Alessandra Valloni

ERL TEST FACILITY FOR LHeC

FFAG'14
2014 International Workshop on FFAG Accelerators

22–26 September 2014,
Brookhaven National Laboratory

Outline

THE LHeC : BASELINE PARAMETERS AND CONFIGURATION

THE ERL TEST FACILITY

1. STAGES OF BUILDING DESIGN

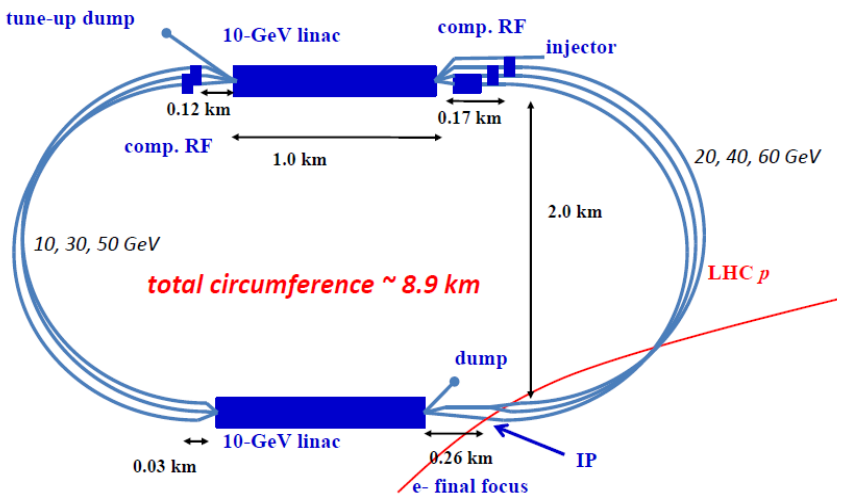
- LAYOUTS
- PARAMETERS

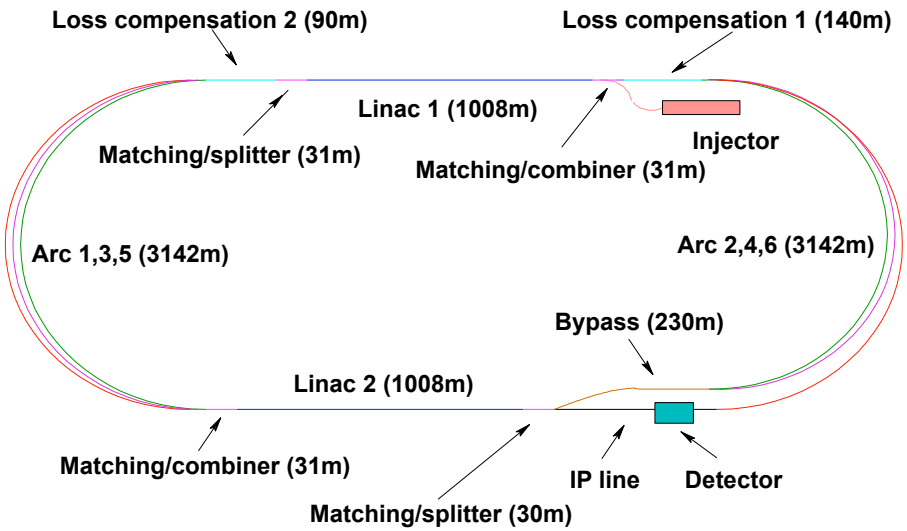
2. ARC OPTICS ARCHITECTURE

3. SUPERCONDUCTING RF

4. PLANNING AND TIMELINE

LHeC Recirculating Linear Accelerator Complex : Schematic Layout





RECIRCULATOR COMPLEX

1. 0.5 Gev injector
2. A pair of SCRF linacs with energy gain 10 GeV per pass
3. Six 180° arcs, each arc 1 km radius
4. Re-accelerating stations to compensate energy lost by SR
5. Switching stations at the beginning and end of each linac
6. Matching optics
7. Extraction dump at 0.5 GeV

LHeC Recirculating Linear Accelerator Complex : IP parameters

10^{33} cm^{-2} s^{-1} Luminosity reach	PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60
Luminosity [10^{33}cm^{-2}s^{-1}]	1	1
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	3.75	50
Beta Function $\beta^*_{x,y}$ [m]	0.1	0.12
rms Beam size $\sigma^*_{x,y}$ [μm]	7	7
rms Beam divergence $\sigma'_{x,y}$ [μrad]	70	58
Beam Current [mA]	430 (860)	6.6
Bunch Spacing [ns]	25 (50)	25 (50)
Bunch Population	$1.7*10^{11}$	$(1*10^9)$ $2*10^9$
Bunch charge [nC]	27	(0.16) 0.32

Luminosity of ≈ 10^{33} cm^{-2}s^{-1} → proposal for 10^{34} cm^{-2}s^{-1} exists
Power consumption for lepton complex ≤ 100 MW

LHeC Recirculating Linear Accelerator Complex : IP parameters

10^{34} cm^{-2} s^{-1} Luminosity reach	PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60
Luminosity [10^{33}cm^{-2}s^{-1}]	16	16
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	2.5	20
Beta Function $\beta^*_{x,y}$ [m]	0.05	0.10
rms Beam size $\sigma^*_{x,y}$ [μm]	4	4
rms Beam divergence $\sigma'_{x,y}$ [μrad]	80	40
Beam Current [mA]	1112	25
Bunch Spacing [ns]	25	25
Bunch Population	$2.2*10^{11}$	$4*10^{9}$
Bunch charge [nC]	35	0.64

LHeC ERL Test Facility & SC RF

FUNDAMENTAL MOTIVATION:

- **Validation of key LHeC Design Choices**

- **Build up expertise in the design and operation for a facility with a fundamentally new operation mode:**
  ERLs are circular machines with tolerances and timing requirements similar to linear accelerators (no ‘automatic’ longitudinal phase stability, etc.)

- **Proof validity of fundamental design choices:**
  Multi-turn recirculation (other existing ERLs have only two passages)
  Implications of high current operation (3 * [6mA – 12mA] > 30mA!!)

- **Verify and test machine and operation tolerances before designing a large scale facility**
  Tolerances in terms of field quality of the arc magnets
  Required RF phase stability (RF power) and LLRF requirements

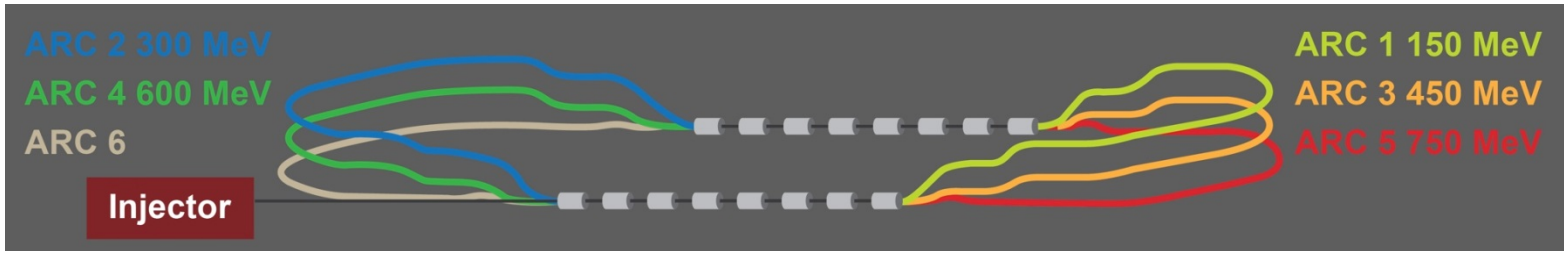
Courtesy of O. Brüning

Goals of a CERN ERL Test Facility

- Test facility for SCRF cavities and modules
- Test facility for multi-pass multiple cavity ERL
- Injector studies: DC gun or SRF gun
- Study reliability issues, operational issues
- Vacuum studies related to FCC
- Possible use for detector development, experiments and injector suggests ~1 GeV as final stage energy
- Test facility for controlled SC magnet quench tests
- Could it be foreseen as the injector to LHeC ERL and to FCC?

TARGET PARAMETER*	VALUE
Injection Energy [MeV]	5
Final Beam Energy [MeV]	900
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	50
Beam Current [mA]	10
Bunch Spacing [ns]	25 (50)
Passes	3

