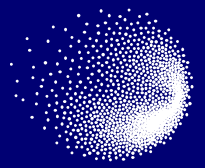

PSI Center for Accelerator Science and Engineering

CERN

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

CHART Swiss Accelerator Research and Technology

FCC

(Unlimited) Injector complex: status and outlook

Paolo Craievich on behalf of the CHART/FCCee Injector Study collaboration

FCC week, The Westin St. Francis San Francisco, June 2024

Credits

PSI	R. Zennaro, M. Schär, N. Vallis, B. Auchmann, I. M. Besana, S. Bettoni, M. Duda, R. Fortunati, H. Garcia-Rodrigues, D. Hauenstein, R. Ischebeck, P. Juranic, J. Kosse, F. Marcellini, U. Michlmayr, G. L. Orlandi, M. Pedrozzi, J.-Y. Raguin, S. Reiche, R. Rotundo, S. Sanfilippo, N. Strohmaier, M. Zykova, H.H. Braun, M. Seidel all the technical groups involved in the P3 experiment
IJCLab	I. Chaikovska, F. Alharthi, R. Chehab, V. Mytrochenko, Y. Wang
CERN	A. Grudiev, A. Latina, S. Doebert, Z. Vostrel, Y. Zhao, B. Humann, A. Lechner, A. Kurtulus, R. Mena Andrade, J. L. Grenard, A. Perillo Marcone, M. Calviani, W. Bartmann, Y. Duthell, H. Bartosik, K. Oide, F. Zimmermann, M. Benedikt
INFN-LNF	C. Milardi, A. De Santis, O. Etisken, S. Spampinati
SLAC	T. Raubenheimer
KEK	Y. Enomoto, K. Furukawa

and L. Bandiera, M. Soldani, A. Sytov (INFN/Ferrara), A. Bacci, M. Rossetti Conti (INFN/Milano)

Swiss Accelerator Research and Technology

This work was done under the auspices of CHART (Swiss Accelerator Research and Technology) Collaboration, https://chart.ch - **CHART Scientific Report: https://chart.ch/reports/**

FUTURE CIRCULAR COLLIDER

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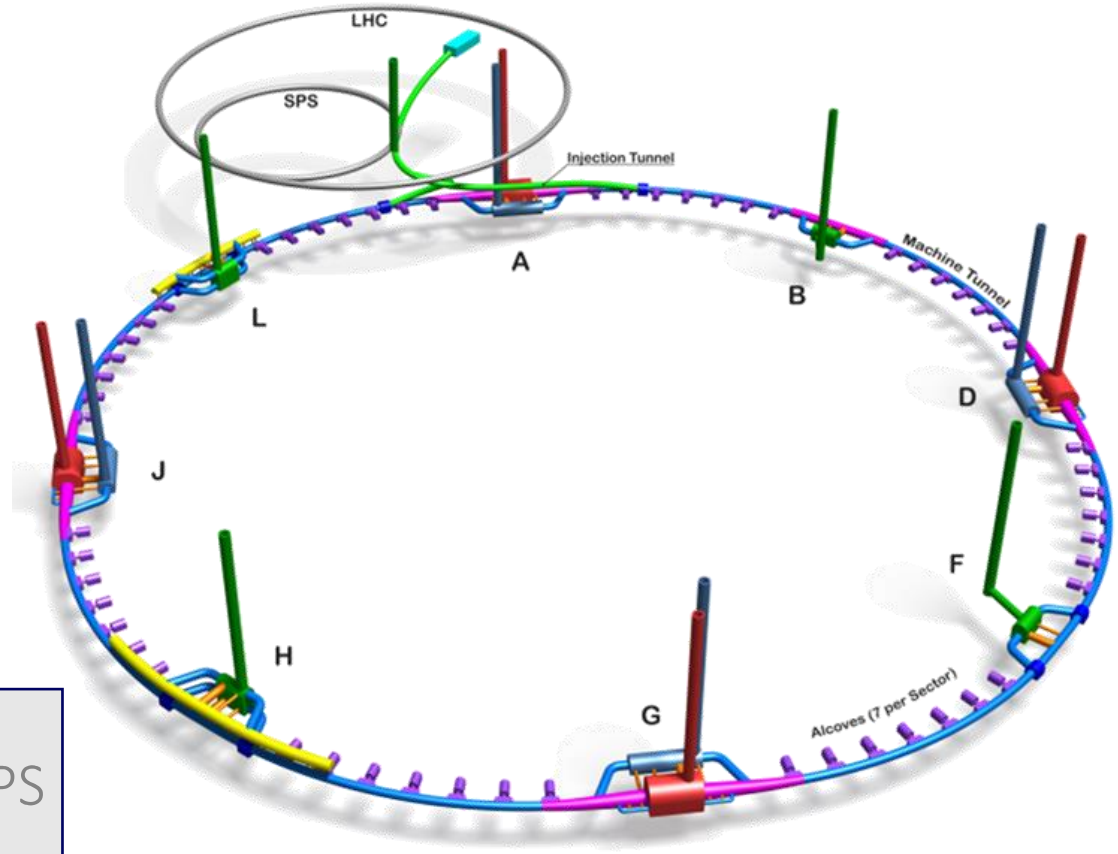
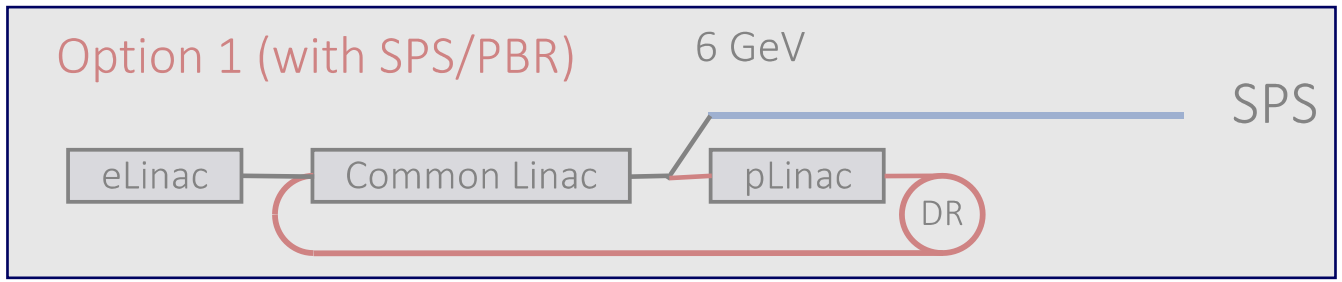
Outline

