FCC-ee Accelerator Developments

LCWS2024, The University of Tokyo, 8 July 2024

Frank Zimmermann, CERN
on behalf of FCC collaboration & FCCIS DS team

Swiss Accelerator Research and Technology

http://cern.ch/fcc

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MTR recommendations on FCC-ee machine

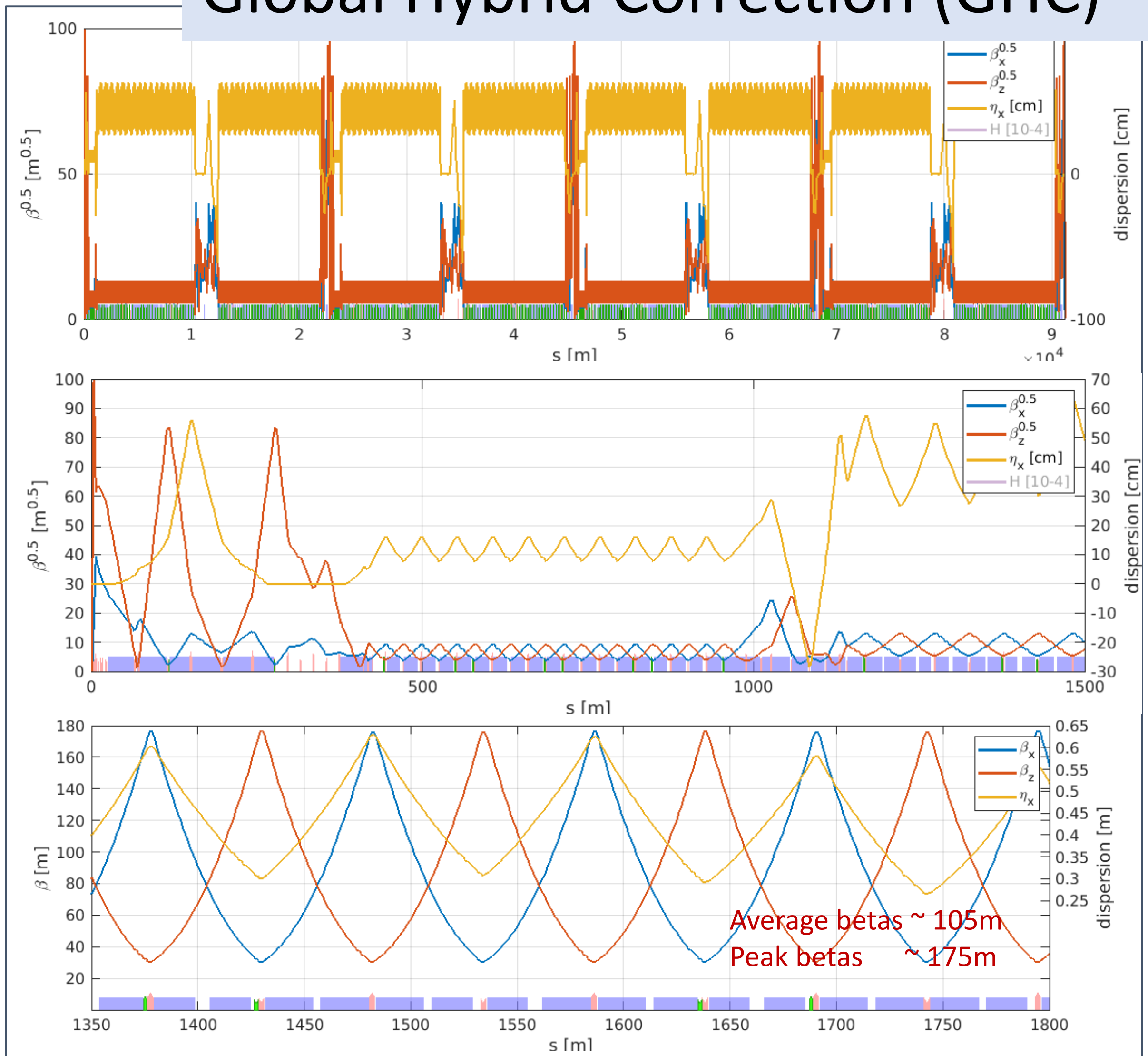
from FCC SAC, FCC CRP, CERN SPC, and CERN FC

- ✓ **well-defined baseline layout for entire FCC-ee, including optimised e^+e^- injector, especially the linac**
- clarify **order of the energy stages**, with motivation for running order linked explicitly to the physics case
- ✓ **consolidate design of the RF system** to allow efficient energy-staging, as well as to reduce complexity, risk, and cost; study **options to avoid the 1-cell/2-cell RF cavity reconfiguration between Z and ZH/WW running**
- **alternative beam optics, to improve the dynamic aperture with relaxed mechanical alignment tolerances**
- **develop survey and alignment techniques**, procedures and instrumentation, **to guarantee the alignment of magnets [on the girder] to ~50 μm at 1 σ**; **develop and apply, in simulations, the whole set of beam-based correction techniques**
- **identify residual risks to achieving the design luminosity, with lessons to be learnt from other facilities like SuperKEKB, and specify required further critical-path R&D**

Baseline lattice: two options

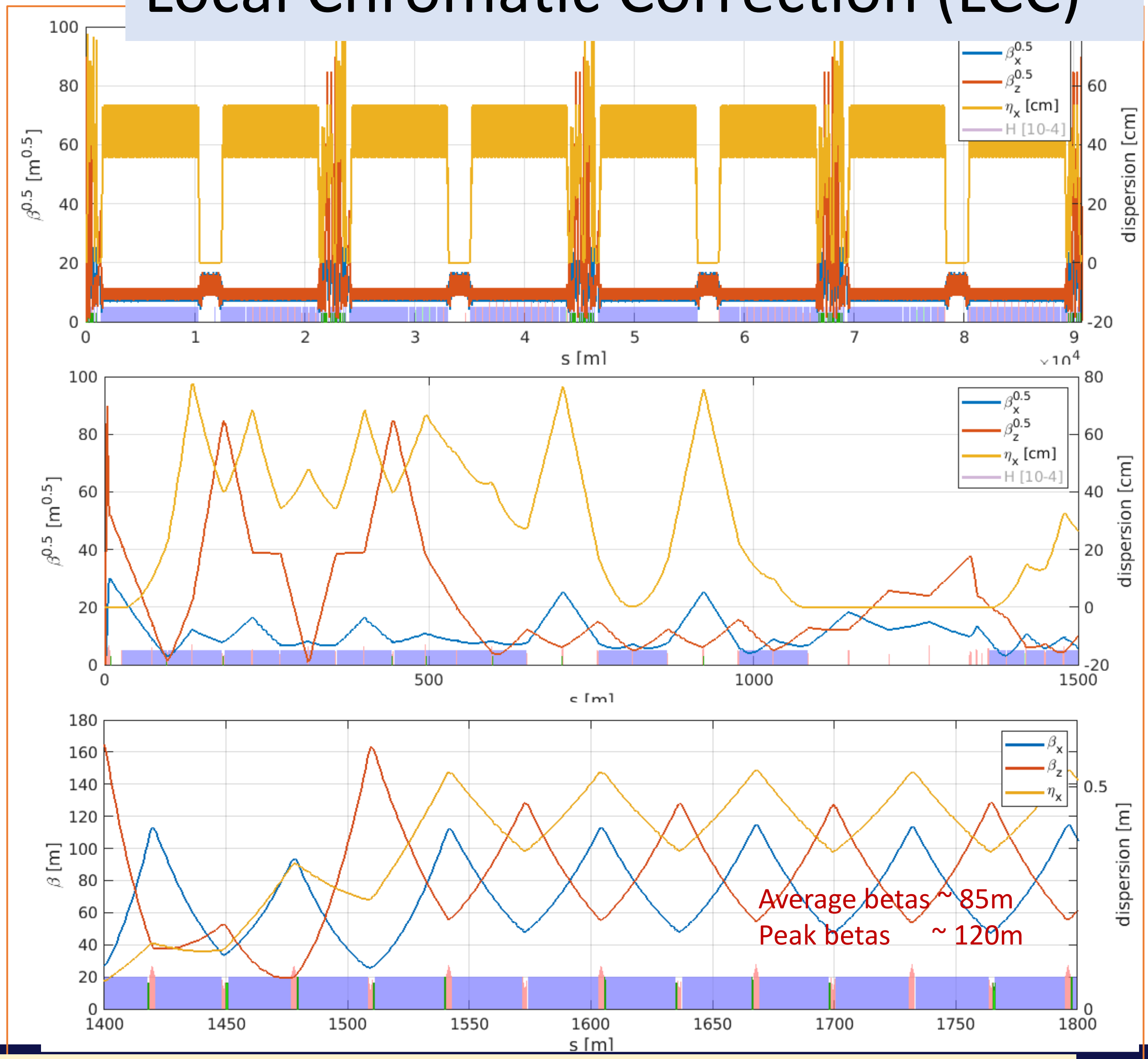
GHC

Global Hybrid Correction (GHC)



