Perspective on future challenges for very high energy hadron colliders

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Layout

- Laundry list for FCC
  - Challenges
  - R&D
- What means Very High Energy Hadron Colliders
- Prospects for future problems

FCC challenges are mostly extensions of those faced LHC and are facing HL LHC

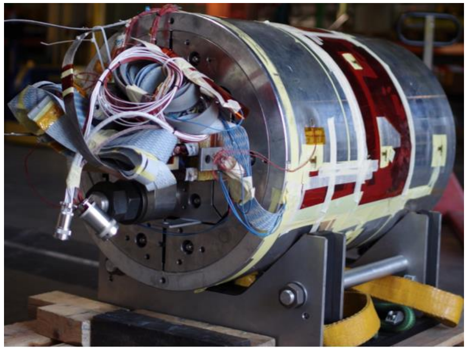
Laundry list – technology challenges

(from presentation by J. M. JIMENEZ and O. BRUNNER

- 1.1 **Cryogenic beam vacuum system conception**
  - 2.1 **Magnetic refrigeration for SC RF cavities**
  - 2.2 **Proximity Cryogenics for FCC-hh**
  - 3.1 **Kicker generator with solid state switch technology**
  - 3.2 **Kicker magnet R&D**
  - 3.3 **Septum magnet R&D**
  - 3.4 **Fast electronics, triggering and switch controls**
  - 6.1 **Transverse Feedback (TFB)**
  - 7.1 **Studies on beam intercepting devices for FCC**
  - 8.1 **Beam loss monitors (BLM) for FCC-hh**
  - 9.1 **FCC hh Vacuum challenges**
  - 9.3 **TL-based superconducting coatings for the FCC-hh**
  - 10.1 **Helium leaks mitigation**
  - 11.1 **Radiation Hardness**
  - 12.1 **Powering, protection architecture for high field circuits**
  - 12.2 **Concept & Architecture of the machine protection and interlock systems**
  - 12.3 **HTS magnet protection**

Identified FCC Challenges

- Operational 16T (edge for Nb_3Sn) SM magnets (means reaching 20 T in tests)



- Synchrotron radiation
  - blessing: damping, higher luminosity
  - and curse: 30 W/m power to absorb at cryogenic t° 300 kW x Carnot
  - compare with room t° : 10 kW/m
  - SR caused desorption and vacuum

- Energy stored in the beam ~8.4 GJ
  - protection from accidental beam loss
  - the special beam abort dumps
  - sophisticated collimation system
  - …..

FCC CHALLENGES ARE LHC CHALLENGES ON STEROIDS

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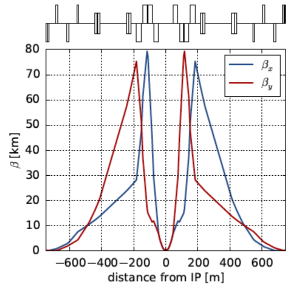
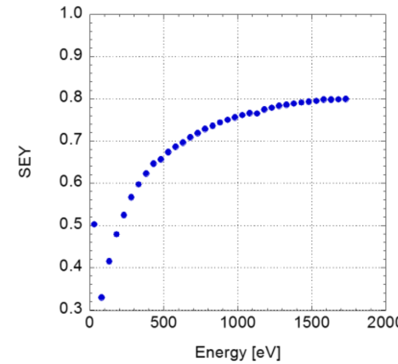
Identified FCC Challenges

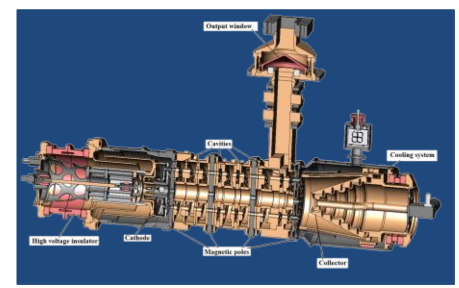
- Small β* at L*=45m
  - Dynamic aperture, energy acceptance for 100 hrs beam lifetime



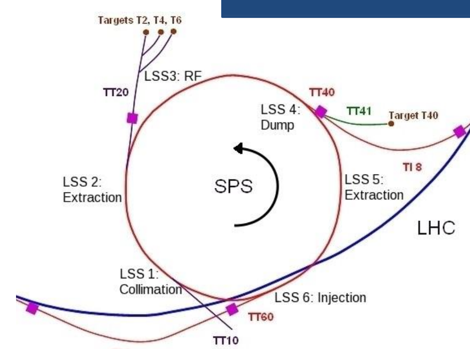
Optics for $\beta^* = 0.3$ m



- Electron cloud at 25 nsec bunch pattern (SEY)
- 9 GW power consumption and related energy efficiency problems (SRF, Cryo, vacuum SR absorbers, RF transmitters..)



