FCC: Overview and Study Status

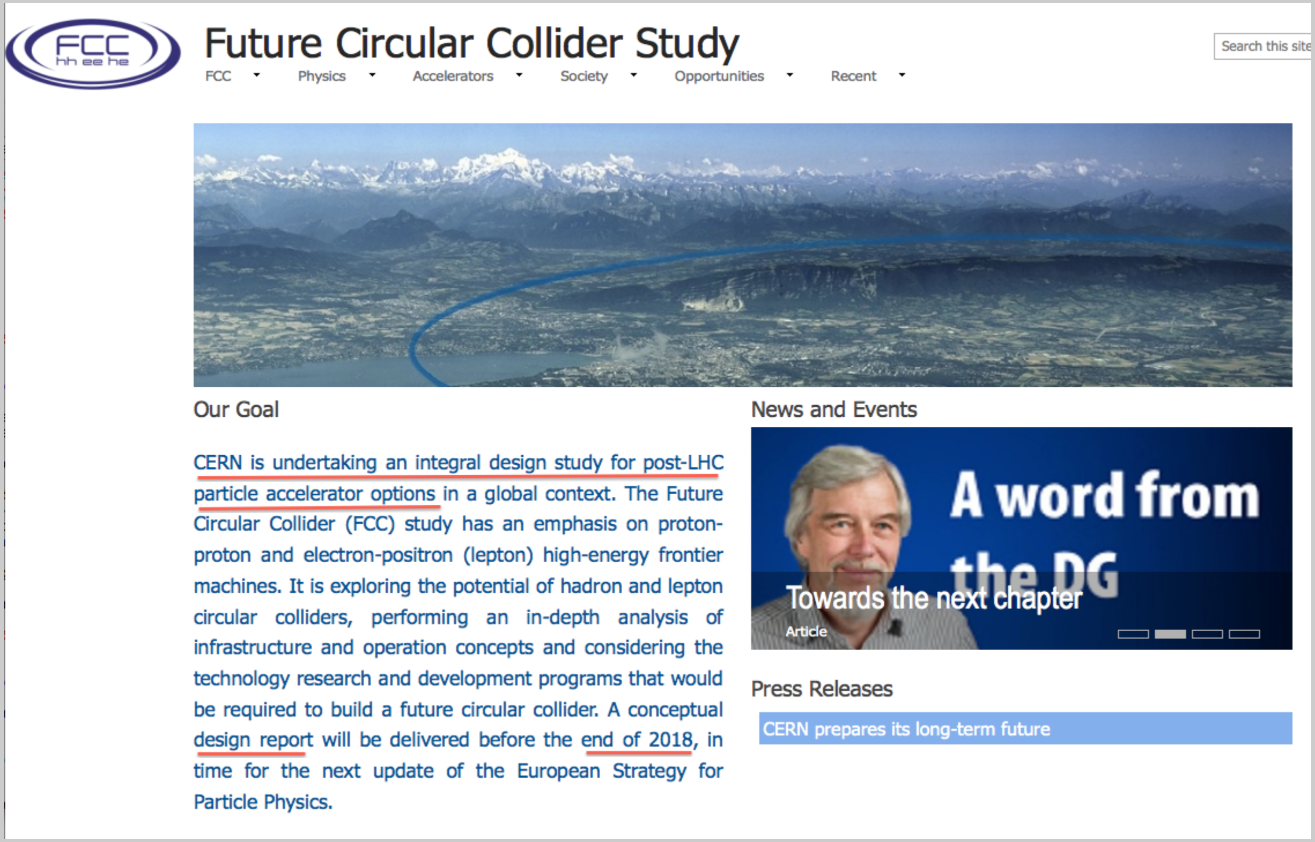
Eliana Gianfelice

Fermilab, June 23, 2015

Preamble

CERN is planning its future at the energy frontier after the completion of the LHC program.

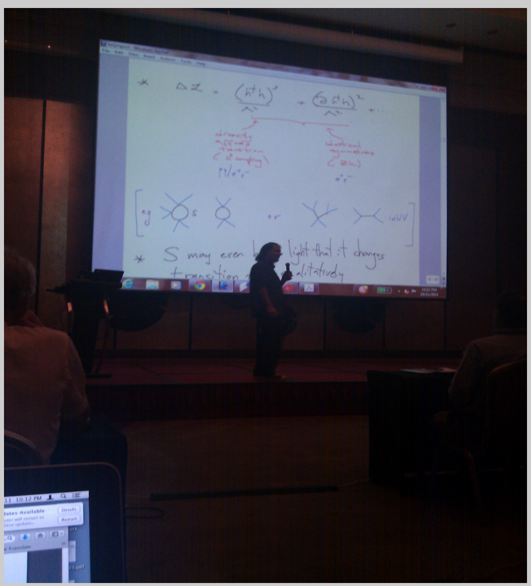
Following 2013 recommendations of the Council on European Strategy for Particle Physics, CERN has launched a 5 years *international* design study for a Future Circular Collider (FCC).

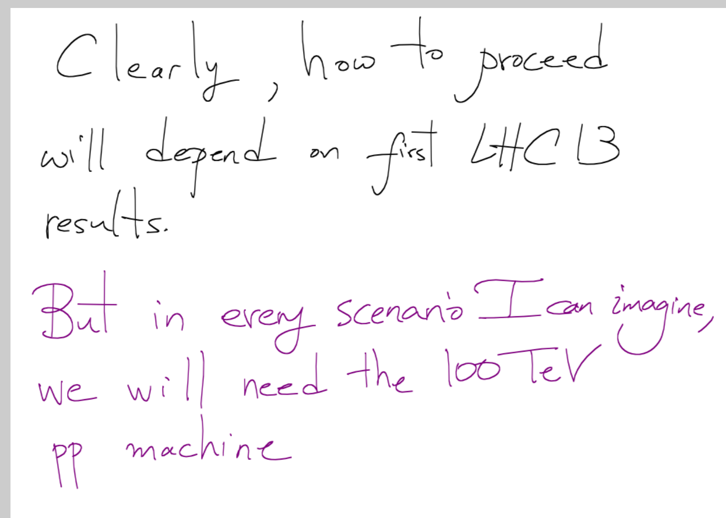


Past FCC events:

- FCC study kick-off meeting in Geneva (February 2014)
- HF2014 (ICFA Workshop on High Luminosity Circular e+e- Colliders Higgs Factory) in Beijing (October 2014)
- FCC Week in Washington (March 2015)

A pp circular collider with a center of mass energy of about 100 TeV is believed to have the necessary discovery potential





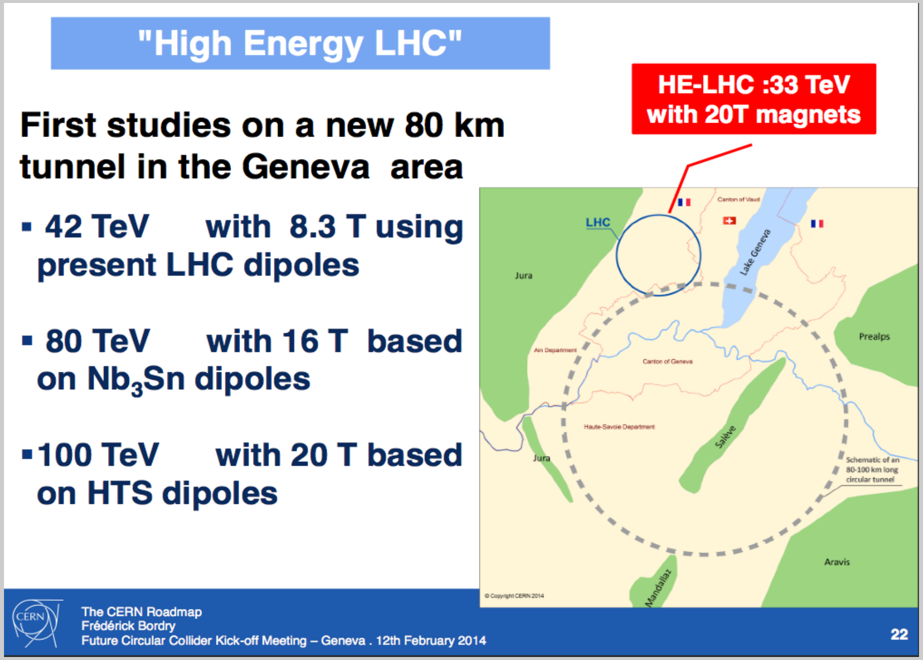
(N. Arkani-Hamed, Kick-off meeting)

The c.m. energy reachable by re-placing LHC dipoles with 20 T dipoles is 33 TeV.

For 100 TeV a *new* tunnel is needed.

It could first host a e^+e^- collider.

Further options: ions, ep collider.



(F. Bordry, Kick-off meeting)

Goal of the study:

- examining feasibility and costs, including physics and detectors
- push R&D programs (high field dipoles, SRF, machine protection...)
- prepare a conceptual design report by the end of 2018 when results from LHC should show the best path to follow.

The study is a complement to the linear collider studies.

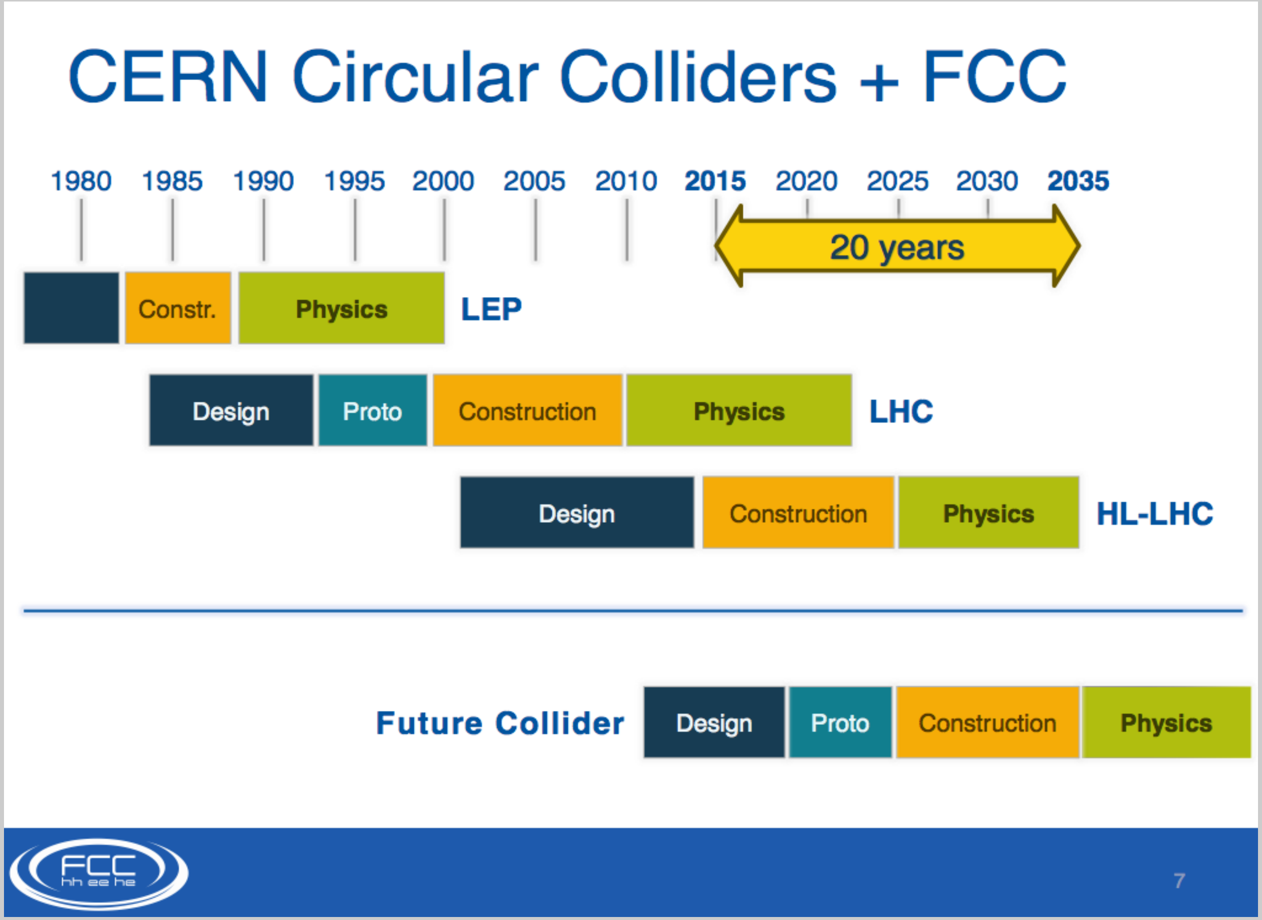
A quite challenging project!

The FCC week included a supportive opening address by congressman G. W. Foster

> *"..never be shy in standing up for the unique nature of your field and never be afraid of big numbers."*

(from CERN Courier, May 2015)

Time scale:



(M. Benedikt, FCC week)

FCC collaboration members working on the basis of a Memorandum Of Understanding

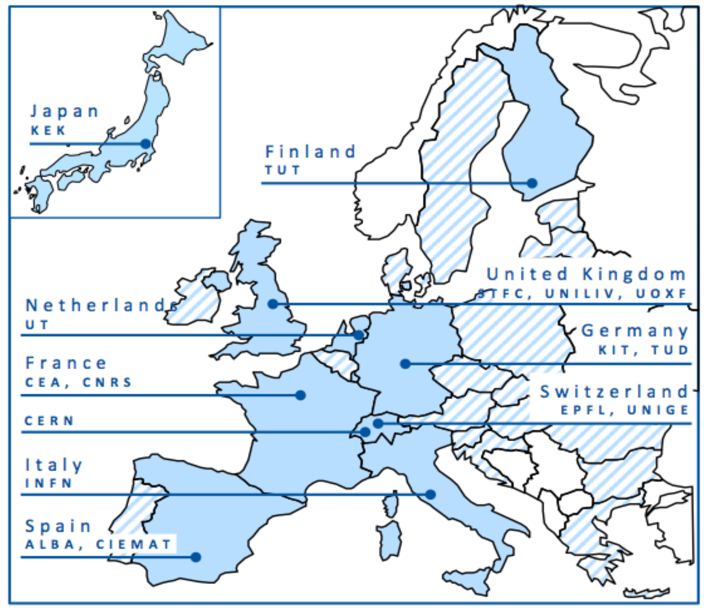
51 FCC collaboration members & CERN as host institute, 22 March 2015

ALBA/CELLS, Spain
Ankara U., Turkey
U Bern, Switzerland
BINP, Russia
CASE (SUNY/BNL), USA
CBPF, Brazil
CEA Grenoble, France
CEA Saclay, France
CIEMAT, Spain
CNRS, France
Cockcroft Institute, UK
U Colima, Mexico
CSIC/IFIC, Spain
TU Darmstadt, Germany
DESY, Germany
TU Dresden, Germany
Duke U, USA
EPFL, Switzerland
GWNU, Korea
U Geneva, Switzerland
Goethe U Frankfurt, Germany
GSI, Germany
Hellenic Open U, Greece
HEPHY, Austria
IFJ PAN Krakow, Poland
INFN, Italy
INP Minsk, Belarus
U Iowa, USA
IPM, Iran
UC Irvine, USA
Istanbul Aydin U., Turkey
JAI/Oxford, UK
JINR Dubna, Russia
FZ Jülich, Germany
KAIST, Korea
KEK, Japan
KIAS, Korea
King's College London, UK
KIT Karlsruhe, Germany
Korea U Sejong, Korea
MEPhI, Russia
MIT, USA
NBI, Denmark
Northern Illinois U., USA
NC PHEP Minsk, Belarus
U. Liverpool, UK
PSI, Switzerland
Sapienza/Roma, Italy
UC Santa Barbara, USA
U Silesia, Poland
TU Tampere, Finland

The FCC study is supported by the newly created EuroCirCol consortium

EuroCirCol Consortium + Associates

CERN	IEIO
TUT	Finland
CEA	France
CNRS	France
KIT	Germany
TUD	Germany
INFN	Italy
UT	Netherlands
ALBA	Spain
CIEMAT	Spain
STFC	United Kingdom
UNILIV	United Kingdom
UOXF	United Kingdom
KEK	Japan
EPFL	Switzerland
UNIGE	Switzerland
NHFML-FSU	USA
BNL	USA
FNAL	USA
LBNL	USA



Consortium Beneficiaries, signing the Grant Agreement

Associated Partners contributions:

Associated Partners

Short Name	Country	Contribution
NHFML /FSU	USA	Explore potential to double Jc of superconducting Nb_3Sn at 16 T. Propose improvements in strand architecture and reaction optimization. Material research in BSCCO-2212 as alternative to A15 and high field magnet technology using HTS materials.
BNL	USA	Participate in the study of magnet coil design concepts (common coils, racetrack) and in the engineering for a US-based 16 T model. Develop YBCO HTS technology for high field inserts for 20 T option or for use in high heat load/radiation cases.
FNAL	USA	Participate in the study of magnet coil design concepts (cos-theta, collars) and in the engineering for a US-based 16 T model. Prepare tooling for model construction. Develop BSCCO-2212 HTS magnet technology for high field inserts for 20 T option.
LBNL	USA	Participate in the study of magnet coil design concepts (blocks, canted-cosinus-theta) and in the engineering for a US-based 16 T model. Develop BSCCO-2212 HTS magnet technology for high field inserts.

