Overview of the LhARA Facility

Review of the LhARA pre-CDR

Ajit Kurup

31st March 2020

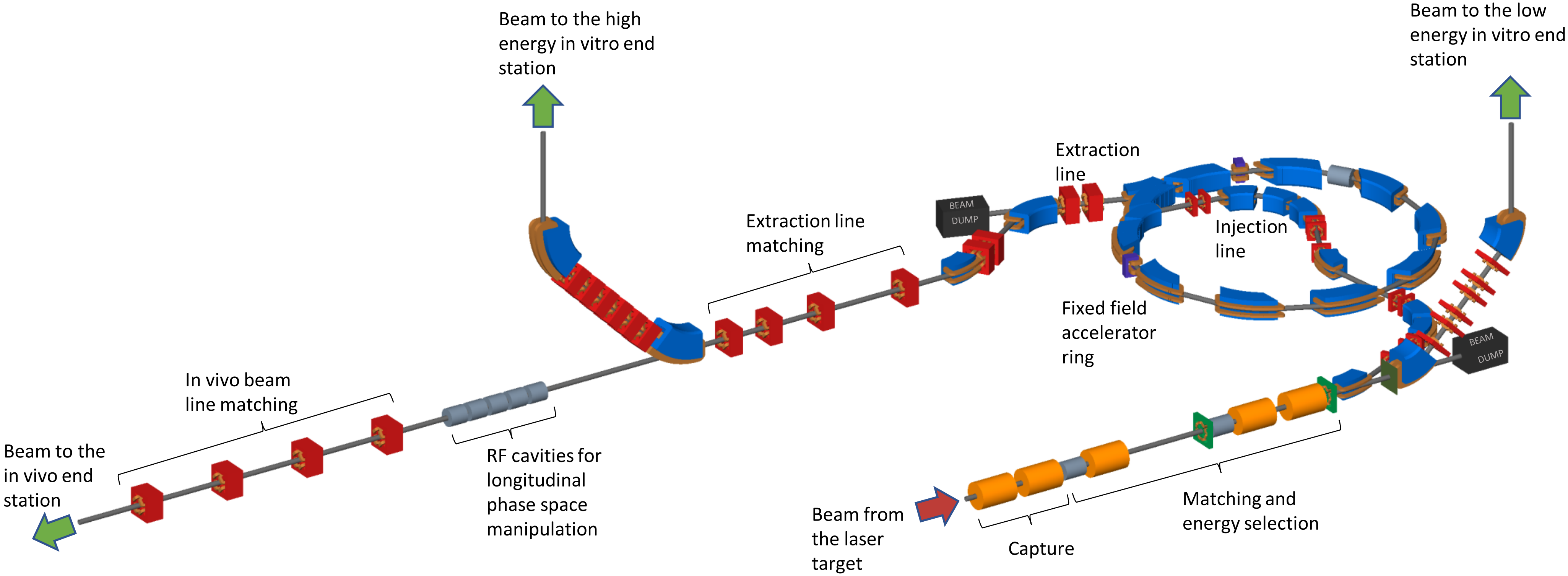
CCAP Centre for the Clinical Application of Particles

Imperial College London

Introduction

- Overview of the design of the facility.
- Design parameters.
- Staging.
- Accelerator.
- Instrumentation.
- Project schedule and R&D plan.

Accelerator



Design parameters

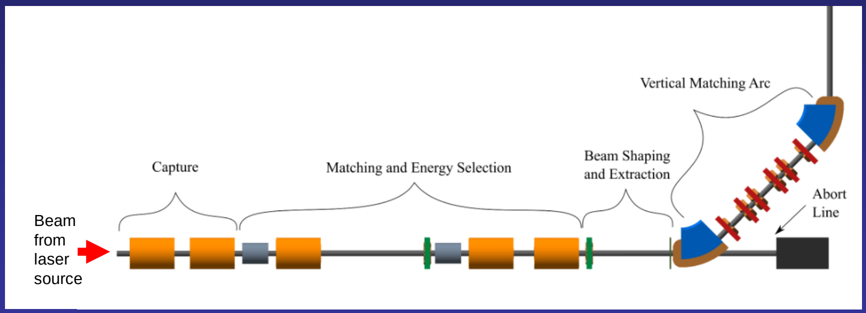
Parameter	Value or range	Unit
Laser driven proton and ion source		
Laser power	100	TW
Laser Energy	1	J
Laser pulse length	30	fs
Laser rep. rate	10	Hz
Proton energy	15	MeV
Proton and ion capture		
Beam divergence to be captured	50	mrad
Gabor lens effective length	0.857	m
Gabor lens length (end-flange to end-flange)	1.157	m
Gabor lens cathode radius	0.0365	m
Gabor lens maximum voltage	65	kV
Number of Gabor lenses	2	
Alternative technology: solenoid length	1.157	m
Alternative technology: solenoid max field strength	1.3	T
Stage 1 beam transport: matching & energy selection, beam delivery to low energy end station		
Number of Gabor lenses	3	
Number of re–bunching cavities	2	
Number of collimators for energy selection	1	
Arc bending angle	90	Degrees
Number of bending magnets	2	
Number of quadrupoles in the arc	6	
Alternative technology: solenoid length	1.157	m
Alternative technology: solenoid max field strength (to serve the injection line to the Stage 2)	0.8 (1.4)	T

