THE ESS SUPERCONDUCTING LINEAR ACCELERATOR

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Abstract

In 2003 the joint effort to design a European Spallation Source resulted in a set of reports. Two new designs were presented at PAC09 by ESS-Bilbao and ESS-Scandinavia. Both designs exploit synergies with projects such as SPL at CERN, eRHIC at BNL, and the EURISOL Design Study. Lund was agreed to be the ESS site in late May 2009. ESS-S then began to prepare for a coordinated European effort to update the design, and to prepare all legal and organisational matters that will be needed during the construction phase. The design update phase is expected to end in 2012. The present status of the preparatory work is presented, together with an outline of future work. The baseline for the updated design is presented and discussed. It delivers 5 MW of 2.5 GeV protons to a single target, in 2 ms long pulses with a 20 Hz repetition rate. Potential future upgrades of power and intensity are considered, with the possibility of increasing the average beam power to as much as 7.5 MW, for delivery to one or perhaps two target stations.

ESS-BILBAO INITIATIVE WORKSHOP

During its phase as candidature for hosting ESS, ESS-Bilbao designed a comprehensive, international and collaborative R&D programme which addresses some of the critical design challenges of the ESS and provides a collaborative platform for research efforts across Europe.

Within this R&D programme ESS-Bilbao organised the ESS-Bilbao Initiative Workshop *Multi-MW Spallation Neutron Sources: Current Challenges and Future Prospects*, held in Bilbao in March 2009. More than 160 worldwide experts gathered to discuss the status, plans, issues and challenges facing the development of high power, long pulse spallation sources and synergies with other ongoing related projects. The workshop succeeded in its goal of bringing together people working on programmes of relevance to high power spallation neutron sources, to identify:

1. The challenges next generation machines will encounter.
2. How these challenges might be addressed by a series of truly collaborative, international research efforts.

The workshop proceedings[1] highlight the current challenges, address future prospects, and define some collaborative development programmes. The workshop tried also to put together the user's point of view of such a neutron facility, and the requirements from the accelerator and target experts, in order to get a preliminary set of parameters that fulfils the needs of the three groups.

Table 1: Primary ESS Performance Parameters in the Long Pulse Conceptual Design. Columns **B** and **S** show the minor differences between the ESS-Bilbao and ESS-Scandinavia nominal parameters.

INPUT		**B**		**S**
Average beam power	[MW]		5.0	
No. of instruments			22	
Macro-pulse length	[ms]	1.5		2.0
Pulse repetition rate	[Hz]		20	
Proton kinetic energy	[GeV]	2.2		2.5
Peak coupler power	[MW]	1.2		1.0
Beam loss rate	[W/m]		<1.0	
OUTPUT				
Duty factor		0.03		0.04
Ave. current on target	[mA]	2.3		2.0
Ave. pulse current	[mA]	75		50
Ion source current	[mA]	$\sim$90		60
Total linac length	[m]		$\sim$420	

Table 1 shows the tentative set of primary ESS parameters that were established at the workshop (column **B**) side-by-side with the nominal parameters developed by ESS-Scandinavia (column **S**). In many cases the values are identical. The differences are relatively minor, where they do deviate. The ESS-B parameters take the ESFRI road map values (5MW, 1 GeV, 150 MA, 16,7 Hz) as a starting point, and take advantage of on-going research activity established by ESS-Bilbao, with the aim of simplifying the linac design and increasing reliability. In essence the current has been decreased (75 mA) and the final energy has been increased (2.2 GeV), keeping the linac elements essentially the same. The decrease of the current allows an increase of the cavity gradient, which results in an increase of the linac energy while keeping the linac length unchanged. The repetition rate has been increased to 20 Hz, a value that is acceptable by the user community and avoids problems for linac operation. The pulse length may also be reduced to 1.5 ms, since this value is preferred by neutron scientists and also eases some design efforts for the RF equipment.