*in few stages



Outline

1. **STAGES OF BUILDING DESIGN**
   - LAYOUTS
   - BASELINE PARAMETERS

2. **ARC OPTICS ARCHITECTURE**

3. **SUPERCONDUCTING RF**

4. **PLANNING AND TIMELINE**

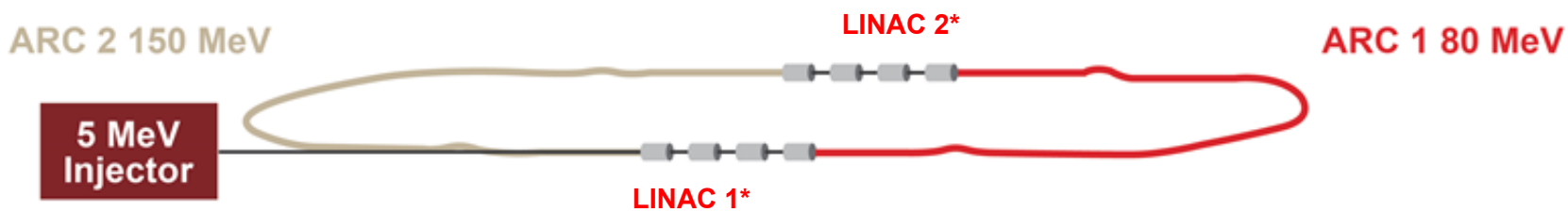
Planning for each stage

STEP 1

SC RF cavities, modules and e^- source tests

- Injection at 5 MeV
- 1 turn
- 75 MeV/linac
- Final energy 150 MeV

ARC	ENERGY
ARC 1	80 MeV
ARC 2	155 MeV



*4 SRF 5-cell cavities at 802 MHz

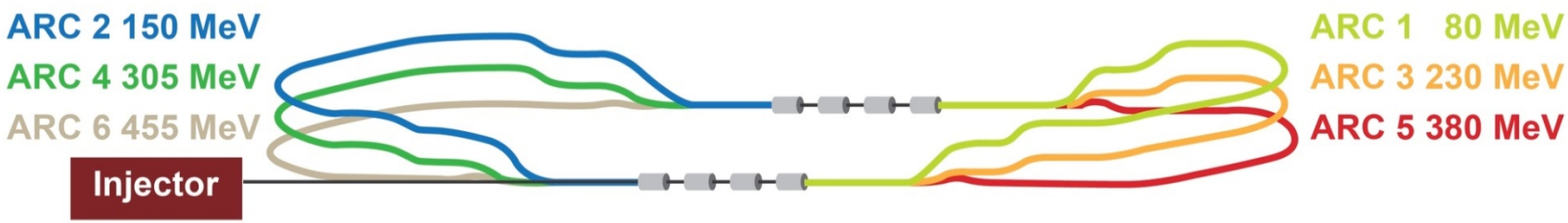
Planning for each stage

STEP 2

Test the machine in Energy Recovery Mode

- Injection at 5 MeV
- 3 turns
- 75 MeV/linac
- Final energy 450 MeV

ARC	ENERGY
ARC 1	80 MeV
ARC 2	155 MeV
ARC 3	230 MeV
ARC 4	305 MeV
ARC 5	380 MeV
ARC 6	455 MeV



Recirculation realized with vertically stacked recirculation passes

Planning for each stage

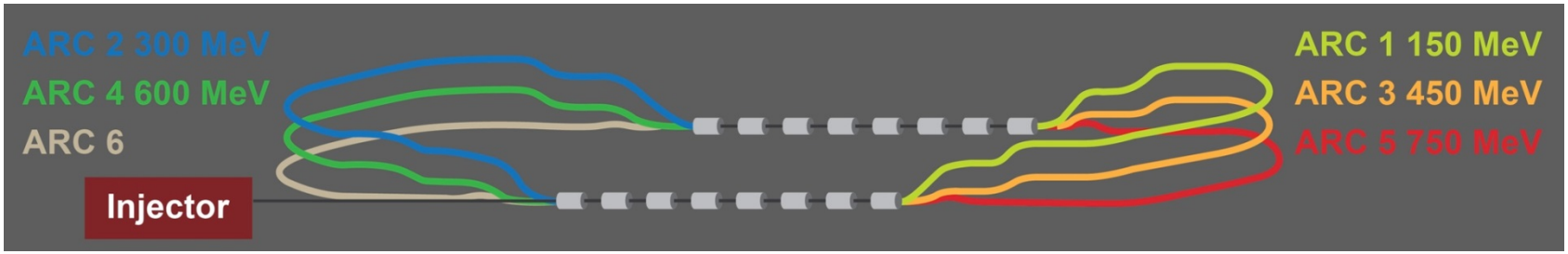
STEP 3

Additional SC RF modules test

Full energy test in Energy Recovery Mode

- Injection at 5 MeV
- 3 turns
- 150 MeV/linac
- Final energy 900 MeV

ARC	ENERGY
ARC 1	150 MeV
ARC 2	300 MeV
ARC 3	450 MeV
ARC 4	600 MeV
ARC 5	750 MeV
ARC 6	900 MeV



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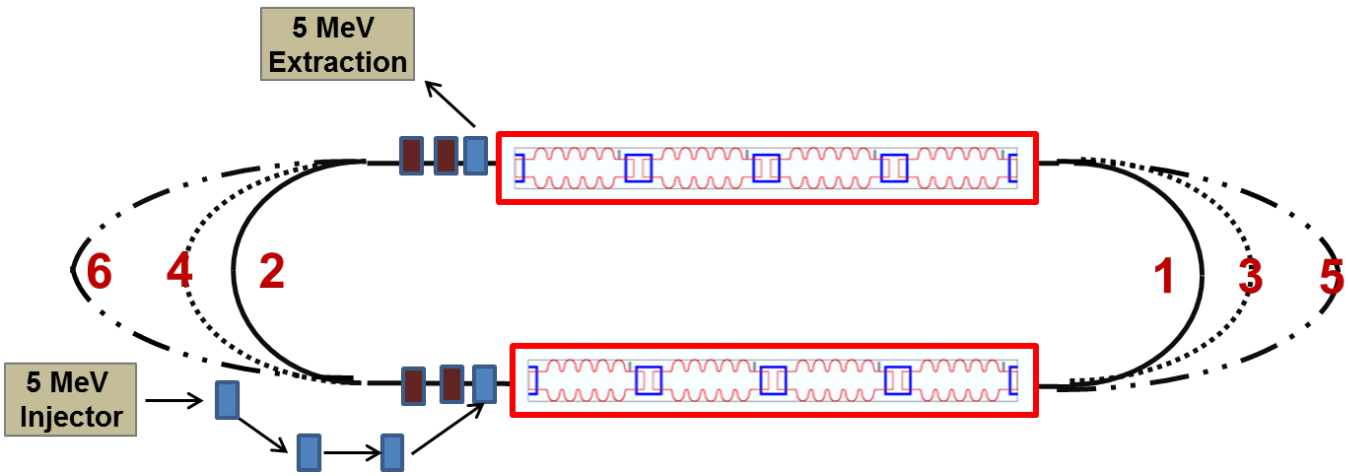
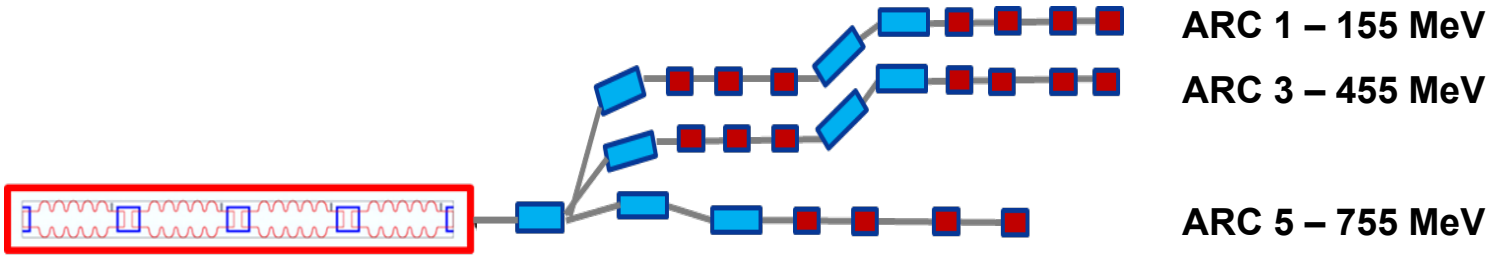
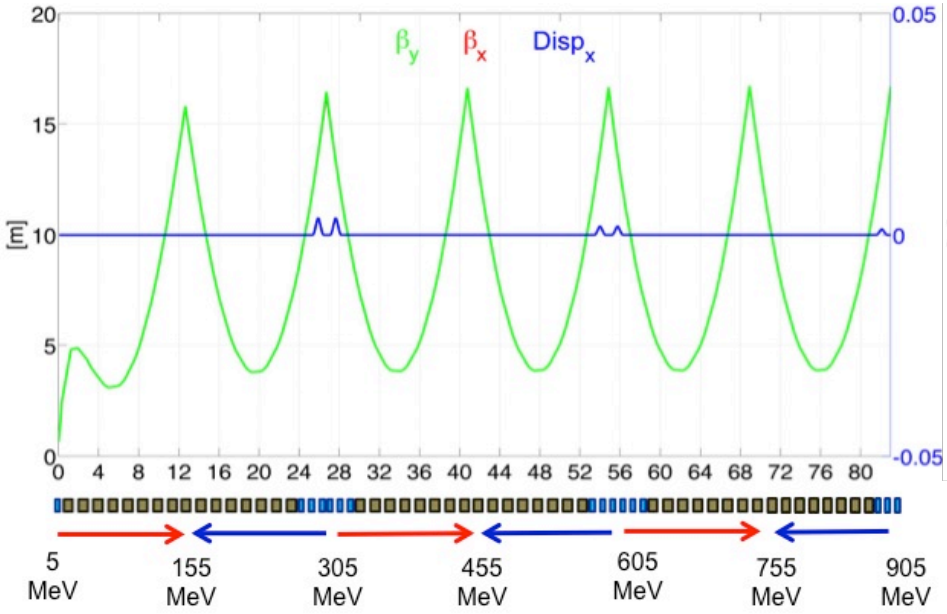
Layout

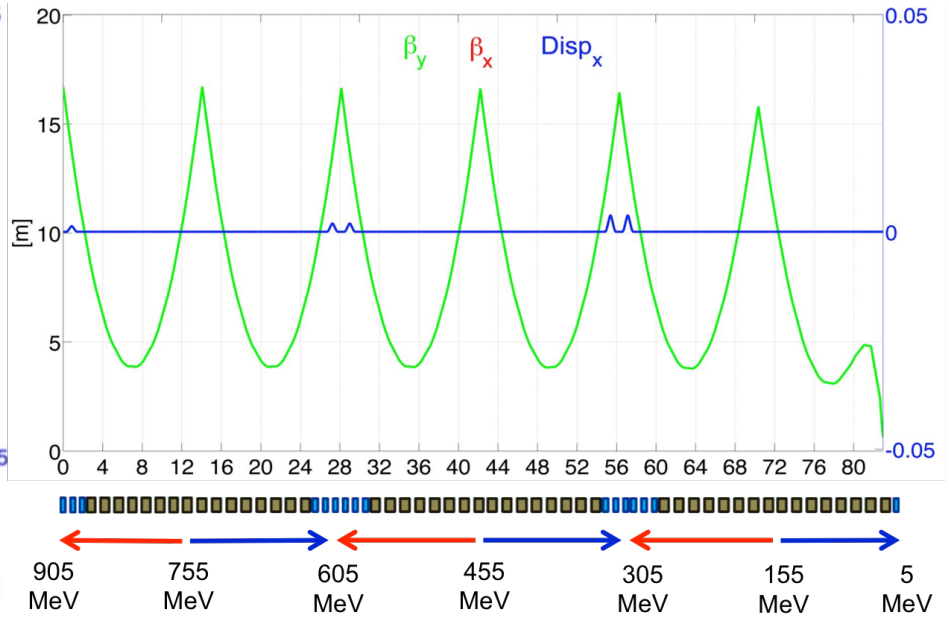

5 MeV
Extraction
6
4
2
1
3
5
5 MeV
Injector


ARC 1 – 155 MeV
ARC 3 – 455 MeV
ARC 5 – 755 MeV

Linac Multi-Pass Optics



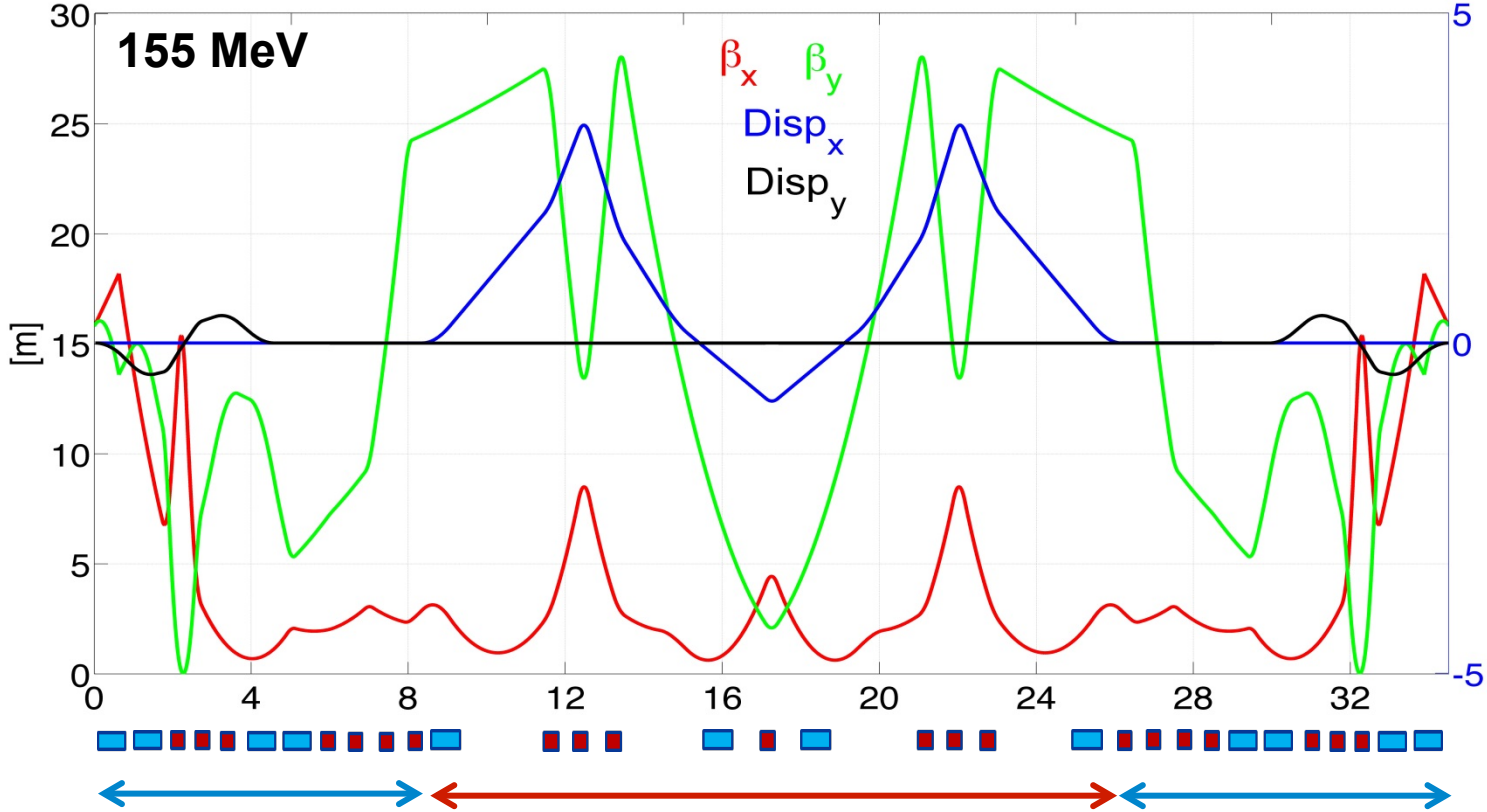
LINAC 1



LINAC 2

Concise representation of multi-pass ERL linac optics for all six passes, with constraints imposed on Twiss functions by ‘sharing’ the same return arcs by the accelerating and decelerating passes

Arc 1 optics



2-step vert. Spreader

30° bends

(1 rec. + 3 sec.)