Design parameters

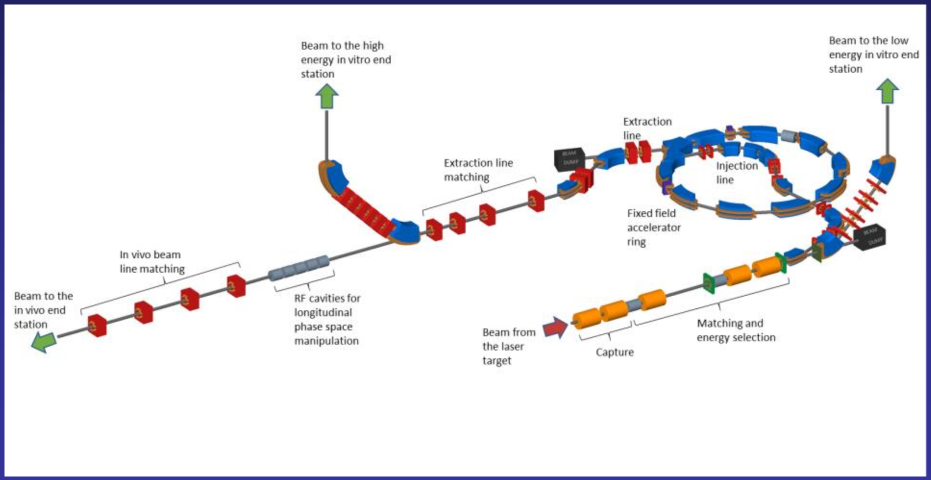
Parameter	Value or range	Unit
Stage 2 beam transport: FFA, transfer line, beam delivery to high-energy endstations		
Number of bending magnets in the injection line	7	
Number of quadrupoles in the injection line	10	
FFA: Machine type	single spiral scaling FFA	
FFA: Extraction energy	20-127	MeV
FFA: Number of cells	10	
FFA: Orbit R_{min}	2.92	m
FFA: Orbit R_{max}	3.48	m
FFA: External R	4	m
FFA: Number of RF cavities	2	
FFA: RF frequency	1.46-6.48	MHz
FFA: spiral angle	48.7	Degrees
FFA: Max B field	1.4	T
FFA: k	5.33	
FFA: Magnet packing factor	0.34	
FFA: Magnet gap	0.047	m
FFA: Number of kickers	2	
FFA: Number of septa	2	
Number of bending magnets in the extraction line	2	
Number of quadrupoles in the extraction line	8	
Arc bending angle	90	Degrees
Number of bending magnets in the vertical arc	2	
Number of quadrupoles in the vertical arc	6	
Number of cavities for longitudinal phase space manipulation	5	
Number of quadrupoles in the in vivo beam line	4	
In vitro biological end stations		
Maximum input beam diameter	1-3	cm
Input beam energy spread	< 2	%
Input beam uniformity	< 5	%
Scintillating fibre layer thickness	0.25	mm
Air gap length	5	mm
Cell culture plate thickness	1.15	mm
Cell layer thickness	0.03	mm
Cell nutrient solution	15	mm
Number of end stations	2	
In vivo biological end station		
Maximum input beam diameter	1-3	cm
Input beam energy spread	< 2	%
Input beam uniformity	< 5	%
Beam options	Spot-scanning, passive scattering, micro-beam	

Staging

- Construction will be done in two stages.



