From LHeC to HE-LHC and FCC: Some Detector Design Considerations

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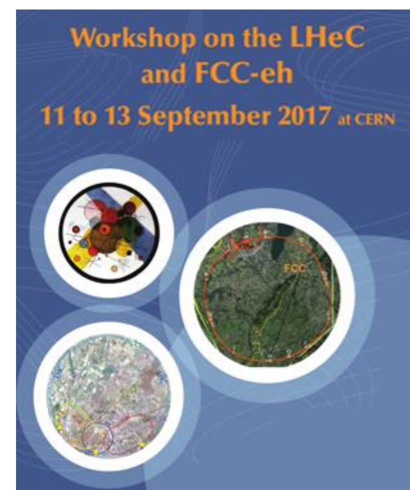
on behalf of the LHeC Study Group

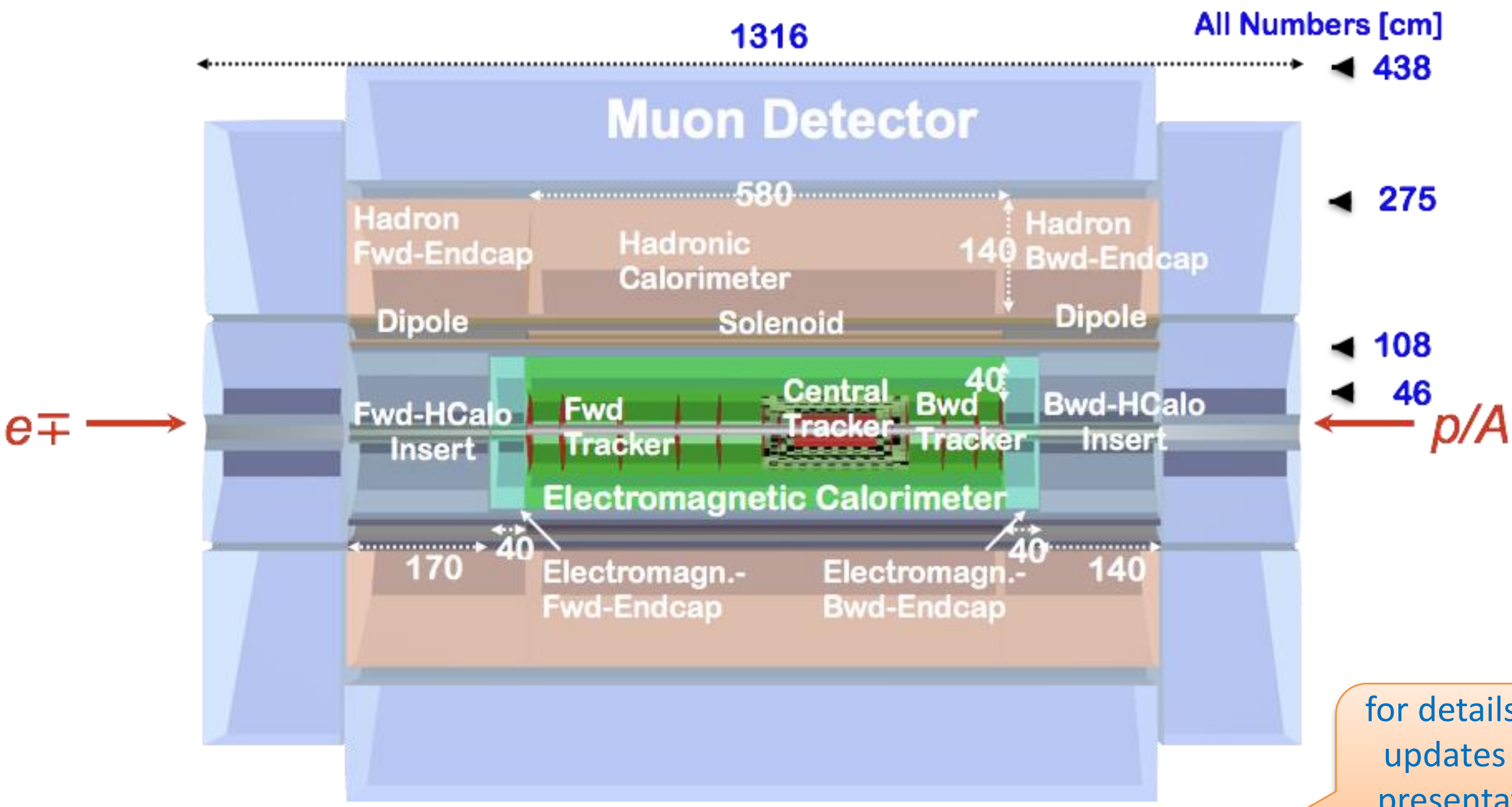
LHeC Workshop, CERN, September 11-13

Outline:

- LHeC baseline detector
- CERN Long Term Plan and the LHeC
  - Project specifications and constraints
  - Detector design considerations
  - (HL)-LHeC
  - HE-LHeC
  - FCC-he
- Plans and Outlook



LHeC Baseline Detector (*)



for details and updates see presentation by P. Kostka

(*) Design, constraints, detector choices and dimensions ≈ CDR(2012)

- Forward / backward asymmetry reflecting beam energies (870mm offset)
- Dipole for head-on e-p collisions and central solenoid in common cryostat
- The central detector fits inside 14m x 9m (c.f. CMS 21m x 15m, ATLAS 45m x 25m)

LHeC Prospects

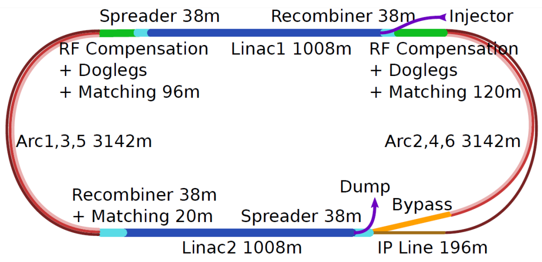
- Three main scenarios available:
  - LHeC (corresponding to the High Lumi LHC period 2035+)
  - HE-LHeC (if LHC will upgrade to High Energy 2040++)
  - FCC-eh (earliest start 2045++)

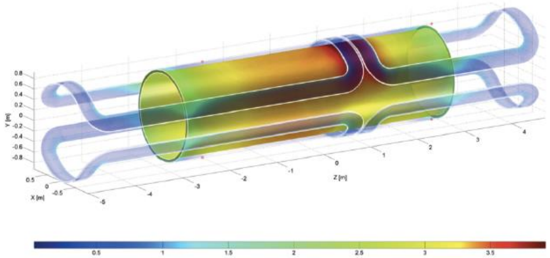
A baseline for FCC-eh
CERN-ACC-2017-0019

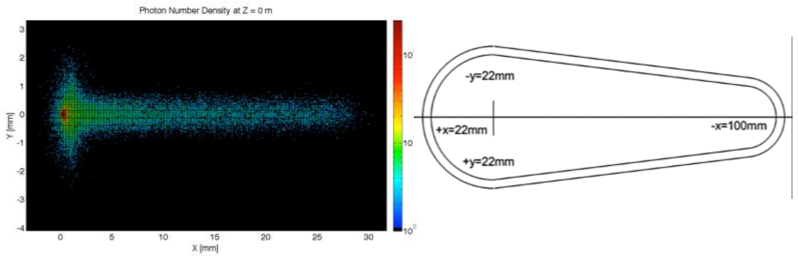
parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	12.5	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.7	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.5	1
$\gamma\epsilon_p$ [μm]	3.7	2	2.5	2.2
electrons per bunch [10^9]	1	2.3	3.0	3.0
electron current [mA]	6.4	15	20	20
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3	1.3
proton filling H_{coll}	0.8	0.8	0.8	0.8
luminosity [10^{33}cm^{-2}s^{-1}]	1	8	12	15

Detector Design (i)

- Design commonalities:
  - Electron Machine:
    - 60 GeV $e^{\pm}$ Energy Recovery Linac
    - Concurrent running with hadron machine
  - Interaction Region:
    - dipole field across the whole detector
    - $e^{\pm}$ syn radiation → elliptical beam-pipe
    - Precise design of masks and absorbers
  - Beam Pipe Design:
    - low X_0, λ_I material, stable, capable for 1° tracks
    - Design allow for Syn. Rad. output fan
    - allowing low p_T particle measurement
    - R&D needed (new ideas) in particular for fwd region

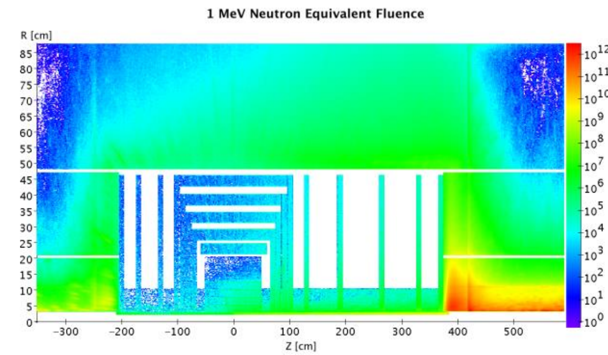


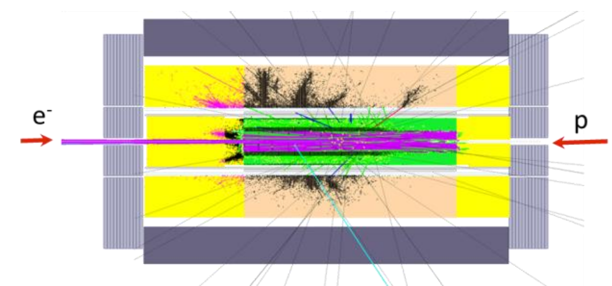




Detector Design (ii)

- Detector:
  - Start from LHeC CDR design
  - Large acceptance over η
  - Higher momenta/energies → Larger BL^2
  - Larger transverse calorimetry (up to 12 λ_I in the fwd region)
  - Bunch spacing (25ns, option of 5ns)
  - Total irradiation and Pile-up less of a problem in ep than LHC/FCC-hh