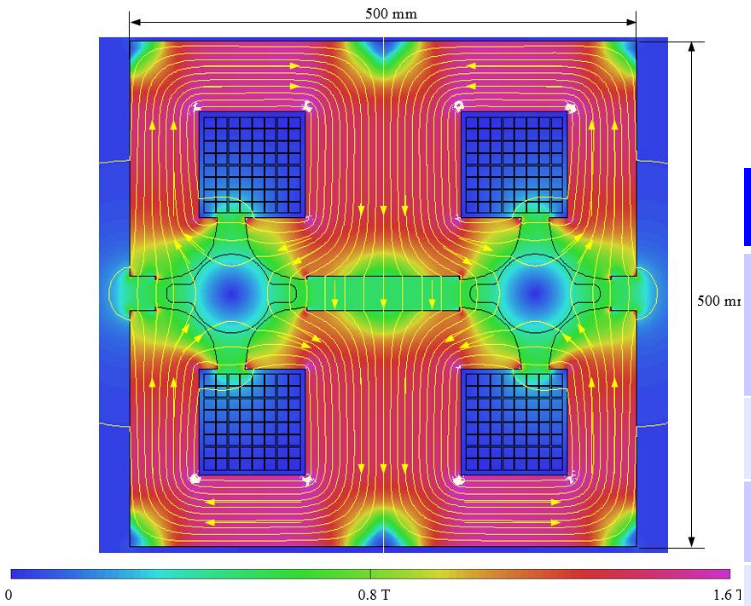
LCC

Local Chromatic Correction (LCC)



K. Oide, UNIGE; P. Raimondi, FNAL; S. Liuzzo, S. White, ESRF; K. Andre, M. Hofer, G. Roy, CERN

The twin quadrupole question



LCC abandons twin quadrupoles

K. Oide, J. Keintzel

$t\bar{t}$	arc quadrupoles	arc sextupoles
	gradient^2 × length × number [T^2/m]	<gradient^2 >× length × number [T^2/m^3]
GHC	$1.2x10^6$	$8.6x10^8$
LCC	$2x7.5x10^5$	$3.7x10^8$
total power ratio LCC/GHC	**1.26**	**0.44**

J.-P. Burnet, J. Bauche, for GHC

Storage Ring	Z	W	H	TT
Beam Energy (GeV)	45.6	80	120	182.5
Magnet current	25%	44%	66%	100%
Power ratio	6%	19%	43%	100%
Dipoles (MW)	0.8	2.6	5.8	13.3
Quadrupoles (MW)	1.4	4.3	9.8	22.6
Sextupoles (MW)	1.3	3.9	8.9	20.5
Power cables (MW)	1.2	3.8	8.6	20
Total magnet losses	4.8	14.7	33.0	76.4
Power demand (MW)	5.6	17.2	38.6	89

Even without twin quadrupoles, overall arc magnet power consumption for LCC may be >10 MW lower than for GHC

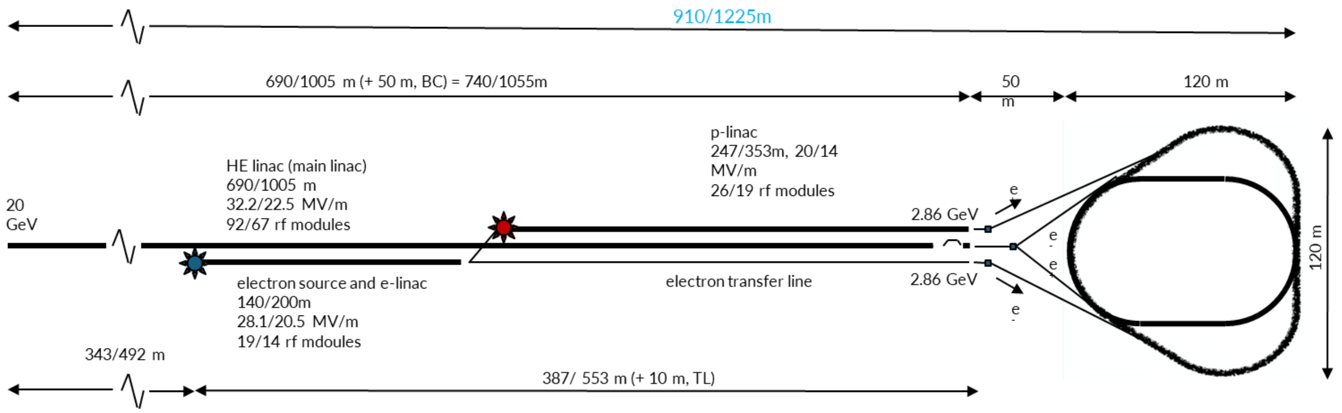
A. Milanese

PRAB 19, 11204 (2016)

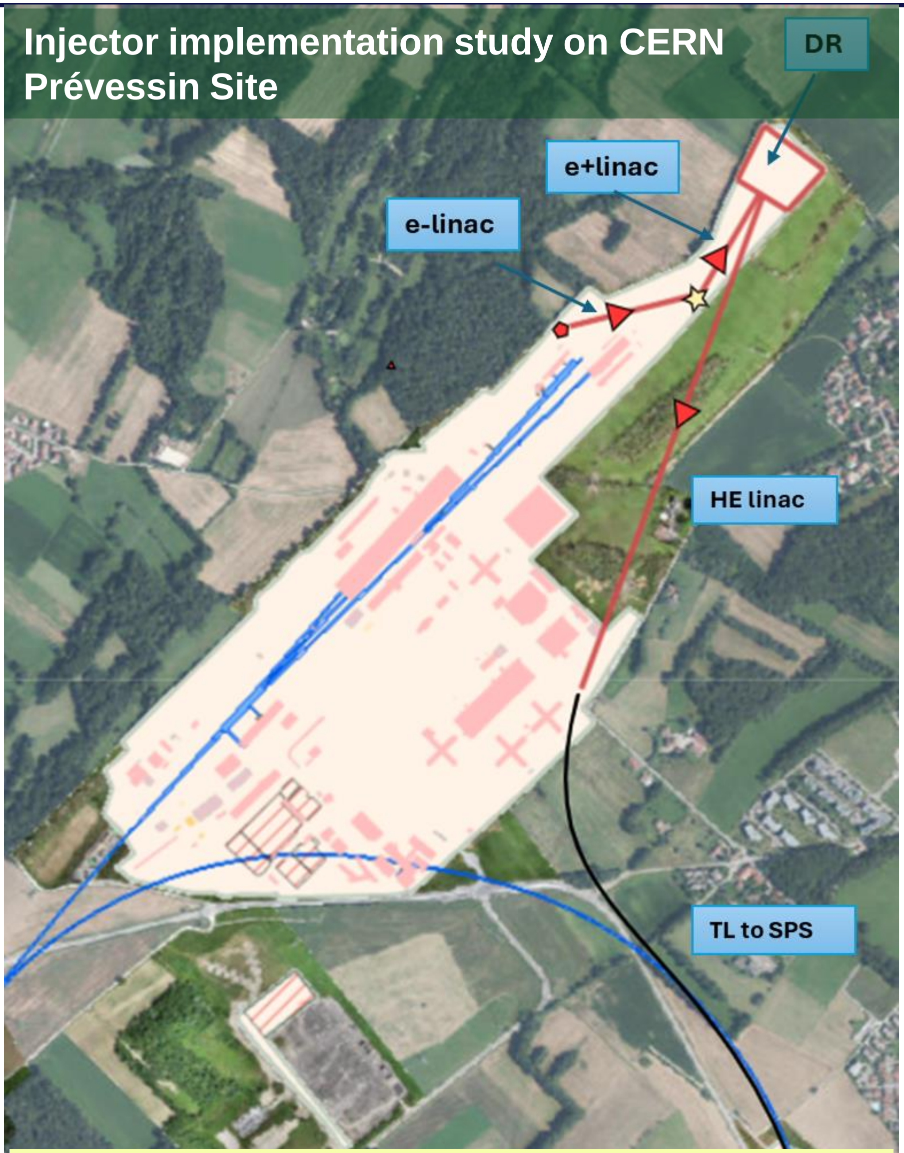
FCC-ee injector

P. Craievich, PSI, et al.

Overall injector parameter optimisation
- Operation frequency (**400 → 100 Hz**, gradient, etc…
- Positron production energy, damping ring energy