(D. Schulte, EuroCirCol Preparatory Coll. Board Meet., September 2014)

FCC-hh parameters

Parameters and Luminosity Target

Two main experiments
Baseline also two other experiments

Baseline
- Promise
- Goal 250fb^{-1} per year
  - 2fb^{-1} per day
- focus on 25ns spacing

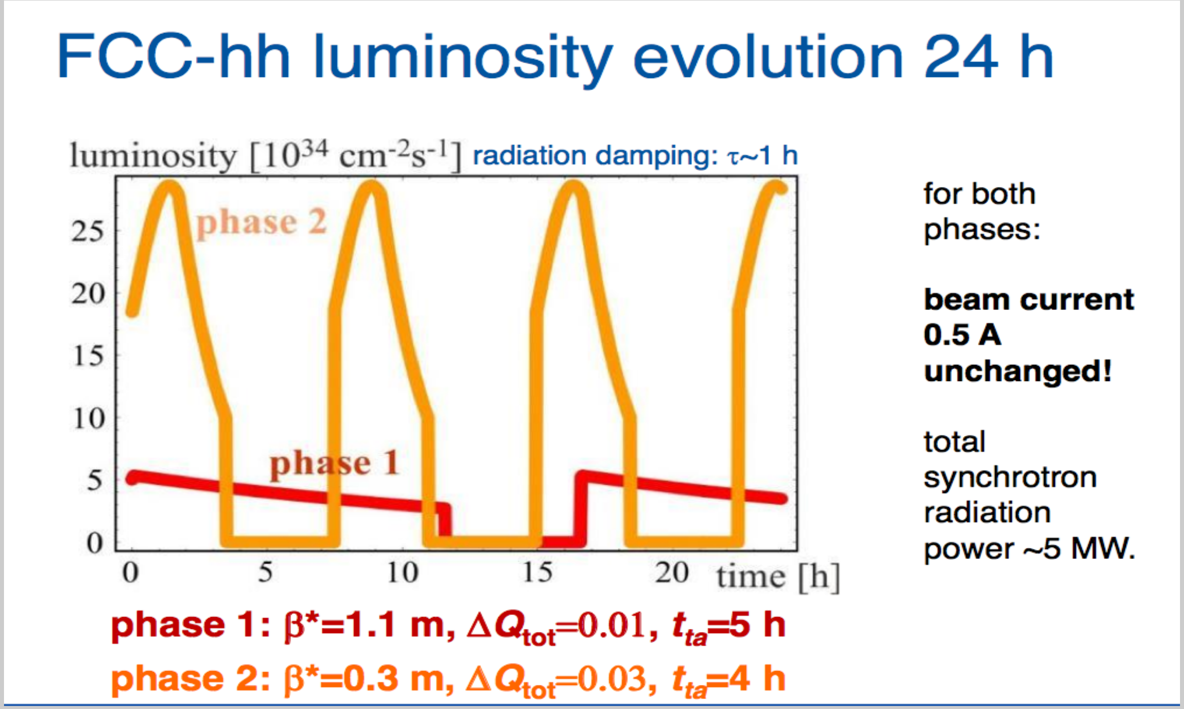
Ultimate
- reasonable hope
- goal 1000fb^{-1} per year
- more emphasis on 5ns

Assume 5 year operation cycles
- 3.5 year run
- 0.75-1.0 year for stops, MDs etc.
- 70% efficiency
- 625-700 effective days per year

	Baseline	**Ultimate**
Luminosity [$10^{34}cm^{-2}s^{-1}$]	5	20
Bunch distance [ns]	25 (5)	
Background events/bx	170 (34)	680 (136)
Bunch charge [10^{11}]	1 (0.2)	
Norm. emitt. [μm]	2.2(0.44)	
RMS bunch length [cm]	8	
IP beta-function [m]	1.1	0.3
IP beam size [μm]	6.8 (3)	3.5 (1.6)
Max ξ for 2 IPs	0.01 (0.02)	0.03
Crossing angle [σ']	12	Crab. Cav.
Turn-around time [h]	5	4

(D. Schulte, FCC Week)

Luminosity performance (baseline & ultimate)



Phase 2: the emittance is allowed to shrinks under SR damping until the limit $\Delta Q_{inch.}$=0.03 is reached.

Goal (Phase 1+2): luminosity integrated over 25 years [a] $\sim$ 20000 fb^{-1}.

[a] 140 effective days/year

FCC-hh challenges

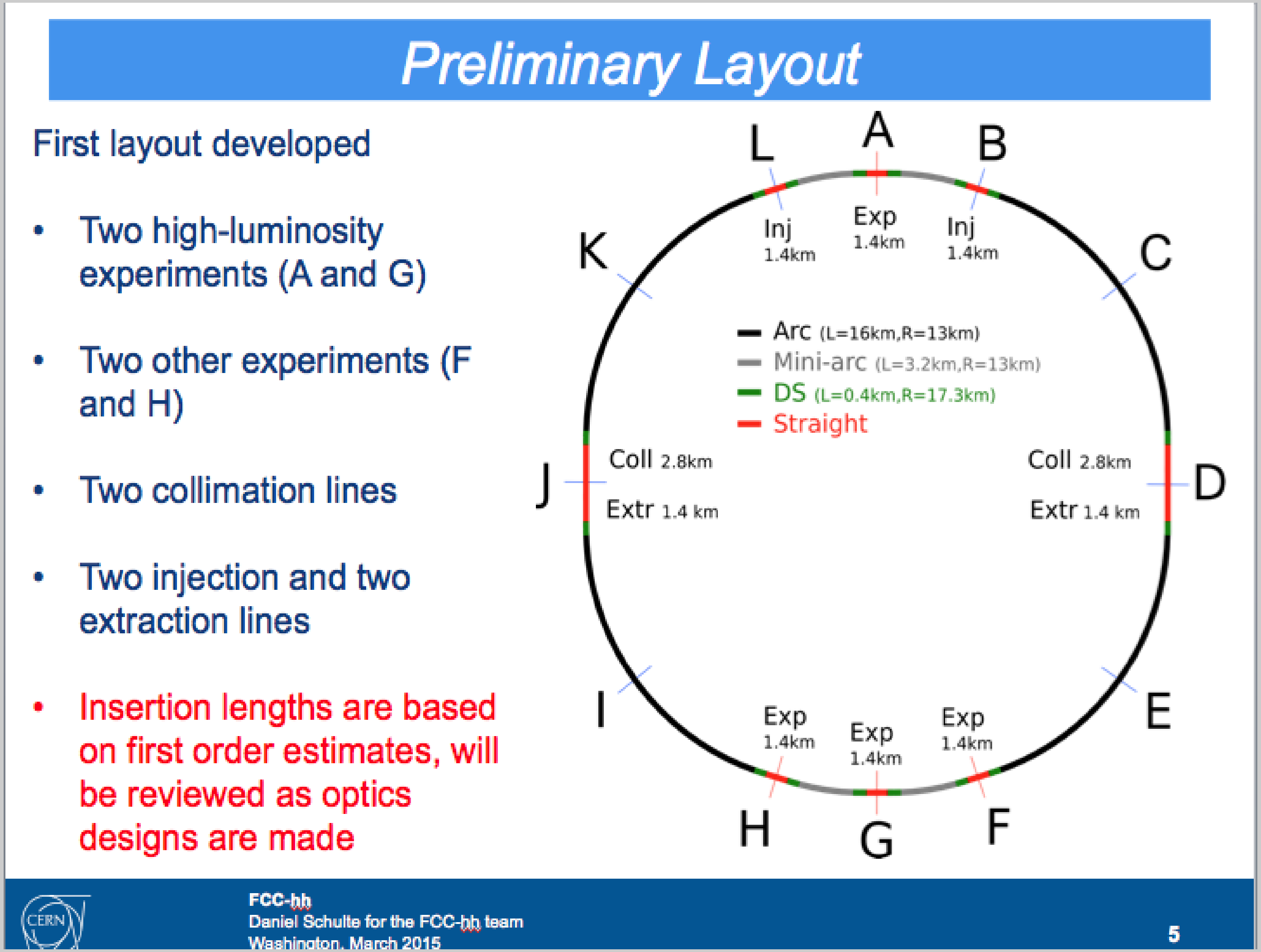
FCC-hh beam and technology related FCC-hh challenges:

- Beam Optics: IR design, Dynamic Aperture, field quality...
- Beam stability: beam-beam, e-clouds, instabilities, feedbacks...
- Synchrotron radiation:
  - heat load from SR in cold environment: 30 W/m/beam in the arcs
  - 1 h damping time: leveling, controlled blow-up...
- Stored energy in beams and magnets:
  - collimation, quench protection, shielding, dump...

$\rightarrow$ Synergies with intensity frontier facilities and light sources.

- High field dipoles
  - R&D targets
    - Nb_3Sn based 16 T (100 km ring) dipoles with 40 mm aperture
    - HTS development targeting 20 T field
- Civil engineering, infrastructures
- Operational challenges related to the large scale of the facility.

FCC-hh schematic layout



(D. Schulte, FCC Week)

Work lead by Saclay CEA laboratory.

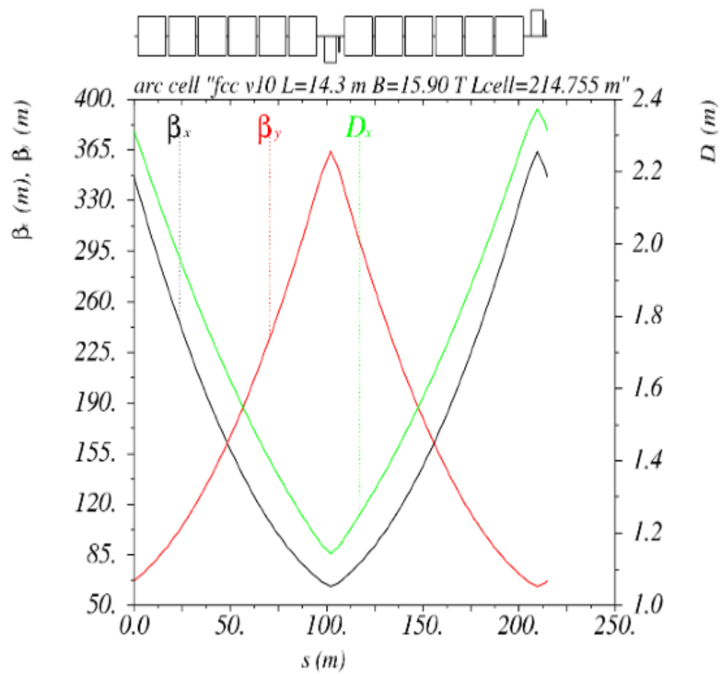
90^o FODO cells, LHC-scaled.

ARC CELL

# dipoles	B max [T]	Length [m]
4368	15.90	14.3

# quadrupoles	G max/min [T/m]	Length [m]
812*	356/-356.26	6.29

# sextupoles	G max/min [T/m²]	Length [m]
700	-7144.37/ 3551.32	0.5 (fixed)



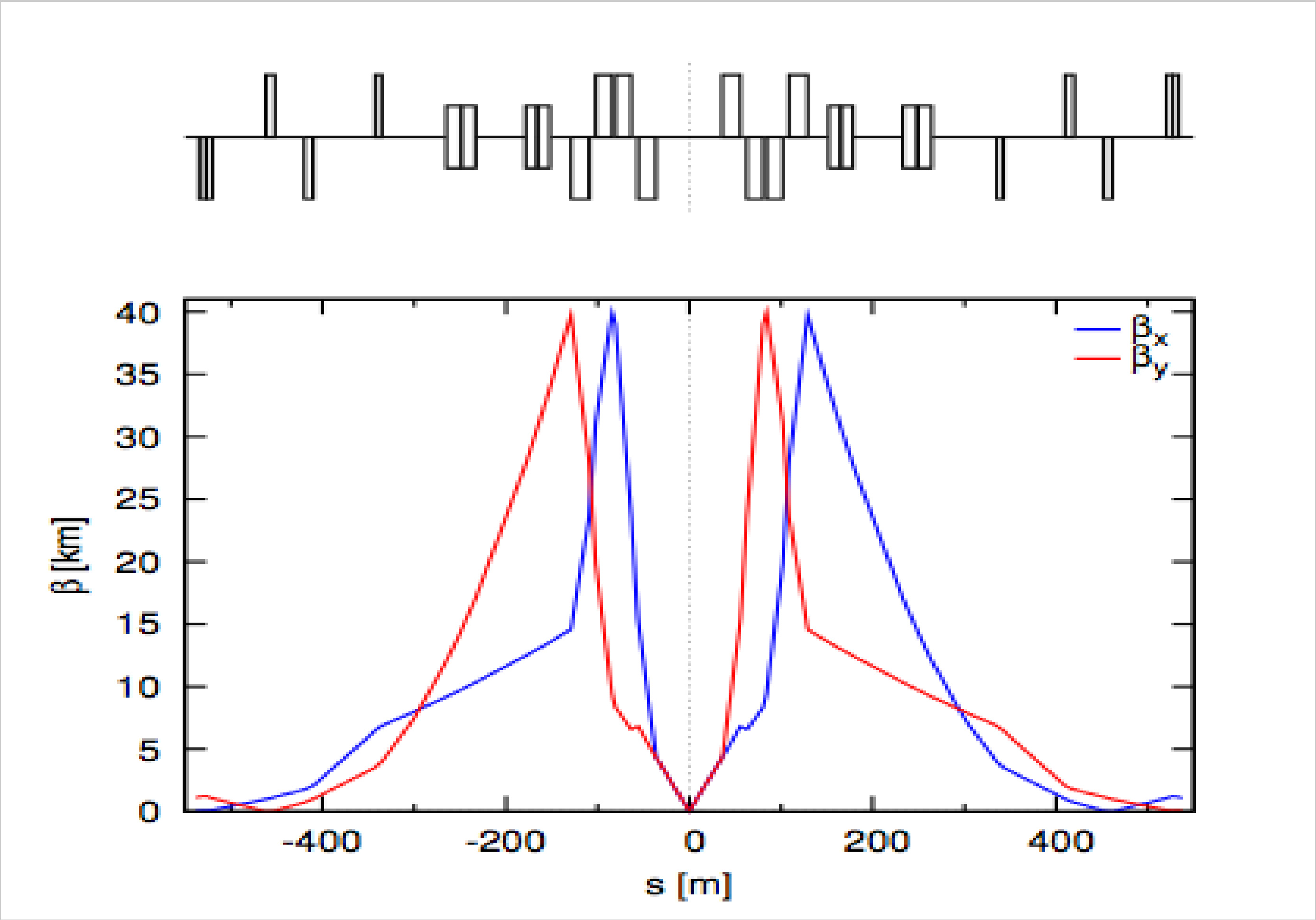
Interaction Region

The IR design study is a joint effort from JAI, CI, INFN, EPFL, CERN.

