Dario Pellegrini
on behalf of Alessandra Valloni

CERN SC RF AND ERL TEST FACILITY PLANS

ERL 2015
Workshop on Energy Recovery Linacs

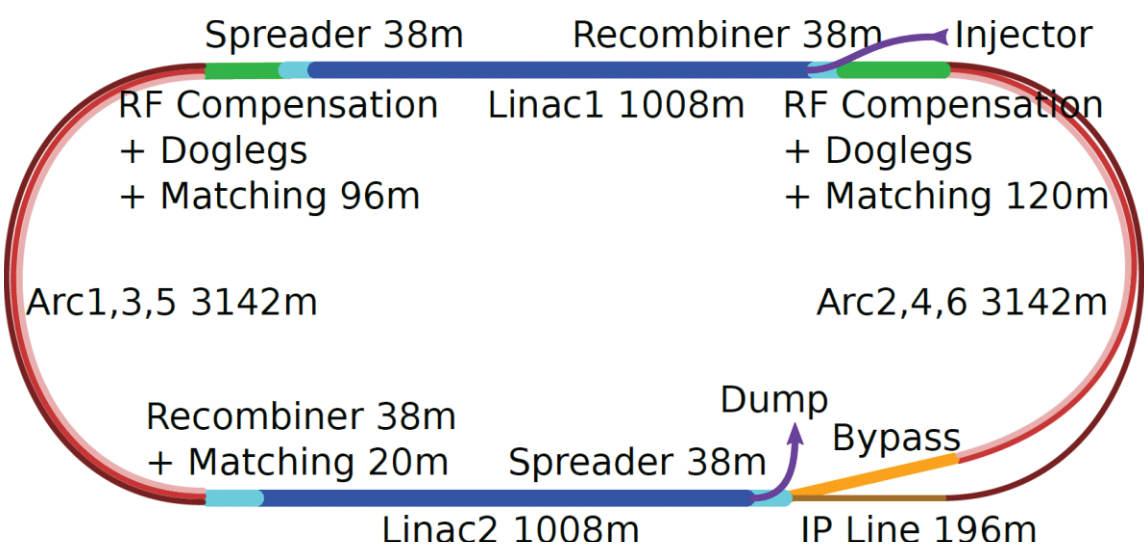
CERN

Electron-Hadron collisions at CERN

The **LHeC** is an accelerator study for a possible upgrade of the existing LHC

By adding a new electron accelerator, the LHeC would enable the investigation of electron-proton collisions at unprecedented high energies and rate.

The baseline design consists of a 3-pass ERL to provide a 60 GeV, high-current e^- beam



In parallel a design study for an ERL test platform is being pursued at CERN to test machine and operation issues before designing a large scale facility

LHeC ERL Facility & SC RF

FUNDAMENTAL MOTIVATION:

- **Proof validity of fundamental design choices:**
  Three-turns acceleration + three-turns deceleration
  (other existing ERLs have only two passages)
  Implications of high current operation (6 * 10mA > 60mA in the linacs!)

- **Build up expertise 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.)

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

Goals of the ERL Facility

Dedicated Accelerator physics studies and R&D:

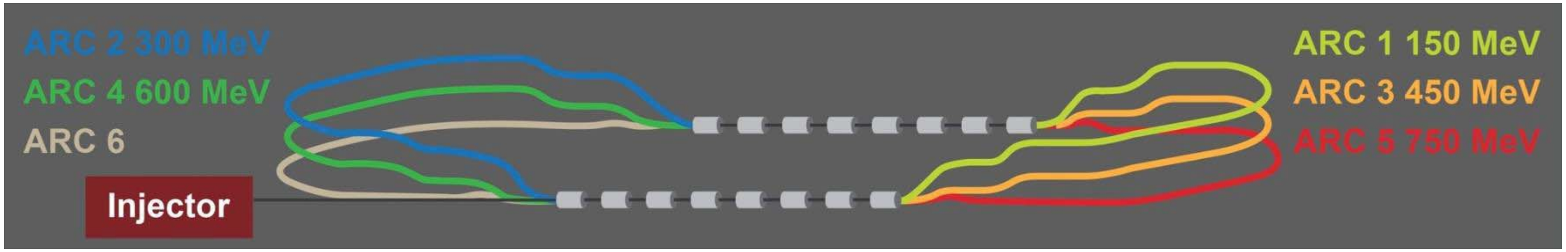
- Injector studies
- Beam diagnostics developments and testing with beam
- Could it be foreseen as the injector to LHeC ERL and to FCC?

Scientific and technical applications:

- Possible use for detector development
- Controlled quench and damage test for SC magnets
- Generation of gamma-ray beams via Compton backscattering

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

*in few stages



Outline

1. DESIGN STAGES AND PARAMETERS
2. MACHINE DESIGN
3. SC RF
4. PLANNING AND TIMELINE

Planning for each stage

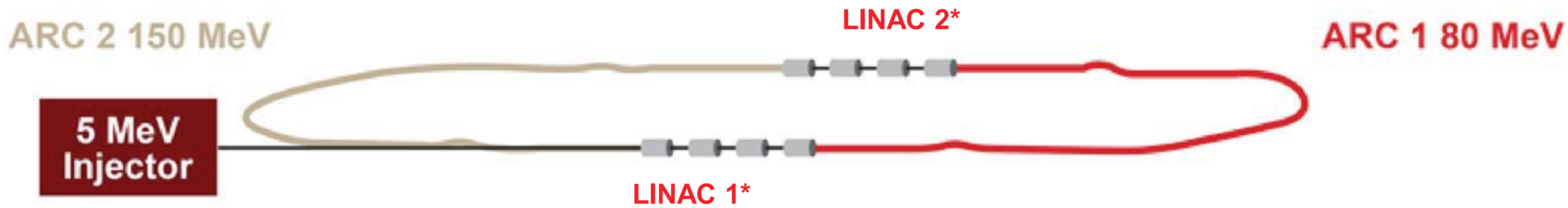
STEP 1

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

Two cryomodules with 4 SRF 5-cell cavities at 801.58 MHz.
Clear path already established in collaboration with JLab to obtain a prototype.



