Future Collider Technologies
II. Circular Colliders

D. Schulte

FCC

FCC-hh:

- 100TeV pp cms energy
- Can use ions

$\Rightarrow$ Defining infrastructure requirements

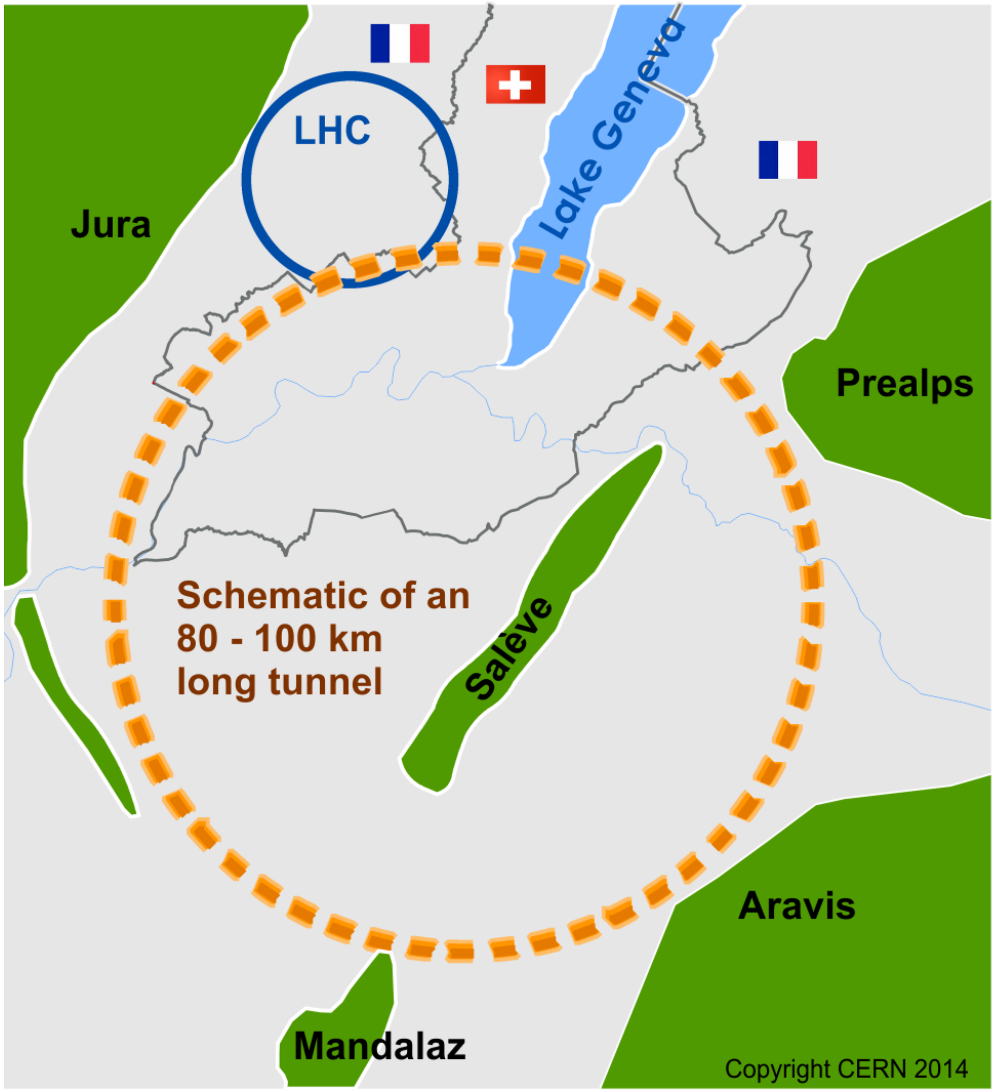
$\Rightarrow$ 100km circumference

FCC-ee:

- e^+e^- collider, 90-350 GeV cms
- Potential intermediate step

FCC-he:

- Hadron-electron option



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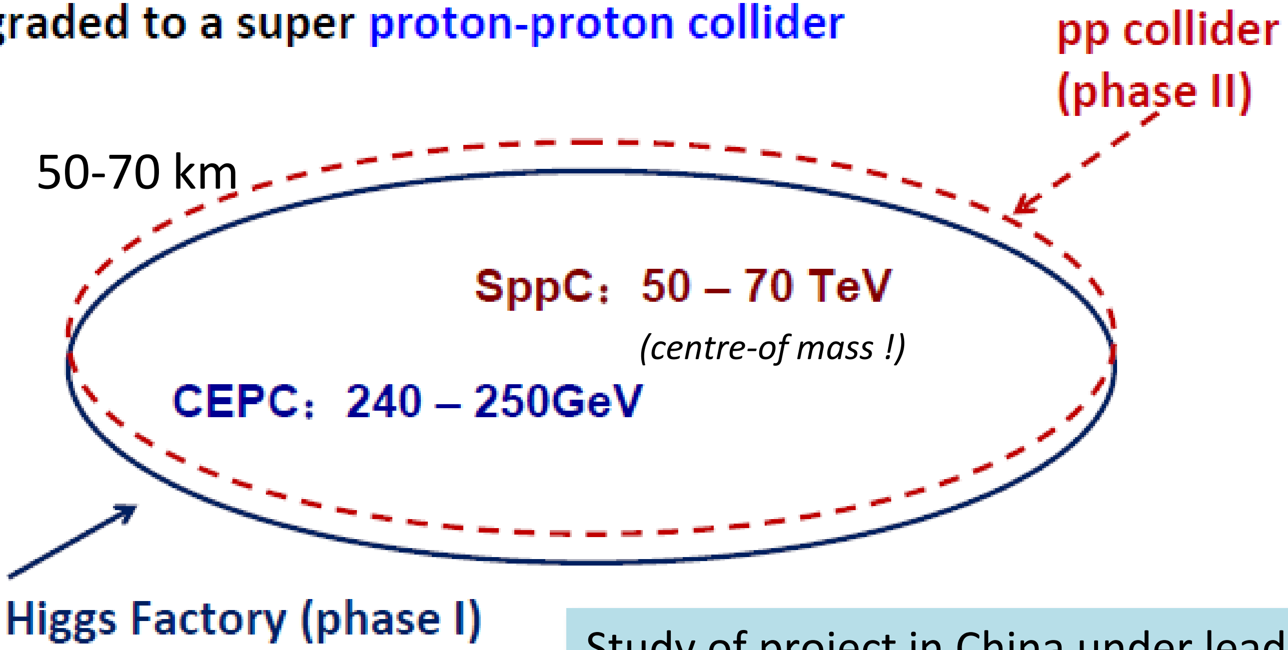
Note: CEPC/SppC

D. Wang & H. Geng

6th TLEP Workshop

CEPC is

- an Circular Electron Positron Collider
- proposed to carry out high precision study on Higgs bosons
- to be upgraded to a super proton-proton collider



pp collider (phase II)

50-70 km

SppC: 50 – 70 TeV

(centre-of mass !)

CEPC: 240 – 250GeV

e^-e^+ Higgs Factory (phase I)

Study of project in China under leadership of IHEP

Emphasis is on lepton collider

CEPC is similar to FCC-ee, SppC similar to FCC-hh

⇒ Will not go into any detail

FCC-hh

Main FCC-hh Parameters

	LHC	HL-LHC	FCC-hh	
Cms energy [TeV]	14	14	100	100
Luminosity [$10^{34}cm^{-2}s^{-1}$]	1	5	5	20
Bunch distance [ns]	25	25	25	25/5
Background events/bx	27	135	170	680 (136)
Bunch length [cm]	7.5	7.5	8	8

Two main experiments
- Two reserve experimental areas used in baseline

80% of circumference filled with bunches

Baseline: 250fb^{-1} per year (including shutdowns)
- focus on 25ns spacing

Ultimate: 1000fb^{-1} per year
- more emphasis on 5ns

The Key Challenges

- Energy
  - Limited by the machine size and the strength of the bending dipole

  ⇒ Have to maximise the magnet strength

⇒ Paolo Ferracin, Aug. 3+4

- Luminosity

  ⇒ Need to maximise the use of the beam for luminosity production

- Beam power handling
  - Small losses lead to background in detectors and machine
  - Accidental losses

  ⇒ Need a concept to deal with the beam power

⇒ Stefano Redaelli, Aug. 5+6

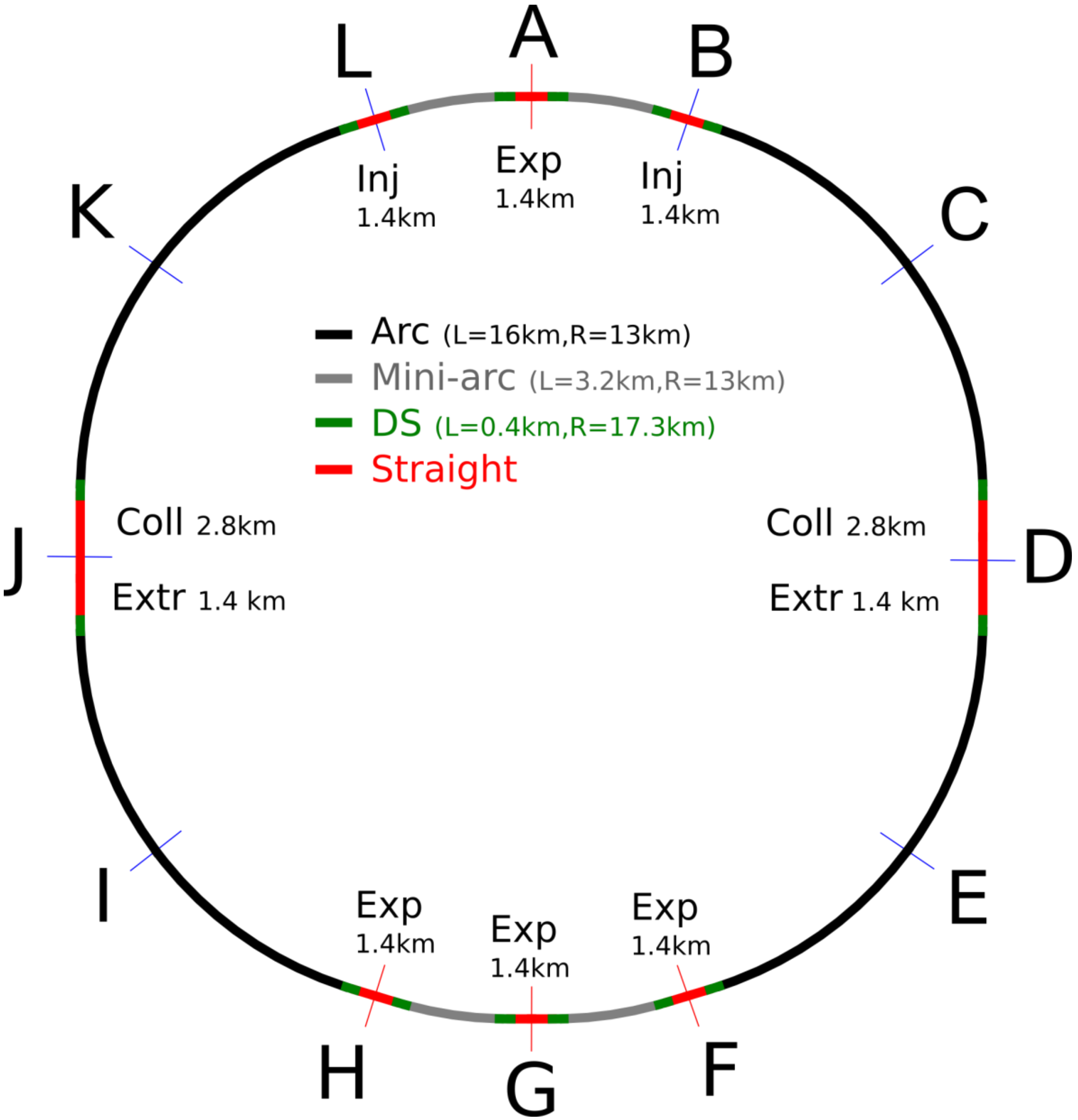
- Cost
  - Push to the limits to reduce cost
- Site
  - Do we have a fitting site (next to CERN)?

Baseline Layout

Circumference 100km

- Two high-luminosity experiments (A and G)
- Two other experiments (F and H)
- Two collimation/extraction insertions
- Two injection insertions, should include RF

Length for arcs 83km

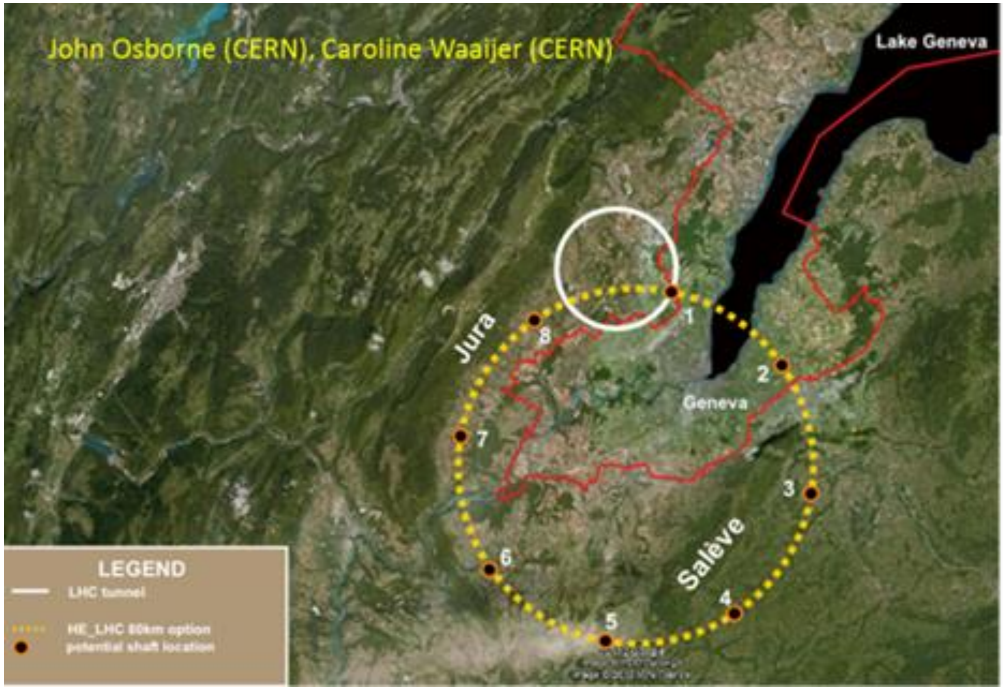


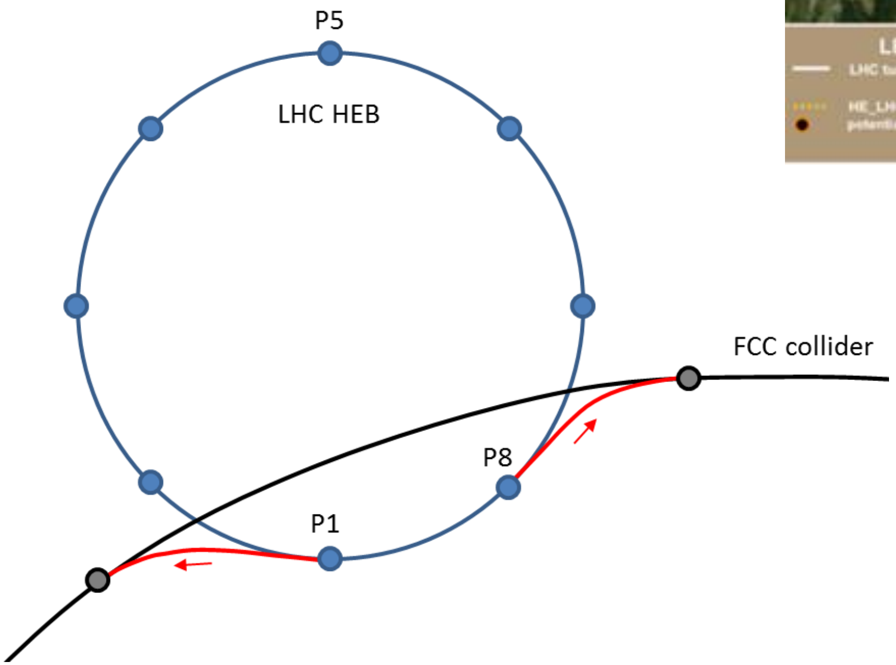
Site Studies

First site studies of

- Geology
- Surface buildings
- …

⇒ 100km ring fits well into the Geneva area


John Osborne (CERN), Caroline Waaijer (CERN)



Can LHC be used as injector?

- Machine is OK
- The two tunnels would match nicely

Will also consider SPS and FCC tunnel for injector

Arc Cell Layout

Longer cell

⇒ better dipole filling factor

Shorter cells

⇒ more stable beam

12 dipoles with L=14.3m

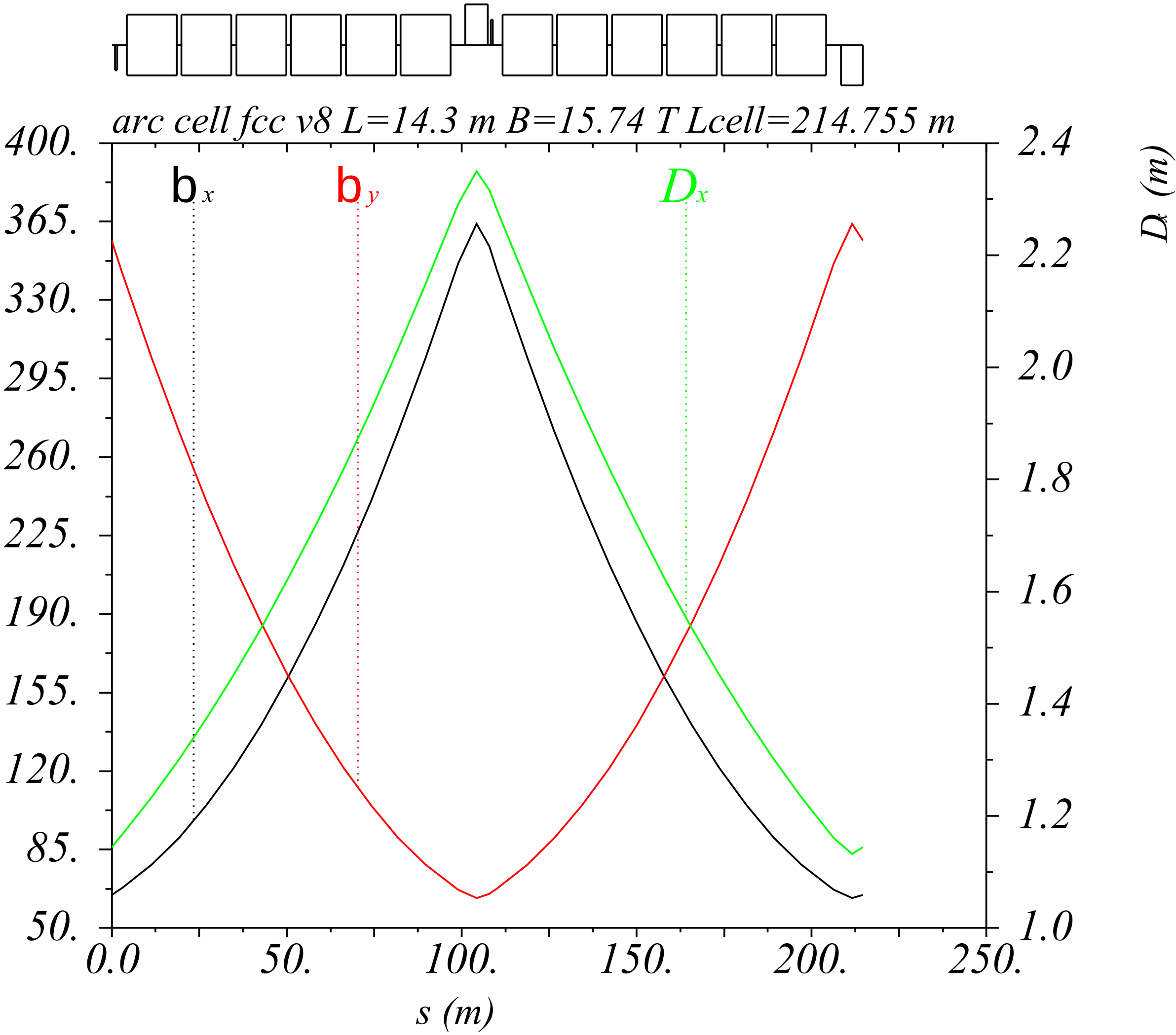
L_{cell}=214.755m

Fill factor about 80% (as in LHC)

