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Proposal to Detector Research and Development Committee

Superconducting Microstrip Detectors

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Abstract

We propose to develop and study superconducting NbN microstrip counters. These devices feature radiation hardness two orders of magnitude higher than conventional silicon strip detectors, spatial resolution limited only by lithographic techniques (typically 0.1 - 2 μm), an intrinsic signal rise time of 2 ps, and signal transport over large distances without losses. The initial study proposed here aims at improved understanding of the physics of such detectors, with the purpose of establishing their large-scale feasibility. Such devices could have important applications in the inmost vertex detectors of LHC experiments operated at high luminosities.

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1. INTRODUCTION

We propose to study the feasibility of superconducting strip tracking devices for applications in experiments at the Large Hadron Collider LHC. At this machine, high radiation levels, high energy and luminosity and the resulting high multiplicities per bunch crossing, and small signal-to-noise ratios for most of the relevant physical processes are unprecedented challenges for high resolution tracking near the interaction region.

High-resolution silicon strip vertex detectors are and will be used in many present and future collider experiments. These detectors and their readout are complex devices which already today are pushed close to the limits of available technology. At the LHC, the radiation damage to silicon strip vertex detectors could determine the maximum available integrated luminosity for certain measurements. High-resolution microstrip gas detectors (MSGD) and their readout electronics suffer from similar limitations and their use may be impossible close to the collision area. For these reasons, it is generally thought that the study of physics processes requiring high-resolution vertex detection, in particular the detection of secondary vertices from b-, t- and τ-decays, is limited to the initial phase of LHC operation with low luminosities. The technology which we propose to investigate has the potential of overcoming this limitation.

Superconducting MicroStrip Detectors (SMSD) offer advantages over silicon strip detectors in at least four areas: (1) radiation hardness, which is critical because of the combination of high luminosity and large multiplicity; (2) spatial resolution, which is equally critical because of short decay paths and high multiplicities per bunch crossing; (3) readout, since the combination of picosecond pulses and slow signal propagation makes serial readout possible, vastly reducing complexity and cost; and (4) signal processing, since the picosecond signals can be preserved in superconducting microstrip lines and processed by picosecond superconducting logic, which is very compact and uses little power. The combination of advantages (3) and (4) is important in trying to achieve a hermetic detector and may also be applied in some cases to the time-of-flight particle identification. More details on these features are given below in Section 2, before the description of the Project in subsequent Sections. The technical background of this new detector principle is reviewed in the Appendix.

First tests[1] of a superconducting NbN strip detector, using near-minimum ionising electrons from a ^{106}Ru source, show good evidence for 10 mW signals (5 mV in a 50 Ω line) with less than 300 ps rise time; some such signals are displayed in Fig. 1. The analysis[2,3] of the results of these tests, based on our earlier Proposal[4], suggests that non-equilibrium phenomena could be responsible for the speed and self-recovery of the observed signals. A new regime of operation becomes therefore available, enabling one to obtain large signals in strips made of materials with high resistivity in the normal state.

2. PROPERTIES OF SUPERCONDUCTING MATERIALS IN MICROSTRIP LINE DETECTORS

The most important characteristics for the SMSD, namely the radiation resistance, the spatial definition in tracking, and factors influencing the signal readout and processing, will be briefly discussed below. The SMSD operating principles, the theory of superconducting transmission lines, and the Josephson junction logic circuits will be outlined in the Appendix.

2.1 Radiation hardness

Radiation hardness will probably become one of the main limiting factors in the detectors of future hadron colliders, since silicon microstrip detectors, for example, are known to start seriously deteriorating already before 1 MRad dose. Superconducting materials such as pure metals and A15 compounds (Nb_3Sn and Nb_3Ge) show only very small decrease of T_c and I_c at 100 MRad, and various alloys, such as NbTi, have no damage up to 700 MRad. The oxide isolation materials, such as Al_2O_3 and SiO_2 are likely to withstand 500 MRad. In superconducting tunnel junction devices, for example, the normal conductivity starts to change only at an electron fluence around 10^{10} e/μm^2.

It is thus clear that the intrinsic high radiation resistance of the superconducting and isolating materials enable operation at luminosities about two orders of magnitude higher than is possible when silicon strip devices are used for tracking. These factors have already been discussed in a proposed scheme for a superconducting thin film vertex detector for SSC applications[5].

2.2 Spatial resolution

The SMSD has an almost constant signal size when an ionizing particle traverses the strip. The principle of the detector, which will be discussed in detail in Section A1, is thus digital, unlike the ionisation detectors where the charge is divided between collector strips or wires, and interpolation is used for defining the position of a track. Therefore the position resolution in the superconducting detector must be achieved by a larger number of individual strips. On the other hand, when comparing its resolution with that of a device such as the silicon strip or gas microstrip detector, the SMSD has an equivalent position resolution of $\delta x \approx w/3$, where w is the line width of the microstrip.

The uncertainty of the coordinate definition in modern laser interferometric photolithography is in the range of 0.5 µm in the whole mask area of 500^2 mm^2. The width and separation between strips on a substrate is only limited by such techniques. Smallest strips may be physically best detectors, but with the present understanding[3] of the dynamics of the non-equilibrium self-recovering signals, the optimum strip size could be around 2 µm which is available to us using this technique.

It may be advantageous to use interleaved strips etched out on opposite sides of a ground plane; this leads to a twice larger number of strip planes while keeping the detector thickness constant, and to excellent relative positioning of these planes. Because the active detector part is the strip itself and not the substrate, multilayer detectors are also possible, provided that sufficiently thick ground planes can be deposited between the planes on which microstrips are etched.

2.3 Readout and timing resolution

The superconducting microstrip lines offer two features which should greatly ease the readout problem:

Firstly, the timing resolution is very much superior to the known detectors. Superconducting phenomena have intrinsic speeds in the picosecond range, and the pulse edge could be conserved in a superconducting microstrip line much better than in a classical transmission line.

