Review of Experience with Superconducting Cavities

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Abstract

Superconducting acceleration systems have been used in beam operation for more than 15 years. Their number is constantly increasing all over the world. Beginning with a short historical introduction, the operational experience with these systems will be reviewed, the main part covering the most recent large installations: TRISTAN, HERA, LEP and others. Their highlights but also today's weak points will be discussed. The speaker will endeavor to draw a realistic picture of what can be expected from these systems for present-day accelerators, not forgetting a tiny glance in the future, based on actual laboratory results.

1. INTRODUCTION

The size of built and suggested superconducting (sc) acceleration systems shows the growing confidence into this still relatively young technology, the first superconducting (electron) accelerator coming into life in 1974 at HEPL[1] with an operational gradient of 2-3 MV/m. This machine allowed to study different phenomena of sc. RF systems. It was part of the first FEL experiment and is still in operation today. Another pioneering machine is the ATLAS heavy ion accelerator at the ANL[2], whose first stage (split-ring resonators) became operational in 1979. This machine has accumulated more than 50,000 hours beam time without any serious problem and is permanently upgraded using newer types (interdigital) of low-ß resonators. The total beam time accumulated by all superconducting low-ß machines all over the world exceeds 100,000 h meanwhile [3]. These two examples of ground breaking but still fully active machines shows that the sc. accelerating technology has a sound base. However, even today this technology has not reached its theoretical limits at all.

Machine	HEPL	S-DALIN.	CEBAF	MACSE	TRISTAN	HERA	LEP	SPS
type	Recycl.	Recycl.	Recycl.	e-linac	e-collider	ep-collider	e-collider.	Acc./Inj.
f [MHz]	1300	3000	1500	1500	508	500	352	352
material	Nb	Nb	Nb	Nb	Nb	Nb	Nb, Nb/Cu	Nb, Nb/Cu
op. T [K]	2	2.	2.	2.	4.2	4.2	4.2	4.2
cells	7,23,55	5, 20	5	5	5	4	4	4
cavities	1,1,5	1, 10	338	5	32	16	24,168	1,2

Tab. 1 : Characteristics of sc. high-ß machines (final stage), performance data and references see text

2. RECENT INSTALLATIONS

In this chapter we will have a short look at some recent high-ß facilities being (at least partly) operational. Hardware details will be discussed in the following chapter.

The actually largest sc. RF installation is at **KEK.** Cavities are located symmetrically around one interaction point (IP) and are used to boost the e-collider **TRISTAN** [4] up to 32 GeV. 4 cavities are driven by a 1 MW klystron, each cavity has a circulator. Amplitude and phase are controlled by a vector sum loop. Installation started autumn 1988 and cavities have been operational for 16000 h including 8300 h beam time. Without beam in average gradients around 7 MV/m were obtained but *operational* gradients between 3.3 and 4.7 MV/m were used with a beam current up to 13 mA. The field limit was *not a hard one*, but was defined by the trip probability. Break-downs happened with very high probability in cavities which receive the highest doses of synchrotron radiation and a recent improvement of radiation masks has largely improved the situation.

At **Darmstadt** (Germany) the tunable 10-130 MeV e-recyclotron (up to 3 passes) **S-DALINAC** [5] was built in collaboration with the University Wuppertal and is officially in operation since end 1991. It is used for nuclear physics and has recently also produced channeling radiation and FEL in the near infrared with 10 µA cw current and a repetition rate of 1 kHz. The average gradient obtained is 5.6 MV/m with a large spread (4.4-10.1 for the high RRR cavities), with 3 passes 78 MeV energy were obtained. Each cavity has its own power source. A beam current of up to 40 µA was operated, the (norm.) transversal emittance was ≈ 1 π mm mrad. More than 4000 h beam operation have been achieved.

