FCC-eh Configuration and Performance

- Configuration:

Modular design elements:

-60 GeV ERL configuration for the ‘e’ beam

documented in the LHeC CDR ➔ varied sizes;

applicable to LHC, HE-LHC and FCC

-800MHz SRF: synergy with FCC-ee and FCC-hh

-IR configuration with head-on collisions

➔ without Crab Cavities (vs EI in US)!

➔ SR acceptance in detector and beam separation

➔ Dipole integrated into detector

➔ ‘Sweetspot’ IR magnet design

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

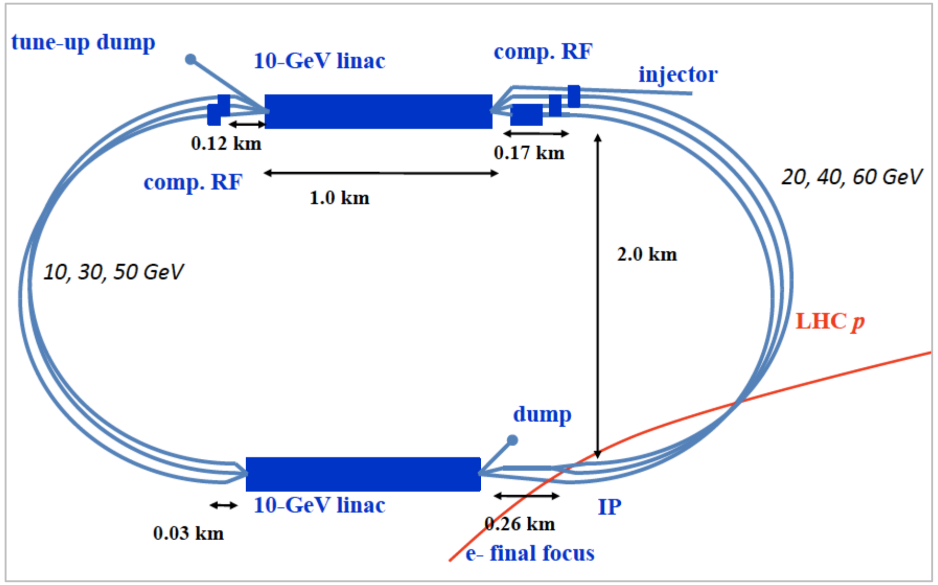
-Peak Luminosity > 10^{33} $cm^{-2}s^{-1}$

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

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)

LHeC: RL with ERL Operation as Baseline

LHeC

Super Conducting Recirculating Linac with Energy Recovery

Choose ⅓ of LHC circumference ➔

Two 1 km long, 10 GeV SC LINACs with 3 accelerating and

10^{34} cm^{-2} s^{-1} Luminosity reach	PROTONS	ELECTRONS	PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60	7000	60
Luminosity [$10^{33}cm^{-2}s^{-1}$]	16	16	1	1
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	2.5	20	3.75	50
Beta Funtion $\beta^*_{x,y}$ [m]	0.05	0.10	0.1	0.12
rms Beam size $\sigma^*_{x,y}$ [μm]	4	4	7	7
rms Beam divergence σ□$^*_{x,y}$ [μrad]	80	40	70	58
Beam Current @ IP[mA]	1112	25	860	6.6
Bunch Spacing [ns]	25	25	25	25
Bunch Population	$2.2*10^{11}$	$4*10^{9}$	$1.7*10^{11}$	$1*10^{9}$
Bunch charge [nC]	35	0.64	27	0.16

FCC-eh Configuration: Layout & Civil Engineering

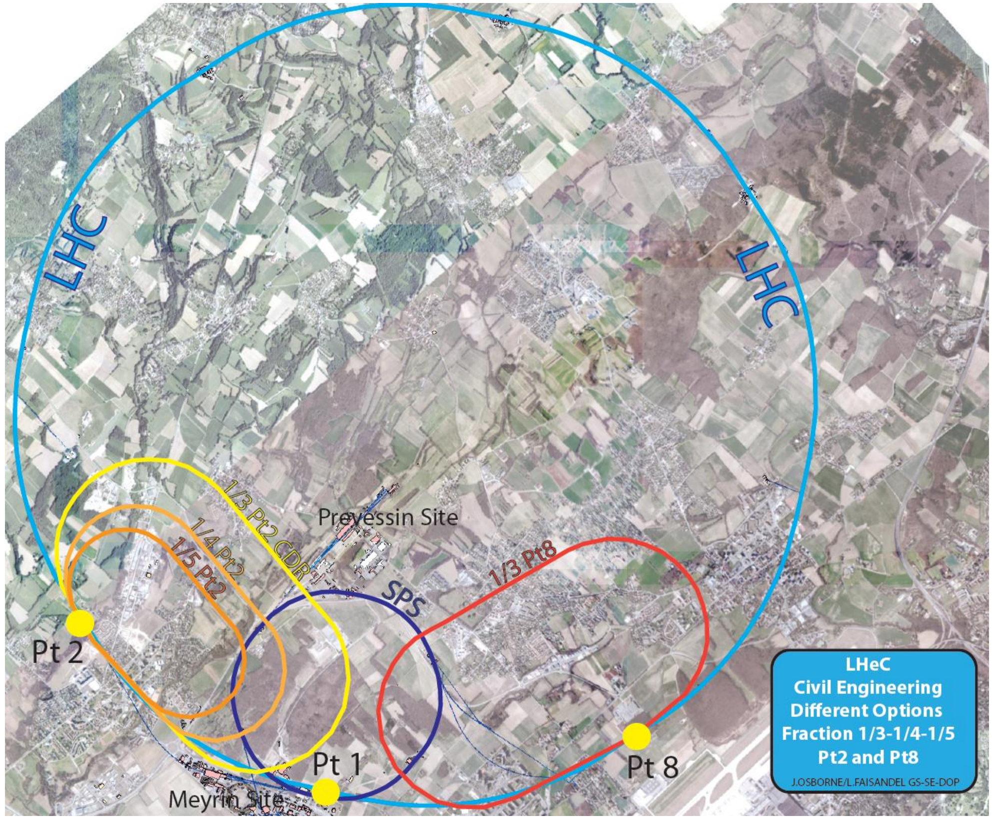
C. Cook @ FCC week in Rome

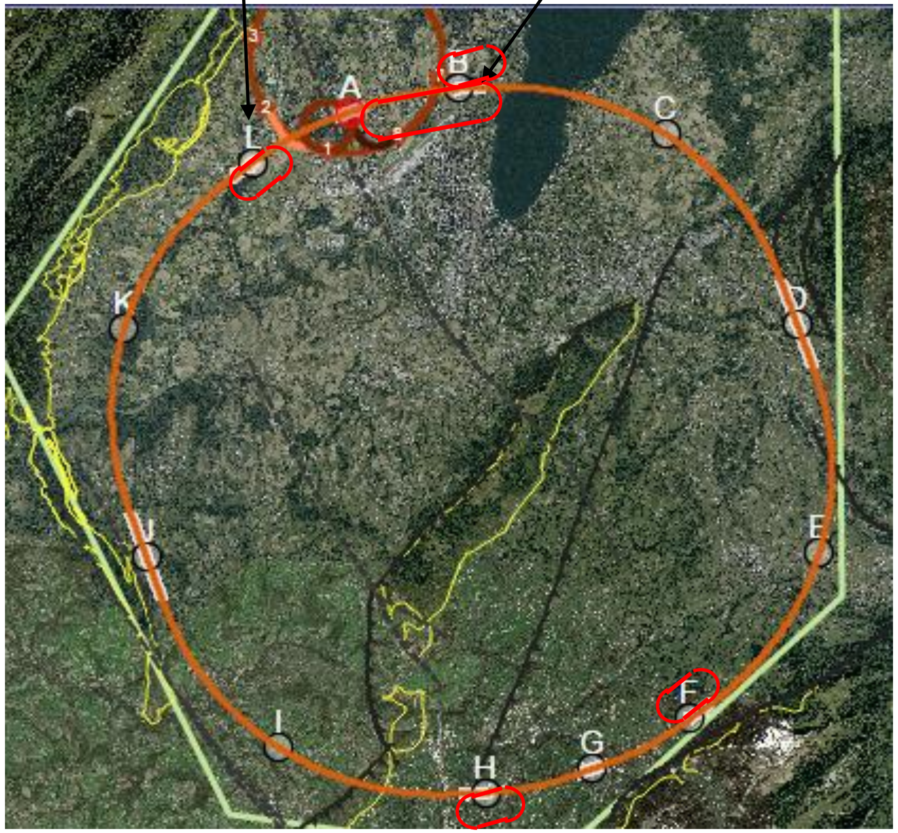
Configuration:

LHeC Machine

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

LHeC / FCC-he LHC P8 & FCC PB



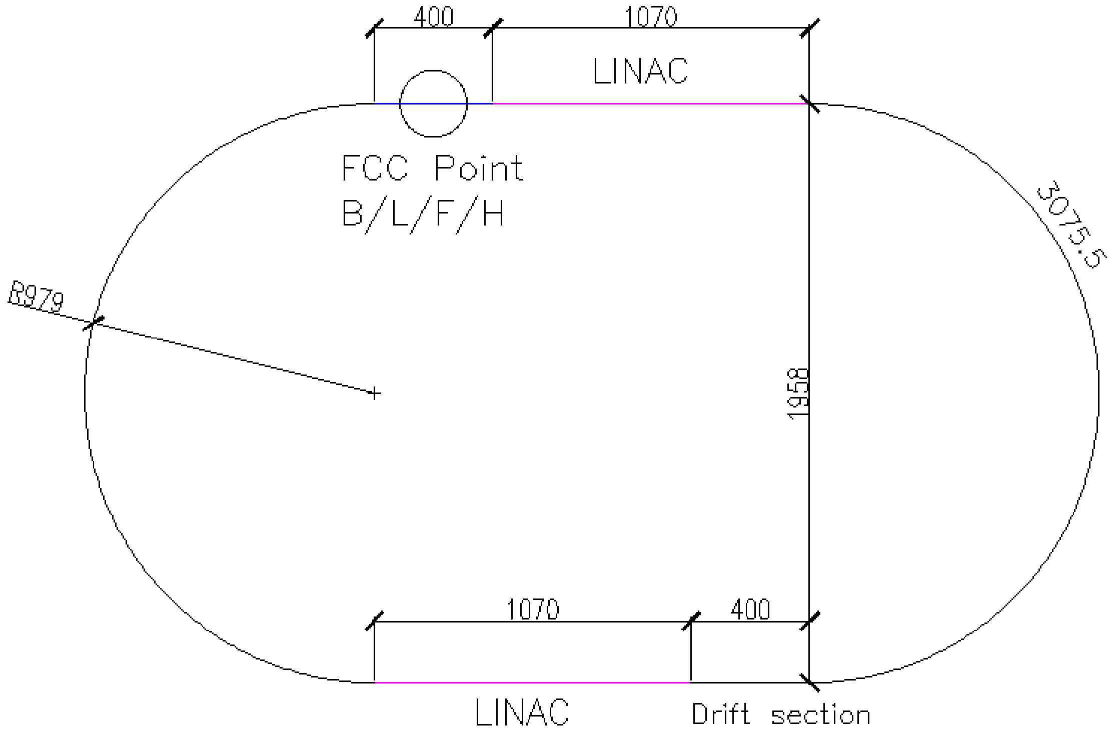


FCC-eh Configuration: Layout & Civil Engineering

C. Cook @ FCC week in Rome

Racetrack Layout:

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



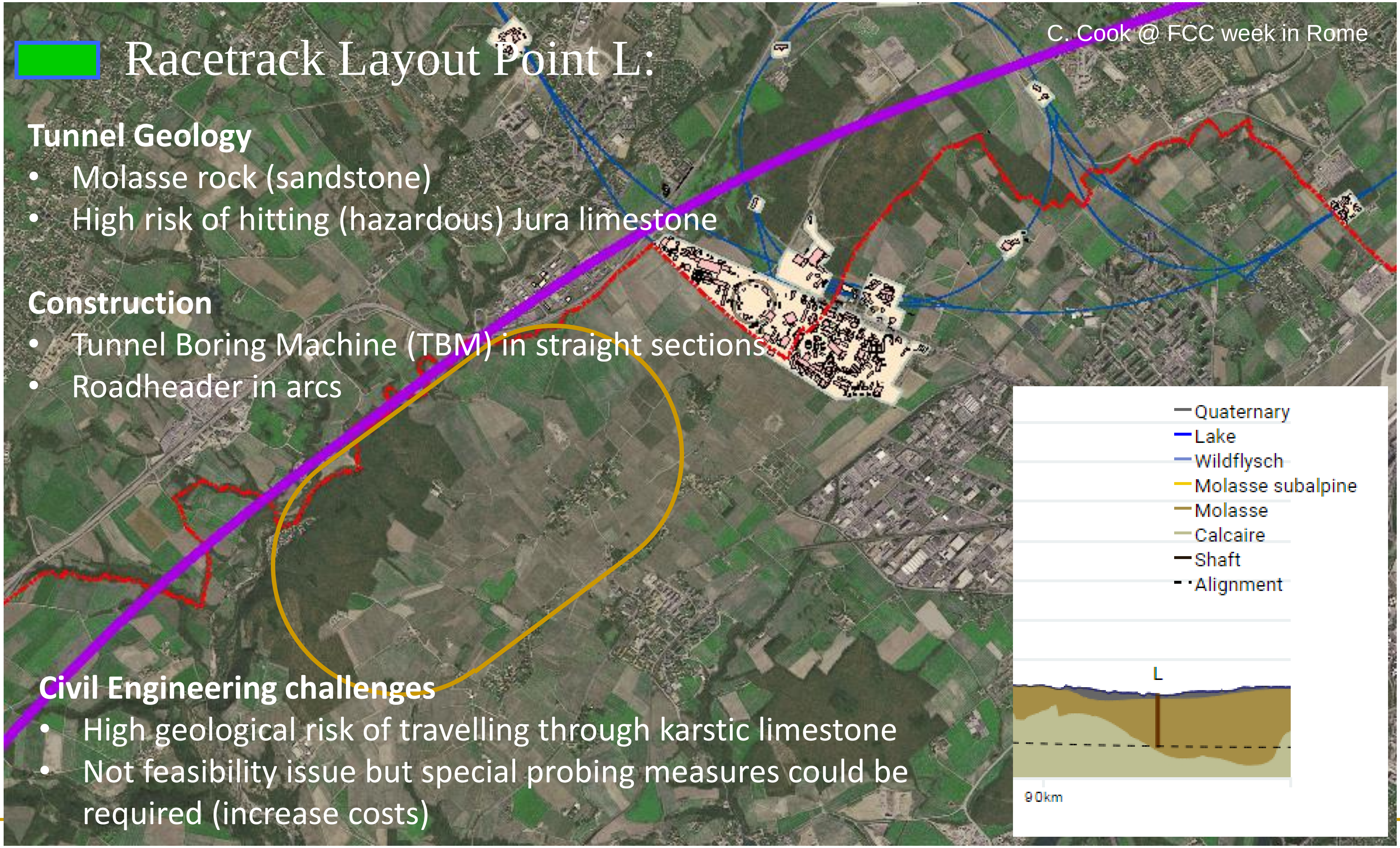
FCC-eh Configuration: Layout & Civil Engineering

Racetrack Layout Point L:

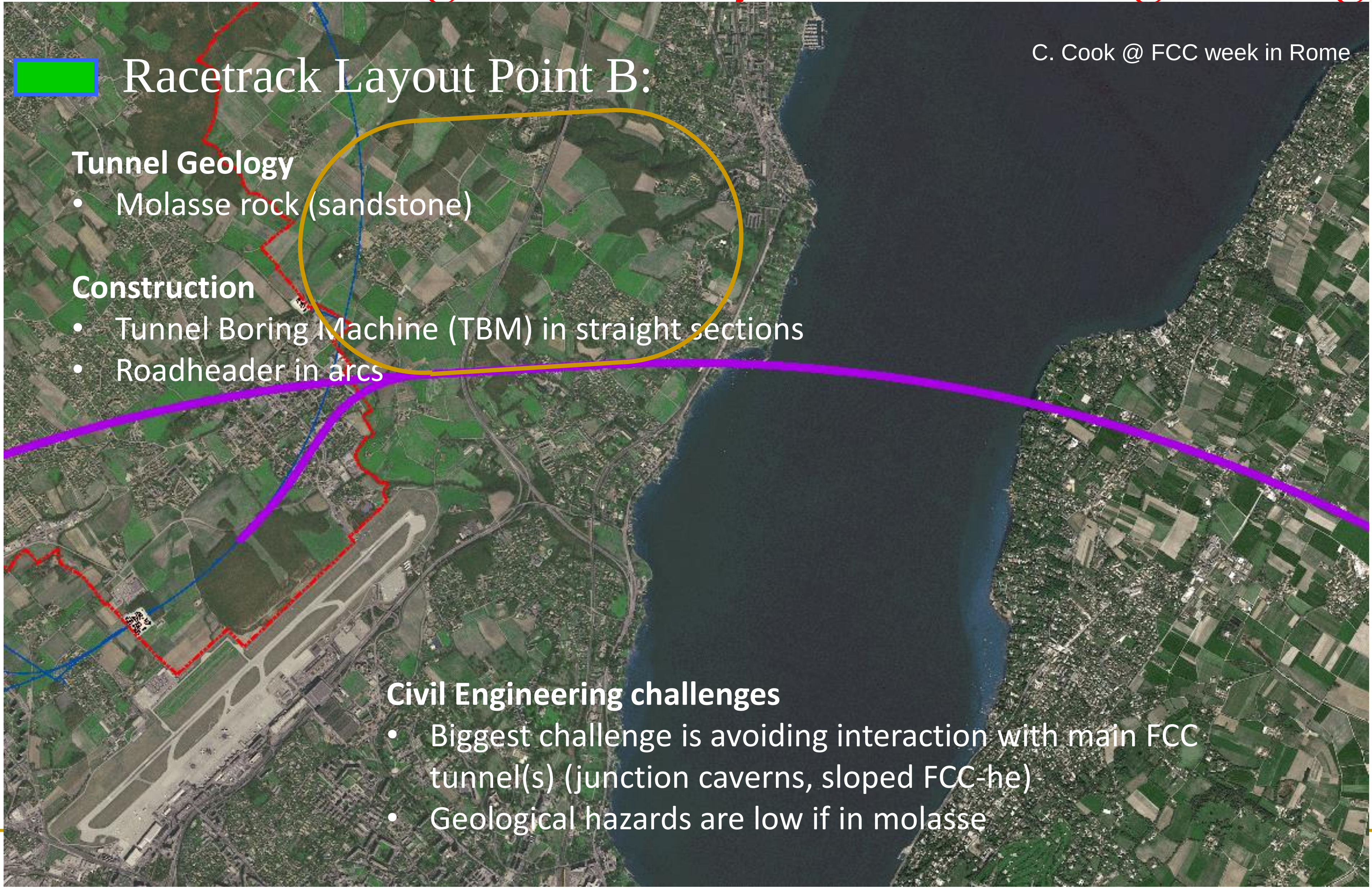
Tunnel Geology
- Molasse rock (sandstone)
- High risk of hitting (hazardous) Jura limestone

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

Civil Engineering challenges
- High geological risk of travelling through karstic limestone
- Not feasibility issue but special probing measures could be required (increase costs)



FCC-eh Configuration: Layout & Civil Engineering



Tunnel Geology
- Molasse rock (sandstone)