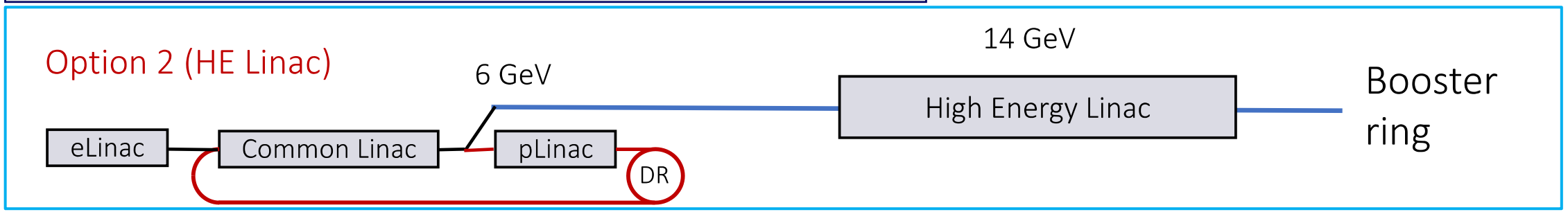
- Recap and comments on the injector parameters
- Present baseline and Mid-Term Review (MTR) recommendations
- New (general) baseline layout with new DR at 2.86 GeV
- Availability and breakdown rate (in the SwissFEL 6 GeV linac)
- Electron source recap
- Overview of further detailed studies for the injector (presented at this FCC week)
- Summary and open questions

Recap (a recommendation on the layout)

- For final report provide well-defined baseline layout for all aspects of the FCCee machine (SPC)
  - SPS vs HE linac, after mid-term review, HE-linac option is only considered after MTR
  - Injector baseline layout → we are converging to a new baseline







Collider and booster parameters related to the Injector

Source: mid-term review report

Running mode	Z	WW	ZH	ttbar	Unit
Beam energy at inj. end	20				GeV
Number bunches/ring	11200	1780	440	60	
Maximum bunch charge	≥ 4				nC
Bunch charge in top up	3.43	1.39	1.11	1.49	nC
Number of bunches	2	2	2	2	
Linac rep. rate	200	100	50	50	Hz
Bunch spacing	25	150	600	4400	ns
Norm. emittance (x, y) (rms) (BR)	<10,10				mm mrad
Bunch length (rms) (BR)	~1				mm
Energy spread (rms) (BR)	~0.1				%

For filling from scratch

For top-up injection

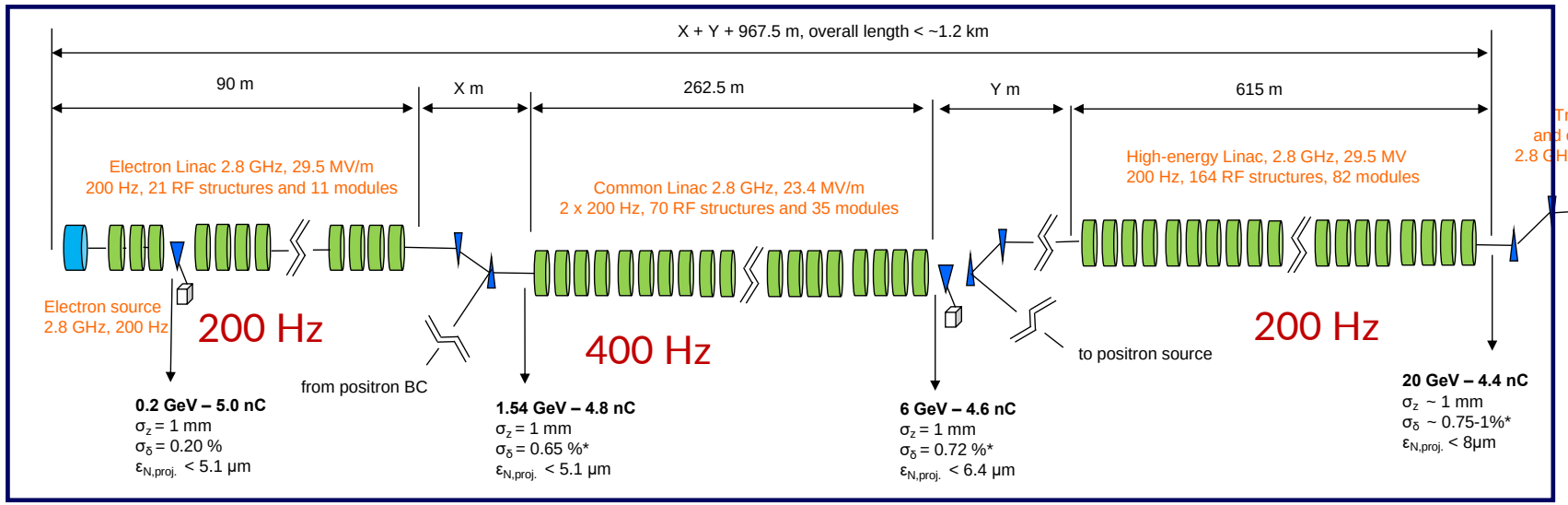
Target values for injector design

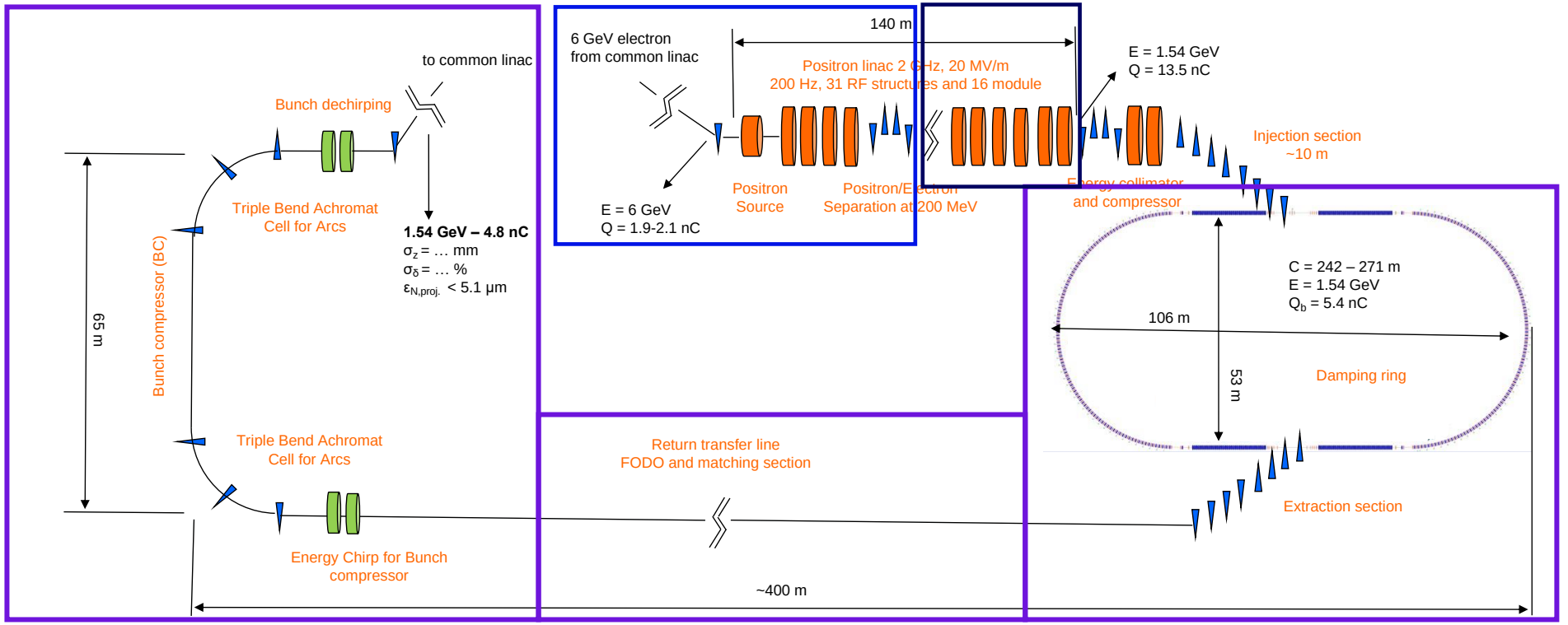
- Z-mode: max charge at the injector end is 5 nC, is a trasmission efficiency of 80% between injector end and collider ring resonable?
- Considering the charge (3.43nC) needed for top-up, trasmission efficiency is 67%.