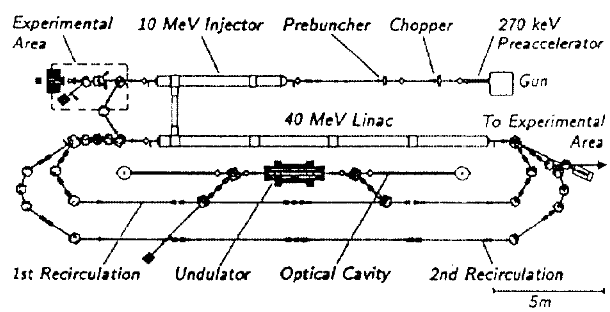

Fig. 1 : S/DALINAC layout

At **DESY** the e-beam energy of the ep collider **HERA** [6] is being upgraded from 28 to 30.4 GeV. All 16 cavities are driven by a common klystron (max. 1.6 MW). The average gradient in the horizontal cryostat test was above 6 MV/m. Installation of 12 cavities was done between February and October 91, and a voltage of up to 50 MV was applied, limited by the circulator. The field will in future be power limited due to the large beam current (58 mA design). A vector sum controller is prepared but not yet operational. Cavities were operational for 3000 h and had 840 h of RF operation.

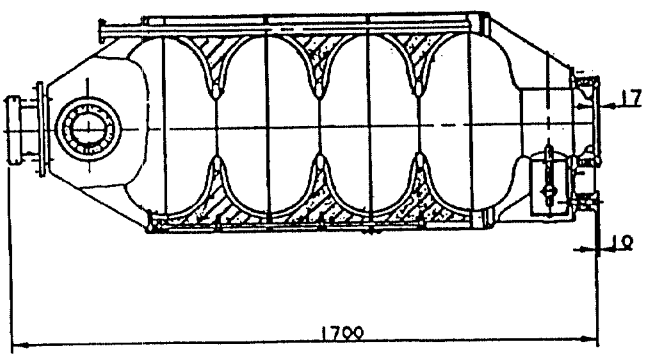

Fig. 2: DESY 4-cell cavity with He-tank and Al-'fillers'

At CEBAF [7][8] a recirculating 4 GeV 'CW'-linac is under construction, the total beam current will be 200 μA with 5 passes.Cavities are actually received, each one will have its power source. The average (65 cavities) test gradient is 8.2 MV/m, the average Q values 5.3 10^{9}. In fall 91 an injector test with 18 cavities was done, 45 MeV with a current up to 200 μA were obtained.. The energy spread was 4 10^{-4} and the transversal emittance less than half of specifications. Actually additional 24 cavities have been installed in the main tunnel.

At Saclay a test facility (MACSE [9]) has been constructed in the existing linac tunnel. The goal is to test different types of cavities, HOM couplers, cryostats and RF systems with beam for future use. Gradients between 6 and 16.5 MV/m were obtained in the test stand. A 10 MeV low current beam was accelerated with 4 cavities, gradients between 4.1 and 7.5 MV/m, the 5th cavity was disabled due to a vacuum accident.

At the CERN SPS in 1987 a LEP type sc. cavity was installed as injection booster, driven with a feedback system using a 50 kW tetrode [10].It was pulsed for each lepton cycle and without beam 7.1 MV/m peak were obtained, with beam induced voltage the field had to be limited to 5.5 MV/m to avoid overloading of the high gain feedback system. Due to 'accelerator politics', twice exchanges have taken place, working successfully without degradation for a total operational time of >20000 h. Actually an *additional* 2-cavity module is installed with a new refrigerator for the next running period.

The first three 4-modules (4 Nb, 8 Nb/Cu cavities) have been installed in LEP since end 1989 [11]; cavities have to be cold when LEP is operational. Up to 16 cavities will be driven by a 1 MW klystron with unique circulator; plans for 8 cavities per 1.3 MW klystron exist. Voltage control is done with scalar sum. Individual fully equipped cavities made 5 MV/m in the module acceptance test, however, the average field in the tunnel had to be limited to 3.5 MV/m for a safe operation (trip rate) a maximum of 4.25 MV/m was used for a few minutes. Since trips were mainly in the first Nb/Cu module (switching off the whole unit) and fundamental power coupled out of 3 HOM couplers was increasing, this module was removed from the tunnel to investigate on the surface.

All 20 industry made Nb cavities have been delivered, 16 have made a successful acceptance test meanwhile with fields generally in the 6-8 MV/m range, Q > 3 10^9 at 5 MV/m.

3.HARDWARE COMPONENTS

To get a realistic picture where the state of the art is today, we will have a look in the different components of a sc. accelerating system.