Interconnected tasks:

- Develop the IR collision optics
- Integrate Detector components
- Maximize luminosity while ensuring the design is consistent with detector performance
- Estimate radiation and background in the IR
- Provide input on IR magnet design
- Study beam-beam effects, round vs. flat beam options, compensation schemes (wire, electron lenses, crab cavities....)
- Provide input on beam current

A design proposal for β^*=0.3 m (ultimate) and L^*=±36 m: LHC IR scaling + optimizations for mitigating the radiation dose on the triplet



(R. Martin et al., IPAC2015)

Efforts conducted by CERN team.

Purpose:

- Halo removal for reducing doses on equipment and background in the experiments
- First line defense in case of failure

	LHC (Design)	HL-LHC	FCC-hh (Baseline)
Beam energy	7 TeV	7 TeV	50 TeV
Beam intensity	3×10^{14}	6×10^{14}	10×10^{14}
Stored energy	360 MJ	690 MJ	8500 MJ
Power load (τ=0.2h)	~500 kW	~960 kW	~11800 kW
Energy density	~1 GJ/mm²	~1.5 GJ/mm²	~200 GJ/mm²

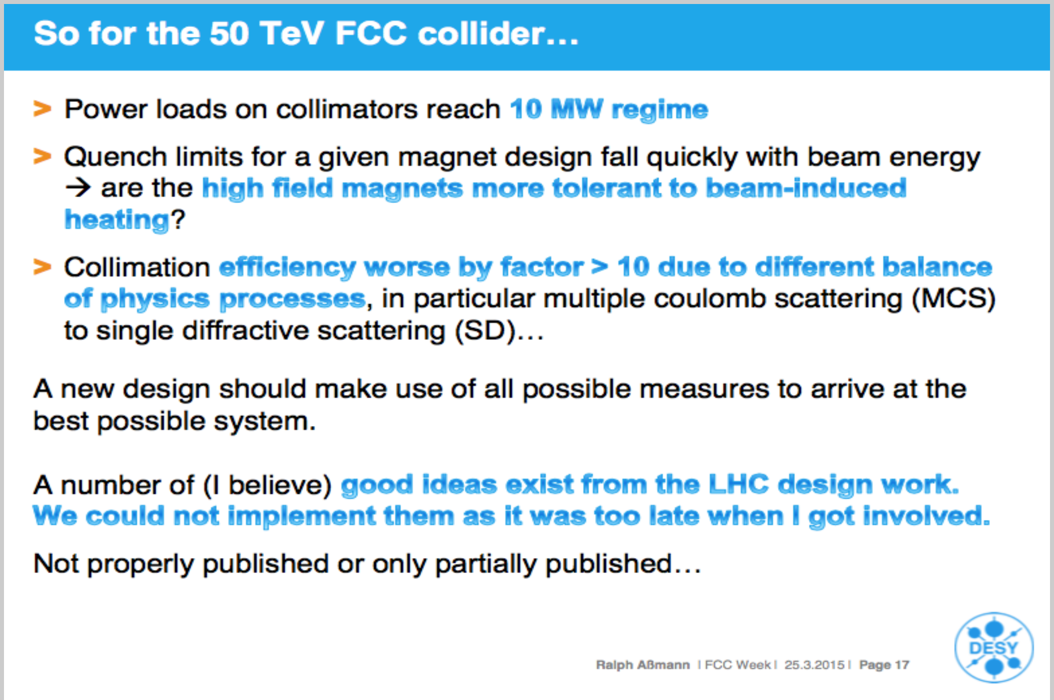
$\sim 20 \times$ LHC

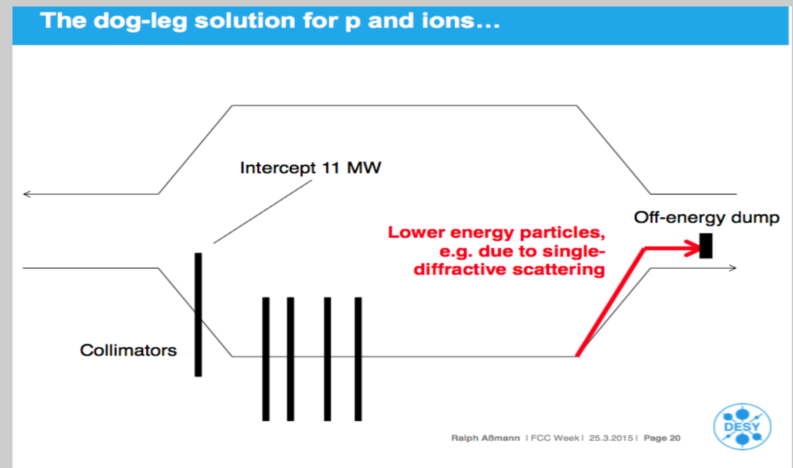
(M. Fiascaris, FCC Week)

LHC scheme scaled up as starting point: longer cleaning sections with larger β.

Hollow e-beam and crystal collimation under consideration.

R. Aßmann warned about just scaling the LHC scheme: increased collimation inefficiency at 50 TeV!





(R. Aßmann, FCC Week)

2) Combined Betatron and Momentum Cleaning

- One of the **strongest sources of off-momentum halo are the betatron collimators**.
- Systems can easily be combined, saving overall length, costs and improving performance.
- The **momentum collimation must, of course, be downstream of the betatron collimation system**.
- This **solves ion leakage problem**.
- Clever **combination with strong dog-leg magnets** reduces needs on number of collimators.
- We had a solution for LHC ready worked out…

Notes on Combined Betatron/Momentum Collimation

- The LHC momentum collimation was designed as a fully horizontal system.
- By placing 6 additional collimators at existing (non-optimized) locations, excellent performance was shown in simulations with such a combined system.
- Would have reduced the total number of LHC collimators by 28. **Therefore also reduced impedance**.
- Not done, because the LHC phase 1 collimation at 4 TeV good enough, so improvements not needed.
- Based on this, I believe that **an optimal FCC solution can be worked out with important gains and improvements.**

(R. Aßmann, FCC Week)

Energy deposition in collimators

Currently used in LHC: Graphite and CfC

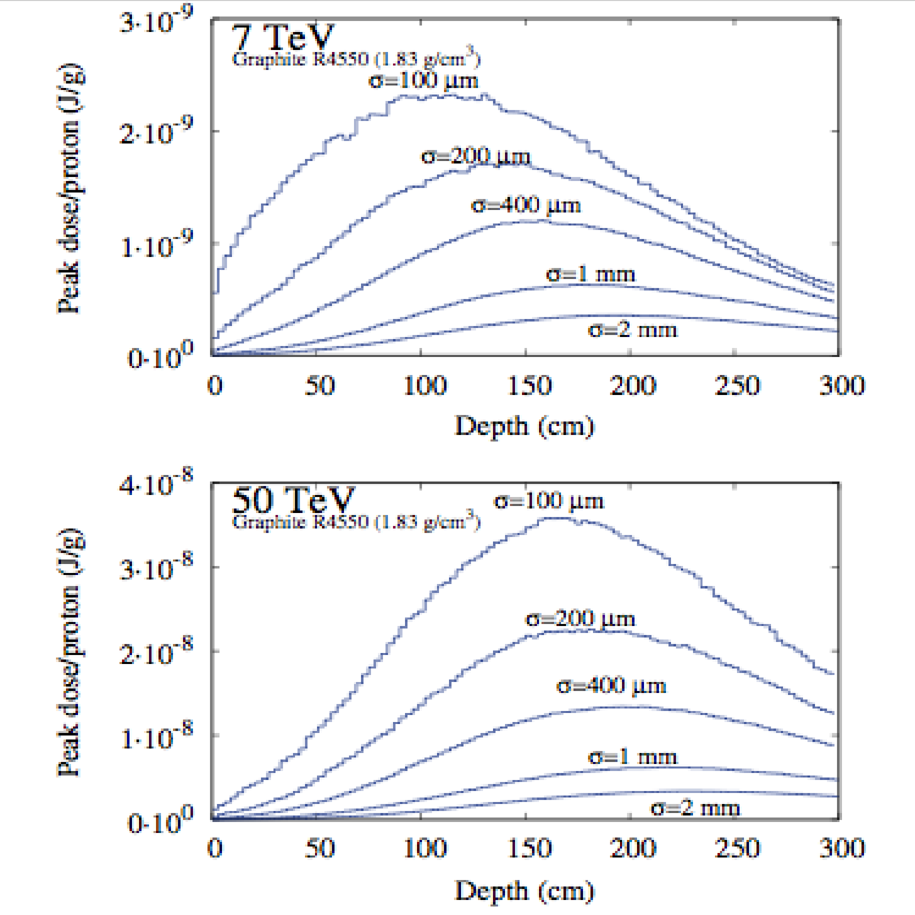
Scenarios for energy deposition

- finite beam lifetime
- beam loss

Energy deposition on primary collimators with τ=0.2 h

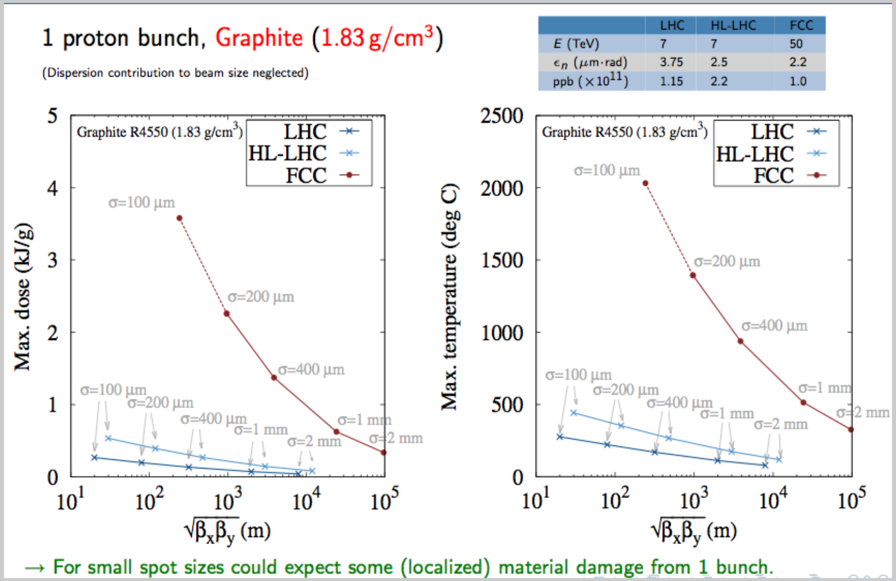
	LHC	HL-LHC	FCC-hh
Energy	7 TeV	7 TeV	50 TeV
Bunch intensity	1.15×10^{11}	2.2×10^{11}	1.0×10^{11}
Bunches	2808	2748	10600
Proton loss rate (τ=0.2 h)	4.5×10^{11} sec^{-1}	8.4×10^{11} sec^{-1}	1.5×10^{12} sec^{-1}
Power loss (τ=0.2 h)	503 kW	941 kW	11786 kW
Distance betw. TCPs	2 m	2 m	10 m
Power deposition in horizontal TCP (most impacted jaw)			
Entire jaw	1.6 kW	3.0 kW	13 kW
CfC block (AC150)	0.6 kW	1.2 kW	5.2 kW
Power deposition in skew TCP (most impacted jaw)			
Entire jaw	7.7 kW	15 kW	121 kW
CfC block (AC150)	3.2 kW	6.0 kW	45 kW

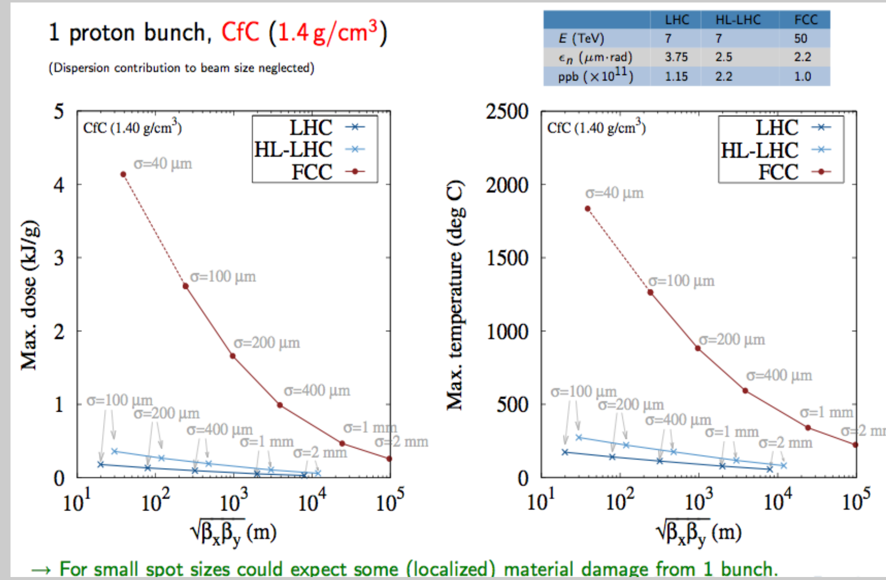
(A. Lechner, FCC Week)



Longitudinal peak dose scales with a factor larger then the energy ratio.