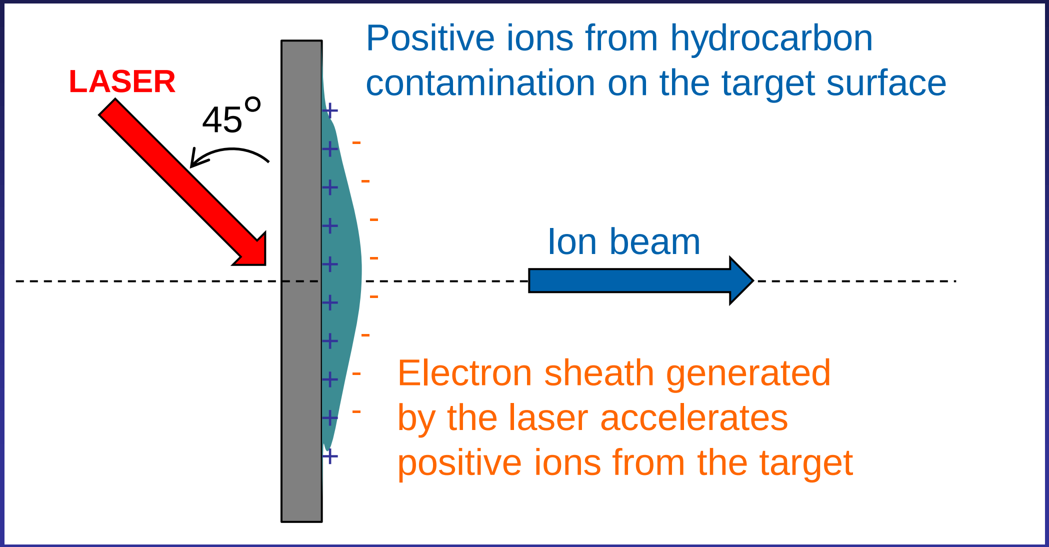
Stage 1



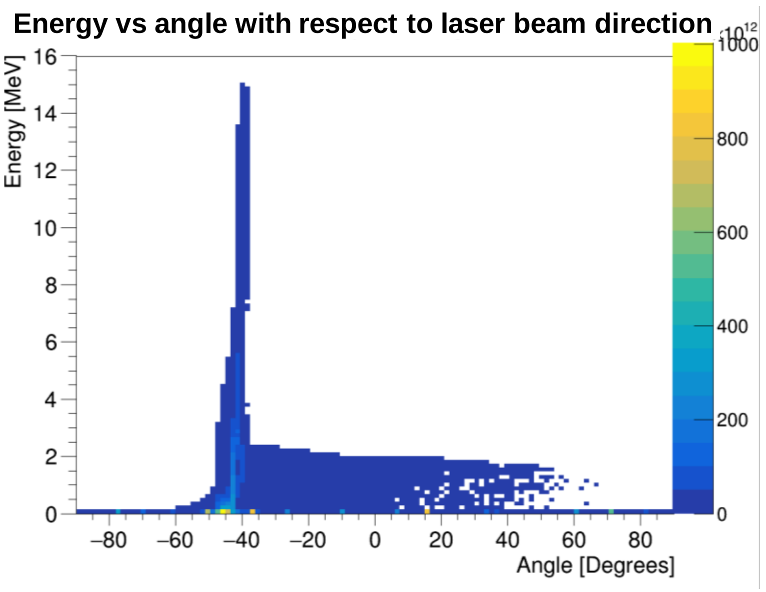
Stage 2

- The goal is maximise scientific output.
  - Generate scientific output during construction of Stage 1.
  - Radiobiology programme using Stage 1 whilst constructing Stage 2.

Laser source



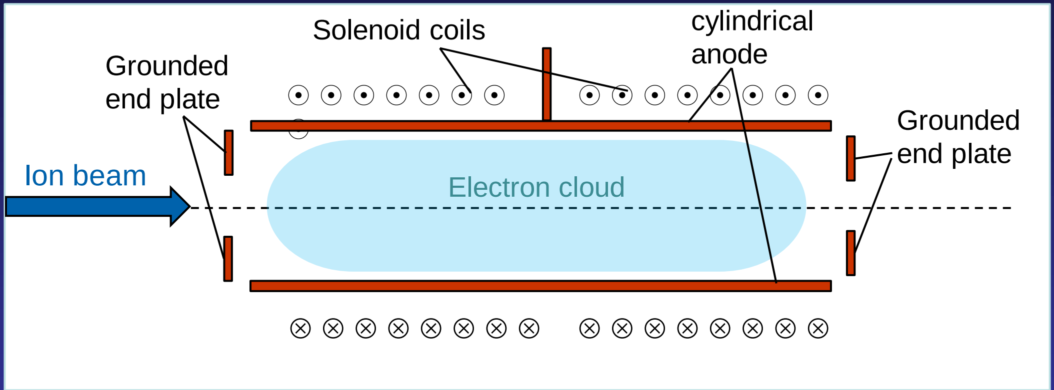
Principle of target normal sheath acceleration (TNSA).

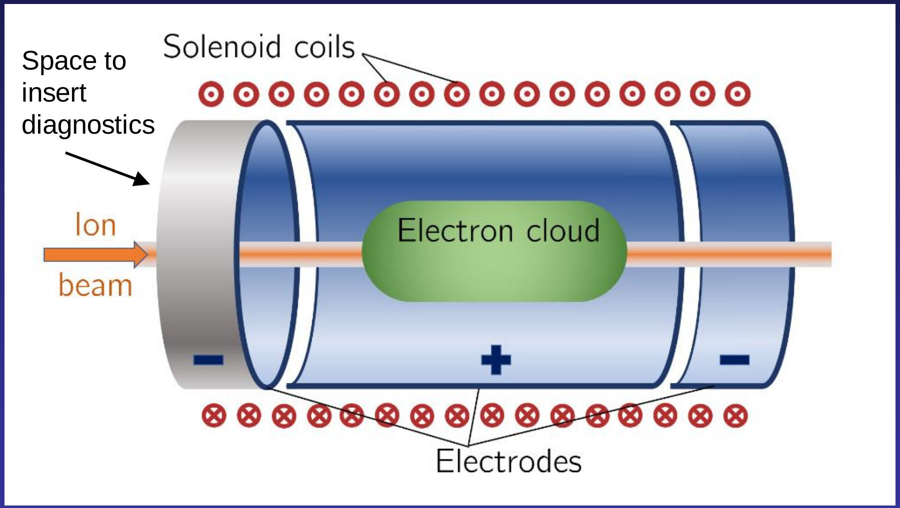


Laser driven ion beam simulation using EPOCH.

- Produces intense beams and multiple species, e.g. proton and carbon ions.
  - Overcome space charge limit of conventional sources since beams are produced with energies *O*(10) MeV.
- Issues to consider
  - Large energy spread.
  - Large divergence.
  - Ion beam stability.
    - Laser has been over specified so it is not operated near it limits.
    - Target.