3.1 Cavities

Several advances have been made with respect to early designs. Today the cells of all high-ß cavities look very similar having a 'spherical' shape avoiding the multipacting[12] limiting the early pill-box like cavities. To avoid HOM couplers on the cells - difficult and thus expensive - and put them onto the cut-off tubes (respecting a safe HOM damping), multimode endcell compensation[13] is used at CERN and DESY. KEK has developed an independent[14] but similar design.

At CEBAF power- and HOM couplers are at opposite sides of the cavity and are integral part of it.

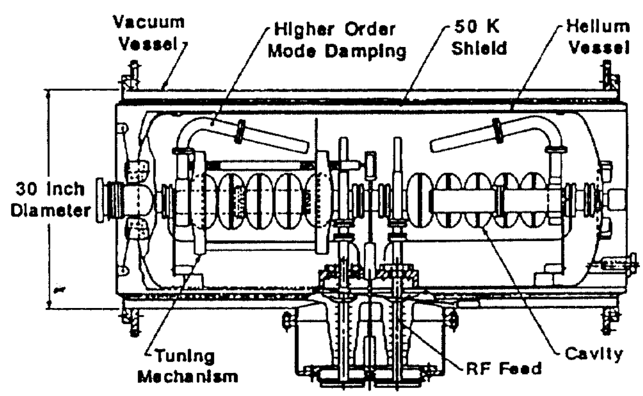

Fig. 3: CEBAF cavity pair with power- and HOM couplers

To increase the performance of large multicell cavities, a further reduction of size and number of defects asks for expensive measures during the manufacturing process. Therefore actually cavities are made to better withstand the effects of remaining defects in using material of increased thermal conductivity tolerating higher losses and thus higher fields with the same defects. Technologically two paths were followed: Niobium of higher purity can be produced by repeated furnace treatment and solid state gettering [15]. After some reluctance several suppliers offer such material now and actual bulk Nb cavities are made from such 'high RRR' material. For higher RRR material the cavity Q-value is slightly reduced.

A Copper 'support cavity' on which a thin layer of a superconductor is deposited fulfils the desired task even better (and cheaper). Pioneering work has been done at CERN with Copper cavities of the same shape as the bulk Nb cavities[16]. This technology is advanced so far today that CERN has placed orders for 168 ,i.e. the majority, of the LEP sc. cavities to industry. Another advantage of this technology is the possibility to sputter different layers having even better RF properties than pure Niobium. Also other laboratories have started meanwhile to do R&D work on this type of cavities.

5-6 MV/m is today a usual design value; one should not forget that generally a sc. cavity cannot surpass its quench limit without break-down even for transient periods, i.e. sc. cavities have to be built with a certain 'overvoltage factor'.
Also the cavity Q is an important parameter, but a *small* degradation of the cavity Q is of lower importance provided enough cooling power is available. At DESY the 'Q-disease' was detected, a *serious* Q-degradation after the first cooldown. Meanwhile the effect was reproduced at other laboratories and the origins were traced to the common use of high RRR material and hydrogen rich chemical treatment [17] giving the clue to avoid it for future cavities. This event delayed DESY's cavity installation and since a complete cure (high T treatment) cannot be applied without complete disassembly, cavities work with reduced Q actually.
Concerning vacuum tightness, a few problems with Indium joints have been reported by KEK and CEBAF

PERFORMANCE DEGRADATIONS: At Argonne (having the longest sc.on-time) no performance degradation was observed during the operational period since 1979. Actually the largest and well documented experience of high-ß systems is at KEK where the performances concerning field, Q-value and electron activity does not show a significant degradation of those parameters. In fact 25 of 32 cavities did not show any degradation and 4 cavities could be recovered simply by warm up. The supposed reason for the degradation of the remaining 3 cavities is a dust accident (2) and a coupler leak (1). Also the SPS cavitie(s) did not show any degradation, only after shut down a few minutes RF processing was necessary. In LEP the cavities did not show degradation with time in the ring. This means that a sc. RF system can work for many years reliably if it is well maintained.

