2006/11/17

To: Files
From: Nobu Toge
Subject: Minutes of the CCB Hearing on ML CCR (CCR#20) Cost Implications

Date: Thursday, 2006/11/09
Venue: ADEIT Sala profesores, Valencia, Spain
Time: 08:00-09:00 and 11:00-12:00 EST
Present: N.Toge, H.Hayano, T.Shidara, K.Yokoya, P.Garbincius, L.Lilje, S.Mishra, C.Pagani, C.Adolphsen, K.Kubo, W.Funk, T.Peterson, N.Solyak, T.Markiewicz

1. Opening
   - Toge welcomed the participants, and noted that the purpose of this hearing is for CCB to understand the costing implications and the current status of design development concerning the ML baseline configuration change request (CCR#20) that was submitted on 2006/10/30.
   - Garbincius confirmed that all present at the hearing had signed up on the GDE costing NDA in the past.

2. Presentation by C.Adolphsen
   - Adolphsen gave a brief summary of responses to the CCB inquiries that had been sent to the requesters on Nov.1 (A memo that has been returned to CCB by Adolphsen prior to the hearing is attached as Appendix A).

3. Cost impacts
   - Adolphsen summarized the cost impacts as follows:
     a) RF system cost saving due to reduction of number of RF units in accordance with the cryomodule layout change (i.e. 8-8-8 → 9-8-9): 1.2% of the total ML construction cost.
     b) Elimination of the 3.5% energy overhead: 3.5% of the total ML construction cost.
     c) Elimination of the over-capacity factor (40%) of the static heat load to assume in the ML cryogenic system: 0.5% of the total ML construction cost.
   - The "total ML construction cost" here includes the cost for the conventional facilities related to the ML.
   - The calculation of the percentage cost changes is based on a total ML cost which uses the scaled TESLA estimates for the cryomodules..

4. Discussion
   - Q (Funk): The beam current 9.5mA assumed in the calculations for the LLRF tuning overhead is not consistent with the Parameter section of present BCD.
   - C (Kubo, Mishra): Around the time of the Frascati in 2005, the bunch spacing was revised from 308ns to 337ns. The Damping Ring section of BCD assumes 337ns, and this ML CCR also assumes 337ns, but the Parameter section of BCD has not been updated to reflect 308ns.
   - A (Yokoya): It was an oversight and the Parameter section of BCD has to be updated to incorporate the following. Yokoya will submit a Class-0 CCR:
     a) Bunch spacing: 337ns.
     b) Bunch intensity: $2\times10^{10}$
     c) Bunch train length: 1ms
     d) Beam current: 9.5mA
   - Q (Toge): Is the assumed improvement of the RF transmission factor (less attenuation) for WR770, as opposed to the previous WR650, considered adequate, numerically?

- A : General concurrence.
- Q (Toge): If the proposed changes are to be applied, do the quoted cost reduction factors look reasonable?
- C : General concurrence.
- C (Garbincius): The calculation of the cost impacts is based on using the scaled TESLA estimates of the cryomodules, and it should be noted.
- Q (Toge): The tuning overhead for LLRF is quoted to be 10% for the 9-8-9 configuration (proposed), and 11% for 8-8-8 configuration (present BCD), and they appear close. Can everyone concur with this arithmetics?
- A: General concurrence.
- C (Toge): The LLRF experts seem unable to give definitive remarks as to how the assumed tuning overhead is sufficient, since they lack real-life data on the cavity performance uniformity as well as actual stability of beam intensities. Also note that the overhead numbers quoted above are with respect to the top gradient, i.e. 33.5MV/m for the 9-8-9 and 35.0MV/m for the 8-8-8 configuration.
- C (Funk): If the LLRF tuning overhead is not sufficient, one could maintain the top energy by lowering the beam current, thereby sacrificing the luminosity for sake of energy. The issue is that the system cannot be kept stable at the reference gradient (31.5 MV/m) and the reference current. One can reduce the klystron output power, improving linearity, by either reducing gradient or by reducing current. Reducing gradient is cleaner, because there is no change in the match between the RF distribution system and the cavity. Reducing the current will change the match, but additional power reflection (assuming a perfect match at the design current) should be modest. I thought users would prefer to preserve energy, but according to the material in Albrecht's summary, they would rather preserve current.
- Q (Toge + ): Is there a worksheet or a report available for how the experts did the accounting for the cryogenic load?
- A (Pertersen): The calculation is based on initial studies by the TESLA group, while incorporating what is considered the adequate scaling of numbers for each of the items specifically revised for ILC. More details will be provided separately (A memo provided by Petersen after the hearing is attached as Appendix B).
- Q (?): Concerning the 3.5% energy overhead that is assumed in the present BCD, where did this number come from?
- A: It came from a report from a workgroup led by T.Himel in 2005.
- C: The report above assumes a number of assumptions on the MTTF and MTTR for the ML subsystem components.
- Q (Toge + ): Understand that elimination of 3.5% energy overhead results in 3.5% reduction of construction cost of ML. How much fraction of this 3.5% comes from CF/S?
- A: Garbincius or Adolphsen will provide the answer separately.