4×45° sector bends

Arc dipoles :

Ldip = 71.8 cm

B = 5.67 kGauss

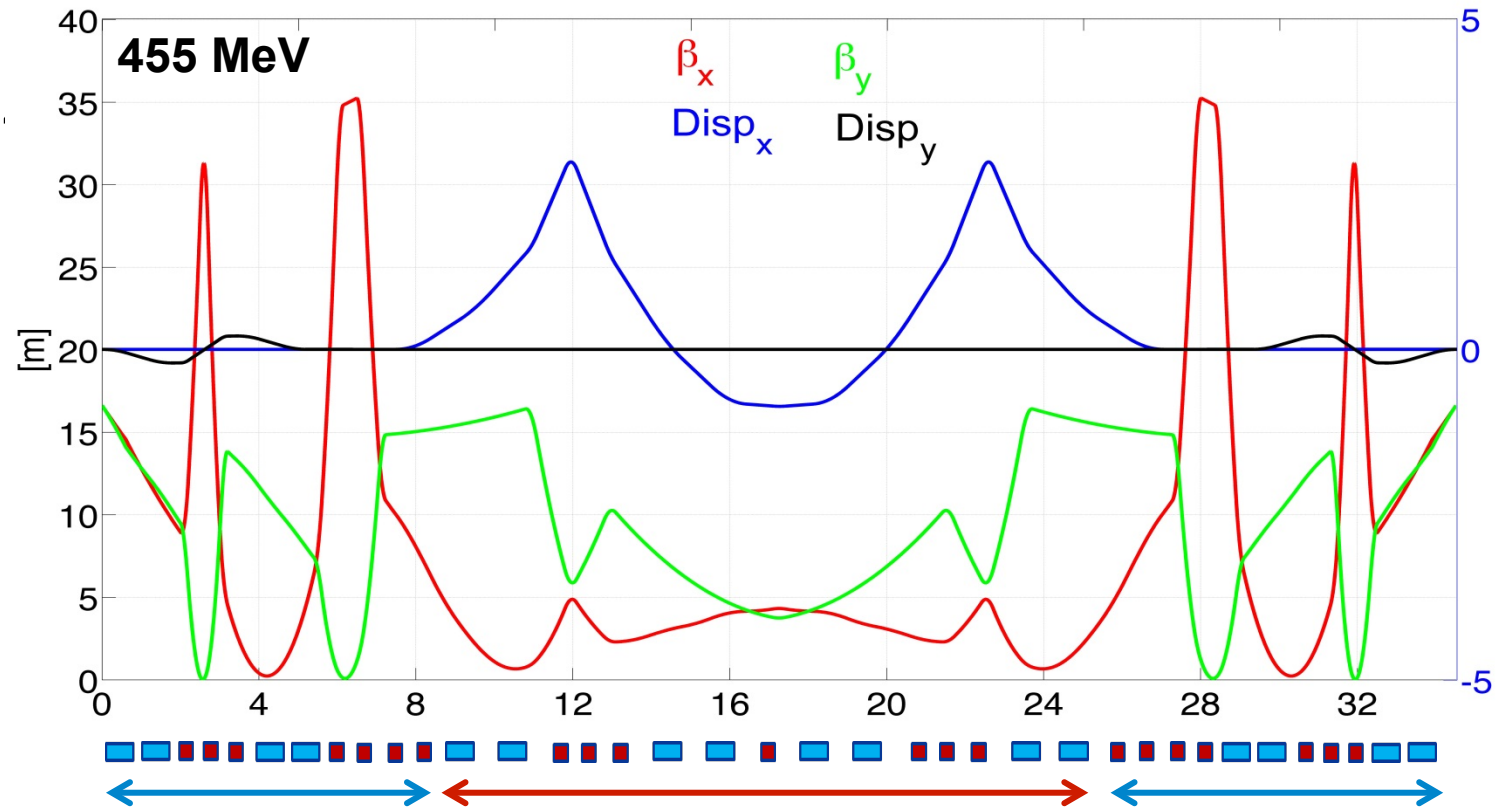
ρ = 91.45 cm

2-step vert. Combiner

30° bends

(1 rec. + 3 sec.)

Arc 3 optics



2-step vert. Spreader

9.8° bends

(1 rec. + 3 sec.)

8×22.5° sector bends

Arc dipoles :

Ldip = 90.58 cm

B = 6.58 kGauss

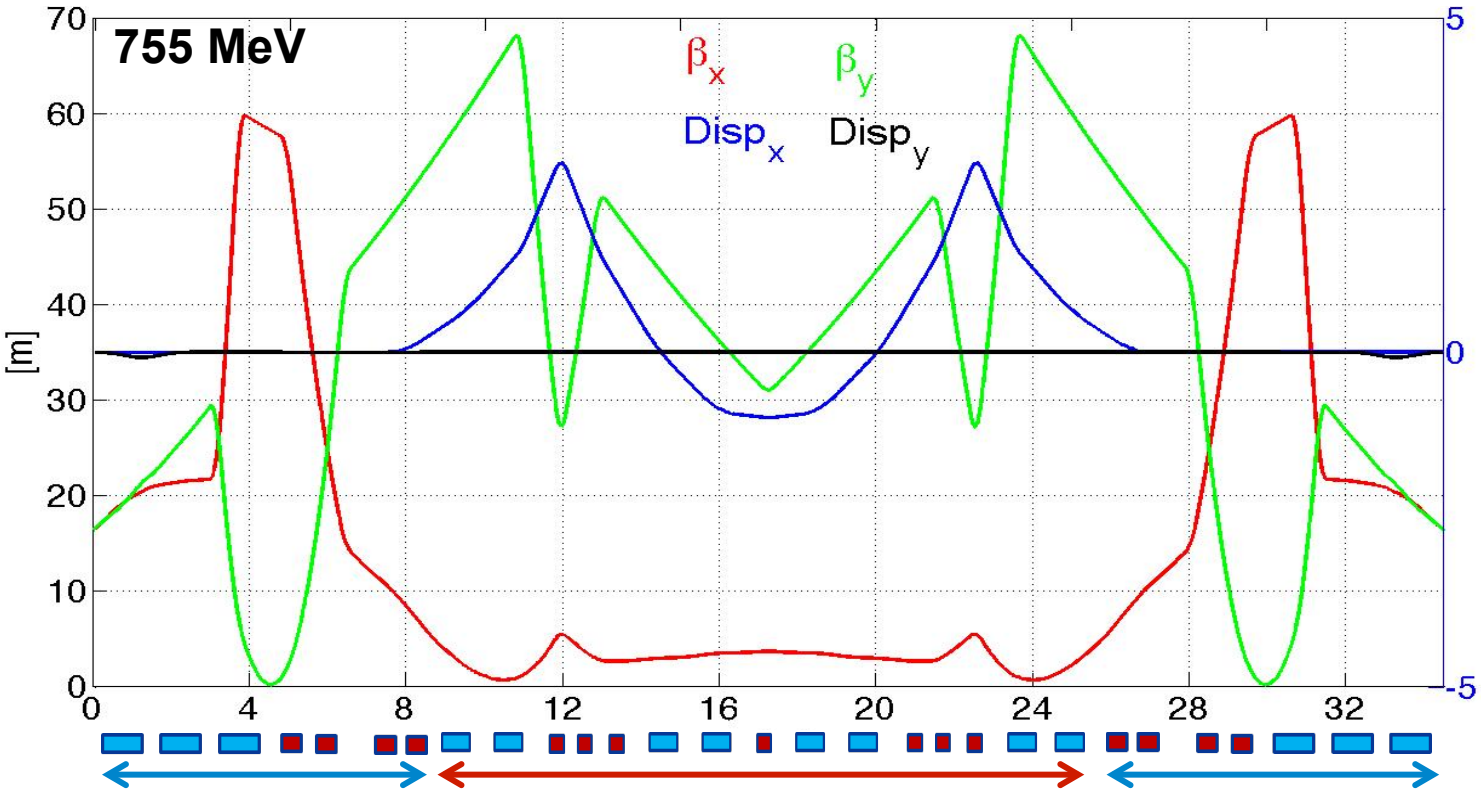
ρ = 230.66 cm

2-step vert. Combiner

9.8° bends

(1 rec. + 3 sec.)

Arc 5 optics



Vertical chicane

8×22.5° sector bends

Vertical chicane

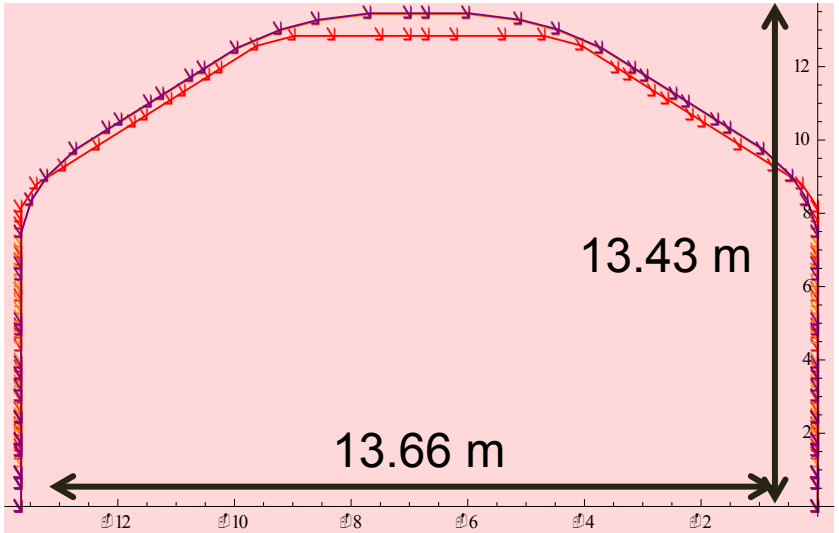
Arc dipoles :

Ldip = 90.58 cm

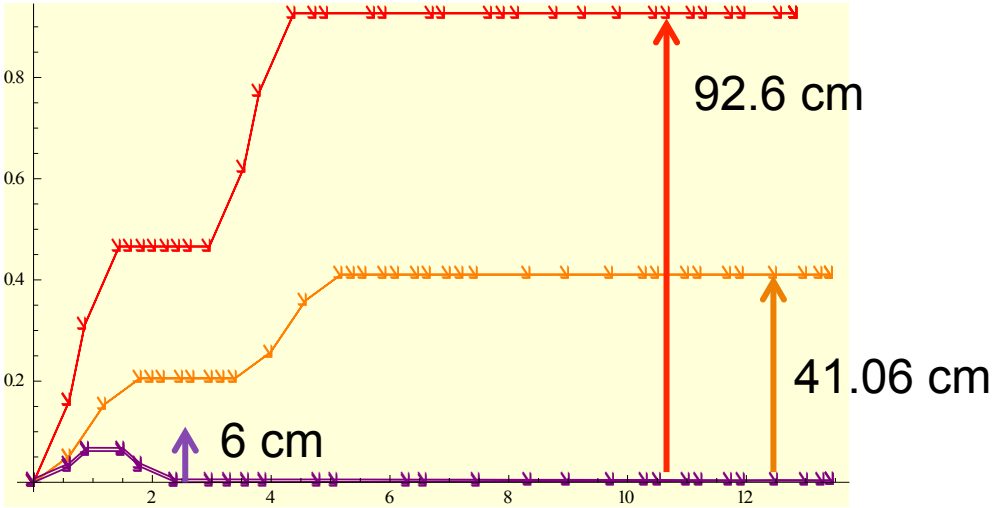
B = 10.92 kGauss

ρ = 230.66 cm

Arc 1,3,5 layout



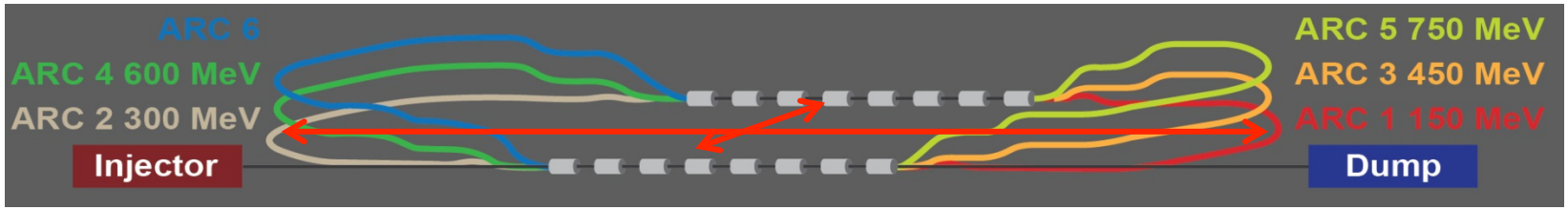
- Synchronous acceleration
  Isochronous arcs
- Achromatic arc
- Dogleg for path-length adjustment
  3 - 13 cm long dipoles,
  Bending angle 18º, B = 1.3 T
  Adjustment: 10º of RF →
  1.04 cm @ 801.58 MHz



Total Arc length for Arc 1,2,3
34.5112 m
94 x λrf

For 6 arcs:
84 DIPOLES
114 QUADRUPOLES

Footprint



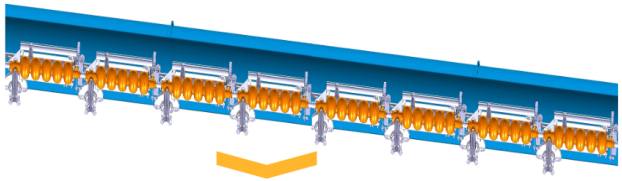
ARCS

Total length for Arc 1,2,3
34.5112 m
94 x λrf
(last cavity linac1 to first cavity linac 2)

Total length for Arc 2,4
34.2704 m
101 x λrf
(last cavity linac1 to first cavity linac 2)

Total length for Arc 6
34.4574 m
101.5 x λrf
(last cavity linac 1 to first cavity linac 2)

