

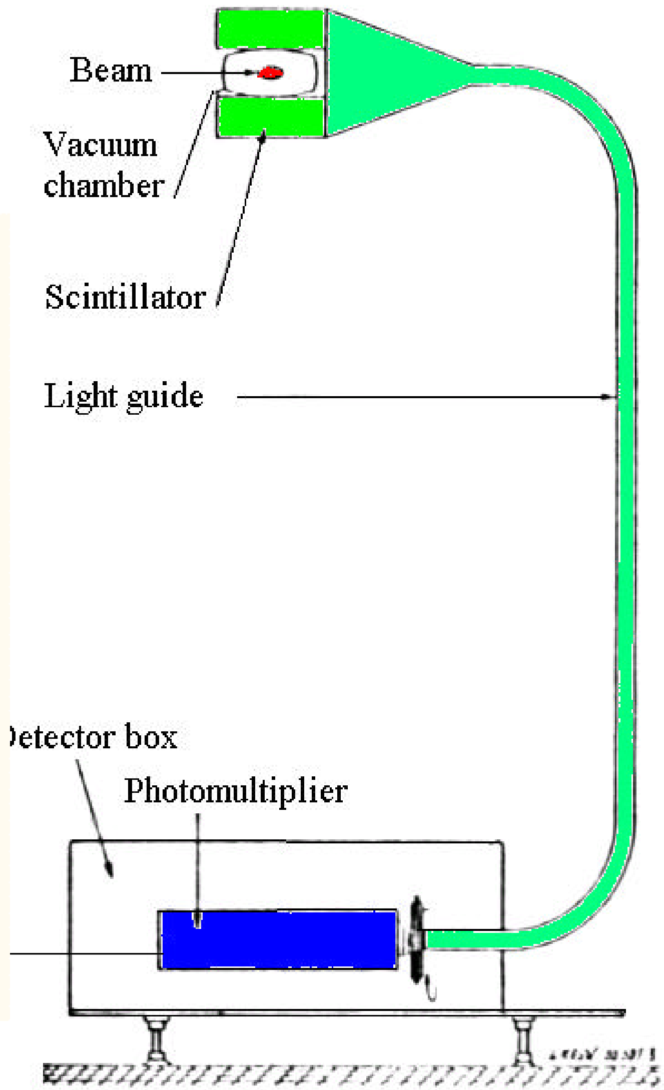
3. High beam intensities combined with small beam sizes will destroy the wire due to the high heat load.

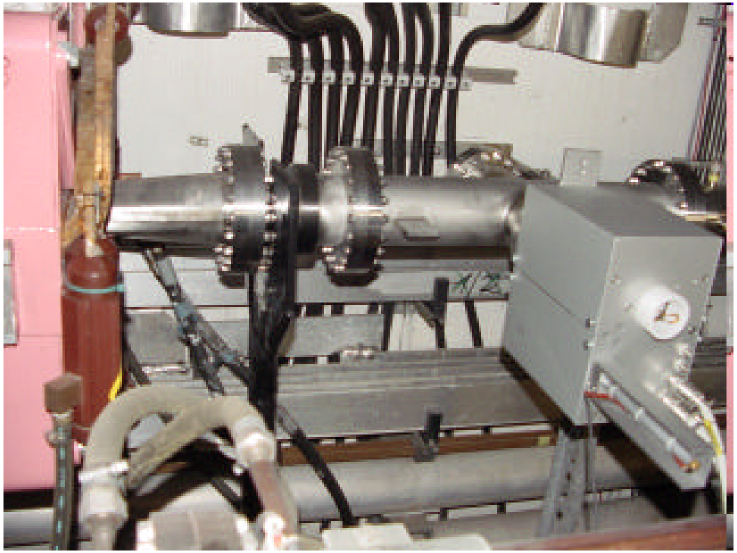
4. Emittance blow up

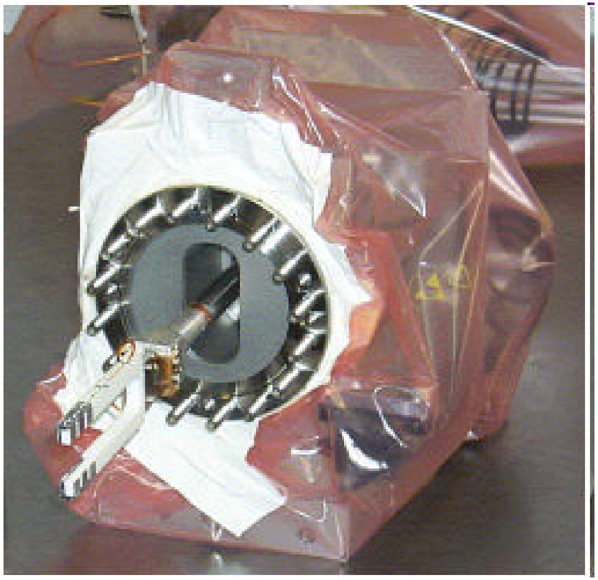
0.1 micron position resolution is possible

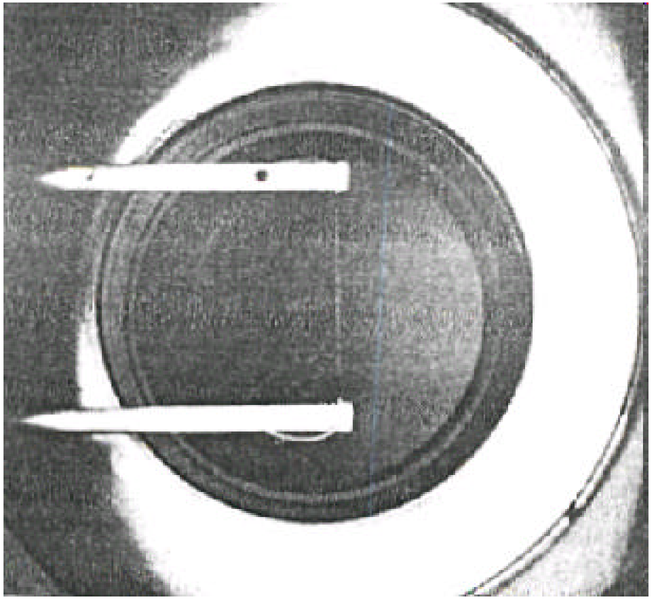












CERN/DESY 1990-2003

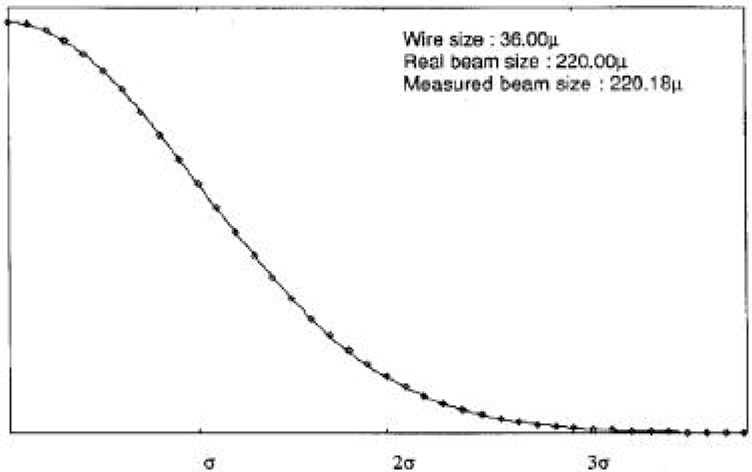
Speed: 1 m/s
Scanning area: approx. 10 cm
Wire material: Carbon/Quartz
Wire diameter: 7 microns
Signal: shower