**E N D**

# Appendix A

**To: Files**
**From: N.Toge**
**Subject: CCR#20 Worksheet**

This is a work sheet for use by CCB to assess the adequacy of individual contents of CCR#20 – ML Cryomodule configuration change request.

| | | |
|---|---|---|
| History: | 20061030 | Toge |
| | 20061101 | Funk |
| | 20061103 | Adolphsen (**Comments in blue**) |

## Cryomodule

- Changes to the basic unit configuration
  - Previous: 8-cav ... 8-cav with magnet … 8-cav → 24 cav/unit
  - New:9-cav … 8-cav with magnet … 9-cav → 26 cav / unit
  - Maintain Eacc at 31.5MV/m → # of RF units reduced by 2/26 = 7.69%
  - Peak gradient previously 35MV/m → 35*24/26*ATT-factor = (quoted as 33.5MV/m). Is it that improved ATT-factor with WR770 = 1.037 ??

That and ~ 1% less tuning overhead – see below

- Q1 (Toge): CA claims that the length of 9-cav CM will be similar to the length of 8-cav CM with mag (12.543m / 12.590m). Someone (eg. Carlo) please, confirm, numerically.

The quad package (1.2 m) is about the same length as the cavity (1.25 m)

- Q2 (Toge): Someone please numerically check the new max gradient value (i.e. check accounting of the power loss, etc)

See below

- C2 (Funk): Since the cavities are superconducting, essentially all power goes into beam loading. Thus, all other things being equal, the maximum gradient sustainable with 13/12 times as many cavities will be 12*35 MV/m/13 = 32.3 MV/m.
  Total power consumption by the beam at 35 MV/m will be 8.1 MW. I believe the control allowance is 15% (1.2 MW), which leaves about 680 kW for W/G losses. Chris claims that larger W/G saves about 1/3 of the latter. Adding that back gets me up to 33.2 MV/m. Obviously if I can eat into the control margin, I can get up to 33.5 MV/m.

The numbers are given in the updated BCD – listed below is the math

33.5 MV/m * 9.5 mA * 1.038 m = 330.3 kW (Cavity Input Power)
* 26 Cavities
* 1 / 0.95 (Distribution Losses with WR770/WR650)
* 1 / 0.90 (Tuning Overhead)
= 10.0 MW

The current configure is

35.0 MV/m * 9.5 mA * 1.038 m = 345.1 kW (Cavity Input Power)
* 24 Cavities
* 1 / 0.93 (Distribution Losses with WR650 only)
* 1 / 0.89 (Tuning Overhead)
= 10.0 MW

Note that the overhead for 5 deg off-crest operation is included in the length of the machine, that is

Number of rf units per Main Linac = (250-15)/[cos(5*pi/180)*26*1.038*.0315]

- Q3 (Toge): Technical issues with 9-cav CM which is longer than the previous BC, but similar to the CM with Q anyways? Who can comment?
- C3 (Funk): It is possible that there could be cryo control issues. I don't know how frequently the cryo group plans to monitor helium levels. If it was once in every RF module, the responsiveness of the control system will be reduced. If it was every cryo unit, there's probably no significant difference.

I believe this is done at the cryo-string level (12 cryomodules)

- C4 (Toge): ML section is lacking a table of critical component counts, which is not nice. CCB should request ML AG to provide BCD with some such tables. Can anyone in CCB draft one, if ML AG won't do ?????

There is one on the linac RDR wiki page – we are working on new tables for the RDR

- C5 (Toge): ML section is lacking a table of power accounting of an RF unit. I.e. power from klystron (Funk: assume nominal 10 MW), transmission loss (from above, 6-7%, reduced to ~4% by larger W/G), cavity R/Q, peak gradient, crest angle (5° off crest ➔ 0.996), energy gain per cav or per unit, # of RF units, total energy gain, and so on, in one place. CCB should request ML AG to provide BCD with some such tables. Or can anyone in CCB draft one, if ML AG won't do ?????