(A. Lechner, FCC Week)





(A. Lechner, FCC Week)

- halo cleaning: ok
- accidental losses of more then few bunches *are* an issue

The wish list

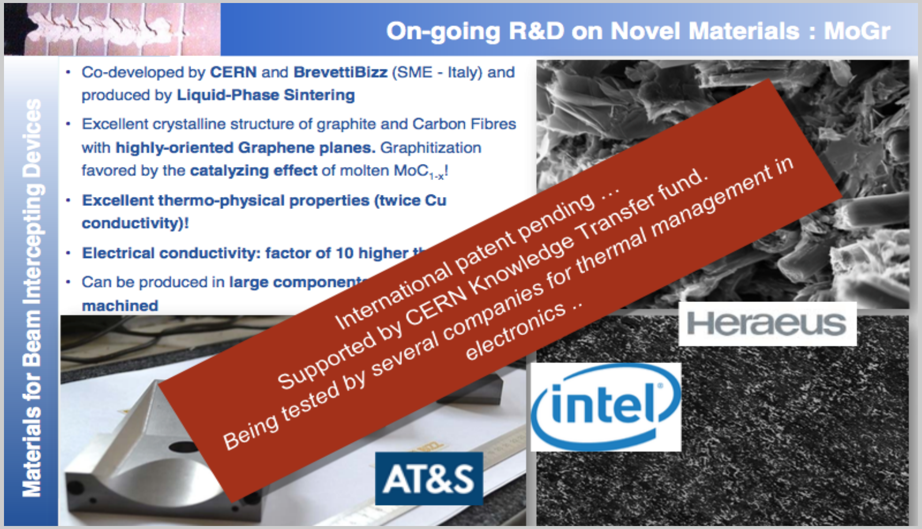
- **Thermal Conductivity.** Maximize to maintain geometrical stability under steady-state losses
- **Coefficient of Thermal Expansion.** Minimize to increase resistance to thermal shock induced by accidental beam impact
- **Melting/Degradation Temperature.** Maximize to withstand high temperatures reached in case of accidents
- **Specific Heat.** Maximize to improve thermal shock resistance (lowers temperature increase)
- **Ultimate Strength.** Maximize to improve thermal shock resistance
- **Density.** Balance to limit peak energy deposition while maintaining adequate cleaning efficiency
- **Electrical Conductivity.** Maximize to limit Resistive-wall Impedance
- **Radiation-induced Damage.** Minimize to improve component lifetime under long term particle irradiation
- **Outgassing Rate**. Minimize to ensure compatibility with UHV environment.

(A. Bertarelli, FCC Week)

Rich R&D program for the search of new materials involving laboratories and industries

- Simulations:
  - Energy deposition maps (by FLUKA, MARS, Geant)
  - Target response by "Hydrocodes" (wave-propagation codes)
- Material irradiation tests: HiRadMat (CERN, SPS beam), M-Branch (GSI, intense ions), BNL etc.

Molybdenum Carbide-Graphite: the most promising (robustness/low impedance)



(A. Bertarelli, FCC Week)

Beam-beam effects

FCC beam-beam compared to other pp Colliders

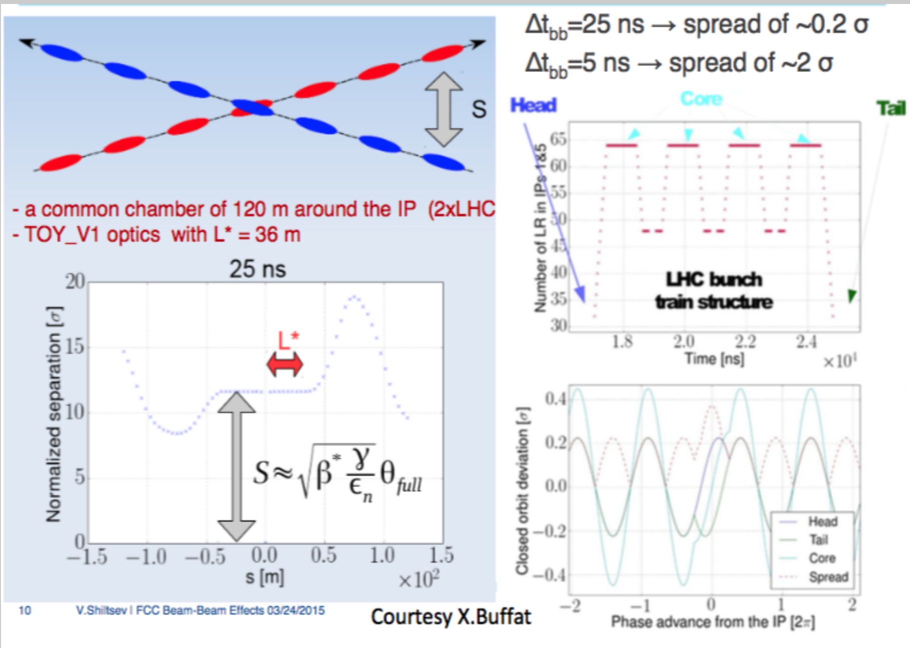
	E_{cm} TeV	Peak L, 10^{34} cm^{-2}s^{-1}	$N_{p(a)}$ 10^{11}	N_B	$\varepsilon_{p(a)}$ μm	β^* cm	ξ	W MJ
Tevatron	1.96	0.043	2.9/0.8	36	3/1.5	28	0.025	1.7
SSC	40	0.1	0.075	17,240	1	50	0.004	418
UNK	6	0.1	3	348	7.5	150	0.005	50
RHIC	0.5	0.025	1.9	111	3.1	65	0.018	0.8
LHC	14	1.0	1.15	2,808	3.7	55	0.01	360
FCC	100	5.0	1	10,600	2.2	110	0.01	8400

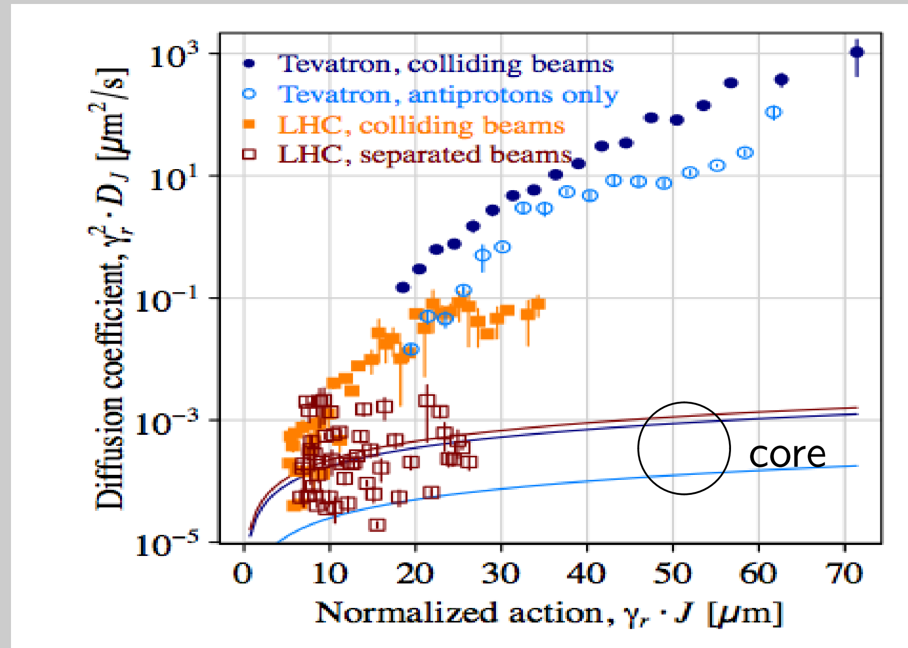
NB: FCC the 1st one hh collider to be dominated by SR damping

(V. Shiltsev, FCC Week)

V. Shiltsev warned about

- enhanced long range beam-beam effects
- experimental background due to the beam-beam halo enhancement





Measurements by G. Stancari et al.

Countermeasures

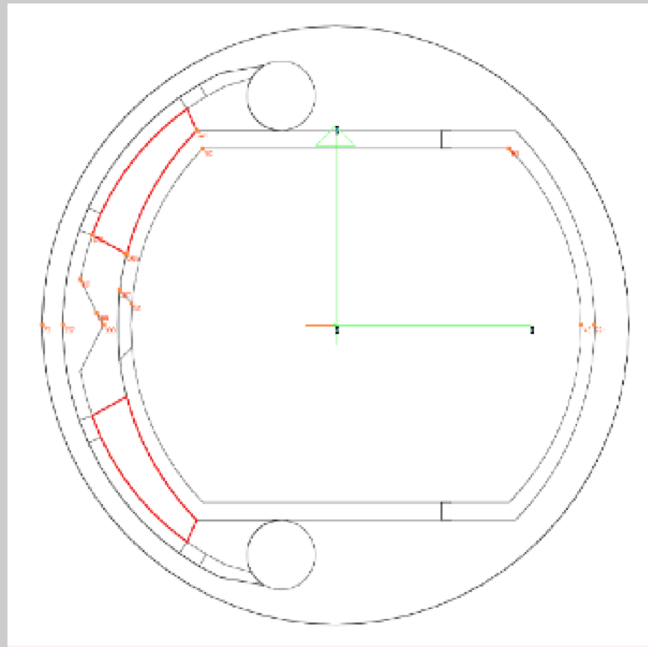
- Keep the beam-beam interaction parameters small, e.g. ξ_{BB} <0.02, $\Delta X_{separation}$ >10σ, etc
- Choice of the WP, reduce Q' and Q", minimize other nonlinearities
- (More) effective beam collimation system
- Active beam-beam compensation:
  - Compensation of tuneshifts (linear, eg bunch-by-bunch)
  - Compensation of tunes spread and NL-driving terms (head-on)
  - Compensation of all effects at once when possible ("wire compensation of LR effects")
  - Electron Lenses and Compensating Wires

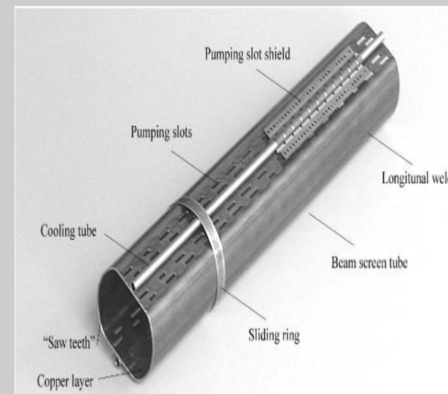
(V. Shiltsev, FCC Week)

Studies by CERN, TU Darmstadt, EPFL.

Vacuum chamber impedance:

- Stainless steel pipe
- Titanium screen with copper coating
- Carbon collimators, closed at 50 TeV

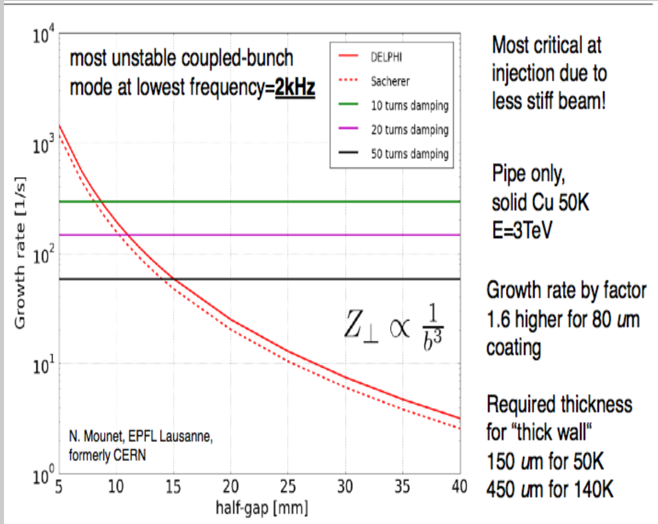




Beam parameters (baseline)

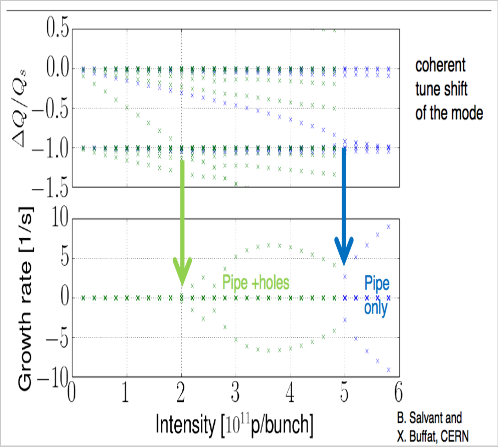
- 13344 bunches (25 ns spacing)
- 1×10^{11} p/bunch
- Q_x=120.31, Q_y=120.32, $\xi_x=\xi_y$=0, Q_s=0.0028 (3 TeV), 0.0078 (50 TeV)

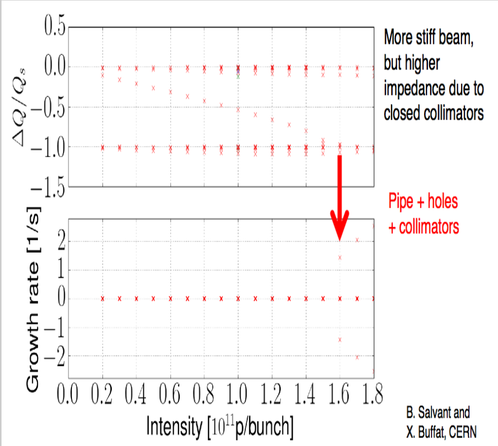
Coupled Bunch Mode Instabilities (3 TeV)



- Growth rate increases by a factor 1.6 for a 80 μm copper coating
  - thickness must be increased to $\sim$300 μm
- MB instability rise time is about 25 turns for a 13 mm radius $\Rightarrow$ Feed-back?

Transverse Mode Coupling Instability (or "fast head-tail", single bunch)





- Pumping holes reduce thresholds
- At 50 TeV with closed collimators the threshold is $\sim 1.6 \times 10^{11}$ p/bunch

(U. Niedermayer, FCC Week)

U. Niedermayer conclusions at FCC Week:

Conclusion

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- FCC-hh already on the edge of stability only with resistive pipe

- 50 turns feedback possible but maybe insufficient
- 10 turns feedback possible?

- Kickers not yet considered
- Landau damping and Octupoles not yet considered

- Impedance should play an important role in collimator design

From W. Höle talk at FCC Week:

- For transverse CBMI a FB with up to 100 MHz bandwidth is required
- TMCI GHz FB development can profit from the US LARP supported studies for the SPS

Electron clouds

Studies by KEK and CERN.

