The ILC Minimum Machine Definition

Release x

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Prepared by the Technical Design Phase Project Management

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1 Introduction

1.1 The Minimum Machine Philosophy

The concept of the “minimum machine” has evolved over the last twelve-months and has now become the corner-stone of the project management’s cost-reduction strategy for Phase 1 of the Technical Design Phase, as described in the published R&D Plan. Specifically:

- Definition of the basic parameters and layout of a “minimum machine configuration”, as a basis for understand cost-increments and cost-performance trade-offs (beginning 2009)
- Cost-reduction and performance studies (parametric studies) of the minimum machine, leading to possible options for the re-baseline. Evaluation of estimated cost and performance risk impact (end 2009).
- Evaluation of cost-reduction studies and status of critical R&D, leading to an agreed re-baseline of the reference machine (end of TD Phase 1, 2010)

It is important to emphasise that adopting a new baseline in 2010 is for the purposes of producing a new defendable updated VALUE estimate for the TDR in 2012 – a primary GDE deliverable.

The term “minimum machine” does not refer to any definable true ‘minimum’, but instead is a euphemism for high-level alternative design concepts which promise significant cost-reduction while maintaining the physics scope: the machine is “minimum” in the sense many of the cost-reduction concepts come at the expense of perceived risk to the machine performance (accessibility, operations, commissioning *etc*.).

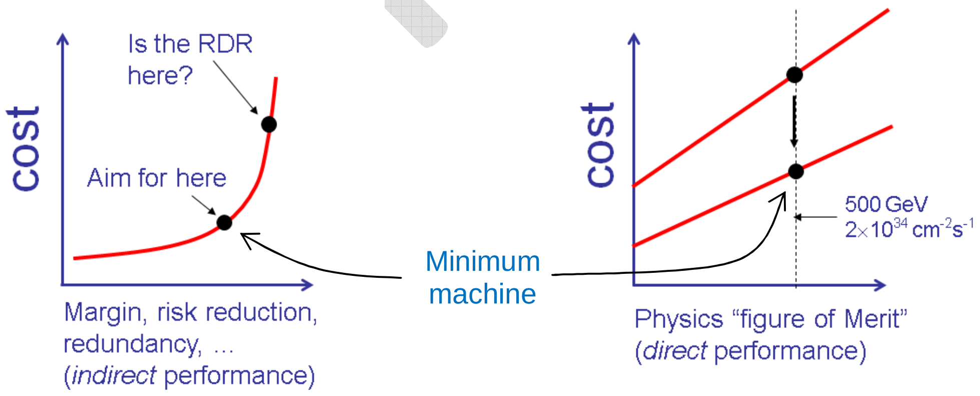

Figure 1: Understanding cost drivers: the Minimum Machine study concept

The RDR baseline design is considered sound but assumed in many aspects to represent a conservative approach, primarily to mitigate potential performance risk. Figure 1 depicts the rationale behind the minimum machine cost-reduction strategy by introducing two concepts:

- *Direct* performance (right-hand diagram), which can be considered a physics ‘figure of merit’ such as centre-of-mass energy or peak luminosity. Understanding the derivatives of the direct cost of these physics performance parameters is an important part of the minimum machine studies.
- *Indirect* performance (left-had diagram), into which we place margin, redundancy, *etc*. i.e. those design elements which do not directly affect (for example) peak luminosity, but tend to impact operational aspects of the machine or performance risk (potentially affecting integrated luminosity within a given time frame)

The minimum machine study is primarily focused on understanding the indirect performance related costs, by attempting to quantify the cost-performance gain.

With the expected resource situation in calendar year 2009, it is not practical to attempt to make a comprehensive study of all design elements of the RDR baseline to establish such cost-performance ratios. Instead a more pragmatic approach is proposed which concentrates on the identified critical RDR cost-drivers – specifically CFS.

A reduction in the total required underground tunnel length is essentially proposed by a significant re-design of the machine layout and (in some cases) alternative approaches to critical technical sub-systems. The project management, after review, has decided to focus on seven key areas (minimum machine elements) which are believed to offer substantial cost reduction, while acceptably increasing the performance risk. Figure 2 introduces the primary machine elements, which are described in detail in section 2.

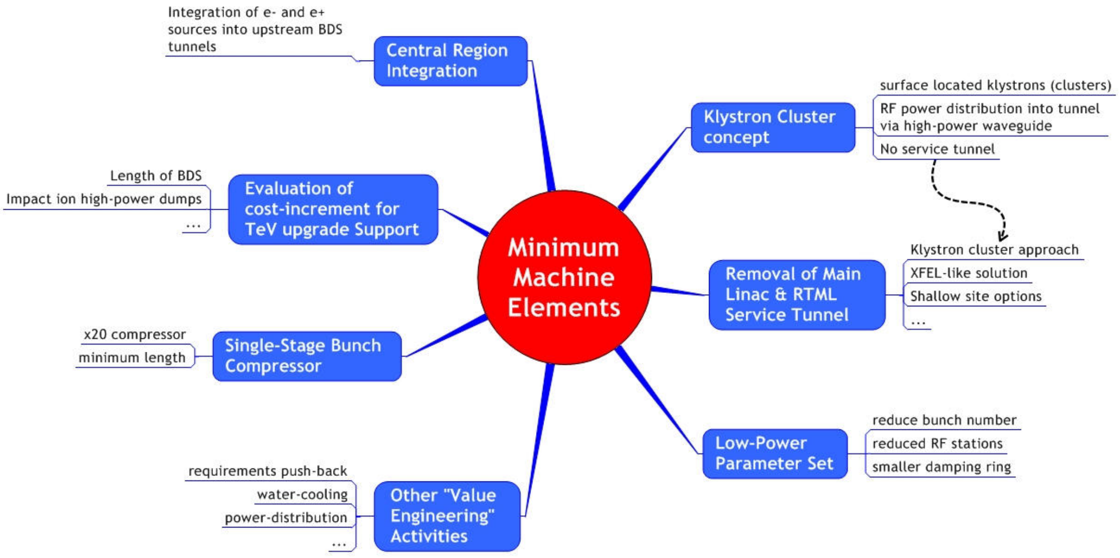

Figure 2: The Minimum Machine study elements.

1.2 Relationship to the Current RDR Baseline

The RDR baseline is the basis for the published VALUE estimate, and represents a relatively detailed design in support of that estimate. The RDR baseline is also the result of a consensus driven international process.