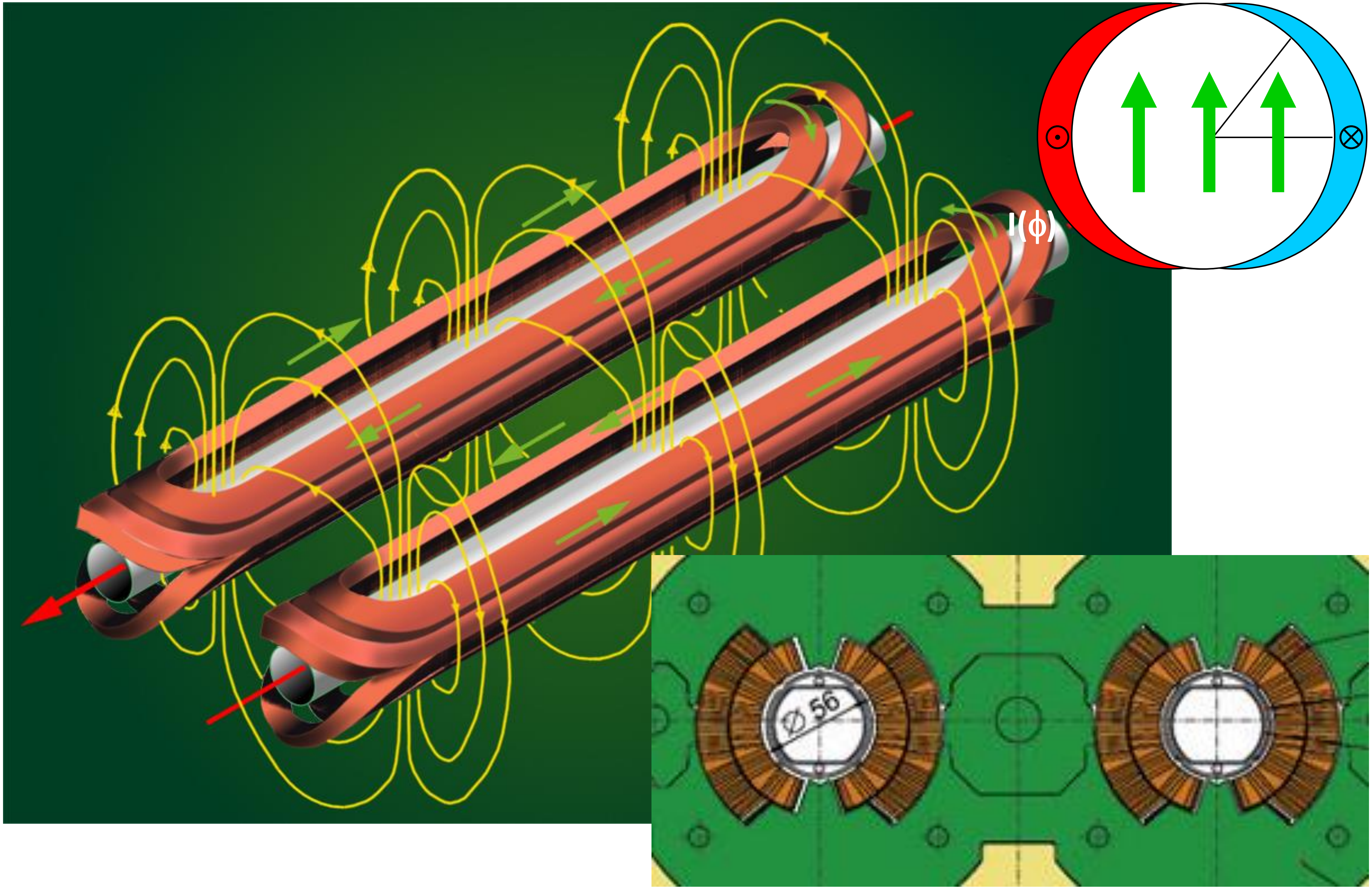
Bending radius in magnets ρ=10.5km

$$r = \frac{T}{0.3GeV}\frac{E}{B}$$

⇒ Field: (16-ε)T

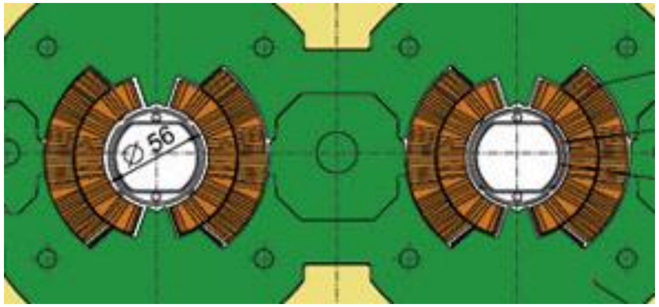


Dipole Basic Concept (“Cosine Theta”)



Magnet Design Issues

- Field level
  - Higher field level allows to use a smaller ring
  - But is technically challenging
- Aperture
  - A larger aperture means more volume with the magnetic field
  - Larger stored energy and larger forces
  - Higher cost

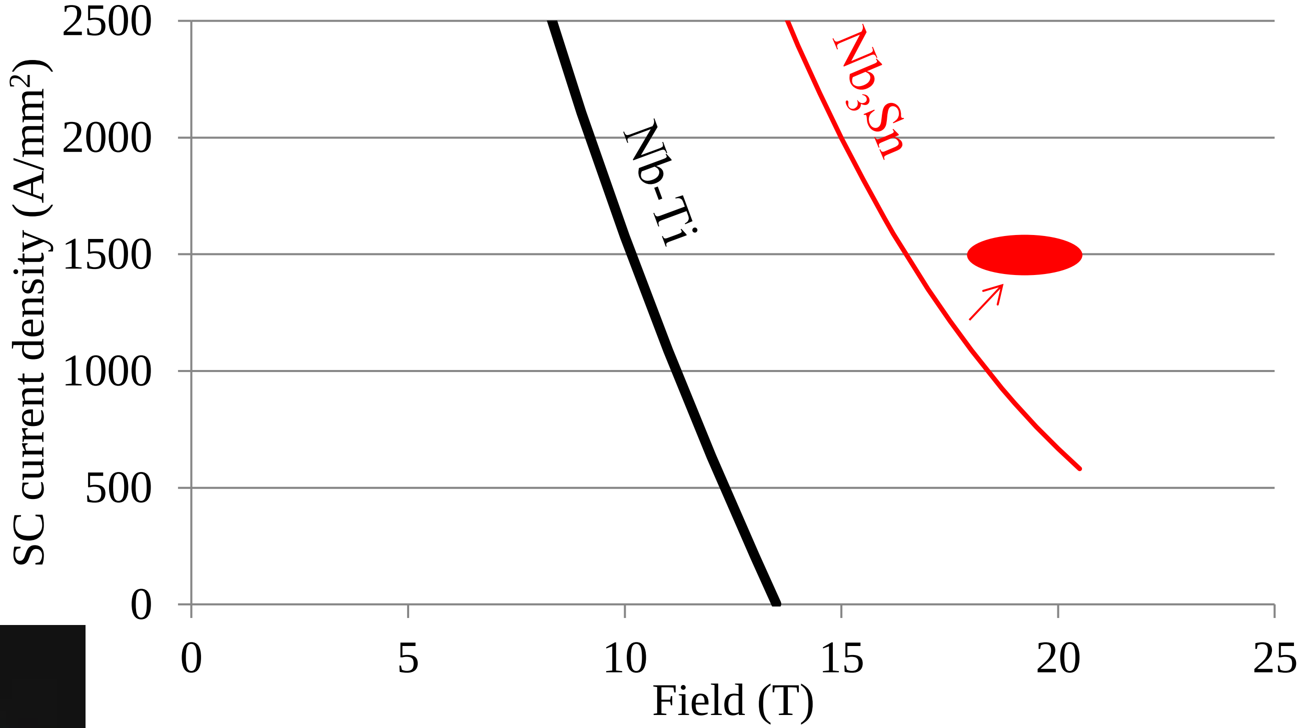


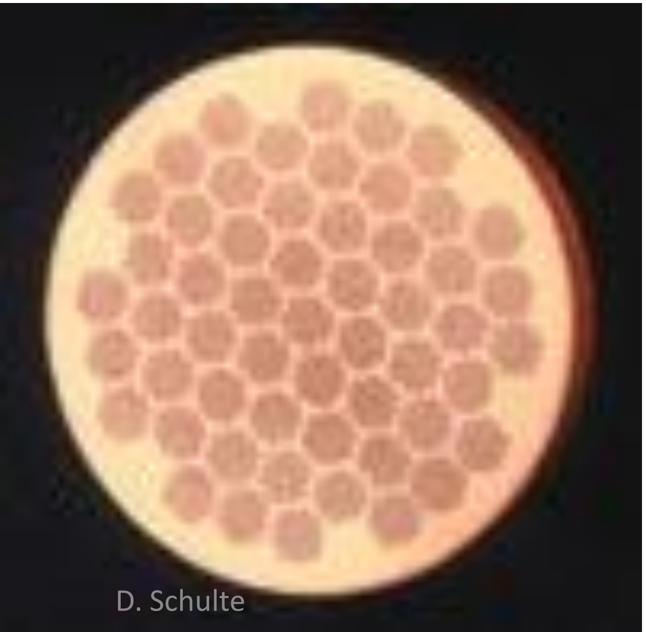
- The field quality
  - Unwanted non-linear field components
  - Especially at injection (low field)
  - Can make particles move chaotic and be lost
- The cost
  - The most costly component in the machine

Limits for the Field

The cable can quench (superconductivity breaks down)

- if the current is too high
- If the magnetic field is too high





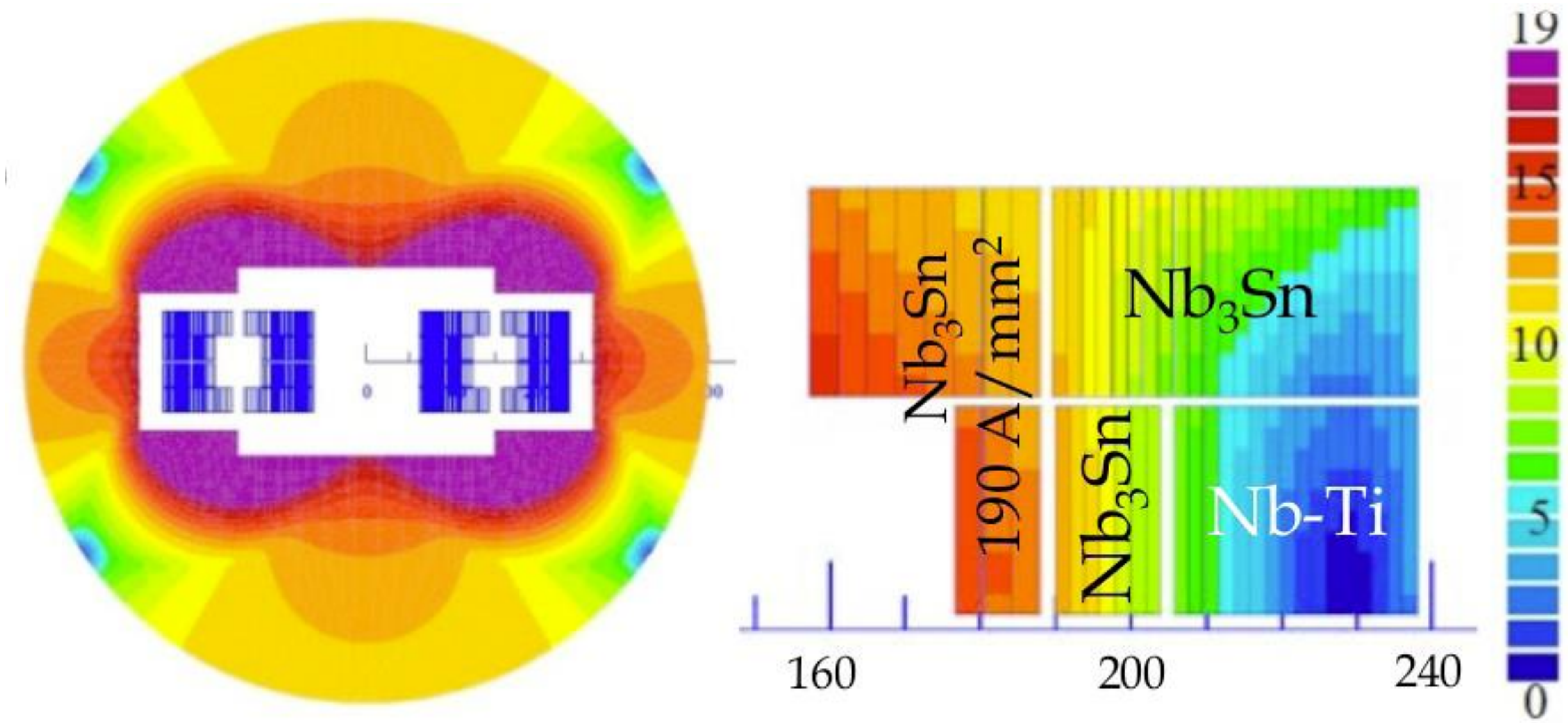
- This limits the achievable field
  - In theory
  - Even lower limit in practice

- Can use different materials
  - Nb-Ti is used for LHC
  - Nb_3Sn is used for high luminosity upgrade

Cost Effective Magnet Design

Nb_3Sn is more costly than Nb-Ti

$\Rightarrow$Use both materials



Coil sketch of a 15 T magnet with grading, E. Todesco

Parameters and Luminosity Target

$$\mathcal{L} = \frac{N^2}{4\pi\sigma_x\sigma_y} n_b f_r$$

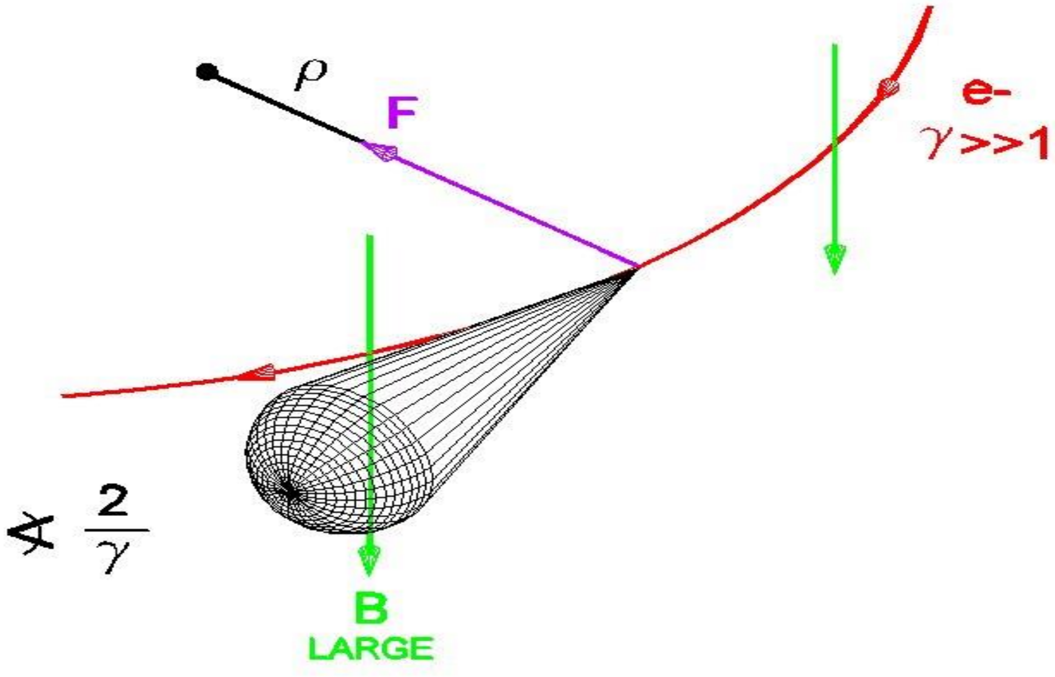
$$\sigma^2 \propto \beta\epsilon$$

$$\mathcal{L} \propto \frac{N}{\epsilon}\frac{1}{\beta_y} N n_b f_r$$

$$\mathcal{L} = \xi \frac{1}{\beta}\frac{N}{\Delta t}\eta_{fill}$$

	Baseline	Ultimate
Luminosity L [10^{34}cm^{-2}s^{-1}]	5	20
Background events/bx	170 (34)	680 (136)
Bunch distance Δt [ns]	25 (5)	
Bunch charge N [10^{11}]	1 (0.2)	
Fract. of ring filled η_{fill} [%]	80	
Norm. emitt. [μm]	2.2(0.44)	
Max ξ for 2 IPs	0.01 (0.02)	0.03
IP beta-function β [m]	1.1	0.3
IP beam size σ [μm]	6.8 (3)	3.5 (1.6)
RMS bunch length σ_z [cm]	8	
Crossing angle [σ□]	12	Crab. Cav.
Turn-around time [h]	5	4

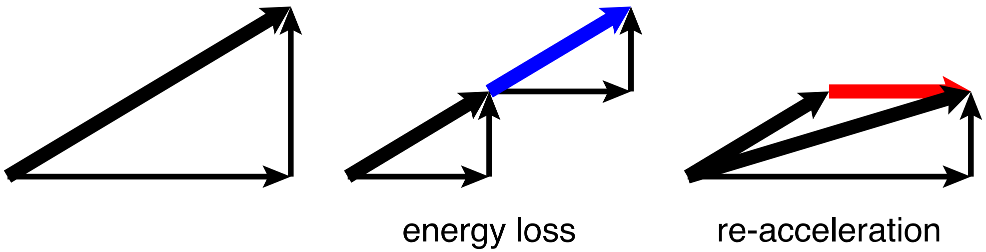
Synchrotron Radiation



At 100 TeV even protons radiate significantly

Total power of 5 MW
⇒ Needs to be cooled away

Equivalent to 30W/m /beam in the arcs



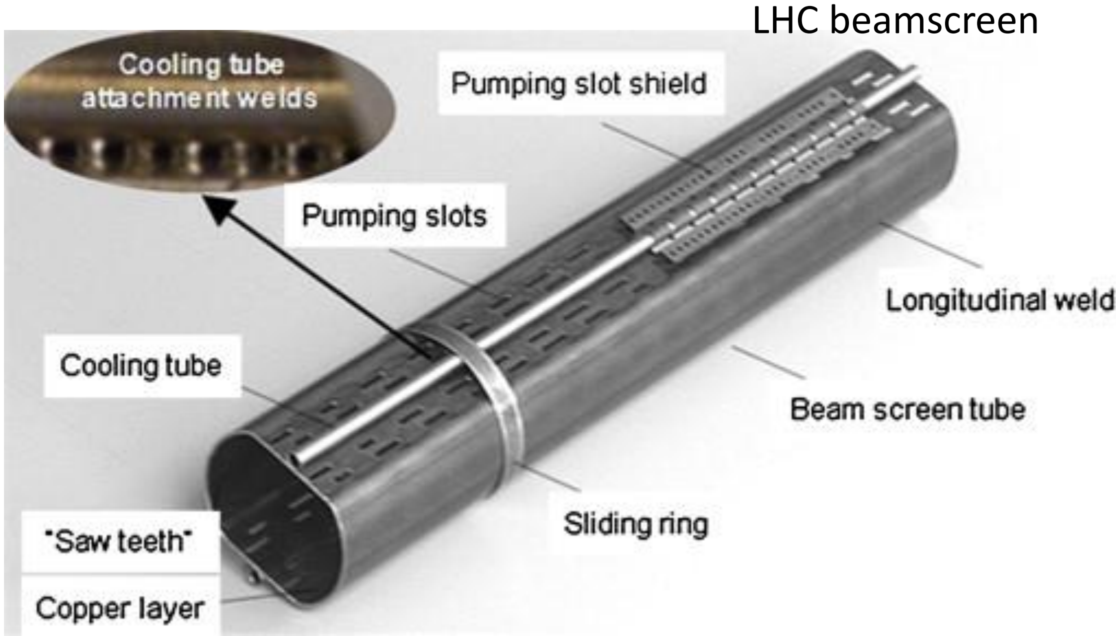
Protons loose energy
⇒ They are damped
⇒ Emittance improves with time
- Typical damping time 1 hour

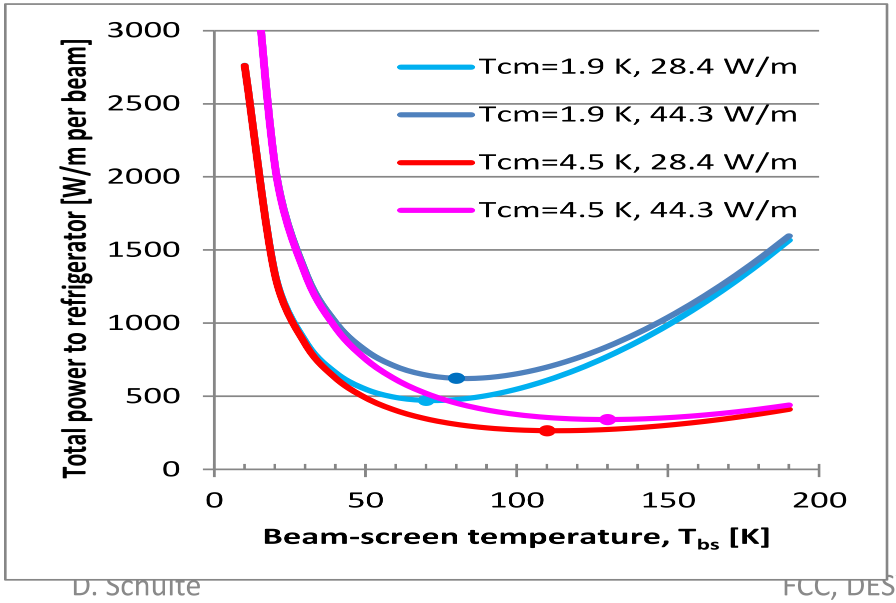
Synchrotron Radiation and Beamscreen

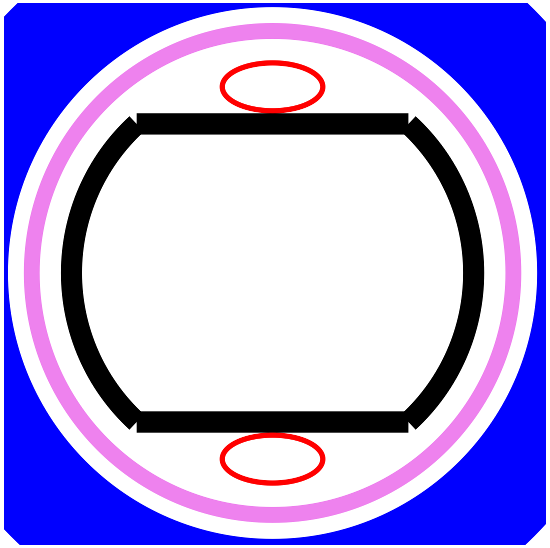
$$\mathcal{L} = \xi \frac{1}{\beta} \boxed{\frac{N}{\Delta t}\eta_{fill}}$$