LINAC



ONE CRYOMODULE: 8 RF CAVITIES

PARAMETER	VALUE
Frequency	801.58 MHz
Wavelength	37.4 cm
Lcavity= 5λ/2	93.5 cm
Grad	20.02 MeV/m
ΔE	18.71 MV per cavity

Total length ~ 13 m

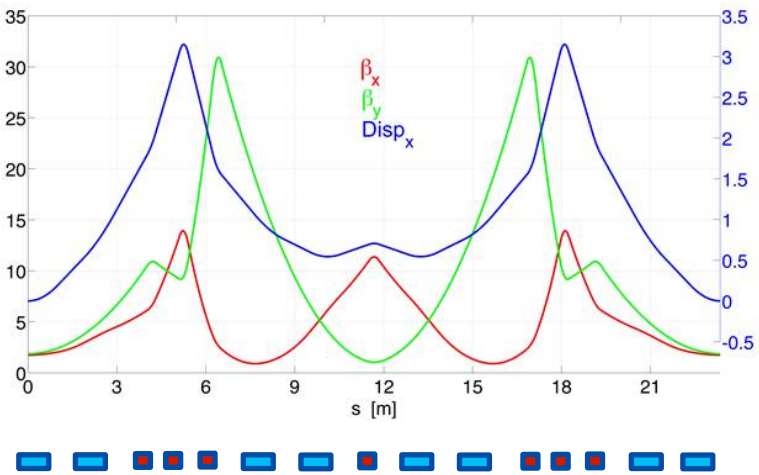
CHICANE INJ/EXTR

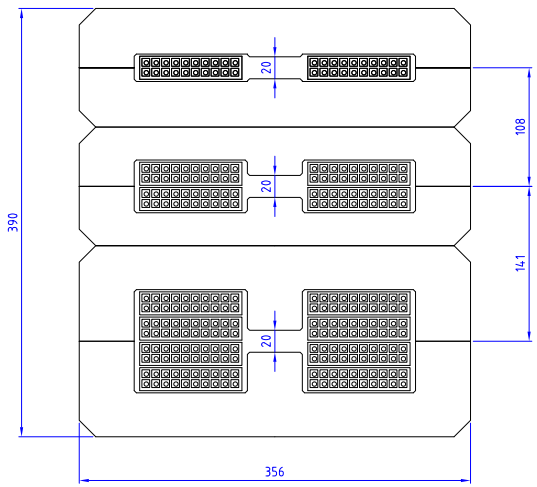
Length ~ 1.75 m

TOTAL DIMENSIONS
42 m x 13.7 m

Arc optics OPTION 2

SAME OPTICS LAYOUT FOR ALL THE ARCS 900/750/600/450/300/150 MeV





3 DIPOLES ON TOP OF EACH OTHER

*Attilio Milanese

Arc dipoles :

8×22.5^0 bends

Ldip = 100.6 cm

ρ = 256.3 cm

	1GeV	750MeV	600MeV	450MeV	300MeV	150MeV
B FIELD	1.30 T	0.97 T	0.78 T	0.58 T	0.39 T	0.19 T

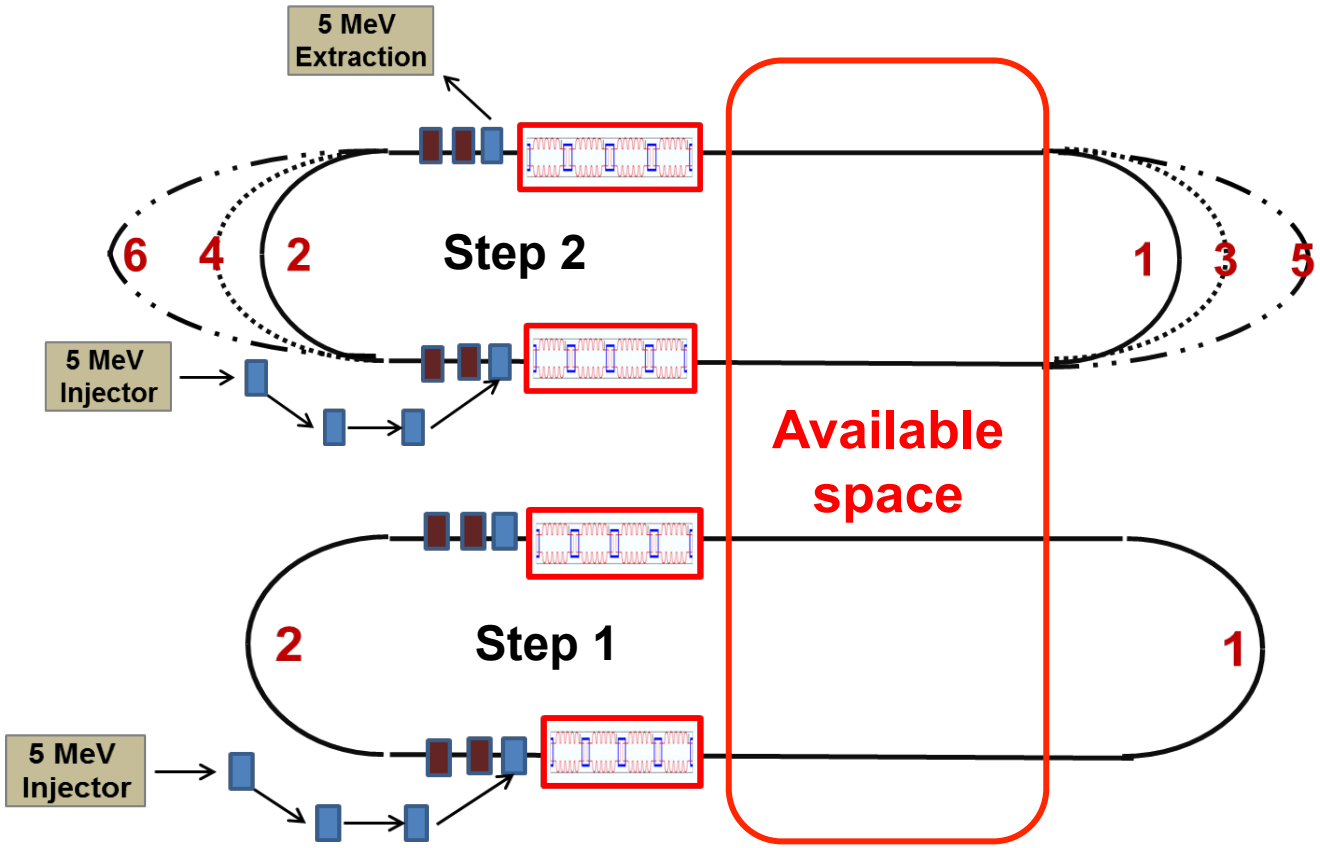
Arc quadrupoles

Lquads = 30 cm

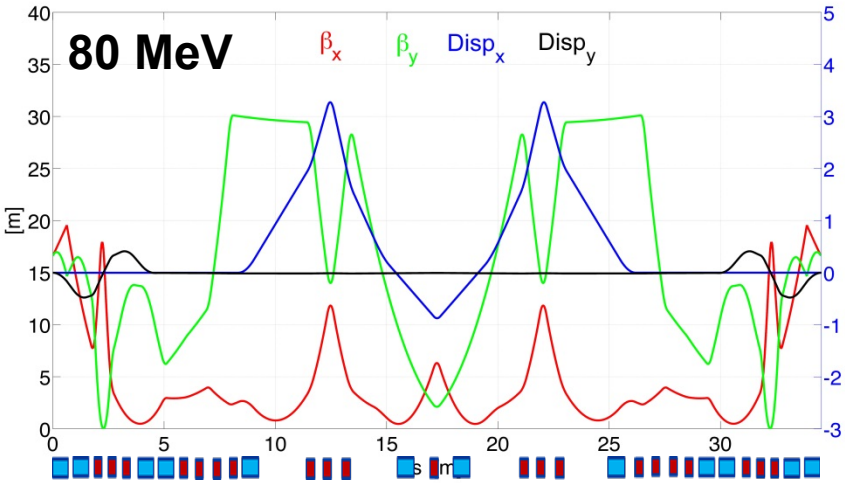
	Q1	Q2	Q3	Q4
Kq[m^{-2}]	-1.01	2.91	2.09	1.19

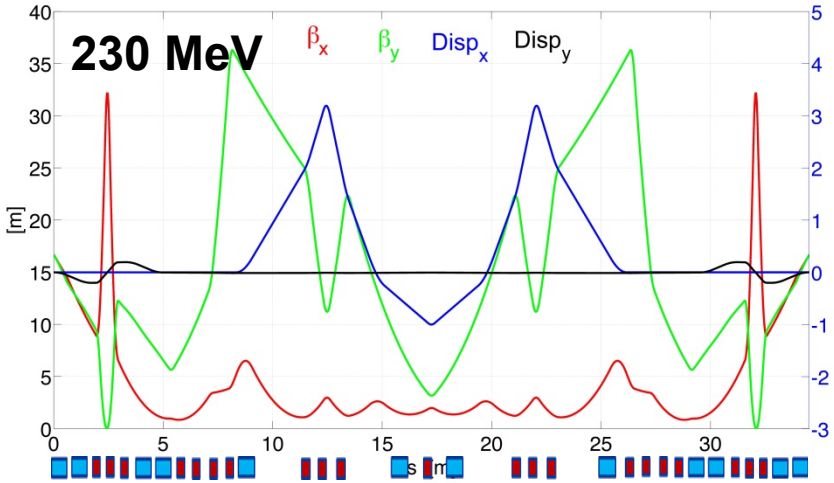
Optics for steps 1 and 2

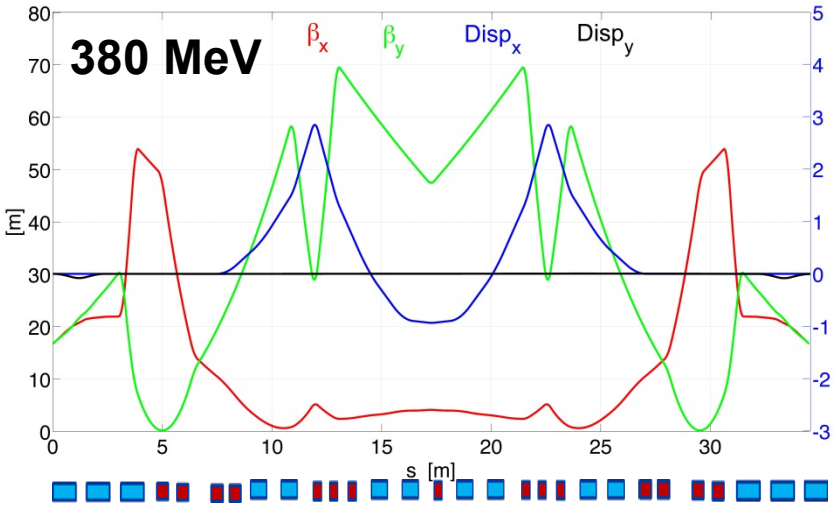
- Complete Step 2 and Step 1 configuration and optics layout

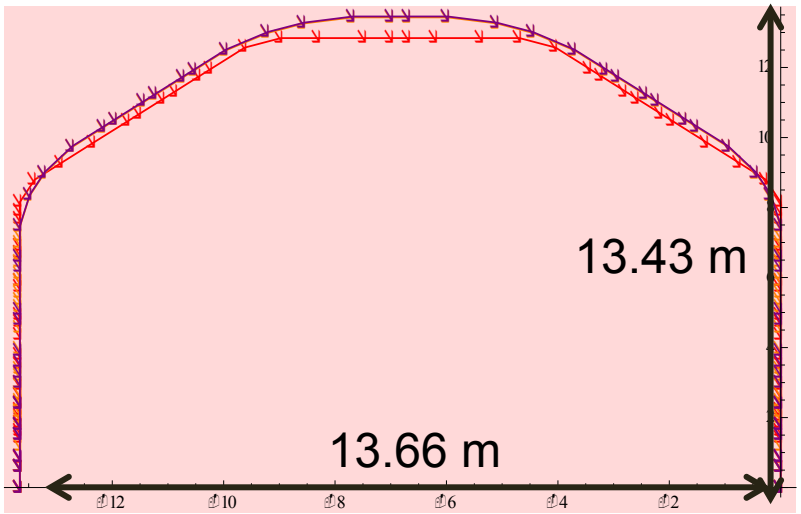


Step 2 optics









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3. SUPERCONDUCTING RF

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Superconducting RF

CERN needs to study and develop the technologies to prepare for a possible next energy-frontier machine (European Strategy for Particle Physics)

Superconducting RF is a key area –
this is where this planned facility comes in

CERN management has asked us to conduct a **Conceptual Design Study** for an Energy Recovery Linac Test Facility (ERL-TF)