With this set of parameters in mind, the accelerator component group discussed the present status, issues and challenges, and future R&D developments needed for cavities and cryomodules. Special focus was placed on power couplers, transitions from warm to cold sections, the use of spoke cavities, higher order modes, cryomodules and cryogenics. They also established some recommendations for the area of high power RF architecture

The beam dynamics and diagnostics group addressed the problems of modelling codes, radiation issues and longitudinal and transverse measuring techniques. Their recommendations came in three main sub-areas:

1. **Beam diagnostics:** the working group clearly recommended more diagnostic equipment than previously envisaged.
2. **Linac Front End:** an approach for obtaining high reliability FE system capable of meeting the specified parameters was specified, considering each major component of the FE separately – ion source, LEBT and RFQ.
3. **Beam dynamics:** the clear conclusion was that a detailed study of the beam line, from the ion source to the target, must be completed.

PARAMETER OVERVIEW

Proton beam macro-pulses around 1.0 ms are close to ideal from the ***users point of view***[2]. Pulse repetition rates as large as 33 Hz are viable, although rates of 20 Hz or less are preferred. The 22 neutron instruments must be served with very high reliability. Currently the PSI SINQ cyclotron achieves $\sim$90% reliability, while the more complex SNS SRF linac achieves $\sim$80% at 680 kW. Reliability is related to maintainability, so the ESS requires low beam loss rates (preferably $\ll$1 W/m with localized exceptions) to control beam component activation. Reliability and low losses run counter to the desire for high performance, low cost, and low risk in construction and commissioning.

The ***primary parameters*** in Table 1 evolved from the values originally proposed in 2003, with almost the same linac components[3]. The most significant changes are the current decrease (from 150 mA) and the energy increase (from 1.0 GeV).

The ***beam energy*** is increased while keeping the overall length almost constant by raising the SC elliptical cavity gradient. The neutron flux is almost unchanged – the number of neutrons per proton-Joule appears to be almost constant above 1 GeV. The final focusing system is modified. An active beam painting scheme is being considered.

The ***average beam current*** reduction, enabled mainly by the increased beam energy, in turn reduces the space charge forces and so helps to minimize halo generation at low energies, where the beam quality for the whole linac is defined. Lowering the beam current eliminates the need for a beam funnel to combine beams from two front-ends. Beam funnels have never been used in routine accelerator operations, although proof-of-principle experiments have been successful. Lower beam currents reduce the commissioning time, reduce beam losses, and facilitate an upgrade to higher beam powers.

The maximum ***cavity gradient*** in the high current SRF linac is limited by the maximum peak power that can be fed via the ***power couplers***. Current technologies limit the peak coupler power to about 1.0 MW, sufficient for a peak gradient of 15 MV/m in a 5-cell 704 MHz cavity accelerating a 60 mA beam. This is consistent with present technology.

Increasing the ***repetition rate*** slightly from 16.67 Hz to 20 Hz appears to be acceptable to the user community and helps keep the average current low. It also avoids possible problems related to subharmonics at 1/3 of the power grid frequency.

Design Update

The ESS-B and ESS-S parameter sets and designs – both of which evolved from the 2003 design – will converge during the process of writing the ESS Conceptual Design Report, scheduled for release and critical review in 2012. Strategic questions that remain to be resolved more clearly by future ESS users and by ESS technical teams, working closely together, include:

1. How long is the ideal "long pulse" and what is ideal repetition rate?
2. Can the neutron pulse be shaped more usefully for the instruments, by pre-shaping the proton pulse, not in a square wave?
3. Can it be confirmed that the number of neutrons delivered to the instruments is proportional to the proton-Joules delivered to the target, for energies up to 3 GeV or more?
4. What flexibility can be left in the design for future upgrades, without compromising construction time, schedule and budget?
5. Using the best SCRF technology, what is the optimum design of the linac with given objectives?

FLEXIBLE PULSE STRUCTURE

Although the nominal ESS pulse rate is 20 Hz, the capability of operating at 40 Hz can be built-in from day one, providing technical headroom and avoiding unnecessarily precluding future upgrade possibilities, however unlikely they may seem at this point. During nominal operation there would only be beam in every second macropulse. We are examining the ability of the ESS to re-tune the macropulse length – and possibly intensity – on a pulse-to-pulse basis. Pre-shaped pulses – not square waves – are also a possibility, with advantages to the beam user.

It is far from clear what an upgrade would look like, but there are various paths towards 7.5 MW operation. Generic classes of upgrade options include:

1. Increasing the ion source current from (for example) 60 mA to 90 mA, with all other parameters held constant, to deliver ***7.5 MW long pulses***.
2. Adding an accumulator ring to provide ***2.5 MW short pulses*** to a second target station, in addition to 5 MW long pulses.
3. Doubling the rate to 40 Hz, filling 3 out of 4 buckets, with ***2.5 and 5 MW long pulses*** at 10 and 20 Hz to 2 target stations.