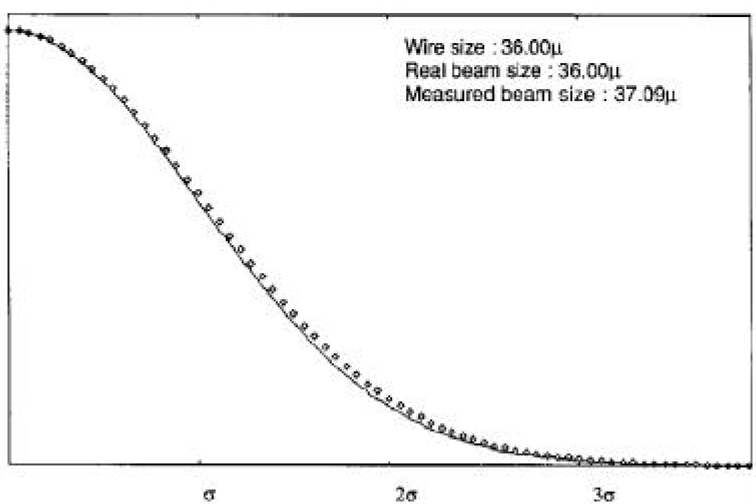
1 micron resolution

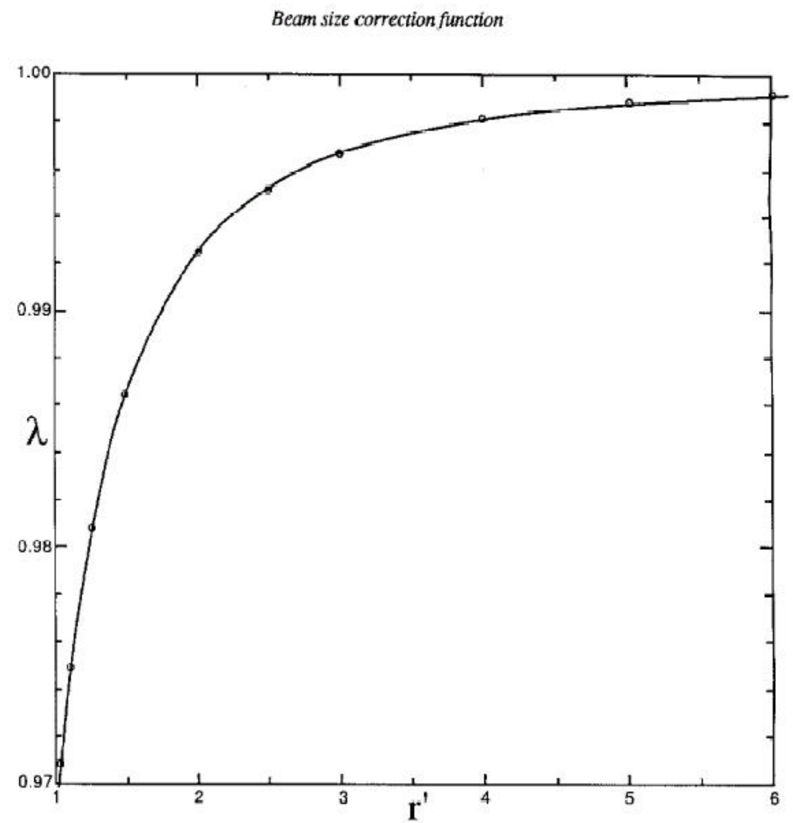
Limitations:

1. Wire size

The smallest achievable wires have a diameter of about 5-6 μm. This limits the use of wire scanners to beam sizes of a few microns. An example of the error in the beam width determination is shown for a 36 μm wire.







Influence of the wire diameter on the measured beam width.
(All figures from: Q. King; Analysis of the Influence of Fibre Diameter on Wirescanner Beam Profile Measurements, SPS-ABM-TM/Note/8802 (1988))

Limitations:

2. Higher Order modes

An early observation (1972 DORIS) with wire scanners in electron accelerators was, that the wire was always broken, even without moving the scanner into the beam. An explanation was Higher Order Modes coupling into the cavity of the vacuum chamber extension housing the wire scanner fork. The wire absorbs part of the RF which led to strong RF heating.

Methods of proving this behavior: What are possible solutions against the RF coupling?

Methods:

1. Measurement of wire resistivity
2. Measurement of thermo-ionic emission
3. Optical observation of glowing wire
4. Measurement of RF coupling in Laboratory with spectrum analyzer

1. Measurement of wire resistivity

The wire resistivity will change depending on the temperature of the wire, even without scanning.

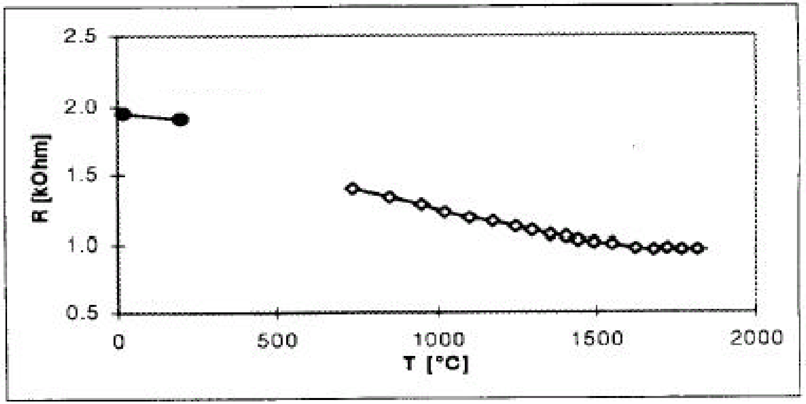


Fig 4: Measured wire resistance variations with temperature.

Here: 8 μm Carbon wire

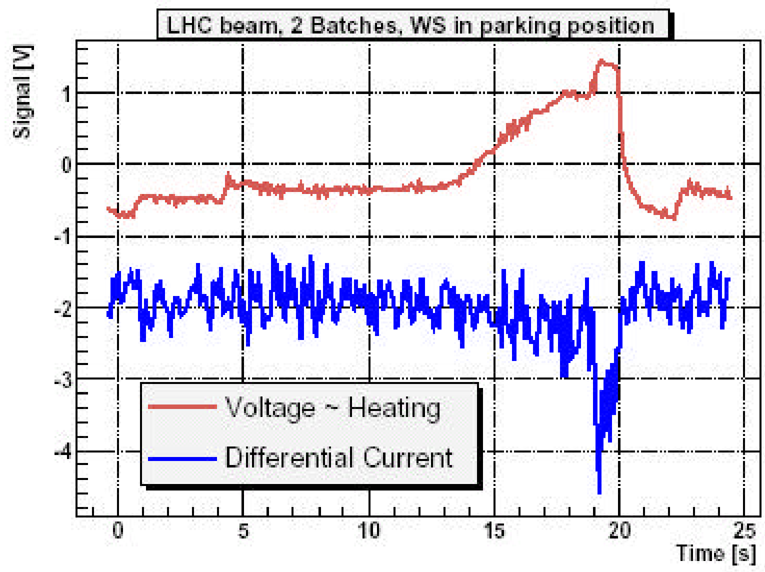
(from OBSERVATION OF THERMAL EFFECTS ON THE LEP WIRE SCANNERS. By J. Camas, C. Fischer, J.J. Gras, R. Jung, J. Koopman (CERN). CERN-SL-95-20-BI, May 1995. 4pp. Presented at the 16th Particle Accelerator Conference - PAC 95, Dallas, TX, USA, 1 - 5 May 1995. Published in IEEE PAC 1995:2649-2651)

Table 1: Normalised average temperature increase of wires

Location	Tank	Fork	Wire length	ΔTpark.	ΔT max
139/ V e^-	old	old#2	56mm	80°/mA	620°/mA
140/ H e^-	old	old#2	56 mm	200°/mA	640°/mA
160/ H e^+	old	old#2	29 mm	30°/mA	520°/mA
161/ V e^+	new	new	3 of 29 mm	20°/mA	500°/mA

As a consequence of the new design, the wire heating in the parking position is now negligible and the maximum temperature reached during a scan has decreased confirming the heating by coupling to the electro-magnetic fields. Recordings show again a temperature increase well before reaching the beam and a slow decrease after the traversal.

