EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN - BEAMS DEPARTMENT

CERN-BE-2010-029 OP

ELENA – An Updated Cost and Feasibility Study

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Abstract

To produce dense antiproton beams at very low energies (100 keV), it has been proposed to install a small decelerator ring between the existing AD ring and the experimental area. Phase-space blowup during deceleration is compensated by electron cooling such that the final emittances are comparable to the 5MeV beam presently delivered by the AD. An immediate consequence is a significant increase in the number of trapped antiprotons at the experiments as outlined in the proposal CERN/SPSC-2009-026; SPSC-P-338.

This report describes the machine parameters and layout of the proposed ELENA (Extra Low ENergy Antiproton) ring and also gives an approximate estimate of cost and manpower needs. Since the initial estimate, published in 2007 (CERN-AB-2007-079), the ELENA design has evolved considerably. This is due to a new location in the AD hall to accommodate for the possibility of another experimental zone, as suggested by the SPSC, and also due to improvements in the ring optics and layout. The cost estimate that is presented is based on the initial document and has been updated according to the improvements in the design and layout. Where applicable, inflation has also been taken into account.

The SPSC has recognized the substantial potential impact of ELENA on the AD experimental program and "strongly supports the ELENA proposal" (minutes of the meeting 29.09.2009) and the RB endorsed the conclusion from the SPSC concerning the strong scientific case for ELENA (minutes of the meeting 02.12.2009).

Geneva, Switzerland
November, 2010

Contents:

1. Introduction

ELENA is a compact ring for cooling and further deceleration of 5.3 MeV antiprotons delivered by the CERN Antiproton Decelerator. The AD physics program is focused on trapping antiprotons in Penning traps where antihydrogen is formed after recombination with positrons. The ultimate physics goal is to perform spectroscopy on antihydrogen atoms at rest and to investigate the effect of the gravitational force on matter and antimatter.

In today's set-up, most (99.9%) of the antiprotons produced are lost due to the use of degrader foils needed to decelerate them from the AD ejection energy down to around 5 keV; an energy suitable for trapping. By using a ring equipped with beam cooling, high deceleration efficiency and an important increase in phase-space density can be obtained, resulting in an increased number of trapped antiprotons. For the ATRAP and ALPHA experiments, improvements of up to 2 orders of magnitude can be expected. The same holds for the AEGIS experiment which is currently being installed and has foreseen to also use a thick degrader to reduce the antiproton energy. ASACUSA, on the other hand, presently uses an RFQD for deceleration to 100 keV followed by an ultra-thin degrader (1 micron thick) for deceleration to 5 keV. In this case a 10-fold increase in the trapping efficiency can be expected primarily due to reduced transverse and longitudinal emittances. ASACUSA will also benefit from more real physics beam time as in the present situation tuning of the RFQD is very delicate and time consuming.

In addition to the increased number of antiprotons, ELENA will be able to deliver beams almost simultaneously to all four experiments resulting in an essential gain in total beam time for each experiment. This also opens up the possibility to accommodate an extra experimental zone.

With a circumference of about 30 m, ELENA can be located in the AD hall where assembly and commissioning would not disturb the current AD operation.

Decelerating to these low energies is new and will be very challenging both in the design of the different elements and for the operation of the ring. ELENA will provide a unique facility that will deliver low energy antiproton beams of the highest quality.

2. ELENA overview

ELENA is to be located inside of AD Hall with a circumference as small as possible to minimize space requirements and to reduce intensity limitations due to the space-charge induced tune shift. The new ring is located such that its assembly and commissioning will have a negligible impact on the current AD operation. In fact, the commissioning of the ELENA ring could take place in parallel with the present physics program with short periods dedicated to commissioning during the physics run.

The AD experimental area layout will not be significantly modified, but the much lower beam energies require the design and construction of completely new electrostatic transfer lines.

The new ELENA location has been chosen based on:

- Modifications to the ELENA circumference and ring layout as compared to the study presented in 2007 (CERN-AB-2007-079).
- Use of the existing AD ejection line for the transfer of antiprotons from AD to ELENA.
- Possibility to install an additional optional ELENA ejection line and a new experimental area to serve future experiment(s).
- Considerations for safety and crane access.
- Location of the new AEGIS experiment.
- Minimizing the cost and complications of creating floor space.

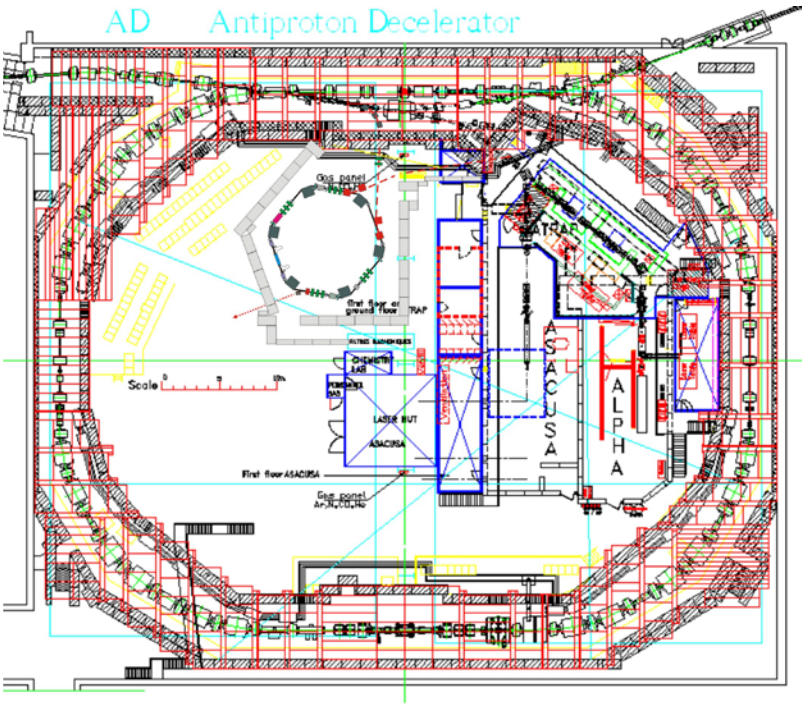


Figure 1: ELENA placement in the AD hall.

ELENA ring

In the original rectangular ring circumference of 26.2m (1/7 of AD ring), apart from the challenge of fitting all the ring elements, it was not possible to insert the necessary equipment for an additional (optional) ejection line. The new circumference is 30.4m (1/6 of AD ring) and has a hexagonal layout of the ring.

The benefits of the new design are:

- More flexibility for injection and extraction.
- The total length of bending magnets is shorter, leaving more space for other equipment.
- The minimum magnetic field in the bending magnets (at 100 keV) is increased from 399 Gauss to 493 Gauss.
- The new 6 fold ring with its circumference increased to 30.4 m has a wider choice of tunes compared to the former design.
- Smaller beta function values resulting in a much reduced aperture required by the beam.

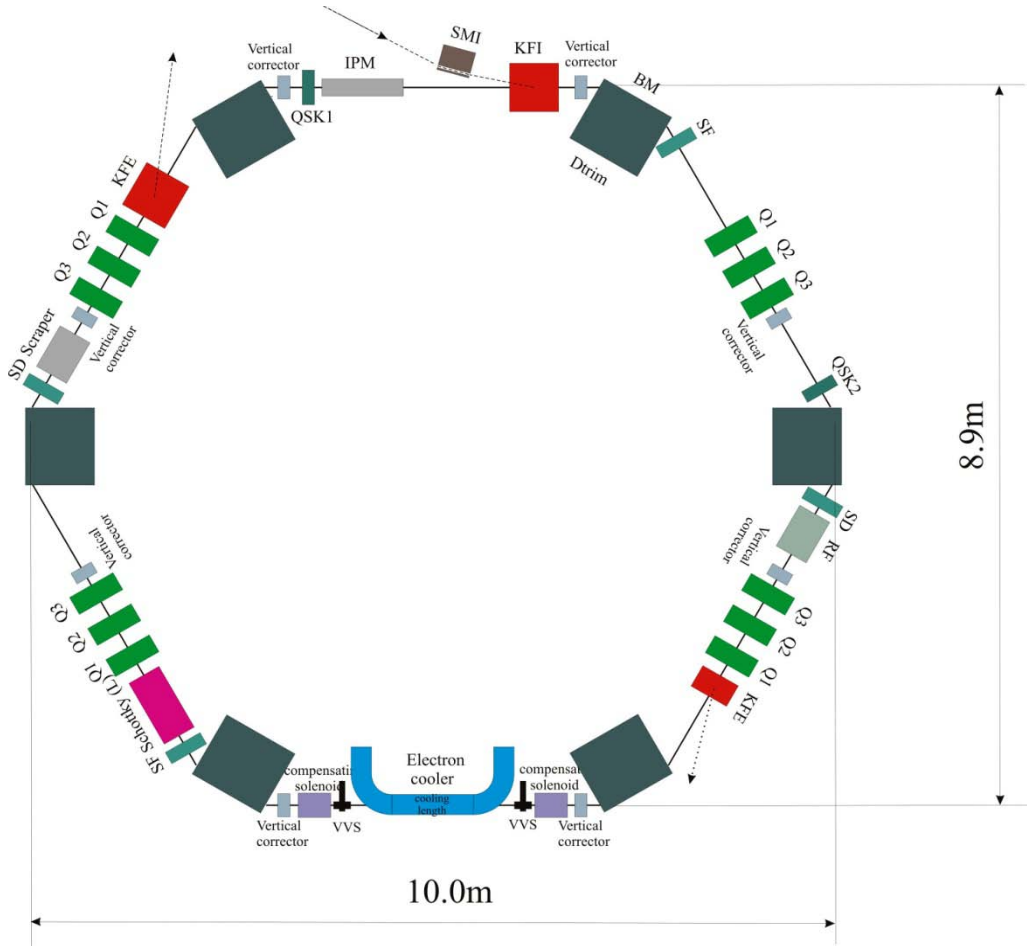


Figure 2: ELENA layout

Momentum range, MeV/c	100 - 13.7
Energy range, MeV	5.3 - 0.1
Circumference, m	30.4
Intensity of injected beam	3×10^{7}
Intensity of ejected beam	2.5×10^{7}
Number of extracted bunches	1 - 4
Emittance at 100 KeV,π.mm.mrad, [H & V at 95%]	4 / 4
Δp/p after cooling, [95%]	10^{-4}
Bunch length at 100 keV, m / ns	1.3 / 300
Required vacuum, Torr	3×10^{-12}

Table 1: ELENA basic parameter

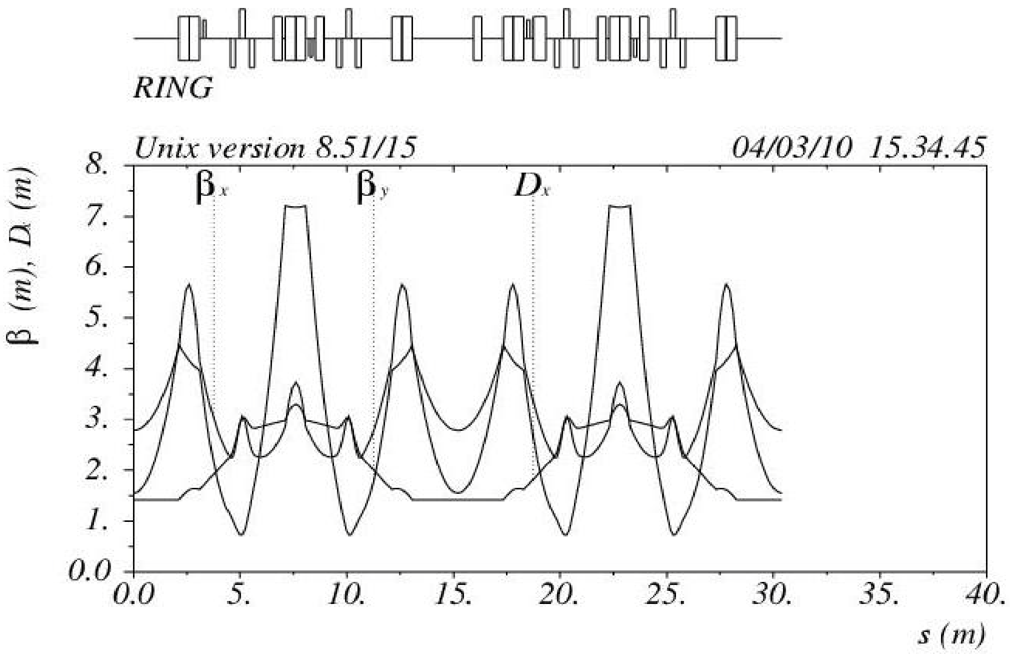


Figure 3: ELENA lattice functions (electron cooler off)

Injection into ELENA

Due to the new location of ELENA, injection into and the ejection from the ring has to be made in different straight sections. To relax the requirements for the injection kicker it will be placed at the end of a long straight section before the combined HV dipole corrector magnet (see Figure 4). The kicker angle is foreseen to be 100 mrad with an integrated magnetic field of 300 Gm and a magnetic length of 0.6 m. The magnetic septum that will be used is the existing LEAR septum SMH12. It has to be separated from the circulating beam by at least 66 mm in the horizontal plane. For the given kicker angle, the distance between the kicker centre and the septum exit should be 0.66 m minimum. For the moment the septum angle is specified as 303 mrad. The total angle made by the kicker and the septum is 403 mrad, or about 23 degrees. This sets a limit on the layout of the transfer line from AD to ELENA.

