FCC-eh Configuration and Performance

- Configuration:

Energy Recovery Linac Layout:

- ⅓ LHC configuration with 60 GeV ERL for the ‘e’ beam

LHeC CDR ➔ applicable to LHC, HE-LHC and FCC

-1/4th and 1/5th LHC configurations with 55GeV & 51GeV

IR configuration with head-on collisions

➔ without Crab Cavities (vs EI in US)!

➔ SR acceptance in detector & beam separation

➔ Dipole integrated into detector

➔ ‘Sweetspot’ IR magnet design

802MHz SRF: synergy with FCC-ee and FCC-hh

CDR Options for LHeC Infrastructure:

CDR Study assumptions:

-Assume parallel operation [HL-LHC & FCC]

-TeV Scale collision energy

➔ 50-150 GeV Beam Energy

-Limit power consumption to 100 MW

➔ (beam & SR power < 70 MW)

➔ 60 GeV beam energy

-Int. Luminosity > 100 * HERA

-Peak Luminosity > 10^{33} cm^{-2}s^{-1}

Higgs @ 125GeV➔ > 10^{34} cm^{-2}s^{-1}

LHeC: RL with ERL Operation as Baseline

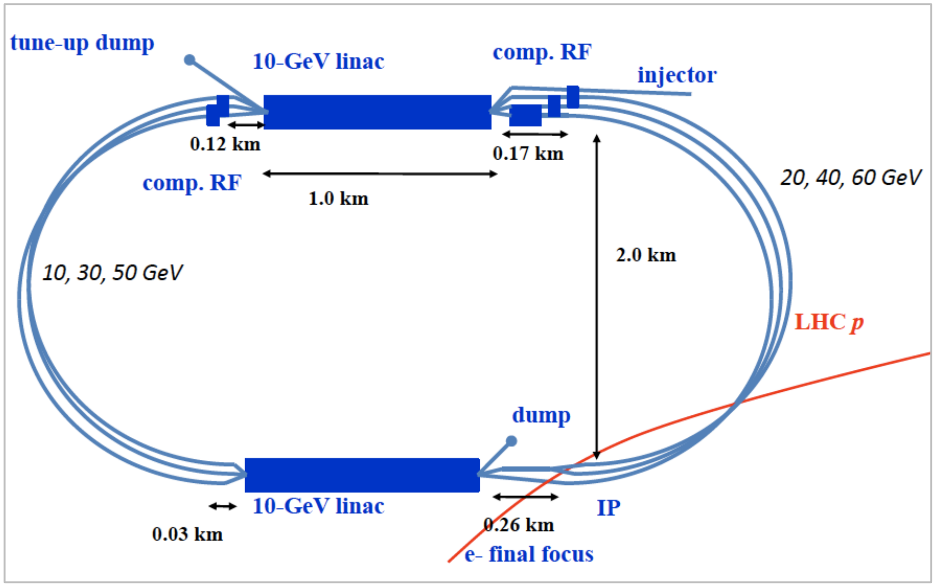
Performance:

10^{33} cm^{-2} s^{-1} Luminosity reach	PROTONS	ELECTRONS	PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60	7000	60
Luminosity [10^{33}cm^{-2}s^{-1}]	1	1	16	16
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	3.75	50	2.5	20
Beta Funtion $\beta^*_{x,y}$ [m]	0.1	0.12	0.05	0.10
rms Beam size $\sigma^*_{x,y}$ [μm]	7	7	4	4
rms Beam divergence $\sigma\square^*_{x,y}$ [μrad]	70	58	80	40
Beam Current @ IP [mA]	860	6.6	1112	25
Bunch Spacing [ns]	25	25	25	25
Bunch Population	$1.7*10^{11}$	$1*10^{9}$	$2.2*10^{11}$	$4*10^{9}$
Bunch charge [nC]	27	0.16	35	0.64

60GeV ERL Configuration:

- Super Conducting Recirculating Linac with Energy Recovery

Choose ⅓ of LHC circumference ➔



Two 1 km long, 10 GeV SC LINACs with 3 accelerating and 3 decelerating passes in CW operation

➔ SRF sees 6*current at the IP (≈ 4ns spacing)

➔ $Q_0 = 10^{10}$ requires cryogenic system comparable to LHC system! $Q_0 > 10^{10}$

➔ 944 cavities; 59 cryo modules per linac

➔ ca. 9 km underground tunnel installation

➔ more than 4500 magnets (same magnet design as for RR option)