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

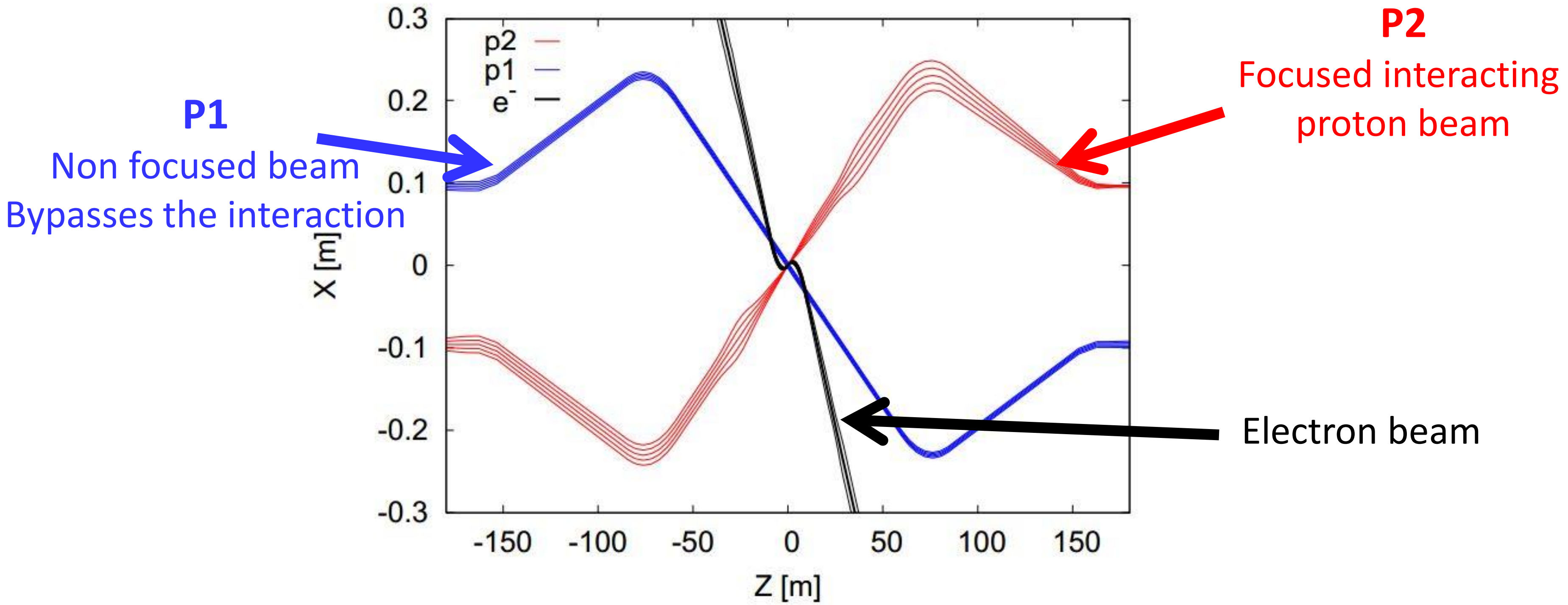
Civil Engineering challenges
- Biggest challenge is avoiding interaction with main FCC tunnel(s) (junction caverns, sloped FCC-he)
- Geological hazards are low if in molasse

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.

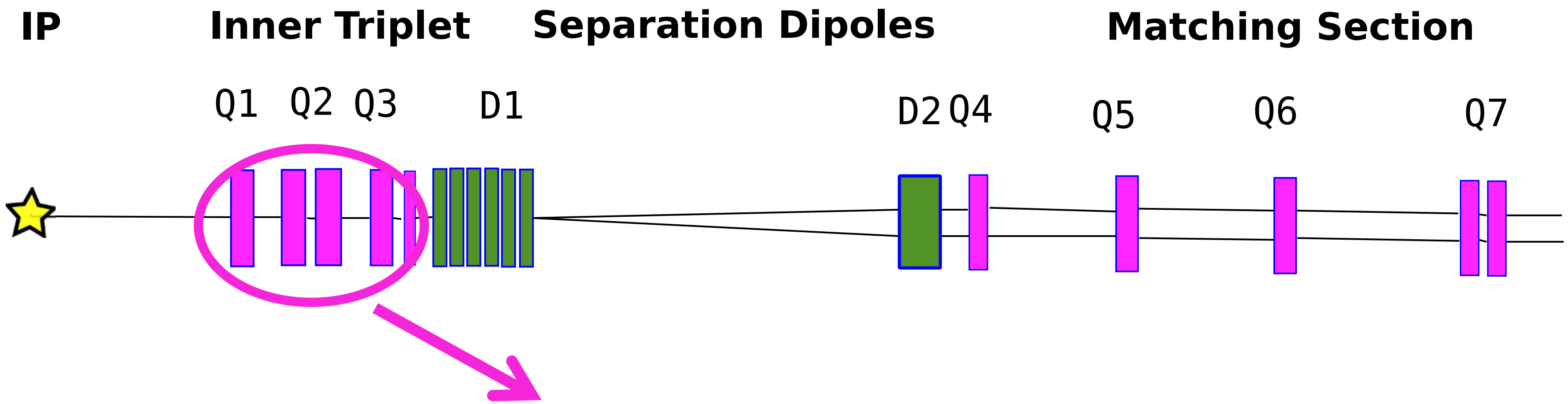


- LHeC has to work alongside HL-LHC and built within an existing IR2 cavern layout, designed for a different experiment.
- FCC-he can be designed for the required purposes.

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

We need:

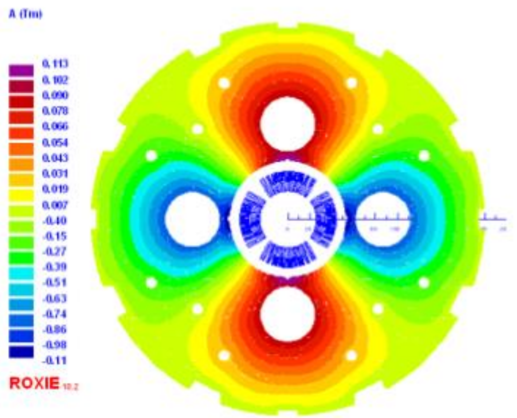
- β*=10 cm (10^{33} $cm^2 s^{-1}$)
- β*=5 cm (10^{34} $cm^2 s^{-1}$)

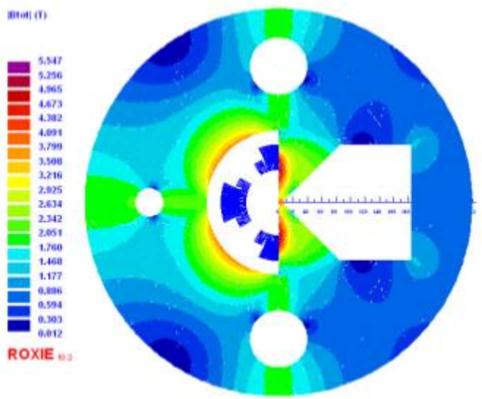
SEVERE LIMITATIONS

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

Asymmetric IR Layout: Magnet Design

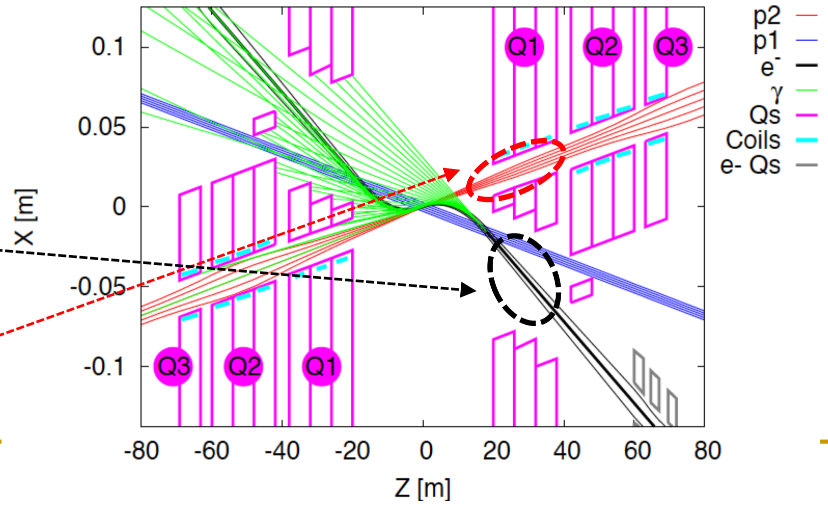
The design of the magnets for the LHeC included a normal-aperture to focus the proton beam and a field-free aperture for the electron and unfocussed proton beam.



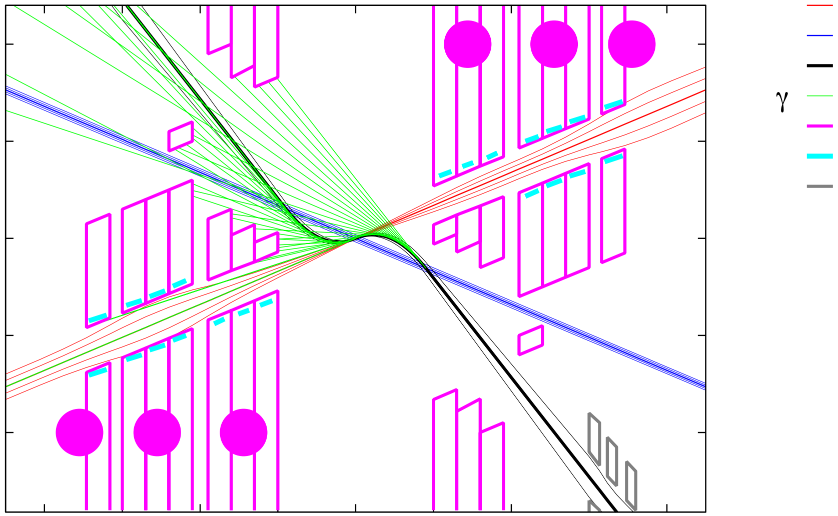


Consideration of the magnets for the LHeC included the design of a half quadrupole for Q1 given the short distance between the proton beam and the electron beam

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.