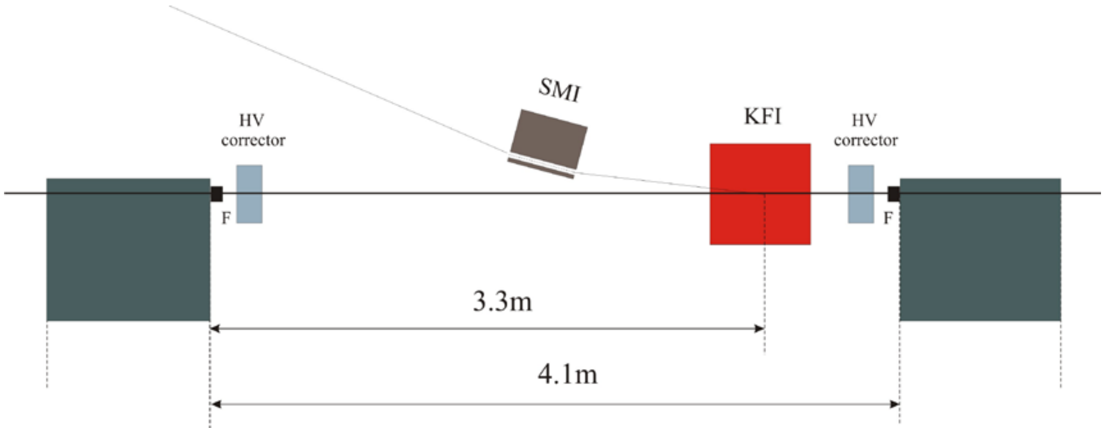


Figure 4: Schematic layout of injection into ELENA.

Ejection from ELENA

Ejection at the low momentum of 13.7 MeV/c requires moderate kicker strength and enables the use of an existing module. In this scenario an extraction septum is not required as the deflection angle is large enough to steer the beam past the ring bending magnet (Figure 5). If needed, a second septum magnet is available for use as a bending element in the transfer line.

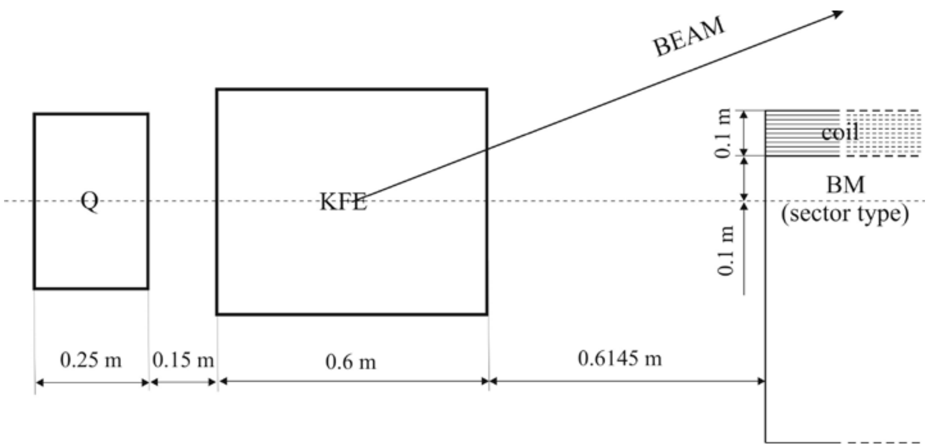


Figure 5: Extraction from ELENA with kicker and septum.

3. Ring and injection line magnets

The magnet system of ELENA consists of C-shaped bending magnets, quadrupoles, sextupoles, skew quadrupoles, orbit correctors and solenoid compensators. The main parameters for these magnets are given below in [Table 2]. A schematic representation of the edge-angle focusing is seen in [Fig. 6].

	Number of magnets	Aperture [mm]	GFR [mm]	Field error in GFR	Magnetic length/ Mechanical length(*), [m]	Field strength	Pole field [T]
Bending magnet (**)	6+1(spare)	91	45x41	$\pm 2\cdot 10^{-4}$	0.97/1.25	0.36 [T]	0.36
Quadrupole	12+1(spare)	91	36	$\pm 5\cdot 10^{-4}$	0.25/0.35	1.4 [T/m]	0.064
Sextupole	4+1(spare)	91	43	$\pm 2\cdot 10^{-3}$	0.15/0.23	13 [T/m^2]	0.0134
H/V corrector	8+1(spare)	91	43	<1%	0.15/0.21	6×10^{-3} Tm (integrated)	0.04
Skew quadrupole	2+1(spare)	91	40	<1%	0.15/0.23	0.4 [T/m]	0.0182
Solenoid	2+1(spare)	100	38	$\pm 3\cdot 10^{-4}$	0.4/0.5	0.0147 [T]	0.0147

(*): the mechanical length is the space reserved in the ring for all magnet components including the coils. For all types of magnetic elements, except the bending magnets, the magnetic length can be modified (keeping the integral constant) to fit the required mechanical length.
(**): the bending magnet is of C type, with edge (pole face) angles of 20 degrees on each side.

Table 2: Ring magnet parameters

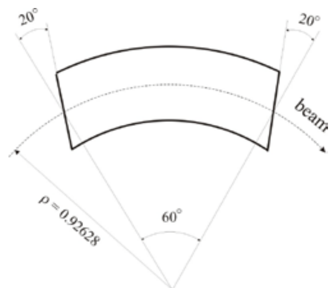


Fig.6: ELENA main bending magnet basic layout.

The transfer line from the AD to ELENA (Figure 7) starts with a branch-off from the existing 7000 line. The large BHZ8000 magnet further downstream is not required for today's AD program and could be removed to free up some space inside the AD ring enclosure. Three bending magnets will be installed within the AD ring shielding with the remaining elements (2 quadrupoles for matching and 1 combined H/V corrector) situated in the AD hall. Table 3 shows the main parameters of these magnets.

	Number of magnets	Aperture [mm]	GFR [mm]	Field error in GFR	Magnetic length [m]	Field strength	Pole field [T]
Bending magnet	3+1(spare)	71	45x40	$\pm 5\cdot 10^{-4}$	0.552	0.32 [T]	0.32
Quadrupole	2+1(spare)	71	50	$\pm 1\cdot 10^{-3}$	0.4	1 [T/m]	0.036
H/V corrector	1+0(*)	71(91*)	40	<1%	0.15	6×10^{-3} Tm (integrated)	0.04

*The same H/V corrector as for the ELENA ring can be used, no spare magnet required.
The transfer line magnets (except for the H/V corrector) are available at CERN.

Table 3: Injection line magnet parameters

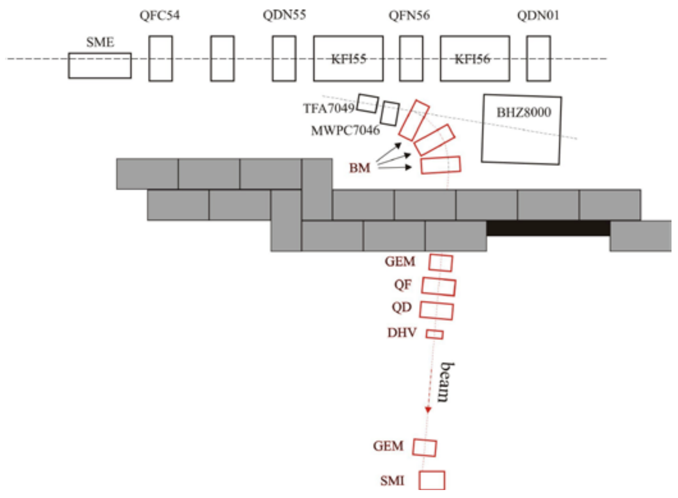


Figure 7: AD to ELENA transfer line

Summary of manufacturing costs:

Name	Magnet type	Number of magnets	COST Magnet [kCHF]	
			Per magnet	TOTAL
ELENA Ring Magnets				
BM0.36	Bending magnet	7	76.118	532.826
Q1.4	Quadrupole	13	16.122	209.587
SX13	Sextupole	5	11.665	58.325
H/V C1	H/V Corrector	9	20.292	182.628
SkQ0.4	Skew Quadrupole	3	12.420	37.260
SOL	Solenoid	3	12.855	38.566
TOTAL for Elena Ring:		**40**		**1059.2**
Magnets for the Transfer line from AD to ELENA				
BM0.32	Bending magnet	4	49.848	199.39
Q1	Quadrupole	3	18.206	54.617
H/V C2(C1)	H/V Corrector	1	20.292	20.292
TOTAL for Transfer Line:		**8**		**274.3**
TOTAL:		**48**		**1333.5**

Table 4: Magnet manufacturing costs

Resource Estimate Summary:

Ring + injection line magnets	Material (kCHF)	Manpower FSU or charged (kCHF)	CERN Manpower FTE (MY)	External manpower FTE(MY)
Ring Bending Magnets (6 + 1 spare)	533			
Ring Quadrupoles (12 + 1)	210			
Ring Sextupoles (4+1)	58			
Ring orbit correctors H/V (8+1)	183			
Ring Skew quadrupoles (2+1)	37			
Electron Cooler Compensation Solenoids (2 + 1)	39			
Injection Line Bending Magnets (3 + 1)	200 (**)			
Injection Line Quadrupoles (2 + 1)	55(**)			
Injection Line Correctors (1 + 0)	20			
Supports, girders, feet	150			
Electric and hydraulic connections, water hoses	30			
Final magnet design (engineer)				0.8
Tech specifications + tendering (engineer/technician)				0.3/0.2
Follow-up of magnet procurement (engineer/technician)				1.0/0.5
Tech.follow-up of in-kind contribution (3 points above) (engineer/technician)			0.4/0.2 (*)	
QA and tech.follow-up of magnet reception (eng./tech.)			0.1/0.1	
Technical assistance to magnet installation + commissioning (engineer/technician)			0.4/0.1	
Industrial support for magnet reception		60		
Survey	35		0.2	
Magnetic measurements	40	75	1.0	
Total	1590	135	2.5	2.8

(*)Only required in case of external manpower contribution

(**) Existing magnets could be used

Table 5: Magnet resources

4. Power converters and cabling

The magnet data and requirements are recapitulated in table 6. Considering the relatively low power needed, all converters are rated for DC performance. The current overall precision considered is $\pm 10^{-4}$ of the maximum current of the converter.
The cycle considered for the ELENA ring is shown below:

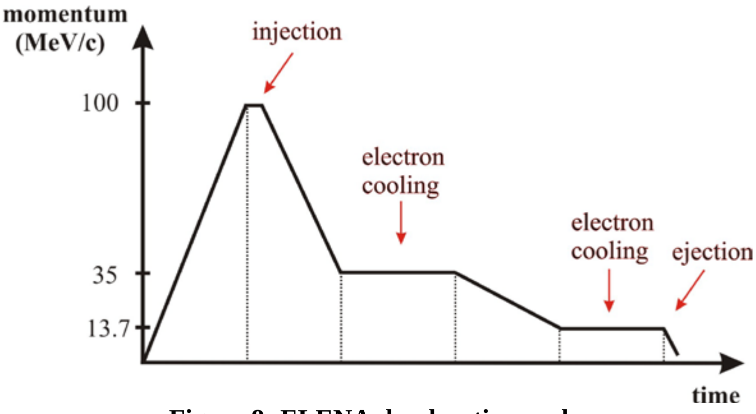


Figure 8: ELENA deceleration cycle

Circuit name	Magnet					Load		Proposed converter ratings			
	Nb. of magnets in series	R (mΩ)	L (mH)	In (A)	Rise time (s)	Voltage (V)	Converter Type	Current (A)	Voltage (V)	Qty	Quadrants
Ring – cycling Mode											
Bending	6	16.6	8.7	600	1	105	1	650	150	1	2Q
Quad	4	46	1.26	90	1	27	2	200	50	3	1Q
Sext	2	608	7.1	5	1	8	3	10	15	2	1Q
H/V Corr *	1	119	9.4	30	1	10	4	50	30	16	4Q
Skew	1	788	18	5	1	6	3	10	15	2	1Q
Transfer Line – DC Mode											
Bending	3	26.7	9.1	335	-	36	5	340	50	1	1Q
Quad	1	75	1.16	55	-	12	6	100	50	2	1Q
H/V Corr *	1	119	9.4	30	-	9	4	50	30	1	4Q
Electron Cooler – Cycling or DC Mode											
Main solenoid - DC				200		50	2	200	50	1	1Q
Solenoid Compensator - DC		52	1.1	35	-	7	4	50	30	2	1Q
Electron Beam correction coils *-Cycling	1			10	-	24	4	50	30	10	4Q
Orbit correctors * - Cycling				10	-	24	4	50	30	4	4Q
Cathode HV - Cycling, +-10-5 precision				0.1		1000	7	0.1	1000	1	
Collector and Anode - DC				0.1		1000	7	0.1	1000	2	
Filament - DC				10		15	3	10	15	1	1Q
Septum											
Injection	1	6.7	0.4	1000		13	8	1000	20	1	1Q
Extraction	2	6.7	0.4	250		11	9	250	20	1	1Q

Table 6: Power converter requirements

The proposed power converter ratings and quantities are deduced from magnet parameters and DC cable voltage drop (estimations). Standardisation on existing CERN or commercial products is also taken into account. All corrector (marked by*) require the 4 quadrants behaviour. The various types of converters are recapitulated in table 7 with their estimated prices. Spare converters are taken into account for types 1, 3, 4, 5, and 7.

Converter Type	current (A)	Voltage (V)	Comment	Qty in operation	Spares	unit	Total
1	650	150	New	1	1	85	170
2	200	50	Heinzinger 50-200	4	0	9,4	37,6
3	10	15	DELTA LPSS 15V-10A	5	1	4,3	25,8
4	50	30	SMILE	33	3	7	252
5	340	50	Heinzinger 50-340	2	1	10,9	32,7
6	100	50	HEinzinger 50-100	2	0	7,7	15,4
7	0,1	1000	FUG	3	1	5	20
8	1000	20	New	1			
9	250	20		1			
				52			
Total							**553,5**

Table 7: Power converter summary and costs

Remote control

The converters will be controlled either by the existing Mil 1553, RS 422 or the foreseen new control system. It will provide the control, command and status of the power convertors as well as the function generator (analogue and digital) and the acquisition over the full machine cycle. The remote control costs are not taken into account in the above estimation.

Installation

The power converter installation is foreseen in building 193; in place of the AD return loop power converters which have been dismantled in 2005. The converter type 1 and 8 will occupy each a space of 2 racks. The rest of the converter will be installed in 12 individual racks; resulting in a total cost of 50 kCHF (racks = 24 kCHF, resources = 26 kCHF).

The Electron Cooling system will require the following additional equipment:

- Isolation transformer: 10 kCHF,
- Control electronic: 9 kCHF,
- HV distribution: 2 kCHF,

AC cabling

The AC supply of the converter system shall be feed from the existing distribution panel whose feeders have been free from the AD return Loop. The need is two lines of 3x400V-16 A per racks, over a distance of ~ 20 m. The estimated price (including circuit breaker protection) is 13 kCHF for 12 racks. One 160 A line has to be added for converter type 1 which will bring the total for the AC cabling to 15 kCHF. The AC line for the converter type 8 is a pending issue.
EN/EL is responsible for this item, and shall be submitted for approval.

DC cabling

The EPC group is not responsible for the DC cables and these costs shall be charged to a budget code owned by EN/EL. However, DC cables are part of the electrical circuit and have an impact on the converter choice; this is the reason why EPC has made the following assumption: the cable length between the equipment in building 193 and the ELENA ring is estimated to be 120 m. EN/EL is responsible for this item. Estimated cost for installation, connection and tests is 100 kCHF. An additional 15 kCHF should be foreseen for cable trays around the ELENA ring.

Converter Type	DC RMS current	Total DC cable length(m)	Number of circuits	Proposed Cu cross-section(mm2)
1	650	240	1	2x150
2	200	240	3	95
3	10	240	6	10
4	50	240	31	25
5	340	240	2	185
6	100	240	2	50
7	0.1	20	3	2.5
8	1000	20	1	
9	250	20	1	

Table 8: DC cables

Interlocks

TE/MPE is responsible for this PLC-based system (WIC – "Warm magnet Interlock Controller" as used in LHC, SPS transfer lines Linac3 and LEIR) and estimates that 100 kCHF will be needed (~1.5 kCHF per magnet) for the complete system.

Resource estimate summary

The estimated costs and resources for the project are:

Power converters Ring-Transfer Line – Electron cooler	Material (kCHF)	Manpower FSU or charged (kCHF)	CERN Manpower FTE (MY)	External manpower FTE(MY)
Power converter including installation	624.5		3	
Cabling AC	15		0.5	
Cabling DC incl. trays	115			
Magnet interlocks	100		0.1	
Septa converters	100		0.2	
Total	955		3.8	

Table 9: Budgets

The power converter group is in charge of the power converter and their installation in the building. All cabling (AC, DC) is the responsibility of EN/EL. The Interlock system is the responsibility of TE/MPE. Connections to the remote control system are not included.

5. Injection/ejection septa

The magnets and coils already exist at CERN and can be installed in the injection and extraction lines to and from ELENA. No spare coil is foreseen to be built, taking into consideration the fact that the magnets will operate at less than half of their design current. New mechanical supports need to be designed and constructed for the magnets and the vacuum chambers. Removal of the magnets is foreseen to allow the vacuum chambers to be baked out. Purpose built electrical bus bars and new demineralised water manifolds need to be designed, manufactured and installed. A dedicated interlock system (PLC based) will also be required. It should be noted that the supply of the power converters as well as the design and supply of the vacuum chambers is not considered to be under the responsibility of the ABT group.

Magnetic septa	Injection septum	Extraction septum	
Deflection angle	303	383	mrad
Beam momentum	100	13.7	MeV/c
Beam energy	5.3	0.100	MeV
Integrated magnetic field (∫B.dl)	0.101	0.018	T.m
Gap field	0.337	0.060	T
Gap height	74		mm
Gap width between conductors	135		mm
Magnet length (physical)	400		mm
Magnetic equivalent length	300		mm
Septum conductor thickness	22.8		mm
Number of conductor turns	20		
Current (DC.)	991	172	A
Magnet inductance	400		μH
Magnet resistance	6.7		mΩ
Demineralised cooling water requirement	TBC	TBC	l/min.

Table 10: Technical specifications of the magnetic septa

Resources

The budget estimate is given in 2010 prices. For both magnetic septa the installation cost amounts to 75 kCHF (excluding the magnets already available at CERN) and 1.0 man years (MY) of manpower (see table 11). Items like design office and industrial support are included under the material cost.

Magnetic septa	Total resource needs	Personnel from total that could be funded by users
Mechanical supports	20 kCHF	
Water battery	10 kCHF	
Interlock system, PLC's	30 kCHF	
Bus bar	5 kCHF	
Cabling, installation	10 kCHF	
Total for both magnetic septa	**75 k**CHF	
Cat 2	0.1 man years	
Cat 3	0.3 + 0.3 man years	0.2 + 0.2 man years
Cat 4	0.3 man years	0.3 man years
Total manpower	**1.0** man years	**0.7** man years

Table 11: Resource estimate for the Magnetic Septa (magnets not included)

Resource estimate summary:

Injection/ejection septa	Material (kCHF)	Manpower FSU or Charged (kCHF)	CERN Manpower FTE (MY)	External manpower FTE (MY)
2 magnetic septa	75*		0.3	0.7

(*) Foresees the use of existing magnets

Table 12: Injection/ejection septa resources

6. Injection/ejection kickers

Kicker modules

Assumptions:

- This cost estimate doesn't take into account the displacement of the kicker generator platform. It has been presented in another document.
- It is based on the re-use of kicker magnet modules previously installed in the AD kicker KFE35.
- The magnets will be installed in two new identical bake-able vacuum tanks.
- The HV generators will also be re-used. No upgrade of generators is considered.

Injection kicker

The injection kicker will be the ex K35-1 magnet module. This magnet is a 24 cell delay line. It has been built to be bake-able but has never been baked. The magnet frame is made of aluminum and a vacuum test in the final tank will have to be performed to check that the ultimate value of 10^{-12} torr can be reached. If not, a stainless steel frame will have to be manufactured. The magnet will be short-circuited to achieve the required kick strength.

Data	Unit	Required	Present or achievable
Deflection angle @5.3 MeV	mrad	100	
Magnetic length	mm	505	600
Magnetic strength	G.m	333	392
Max. rise time (2-98)%	ns	300	~300
Max. fall time (98-2)%	ns	300	~300
Flat-top length	ns	400	~400
Good field region ±0.5%, h×w	mm×mm	50×50	50×50 (to be confirmed)
Magnet aperture h×w	mm×mm	50×50	100×250
Magnet length	mm	-	576
Magnet Z_0	Ω	-	15
PFL voltage	kV	66.3	80
Magnet current	A	4417	5200
Vacuum tank length (flange to flange)	mm	-	~1000
Vacuum tube outer Ø	mm	100	100

Ejection kicker

The ejection kicker will be the ex K35-2 magnet module. This magnet is a 24 cell delay line. It has been built to be bake-able but has never been baked. The magnet frame is made of aluminum and a vacuum test in the final tank will have to be performed to check that the ultimate value of 10^{-12} torr can be reached. If not, a stainless steel frame will have to be manufactured. The magnet will be short-circuited to achieve the required kick strength. The magnet is oversized but the kicker section has nothing else in stock with a sufficient gap height. The design of a new kicker is not expected to be less expensive. Design and procurements cost increase will compensate for the gain in material cost.

Data	**Unit**	**Required**	**Present or achievable**
Deflection angle @200 keV	mrad	383	
Magnetic length	mm	400	600
Magnetic strength	G.m	248	435
Max. rise time (2-98)%	ns	500	~350
Max. fall time (98-2)%	ns	500	~350
Flat-top length	ns	400	~400
Good field region ±0.5%, h×w	mm×mm	50×50	50×50 (to be confirmed)
Magnet aperture h×w	mm×mm	50×50	90×292
Magnet length	mm	-	576
Magnet Z_0	Ω	-	15
PFL voltage	kV	44.5	80
Magnet current	A	2964	5200
Vacuum tank length(flange to flange)	mm	-	~1000
Vacuum tube outer Ø	mm	100	100

Cost estimate (per magnet)

- magnet frame modification (if necessary): 20 kCHF
- vacuum tank and vacuum equipment: 100 kCHF
- magnet feedthroughs: 8 kCHF
- magnet connection boxes: 30 kCHF
- transmission cables (assumed 50 m) and connectors: 10 kCHF
- Low voltage cables: 2 kCHF
- SF_6 : 5 kCHF
- HV generator upgrade: 50 kCHF
- Thyratrons: 40 kCHF
- Fluids system: 20 kCHF

Total: 2 × 285 kCHF = 570 kCHF

Manpower

- ABT Electrical Engineer: 0.2 man.year
- ABT Mechanical Engineer: 0.3 man.year
- ABT Technical assistant (Mechanical): 0.5 man.year
- ABT Technician (electrical or electromechanical): 0.5 man.year
- ABT Technician (mechanical-vacuum): 0.5 man.year
- ABT Electro-mechanic: 0.5 man.year
- Draughtsman (FSU or Elena team external help): 0.5 man.year

Note: if a gap height of 45 mm could be accepted for both magnets, two AA injection magnets could be re-used. Those magnets have stainless steel frames and are 168 mm shorter. This would lead to a vacuum tank length of about 830 mm.
The money saving is estimated to be 50 kCHF.