There is one on the linac RDR wiki page – we are working on new tables for the RDR

### RF System

- Use of WR770 instead of WR650
  - Q1 (Toge) : Any remarks, concerns over the space requirements stemming from the use of WR770?.
  - C1 (Funk): The only place where the increased size <u>might</u> be an issue will be in the penetrations between the tunnels. I don't think it will be an issue.

We have a new layout that has only two waveguides in each penetration – it has not been officially adopted yet.

### Cryogenic System

- 40% over-capacity factor to allocate. It consists of
  - 20% provision for system degradation
  - 10% provision for control
  - 8% provision for warm seasons conditions.

- Q1 (Toge) : Any reference materials which substantiate the adequacy of the accounting above for 20+10+8% (e.g. past similar examples) ???
- Q2 (Toge): How much is the required capacity (before incorporating 40% over-capacity) and what is its accounting? Where is it? Give us one.
- C1 (Funk): It is very curious to find this information here. The ML section should state the cooling requirements of the linac, and let the cryo group specify this stuff. The numbers are plausible, but I can't validate them.

The BCD, which is a design report not a requirements document, does not have technical sections – this information is thus included in the linac sections. These values were not in the orginal BCD, and were added as part of this change request to clarify what overhead is assumed (i.e., these values are not being changed, only reported).

### Energy Overhead

- Q for WWS: has been already sent out. Wait for their response

### Additional Comments

- Q1(Toge): We should ask remarks from e- and e+ source forces, besides RTML, about the CM change.
- C2 (Toge): BCD should specify the quad length and strength (or its range)
- C3 (Toge): BCD should make a statement on tilted or non-tilted tunnel installation.
- C4 (Toge): [REPEAT] Put some tables for
  - RF power accounting
  - RF component count
  - Cryogenic accounting
- C5 (Toge): [SEMI-REPEAT] Put some illustrations for
  - RF unit installation with CMs with cavities in them
  - Which tunnels are supposed to contain which components of MLs (can be done with tables).

All of this information will be in the RDR

### Costing Questions

- Approx 7% reduction of # of RF units (due to 8+8+8 → 9+8+9) → how much cost saving from CM reduction and from RF reduction?

The RF cost savings are 1.2 % of the linac cost – the number of cavities remain the same, so to first order, the CM cost does not change.

- C1 (Funk): There's no reason to believe that the cryomodule cost will be significantly reduced by this change.

Yes, and none was assumed

- Approx 3.5% reduction of # of RF units (killing the overhead) → how much cost saving from CM reduction and from RF reduction?

As might be expected, 3.5% from both, so the linac cost is reduced by 3.5%

- Approx 13% reduction of required cryogenic capacity → how much cost saving?

About 0.5% of the linac cost

## Appendix B

Comments on Main Linac cryogenics for the Change Control Board
Reference: CCR#20

Tom Peterson and Laurent Tavian
10 November 2006

Module heat loads are estimated by means of scaling both static and dynamic heat from the TESLA TDR numbers. Methods for scaling heat have been developed by Chris Adolphsen (SLAC), Nikolay Solyak (Fermilab), Laurent Tavian (CERN), Vittorio Parma (CERN), Arkadiy Klebaner (Fermilab), Jay Theilacker (Fermilab), Tom Peterson (Fermilab), and others. An excerpt from the spreadsheet, just to illustrate the comparison at 2 K, is shown below. (ILC 8-8-8 refers to the number of cavities in the modules of an ILC RF unit. All analyses below are for the 8-cavity modules.)