Secondly, as will be discussed in Section A2, a superconducting strip on a thin insulator makes a transmission line with a velocity of propagation in the range of a few percent of the speed of light in vacuum. The kinetic inductance in lines made of very thin films leads to even lower speed of signal propagation.

If the strips are etched out in a continuous pattern so that they are connected in series, the longitudinal position of the passage of a particle through the strip can be located to a few millimetres by measuring the arrival time of the signal. Since the strip that is hit is determined by knowing that time, a large number of strips can be read out with one set of multi-hit electronics.

The hit position can be located with sufficient accuracy along a given strip so that hit ambiguities can be eliminated without having the additional sets of strips which the ambiguity resolution usually requires. The track finding is then simplified, since for two nearby tracks one has superb spatial resolution in one direction and fairly good in the other.

2.4 Signal processing

Superconducting NbN detectors produce signals in the 10 mW range[1], comparable with other solid state detectors. The detector development work, therefore, can be done using classical fast electronics, including thin-film impedance transformers, and discrete coils and capacitors. Such components can be integrated with the detector in a straightforward way. Commercial MESFET and HEMT amplifiers and GaAs diodes can be mounted on the substrate by bonding with wires or using the flip-chip technique.

In the near future an enlarged programme should be started which includes the development of very low power superconducting logic. These circuits could share the substrate with the strips and they could be built in the same deposition process. We propose here to study only the feasibility of their fabrication and integration, by designing the masks so that some of the basic components can be tested.

The intrinsic fast speed of superconducting phenomena due to the high velocity of the quasiparticles, and the absence of dispersion in superconducting transmission lines, ultimately enable to make full use of Josephson logic circuits in the readout. The logic circuits could be placed in the immediate vicinity of the detector, and they should be made relatively immune to radiation. This would avoid the problems associated with long parallel readout lines: large space requirement, thermal load due to line driver amplifiers, and losses in time resolution. The superconducting logic would operate at such low thermal loss level that crude processing and filtering can be performed before the signals are transmitted outside the detector.

It should be emphasised that superconducting logic circuits based on Josephson junctions were already highly developed by many companies, particularly IBM and Fujitsu. The latter, for example, has a 2.5 ps gate, and Hypres makes and markets digital sampling oscilloscopes based on Josephson junctions, with 5 ps rise time. The development of superfast computers based on them has been frustrated so far by the problems of making sufficiently fast very large memories.

3. PROPOSED PROGRAMME

We propose to use our existing facilities and equipment for an initial study of 12 months. This equipment and programme is briefly outlined below.

3.1 Equipment for the test programme

We have built at CERN a rapid-cycling test bench for the cryogenic measurements of small substrates. This device features 1 K base temperature, sample cooldown in a few minutes, three micro miniature cryogenic coaxial lines, thin windows for electron irradiation using external sources, and instrumentation for temperature measurement and control. This test bench needs a minor adaptation for the mounting of substrates, and it has to be installed in a suitable laboratory space. An existing microscope can be installed on the test bench for facilitating the attachment of the coaxial lines and instrumentation wires during sample mounting.

The control system also might need a small revision for obtaining automatic cooldown and programmable temperature control. However, first tests can (and should) be performed under manual control of the cryogenics.

At CERN we also have a room-temperature probing bench with a suitable optical system for circuit inspection and testing. An existing ultrasonic wedge bonder allows the wiring of the substrates.

Existing rapid oscilloscope combined with a CCD camera will be used for the pulse characterisation of the strip counters. Some of the other test electronics can also be reused, and only a minor amount of new equipment needs to be purchased. We plan to purchase a new 486-based PC with a larger memory and higher-capacity hard disc for the acquisition and storage of the CCD camera images. It is also desirable to upgrade the commercial data acquisition software. Some new wide-band electronic components will have to be procured.

VTT has computing facilities for the design and simulation on superconducting microwave circuits, which will be used for the microstrip line and circuit optimisation. Simulation software includes most superconducting components, and there exists long experience in the microwave design and simulation of DC SQUIDS. There is also in-house software and equipment for the mask design and fabrication.

In VTT an existing magnetron sputtering chamber will be modified and adopted for the sputtering of NbN, for which experience has already been gained in another project. Test equipment exists for the film and junction characterisation at room temperature and helium temperatures, using a variable temperature dewar. The test instrumentation includes microwave equipment for characterizing superconducting circuits.

3.2 Detector development programme

We plan to build, test and optimize strip detectors based on the above principles. Masks will be designed so that on each wafer several substrates can be deposited simultaneously. The substrates will contain many different types of strip geometries and types, in order to enable the testing of various film properties in addition to the particle detection. The tests could be done initially in the laboratory using sources of electrons, α-particles and γ- and X-rays.

Tests in the particle beams require a minor modification of the cryogenic test bench. These tests should be done with other tracking devices with known efficiency, or they should include several strip planes in coincidence, so as to be able to derive the efficiency of the detector. Initially, the beam tests will be performed parasitically in the SPS muon beam M2, or in the halo of this beam.

Summarizing Sections 1 and 2, we plan to study the feasibility of using superconducting microstrip counters in LHC inner detectors, by measuring the parameters of test microstrip lines fabricated under controlled conditions. The parameters to be varied are:

- Film thickness
- Isolator thickness
- Strip width
- Strip separation and geometry
- Magnetic field and its orientation
- Temperature

The parameters to be measured and studied are:

- Strip material properties (resistivity, specific heat, speed of propagation, critical currents and temperature, microscopic non-equilibrium parameters)
- Substrate material effects
- Pulse shape: height, duration (recovery time), and in particular rise time
- Sensitivity to different particles (electrons, α-particles, X-rays, γ, high-energy beams)
- Detection efficiency
- Radiation resistance

3.3 Transmission line and superconducting circuit development

We plan to make systematic characterisation of narrow superconducting strip lines with dielectrics made of various materials and thicknesses. The tests of the superconducting transmission lines could be done using standard time domain reflectometry and network analysis. Other stripline components and circuits could also be tested out as needs will appear. The tests will be made in VTT and at CERN in the cryogenic test bench.