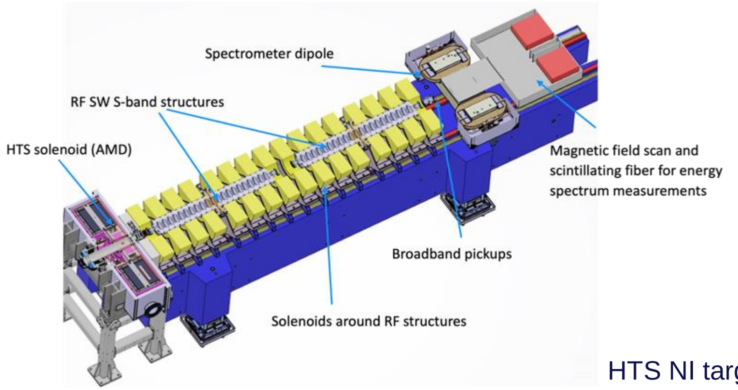


C. Milardi, A. De Santis, INFN, et al.

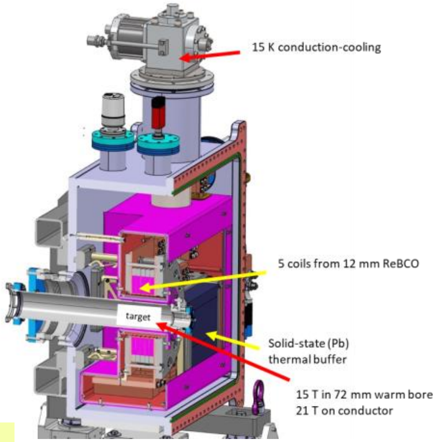


P. Craievich, W. Bartmann, Y. Papaphilippou, C. Milardi

“Positron production experiment” at PSI’s SwissFEL, beam tests from 2025/26



HTS NI target solenoid



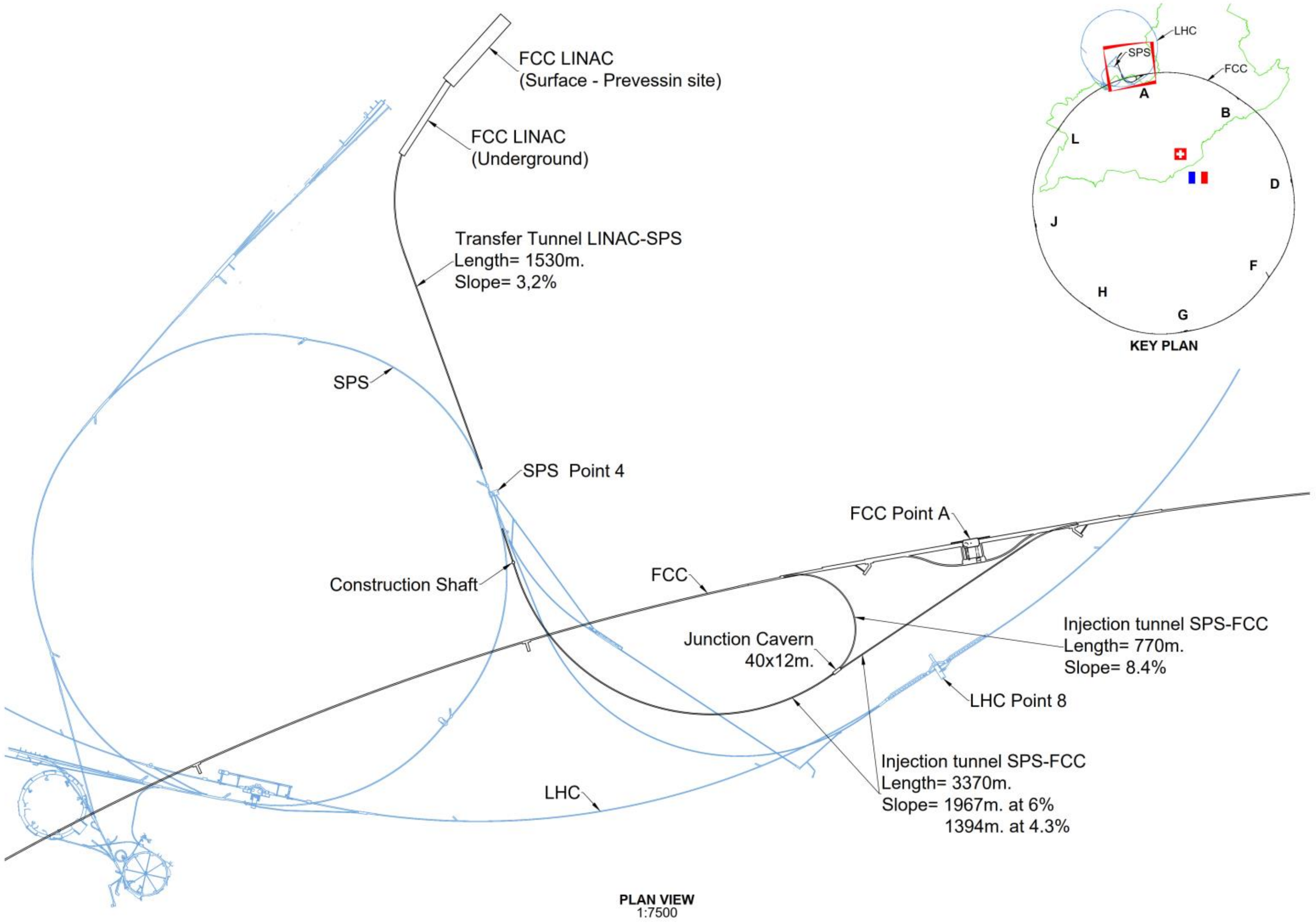
J. Kosse, T. Michlmayr, H. Rodrigues, PSI

Transfer line FCC-ee

(option with SPS for FCC-hh)

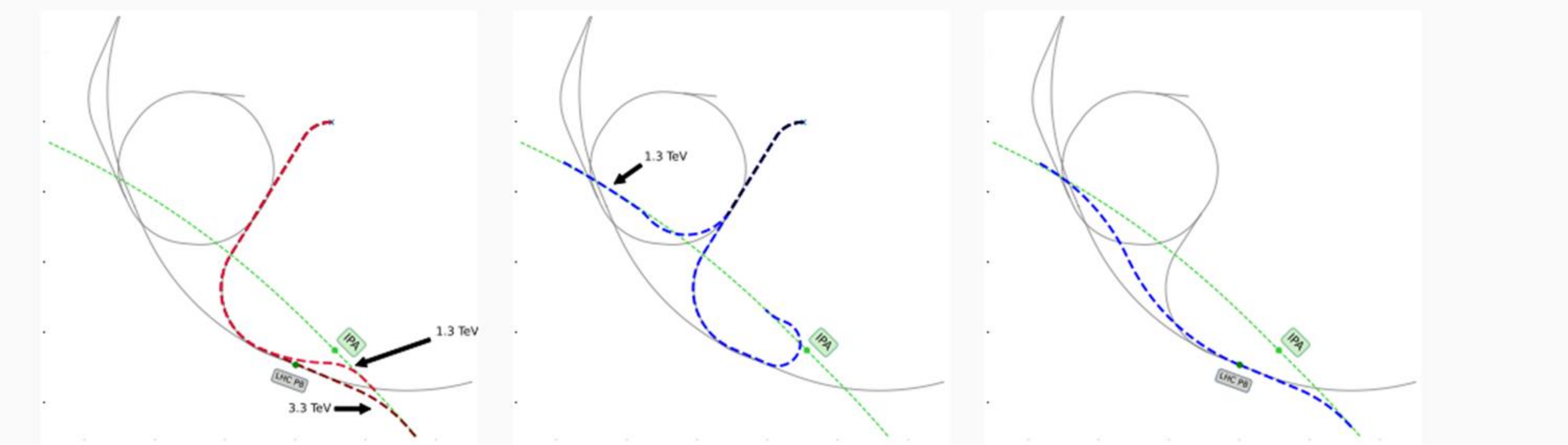
LINAC and Injection Tunnels

- Enables injection
  - from SPS as pre-booster, or
  - from a new HE Linac sited at Prévessin
- Single tunnel with spur to enable anticlockwise injection
- Design allows re-use for FCC-hh if injector in the SPS tunnel (SC-SPS option)
  - SPS Point 4 to FCC (clockwise)
  - SPS Point 6 to FCC (counter-c.w.)



W. Bartmann, T. Watson

Transfer lines FCC-ee&hh: options & tunnel lengths



	Tunnel [km]	TL length [km]	SR loss/spread [MeV]/[‰]	hadrons compatible	comments
PB-1.3TeV	1.8	5.8	16/0.8	yes, 1.3 TeV	positrons and SPS hadrons
PB-3.3TeV	1.9	6.7	13/0.8	yes, 3.3 TeV	positrons and LHC hadrons
PL-direct	2.8	4.5	15/0.8	yes, 1.3 TeV	electrons and SPS hadrons
PL-uturn	1.9	6.0	43/1.0	no	pure electron line
PL-3.3TeV	3.9	3.9	NA	yes, 3.3 TeV	pure LHC hadron line

W. Bartmann, T. Watson

FCC-ee main machine parameters

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter x_x / x_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	140	20	≥5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11
	4 years 5 x 10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years 2 x 10^6 H	5 years 2 x 10^6 tt pairs

F. Gianotti

Design and parameters to maximise luminosity at all working points:

- allow for 50 MW synchrotron radiation per beam
.
- Independent vacuum systems for electrons and positrons
- full energy booster ring with top-up injection, collider permanent in collision mode

Improvements:

- x10-50 on all EW observables
- up to x 10 on Higgs coupling (model-indep.) measurements over HL-LHC
- x10 Belle II statistics for b, c, τ
- indirect discovery potential up to ~ 70 TeV
- direct discovery potential for feebly-interacting particles over 5-100 GeV mass range

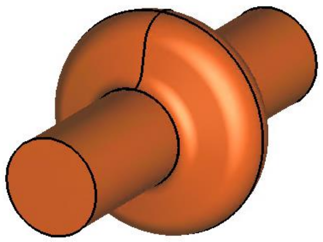
Up to 4 interaction points

→ robustness, statistics, possibility of specialised detectors to maximise physics output

FCC-ee baseline RF configuration so far

Z

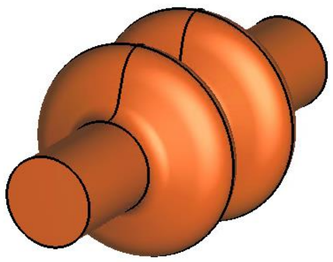
1-cell
400 MHz,
Nb/Cu



low R/Q, HOM damping, powered by 1 MW RF coupler and high efficiency klystron

W, H

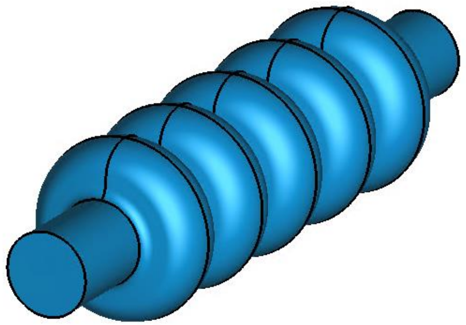
2-cell
400 MHz,
Nb/Cu



moderate gradient and HOM damping requirements; 500 kW / cavity, allowing reuse of klystrons already installed for Z