| **Cryomodule** | **TESLA** | | **ILC 8-8-8** | |
|---|---|---|---|---|
| E, [MV/m] | 23.4 | | 31.5 | |
| Q | 1.E+10 | | 1.E+10 | |
| Rep rate, [Hz] | 5 | | 5 | |
| Number of Cavities | 12 | | 8 | |
| Fill time [µsec] | 420 | | 565 | |
| Beam pulse [µsec] | 950 | | 1000 | |
| Number of bunches | 2820 | | 2968 | |
| Bunch spacing [nsec] | 337 | | 337 | |
| Gfac | | | 2.08 | |
| Pfac | | | 1.60 | |
| Bfac | | | 1.05 | |
| Cfac | | | 1.00 | |
| | Static | Dynamic | Static | Dynamic |
| **Temperature Level** | **2K** | | | |
| RF load | | 4.95 | | 6.87 |
| Supports | 0.60 | | 0.60 | - |
| Input coupler | 0.76 | 0.14 | 0.51 | 0.15 |
| HOM coupler (cables) | 0.01 | 0.27 | 0.01 | 0.18 |
| HOM absorber | 0.14 | 0.02 | 0.14 | 0.02 |
| Beam tube bellows | | 0.24 | | 0.33 |
| Current leads | 0.04 | | 0.28 | 0.28 |
| HOM to structure | | 1.68 | | 1.18 |
| Coax cable (4) | 0.05 | | 0.05 | |
| Instrumentation taps | 0.07 | | 0.07 | |
| Scales as Gfac | | **5.19** | | **7.21** |
| Scales as Pfac | | **0.14** | | **0.15** |
| Independent of G,Tf | **1.67** | **1.97** | **1.66** | **1.66** |
| Static, dynamic sum | **1.67** | **7.30** | **1.66** | **9.02** |
| **2K Sum [W]** | **9.0** | | **10.7** | |

These heat loads are “best estimates”, not yet multiplied by any safety factor.

An excerpt from another spreadsheet, below, illustrates the method used to convert this heat load per module to a cryogenic plant size. In this illustration, a cryogenic unit of 204 modules is shown, which is the longest cryogenic unit anticipated.

Heat and Power Summary

| | | 40 K to 80 K | 5 K to 8 K | 2 K |
|---|---|---|---|---|
| Predicted module static heat load | (W/module) | 55.36 | 10.32 | 1.66 |
| Predicted module dynamic heat load | (W/module) | 92.48 | 4.32 | 9.02 |
| Number of modules per cryo unit (8-cavity modules) | | 204.00 | 204.00 | 204.00 |
| Non-module heat load per cryo unit | (kW) | 1.00 | 0.20 | 0.20 |
| Total predicted heat per cryogenic unit | (kW) | 31.16 | 3.19 | 2.38 |
| Heat uncertainty factor on static heat (Fus) | | 1.50 | 1.50 | 1.50 |
| Heat uncertainty factor on dynamic heat (Fud) | | 1.00 | 1.00 | 1.00 |
| Heat load per cryogenic unit including uncertainty | (kW) | 37.30 | 4.34 | 2.65 |
| Mass flow per cryogenic unit including uncertainty | (g/s) | 178.76 | 135.40 | 128.13 |
| Weighted ideal power | (kW) | 171.79 | 206.15 | 409.34 |
| Efficiency (fraction Carnot) | | 0.30 | 0.30 | 0.20 |
| Efficiency in Watts/Watt | (W/W) | 15.35 | 158.35 | 773.28 |
| Operating power including uncertainty | (kW) | 572.62 | 687.17 | 2046.72 |
| | | | | |
| Overcapacity factor (Fo) | | 1.40 | 1.40 | 1.40 |
| Overall net cryogenic capacity multiplier | | 1.68 | 1.91 | 1.56 |
| Heat load per cryogenic unit including Fus, Fud, and Fo | (kW) | 52.23 | 6.08 | 3.71 |
| Installed power | (kW) | 801.67 | 962.04 | 2865.41 |
| Installed 4.5 K equiv | (kW) | 3.66 | 4.40 | 13.09 |
| Installed 4.5 K equiv per unit length | (W/m) | 1.51 | 1.81 | 5.39 |
| Percent of total power at each level | | 17% | 21% | 62% |
| | | | | |
| Total operating power for one cryo unit including uncertainty factor (MW) | | | 3.64 | |
| Total installed power for one cryo unit (MW) | | | 4.63 | |
| Total installed 4.5 K equivalent power for one cryo unit (kW) | | | 21.15 | |

As you can see, we have the capability to apply a different uncertainty factor to static heat loads at each temperature level and to dynamic heat loads at each temperature level. We also apply an overcapacity factor for operational inefficiency and control to each temperature level. For simplicity and as a first pass, we have used a factor 1.5 on static heat load only, a factor 1.0 (no margin) on dynamic heat load, and a factor 1.4 for overcapacity. The overall result of the above analysis is that the cryogenic plant size divided by a plant size equivalent to only the predicted heat load is 1.64.