The items to be included in these preliminary studies are:

- Transmission line characteristics
- Impedance transformers
- Microwave spectrum analyser circuits
- Circuits for signal processing and detector readout
- Interfacing of HEMT devices on the substrate

3.4 Josephson junction logic development

The Josephson junctions required for the detector readout logic would require a relatively large initial investment in the mask design and deposition process development. We foresee the development of Josephson junction logic readout after the successful completion of the presently planified initial programme, and provisions will be made in the mask design so that the design can later be easily adopted to include additional circuitry on the substrates.

4. MANPOWER PLAN

Most of the responsibilities will be shared among the participating Institutes during the proposed project of 12 month duration.

The responsibilities of the CERN group include:
- Device physics and modelling
- Setting-up of the cryogenic test bench and helium recovery line in 892-1D-12
- Setting-up of the sample mounting equipment in 892-1D-12
- Mask design and fabrication
- Substrate mounting
- Detector tests in laboratory using sources
- Beam test preparation (test cryostat modification for beam windows)
- Detector tests in beam line

The VTT group is responsible for the following:
- Device physics and modelling
- NbN process development
- Microwave circuit design
- Mask design and fabrication
- Deposition
- Etching
- Film and device characterisation

The HUT group responsibilities are:
- Device physics and modelling
- Film and device characterisation
- Beam test preparation (test cryostat modification for beam windows)
- Detector tests in beam line

5. 1994 BUDGET PLAN AND PROPOSED FINANCING

The table below gives estimated costs for the relevant items, and the proposed sharing between CERN and Finland. This covers the proposed programme of 12 months:

Item	CERN (kCHF)	Finland (kCHF)
Technical services		30
Travel	12	10
PC486	8	
Substrates	10	
Cryogenic test bench upgrade and installation	13	
Software upgrade for LabVIEW and CCD camera	2	
Wide-band electronic components	5	10
Mask design and fabrication	15	50
Installation of ultrasonic wedge bonder (existing)	5	
Deposition of NbN films and contact pads + etching	20	30
TOTAL (applied for 1994)	**90**	**130**

The funding applications have been made at CERN on 17.11.1993, and in Finland on 16.12.1993 for the Helsinki University of Technology (one part); other funding applications in Finland are in progress and they will be submitted in February 1994.

APPENDIX

TECHNICAL DESCRIPTION OF SUPERCONDUCTING MICROSTRIP LINE DETECTORS (SMSD)

A1. PRINCIPLE OF OPERATION

Several schemes for implementing superconducting strip counters have been proposed and studied. At present one of them shows good promise and offers perspectives for vertex detectors and other applications where present technology limits the performance of the apparatus. In this scheme a portion of the superconducting microstrip line is driven normal by the heat generated by the passage of a particle through it. Such strips, made of a metal or a metallic compound, were suggested[5] for use at the SSC.

Two main models explain the behaviour of the transient phenomena leading to the detection of particles: 1) Equilibrium models, and 2) Non-equilibrium models. These differ in the extent of thermal equilibrium between the phonon and electronic systems of the material. A further class of models also takes into account the inertia of the conduction electrons, which leads to the concept of kinetic inductance, visible in very small lines.

A1.1 Equilibrium models

The use of superconducting strips as an alpha particle detector was proposed already in 1962 by N.K. Sherman[6], and was demonstrated using Sn and In film strips in 1965 by Spiel, Boom and Crittenden[7]. The operation of the detector was shown to be bolometric; i.e. the bulk of the film material was heated up sufficiently by α-particles so that a section underwent a transition to normal state. In this mode the pulse rise time may be limited by the speed of heat diffusion, which depends on the speed of phonons and on the electron-phonon scattering. From a thermodynamic model, Crittenden and Spiel[4] estimate the intrinsic pulse rise time t_r = 100 ps.

The use of pure metal films has the inconvenience that the strip critical current and resistance in the normal state are low, both of which reduce the signal substantially. A systematic experimental study by Crittenden and Spiel[8] confirms that the diameter of the effective normal zone created by alpha particles is given by thermodynamic treatment and reads

$$r_c = \sqrt{\frac{dE\,/\,dx}{\pi \Delta h}}, \tag{1}$$

where $\mathrm{d}E/\mathrm{d}x$ is the energy loss per unit thickness and Δh the enthalpy difference per unit volume for the superconducting transition. Wagner and Gray[5] estimate that minimum ionising particles could produce a normal radius of a few hundred nm, which results in a normal zone of length $2r_c$ and voltage drop

$$V = 2r_c \rho J, \tag{2}$$

where ρ is the resistivity in the normal state and $J \leq J_c$ is the current density, slightly below the critical current density J_c of the material. In high-resistivity materials, pulses up to hundred millivolts could be expected, as opposed to (relatively) pure metals in where the pulse height tends to stay below one millivolt. As an example, NbN may have a resistivity[9] above 200 μΩcm and critical current up to[10] 10^7 A/cm^2 . With 200 nm normal zone the resulting voltage pulse is 80 mV using the above numbers. Adjusting the resistance of the normal zone by proper choice of the isolating film height so that impedance match with the line is near perfect, the signal observed at the end of the strip can be expected to have the same height and very nearly the same shape, because attenuation and dispersion are very low in superconducting transmission lines. These points will be described below in more detail.

In a vertex detector a relatively high field is required, and we therefore propose to study strip detectors made of the type II material NbN with a high critical field, current and temperature. Other high-resistivity materials such as PbBi alloys, Chevrel phase compounds, A15 compounds (such as Nb_3Ge), or HTSC perovskite materials are also attractive, but their study is beyond the scope of the present Proposal.