Kicker unit resources:

Injection/ejection modules	Material (kCHF)	Manpower FSU(kCHF)	Total Manpower FTE (MY)	External manpower (to be deducted)
Total	570		3.0	0.5

Table 14: Kicker unit resources

Displacement of the kicker platform

The kicker platform which contains the equipment for the 10 kicker modules has to be relocated in order to make space for the ELENA ring. The smaller of the two blocks represents one of the PFN cable drums, whilst the larger one represents the steel platform holding the HV switches and its associated equipment. Rack space for the control electronics can be found by reconfiguring and re-cabling of adjacent racks.

Assumptions:

- The ELENA ring will be built in the present kicker area. The kicker platform will be dismounted and put back where at present the workshop corner is located.
- In the rack area if space permits, existing empty racks XY0 to 20 could be used. Otherwise one has to foresee re-using the racks presently used for kicker controls/electronics.
- The two cabins (TE/VSC and TE/ABT) located in the area will be moved.
- A new kicker electrical board will be installed for electrical conformity.
- New halogen free cables will be pulled.
- PFL cable drums stay in the hall, near the platform.
- The area under the platform must be a leak tray.
- This estimate does not include new kickers for ELENA but the two unused kicker generators are kept on the platform assuming they can be used for ELENA. If more kicker modules are needed for the second extraction channel, the platform will have to be extended.
- No upgrade of the generators is considered. Possible upgrades are the replacement of the Diala insulating oil by safer ester oil. This requires a new pumping and plumbing system.

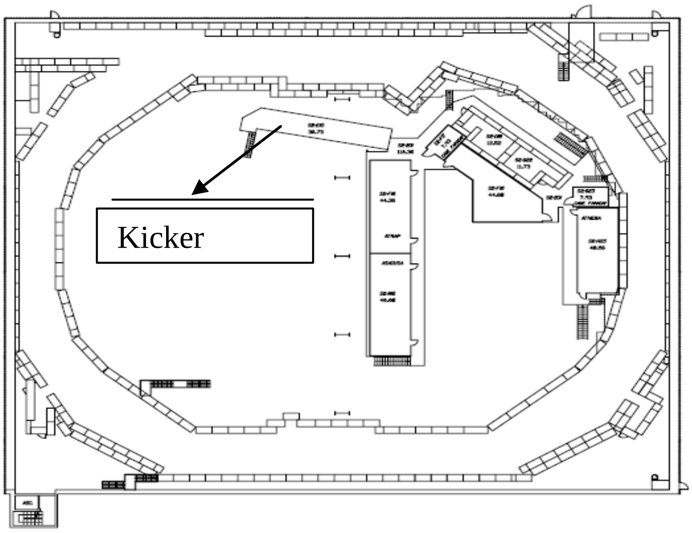


Figure 9: Kicker platform relocation

Summary		
Material and services costs	306	kCHF
ABT FSU	25	kCHF (*)
ABT Engineer	0.1	MY
ABT Technical engineer	0.1	MY
ABT Senior Technician Mechanic	0.1	MY
ABT Mechanic Electro-mechanic	0.6	MY (**)
ABT Electronics technician	0.2	MY

(*) could be done by external manpower
(**) 0.3MY of this could be done by external manpower

Kicker relocation resources:

Injection/ejection modules	Material (kCHF)	Manpower FSU(kCHF)	Total Manpower FTE (MY)	External manpower (to be deducted)
Total	306	25	1.1	0.3

Table15: Kicker relocation resource summary

Kicker controls

New controls

The new kicker control is based on the latest TE-ABT-EC design and will be installed for the ELENA injection and extraction kickers:

New ELENA kickers	**Cost (kCHF)**	**Resources (FTE)**
Injection kicker controls:	100	0.5
Extraction kicker controls:	100	0.5
Fluid system controls:	40	0.5
Common controls:	60	0.5
Total	**300**	**2.0**

Table16: Kicker controls resources

Displacement of existing controls

This will require the installation of a new electrical distribution and the consequent replacement of the power distribution in the individual racks. Re-cabling of all equipment (internal rack, inter-rack, rack-pulse generator, rack-magnet, and rack-fluid system) will also be imposed to eliminate cables containing halogen.

The communication between the FEC and individual modules will need to be modified to allow the upgrade to the new TE-ABT-EC protocol. This will require a replacement of the obsolete G64 cards by a PXI crate containing an Ethernet interface. A new patch panel will also be required.

The opportunity should be taken to replace a certain amount of common control electronics (monitoring, fluid system, interlock fan-out, etc.). This equipment is already 31 years old, with many spare parts no longer available, and realistically cannot be expected to serve for a further 10-15 years.

<table>
<tr><th colspan="2">Displacement ADE kickers</th><th>Cost (kCHF)</th><th>Resources (FTE)</th></tr>
<tr><td colspan="2">Power distribution:</td><td>150</td><td>0.75</td></tr>
<tr><td colspan="2">Re-cabling:</td><td>100</td><td>0.2</td></tr>
<tr><td colspan="2">PXI control:</td><td>100</td><td>0.25</td></tr>
<tr><td rowspan="3">Common controls:</td><td>Monitoring</td><td>60</td><td>0.8</td></tr>
<tr><td>Fluid system</td><td>70</td><td>0.5</td></tr>
<tr><td>Safety/Interlocks</td><td>50</td><td>0.5</td></tr>
<tr><td colspan="2">Total</td><td>530</td><td>3.0</td></tr>
</table>

Table17: Kicker controls relocation resources

Manpower

Of the 5 FTE total required we foresee 0.5 FTE Electronics Engineer (CERN), 2.5 FTE Electronics Technician (CERN) and 2 FTE Electronics Technician (ELENA Collaboration). The latter should be one technician available for a period of two years.

Resource Estimate Summary:

Injection/ejection kickers	Material (kCHF)	Manpower FSU or Charged (kCHF)	CERN Manpower FTE (MY)	External manpower FTE(MY)
Total	1706		6.3	2.8

Table 18: Injection/ejection kicker resources

7. Electron cooler

Electron Cooling for ELENA

Electron cooling will be essential in ELENA in order to obtain the small emittance antiproton beams needed for deceleration and extraction to the trap experiments. The cooler will be installed in one of the long straight sections of the machine and will take up almost half the available space. The rest of the section will accommodate the orbit correctors and the compensation solenoids of the cooler.

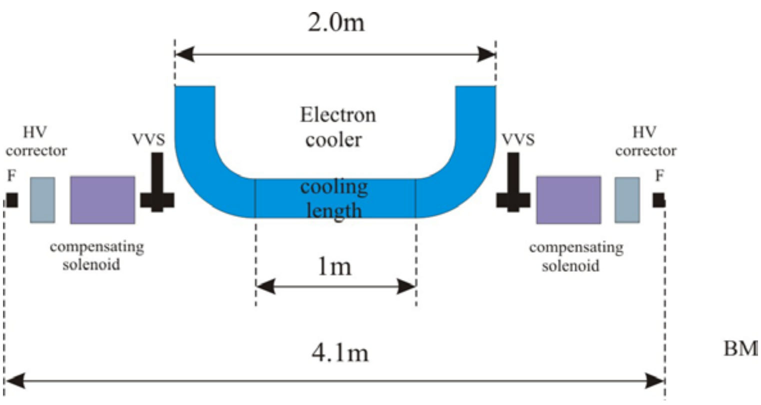


Figure 10: Electron cooler section

Cooling will be needed at two momenta during the ELENA deceleration cycle. At the intermediate momentum of 35 MeV/c the antiproton beam will need to be cooled in order to guarantee that it can be decelerated further to 13.7 MeV/c without any excessive blowup of the beam dimensions which could lead to beam loss. At the lower momentum the cooling will ensure that the phase-space characteristics of the extracted antiproton beam fit the requirements of the experiments. For fast and efficient cooling special attention must be paid to the design of the electron gun and the quality of the longitudinal magnetic field guiding the electrons form the gun to the collector. The main characteristics of the proposed device are summarized in table 19.

The electron gun must produce a cold ($T_\perp$ < 0.1 eV, $T_\parallel$< 1meV) and relatively intense electron beam ($n_e \approx 3\text{x}10^{12}$ cm^{-3}). The use of a photocathode cannot be considered as it is complicated to operate and has a short lifetime. Instead a conventional thermionic cathode will be used and the electrodes will be designed to minimize the transverse temperature after acceleration to the desired energy. The gun is immersed in a longitudinal field of 400 G which is adiabatically reduced to a maximum field of 100 G in the transition between the gun solenoid and the toroid. In this manner the transverse temperature is reduced further through an adiabatic beam expansion. The lower field in the toroids and cooling section is also necessary to facilitate the compensation of the perturbations (closed orbit distortion and coupling) induced by the electron cooler. After the gun, the electrons are bent by 90º in a toroid and merge with the circulating antiprotons over a distance of 1m. At the exit of this cooling section, the electrons are bent away from the antiprotons by a second 90º toroid. The complete magnetic guiding system will consist of a series of small solenoid “pancakes” which can be individually adjusted. In this manner the transverse components of the longitudinal field are kept small ($B_\perp/B_\parallel$ < 10^{-4}) ensuring a minimal perturbation to the electron beam transverse temperature. To improve the electron beam collection efficiency, the use of electrostatic bending plates in the toroids can also be envisaged. Their usefulness has been demonstrated on recent coolers and in a machine like ELENA, where the vacuum must be kept as low as possible, they will help to ensure that electron losses are kept to a minimum. The vacuum system will be the same as was used for the LEIR cooler, namely; NEG cartridges at the gun and collector where the gas load is the highest, NEG strips in the toroid chambers, and NEG coating of the vacuum chamber as well as ion pumps in the cooling section.

Momentum (MeV/c)	35	13.7
β	0.037	0.015
Electron beam energy (eV)	355	55
Electron current (mA)	15	2
Electron beam density (cm^{-3})	4.3×10^{12}	1.4×10^{12}
Bgun (G)	400	
Bcooling section (G)	100	
Expansion factor	4	
Cathode radius (mm)	12.7	
Electron beam radius (mm)	25.4	

Table 19: Main characteristics of the ELENA cooler

The estimated cost of such a cooler is about 1.3MCHF (not including power supplies or solenoid compensators) over a 3 year period. The breakdown of the required resources over this period is summarized in the table below. 50 kCHF is estimated for controls equipment: VME crate + modules.

	Year 1	Year 2	Year 3
Budget	200 kCHF	750 kCHF	350 kCHF
Manpower CERN Manpower ext.	0.5 Eng., 0.5 Tech.	1 Eng., 0.5 Tech 0.5 Tech. electronics	1 Eng., 0.5 Tech., 1 Mech. 0.5 Tech. electronics

Table 20: Breakdown of resources required for the ELENA cooler design, construction and commissioning

The cost for software development for the cooler controls is not included in this estimate.

Resource Estimate Summary:

Electron cooler	Material (kCHF)	Manpower FSU or Charged (kCHF)	CERN Manpower FTE (MY)	External manpower FTE(MY)
Total	1300		5.0	1.0 (Tech.)

Table21: Electron cooler resources

8. Vacuum system

The ELENA ring will be fully bakeable (300°C) with NEG coated chambers. The average pressure should be around $3x10^{-12}$ torr. Permanent bake-out equipment is installed in the magnets. Mobile mechanical pumping groups and mobile diagnostics (RGA) will be used. The cost estimate is based on recent experience from the LEIR ring.

The details in the table below are based on the previous version of the ELENA design and does not neccesarely reflect all details correctly. The total estimate has simply been scaled up to reflect the increased circumference, the additional length of the injection line and inflation since 2007.