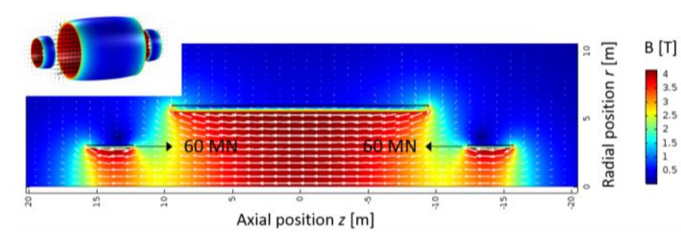




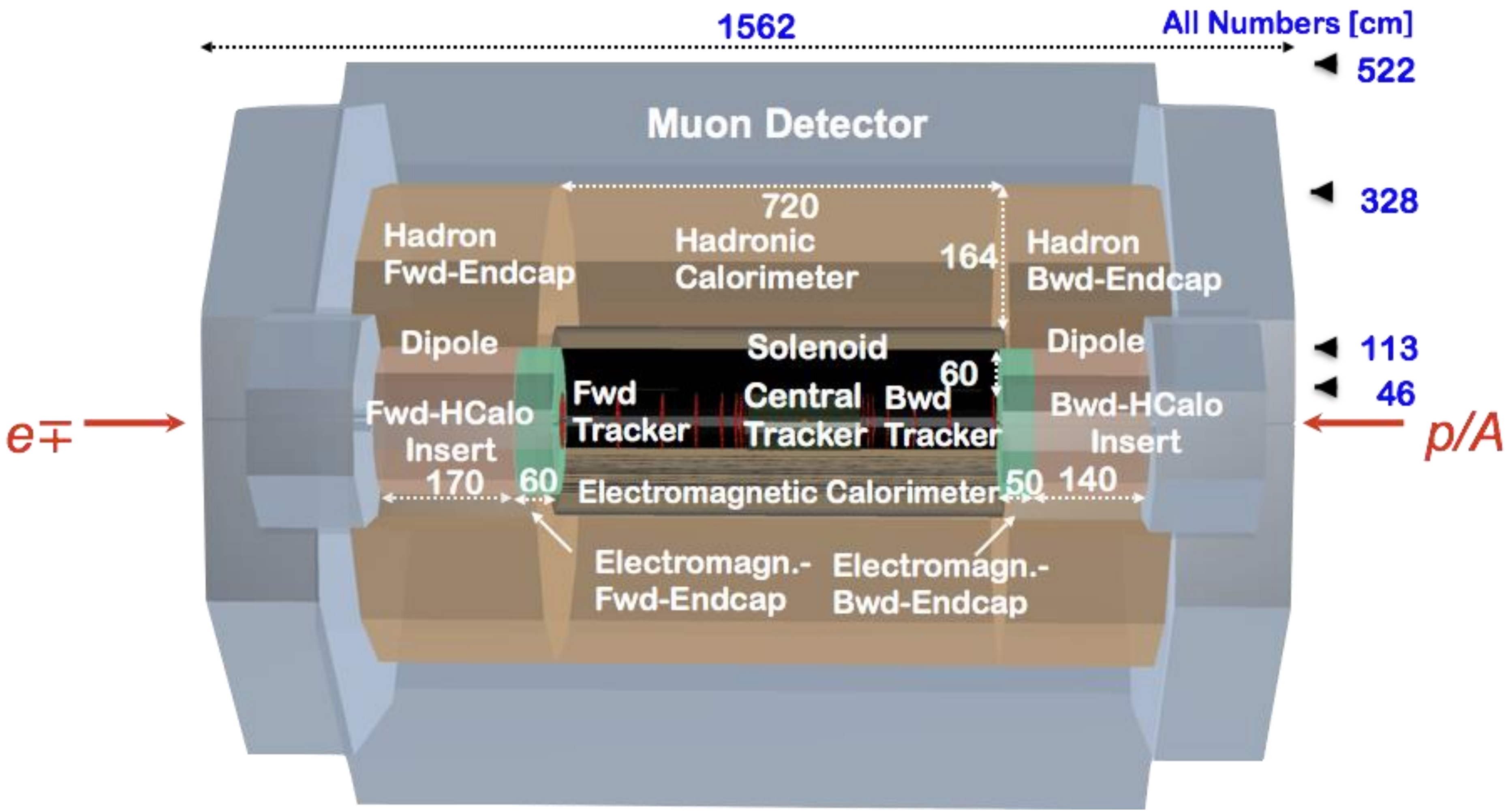
- Magnets:

See presentation by H. TenKate

  - Baseline: keep CDR design. Solenoid between EMC and HAC calorimetry in central region
  - Study options for field in the fwd/bwd region to improve resolution to be investigated.
  - Design not written in stone, follow R&D and trends

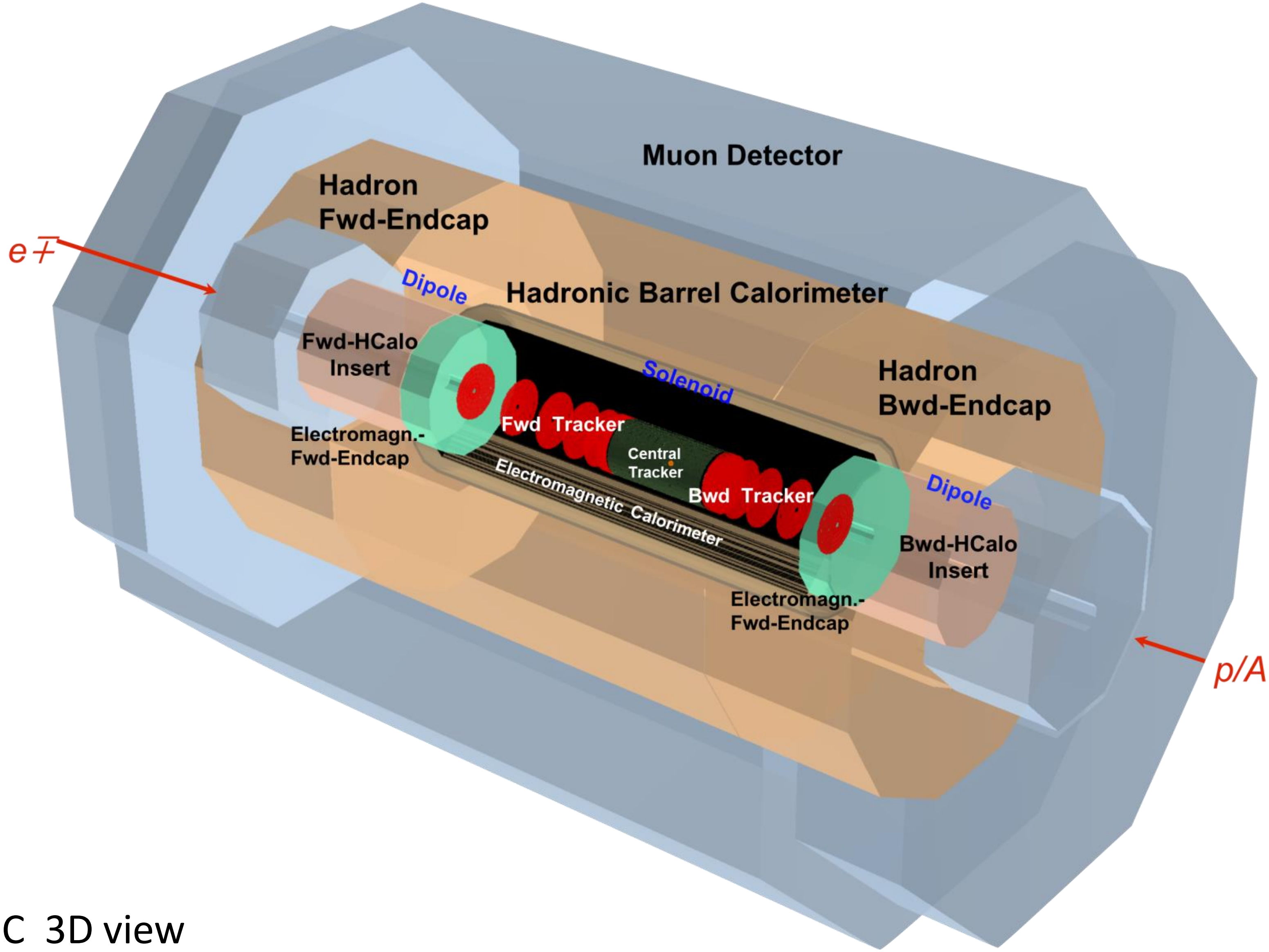


HE-LHC LHeC detector



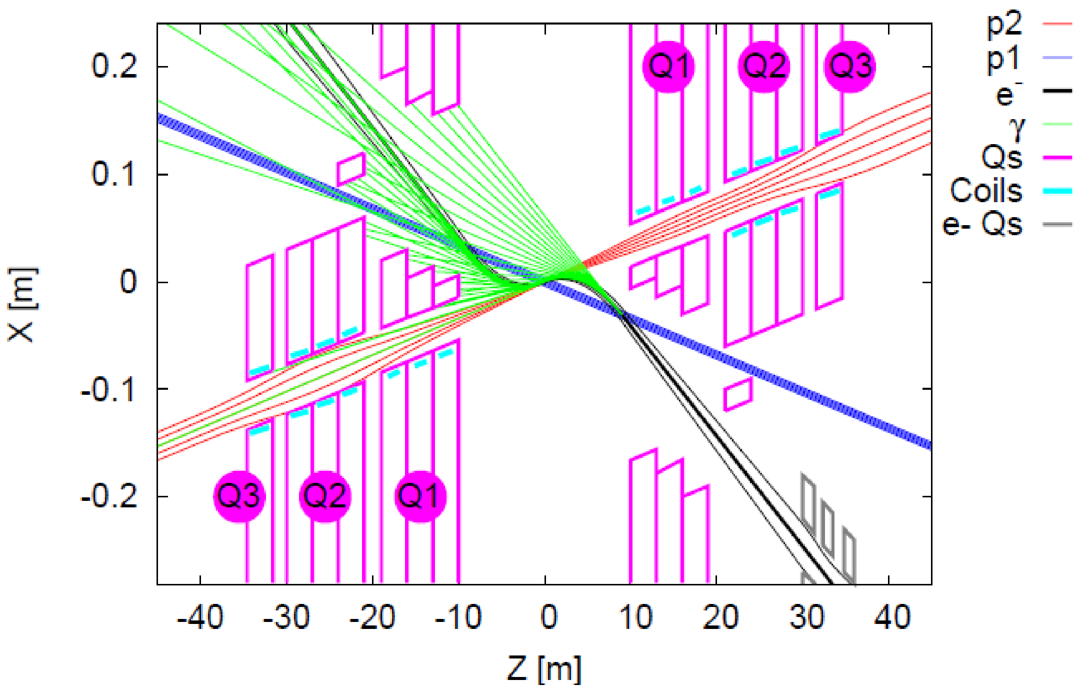
- Present HE-LHC design of the central detector firs 16.0m x 10.5m
- Dimensions still compatible with the insertion of the detector in the L3/ALICE magnet (11.20 min diameter). More precise studies needed.

HE-LHeC detector



HE-LHeC 3D view

About the HE-LHeC



Preliminary assumptions:

- Similar interaction region as for HL-LHeC:
- 3 beam interaction region with only the p beam colliding with the e^- is focused
- Head-on collisions achieved via long dipole across interaction region with same dipole field of B=±0.3 Tesla as for LHeC
- High Synchrotron Radiation Load
- Crab cavities not applicable in LHeC due to the large crossing angle of ~60 mrad and power required (HL-LHC crossing angle ≈ 500 µrad)

- The present HE design and transversal dimensions still fit into the ALICE/L3 Magnet

Assuming the installation in LHC IP2:

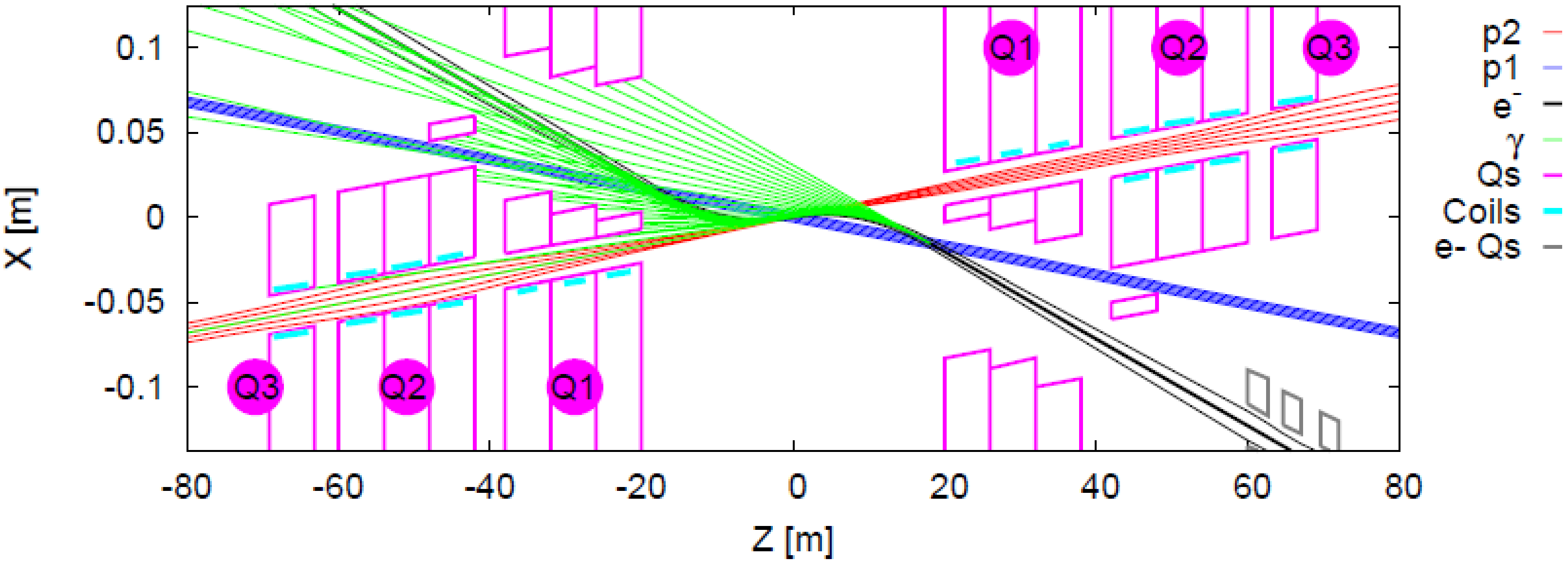
- If the LHeC will start during HL-LHC, to minimize costs and maximize longevity, the detector should be already HE ready (magnets, cryo, modularity, dimensions, etc.).
- If LHeC will start in the HE phase, then the detector assembly and commissioning can profit of the longer availability of the experimental hall, including the possible dismantling of the ALICE/L3 magnet.