5MW synchrotron radiation
3,500 MW cooling power at 2K

Beamscreen at 50K
100MW power for cooling

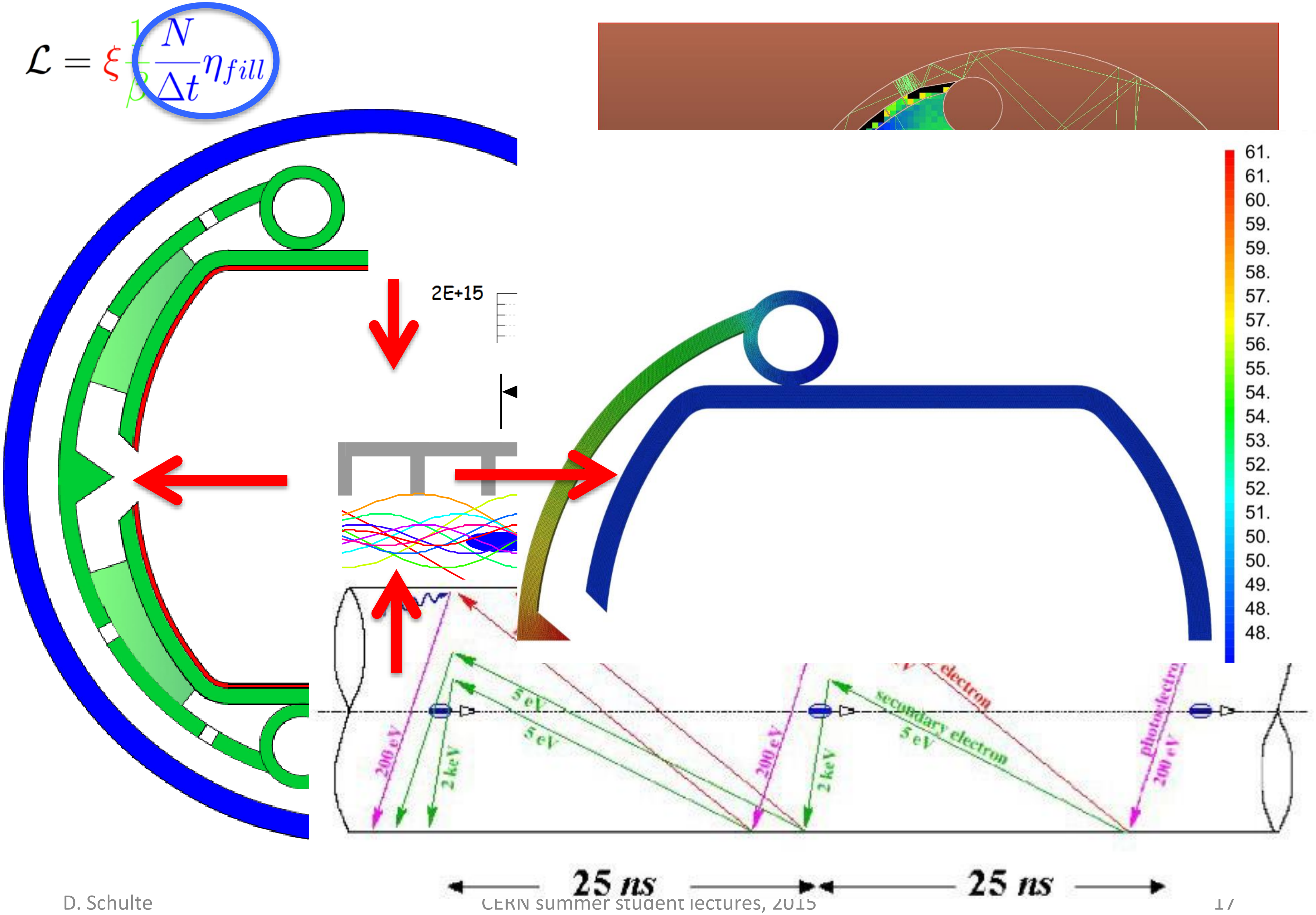

LHC beamscreen





Example Beamdscreen Design

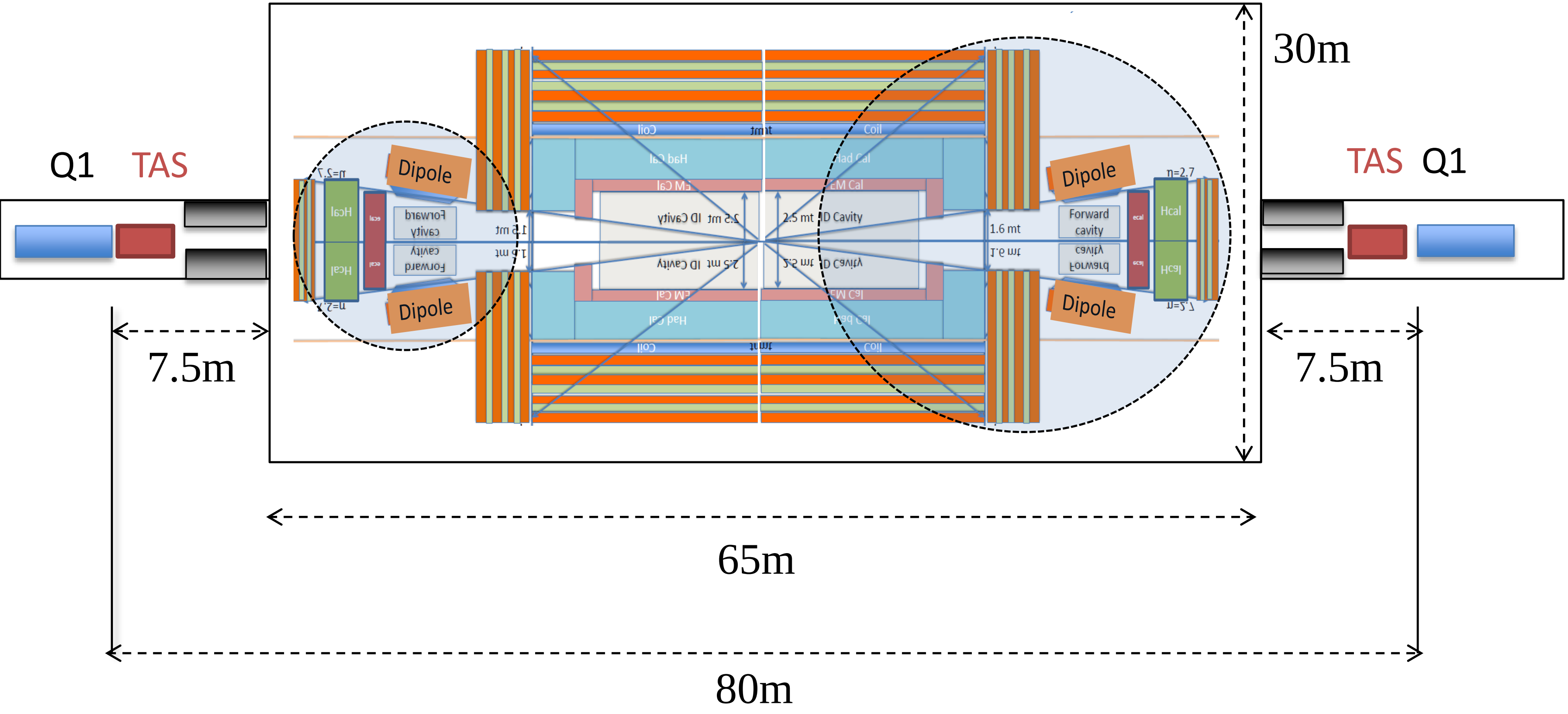
$$\mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t}\eta_{fill}$$



Interaction Region

L* >40m allows the the triplet (Q1-Q3) and the triplet shielding (TAS) to be ‘hidden’ in the tunnel

→ very comfortable situation for cavern infrastructure and ALARA related items.



Interaction Region and Final Focus Design

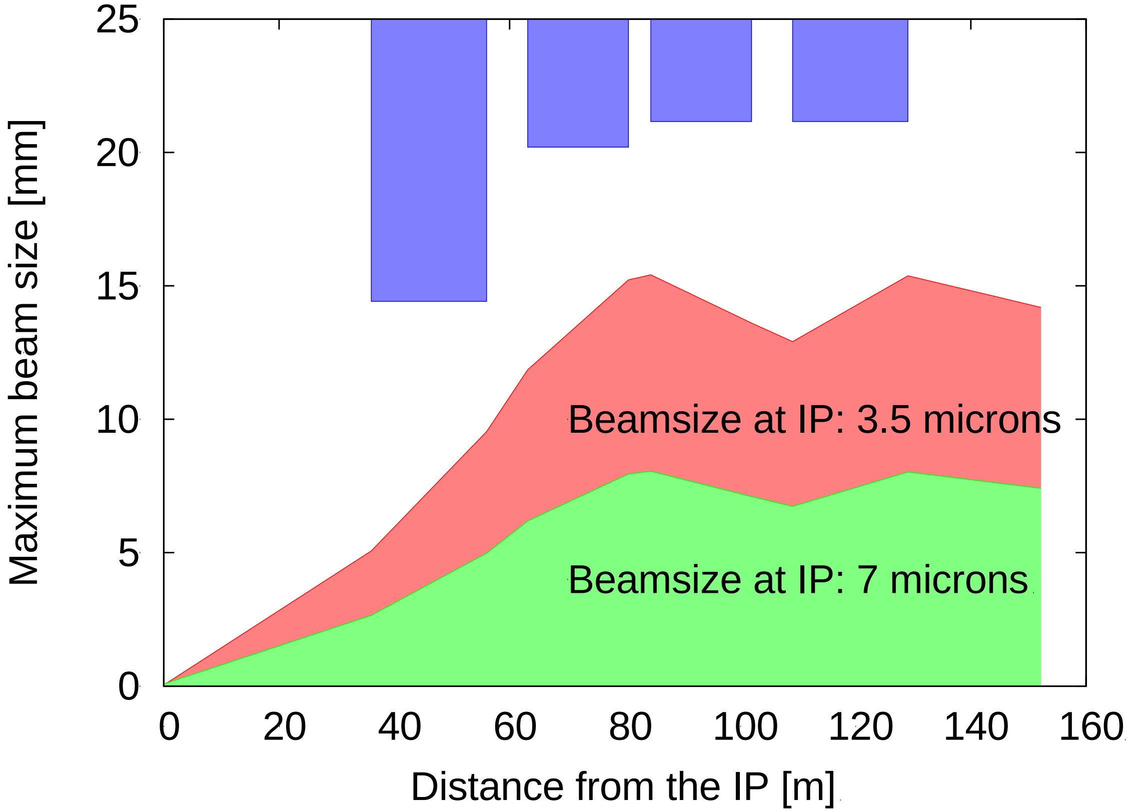
$$\mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{fill}$$

Quadrupole aperture depends on focal strength

Smaller beam at IP => larger beam at quadrupole

The larger L*, the larger the beam but less focusing required

R. Martin, R. Tomas

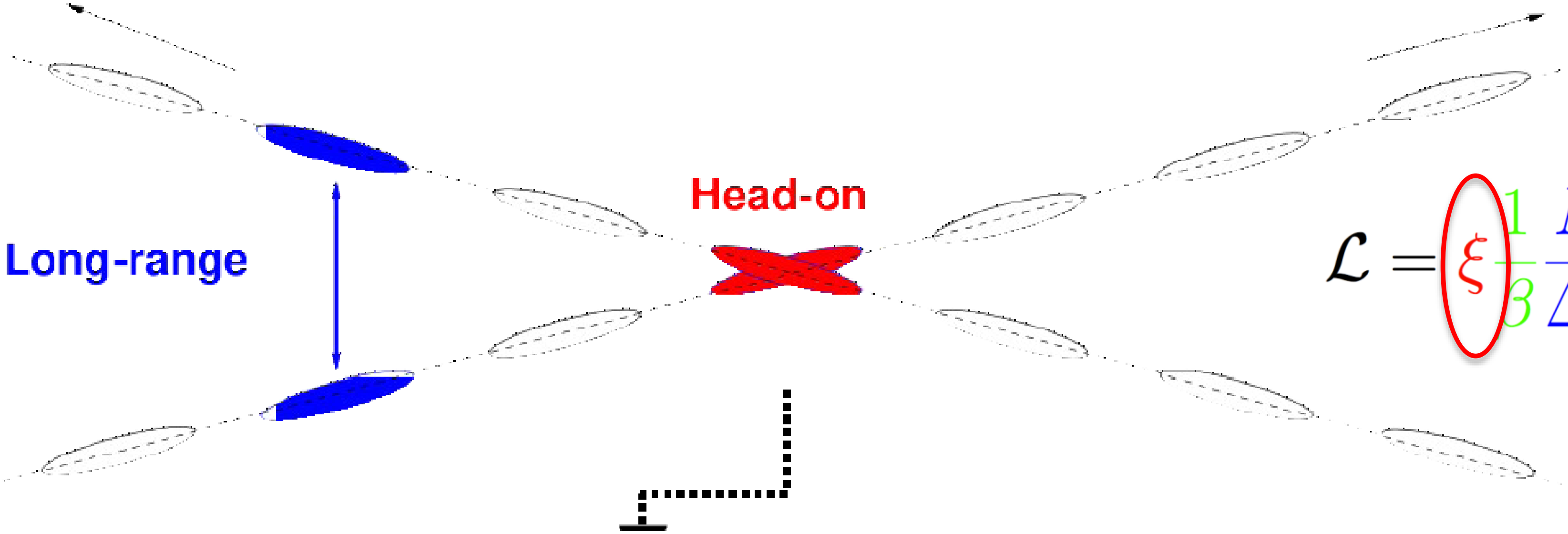


$\Rightarrow$ The final triplet will be a critical aperture limitation

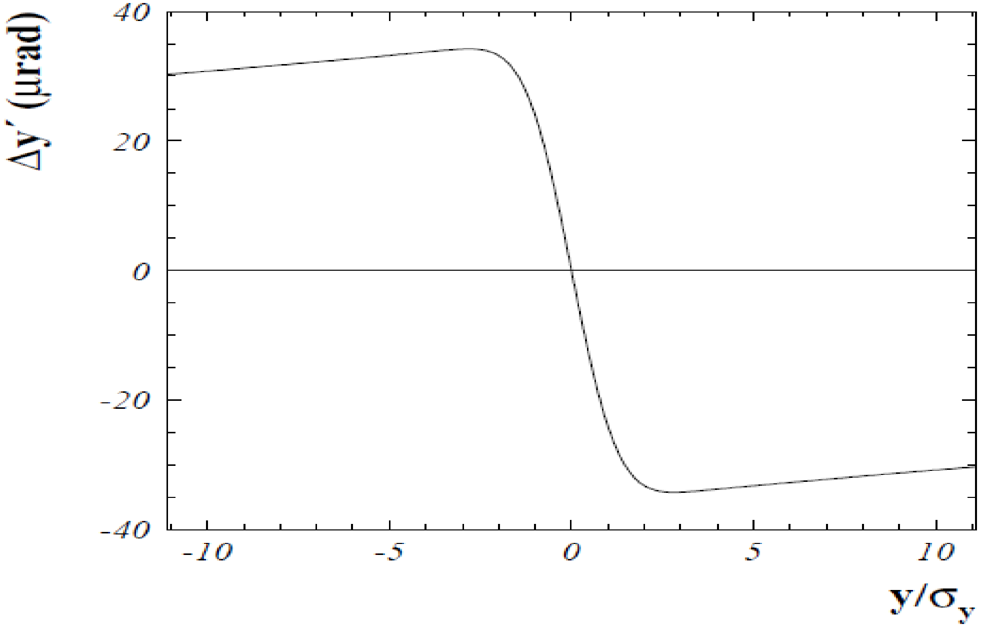
$\Rightarrow$ Limits the beta-function

Why not simply reduce the emittance?

Beam-beam Effects



$$\mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{fill}$$



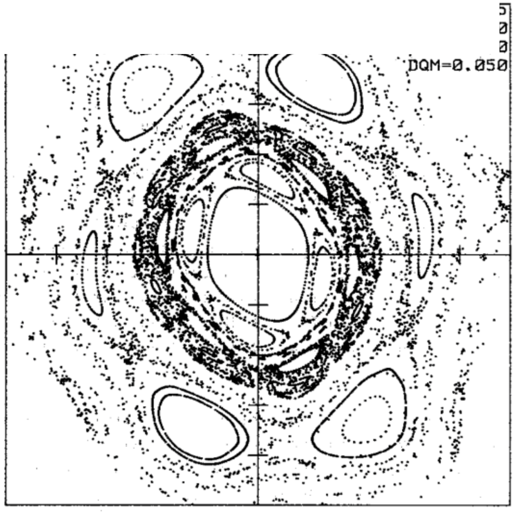
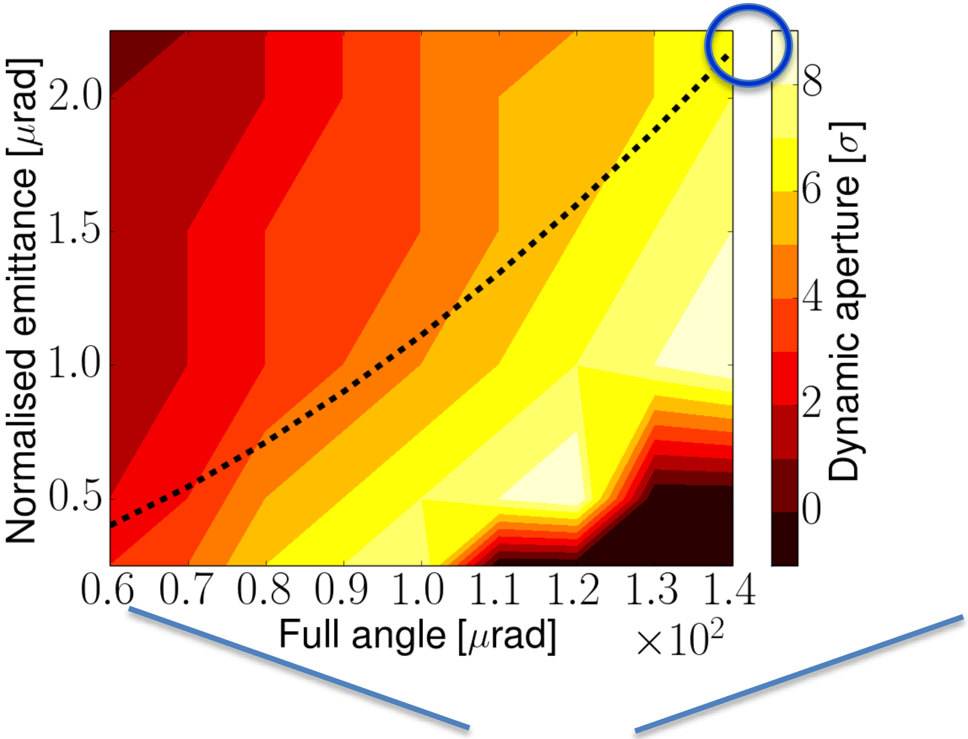