Comments on the injector parameters for Z-mode

- Number of bunches/ring (11200) and bunch spacing (25 ns): These two parameters may change (i.e. e-cloud instability) but still compatible with present injector parameters and performances.
- Repetition rate (200 Hz, common linac at 400 Hz) and number of bunches/rf pulse (2): New baseline to (also) avoid the common linac at 400 Hz, up to 4 bunches to further reduce the rep rate to 100 Hz.
- The bunch-by-bunch charge will arbitrarily vary from 0 to 100%, depending on the intensity balance in the collider rings (for top-up injection) → electron source and linac must keep the beam quality for different charges.
- Top-up operation: Injector will run continuously, and the reliability and availability become important aspect for the new baseline (→ low-gradient injector!)
- Target values (BR) for the normalized emittance (10x10 μm) and relative energy spread (0.1%):
  - Vertical emittance: a smaller vertical emittance will help to reduce the flat-top in the BR cycle. New indicative values for the new baseline are 20x2 μm.
  - Energy spread: using an energy compressor at the injector end OR operating the linac off-crest (not our case!), energy spread even below 0.1%, specification for the transfer line is <0.25% (more details on this point in the Simona's talk).

Baseline layout presented at MTR (2 bunches/rf pulse)





WP1. Electron source and e^- and e^+ linacs (A. Grudiev, CERN)

WP3. Positron source and capture system (I. Chiakovska, IJCLab)

WP4. Damping ring and return transfer line (C. Milardi INFN LNF)

Baseline layout presented at MTR – linac parameters

Bunch repetition rate:

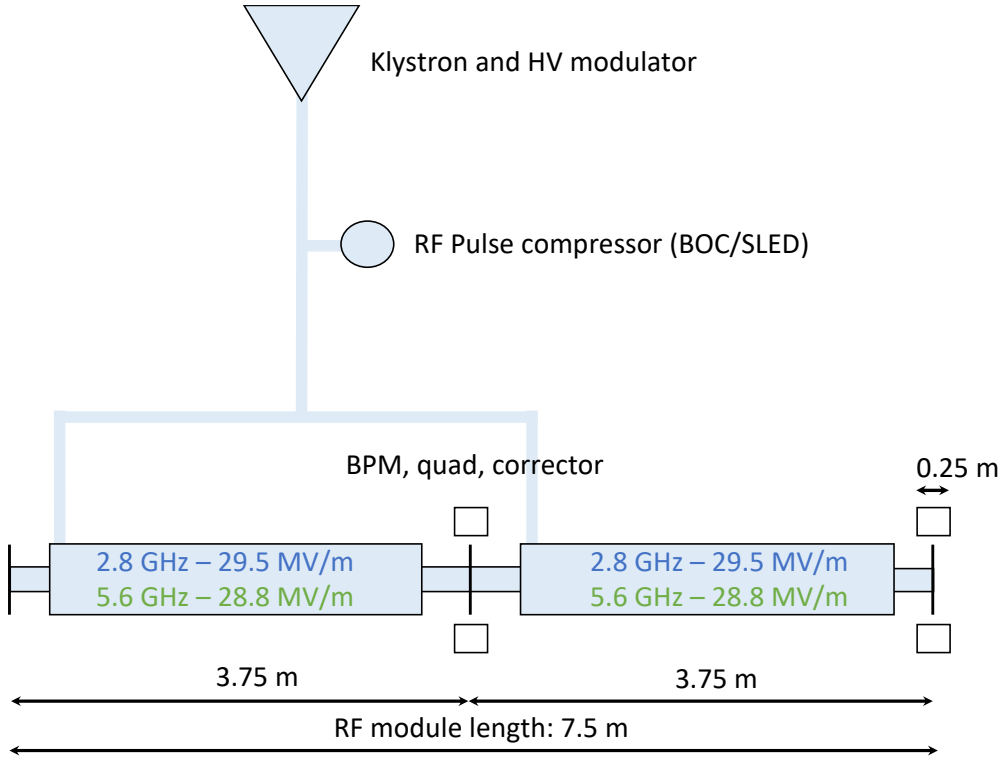
- 200 Hz x 2 bunches in Z-mode,
- 100 Hz or lower in other operational modes

RF module layout:

- 2 Accelerating Structures (ASs) per module,
- 1 quadrupole per AS

Acc. Structure (AS):

- Active length = 3 m,
- average aperture <a>/λ = 0.15 (~16 mm),
- RF frequency = 2.8 GHz, gradient up to 29.5 MeV/m



MTR recommendations:

- **Optimize linac design in term of cost and power!**
- **Overall power consumption 43.5 MW is too high**. Reduction of at least factor 2 or more is necessary
- **High average and peak power** (relatively high gradient for S-band) **operation reliability** has been questioned.