2. <u>Measurement of thermo-ionic emission</u>

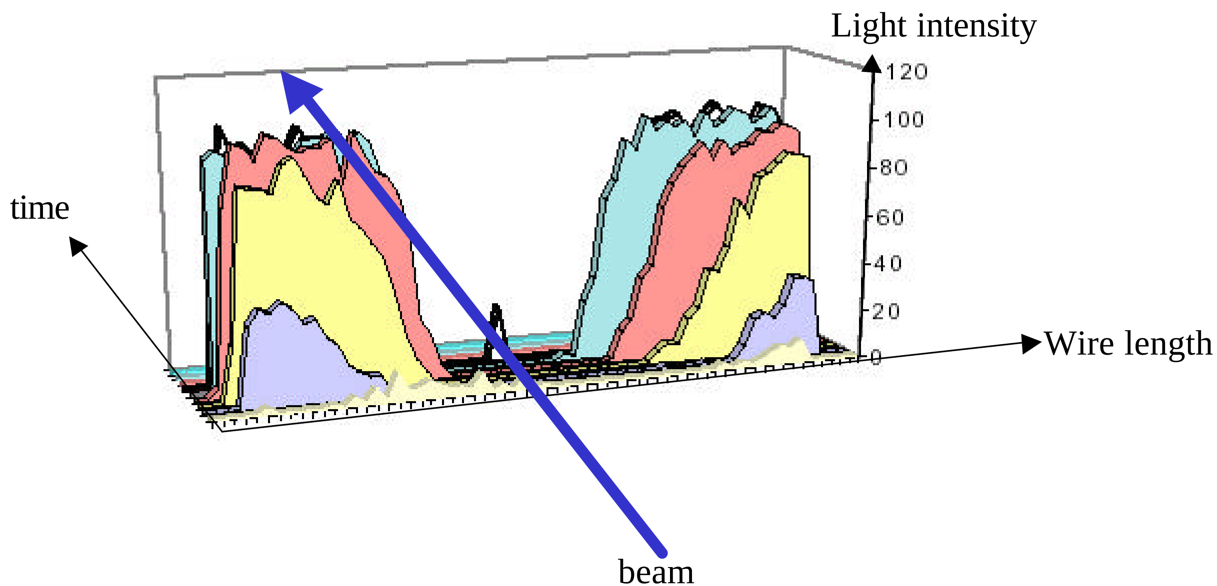


Wire heating due to the LHC beam injection in the SPS (No scan, wire in parking position).
The beam energy ramp/bunch length decreasing begin t=11 s.

A constant current was supplied to the wire and the voltage drop across it was fed to a digital scope together with the difference between the input and output currents. The differential current (I_{out}-I_{in}) grow up is due to the wire heating and consequent emission of electrons for thermionic effect. Fig. WIRE5 shows such voltage and differential current evolutions during the SPS cycle with LHC type beam. No scans were performed along this cycle. It is thus evident that the wire heating does not depend on the direct wire-beam interaction only.

(From CAVITY MODE RELATED WIRE BREAKING OF THE SPS WIRE SCANNERS AND LOSS MEASUREMENTS OF WIRE MATERIALS
F. Caspers, B. Dehning, E.Jensen, J. Koopman, J.F. Malo, CERN, Geneva, Switzerland
F. Roncarolo, CERN/University of Lausanne, Switzerland; DIPAC03)

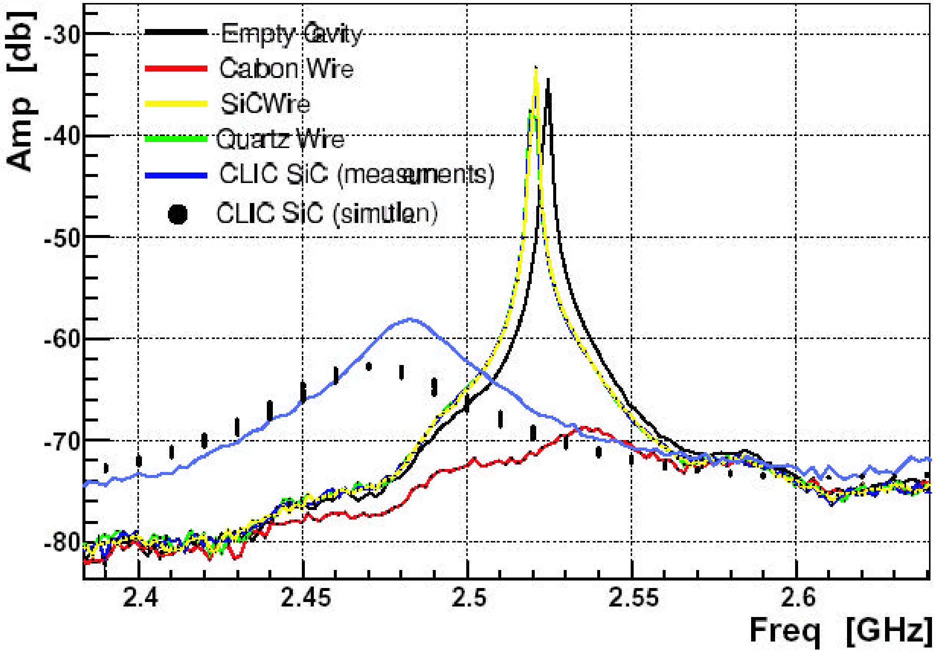
3. Optical observation of glowing wire



Digitized video recording of an 8 μm carbon wire scanning a 0.8 mA beam. The wire is parallel to the horizontal axis, and the light intensity is plotted along the vertical axis (arbitrary units). Successive profiles are separated by 20 ms. The central spot corresponds to the passage of the wire through the beam. Thus, RF heating led to (huge) thermal glowing before the beam interacts with the wire.

(from: QUARTZ WIRES VERSUS CARBON FIBERS FOR IMPROVED BEAM HANDLING CAPACITY OF THE LEP WIRE SCANNERS.
By C. Fischer, R. Jung, J. Koopman (CERN). CERN-SL-96-09-BI, May 1996. 8pp. Talk given at 7th Beam Instrumentation Workshop (BIW 96), Argonne, IL, 6-9 May 1996.

4. Measurement of RF coupling with spectrum analyzer



Resonant cavity signal in presence of Carbon (36 μm), Silicon Carbide and Quartz wires

The plot qualitatively proves the RF power absorption of Carbon, and the non-absorption of Silicon Carbide and Quartz. Absorbed energy is mainly converted into heat.