Plate 3b

- ⇒ About ξ=0.03 is acceptable
- ⇒ More study needed

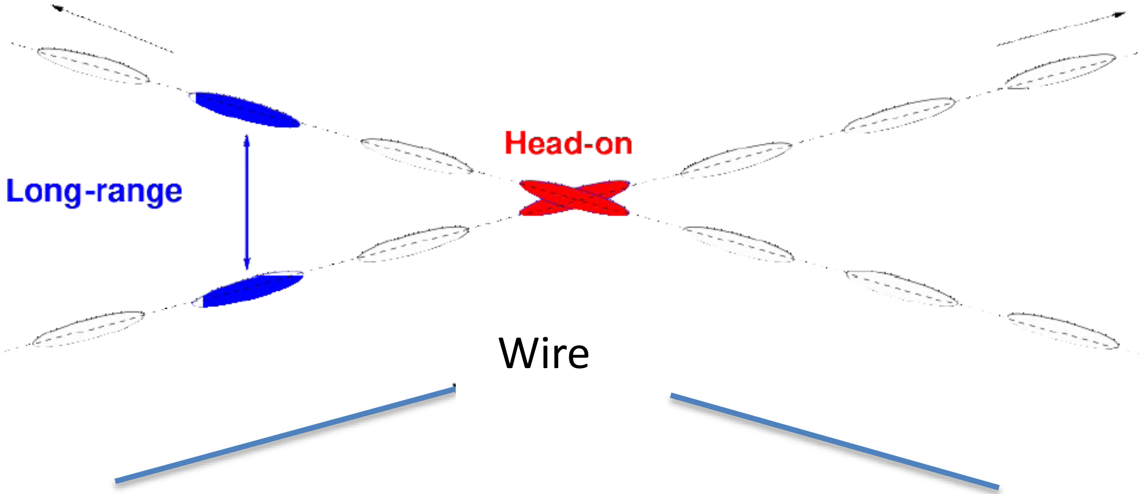
Beam-beam Effect Mitigation



Effect is about OK

But would like to have margin and to push further

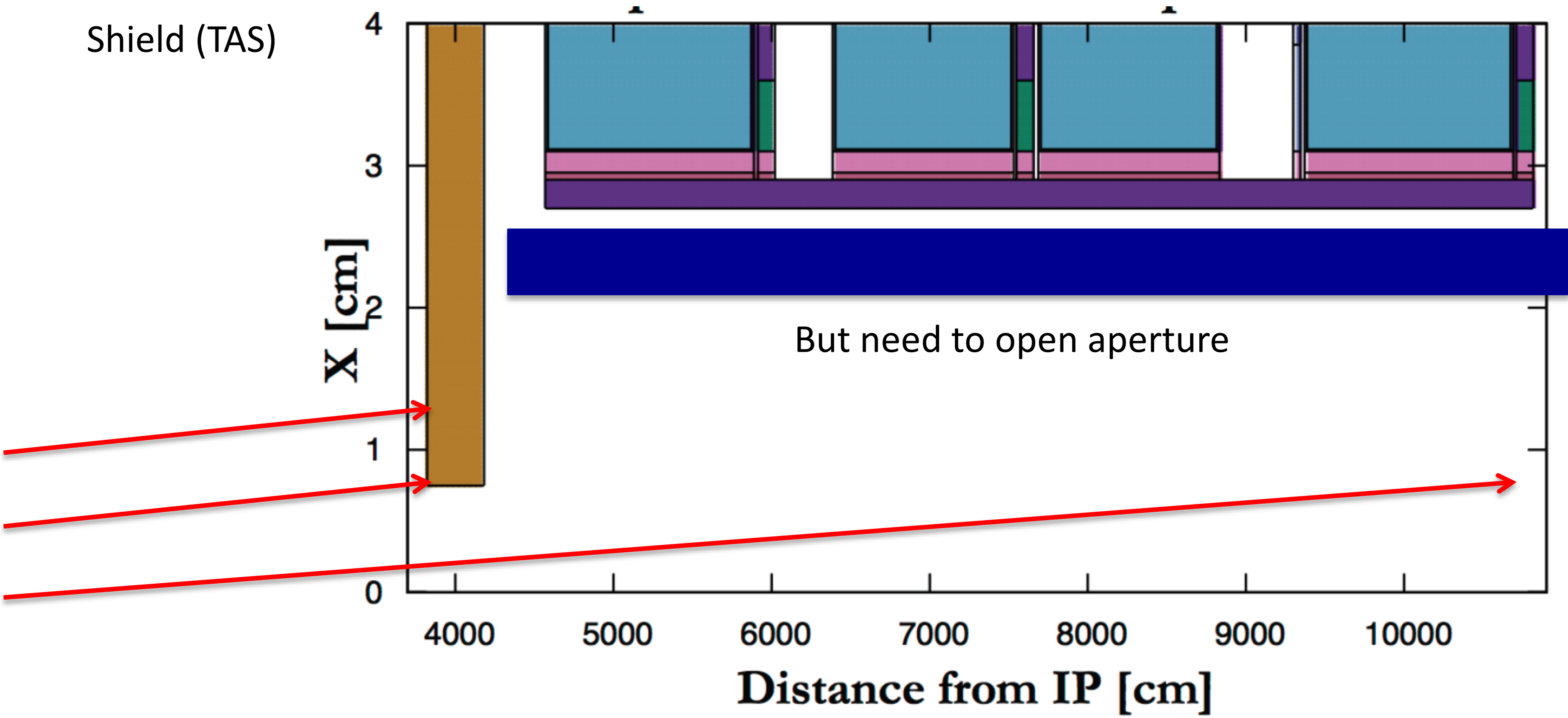
Some mitigation techniques are possible:



Head-on:
Electron lens

Long-range:
Larger crossing angle (and crab crossing)
Compensating wire (to be tested for HL-LHC)

Radiation from Beam-beam



- Total power of background events 100-500kW per experiment
  - A good car engine
- Already a problem in LHC and HL-LHC
  - Lifetime of magnets, heat load and quench
- Need to improve shielding

Radiation in Final Triplet II

Heat load seems OK for baseline and ultimate

With 20mm liner magnets survive O(3000fb^{-1})

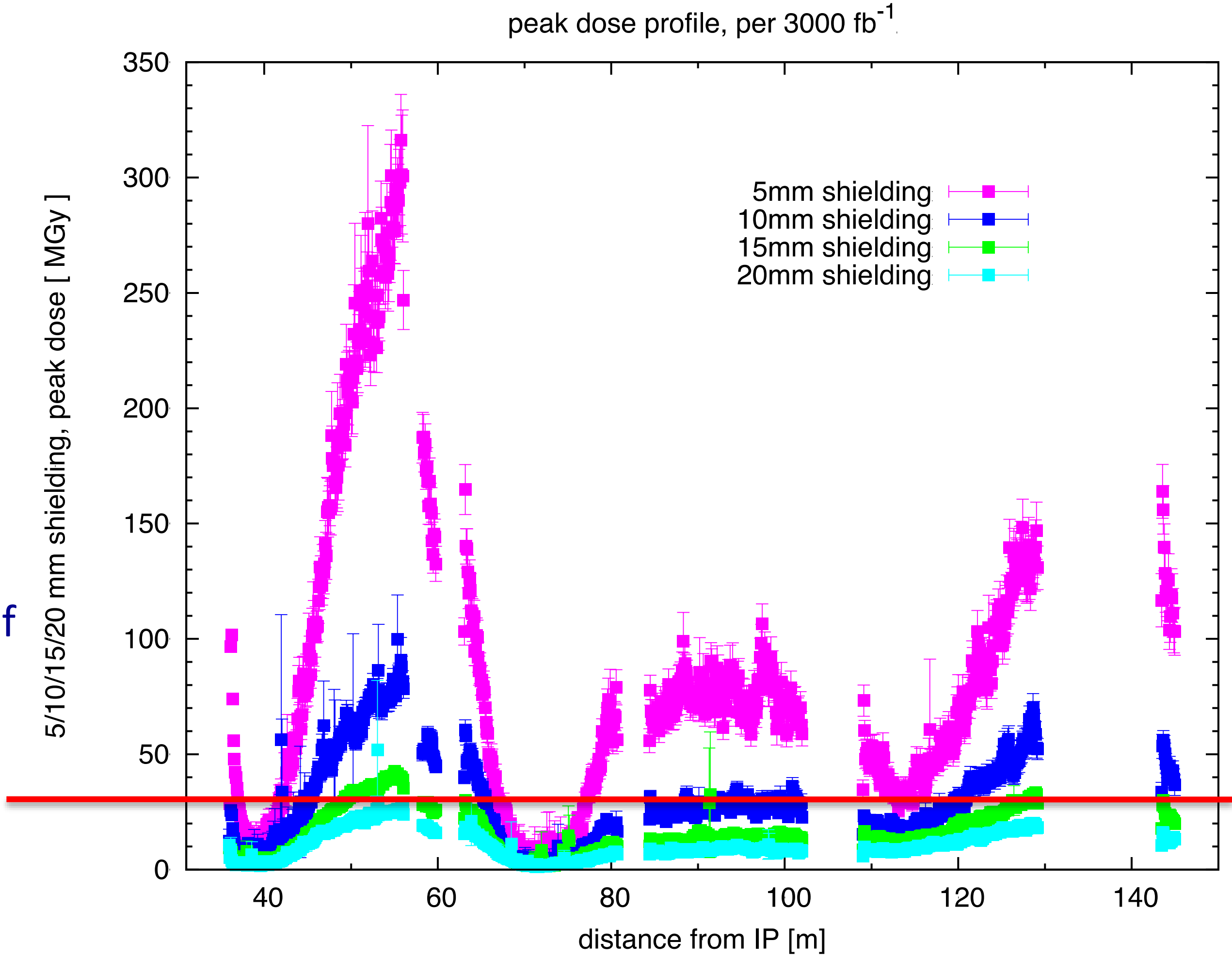
$\Rightarrow$ 10% of the total dose

$\Rightarrow$ OK for 5 year baseline run

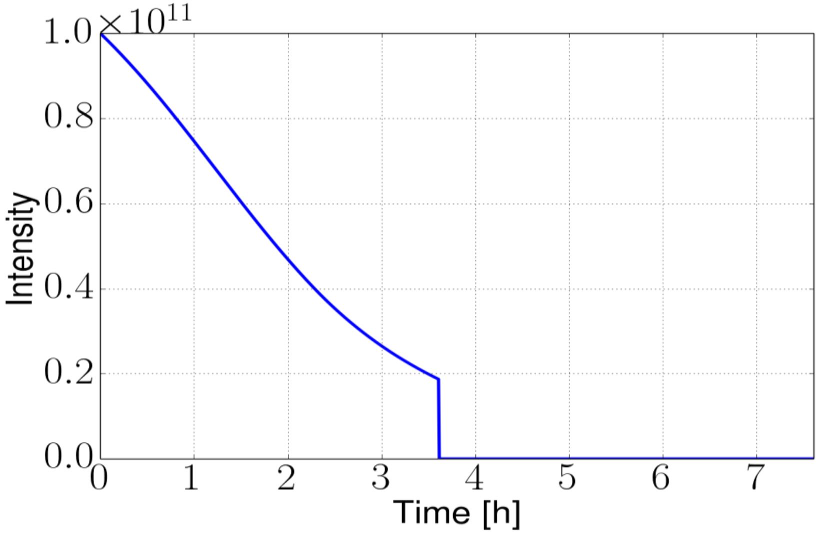
$\Rightarrow$ Not OK for an ultimate run

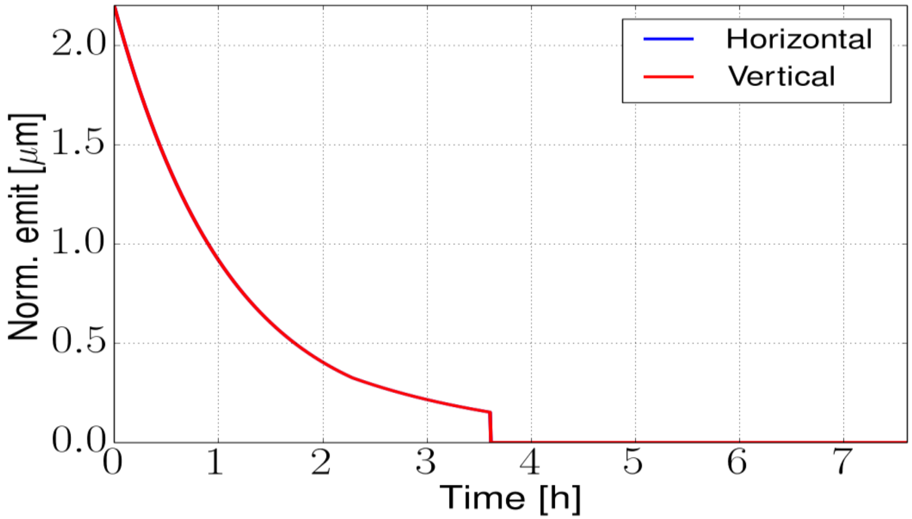
Need to

- Further improve shielding
- Improved radiation hardness of magnets
- Think about replacement of triplets
- Play with optics
- …



Luminosity During the Run





Main loss mechanism is luminosity

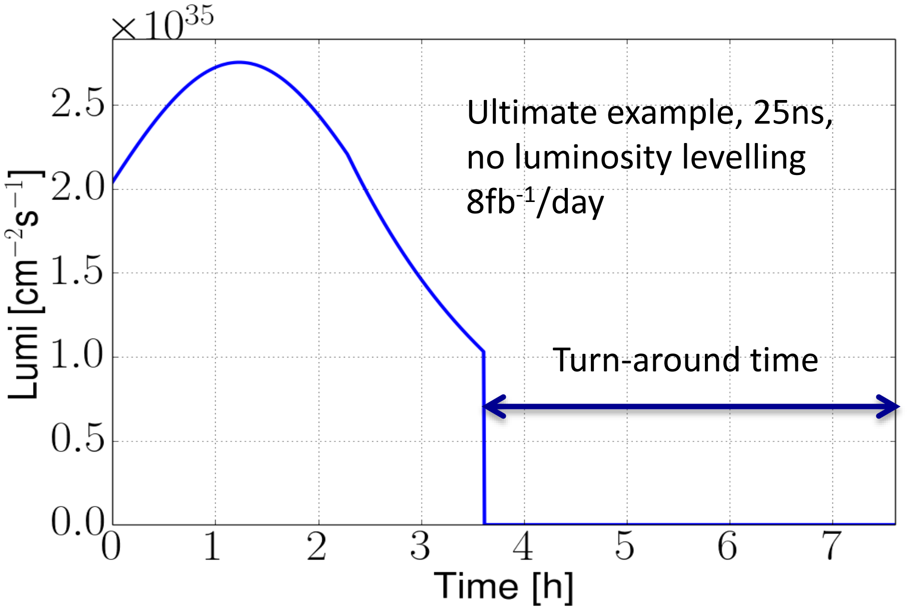
⇒ This is what we want

⇒ Can reach >8fb^{-1} with ultimate for ξ=0.03

  ⇒ 5000fb^{-1} per 5 year run

⇒ Beam is burned quickly

  ⇒ Another reason to have enough charge stored


Ultimate example, 25ns, no luminosity levelling 8fb^{-1}/day

Turn-around time

Collimation/Machine Protection

8GJ kinetic energy per beam

- Airbus A380 at 720km/h
- 2000kg TNT per beam
- O(20) times LHC

⇒ Machine protection

High risk at injection and extraction

Instrumentation to detect failures

Interlock system

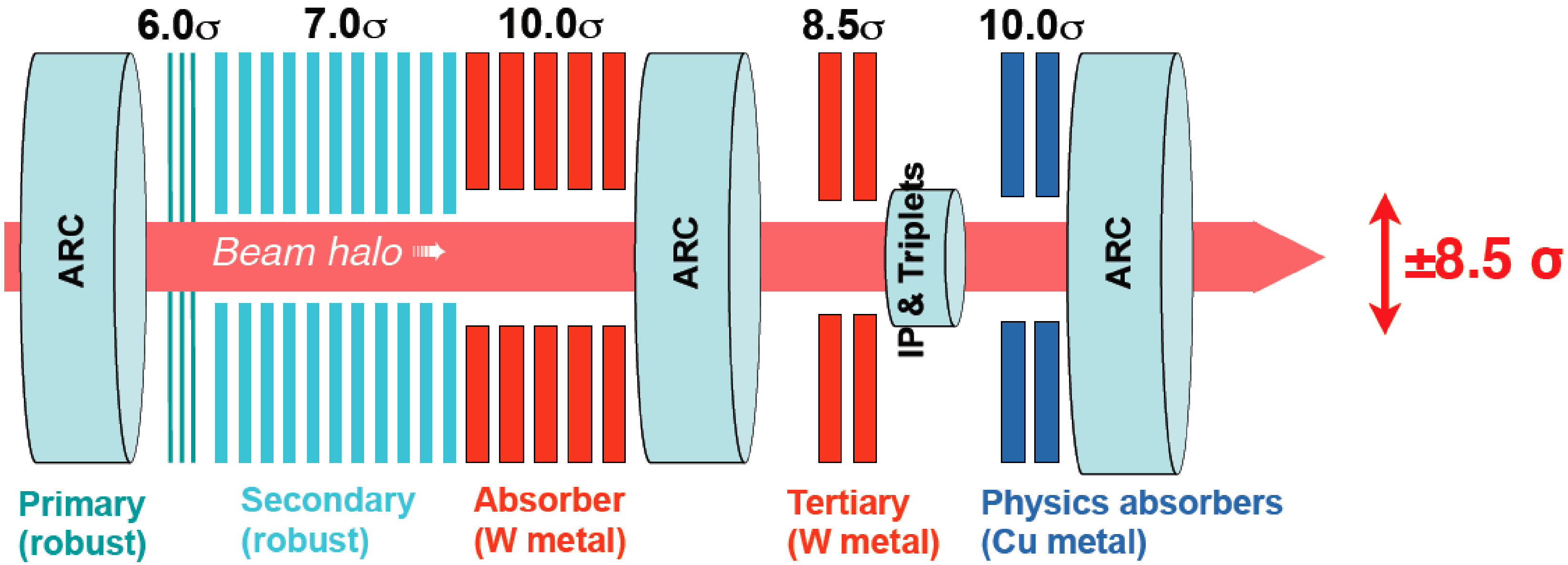
Passive protection and collimation system

Machine protection strategy

O(160GJ) in magnets
O(20) times LHC

⇒ Serious protection issue

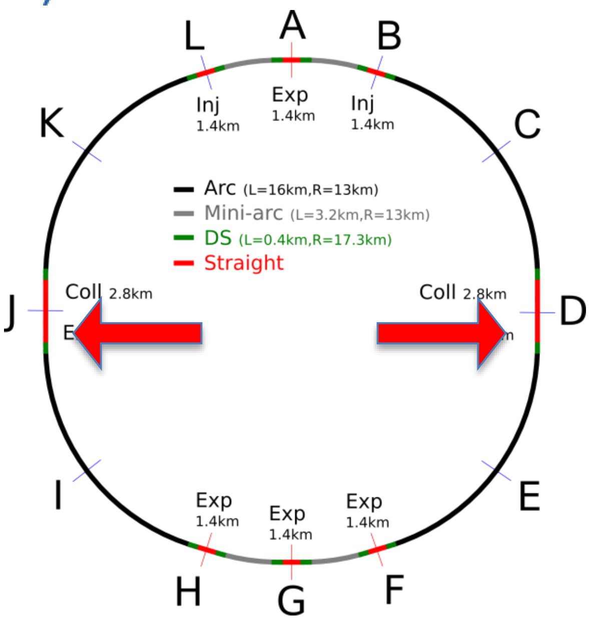
Collimation System



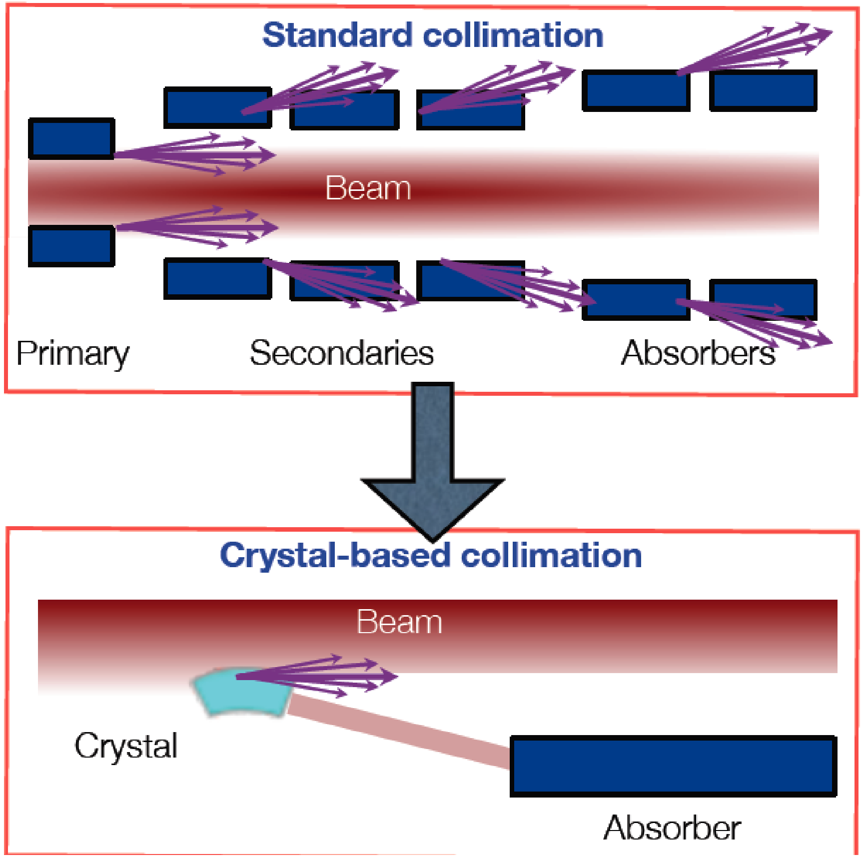
- Efficiency is important

- Robustness in case of fast beam loss (in a few minutes)
  ⇒ Materials, …

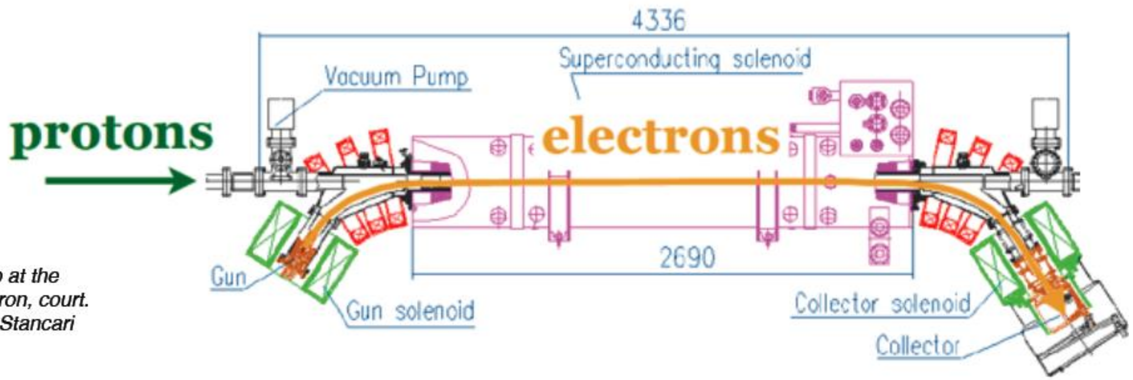
- Main impedance at collision energy
  => Optics, materials, …