Study, prototypes, follow-up	**Number**	**Unit price(CHF)**	**Price (kCHF)**
Design office (hours) *	1'000	51	(51*)
Prototypes			80
Travel, visits	10	5'000	50
		Total study, prototypes, follow-up:	**130**

Arcs (4 cells w. 2 dipoles + 1 multipole)	**Number**	**Unit price (CHF)**	**Price (kCHF)**
Dipole chambers ("vacuum fired & NEG coated")	8	5000	40
Quad chambers ("vacuum fired & NEG coated")	8	3'500	28
Compensators (with RF contacts)	16	4'500	72
Pumping chambers	4	5'000	20
Ion pumps (incl. power supplies)	4	8'000	32
Pirani gauges (incl. power supplies)	4	1'000	4
Penning gauges(incl. power supplies)	4	1'500	6
Sector valves	8	20'000	160
Roughing valves	4	2'500	10
Cabling (m)	500	10	5
		Total arcs:	**377**

Straight sections	**Number**	**Unit price (CHF)**	**Price (kCHF)**
Chambers ("vacuum fired & NEG coated")	8	3'000	24
Compensators (with RF contacts)	16	4'500	72
Pumping chambers	6	5'000	30
Transitions	8	2'500	20
Ion pumps (incl. power supplies)	8	8'000	64
Pirani gauges (incl. power supplies)	4	1'000	4
Penning gauges(incl. power supplies)	4	1'500	6
Sector valves	0	2'000	0
Roughing valves	4	2'500	10
Cabling (m)	300	10	3
Supports	30	500	15
		Total sections droites:	**248**

Bake-out	**Number**	**Unit price (CHF)**	**Price (kCHF)**
Heating and thermocouple equipment	50	1’500	75
Control racks	4	15’000	60
Div.			5
		Total bake-out:	**140**

Mobile pumping and diagnostics	**Number**	**Unit price (CHF)**	**Price (kCHF)**
Pumping groups	2	20’000	40
Magic boxes	2	50’000	100
Leak detectors	1	20’000	20
		Total mobile pumping and diagnostics:	**160**

Control system and interlocks	**Number**	**Unit price (CHF)**	**Price (kCHF)**
PLC (sector)	2	6’000	12
PLC (groups, magic boxes)	4	4’000	16
Interlock chassis	1	5’000	5
Valve chassis	8	4’000	32
Displaced connections	4	3’000	12
Cabling (m)	100	30	3
Racks	4	2’500	10
Supervision software (collaboration)	1	30’000	30
		Total control system and interlocks:	**120**

Installation	**Number**	**Unit price (CHF)**	**Price (kCHF)**
Mechanical (h)	200	60	12
Detection, repairs (h)	40	80	3
Controls	40	60	2
Quality control	80	120	10
		Total installation:	**27**
		Grand total:	***1’202***

(*) Accounted for in the design and drawings chapter

Table 22: Vacuum equipment

Resource Estimate Summary:

Vacuum	Material (kCHF)	Manpower FSU or Charged (kCHF)	CERN Manpower FTE (MY)	External manpower FTE(MY)
Total	1475	50	3.0	2.0 (engineer)

Table 23: Vacuum resources

9. RF system and Schottky diagnostics

RF System

RF Operations and Components

The ELENA RF system serves to capture the injected antiproton beam from the AD through bucket to bucket transfer, decelerate the beam from the injection momentum of 100 MeV/c (T = 5.3 MeV) to an intermediate momentum of typically 35 MeV/c (T= 653 keV) and adiabatically debunch the beam for electron cooling.
This if followed by an adiabatic rebunching of the beam for further deceleration to the extraction momentum of 13.7 MeV/c (T = 100 keV), another debunching, cooling and rebunching for extraction to the experiments.
The RF system consists of an RF cavity, an ultra low noise longitudinal pick-up system, and a low level RF system. As in the AD, the ultra low noise longitudinal pick-up will also be used to determine the beam intensity by RF current measurements when the beam is bunched as well as for longitudinal Schottky scan (momentum spread and intensity) when the beam is debunched. The signal processing for these measurements are an integral part of the low level RF system.

Typical Beam and Machine Parameters and RF Voltage Requirements

The circumference of ELENA is C_{ELENA} = 30.4 m = C_{AD} / 6 such that straightforward synchronized bucket to bucket transfer can take place at every turn from AD to ELENA. The required RF frequency range for h = 1 operation is therefore a ratio of about 7 from 1.06 MHz to 145 kHz. The ELENA lattice is assumed to have a momentum compaction factor of $\alpha = 1/\gamma_{tr}^2 = 0.625$ or $\gamma_{tr} = 1.26$.
With a well adjusted electron cooling in the AD and using electron cooling during the iso-adiabatic capture at 100 MeV/c, the AD is capable of delivering a longitudinal emittance of 1.3 meVs [95%]. Assuming that the electron cooling is capable to cool the debunched beam to a relative momentum spread of $\Delta p/p = 10^{-4}$ both at 35 and 13.7 MeV/c, the longitudinal emittance is further reduced to 0.3 meVs at 35 MeV/c and 0.1 meVs at the extraction momentum of 13.7 MeV/c.
At injection the required voltage to match the ELENA bucket to the AD bucket (using 500 V_p in the AD) is 4 V_p. This corresponds to a bunch length of 230 ns for E_{lon} = 1.3 meVs. Much larger longitudinal emittances can easily be transferred if needed by using a higher RF voltage in ELENA and bunch rotation in the AD.
To obtain an extracted bunch length of about 300 ns with E_{lon} = 0.1 meVs an RF voltage of 11 V_p is required. The corresponding $\Delta p/p = 1.4\ 10^{-3}$ [4σ, 95%].
The bucket area with V_{RF} = 11 V_p produces a stationary bucket area of about 15 meVs without much variation with energy. Assuming a deceleration or ramp time of 5 seconds, an energy loss of 1.5 Volts per turn is required, and the moving bucket area will be reduced to about 11.5 meVs, which seems adequate.

The minimum RF voltage required is the initial RF voltage required for iso-adiabatic capture of the cooled (0.1 meVs) beam prior to extraction. A full bucket is obtained with only V_{RF} = 0.7 mV, and even with such an initial capture voltage significant longitudinal blow-up will take place. With an adiabaticity coefficient of 0.3, the required duration of the capture is 1.4

seconds. Like in the AD, better extracted longitudinal emittances may be obtained by keeping the electron cooling on during a part of the capture.
A controlled voltage range of 0.7 mV to 11 V is therefore suggested. This corresponds to a dynamic range of 16000 or 84 dB which is larger than the 70 dB currently achieved in the AD with analogue logarithmic detectors. However, by using digital receivers and digital modulators with a switchable DAC range, as used for the LEIR RF system, this can very likely be achieved.
The challenge in the ELENA RF system therefore is the large dynamic voltage range required.

Longitudinal Pick-up

A low noise phase pick-up is required for the low level RF system phase loop, additionally with an adequate bandwidth to measure the bunch length at the lowest revolution frequency (low frequency cut-off ~20 kHz, base line droop) and at the shortest bunch length encountered (high frequency cut-off ~20 MHz).
Additionally, if the noise level is low enough, the same pick-up can be used to measure longitudinal Schottky scans.
A pick-up composed of two doubly shielded ferrite cavities with integral ultra low noise JFET head amplifiers with low noise feedback like those built for the AD is proposed [2]. It consist of a high frequency unit like DR.USY4104 (high frequency 4L2 ferrites, μ = 200, bandwidth 0.3 – 20 MHz, noise current) and a low frequency unit like DR.USY4105 (low frequency 4A15 ferrites, μ = 1200, bandwidth 0.02 – 3 MHz). The two signals are summed in an amplifier with appropriate equalizers to ensure a combined bandwidth of 0.02 – 20 MHz. The crossover frequency is 1 MHz as the low frequency unit has the lowest noise below that frequency (typically 2.5 pA/sqrt(Hz)) while the high frequency unit has the lowest noise above that frequency (typically 1.5 pA/sqrt(Hz)).
If space is a problem (each unit is 54 cm flange to flange), shorter units (with higher noise levels) or a combined unit with both cavities within the same outer shielding could be developed.
Surplus 4L2 rings are available from the Booster, and do not need to be purchased.
The Schottky currents per particle and the number of particles are comparable to the AD numbers as the range of revolution frequencies are about the same. Even in the worst case, longitudinal Schottky signal to noise ratios are slightly better than at the AD as nowhere in the ELENA cycle is the width of the Schottky bands as wide as at the initial distribution in the AD after debunching at 100 MeV/c.
It remains to be seen which group will take responsibility for the building of these pick-ups. It should also be noted that any change in the design will impact on the delivery time and cost, as the figures quoted below are for exact copies of the existing hardware.

RF Cavity and Power Amplifier

The RF cavity can be built with either finemet or ferrite cores. Due to the low voltage requirements, there is no need to tune the cavity, and adequate broad band response is obtained by loading the cavity. With ten 4A15 ferrite rings (ferrite length 30 cm, μ = 1200) as used in the low frequency pick-up cavity, sufficient inductance (40 μH) is obtained to drive the resistively loaded cavity to the required voltage with a modest power amplifier of only 20W. A 4:1 step down transformer (like DR.USY4105) transforms the 50 ohm load impedance to 3.125 ohms at the gap. To obtain 11 Volts peak at the gap, 44 Volts peak must be applied to the input of the 4:1 transformer integrated in the cavity.
A cheaper and shorter RF cavity may possibly be built using finemet cores.

Low Level RF System, Intensity measurements

The low level RF system is based on the software and digital building blocks developed for the new digital PSB LLRF [1]. Figure 11 gives an overview of the LLRF as it is foreseen for AD. The three daughtercards (MDDS, DDC and SDDS) and all hardware modules depicted in blue are custom-built and are under the responsibility of the RF group.