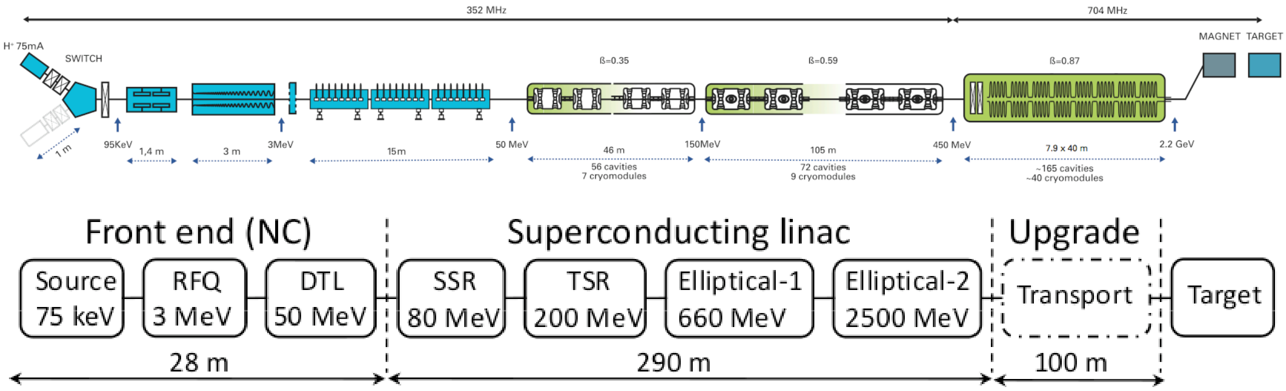

Figure 1: Block layout of the ESS linac. (TOP) The ESS-B layout, as it had evolved by the end of the *Initiative Workshop*, and as discussed at this conference [10]. (BOTTOM) A block diagram of the ESS-S layout, showing space in a "Transport" section that is reserved for a potential upgrade, in which additional cryomodules are installed to increase the beam power to 7.5 MW at a constant top energy of 2.5 GeV.

Table 2: Possible ESS upgrade performance that will be built into the flexible pulse structure during baseline construction.

INPUT		**Nominal**	**Upgrade**
Average beam power	[MW]	5.0	7.5
Macro-pulse length	[ms]	2.0	2.0
Pulse repetition rate	[Hz]	20	20
Proton kinetic energy	[GeV]	2.5	2.5
Peak coupler power	[MW]	1.0	1.0
Beam loss rate	[W/m]	< 1.0	< 1.0
OUTPUT			
Duty factor		0.04	0.04
Ave. pulse current	[mA]	50	75
Ion source current	[mA]	60	90
Total linac length	[m]	418	418

RADIO FREQUENCY SYSTEMS

Front End (Normal Conducting)

Linac sub-systems are summarized in Fig. 1 and Table 3. A single ECR proton ***ion source*** generates 60 mA, 2 ms pulses[4, 5]. Such sources have demonstrated routine operation with currents >100 mA, with >99% reliability. The beam pulse rise time of 1 to 2 ms is reduced to ∼100 ns using a chopper included in the extraction system by segmenting one electrode.

The ***LEBT*** line matches the beam extracted from the ion source into the RFQ with minimal emittance growth, using a dual solenoid system. Magnetic focusing permits space charge neutralization via the ionization of the residual gas. The slow chopper system beam dump embedded in the first part of the LEBT is mainly an aperture reduction of the cooled vacuum chamber. A negatively polarized ring located at the RFQ entrance acts as an electron barrier, and provides two functions:

1. Eliminating an electron flow from the LEBT into the RFQ which would provoke incorrect DCCT current measurements;
2. Inducing a better space charge neutralization near the RFQ entrance, helping beam focusing into the cavity.

The pressure of a few 10^{-5} hPa gives a rise time for space charge neutralization of a few tens of microseconds.