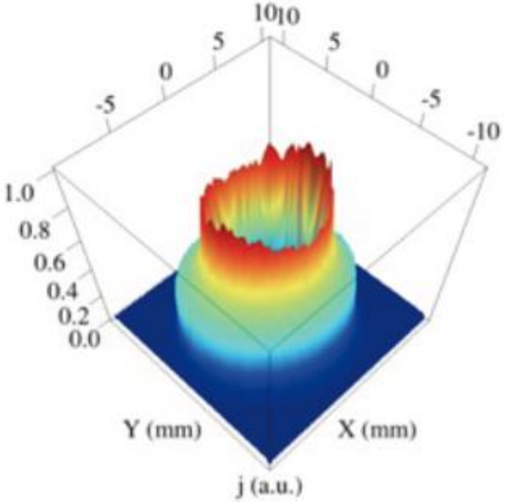
Collimation System Issues



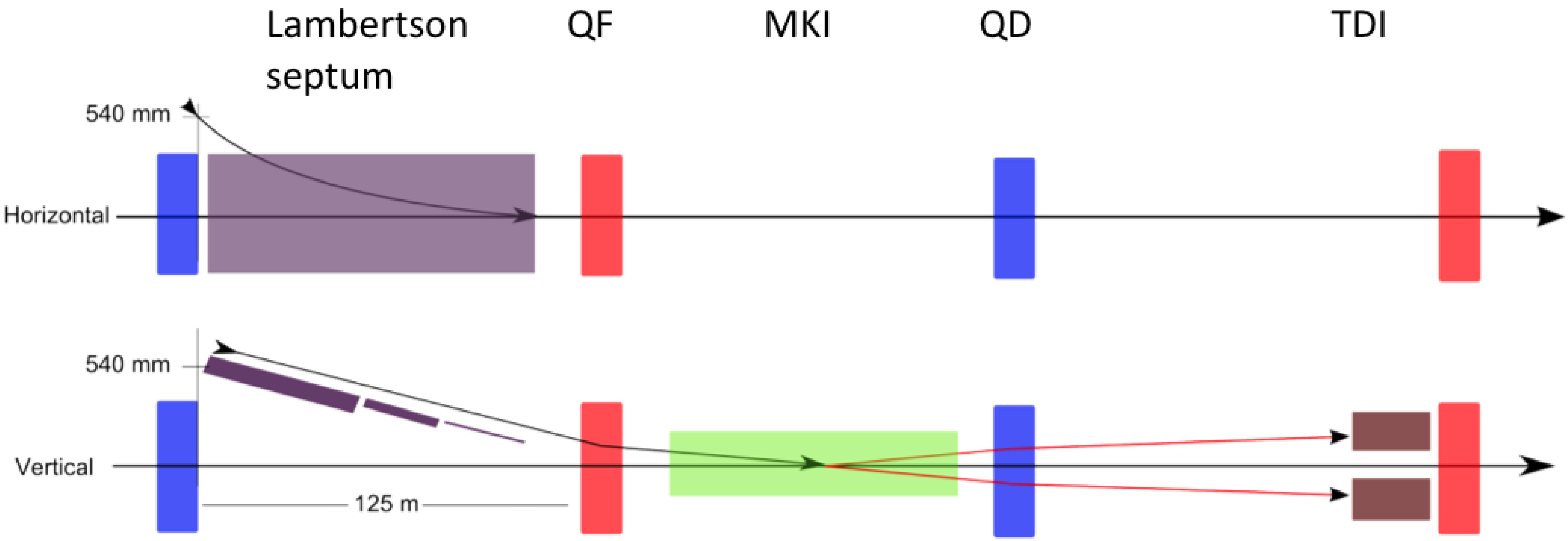
Other solutions are being investigated
- hollow beams
- crystals
- renewable collimators



Setup at the Tevatron, court. of G. Stancari



Injection/Extraction Challenge



- Total energy in beam batch injected needs to be limited
- With LHC limit can inject O(100) bunches

⇒ Very fast kicker (O(300ns)) for short gaps and beam filling factor of 80%
⇒ Design improvements? Massless septum?

- Miss-firing of extraction kicker can lead to losses

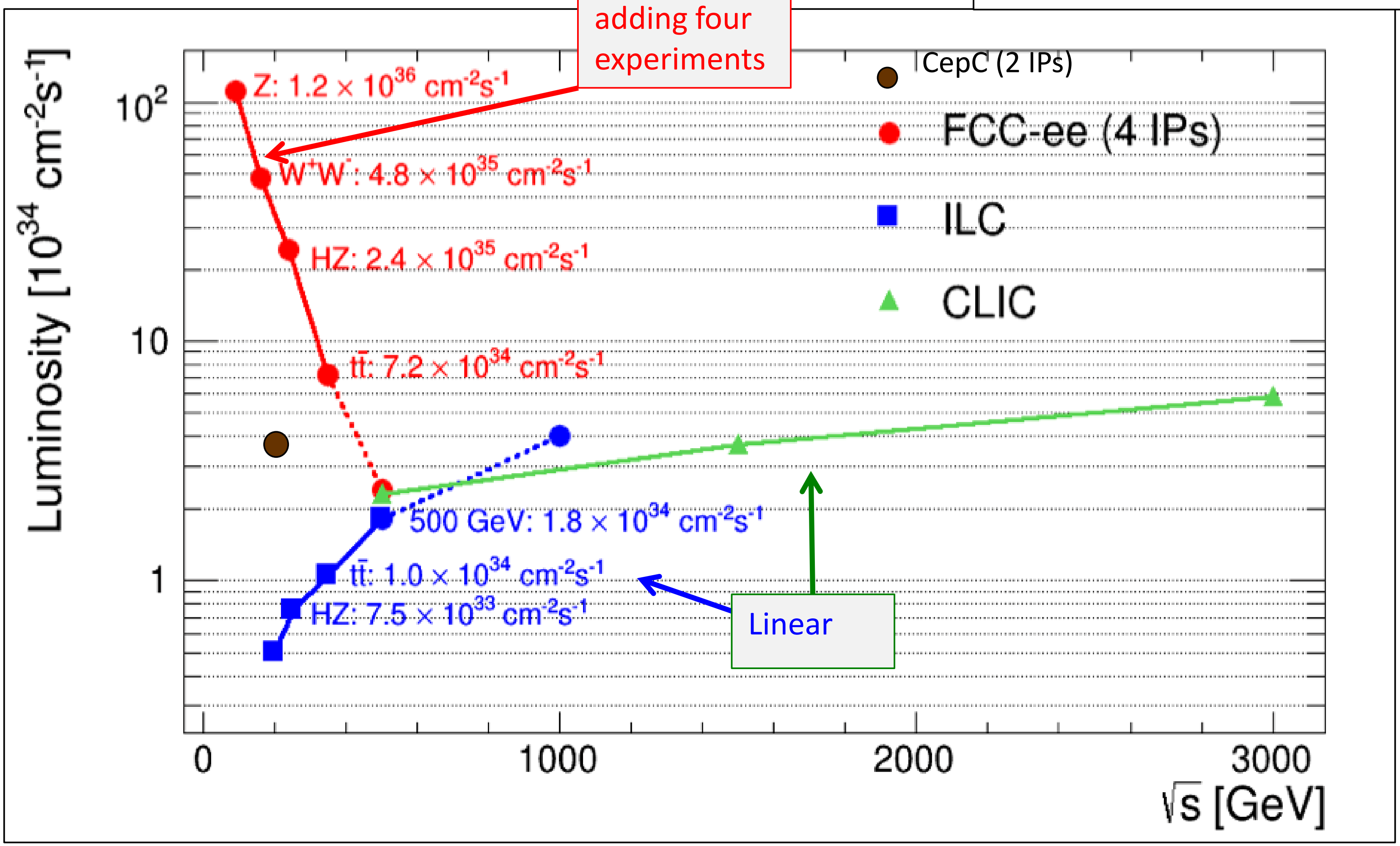
⇒ Which strategy?

FCC-ee

FCC-ee vs. Linear Colliders

F. Gianotti

Modified from original version: http://arxiv.org/pdf/1308.6176v3.pdf



Circular, adding four experiments

Linear

FCC-ee Parameters

Parameter	Z	W	H	t	LEP2
Cms E (GeV)	90	160	240	350	208
I (mA)	1450	152	30	7	4
No. bunches	16’700	4’490	1’360	98	4
$\beta^*_{x/y}$ (mm)	500 / 1	500 / 1	500 / 1	1000 / 1	1500 / 50
ε_x (nm)/ε_y (pm)	29/60	3.3/7	1/2	2/2	30-50/~250
σ_x(μm)/σ_y(nm)	120/250	40/84	22/45	45/45	250/3500
ξ_y	0.03	0.06	0.09	0.09	0.07
L (10^{34} cm^{-2}s^{-1})	28	12	6.0	1.8	0.012

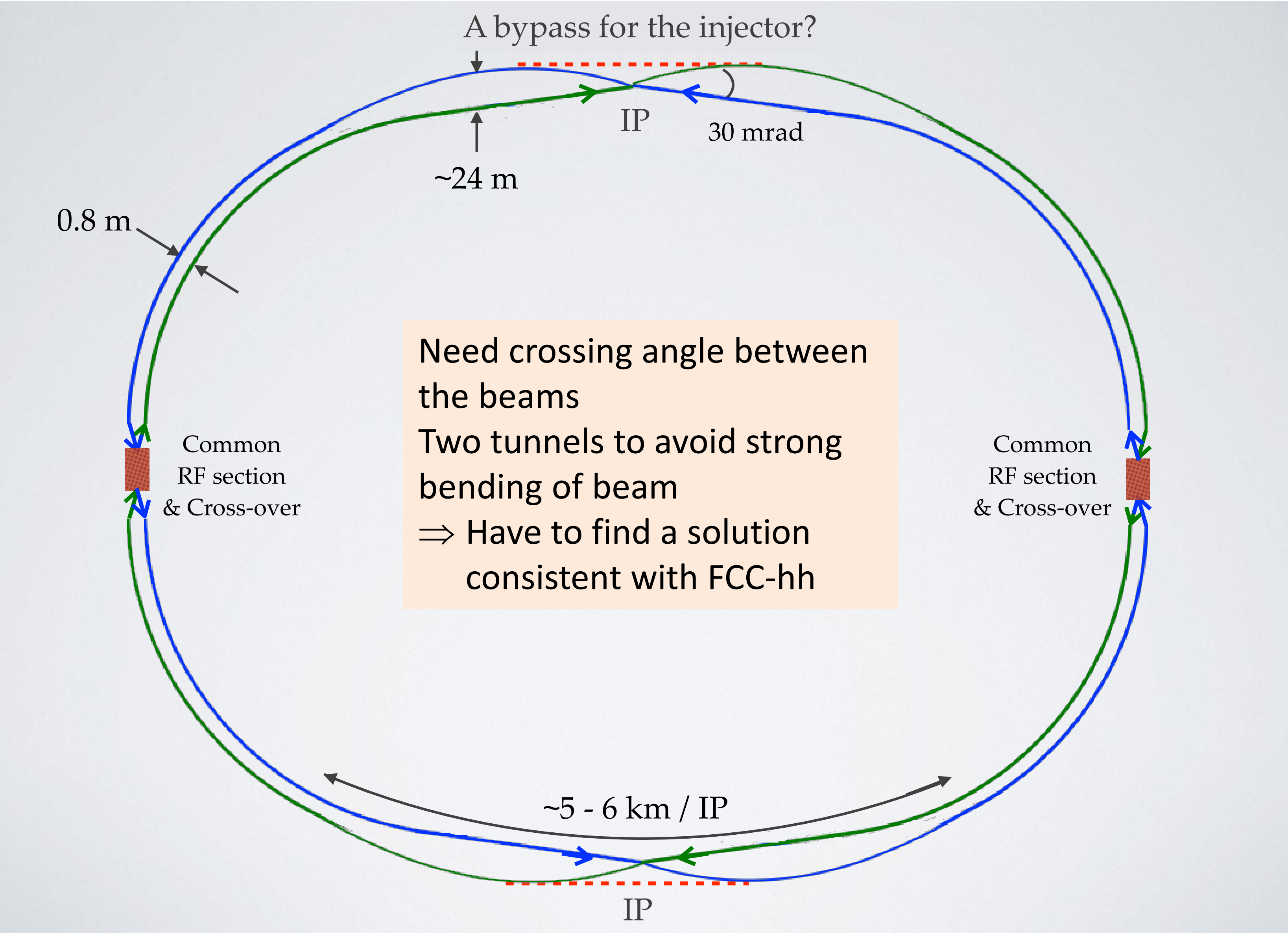
Using flat beams

Significant luminosity increase compared to LEP:
Smaller emittances, beta-functions, larger power consumption
Current limit 100MW of synchrotron radiation (both beams)

$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

More aggressive parameter sets also considered

Layout



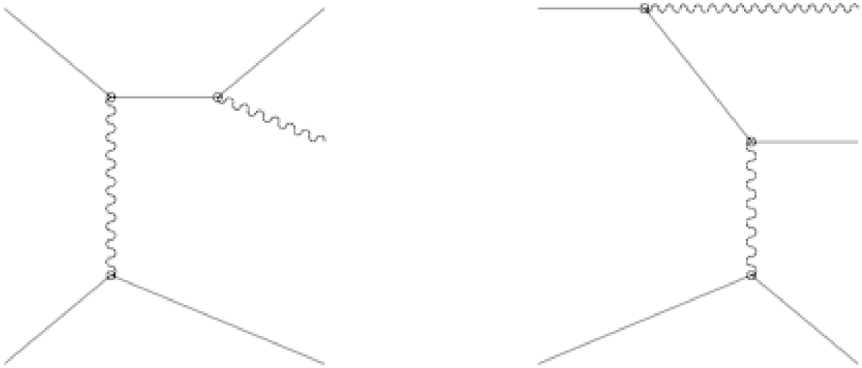
Need crossing angle between the beams

Two tunnels to avoid strong bending of beam

⇒ Have to find a solution consistent with FCC-hh

Luminosity Lifetime

Luminosity lifetime is dominated by radiative Bhabha scattering

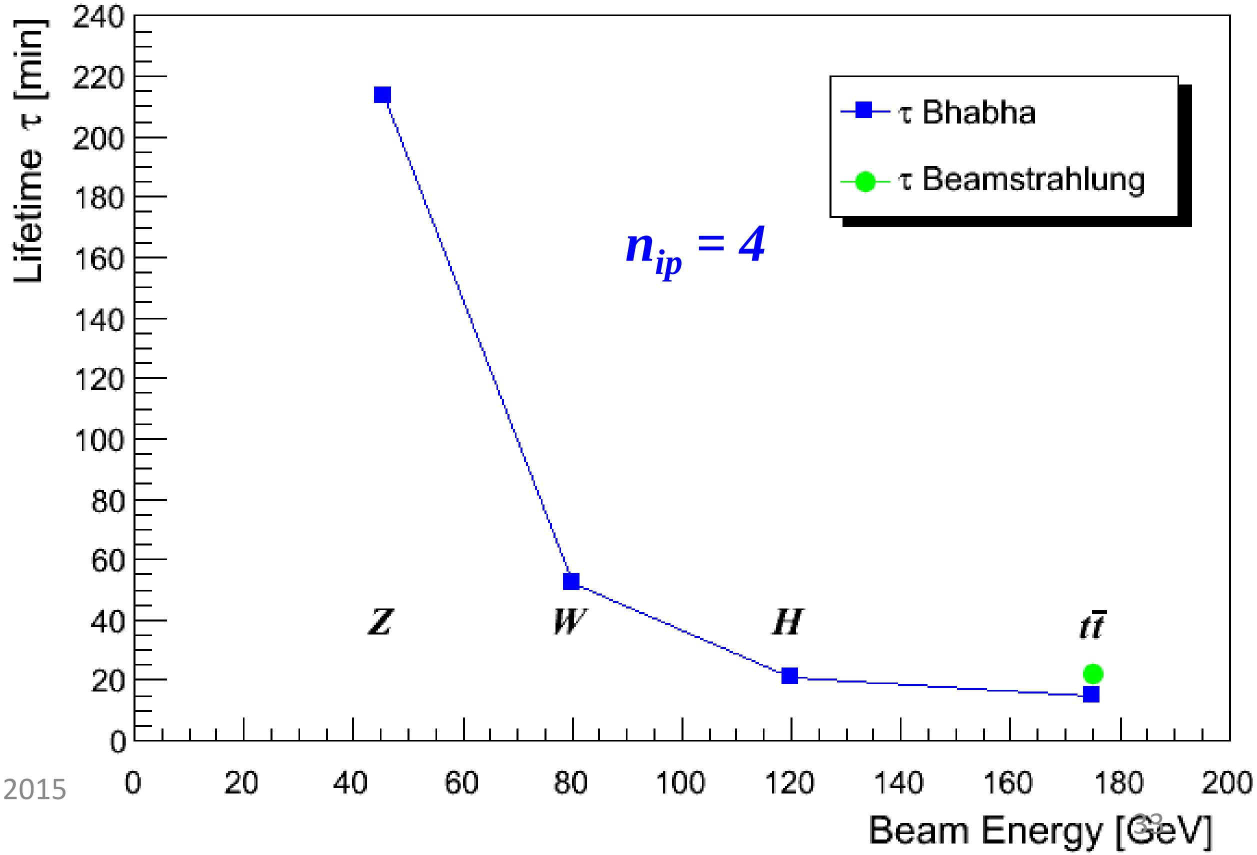


$$\tau_{ee} \propto \frac{I}{L\,\sigma_{ee}\,n_{ip}}$$

(total cross-section $\sigma_{ee} \approx 0.21\text{b}$)

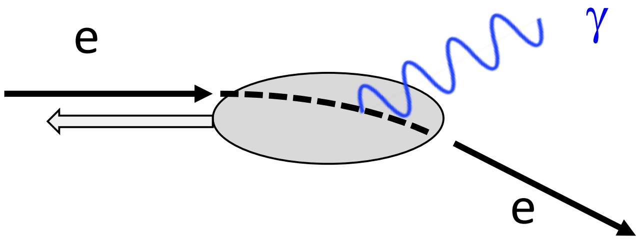
=> Lifetimes down to ~15 minutes at 350GeV

=> Continuous top-up injection



Beamstrahlung

- The colliding beams emit beamstrahlung like in a linear collider
- The average photon energy is small
- But a few photons have a large energy
- The electrons will be lost due to the energy error



To keep losses small require critical energy E_{crit} (3/2 average photon energy) to be much smaller than energy acceptance (η)

$$\frac{E_{crit}}{E} << h$$

$$\frac{E_{crit}}{E} \mu \frac{1}{E}\frac{E^3}{r} \mu \frac{N r_e E}{(s_x + s_y) s_z}$$

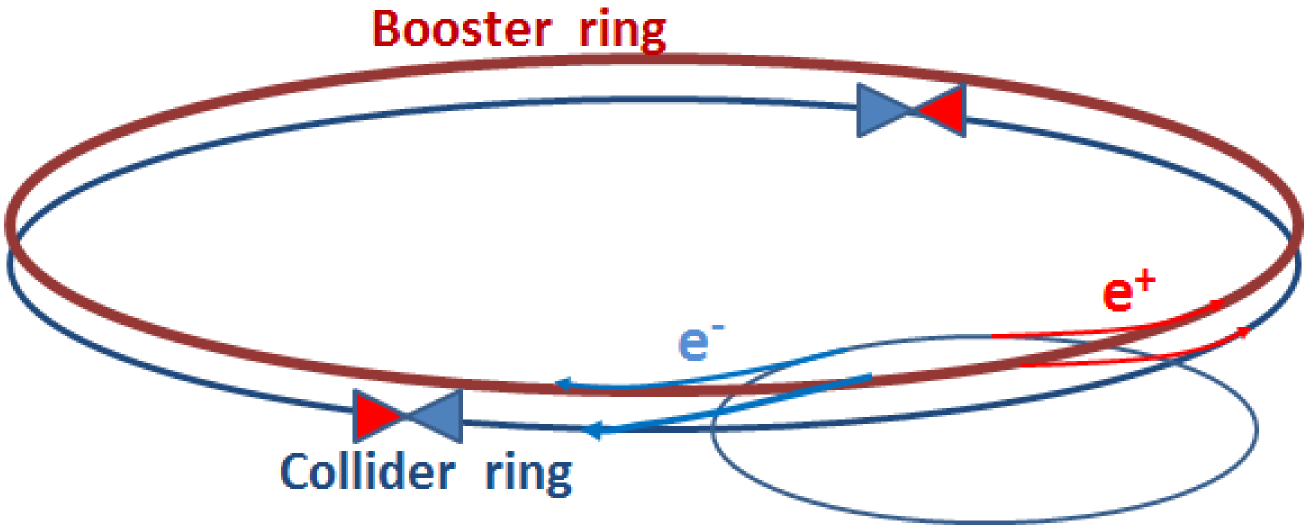
$\Rightarrow$ Flat beams

$\Rightarrow$ Beamstrahlung is an issue at higher energies

Top-up Injection

- Boost energy in booster ring to collision energy
- Inject into collider ring on top of circulating beam

- Requires third ring
- Can keep collider current almost constant, even with short lifetimes
- Tested in B-factories