Cryogenics people like to normalize plant capacity to an overall 4.5 K equivalent capacity. For reference, LHC cryogenic plants are 18 kW equivalent capacity at 4.5 K. As you can see, we are predicting slightly larger for the above ILC plant.

The same cryogenic power spreadsheet summary is shown below with the only change being that the static heat load uncertainty factor is set to 1.0 rather than 1.5.

Heat and Power Summary

| | | 40 K to 80 K | 5 K to 8 K | 2 K |
|---|---|---|---|---|
| Predicted module static heat load | (W/module) | 55.36 | 10.32 | 1.66 |
| Predicted module dynamic heat load | (W/module) | 92.48 | 4.32 | 9.02 |
| Number of modules per cryo unit (8-cavity modules) | | 204.00 | 204.00 | 204.00 |
| Non-module heat load per cryo unit | (kW) | 1.00 | 0.20 | 0.20 |
| Total predicted heat per cryogenic unit | (kW) | 31.16 | 3.19 | 2.38 |
| Heat uncertainty factor on static heat (Fus) | | 1.00 | 1.00 | 1.00 |
| Heat uncertainty factor on dynamic heat (Fud) | | 1.00 | 1.00 | 1.00 |
| Heat load per cryogenic unit including uncertainty | (kW) | 31.16 | 3.19 | 2.38 |
| Mass flow per cryogenic unit including uncertainty | (g/s) | 149.31 | 99.43 | 115.11 |
| Weighted ideal power | (kW) | 143.48 | 151.39 | 367.75 |
| Efficiency (fraction Carnot) | | 0.30 | 0.30 | 0.20 |
| Efficiency in Watts/Watt | (W/W) | 15.35 | 158.35 | 773.28 |
| Operating power including uncertainty | (kW) | 478.28 | 504.65 | 1838.73 |
| | | | | |
| Overcapacity factor (Fo) | | 1.40 | 1.40 | 1.40 |
| Overall net cryogenic capacity multiplier | | 1.40 | 1.40 | 1.40 |
| Heat load per cryogenic unit including Fus, Fud, and Fo | (kW) | 43.62 | 4.46 | 3.33 |
| Installed power | (kW) | 669.59 | 706.50 | 2574.22 |
| Installed 4.5 K equiv | (kW) | 3.06 | 3.23 | 11.76 |
| Installed 4.5 K equiv per unit length | (W/m) | 1.26 | 1.33 | 4.84 |
| Percent of total power at each level | | 17% | 18% | 65% |
| | | | | |
| Total operating power for one cryo unit including uncertainty factor (MW) | | | 3.10 | |
| Total installed power for one cryo unit (MW) | | | 3.95 | |
| Total installed 4.5 K equivalent power for one cryo unit (kW) | | | 18.05 | |

The result is a plant size equivalent to 18.05 kW at 4.5 K rather than 21.15 kW at 4.5 K, a 15% smaller plant. The overall net cryogenic plant size multiplier is 1.40, due to the 1.40 overcapacity factor, rather than 1.64.

Comments from the cryogenics global group.
Our experience is that there are indeed heat load uncertainties in cryogenic systems, even after components are tested, due for example to insulating vacuum degradation and unforeseen dynamic effects such as the electron cloud issue in LHC. In the longer term, for the EDR, we should evaluate heat load uncertainty for static and dynamic heat at each temperature level. We may then oversize only the heat exchangers and piping within the plants to accommodate possible future upgrades based on the uncertainty factors and machine upgrades, like CERN did for LEP, while initially procuring compressors and expanders to match the predicted heat loads.

The cost impact of the reduction of the static heat load uncertainty factor from 1.50 to 1.00 is a reduction of total ILC cryogenic system costs by about 4%. Cost is somewhat insensitive to marginal changes in capacity due to the cryogenic plant costs going like plant capacity to the 0.6 power, and roughly half of the cryogenic system being fixed costs like helium storage tanks, transfer lines, controls systems, and tunnel distribution boxes.

Quoting Tom Peterson's response to CCR#20 in a 30 October e-mail:
"With the elimination of 3.5% rf unit installed overhead, the elimination of the static heat load uncertainty factor, and the definition of a power gradient up to 33.5 MV/m as overhead, I suggest that we take 33.5 MV/m as the gradient for which we estimate dynamic heating and cryogenic cooling required. Our cryogenic system would then be matched to the rf system in terms of

providing additional power to the cavities. Previously, we took 31.5 MV/m for sizing the cryogenic system under the assumption that some strings of cavities might operate at up to 35 MV/m, but that the average dynamic heating would remain equivalent to 31.5 MV/m on the scale of the 2.5 km cryogenic units. Now, with the extra installed rf units gone, compensation for missing rf will have to be taken with an average higher gradient. I believe that sizing the cryogenic system for 33.5 MV/m would now be not only appropriate but required. The result is about a 7% increase in cryo power, so we take back some but not all of the reduction in cryo system size resulting from your proposal."