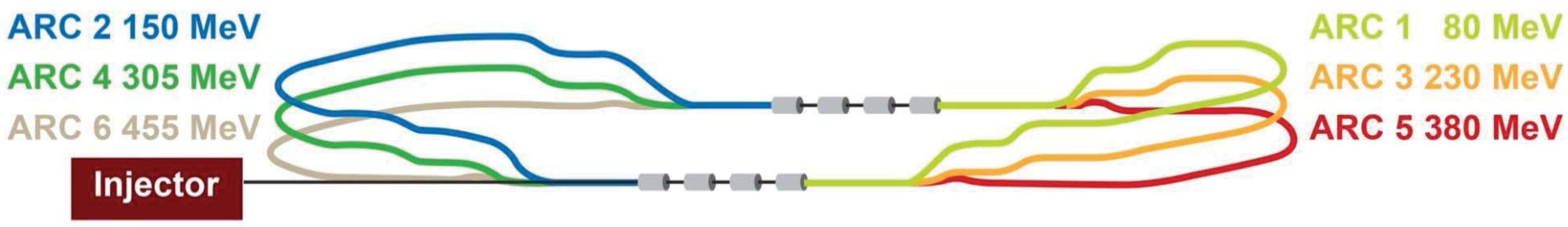
Planning for each stage

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

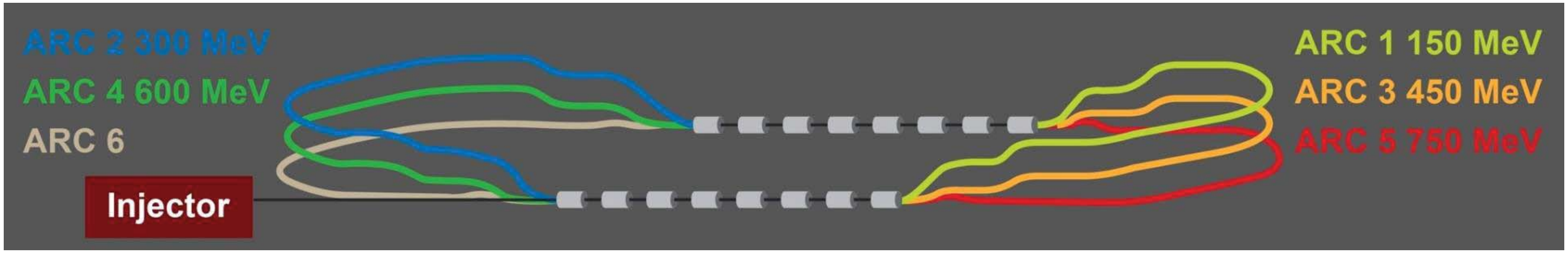
STEP 3

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



Outline

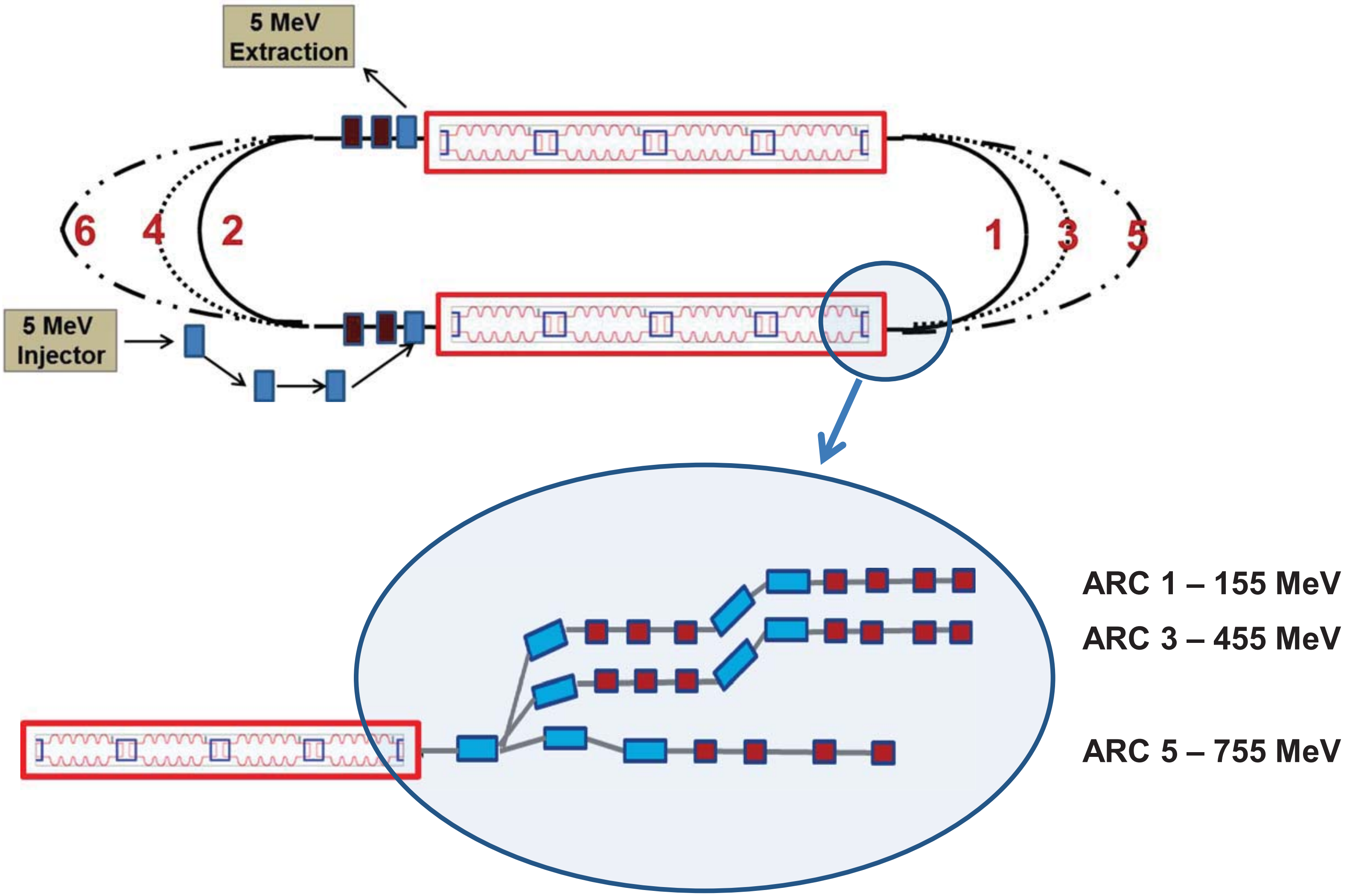
1. DESIGN STAGES AND PARAMETERS

2. MACHINE DESIGN: LAYOUT AND OPTICS
   MAGNET INVENTORY
   TRACKING SIMULATIONS

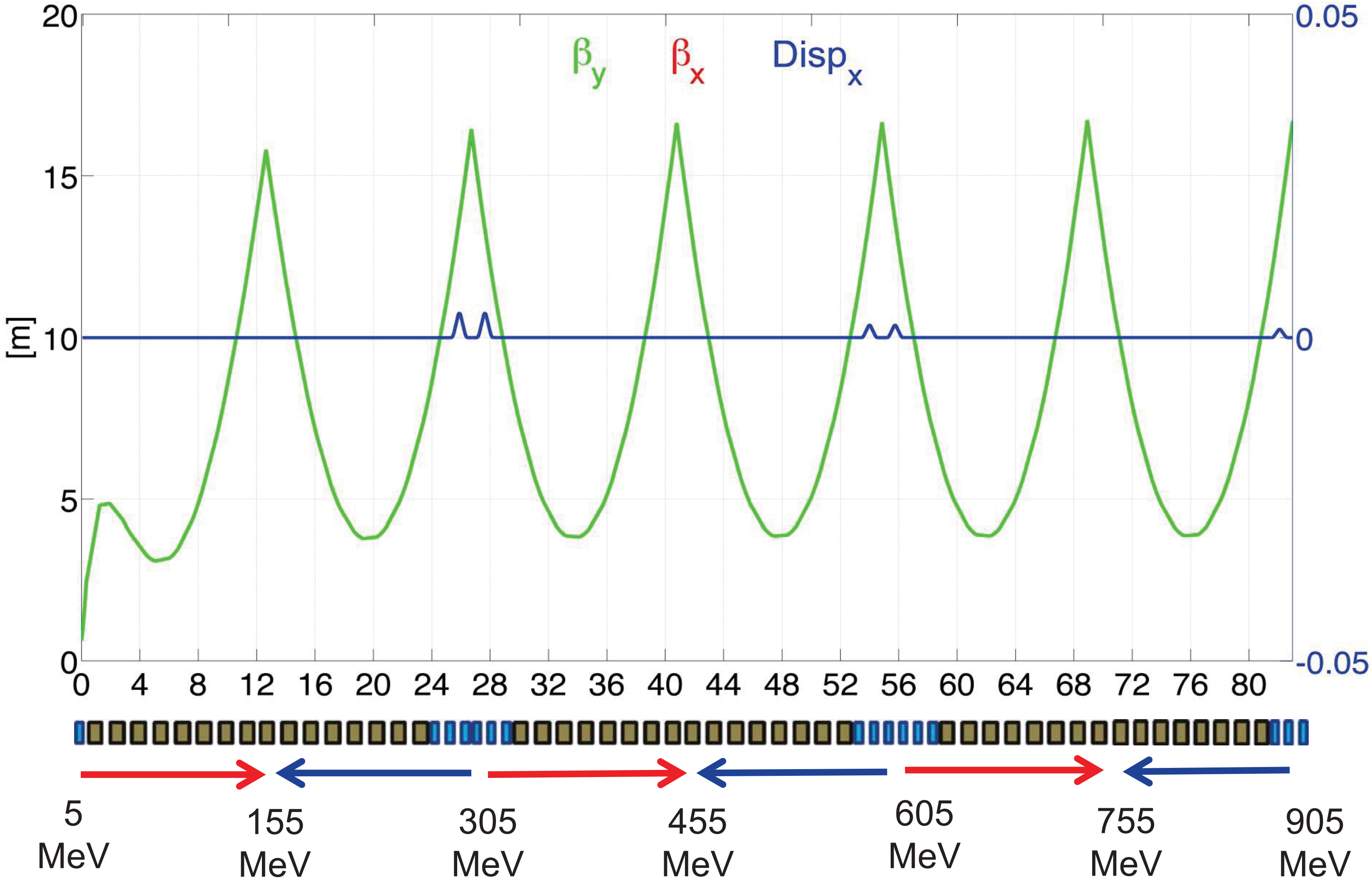
3. SC RF

4. PLANNING AND TIMELINE

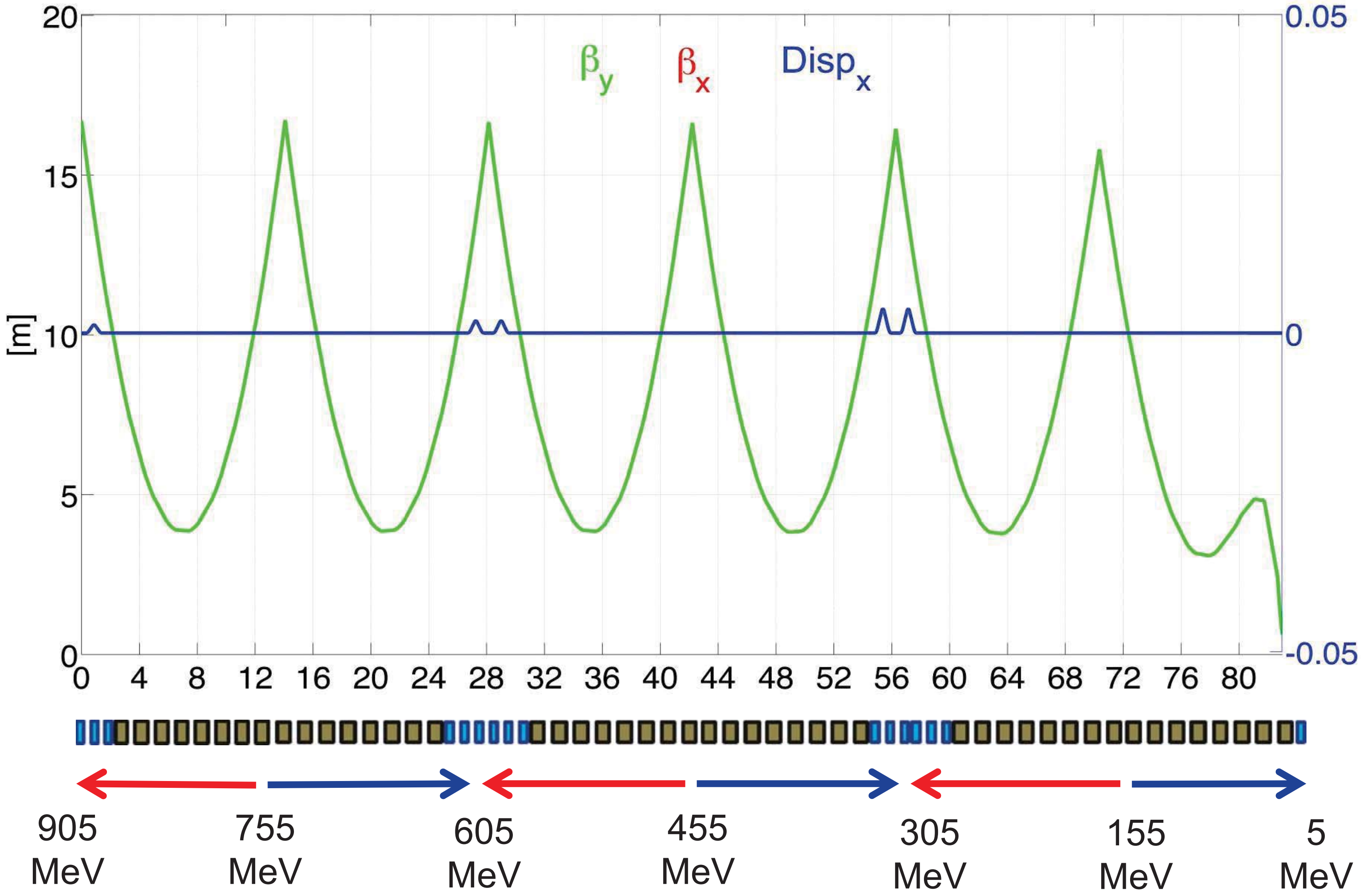
Layout


5 MeV Extraction
6
4
2
1
3
5
5 MeV Injector
ARC 1 – 155 MeV
ARC 3 – 455 MeV
ARC 5 – 755 MeV

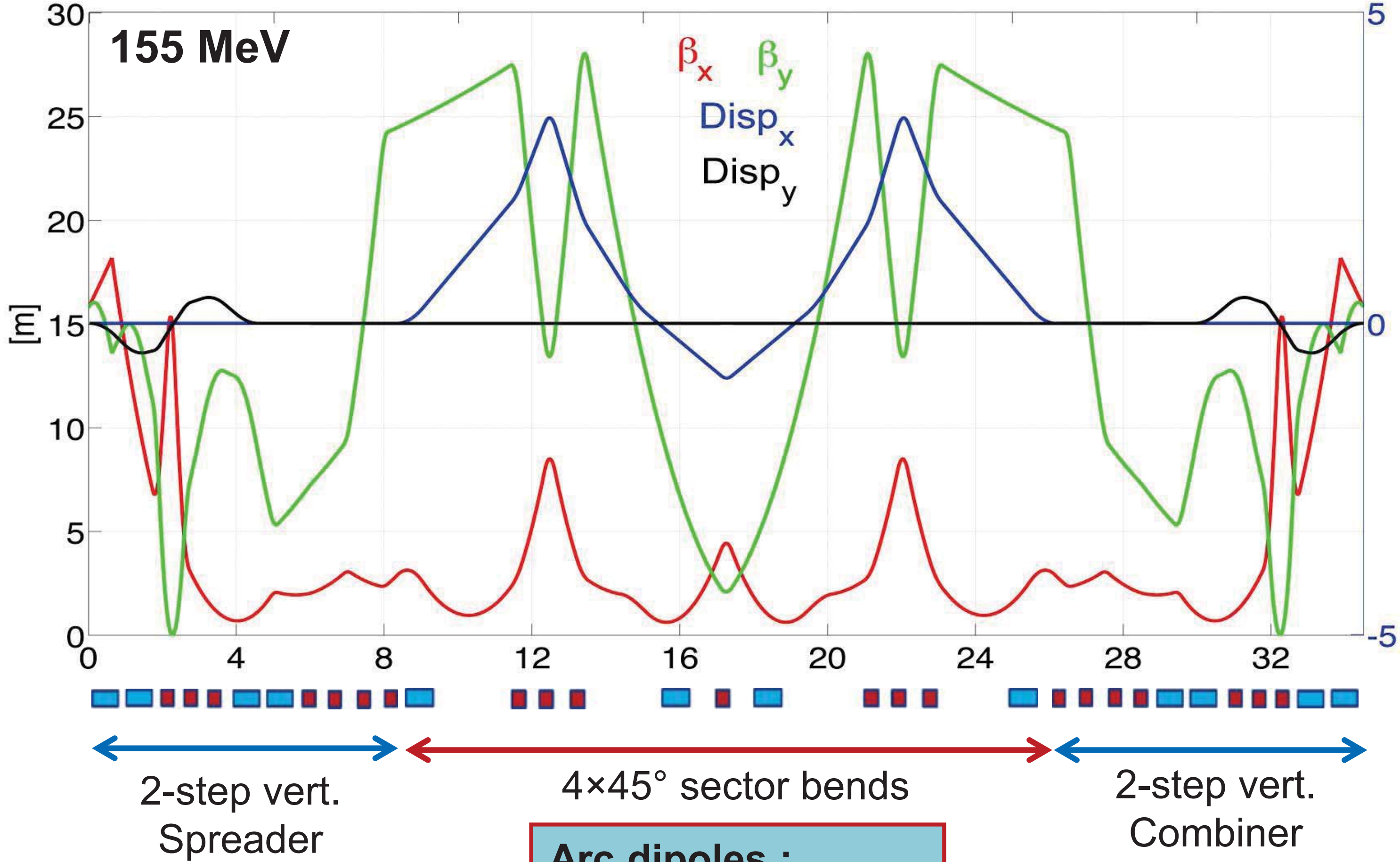
Linac 1 Multi-Pass Optics



Linac 2 Multi-Pass Optics



Arc 1 optics



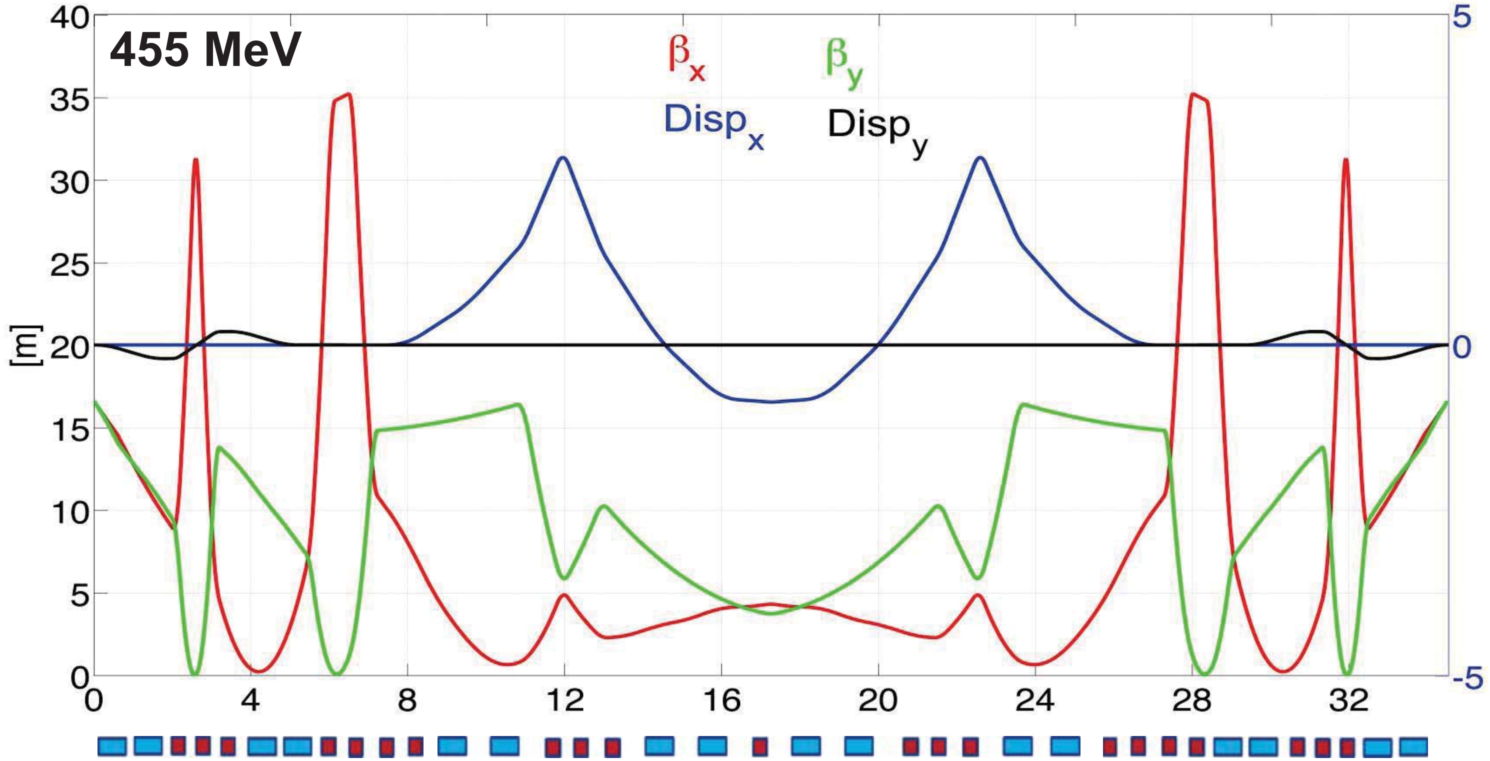
Arc dipoles :

Ldip = 71.8 cm

B = 5.67 kGauss

ρ = 91.45 cm

Arc 3 optics



2-step vert. Spreader

8×22.5° sector bends

2-step vert. Combiner

9.8° bends

(1 rec. + 3 sec.)

Arc dipoles :

Ldip = 90.58 cm

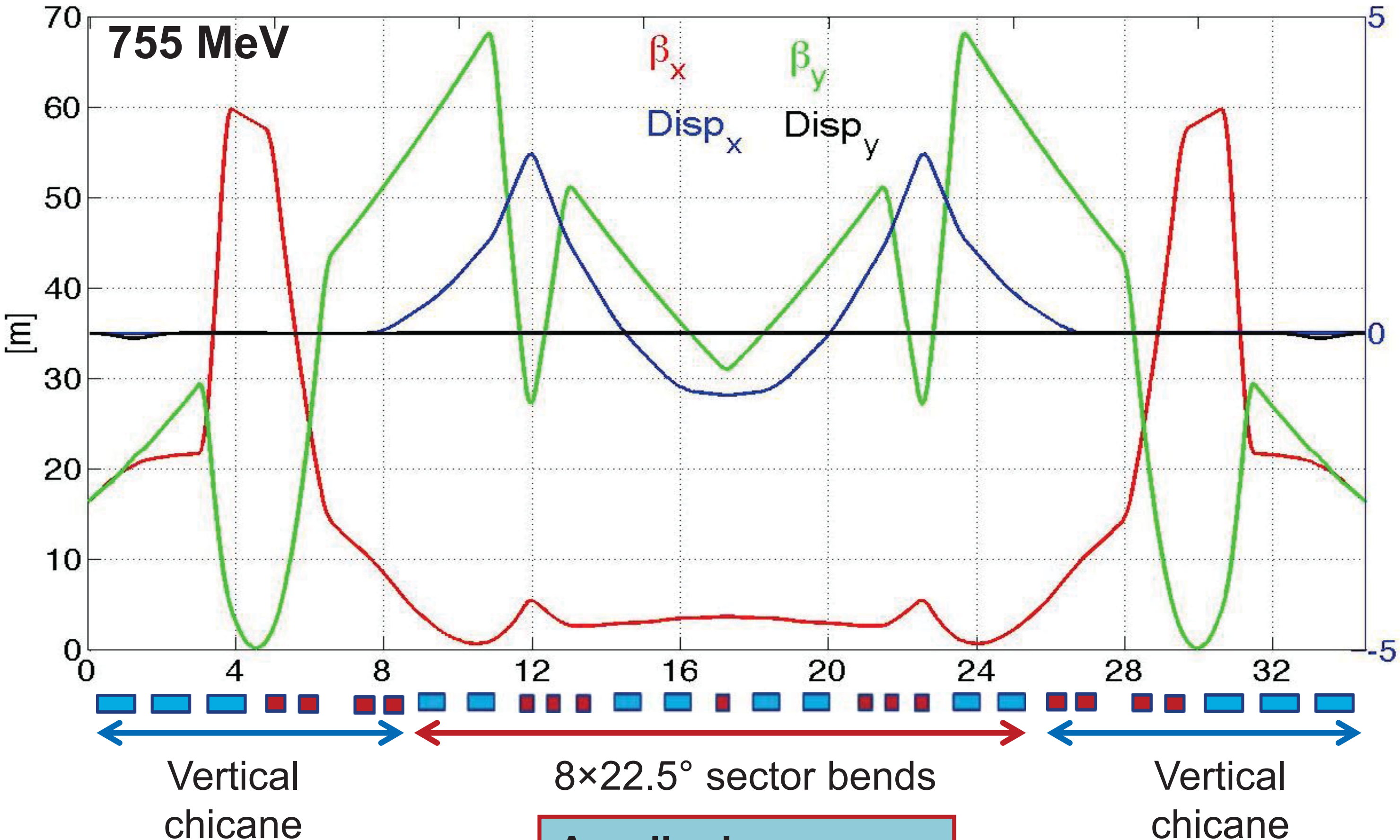
B = 6.58 kGauss

ρ = 230.66 cm

9.8° bends

(1 rec. + 3 sec.)