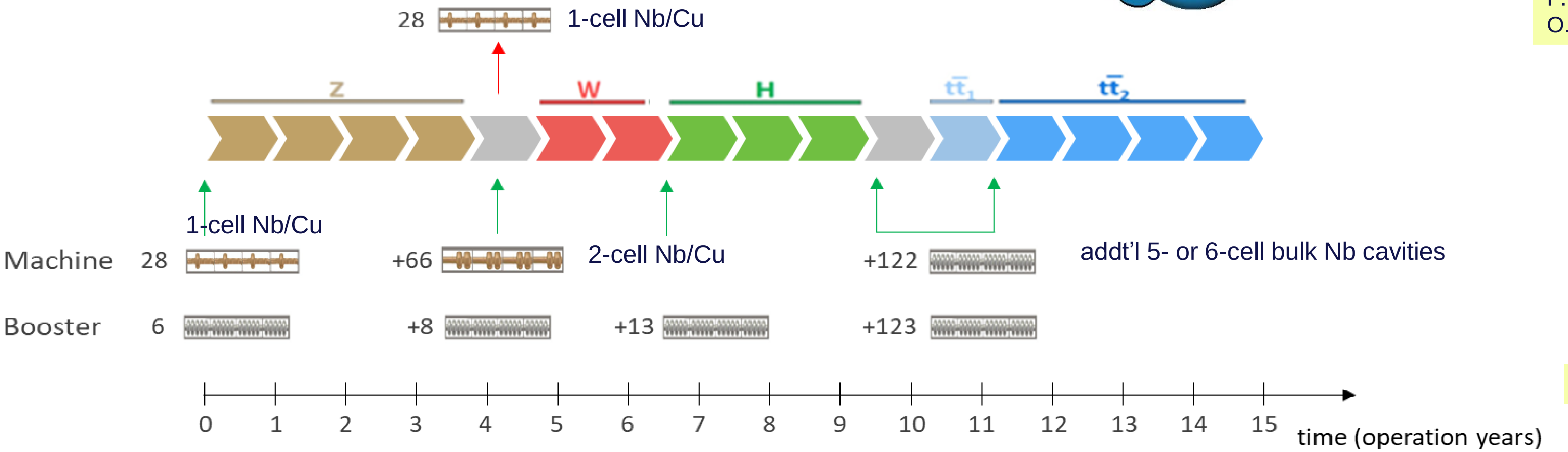
ttbar, booster

5-cell
800 MHz,
bulk Nb



high RF voltage and limited footprint thanks to multicell cavities and higher RF frequency; 200 kW/ cavity

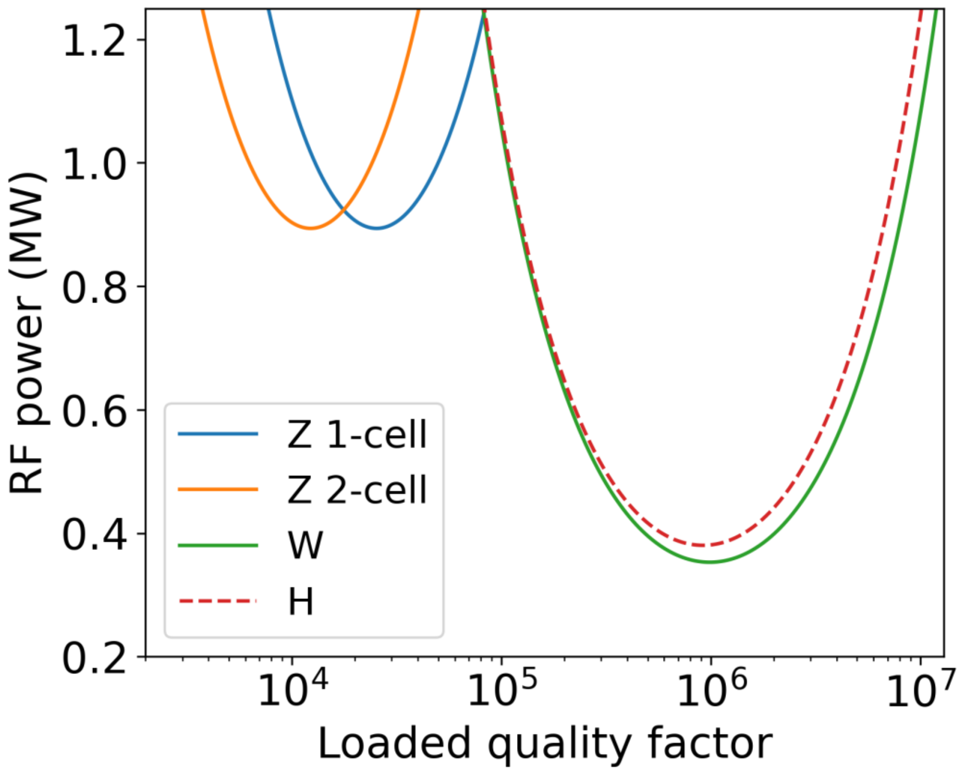
F. Peauger,
O. Brunner



O. Brunner

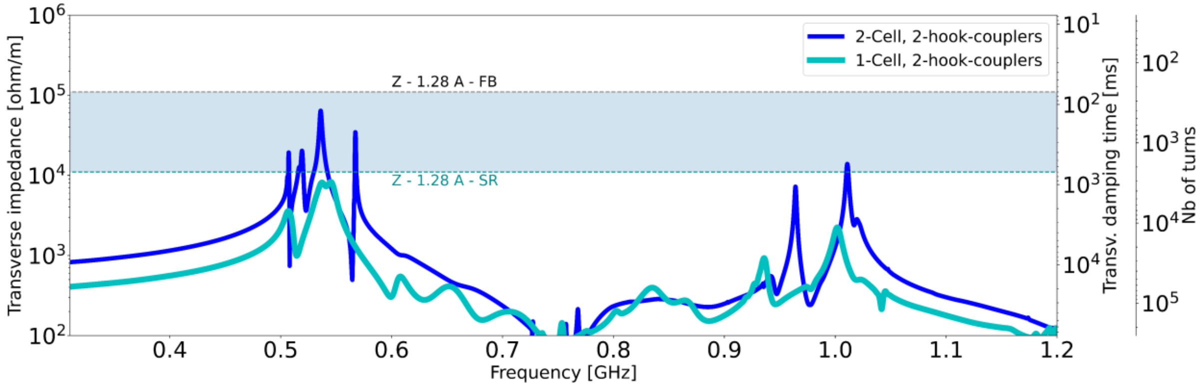
A 2-cell 400 MHz SRF cavity for all energies ?

Input RF power for optimum detuning

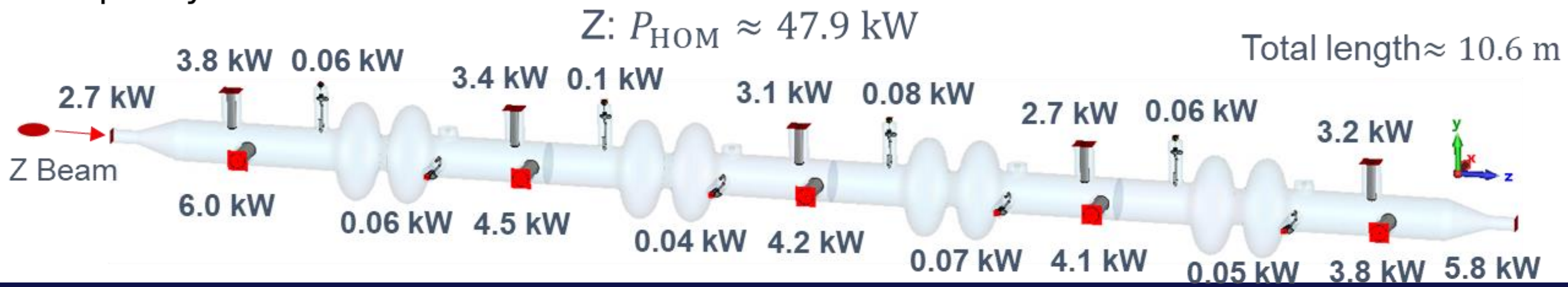


I. Karpov, R. Calaga, E. Montesinos, S. Zadeh, F. Peauger, O. Brunner

- Need for **adjustable/variable fundamental power coupler with wide range of coupling** (2 orders of magnitude)
- Presence of 0-mode requires additional longitudinal feedback
  Transverse feedback needed