Solutions:
Damping of Higher Order Modes with Ferrites etc.
Non conducting wires

Limitations:

3. Wire heat load

According to Bethe-Blochs formula, a fraction of energy dE/dx of high energy particles crossing the wire is deposit in the wire. Each beam particle which crosses the wire deposits energy inside the wire. The energy loss is defined by dE/dx (minimum ionization loss) and is taken to be that for a minimum ionizing particle. In this case the temperature increase of the wire can be calculated by:

$$\boxed{T = C \cdot dE/dx_m \cdot d' \cdot N \cdot \frac{1}{c_p \cdot G} \quad [{}^0C]}$$

unknown

where N is the number of particles hitting the wire during one scan, d' is the thickness of a quadratic wire with the same area as a round one and G [g] is the mass of the part of the wire interacting with the beam. The mass G is defined by the beam dimension in the direction of the wire (perpendicular to the measuring direction):

Estimation of the wire temperature after one scan with a speed v (assume no cooling mechanisms):

Solving G: G [g] is the mass of the part of the wire interacting with the beam. The mass G is defined by the beam dimension in the direction of the wire (= σ_v, perpendicular to the measuring direction) and by the wire diameter d':

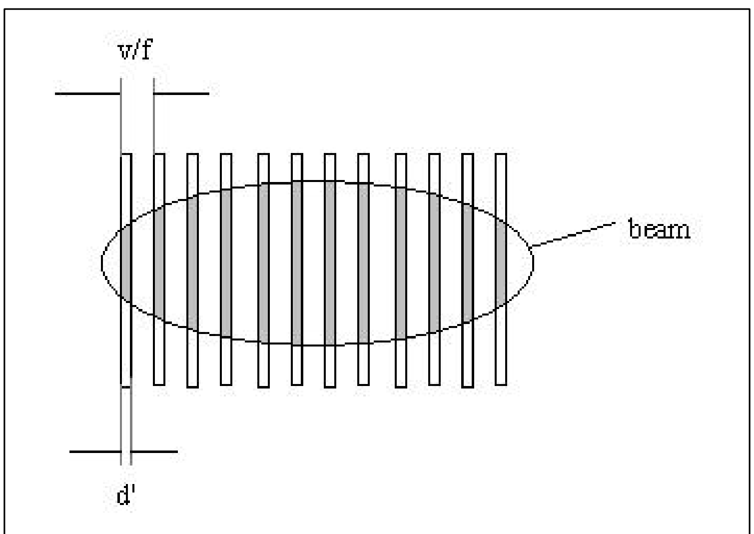
$$\boxed{G = wire\ volume \cdot r = 2 \cdot s_{v} \cdot d'^{2} \cdot r \quad [g]}$$

Solving N:

The number of particles N hitting the wire during one scan depends on the speed of the scan (~1/v), the revolution frequency (~f_{rev}), the wire diameter (~d') and the beam current (~$NB \cdot n_{bunch} = N_{tot}$):

$$\boxed{N = \frac{d' \cdot f_{rev}}{v} \cdot (NB \cdot n_{bunch})}$$

The figure shows the a graphical representation of the parameters. The quotient d·f/v is the ratio of the scanned beam area or, in other words, like a grid seen by one bunch, assuming that all bunches are equal. However, the ratio can exceed the value 1 (a foil) if the scanning distance between two bunches is smaller than the wire diameter. Note that N does not depend on the beam widths σ.



Geometrical meaning of the parameters v/f and d'

Therefore, the temperature increase of the wire after one scan becomes:

$$T = C \cdot dE/dx_m \cdot d' \cdot N \cdot \frac{1}{c_p \cdot G} \quad [{}^0C]$$

$$G = wire\ volume \cdot r = 2 \cdot s_v \cdot d'^2 \cdot r \quad [g]$$

$$N = \frac{d' \cdot f_{rev}}{v} \cdot (NB \cdot n_{bunch})$$

n_{bunch}*NB = N_{tot}

dE/dx = $dE/dx_m/\rho$ [MeV cm^2 / g]

$$T_h = C \cdot dE/dx \cdot N_{tot} \cdot \frac{f_{rev}}{v} \cdot \frac{1}{c_p \cdot 2 \cdot s_v} \cdot a \quad [{}^0C]$$

Where $_{h,}$ denotes horizontal (h) scanning direction. The cooling factor 'α' is described in the next section. **Note that the temperature does not depend on the wire diameter and that it depends on the beam dimension perpendicular to the measuring direction. The temperature increase is inverse proportional to the scanning speed**, therefore a faster scanner has a correspondingly smaller temperature increase.

Mathcad File

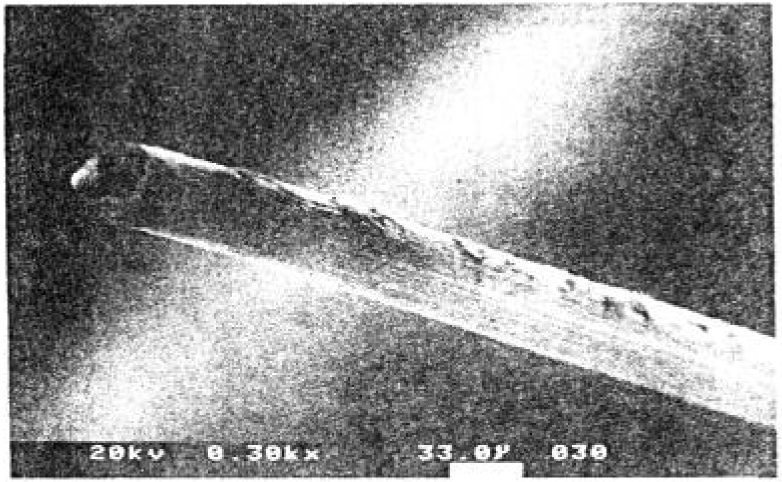
Parameter table

The wire parameters $dE/dx / c_p$ and the Quotient T_h/T_m should be minimal for a choice of the material ($\alpha = 1$):

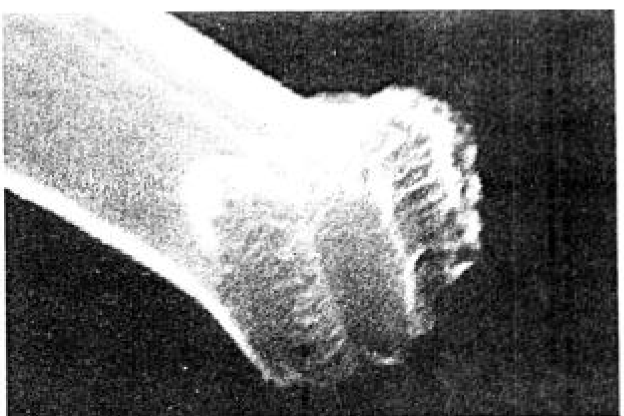
Material	$dE/dx / c_p$	T_h [^{0}C]	T_h/T_m
AL	7.7	$1.1 \cdot 10^4$	16.9
W	50.6	$7.1 \cdot 10^4$	20.9
C	5.4	$0.77 \cdot 10^4$	2.2
Be	4.1	$0.58 \cdot 10^4$	4.8
SiO2	12.9	$1.8 \cdot 10^4$	10.6

TableWire3: calculated Temperatures

From Table WIRE3 follows, that even the best material (Carbon) will be a Factor 2.2 above its melting temperature.



Small pit marks seen near the end of the wire are further evidence for arcing.



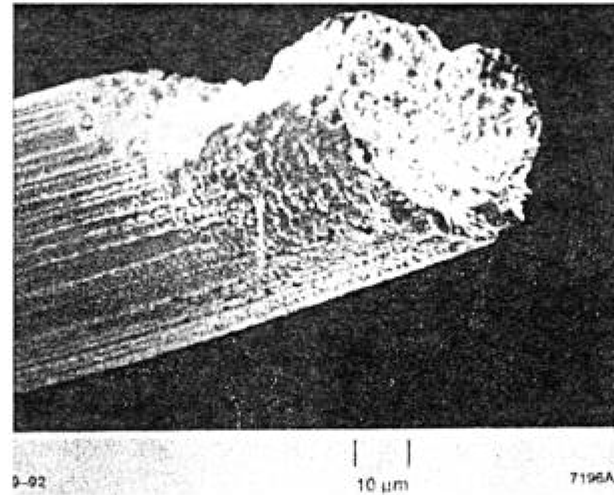


Figure 3. Electron microscope picture of a 40 µm tungsten wire break. This wire was installed in an SLC linac wire scanner.