Arc 5 optics



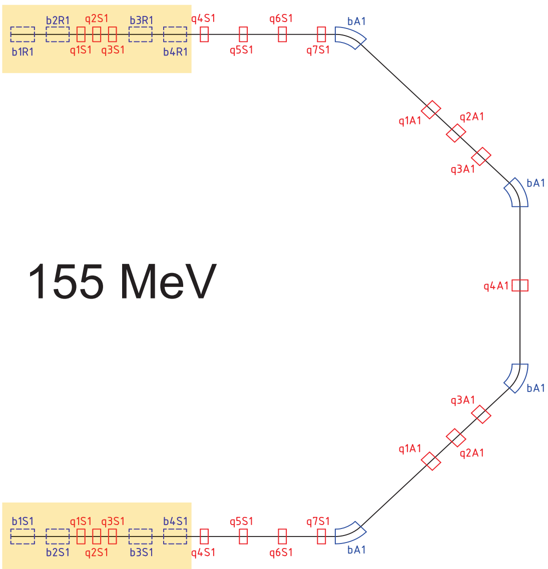
Arc dipoles :

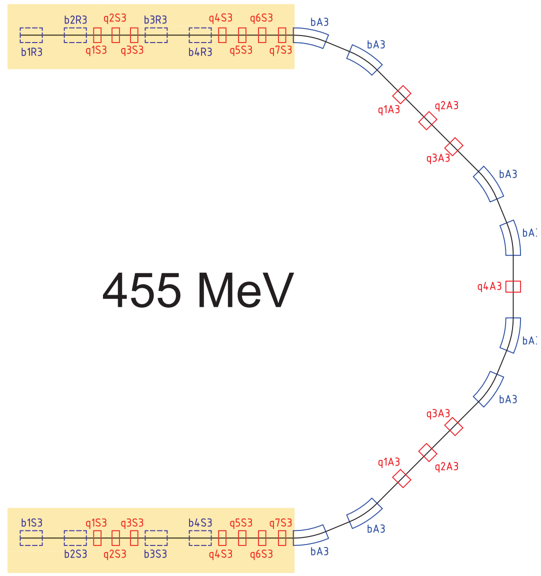
Ldip = 90.58 cm

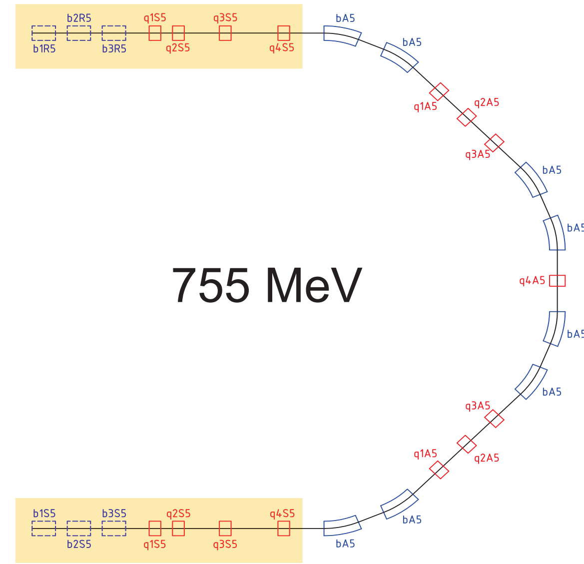
B = 10.92 kGauss

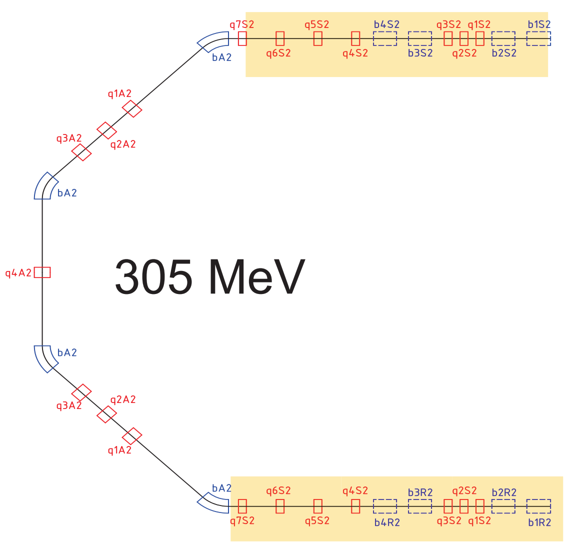
ρ = 230.66 cm

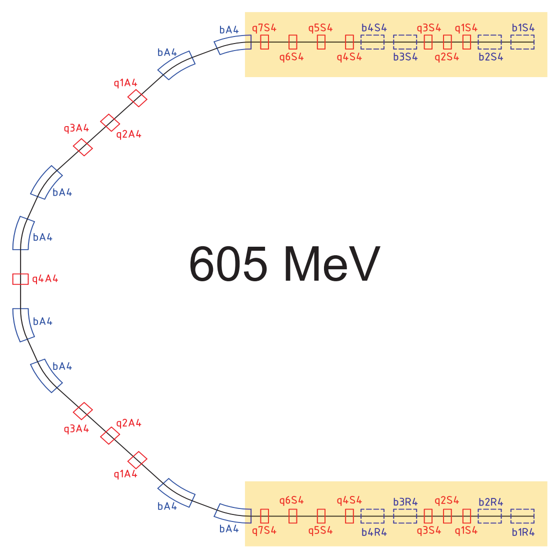
Magnets inventory

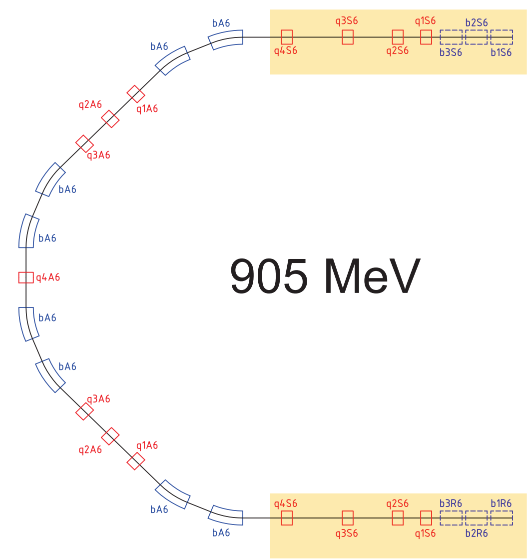












Summary of magnets inventory

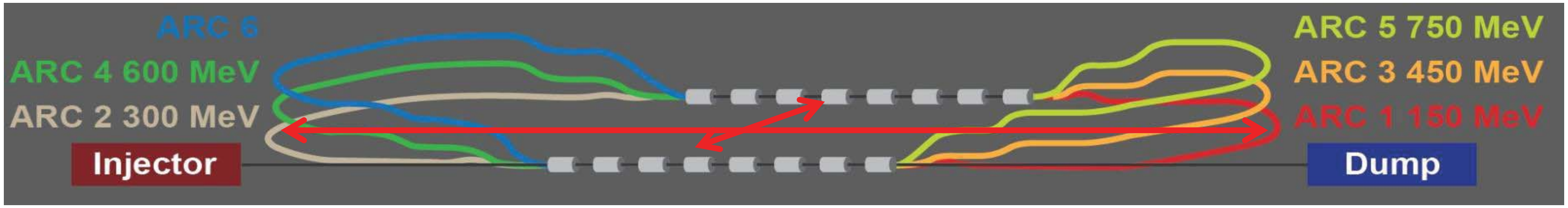
A preliminary inventory of the magnets of the ERL Facility lists:

- 40 bending magnets (vertical field)
- 36 bending magnets (horizontal field) in the spreaders / combiners
- 114 quadrupole magnets
- a few magnets in the injection / extraction parts

Conventional iron-dominated resistive magnets can be used

ARC	ENERGY	LENGTH	# QUADS	# DIPOLES
ARC 1	150 MeV	35.98 m	21	12
ARC 2	300 MeV	35.74 m	21	12
ARC 3	450 MeV	35.61 m	21	14
ARC 4	600 MeV	35.74 m	21	14
ARC 5	750 MeV	35.98 m	15	12
ARC 6	900 MeV	34.43 m	15	12
TOTAL		297.9 m	114	76

Footprint



ARCS

Total length for Pass 1
99.86 m
267 x λrf = 20*n* λrf +7*λrf

Total length for Pass 2
99.48 m
266 x λrf = 20*n* λrf +6*λrf

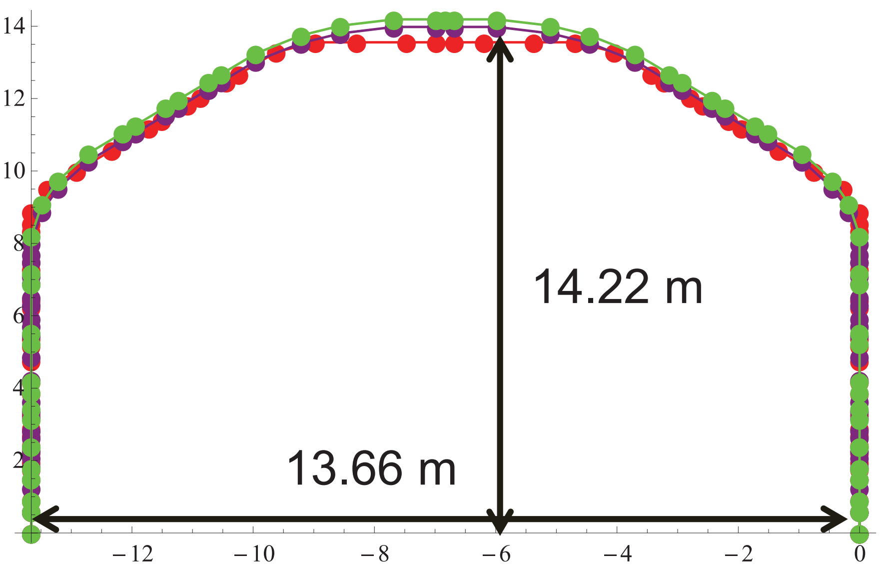
Total length for Pass 3
98.55 m
263.5 x λrf = 20*n* λrf +**3.5***λrf

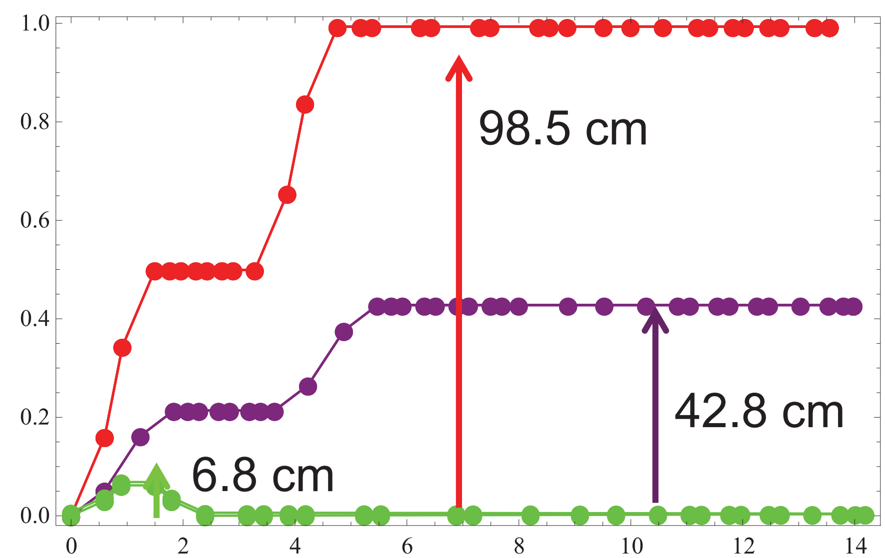
LINAC

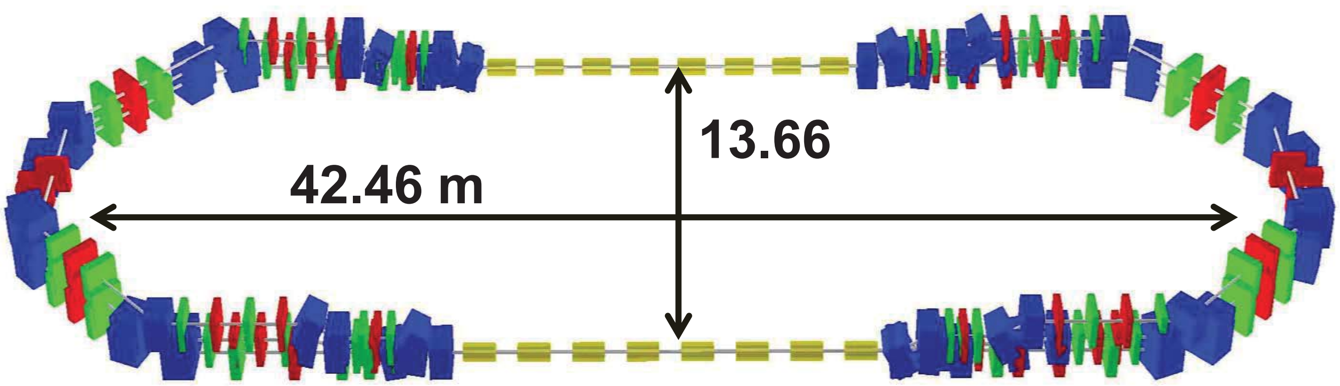
Linac length ~ 12.6 m
Chicane inj/extr length ~ 1.42 m
F= 801.58 MHz
λrf = 37.4 cm