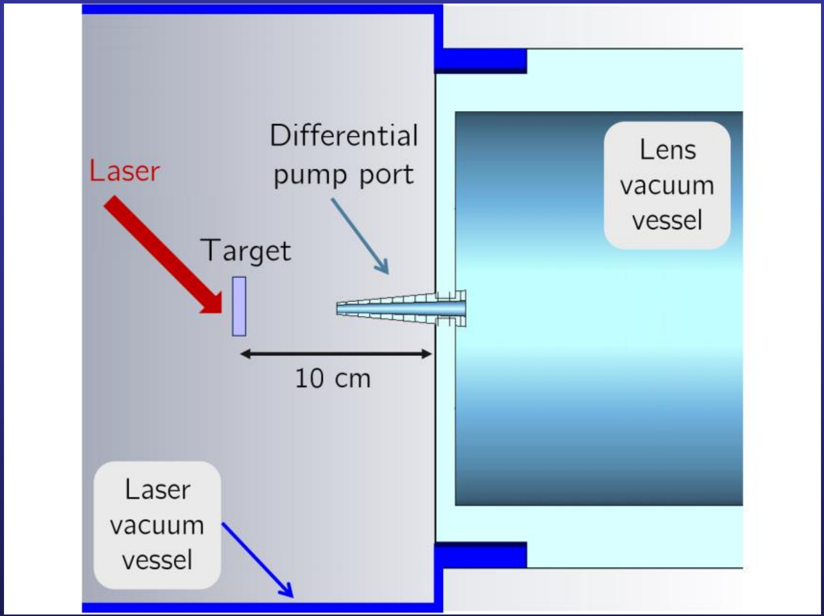
Capture





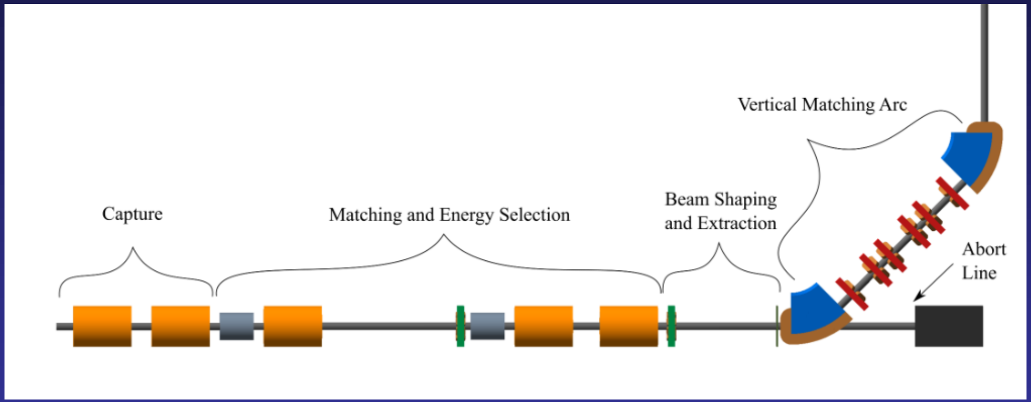
Different electrode configuration to allow inserting diagnostic probes

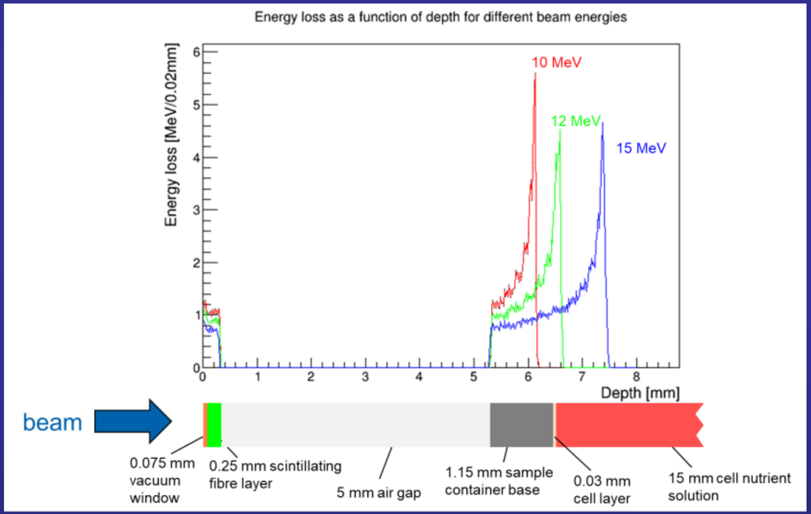
- Strong focusing essential to capture the beam from the laser source.
- The Gabor lens uses a plasma to generate a strong electro-static focusing field.
  - Focal point is energy dependent.
- Equivalent solenoids require field of 1.3T
- Prototype development to study plasma stability, electron density and verify operation in relatively high vacuum.