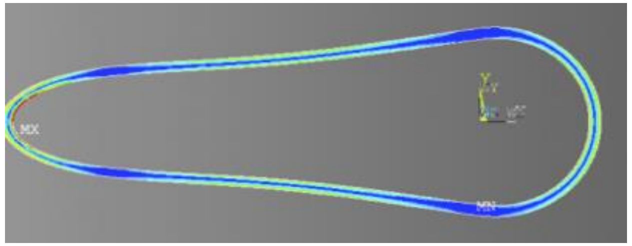


Asymmetric IR Layout: example LHeC



Beam pipe: in CDR 6m, Be, ANSYS calculations

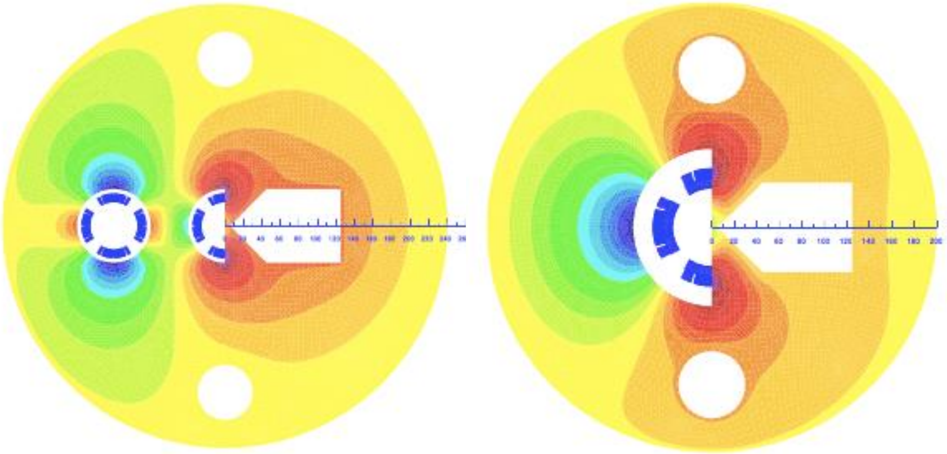
Composite material R+D, prototype, support..
→ Essential for tracking, acceptance and Higgs



S. Russenschuck

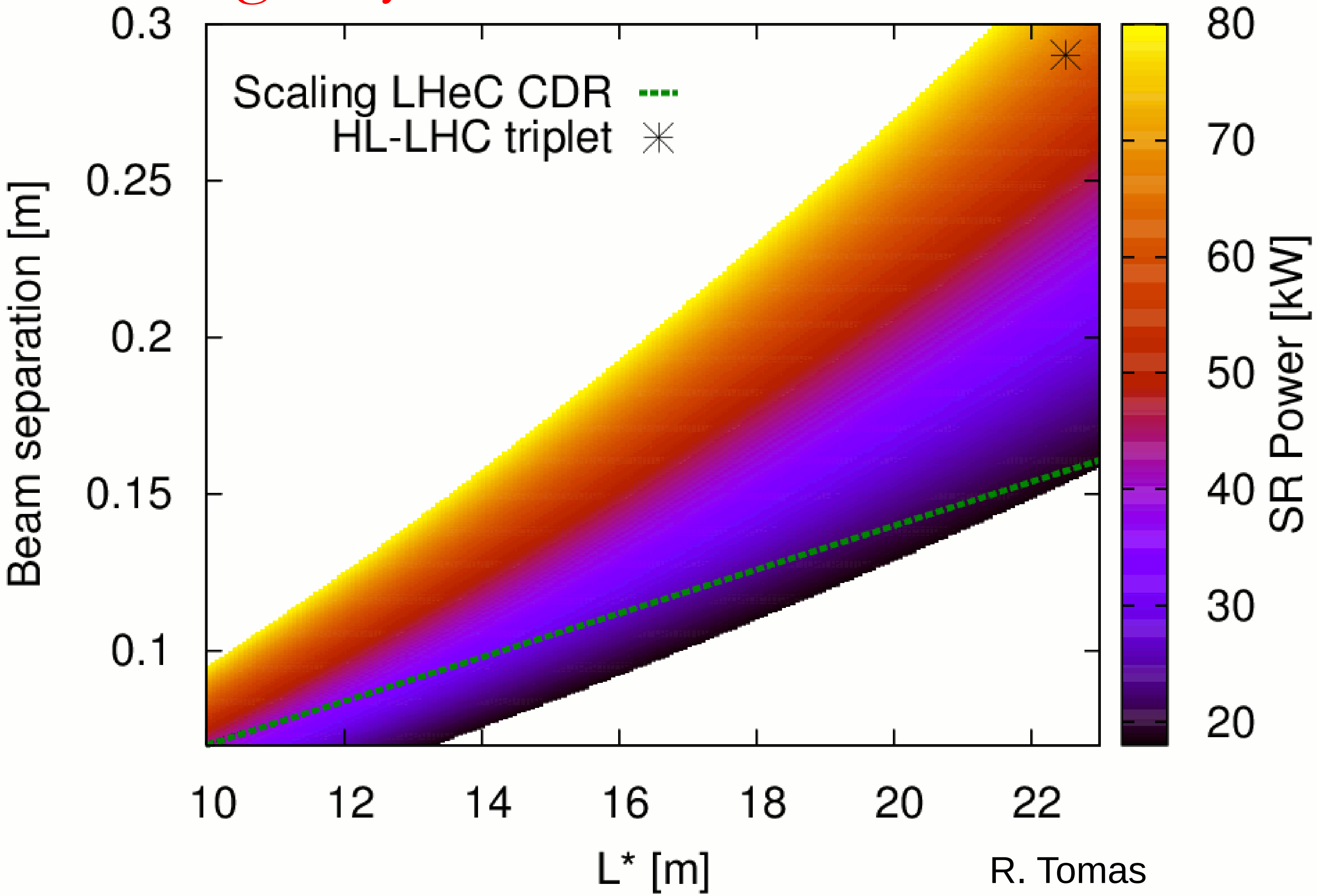
Have optics compatible with HL-LHC ATS optics and β*=0.1m
Head-on collisions mandatory →
High synchrotron radiation load, dipole in detector

Optimize LHeC to LHC ATS optics
Specification of Q1 – NbTi prototype

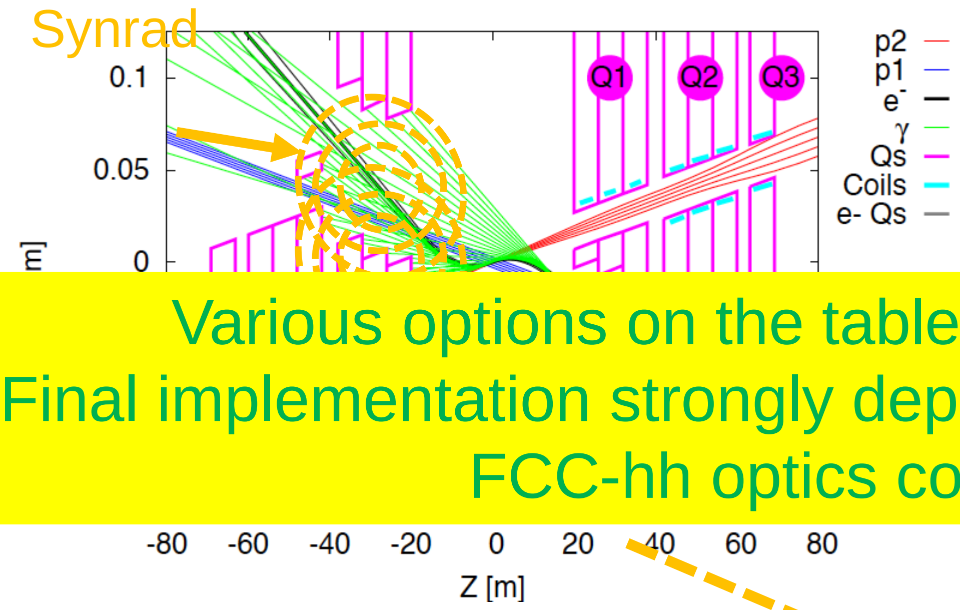


Synchrotron Radiation (direct and backscattered),
Masks+collimators
Beam-beam dynamics and 3 beam operation studies

IR Design: Synchrotron Radiation



Asymmetric IR Layout: Magnet Design

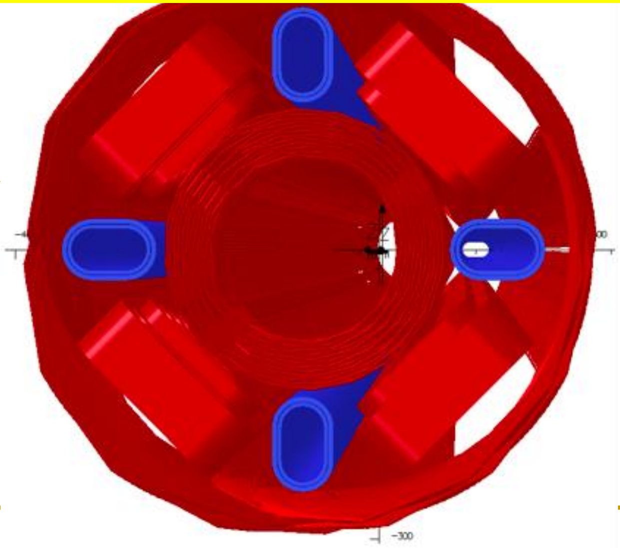


Magnet design planned for eRHIC IR.

With the use of outer coils a reduced field region is created inside the

Various options on the table with solutions at hand!
Final implementation strongly depends on actual IR choice and FCC-hh optics configuration!!!