FCC-eh Configuration: Layout & Civil Engineering

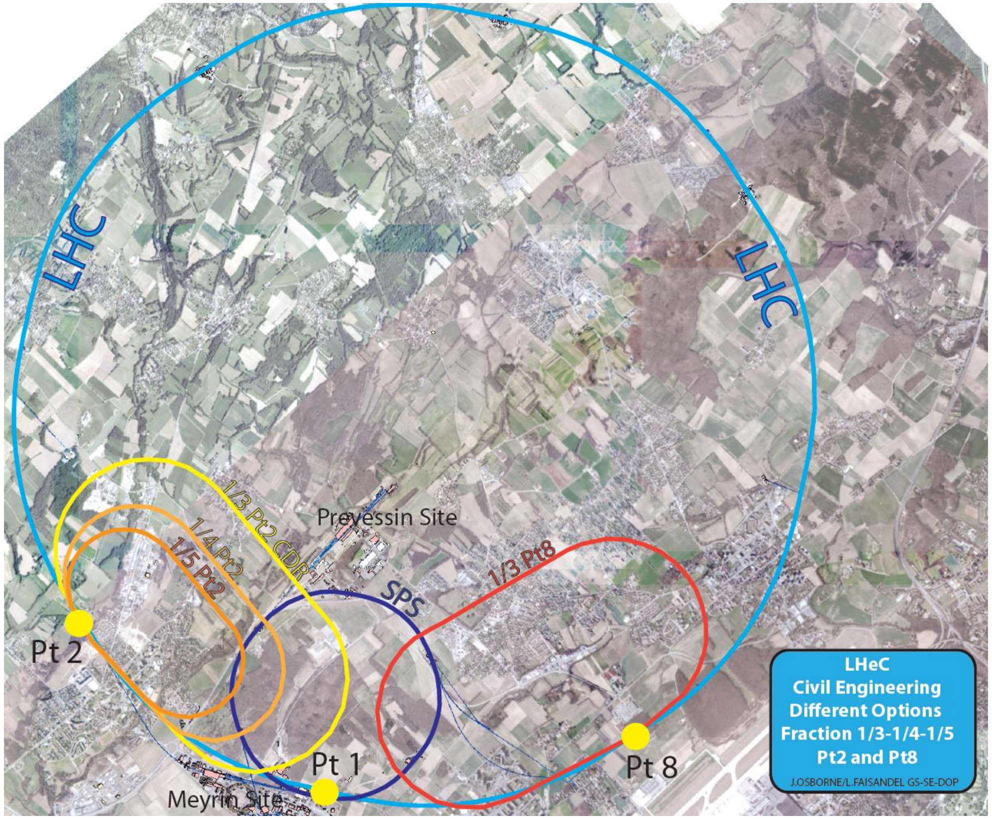
C. Cook @ FCC week in Rome

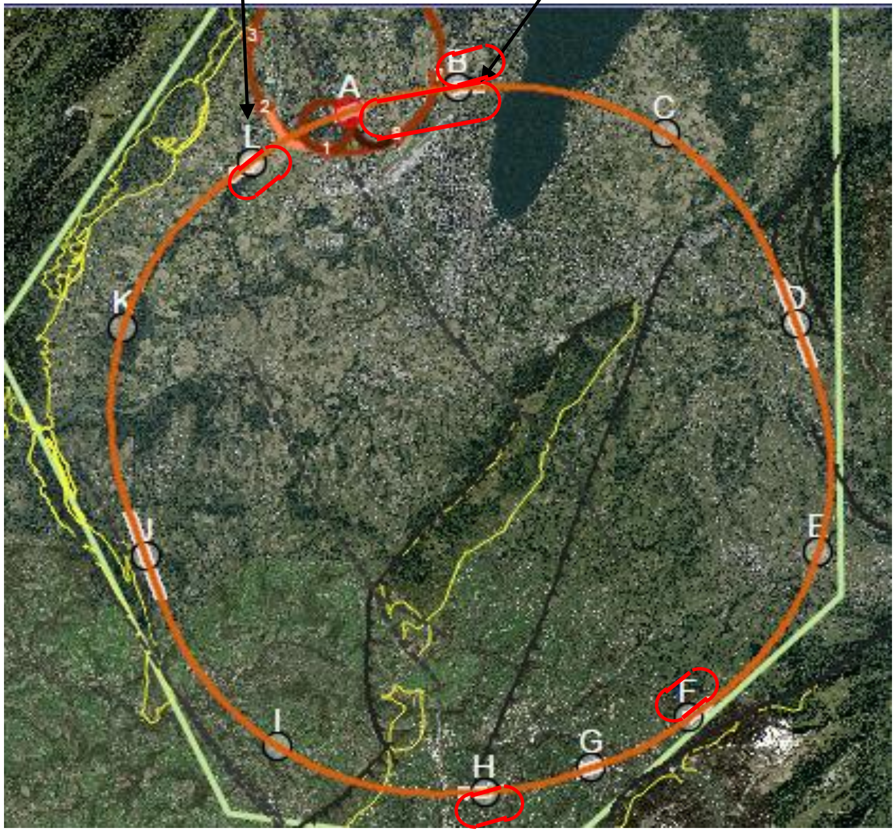
Configuration:

LHeC Machine

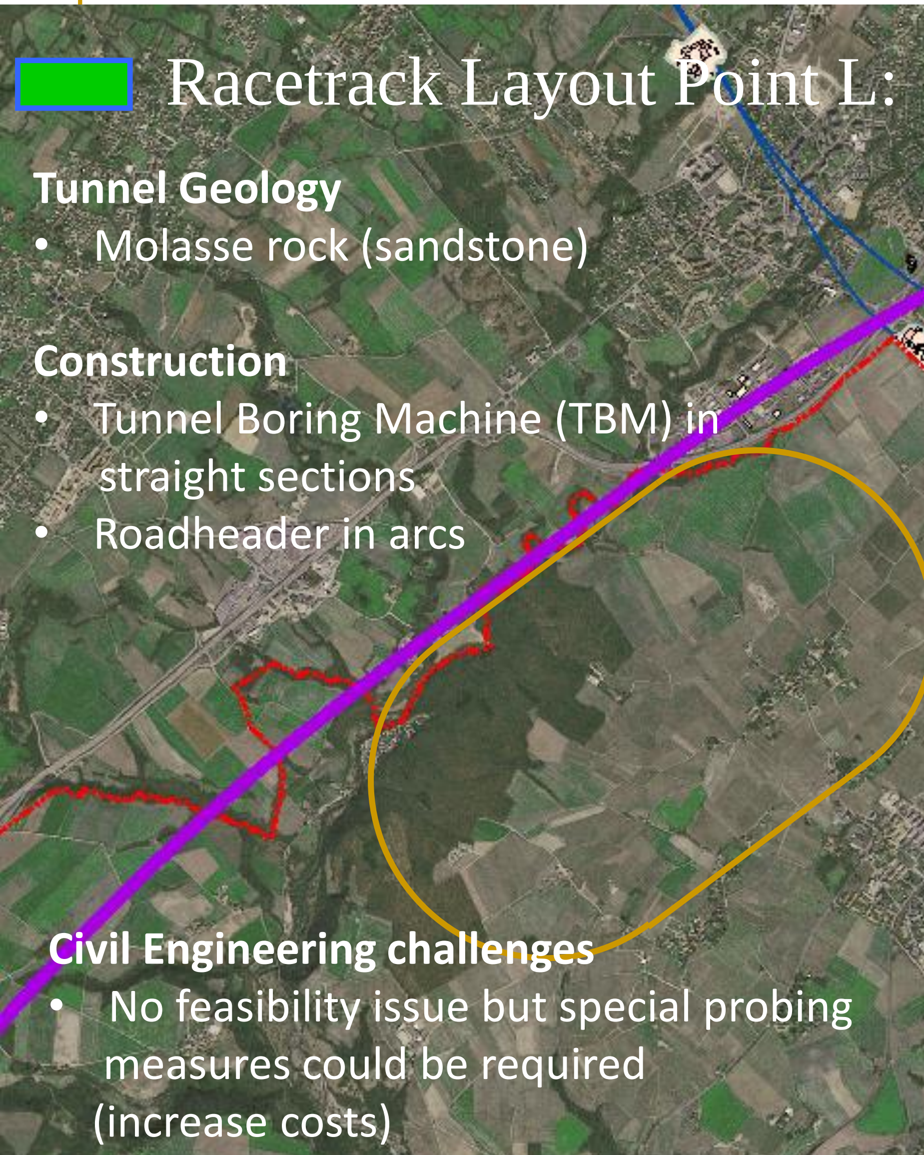
Independent FCC-he Point L, F, H or B

LHeC / FCC-he LHC P8 & FCC PB





FCC-eh Configuration: Layout & Civil Engineering



Racetrack Layout Point L:

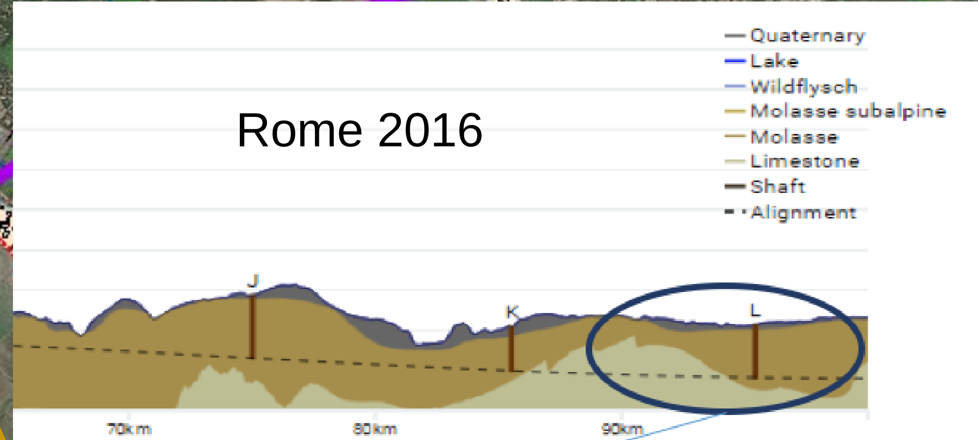
C. Cook @ FCC week in Rome
Updated with data from Berlin

Tunnel Geology

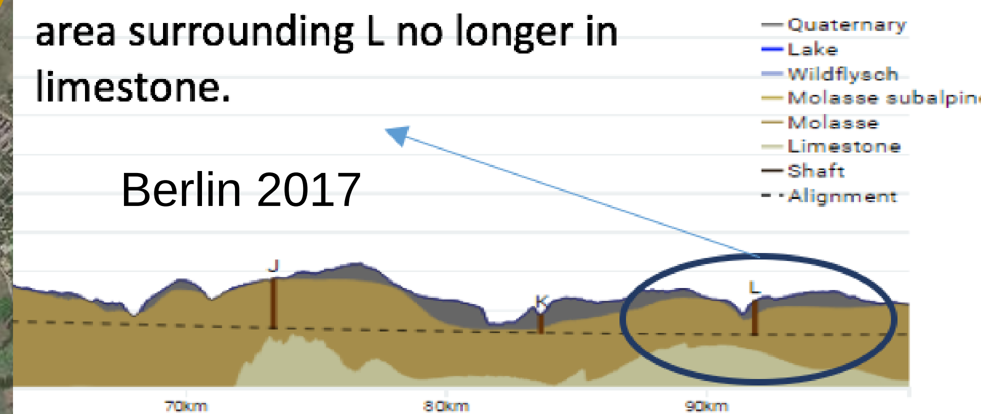
- Molasse rock (sandstone)

Construction

- Tunnel Boring Machine (TBM) in straight sections
- Roadheader in arcs



Reduced Depth & alignment change; area surrounding L no longer in limestone.



