FRONTIER APPLICATIONS OF RF SUPERCONDUCTIVITY FOR HIGH ENERGY PHYSICS IN THE TEV REGION

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> "If you can look into the seeds of time and say which ones will grow and which will not - speak then to me"
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> Banqou to the Witches

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Our present understanding of the fundamental nature of matter is embodied in the standard theory. This theory views all matter as composed of families of quarks and leptons with their interactions mediated by the family of force-carrying particles. Progress in particle accelerators has been a vital element in bringing about this level of understanding.

Athough the standard theory is successful in relating a wide range of phenomena, it raises deeper questions about the basic nature of matter and energy. Among these are: why are the masses of the various elementary particles and the strengths of the basic forces what they are ? Other unanswered fundamental questions are:

How many generations of quarks and leptons are there?
Are the quarks and leptons really elemenentary?
Can the strong force be unified with the electromagnetic and weak forces?
Can gravitation be treated quantum mechanically as other forces are, and can it be unified with them?

We expect that over the next decade a new generation of accelerators spanning the 100 Gev mass range will shed light on some of these questions. These accelerators, which are listed in Table 1 will provide the means to thoroughly explore the energy regime corresponding to the mass scale of the weak interactions to reveal intimate details of the force carrying particles, the weak bosons, Z0 and W+-. Superconducting rf technology will feature in a major way in the electron storage rings listed in this Table.

Table 1.

Tevatron	storage ring pp- collider	2 TeV
LEP	storage ring e+e- collider	100 - 200 GeV
TRISTAN	storage ring e+e- collider	54 - 70 GeV
HERA	storage ring e p collider	30 on 800 GeV
SLC	linear e+e- collider	100 GeV

Current theoretical ideas predict that to make further progress towards a more fundamental theory of matter, it will be necessary to penetrate the TeV energy regime. At this scale a whole new range of phenomena will manifest the nature of the symmetry breaking mechanism that must be responsible for the differences we observe in the familiar weak and electromagnetic forces. History has shown that unexpected discoveries made in a new energy regime have proven to be the main engine of progress. The experimental challenge to accelerator designers and builders is clear.

How to Meet the Need

Colliding beam accelerators have proven their great kinematic advantage in pushing the energy frontier. The cleanest interactions are provided by collisions between elementary particles such as electrons and positrons. When e- and e+ annihilate each other they give all their energy to the production of new particles. Unfortunately we do not have in our grasp today the technology to accelerate elementary particles to TeV energies. The success of superconducting magnet technology at the Fermilab Tevatron, however, demonstrates that we have the knowledge and experience needed to build a storage ring $p^{-}p$ collider that will probe the TeV energy scale. Proton-proton colliders require more total energy than the mass of the particle produced because the production process actually occurs through collisions of a single quark or gluon in one proton with another quark or gluon in the other proton or anti-proton). On the average a single constituent carries only 1/10 the total energy. As a rough rule therefore, proton beam energies must exceed the wanted elementary interaction energies by ten times. The SSC is an accelerator system designed to produce 40 TeV proton-proton collisions using storage rings with state-of-the-art superconducting magnet technology. Before the turn of the century, this pioneering effort will provide the capability needed to continue important advances in elementary particle physics.

Full understanding of the new perspectives stemming from such a proton collider will require a cleaner view that can only be made available through illumination with e+e- interactions. In a lepton collider, the total event rate at a given luminosity is much lower than for a proton collider, so that the interesting events stand out more clearly above the competing background. Although the electron storage ring is the favored technique to explore the 0.1 TeV mass region, it is not an economically viable avenue for the future. The dominant problem is energy lost to synchrotron radiation as electrons are forced into circular orbits. Electron storage ring technology has advanced to the point that performance and cost can be predicted with reasonable confidence. It is generally agreed that, after optimizing both the construction and operating costs, the size and cost increase with the square of the beam energy. Several studies of alternative approaches have been made with the conclusion that a significant increase in beam energy beyond 0.1 TeV will require a new approach that will drastically lower the cost. The most practical approach now known uses linear colliders which avoid the synchrotron radiation problem. Figure 1 compares the cost of e+e- storage rings with the cost of colliding linacs[1]. The comparison is made both for accelerators based on conventional room temperature cavities as well as those based on superconducting cavities. While it is clear that above 0.1 TeV, linear collider technology is economically favored over storage rings, it is equally clear that an extrapolation of the present state of the art of either normal or superconducting technology to 1 TeV /beam yields excessive cost.