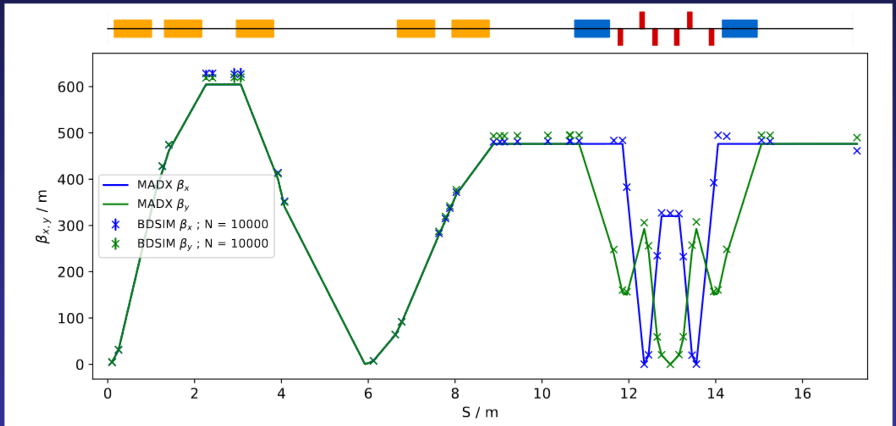


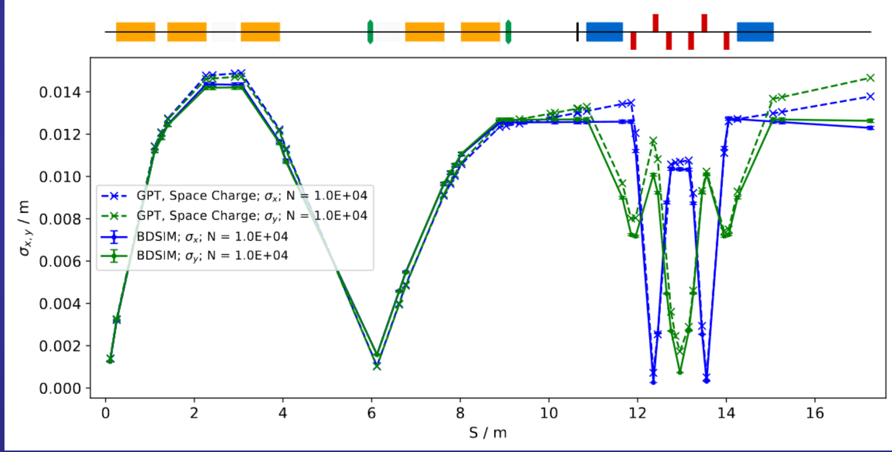
Schematic of proposed differential pumping scheme.

Beam transport – Stage 1

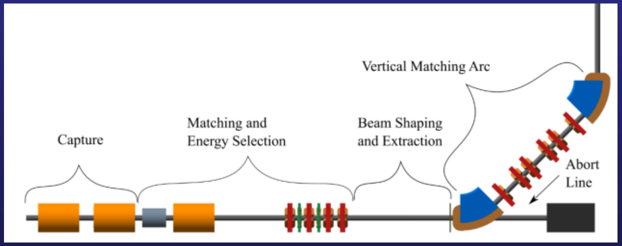






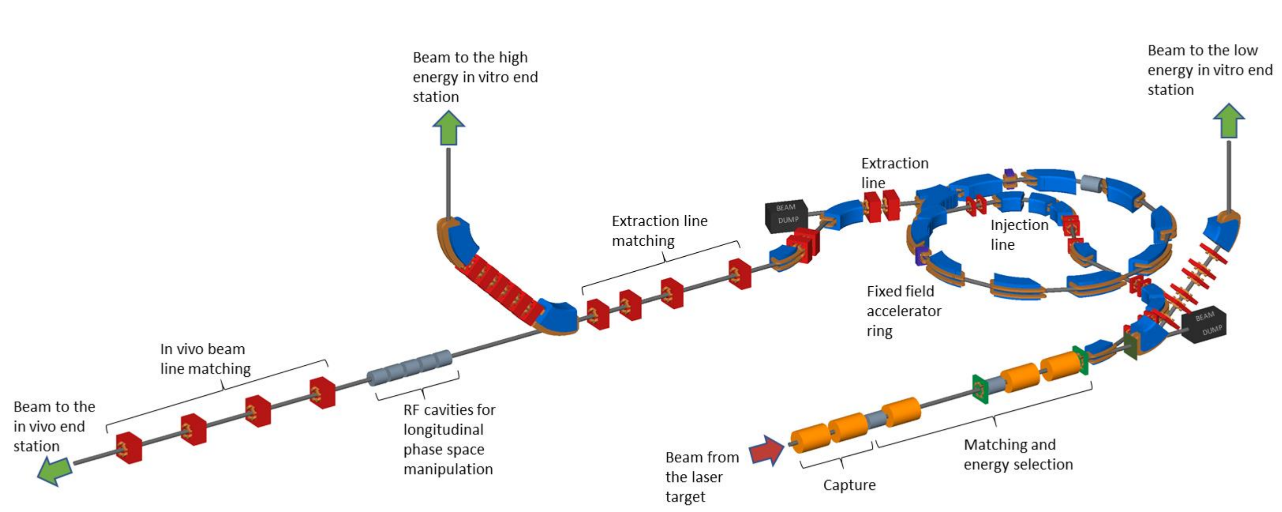


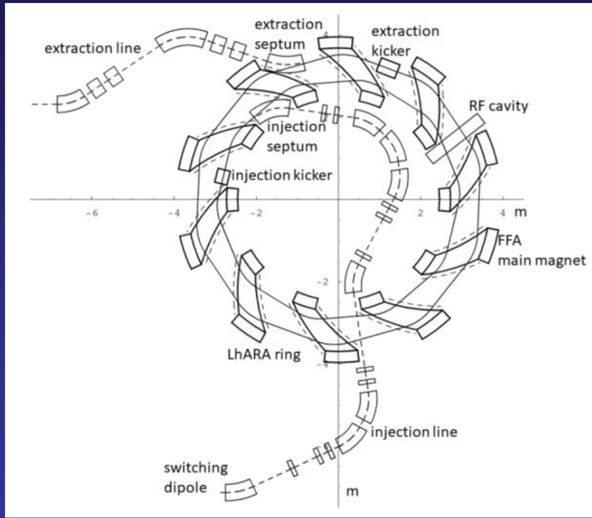
- Optics design: BeamOptics and MADX.
- Particle tracking simulations: BDSIM and GPT.
- Energy deposition in the end station: BDSIM.