More details on logistics and installation in the presentation by A. Gaddi

FCC-eh Interaction Region

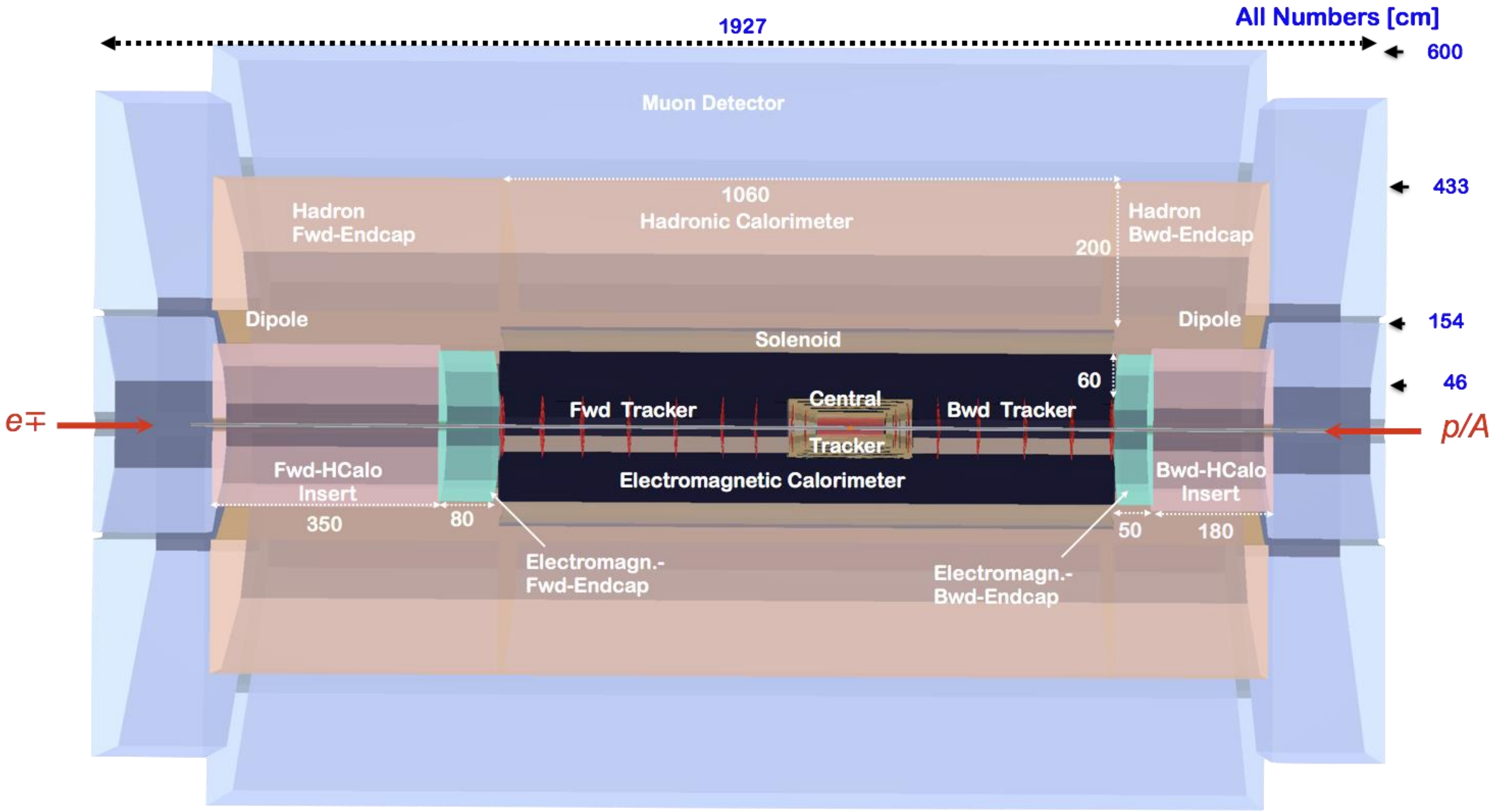
- Preliminary studies on the FCC-eh interaction region indicate a factor 2 in length and β scale:

E. Cruz et al, Phys. Rev. ST Accel. Beams 18, 111001 (2015)



- Detector baseline: similar Solenoidal Field (3.5 T)
- FCC-eh Dipole field reduced by factor 2 → B=0.15 T

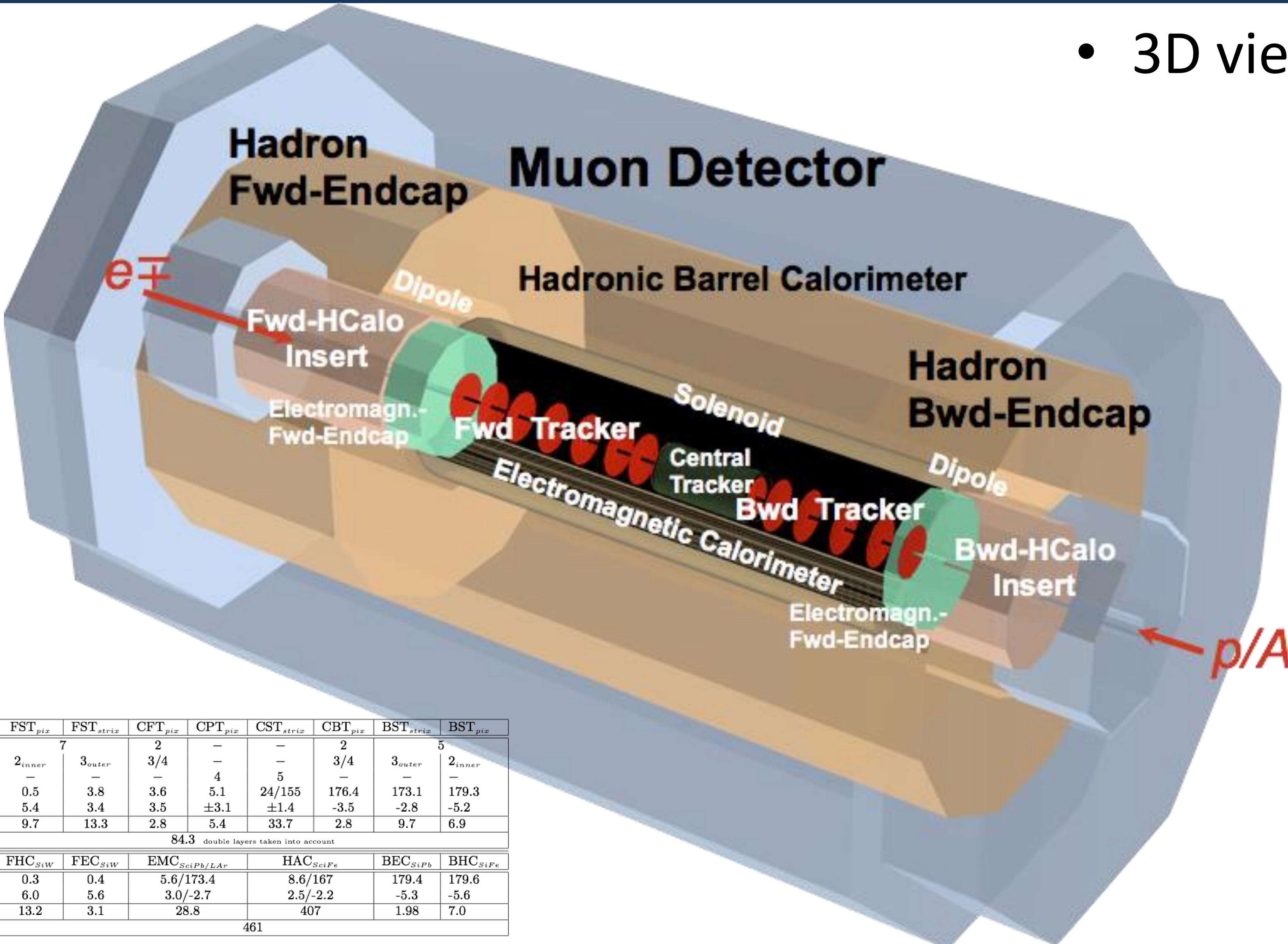
FCC-eh Detector base-line



- Very preliminary FCC detector design: extension of LHeC baseline detector
- Dimensions 20 x 12 m, transverse and longitudinal (fwd) sizes scaled w.r.t. LHeC
- B field still 3.5 T. Dimensions small compared to present FCC-hh design

FCC-he Detector

- 3D view



Tracker	FST_{pix}	FST_{strix}	CFT_{pix}	CPT_{pix}	CST_{strix}	CBT_{pix}	BST_{strix}	BST_{pix}
#Wheels	7		2	–	–	2	5	
#Rings/Wheel	2_{inner}	3_{outer}	3/4	–	–	3/4	3_{outer}	2_{inner}
#Layers	–	–	–	4	5	–	–	–
$\theta_{min/max}$ [^{0}]	0.5	3.8	3.6	5.1	24/155	176.4	173.1	179.3
$\eta_{max/min}$	5.4	3.4	3.5	±3.1	±1.4	-3.5	-2.8	-5.2
$Si_{pix/strix}$ [m^2]	9.7	13.3	2.8	5.4	33.7	2.8	9.7	6.9
Sum-Si [m^2]	84.3 double layers taken into account							

Calo	FHC_{SiW}	FEC_{SiW}	$EMC_{SciPb/LAr}$	HAC_{SciFe}	BEC_{SiPb}	BHC_{SiFe}
$\theta_{min/max}$ [^{0}]	0.3	0.4	5.6/173.4	8.6/167	179.4	179.6
$\eta_{max/min}$	6.0	5.6	3.0/-2.7	2.5/-2.2	-5.3	-5.6
Volume [m^3]	13.2	3.1	28.8	407	1.98	7.0
Sum-Si [m^2]	461					

Few more considerations

Present Design:

- The Present design for all LHeC detectors similar: the strongest constraints coming from the Interaction Region and the Machine Detector Interface.
- Overall Detector dimensions scaled due to the increased beam energies required improved tracking and calorimetry.
- Differences and optimizations will follow based on more precise design from the machine and interaction region.
- The final choice of detector technologies is important to demonstrate the feasibility and the physics reach but will be addressed more in detail later.