A1.2 Non-equilibrium models

Non-equilibrium phenomena play a decisive role in the initial evolution of the hot spot created by a fast traversing particle in a thin superconducting microstrip counter. The thermalization of the hot spot is a relatively slow process, and a rigorous treatment of the initial evolution problem would require the solution of the Boltzmann equation. This is clearly very difficult, although many simple cases can be rather well approximated by the Rothwarf-Taylor equations[11], which explain successfully the quasiparticle and phonon dynamics in tunnel junctions for example.

In addition to the quasiparticles and phonons, the electromagnetic fields need to be taken into account. This requires the simultaneous solution of Maxwell's equations. Superconductivity can be taken into account by adapting the Landau-Ginzburg equations into the time-evolution equations. We shall discuss these phenomena below mainly qualitatively and, where possible, semiquantitatively. In our discussion we shall refer to Fig. 2 which schematically illustrates the dynamics of the hotspot growth in a NbN film with $\rho_N = 120$ μΩcm resistivity and $J = 10^6$ A/cm^2 current density.

Relativistic particles traverse a 300 nm thick film in 1 fs. A major portion of the ionization deposited in the material is dissipated in the conduction electrons in about 10 fs. During this time quasiparticles, with Fermi velocity of 2.1 μm/ps, may transport the heat to a distance of 20 nm, if they are not scattered. The atomic oscillations have minimum periods of about 100 fs; in the 10 fs time scale we may ignore the ionic lattice contribution to the sharing and transport of energy. The phonon system will begin to be heated by energetic electrons in about 1 ps after the passage of the particle, but for thermal excitations near gap energy, the electron-phonon relaxation time is much longer, of order $\tau_{e\text{-}ph} \approx 60$ ps in NbN for example. The electron-phonon relaxation process has been discussed recently by Gray[12].

Because quasiparticles will be ultimately scattered in the material, the propagation of the initial 'normal current zone' is controllable by the microscopic structure of the material, which may reveal itself very important in the present application.

Let us now assume that in the subpicosecond time scale, energy is mainly shared and transported by quasiparticles, and that the current with uniform density will continue to flow in the normal conducting volume, thus heating the quasiparticles and therefore enlarging the spot radius. This is depicted in Fig. 2a, which shows the hotspot with maximum diameter of 60 nm at approximate time $t = 100$ fs, sufficient for the propagation of the quasiparticles within the spot but clearly insufficient for sharing a substantial part of the energy with the equilibrium phonons.

The assumption of an almost undisturbed current distribution (Fig. 2a) may be justified in the subpicosecond time scale, because eddy currents will allow changes in the self-induced flux, and therefore in the current distribution, only very slowly. We estimate that in NbN the time constant for magnetic flux to creep out of the hotspot is of the order

$$\frac{B}{\dot{B}} \cong \frac{B^2}{2\mu_0 \rho_N J^2} \cong \frac{\mu_0 d^2}{2\rho_N} \cong 0.5 \text{ ps} \tag{3}$$

In the zone heated above the critical temperature, once greater in diameter than the correlation length (≈ 5 nm), the current flow will therefore be dissipative, and a voltage drop will occur in it. An electric field will also leak out of the film, if the hotspot traverses the film, as is expected in the case of fast projectiles. The electric field pulse will begin to propagate in the dielectric at a speed characteristic of the superconducting line.

In the first picoseconds the energy dissipated in the electronic system by the bias current cannot be coupled to the phonons, and one may make the simple assumption that this energy will heat and enlarge the non-equilibrium 'quasiparticle hotspot'. We estimate the growth speed of the radius in the following simple way. Equating the Joule heat generated in the hot spot of area A, with the rates of energy change due to the growth of the spot and due to the coupling of the electrons with the phonons, one obtains the equation

$$\rho_N J^2 A d = \Delta h \dot{A} d - \frac{C_e (T_c - T_b)}{\tau_{e-ph}} A d. \tag{4}$$

Here T_c is the critical temperature, T_b is the phonon temperature (close to the initial substrate temperature), and d is the strip thickness. Because of the long correlation time $\tau_{e\text{-}ph}$ between the electrons and phonons in NbN, the last term is small compared with the first one on the right side, and we can get a simple expression for the growth time constant of the surface of the hot spot:

$$\tau_A = \frac{\Delta h}{\rho_N J^2} \approx 0.7 \text{ ps} \tag{5}$$

in the case of NbN. Assuming that the spot is circular and will not deform in the very beginning, the radius will the grow exponentially with an initial rate of

$$\dot{r} = \frac{r}{2\tau_A} \approx 40 \text{ nm / ps} \tag{6}$$

so that the initial "equilibrium" radius of 60 nm, due to a MIP, would be roughly doubled in about 1 ps. The current and flux, however, move out of the centre of the spot (Fig. 2b) somewhat faster as shown by Eq. (3), enabling the quasiparticles of the currentless centre of the spot to cool at a speed determined by the quasiparticle heat transfer to the surface of the strip ($\approx$ 100 fs), by the phonon-quasiparticle correlation time ($\approx$ 60 ps), by the acoustic mismatch of the phonons at the film-substrate interface, and, after phonons are heated in the whole volume, by the time for an acoustic phonon to traverse the film $\tau_{ph} = d/v_a \approx 100$ ps. The *hot spot* now becomes a *hot ring*, heated on the perimeter by the current but cooled in the centre by heat transfer between the electronic and phonon systems, and via the interface between the film and the substrate. The ring diameter at $t = 1$ ps (Fig. 2c) is of the order of the thermal healing length in NbN, and it has become slightly oval because the heated ring-shaped zone will expand faster towards the sides of the strip than along its length, due to the fact that the current density will grow on the sides whereas it will drop on the ends of the ring.