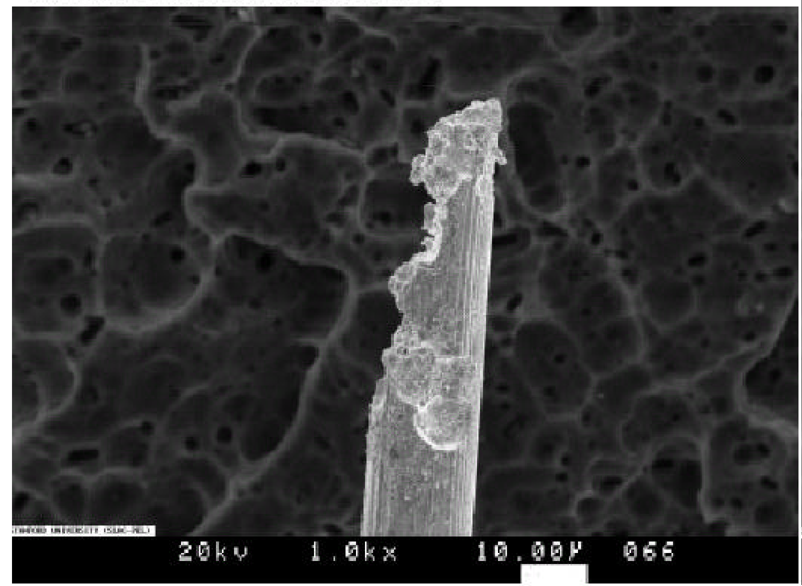


FIGURE 3. Failed 15 µm diameter tungsten wire showing the rough surface resulting from many discharges.

Burned by the e-beam at SLC

Mechanisms which will cool the wire.

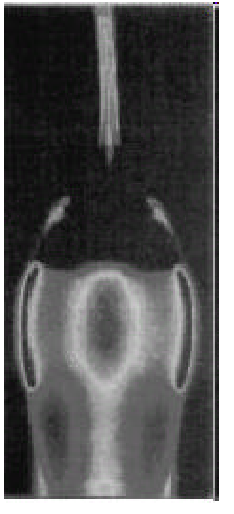
1) Secondary particles emitted from the wire

2) Heat transport along the wire

3) Black body radiation

4) Change of c_p with temperature

1) Secondaries: Some energy is lost from the wire by secondary particles. In the work in (J. Bosser et al.; The micron wire scanner at the SPS, CERN SPS/86-26 (MS) (1986)) about 70% is assumed. In DESY III (example above) no carbon wire was broken during more than 10 years of operation. At HERA, the theoretical temperature of the carbon wire (without secondaries) exceeds the melting temperature after a scan by far (T = 12 800 ^{0}C). Considering the loss by secondaries of 70%, the temperature reaches nearly the melting point. In practice, the wire breaks about once in 6 months. The observation is that the wire becomes thinner at the beam center. This may indicate, that during a scan some material of the wire is emitted because of nuclear interactions or is vaporized because it is very close to the melting temperature. This supports the estimate of the 70% loss and one has to multiply the factor $\alpha = 0.3$ in the equation above



A 30 µm Quartz wire, used in a LEP wire-scanner monitor, after scans through 7mA beams. The thickness of the top part, traversed by the beam, is a few microns.

2) Heat transport: The transport of heat along the wire does not contribute to short time cooling of the wire (P. Lefevre; Measure tres peu destructive des distribution transversales dans le PS de 800 MeV a 26 GeV, CERN PS/DL/Note 78-8). However, frequent use of the scanner heats up also the ends of the wire and its connection to the wire holders (fork).

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3) Black body radiation: The temperature T_{bb} at which the radiated power is equal to the deposited power in the wire during one scan P_{dep} [MeV/s] can be calculated from the Stefan-Bolzmann-law:

$$T_{bb} = \sqrt{\sqrt{\frac{P_{dep}}{s \cdot A}}}$$

where s = 35.4 MeV / (s^1 cm^2 $^0K^4$) is the Stefan-Bolzmann-constant and A is the area of radiating surface. The surface of the heated wire portion A is $2 \cdot \sigma_v \cdot d \cdot \pi$ [cm^2]. The power can be calculated by:

$$P_{dep\ h,v} = a \cdot dE/dx \cdot d' \cdot N_{tot} \cdot \frac{f_{rev} \cdot d'}{v} \cdot \frac{1}{t_{scan}} \quad [MeV/s]$$

where $t_{scan} = 2 \cdot \sigma_{h,v} / v$ is the time for a scan (in the assumpion of 2 σ it is neglected that only about 70% of the power is concentrated within 2 σ). α is the expected loss from secondaries.

For the example above T_{bb} = 3900 ^{0}C. Therefore the black body radiation is a fraction of cooling in case of fast scans.

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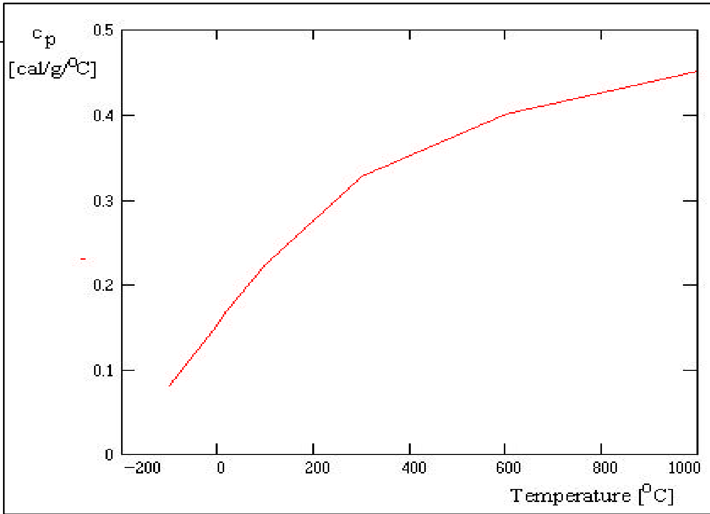
4) c_p(T): The heat capacitance is a function of the temperature. Fig. 2 shows the increase of c_p for Carbon with T. The expected temperature after a scan is inversely proportional to c_p. Therefore one can expect a slightly smaller resulting temperature because of this dependence.