Civil Engineering challenges

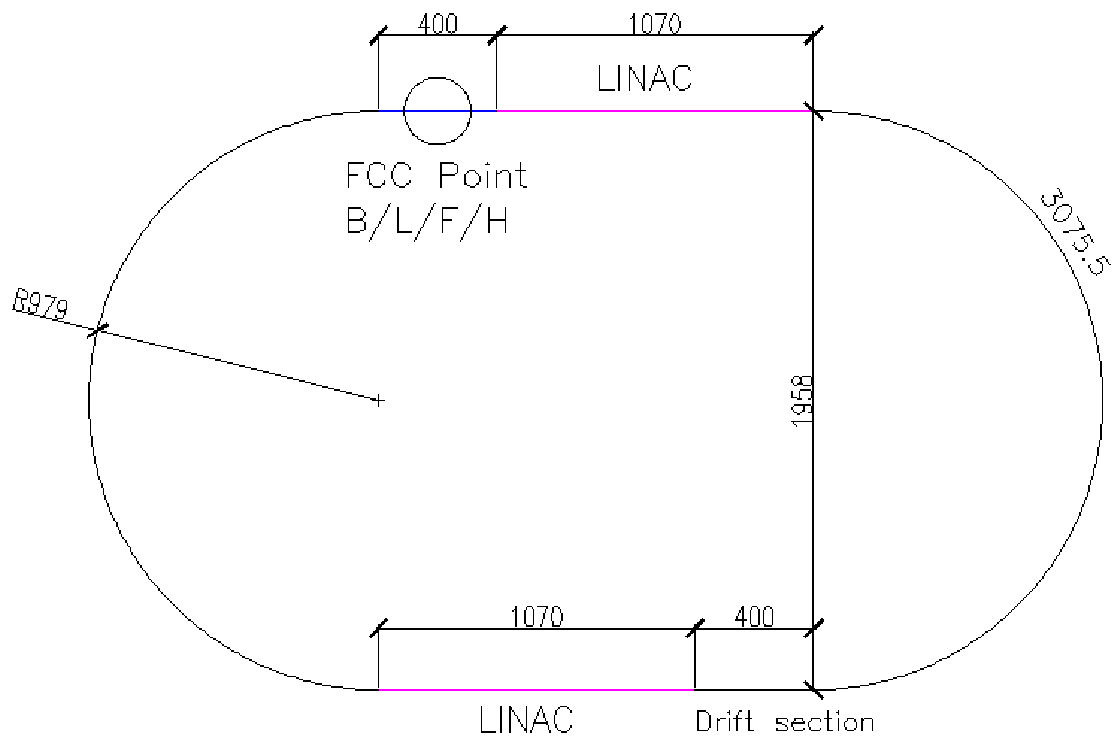
- No feasibility issue but special probing measures could be required (increase costs)

FCC-eh Configuration: Layout & Civil Engineering

C. Cook @ FCC week in Rome

Racetrack Layout:

- Connection to FCC straight section at point L
- 1070m ERLs - 400m BDS – 979m radius arcs - 400m beam transfer
- 9091m total length, $\frac{1}{11}$ of FCC

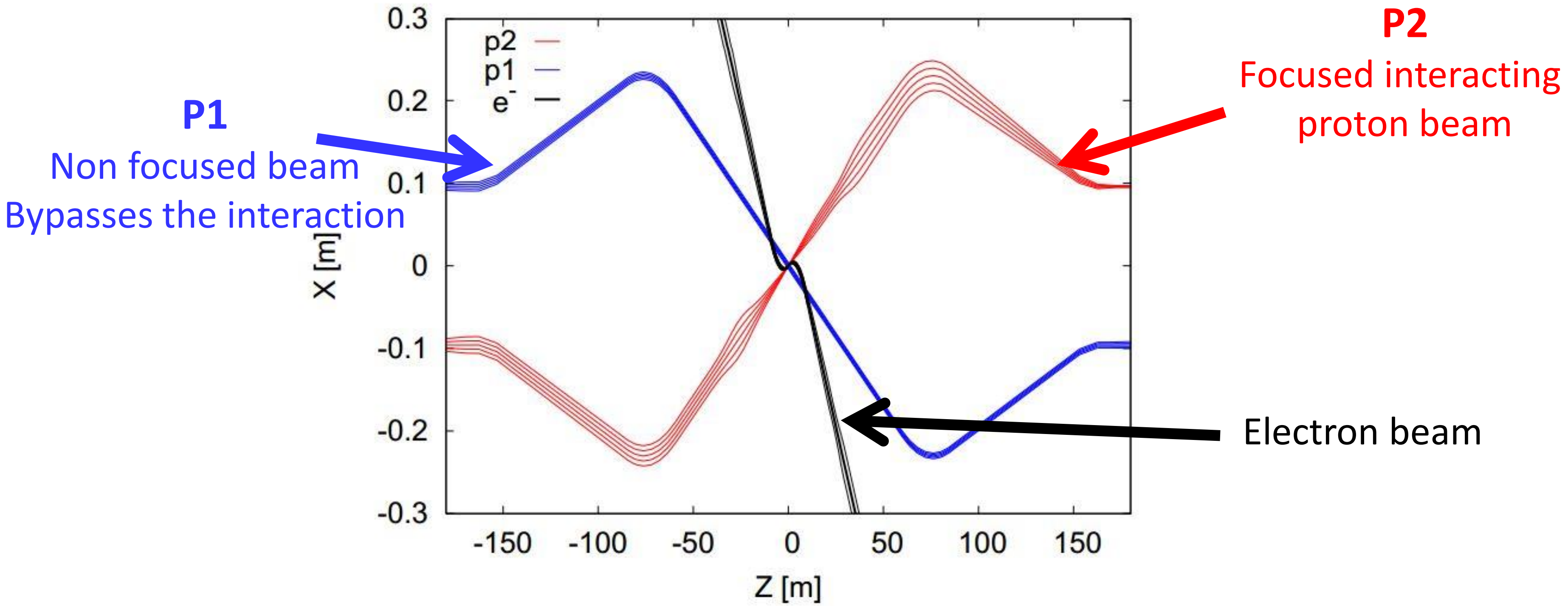


FCC-eh Configuration and Performance

IR challenges and configurations:

E. Cruz @ FCC week in Rome

- Aim of the interaction region design: Collide one of the proton beams head-on with the electron beam from the ERL while the other proton beam bypasses the interaction.

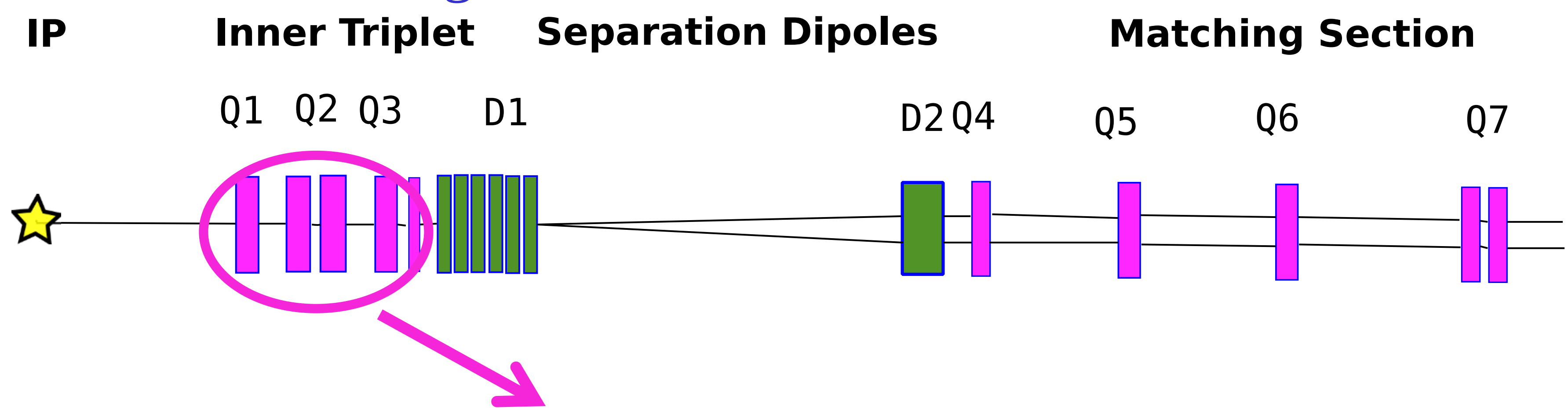


- LHeC has to work alongside HL-LHC and built within an existing IR2 cavern layout, designed for a different experiment.
- FCC-he integration will be easier: the IR can be designed for the required purposes.