- 40%-increase of **HOM power** / cryomodule → **"2-coax concept"**



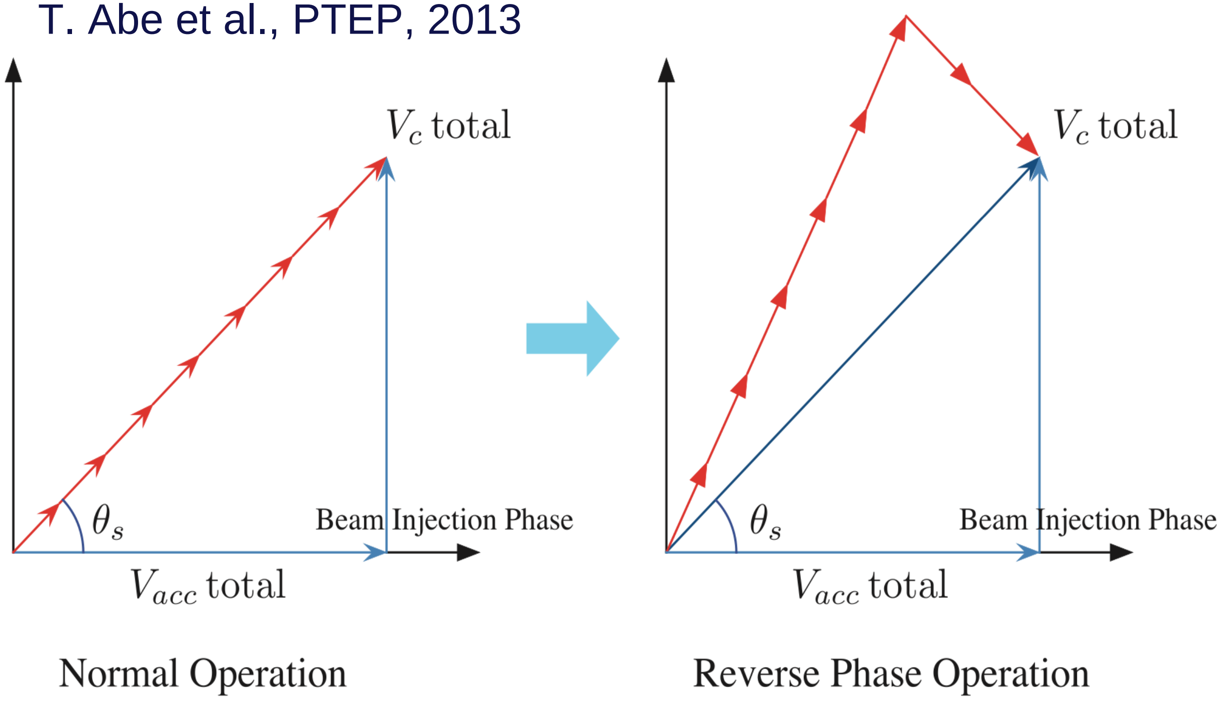
Solution for FCC-ee simplified RF system !

2-cell for all energies

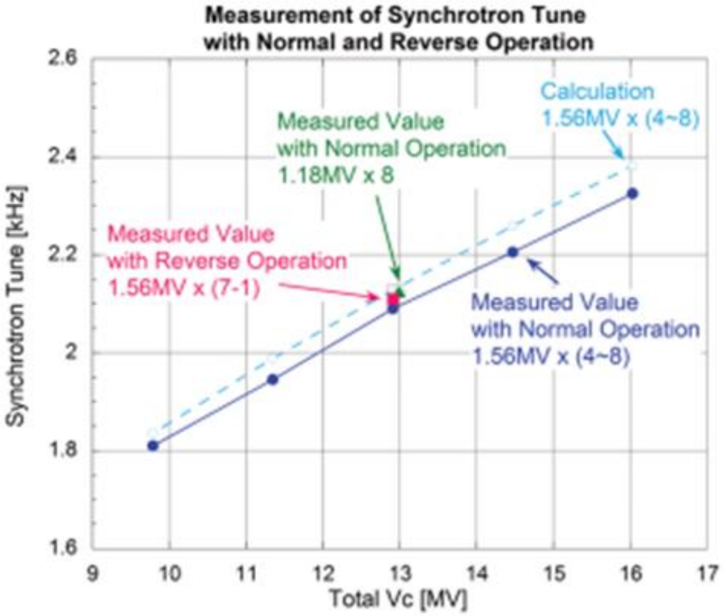
Reverse phase operation (RPO) → higher RF cavity voltage *(Y. Morita et al., SRF, 2009)*
- **Experimentally verified** with high beam loading **in KEKB** *(Y. Morita et al., IPAC, 2010)*
- **Baseline solution for EIC ESR** *(e.g., J. Guo et al., IPAC, 2022)*

$$Q_{L,opt} = \frac{V_{\mathrm{cav}}^2 N_{\mathrm{cav}}}{2 V_{tot} (R/Q) I_{b,DC} \cos\phi_s}$$

T. Abe et al., PTEP, 2013



KEKB HER synchrotron tune measured for several SC cavity configurations. RPO "(7 - 1)" case with1.56 MV/cavity yielded about the same f_s as for 8 in-phase cavities with 1.18 MV/cavity [T. Abe et al., 2013]



→ RPO potentially allows same optimal quality factor for Z, W, and H modes

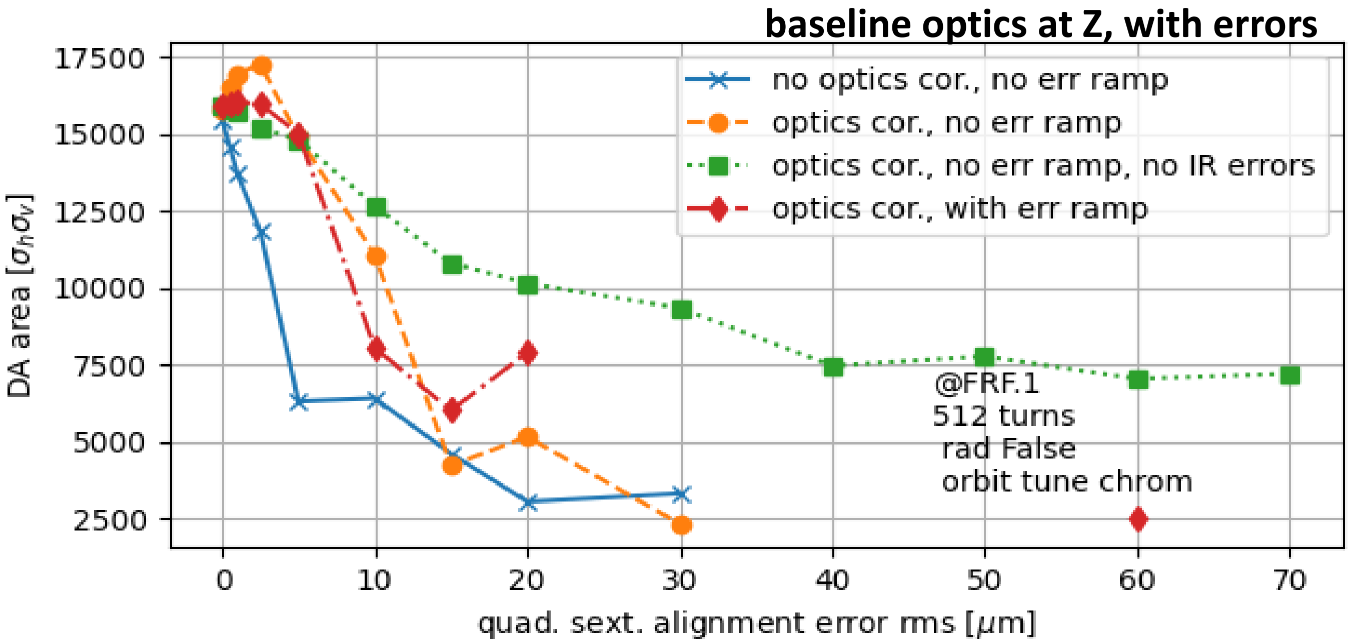
I. Karpov

Advantages:

- ❑ Rationalize RF resources during the development process (3 → 2 cavity types)
- ❑ Simplify, shorten the installation sequence (no cryo-module removal)
- ❑ **Great flexibility in physics running modes**
- ❑ Potential savings (cost, manpower, and time)

FCC-ee dynamic aperture with alignment errors

S. Liuzzo, ESRF

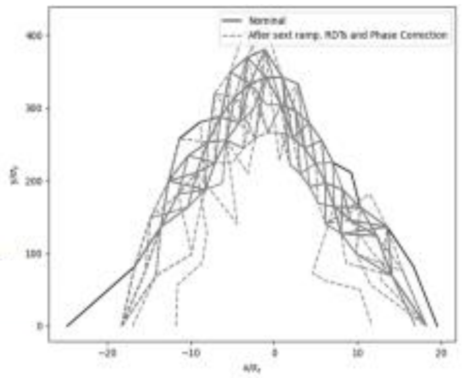


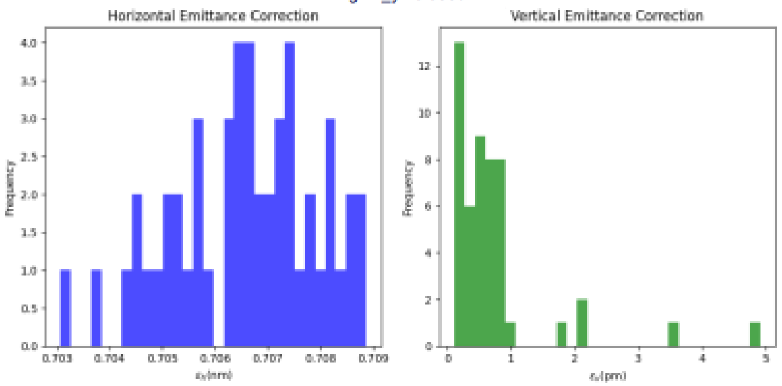
>100 μm alignment errors in the arcs acceptable for present baseline optics