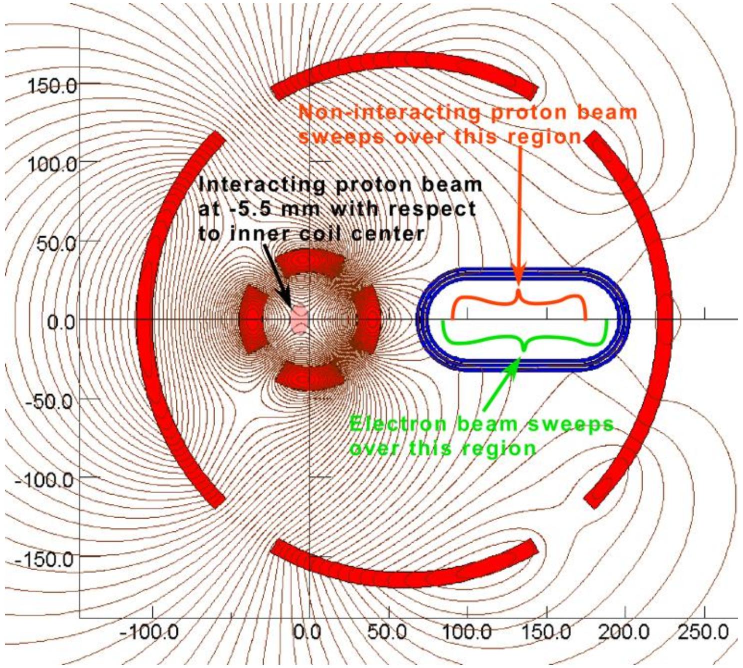
Possible new design for the Q1



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

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.



Design by B. Parker

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.

ERL Arc Optics: Emittance preservation

[Flexible Momentum Compaction]

A. Bogacz (JLab) @ ERL2015, Stony Brook University, June 9, 2015

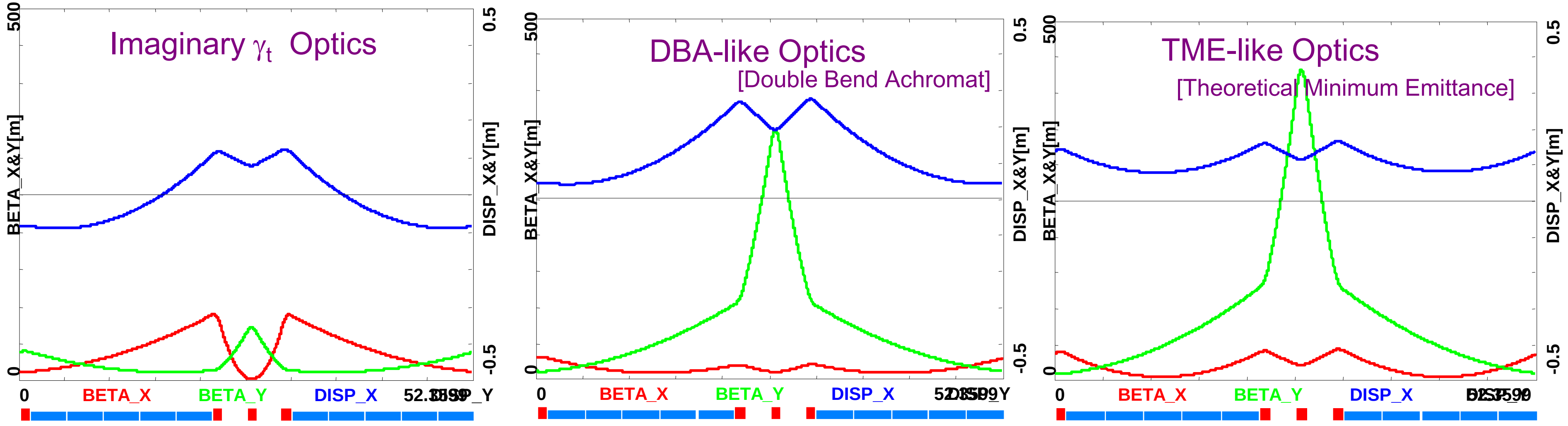
- Emittance dilution due to quantum excitations:

$$\Delta\varepsilon^N = \frac{55\, r_0}{48\sqrt{3}} \frac{\hbar c}{mc^2} \gamma^6 I_5$$

$$I_5 = \int_0^L \frac{H}{|\rho|^3} ds = \frac{\theta \langle H \rangle}{\rho^2}$$

$$H = \gamma D^2 + 2\alpha D D' + \beta D'^2$$

Arc 1 , Arc2 | Arc 3, Arc 4 | Arc5, Arc 6



$\langle H \rangle = 8.8 \times 10^{-3}\ m$ | $\langle H \rangle = 2.2 \times 10^{-3}\ m$ | $\langle H \rangle = 1.2 \times 10^{-3}\ m$

factor of 20 smaller than FODO

total emittance increase in Arc 1- 5: $\Delta\varepsilon_x^N = 4.9\ \mu\text{m rad}$

ERL Beam Dynamics: HOM and Beam Stability

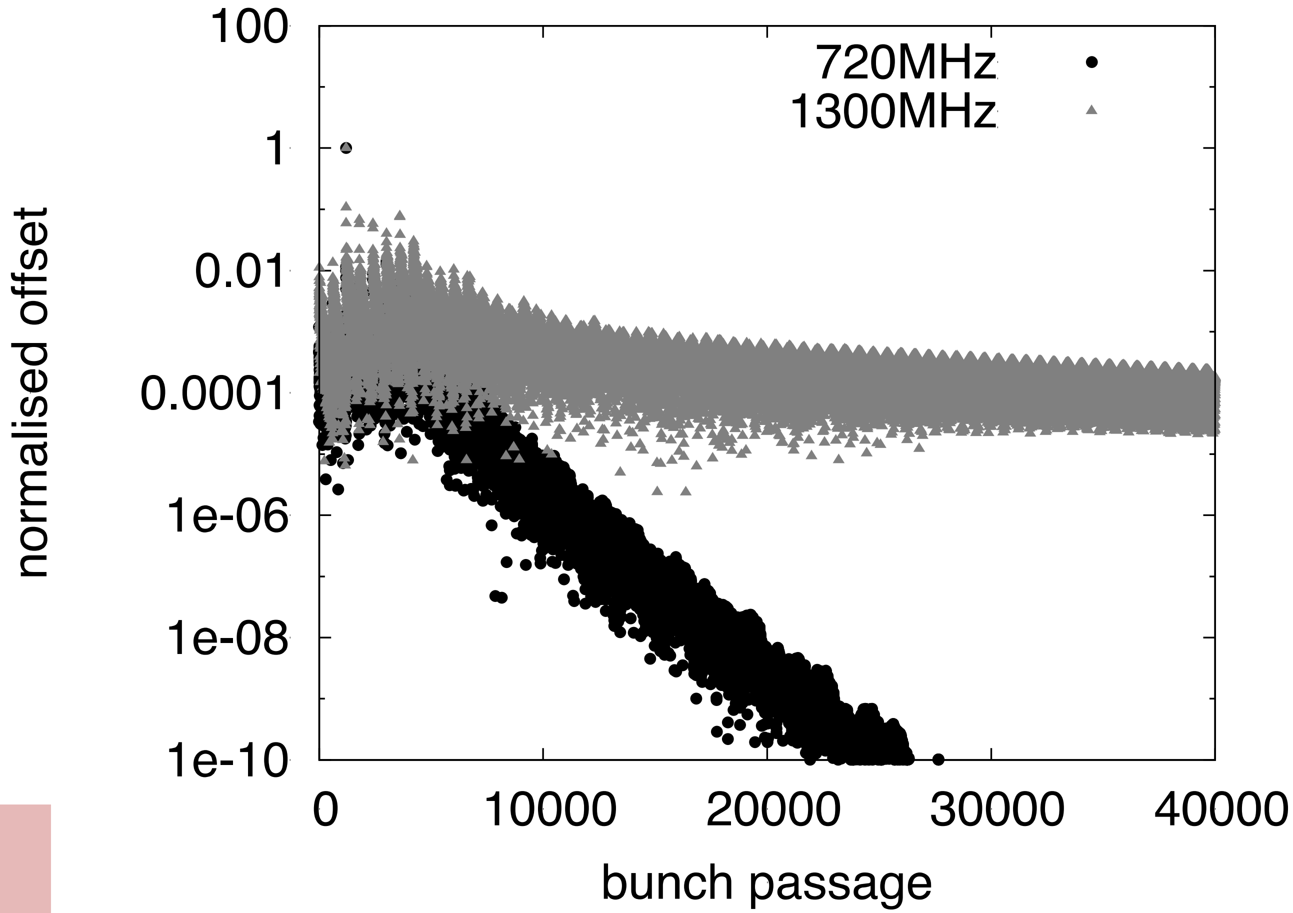
HOM & Beam-Beam

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

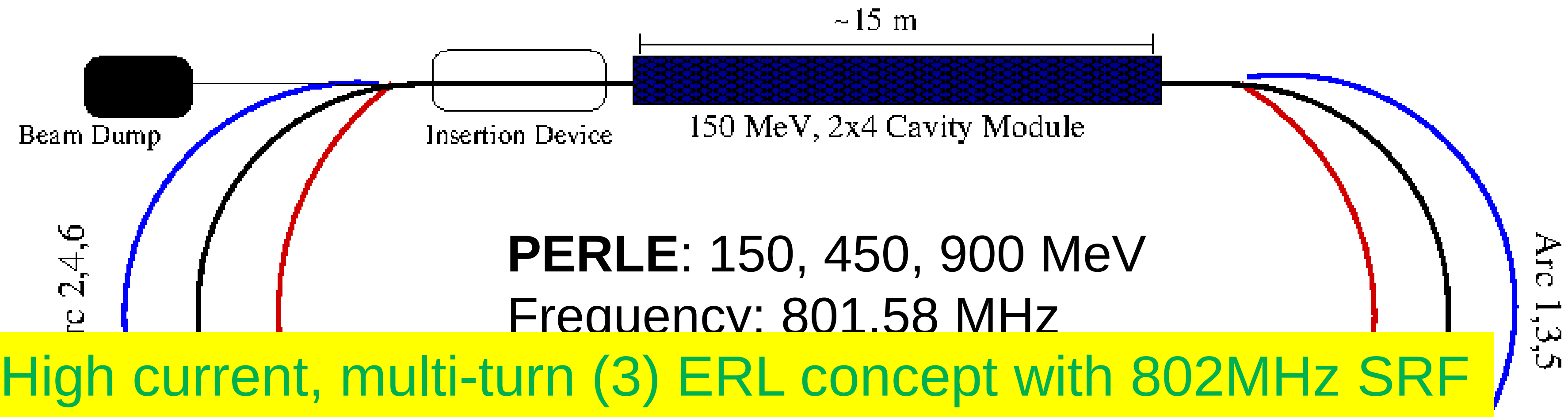
F_{rms}=1.135 for ILC cavity
F_{rms}=1.002 for SPL cavity



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

➔ Choice of 802MHz for FCC-eh & LHeC!