We have started this study and have started to establish collaborations

Courtesy of E. Jensen

Superconducting RF

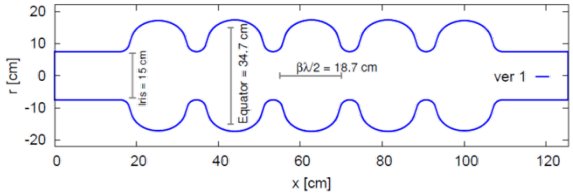
PARAMETER	VALUE
RF frequency	801.59 MHz
Acc. Voltage/cavity	18.7 MV/m
# Cells/cavity	5
Cavity length	~ 1.2 m
# Cavities/cryomodule	4
RF power/cryomodule	< 50 MW
# Cryomodules	8
Acceleration/pass	299.4 MeV
Bunch repetition	36.44 MHz
Duty factor	CW

Tests of SC cavities at different frequencies
- 704.42 MHz (ESS, SPL..)
- 801.59 MHz (SPS, LHeC, FCC..)
- 1.3 GHz (XFEL, ILC..)

with a photocathode pulsed at

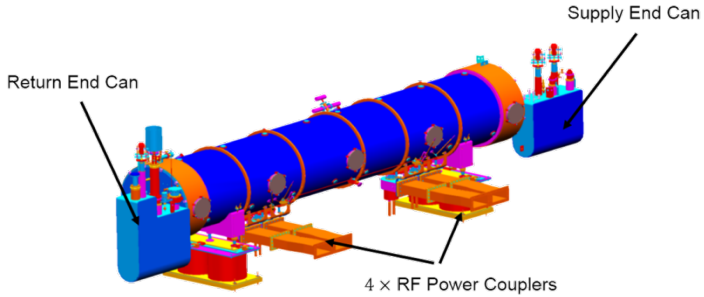
$$f = (12.1474 \pm 0.0022)\ \text{MHz}$$

Initial Cavity Design (SPL, JLAB and BNL experience)

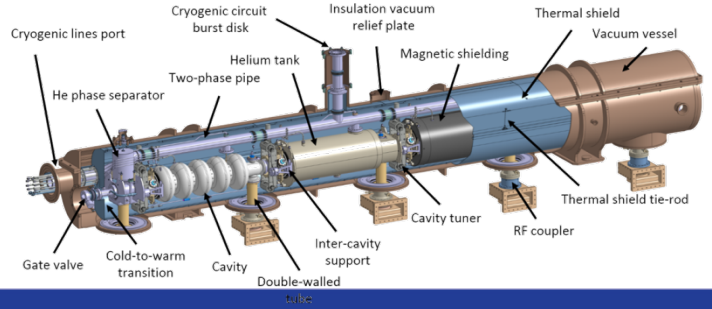


Cryomodule Design

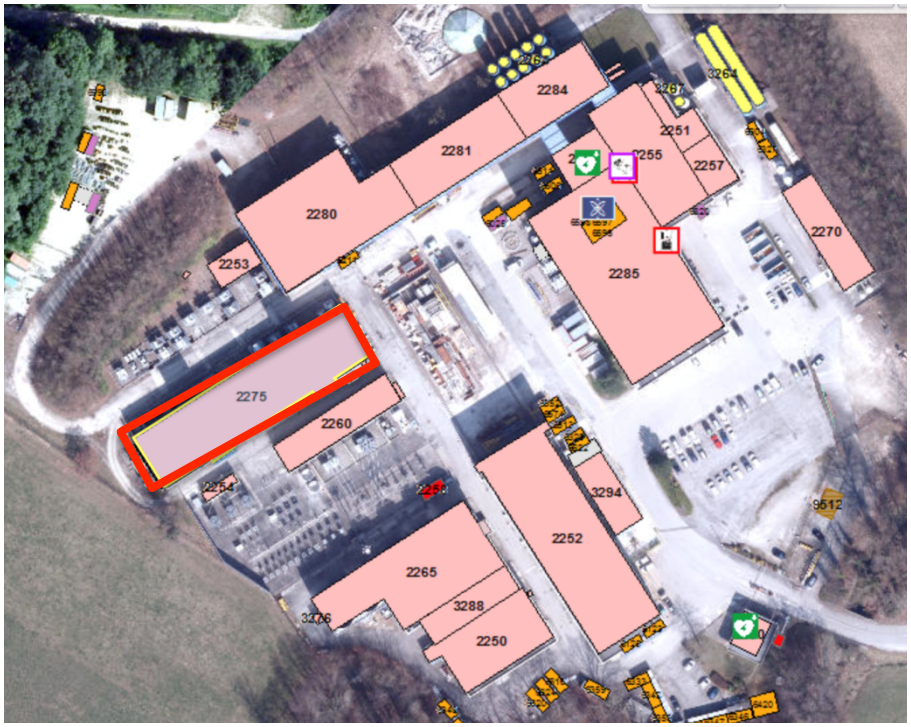
JLAB had designed an 805 MHz cryomodule for SNS
(concept for the 802 MHz baseline design)



CERN is following for SPL (704 MHz) an alternative path using SS helium vessels and support by the power couplers



LTF Possible Site Choice



We have started to look into possible existing buildings suited to host the ERL test facility.

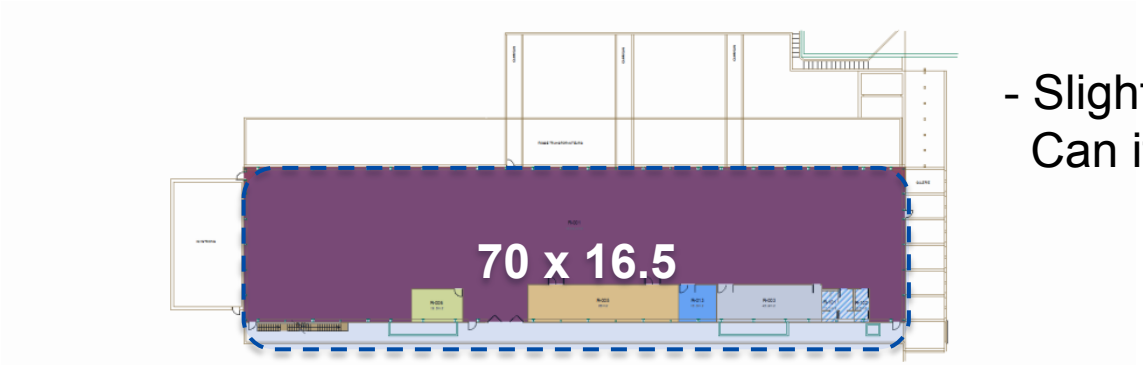
A suitable hall could be in **Building 2275, near LHC P2**

- Current use under investigation

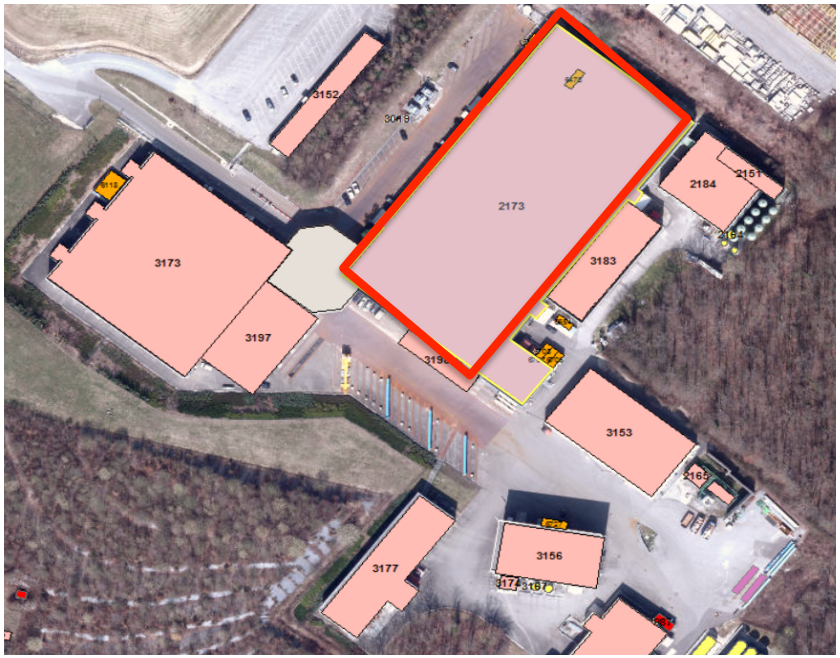
- Power converters already in place

- Geographically perfect as injector for LHeC ERL

- Slightly narrower than required Can it be extended?



LTF Possible Site Choice

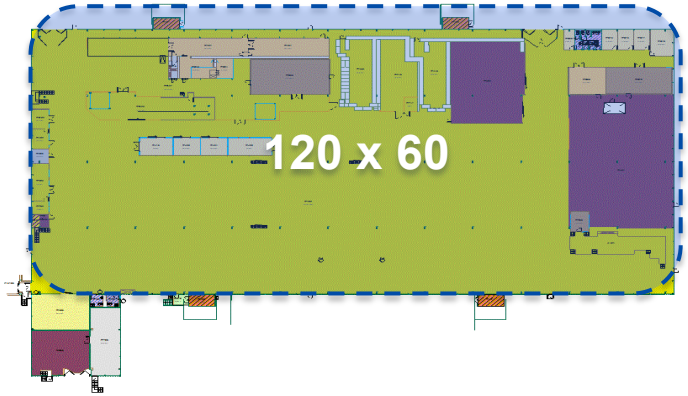


A suitable hall could be in
Building 2173 (SM18)

- Current use under investigation

- Powering infrastructure in place

- Cryogenics installation in place
  (capacity to be checked???)



Next steps

CERN management has asked us to conduct a **Conceptual Design Study** for an Energy Recovery Linac Test Facility (ERL-TF)

We have started this study and have started to establish collaborations

Goals
2014 Preliminary CDR
2015 Complete CDR

Looking for collaborations
Establishing collaborations

- Lattice Design
- SCRF
- Injector studies
- Magnets design
- Beam Instrumentation

Summary

- The concept of the ERLTF is designed to allow for a staged construction with verifiable and useful stages for an ultimate beam energy in the order of 1 GeV

- Design complementary to & synergetic with other proposals

- A Design Study of the ERL-TF has started (a sketch of the optics configuration is provided and other options are under investigation) in collaboration with other institutes (as JLAB)

- First analysis of having controlled quench tests of next generation superconducting magnets has been carried out. Beam parameters seem to match the requirements….further investigation is required!

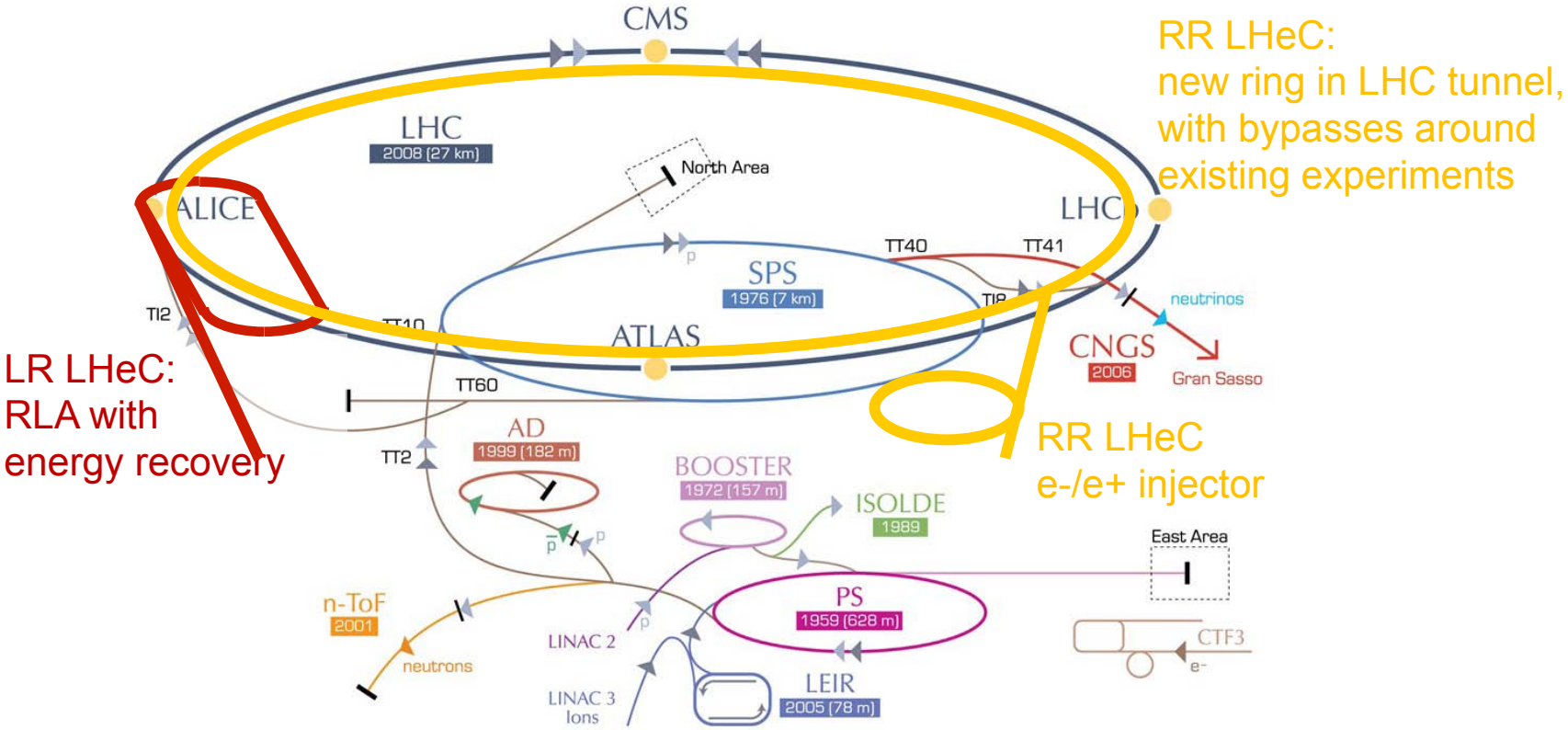
- Completion of Conceptual design study of an ERL-TF at CERN by the end of 2015