FCC-he:

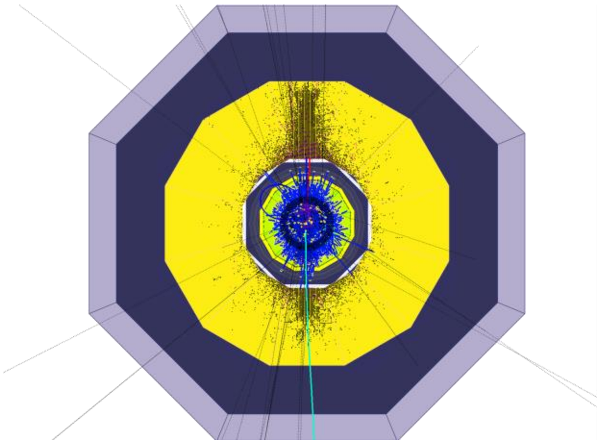
- Magnet design in particular for FCC could take advantage of latest FCC trends, including the possible absence of field shielding as the experimental halls are 300m below ground.
- A high level of synergy with the other LHC upgrade projects and FCC is clear. This is already seen in the use of similar software for physics and detector simulation.

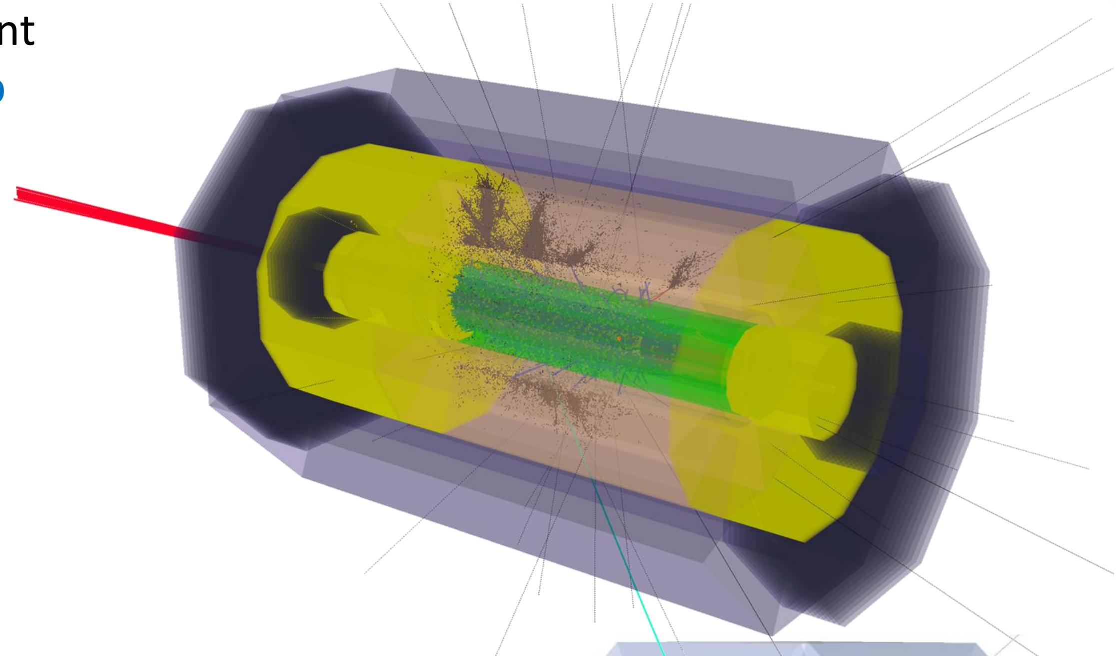
Detector Simulation Software:

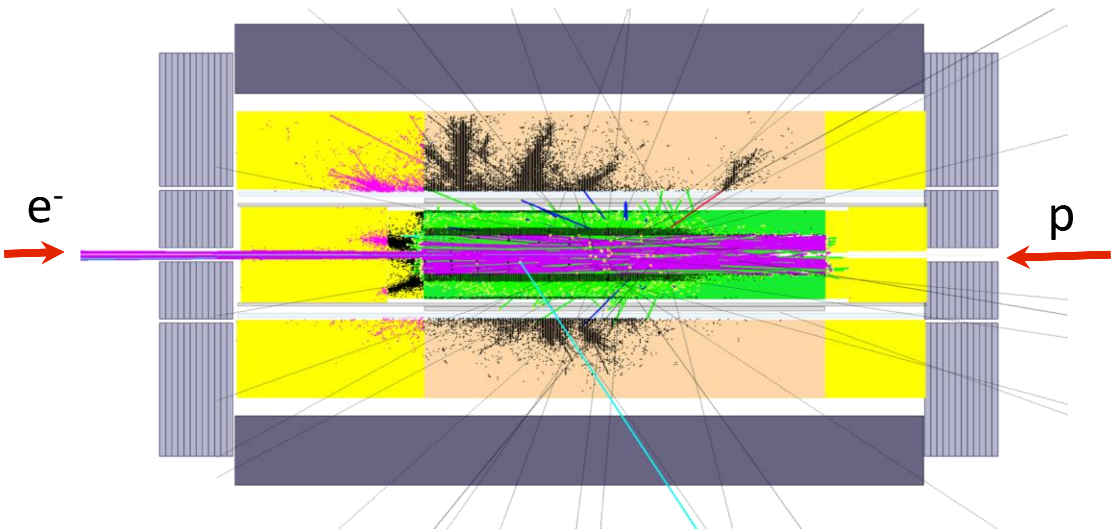
- Presently using several dedicated tools for fast simulation and working on DD4Hep/DDG4 software environment in collaboration with the other upgrade and future projects
- Pursue and improve full detector simulation
- Aim at more realistic design including services, dead material, machine detector interaction
- Follow R&D and design trends Tracking, Calorimetry, Magnets …

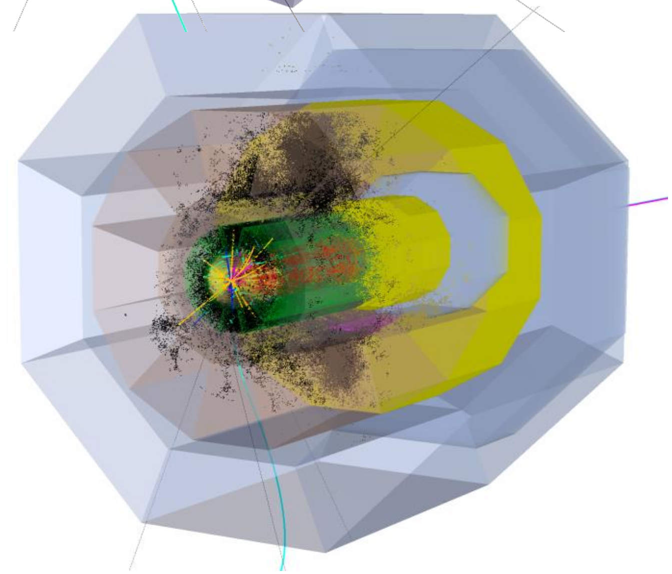
LHeC/FCC-eh in Pictures

DD4Hep/DDG4 Software Environment
http://aidasoft.web.cern.ch/DD4hep



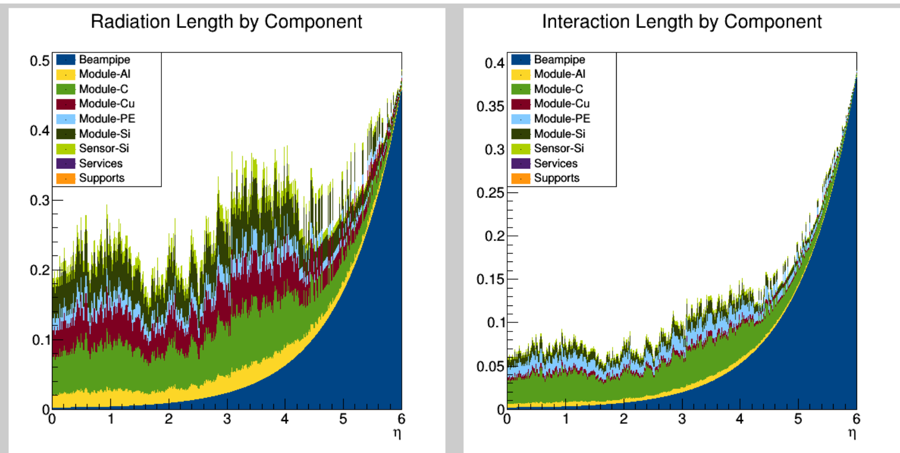


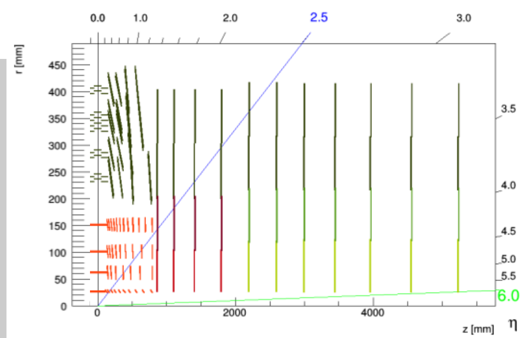


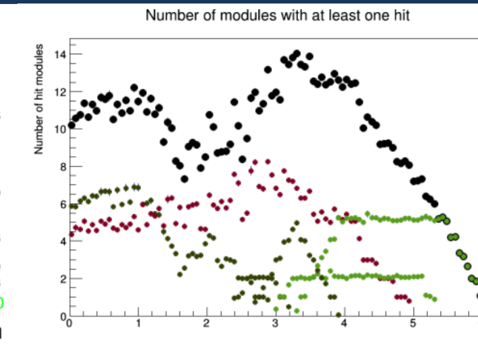


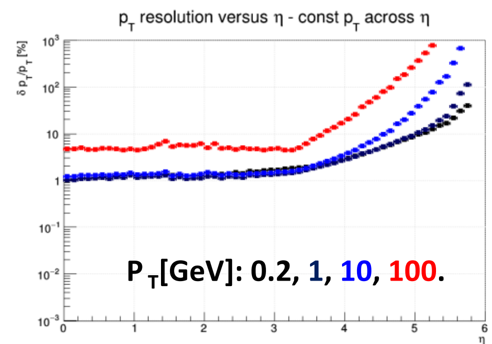
FCC-eh Tracking (work in progress)

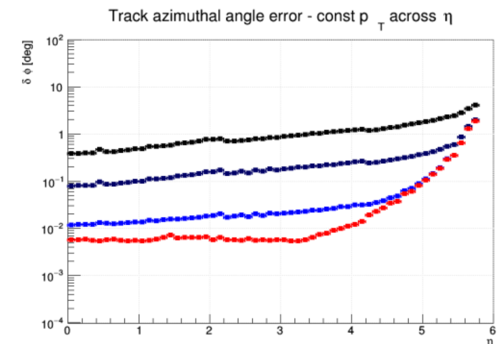
Tilted sensor planes





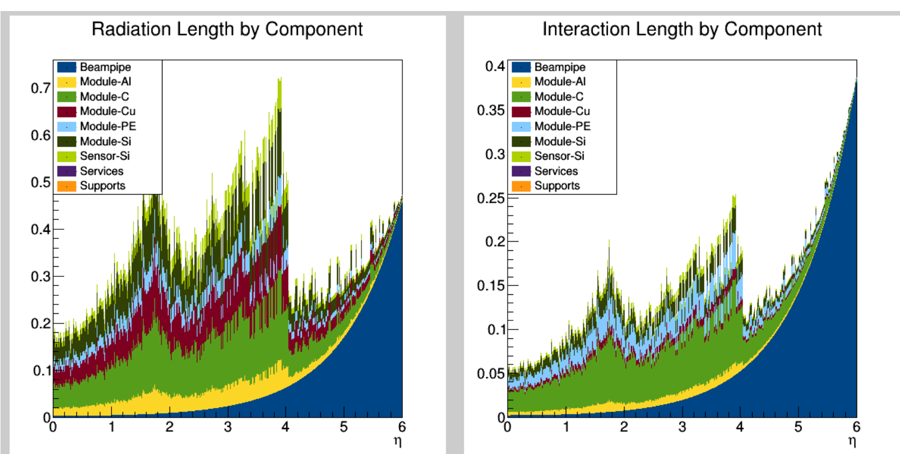


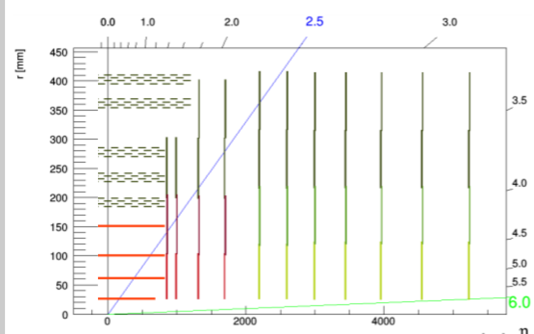


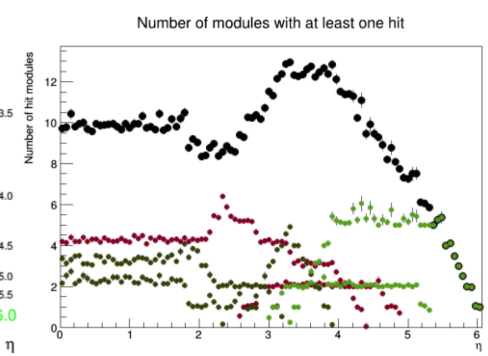


tklayout: http://tklayout.web.cern.ch/
https://github.com/drasal/tkLayout/tree/masterLite