Total length for 3 passes
297.9 m

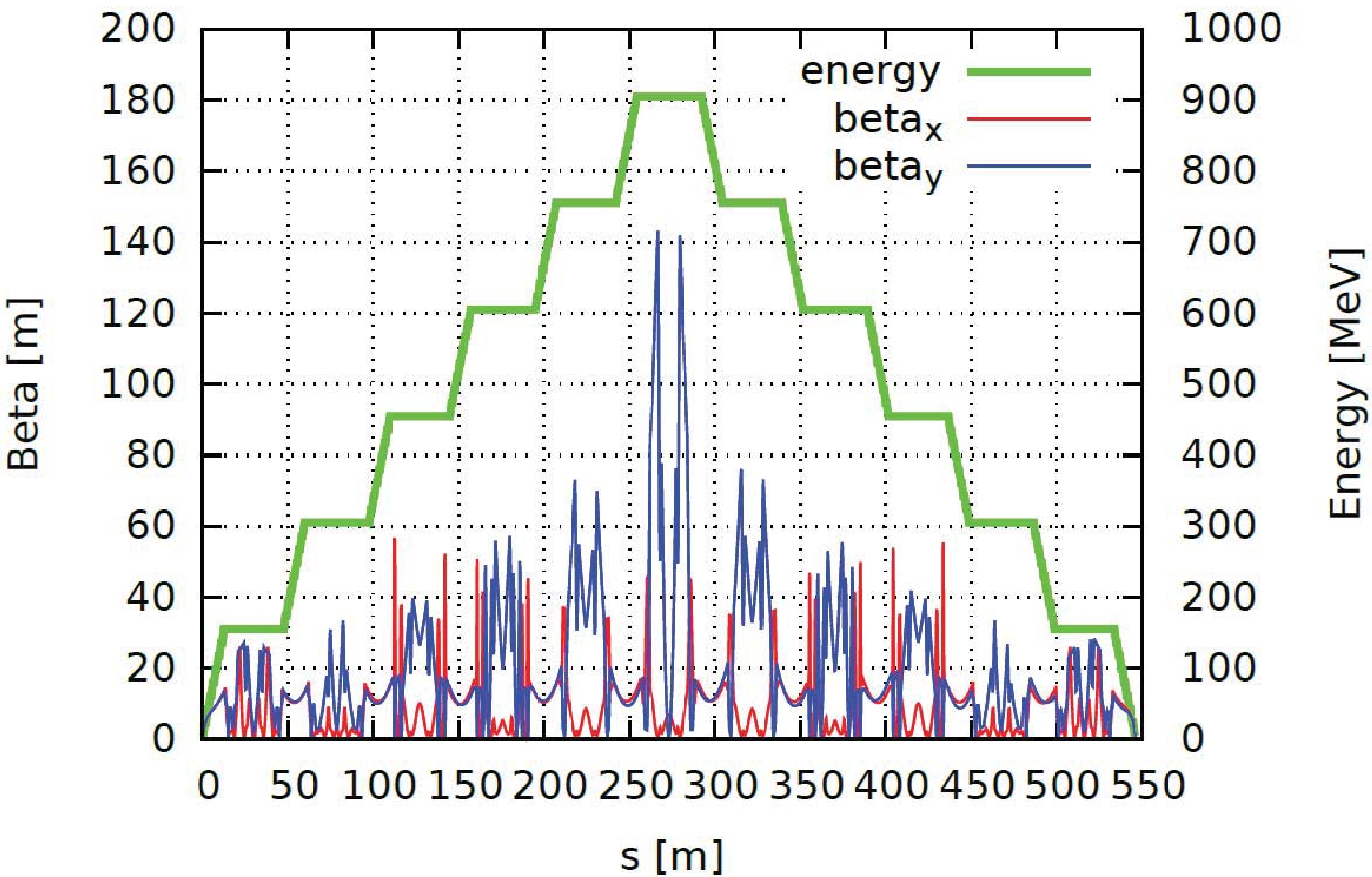
Arc layout


14.22 m
13.66 m
14
12
10
8
6
4
2
−12
−10
−8
−6
−4
−2
0


98.5 cm
42.8 cm
6.8 cm
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10
12
14

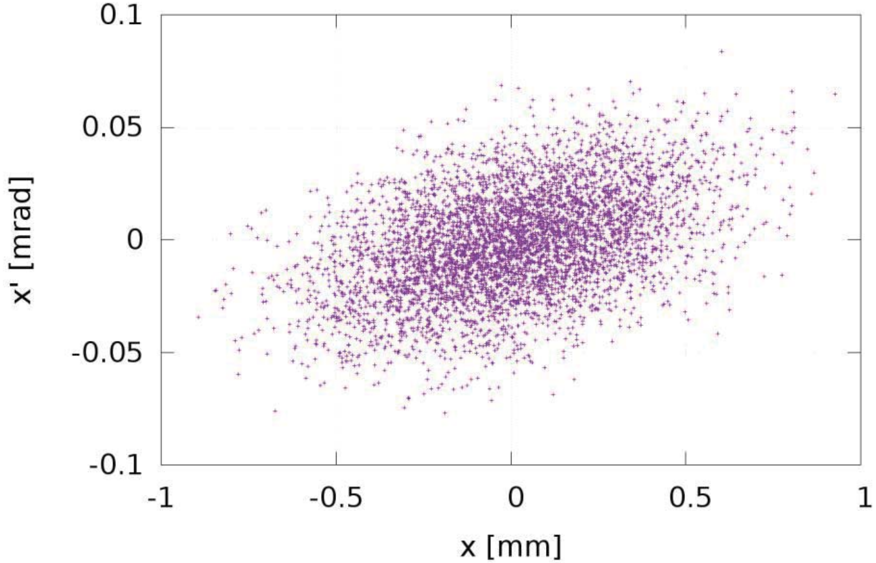

13.66
42.46 m

Start-to-end Optics with PLACET2*

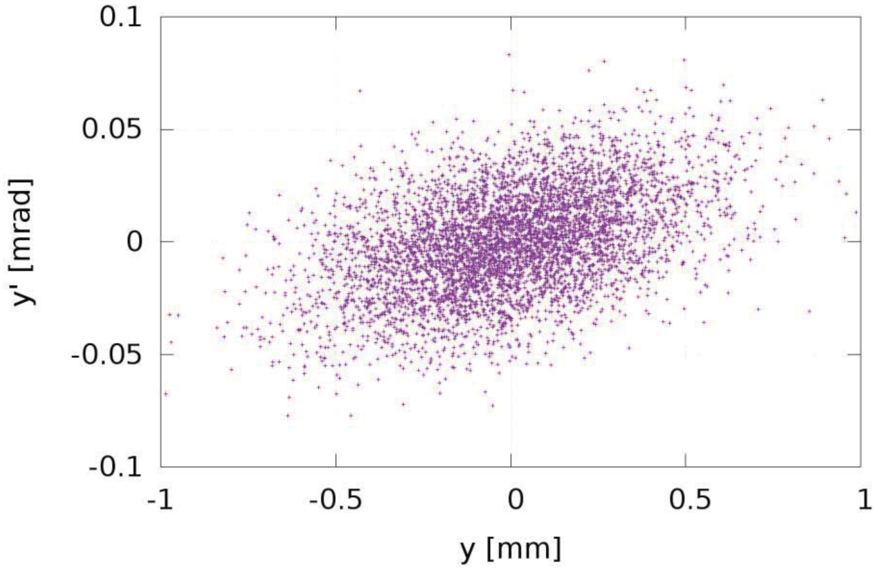


Transverse Phase space at 900 MeV
(PLACET2 – only optics)

Horizonal phase space
at 900 MeV



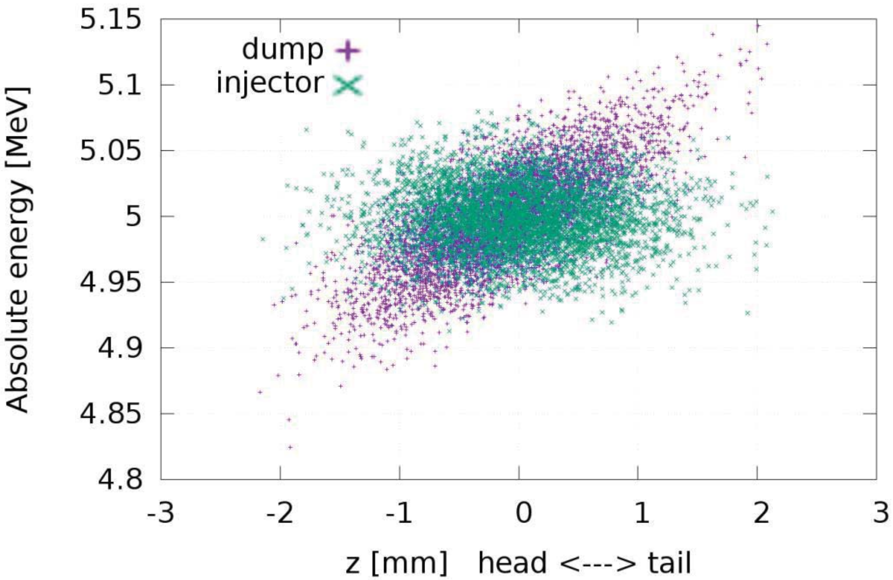
Vertical phase space
at 900 MeV

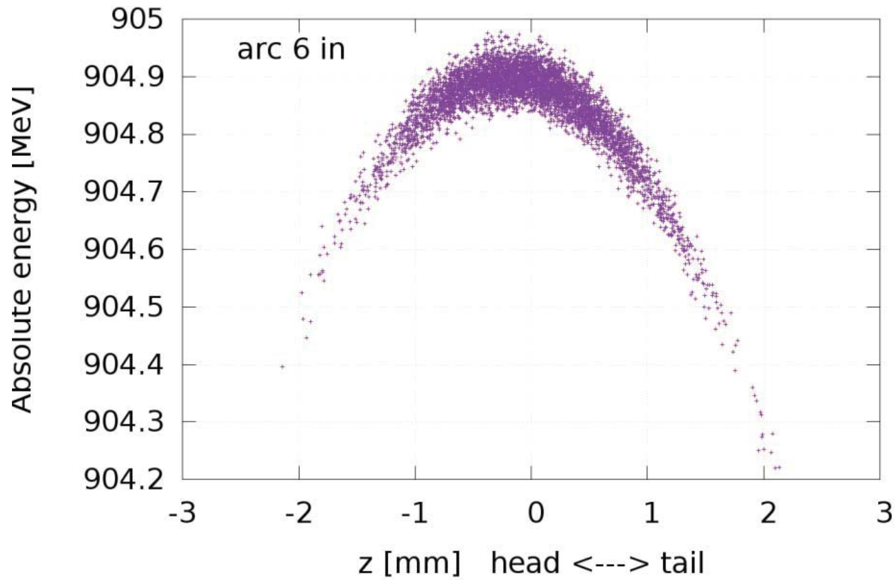


Very well preserved phase space and transverse emittance at 900 MeV and down to the dump

Small impact of (coherent) synchrotron radiation verified with Elegant
Small impact of short-range wakefields expected (to be futher investigated)

Longitudinal Phase Space
(PLACET2 – only optics)





Bunch length preservation down to dump (very good isochronicity)
Some energy chirp at dump -> requires fine tuning of the arc lengths

With 6 mm long bunches, the RF curvature can be seen at high energy, still extremely small energy spread: 5 ‰ at injector -> 0.1 ‰ at 900 MeV

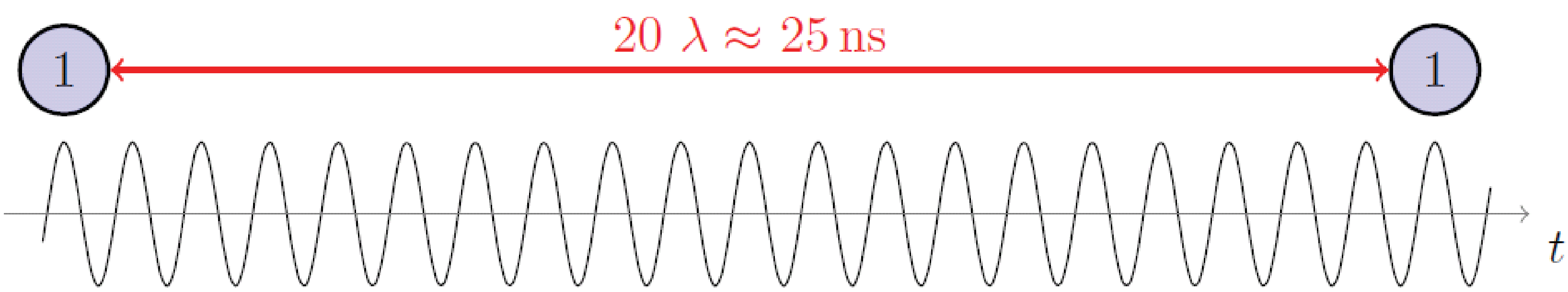
Possibility to introduce enegy chirp and tune the arcs R_{56} to manipulate the phase space

Recombination Pattern

Multi-bunch effects are enhanced by the parameter:

$$\int \frac{\beta}{E} ds$$

- β → Almost the same for every passage in the linacs
- E → Varies substantially



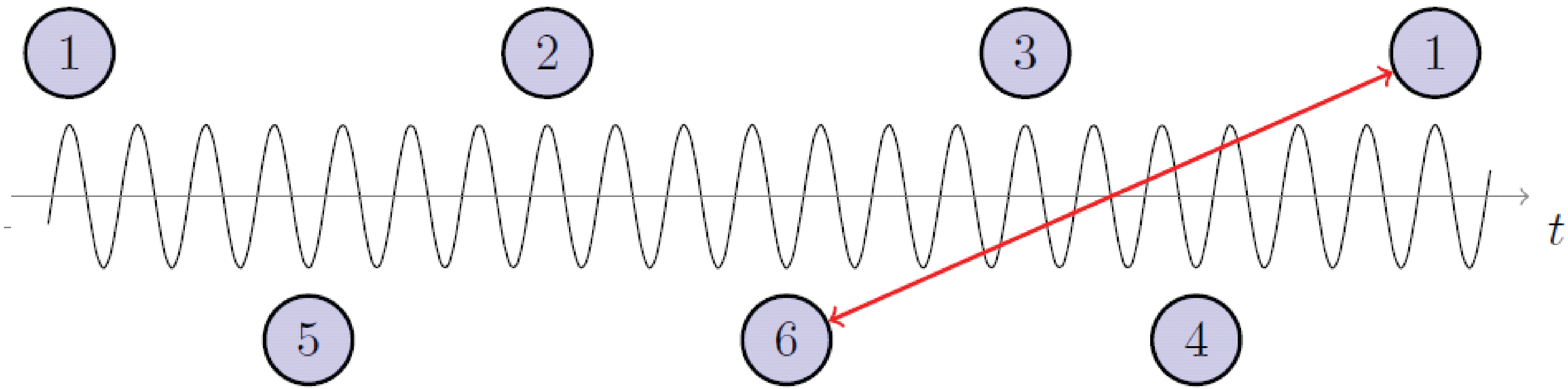
The bucket filling at subsequent turns can be controlled tuning the length of the arcs