By contrast, the minimum machine studies in 2009 cannot be an equivalent design effort, and the specific design elements have been selected by the project management. In addition, it is not foreseen to make any new or updated cost estimates during this period (TD Phase 1). It will therefore be necessary to base all the incremental cost estimates associated with these alternative designs on the existing RDR cost data (as far as possible). The RDR baseline will remain the effective 'baseline' for all reference, until the top-down driven studies are concluded (end of 2009), at which point the results can be reviewed by the community, and a final consensus-driven decision on a new baseline can be made (see section 1.3).

1.3 The Process towards Formal Re-Baseline

The minimum machine studies represent a method to reduce the costs of a design which is considered conservative, in an attempt to understand the cost-performance gains for those elements proposed. The results of these studies – together with a review of the on-going risk mitigating R&D programmes – will allow the community to re-define the baseline in early 2010. The time scale for this process is shown in Figure 3, and is consistent with the goals and milestones outlined in the R&D Plan.

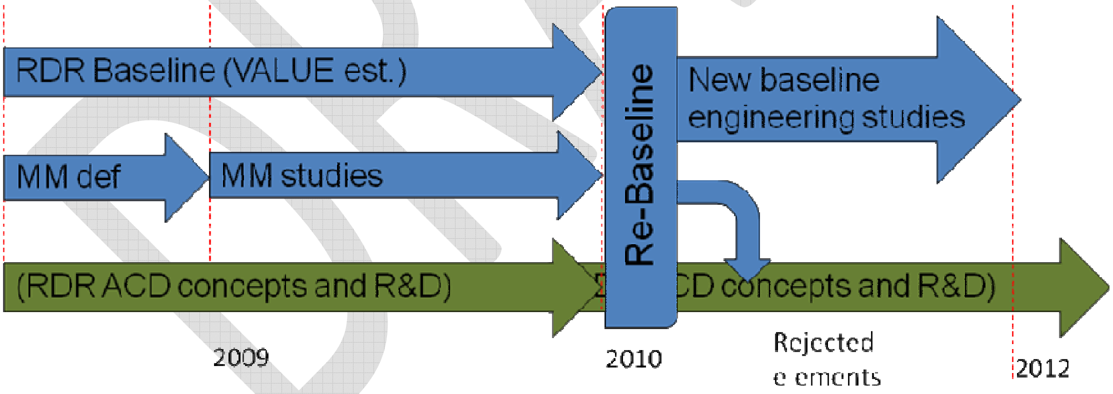

Figure 3: Time-line for minimum machine studies

Figure 3 indicates several key-points of the proposed process:

- The Minimum Machine definition ("MM def" in Figure 3) is essentially this document, which outlines the scope of the elements and plans for the identified studies during calendar year 2009 ("MM studies", see section 2.8).

- The formal support for the RDR baseline as the primary cost-basis for the studies (as described in section 1.2). The RDR baseline will be superseded in 2010 after due process and subsequent consensus-driven agreement by the community.
- The continued formal support for the so-called ACD R&D activities, some of which may be considered mature enough by the end of 2009 to be considered for baseline adoption in 2010.

During the process of re-baselining in 2010, it is important to note that all options considered viable and suitably mature enough to support an updated cost-estimate in 2012 can be considered. The specific minimum machine elements outlined in this document will be evaluated in terms of estimated cost saving and their potential impact on the risk. If the increased risk is deemed not acceptable in light of the cost benefit, then the proposed design modification will not be adopted as baseline (as depicted by the "elements rejected" arrow in Figure 3).

The exact formal process of baseline adoption remains to be defined, and will be developed in parallel to the studies during 2009 by the Project Management[1].

2 Minimum Machine Study Elements

In the following sections, the main elements of the minimum machine studies will be briefly described.

2.1 Main Linac

As the single-largest cost, the main linac remains the primary focus of the TD Phase activities. Specifically, the world-wide investment in SCRF technology – and particularly the high-gradient programme – represents the largest cost-leverage per R&D investment.

Beyond the SCRF linac technology itself, three possible cost-reduction design modifications have been identified which will form part of the minimum machine studies:

- removal of the underground service tunnel (single underground tunnel housing the accelerator);
- klystron cluster concept (RF power distribution alternative);
- processed water cooling specifications (higher ΔT solutions).

These three concepts are not independent from each other: the specific engineering solutions for each case are necessarily integrated with choices made for the other two. Therefore it will certainly be necessary to look for self-consistent cost-optimum solutions

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[1] The process itself will require community consensus.

for several scenarios. For the purposes of this document, however, we will deal with each of these concepts separately in the following sections.

2.1.1 Removal of the service tunnel

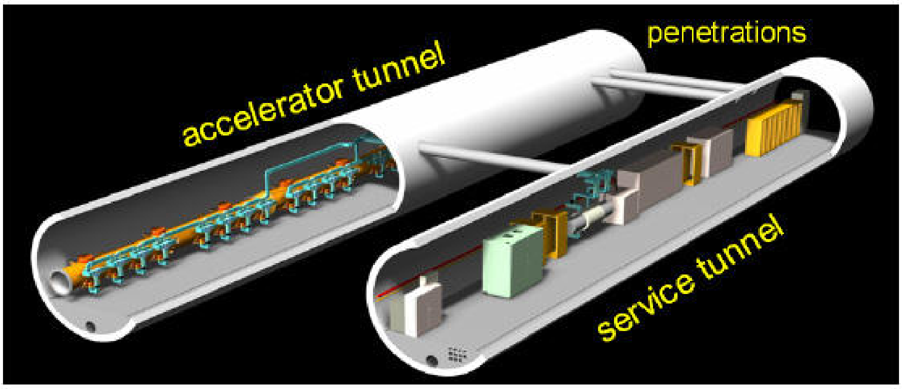


Figure 4: RDR two-tunnel solution

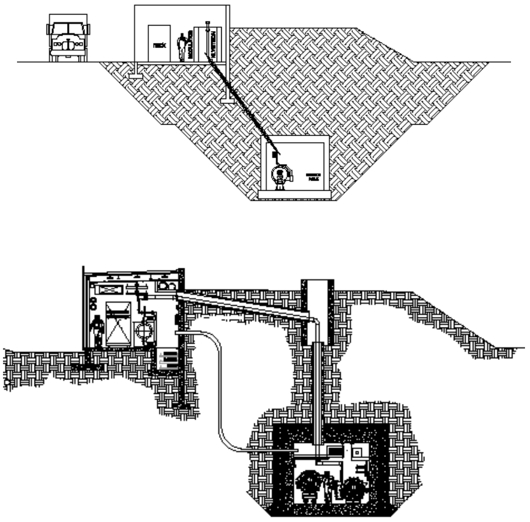
Figure 4 shows the RDR solution for the Main Linac twin-tunnel housing. The choice of a separate tunnel (service tunnel) to house the RF power sources, power supplies and electronics was primarily driven by:

- concerns over reliability and in particular access to klystrons and other hardware during beam operation to achieve high availabilities (and in particular required access to during beam commissioning);
- use of the twin-tunnel solution as the corner-stone for the adopted emergency egress philosophy.