3.2 Power Coupler

The power coupler of a sc. cavity has to transport RF energy (e.g. 100 kW) into the cavity with a *minimum of cryogenic losses*. The size of waveguides is defined by the frequency, thus waveguide couplers are prohibitive for lower frequencies, but are used e.g. at CEBAF at 1.5 GHz. For rectangular guides vacuum tightness at flanges can become a problem and special precautions for the torque on bolts had to be taken at CEBAF. At KEK, DESY (500 MHz) and CERN (352 MHz) coaxial antenna couplers with ceramic window (KEK planar, DESY and CERN coaxial) are used. Problems with ceramic RF windows at high power are no typical sc. cavity problem, but if air (with dust from the tunnel) enters a sc. cavity, the effect may be catastrophic. At KEK (up to 200 kW processing) 6 times window leaks developed at 4.2K and 3 cavities had to be retreated and recently a water leak developed. For the CERN sc. cavities no such problems have been encountered but identical windows broke twice on Copper cavities. The original LEP design asked for a maximum power of 60 kW, thus the ceramic windows of the Copper cavities (design 120 kW) guarantied a sufficient safety margin. However, for more power (multi bunch) new diagnostics and interlocks have to be incorporated as done at KEK and DESY: electron pick-up, light- and local vacuum gauges.
Another problem encountered with the first module at CERN was the heating of the RF joint on the power coupler in the detuned, but not in the normal, state. The following module did not show this problem. But when inspecting the doorknob transition, traces of sparking and corrosion were found, i.e. the problem is not yet completely solved.
DESY uses a similar coupler with coaxial window and a modified prototype was tested up to 300 kW. Problems during operation were not reported but using electron and light detectors on the main coupler, multipacting was identified during the processing stage.
A large scatter (≈25%) of the Q_{ext} of the input couplers, as observed at CERN and DESY, causes a similar scatter in cavity excitation (common generator), the origin is not yet understood. At DESY a 3-stub RF transformer is used for compensation and at CERN an adjustable coupler - allowing even to measure the cavity Q-value in the tunnel - is under development.

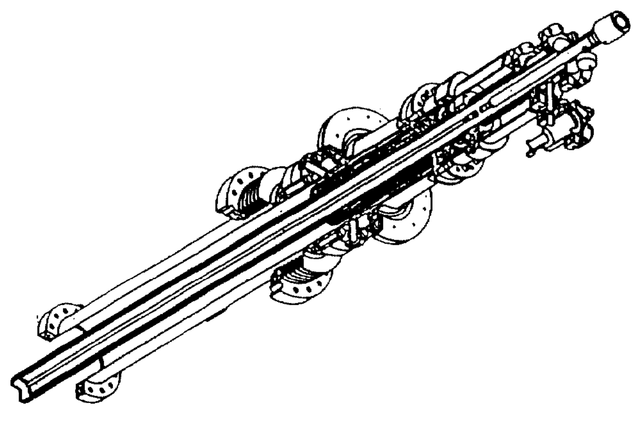

Fig. 4: CERN adjustable power coupler

3.3 Higher Order Mode Damping System

Generally people talk only about HOM couplers but in fact there are three components [18]:HOM coupler(s) with incorporated stop filter, a *large-band* RF energy transport system : Cables, connectors or rigid lines and RF-Loads

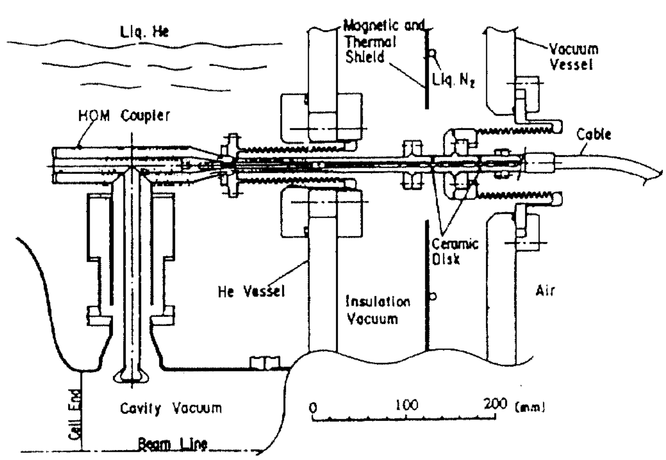

Fig. 5: KEK HOM damping system

For low current machines the parasitic coupling to the main coupler is sufficient. At CEBAF the cutoff property of wave guides is used as stop filter and the RF power - a fraction of Watt - is immediately dumped into the He bath, which is