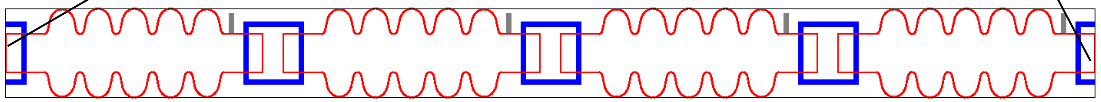
ERL SRF: FCC-eh, LHeC, PERLE



PERLE: 150, 450, 900 MeV
Frequency: 801.58 MHz

High current, multi-turn (3) ERL concept with 802MHz SRF to be tested at PERLE facility in LAL in Orsay!!!

➔Max Klein later in this session

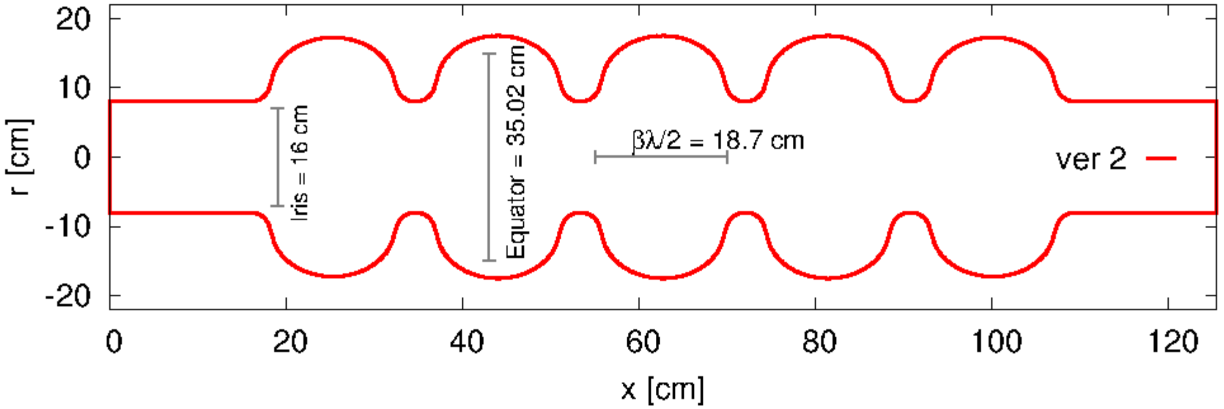


FCC-eh: 60 GeV, ERL
1km SRF linac; 944 cavities; 59 cryo modules / linac
Number of passes: 6
Beam current: 6.6-25.6 mA

Basic unit: 5-cell cavity into 4-cavity module

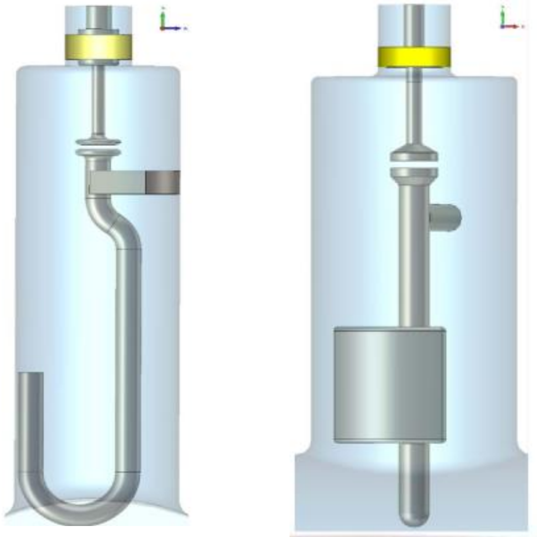
SRF: 802 MHz 5-Cell design minimizing HOM

Rama Calaga



Parameter	Ver 1 (Scaled)	Ver 2
Frequency [MHz]	801.58	801.58
Number of cells	5	5
Active cavity length [mm]	935	935
Voltage [MV]	18.7	18.7
E_p [MV/m]	45.1	48.0
B_p [mT]	95.4	98.3
R/Q [Ω]	430	393
Cell-cell coupling (mid-cell)	4.47%	5.75%
Stored Energy [J]	154	141
Geometry Factor [Ω]	276	283
Field Flatness	97%	96%

HOM Coupler: LHC-like dual concept

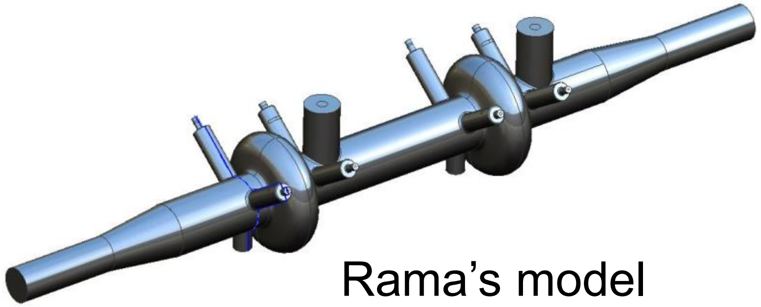


SRF: Prototyping in collaboration with JLab

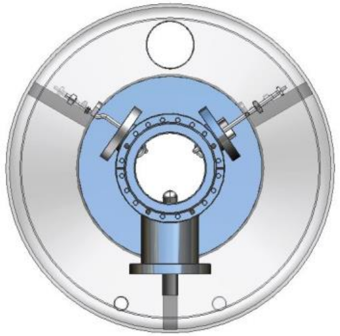
Robert Rimmer JLab

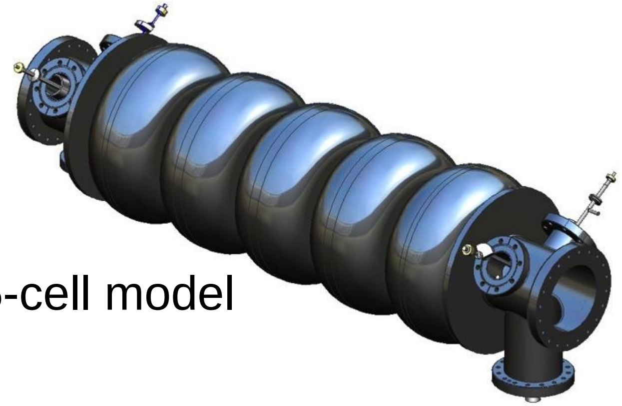
Evaluate scaled LHC type coupler and HOM dampers [CERN model by Rama Calaga]

- LHC power coupler is well proven but may be overkill
- JLab FEL waveguide dampers may be overkill*
- LHC HOM dampers are somewhat narrow band (tuned)
- High power capability (~1 kW), active cooling
- Demountable
- Evaluate scaled TESLA couplers in the same location