TeV Linear Colliders

The challenge to the superconducting rf community is therefore to provide a technically and economically viable TeV linear collider technology. The basic terms of that challenge are set forth by the physics needs and economical reality. A multi-TeV electron linear collider must have the highest possible luminosity, with 10^{33} (cm^{-2} sec^{-1}) as a minimum requirement. Given the probable high cost of such a machine, a high luminosity goal is necessary to ensure productivity on the basis of now recognized physics principles. As a frontier physics instrument, a linear collider should satisfy the following requirements:

$E > 1$ TeV/beam , $L > 10^{33}$ cm^{-2} sec^{-1}, Energy spread $< 10\%$.

Such a machine would be complementary to the SSC, and as such cannot be more expensive to build and operate. These considerations impose certain economic boundary conditions:

$C < 3 \times 10^9$ \$, $P_{ac} < 200$ MW

Because of the high capital investment that such a machine will involve, it will be important to ensure that the design energy and luminosity fully meet physics needs.

Optimization of linear collider design is a science still in its infancy in which the balance of machine physics, practical engineering and economics is carried out. Deeply involved are the physics of the beam-beam interactions with its self-focussing and intense collective bremsstrahlung effects, beam-structure interaction which limits achievable beam brightness, final focus possibilities which will influence the beam current, efficiencies of various components and systems, etc. The first attempt (the SLC at SLAC) to achieve e+e- collisions with a linear collider is on the way, albeit at a low energy of 0.05 TeV/beam. The results will be crucial in guiding future optimization studies. A 1 TeV/beam collider will require significant extensions of accelerator physics and technology beyond the SLC. It will involve substantially higher beam power and particle density at the collision point. The high beam powers involved demand suitable power sources and high efficiency of conversion of line power to beam power. The high particle density requirement demands that source brightness, alignment tolerances, beam stability and beam-beam interaction effects be pushed well beyond the limits tested at the SLC. An accelerating mechanism with high gradient is clearly desirable to limit machine length, but the highest gradient technically feasible may not fall at the economic optimum. The efficiency with which a bunch can extract stored energy from a cavity falls with increasing gradient and the peak power demand grows. The choice of operating wavelength needs thorough exploration as this interacts both with the beam dynamics questions as well as with the availability and efficiency of power sources and efficiency of accelerating structures.

In our judgement, these complex interacting issues are likely to remain unresolved until a viable accelerating system emerges that can serve as a focus for further study and optimization.

In recent years a number of new acceleratior concepts have been put forward and are being studied. Among these are the plasma beat-wave accelerator, the plasma wake-field accelerator, the grating accelerator, the various 'two beam' accelerators, the switched power accelerator, etc. The physical mechanisms involved in any of these novel methods will take several more years of study. Technologies that employ rf power sources driving near field accelerating structures are most developed. In this traditional method, a longitudinal electric field for acceleration is engendered by the configuration of the surrounding conducting device. While no one knows for sure, today it seems likely that the next linear collider will be built with some version of this technology which is already well along in development. Laser, beam-excited plasma-accelerators, etc. will not come along fast enough to compete.

All of the "classical" technologies have potential for improvement and are being studied. The rf superconductivity community should not be laggard in accepting the challenge.