For Carbon:

Temperature of the wire (v=1m/s)

	Num. of part.	Typ. Beam diam.	Temp. after scan [C]	Eqi. - Temp [Celsius]
HERAp	1 *10^13	0.7 mm	3900	5100
HERAe	6.5 * 10^12	0.2 mm	4800	4500
PETRAp	4.8*10^12	2 mm	980	3500
PETRAe	1.5*10^12	0.1 mm	4700	6800
DESYIII	1.2*10^12	1 mm	3400	5300
TTF fast	2.8*10^13	0.05 mm	4000	7400
TTF slow	2.8*10^13	0.05 mm	286 000	2900

Melting temperature = 3500 ºC for Carbon
= 1700 ºC for Quartz

The wire in DESY III still exists with 200 mA = $1.25 \cdot 10^{12}$ p
In HERA 2 burned wires in the last two years

Limitations

Parameter table

4: Emittance blow up

<u>Calculation of the emittance blowup of the proton beam after one scan at a position with b = 11.8 m for p =0.3 and 7 GeV/c (Carbon wire):</u>

<u>Assuming a measurement position close to a Quadrupole (a=0)</u>

For small deflection angles a good approximation for average root mean square scattering angle is given by:

$$d\,\Theta = \frac{0.014\,GeV}{pc}\cdot\sqrt{\frac{d'}{L_{rad}}}\cdot\left(1+1/9\cdot\log_{10}\frac{d'}{L_{rad}}\right)$$

Remember:

$$g(s)^2\,y + 2a(s)\,yy' + b(s)\,y'^2 = e$$

A fraction Ψ of the circulating beam particles will hit the wire:

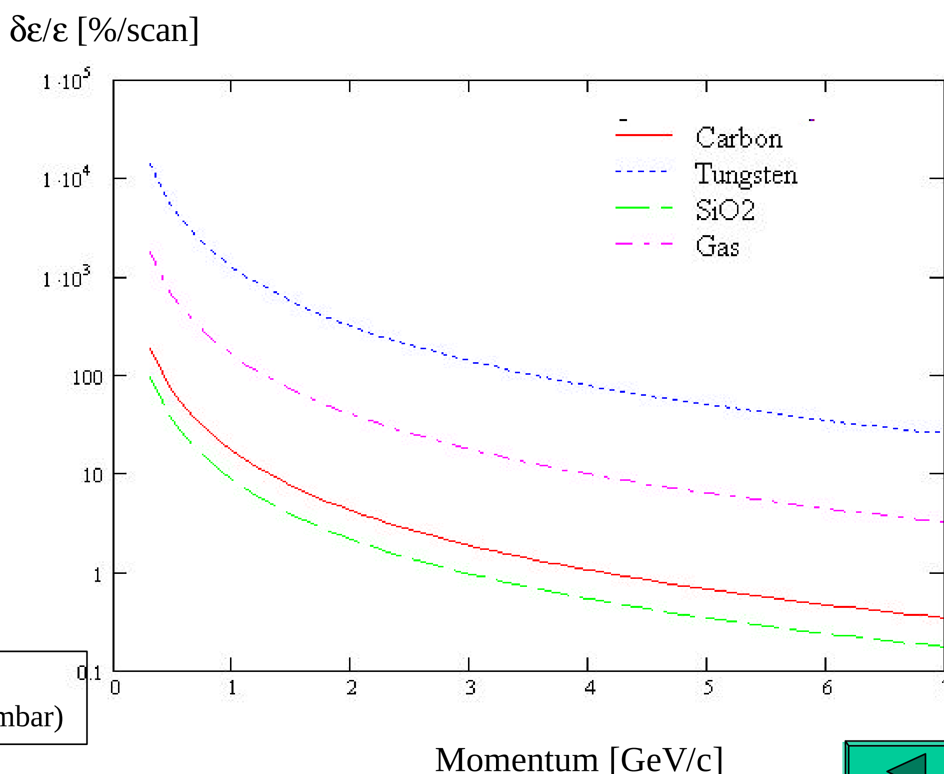
$$\Psi = \frac{d'\cdot f_{rev}}{v}$$

(see exercise WIRE2)

The resulting emittance blowup is than:

$$d\,e_{rms} = \sqrt{2p}\;d\,\Theta^2\cdot\Psi^2\cdot b = 5.1\cdot 10^{-2}\,p\;mm\,mrad$$

$\sqrt{2p}$ *from Literature*



Gas: emittance growth due to residual gas per hour ($P=10^{-9}$ mbar)

D. Möhl today

$$\boxed{d\, e = p\, \frac{1}{2} \cdot \Theta_{rms}{}^{2} \cdot b}$$

Averaging over all Betatron-phases

Unit of phase space emittance

Wire Parameters

Parameter	Symbol	Unit	wire material				
			AL	W	Carbon	Beryllium	Quartz (SiO_2)
wire diameter	d $= 7 \cdot 10^{-4}$	cm					
mean wire diameter	$d' = d/2 \cdot \sqrt{\pi}$ $= 5.5 \cdot 10^{-4}$	cm					
Conversion	0.239	cal/Joule					
Conversion factor	$C = 3.8 \cdot 10^{-14}$	MeV / cal					
Speed of wire	v = 100	cm/s					
specific heat capacity*	c_p	cal / g / ^{0}C	0.21	0.036	0.42 (>400^{0}C) 0.17 (< 400^{0}C)	0.43	0.18
Energy loss of min. ion. part. (MIPs)	dE/dx dE/dx_m	MeV cm^2 / g MeV/cm	1.62 4.37	1.82 35.13	2.3 5.3	1.78 3.3	2.33 5.3
density	ρ	g/cm^3	2.7	19.3	2.3	1.85	2.29
melting temp.	T_m	^{0}C	650	3400	ca. 3500	1200	1700
Heat conductivity	l	W/(m K)	230	100-160	30-3000	200	1.2-1.4
Radiation length	l_{rad}	cm	8.9	0.35	18.8	34.7	12.3
Nuclear coll length	lnuc	cm	26	9.6	34	30	25.4

Table WIRE1: Parameters of wire materials. *> 500 ^{0}C

The beam parameters used in this exercise are shown in the following table:

Parameter	Symbol	Unit	Value
circumference of accel.	circ.	m	300
particle		Proton	
Beam particle momentum	p	GeV/c	0.3-7
Beta function	$\beta_h = \beta_v$	m	11.8
Emittance	$\varepsilon_h = \varepsilon_v$	π mm mrad	15
revolution Frequency	f_{rev}	MHz	0.93
Bunch spacing	t_{bunch} f_{bunch}	ns MHz	98 10.2
Number of bunches in accel.	NB		11
Bunch charge	n_{bunch}	1/e	$1.1 \cdot 10^{11}$
Beam width measurement [1]	σ_h	mm	1.5
Beam width perpendicular to meas. [1]	σ_v	mm	1

Table WIRE2: Parameters of Beam

Signals:

Monte Carlo Calculations

Real field. Quadrupoles only.