Injection into booster at 20GeV
Injection into collider ring very 10s or so

FCC-he/LHeC

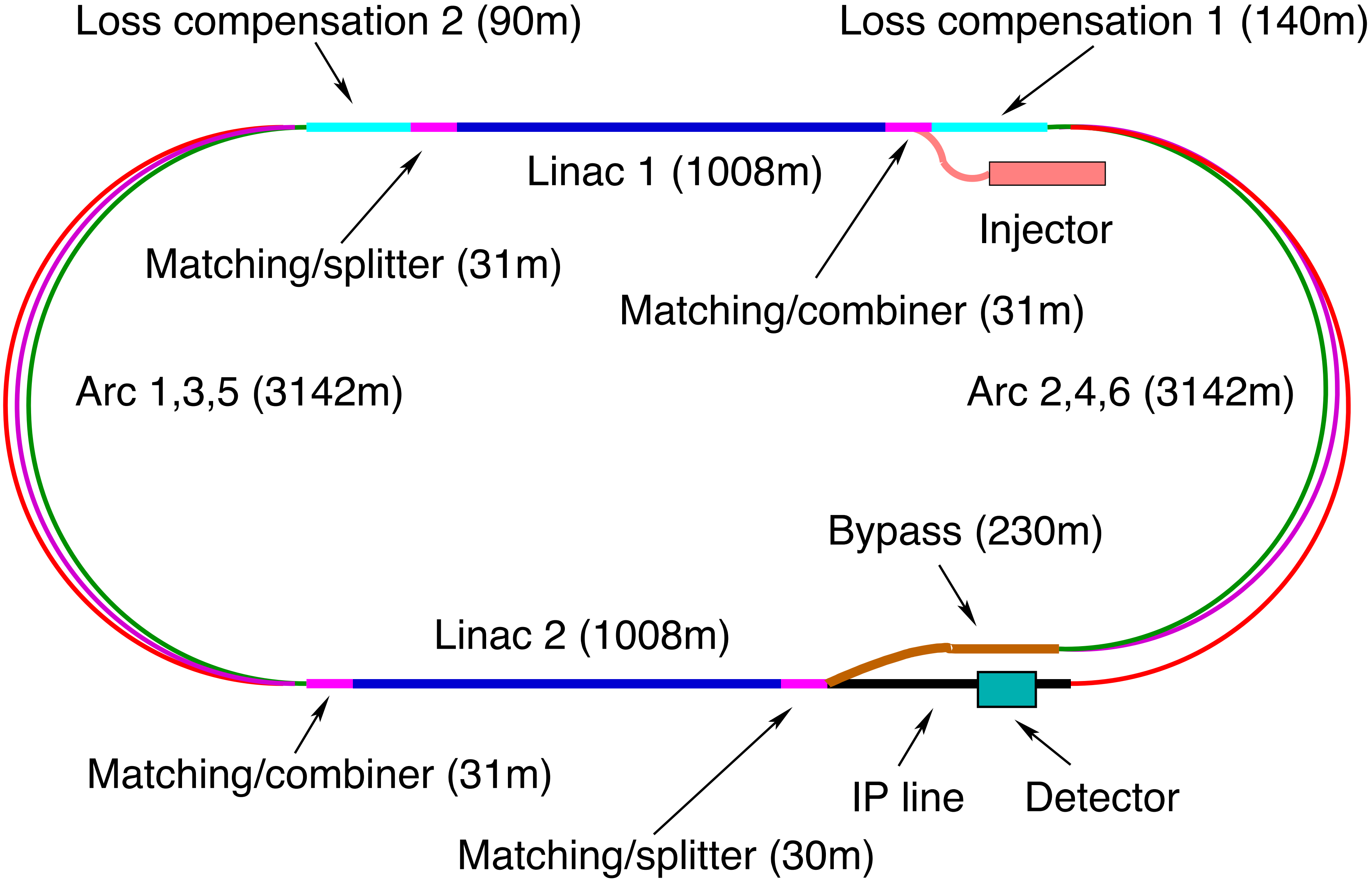
LHeC

- Collide LHC beam with electrons or positrons

- Study provided CDR (http://arxiv.org/abs/1206.2913)
  - Required electron energy is 60GeV
  - Luminosity of 10^{33}cm^{-2}s^{-1} (or now even 10^{34}cm^{-2}s^{-1})

- Two solutions
  - Ring-ring option
    - LEP-like ring
      - Feasible
      - But installation interferes with LHC operation and space requirements
  - Linac-ring option
    - Preferred solution, as it does interfere less with LHC

LHeC Linac-ring Option



Loss compensation 2 (90m)

Loss compensation 1 (140m)

Linac 1 (1008m)

Injector

Matching/splitter (31m)

Matching/combiner (31m)

Arc 1,3,5 (3142m)

Arc 2,4,6 (3142m)

Bypass (230m)

Linac 2 (1008m)

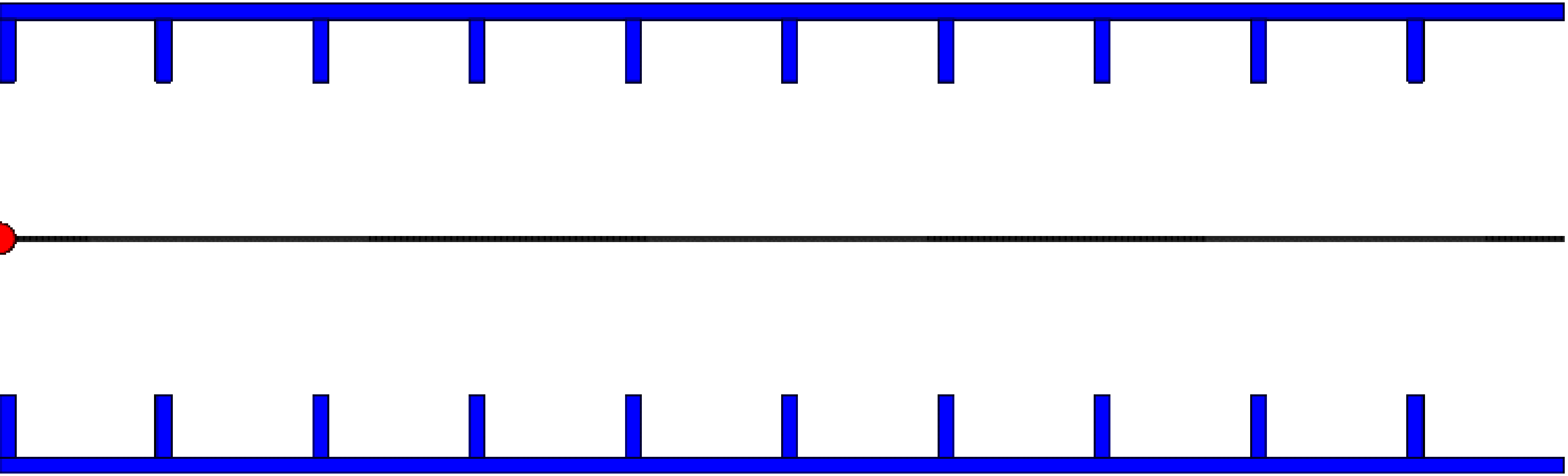
Matching/combiner (31m)

IP line

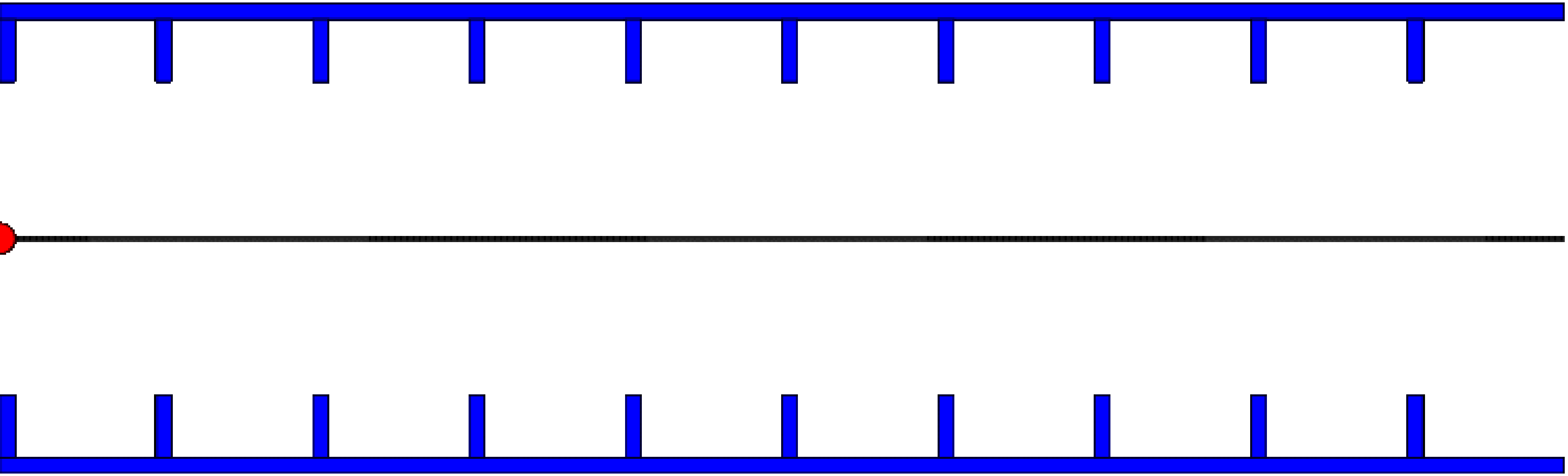
Detector

Matching/splitter (30m)

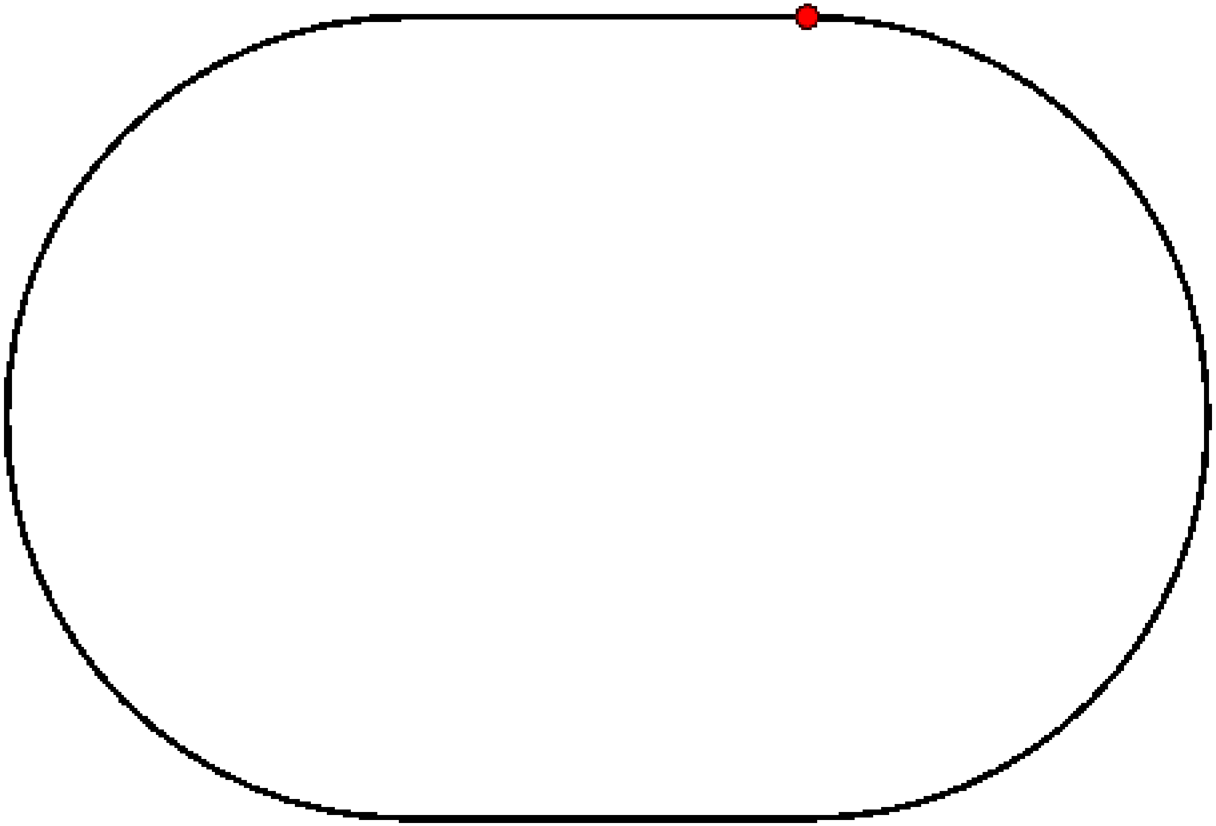
Cavity Principle



Energy Recovery Principle



LHeC Linac-ring Option



Principle has been tested at CEBAF (JLAB), but with small current/little beam-loading

IP Parameters

	protons	**electrons**
beam energy [GeV]	7000	60
Luminosity [10^{33}]	10	
normalized emittance $\gamma\epsilon_{x,y}$ [μm]	3.75 -> 2	50
IP beta function $\beta^*_{x,y}$ [m]	0.05	0.032
rms IP beam size $\sigma^*_{x,y}$ [μm]	3.7	3.7
beam current [mA]	860	12.8
bunch spacing [ns]	25	25
bunch population	2.2×10^{11}	2×10^{9}
Effective crossing angle	0.0	

Electron beam power

$P=E \times N_e/\Delta t \approx$ 800MW >> 100MW consumption

Note: Muon Collider

Muon Collider Concept

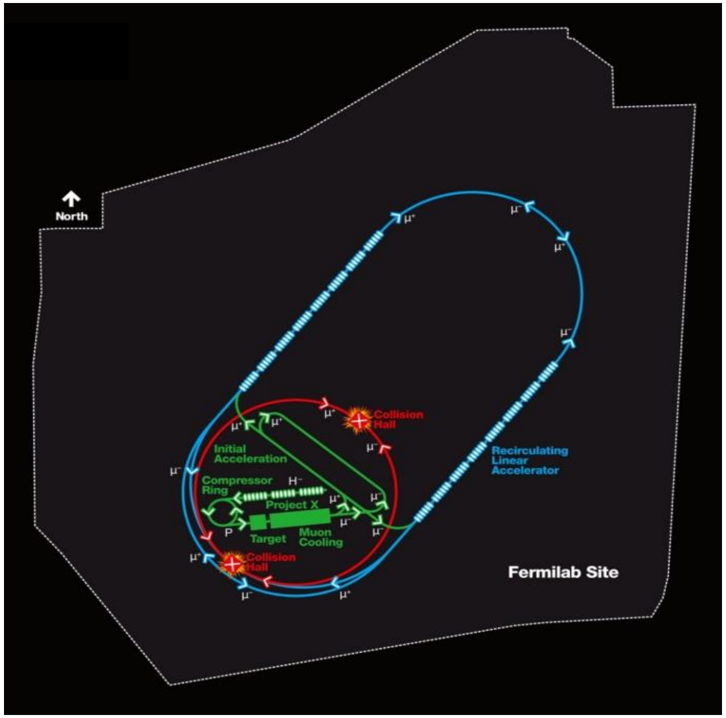
Muon are heavy so they emit little synchrotron radiation

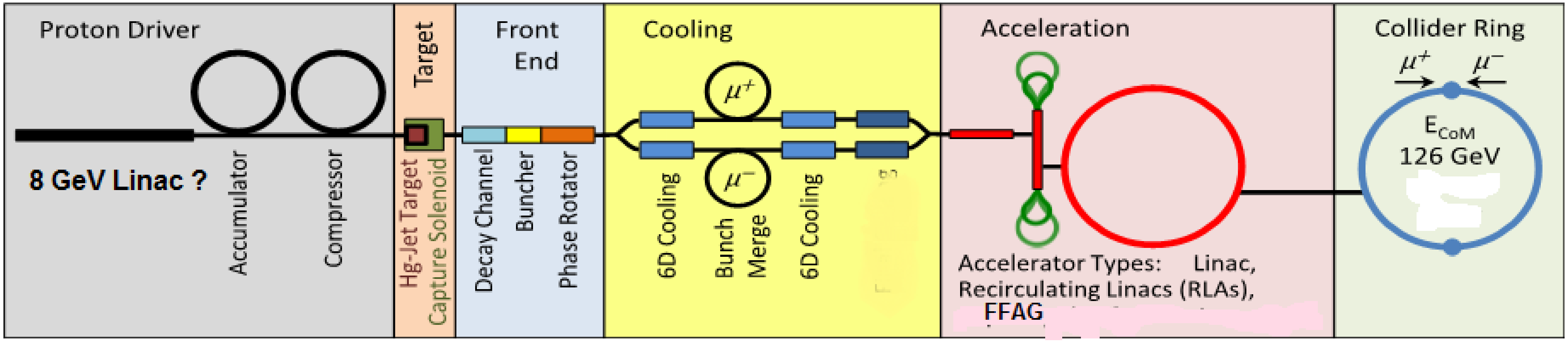
$$m_{m} » 106\,MeV/c^{2} » 207\,m_{e}$$

But they do not live very long

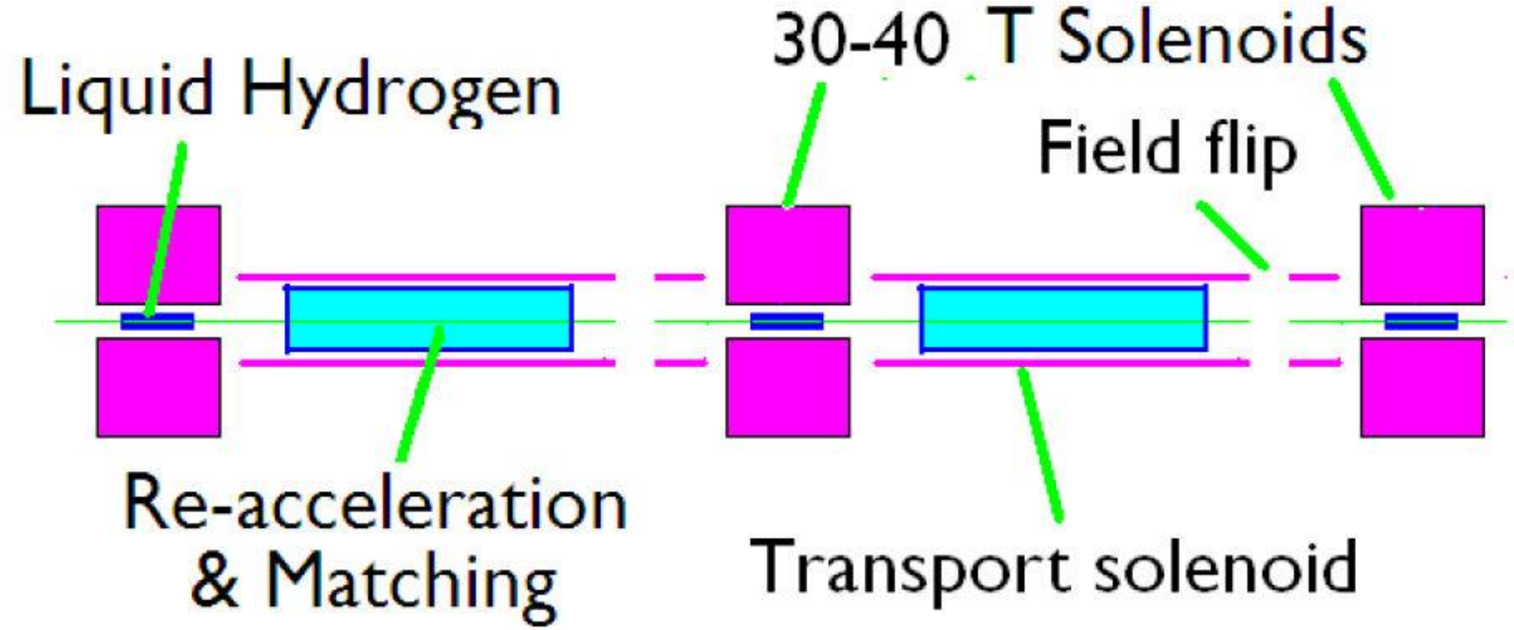
$$t_{m} » 2.2\,ms\ ´\ g$$

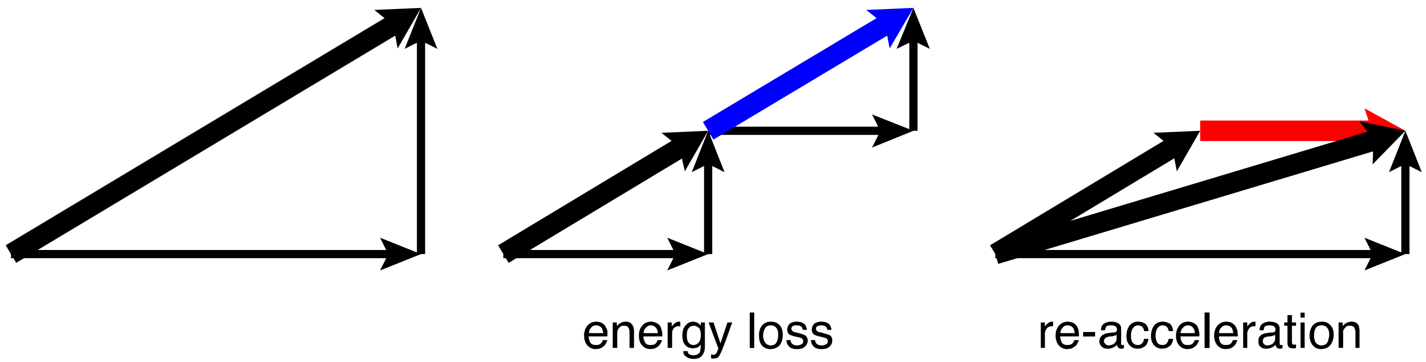
Produce them, cool them quickly and let them collide in a small ring