Comparison of Suggested Systems

The unique advantage of rf superconductivity is its potential gain of a factor of 10^6 or more in the surface losses. Even though the refrigerator efficiency reduces the effective gain, the net advantage remains substantial and can be exploited in several ways simultaneously. Most obviously the need for expensive, complex, ultra high peak power rf sources is eliminated. In addition one can exploit the ability to store rf energy for many rf cycles to enhance both the efficiency of energy transfer to the beam and increase the average beam current. The operating cost for a high luminosity machine with useful energy resolution can thereby be held to an acceptable value. These considerations provide more flexibility in optimization of the overall machine and allow greater simplicity in the design by comparison with other schemes.

Figure 2 compares the principal elements of a 2 TeV c.m. linear collider in three versions of paper concept designs that have been put forward. The injector sections in all versions have very similar features. All must make provisions for positron production and damping rings to provide a low source emittance. For the normal conducting versions depicted in (a) and (b), substantial improvements over the SLC emittances are essential. The main accelerating structure must provide a high gradient with a high efficiency of conversion of energy supplied into beam energy without creating intolerable wakefield effects. Focussing elements must be interspersed within the main linac to control the beam emittance. A sophisticated final lens system is required before the collision point to focus the beams to submicron transverse dimensions to achieve the required luminosity.

The "standard" linac (version a) capitalizes on high gradient normal conducting structures. Recent experiments have achieved gradients of 200 MV/m in short disk loaded structure segments at pulse lengths of 1.5 - 3 µsecs.[2] The principal difficulty with the standard linac version is the magnitude of the rf drive system. If an acceleration gradient of 167 MeV/m is required at 2.63 cm wavelength in a normal conducting structure, then the peak power that must be supplied over a fill time of the order of 0.1 µsecs would be 5 Terawatt [3]. In one scheme, which consists of klystrons and pulse compressor units, each delivering over 400 MWatts peak power, over 10^4 such units will be required. Several klystron designs are being studied at SLAC which might deliver 100 MW peak power at 3 -4 x SLAC frequency. In addition gyroklystrons and lasertrons are also under consideration as high peak power sources. Formidable technical problems need to be overcome to make these schemes achieve the needed peak power output at an acceptable price.

Discrete microwave power units is one of the ways that have been proposed for producing the required rf peak power to drive high gradient normal conducting structures. Various two beam acceleration schemes form the basis of an alternate strategy. Here rf is produced by a high current drive beam running parallel to the main accelerator. Along the driving beam, transfer elements periodically extract rf energy, which is delivered through waveguides to the structures of the main accelerator. These elements may be free electron lasers (FEL) or RF decelerating sections. The first option limits the drive beam energy to 100 MeV and presents phasing problems between the two linacs. In the second version, phasing is assured by the highly relativistic beam. Interspersed with the transfer elements are re-acceleration elements, which put energy back into the driving beam. In one example the output port of each main accelerating section is connected to the input port of the following transfer section, permitting recovery of left-over energy. The recovery pulse has to be phased for acceleration in the transfer structure and deceleration in the drive structure, increasing the complexity of the scheme. Superconducting rf cavites are proposed as drive beam re-accelerators in both versions of the two beam schemes. The current level of performance achievable with superconducting cavities would be adequate to fulfil the need. Paper design examples for two beam accelerators have been worked out. The only prototype experiment is at a very short wavelength (0.8 cm), but has demonstrated > 1 Gwatt peak power capability using an induction linac to accelerate the drive beam. A disc loaded accelerating section has been constructed and fed with power from the FEL to achieve high gradients[5].

Power consumption is a major concern related to the operating cost for both normal conducting versions. Structures and RF power sources must be capable of efficient conversion of energy from the wall-plug to the beam. The incentive for efficient extraction of the energy stored in the structure pushes structure wavelengths to values substantially lower than 10 cm, exacerabating wakefield effects and the problem of achieving acceptable fabrication tolerances. The same incentive promotes closely spaced multiple bunches within each RF pulse. This approach is restricted by long range wakefields and complications in the final focus that could compromise the physics potential of the machine.