more economic than cooling large guides to evacuate it. Absorbers are at He bath temperature; damping values measured at 4.2 K were higher than found later at the operational temperature around 2 K [19] , but still leaving a large margin for beam current limitations.
KEK, DESY and CERN use several models of HOM couplers with incorporated (sc.) stop-filters and cables for RF transport. Cooling coupler parts by liquid helium has to respect cryogenic *and* RF requirements. Under normal conditions the RF power loss in the coupler is fractions of a Watt. However, when processing cavities e.g. after shut down, multipacting can develop or the coupler may be hit by field emitted electrons, producing (local) quenches, sometimes persisting for quite some time. At HERA the electron beam current of up to 58 mA asks for very strong attenuation and the lower part of the HOM coupler is welded onto the cavity, guaranteeing a good cooling that no such problems have been encountered. CERN and KEK use *fully demountable* couplers to avoid that a coupler defect ruins a whole cavity and for the Nb/Cu cavities welded coupler parts can hardly be sputtered. At CERN local coupler quenches were observed on coupler type 2 - abandoned meanwhile - and seem recently also to plague coupler 5. For the latter one origin of the problem was identified in a weakness in the cooling circuit (easy to be changed), but also electron activity was observed in the coupler and tests are continuing.
A connected problem is the run-away by heating of the stop filters by coupled RF power. Such heating can lead to originally very small mechanical deformations but sufficient to detune the filter (capacitance with mm gap) giving rise to thermal run away. This was observed at CERN for the coupler type 2 and lead to its abandon. At KEK 2 connectors burnt and the corresponding cavities had to be removed from the TRISTAN ring for a few weeks. A degradation of the rejection quality of the stop filter on 3 couplers (type 5) in LEP without run away was observed.
The coupled power has to pass the insulation vacuum with reduced cooling of cables. This can represent a serious limit: At KEK twice connectors burnt due to excess HOM power and the cavities had to be removed for repair. Therefore the current in TRISTAN had to be limited below 13.5 mA. During the 90/91 shut-down all 64 connectors were replaced by a more performant design, after which a current of 25 mA is considered safe. DESY has not tested with very high beam currents yet.
Flexible cables are easy to install, however for higher currents solid lines have to be used. To keep the possibility of a later transformation, the recently modified design for the LEP cryostat has already ports above the HOM locations to house future rigid lines.