Rama's model





5-cell model

* Or not, depending on filling pattern

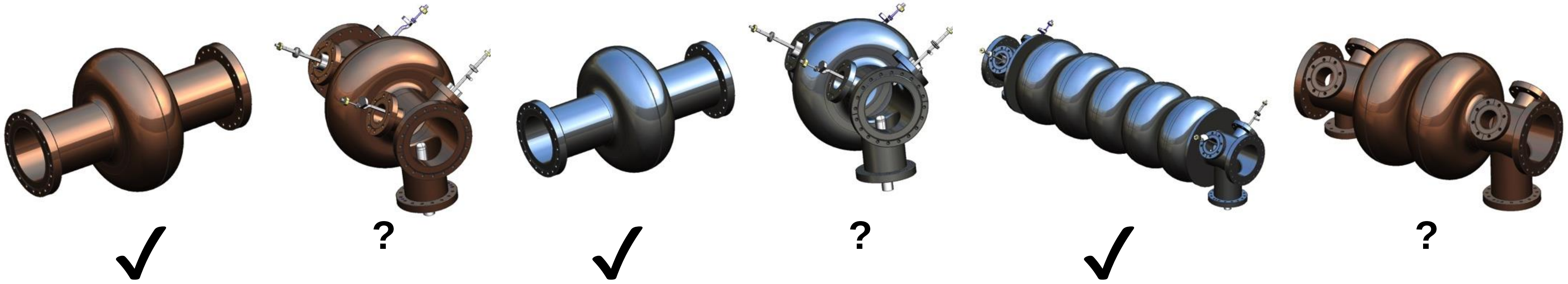
SRF: JLab Collaboration

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

SRF Design: Power

Rama Calaga

800 MHz IOTs (~60 kW) for the SPS 3rd harmonic system

Chain of 8 IOTs installed powering two cavities in the SPS

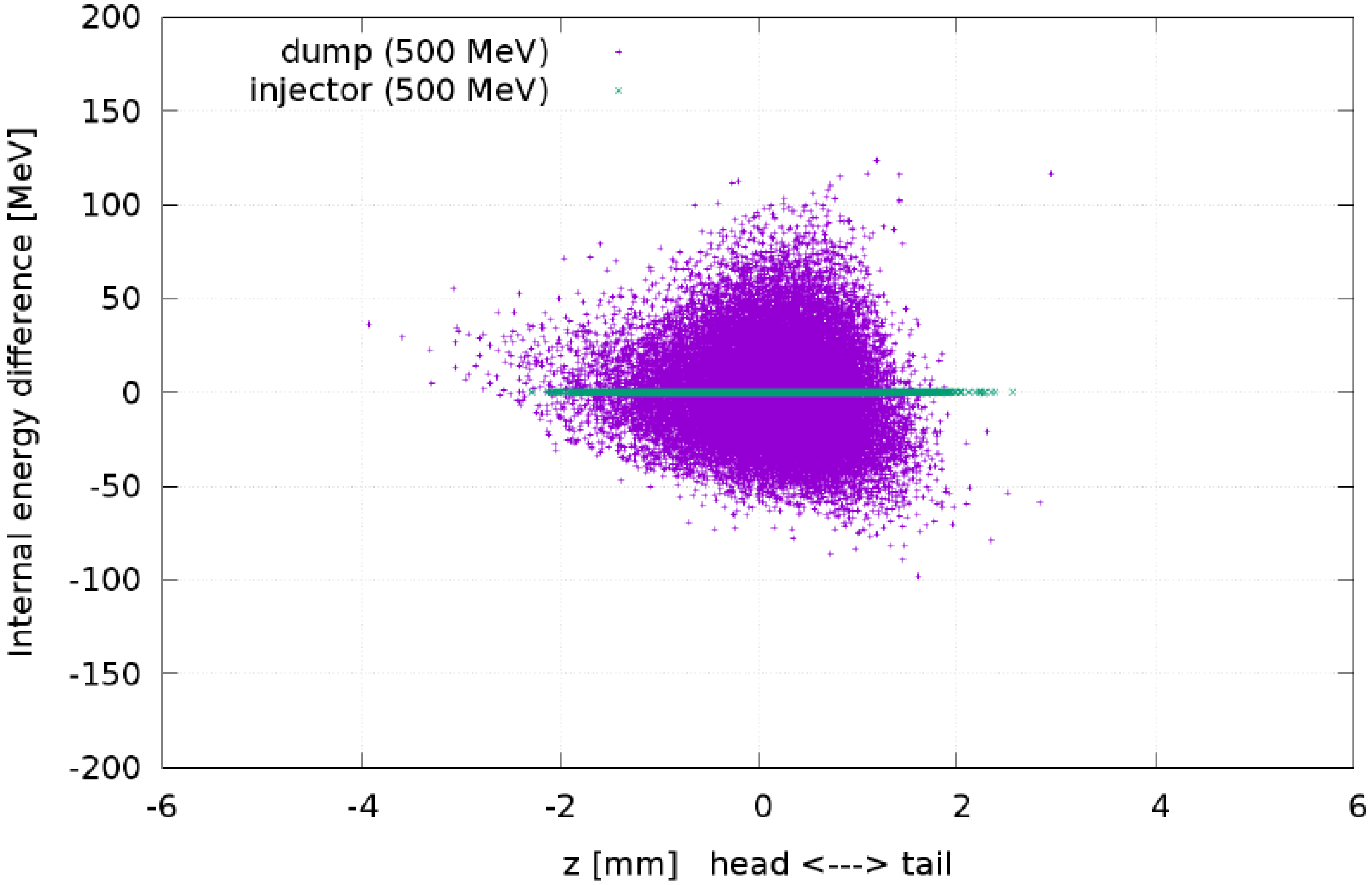
Beam Dynamics and 'front-end' Simulations:

- 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

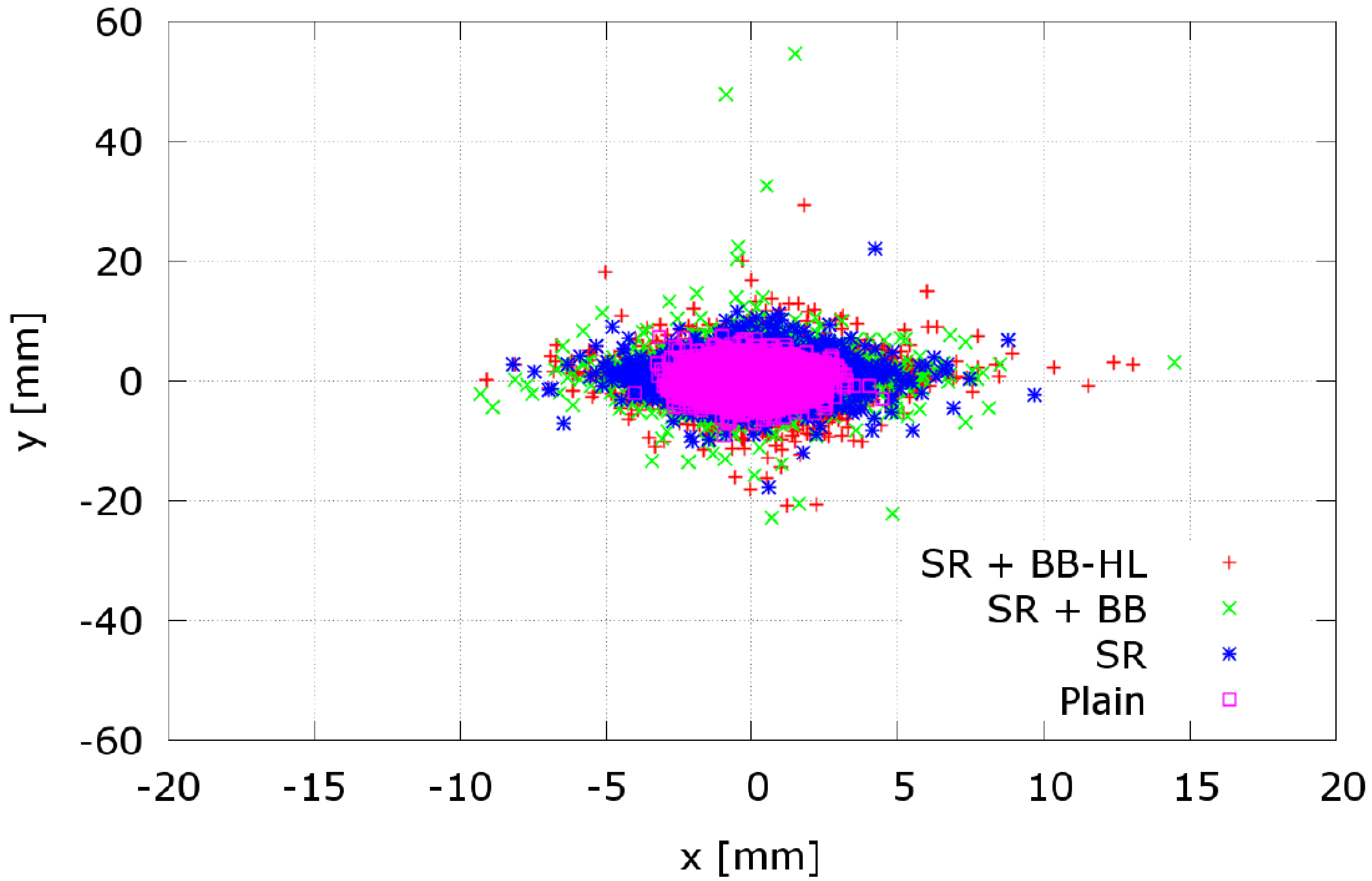
D. Pellegrini (EPFL/CERN) @ ERL'15



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}cm^{-2}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	$2.2 \rightarrow 1.1$	10
IP betafunction	mm	150	$42 \rightarrow 52$
Nominal RMS beam size	μm	$2.5 \rightarrow 1.8$	$1.9 \rightarrow 2.1$
Waist shift	mm	0	$65 \rightarrow 70$
Bunch population	10^{10}	$10 \rightarrow 5$	0.31
Bunch spacing	ns	25	25
Luminosity	$10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	$18.3 \rightarrow 14.3$	
Int. luminosity per 10 years	$[\mathrm{ab}^{-1}]$	1.2	

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

Daniel Schulte

FCC-eh ERL Configuration:

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

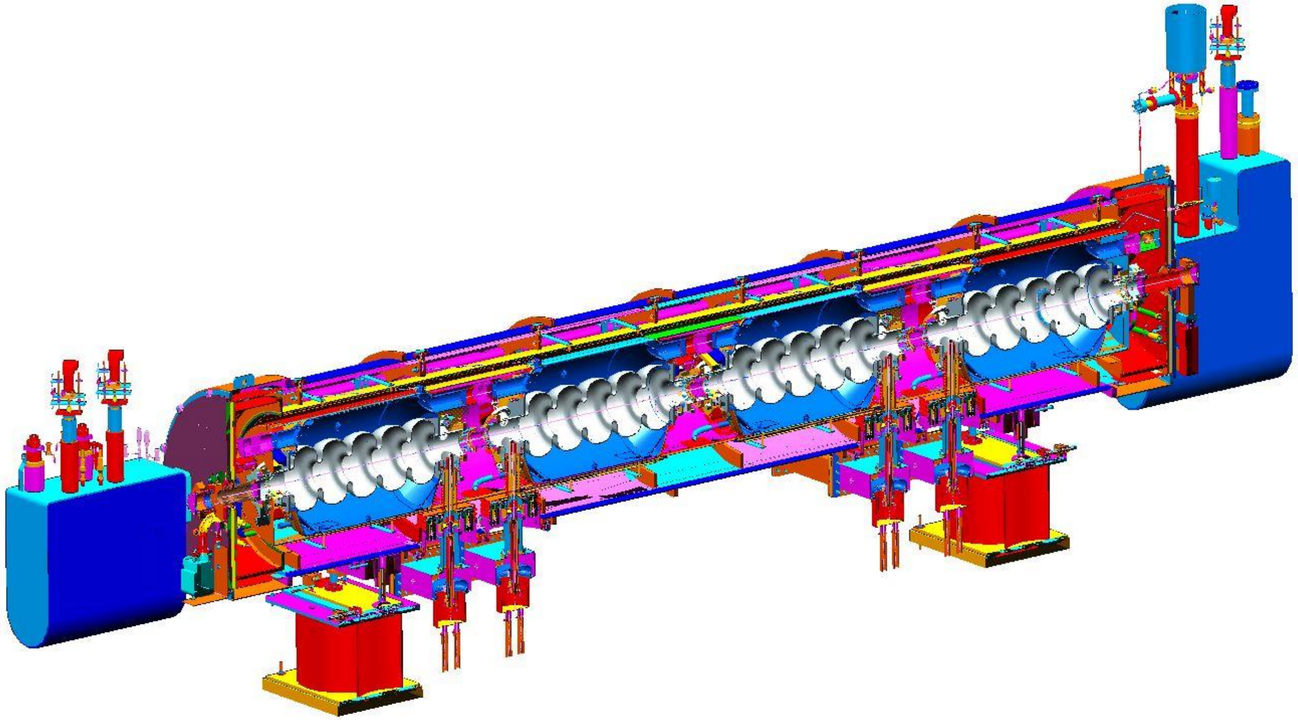
EDMS 17979910 FCC-ACC-RPT-0012 V1.0, 6 April, 2017,
"A Baseline for the FCC-he"