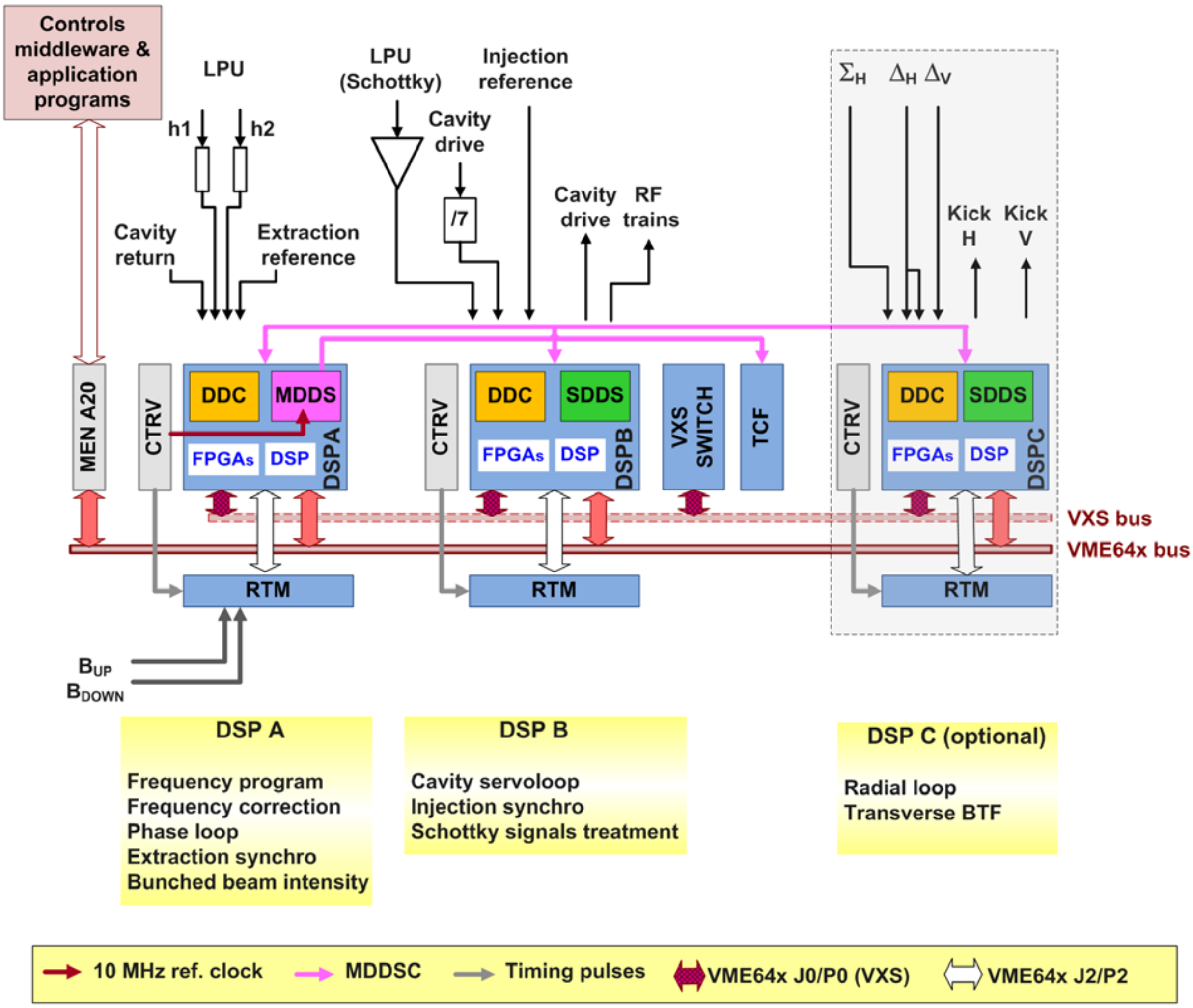


Figure 11: Block diagram of the Elena RF and intensity diagnostics system.
Keys: MDDS – Master Direct Digital Synthesiser (DDS); SDDS - Slave DDS; DDC – Digital Down Converter; MDDSC – Tagged Clock; TCF – Tagged Clock Fanout; CTRV – Timing Receiver Module; MEN A20 – master VME board; VXS Switch – Switch board for VXS crate; B_{up}/B_{down} – magnetic field.

As in the AD, the beam currents are much too low to enable intensity measurements by a DC beam current transformer. RF current measurements at two harmonics (h = 1 and 2) are used for intensity measurements when the beam is bunched, and longitudinal Schottky power is used when the beam is debunched. The implementation of these functions (similar to AD [3]) in the digital low level RF system architecture is straightforward as the beam phase signal is already received in a DDC (Digital Down Converter) for use in the beam phase loop.
The basic low level RF system including the intensity and momentum distribution diagnostics can be implemented on two VXS DSP mother boards (see figure 11).

The Master DDS (located on DSP A mother board) operates on a suitable high harmonic of the revolution frequency, and drives all NCO's (Numerically Controlled Oscillators) in the Slave DDS's and DDC's with controlled relative phases.
DSP A receives a B-train derived from a coil in one of the bending magnets, and generates the basic frequency program. A software function generator generates a frequency correction function to correct for errors in the measured B-train. The DSP A also looks after the beam phase loop, the extraction synchro loop and the bunched beam intensity measurement based on the amplitude of the first and second harmonic of the beam RF current. **Different extraction schemes are under consideration hence the final choice might have an impact on the hardware and software complexity of the system.**
The RF system requires a B-train system (preferably measured and synthetic as in the AD) to generate the frequency program, this sub-system is treated in a separate chapter.
The second board DSP B looks after the digital cavity voltage servo loop, the injection synchro loop where the 7^{th} sub-harmonic of the ELENA RF signal is locked to the AD RF (= injection reference) prior to bucket to bucket transfer. The longitudinal Schottky treatment when the beam is debunched is also treated in DSP B: a high gain version of the longitudinal pick-up is connected to a DDC clocked at a fixed 40 MHz rate and tuned to an appropriate revolution harmonic (optimized for signal to noise ratio and best Schottky statistics).
If the tune measurement system using transverse BTF (Beam Transfer Function) as in the AD is required [3], a third DSP C board is needed. The generation of the digital M-shaped coloured noise excitation signal is straightforward with the SDDS daughter card using an appropriately filtered baseband noise excitation file. Besides transverse BTF, this board could also implement a radial loop (using a single pick-up) as has been developed for LEIR.

Estimate of Elena RF and Longitudinal Schottky diagnostics system

This cost and manpower estimate is based upon the assumption that the PSB development is completed and commissioned, hence the hardware and most of the software for the LLRF part exists already.

		Material	Personnel
Item	Description	[kCHF]	[FTE]
Low noise pick-ups for bunch lengths, RF intensity, beam phase loop and long. Schottky			
PU LF (4A15 ferr.)	Low frequency pick-up (0.02 - 5 MHz	60	0.2
PU HF (4L2 ferr.) *)	High frequency pick-up (0.3 - 25MHz)	30	0.2
PU electr.	Electronics PU's (head+sum)	10	0.2

Low voltage broadband cavity and amplifier (1 mVp - 10Vp, 0.145 - 1.06 MHz)			
Cavity LF	Loaded ferrite/finemet cavity	60	0.2
Power Amplifier	~20 W if 4A15 ferrites used	5	

Digital low level RF, incl. bunch beam intensity and Schottky diagnostics			
VXS crate	VME 64x with CPU	4.0	
CPU	MEN A20	2.5	
2 DSP mother boards	2 x (RTM+DSP)	8.0	
Timing	2 x CTRV VME modules	1.4	
Master DDS	1 x MDDS	1.2	
VXS Switch module	1	4.0	
Clock Fan-Out	1 x VME Clock Fan-out	1.0	
4 ch. Receiver	2 x 4 ch DDC daughter cards	4.0	
4 ch. Modulator	1 x 4 ch. SDDS daughter card	2.0	
Components ordering, hardware manufacturing, tests and commissioning			0.4

Transverse BTF and Radial loop			
1 DSP mother boards	1 x (RTM+DSP)	4.0	
4 ch. Receiver	1 x 4 ch DDC daughter cards	2.0	
4 ch. Modulator	1 x 4 ch. SDDS daughter card	2.0	
Timing	2 x CTRV VME modules	1.4	
Components ordering, hardware manufacturing, tests and commissioning			0.2

Lab equipment and spares			
Lab equipment	VXS crate, MEN A20, scope etc.	30	
Spare modules	Approx. 50% of system	20	

Digital LLRF and Longitudinal Diagnostic Software			
Global system design	All 3 layers for the 3 main items below		0.2
FPGA, DSP, FESA, Appl.	Digital LLRF Software integration (DSP, RTT,App)		0.5
FPGA, DSP, FESA, Appl.	Longit. Bunched beam intensity and Schottky		0.8
FPGA, DSP, FESA, Appl.	Transverse BTF and Radial loop		0.6
Global system integration, commissioning with beam and setup			0.4
Diagnostic specific application (as for AD), provided by OP?			0.3

Cables, installation (FSU)	50.0	0.3 (FSU)

Total	302.5	4.5

*) ferrites for HF PU cavity recuperated from PSB stock

Table 24: RF and Schottky system components

Resource Estimate Summary:

RF+Schottky	Material (kCHF)	Manpower FSU or Charged (kCHF)	CERN Manpower FTE (MY)	External manpower FTE(MY)
Total	303	30	3.8	0.4

Table 25: RF and Schottky diagnostics resources

NOTE ON THE OUTSORCING for LLRF part: the part “Components ordering, hardware manufacturing, tests and commissioning” could be outsourced, for a total of 0.4 FTE (0.6 if one includes the optional board).

10. B-train systems

Both synthetic and measured B-trains will be used, with systems based on what is presently used in the AD and other machines in the PS-complex. Modernized electronics for the measured B-train is under study and will replace existing systems CERN-wide.

Synthetic B-train:

- VME-crate: 7 kCHF
- CPU: 6 kCHF
- CTRV+BTG cards: 2 kCHF
- Development (modeling/SW): 4 man-months

Measured B-train:

- Electronics: 15 kCHF
  (VME rack, data conditioning and acquisition, interface to machine control)

- NMR: 30 kCHF
  (estimated for the upcoming Metrolab PT2026, which should be fast enough for ELENA purposes, with one probe)

- Flux coil: 20 kCHF
  (1.5 m long coil, 45° bend, 1 unit + 1 spare)

- Installation and testing: 4 man-months

Resource Estimate Summary:

B-trains	Material (kCHF)	Manpower FSU or Charged (kCHF)	CERN Manpower FTE (MY)	External manpower FTE(MY)
Total	80		0.7	

Table 26: B-train resources

11. Diagnostics

ELENA ring BPM Pickups

The proposed design is based on a stainless steel body containing two diagonal cut electrodes. Two such elements can be inserted into a vacuum tank of approximately 90mm diameter and 300mm long in order to have a position measurement in both planes. In contrary to the ring PU no sigma electrode will be installed, but the sigma signal will be generated in the head amplifier. An existing head amplifier design made for Aarhus University a few years ago can be used.

The Delta and Sigma signals will be acquired by a network analyzer as in the AD in order to obtain a good signal to noise ratio (BW~ 100Hz). Measurement time per pickup is ~30ms.

The theoretical resolution at $1x10^7$ charges in a 3.4S bunch (15m) with beta = 0.0146 and a bunching factor of ~2 is **0.1mm** (S/N=20). This resolution is calculated using theoretical white noise only, but as we know from the AD interference can be much higher. A similar performance as for the AD orbit should be possible.

	Units	**CHF/Unit**	**CHF**
Prototype	1	10k	10k
Manufacturing of Pickupus (H+V)	9	10k	90k
Cables	9	5k	45k
Head amplifier design	0	0	0
Manufacturing of HA	12	1k	12k
Other electronics design	1	6k	6k
Manufacturing other electronics	9	1k	9k
VME crate + VME module	1	17k	17k
Network analyzer	1	50k	50k
Other	1	20k	20k
TOTAL			**259 kCHF**

Table 27: Estimated pickup costs

<table>
<tr><th></th><th>Total Man-months</th><th>Comments</th><th>External man-months
(to deduct)</th></tr>
<tr><td>PU design</td><td>6 (Eng)</td><td>In coll. with mech. designer</td><td rowspan="5">8 (Eng)</td></tr>
<tr><td>Prototype test</td><td>1 (Eng)</td><td>On test bench</td></tr>
<tr><td>Other electronics design</td><td>1 (Eng)</td><td>Control mod, signal distr.</td></tr>
<tr><td>Tests and commissioning</td><td>1 (Eng)</td><td></td></tr>
<tr><td>Head amplifier design</td><td>1 (Eng)</td><td>Existing Aarhus amp.</td></tr>
<tr><td>Software</td><td>3 (Eng)</td><td>Copy from AD but on FESA</td><td>0</td></tr>
<tr><td>Other</td><td>1 (Eng)</td><td></td><td>0</td></tr>
<tr><td>Manufacturing of Pickups (H+V)</td><td>1 (Tech)</td><td>Follow up of AP work</td><td rowspan="6">5 (Tech.)</td></tr>
<tr><td>Tests of PUs</td><td>2 (Tech)</td><td>On test bench</td></tr>
<tr><td>Manufacturing and tests of HA</td><td>1 (Tech)</td><td></td></tr>
<tr><td>Manufacturing other electronics</td><td>1 (Tech)</td><td></td></tr>
<tr><td>Installation</td><td>1 (Tech)</td><td></td></tr>
<tr><td>TOTAL (man-months)</td><td>6 Tech.;14 Eng.</td><td></td></tr>
</table>

Table 28: Estimated pickup manpower

ELENA emittance measurement using scrapers

This is a very rough cost estimate made under the assumption that the existing system of the AD can be copied, and that the drawings can be found. The system consists of four motorized scrapers, two scintillators with photo multipliers and high voltage power supplies. Outside the ring a discriminator and summing modules (NIM) and a counter module (VME scaler) are needed.