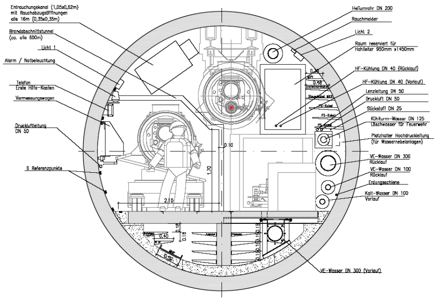
However, there is a general agreement that there is a significant cost incursion for the second tunnel. At the time for the RDR, it was accepted that the incremental cost of service tunnel solution justified the gains in performance and safety. It should also be noted that such a twin-tunnel scheme was consider in the light of the deep-tunnel solutions studied for all three RDR sample sites.

Given the level of maturity of the RDR twin-tunnel baseline design, it would seem prudent to attempt to quantify the above statements as part of the minimum machine studies. To that end, it is proposed to study options towards a single underground tunnel solution. As with all the minimum machine studies, the primary goal will be to evaluate the potential cost saving while attempting to quantify the increased risk.

RDR twin-tunnel solution (deep rock site). Klystrons, modulators, power supplies and electronics are located in service tunnel, allowing access during beam operation.



Possible cut and cover solutions for a suitable shallow site. Use of surface gallery still maintains access to klystrons, modulators, power supplies *etc.* during operations.



European XFEL tunnel solution:

- Single underground tunnel
- Cryomodules suspended from tunnel ceiling
- Pulse transformers, klystrons, power supplied and electronics in tunnel (no access during operation)
- Modulators in localised surface buildings; many long pulsed cables (~2km) connect modulators to klystrons.

Figure 5: single underground tunnel options (RDR solution included for comparison)

Figure 5 shows the possible scenarios for single underground tunnel solutions. They fall into two generic types:

1. Shallow site-like solutions – basically a near-surface underground structure (tunnel or cut-and-cover construction) with surface support building for housing klystrons, modulators and cryogenic plants. Such a solution maintains access to critical components during beam operation. The primary cost savings are via replacement of an underground tunnel with a suitable surface building, and the arrangement (and depth) of shafts. Such a solution does not negatively impact availability over the existing two-tunnel solution, and would ease the water cooling requirements for the RF power sources (a further cost saving). However, the solution is geographically constrained to potential sites which are relatively flat with no or limited existing surface construction (unpopulated area).

2. European XFEL solution (or similar variant): A single underground tunnel which houses the accelerator (cryomodules), klystrons, pulse transformers, power supplies and electronics. Modulators (considered a reliability risk) are located in surface buildings and connected to the in-tunnel RF stations via long pulsed cables. The primary cost saving is the removal of the service tunnel and the associated transverse penetrations; this saving must be offset by: (i) the cost of the many long pulsed cables; (ii) the additional surface building area to house the modulators; (iii) any increase in tunnel diameter required to accommodate the higher volume of components in the single-tunnel[2]. A critique of the XFEL single-tunnel solution is the lack of access to klystrons *etc*. during beam operations, mandating down-time to replace or repair components. An additional investment will be warranted to offset this (to some degree) using redundancy or high(er)-availability specified components. Since the European XFEL is an approved construction project, all of these challenges will need to be addressed. The GDE needs to maintain close contacts with the XFEL project during the engineering design, construction and ultimately commissioning and operations phase to evaluate the suitability (and cost saving) of the solution extrapolated to the ILC. The XFEL will be constructed in a relatively shallow site (≤25 m deep); however there is no fundamental reason why the solution cannot be extended to deep-rock sites similar to the RDR sample sites.

A third single-tunnel variant is associated with the klystron cluster concept, where the klystrons are located together with the modulators in localised surface buildings separated by approximately 2 km. Compared to the XFEL solution, the klystron cluster concept removes the need for the long pulsed cables, and by placing the complete RF power source on the surface, addresses several of the concerns over availability. A more detailed discussion is given in the next section (section 2.1.2).

2.1.2 Klystron cluster concept

A linac configuration that would make use of a single tunnel and reduce electrical/cooling costs significantly is to have the RF power generated in modulator/klystron clusters on the surface and then transported down and along the beam tunnel; this solution is in many ways analogous to the XFEL solution (section 2.1.1), except that the power is transported into the tunnel as microwaves in a high-power low-loss over-moded waveguide, instead of via 10 kV HV pulsed cables. The tunnel power and cooling systems are much simpler (no underground klystron collector heat loads). Also, with the RF sources in ~300 MW clusters, it may be easier to recover power from the dissipated heat. Having both klystrons and modulators now on the surface – and therefore accessible during beam operation – will help alleviate many of the concerns of availability associated with the