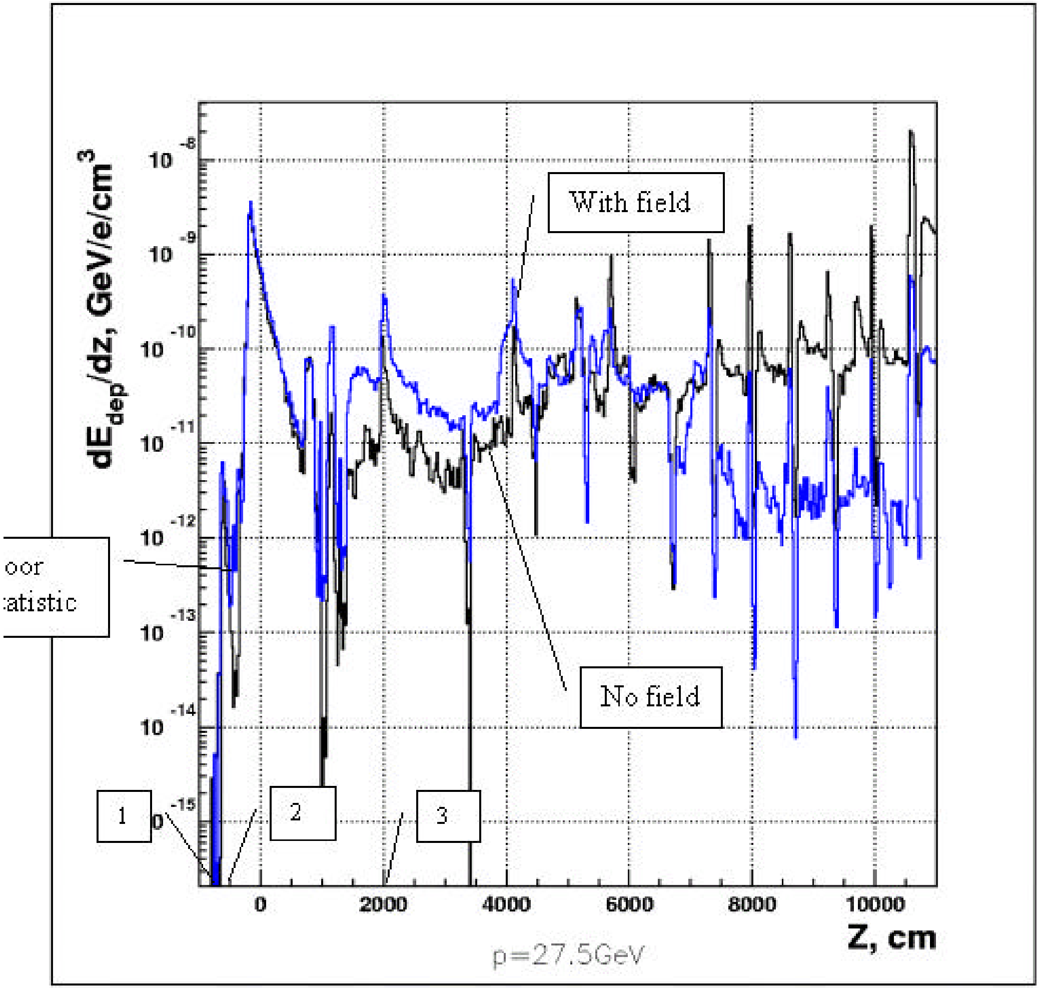


Figure 9. Dependence of energy deposited from Z position. Two diameters of wire 15µm and 150µm. 1) position of wire = -810cm, 2) old position of scintillator = -450cm, 3) new position of scintillator = 2040cm.

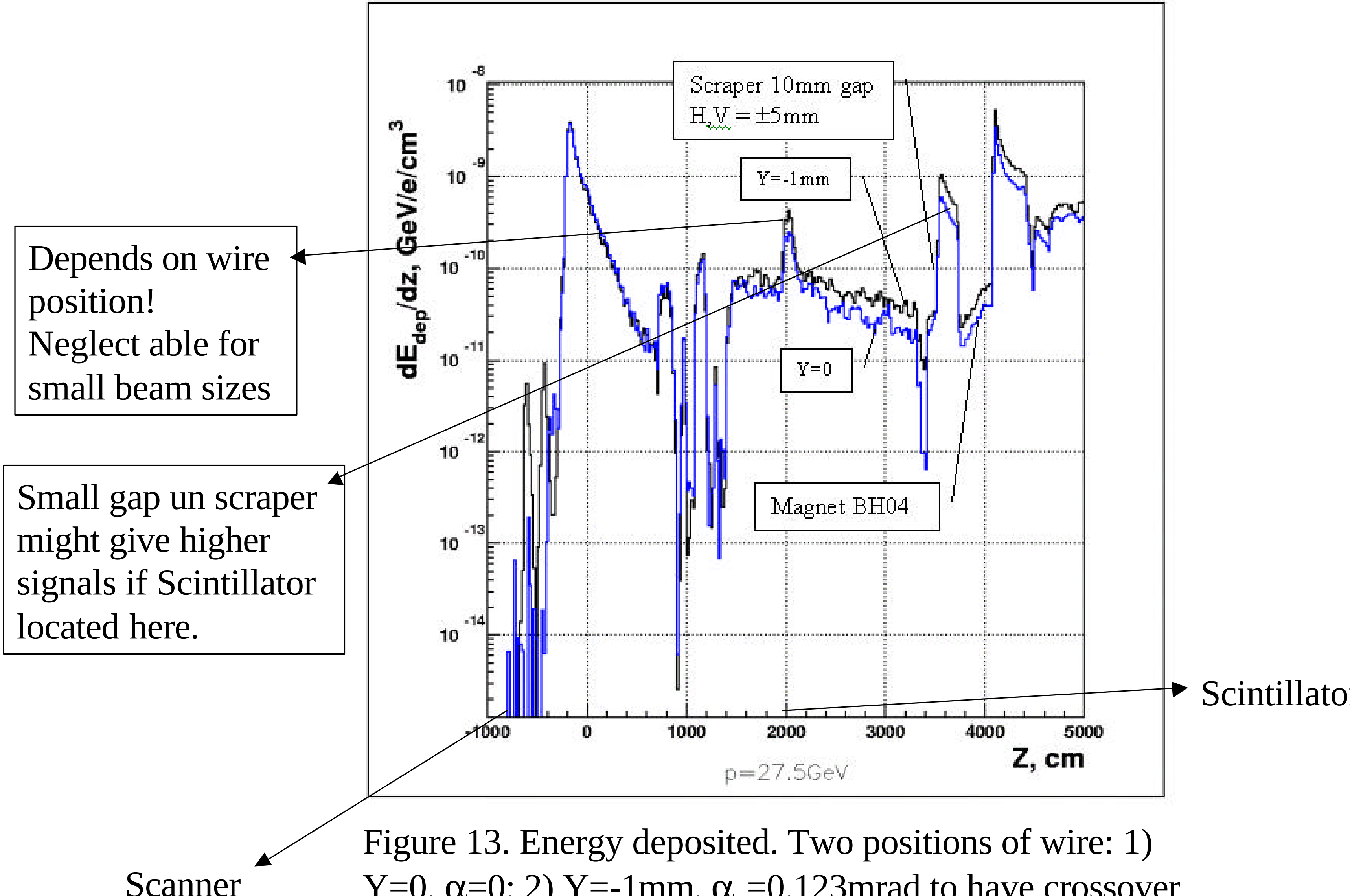


Figure 13. Energy deposited. Two positions of wire: 1) Y=0, α=0; 2) Y=-1mm, α_y=0.123mrad to have crossover in IP.