Non tilted sensor planes







Heavy Ion Running

CERN-ACC-2017-0019

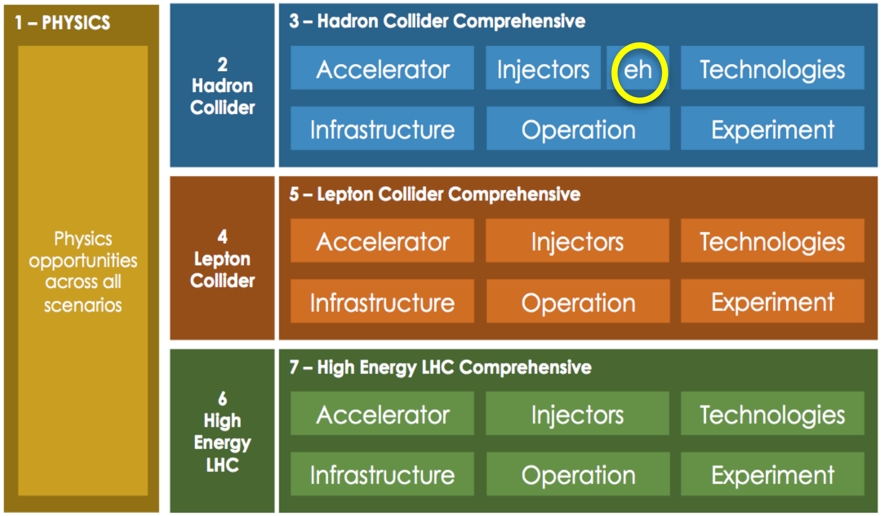
parameter [unit]	LHeC (HL-LHC)	eA at HE-LHC	FCC-he
E_{Pb} [PeV]	0.574	1.03	4.1
E_e [GeV]	60	60	60
$\sqrt{s_{eN}}$ electron-nucleon [TeV]	0.8	1.1	2.2
bunch spacing [ns]	50	50	100
no. of bunches	1200	1200	2072
ions per bunch [10^8]	1.8	1.8	1.8
$\gamma\epsilon_A$ [μm]	1.5	1.0	0.9
electrons per bunch [10^9]	4.67	6.2	12.5
electron current [mA]	15	20	20
IP beta function β_A^* [cm]	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3
bunch filling H_{coll}	0.8	0.8	0.8
luminosity [$10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	7	18	54

Improved Instantaneous Luminosity estimates w.r.t. last year following the gained experience in LHC ion running.

Conclusions and Outlook

- A wide horizon of upgrades and new HEP projects is coming to us.
- The design concepts of the CDR are being revised and updated in view of the many options available.
- No fundamental showstopper.
- The present detector design is for all machines similar. Differences and optimizations will follow from precise detector simulations once more precise requirements and constraints from the machine and interaction region are available.
- Aim at an update of the CDR (LHeC+ FCC-he) by 2018
  - Establish Interaction Region/ Machine detector Interface.
  - Focus on Software simulations, follow detector R&D
  - Key aspect: Manpower, Synergies with other FCC projects

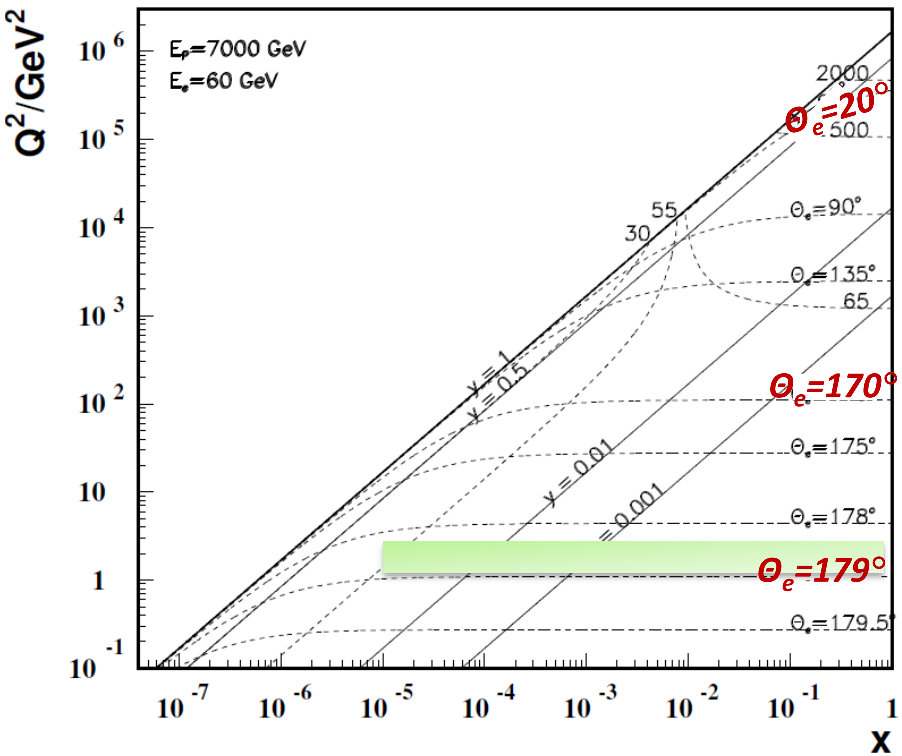
FCC CDR



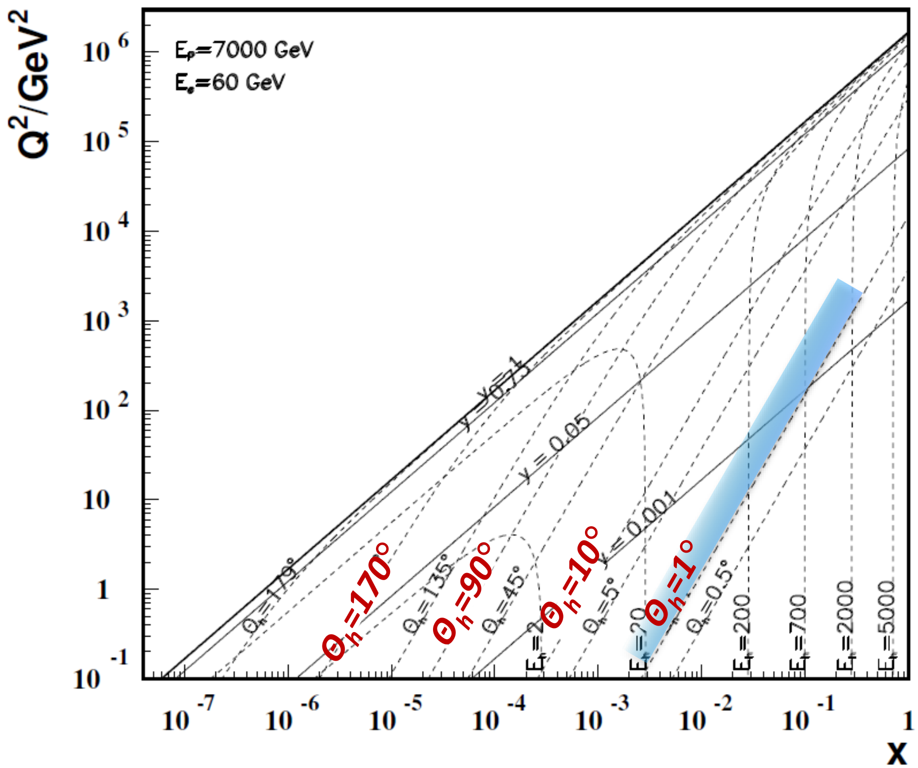
Backup

LHeC Kinematics

LHeC – electron kinematics

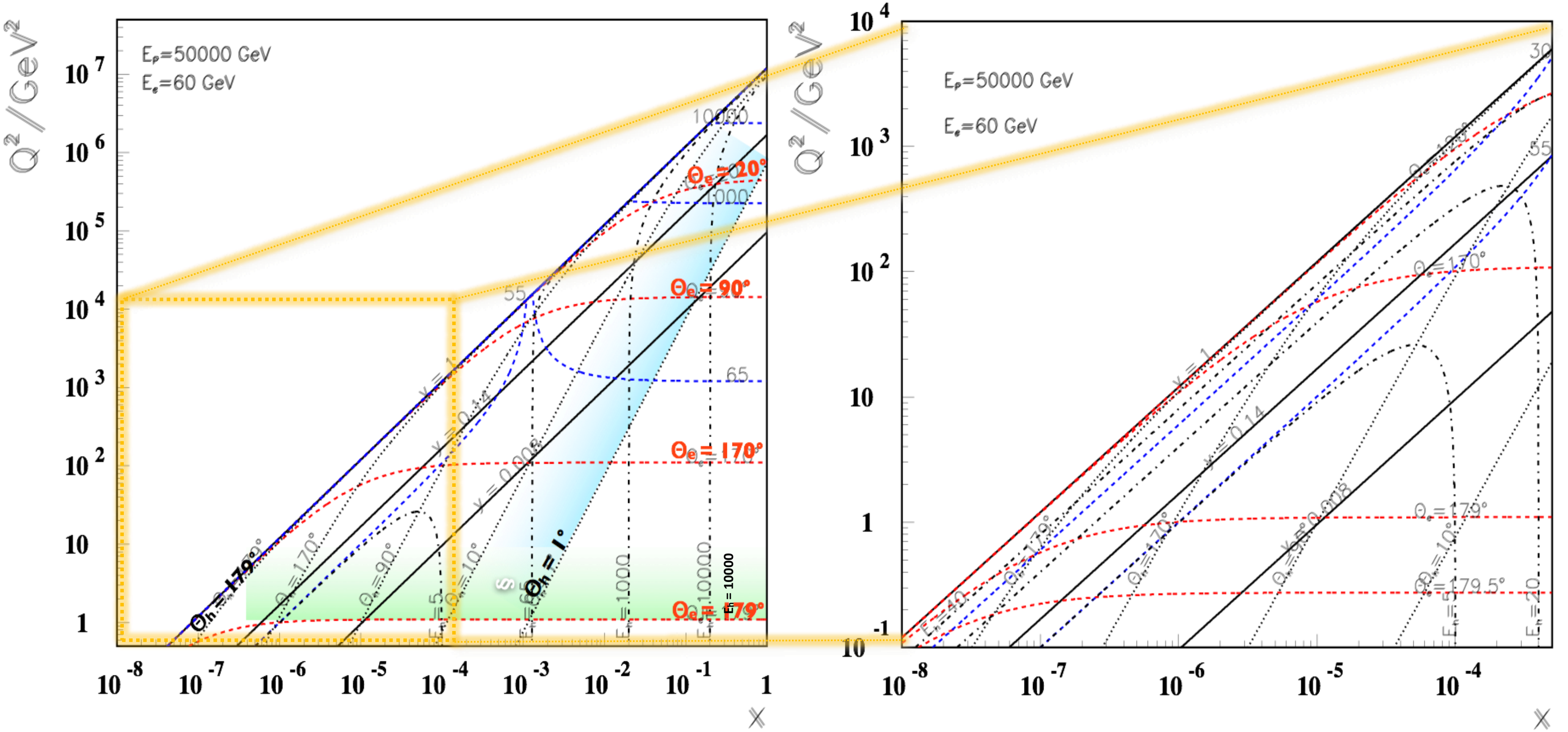


LHeC – jet kinematics



- High x and high Q^2: few TeV HFS scattered forward:
- → Need forward calorimeter of few TeV energy range down to 1^0
- Mandatory for charged currents where the outgoing electron is missing
- Scattered electron:
  → Need small bwd angle acceptance for accessing the low Q^2 and high y region