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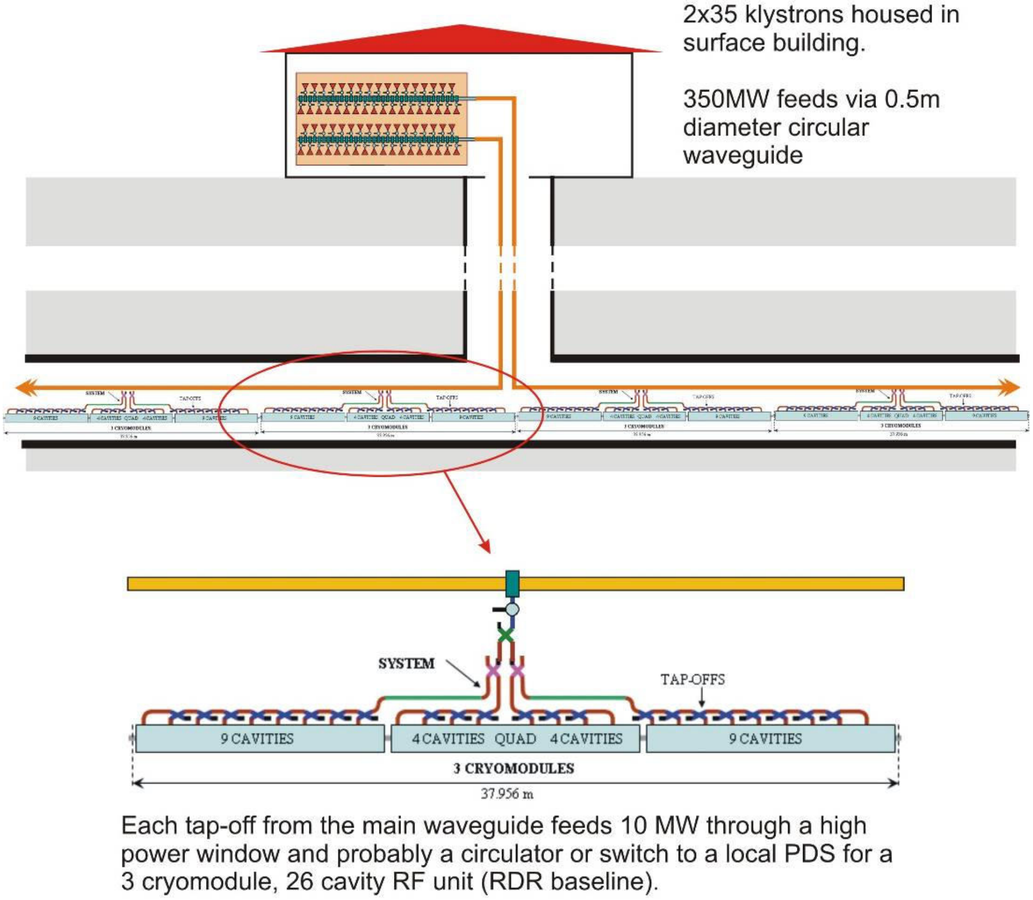
[2] The XFEL design currently has a 5.2 m diameter tunnel, compared to the 4.5 m diameter tunnel for the RDR baseline.

XFEL solution, although some electronics (LLRF, BPM etc) and possibly magnet power supplies would still be located in the accelerator tunnel.

The current proposal is to have 35 klystrons in a cluster, requiring a ~350 MW peak power in the RF transport (over-moded waveguide) feeding 32 standard RDR RF units (96 cryomodules, or 2496 cavities). Two such clusters would be located together on the surface, supplying ±1.2 km of linac, with the surface buildings and shafts being ~2.4 km apart (see Figure 6).



2x35 klystrons housed in surface building.

350MW feeds via 0.5m diameter circular waveguide

Each tap-off from the main waveguide feeds 10 MW through a high power window and probably a circulator or switch to a local PDS for a 3 cryomodule, 26 cavity RF unit (RDR baseline).

Figure 6: klystron cluster concept.

The two rows of 35 modulators, klystrons and isolators that would tap-in to two transport lines in a way that the power flows in one direction (with the isolators, directional launchers are not required). The tap-offs (every RF unit, ~38m) in the accelerator tunnel could be implemented in a similar way although they would probably be directional. Once the 10 MW is extracted, a variable tap-off (VTO) in each RF unit with adjustability could be used for control of the RF power to that unit (if needed). Inter-pulse shutoff should also be possible to individual RF units, although not intra-pulse without turning off the whole cluster. As in the current RDR design, the individual cavity phase shifters would be used to adjust the RF phase, although one high-power phase shifter per RF unit would be preferable.

The main feasibility questions are

- Reliably sustaining ~350 MW 1.6 ms RF pulses: the waveguide pipe itself should not be a problem as there are no electric fields terminating on the surfaces[3]. The tap-in, tap-off devices and bends will require R&D. Based the X-band results and recent long pulse (1 ms) L-band cavity results from SLAC, it is estimate the system would be robust if the surface fields were kept below 10 MV/m, which should be feasible with such a large diameter pipe around which the tap-ins and tap-offs would be wrapped (this field level is less than half of that sustainable in low power, long pulse L-band systems).
- The intra-pulse LLRF control could only be done over lengths of ~1.2 unless fast I/Q controllers like those being developed for low-beta machines are used. Thus we would need to assess whether this coarse granularity would provide adequate energy control along the bunch trains. The cavity piezo controllers could be used to provide more than Lorentz detuning compensation (at least on average in an RF unit).

The primary expected cost reduction (compared to the RDR) comes from:

- having only one, smaller diameter tunnel (independent of tunnel depth);
- not having to distribute extensive AC power and water cooling in the tunnel (would only have necessary LLRF and beam instrumentation electronics as well as magnet power supplies);
- not having to deal with air heat removal and the safety issues of operating the beam with people in the service tunnel;
- simplifying the installation process;
- decoupling the RF system heat removal issue from the tunnel air temperature issue, potentially allowing the energy to be recovered from the heat losses (e.g. running the collectors at very high temperatures).

Finally, adoption of the Marx modulator (an existing ACD item and currently being prototyped at SLAC) is included, which will hopefully lead to further cost reduction, as well as a potential increase in reliability over the existing bouncer modulator baseline.

2.2 Low power option

2.2.1 A brief review of the RDR parameter plane

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[3] SLAC has transported 600 MW in much smaller pipe at X-band, but using 400 ns pulses, and have transported 300 MW in 2 cm rectangular waveguide where the E-fields do terminate on the walls.

All sub-systems of the RDR baseline are designed to accommodate the so-called *parameter plane* in an attempt to mitigate risk in achieving the desired luminosity performance. The parameter plane is defined in terms of four self-consistent parameter sets – one nominal parameter set, and three parameter sets which are scaled from the nominal set. Each of these latter three sets assumes that a critical parameter in the nominal set (single-bunch charge, vertical emittance, number of bunches) is not achieved, and that the subsequent reduction in luminosity performance can be mitigated by adjustment of other (sub-system) parameters. Taken together, the parameter plane represents a low-risk conservative design, but one which may not represent a low-cost design. Therefore, within the context of the minimum machine studies, it is considered prudent to re-evaluate the parameter plane from the context of lowest cost, although at the same time accepting that this would inevitably increase the performance risk.