Thank you for your attention

Many thanks to the
LHeC Study Group Collaboration

Backup slides

LHeC option: RR and LR



Study team provided CDR:

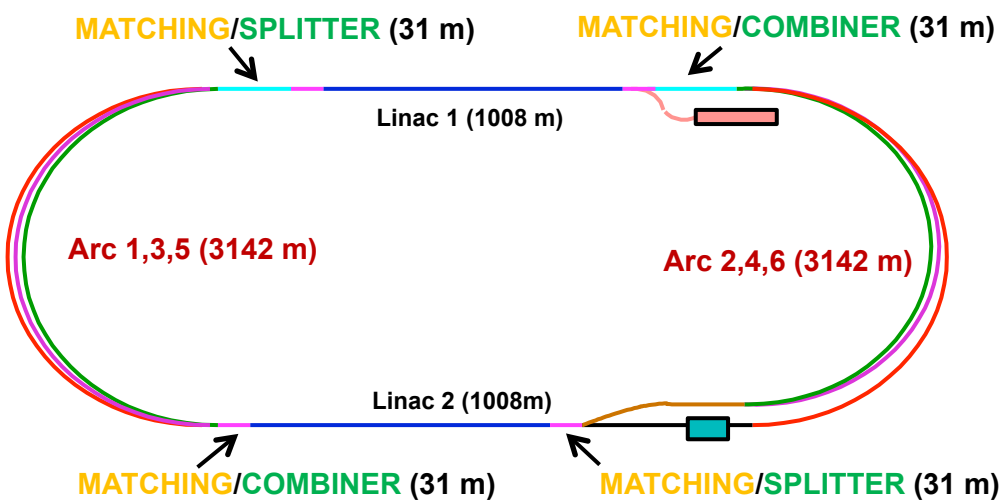
Ring-ring option, feasible but impact LHC operation during installation

Linac-ring option, the baseline

A solution exists, will now have to find the best solution

Already have a baseline and alternatives for some components

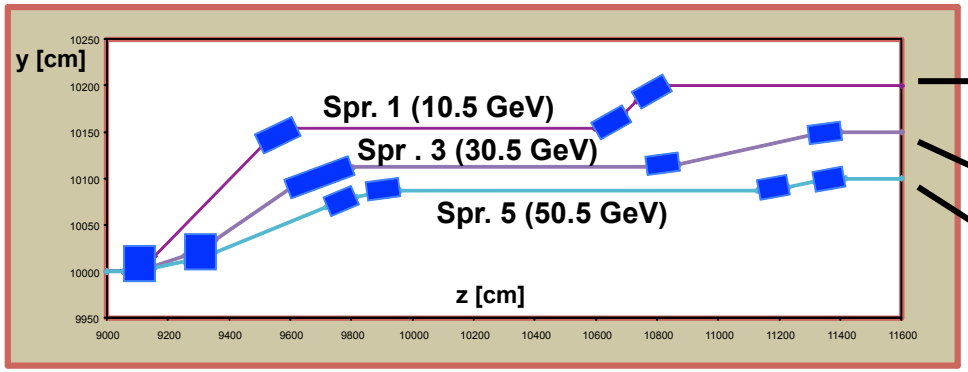
Return Arc Optics

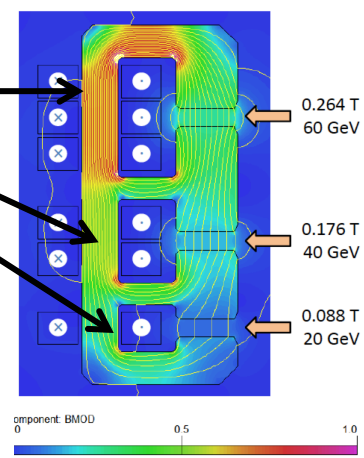


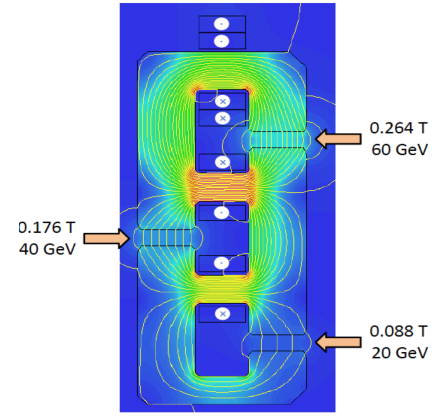
Switchyard
Matching sections
Arc lattices

- Arc-to-Linac Synchronization - Momentum compaction
  - Quasi-isochronous lattices
  - Choice of Arc Optics - Flexible Momentum Compaction
- Arc Optics Choice - Emittance preserving lattices
  - Arcs based on variations of FMC optics (Im. γ_t, DBA, TEM)
- Acceptable level of emittance dilution and momentum spread
  - Magnet apertures

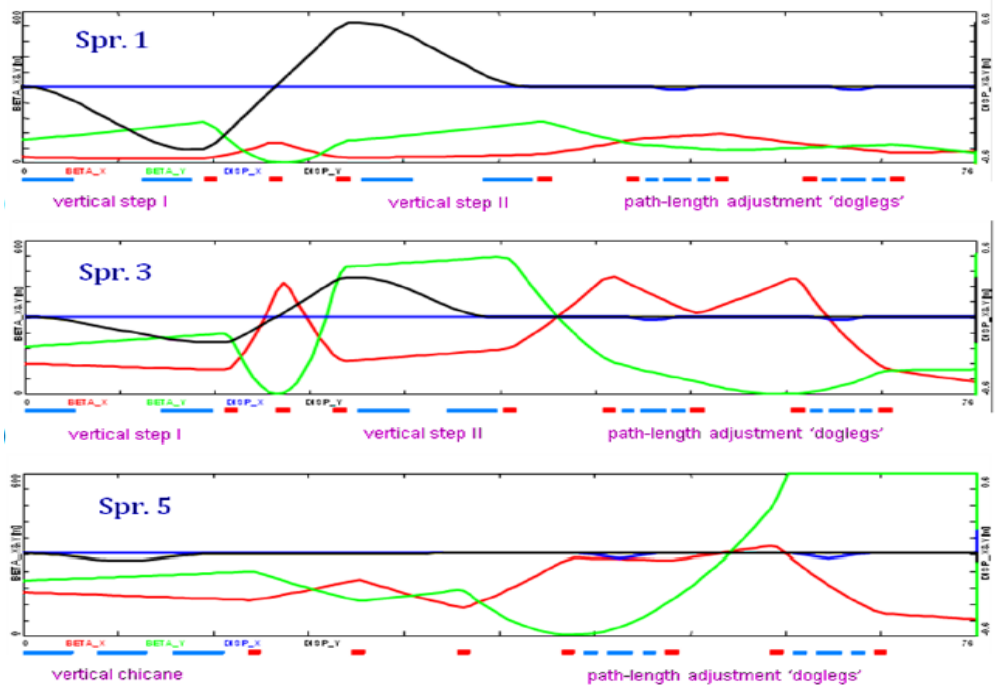
Switchyards







A. Milanese



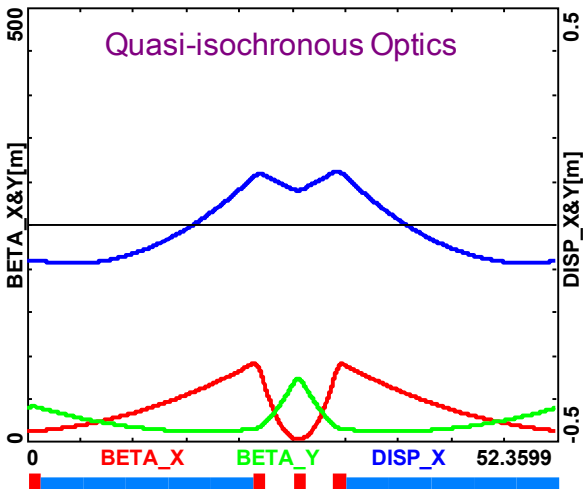
- Two-step-achromat spreaders and mirror symmetric recombiners
- Arcs are separated into 1m high vertical stack
- Very compact switchyard system (~20 m long)
- Horizontal doglegs used for path-length adjustment

Emittance Preserving Arc Optics

Proper lattice design in the arcs to address
the effect of SR on electron beam phase-space:
cumulative emittance and momentum growth due to quantum excitations

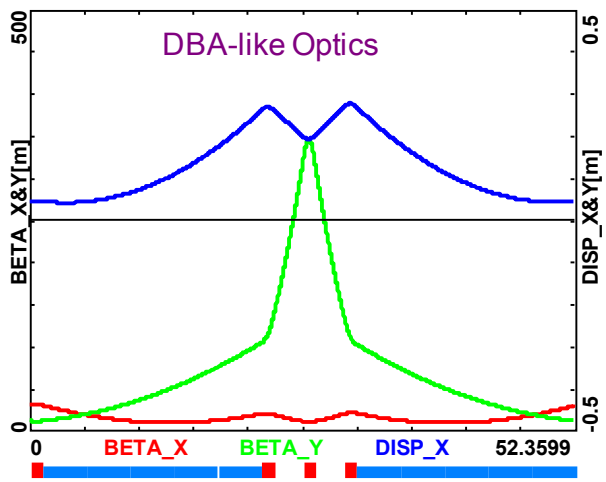
$$\Delta\varepsilon^N = \frac{2}{3} C_q \, r_0 \, \gamma^6 \langle H \rangle \frac{\pi}{\rho^2} \qquad H = \gamma D^2 + 2\alpha D D' + \beta D'^2$$

Arc 1 and 2



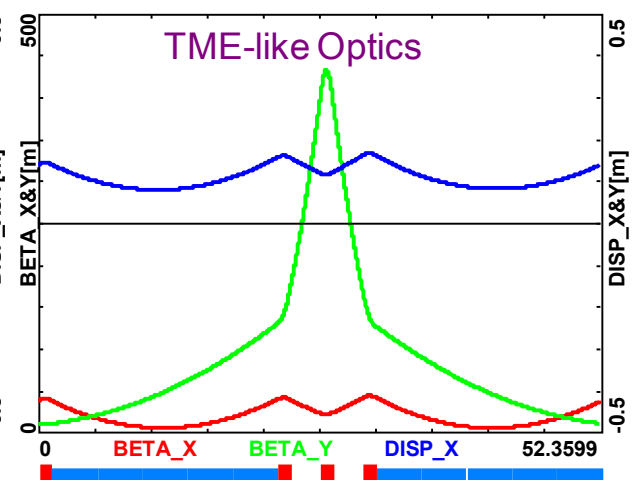
$$\langle H \rangle = 8.8 \times 10^{-3} \; m$$

Arc 3 and 4



$$\langle H \rangle = 2.2 \times 10^{-3} \; m$$

Arc 5 and 6



$$\langle H \rangle = 1.2 \times 10^{-3} \; m$$

Various flavors of FMC Optics used

Emittance not exceeding 50 μrad required for the LHeC luminosity

Synchrotron radiation in return arcs (1/2)

- Energy loss due to synchrotron radiation in the arcs
- Integrated energy spread induced by synchrotron radiation

ARC	E [GeV]	ΔE [MeV]	σE/E [%]
1	10.4	0.678	0.00052
2	20.3	9.844	0.00278
3	30.3	48.86	0.00776
4	40.2	151.3	0.01636
5	50.1	362.3	0.02946
6	60	751.3	0.04829
7	50.1	362.3	0.06366
8	40.2	151.3	0.08065
9	30.3	48.86	0.10808
10	20.3	9.844	0.16205
11	10.4	0.678	0.31668
dump	0.500	0	6.66645