50 seeds (mean values)		rms orbit x (μm)	rms orbit y (μm)	Δβx/βx %	Δβy/βy %	Δ ηx (mm)	Δ ηy (mm)	ε_h (nm)	ε_v (pm)
100 μm on arc quads & sexts	With err	6224.8	7276.7	1e-6	1e-4	11985	73458	-	-
	After Sext ramping	8.55	8.35	5.98	9.91	45.23	45.96	0.71	9.61
	RDTs & ηy Cor	8.58	8.42	6.01	9.94	45.09	4.49	0.71	2.32
	Phase Cor	8.55	8.35	0.35	0.79	2.94	4.36	0.70	0.88
	Final cor. result	8.55	8.35	0.35	0.89	2.94	4.37	0.70	0.73

E. Musa, DESY

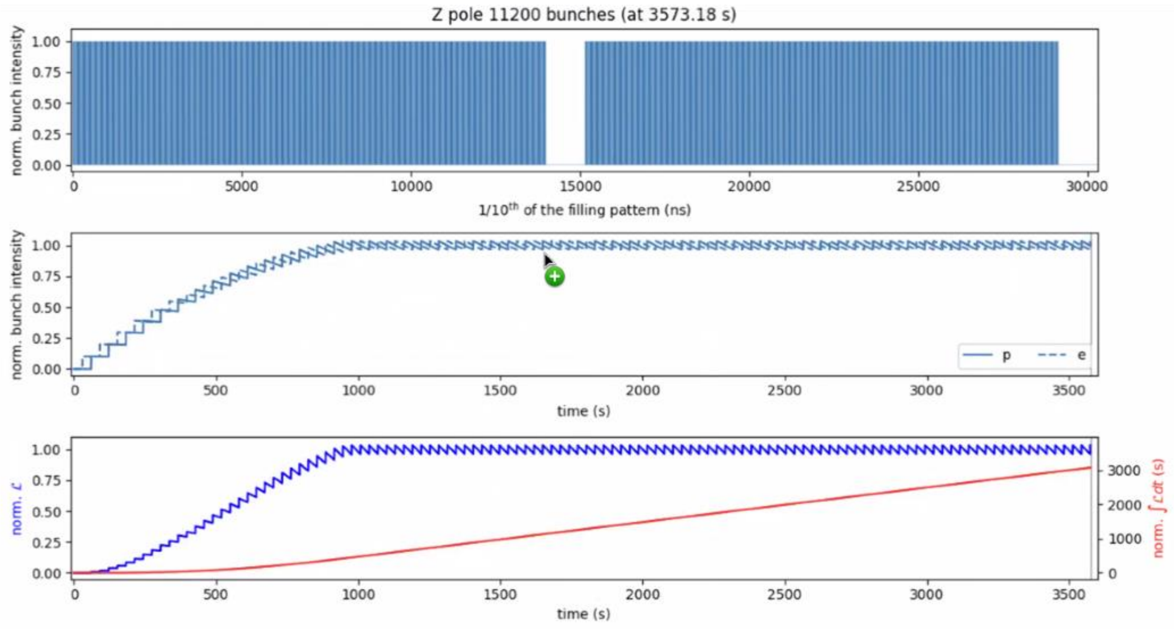
@FRF.1
Sigma_x =0.000362m
Sigma_y =0.000012m



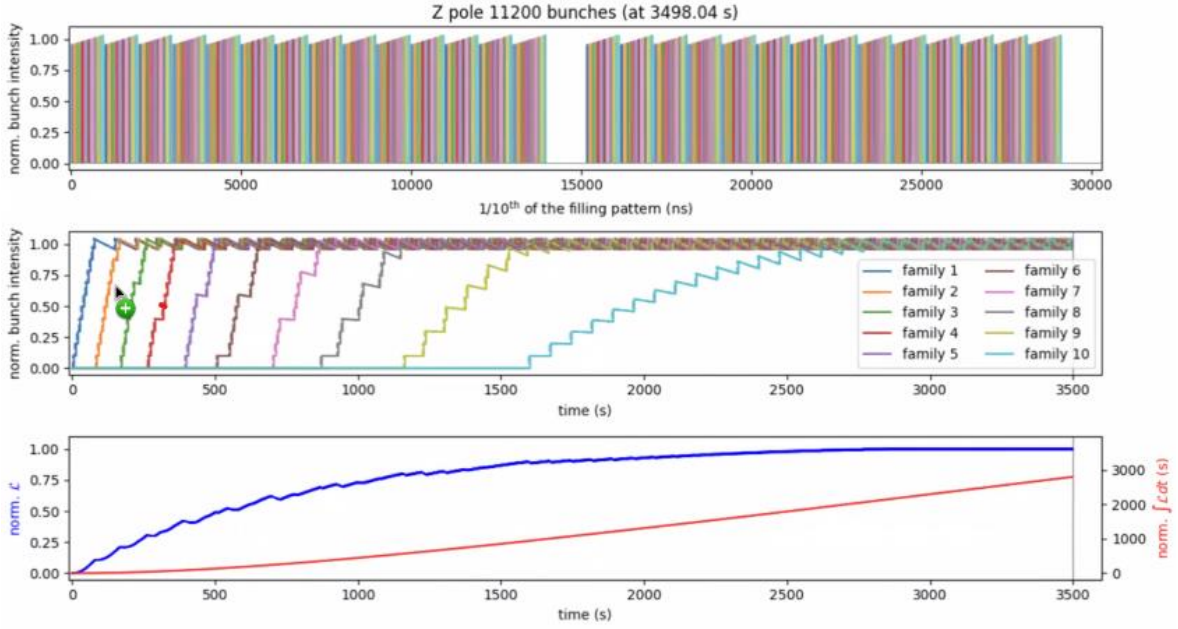


FCC-ee filling scheme & e-cloud mitigation

“CDR scheme”



“Carli-Bartosik scheme”



only 1/10 of intensity per booster cycle
→ vacuum pressure-tolerant
OK w/o NEG coating & bakeout in the booster
only 1/10 of collider bunches at intermediate intensity
→ anti e-cloud build up in the collider

H. Bartosik, C. Carli, L. Mether, F. Zimmermann

→ yet same integrated luminosity as for CDR scheme !