Recombination Pattern

Multi-bunch effects are enhanced by the parameter:

$$\int \frac{\beta}{E} ds$$

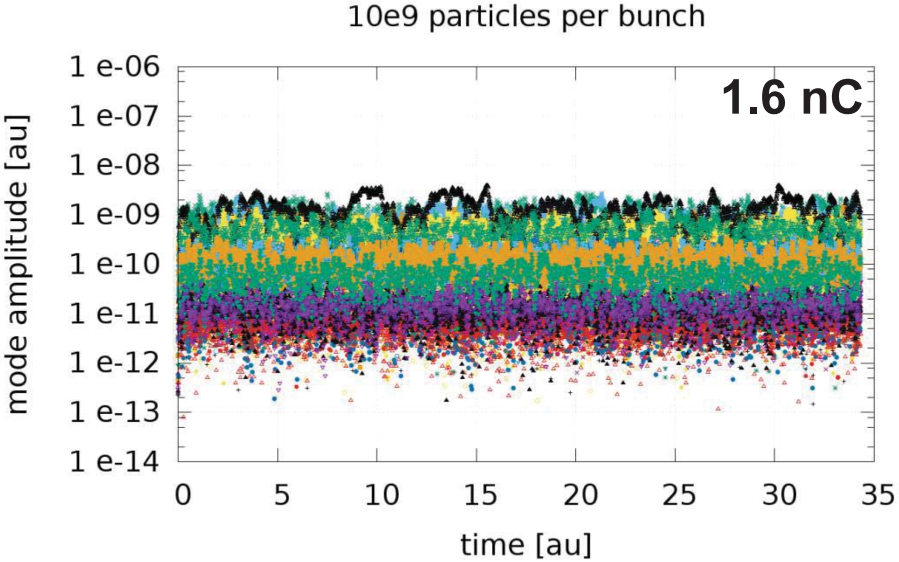
- β → Almost the same for every passage in the linacs
- E → Varies substantially

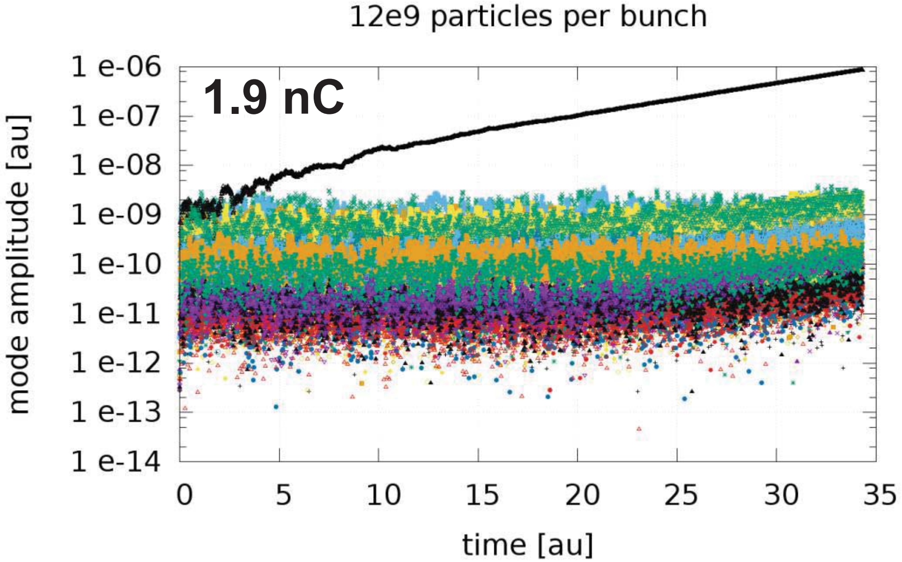


Maximum separation between lowest energy passages minimizes the bunch cross-talk

Long Range Wakefields Threshold Current

Multi-bunch tracking simulations with PLACET2 and optimal recombination pattern
26 dipole modes of the SPL cavity scaled to 802 MHz
100 particles per bunch – BBU triggered by statistical fluctuations of the centroid



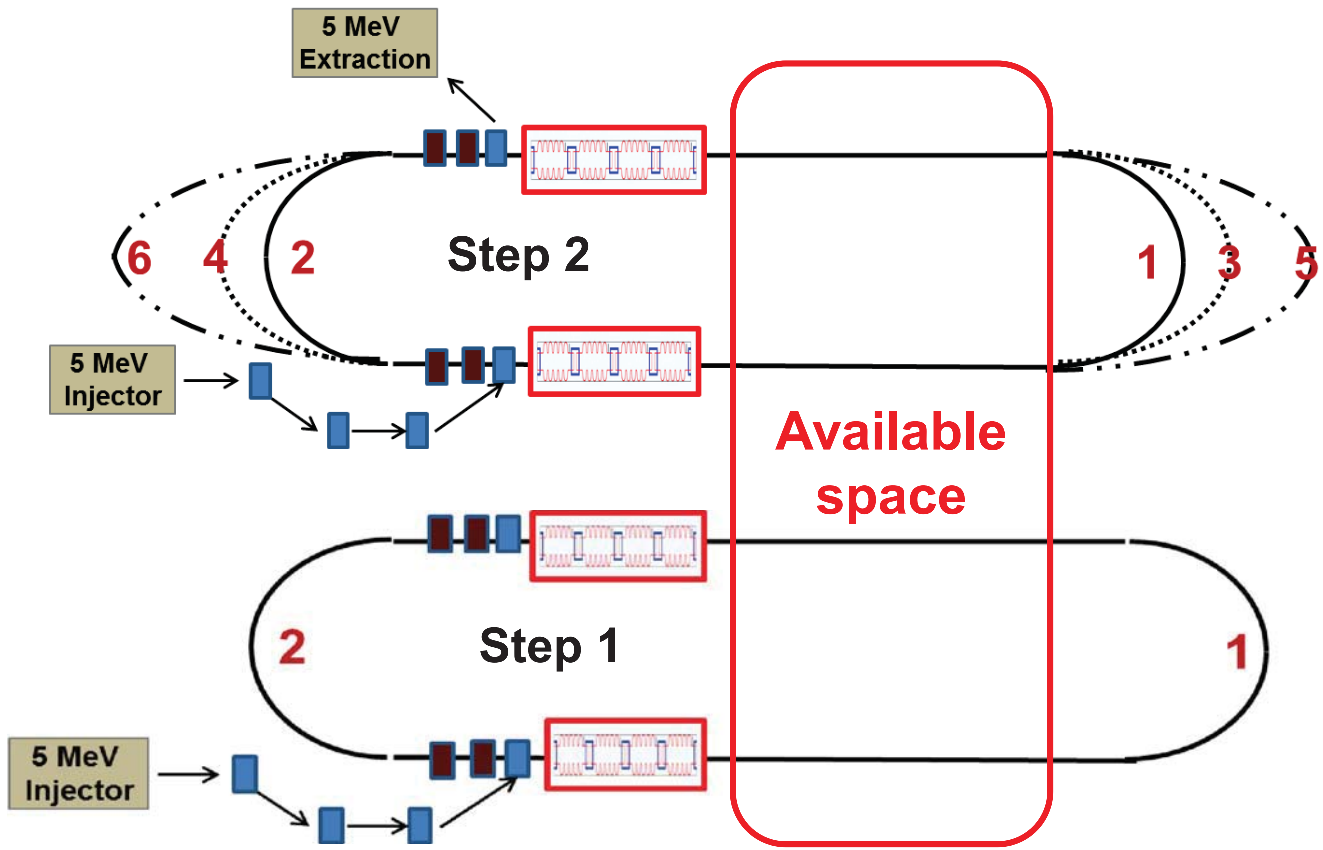


Offending mode builds up in the vertical plane (coupling between a specific mode frequency, time of flight and the vertical betatron tune)

Threshold current >5 times higher than the nominal (2e9 particles per bunch)

Optics for steps 1 and 2

- Complete Step 2 and Step 1 configuration and optics layout



Outline

1. DESIGN STAGES AND PARAMETERS

2. MACHINE DESIGN

3. SC RF

4. PLANNING AND TIMELINE

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 Facility (ERLF)

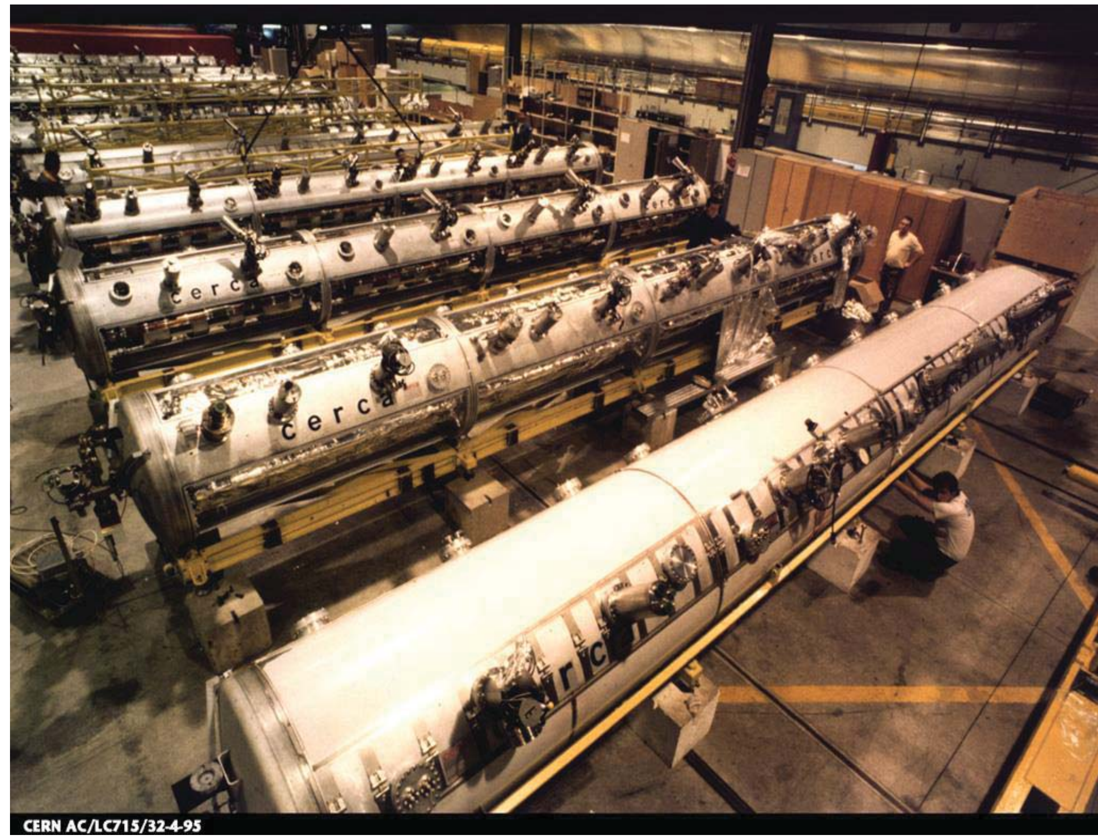
We have started this study and have started to establish collaborations

SC RF Activities at CERN

… in the nineties (LEP)

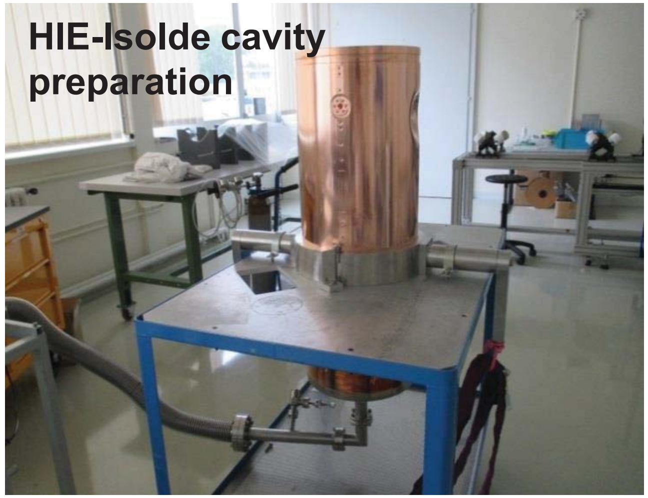
At LEP II times, CERN had the largest SRF installation

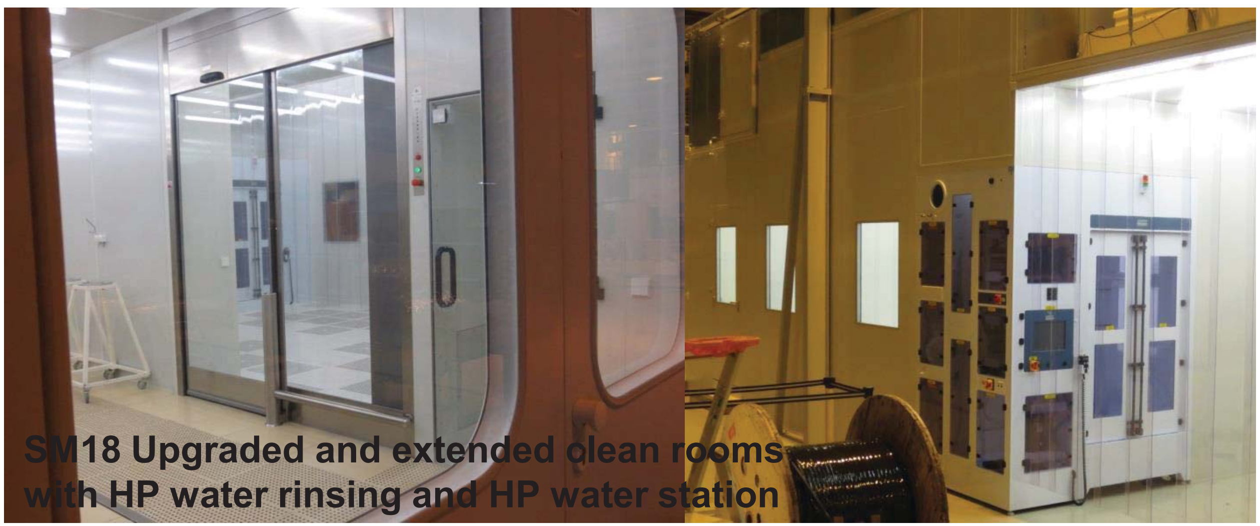
Karl Schirm and Albert Insomby 'operate' on a superconducting radio frequency cavity in a clean room



SC RF Activities at CERN

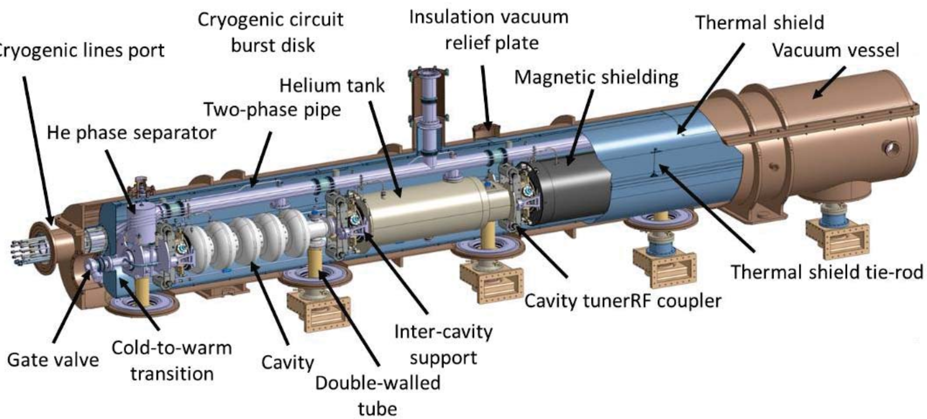
…today (1/2)



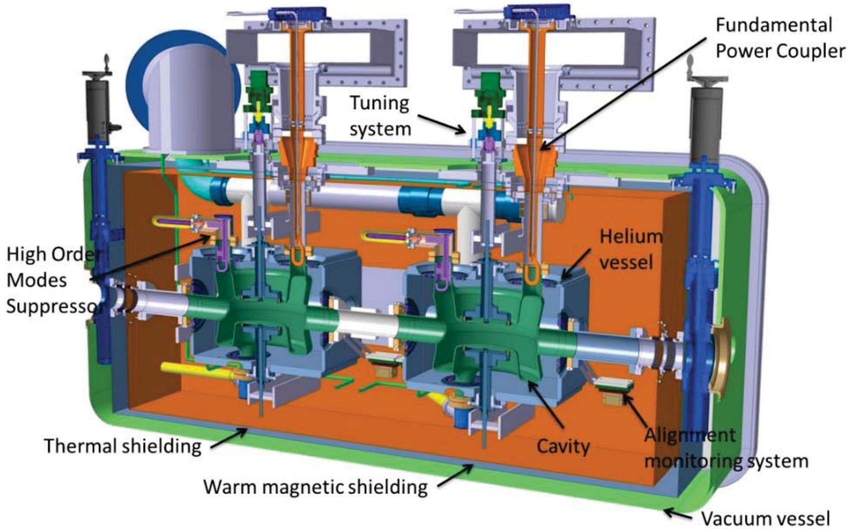


SC RF Activities at CERN

…today (2/2)



SPL cryomodule
Frequency = 704 MHz
Novel cavity suspension by FPC
cavities in bulk Nb



HL-LHC crab cavities,
Frequency = 400 MHz,
2-cavity prototype CM
cavities in bulk Nb
(fabricated at Niowave)

SC RF Activities at CERN

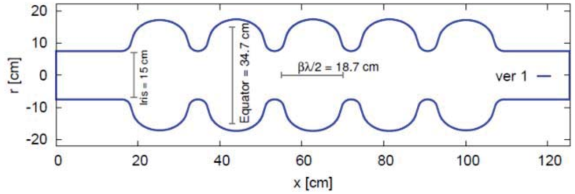
The CERN SRF R&D has to cover many areas, accelerators, technologies.
Where possible, choices were made to exploit synergies!