Electron cloud build-up mechanism

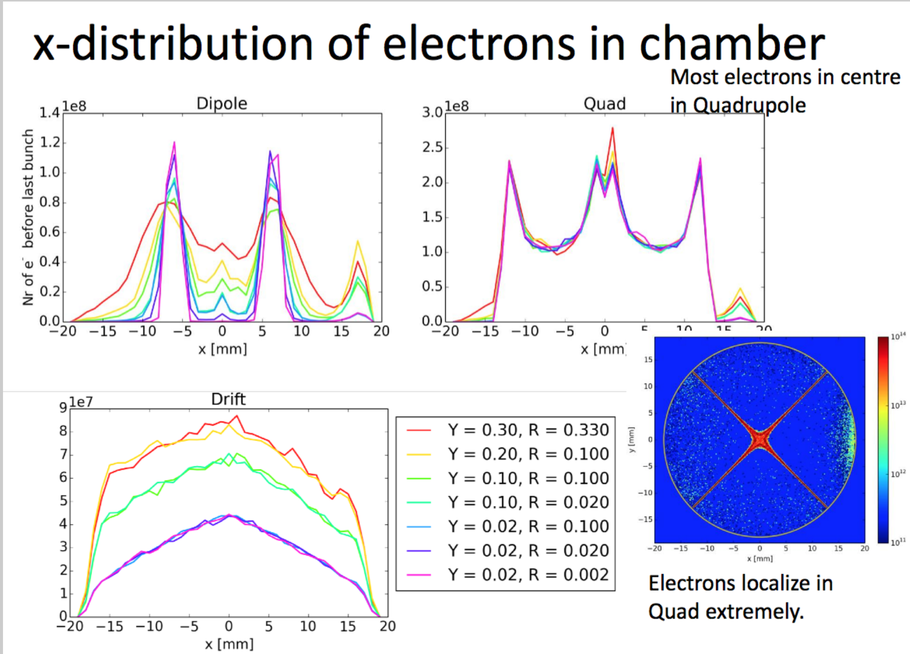
- Photoelectrons
  - Photons (emitted by the beam) ($\boldsymbol{Y}$)
  - Reflected photons ($\boldsymbol{R}$)
- Secondary electrons, produced by the shaken electrons ($\boldsymbol{SEY}$)

Ingredients for computation

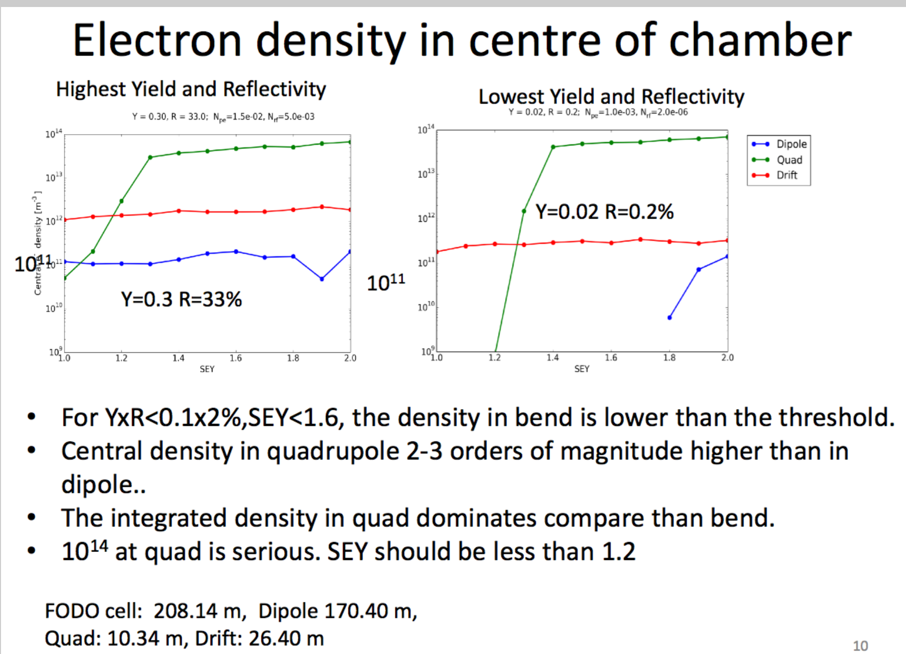
- Synchrotron radiation characteristics
- Vacuum chamber material and geometry
- Magnetic fields
- Beam parameters

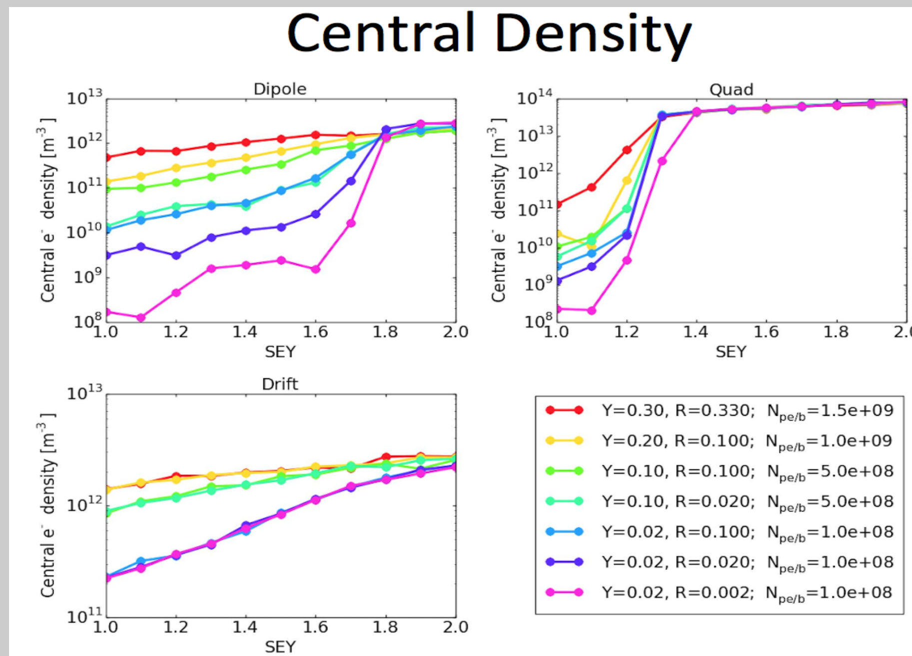
Effects on beam

- Single and Multi bunch instabilities
- Tune spread, resonances, emittance growth



(K. Ohmi, FCC Week)





Beam parameter and electron cloud instability (3.3TeV-50TeV)

		25 ns inj	25ns top	5ns inj	5ns top
beam energy	E (TeV)	3.3	50	3.3	50
bunch population	N_p (10^{10})	10	10	2	2
emittance	ε_{xy}(nm)	0.625	0.0413	0.125	0.00826
typical beta	β_{xy}(m)	200	200	200	200
bunch length	σ_z(cm)	8	8	8	8
synchrotron tune	ν_s	0.002	0.002	0.002	0.002
electron freq.	$\omega_e/2\pi$(GHz)	3.56	13.9	3.58	13.9
electron osc.	$\omega_e\sigma_z/c$	5.97	23.3	6.00	23.3
threshold density	$\rho_{e,th}$(m^{-3})	4.4×10^{10}	5.72×10^{11}	4.4×10^{10}	5.73×10^{11}
tune shift at thres.	$\Delta\nu(\rho_{e,th})$	0.00039	0.00033	0.00039	0.00033

Electron frequency in a bunch $\omega_e = \sqrt{\frac{\lambda_p r_e c^2}{\sigma_y(\sigma_x+\sigma_y)}}$
The electron density is averaged over ring

TMCI threshold density:

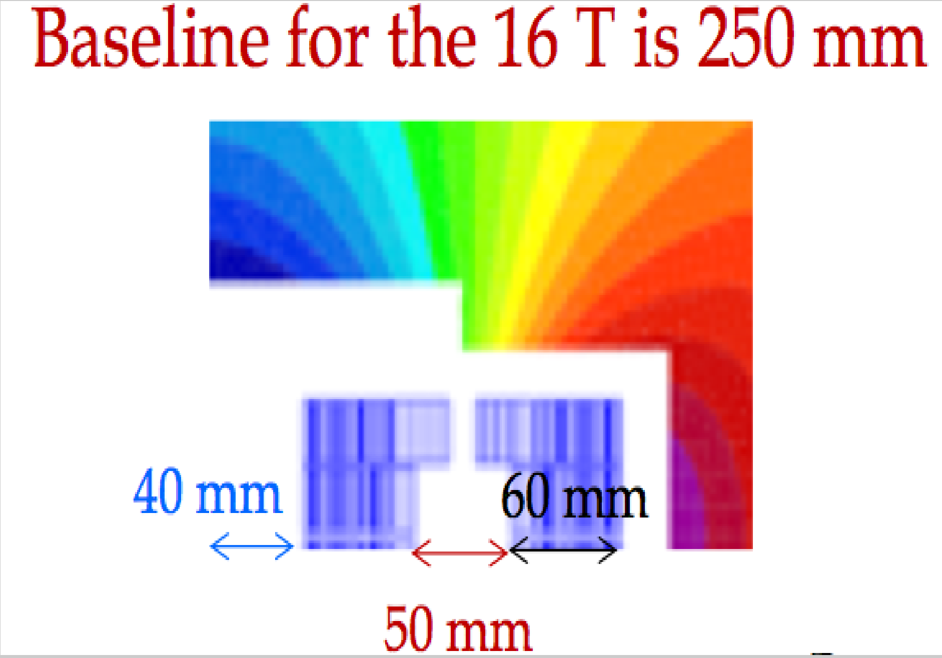
$$\rho_e \propto \gamma\omega_e\sigma_\ell$$

Preliminary conclusions from K. Ohmi (FCC Week)

- ρ_e smaller than TMCI threshold for $Y \times R \lesssim 0.1\times2\%$
  - SEY <1.6 in bends
  - SEY <1.2 required in quads
- Tune spread small

Multi-bunch instabilities evaluation + feed-back requirements yet to come.

Magnets



Arc dipoles. Wrt LHC

- aperture decreased from 56 to 50 mm (beam size ↓ + shielding ↑)
- coil width increased from 30 to 60 mm
- distance between beams: 250 mm

Arc quadrupoles

- LHC: g=220 T/m with ℓ_q= 3.15
- scaling with cell length (2.15 times longer for FCC): g= 340 T/m
- aim: 420 T/m and ℓ_q=5.4 m

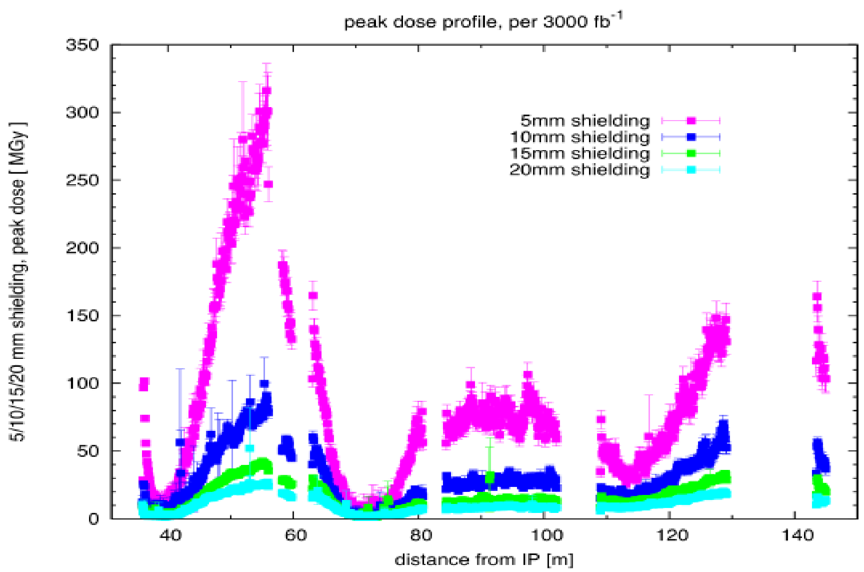
(E. Todesco, FCC Week)

Triplet quadrupoles:

Scaling with HL-LHC would require $7 \times 30 \sim 200$ m long triplets...

- $\boldsymbol{L^*}$ increases from 23 to 36 m
- $\boldsymbol{K\ell_q} \sim 1/\boldsymbol{L^*}$: integrated strength reduced by 1.5
- 75 m long triplet
- increase gradient by a factor 1.5 (140 T/m $\rightarrow$ 215 T/m)

It seems feasible with 100 mm aperture magnets, but *problematic doses*:



Dose in the triplet after 3000 fb-1 [M. I. BesanaF. Cerutti]

HL-LHC level with 20 mm shielding: further R&D needed!

How do we get to 16 T dipoles?

- Two days of presentations on High Field SC Magnets at the FCC Week
- Contributions from US, Europe and Asia labs
- Large presence of industry

The only practical successor of Nb-Ti seems to be Nb_3Sn .

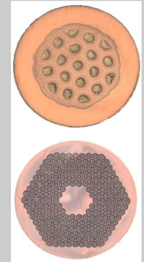
The wish list for suitable sc wires

Property	Units	Values
Strand diameter	(mm)	0.5 mm to 1.0 mm
J_c(4.2 K, 16 T)	(A/mm^2)	≥ 1500
μ_oM(1 T, 4.2 K)	(mT)	≤ 150
$\sigma(\mu_o M)$(1 T, 4.2 K)	(%)	≤ 4.5
D_{eff}	(μm)	≤ 20
RRR		≥ 150
Unit Length	(km)	≥ 5 km

"Targets for R&D on Nb_3Sn conductor for High Energy Physics", Ballarino and Bottura

State of art: FNAL/CERN build model for the HL-LHC 11 T dipoles (collimation upgrade) .

Property	Units	Values	RRP®	Single bar.
Strand diameter	(mm)	0.5 mm to 1.0 mm	✓	✓
J_c(4.2 K, 16 T)	(A/mm^2)	≥ 1500	close	X
$\mu_o M$(1 T, 4.2 K)	(mT)	≤ 150	X	close?
$\sigma(\mu_o M)$(1 T, 4.2 K)	(%)	≤ 4.5	X	X
D_{eff}	(μm)	≤ 20	X	✓
RRR		≥ 150	?	✓
Unit Length	(km)	≥ 5 km	?	?

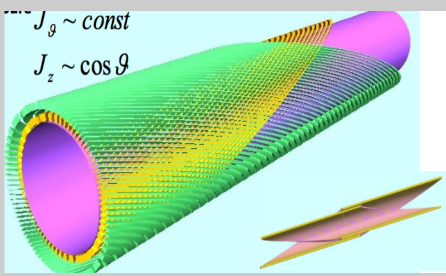


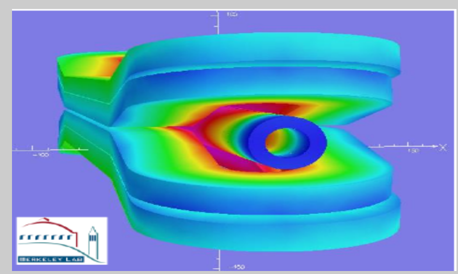
(M. B. Field, Oxford SC Technology)

From A. Ballarino conclusions:

- R&D program on Nb_3Sn conductor is needed for meeting FCC performance targets.
- The required quantity of Nb_3Sn is well <u>above</u> present production capability!
- Present <u>cost</u> of Nb_3Sn is a showstopper to the project.

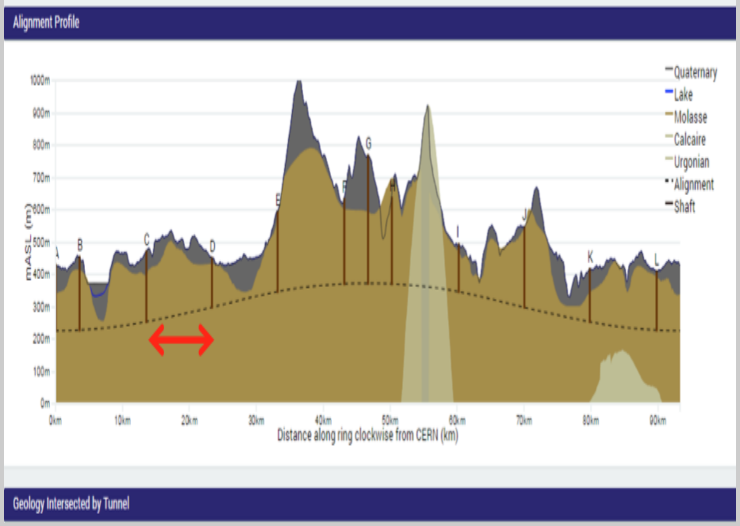
Alternative designs presented by S. Caspi, R. Gupta, G. L. Sabbi.