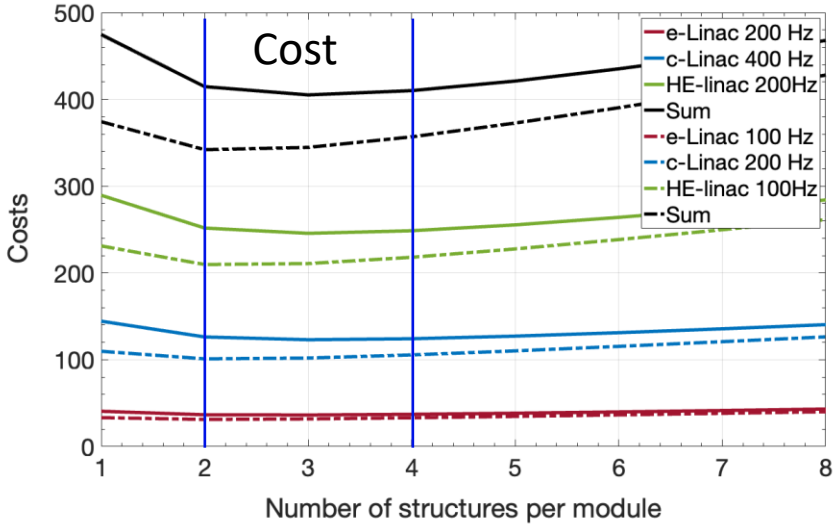
Addressing the recommendations

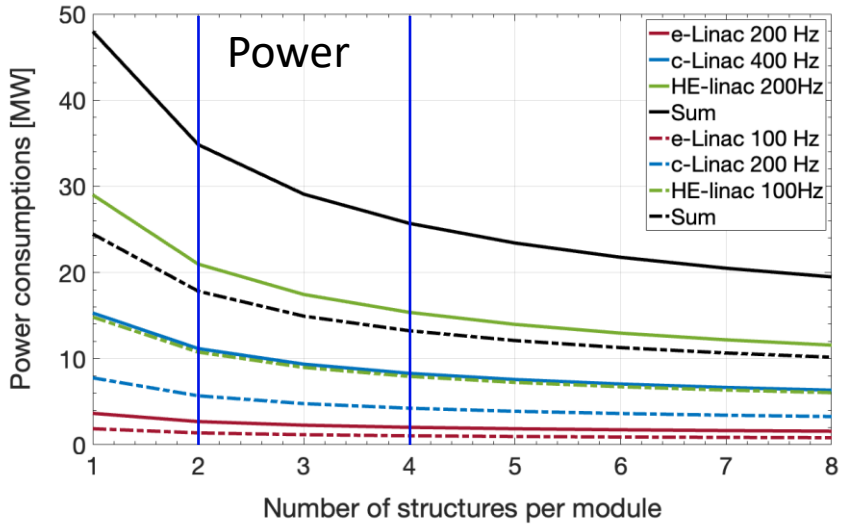
- Gradient and power consumption reduction: First approach, 2 AS per module → 4 AS per module
  - BUT linac length from ~1.2 km to 1.6 km, 400 m longer!!
  - What are the consequences for cost? Can this still be improved?

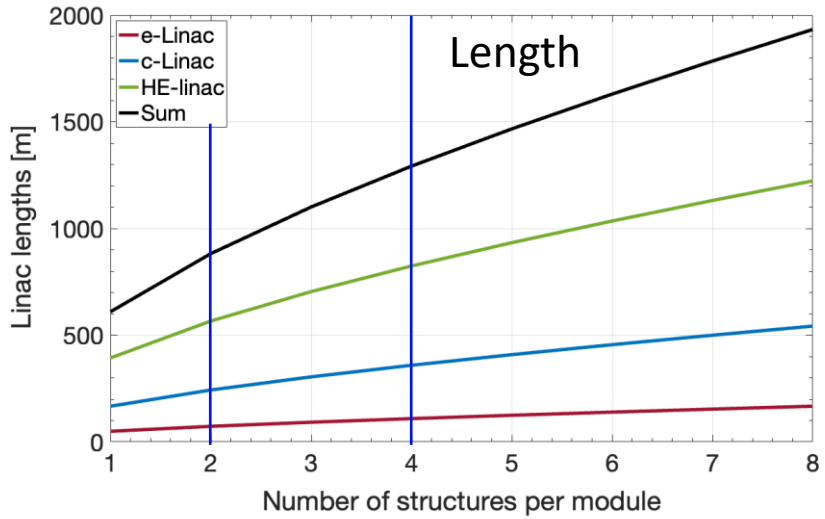
- Accelerating Structure (AS) parameters for new baseline (see Adnan's talk and paper at IPAC'24)
  - AS length remains 3 m, since not strong motivation to change
  - AS aperture has been defined in different linacs based on acceptable jitter amplification budget (see Simona's talk):
    - e-linac: $\langle a \rangle/\lambda=0.15$ (~16 mm)
    - c-linac: $\langle a \rangle/\lambda=0.15$ below 2.86 GeV and $\langle a \rangle/\lambda=0.12$ above
    - HE-linac: $\langle a \rangle/\lambda=0.12$ (~12.9 mm)
  - What about repetition rate (and number of bunches per pulse) and the accelerating gradient (number of structures per klystron)?

Reference: A. Grudiev, A. Kurtulus and WP1 working group members

Latest round of cost, power and length optimizations







Linac	Total cost			
Rep. rate [Hz]	200 x 2b		**100 x 4b**	
N of AS/module	2	4	2	**4**
e-linac	37.5	39.5	32	**35.5**
c-linac	127	124.5	102	**106**
HE-linac	252.5	249	211	**218**
All together	417	413	345	**359.5**

- Small cost difference between 2 and 4 AS/module
- Lower cost for lower rep. rate

Linac	Power consumption [MW]			
Rep. rate [Hz]	200 x 2b		**100 x 4b**	
N of AS/module	2	4	2	**4**
e-linac	2.7	1.8	1.4	**1**
c-linac	11	8.3	5.6	**4.2**
HE-linac	20.8	15.3	10.7	**7.9**
All together	34.5	25.4	17.7	**13.1**

- Power consumption is reduced:
- **200 and 100 Hz, by factor 2**
- **2 and 4 AS/module, by ~30%**

Linac	Length [m]		Gradient [MV/m]	
N of AS/module	2	**4**	2	**4**
e-linac	100	**145**	29.5	**18.8**
c-linac <2.86GeV	267.5	**380**	22.5	**16.1**
c-linac >2.86GeV			25.4	**17.9**
HE-linac	350+ 220	**605+2 20**	32	**22.5**
All together	717.5 +220	**1130+ 220**		

- Linacs are longer for 4 AS/module, 40% ☹

Courtesy of J.-Y. Raguin

New Baseline for linacs

Bunch repetition rate:

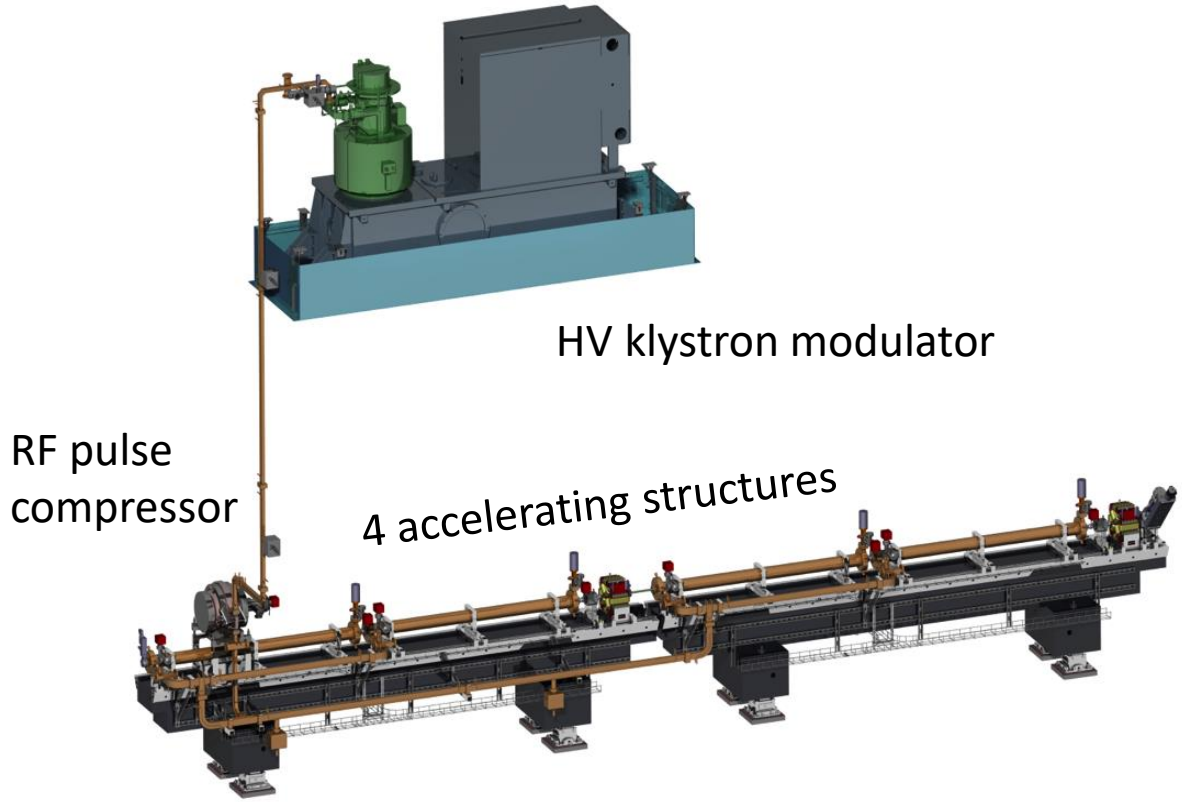
- **100 Hz x 4 bunches in Z-mode**,
- 100 Hz or lower in other modes

RF module layout:

- **4 AS per module**,
- 1 quad per AS

Acc. Structure (AS):

- Active length = 3 m,
- average aperture <a>/λ:
  - 0.15 <2.86GeV
  - **0.12 >2.86GeV**
- RF frequency = 2.8 GHz
- Max gradient 22.5 MV/m



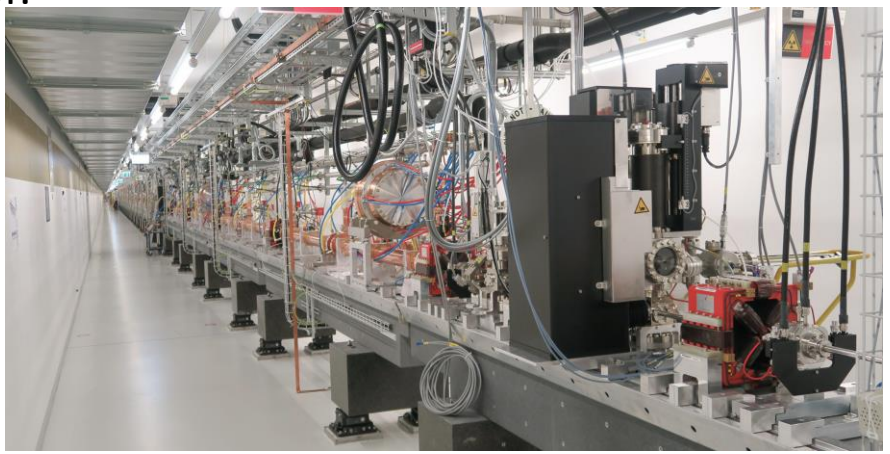
Esample of rf module composed from a power source (klystron and HV modulator), a rf pulse compressor and 4 rf accelerating structures.
For the FCCee injector ~100 rf module are needed.

Reference: A. Grudiev, A. Kurtulus and WP1 working group members

New Baseline for linacs (remarks)

Mid-term review recommendations addressed:

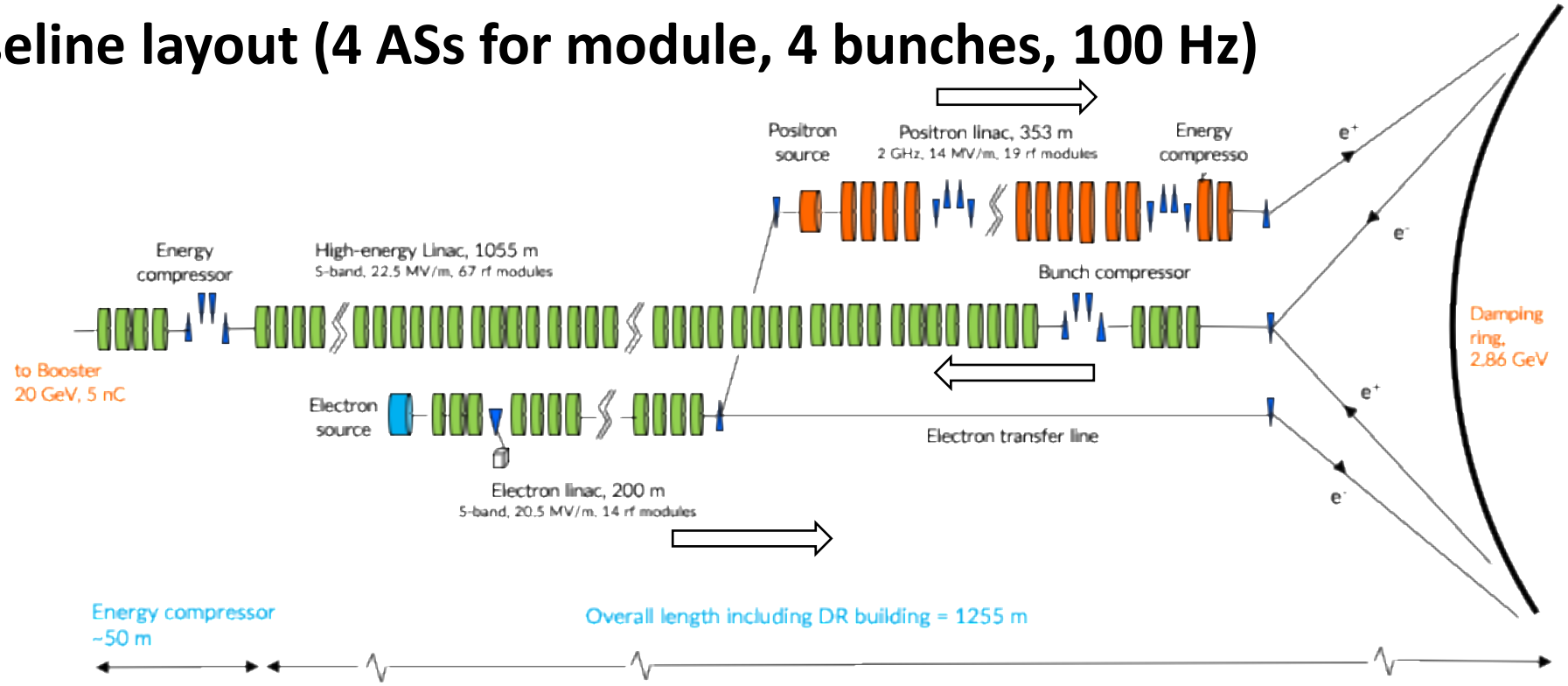
- ☺ Linac design is optimized in term of cost and power including new accelerating structure design with high shunt impedance
- ☺ Overall power consumption is reduced by more than factor 3, by means of:
  - New AS design with higher shunt impedance
  - Lower gradient
  - Lower repetition rate
- ☺ High average and peak power operation reliability is improved:
  - Lower gradient
  - Lower repetition rate
- 😐 4 bunches per pulse require more sophisticated
  - electron and positron sources (seems to be no problem, also see Iryna's talk)
  - beam loading compensation (first approach in Adnan's talk, AND/OR energy compressor)
  - Long range wakefield suppression (no problem, see Adnan's talk)
- ☹ Total length of the linacs is longer, Injector siting on the CERN site under study (W. Bartmann)
  - ☺ it has small impact on total cost
  - ☺ This potentially allows easier upgrade to higher energy by adding more RF power sources, in case it is needed in the future…