Alternative design

Beam transport – Stage 2





	40 MeV protons (Nominal)	127.4 MeV protons (Nominal)	127.4 MeV protons (Pessimistic)
RMS Emittance (ϵ_x, ϵ_y) [π mm mrad]	0.137	0.137	1.37
β [m] for a 1 mm spot size	0.46	0.46	0.039
β [m] for a 10 mm spot size	46	46	4.5
β [m] for a 30 mm spot size	410	410	40

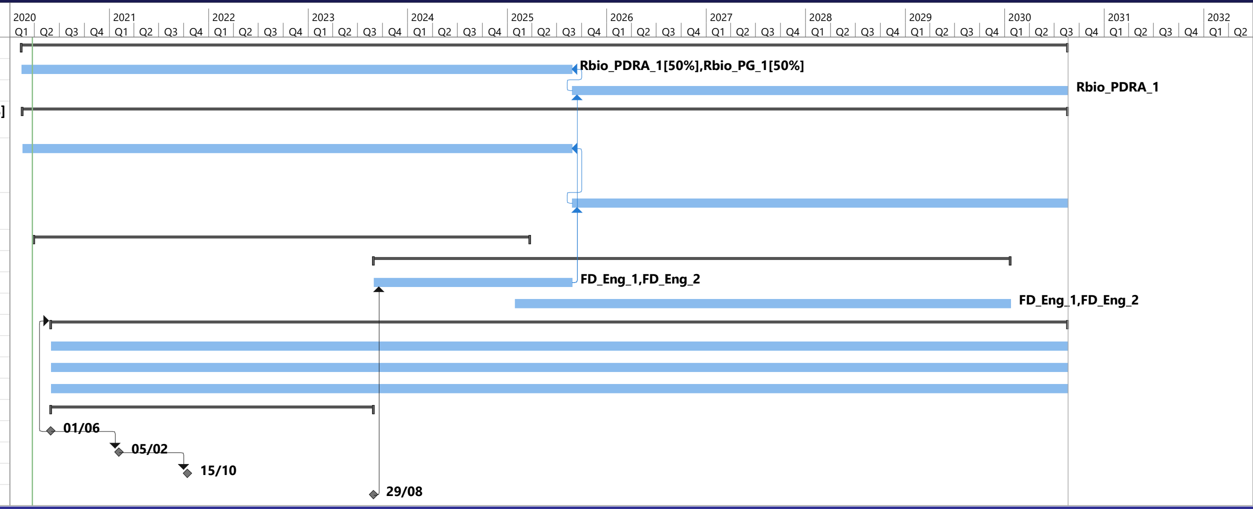
- Post acceleration done using a spiral scaling fixed field accelerator (FFA).
- Injection and extraction lines for the FFA.
- High energy arc for in vitro end station.
- In vivo beam line.
  - Cavities for longitudinal phase space manipulation.

Instrumentation

- Beam diagnostics.
  - Low energy.
    - Novel detectors.
  - High energy.
    - Conventional methods.
- Dosimetry.
  - Online dosimetry of high intensity beams.
  - Calibration.
- Fast feedback and control.

Schedule

ID	Task Name	Duration	Start	Finish	Predecessors	Resource Names
1	**Radiobiology**	**2743 days**	**Fri 14/02/20**	**Tue 20/08/30**		**Rbio_WPM_1[20%]**
2	Radiobiology at partner facili	1443 days	Fri 14/02/20	Wed 27/08/25	3SF	Rbio_PDRA_1[50%],Rbio_PG_1[50%]
3	Radiobiology at LhARA	1300 days	Wed 27/08/25	Tue 20/08/30	50	Rbio_PDRA_1
4	**System/near clinical aspects and outreach**	**2742 days**	**Mon 17/02/20**	**Tue 20/08/30**		**Rbio_PDRA_2,Outreach_Coord_1[20%]**
5	Pre-LhARA: in collaboration with RFI SnL theme and other partners	1442 days	Mon 17/02/20	Wed 27/08/25	6SF	
6	LhARA: in collaboration with RFI SnL theme and other	1300 days	Wed 27/08/25	Tue 20/08/30	50	
7	**LhARA 5yr R&D plan**	**1300 days**	**Wed 01/04/20**	**Tue 25/03/25**		
49	**Construction**	**1670 days**	**Wed 30/08/23**	**Tue 22/01/30**		
50	LhARA Stage 1 construction	520 days	Wed 30/08/23	Tue 26/08/25	60	FD_Eng_1,FD_Eng_2
51	LhARA Stage 2 construction	1300 days	Wed 29/01/25	Tue 22/01/30	13	FD_Eng_1,FD_Eng_2
52	**Project office**	**2666.5 days**	**Mon 01/06/20**	**Tue 20/08/30**	**57SS**	**PO_ADMIN_1**
53	Project leader	2666.5 days	Mon 01/06/20	Tue 20/08/30		
54	Project manager	2666.5 days	Mon 01/06/20	Tue 20/08/30		
55	WP managers	2666.5 days	Mon 01/06/20	Tue 20/08/30		
56	**Gateway process**	**847 days**	**Mon 01/06/20**	**Tue 29/08/23**		
57	GW0 -- Strategic assessment	0 days	Mon 01/06/20	Mon 01/06/20		
58	GW1 -- Business justification	0 days	Fri 05/02/21	Fri 05/02/21	57FS+9 mons	
59	GW2 -- Delivery strategy	0 days	Fri 15/10/21	Fri 15/10/21	58FS+9 mons,11	
60	GW3 -- Investment decision	0 days	Tue 29/08/23	Tue 29/08/23	12FS+1 mon	