- Complicated and expensive injection chain, turn-around time and beam-beam burn off



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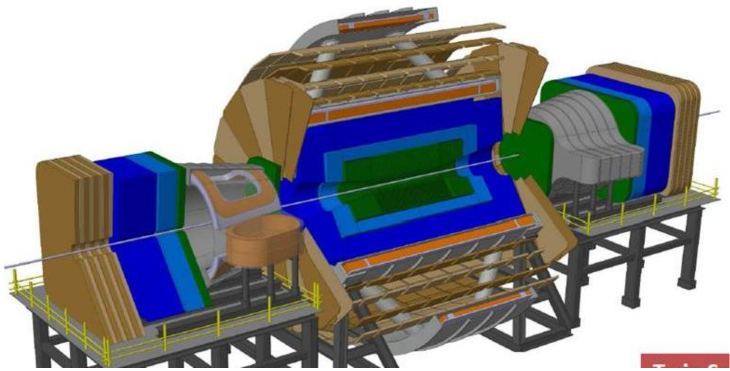
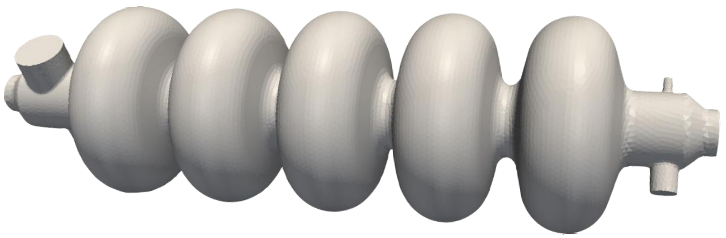
Identified FCC Challenges

- Noise and ground motion effects
- Design and technology for the interaction region (for example SR in hadron detectors)
- Efficient HOM-damped SRF technology
- …..





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R&D toward FCC

- 16 T SM magnets (20 T in tests) – CERN, LARP…
- Vacuum chambers with effective SR absorbers and SEY < 1
  - tests at ANKA + Cornell U
- Novel SRF (N-doping, HOM dumping, Nb^3Sn coating)
- DA studies, large aperture SC quads
- Septum, kickers and beam dump
- High efficiency RF transmitters/amplifiers
- Radiation resistive components

…………

What it really means:

very high energy hadron colliders?

FCC, what next?