To keep the operating cost at an acceptable level there is a real premium in minimizing beam power. Reducing the beam power in turn demands an infinitesimal collision spot size to reach the desired luminosity, so that a source with emittance several orders of magnitude lower than presently achieved for the SLC is required, coupled with a sophisticated final focus system.

Version (c) is a fully surperconducting linac approach. Use of superconducting cavities allows the filling time to be increased by many orders of magnitude, effectively eliminating the need for ultrahigh peak power sources. In the example presented, 100 klystrons delivering 1 Mwatt peak power would adequately fill the need. Such klystrons are readily available today. Superconducting cavities are ideally suited for efficient conversion of wall-plug to beam power. High efficiency is achieved by accelerating many bunches in each RF pulse without concern for degradation by long range wake fields. Ratios > 10^4 can be achieved between the Qs of the accelerating and the higher order modes responsible for the long range wake so that bunches can be separated by long intervals during which the higher mode fields die out. There is no longer a high premium on reducing beam power or in using ultra-short wavelengths. This scheme is inherently simpler; it can be based on beam emittances, focussing parameters and structure wavelength which are near to those already realized with the SLC.

A superconducting linear collider is dominated by the structure. Even at Q values of $3x10^9$ to 10^{10}, refrigerator associated capital and operating cost can be reduced to a small fraction of the overall costs by running at a duty cycle as low as 1% without compromising the extraction efficiency or the luminosity[6]. These Q values are achievable with current technology, albeit at gradients of 5 -10 Mev/m. Thus the challenge for the fully superconducting machine is to reduce the capital cost of the accelerating structure while achieving higher accelerating gradients.

The threshold gradient for a TeV superconducting linac to be competitive with a proton storage ring such as the SSC can be estimated as follows. Equating the momentum (GxLxe/c) achieved in the linac with gradient G and length L to 1/10 the momentum (exBxR) achieved in a proton ring of radius R, where B= 6.6 Tesla, we obtain GxL = 31.5 Mev/m x(2xpixR). This simple comparison reveals that for a linac with total length comparable to the SSC circumference, a minimum gradient near 30 Mev/m is needed. Fig 3 compares a superconducting accelerator structure[7] with a superconducting magnet[8], showing that cavities are inherently no more complex than magnets. SSC magnets weigh 200 Kg/m, use 7 Kg/m of Nb-Ti superconductor and, with economies of scale, are expected to cost $10K/m. It is reasonable to expect that, as cavity technology continues to mature and the technological and application base broadens, unit costs should approach the magnet costs quoted above.

Nb cavity technology is an attractive option for further advances in achievable voltage at reasonable cost for future accelerators. The inherent properties of Nb imply the potential for an order of magnitude improvement beyond current capabilities of 5 Mev/m and Qs of $3x10^9$ - $1x10^{10}$. At this conceptual stage, it appears that even Nb can satisfy the needs for a fully superconducting linear collider.

Obviously, if gradients can be increased, costs go down in proportion. For linear collider needs, it will be important to assess the potential of high T_c superconductors. Very recently, intrinsic properties of the new superconductors measured on single crystals reveal possibilities of spectacular gains over the superconductors in use today.

For application to accelerator cavities, the discovery that the energy gap to critical temperature ratio is 2X that of Niobium[9] opens the exciting possibility of operating superconducting accelerator cavities at LN2 temperatures. Earlier measurements on ceramic forms showed much lower gap ratios, indicating that even though the dc transition was at 90K, rf applications would be restricted to temperatures below 40K, when a sufficient number of current carriers have frozen into pairs, and losses presented by the remaining normal carriers would become negligible. Another exciting property derived from single crystal measurements is that the thermodynamic critical field of the new superconductor is a factor of 13 higher than for Nb[10]. Once again, the impact for accelerator cavities could be striking. Rf surface magnetic fields that approach the critical field at which superconductivity breaks down would allow gradients in accelerating structures as high as 400 MeV/m. It should be emphasized that no predictions of inherent surface resistance is available. Loss measurements to date show very high R_s values by comparison with Nb. Considerable improvement in sample quality is needed before there is confidence that inherent values are being measured.