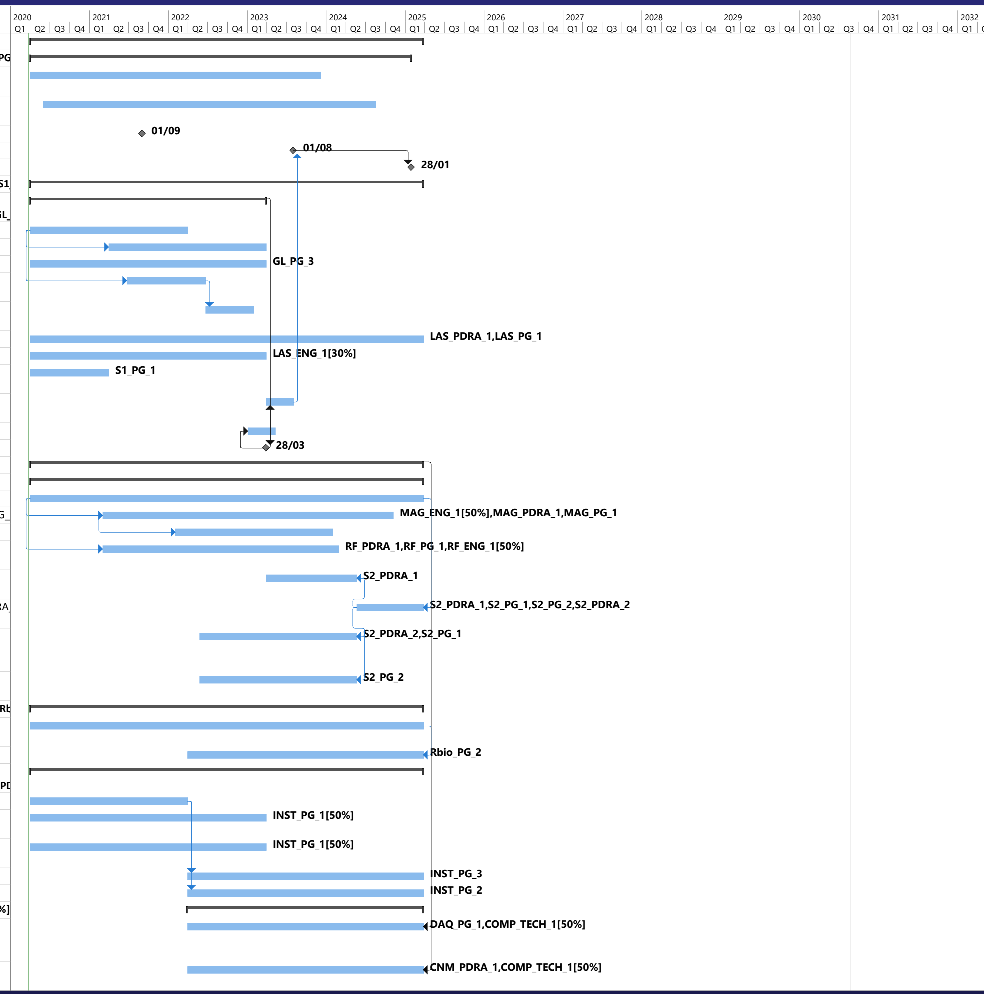


- Radiobiology programme.
- System/near clinical aspects and outreach.
- 5 year R&D plan.
- Construction
  - 2 years for Stage 1.
  - 5 years for Stage 2.

Five year R&D plan

- Aims to address the technical challenges highlighted in the pre-CDR and deliver technical designs for the LhARA facility.