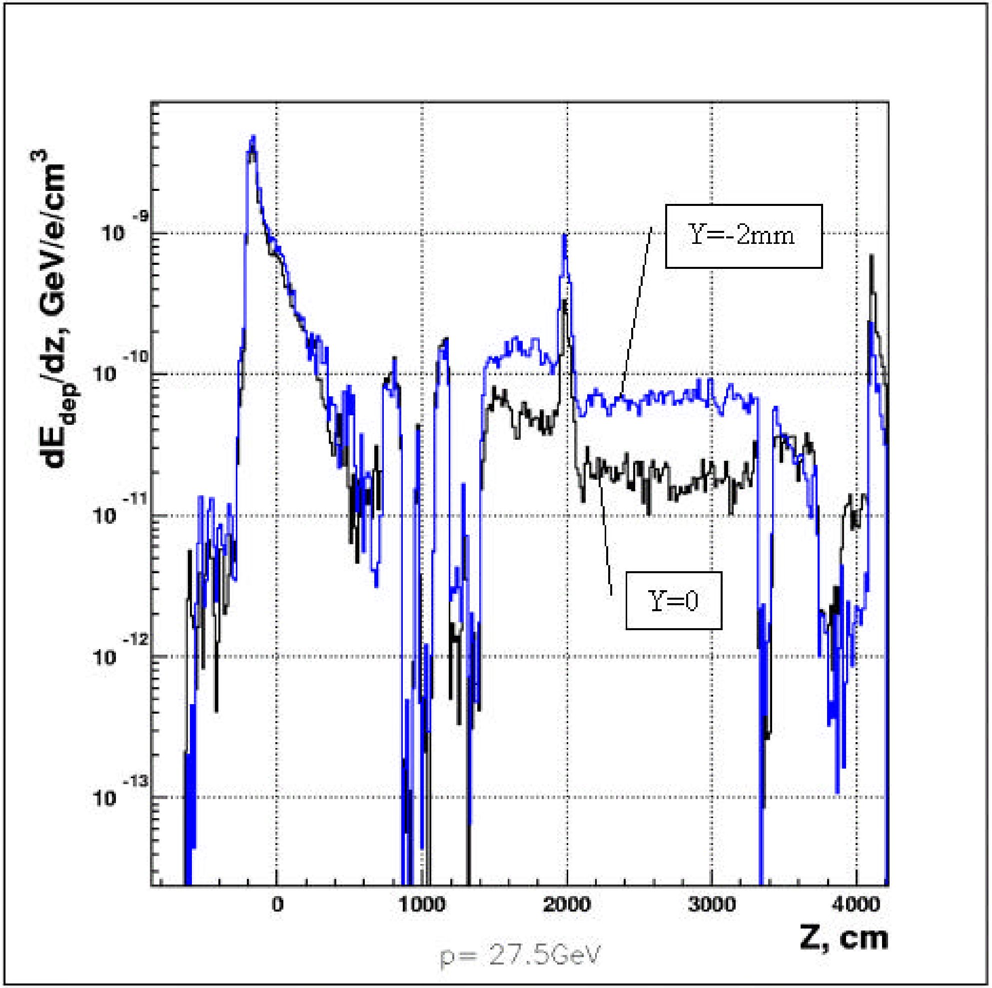


Figure 18. Y=-2mm. No scraper. Two positions of wire: 1) Y=0, α=0; 2) Y=-2mm, α_y=0.247mrad to have crossover in IP.

Carbon wire:

HERAp

$d := 0.0007$ Drahtdurchmesser

$cp := 0.42$ Spez. Waermecap.

$dedxM := 5.2$ dE/Dx in MeV/cm

$dedx := 2.3$ dE/Dx in MeV cm^2/g

$F := 47.6 \cdot 10^{3}$ Umlauffrequenz

$sig := 1 \cdot 10^{-1}$ Strahlbreite in Messrichtung

$sigx := 0.5 \cdot 10^{-1}$ Srahlbreite senkr. Messrichtung

$v := 100$ wire Geschwindigkeit

$N := 1.3 \cdot 10^{13}$ gesamtzahl der Teilchen

$1.6 \cdot 10^{-19} \cdot N \cdot F = 0.099$ Strahlstrom [A]

Herleitung der Formeln:
3.8e-14 = Umrechnung MeV-cal; Energiedeposition: d*dedx fuer ein Teilchen, d*f/v: Umlaeufe pro Drahtdicke = wieviel mal trifft ein Teilchen den Draht (bei Linac: Buchwiederholung und Teilchen pro Bunch wenn scan bei 1. Bunch startet und bei letzten Bunch aufhoert: v=sigx/L); cp *Gewicht = Waermeerzeugung durch energiedeposition,
Volumen = (d/2)^2 *pi * 2sigx (sigx = Bereich des Drahtes der vom Strahl erhitzt wird), Dichte in dedx mit drin;
Kuerzen von d (unabhaengig von d), pi/4 =1.

$$T := 3.8 \cdot 10^{-14} \cdot dedx \cdot N \cdot \frac{F}{(cp \cdot 2 \cdot sigx \cdot v)} \qquad T = 1.288 \cdot 10^{4}$$ theor. Temp

$$Ta := T \cdot 0.3 \qquad Ta = 3.863 \cdot 10^{3}$$ Temp nach 70% Abstrahlung

$$da := \frac{d}{2} \cdot \sqrt{\pi}$$ mittlerer Drahtdurchmesser

$$E := \frac{dedxM \cdot da \cdot N \cdot \frac{F \cdot d}{v}}{2 \cdot \frac{sig}{v}}$$ deponierte Leistung pro scan in MeV/s

$$2 \cdot \frac{sig}{v} = 2 \cdot 10^{-3}$$ Zeit um durch Strahl zu scannen

$$E = 6.987 \cdot 10^{12}$$

$$sa := 35.4 \cdot 2 \cdot sigx \cdot \pi \cdot d$$ aus Stphan Bolzmann, sigma/Oberflaeche

$$Te := \sqrt{\sqrt{\frac{E}{sa}}} \qquad Te = 5.473 \cdot 10^{3}$$

Te ist die Temperatur die man braeuchte um die Energiemenge/s (Leistung) die bei einem Scan in den Draht geht wieder abzustrahlen innerhalb der gleichen Zeit (die fuer eine Strahldurchqueerung)

Quarz Wire:

HERAe

$d := 0.0007$ Drahtdurchmesser [cm]

$F := 47.6 \cdot 10^{3}$ Umlauffrequenz [Hz]

$cp := 0.18$ Spez. Waermecap. [cal / g / 0C]

$sig := 1.0 \cdot 10^{-1}$ Strahlbreite in Messrichtung [cm]

$dedxM := 5.2$ dE/Dx in MeV/cm

$sigx := 0.2 \cdot 10^{-1}$ Srahlbreite senkr. Messrichtung [cm]

$dedx := 2.33$ dE/Dx in MeV cm^2/g

$v := 100$ wire Geschwindigkeit [cm/s]

$N := 8 \cdot 10^{11}$ gesamtzahl der Teilchen

$N \cdot 1.6 \cdot 10^{-19} \cdot F = 6.093 \cdot 10^{-3}$ Strahlstrom [A]

Herleitung der Formeln:
3.8e-14 = Umrechnung MeV-cal; Energiedeposition: d*dedx fuer ein Teilchen, d*f/v: Umlaeufe pro Drahtdicke = wieviel mal trifft ein Teilchen den Draht (bei Linac: Buchwiederholung und Teilchen pro Bunch wenn scan bei 1. Bunch startet und bei letzten Bunch aufhoert: v=sigx/L); cp *Gewicht = Waermeerzeugung durch energiedeposition,
Volumen = (d/2)^2 *pi * 2sigx (sigx = Bereich des Drahtes der vom Strahl erhitzt wird), Dichte in dedx mit drin;
Kuerzen von d (unabhaengig von d), pi/4 =1.

C= 3.8 10-14cal / MeV

$$T := 3.8 \cdot 10^{-14} \cdot dedx \cdot N \cdot \frac{F}{(cp \cdot 2 \cdot sigx \cdot v)}$$

$T = 4.683 \cdot 10^{3}$ theor. Temp

$Ta := T \cdot 0.3$

$Ta = 1.405 \cdot 10^{3}$ Temp nach 70% Abstrahlung

$$da := \frac{d}{2} \cdot \sqrt{\pi}$$ mittlerer Drahtdurchmesser

$$E := \frac{dedxM \cdot da \cdot N \cdot \frac{F \cdot da}{v}}{2 \cdot \frac{sig}{v}}$$ deponierte Leistung pro scan in MeV/s

$$2 \cdot \frac{sig}{v} = 2 \cdot 10^{-3}$$ Zeit um durch Strahl zu scannen

$E = 3.81 \cdot 10^{11}$

$sa := 35.4 \cdot 2 \cdot sigx \cdot \pi \cdot d$ aus Stphan Bolzmann, sigma/Oberflaeche

$$Te := \sqrt{\sqrt{\frac{E}{sa}}}$$

$Te = 3.326 \cdot 10^{3}$

Te ist die Temperatur die man braeuchte um die Energiemenge/s (Leistung) die bei einem Scan in den Draht geht wieder abzustrahlen innerhalb der gleichen Zeit (die fuer eine Strahldurchqueerung)