FCC-eh Configuration and Performance

Hadron IR design:

E. Cruz @ FCC week in Rome



Implementation of new triplet Q1-Q3 with aperture for 2 proton beams and one electron beam ➔ current studies based on layout WITHOUT Crab Cavities!
➔ strong synchrotron radiation and dipole inside detector!

We need:

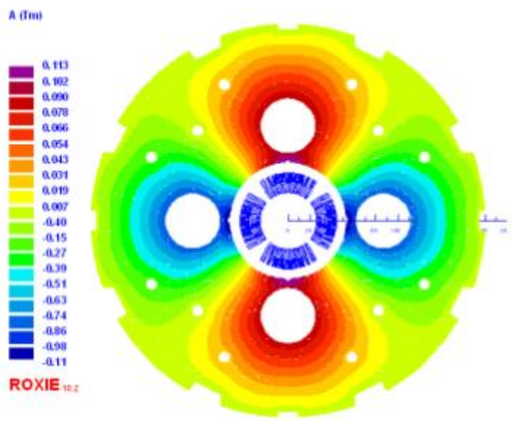
- β*=20 cm

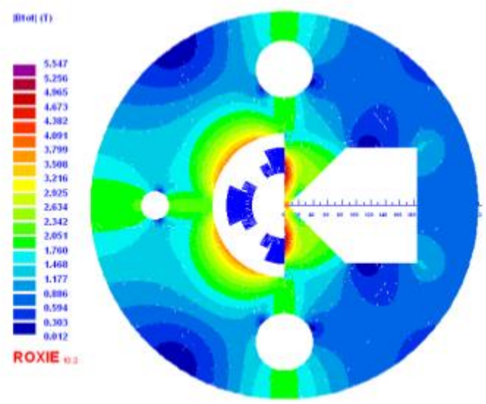
LIMITATIONS / Challenges

1. Quadrupole apertures
2. Quadrupole gradients
3. Limits of the chromatic correction scheme

Asymmetric IR Layout: Magnet Design

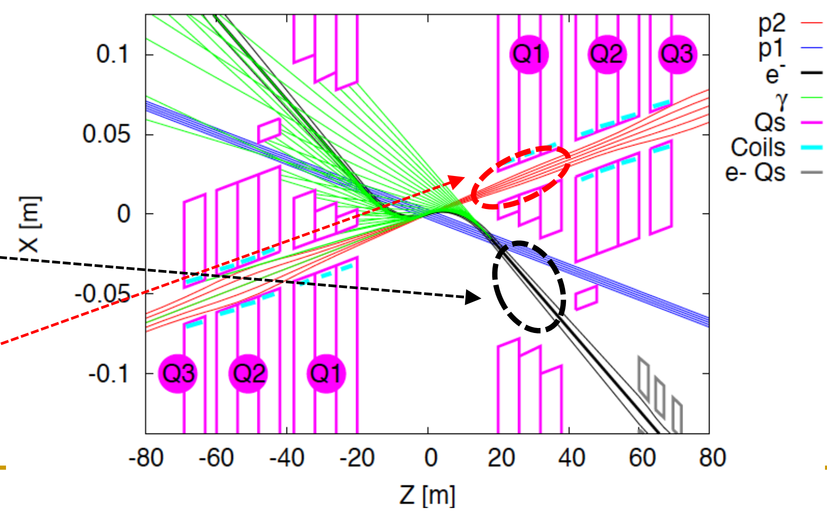
The design of the magnets for the LHeC included a normal-aperture to focus the proton beam and a field-free aperture for the electron and unfocussed proton beam.





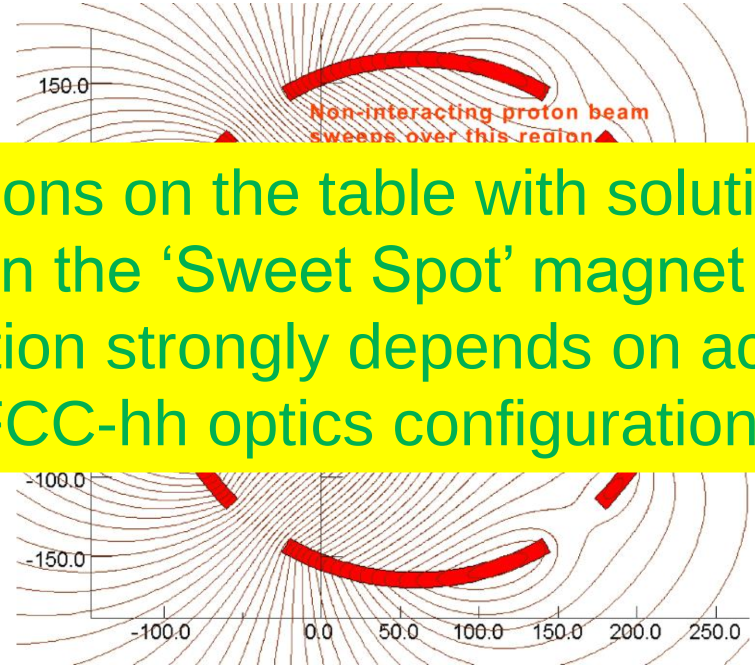
Consideration of the magnets for the LHeC included the design of a half quadrupole for Q1 given the short distance between the proton beam and the electron beam

This design presents stray fields in the 'field-free' region difficulting to match the **electron beam**. Also, beam is off-axis so there is a deflection on the focussed proton beam.



Asymmetric IR Layout: Magnet Design

The sweet spot quadrupole has double the gradient for a given aperture, or double the aperture for the same gradients. Leaving more space to put masks through the whole length of Q1.