SwissFEL linac

Courtesy of A. Grudiev, A. Kurtulus and WP1 working group members

New baseline layout (4 ASs for module, 4 bunches, 100 Hz)



New DR (new cost estimate needed)

- The present positron yield would allow positrons to be generated at a lower electron beam energy (more details in the Iryna's talk) → Higher energy DR (2.86 GeV), no common linac with 2x repetition rate, no large arc.
- More stable electron and positron bunches at beginning of the HE linac.
- DR for both species with flat emittances (and polarized positrons?), first consideration in Antonio's talk
- Linac cost, length and power consumption optimizations presented for the previous layout are still valid BUT higher power consumption and costs for DR (to be estimated).

New baseline: Linacs Specs, Power Consumption and Cost Estimates

2 bunches, 200 Hz, 2/4 rf structures per module

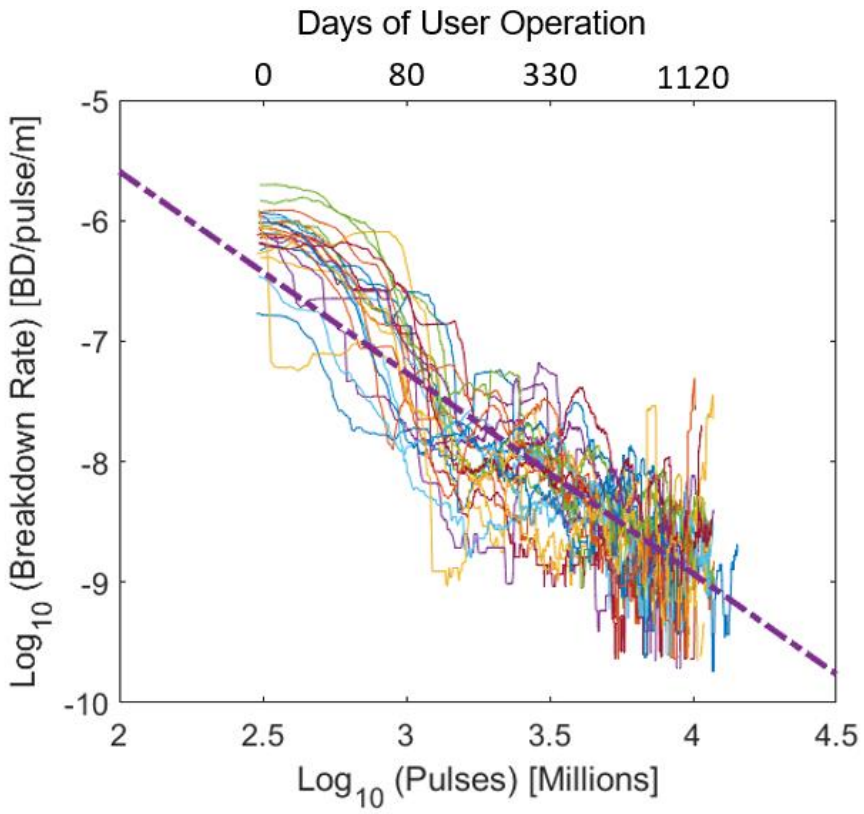
Linac	Rep. rate [Hz]	Nb. struct. per mod.	Nb. modules	Acc. gradients [MV/m]	Linac lengths [m]	Power consumptions [MW]
e-linac	200	2 / 4	18+1 / 13+1	28.1 / 20.5 <a/λ>=0.15	140 / 200	5 / 4
p-linac	200	2 / 4	26 / 19	20 / 14	247 / 353	10 / 7
HE-linac	200	2 / 4	92 / 67	32.2 / 22.5 <a/λ>=0.12	690 / 1005	26 / 19
Total						**41 / 30**

4 bunches, 100 Hz: factor 2 in power consumtion and also an important impact on the costs

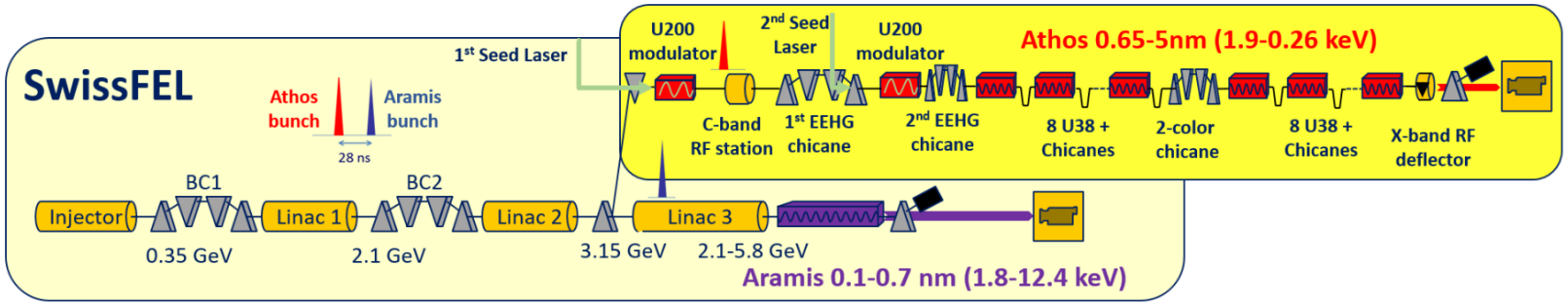
Linac	Nb. struct. per mod.	Hardware costs	10-year operating costs	Building lengths [m]	Building costs	Total costs
e-linac	2 / 4	38 / 37	17 / 14	407 / 573	49 / 69	
p-linac	2 / 4	56 / 54	34 / 25			
HE-linac	2 / 4	182 / 178	91 / 66	343 / 492	27 / 39	
Total		**276 / 269**	**142 / 105**	**750 / 1065**	**76 / 108**	**494 / 482**