PROGRAMME	FREQUENCY	TECHNOLOGY
LHC, spare and more	400 MHz	Nb on Cu
LHC upgrade	800 MHz	Nb on Cu? Bulk?
HIE-ISOLDE	101 MHz	Nb on Cu
CRAB	400 MHz	Bulk Nb
SPL (ESS)	704 MHz	Bulk Nb
ERL-Facility, FCC-he	800 MHz	Bulk Nb
FCC-ee, FCC-hh	400 & 800 MHz	Nb on Cu & bulk

SCRF @ the ERL FACILITY

PARAMETER	VALUE
RF frequency	801.58 MHz
Acc. Voltage/cavity	18.7
# Cells/cavity	5
Cavity length	~ 1.2 m
# Cavities/cryomodule	4
RF power/cryomodule	< 50 MW
# Cryomodules	4
Acceleration/pass	300 MeV
Bunch repetition	40 MHz
Duty factor	CW

Initial Cavity Design (SPL, JLAB and BNL experience)

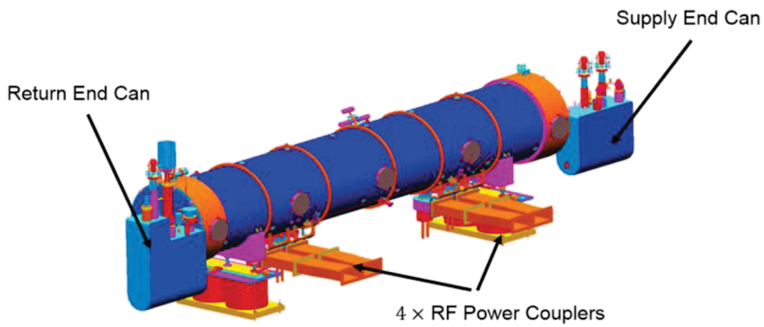


Possibility to install and test cavities at other European frequencies (ESS, SPL,…), (LHC harmonic, SPS, LHeC, FCC,…) (XFEL, ILC) if:

- Photocathode pulsing at a sub-harmonic (12.16 MHz)
- Tunable arc length (10 cm) to match the phase

Cryomodule Design

JLAB had designed an 805 MHz cryomodule for SNS (concept for the 801.58 MHz baseline design)



Established collaboration with JLab taking advantage of their experience with CEBAF and the FEL in ERL mode:

- crucial contributions already obtained for the machine layout and lattice
- design and construct the 801.58 MHz cavities and cryomodules.

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1. DESIGN STAGES AND PARAMETERS

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4. **PLANNING AND TIMELINE**

ERL Facility at CERN for Applications

- Facility for testing quench and damage levels of SC wires and SC magnets
  - Intensities and repetition rates
  - Space, powering and other requirements

- Generation of high-energy monochromatic polarized photons via Compton backscattering of laser light from relativistic electrons for nuclear physics research
  - Investigate the maximum energy and flux of the gamma-beam generated
  - Define the laser requirements according to the electron beam parameters

ERL facility at CERN for applications, *Erk Jensen*
WG5 Session 1: ERL Applications
Wednesday June 10, 9:50 am

Possible Site options

- Many site possibilities presented @ January 2014 LHeC Workshop

Three main options:

- **Point 2 @ ALICE –** apparently hosting power converters (tbc)
- **SM18 –** existing cryogenic and powering infrastructure, but no available space
- **Prevessin site** – still under investigation

Site specific studies are foreseen
for the ERL TF and auxiliary applications
in preparation for the ERL TF CDR

Planning for the CDR

- Draft a preliminary version by the end of June 2015:

To be presented at the next **LHeC Workshop***

CERN (24 June) and Chavannes-de-Bogis (25-26 June)

Organization committee:
S. Bertolucci, F. Bordry, O. Bruning, L. Hemery, M. Klein

- Complete CDR by the end of 2015

* https://indico.cern.ch/event/356714/

LHeC Workshop

<u>**International Advisory Committee:**</u>
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Frederick Bordry (CERN)
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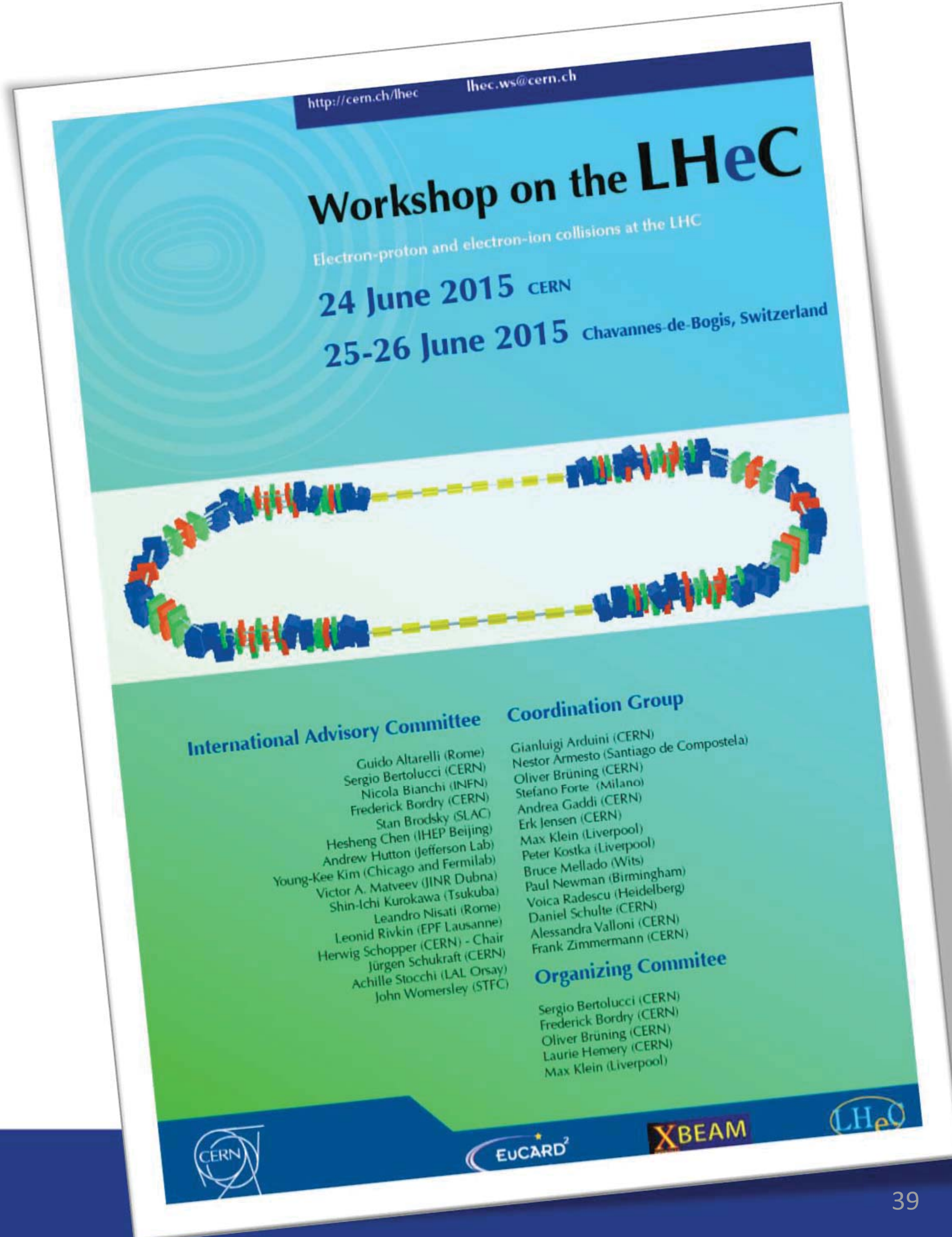
Erk Jensen (CERN)



Summary

- **An ERL platform is being pursued at CERN to validate the LHeC key design choices along with dedicated physical and technical applications**
- The concept of the ERL Facility is designed to allow for a staged construction with verifiable and useful stages for an ultimate beam energy in the order of 900 MeV
- An optics design study of the ERLF has been completed and start-to-end analysis are on going
- Design complementary to & synergetic with other proposals worldwide
- Collaborations with other institutes have been started
- Completion of Conceptual design study of an ERLF at CERN by 2015

Thank you for your attention

...and thanks to the LHeC collaboration, in particular to

A. Bogacz, O. Bruning, V. Chetvertkova, *E. Jensen, M. Klein*, D. Wollmann, *F. Zomer*

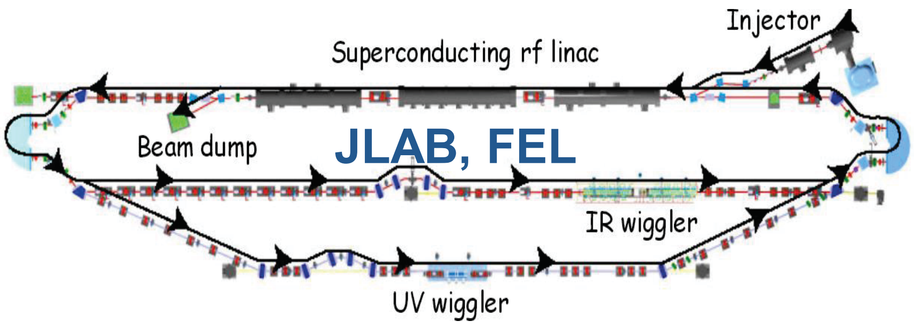
http://lhec.web.cern.ch

www.cern.ch

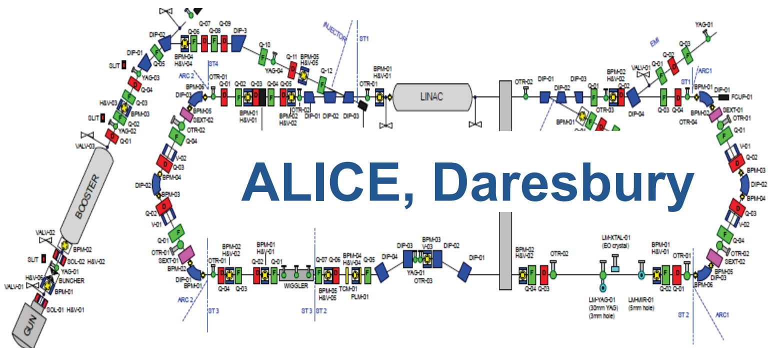
LHeC as an Higgs Factory: ultimate IP parameters

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
Average Beam Current [mA]	1112	25 delivered 150 in linacs
Bunch Spacing [ns]	25	25
Bunch Population	$2.2*10^{11}$	$4*10^{9}$
Bunch charge [nC]	35	0.64

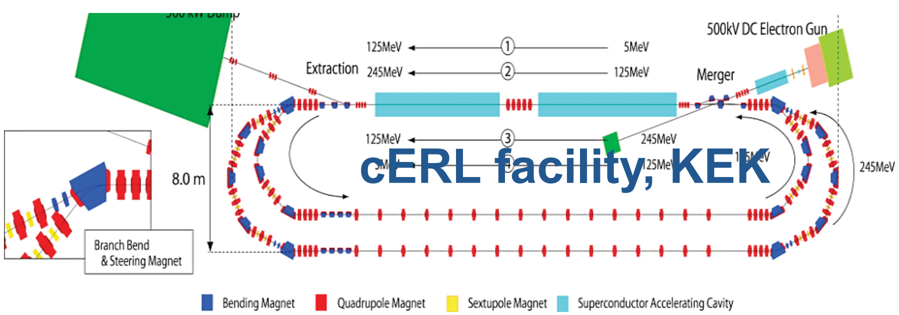
Review of some ERL-based machines worldwide (planned/existing/operating)



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

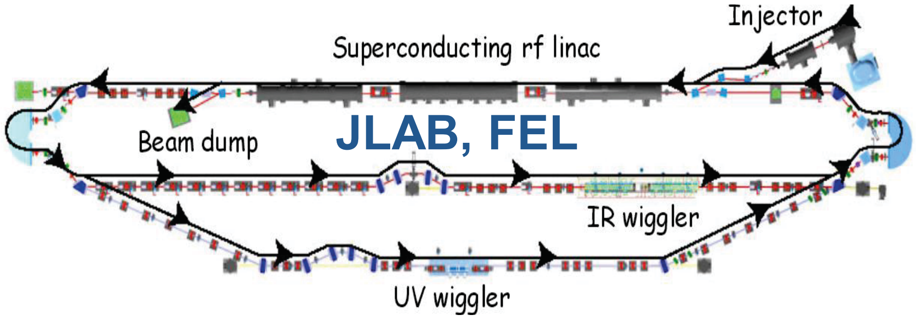


Beam Energy	12-26 MeV
Bunch charge	40-60-200 pC
RF frequency	1300 MHz
Passes	1

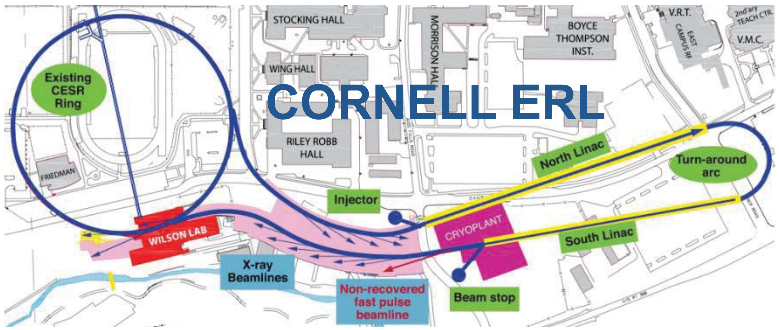


Beam Energy	35-125-250 MeV
Beam Current	10mA (100mA)
Bunch charge	7.7pC- 77pC
RF frequency	1300 MHz
Passes	1- 2