High beam intensity and low emittance growth are driving forces in the ***RFQ*** design, since it plays a significant role in determining the quality of the beam in the rest of the linac. The length of the bunching section exceeds 1 m in order to bunch the beam as adiabatically as possible. The conservative Kilpatrick value of 1.8 allows significant margin for a 4% duty cycle. The four vane structure has a variable voltage increasing from 66 kV to 100 kV, providing a high current limit. No resonant coupling gap is needed, thanks to the 4 m length. The resonator is mechanically divided into four segments, each with four tuners per quadrant.

The ***DTL*** accelerates beam to 50 MeV, using a Linac4 based scheme in which three tanks are each fed by a single klystron (1.3 and 2.5 MW), for an accelerating gradient of more than 3 MV/m[6]. Post-couplers installed at every third drift tube stabilize the field profile against structural perturbations. The DTL has a very high shunt impedance thanks to the compact size of the drift tubes, which contain PMQs in an FFDD lattice.

Superconducting Linac

Single and Triple ***Spoke Resonator*** cavities are chosen to accelerate beam to 200 MeV because they are much less sensitive to mechanical perturbations than elliptical cavities, and because they provide large transit time factors in the β range from 0.3 to 0.5[7]. Installing SSRs with a

FODO lattice just after the DTL enables cavities to be independently phased at relatively low energies, responding to the SNS experience that this is very useful for longitudinal acceptance tuning.

Table 3: Primary Linac Sub-system Parameters

System	T [K]	Energy [MeV]	Freq. [MHz]	β v/c	Length [m]
Source	300	0.075	–	–	2.5
LEBT	300	–	–	–	1.1
RFQ	300	3	352.2	–	4.0
MEBT	300	–	352.2	–	1.1
DTL	300	50	352.2	–	19.2
SSR	4	80	352.2	0.35	23.3
TSR	4	200	352.2	0.50	48.8
Ellipt-1	2	660	704.4	0.65	61.7
Ellipt-2	2	2500	704.4	0.92	154.0

The electromagnetic design of the ***elliptical cavities*** originates in a single-cell cavity currently under testing for use in a BNL high-current ERL[8]. The design in Fig. 2 reduces the surface fields and relaxes tuning criteria[9].

The power couplers will deliver 1.0 or 1.2 MW of peak power with a 3 or 4% duty factor, causing the accelerating gradient to decrease in inverse proportion to the beam current. There is one coupler per cavity, with a single disk-type ceramic window to isolate the cavity vacuum.

Lorentz detuning is dynamically compensated in order to constrain the resonant frequency of each cavity within the available bandwidth, maximizing the efficiency of energy transfer to the beam. Microphonics due to ambient acoustical noise also need to be considered. Stiffeners may be needed, to compensate for the inherent structural weakness of elliptical cavities. Detailed finite element analysis is underway to evaluate and optimize the closed loop system, including RF fill factor, cavity response, and dynamic tuning.

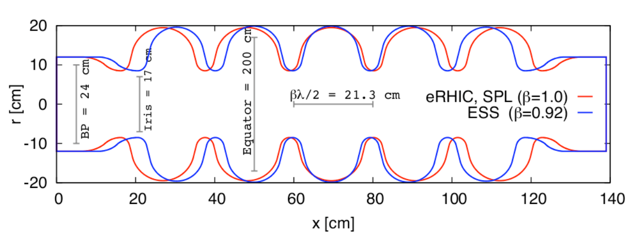

Figure 2: The five-cell 704 MHz cavity, showing the similarities between ESS, SPL and eRHIC structures.

Two families of elliptical cavities accelerate the beam to its final energy, using a ***cryomodule*** with 8 five-cell 704 MHz cavities that extends approximately 13 m. A continuous superconducting channel providing 2 K superfluid helium reduces cryogenic complexity and minimizes the number of external noise sources. Reducing the cryomodule length by shortening the transition section between cavities tends to reduce accelerating structure and civil engineering costs, but requires careful attention to the suppression of cross talk between neighboring cavities, and to efficient HOM damping and power extraction outside the cryogenic environment[9]. The transition section strongly damps the HOMs with a combination of multiple coaxial couplers and 80 K ferrites. The RF parameters of interest for the fundamental mode are listed in Table 4.

Cavity fabrication, testing and cryomodule assembly is complex and expensive, while quality control to assure the performance of ultra-clean cavity surfaces over hundreds of meters is challenging. Complex procedures need to be established in a horizontal cryomodule test stand, to reliably reach 15 MV/m with a quality factor $Q_0 \geq 10^{10}$. A joint collaboration between ESS, BNL, CERN, Saclay and other institutes will develop a standard 704 MHz cryomodule to meet specific requirements of cavity-coupler performance, RF controls, cryogenics and operations.