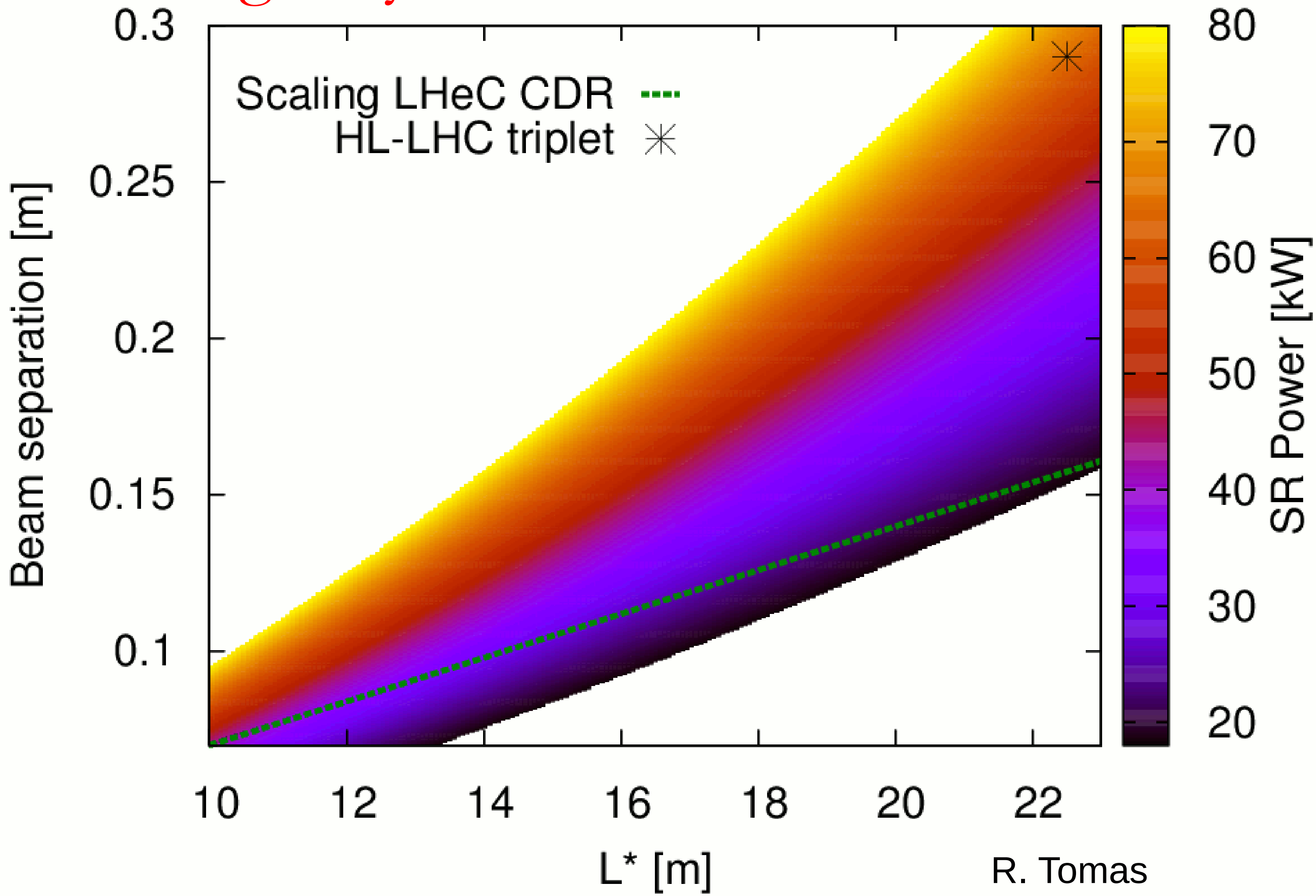


Various options on the table with solutions at hand!
Design work on the ‘Sweet Spot’ magnet is still ongoing!
Final implementation strongly depends on actual IR choice and FCC-hh optics configuration!!!

The baseline LHeC IR geometry is particularly challenging as it requires very wide Sweet Spot regions to locate both the electron and proton beams.

B. Parker, LHeC Workshop, Chavannes, 2015.

IR Design: Synchrotron Radiation



ERL Beam Dynamics: HOM and Beam Stability

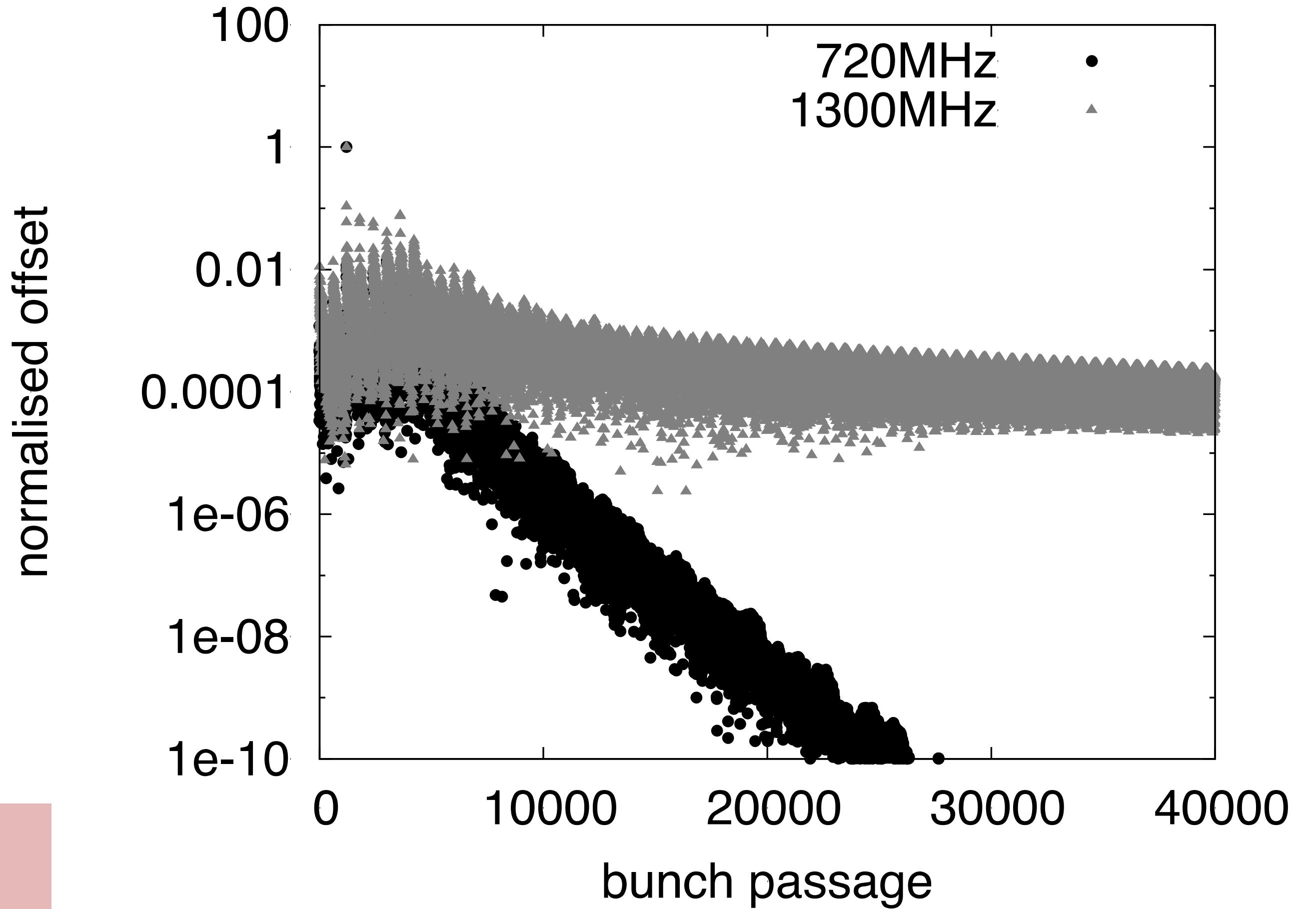
HOM & Beam-Beam

Daniel Schulte @ LHeC Seminar 12. March 2013

$N=3\ 10^9$
Beam-beam effect included as linear kick

Result depends on seed for frequency spread
"worst" of ten seed shown

F_{rms}=1.135 for ILC cavity
F_{rms}=1.002 for SPL cavity

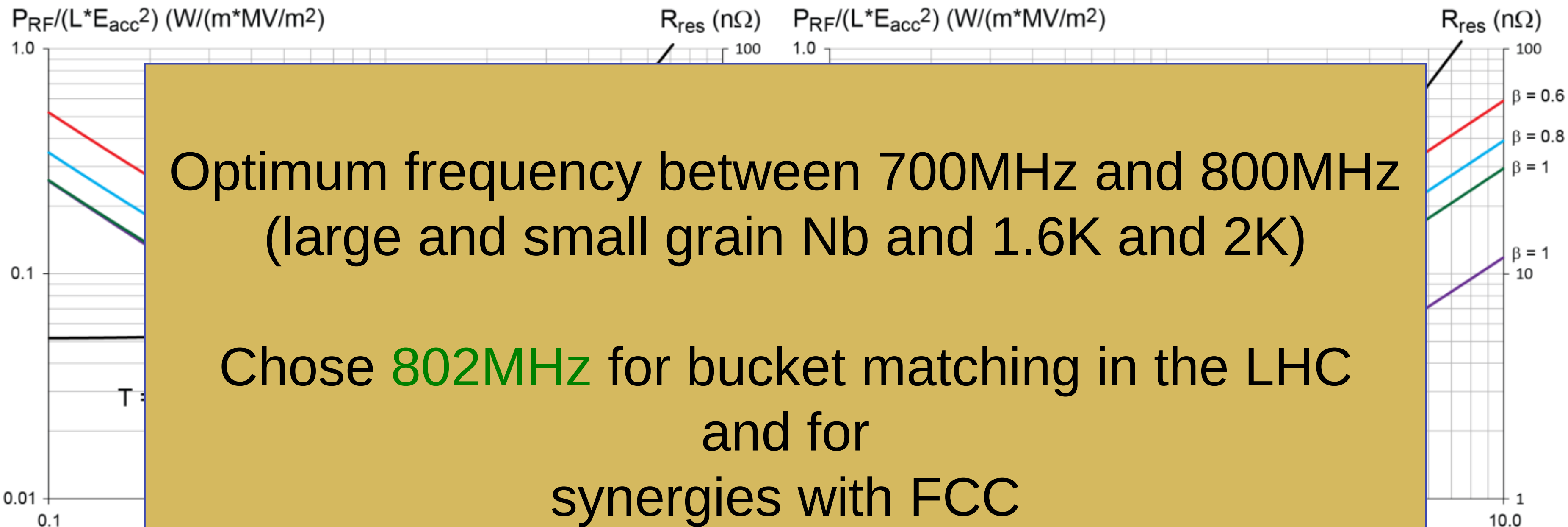


Beam is stable but very small margin with 1.3GHz cavity → lower frequency

Optimum RF Frequency: Power Considerations

Results from F. Marhauser

Erk Jensen at Daresbury meeting 12 March 2013



Optimum frequency between 700MHz and 800MHz (large and small grain Nb and 1.6K and 2K)