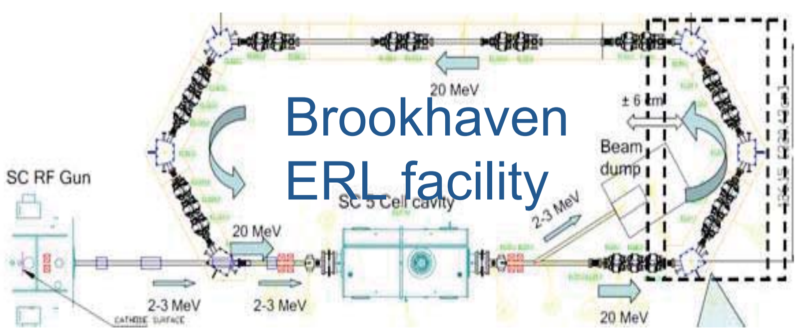
Review of some ERL-based machines worldwide (planned/existing/operating)



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

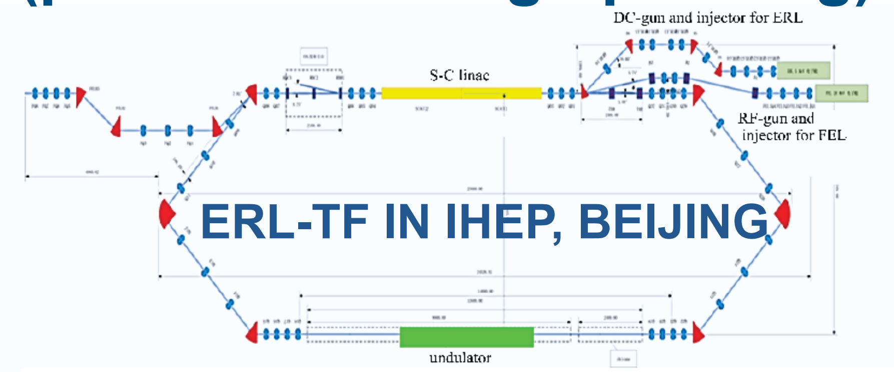


Beam Energy	5 GeV
Bunch charge	77 pC
Beam Current	100 mA
RF frequency	1300 MHz

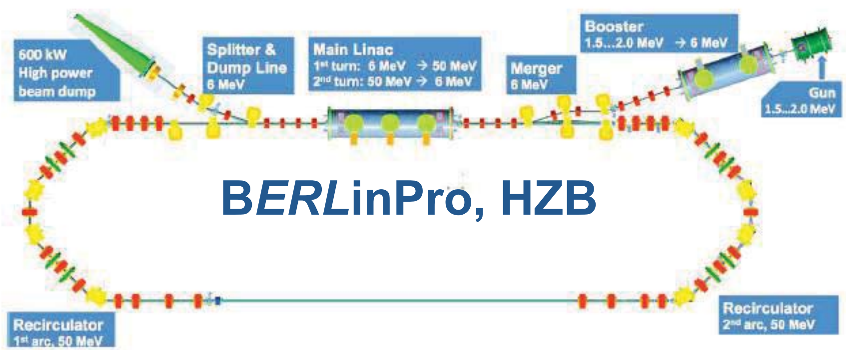


Beam Energy	20 MeV
Bunch charge	0.5-5 nC
Bunch current	300 mA
RF frequency	704 MHz
Passes	1

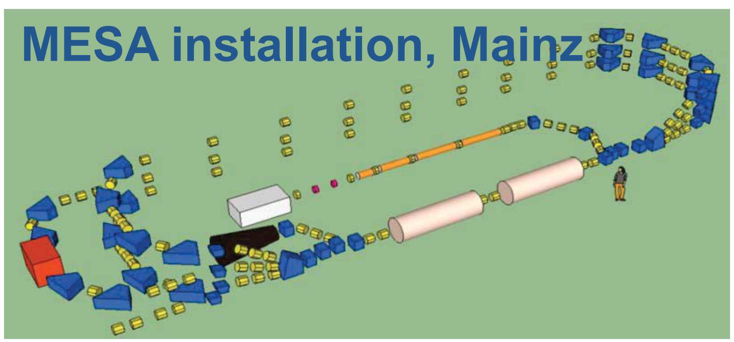
Review of some ERL-based machines worldwide (planned/existing/operating)



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

Possible Site option: SM18

- Superconducting magnets and RF test facility.
  - Horizontal benches for SC magnets
  - Vertical cryostats for prototypes
  - RF powering and bunkers for RF SC cavities
- Cryogenics water power and other services already available.

- No space inside existing buildings.
- Adjacent positioning may interfere with SM18 activities.

- Parking space over the hill is not in use.
- South area less convenient as requires excavation

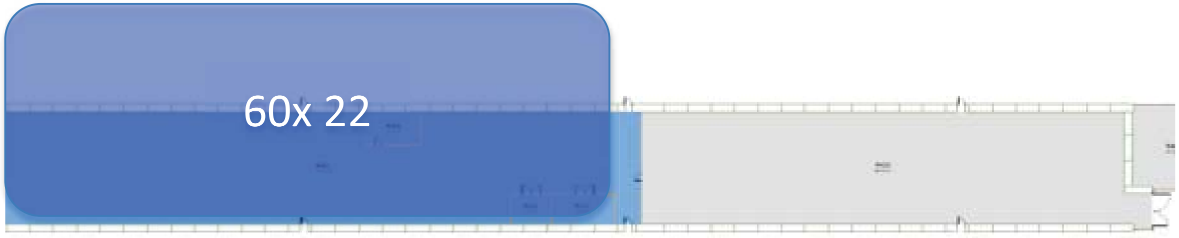
- All this possibilities are being discussed with the area managers

Prevessin Site Investigation

On the limit of the Prevessin site.

Constructed from shielding blocks, smaller than required but may be easily extended or rebuilt.

Some cryogenic infrastructure already available



Controlled quench and damage tests

MOTIVATION
FACILITY FOR TESTING QUENCH AND DAMAGE LEVELS
OF SC WIRES AND SC MAGNETS

Question:
Are the intensities at extraction and repetition rates sufficient for the tests?

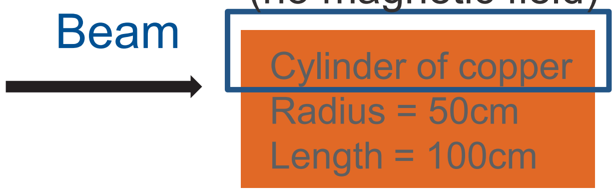
Requirements in terms of:

- 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

Beam parameters to generate a given amount of energy deposition

CALCULATIONS AND FLUKA SIMULATIONS

Copper target
(no magnetic field)



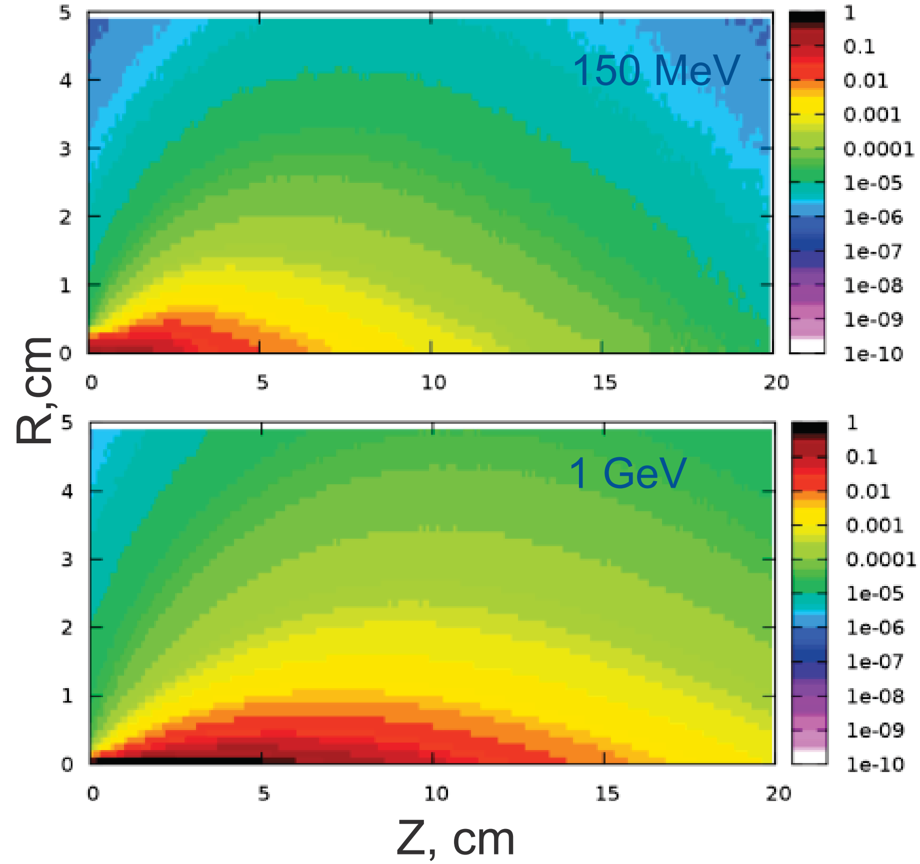
Beam parameters

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

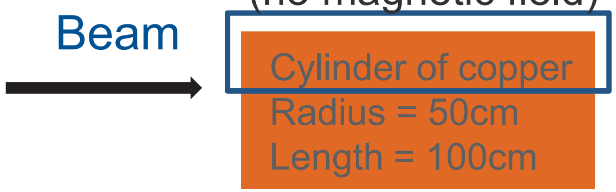
Energy deposition, $GeV/cm^3/e^-$



Beam parameters to generate a given amount of energy deposition

CALCULATIONS AND FLUKA SIMULATIONS

Copper target
(no magnetic field)



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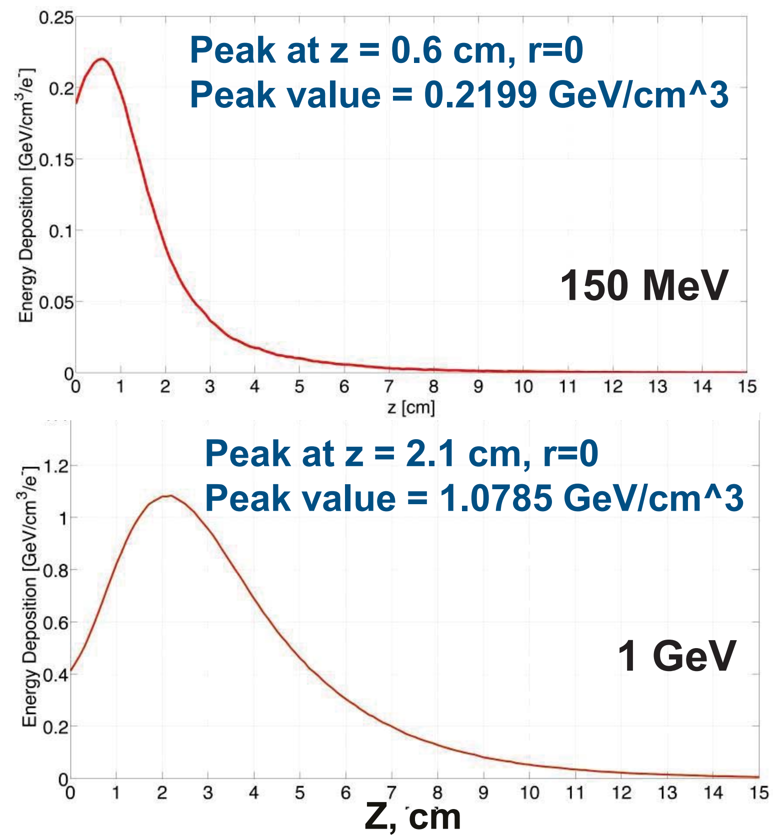
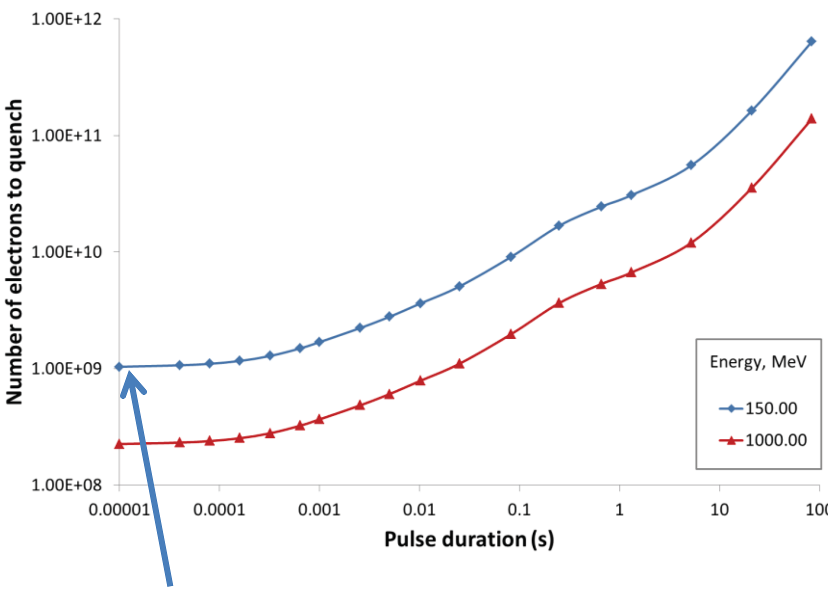
Energy deposition, $GeV/cm^3/e^-$



Quench & Damage

For **quenching** an LHC MB (main dipole magnet) a certain amount of energy should be deposited in 1mm^3

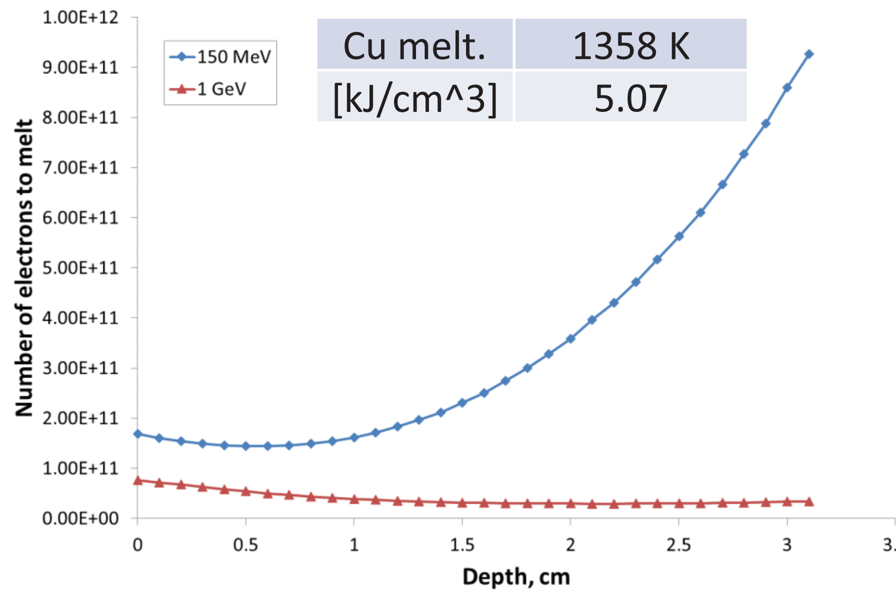
electrons needed to quench the magnet = Quench threshold / Maximum value for the energy deposition