FCC-he Kinematics



Requirements in particular for the forward region even more demanding for full energy containment especially at high eta.
→ increase the calorimeter depth compared to LHeC (especially in forward region)

FCC-he detector preliminary table

Tracker	FST_{pix}	FST_{strix}	CFT_{pix}	CPT_{pix}	CST_{strix}	CBT_{pix}	BST_{strix}	BST_{pix}
#Wheels	7		2	–	–	2	5	
#Rings/Wheel	2_{inner}	3_{outer}	3/4	–	–	3/4	3_{outer}	2_{inner}
#Layers	–	–	–	4	5	–	–	–
$\theta_{min/max}$ $[^0]$	0.5	3.8	3.6	5.1	24/155	176.4	173.1	179.3
$\eta_{max/min}$	5.4	3.4	3.5	±3.1	±1.4	-3.5	-2.8	-5.2
$Si_{pix/strix}$ $[m^2]$	9.7	13.3	2.8	5.4	33.7	2.8	9.7	6.9
Sum-Si $[m^2]$	84.3 double layers taken into account							

Calo	FHC_{SiW}	FEC_{SiW}	$EMC_{SciPb/LAr}$	HAC_{SciFe}	BEC_{SiPb}	BHC_{SiFe}
$\theta_{min/max}$ $[^0]$	0.3	0.4	5.6/173.4	8.6/167	179.4	179.6
$\eta_{max/min}$	6.0	5.6	3.0/-2.7	2.5/-2.2	-5.3	-5.6
Volume $[m^3]$	13.2	3.1	28.8	407	1.98	7.0
Sum-Si $[m^2]$	461					

(*) FCC-he work in progress

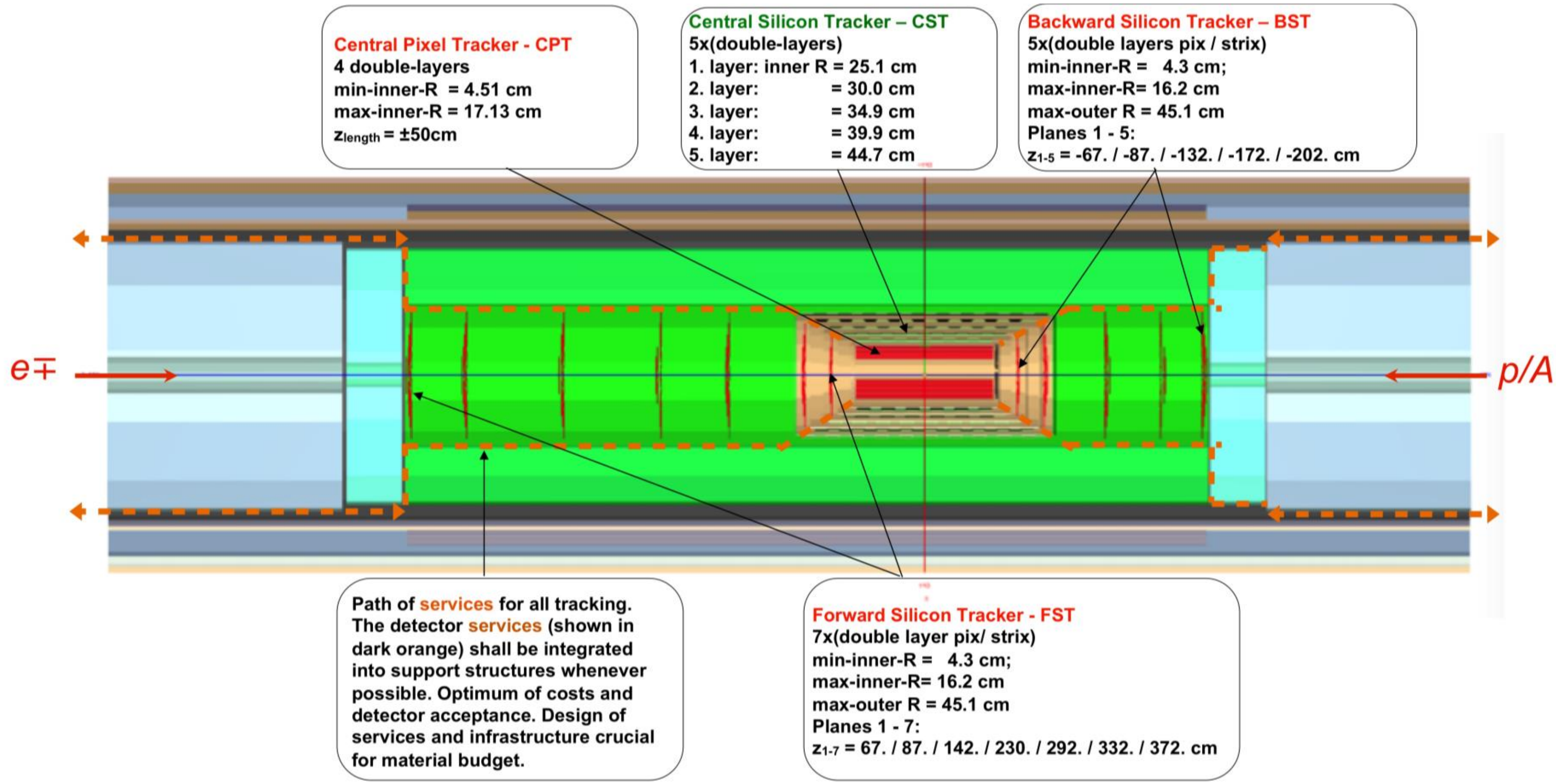
Detector geometry table LHeC

Tracker	FST_{pix}	FST_{strix}	CFT_{pix}	CPT_{pix}	CST_{strix}	CBT_{pix}	BST_{strix}	BST_{pix}
#Wheels	5		2	–	–	2	3	
#Rings/Wheel	2_{inner}	3_{outer}	3/4	–	–	3/4	3_{outer}	2_{inner}
#Layers	–	–	–	4	5	–	–	–
$\theta_{min/max}$ $[^0]$	0.7	3.8	3.0	5.1	24/155	177.8	173.1	178.7
$\eta_{max/min}$	5.1	3.4	3.6	±3.1	±1.4	-3.6	-2.8	-4.5
$Si_{pix/strix}$ $[m^2]$	6.9	9.5	2.8	5.4	33.7	2.8	5.7	4.1
Sum-Si $[m^2]$	70.9 double layers taken into account							

Calo	FHC_{SiW}	FEC_{SiW}	$EMC_{SciPb/LAr}$	HAC_{SciFe}	BEC_{SiPb}	BHC_{SiFe}
$\theta_{min/max}$ $[^0]$	0.61	0.68	8/166	14.2/160	178.7	178.9
$\eta_{max/min}$	5.2	5.1	2.7/-2.1	2.1/-1.7	-4.5	-4.7
Volume $[m^3]$	6.7	1.6	15.1	165	1.6	5.8
Sum-Si $[m^2]$	197.4					

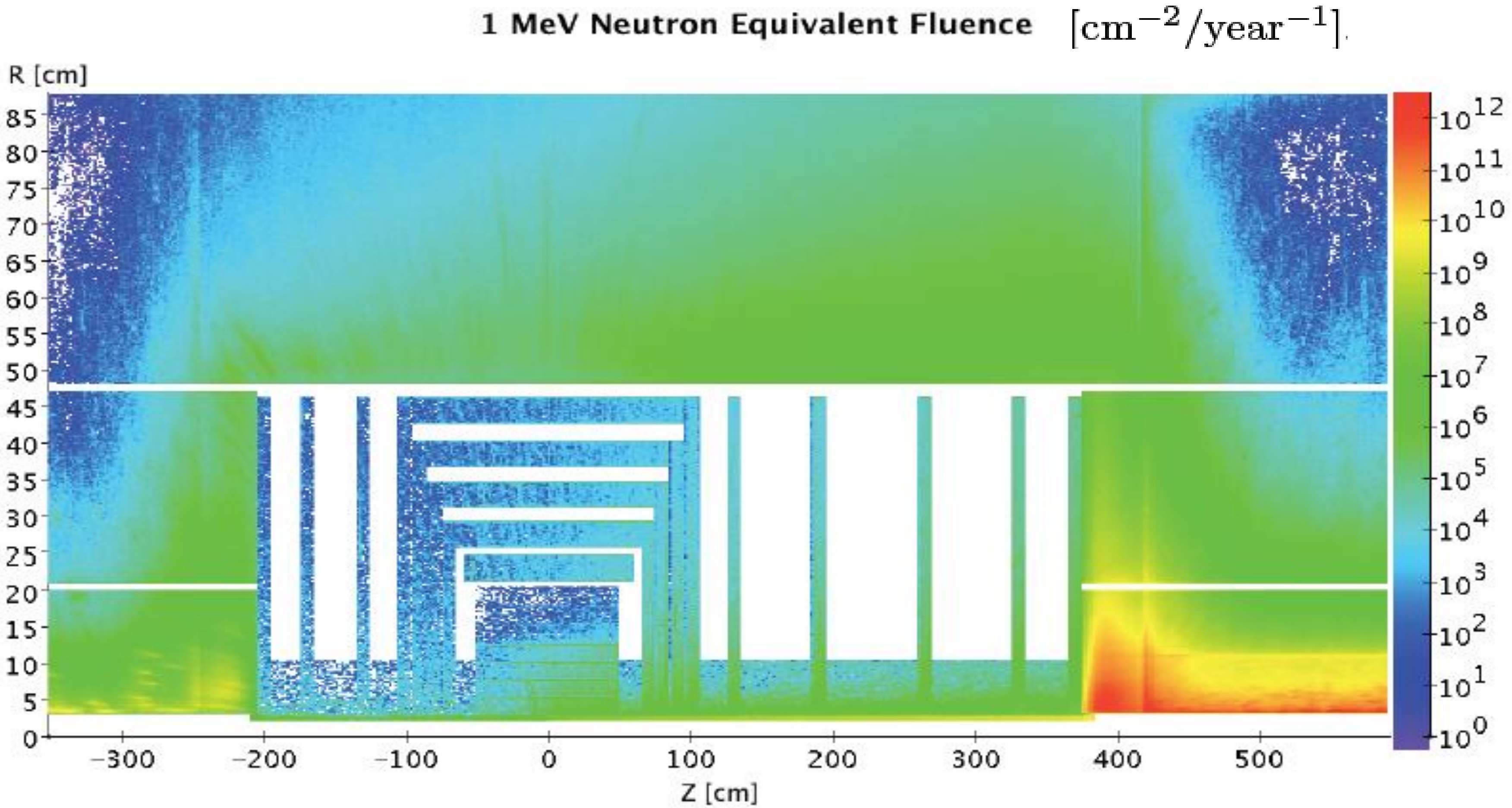
- LHeC CDR version

Services and Infrastructure



- Detector of very compact design: It might be necessary to open places/grooves/tunnels for services affecting the aperture of the detector; Optimum between costs and detector acceptance needs to be found.
- Service and Infrastructure need very careful design being the main contributor to Material Budget