We must keep in mind that significant R&D effort will be required to prove whether the superior intrinsic properties recently discovered do indeed offer the expected advantages. If the basic properties can be verified, several years of additional R&D will be required to exploit these advantages. In particular, field emission at high surface electric fields will need to be understood and controlled before the advantages inherent in the high critical magnetic fields can be realized[11]. In the meantime, Nb retains its superiority for exploration of field emission, surface resistance and structure optimization.

Concluding Remarks

Current ideas predict a rich world of new phenomena, central to the resolution of very basic questions about the physical world that can be explored for the first time by accelerators at the TeV mass scale. Further advances in rf superconductivity may provide the basis for powerful accelerators that can explore at this energy frontier.

This community of superconducting RF accelerator developers has achieved major successess in the last five years, with major benefits to high energy and nuclear physics accelerator technology. Oppportunity knocks again.

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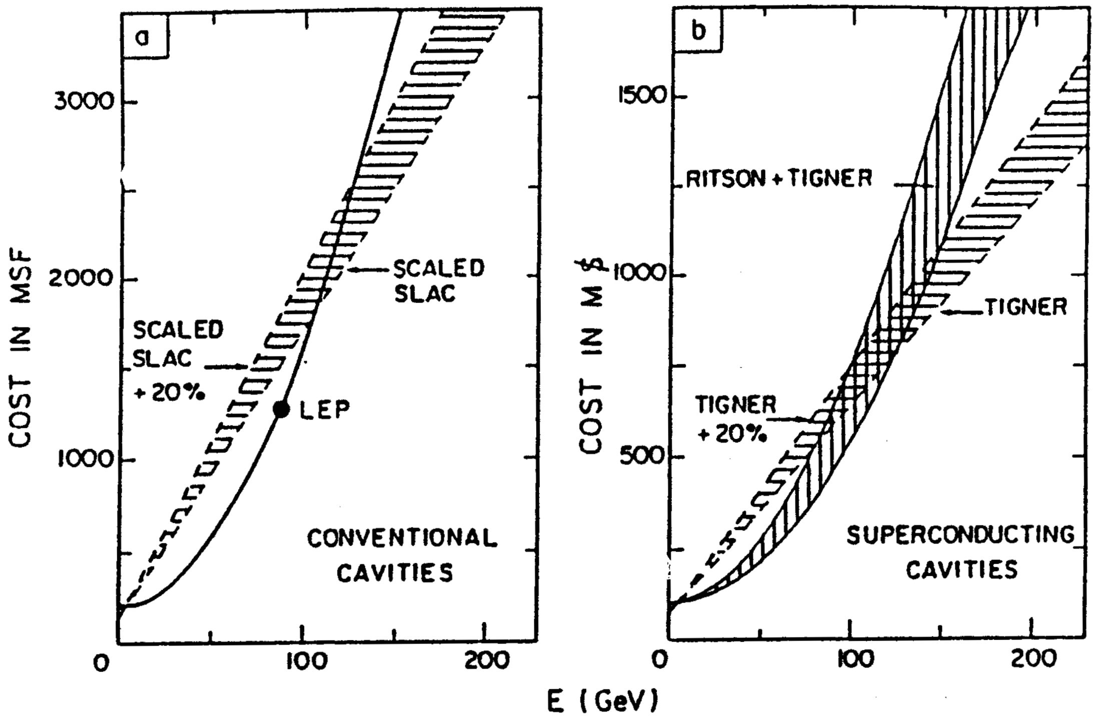
Figure Captions

Fig. 1 (Refs. 1) Comparison between costs of electron-positron storage rings and colliding linacs. Accelerators based on conventional room temperature cavities as well as accelerators based on superconducting cavities are considered.

Fig. 2 Comparision of schemes for TeV linear colliders. (a) "standard linac" (b) a two-beam accelerator (c) a fully superconducting linac.