ID	Task Name	Duration	Start	Finish	Predecessors	Resource Names
7	**LhARA 5yr R&D plan**	**1300 days**	**Wed 01/04/20**	**Tue 25/03/25**		
8	**Facility design**	**1260 days**	**Wed 01/04/20**	**Tue 28/01/25**		**FD_Eng_1,FD_Eng_2,FD_PDRA_1,FD_PG**
9	Development of conceptual design	960 days	Wed 01/04/20	Tue 05/12/23		
10	Development of technical design	1100 days	Mon 01/06/20	Fri 16/08/24	57	
11	CDR (detailed for Stage 1)	0 days	Wed 01/09/21	Wed 01/09/21		
12	TDR Stage 1	0 days	Tue 01/08/23	Tue 01/08/23	24	
13	TDR Stage 2	0 days	Tue 28/01/25	Tue 28/01/25	12FS+390 days	
14	**Stage 1 R&D**	**1300 days**	**Wed 01/04/20**	**Tue 25/03/25**		**GL_WPM_1[20%],LAS_WPM_1[20%],S1**
15	**Gabor lens**	**780 days**	**Wed 01/04/20**	**Tue 28/03/23**		**GL material[1],GL_PDRA_1,GL_PDRA_2,GL_**
16	First generation prototy	520 days	Wed 01/04/20	Tue 29/03/22		
17	Second generation prot	520 days	Wed 31/03/21	Tue 28/03/23	16SS+260 days	
18	Theoretical studies	780 days	Wed 01/04/20	Tue 28/03/23		GL_PG_3
19	Electron density measurements	260 days	Wed 23/06/21	Tue 21/06/22	16SS+320 days	
20	Alpha source and detector tests	160 days	Wed 22/06/22	Tue 31/01/23	19	
21	Laser-driven source	1300 days	Wed 01/04/20	Tue 25/03/25		LAS_PDRA_1,LAS_PG_1
22	Laser-capture interface	780 days	Wed 01/04/20	Tue 28/03/23		LAS_ENG_1[30%]
23	Investigation of space charge algorithms	260 days	Wed 01/04/20	Tue 30/03/21		S1_PG_1
24	Stage 1 beam line performance evaluation	90 days	Wed 29/03/23	Tue 01/08/23	26	
25	Vertical bend	90 days	Wed 04/01/23	Tue 09/05/23	26SS-60 days	
26	Capture technology	0 days	Tue 28/03/23	Tue 28/03/23	15	
27	**Stage 2 R&D**	**1300 days**	**Wed 01/04/20**	**Tue 25/03/25**		**FFA_WPM_1[20%],S2_WPM_1[20%]**
28	**FFA**	**1300 days**	**Wed 01/04/20**	**Tue 25/03/25**		**FFA_PG_1**
29	Design and simulation	1300 days	Wed 01/04/20	Tue 25/03/25		
30	Detailed magnet design	960 days	Wed 03/03/21	Tue 05/11/24		MAG_ENG_1[50%],MAG_PDRA_1,MAG_
31	Magnet prototype	520 days	Wed 02/02/22	Tue 30/01/24		
32	RF cavity design and performance	780 days	Wed 03/03/21	Tue 27/02/24		RF_PDRA_1,RF_PG_1,RF_ENG_1[50%]
33	Injection and extraction design	300 days	Wed 29/03/23	Wed 22/05/24	34SF	S2_PDRA_1
34	Stage 2 performance evaluation	220 days	Wed 22/05/24	Tue 25/03/25	29FF	S2_PDRA_1,S2_PG_1,S2_PG_2,S2_PDRA_
35	Longitudinal phase space manipulation design, simulation and	520 days	Wed 25/05/22	Wed 22/05/24	34SF	S2_PDRA_2,S2_PG_1
36	Final beam preparation for in vivo end station	520 days	Wed 25/05/22	Wed 22/05/24	34SF	S2_PG_2
37	**End stations**	**1300 days**	**Wed 01/04/20**	**Tue 25/03/25**		**Rbio_PDRA_1[50%],Rbio_PG_1[50%],Rb**
38	Automation, sample handling, imaging	1300 days	Wed 01/04/20	Tue 25/03/25		
39	Simulation of the end stati	780 days	Wed 30/03/22	Tue 25/03/25	38FF	Rbio_PG_2
40	**Instrumentation**	**1300 days**	**Wed 01/04/20**	**Tue 25/03/25**		**INST_PDRA_1,INST material[1],INST_WPM_1[20%],INST_PD**
41	Low-energy beam diagnos	520 days	Wed 01/04/20	Tue 29/03/22		
42	Online dosimetry and dose profile	780 days	Wed 01/04/20	Tue 28/03/23		INST_PG_1[50%]
43	Absolute dosimetry at ultra-high dose rates	780 days	Wed 01/04/20	Tue 28/03/23		INST_PG_1[50%]
44	Fast feedback and control	780 days	Wed 30/03/22	Tue 25/03/25	41	INST_PG_3
45	High-energy beam diagno	780 days	Wed 30/03/22	Tue 25/03/25	41	INST_PG_2
46	**Software and Computing**	**780 days**	**Wed 30/03/22**	**Tue 25/03/25**		**COMP material[1],COMP_WPM_1[20%]**
47	Development of a global data acquisition and processing system	780 days	Wed 30/03/22	Tue 25/03/25	27FF	DAQ_PG_1,COMP_TECH_1[50%]
48	Development of the controls and monitoring	780 days	Wed 30/03/22	Tue 25/03/25	27FF	CNM_PDRA_1,COMP_TECH_1[50%]



Five year R&D plan

- Facility design.
  - Development of conceptual design.
  - Development of technical design.
  - CDR (detailed for Stage 1).
  - TDR Stage 1.
  - TDR Stage 2.
- Gabor lens.
  - First generation prototype.
  - Second generation prototype.
  - Theoretical studies.
  - Electron density measurements.
  - Alpha source and detector tests.
- Laser-driven source.
- Laser-capture interface.
- Investigation of space charge algorithms.
- Stage 1 beam line performance evaluation.
- Vertical bend.
- Capture technology milestone.

Five year R&D plan

- FFA.
  - Design and simulation.
  - Detailed magnet design.
  - Magnet prototype.
  - RF cavity design and performance evaluation.
  - Injection and extraction design.
- Stage 2 performance evaluation.
- Longitudinal phase space manipulation design, simulation and prototyping.
- Final beam preparation for in vivo end station.
- End stations.
  - Automation, sample handling, imaging.
  - Simulation of the end stations.
- Instrumentation.
  - Low-energy beam diagnostics.
  - Online dosimetry and dose profile.
  - Absolute dosimetry at ultra-high dose rates.
  - Fast feedback and control.
  - High-energy beam diagnostics.
- Software and Computing.
  - Development of a global data acquisition and processing system.
  - Development of the controls and monitoring system.

Summary

- LhARA has the capability to provide unique beams for the study of radiobiology.
- Two stage approach will aim to maximise scientific output whilst optimising the machine performance.
  - Stage 1: protons up to 15 MeV.
  - Stage 2: protons up to 127 MeV and C^{6+} ions up to 33MeV/u.
- Conceptual design and initial simulations show the required performance can be achieved in principle.
- Technical challenges will be addressed by the R&D plan.