Courtesy of Jean-Yves Raguin

Availability and breakdown rate (SwissFEL 6 GeV linac)

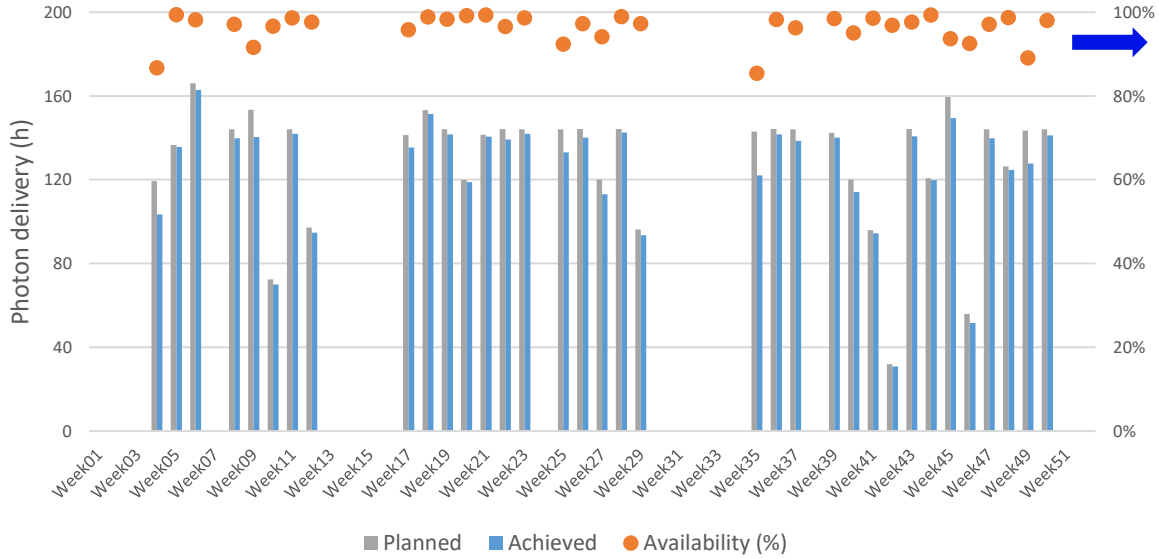


SwissFEL C-band linacs: RF breakdown rate change against the cumulative number of pulses at the nominal operational gradient (30 MV/m)
T. Lucas et al., to be submitted.



Linac 1, 2 and 3: C-band, 100 Hz, 26 rf module, 104 rf structures

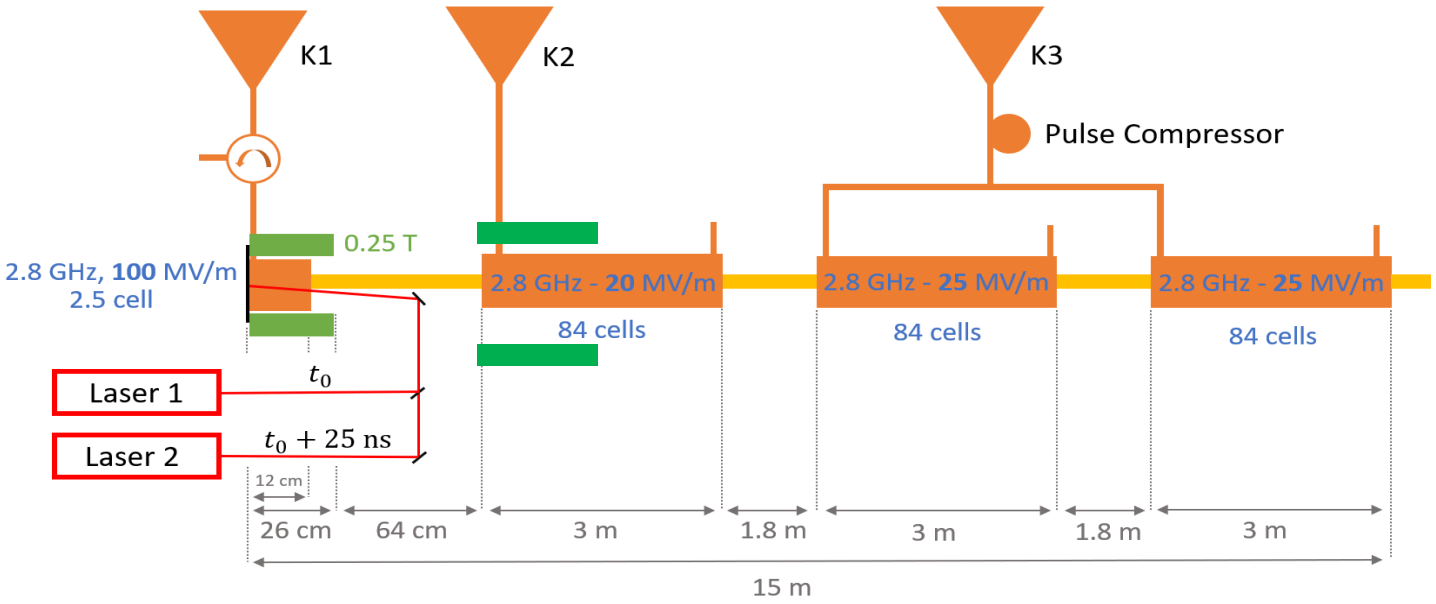
Beam availability in photon-delivery weeks (2023)