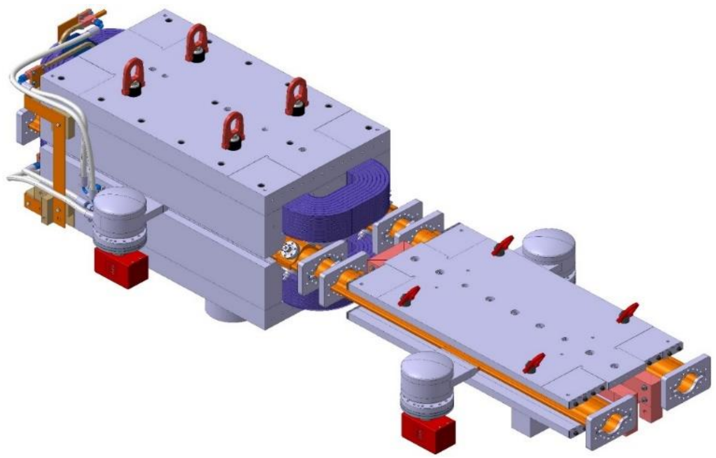
Arc layout and integration optimisation

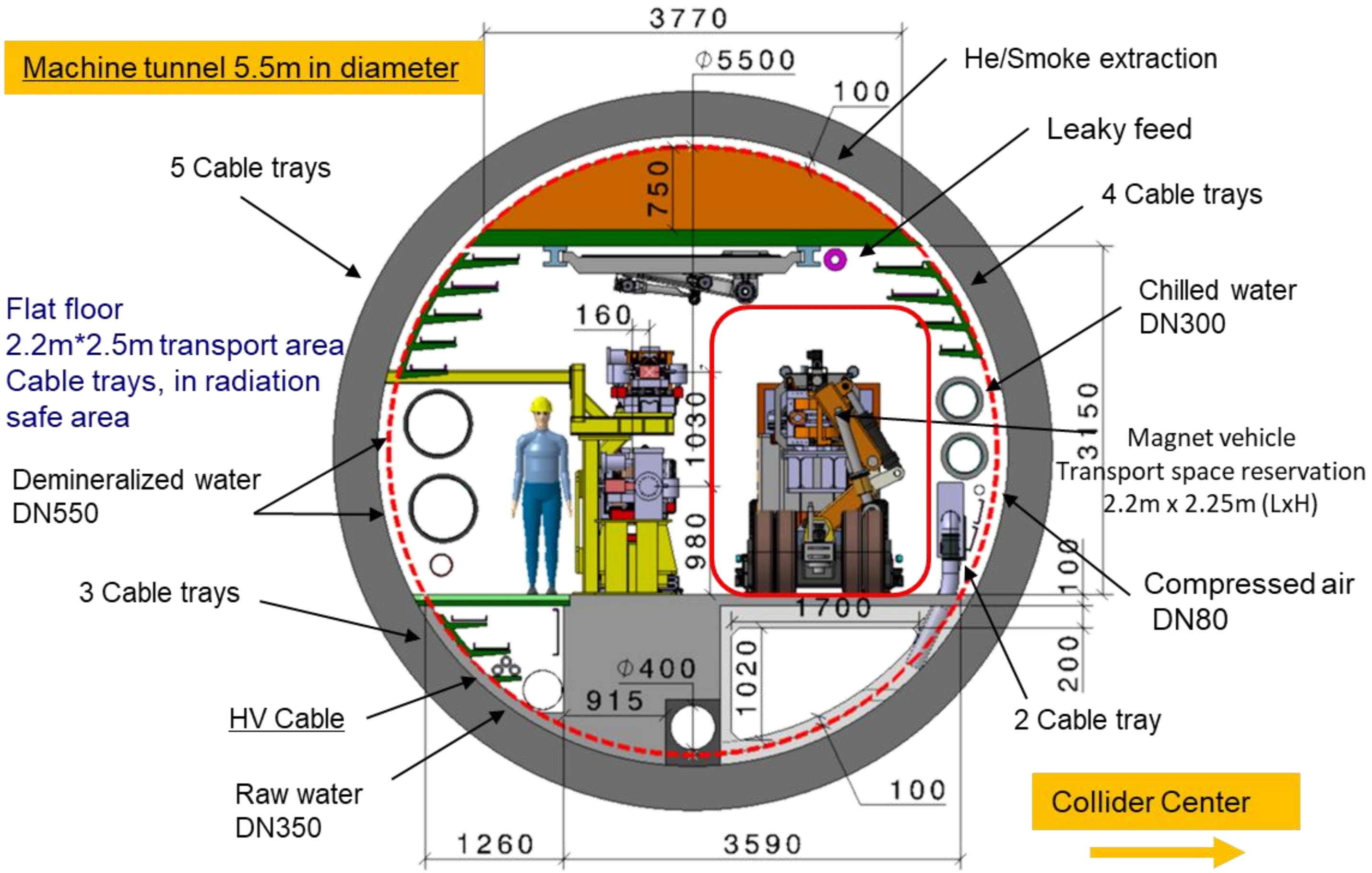
Arc cell optimisation – 80 km total length, dedicated working group active.

- including support, girder and alignment systems, shielding systems
- vacuum system with antechamber + pumps, dipole, quadrupole + sext. magnets, BPMs
- cabling, cooling & technical infrastructure interfaces
- safety aspects, access and transport concept

→ **Confirmation of tunnel diameter**

FCC-ee arc half-cell mock up



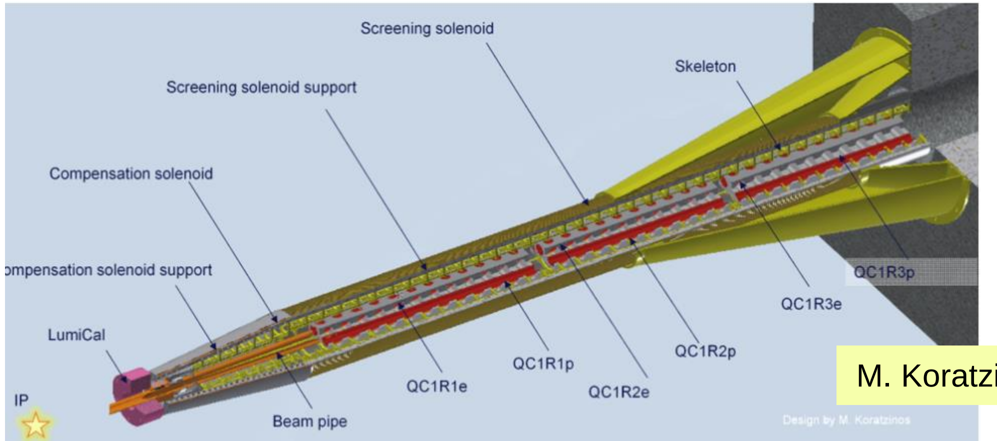


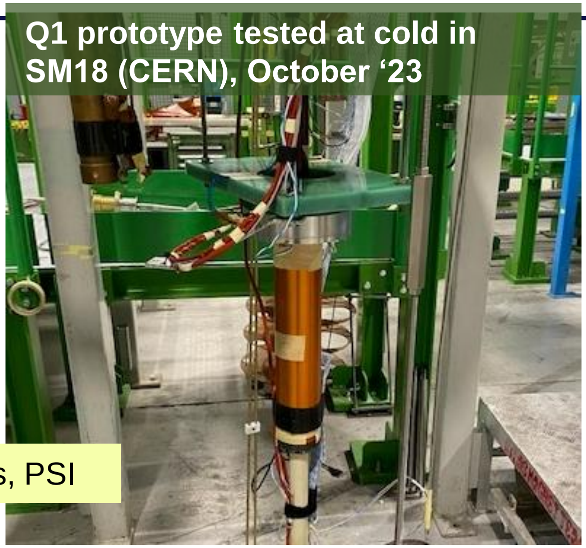
F. Carra, CERN; F. Valchkova

Machine detector interface

Key topics:

- SC IR magnet system & Cryostat design
- 3D integration
- IR mock-up at INFN Frascati !

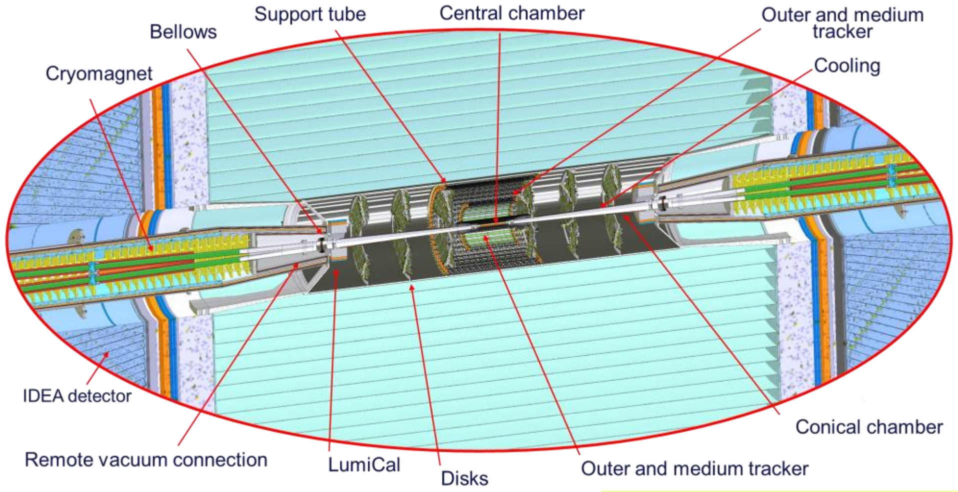




M. Koratzinos, PSI

P. Tavares , CERN
J. Seeman, SLAC

Machine		FCCee	CEPC	ILC	SuperKEKB
Crossing-angle	mrad	30	33	14	83
L*	m	2.2	1.9	3.5	0.935
Vertical β_y* at IP	mm	0.7-1.6	0.9-2.7	0.4	0.3
Detector soln field	T	2/3	3	3.5/5	1.5
Detector stay clear	mrad	100	118/141	90	350/436
Two beam ΔX at L*	mm	66	62.7	49	77.6
He temperature	K	1.9	4.2	4.5	4.5