Recommendation for the new baseline and RDR:
Below is the cryogenic power spreadsheet summary for a cryogenic unit at 33.5 MV/m with 1.00 uncertainty factors and the usual 1.40 overcapacity factor. The result is equivalent to 19.37 kW at 4.5 K, which corresponds to **an overall cryogenic capacity multiplier (relative to the predicted heat at 31.5 MV/m) of 1.50, the same as what was used in the TESLA TDR. Tom Peterson's opinion is that capacity based on 33.5 MV/m, uncertainty factors = 1.0, overcapacity factor = 1.4, would be a good design criterion for a cryogenic system in response to CCR#20.**

Heat and Power Summary

| | | 40 K to 80 K | 5 K to 8 K | 2 K |
|---|---|---|---|---|
| Predicted module static heat load | (W/module) | 55.36 | 10.32 | 1.66 |
| Predicted module dynamic heat load | (W/module) | 98.78 | 4.45 | 10.18 |
| Number of modules per cryo unit (8-cavity modules) | | 204.00 | 204.00 | 204.00 |
| Non-module heat load per cryo unit | (kW) | 1.00 | 0.20 | 0.20 |
| Total predicted heat per cryogenic unit | (kW) | 32.44 | 3.21 | 2.61 |
| Heat uncertainty factor on static heat (Fus) | | 1.00 | 1.00 | 1.00 |
| Heat uncertainty factor on dynamic heat (Fud) | | 1.00 | 1.00 | 1.00 |
| Heat load per cryogenic unit including uncertainty | (kW) | 32.44 | 3.21 | 2.61 |
| Mass flow per cryogenic unit including uncertainty | (g/s) | 155.47 | 100.24 | 126.55 |
| Weighted ideal power | (kW) | 149.40 | 152.62 | 404.30 |
| Efficiency (fraction Carnot) | | 0.30 | 0.30 | 0.20 |
| Efficiency in Watts/Watt | (W/W) | 15.35 | 158.35 | 773.28 |
| Operating power including uncertainty | (kW) | 498.02 | 508.72 | 2021.48 |
| | | | | |
| Overcapacity factor (Fo) | | 1.40 | 1.40 | 1.40 |
| Overall net cryogenic capacity multiplier | | 1.40 | 1.40 | 1.40 |
| Heat load per cryogenic unit including Fus, Fud, and Fo | (kW) | 45.42 | 4.50 | 3.66 |
| Installed power | (kW) | 697.22 | 712.21 | 2830.08 |
| Installed 4.5 K equiv | (kW) | 3.19 | 3.25 | 12.93 |
| Installed 4.5 K equiv per unit length | (W/m) | 1.31 | 1.34 | 5.33 |
| Percent of total power at each level | | 16% | 17% | 67% |
| | | | | |
| Total operating power for one cryo unit including uncertainty factor (MW) | | | 3.33 | |
| Total installed power for one cryo unit (MW) | | | 4.24 | |
| Total installed 4.5 K equivalent power for one cryo unit (kW) | | | 19.37 | |

The cost of a cryogenic system sized per the above suggestion would be about 5.7% less than the cost of that sized before the Vancouver meeting, with about 3.3% due to the downward revision of some heat load estimates since Vancouver, and about 2.4% due to the reduction of the multiplier from 1.64 to 1.50.

| Gradient (MV/m) | Fus (static heat uncertainty factor) | Fo (overcapacity factor) | Main linac plant size (kW at 4.5 K) | Overall effective multiplier relative to 31.5 MV/m and Fus, Fo = 1.00 | Cryogenic system cost estimate scaled relative to July 2006 estimate |
|---|---|---|---|---|---|
| 31.5 | 1.50 | 1.40 | 23.69 | 1.64 | July |
| 31.5 | 1.50 | 1.40 | 21.15 | 1.64 | -3.3% |
| 31.5 | 1.00 | 1.40 | 18.05 | 1.40 | -7.5% |
| **33.5** | **1.00** | **1.40** | **19.37** | **1.50** | **-5.7%** |