Table 4: RF Parameters for 704 MHz Five-cell Cavities

	ESS-1	ESS-2	eRHIC/SPL
Frequency [MHz]	704.4	704.4	703.8/704.4
β_{Geom} [v/c]	0.65	0.92	1.0
Cells/cavity	5	5	5
Cavities/module	8	8	6-8
E_p/E_a	3.52	2.58	2.34
H_p/E_a $[\frac{mT}{(MV/m)}]$	7.51	5.09	5.73
R/Q [Ω]	305	738	930
dF/dR [MHz/mm]	3.48	3.62	3.68
Cell coupling [%]	4.79	5.20	4.68

BEAM INSTRUMENTATION

The exact number of ***Beam Loss Monitors***, and their strategic locations along the linac, are being optimized. They have multiple integration times with different abort limits to shut off the beam based on both small DC losses (causing activation at the $\sim$1 W/m level) and loss spikes (causing problems with SC components).

Beam Current Monitors use toroids that are integrated into the cryostats, limiting maintenance accessibility.

Beam Position Monitors integrated into the cryostats near focusing quadrupoles enable stabilization schemes to center the beam in the aperture, reducing halo generation and minimizing beam losses[11]. Beam positions can also be measured using HOM damper signals.

Candidate noninvasive ***Beam Profile Monitor*** technologies include Ionization Profile Monitors and beam scanners (Profilometers). IPMs, commonly used in rings[12], need a local pressure bump to enable single pass operation. Beam scanners pass a beam of ions or electrons at right angles through the main beam, and infer the profile from the deflection caused by the beam potential well[13]. Wire scanners can only be used at low intensities, and may distribute wire fragments in the vacuum system if they overheat and break[14]. Laser wire profile monitors unfortunately only work with H^- beams.

Quadrupole pick-ups could be used to non-invasively measure the rms beam size, albeit not its distribution[15].

A movable diagnostics plate will be used for initial commissioning.

TARGET AND MODERATOR

A management structure is being put in place to minimize risks in building the long pulse target station, reflectors, moderators and neutron lines, and to complete the construction on time. Design optimization depends on:

1. Integrating diverse user requirements for all 22 instruments.
2. Respecting ambitious but realistic safety objectives for operation, maintenance and de-commissioning.
3. Using robust nuclear industry standard qualifications for design and construction.

User requirements will be quantified as a set of neutronic performance parameters for the instrument suite. The design process will explore several hundred combinations of all possible parameters, using a Design of Experiment methodology to allow the optimum combination of parameters to be determined in a finite amount of time.

Radiation release guidelines will be calculated to limit the radiation doses to the population and the environment during normal operations and accident scenarios. Reference accident sequences will first be defined and documented in an Accident Analysis Specification, based on the actual design and on values in the Project Safety Guidelines. The most relevant parameters and assumptions will be documented in a Safety Analysis Data List, ensuring consistent conservative analysis. The PIE-PIT method will be used to identify paths along which radioactivity could be transported to the environment in an accident[16]. Defined accident sequences will then be analyzed, to verify that the design is robust and that releases would be well below acceptable levels.

Equipment in the target – heavy metal liquid circuits, beam windows, moderator mechanical supports, et cetera – may be exposed to moderate or major ***structural damage*** from irradiation, creep, fatigue, corrosion, pressure, or a combination. Their design, construction and operation – and manufacturers and sub-contractors – will respect qualified ***nuclear industry design standards*** RCC-MR (2007) and RCC-MX (2008), taking into account safety, reliability and cost requirements.

THE ESS LINAC COLLABORATION

The ESS linac collaboration will address the specific challenges of the ESS linac design, to produce a Conceptual Design Report by 2012, followed by a full Engineering Design Report. The collaboration will follow through to manage and monitor distributed industrial contracts during the construction phase, and will participate in linac commissioning.

This collaboration model has the advantage of immediately involving partners from accelerator institutes and universities, so that development work can be performed using the best available individuals and equipment for each given task. It is a bottom-up approach enabling success by sharing rewarding design and development work in the early phases, that can later be translated into industrial contracts. Industrial contacts will be established during the development phase, for the most part local to the collaboration partners. A strong Coordination Team in Lund will take intellectual ownership of the design, in order to assure good project cost control, and to be responsible for project integration.