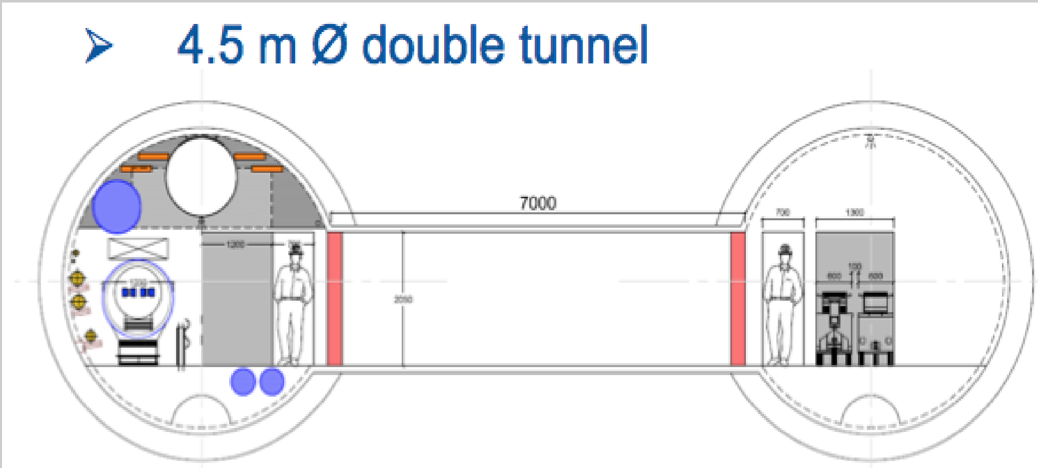
Civil engineering

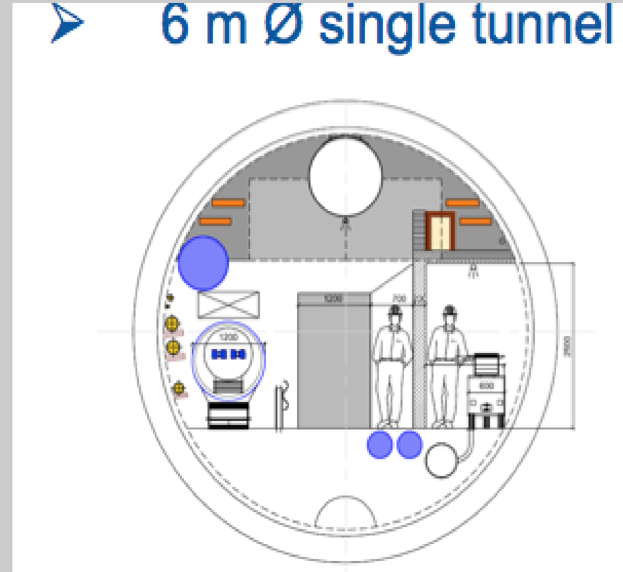
- BIM: Tunnel Optimisation Tool, now to be used for accelerator tunnel design
  - First spin-off: ILC tunnel optimisation in Japan



- Removal of 10 000 000 m^3 of spoil...
- Lifts and cranes for up to 400 m deep shaft feasible
  - Plenty of technical challenges but no show stoppers so far!
- Use of RAMS (Reliability, Availability and Maintainability Studies) in design and operation stage?
- First thoughts on cryogenics and large capacity Helium refrigeration systems
- First thoughts on Controls Systems

- Safety: 2 vs. 1





  – double tunnel preferred for safety and accessibility

My conclusions

- Substantial progress has been achieved in FCC Infrastructure & Operation studies since the First FCC Week in February 2014, **concurrently with developments in accelerator design and technology**
- Several **collaborations with external partners** have been set up and are now operational
- In the second year of study, we need to **home in onto reference design of machines** (with possible variants) enabling to refine configuration and sizing of infrastructure systems
- We welcome **further development** of external collaborations on both site-specific and site-independent topics

(Ph. Lebrun)

How are we concerned?

US involvement scope and limits outlined by DOE HEP office director J. Siegrist.

- **The future machines laid out by P5 reflect the community consensus at Snowmass:**
  - **Multi-MW proton beam to build out global neutrino program**
  - **Upgrade of ILC if it is built**
  - **Very high energy proton-proton (VHEPP) collider**
- **Snowmass did not develop a full community consensus on machine parameters for a future VHEPP machine beyond the HL-LHC**
  - **Snowmass considerations favored the ILC over a circular e^+e^- collider due to the technical readiness of the ILC**
- **In order for any of these future machines to become global options, they must be prioritized by the regions and their energy and luminosity parameters must be agreed to, and supported by, the community at large**

(J. Siegrist, FCC Week)

DOE Goals for FCC work

- Participation by U.S. scientists in FCC planning is aligned with P5 goals, but investments must match priority levels
  - HL-LHC remains the highest priority large offshore project in the near term and there are other more immediate priorities
  - The HEPAP Accelerator R&D Subpanel Report will provide guidance on the prioritization of R&D efforts towards future machines
- Participation will be needed by U.S. University and Laboratory experts to envision a coordinated plan for how to best prioritize and execute efforts needed to solve the technical issues that stand in the way of realizing any of these machines
- A critical first step is for active U.S. theorists to do their part to guide agreement in the U.S. (and global?) community on VHEPP energy and luminosity while fleshing out physics goals and driving discussion in the U.S.
  - The HEP community may want to establish a Snowmass-like process in this focused area to help engage the community in these studies
  - A limited, focused effort is required, since we must maintain balance with the current DOE program dedicated to implementing the exciting but challenging program that has been laid out for us by P5

(J. Siegrist, FCC Week)

DOE Goals for FCC Work: SC Magnets

- Though R&D must be driven by the community consensus on the energy and luminosity parameters needed for a VHEPP to meet its physics goals, superconducting magnets will be the key technology that defines the accelerator
- DOE looks forward to receiving a white paper from the U.S. high-field magnet community for coordinated U.S. participation in an international R&D activity on SC magnets for VHEPP colliders
  - Establishing a coordinated plan within the U.S. and with international partners is crucial for implementing a successful program
  - Builds on the successful collaboration on the LHC and HL-LHC magnets
  - Such a R&D effort would be aligned with the P5 recommendations
- Eventual technical involvement in other R&D subjects will be informed by the HEPAP Accelerator R&D Subpanel Report

(J. Siegrist, FCC Week)

High field magnet program in the US

"Primary goal, ... build the future-generation accelerators at dramatically lower cost. For, example, the primary enabling technology for pp colliders is high-field accelerator magnets, . . ." P5

US National High Field Magnet Program

DOE created an accelerator R&D Subpanel to align accelerator R&D with P5

Report will be presented at the April 6 HEPAP Meeting

US magnet programs (BNL, FNAL, LBNL, and NHMFL) submitted a joint "white paper" outlining a coordinated US magnet R&D program to

Goal 1: Develop accelerator magnets at the limit of Nb_3Sn capabilities. This is presently believed to be approximately 16 T.

Goal 2: Explore LTS accelerator magnets with HTS inserts for fields beyond the Nb_3Sn capabilities. The present target is 20 T or above.

Goal 3: Drive high-field conductor development, both Nb_3Sn and HTS materials, for accelerator magnets.

Goal 4: Address fundamental aspects of magnet design, technology and performance that could lead to substantial reduction of magnet cost.

(S. Gourlay, FCC Week)

FCC ee

The tunnel should host first a e^+e^- collider with energy/beam ranging between 45 and 175 GeV .

FCC-ee parameters – starting point

Design choice: max. synchrotron radiation power set to 50 MW/beam

- Defines the maximum beam current at each energy
- 4 physics operation points (energies) foreseen *Z, WW, H, ttbar*
- Optimization at each operation point, mainly via bunch number and arc cell length

Parameter	*Z*	*WW*	*H*	*ttbar*	*LEP2*
E/beam (GeV)	45	80	120	175	105
L (10^{34} cm^{-2}s^{-1})/IP	28.0	12.0	5.9	1.8	0.012
Bunches/beam	16700	4490	1330	98	4
I (mA)	1450	152	30	6.6	3
Bunch popul. [10^{11}]	1.8	0.7	0.47	1.40	4.2
Cell length [m]	300	100	50	50	79
Tune shift / IP	0.03	0.06	0.09	0.09	0.07

(M. Benedikt, Kick-off meeting)

- High precision beam energy measurement ($\ll$ 100 keV) is needed for Z pole physics at 90 GeV CM energy and W physics at 160 CM energy.
- Z pole physics would profit from longitudinal *beam polarization*.

Maximum radiation power/beam fixed at 50 MW. Tentative parameters for FCC-$e^{\pm}$

parameter	LEP2	FCC-ee				
		Z	Z (c.w.)	W	H	t
E_{beam} [GeV]	104	45	45	80	120	175
beam-beam par. ξ_y/IP	0.06	0.03	0.175	0.06	0.093	0.092
current [mA]	3.0	1450	1431	152	30	6.6
$P_{SR,tot}$ [MW]	22	100	100	100	100	100
no. bunches	4	16700	29791	4490	1360	98
N_b [10^{11}]	4.2	1.8	1.0	0.7	0.46	1.4
ε_x [nm]	22	29	0.14	3.3	0.94	2
ε_y [pm]	250	60	1	1	2	2
β^*_x [m]	1.2	0.5	0.5	0.5	0.5	1.0
β^*_y [mm]	50	1	1	1	1	1
σ^*_y [nm]	3500	250	32	84	44	45
$\sigma_{z,SR}$ [mm]	11.5	1.64	2.7	1.01	0.81	1.16
$\sigma_{z,tot}$ [mm] (w beamstr.)	11.5	2.56	5.9	1.49	1.17	1.49
hourglass factor F_{hg}	0.99	0.64	0.94	0.79	0.80	0.73
L/IP [10^{34} cm^{-2}s^{-1}]	0.01	28	212	12	6	1.7
τ_{beam} [min]	434	298	39	73	29	21

(F. Zimmermann)

Challenges:

- Small $\beta_y^* \rightarrow$ chromaticity and DA
- Beam-beam effects: large beamstrahlung at high energy calls for
  - ± 2 % lattice energy acceptance
  - *top up* injection
- Synchrotron Radiation: small heat load per meter, but large critical energy
- Synchrotron Radiation in the IR

Actually these are 4 machines!

$$U_{loss} = C_\gamma E^4/\rho \qquad (\Delta E/E)^2 = C_q \gamma^2 / J_\epsilon \rho$$

$$\mathcal{I}_2 \equiv \oint ds \frac{1}{\rho^2}$$

$$\mathcal{I}_4 \equiv 2 \oint ds \frac{D_x K}{\rho}$$

$$\mathcal{I}_5 \equiv \oint ds \frac{\beta_x D_x'^2 + 2\alpha_x D_x D_x' + \gamma_x D_x^2}{\rho^3}$$

$$\epsilon_x = C_q \gamma^2 \frac{\mathcal{I}_5}{J_x \mathcal{I}_2} \qquad \tau_x = \frac{2\pi R}{C_x E^3} \frac{1}{\mathcal{I}_2 - \mathcal{I}_4}$$

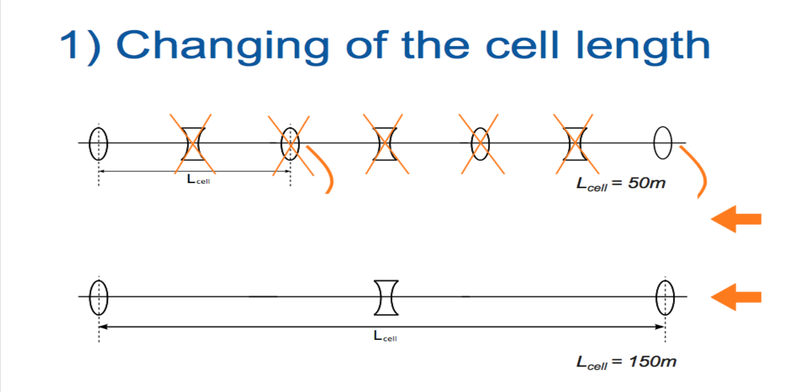
FCC $e^{\pm}$ Arc optics
(B. Harer, B. Holzer)

Isomagnetic guide:

$$\epsilon_x = \frac{C_q \gamma^2}{J_x} \theta_b^3 F \qquad F_{FODO} = \frac{1}{4 \sin \mu_x} \frac{5 + 3 \cos \mu_x}{1 - \cos \mu_x} \frac{L_{cell}}{\ell_b}$$

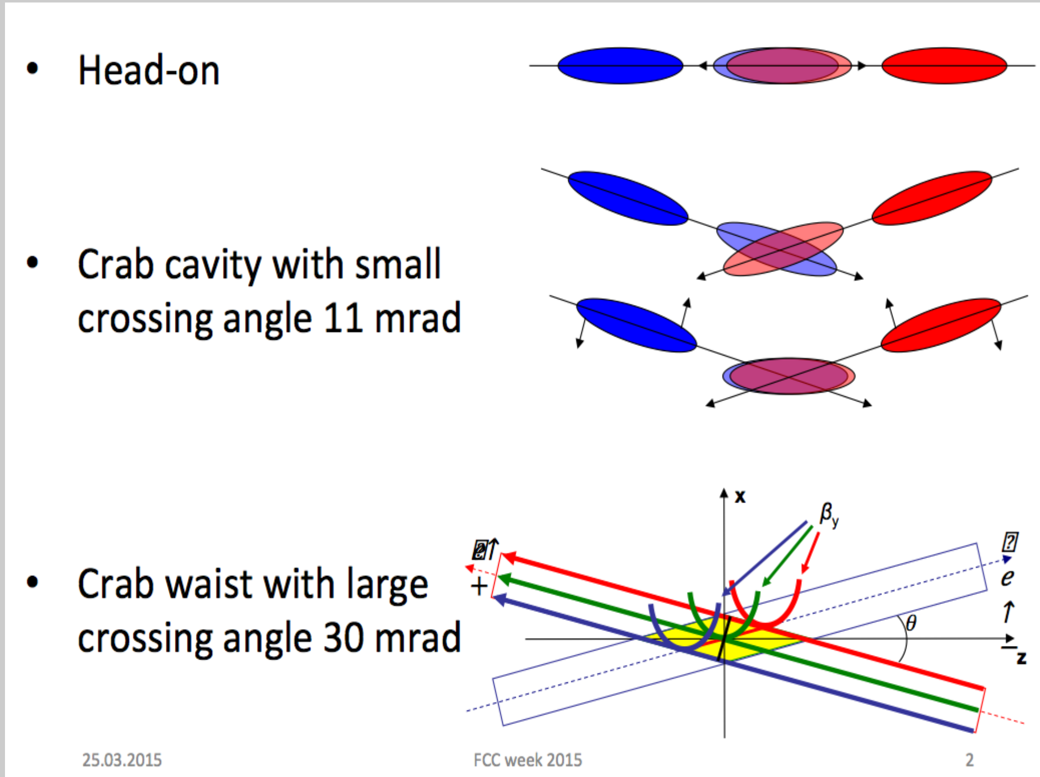
The emittance may be tuned by

- changing the bending angle θ_b
- and/or the phase advance μ_x



Same optics for 120 and 175 GeV operation; different options for other energies.