In the next picosecond the ovalized ring will grow very fast in the direction perpendicular to the original current direction, until it will touch one of the sides of the strip (Fig. 2d). The speed may approach the Fermi velocity $v_F \approx 2$ μm/ps. The whole few-micrometer width of a narrow strip may thus be bridged by a dissipative non-equilibrium hot zone in less than 2 picoseconds, because the current density on the sides of the ovalized ring may exceed the intrinsic critical current of the material.

It is rather logical to expect a rapid growth of the hotspot in the case of high-resistivity film carrying a high current density. It is much more difficult to explain how the hot zone may recover in such a case; intuition says that nothing might prevent the axial extension of the zone, and in the framework of the equilibrium model this is supported by the calculated minimum current beyond which the hot spot will expand[13]. However, our non-equilibrium model, which was qualitatively described above, gives two possible mechanisms providing self-recovery of the hotspot: Firstly, the current distribution across the strip is highly non-uniform just after the whole width of the strip has been bridged by the hot zone, and secondly the quasiparticles may have time to condense back into the superconducting ground state in the currentless areas, due to electron-phonon heat transfer. This may be occurring first in the proximity of the film-substrate interface, which is also strongly suggested by the results showing a strong dependence of the pulse characteristics on the substrate quality[8].

The reason for the non-uniform current distribution across the strip in the hot zone is schematically illustrated in Fig. 2d. Because usually one or the other side of the film is reached first by the hot ring, current density there may drop to zero as soon as the self-induced magnetic flux may rearrange itself. In the high-resistivity material this will be much more rapid than in the pure metals; granular films may also be better in this sense. The final heated zone will certainly have a length in the direction of the strip which is highly non-even across the strip. The current density will therefore readjust itself in a way which reflects the shape of the zone; the readjustment, however, does not happen instantaneously but within the rough time scale of Eq. (3). During this time a supercurrent may start flowing in those areas which carry no or low normal current; the dynamics of this supercurrent zone will now determine whether the original state of the strip can be self-recovered. The dynamics of a supercurrent zone is different from that of a closed zone with normal current, because the electromagnetic field behaves in a different way in these two areas, and because the relative directions of the gradients of various quasi-thermodynamic quantities (heat, magnetic flux, $\partial J/\partial t$ etc.) will be changed in these two cases. The growth of the supercurrent zone is expected to be much slower, and it may depend heavily on the geometry of the hot zone.

It may be actually required that the third dimension should be included in the quantitative estimates of the hot zone recovery, because when the film is contacted only on interface with the substrate, large vertical gradients can appear already during the growth of the non-equilibrium hot zone. This is particularly plausible when the hot zone length is of the same order of magnitude as the height of the film, as was the case in NbN [1]. The supercurrent "shortcircuit" can thus appear on the interface in an area of low normal current density; the supercurrent density in such thin layer may have a very much higher intrinsic critical limit due to the restricted geometry of the layer.

The following question has be often asked, so that we shall briefly discuss it here: If a normal zone is shortcircuited or even surrounded by superconducting material, how can one get an electromagnetic pulse in the stripline?

The explanation can be made as follows: Let us imagine a spot with normal current, giving an electric field in the material due to Ohm's law. The field leaks out above and below the film, and actually fieldlines also reach the return conductor which partly shorts the hot zone. The resulting electric field, appearing in the isolator between the stripline and the return ground plane, is associated with displacement current and resulting magnetic field; the electromagnetic pulse will start to propagate first radially as a planar guided wave, and after reaching the sides of the strip, it will propagate along the strip in opposite directions with opposite polarities. One of the waves will reach the shorted end of the line, and it will be reflected back with opposite polarity so that it will combine with the first wave constructively. An observer (amplifier) in the other end of the line will see first the half-pulse propagating towards it, and after a time delay required for the propagation of the opposite pulse back and forth between the hot zone and the shorted end of the line, he will see a superposed step of equal height, making up the voltage drop in the resistive zone. There is thus no restriction from superconducting currents shorting the normal one, and the first edge of the signal is associated with the first dissipative hotspot rather than with the normal zone bridging the strip.

If the downstream end of the strip is open instead of short circuited (allowing, however, for the dc bias current to flow) for the high-frequency pulse, the reflected wave will not have opposite polarity. The two waves will therefore combine destructively, and the observer will see a pulse with amplitude one-half of the voltage across the normal spot, and duration equal to the time delay required for the propagation of the opposite pulse back and forth between the hot zone and the open end of the line. These timing features might be useful for extracting the information on the location of the hotspot along the strip.

A2. SUPERCONDUCTING TRANSMISSION LINES

Because an important potential advantage of superconducting microstrip line counters is the combination of fast pulses with slow propagation along the line, making serial readout possible, some more information is provided below about superconducting microstrip transmission lines.

A2.1 Speed of propagation

The speed of signal propagation (phase velocity) in a normal strip line is approximately

$$v = \frac{c}{\sqrt{\varepsilon_{r,eff}}}. \tag{7}$$

If the conductors are in the superconducting state, the signal propagation is slower than this because the magnetic field can penetrate about $\lambda \sim 50$ - 500 nm into the metal, while electric fields are almost completely excluded[14]. This results in the signal propagation speed[15,16] which is constant at frequencies below the gap frequency and is given approximately by

$$v = \frac{c}{\sqrt{\varepsilon_{r,eff}}} \frac{1}{\sqrt{1 + 2\frac{\lambda}{h}\coth\frac{d}{\lambda}}}. \tag{8}$$

For thin isolators ($h \sim 1 - 2$ nm in Josephson junctions) this can be less than one percent of the speed of light, and can be of order of few percent of c in the case of 20 nm TiO_2 dielectric; taking $w = 2$ µm, $h = 20$ nm, $d = 300$ nm, $\lambda = 100$ nm and $\varepsilon_{r,eff} = 80$, we find $v = 0.0338c$. If the superconducting films are also thinner than the penetration depth, the propagation speed is reduced even further. This effect is due to the kinetic energy of the charge carrier electrons, which can be included in the field equations as an additional inductance, called kinetic inductance. The properties of the superconducting transmission lines can thus be estimated by replacing the normal inductance of the line by the sum of the magnetic and kinetic inductances.