Chose 802MHz for bucket matching in the LHC and for synergies with FCC

Small-grain (normal) Nb:
Optimum frequency at 2K between 700 MHz and 1050 MHz
Lower T shift optimum f upwards

Large-grain Nb:
Optimum frequency at 2K between 300 MHz and 800 MHz
Lower T shift optimum f upwards

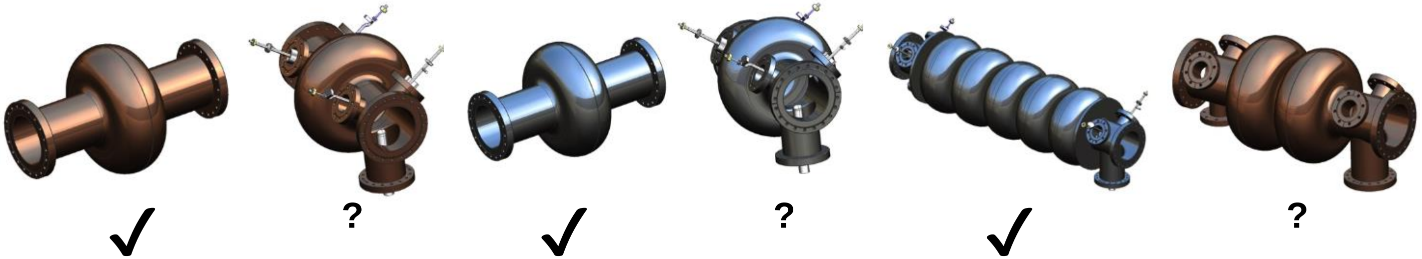
SRF: JLab Collaboration

Robert Rimmer JLab

Fabricate dies. Q2 FY17
Test dies with Al or Cu disks, check dimensions etc.
Fabricate one or more copper 1-cell cavities. Q3 FY17
- Check tuning procedure and useful for CERN coating tests
- Can add ports for development of HOM couplers

Fabricate one bare Nb single cell. Q3 FY17
- Validate frequency, Qo and gradient
- Option to make one large grain single cell

Fabricate bare 5-cell cavity (no He vessel) with ports. Q4 FY17



✓ = in plan, **?** = option

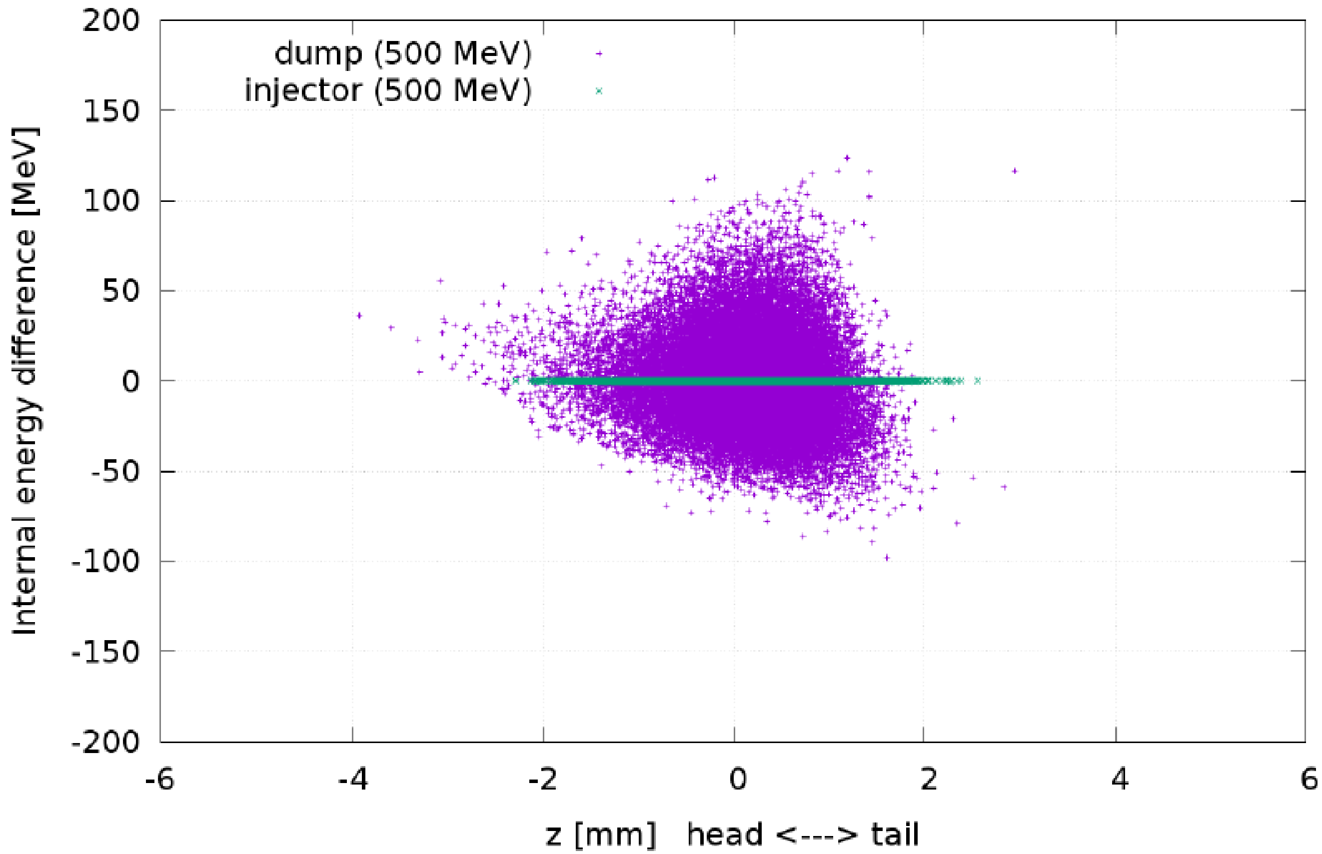
Beam Dynamics and ‘front-end’ Simulations:

- Key Studies (performed with PLACET2 code from CLIC):
  - ➔ Synchrotron radiation
    bunch shape and acceptance for deceleration and dump
  - ➔ Beam-beam interaction
    bunch shape and beam stability
  - ➔ RF Wakefields and HOM
    beam stability
  - ➔ Recombination patters
    beam stability (filling of the RF buckets can be controlled by tuning the arc lengths)
  - ➔ Cavity alignment requirements
    orbit and emittance control