Courtesy of D. Voulot

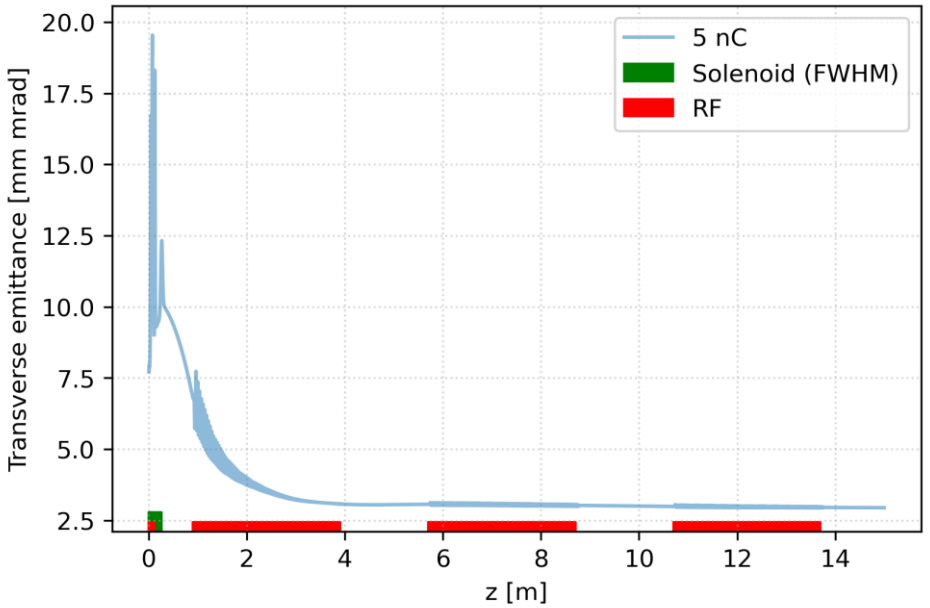
For example: 4 years operation to reduce the the BDR from ~850 per day to 8.5 per day considering 1 km linac and 100 Hz.

Electron source



- Detailed baseline design studied with errors.
- Top-up mode studied: Robust solution to preserve the shot-by-shot emittance for different bunch charges (Digital Micromirror Device).
- Design documented and published in https://doi.org/10.1016/j.nima.2024.169261
- Next steps: Prototyping of hardware and testing of top up mode charge variation

Bunch parameter	Simulation	Target
Transverse emittance	3.14 mm mrad (rms)	< 4 mm mrad
Bunch length	0.96 mm (rms)	~ 1 mm
Energy	~ 190 MeV	~ 200 MeV
Energy spread	390 keV (0.2 %)	< 0.5 %
Bunch charge	5 nC	5 nC

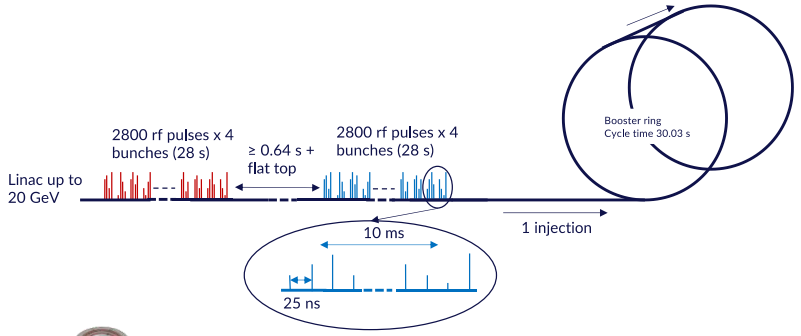


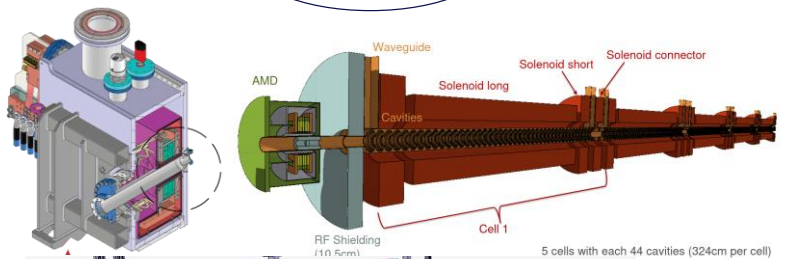
Courtesy of S. Doebert and Z. Vostřel

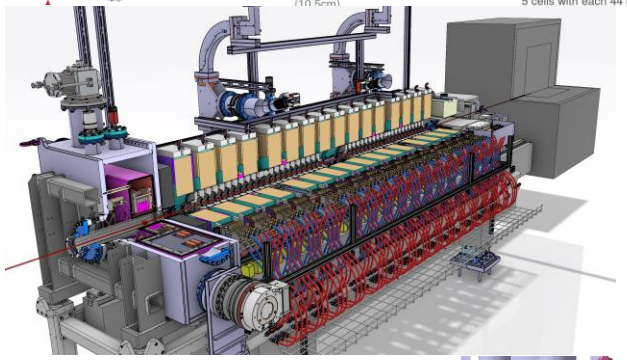
Further detailed studies for the Injector

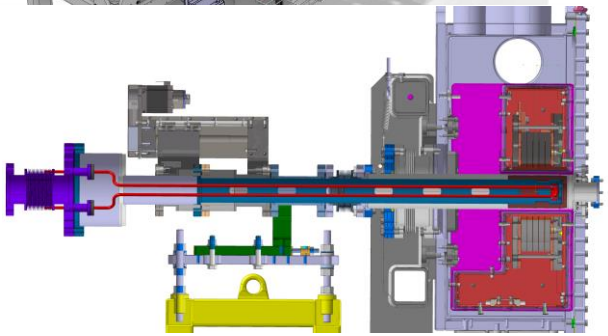
(presented at FCC week 2024)

- Booster and collider filling time, H. Bartosik
- Static and dynamic beam dynamic effects in the electron, common and HE-linac, S. Bettoni, i.e., emittance growth up and trajectory jitter amplification
- RF design studies of accelerating structures for the injector, A. Kurtulus, i.e. new rf structures, beam-loading and energy variation reduction, thermal and mechanical robustness
- Positron source and capture system (HTS-solenoid vs FC options), I. Chaikovska
- Damping ring: status and outlook (including DR at higher energy), A. De Santis
- Positron bunch and energy compressor (to/from DR), S. Spampinati
- PSI Positron Production (P-cubed) project, N. Vallis
- Development of p-cubed and FCCee positron source targets at CERN, R. Mena Andrade









Summary and open questions

- A new baseline for the injector layout has been proposed that can address most of the MTR recommendations
  - including cost estimates for the hardware, technical infrastructures (TI) and civil engineering (CE), based on some assumptions on the TI and CE.
  - new DR at 2.86 GeV: new design and an updated cost estimated are needed by 2024!

Open questions

- Working RF frequency: presently we assume a multiple frequency of the main rings. Some iterations are need to define the S-band working frequency for the injector linac.
- RF frequency for the positron linac is 2 GHz due to the AS aperture of 60 mm, can the aperture be reduced?
- Placement of the injector on the CERN site – working in progress.
- Are the transmission efficiency (80%) and max charge from the injector (5 nC) reasonable? What is the max charge we can assume from the injector considering lower transmission efficiency?
- What is the effect of short interruptions due to BDs in linacs on injection from scratch and for top-up?

Title correction:
~~(Unlimited)~~ Injector complex: status and outlook

That's all, thank you!!