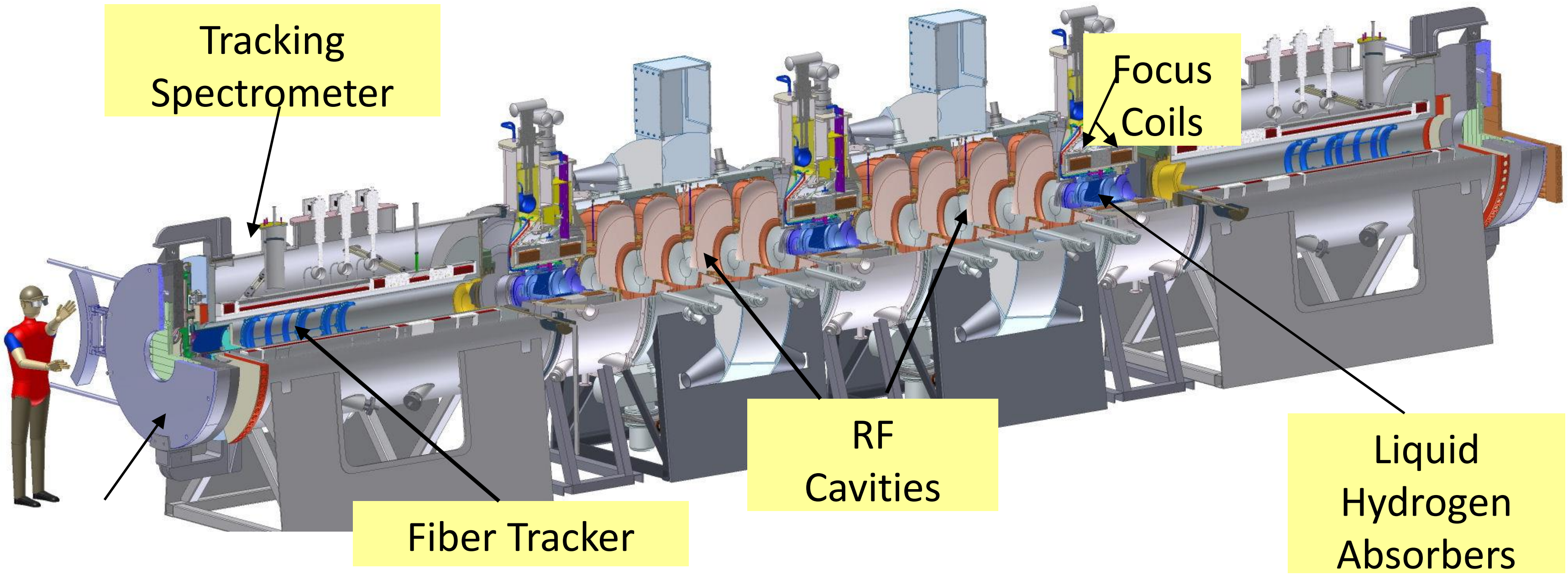


Final Transverse Cooling System





MICE



Under construction

Linda Coney, UCR

Will test 10% 4D emittance reduction (0.1% accuracy)

http://www.mice.iit.edu/

Single particle experiment

Muon Collider Parameters

M. Palmer

Muon Collider Parameters

		Higgs	**Multi-TeV**		
Parameter	***Units***	*Production Operation*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	**0.126**	**1.5**	**3.0**	**6.0**
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7sec		13,500	37,500	200,000	820,000
Circumference	km	0.3	2.5	4.5	6
No. of IPs		1	2	2	2
Repetition Rate	Hz	15	15	12	6
b*	cm	1.7	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	4	2	2	2
Norm. Trans. Emittance, e_{TN}	p mm-rad	0.2	0.025	0.025	0.025
Norm. Long. Emittance, e_{LN}	p mm-rad	1.5	70	70	70
Bunch Length, s_s	cm	6.3	1	0.5	0.2
Proton Driver Power	MW	4	4	4	1.6
Wall Plug Power	MW	200	216	230	270

Summary

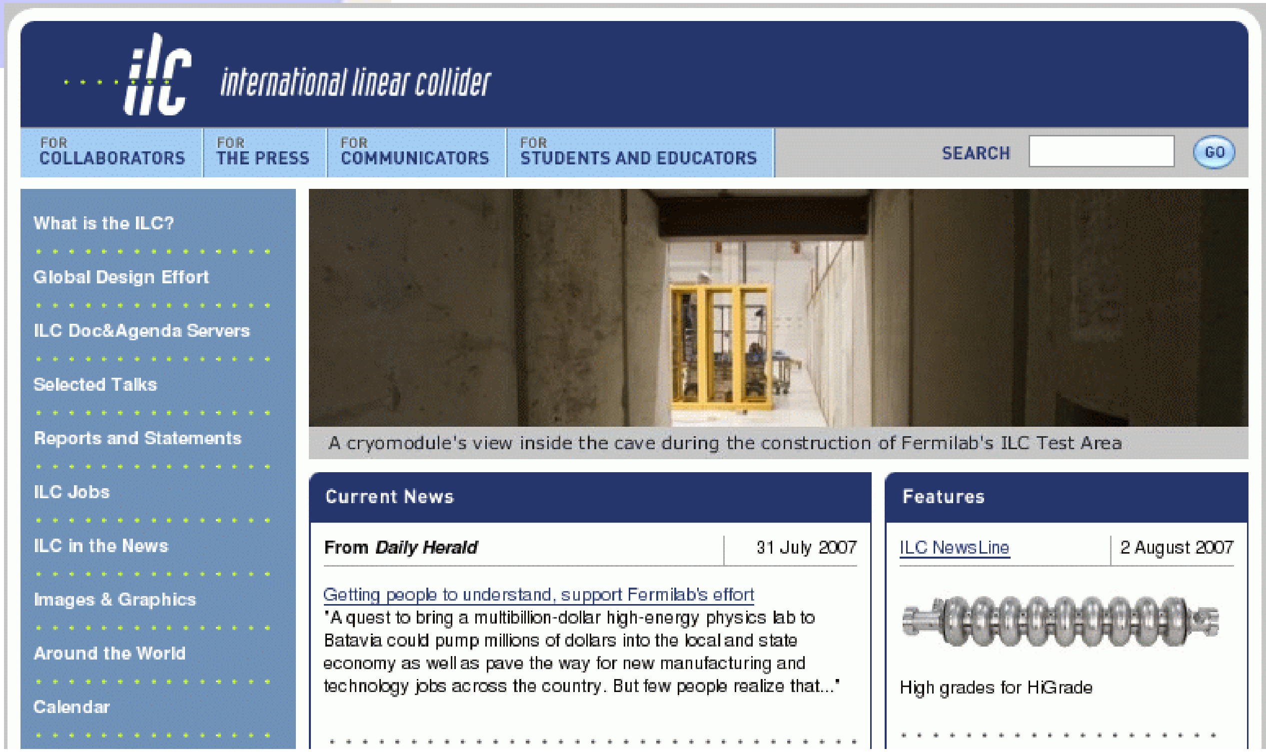
- CLIC
  - Given high priority by European strategy
  - Conceptual design for 3TeV (CDR exists), feasibility demonstrated, many components developed, staged approach exists, which will follow physics findings
  - Project plan to be developed for 2018
- ILC
  - Japan might offer to be the host (decision in 2016 if Japan will continue to study this)
  - Quite mature (TDR exists) for 500GeV, 1TeV under discussion
- Gamma-gamma collider
  - Linear collider add-on?
- Plasma acceleration
  - Very interesting long-term development, a very long way to go

- FCC-hh (potentially FCC-ee, FCC-eh)
  - Given high priority by European strategy
  - A conceptual design will be developed until 2018
- LHeC
  - Conceptual design report exists
  - Linked to FCC/LHC
- Muon collider
  - Cooling technology is being explored, would be a long way to go, will be reassessed

ILC Global Design Effort

- 2400 signatories of TDR (individuals)
- Has been drawing on the resources from O(300) institutes

www.linearcollider.org/ILC



A cryomodule's view inside the cave during the construction of Fermilab's ILC Test Area

Current News

From *Daily Herald* | 31 July 2007

Getting people to understand, support Fermilab's effort
"A quest to bring a multibillion-dollar high-energy physics lab to Batavia could pump millions of dollars into the local and state economy as well as pave the way for new manufacturing and technology jobs across the country. But few people realize that..."

Features

ILC NewsLine | 2 August 2007

High grades for HiGrade

Current CLIC Collaboration

FCC Collaboration

- 51 institutes
- 19 countries
- EC participation

http://cern.ch/fcc

Thanks

- Thanks for your patience

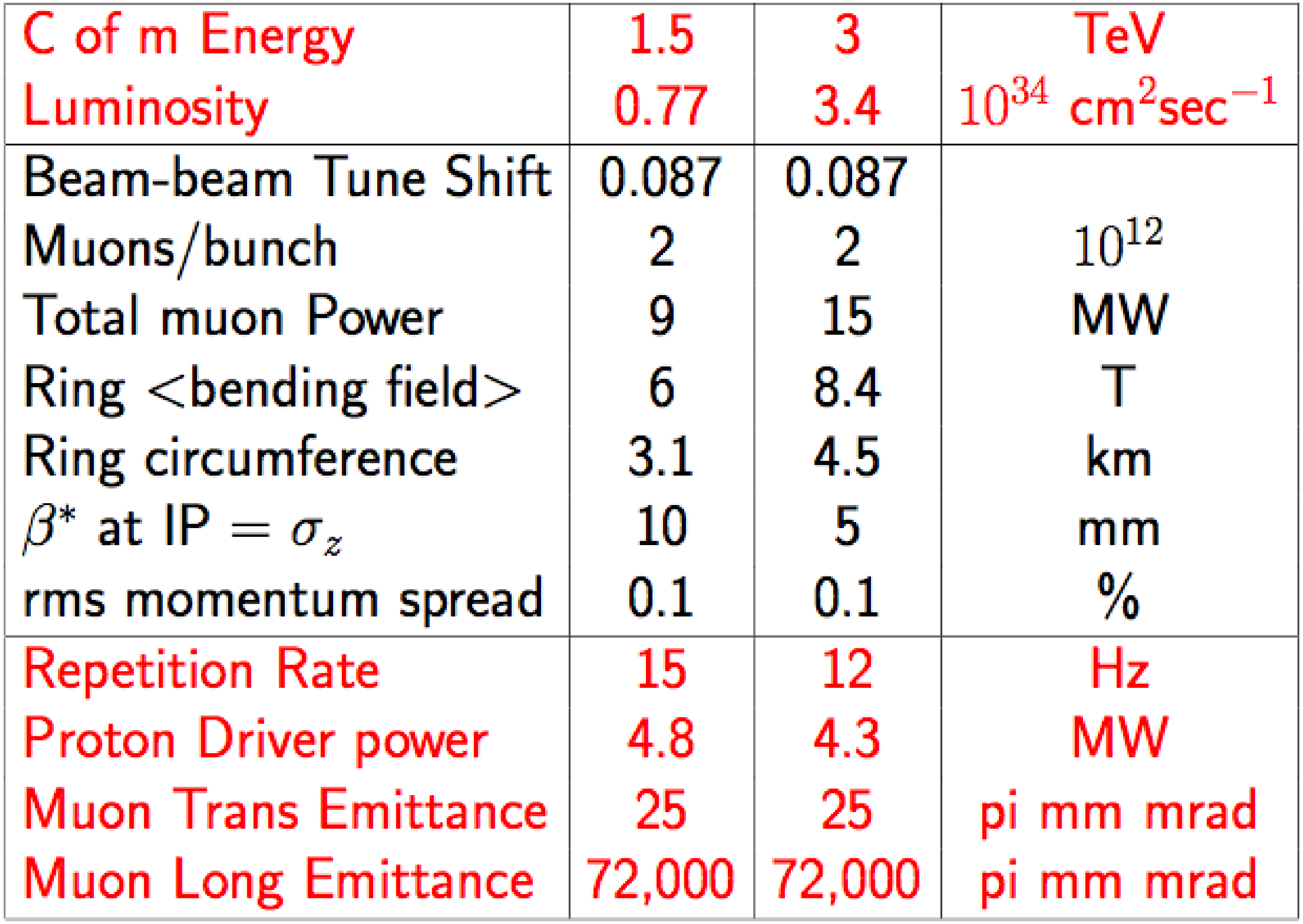
- Thanks to all the people who helped or from whom I stole figures
  - S. Stapnes, L. Rossi, Ralph Assmann, Jean-Pierre Delahaye, Lucie Linssen, Steffen Doebert, Alexej Grudiev, Frank Tecker, Walter Wuensch, Stephane Poss, Jan Strube, Joerg Wenninger, M. Benedikt, Frank Zimmermann, Bernhard Holzer, …

If you can look into the seeds of time, And say which
(Shakespeare)

Reserve

Muon Collider

Muon Collider Parameters

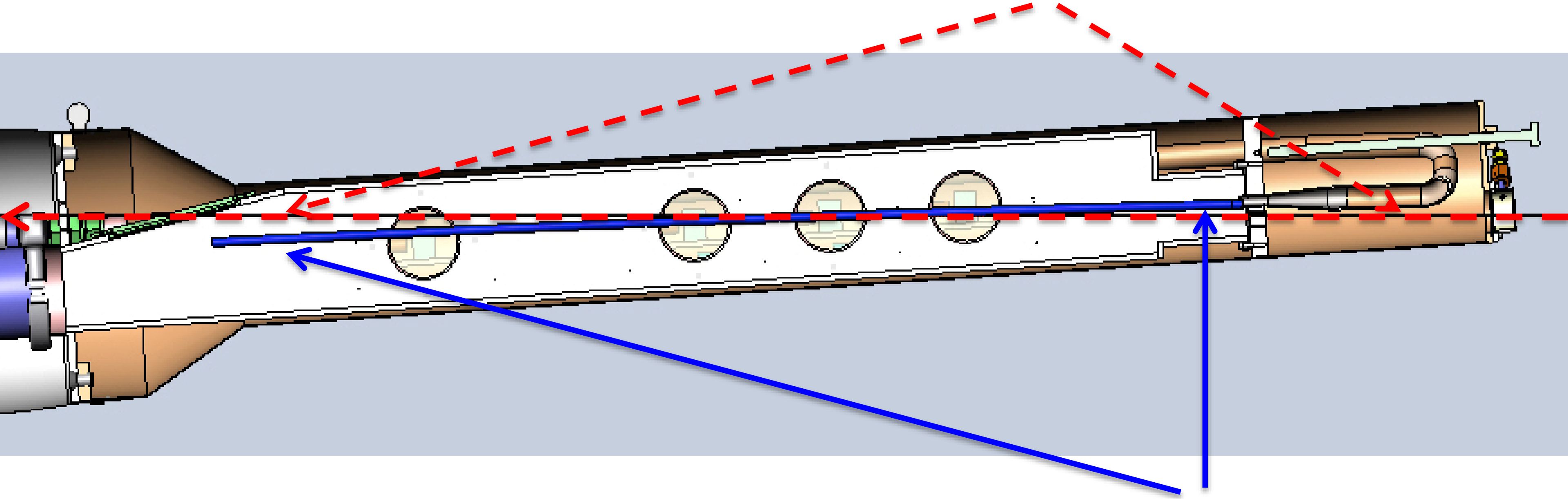


C of m Energy	1.5	3	TeV
Luminosity	0.77	3.4	10^{34} $\mathrm{cm}^2\mathrm{sec}^{-1}$
Beam-beam Tune Shift	0.087	0.087	
Muons/bunch	2	2	10^{12}
Total muon Power	9	15	MW
Ring <bending field>	6	8.4	T
Ring circumference	3.1	4.5	km
β^* at IP $= \sigma_z$	10	5	mm
rms momentum spread	0.1	0.1	%
Repetition Rate	15	12	Hz
Proton Driver power	4.8	4.3	MW
Muon Trans Emittance	25	25	pi mm mrad
Muon Long Emittance	72,000	72,000	pi mm mrad

http://www.fnal.gov/pub/muon_collider/collaboration-links.html

Muon Production: MERIT Experiment

Protons → Target → Pions → Muons

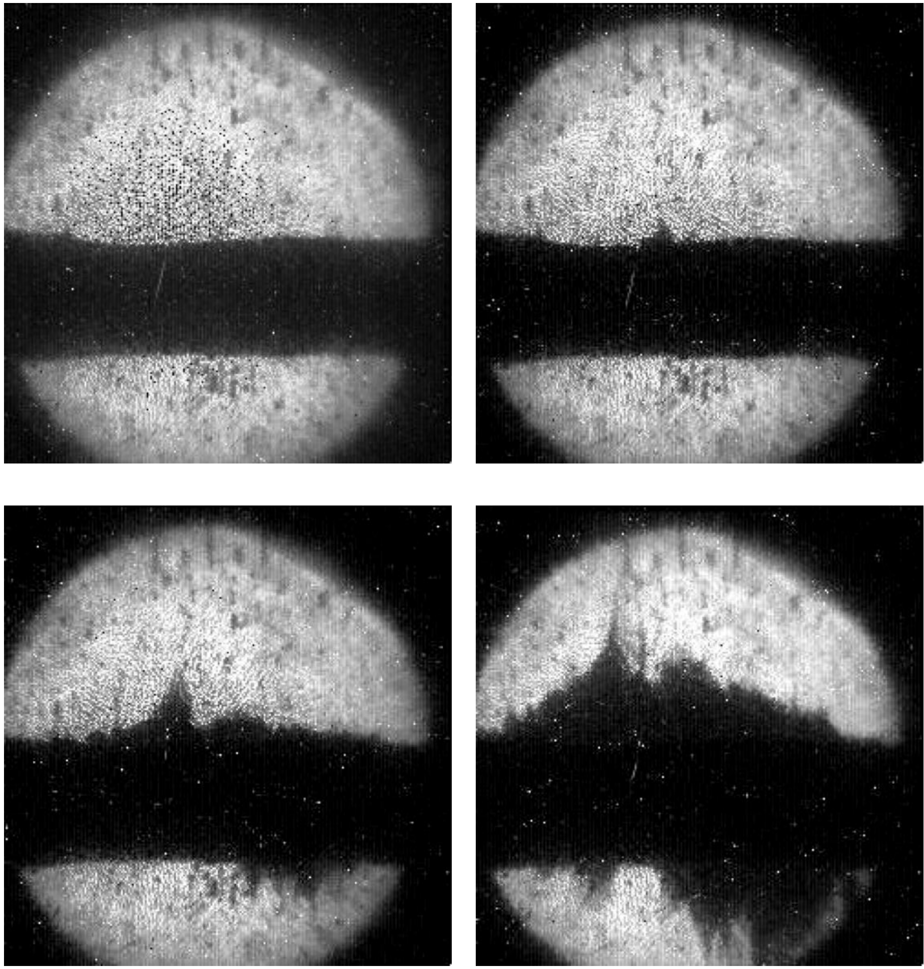


Proton beam

Liquid mercury target to avoid destruction

MERIT experiment at CERN

MERIT

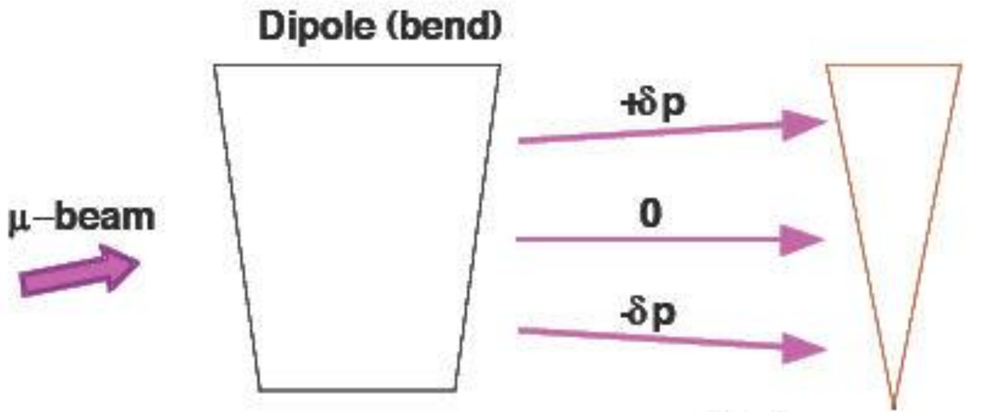


The jet explodes **after** the beam is generated
-> success

Longitudinal Cooling/Emittance Exchange

Used together with transverse cooling at the beginning

Several options under study



Dipole introduces dispersion (η)