In terms of cost reduction, peak RF power has the greatest leverage since it allows reduction of the number of RF stations (klystrons and modulators and associated CF&S costs). In general the luminosity is restored by pushing the beam-beam parameters, which – although an increase in performance risk – are not considered a major cost driver. The peak power can be reduced by either (i) reducing the single-bunch charge N, or (ii) by reducing the number of bunches n_b within the same beam pulse; both result in a lower beam current. However, as the luminosity scales as $L \propto N^2 n_b$, it is more advantageous to reduce the number of bunches, clearly favouring a “Low-P” like parameter set.

The lower number of bunches has the additional attractive feature of being able to reduce the circumference of the damping ring, while maintaining the same inter-bunch distance (critical for the fast injection and extraction kicker – see section 2.2.3).

The RDR Low-P parameter set represents a factor-of-two reduction in the number of bunches. The luminosity is achieved by pushing on the beam-beam – effectively increasing the beamstrahlung from 2.4% (nominal) to 4.5%. It is important to note that this parameter set assumes a reduction in bunch length at the IP from 300 μm (nominal) to 200 μm; this will not be possible if a single-stage bunch compressor is adopted (section 2.4). A proposed work-around is to make use of the so-called *travelling focus* concept, which could allow for the longer bunch length while maintaining the luminosity, at the same time as reducing the beamstrahlung (see Table 1).

Table 1: Possible low-power parameter set using travelling focus concept (new Low P). RDR nominal and Low-P parameter plane sets are shown for reference.

	Nom. RDR	Low P RDR	new Low P
E_{CM} (GeV)	500	500	500
Particles per bunch, N ($\times 10^{10}$)	2.0	2.0	2.0
Bunches per pulse, n_b	2625	1320	1320
Pulse repetition rate (Hz)	5	5	5
Peak beam power, P_b (MW)	10.5	5.3	5.3
$\gamma\varepsilon_x$ (μm)	10	10	10
$\gamma\varepsilon_y$ (nm)	40	36	36

β_x (cm)	2.0	1.1	1.1
β_y (mm)	0.4	0.2	0.2
Traveling focus	No	No	Yes
σ_x (nm)	640	474	474
σ_y (nm)	5.7	3.8	3.8
σ_z (μm)	300	200	300
Beamstrahlung* $\delta E/E$	0.023	0.045	0.036
Luminosity* ($\times 10^{34}$ cm^{-2}s^{-1})	2.0	1.7	1.9

*) simulated using GUINEA-PIG

2.2.2 Implications for the Main Linac

The primary cost saving associated with a reduction in beam power is via the reduction in the number of RF stations; *i.e.* a single 10MW klystron is used to drive a higher number of cavities, resulting in a longer RF unit. In addition to the direct reduction in the number of klystrons, modulators, power-supplies *etc.*, there are also potential cost savings via the associated conventional facilities (processed water cooling and AC power distribution).

Table 2: Examples RF parameters for a low beam-power option. The numbers assume an accelerating gradient of 31.5 MV/m and TESLA-shaped cavities (R/Q = 1.036 kΩ). The bunch charge is 3.2 nC. A maximum usable klystron power of 8 MW is assumed (20% overhead for control and losses).

Reduction in RF stations		RDR	RDR*	33%	50%
# cavities / RF unit		26	26	39	52
RF unit voltage	MV	846.8	846.8	1270.3	1693.7
# bunches		2625	2625	1312	1312
bunch spacing	ns	369	339	509	679
beam current	mA	8.7	9.4	6.3	4.7
beam pulse	µs	969	891	668	890
Q_{ext}		3.63	3.34	5.00	6.67
cavity time constant	µs	888	817	1225	1633
fill time	µs	616	566	849	1132
RF pulse	ms	1.6	1.5	1.5	2.0
Klystron P_{for} (fill)	MW	7.3	8.0	8.0	8.0
Klystron P_{for} (beam)	MW	7.3	8.0	8.0	8.0
Efficiency		61%	61%	44%	44%

Table 2 indicates possible RF parameter settings for 33% and 50% reduction of RF stations, as well as the RDR parameter set for reference. (A second reference full-power RDR* parameter set utilises the assumed maximum 8 MW klystron power.)

In general, the lower beam-power option has the following implications:

- An increase in Q_{ext}, resulting in a longer fill-time and a smaller cavity bandwidth; the latter will have implications for de-tuning errors and possible impact on control overhead (although this may well be more than offset by the reduced beam-loading).
- A reduction in RF power to beam power efficiency: thus a reduction in beam power by a factor of 2 results in a decrease in average RF power by a factor of ~1.4.
- In some cases (50% reduction example in Table 2), an increase in RF pulse length will be required (2 ms in this example).
- Increased RF losses in the longer waveguide distribution system.
- The lower power at the cavity tap-offs and couplers is advantageous. We should also note that this has positive implications for the klystron cluster distribution concept outlined in section 2.1.2.

2.2.3 Implications for the Damping Rings

A reduction in the number of bunches by a factor-of-two allows a reduction by the same factor in the circumference of the damping rings, while keeping the current (bunch spacing) in the rings constant. To first-order this could result in an almost factor-of-two reduction in the damping rings cost. This naïve cost scaling will be offset to some extent by the exact design of the smaller rings; for example the required RF power remains the same (fixed damping time, energy and current), as may the number of shafts. Other points for consideration are:

- smaller bending radius in the arcs may result in more than a factor-of-two reduction in damping wiggler length;
- actually cost saving of lattice will depend strongly on the lattice design to achieve the desired emittance (a simple scaling of the existing FODO arc lattice may not be sufficient)
- care must be taken to allow enough space in the straight-sections for the RF, wiggler and injection and extraction sections, which may affect the ratio of straight-section to arc length; this has consequences for the proposed central integration layout described in section 2.3;

2.2.4 Implications for beam dynamics

As already described in the section 2.2.1, the reduced beam power is compensated by pushing on the beam-beam at the interaction point to maintain the design peak luminosity. A review of Table 1 indicates that this is achieved by a small reduction in the vertical emittance (reduced emittance growth budget), and stronger focusing at the IP in both planes. The higher disruption parameter results in a narrower region of stability which in general leads to tighter alignment tolerances (both static and dynamic), and a greater sensitivity to wakefields. The proposed travelling focus will also have potential repercussions on luminosity stability and tuning. Beyond the accelerator, the impact on the detector design and physics must also be assessed. While none of these are seen as potential show-stoppers or cost-drivers, they are considered as increased risk to the luminosity performance.