The theoretical attenuation[16] in superconducting microstrip lines is due to losses in the dielectric and in the superconductors:

$$\alpha_d = \frac{\omega}{2v}\tan\delta;$$

$$\alpha_s = \frac{\omega^2\lambda^3\mu_0\varepsilon_{r,eff}\sigma v}{2hc^2}\left[\coth\frac{d}{\lambda} + \frac{d}{\lambda}\sinh^{-2}\frac{d}{\lambda}\right],$$

where $\tan\delta$ is the dielectric loss tangent and σ is the conductivity of the charge carriers in the normal state

$$\sigma = \sigma_N\left(\frac{T}{T_c}\right)^4.$$

The resulting attenuation in NbN microstrip lines is very small, and using the dimensions of our planned detector the above equations yield the attenuation less than 10^{-2} dB/m at frequencies below the gap frequency, provided that the operating temperature is below 0.2 T_c. Such low attenuation and the resulting very low dispersion has been beautifully demonstrated using sub-picosecond pulses and optical sampling techniques[17].

We conclude that the detector strip length can be several metres, and that signal transport far from the central region is also possible without degrading the signal quality and timing resolution, provided that the operating temperature is stable.

A2.2 Impedance matching

The impedance of a normal strip line is given by

$$Z_L = Z_0 \frac{h}{w_{eff}} \sqrt{\frac{1}{\varepsilon_{r,eff}}}, \tag{9}$$

where $Z_0 = \sqrt{\mu_0/\varepsilon_0} \approx 120\pi\ \Omega$, h is the thickness of the isolating film on the ground plane and $\varepsilon_{r,eff}$ its effective dielectric coefficient at the frequency of operation. The effective width w_{eff} is calculated from an empirical formula

$$\frac{w_{eff}}{h}=\frac{w}{h}+2.46-0.49\frac{h}{w}+\left(1-\frac{h}{w}\right)^6, \tag{10}$$

where w is the geometric width of the strip. In practice the width of the strip is always much larger than the dielectric height in our case, and therefore the fringing field correction is at most a few percent.

In superconducting materials the penetration of electric and magnetic fields in the conductor behaves in a different manner, and the above formulas cannot be directly applied in the case of isolator thickness $h \sim 20$ nm. Kautz[18] has analysed such lines in terms of the theory of Mattis and Bardeen[19] for the complex conductivity of a BCS superconductor. At frequencies below the gap frequency (~ 1 THz) the impedance is constant and can be approximated by

$$Z_{SC}=Z_0\frac{h}{w_{eff}}\frac{1}{\sqrt{\varepsilon_{r,eff}}}\sqrt{1+\frac{2\lambda}{h}\coth\frac{d}{\lambda}}, \tag{11}$$

where $\lambda \sim 50$ - 500 nm is the magnetic field penetration depth in the superconducting material. This equation also takes into account the kinetic inductance of the microstrip line.

If $w = 2$ µm, $h = 20$ nm, $d = 300$ nm, $\lambda = 100$ nm and $\varepsilon_{r,eff} = 80$, we find $Z_L = 0.41\ \Omega$ and $Z_{SC} = 1.35\ \Omega$. Such low impedance will need to be matched to normal transmission lines when using normal electronics for detector testing. We propose to study the possibility of using a stripline impedance transformer to perform the matching, and we plan to integrate thin film impedance transformers with the detector, in order to match the microstrip impedance around 1 Ω with the standard 50 Ω impedance of coaxial lines, thus conserving the widest possible bandwidth in the course of tests.

The impedance matching of the superconducting transmission lines may be necessary not only if normal 50 ohm transmission lines and electronics will be used, but also for matching the strips with possible superconducting logic circuits.

A2.3 Stripline components

In addition to the matching circuits required for adopting the signal strips with the transmission lines and readout, also other stripline components could be built on the detector substrate. The potentially useful circuits include at least capacitors, inductors, directional couplers, splitters, combiners, loads, shorts etc. The motivation for such functions on the substrate is mainly in the possibility of analogue handling of the signals before entering into the superconducting logic, with view on possibly simplifying the readout logic.

Because normal electronics cannot preserve the rise times of the superconducting microstrip counters, we propose to build integrated superconducting analogue circuits on the substrate for making indirect measurements of the signal properties. This can be accomplished by using the parallel filter techniques, for example. Such a circuit will yield the frequency spectrum of the pulse, from which the temporal evolution can be obtained by Fourier transform.

A3. SUPERCONDUCTING READOUT LOGIC

A3.1 Josephson junction and other superconducting circuits

The Josephson junction consists of two superconductors separated by such a thin (< 2 nm) isolator that supercurrent can flow through without voltage drop, up to a critical current after which a voltage appears across the device. The device is highly non-linear due the phase coherence of the electrons traversing the junction; this phenomenon is called the Josephson effect. It has found a vast range of applications in RF generators, receivers, mixers, magnetometers, voltage standards, amplifiers and gates.

While Josephson junction circuits are well developed technology, some discussion of it may be useful here. It should be emphasised that we do not plan to do major development work in this domain in the framework of the present Proposal. However, because experience in the interfacing of the detector strips with such logic circuitry would be useful, we plan to implement test circuits on the same substrate as is used by the strip counters. This also enables to gain experience in the development of the process to produce these components with our choice of materials. Such circuits can be added at low additional cost on the masks, and they may use existing designs of Josephson oscillators, DC SQUIDs and other test circuits for studying the basic phenomena and the device physics itself.

It is important to note that the advantages of Josephson logic are not only ultra-high speed and remarkable compactness, but also extremely low power consumption. Operating in the microwatt range, the Josephson logic would provide almost negligible heat load in the interior of the detector, whereas this is a major problem with conventional semiconductor logic.