$$x \rightarrow x_0 + \eta \, {}^{dp}\!/\!_{p}$$

Wedge Absorber reduces energy spread

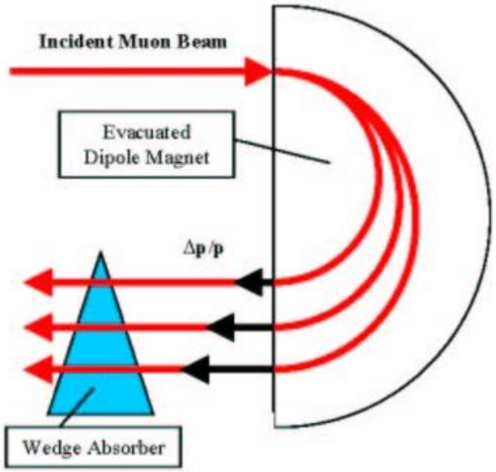


Figure 1. Use of a Wedge Absorber for Emittance Exchange

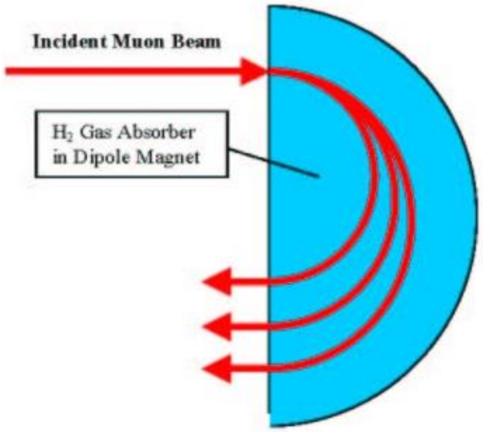
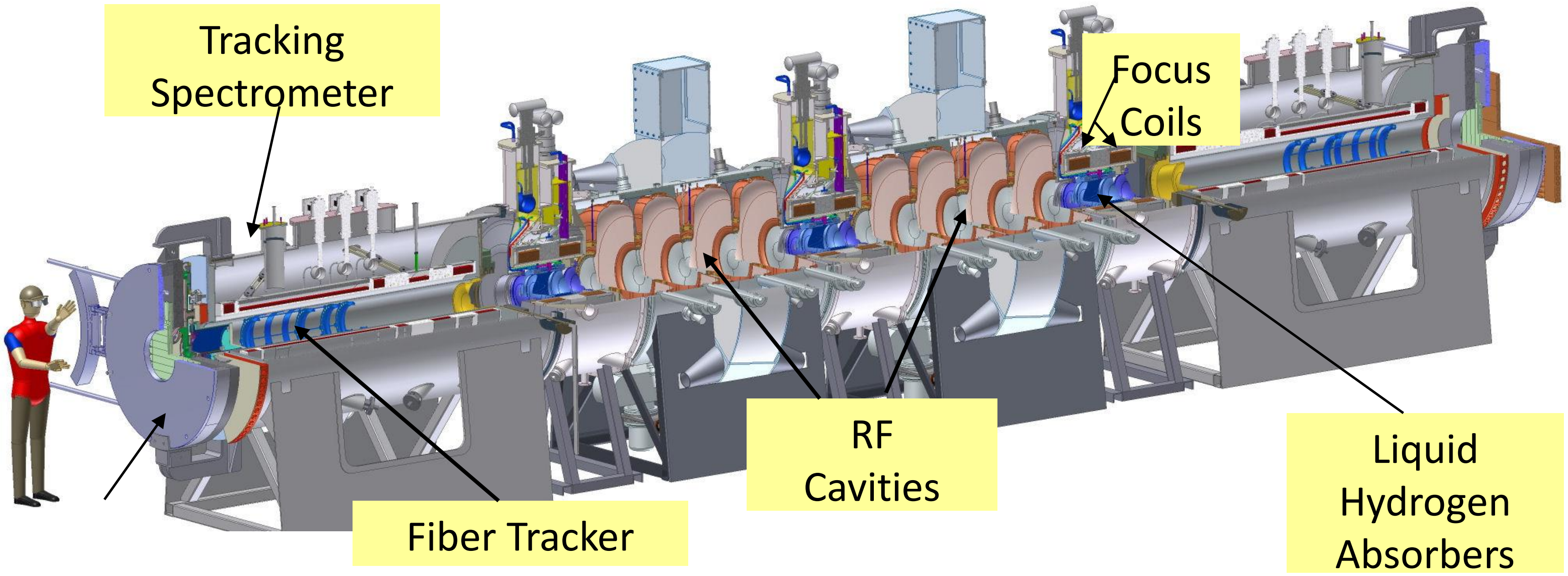


Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

MICE



Under construction

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Will test 10% 4D emittance reduction (0.1% accuracy)

http://www.mice.iit.edu/

Single particle experiment

LHeC

road map to 10^{33} cm^{-2}s^{-1}

luminosity of LR collider:

(round beams)

$$L = \frac{1}{4\pi e}\frac{N_{b,p}}{\varepsilon_p}\frac{1}{\beta_p^*} I_e H_{hg}$$

highest proton
beam brightness “permitted”
(ultimate LHC values)

$\gamma\varepsilon$=3.75 µm

$N_b = 1.7\times10^{11}$

bunch spacing
25 or 50 ns

smallest conceivable
proton β* function:
- reduced *l** (23 m → 10 m)
- squeeze only one *p* beam
- new magnet technology *Nb$_3$Sn*

β^*=0.1 m

average e$^-$
current !

maximize geometric
overlap factor
- head-on collision
- small e- emittance

θ_c=0

$H_{hg} \geq 0.9$

ERL electrical site power

cryo power for two 10-GeV SC linacs: 28.9 MW

MV/m cavity gradient, 37 W/m heat at 1.8 K

700 “W per W” cryo efficiency

RF power to control microphonics: 22.2 MW

10 kW/m (eRHIC), 50% RF efficiency

RF for SR energy loss compensation: 24.1 MW

energy loss from SR 13.2 MW, 50% RF efficiency

cryo power for compensating RF: 2.1 MW

1.44 GeV linacs

microphonics control for compensating RF: 1.6 MW

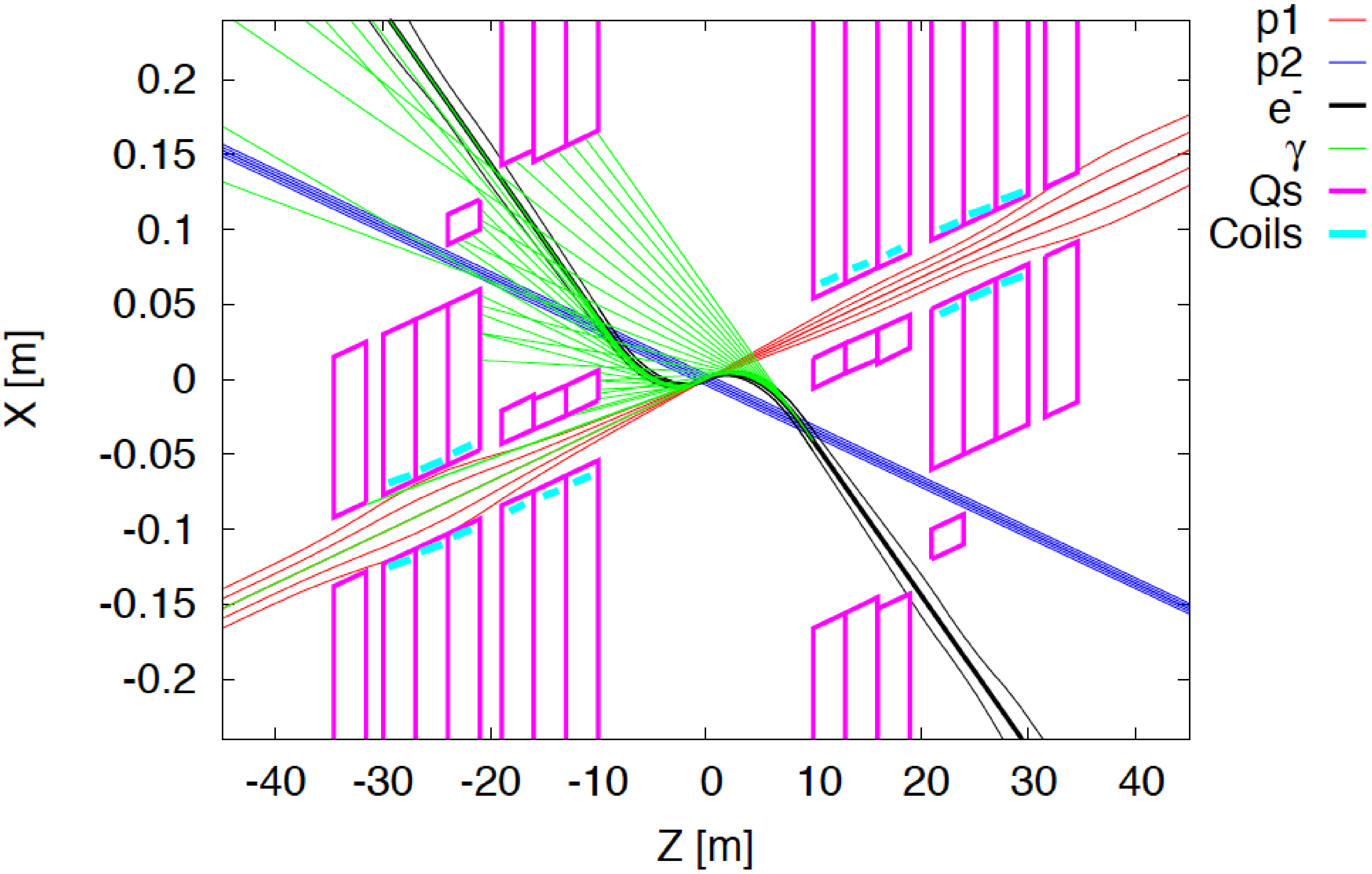
injector RF: 6.4 MW

500 MeV, 6.4 mA, 50% RF efficiency

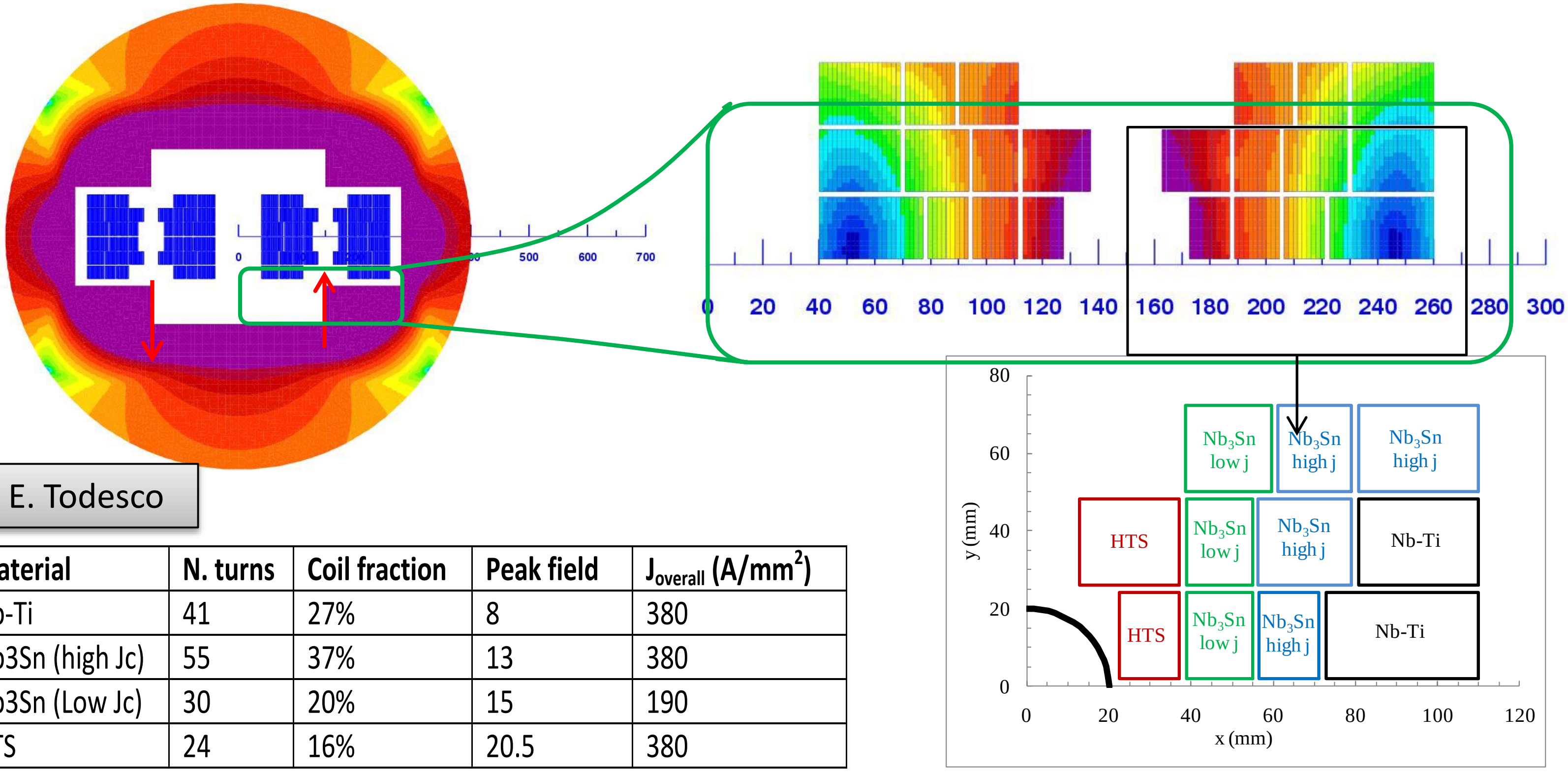
magnets: 3 MW

grand total = 88.3 MW

Interaction Region



Example Magnet Design



L. Rossi and E. Todesco

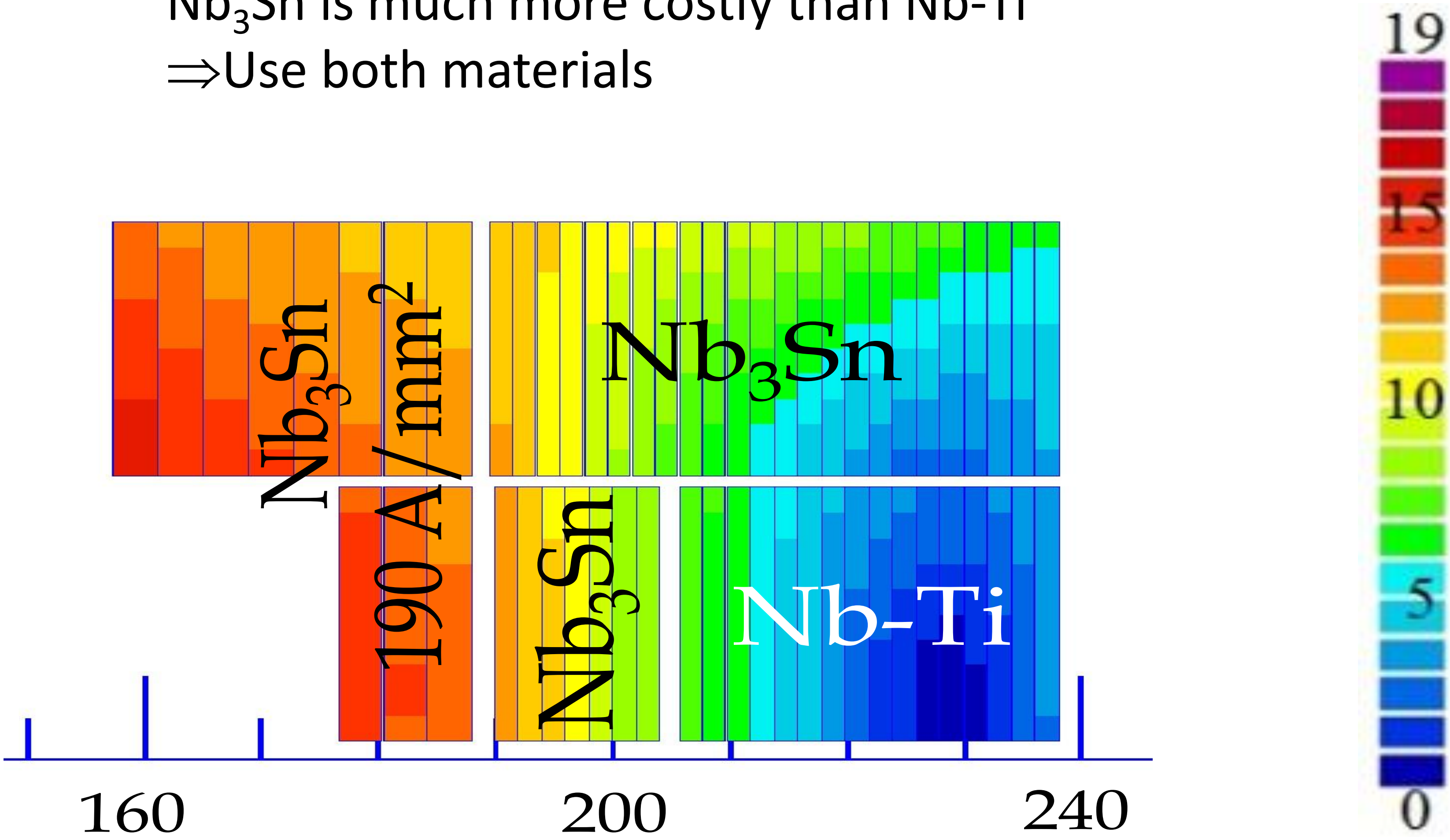
Material	N. turns	Coil fraction	Peak field	$J_{overall}$ (A/mm^2)
Nb-Ti	41	27%	8	380
Nb3Sn (high Jc)	55	37%	13	380
Nb3Sn (Low Jc)	30	20%	15	190
HTS	24	16%	20.5	380

Magnet design: 40 mm bore (depends on injection energy: > 1 Tev)
Very challenging but feasable: 300 mm inter-beam; **anticoils to reduce flux**
Approximately 2.5 times more SC than LHC: 3000 tonnes!
Multiple powering in the same magnet for FQ (and more sectioning for energy)
Certainly only a first attempt: cosϑ and other shapes will be also investigated

Cost Effective Magnet Design

Nb_3Sn is much more costly than Nb-Ti

⇒Use both materials

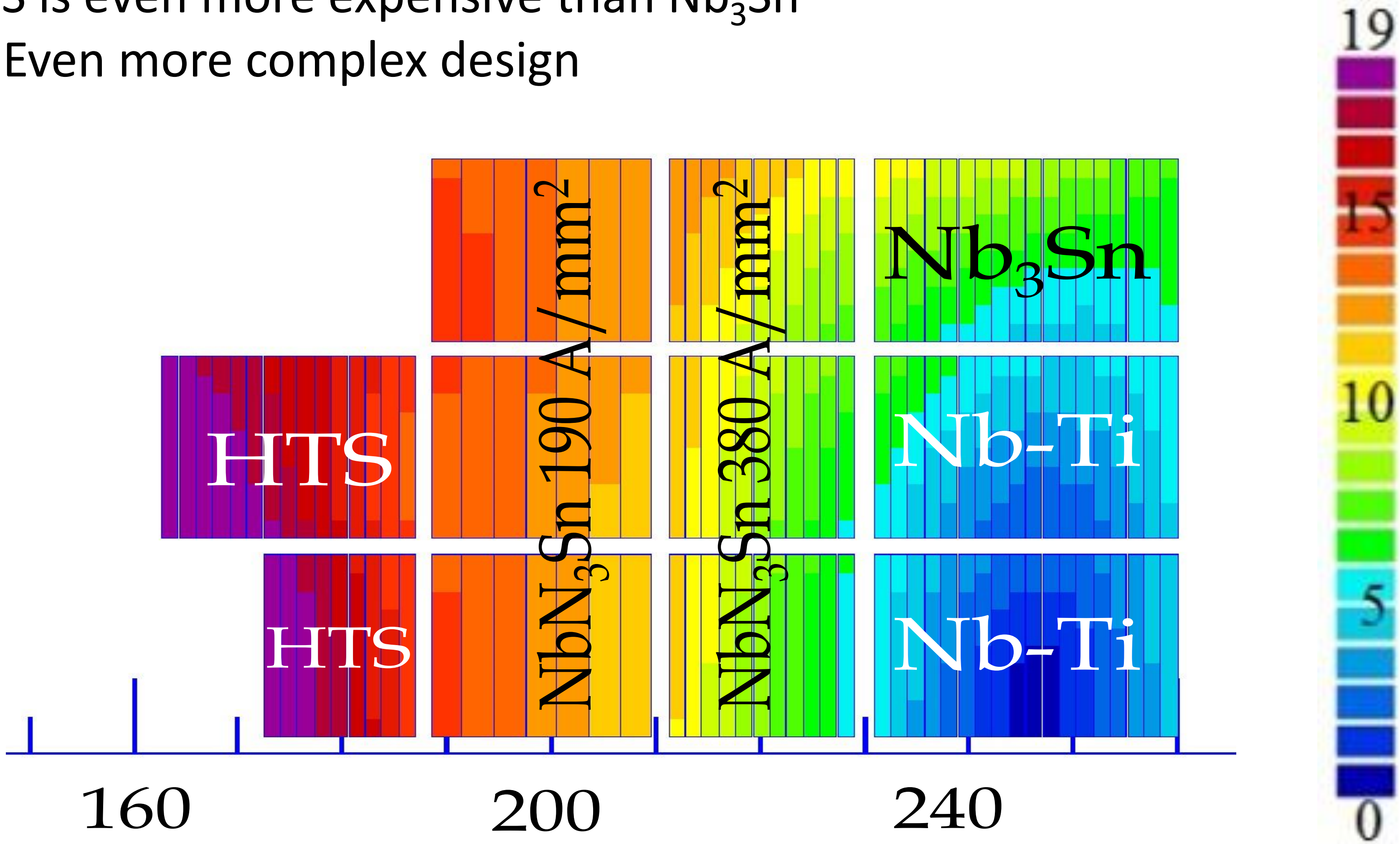


Coil sketch of a 15 T magnet with grading, E. Todesco

Cost Effective Magnet Design II

HTS is even more expensive than Nb_3Sn

⇒ Even more complex design



Coil sketch of a 20 T magnet with grading, E. Todesco

Beam Intensity During Run

Non-linear fields
- Particles can go on unstable points in phase space
- Drift to large amplitudes

⇒ Reduce the probability

Collimation should remove these particles

Beam-gas scattering
- Showers into magnets are a problem

⇒ Very good vacuum

Collimation removes some of these particles
Magnets have to take the rest

Luminosity
- Particles are destroyed in collision

⇒ Proportional to luminosity

Main effect of intensity loss
100-500kW per experiment
Important shielding problem