IR design: CERN & Budker Institute



Crab waist (P. Raimondi, 2006)

- Reduce hour-glass impact on luminosity $\longrightarrow$ small β_y possible
- Suppress beam-beam betatron coupling $\longrightarrow$ larger ξ_y possible

Luminosity lifetime

Beamstrahlung lifetime

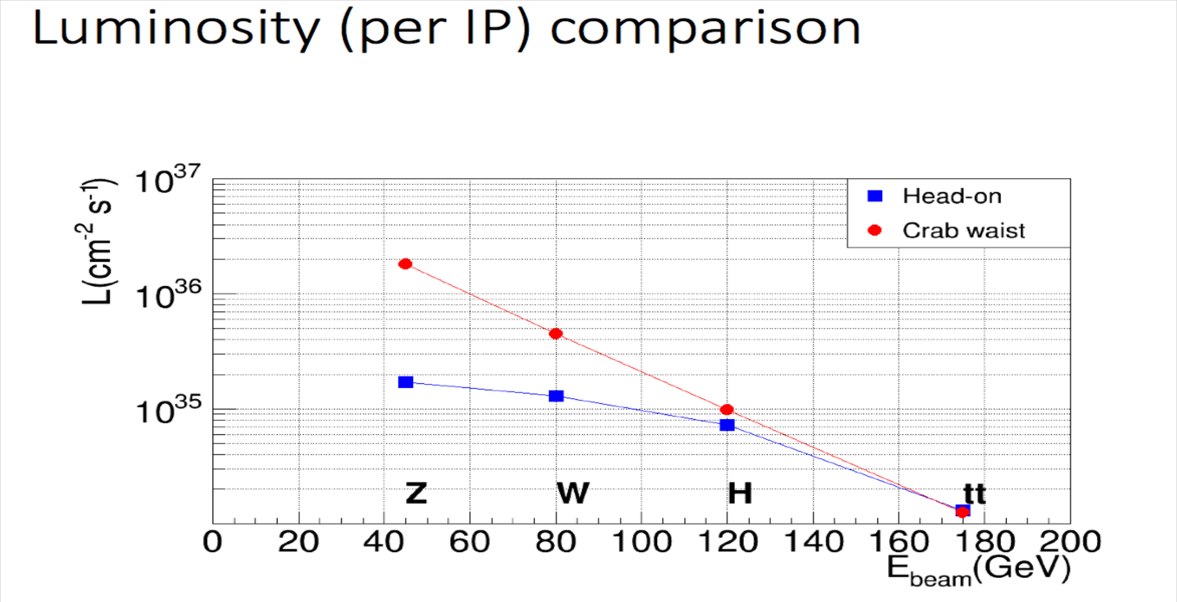
$$\tau_{bs} \sim \frac{\rho_{bb}^{3/2}}{\ell_{int}\gamma^2} \exp \frac{2\eta\alpha\rho_{bb}}{3r_e\gamma^2}$$

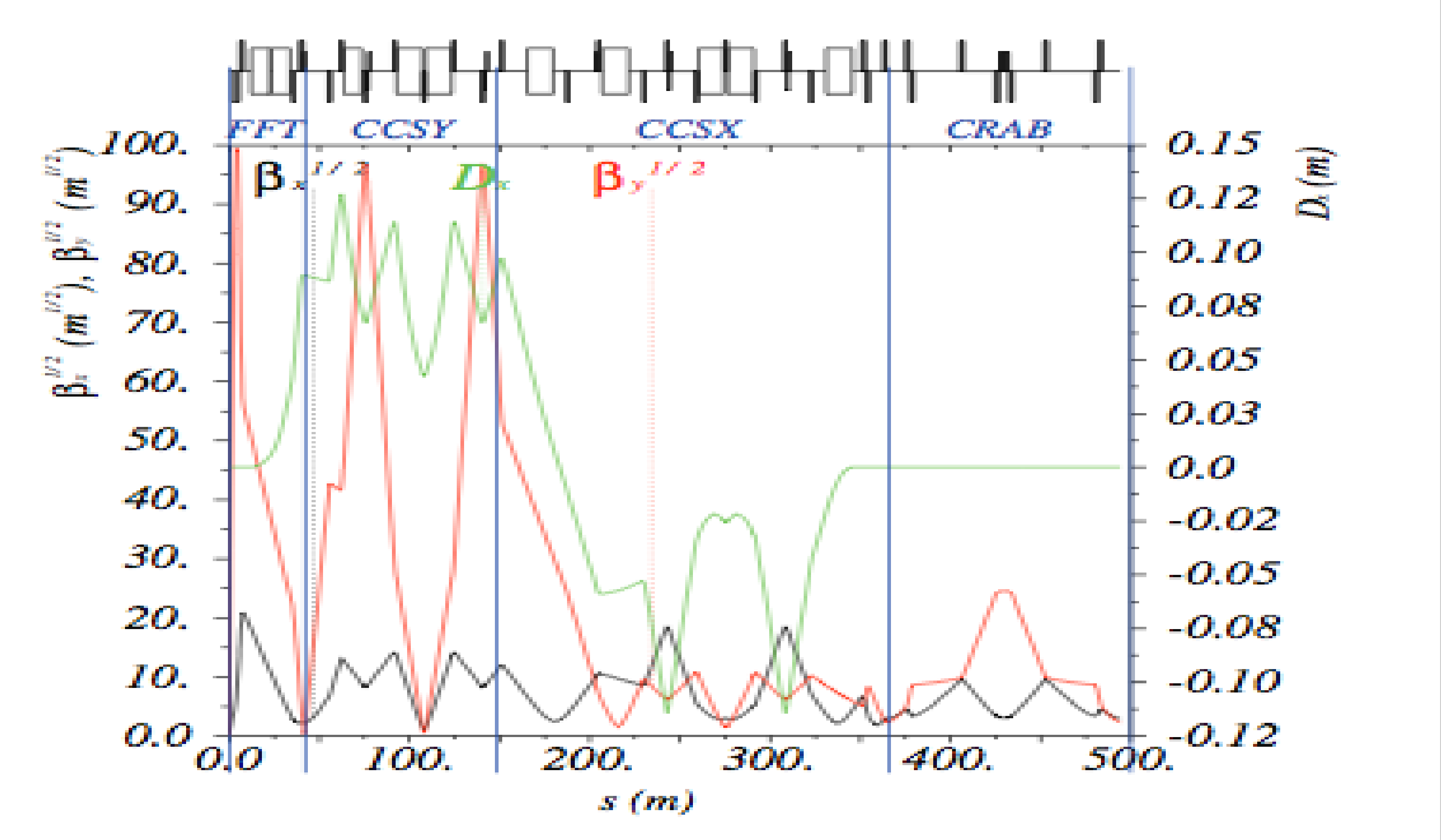
$$\rho_{bb} \equiv \text{ average bb bending radius} \sim \frac{\ell_{int}}{\xi_y}\sqrt{\frac{\beta_y}{\epsilon_y}}$$

- The energy machine acceptance, η, must be as large as possible (at least 2%)
- At high energy reduces beam lifetime
- At low energy beamstrahlung increases bunch length and energy spread impacting achievable luminosity

Different crossing schemes studied with "Lifetrac" by D. Shatilov:

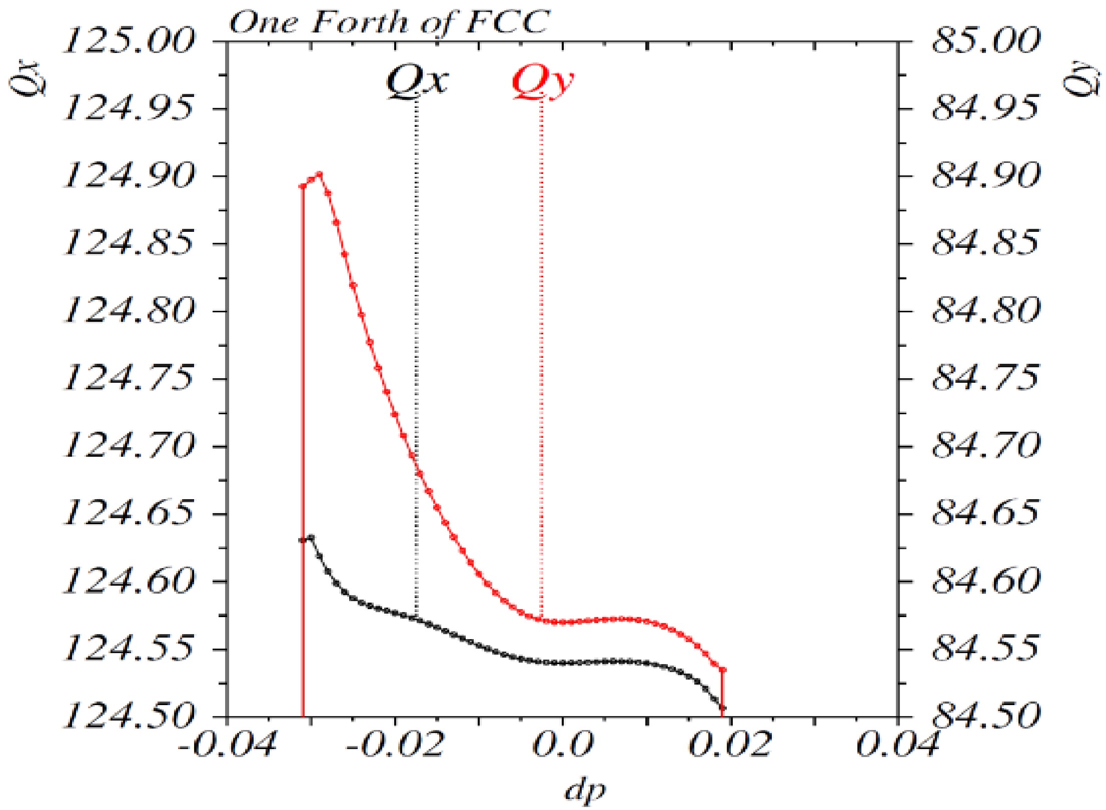
- Linear optics + crab sextupoles
- Synchrotron radiation
- Beam-beam
- Beamstrahung
- Dynamic β and emittance





(R. Martin, FCC Week)

Energy acceptance [-3.1%;+1.9%]



(R. Martin, FCC Week)

Dynamic Aperture

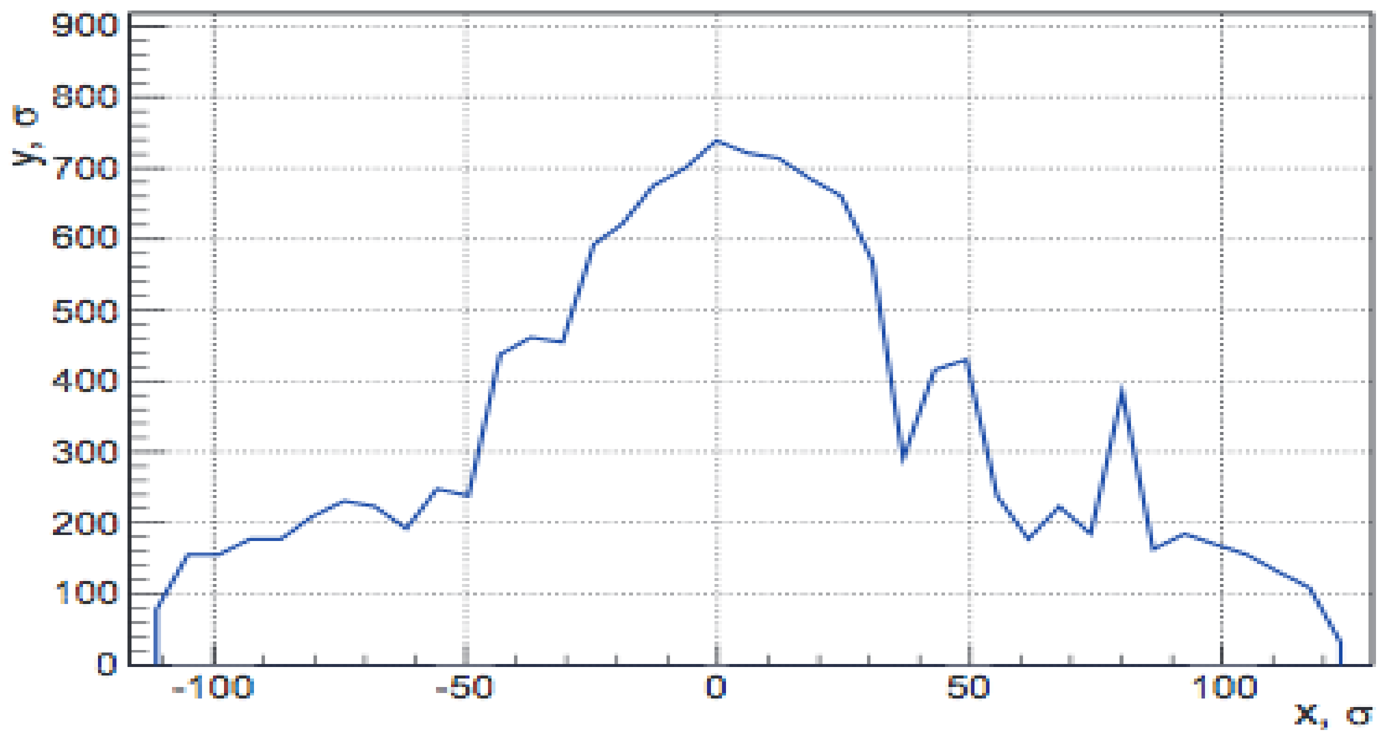
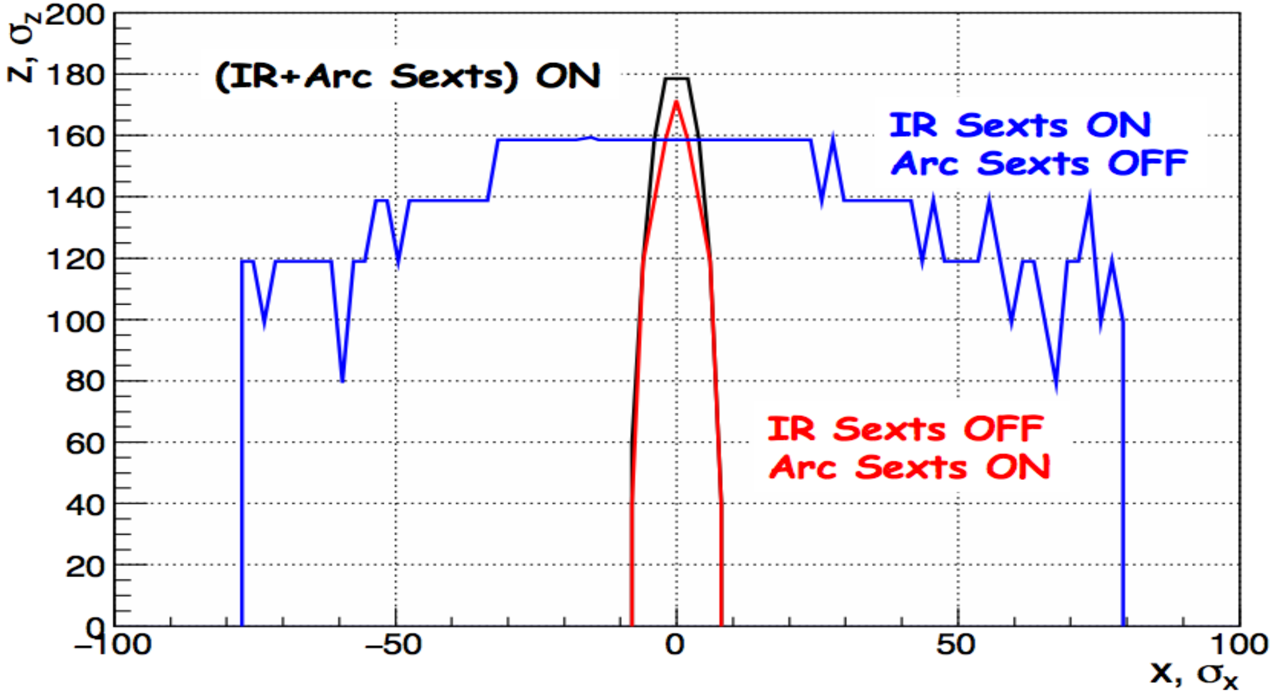


Figure 12: Dynamic aperture of the interaction region closed by the linear map $\sigma_x = 3.26 \cdot 10^{-5}$ m, $\sigma_y = 6.52 \cdot 10^{-8}$ m.