A3.2 Josephson logic circuits

The Josephson junction with zero-voltage Josephson current works as a perfect gate for logic circuits. The two states, steady state and running mode, transmit or reflect clock pulses which may be scaled, shifted, added etc. in the subsequent circuitry. The transition between the two states of a gate can be controlled by a capacitively coupled input or by direct current injection; the signal from a strip detector may be sufficient to set or reset a gate with suitable characteristics, as the pulse energy required is many orders of magnitude below those required for fast semiconductor gates.

The practical realisation of Josephson logic functions was developed already 15 years ago by IBM[20]. The current injection logic (CIL)[21] uses several Josephson junctions for each logic function, and is capable of reasonable fan-in and fan-out so that large logic arrays can be easily designed. The single logic levels are not clocked but latched. The total IBM gate delays were 27 to 45 ps for OR and AND functions, with power dissipations 1.5 to 6.0 μW. Data are read at initial latch and propagate asynchronously through the logic, and are again synchronised at output latches. This suits very well for operation in the readout logic of a collider detector, where the latch frequency can be the accelerating frequency or its harmonic. The vertex detector could thus be easily read out during the 25 ns between the LHC bunch crossings, and it might be possible to resolve events separated by less than one nanosecond. Clock frequencies of 10–30 GHz are possible.

IBM has stopped the Josephson junction logic development, while Japanese companies have continued work in this field. Fujitsu has recently announced a 4-bit microprocessor integrating 5000 Josephson junctions on a single chip. NEC has built a 1 k DRAM with about 1 million Josephson junctions on board. The companies were expected to announce a 16-bit microprocessor in 1991, but their programme has not been discussed in public since then.

The standard Josephson gates cannot be operated at high fields, which is a handicap for vertex detectors. It could, however, be envisaged that the readout logic could be sufficiently shielded from the magnetic field by miniature superconducting shields and/or compensation coils, and they could be located to a region of low field and low flux of particles.

A3.3 Readout circuits

Given the existence of a Josephson gate, the construction of a scaler (for example) based on a Josephson junction gate is rather straightforward. By counting clock pulses at 10 GHz controlled by a Josephson gate, a time-to-digital converter can be built with a resolution compatible with the detector rise time. If a detector stripline is terminated with a short circuit, the output pulse is clipped so that its length corresponds to the double propagation time from the track hit to the shorted end. With propagation speed of 0.06*c* this leads to 1 mm hit resolution along the length of the strip. This information could be used for resolving the ambiguity of multiple hits in a detector with two crossed layers of strips, greatly simplifying the readout of the detector.

The Josephson memory could store the hit information until trigger processors will ask for the readout outside the detector. Some of the information could be pre-processed in the Josephson logic for use in the trigger decision. In this way part of the processing required for a particular trigger can be speeded up, firstly by enabling parallel processing, and secondly by the clock speed about two orders of magnitude above silicon technology.

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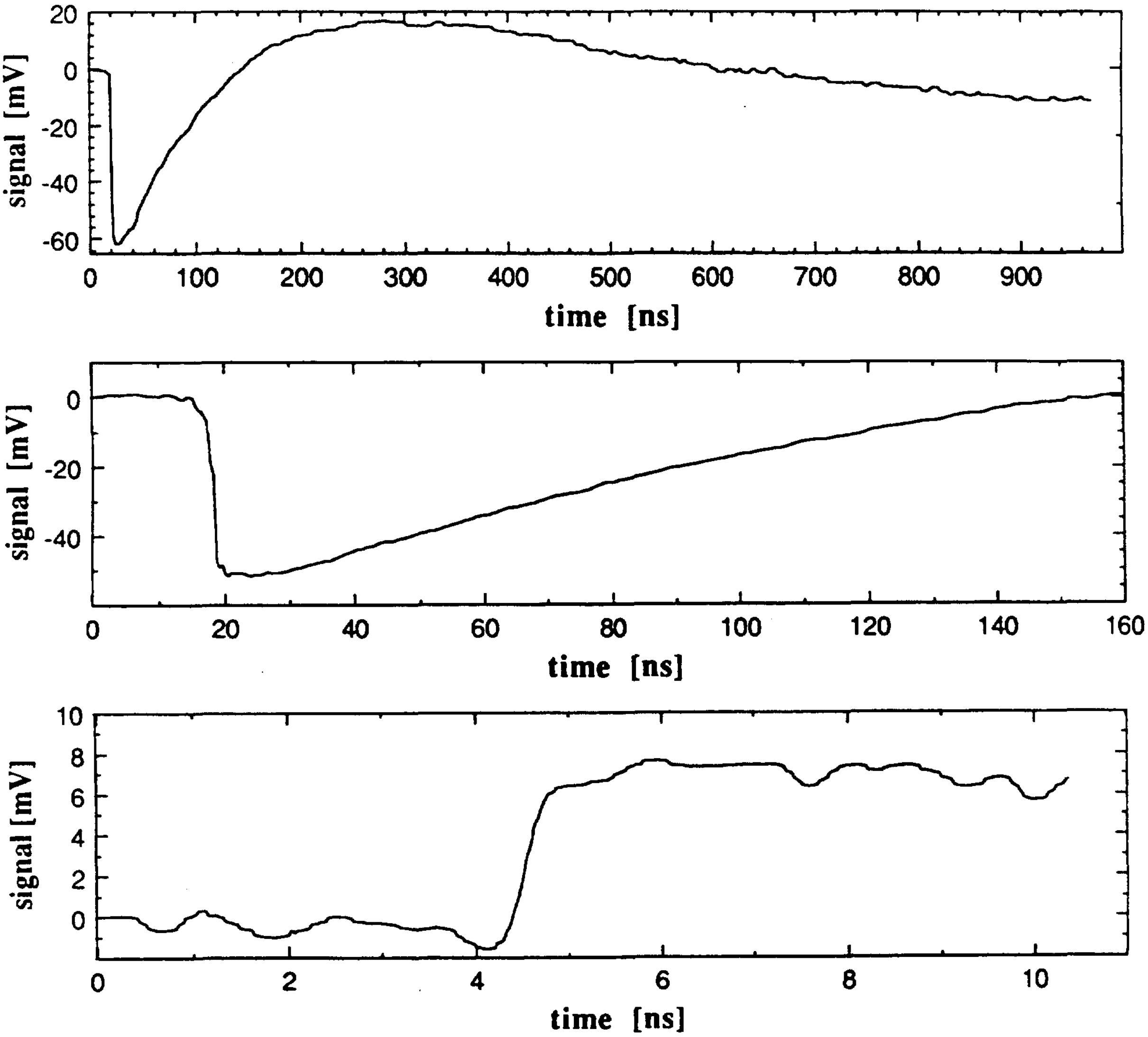
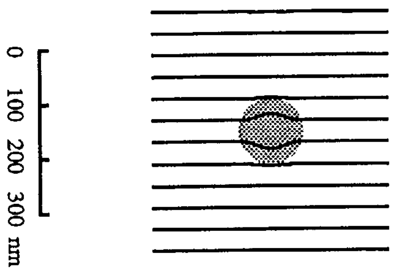
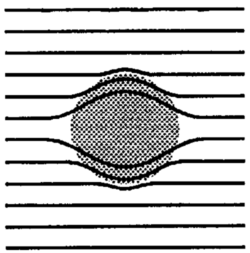