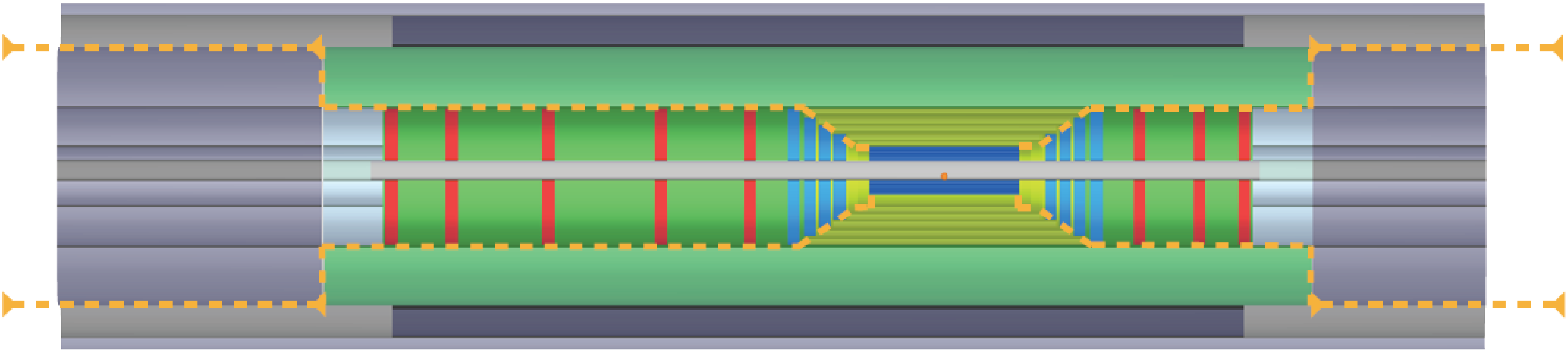
GEANT4 - Fluences

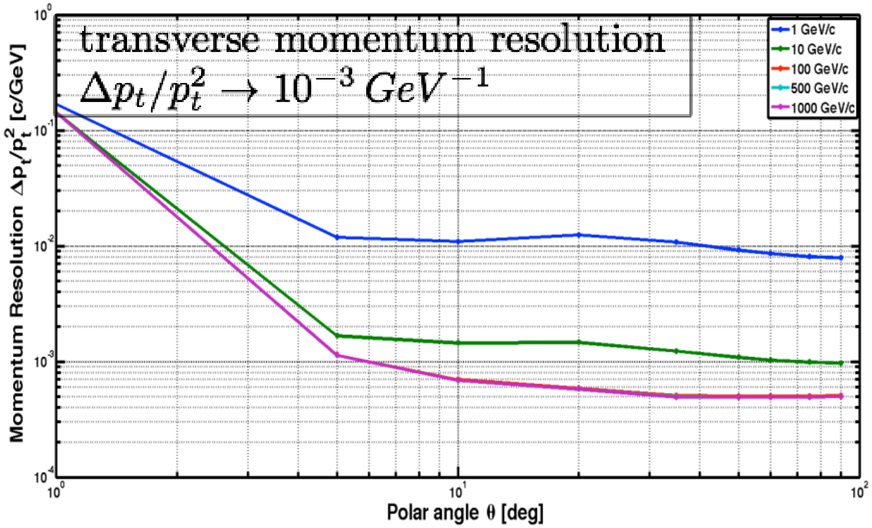


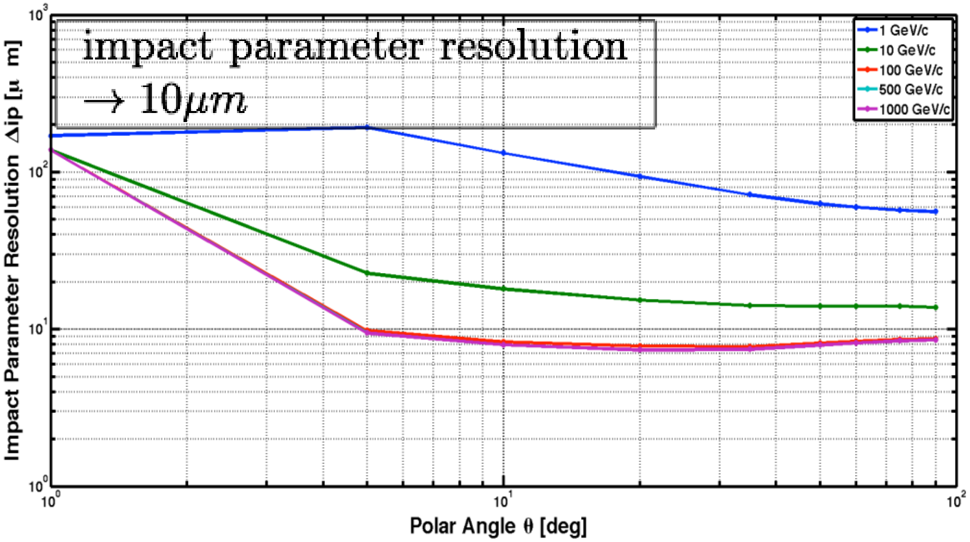
- Similar studies being done with FLUKA
- Most critical the forward region
- Rates far lower than LHC (LHC ~5 x 10^{14})

Tracker Simulation

LicToy http://wwwhephy.oeaw.ac.at/p3w/ilc/lictoy/UserGuide_20.pdf







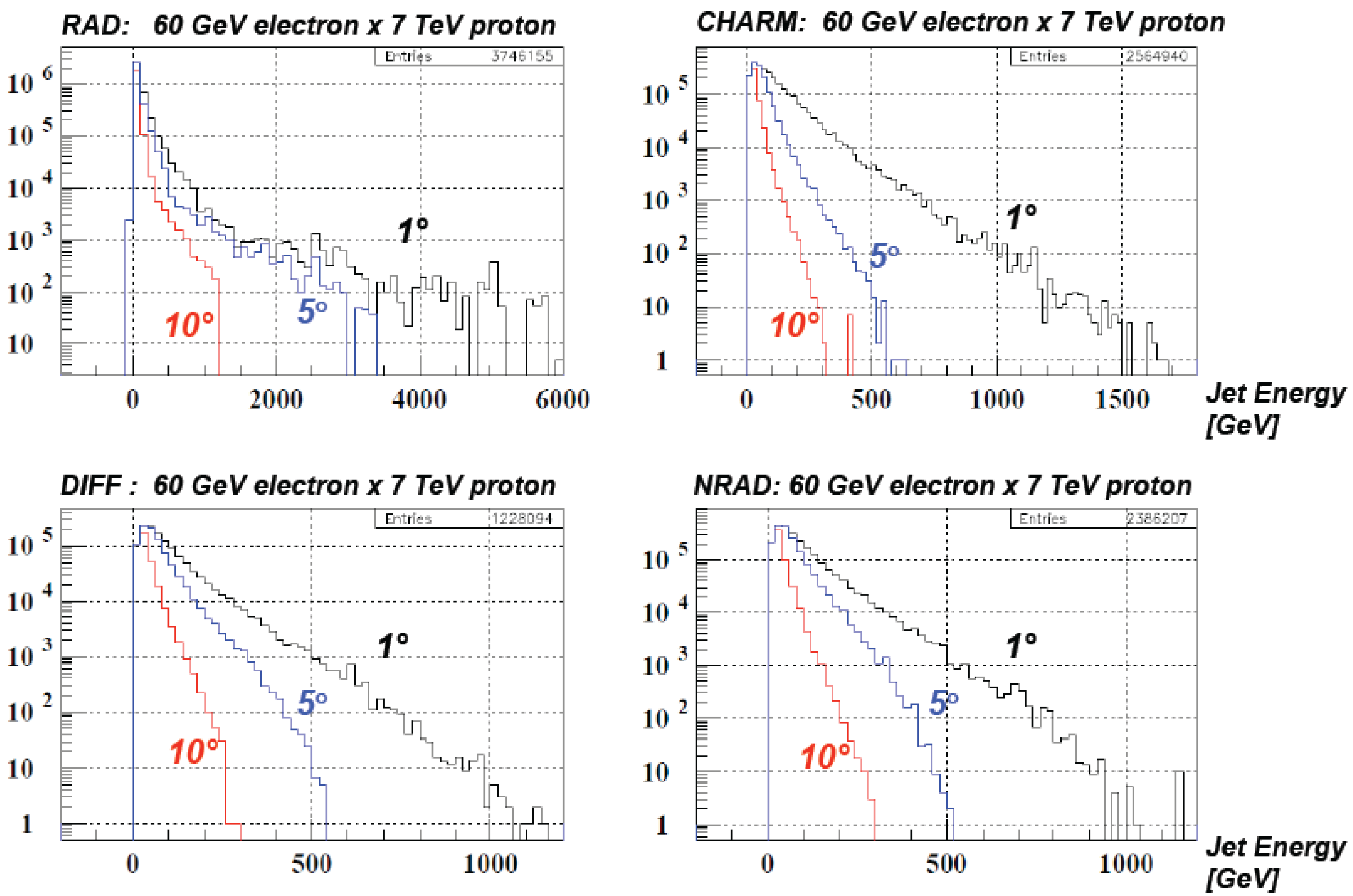
Silicon: compact design, low budget material, radiation hard

Forward Energy and Acceptance

LHeC

RAPGAP-3.2 (H.Jung et.al.- http://www.desy.de/~jung/rapgap.html)
HzTooL-4.2 (H.Jung et.al. - http://projects.hepforge.org/hztool/)
selection: q^2.gt.5