Can easily quench with a single bunch at 150MeV
Bunch charge 2e9 > quench threshold 1e9

Damage limit in present studies is defined as a number of electrons needed for melting 1 mm^3 of Cu

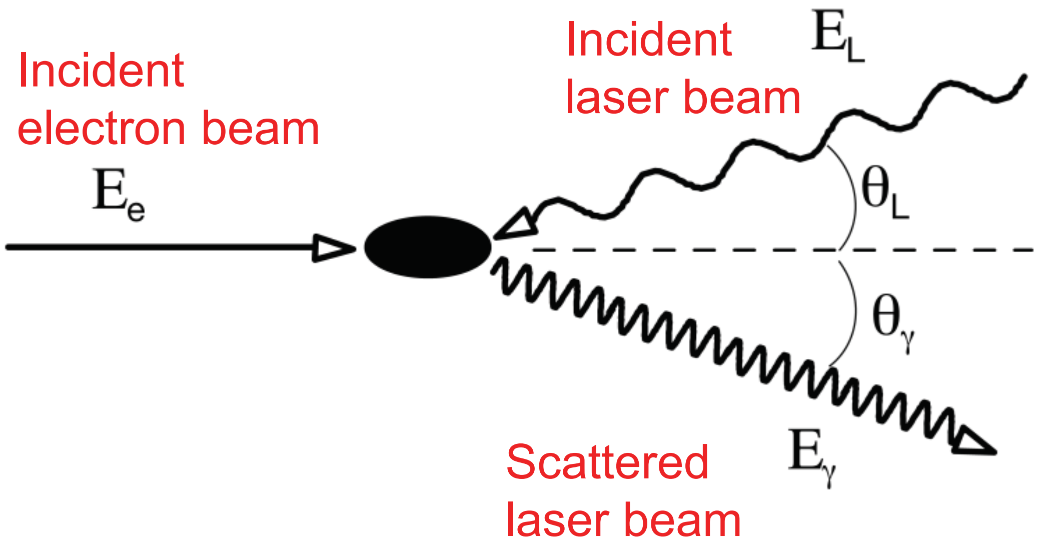
Number of electrons for melting Cu should be delivered to the target within <u>several hundreds ms</u> in order to avoid heat transfer



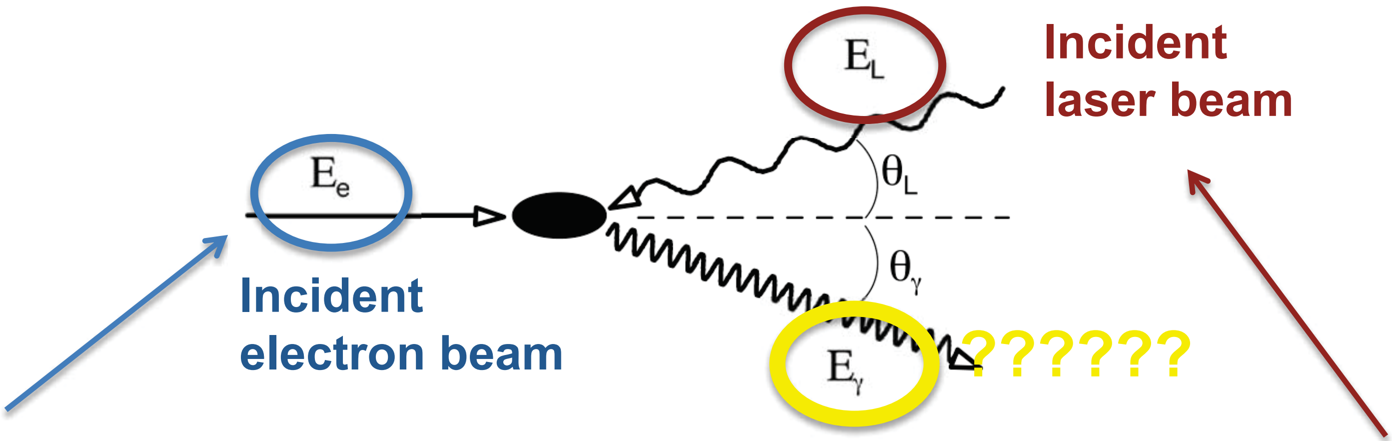
2e11 electrons required over 0.1 s to melt 1 mm^3
8e15 electrons accelerated over 0.1 s
(can extract few bunches with a fast kicker)

Gamma beams at the ERL Facility

GOAL: Generation of high-energy monochromatic polarized photons via Compton backscattering of laser light from relativistic electrons for nuclear physics research



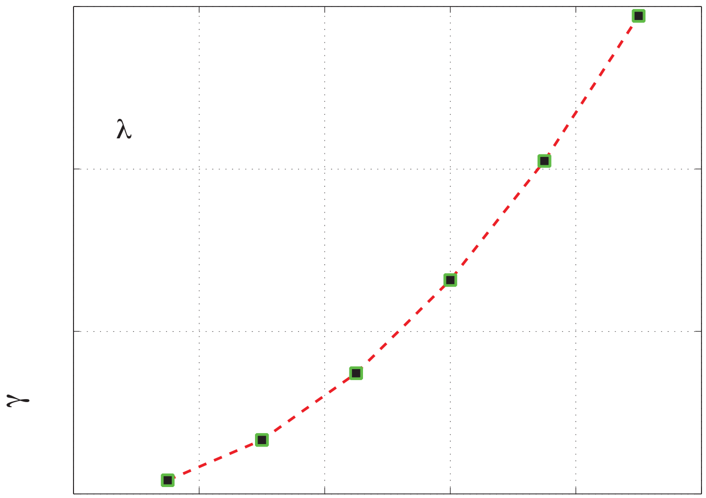
Gamma beams at the ERL Facility: input parameters

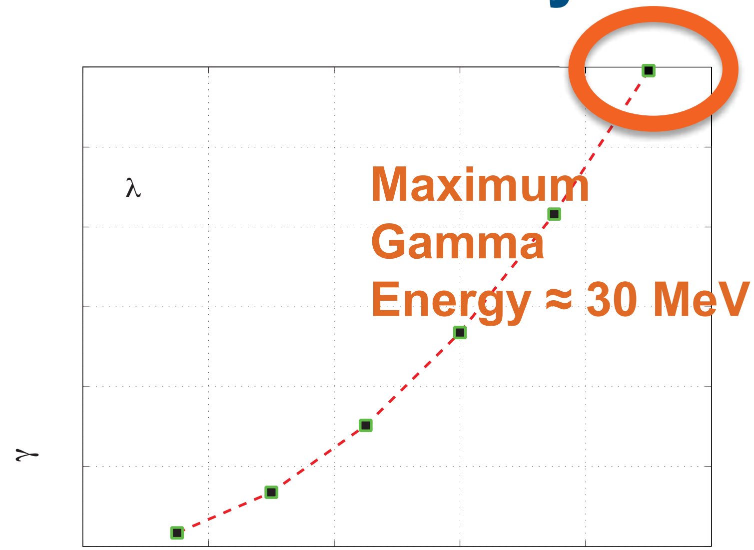


ELECTRON BEAM PARAMETERS	
Energy	900 MeV
Charge	320 pC
Bunch Spacing	25 ns
Spot size	30 um
Norm. Trans. Emittance	5 um
Energy Spread	0.1 %

LASER BEAM PARAMETERS	
Wavelength	515 nm - 1030 nm
Average Power	300kW - 600 kW
Pulse length	3 ps
Pulse energy	7.5mJ - 15 mJ
Spot size	30 um
Bandwidth	0.02 %
Repetition Rate	40 MHz

Gamma beam properties at the ERL facility

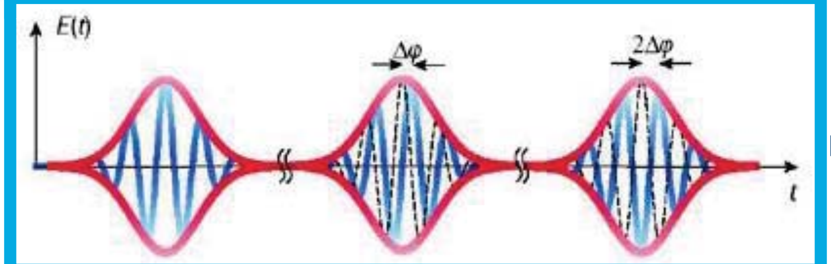




GAMMA BEAM PARAMETERS	
Energy	30 MeV
Spectral density	$9*10^4$ ph/s/eV
Bandwidth	< 5%
Flux within FWHM bdw	$7*10^{10}$ ph/s
ph/e^- within FWHM bdw	10^{-6}
Peak Brilliance	$3*10^{21}$ $ph/s*mm^2*mrad^2$ 0.1%bdw

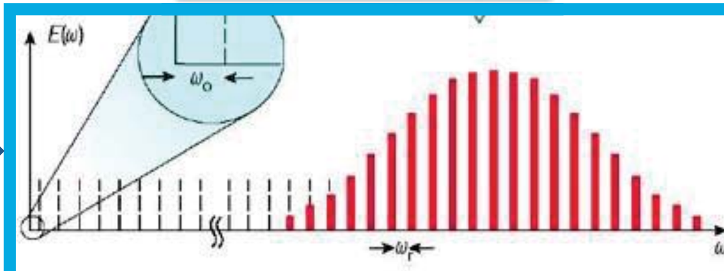
Input laser beam

Mode locked laser beam : electric field



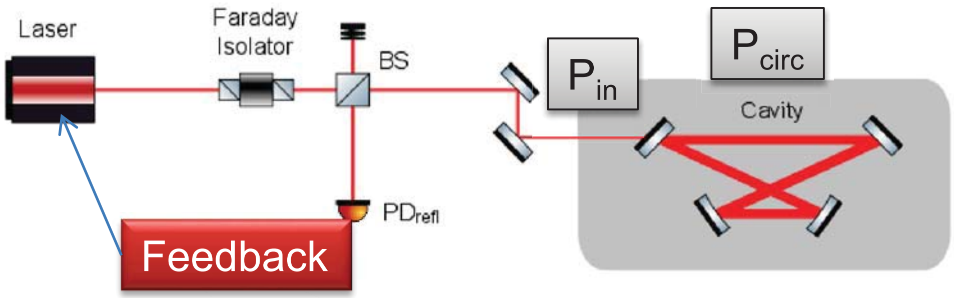
FT

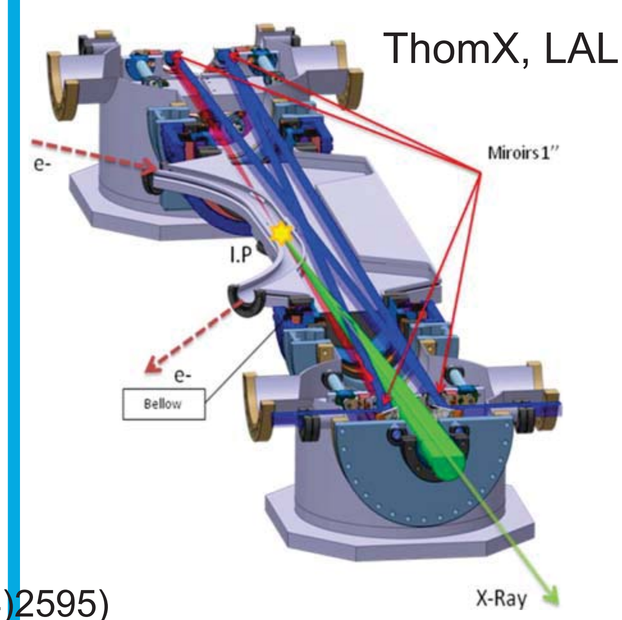
"frequency comb"



Four mirror cavity resonator :
Each tooth of the comb locked to a cavity mode

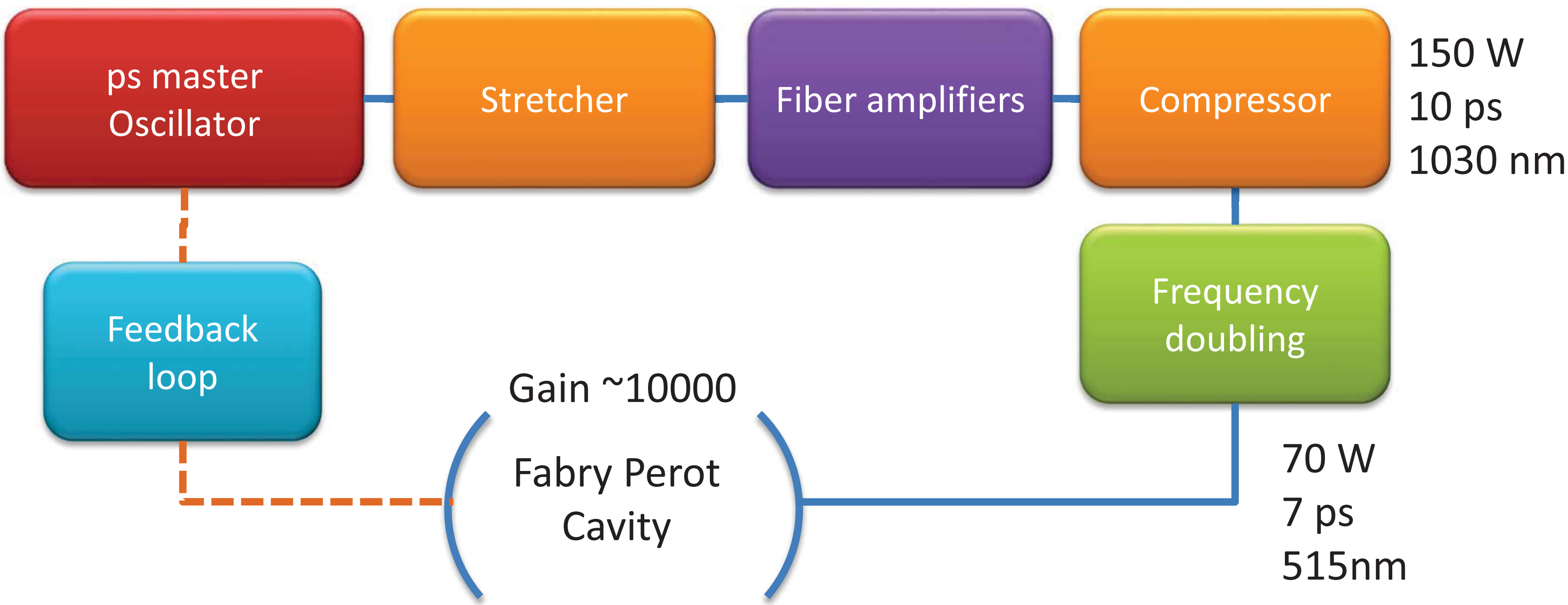
$P_{circ} = G \times P_{in}$





State of the art (average power/ ~10 ps pulses) :
Pcirc~670kW for Pin=315W (250MHz; table top ; Garching, OL39(2014)2595)
Pcirc~50kW for Pin~<10W (178.5MHz;
gamma-ray exp. at ATF/KEK, CELIA/KEK/Hiroshima/LAL/LMA)

Configuration for LHec ERL gamma source :
~same as ThomX project (CELIA, LAL)
R&D going on at LAL and CELIA Labs.



Configuration 2 for LHec ERL gamma source