(A. Bogomyagkov et al., HF2014 Proceedings)

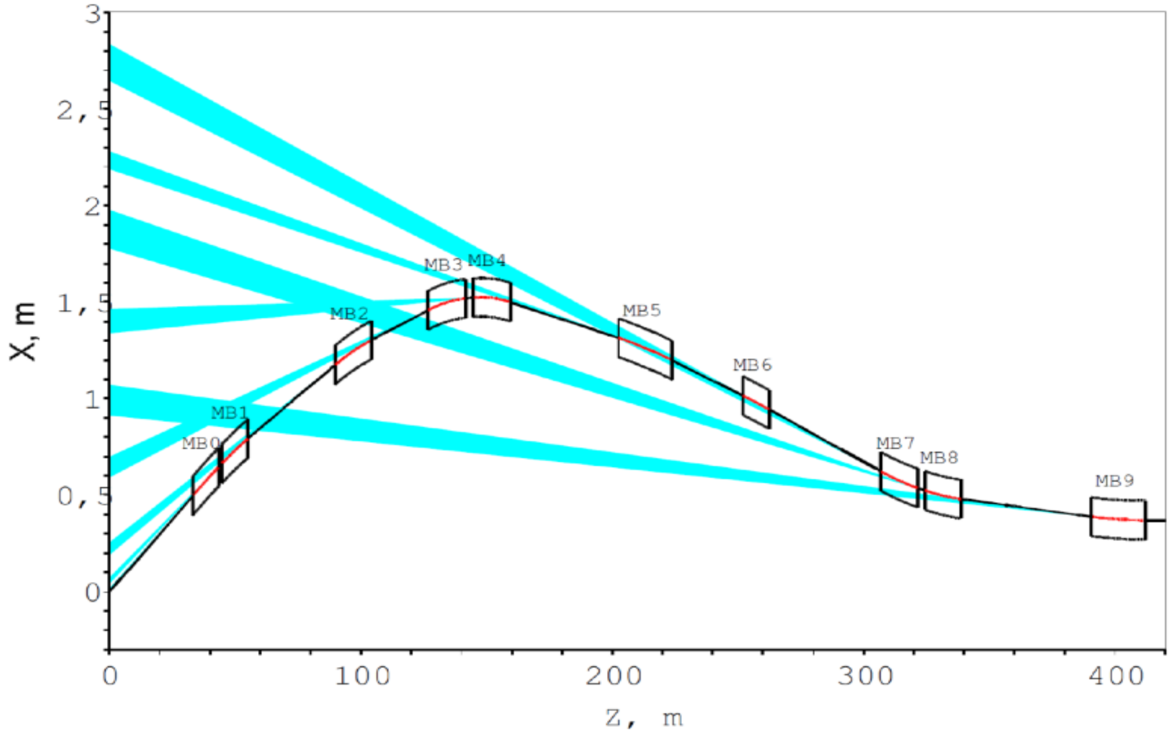
Dynamic aperture at IP: where is a bottleneck?



E=175 GeV, ε_x=1.3 nm, ε_y=0.002 ε_x, β_x = 0.5 m, β_y = 0.001 m

(R. Martin for A. Bogomyagkov et al., FCC Week)

Interaction region: SR fans



2.2 MW/beam
of SR power
into detector
region
at 175 GeV

(R. Martin, FCC Week)

Keeping synchrotron radiation at tolerable level in the IR regions of FCC-ee is very challenging

Photon energies and power comparable to LEP2
where S.R. backgrounds in the IR were acceptable with weak bends, far from IR and using ~100 collimators and local masks, (L ~ 1.e32cm-2s-1)

High luminosity low energy e+e- factory inspired FCC-ee IR designs with large crossing angle and local chromaticity correction tend to generate too high S.R. power and energy

High energy e+e-
Need for optics and layout which simultaneously optimize luminosity and keep synchrotron radiation at tolerable levels

(H. Burkhardt., FCC Week)

Beam Polarization

- High precision beam energy measurement ($\ll$ 100 keV) is needed for Z pole physics at 90 GeV CM energy and W physics at 160 CM energy. RF depolarization widely used at LEP it can provide a $\sim 10^{-6}$ accuracy.
- Z pole physics would profit from longitudinal beam polarization.

Sokolov-Ternov polarization build-up rate

$$\tau_p^{-1} = \frac{5\sqrt{3}}{8}\frac{r_e\gamma^5\hbar}{m_0C}\oint\frac{ds}{|\rho|^3}$$

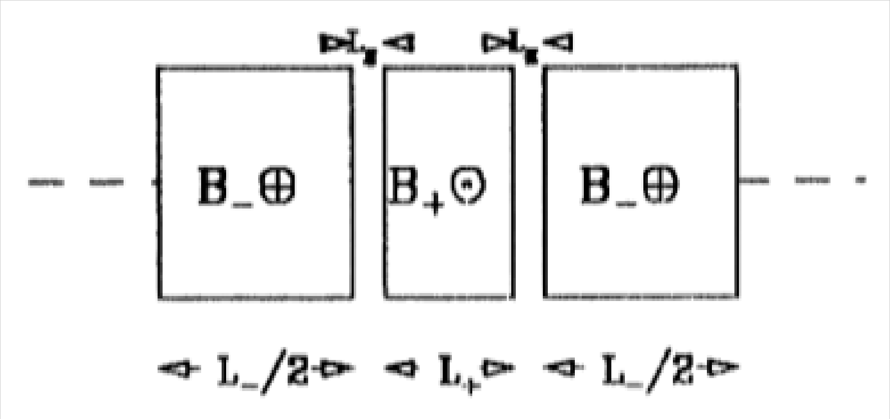
for FCC-ee with $\rho \simeq 10424$ m

E (GeV)	U_0 (MeV)	$\Delta E/E$ (%)	τ_{pol} (h)
45	35	0.038	256
80	349	0.067	14

For decreasing the polarization time keeping the polarization level high wigglers are introduced in the lattice. Constraints:

- $x' = 0$ outside the wiggler $\Rightarrow \int_{wig} ds\, B_w = 0$ (vanishing field integral)
- $x = 0$ outside the wiggler $\Rightarrow \int_{wig} ds\, sB_w = 0$ (true for symmetric field)
- P large $\Rightarrow \int_{wig} ds\, B_w^3$ must be large

LEP polarization wiggler



$$\int_{wig} ds\, \frac{1}{\rho_w^3} = \frac{L_+}{\rho_+^3}\left(1 - \frac{1}{N^2}\right) \qquad N \equiv L_-/L_+ = B_+/B_-$$

N should be large for keeping polarization high!

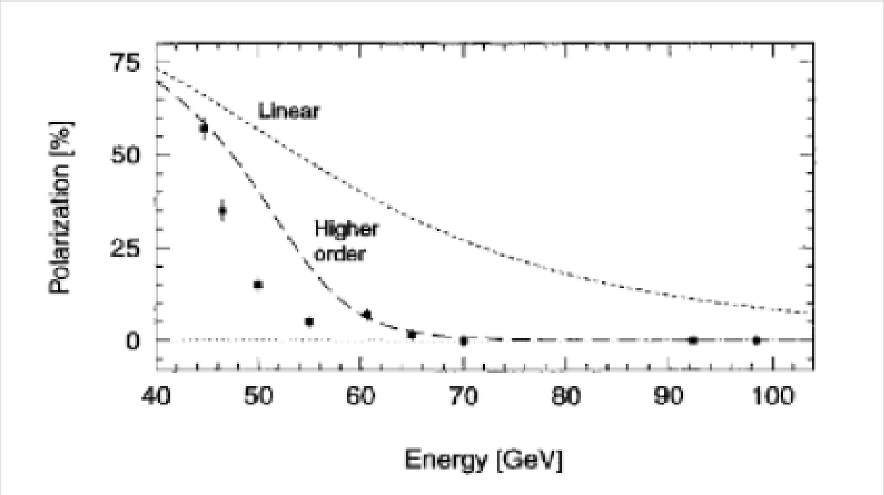
4 wigglers with $N = 6$ and L_+=1.3 m at 45 GeV:

B_+ (T)	U_0 (MeV)	$\Delta E/E$ (%)	ΔE (MeV)	ϵ_x (μm)	τ_x (s)	P (%)	τ_{pol} (min)
0	37	.04	18	.8e-3	.82	92.4	14e3
1.3	64	.22	99	.5e-2	.48	87.6	247
2.6	144	.41	184	.070	.21	87.6	31
3.9	278	.55	247	.274	.11	87.6	9
5.2	466	.65	292	.691	.06	87.6	4

Wiggler drawbacks

- Beam energy spread increases
- SR power increases (locally!)

LEP measured polarization



(R. Assmann et al., SPIN2000, Osaka)

Lack of polarization at high energy is understood as due to the large beam energy spread in a non perfectly planar machine!

No polarization observed above 65 GeV at LEP $\rightarrow \boldsymbol{\Delta E_{max}} \sim$ 50 MeV (conservative)

Question: how *planar* the ring must be for keeping resonances "sleeping"?

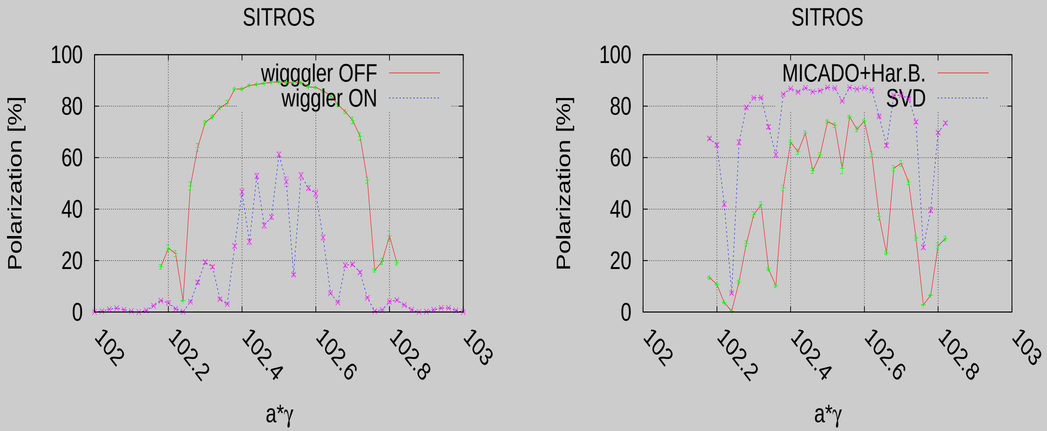
Simulations in presence of realistic errors and corrections are needed.

1 wiggler with B_+=1.35 T for reaching 10% polarization (enough for energy calibration) after 140'.

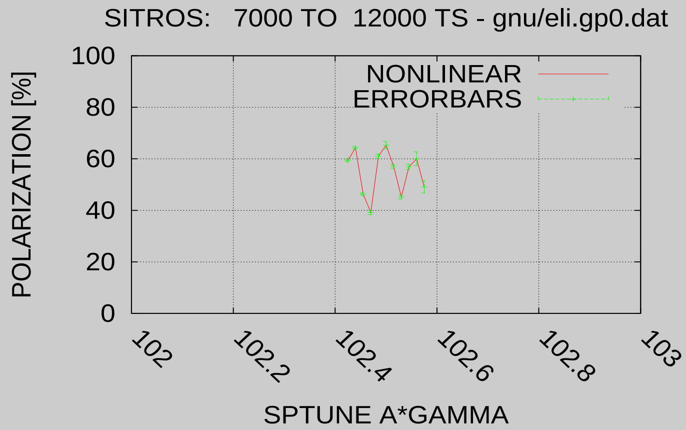
"toy" ring

- 200 μm quadrupole misalignment
- 1 corrector + 1 BPM close to each vertical focusing quad
- correction
  - MICADO like correction + *harmonic bumps*

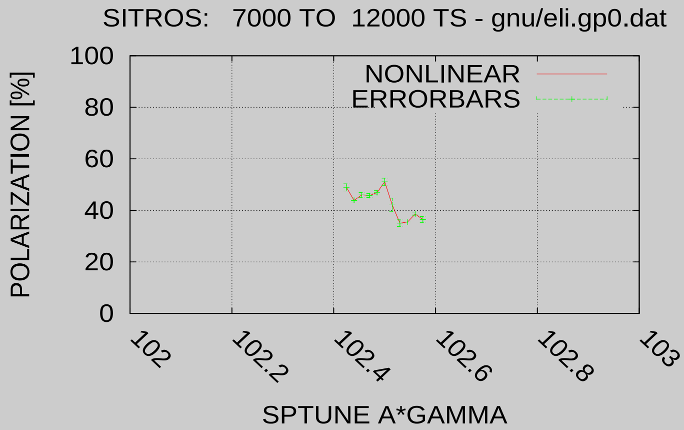
    or
  - use of all BPMs and correctors through SVD analysis



- δ_y^Q= 200 μm $\rightarrow$ y_{rms}= 15 mm, 4 wigglers with B_+=3.9 T :
  - ∗ orbit corrected down to y_{rms}= 0.04 mm with 1096 correctors (SVD)
    ∗ $\delta\hat{n}_0$=0.3 mrad
  - ∗ orbit corrected down to y_{rms}= 0.4 mm with 110 correctors (MICADO)
    ∗ $\delta\hat{n}_0$=2.9 mrad reduced to 1.6 mrad by harmonic bumps



SVD



MICADO + harmonic bumps

Very brief conclusion

- Lot of problems to be solved, but many ideas to be explored and possibilities for R&D $\longrightarrow$ hope for solutions!
- Many enthusiastic participants
- The project is challenging but *...Volere è potere!*