2.2.5 Other implications

Reduction of the beam power has implications for all systems beyond those described in some detail in the previous sections. Although they are not large cost drivers, they do impact on performance at some level. We list them here for completeness:

- For the electron source, the reduce bunch number opens up two possible scenarios:
    - Keeping the average current fixed at ~9 mA but reducing the length of the pulse; this would reduce pulse length for both the laser, DC gun and the warm RF capture sections, but would require the SCRF 5GeV injector linacs to accelerate the full current (i.e. no reduction in RF stations as in the Main Linacs).
    - Keep the pulse length, but reduce the current (as in the Main Linac); this would afford similar cost savings in the 5GeV injector linacs as for the Main Linac, and the longer bunch spacing may help against the cathode charge limit in the photo-injector.
- Positron source: the average power on the target is reduced by a factor-of-two as is the general activation of the area (per unit time).
- All beam dumps in general, and specifically the main high-power dumps in the BDS must only deal with half the power. Reducing the engineering scope of the main dumps could afford some cost savings, but this has implications for future upgrades.
- In principle, the BDS has been designed to accommodate the original RDR low-P parameter set (Table 1). The reduced beamstrahlung afforded by the longer bunch length and the travelling focus could lead to a further cost optimisation of the extraction line energy aperture, although this is not likely to be a major cost saving.

2.3 Source and BDS Integration (Central Region)

2.3.1 The Central Region in the RDR

The "Central Region" in the RDR is the region between the ends of the linacs and contains the injectors, the damping rings, the beam delivery system (BDS) and the interaction region. Figure 7 shows the tunnel complex on the electron linac side where the injectors and damping rings are vertically separated by ~10 m from the beam delivery tunnel system. There is also a single service tunnel (green) which contains power supplies, klystrons etc. and is shared between the injectors and the BDS. The electron side also houses the "keep-alive" positron source – a low-power conventional thick-target source capable of producing ~10% of the required positron current.

This geometry allows commissioning and or tuning operations of the injectors with personnel in the IR, the BDS and the linacs.

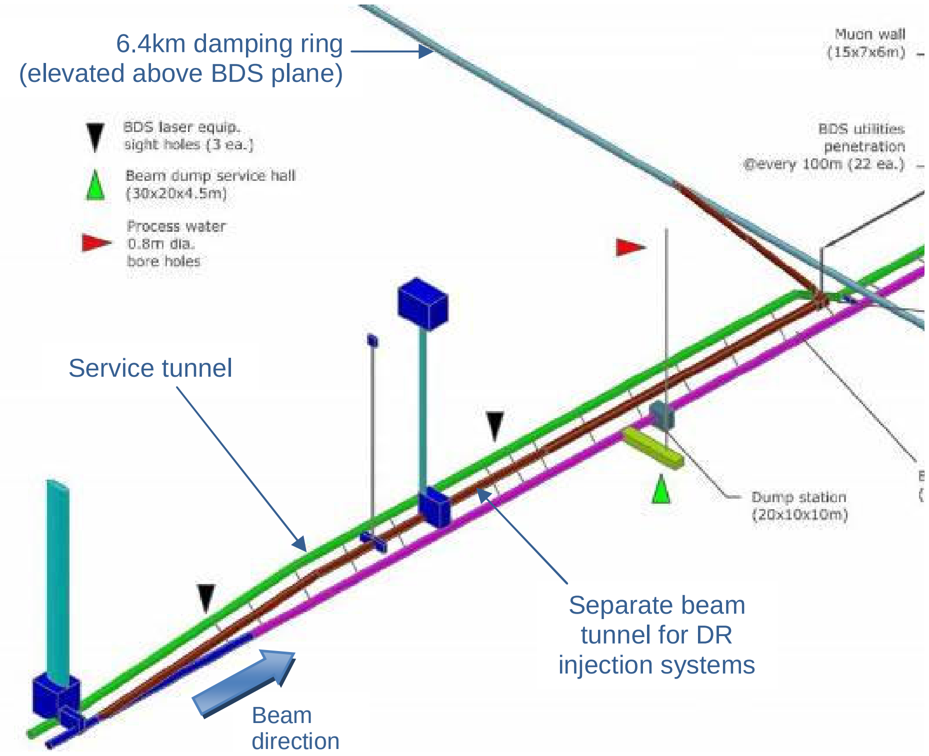

Figure 7: RDR BDS layout (final focus and IR not shown)

If one reconsiders the desirability of this latter statement and accepts a compromise that allows operation with personnel excluded from the first part of the BDS, then one can reconsider having the equipment and tunnels in the same plane and have the injectors share the same tunnel as the BDS. The three tunnels in Figure 7 would then be reduced to two over ±1.5 km. The layout of the DR tunnel could be either in the crossing geometry as shown or off to the side of the main beam line but now in the same plane as the other tunnels. The continuing need for the service tunnel or equivalent buildings will be coupled with the discussions in section 2.1.1.

2.3.2 Consolidation of Main and Keep-Alive Positron Sources

In the RDR the main undulator driven polarized positron source is in the middle of the linac occupying a special 1.2 km insert and the lower power keep-alive source is in the central region. With the in-plane geometry of the central region one can also consider consolidating these two into one system at the location of the keep-alive source, sharing the tunnel with the first part of the BDS. This combined system would have a shared e+ target, capture section and 5 GeV booster linac, and the 1.2 km insert in the Main Linac would be eliminated.

The location of the primary (undulator) positron source at the 150 GeV point in the electron linac was considered to be the best choice when considering overall operation over a wide range of energies. The impact and alternative operating scenarios will have to be revisited as this positron source undulator is now at the end of the linac and at full operating energy.

Figure 8 shows a schematic diagram of how such an positron source system could be combined with the BDS in a single tunnel. It also shows the possibilities of sharing beam dumps for different operating modes and indicates the location of a single major shaft or access point which would be for target replacement and end of linac functions.