Scraper mechanics incl. motors	4	10k	40k
Vacuum Tank	1	6k	6k
Motor controller	4	3k	12k
Cables	6	1k	6k
Scintillators	2	2k	4k
Photo multipliers	2	3k	6k
NIM modules	3	4k	12k
NIM crate	1	5k	5k
VME module (scaler)	1	4k	4k
VME crate	1	15k	15k
TOTAL			**110 kCHF**

	Man months
Design scintillators and support	1 (Tech)
Software	3 (Eng)
Manufacturing and installation	1 (Tech)
TOTAL	**2 Tech.;3 Eng.**

Tables 29 and 30: Estimated emittance measurement material and manpower costs

Electron Cooling Related Diagnostics

In order to observe and optimize the cooling of the low energy antiprotons in ELENA non-destructive diagnostics need to be developed. The measurement of the longitudinal cooling can only be done using Schottky diagnostics. A longitudinal Schottky pick-up will not only give the measurement of the momentum spread of the beam but also the beam intensity. In the transverse planes ionization profile monitors (IPM) are the ideal instruments for measuring the evolution of the beam size throughout the deceleration cycle. However, in a machine like ELENA where the vacuum will be in the 10^{-12} Torr range and the intensity of the circulating beam is low, a gas injection system, similar to what is used on the AD, must also be installed. It is clear that the use of an IPM in ELENA would be limited to the machine commissioning/startup and for machine development. A horizontal monitor could be installed in one of the horizontal bending magnets and the vertical monitor would have its tank in one of the machine straight sections. The resolution of these detectors would be around 1mm.

If H^- injection is to be used on ELENA, a most useful detector would be a recombination detector placed at the exit of the bending magnet downstream from the electron cooler. This detector measures the radiative recombination rate of the electrons with the circulating proton beam. Coupled to a luminescent screen one observes directly on a monitor the transverse cooling of the proton beam.

Cost estimate:

Two IMPs (H & V), including HT power supplies, front-end electronics and DAQ system: 150 kCHF.

Recombination detector, including HT power supplies, CCD camera and DAQ system: 70 kCHF.
VME crate + modules: 30 kCHF

Tune measurement

See RF/Schottky (chapter 9) for the transverse BTF DSP-system. A dedicated kicker of a similar design to the one used in LEIR will be required. The cost, including strip-line structure, vacuum feed-throughs, electronics and amplifiers, is estimated to be 35 kCHF and 0.3 MY.

Intensity measurement

See section RF/Schottky (chapter 9)

Other

General installation costs: 1 FSU during 1 year = 85kCHF

Resource Estimate Summary:

Diagnostics	Material (kCHF)	Manpower FSU or Charged (kCHF)	CERN Manpower FTE (MY)	External manpower FTE(MY)
Total	655	85	1.2	1.3 (0.8Eng+0.5Tech)

Table 31: Diagnostics resources

12. Controls

	Material (kCHF)	Manpower CERN FTE (MY)	QTY	Unit Price (kCHF)
OASIS (150MHz chassis)	150		2	75
OASIS (250MHz chassis)	117		1	117
Communication network	80		1	80
Timing system	40		1	40
General cabling	80		1	80
Controls infrastructure in local control room	0		0	0
Timing DSCs (2DSCs + 30 CO modules)	60		1	60
Power controls FGC3	70		35	2
FGC gateway	2.6		1	2.6
Ethernet switches (24 ports each)	1		2	0.5
Synchronisation patch panel	1		2	0.5
Ethernet cabling	2		1	2
Power controls PLC (HV supplies)	200		200	1
HW installation + SW development/adaptation		0.5		
Cycle generation SW (LSA)		0.5		
Total	**803.6**	**1**		

Table32: Controls resources

13. H^- source

Part of the ELENA setting-up could be done using a local H^- source. The objective is to be able to do part of the commissioning independent of the CERN accelerator complex and its run schedule. A 100 keV H^- source can temporarily be installed in the new section of the AD to ELENA transfer line for commissioning and initial setting up of the electron cooler at 100keV and of the ejection lines.

Resource Estimate Summary:

H^- source	Material (kCHF)	Manpower FSU or Charged (kCHF)	CERN Manpower FTE (MY)	External manpower FTE(MY)
H^- source	100			
Power supply	250			
Div.	50			
Total	400		0.5	

Table 33: H^- source resources

14. Experimental area beam lines and instrumentation

Beam transport

The design of the beamlines to transport the 100-keV antiprotons to the experimental areas will be based on past experience gained in transporting the 20-120 keV antiproton beam of the AD radiofrequency quadrupole decelerator, and the 50-100 keV radioactive beams of the ISOLDE facility. This is a preliminary cost estimate and is likely to change as the design progresses.

Beamline specifications:

Total length: 63 m

- 15 m common ejection line from ELENA to beam switchyard
- 15 m ASACUSA line to entrance of present RFQD
- 20 m ALPHA line
- two 3-m long beamlines for the two ATRAP zones
- 8 m AEGIS line

Energy range:	20-100 keV
Effective beam aperture:	60 mm (70 mm on both sides used for in-vacuum electrodes and insulation).
Beam pipe diameter:	200 mm (CF250).
Lenses:	Electrostatic up to 20 kV maximum in push-pull mode. 4/6-element dipoles, quads, combined-actionelectrodes.
Vacuum:	10^{-9} – 10^{-12} mb depending on position.
Magnetic shielding:	3-layer iron + 1 layer mu-metal.
Valves:	Gate valves positioned with screening to avoid electrostatic discharge from electrodes and distortion of electric fields.
Modular design:	Facilitates easy disassembly of beamlines and removal of in-vacuum electrostatic elements in case of shorts or wire breakages.
Stands:	Non-magnetic, aluminium or stainless steel
Interlocks:	Beam stoppers, high voltage off in case of intervention.

The items included in the cost estimate are:

1) 60 m of UHV beamlines with varying vacuum levels of 10^{-12} mb (for the beamline section lying immediately downstream of ELENA) to 10^{-9} mb (in the experimental zones). To accommodate the electrostatic high-voltage elements and the in-vacuum cabling, a relatively large-diameter pipe (200 mm inner diameter CF250 standard) is needed.
2) Ion, turbo, sublimation, cryogenic, oil, and scroll pumps, all-metal valves, various vacuum gauges, emergency fast-closing valve in case of vacuum breakage.
3) Electrostatic dipole, quadrupole, and combined focusing elements that can transport a 20-mm-diameter beam of 100 keV with minimal distortion. The surfaces of the electrostatic elements must be suitably curved to minimize the lens-induced aberrations in the beam.
Related 20-kV-scale low-noise high-voltage power supplies, high voltage UHV feedthroughs and cables.

4) 4-layer magnetic shielding made of iron and mu-metal surrounding the beam pipes to suppress the effects of fringing magnetic fields from AD and the superconducting solenoids of the antiproton traps of a few Tesla.
5) Beam diagnostics (profile monitors) needed to transport the beam, especially around the bends. Faraday cups to measure the approximate beam intensity, Cherenkov counters to monitor the beam pulse length. These detectors have already been developed and used for the last 10 years at the AD-RFQD.
6) Remote control capability based on e.g. PROFIBUS and VME CERN standards for the various electrostatic elements, valves, and beam monitors, interface to CERN-standard PS controls system.
7) Water, concrete shielding, pressured air, additional power lines, all the instrumentation cabling
8) Mechanical stands to support the beam lines and the heavy magnetic shielding
9) Safety requirements (interlocks)
10) Manpower requirements.

The price of the beamlines will be strongly affected by the beam emittance from ELENA. If the emittance is large, we will need to increase the aperture of the electrostatic lenses to avoid scraping the beam. This will in turn increase the sizes of the vacuum pipe and magnetic shielding, the supporting insulation structures, and the voltages needed to generate the required electrostatic field. Here we assumed a good compromise of aperture 60 mm which seems realistic based on the projected performance of ELENA.

A significant part of the necessary manpower requirements could be supplied from external collaborators.
Total manpower estimation for electrostatic beamlines (FTE):

End-to-end beam optics simulations:	1.0
High voltage power supplies/controls:	1.0
Electrostatic optics design:	1.0
Switchyard design + testing:	1.0
Cabling (electrostatic elements, water, etc.):	1.0
Vacuum design and installation:	3.0
Concrete shielding, doors, interlocks:	1.0
Beam monitors (28 devices + controls + vacuum):	3.8

Total:	12.8 FTE

Low-energy profile monitors

Non-destructive microwire beam profile monitors have been developed and used by the ASACUSA collaboration in the RFQD since 1999, these would suit the new beamlines well.

Beam profile monitor specifications:

Number of detectors:	28 devices
Energy range:	10 keV to 20 MeV
Aperture:	60 x 60 mm
Active area:	48 x 48 mm
Spatial resolution:	1 mm or 1.5 mm
Dynamic range:	10000
Channels:	64 channels parallel readout
Sensitivity:	1e6 antiprotons in a 300-ns-long bunch
Transmission:	1-2% losses per detector.
Vacuum compatibility:	$<10^{-10}$ mb
Readout electronics:	CMOS-based ASIC charge-sensitive amplifier.
Digitization:	14-bit flash ADC controlled by FPGA.
Calibration:	In-situ automatic calibration using a precision DAC pulsar.
Power:	+/-12 V, 2A DC
Interface:	Compatibility with PS control system or Web-based multicasting over normal 100Base-T Ethernet.
Operating system:	Currently FPGA-based real-time operating system muCOSII. But can be adapted to standard PS control system specs.

Pneumatic mechanism to move the beam monitor remotely in and out of the beam

Resource Estimate Summary:

Ejection lines	Material (kCHF)	Manpower FSU or Charged (kCHF)	CERN Manpower FTE (MY)	External manpower FTE(MY)
63 m of beamlines with electrostatic lenses	3835		6.0	3.0
28 Profile monitors including software	400		0.3	3.5
Total	4235		6.3	6.5

Table 35. Exp. Area beamline resources

(*) Manpower could be provided by the ASACUSA collaboration for the profile monitors.

15. Drawings and mechanical design

A global estimate for all work related to the mechanical design and drawings has been made. Included are all ELENA items including injection and ejection lines.
At present, design and mechanical engineering work is charged at 51 CHF/hour. External manpower could be used for up to 80% of the required work. In this case, training time/costs has to be added at 1 month for each collaborator and for the trainer(s).
The global cost is 1500 kCHF, 80% of this which corresponds to approx. 13 FTE (MY) could be done by external collaborators according to conditions defined by the design office.

Resource Estimate Summary:

Design/drawings	Manpower FSU or Charged (kCHF)	CERN Manpower FTE (MY)	External manpower FTE(MY)
Total (~17MY)	347	(4.0)	13.0

Table 35: Design and drawings resources

16. General items, Infrastructure, cooling water, electricity

Resource Estimate Summary:

Design study + general	Material (kCHF)	Manpower FSU or Charged (kCHF)	CERN Manpower FTE (MY)	External manpower FTE(MY)
Design study			3.0	2.0
Coordination			1.5	
Electricity distribution	100			
Cooling water distribution	100			
Concrete shielding + access door	40		0.5	
Div.	50			
Total	290		5.0	2.0