Figure 1: Three typical signals due to MIP's traversing a NbN strip of 3.4 μm width and 350 nm thickness (from Ref. 1). The first one shows the decay time due to the preamplifier high-pass cutoff at about 10 MHz. The third one shows the oscilloscope rise time of about 300 ps, due to the 1 GHz passband of its vertical preamplifier. The two first signals may indicate that a slow recovery of the hotspot is beginning at about $\Delta t = 20$ ns from the rising edge.

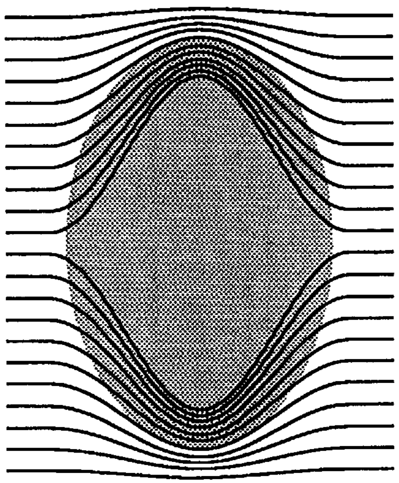
Figure 2: Schematic illustration of the dynamics of the growth of the hotspot created by a MIP traversing a NbN strip with a width of 3.4 μm and thickness of 350 nm. It is assumed that the resistivity of the material is 120 μ cm and the current density is $1.5 \cdot 10^6$ A/cm2; the current density is illustrated by "current lines" which are lines parallel to the local current density vectors. Denser lines thus mean higher current density.



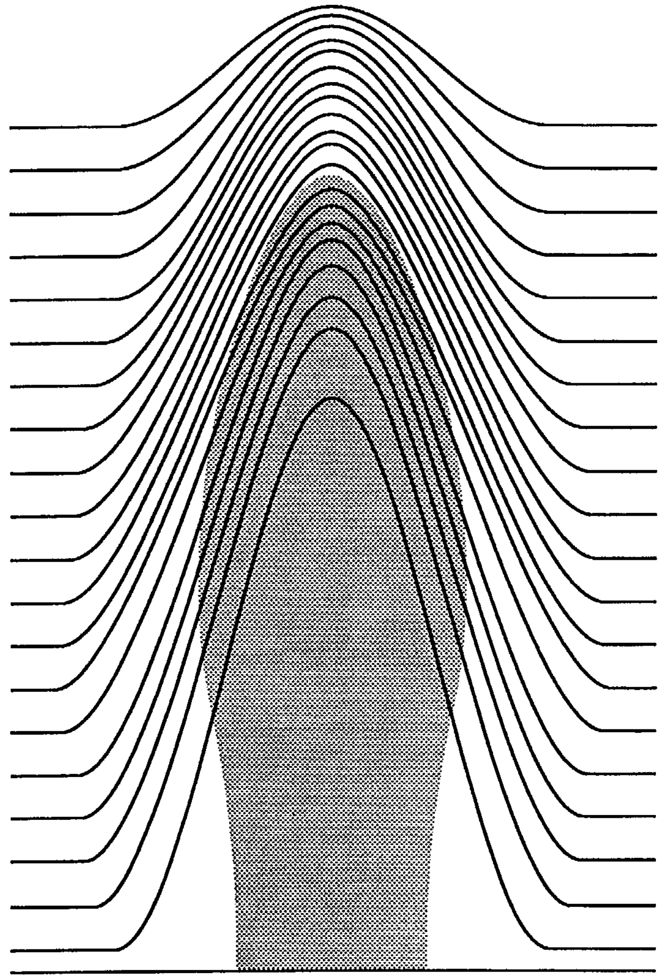
a) t = 100 fs. The initial hotspot is circular and it is assumed to have the maximum radius given by Eq. (1). The quasiparticles have "cooled" to an energy close to the gap value, but the phonons are very far from equilibrium. The current density is almost unperturbed.



b) t = 300 fs; the hotspot has roughly doubled its area due to ohmic heating. At the same time the current has moved out its centre, increasing the current density on the segments of the perimeter parallel to the current, and decreasing the current density on the segments perpendicular to the initial current.



c) t = 1 ps; the circular symmetry of the spot is lost, because it has grown towards the sides of the strip at an accelerated speed.



d) t = 2 ps; one side of the strip has been reached, and the current has jumped to the remaining superconducting segment, where the current density quickly exceeds the intrinsic critical limit. This completes the normal current zone which now bridges the whole width of the strip.