Synchrotron Radiation

Evolution of the Longitudinal Phase Space

D. Pellegrini (EPFL/CERN) @ ERL'15

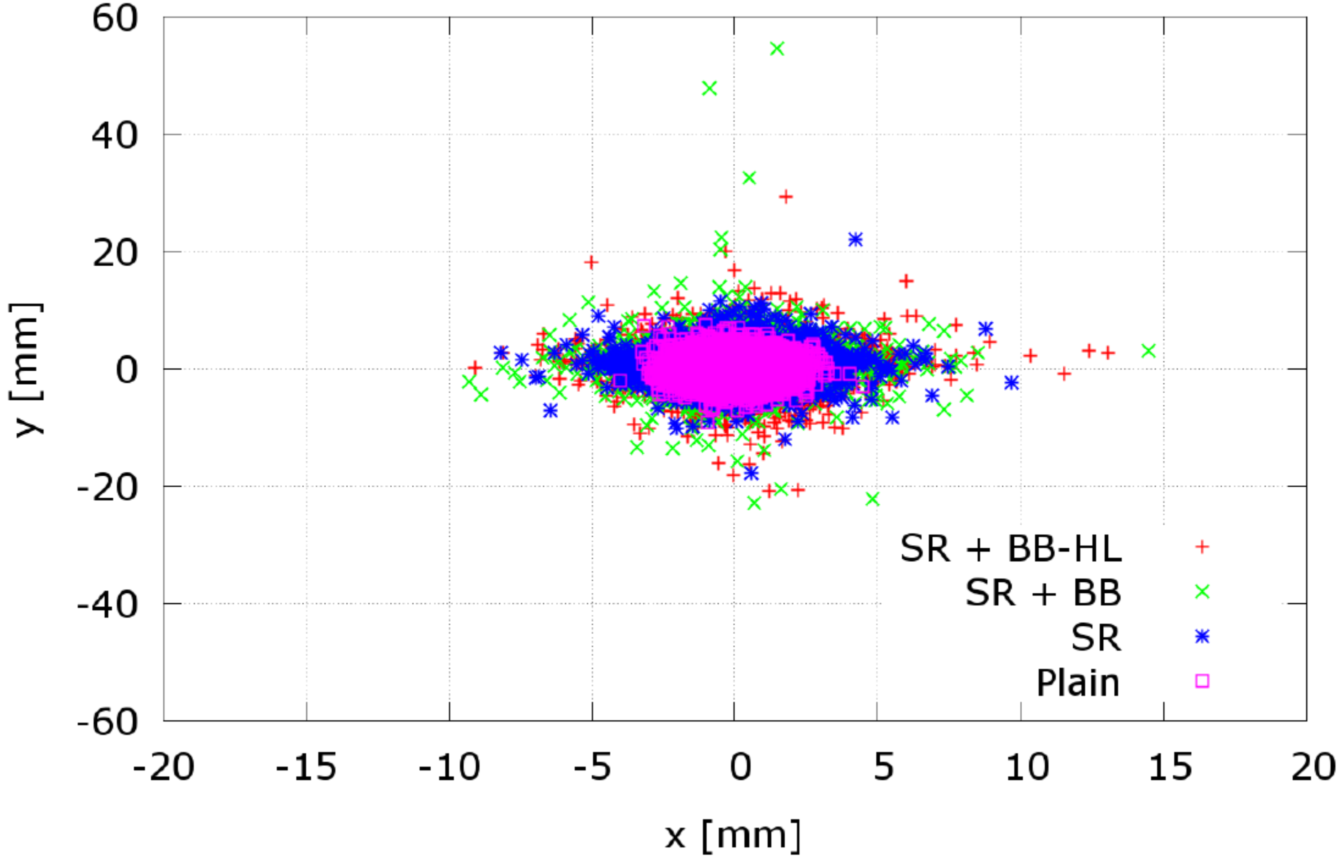


22

Synchrotron Radiation and Beam-Beam

Transverse Plane at Dump

D. Pellegrini (EPFL/CERN) @ ERL'15



Aperture radius of the SPL cavity is 40 mm.

FCC-eh ERL Configuration:

Consistent Performance Projections for ep:

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 [$10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	1	8	12	15

EDMS 17979910 FCC-ACC-RPT-0012 V1.0, 6 April, 2017, "A Baseline for the FCC-he"

Oliver Brüning, John Jowett, Max Klein, Dario Pellegrini, Daniel Schulte, Frank Zimmermann

FCC-eh ERL Configuration:

[Daniel Schulte]

Performance Simulations for FCC-ep:

Parameter	Unit	Protons	Electrons
Beam energy	GeV	50000	60
Normalised emittance	μm	$2.2 \to 1.1$	10
IP betafunction	mm	150	$42 \to 52$
Nominal RMS beam size	μm	$2.5 \to 1.8$	$1.9 \to 2.1$
Waist shift	mm	0	$65 \to 70$
Bunch population	10^{10}	$10 \to 5$	0.31
Bunch spacing	ns	25	25
Luminosity	$10^{33}\text{cm}^{-2}\text{s}^{-1}$	$18.3 \to 14.3$	
Int. luminosity per 10 years	$[\text{ab}^{-1}]$	1.2	

EDMS 17979910 FCC-ACC-RPT-0012 V1.0, 6 April, 2017,
“A Baseline for the FCC-he”

Daniel Schulte

Key Risk Items and Open Issues I:

- Civil Engineering ➔ decoupled from main tunnel construction
  - ➔ Low risk with new FCC tunnel layout
  - ➔ But still requires detailed design: caverns for infrastructure; space for return arcs, ventilation and cooling requirements; cryogenic infrastructure, transfer line, beam dump etc.

- Transfer-line design and integration into FCC IR region
  - ➔ Impact on Interaction region design ➔ Civil Engineering
  - ➔ Not assumed to be a major issue but requires studies

➔ Important for final cost estimate

Key Risk Items and Open Issues II:

- IR Magnet design: ’Sweetspot’ versus mirror design
  - ➔ Minimum beam separation & L^* ➔ Synchrotron Radiation
  - ➔ Requires dedicated magnet R&D;
  - ➔ so far only conducted on a best effort basis

- SRF design
  - ➔ HOM, microphonics, Q_0 and required cryo system
  - ➔ Not assumed to be a major issue but important for infrastructure (e.q. Q_0 defines the required cryo) and performance reach [HOM will limit I_{max}])

➔ Cost driver element

Key Risk Items and Open Issues III:

- Optics integration into final FCC optics
  - ➔ β^* reach ➔ performance reach
  - ➔ Not assumed to be a major issue but requires studies
- Optics for the non-colliding hadron beam
  - ➔ Aperture requirements and IR magnet design
  - ➔ Not assumed to be a major issue but requires studies
- Optics and acceptance for the beam dump
  - ➔ Acceptance ➔ Not assumed to be a major issue but defines minimum injection energy

Key Risk Items and Open Issues IV:

- Synchrotron radiation inside detector
  - ➔ background ➔ acceptable L^* and performance reach
  - ➔ Integrated dipole inside detector and / or crab cavities
  - ➔ Could limit maximum acceptable e-beam intensity
  - ➔ Requires dedicated machine-experiment interface studies
    - ➔ So far only conducted with very limited resources!
    - ➔ Can be a serious concern (e.g. HERA experience)

Key Risk Items and Open Issues V:

- ERL beam dynamics limitations
  - ➔ Beam stability and efficiency ➔ performance reach
  - ➔ PERLE will address most e-beam dynamics issues (e.g. BB and ion capture instabilities)
  - ➔ Effect of e-beam on h-beam addressed in simulations and RHIC: not assumed to be a limitation (rather added value)
  - ➔ Virtual Beam Power and ERL efficiency
    - ➔ O(GW) virtual beam power for < 100MW site power
    - ➔ Operation efficiency and reliability
    - ➔ PERLE (& partially CBETA) will address these aspects [order of 10MW virtual Beam Power, multi-turn ERL]