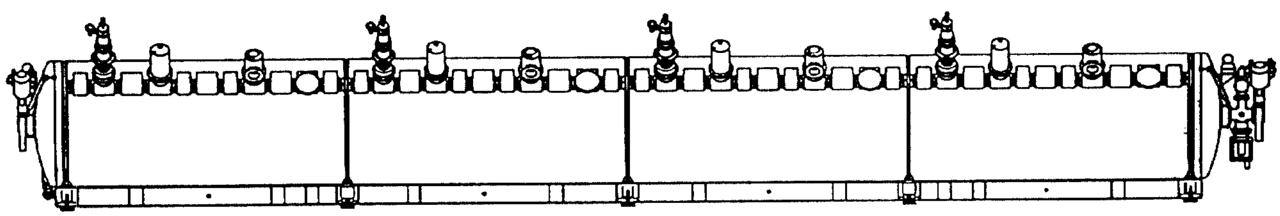

Fig. 6: The CERN 4-cavity module with main coupler and cryogenic domes

3.4 Frequency Tuners

The task of the tuning system is to compensate reactive beam loading, temperature drift of supports, pressure drift of the He bath, external perturbations (pumps, thermo acoustic) and ponderomotive oscillations (any field level increase modifies the cavity shape by radiation pressure detuning it; the corresponding level decrease lets the cavity relax and retune, restarting the cycle)
RF tuning, i.e. connecting a variable external reactance to the cavity,is fast but asks for reactive power transport from and to the cavity. This method works very well for low current machines with very small tuning range (e.g. at ANL) but becomes prohibitive for high current accelerators. Today the high-ß cavities are all tuned by elastic change of the total cavity length. This avoids multipacting due to 'unnatural' objects in the cavity (e.g. plungers) and moving parts (contamination, bellow leaks), but the tuning system gain is limited by the mechanical cavity resonances. System cut-off frequencies of several Hz are typical.
A variety of 'motors' is in operation today. It has to withstand the vacuum and elastic forces of cavity/He tank and has to have enough stroke and speed but avoiding the slightest random movement (μm fraction precision). 2-level systems are used, fast with small and slow with large stroke.
PIEZO CRYSTALS are fast but the range is only a few kHz (e.g. 6 kHz at KEK) Some problems have been encountered: In an early design at Darmstadt piezo crystals were immersed in the He bath. After a few weeks the crystals were penetrated by liquid He disabling the crystal by high voltage break through. At KEK two piezo crystals exposed to strong doses of (synchrotron-) radiation ceased operation and had to be replaced (accessibility!)
MAGNETOSTRICTIVE BARS are used at CERN, Darmstadt, Saclay. The stroke is also only in the kHz range (e.g. CERN 2 kHz) but Nickel - as used everywhere - has the advantage to support forces, shear and twist in all directions and is a reliable cryogenic construction material. The fact that it is a magnetic material (Q-degradation by trapped magnetic flux!) has shown to be of no visible effect. Up till now no real problem has been encountered with such a device.
STEP or DC MOTORs are slow but the range is (nearly) unlimited (CEBAF, Darmstadt, DESY, KEK, Saclay). The

1983 test of the CERN 5-cell at PETRA used screw and gear on the He tank to reduce cryogenic losses, but 2 out of 3 got stuck - despite special surface coatings. Today for the *large* cavities screw, gear and motor are located outside the vacuum tank.

The *THERMAL TUNER* (CERN) uses the expansion of the (magnetostrictive) tube (range 50 kHz), controlled by a heater element. It is slower than a step motor and needs a permanent small He gas flow, but *no moving parts* nor accessibility from the cryostat ends are necessary. No real problems have been encountered until today.

At Darmstadt and CEBAF generators deliver much more power than used by the beam, so additional stabilization can be done by RF feedback techniques. More details on experience with sc. RF control can e.g. be found in[20]

3.5 Cryostats

Until now all high-ß cavities are cooled in a He bath and a study made at CERN showed, that pipe cooling has in total no advantages over this classical method. Open cavities should be handled in a clean room. Therefore today most laboratories prepare so called cryomodules - containing several cavities in a common insulation vacuum tank - outside the tunnel, leaving only one 'dirty' step, the connection of cryomodules to the beam line. Such modules consist at DESY and KEK of 2 cavities (giving access to one end per cavity for tuning motors), CEBAF and CERN have chosen a completely modular design: at CEBAF 4 cavity pairs (common He-tank per pair) form a cryomodule, at CERN 4 (LEP), 2 or 1 (SPS) cavities. Inside such modules are many sensitive components, thus all tanks are made such that access and dismounting is as easy as possible in case of repair. At CERN the outer skin of the insulation tank can even be taken away in the accelerator allowing smaller repairs without removal of the module.

Thermo-acoustic oscillations in the He tank were encountered at MACSE and CERN (3-30 Hz), in the transfer lines at DESY. In LEP the corresponding oscillation of the resonance frequency results in a residual phase error of up to 10^{o}.

3.6 External Components

Sc. cavities depend on the same services as Copper cavities, the only major additional equipment is the cooling plant. Today good experience with such plants exist and laboratories working around 4.2 K (KEK, DESY, CERN) report no real problems. For the more challenging technique with low pressure He (air leaks!) some initial minor problems have been encountered at Darmstadt with the cold pumps.

4. FUTURE ASPECTS

Evidently also R&D continues for this technology to approach the theoretical limits triggered by projects like 'factories' and especially TESLA[21]. *Experimental* work is done in several laboratories to obtain the *performances* for a *reasonable price*. Actually the world record is held by Cornell [22] where a 2-cell 3 GHz cavity was operated in CW at 34 MV/m after High Power Peak processing[23]

5. CONCLUSION

Today bare high-ß cavities show *regularly* the desired performance, 5-10 MV/m for the 300-500 MHz cavities, even higher for the higher frequency ones. In the beam line, however, only performances around 3.5 MV/m are reached easily (but already largely exceeding classical systems); higher performances (≈5 MV/m) have been obtained but with more difficulties, e.g. longer processing, an increased trip rate and possible beam loss. This leads to the conclusion that assembly methods, accessories (couplers, tuners, cryostats..) and accelerator adaptations (e.g. synchrotron radiation masks, cleanliness) are today's bottle-neck. Finally, advances with individual cavities show that there is enough room for future progress ...

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