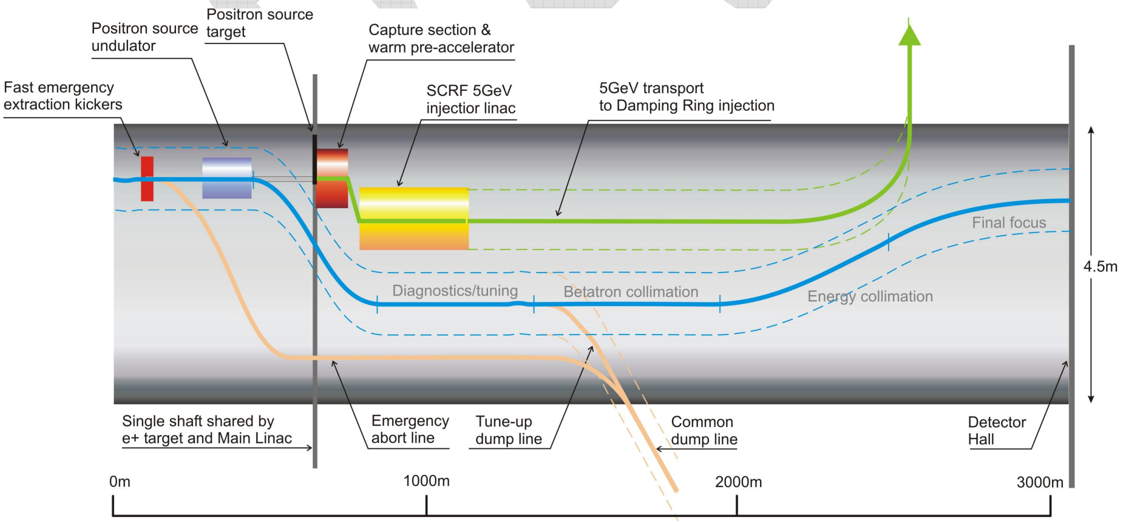

Figure 8: A possible example of positron source integration into the RDR BDS geometry. (Note very different vertical and horizontal scales.)

2.3.3 A Consolidated Central Region

Combining all of the above elements, it is possible to locate both injector complexes and the BDS in a single 5 km region. Figure 9 is a diagram and list of the systems in this region.

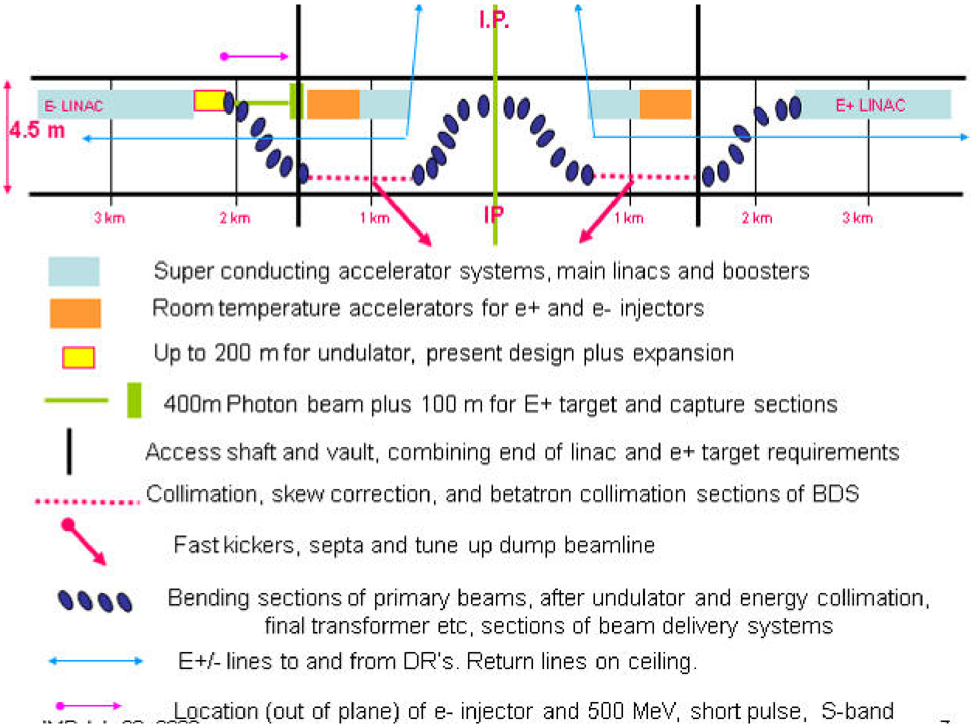

Figure 9: Elements in Consolidated Central Region
(14mr crossing angle is not indicated for simplicity)

There are many questions of detail and practicality that require study including the location and orientation of the DR’s and injection tunnels. These questions are both with technical systems and CF&S systems and are strongly coupled.

Early choices will need to be made in the 2009 Minimum Machine study program to limit the number of combinations of these ideas that will reward further work and allow the necessary evaluation of potential cost reductions and impact on risk and operability. One interesting question is whether the studies of single tunnels, cluster klystrons, *etc*. is cost effective and practical to the central complex, where considerations of the impact of surface structures will be different from that in the extended Main Linacs.

2.4 Single-stage bunch compressor

The baseline (RDR) design includes a two-stage compressor, facilitating an overall maximum bunch compression ratio of a factor of ~45. The main arguments in support of a two-stage compressor are

- Support of the parameter plane (flexibility): Assuming the RDR 9 mm damping bunch length, the two-stage compressor system can achieve bunch lengths of 200 µm (low-P parameter set).
- Reduced RMS energy-spread at the entrance to the Main Linac (at 15 GeV) significantly reducing the emittance growth in the Main Linacs due to chromatic aberrations. (This must be offset by the problems arising from cavity tilts and long bunches in the extended bunch compressor itself.)