Fig. 3 Comparison of a superconducting cavity acclerator assembly (Refs. 7) with a superconducting magnet assembly (Refs. 8).



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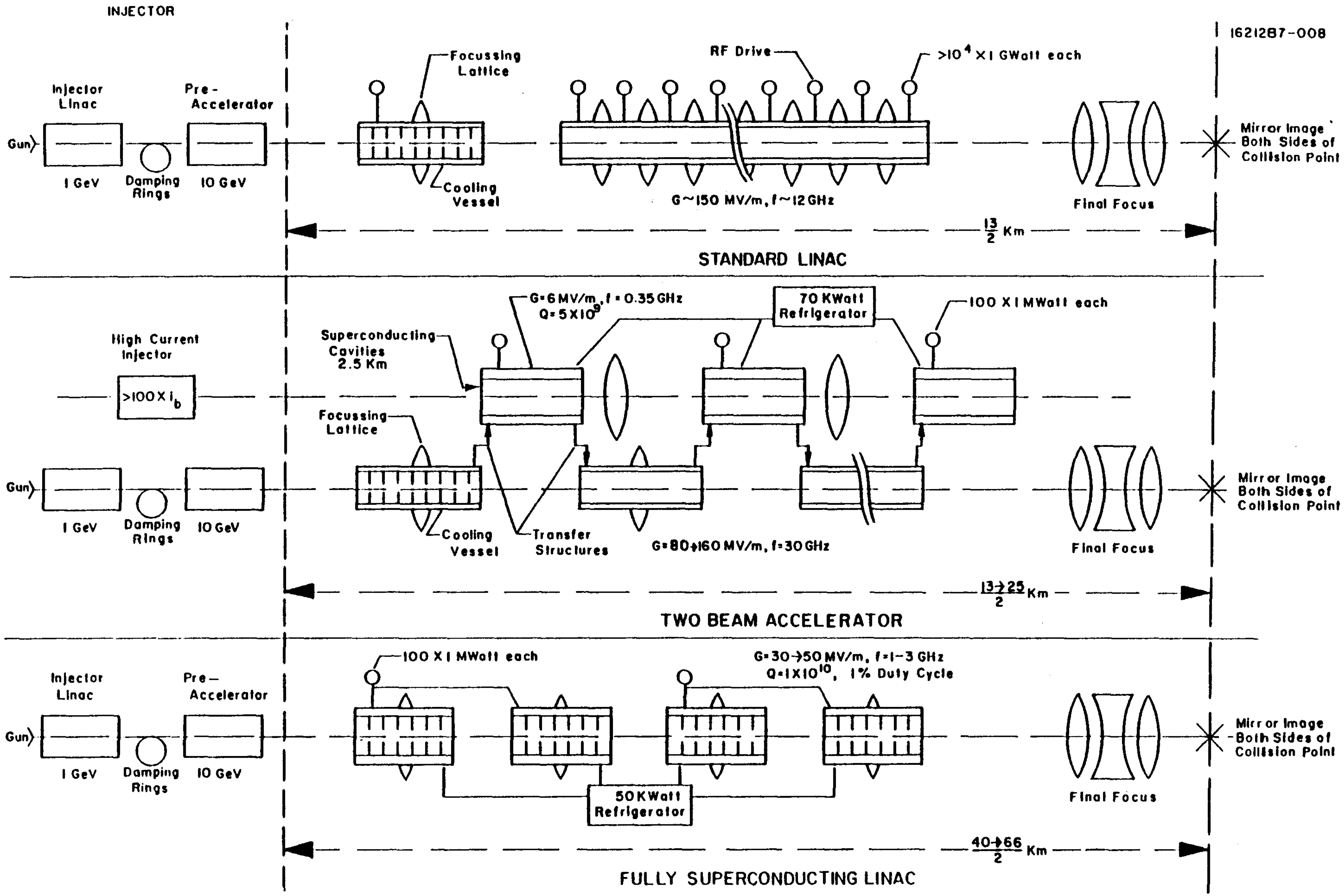