John Jowett, Frank Zimmermann

End

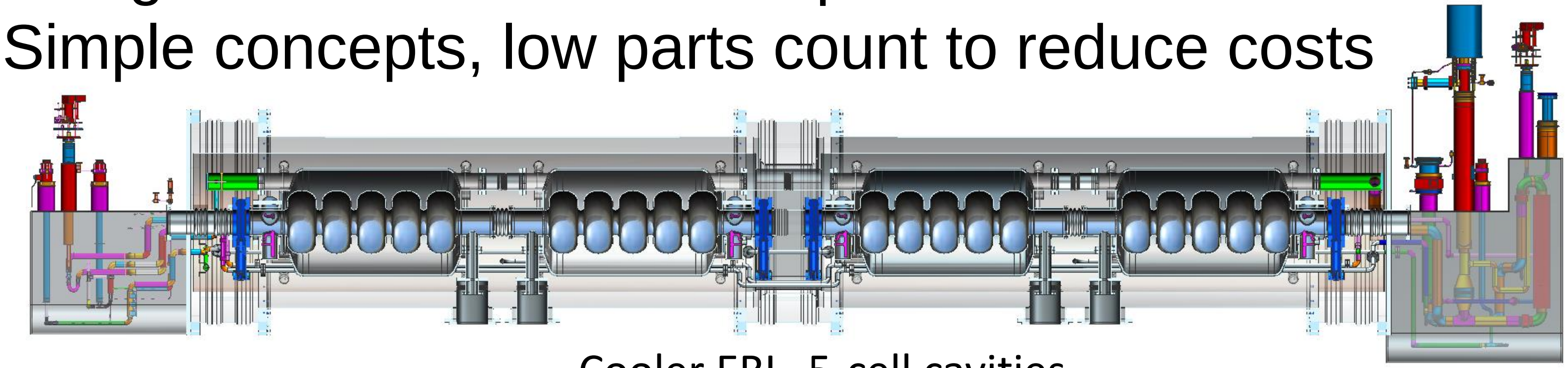
SNS like cryomodule

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

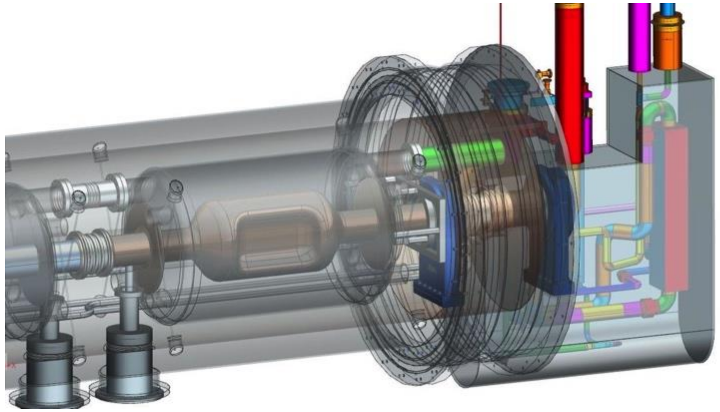


Jlab Modular Cryostat

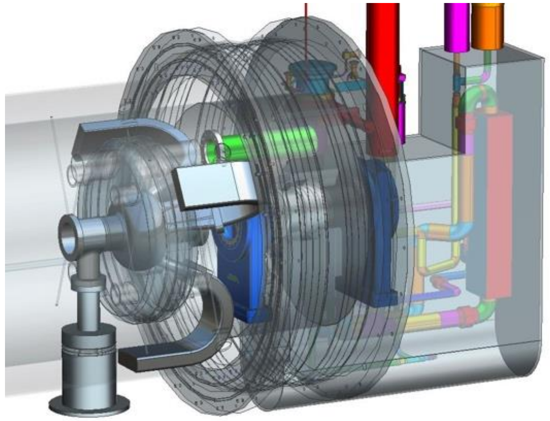
- Take the best features of previous JLab designs
- Modular approach to hold various different cavities
- Design suitable for industrial production
- Simple concepts, low parts count to reduce costs



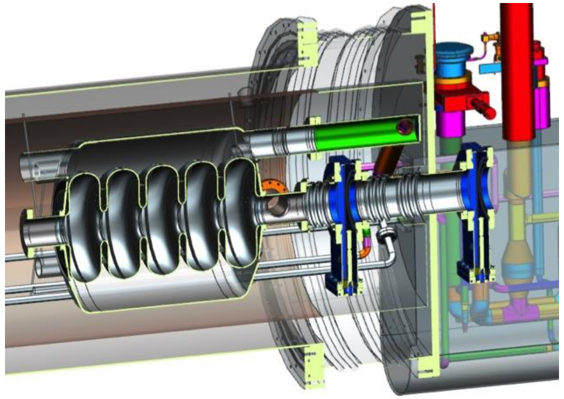
Cooler ERL, 5-cell cavities



476.3 MHz Crab cavity

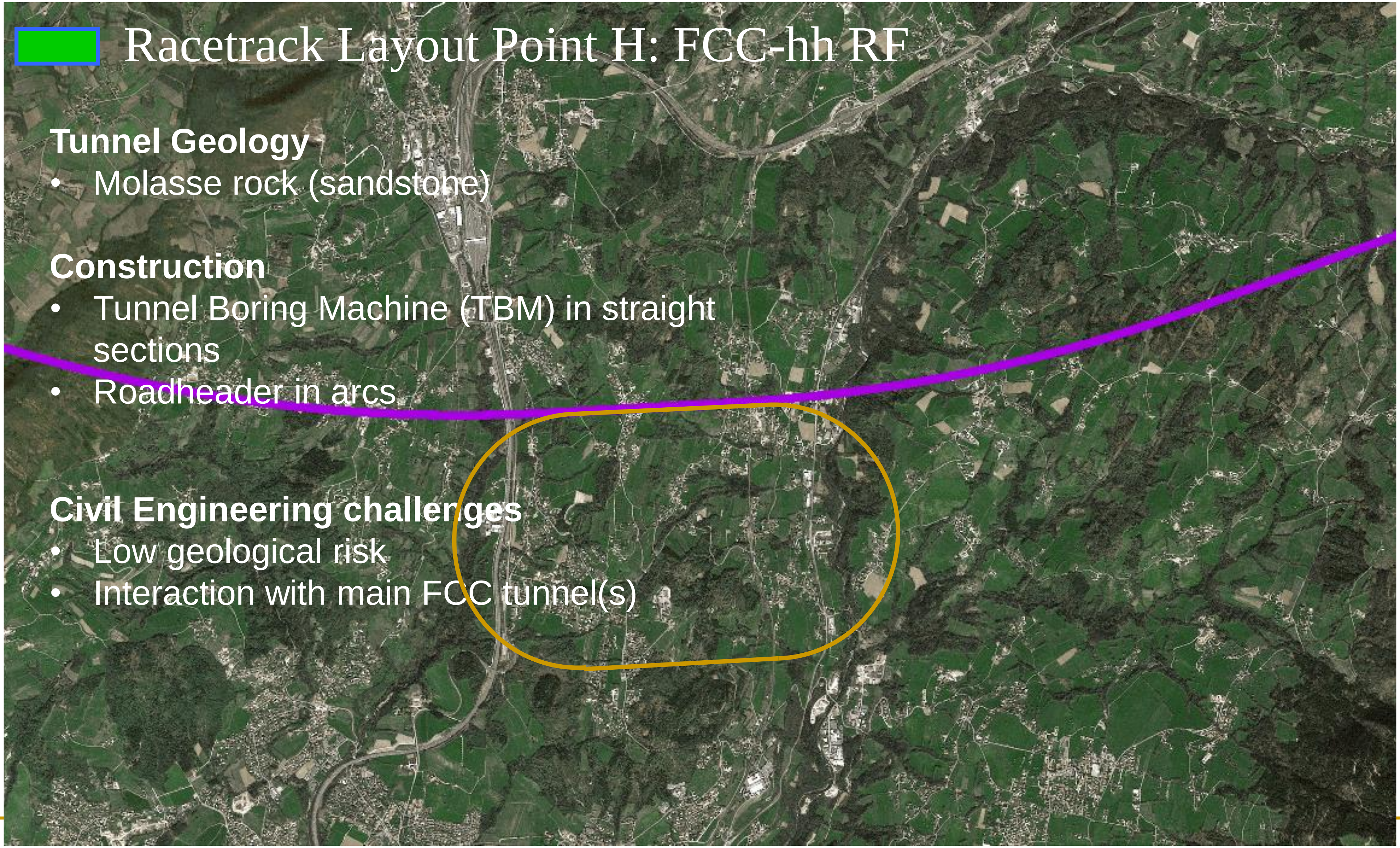


On-cell damper concept



β=0.6 650 MHz cavity

FCC-eh Configuration: Layout & Civil Engineering



Racetrack Layout Point H: FCC-hh RF

Tunnel Geology
- Molasse rock (sandstone)

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

Civil Engineering challenges
- Low geological risk
- Interaction with main FCC tunnel(s)