The collaboration model is well suited to international projects, opening up the possibility for all partners to participate and learn during the development phase. Additional potential returns include training opportunities for partners and industry, new know-how, intellectual property rights for other projects and technology transfer to industry.

Work Packages

The collaboration will have eight major Work Packages lead by different partners. Each Work Package will have several Work Units that can be distributed among other participants. Three Work Packages will be lead by the Coordination Team in Lund – Management Coordination, Beam Physics, and Infrastructure Services. The lead partners for the other Work Packages are in the process of being identified, now that a site decision has been made. Each external Work Package will have a single dedicated link person in the Coordination Team at Lund.

Similar contemporary projects with direct technical links to the ESS linac are the XFEL project at DESY, the SPL project at CERN, Project X at FNAL, and eRHIC at BNL. It is essential (especially during the development phase) for the ESS collaboration to share technical resources with these projects.

Management co-ordination Coordinate the collaboration, with ultimate responsibility for cost control. Integrate all ESS activities into a single coherent project.

Assure the smooth transition between phases: design and development, construction, and commissioning.

Establish and maintain linac parameter lists. Responsible for the configuration control system.

Beam physics Perform detailed studies of all beam dynamics issues for the ESS linac. Perform detailed studies of beam loss and collimation. Propose and develop a collimation system design. Follow the collimator system through construction and installation. Provide support for commissioning.

Develop and maintain appropriate linac layout descriptions for use in other Work Packages. Design and construct the High Energy Beam Transport line, including a chicane or dog-leg system before the target to avoid neutron flow down the linac. Evaluate and possibly design a beam painting system. Maintain the ability to integrate possible upgrade options in the beam transport design.

Design and prototype linac beam diagnostic instrumentation, including beam loss monitors, beam current monitors, beam position monitors and beam profile monitors. Interface with the Spoke Cavities and Elliptical Cavities Work Packages, for the integration of beam current monitors and beam position monitors in the cryostats. Interact with the target group to assure that adequate instrumentation is available for beam observation before the target. Follow the construction and maintain responsibility for the installation and commission of the linac beam instrumentation systems.

Infrastructure services Responsible for all infrastructure and services, including HVAC, water, electricity, and networking.

Spoke Cavities Take responsibility for the superconducting spoke cavities and for the construction of fully equipped cryomodules. Design and prototype the couplers and magnets in the cryomodules. Integrate beam current monitors and beam position monitors into the cryostats. Design and prototype the interconnections between cryomodules and the transition to the NC linac. Follow the construction and installation of the cryomodules and be responsible for their commissioning.

Elliptical Cavities Take responsibility for the superconducting elliptical cavities and for the construction of fully equipped cryomodules. Design and prototype the HOM damping system, high power couplers and magnets in the cryomodules. Integrate beam current monitors and beam position monitors into the cryostats. Design and prototype the interconnection between cryomodules, and the transition to the HE beam transport. Follow the construction and installation of the cryomodules and be responsible for their commissioning. Study upgrade options requiring additional elliptical cavity cryomodules.

Front End and normal conducting linac Design and prototype the proton ion source, RFQ, NC linac, and the chopper section that will initially be used only for low energy beam collimation. Be responsible for the low energy beam transport elements up to warm-cold transition. Follow the construction and installation and be responsible for the commissioning of the ion source, RFQ and NC linac.

Beam transport, normal magnets, and power supplies Responsible for all power supplies and normal conducting magnets. Follow their construction and be responsible for installation and commissioning.

RF systems Responsible for the design of the RF sources, RF distribution system, the low level RF controls and the modulators and klystrons. Follow the construction and be responsible for the installation and commissioning of the systems.

ACKNOWLEDGMENTS

The ESS-Bilbao team appreciates very much the effort of all the persons that helped so much for making the ESS-B Initiative Workshop possible, and hopes this was just the beginning of an exciting endeavour in the realisation of the ESS construction project. The ESS-Scandinavia team sends thanks to all its Reference Group members, and to I. Ben-Zvi, P. Carlsson, J. Delayen, R. Garoby, F. Gerick, and A. Lombardi in particular.

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