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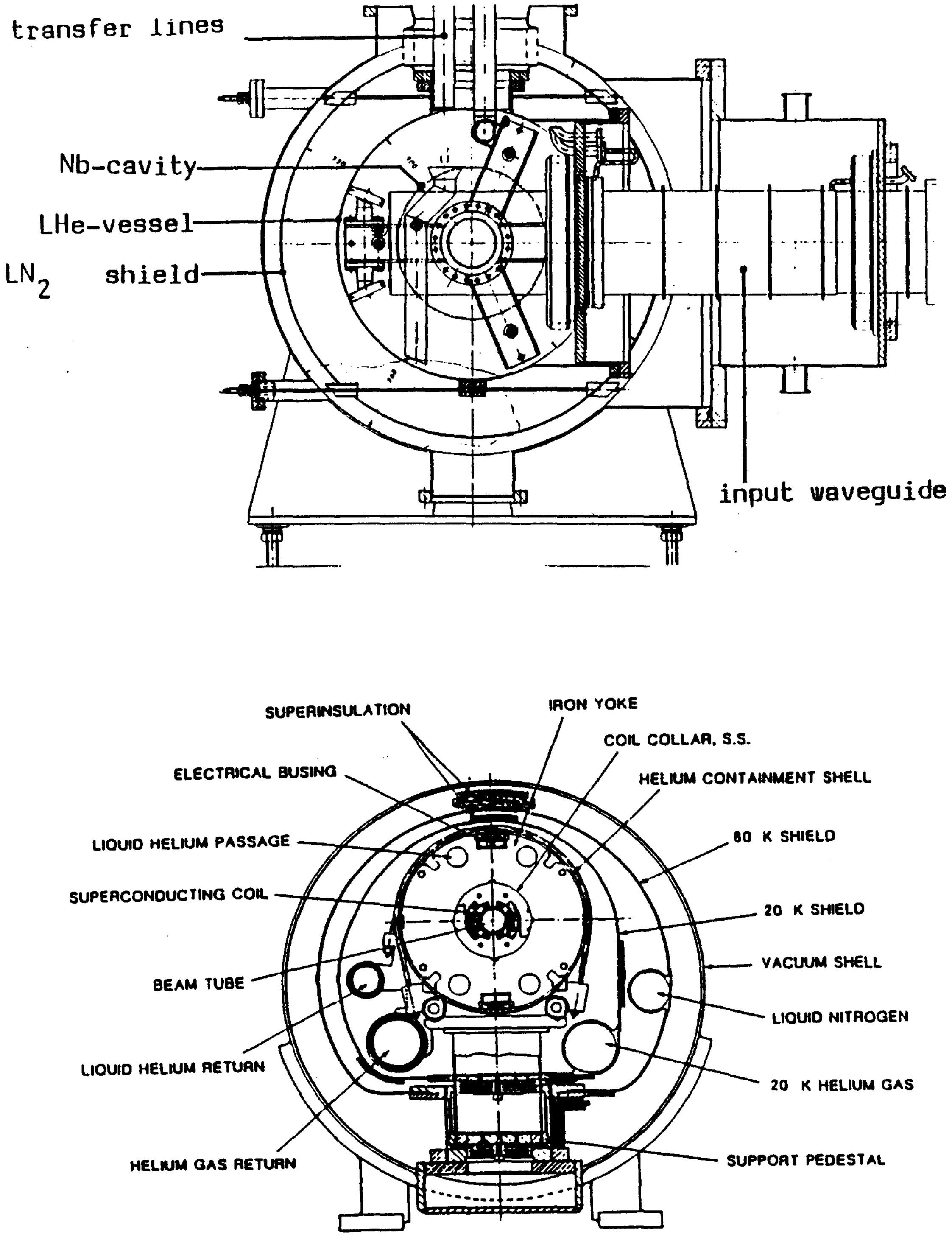

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