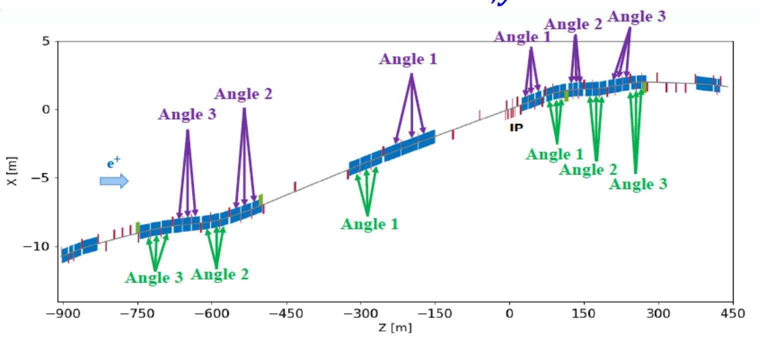


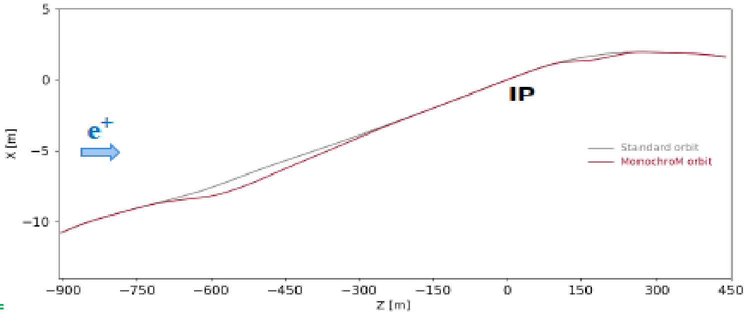
M. Boscolo, F. Palla, INFN

FCC-ee option: Monochromatization at 125 GeV

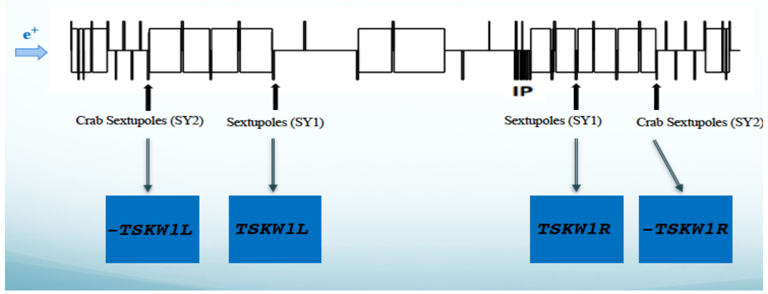
create opposite-sign $D^*_{x,y} \neq 0$

D^*_x



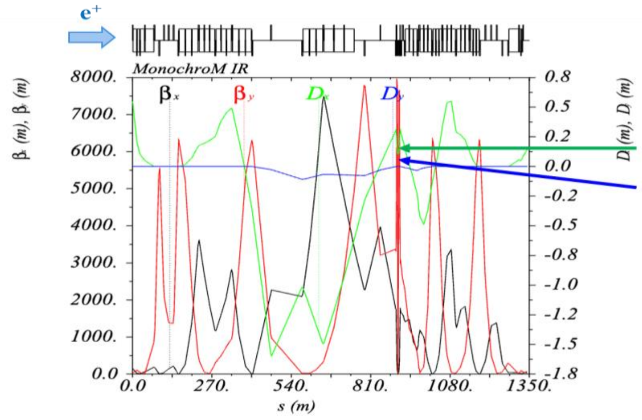


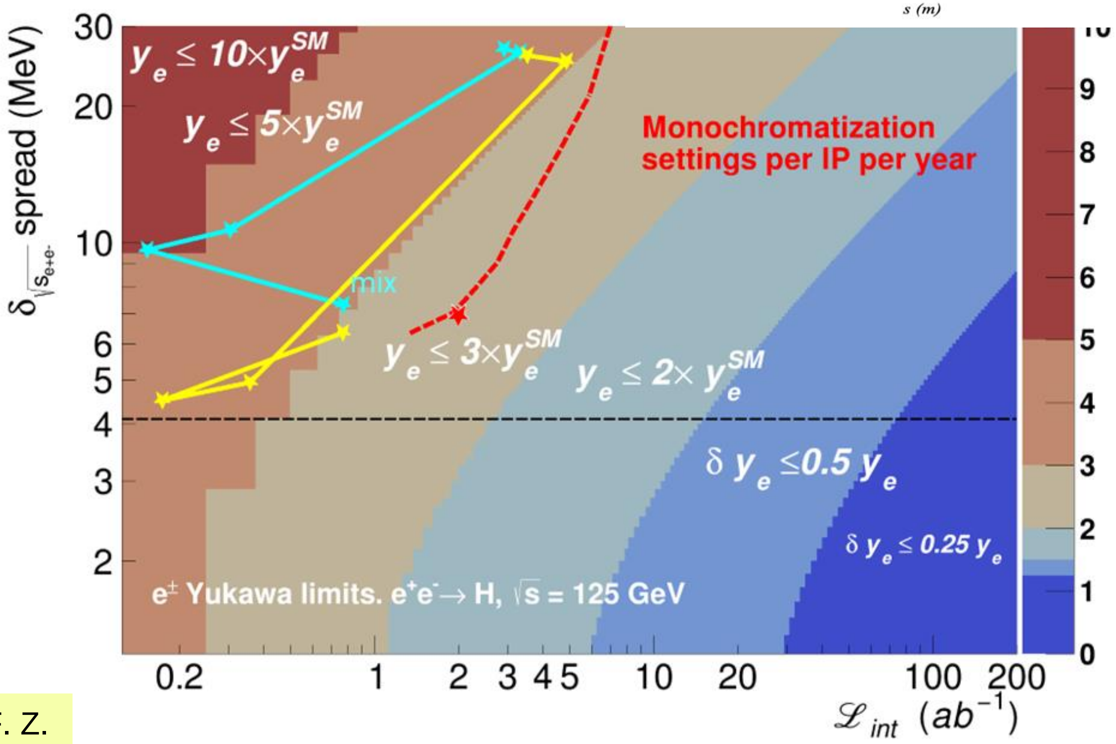
D^*_y



A. Faus-Golfe, Z. Zhang, P. Raimondi, K. Oide, F. Z.

So far best performance is obtained with **ttbar lattice** based **“mix” mode**, which reaches $y_e < 2.9 * y_e(SM)$ in the Higgs-electron Yukawa coupling





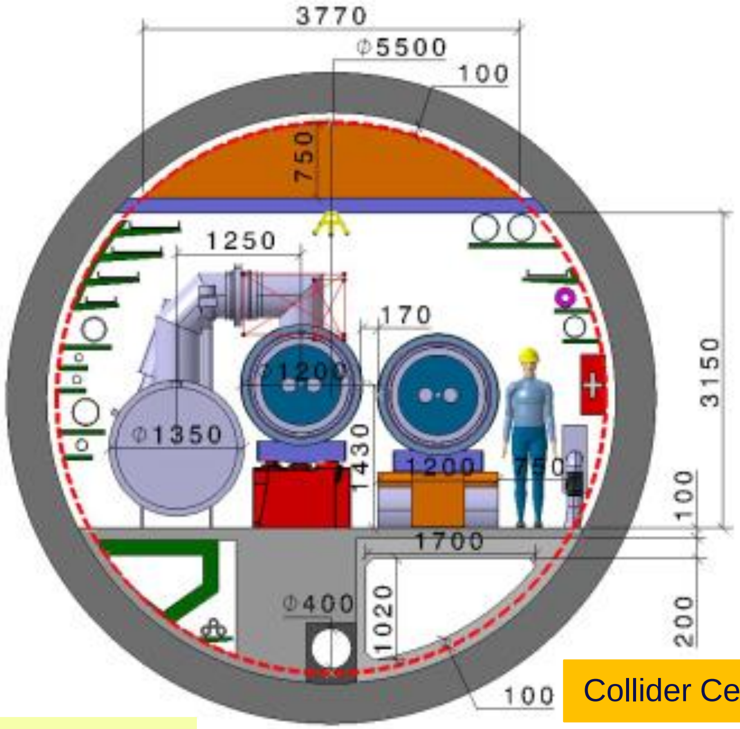
Key activities on FCC-hh

M. Giovannozzi. G. Perez, T. Risselada

Magnet system, optic design

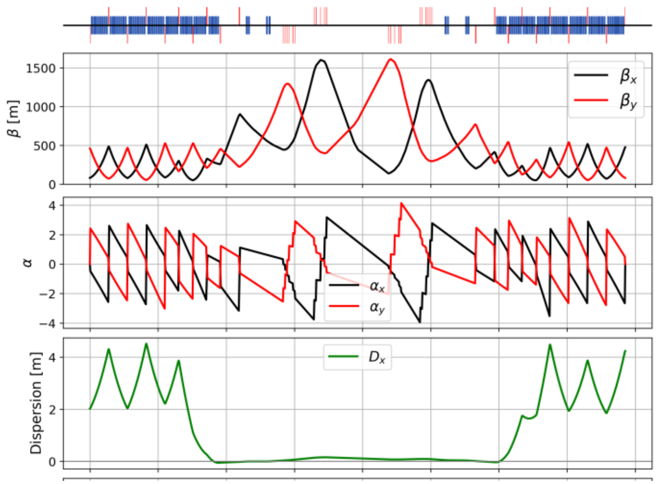
Optics design activities:

- adaptation to new layout and geometry
- shrink β collimation & extraction by ~30%
- optics optimisation (filling factor etc.)

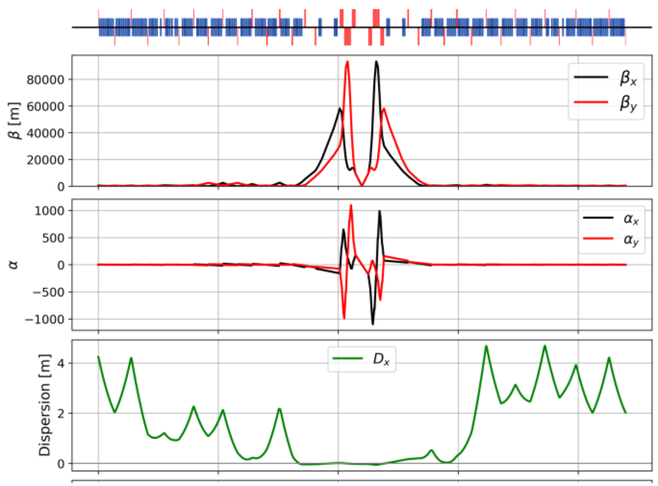


Collider Center

F. Valchkova



betatron collimation straight



experimental straight

High-field cryo-magnet system design

- Conceptual study of cryogenics concept and temperature layout for LTS and HTS based magnets, in view of electrical consumption.
- Update of integration study for the ongoing HFM designs and scaling to preliminary HTS design.
  → **Confirmation of tunnel diameter!**
- HFM R&D (LTS and HTS) on technology and magnet design, aiming also at bridging the TRL gap between HTS and Nb_3Sn.

Summary: present FCC-ee accelerator studies

- **great progress in addressing all points raised by MTR**

- **important lessons from KEKB and SuperKEKB**
  - participation of FCC-ee core team members (from CEA, CERN, DESY, EPFL, IJCLab, INFN, Oxford, Sapienza,…) in SuperKEKB operation & beam studies
  - RPO RF operation scheme demonstrated at KEKB to be used for EIC & FCC-ee

- **on track to completing the Feasibility Study by March 2025 !**

thank you for your attention

今後とも良い
ご協力をよろしく
お願いいたします

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