Total loss per particle about ~1.9 GeV → 12.2 MW beam power
Compensated by additional linacs
60% wall plug to beam efficiency → 20.3 MW

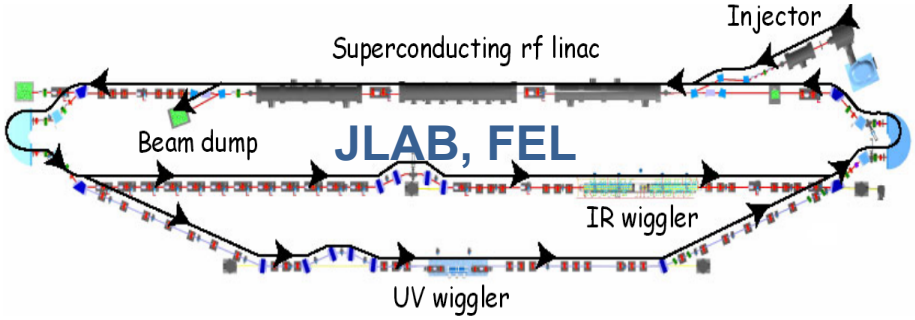
Synchrotron radiation in return arcs (2/2)

- Emittance growth in each individual arc*
- Integrated growth including all previous arcs

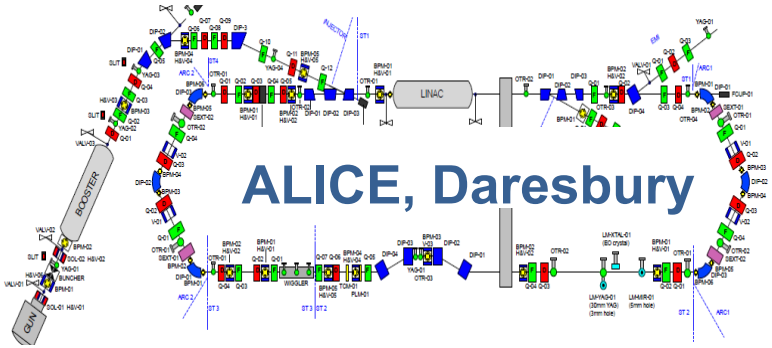
ARC	E [GeV]	$\Delta\varepsilon_{ARC}$ [μm]	$\Delta\varepsilon_t$ [μm]
1	10.4	0.0025	0.0025
2	20.3	0.140	0.143
3	30.3	0.380	0.522
4	40.2	2.082	2.604
5	50.1	4.268	6.872
6	60	12.618	19.490
5	50.1	4.268	23.758
4	40.2	2.082	25.840
3	30.3	0.380	26.220
2	20.3	0.140	26.360
1	10.4	0.0025	26.362

Before the IP a total growth of ~ 7 μm is accumulated
The final value is ~ 26 μm

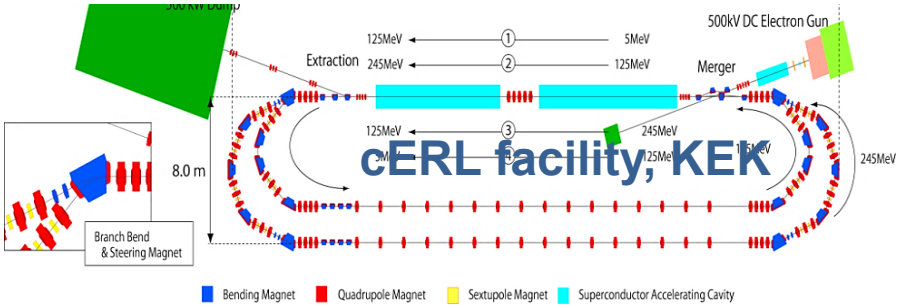
Review of some ERL-based machines worldwide (planned/existing/operating)



Beam Energy	88-165 MeV
Beam Current	10 mA
Bunch charge	135 pC
RF frequency	1500 MHz
Passes	1

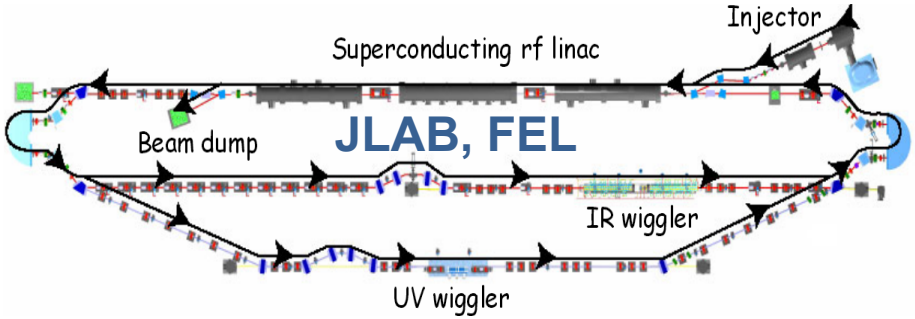


Beam Energy	12-26 MeV
Bunch charge	40-60-200 pC
RF frequency	1300 MHz
Passes	1

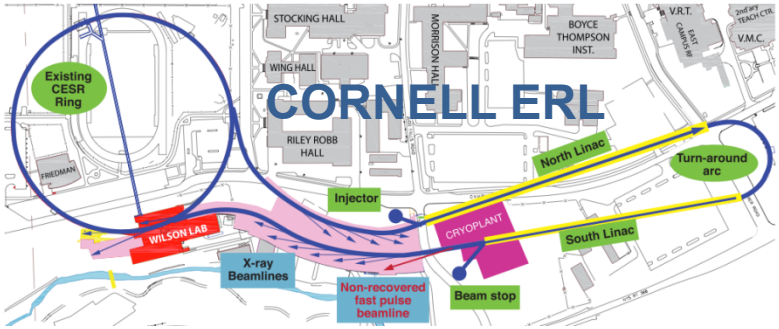


Beam Energy	35-125-250 MeV
Beam Current	10mA (100mA)
Bunch charge	7.7pC- 77pC
RF frequency	1300 MHz
Passes	1- 2

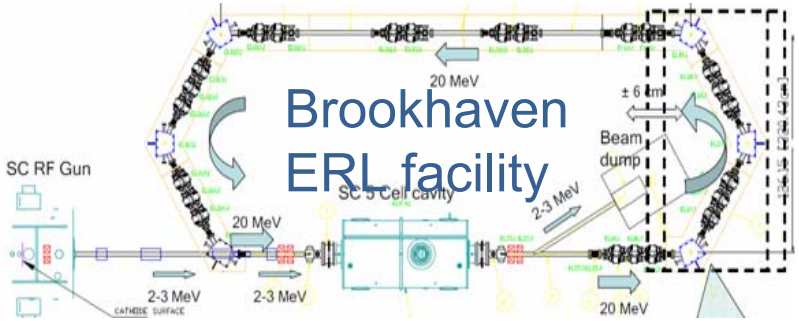
Review of some ERL-based machines worldwide (planned/existing/operating)



Beam Energy	88-165 MeV
Beam Current	10 mA
Bunch charge	135 pC
RF frequency	1500 MHz
Passes	1

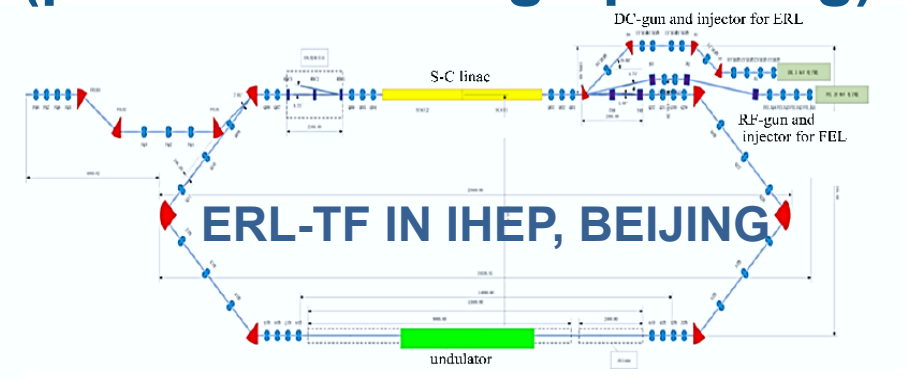


Beam Energy	5 GeV
Bunch charge	77 pC
Beam Current	100 mA
RF frequency	1300 MHz

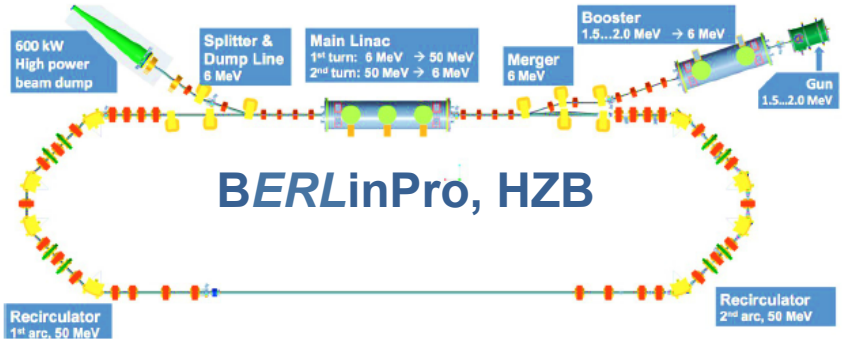


Beam Energy	20 MeV
Bunch charge	0.5-5 nC
Bunch current	300 mA
RF frequency	704 MHz
Passes	1

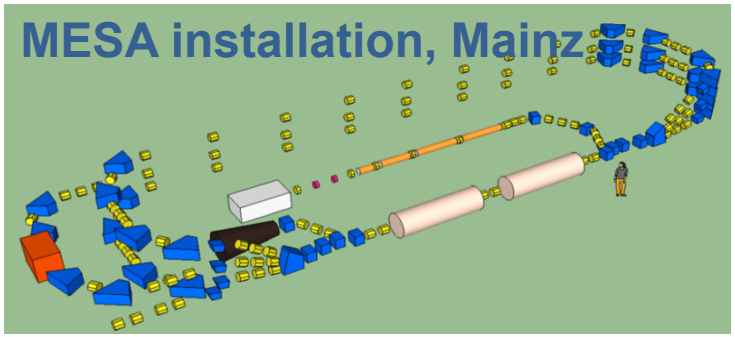
Review of some ERL-based machines worldwide (planned/existing/operating)



Beam Energy	35 MeV
Beam Current	10 mA
Bunch charge	77 pC
RF frequency	1300 MHz
Passes	1



Beam Energy	50 MeV
Beam Current	100 mA
Bunch charge	77 pC
RF frequency	1300 MHz
Passes	1



Beam Energy	105 MeV
Bunch charge	0.77 pC
RF frequency	802/1300 MHz
Passes	2

International Advisory Committee

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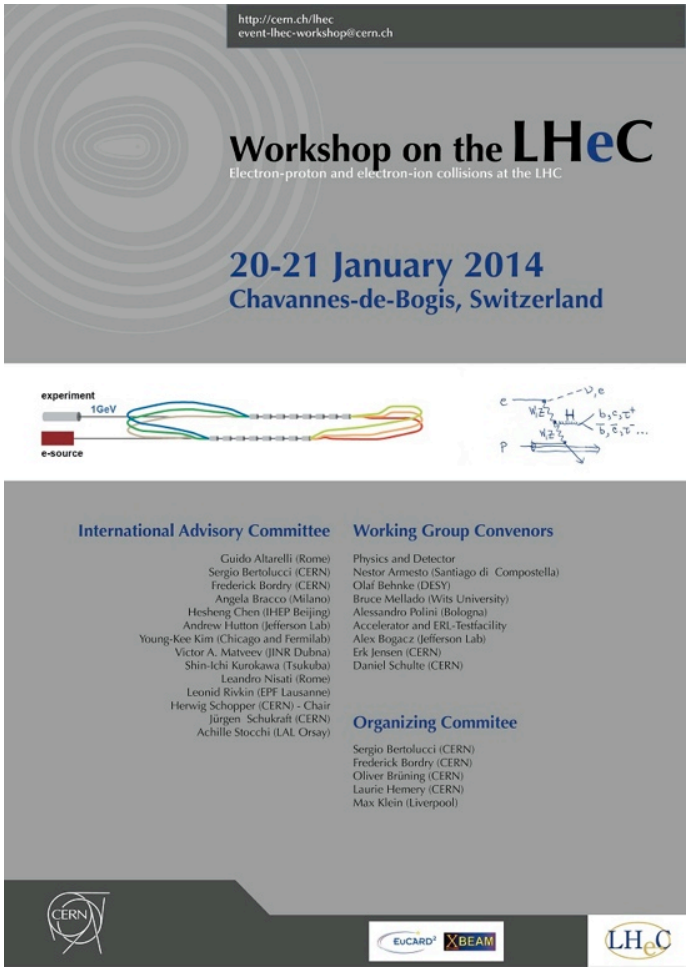
J. Womersley (STFC)