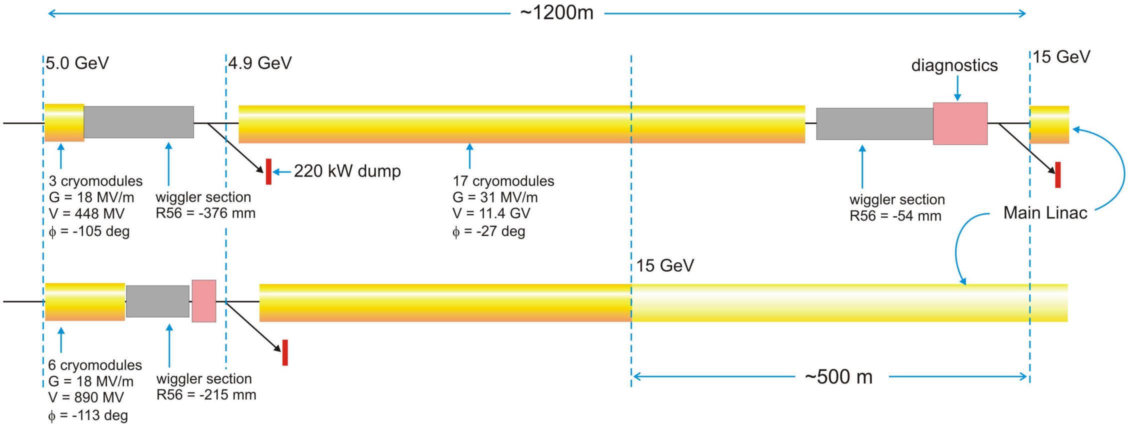

Figure 10: The RTML two-stage compressor (top) and a possible short single-stage compressor (bottom). Not that it is important to compare the total lengths to the same reference energy (15 GeV)

With the adoption of a damping ring lattice capable of achieving a 6 mm bunch length, it is now possible to reconsider the possibility of a single-stage compressor with an overall reduction in compression ratio. Figure 10 compares the geometry of the RDR two-stage system with a possible single-stage system capable of a factor of 20 compression, which is sufficient to achieve the nominal bunch length at the interaction point of 300 µm. The cost advantages of the single-stage system are

- Reduction in beamline and associated tunnel length by an equivalent of ~450-500 m (including ~190 m of SCRF linac)
- Removal of the second 220 kW dump and dump line components
- Possible shortening of the diagnostics sections (lower energy)

The loss of flexibility and achievable bunch-length range has implications for the low-power option discussed in section 2.2, as well as an increased risk with respect of achieving the design damping ring length. The impact of the increased RMS energy spread on the Main Linac emittance growth has been extensibly studied in the past, and must be balanced against the observed problems (in simulation) of the control of the emittance in the two-stage system, which may prove more tractable in the simpler one-stage system.

2.5 Estimation of incremental cost for TeV upgrade support

To help facilitate the desired but optional upgrade to 1 TeV centre-of-mass energy, the geometry of the Beam Delivery System is extensively laid out for 500 GeV beam operation, but with a reduce number of dipole magnets (“missing” magnets). The upgrade scenario is then relatively straightforward, only requiring the installation of the additional dipoles and power supplies. The main high-powered dumps have also been specified for the higher expected beam power.

As part of the minimum machine study, it is intended to evaluate and quantify the cost of this support, by designing a ‘minimum length’ system capable of maximum beam energy of 250 GeV. This study would include estimates of the reduced power main dumps.

It is important to note that this study is not independent from the central region integration described in section 2.3, since the required (minimum) tunnel lengths may be constrained by other requirements.

2.6 Other “Value Engineering”

For completeness, it is important not to overlook possible cost savings across the technical solutions proposed in the RDR design, again specifically in the area of Conventional Facilities (water cooling, power distribution). Other clearly identified areas are the consolidation are the number magnet families (via standardisation); reduced-cost solutions for the power supplies and cables; vacuum requirements and solutions (again potentially via standardisation).

2.7 Scope of Studies and Required Expertise (Resources)

A cursory evaluation has been made of the type and scope of the studies in 2009, as well as the type of expertise that is expected to be required to address them. Essentially four categories of studies have been identified, briefly summarised in Table 3.

Table 3: Identified (top-level) study categories for the Minimum Machines elements.

Category	Scope	Expertise / Comments
Interference / Integration **(*design work*)**	• Lattice layouts • Tunnel cross-section models (3D CAD) • (Installation related) • Component placement *etc*	CAD (CFS) engineer(s), optics (accelerator physics) expert(s). Look for (conceptual) engineering solutions.

Operations, Commissioning, Availability **(*concepts, philosophy, risk assessment*)**	- Less independent machine operation - Reliability issues (accessibility) - Commissioning strategies *etc*.	Much more difficult to quantify. Looks for experienced experts Brainstorm qualitative concepts (solutions)
Hardware R&D **(*hardware development programmes, demonstrations etc.*)**	- High-power RF distribution concept - Marx modulator (on-going) - Increased RF pulse length (low-P)	Engineering / technical as appropriate. FTE and MS required. Well defined goals for R&D programme. Acceptance criteria of proposed solution.
Beam Dynamics **(*simulations*)**	- Emittance preservation - BDS tuning - Travelling focus 'stability' - …	Beam dynamics and simulation specialists (LC experts). (good coordination, well defined questions)

2.8 Special considerations of the impact on the TeV energy upgrade

Although the focus of the minimum machine study is on the 500 GeV baseline machine, one important aspect of evaluating the design elements described above is the potential impact on the energy upgrade to 1 TeV centre-of-mass. It is expected that the central region integration and 'minimum' 500 GeV BDS are most likely to have the greatest impact. It is important to propose – at least conceptually – scenarios to successfully upgrade the machine to 1 TeV, and in particularly to estimate their potential impact on cost and schedule of that upgrade.

3 Detailed Scope and Plans for Minimum Machine Studies

The following sections will detail the plans for the 2009 studies related to the minimum proposed machine elements. The sections are organised via the relevant Technical Area Groups.

3.1 Main Linac (lead editor: Adolphsen)

The following is a template that should be repeated for all the TAG sections.

3.1.1 Identified critical issues

- Catalogue of issues resulting from minimum machine proposal that require study to quantify (this naturally includes the estimate of the cost saving)
- Should be terse and specific
- If a long list, should attempt to prioritise
- Dependencies on other (TAG) studies should be identified (will require consolidation once all the sections are available)

3.1.2 Proposed relevant studies

- One section per study (should clearly link to items in previous section)
- Explicit scope and goal of study
- Estimated resource requirements

3.1.3 Summary of resource requirements

- A roll-up summary of the resources specified in previous sections.

3.2 CFS (lead editor: Kuchler)

3.3 Sources (lead editors: Clarke, Brachmann)

3.4 Damping Ring (lead editor: Wolski)

3.5 RTML (lead editor: Solyak)

3.6 BDS (lead editor: Seryi)

3.7 Simulation (lead editor: Kubo)