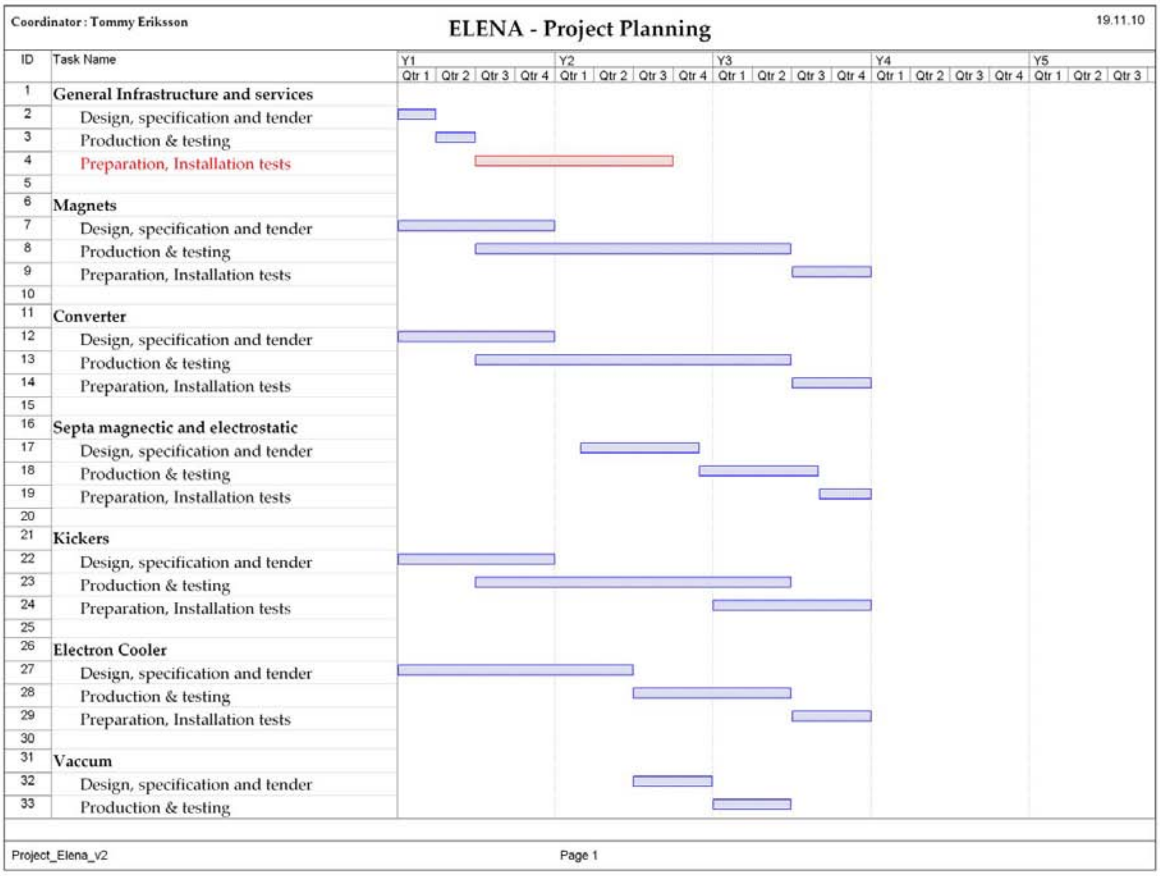
Table 36: General items resources

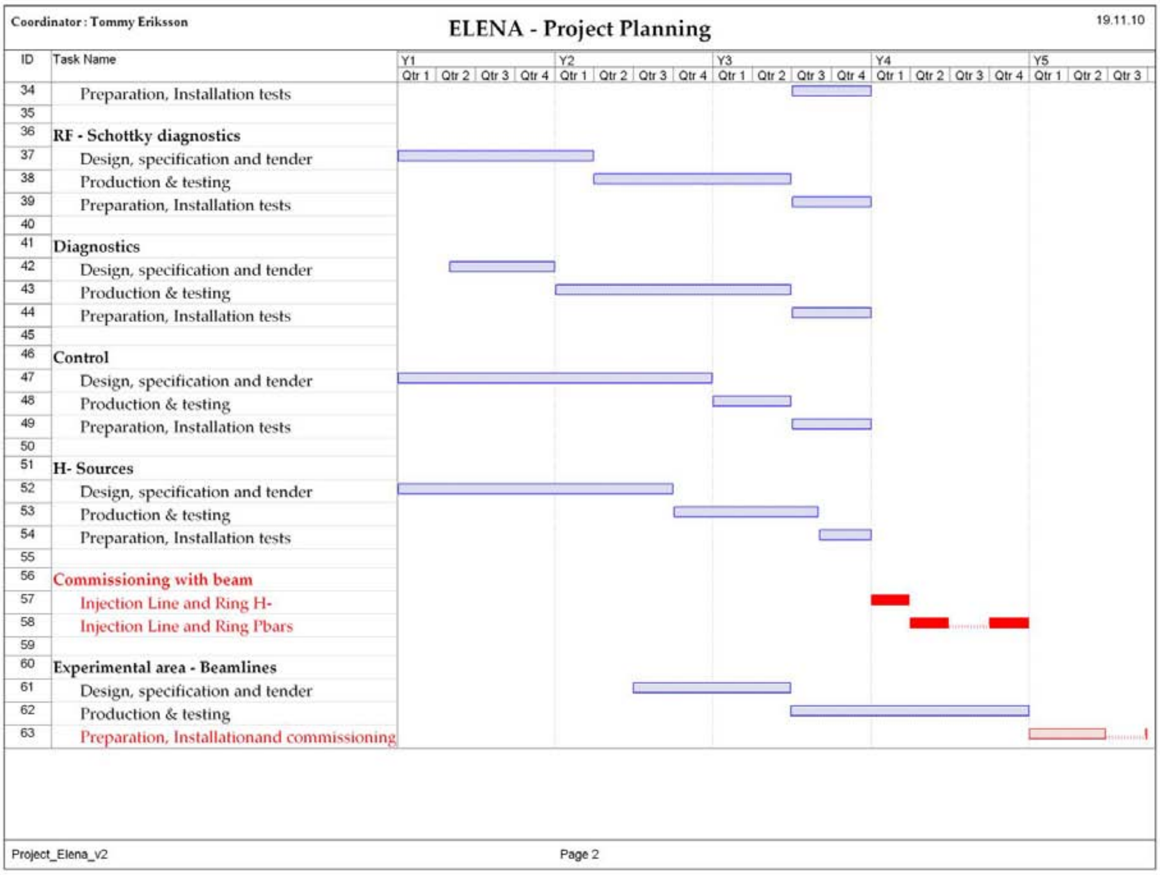
17. Planning

A revised planning with a total duration of around 4.5 years has been worked out in order to minimize impact on the present physics program:

Stage1: Installation and commissioning of the ELENA ring while using the existing beam lines for delivery of pbars at 100MeV/c. Duration will be in the order of 3.5 years.

Stage2: Removal of old ejection lines in all experimental zones. Construction, installation and commissioning of new 100keV electrostatic beam lines. A rough estimate of the duration is around 2 to 2.5 years for design and construction (which will take place during stage1 and then 0.5 to 1 year for installation and commissioning during which time physics will be stopped.




Coordinator : Tommy Eriksson
ELENA - Project Planning
19.11.10
ID
Task Name
Y1 Qtr 1 Qtr 2 Qtr 3 Qtr 4
Y2 Qtr 1 Qtr 2 Qtr 3 Qtr 4
Y3 Qtr 1 Qtr 2 Qtr 3 Qtr 4
Y4 Qtr 1 Qtr 2 Qtr 3 Qtr 4
Y5 Qtr 1 Qtr 2 Qtr 3
34 Preparation, Installation tests
35
36 RF - Schottky diagnostics
37 Design, specification and tender
38 Production & testing
39 Preparation, Installation tests
40
41 Diagnostics
42 Design, specification and tender
43 Production & testing
44 Preparation, Installation tests
45
46 Control
47 Design, specification and tender
48 Production & testing
49 Preparation, Installation tests
50
51 H- Sources
52 Design, specification and tender
53 Production & testing
54 Preparation, Installation tests
55
56 Commissioning with beam
57 Injection Line and Ring H-
58 Injection Line and Ring Pbars
59
60 Experimental area - Beamlines
61 Design, specification and tender
62 Production & testing
63 Preparation, Installationand commissioning
Project_Elena_v2
Page 2

18. Conclusion

This report gives an estimate of the cost and manpower needs for the design and construction of ELENA [Table 37]. This estimate is likely to change as the design study progresses. It is worth noting that ELENA is a new machine with most items (ring, experimental area, electron cooler, use of H^- source etc.) designed from scratch and thereby causing considerate construction costs.

Item	Material (kCHF)	Manpower FSU or charged (kCHF)	CERN Manpower FTE (MY)	Needed manpower contribution FTE (MY)
Magnets (ring+inj. line)	**1590(*)**	**135**	**2.5**	**2.8**
Power converters	**955**		**3.8**	
Injection/ejection septa	**75**		**0.3**	**0.7**
Injection/ejection kickers	**1706**		**6.3**	**2.8**
Electron cooler	**1300**		**5.0**	**1.0**
Vacuum, ring+inj.line	**1475**	**50**	**3.0**	**2.0**
RF + Schottky diagnostics	**303**	**30**	**3.8**	**0.4**
B-trains	**80**		**0.7**	
Diagnostics	**655**	**85**	**1.2**	**1.3**
Controls	**804**		**1.0**	
H- source	**400**		**0.5**	
Experimental area:lines, vacuum, monitors	**4235**		**6.3**	**6.5**
Mech. Design/Drawings		**347kCHF/4 MY (**)**		**13.0**
Div.	**290**		**5.0**	**2.0**
Total (MCHF/MY)	**13.868**	**.647**	**39.4**	**32.5**
Grand Total (MCHF/MY)	**14.515**		**71.9**	

(*) 1335 kCHF if existing injection line magnets are used
(**) On demand of the design office, both charged cost and number of manyears are listed

Table 37: ELENA cost estimate

External Contributions to the construction of ELENA

List of contributions available or to be applied for according to letters/e-mails sent to Walter Oelert.

Money in Million CHF, Man-power (MY) in Man-Years

No.	Institution	Cash available	Cash applied for	MY available	MY applied for
1	Univ. Tokyo and MPQ–MPI	2.0		7	
2	Cockcroft Accel. Inst. plus Swansea		1.0	1.5	2.5
3	Denmark		0.8 0.8*		2
4	IKP Research Center Jülich			3	
5	CEA-IRFU Saclay (France)		0.3**		1**
6	Physicists from US (Berkeley) LBNL and DOE		1.2		6
7	GSI/Mainz HIM/MAM		0.15		3
8	MSL Stockholm				2.5
9	Aarhus Univ.		0.4		
10	ELSE to be named				
	very optimal SUM	2.0	4.65	11.5	17.0

* This second amount of 0.8 Million CHF will only be applied for if the first application is successful

** These numbers are not yet approved and need confirmation

Table 38: ELENA external contributions

From the above table one sees that, optimistically, 6.65 MCHF of the 14.3 MCHF required to build ELENA could be funded by external contributions. A minimum of 2 MCHF is at present guaranteed and the remainder could be applied for if the desire for ELENA to become a reality is clearly expressed. Similarly, almost half the manpower requirements (28.5 MY from a total of 71.9 MY) could be provided by external institutes.

References

[1] M. E. Angoletta, A. Blas, A. Butterworth, A. Findlay, P. M. Leinonen, J. C. Molendijk, F. Pedersen, J. Sanchez-Quesada, M. Schokker, CERN'S PS Booster llrf renovation: plans and initial beam tests, IPAC2010.
[2] M. E. Angoletta, Chohan, M. Ludwig, O. Marqversen, F. Pedersen, The New Digital-Receiver- Based System for Antiproton Beam Diagnostics, PAC 2001
[3] M. E. Angoletta, M. Ludwig, N. Madsen, O. Marqversen and F. Pedersen, Real-Time Tune
Measurements on the CERN Antiproton Decelerator, DIPAC 2001

Annexe 1: External manpower breakdown

Workpackage	Period	Cat2	Cat3	Cat4	Total 2+3+4
Magnets	**Y1**				
	Y2				
	Y3				
	Total	**2.1**	**0.7**		**2.8**
Power converters	**Y1**				
	Y2				
	Y3				
	Total				
Septa	**Y1**				
	Y2				
	Y3				
	Total		**0.2+0.2**	**0.3**	**0.7**
Kickers	**Y1**				
	Y2				
	Y3				
	Total		**2.5**	**0.3**	**2.8**
Electron cooler	**Y1**				
	Y2		**0.5**		
	Y3		**0.5**		
	Total		**1.0**		**1.0**
Vacuum	**Y1**				
	Y2				
	Y3				
	Total	**2.0**			**2.0**
RF	**Y1**		**0.15**		
	Y2		**0.15**		
	Y3		**0.1**		
	Total		**0.4**		**0.4**
B-train	**Y1**				
	Y2				
	Y3				
	Total				**0**
Diagnostics	**Y1**				
	Y2				
	Y3				
	Total	**0.8**	**0.5**		**1.3**
Controls	**Y1**				
	Y2				
	Y3				
	Total				**0**
H- source	**Y1**				
	Y2				
	Y3				
	Total				**0**
Exp. area	**Y1**				
	Y2				
	Y3				
	Total				**6.5**
Design/drawings	**Y1**				
	Y2				
	Y3				
	Total		**13.0**		**13.0**
General items	**Y1**				
	Y2				
	Y3				
	Total				**2.0**
GRAND TOTAL					**32.5**