First IAC meeting at the
LHeC 5th workshop, Switzerland, January 2014



Controlled quench tests of SC magnets

WE ARE INVESTIGATING THE POSSIBILITY OF USING THE TEST FACILITY FOR SC MAGNET TESTS

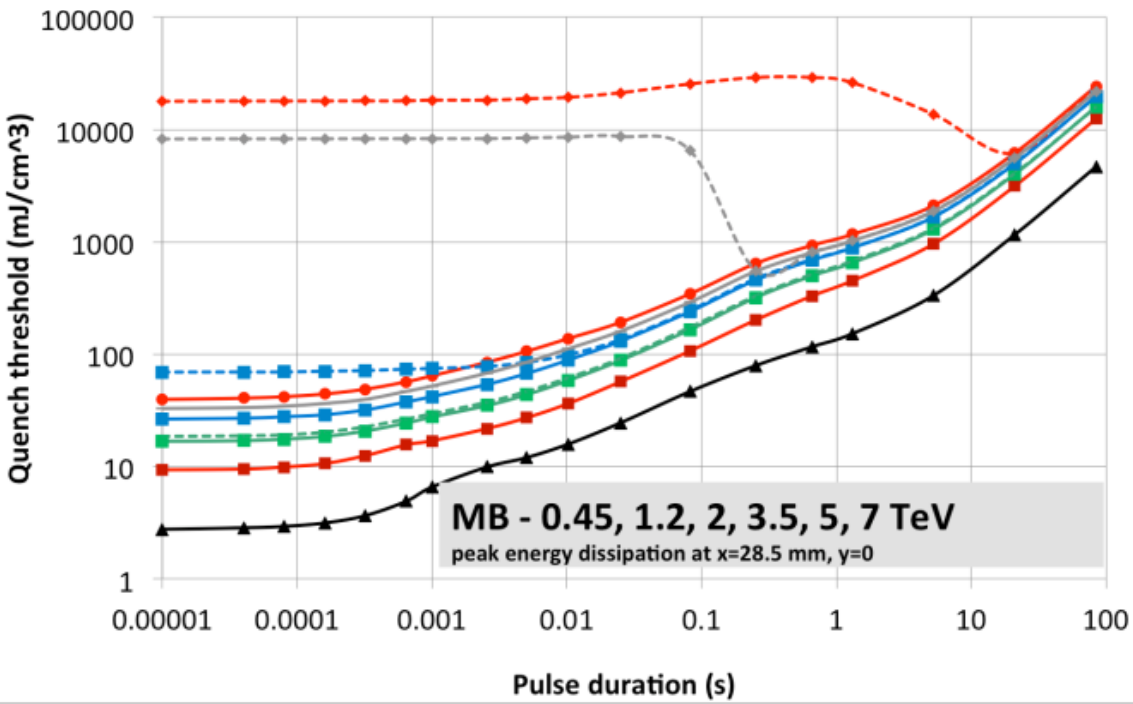
Requirements in terms of:

- Beam energy, intensity and pulse length (energy deposition)
- Space for the magnets installation (possible tests of cable samples and full cryo magnets)
- Cryo requirements
- Vacuum requirements
- Powering needs

Controlled quench tests of SC magnets

Study beam induced quenches (quench thresholds, quenchino thresholds) at different time scales for:

- SC cables and cable stacks in an adjustable external magnetic field
- Short sample magnets
- Full length LHC type SC magnets



Quench limits of LHC dipole as expected from QP3 simulations for different pulse durations

Courtesy A. Verweij

Beam parameters to generate a given amount of energy deposition

CALCULATIONS AND FLUKA SIMULATIONS

Copper target
(no magnetic field)

Beam →

Cylinder of copper
Radius = 50cm
Length = 100cm

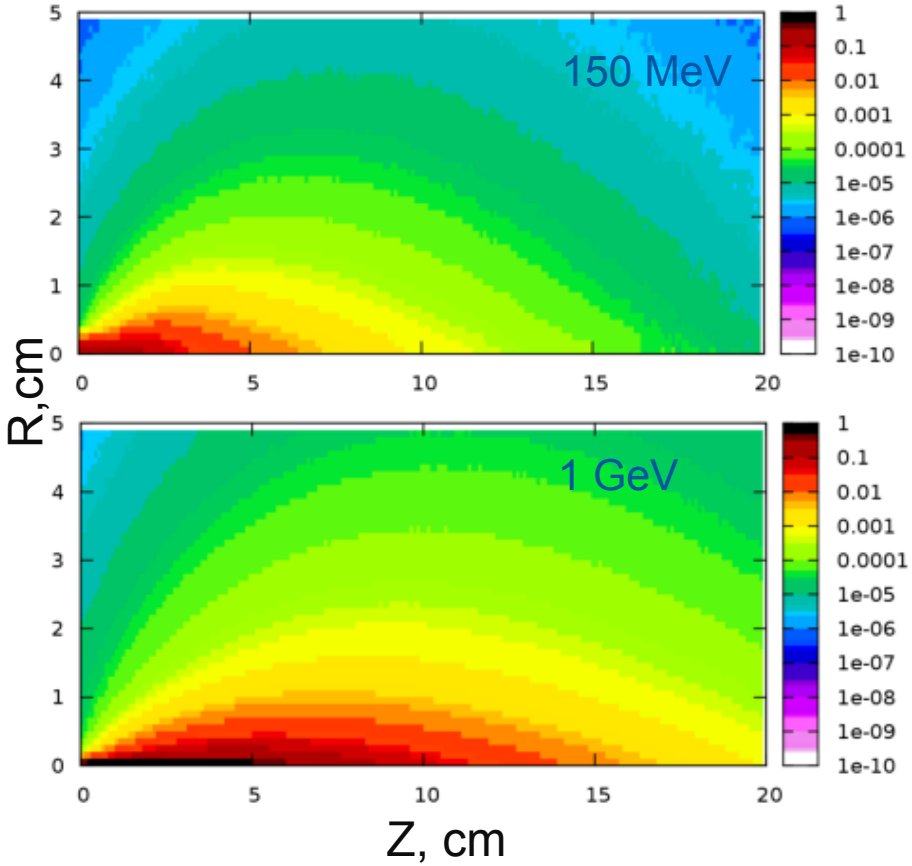
Beam parameters

Energy, MeV	Emittance, m	Sigma, cm	FWHM, cm
150	1.70E-07	0.092	0.22
300	8.52E-08	0.065	0.15
450	5.68E-08	0.053	0.13
600	4.26E-08	0.046	0.11
750	3.41E-08	0.041	0.10
900	2.84E-08	0.038	0.09
1000	2.55E-08	0.036	0.08

Results are given for half of bulky target because of symmetry

Binning: 1 mm^3 bins

Energy deposition, GeV/cm^3/e^-



V. Chetvertkova, D. Wollmann

Beam parameters to generate a given amount of energy deposition

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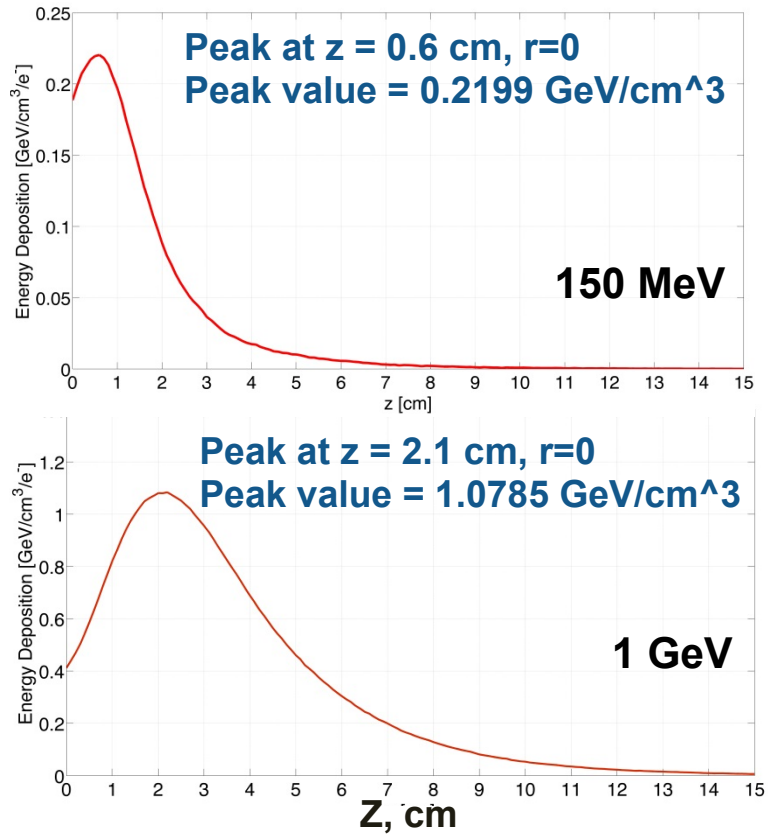
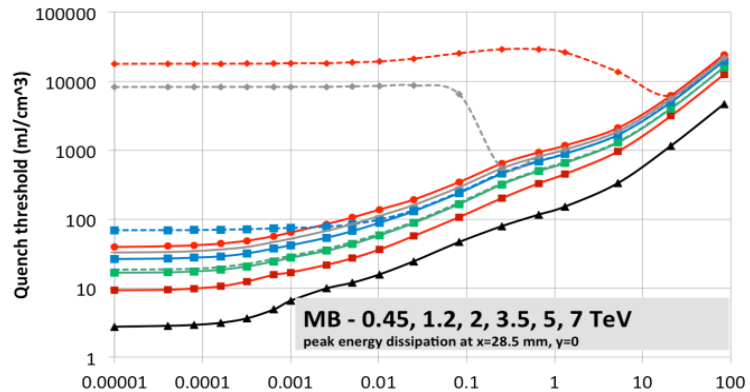
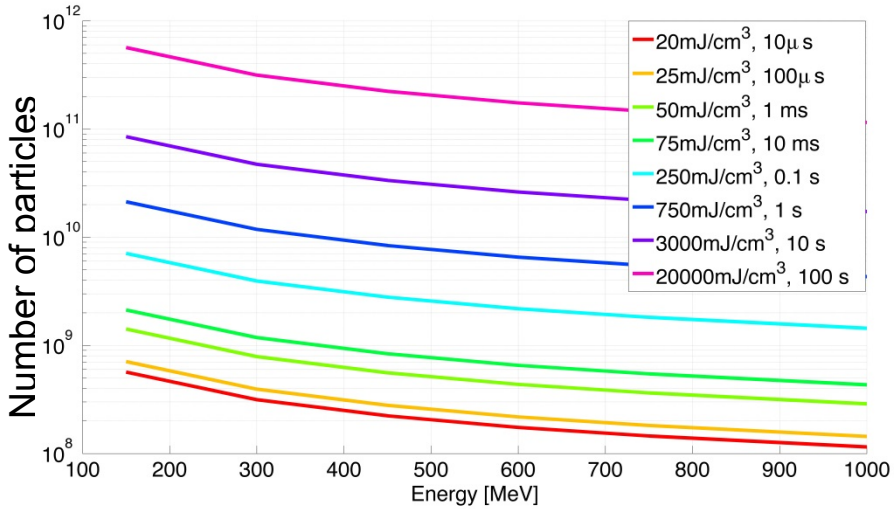


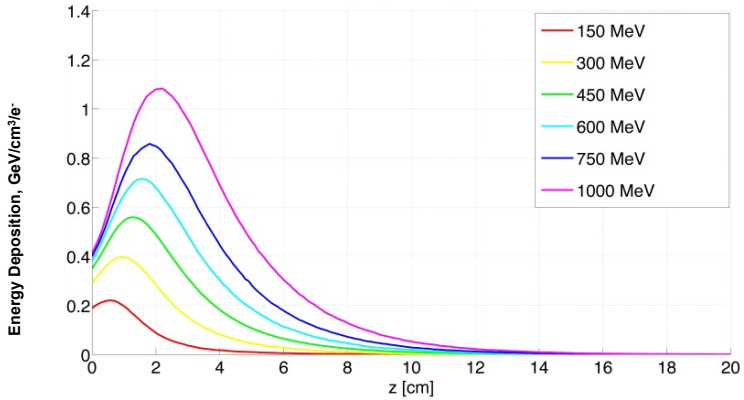
Beam parameters to generate a given amount of energy deposition

electrons needed to quench the magnet = $\frac{\text{Quench threshold}}{\text{Maximum value for the energy deposition}}$



MB quench limit @ 3.5 TeV





1 GeV = 1.602 x 10^{-7} mJ

MB quench limit 450 GeV is 140mJ/cm^3 in 10ms:

~2.2 x 10^9 e$^-$ @ 1GeV necessary

MB quench limit 7 TeV is 16 mJ/cm^3 in 10ms:

~2.6 x 10^8 e$^-$ @ 1GeV necessary