→ Highest acceptance desirable

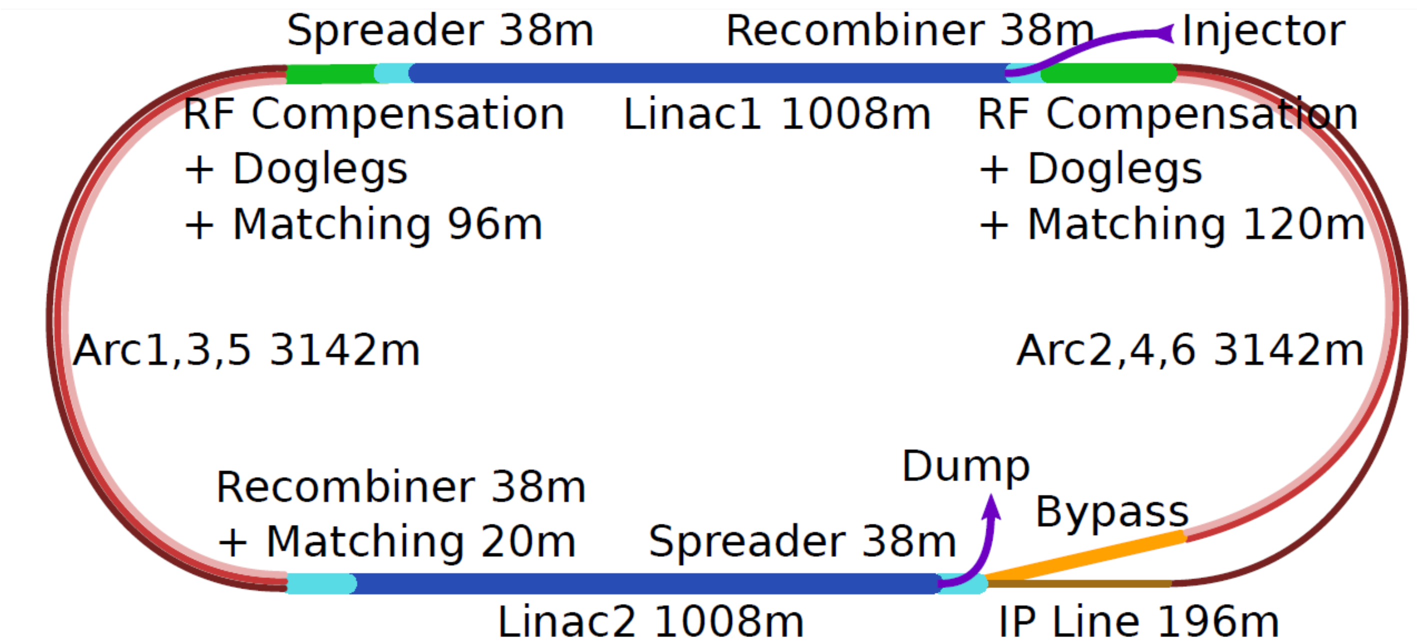


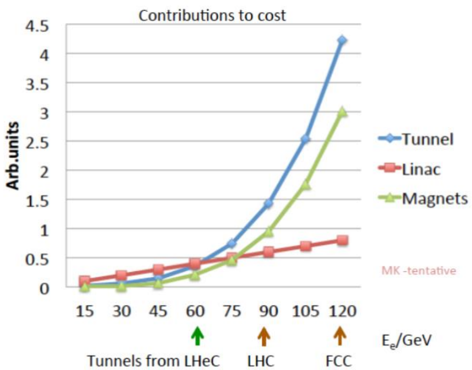
Detector Requirements from Physics

- High resolution tracking system
  - excellent primary vertex resolution
  - resolution of secondary vertices down to small angles in forward direction for high x heavy flavor physics and searches
  - precise p_t measurement matching to calorimeter signals (high granularity), calibrated and aligned to 1 mrad accuracy
- The calorimeters
  - electron energy to about $10\%/\sqrt{E}$ calibrated using the kinematic peak and double angle method, to permille level

    Tagging of γ's and backward scattered electrons - precise measurement of luminosity and photo-production physics
  - hadronic part $40\%/\sqrt{E}$ calibrated with p_{t_e}/p_{t_h} to 1% accuracy
  - Tagging of forward scattered proton, neutron and deuteron - diffractive and deuteron physics
- Muon system, very forward detectors, luminosity measurements

e⁻ Energy Recovery Linac



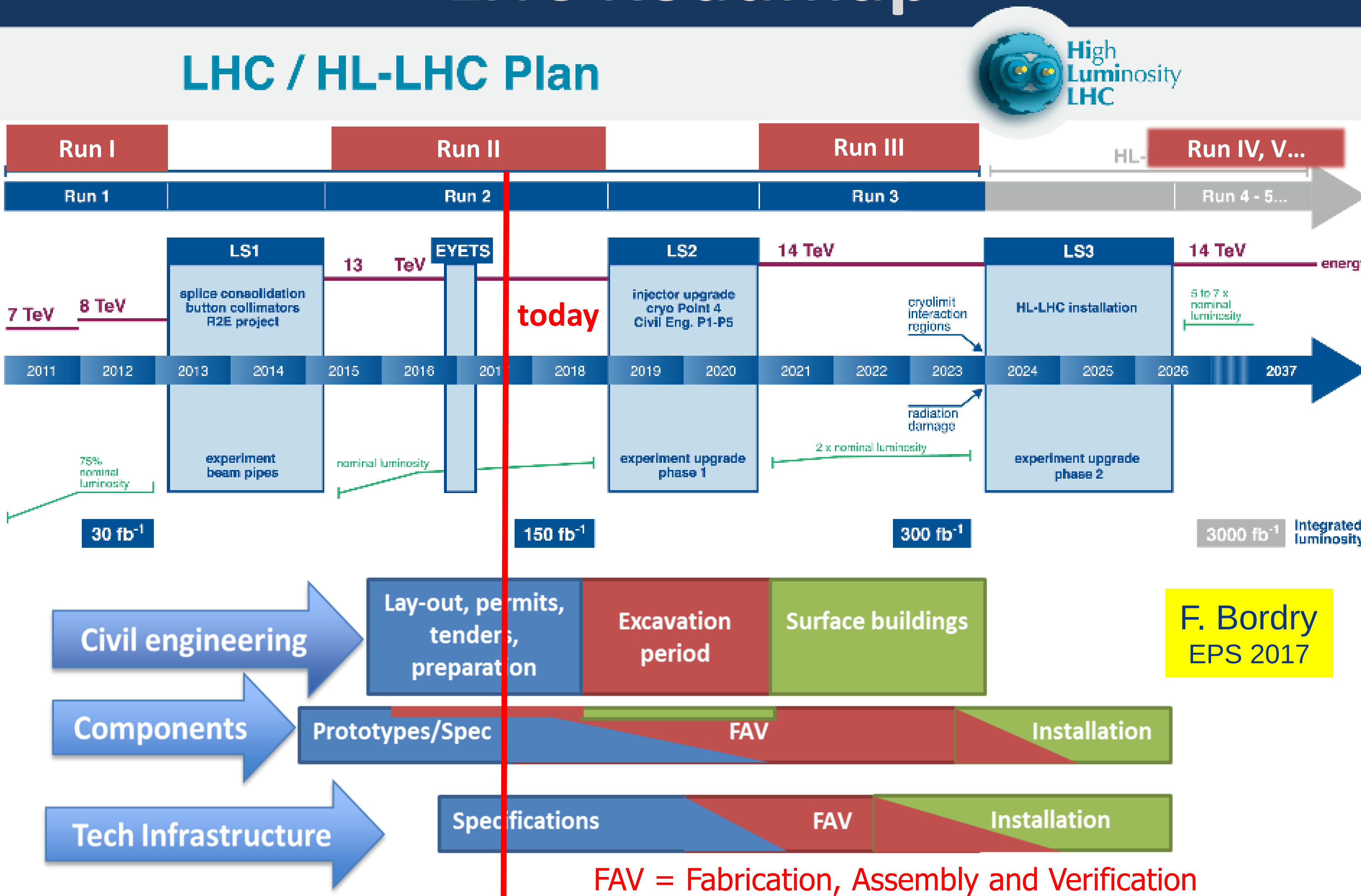


- ERL: Baseline for all LHeC Options (LHEC → FCC-he)
- Simultaneous Operation with hadron machine
  - Power consumption < 100 MW → E_e = 60 GeV
  - Two 10 GeV linacs, 3 returns, 20 MV/m
  - Polarized beam available
- CW operation: bunches are continuously injected and extracted from the racetrack.
- Bunches at different number of turns (accelerating and decelerating) are interleaved.
- Integer fraction of the LHC length (1=3) so that a gap for ion clearing does not shift with respect to the proton beam.

LHC and FCC Baseline Parameters

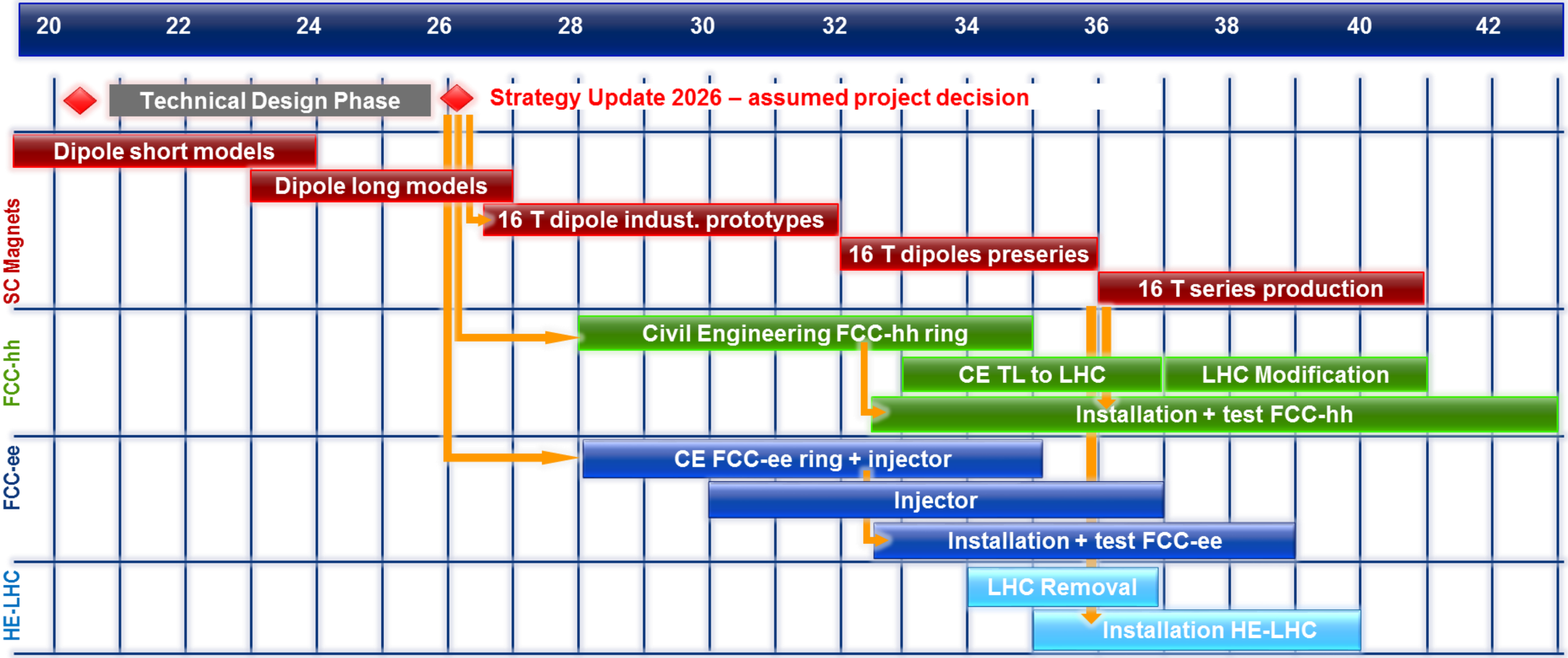
parameter	LHC	HL-LHC	HE-LHC	FCC-hh
collision energy cms [TeV]	**14**	**14**	**27**	**100**
dipole field [T]	**8.33**	**8.33**	**16**	**16**
circumference [km]	**26.7**	**26.7**	**26.7**	**97.75**
beam current [A]	0.58	1.12	1.12	0.5
bunch intensity [10^{11}]	**1.15**	**2.2**	**2.2 (0.44)**	**1**
bunch spacing [ns]	25	25	25 (5)	25
synchr. rad. power / ring [kW]	**3.6**	**7.3**	**101**	**2400**
SR power / length [W/m/ap.]	0.17	0.33	4.6	28.4
long. emit. damping time [h]	12.9	12.9	1.8	0.54
beta* [m]	0.55	0.20	0.25	1.1
normalized emittance [μm]	3.75	2.5	2.5 (0.5)	2.2 (0.4)
peak luminosity [10^{34} cm^{-2}s^{-1}]	1	5	25	5
events/bunch crossing	27	135	~800 (160)	170
stored energy/beam [GJ]	**0.36**	**0.7**	**1.3**	**8.4**

LHC Roadmap



FAV = Fabrication, Assembly and Verification

FCC Fastest Possible Technical Schedule



- Technical schedule defined by magnets program and by Civil Engineering:

→ Earliest possible physics starting dates:
  - FCC-hh: 2043
  - FCC-ee: 2039
  - HE-LHC: 2040 (with HL-LHC stop at LS5 / 2034)

M. Benedikt
FCC 2017 week