Summary

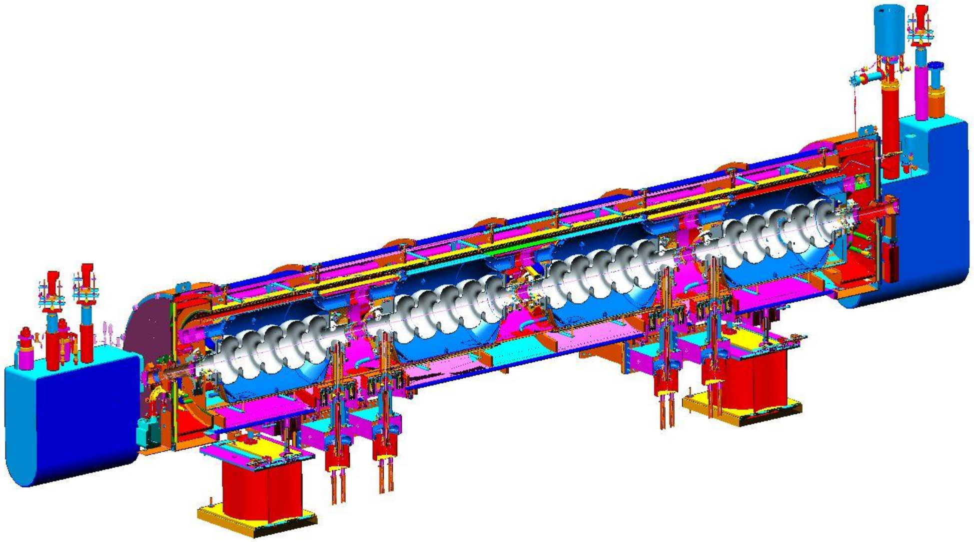
- eh Collisions can be realized at interesting performance levels
  - ➔ No intrinsic technical problems identified
  - ➔ Luminosities in excess of 10^{34} cm^{-2} s^{-1} within reach

- eh Collisions can be realized at ‘moderate’ cost
  - ➔ Cost comparable to LHC machine or HE-LHC

- Unique new Facility
  - ➔ ERL Technology and concept
  - ➔ Full exploitation of the LHC / FCC infrastructure
  - ➔ Physics: talk by Mangano
  - ➔ Physics potential beyond FCC and HEP

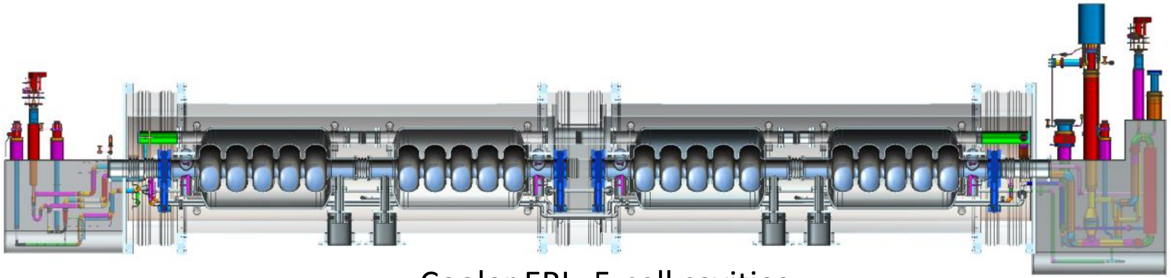
SNS like cryomodule:

Cavity fits well in SNS type (805 MHz) cryomodule
Cost and fabrication processes well understood
Some updates for pressure code have been made by ORNL
Plans to build new modules for SNS Power Upgrade
Fresh cost estimate in hand, can be adapted to PERLE

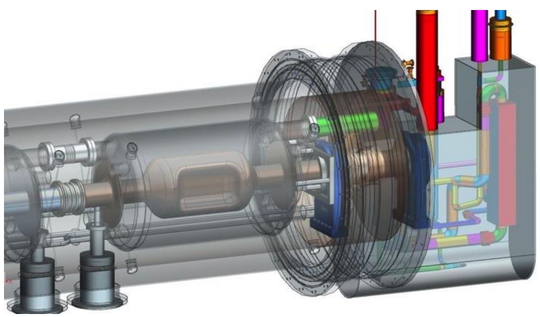


JLab Modular Cryostat:

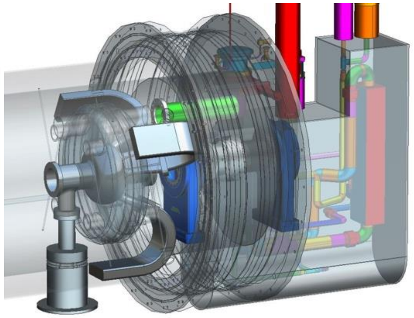
- Take the best features of previous JLab designs
- Modular approach to hold various different cavities
- Design suitable for industrial production
- Simple concepts, low parts count to reduce costs



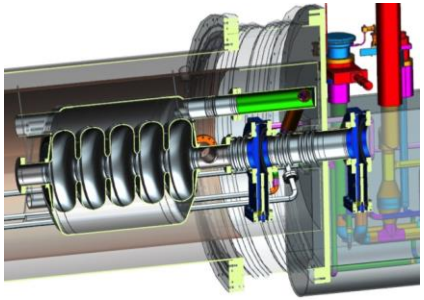
Cooler ERL, 5-cell cavities



476.3 MHz Crab cavity



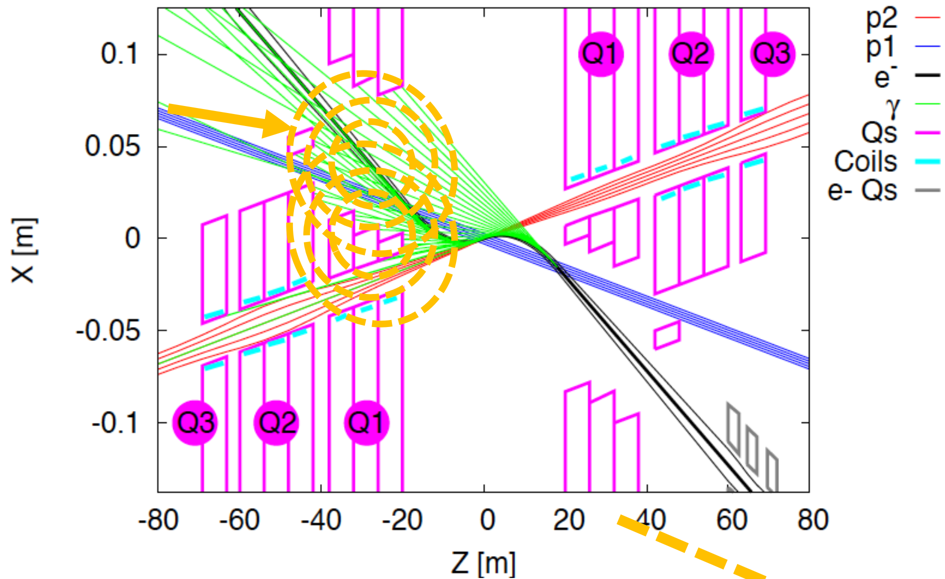
On-cell damper concept



β=0.6 650 MHz cavity

Asymmetric IR Layout: Magnet Design

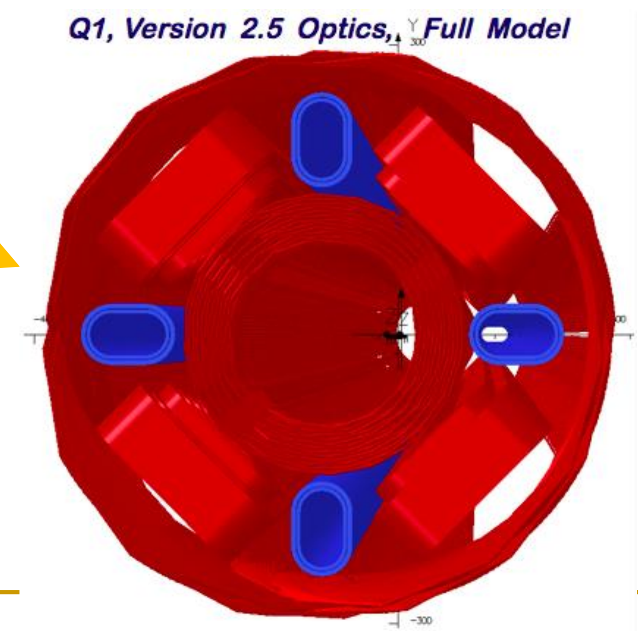
Synrad



Magnet design planned for eRHIC IR.

With the use of outer coils a reduced field region is created inside the quadrupole -> Sweet Spot.

Possible new design for the Q1



"Sweet Spot" design for Interaction Region Septum Magnets in IPAC 2016 by Brett Parker.