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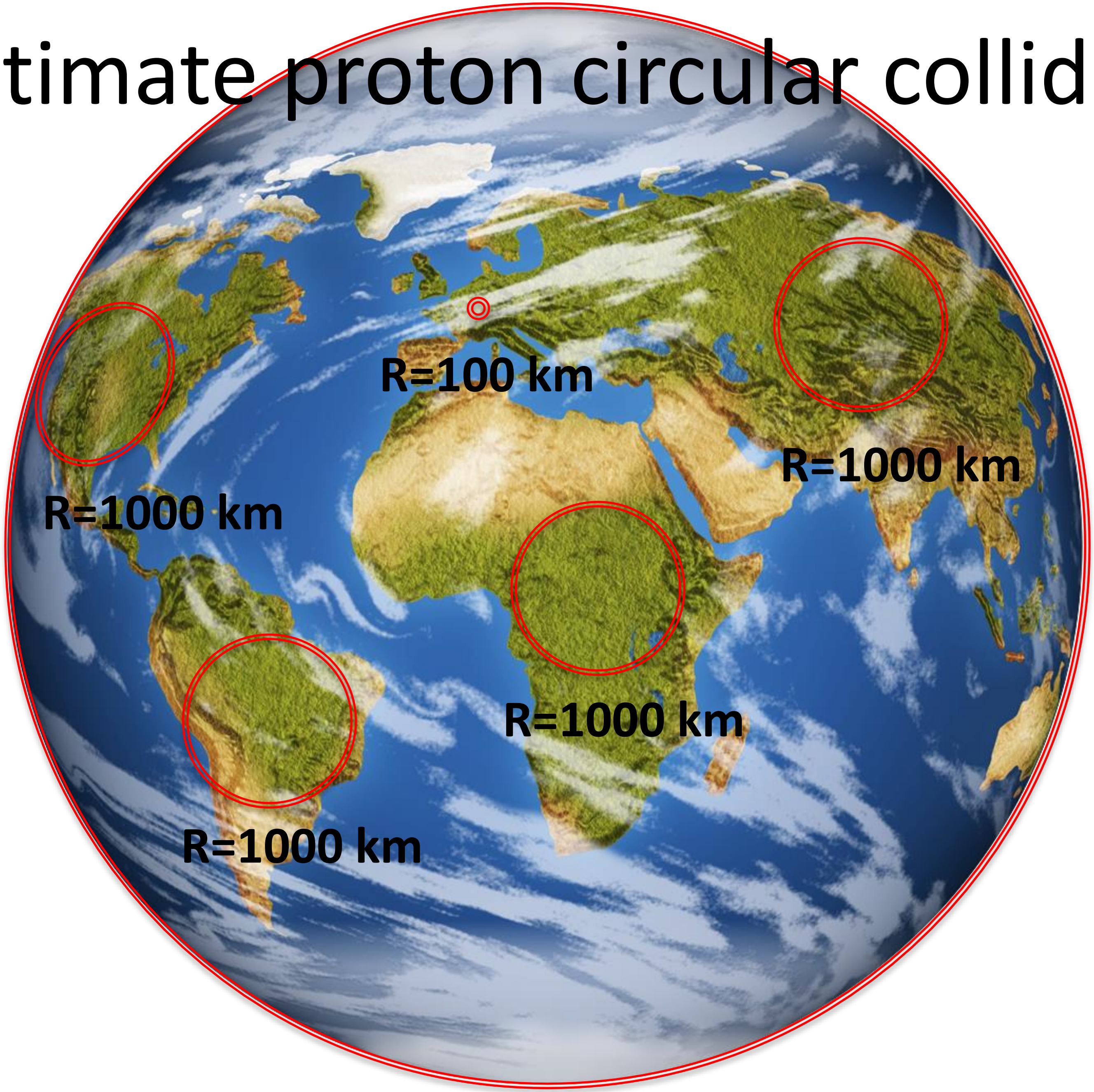
Ultimate proton circular collider



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PHY 564 HW 18 Problem 1 Academic excersize

Homework 18. Due November 16

Problem 1. 15 points. Turning the beam around – ultimate storage rings

Let's consider that we build a storage ring (magnets only), where ultra-relativistic charged particles traveling in circle of constant radius ***R*** while radiating synchrotron radiation. It means that the magnetic field is adjusted to the loss of its energy.

(a) Find the energy of the particle as function of the traveled distance ***s*** or angle ***s/R***;
(b) Find the distance when the particle's energy is reduced by a factor 2.
(c) Loosing half of the energy is considered to be "dead-end" for recirculating the beams – than linear accelerators have to do the job. For R being 6,371 kilometers – that of the Earth, find critical energy of electrons, muons and protons when particles are loosing ½ of the energy in a single turn.

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Problem 1: since we are considering ultra-relativistic particles, we can assume that *s=ct*, e.g. neglect *(1-β) <<< 1*. (a)Losses for radiation with fixed radius are

$$\frac{d\mathsf{E}_{SR}}{ds} = -mc^2\frac{d\gamma}{ds} \cong \frac{2}{3}\gamma^4\frac{e^2}{R^2}; \qquad (22\text{-}12)$$

where we used obvious: $E = \gamma mc^2; dE = -d\mathsf{E}_{SR}$. Solution is straightforward:

$$-\frac{d\gamma}{\gamma^4} = \frac{2}{3}\frac{r_c}{R^2}ds;\ r_c = \frac{e^2}{mc^2};\ \frac{\gamma^{-3}-\gamma_o^{-3}}{3} = \frac{2}{3}\frac{r_c}{R^2}s = \frac{2}{3}\frac{r_c}{R}\theta; \theta = \frac{s}{R};$$

$$\gamma = \frac{\gamma_o}{\sqrt[3]{1+2\gamma_o{}^3\frac{r_c}{R^2}s}} = \frac{\gamma_o}{\sqrt[3]{1+2\gamma_o{}^3\frac{r_c}{R}\theta}};$$

(b) $\gamma = \gamma_o/2$ means

$$\sqrt[3]{1+2\gamma_o{}^3\frac{r_c}{R^2}s} = 2 \to s_{1/2} = \frac{7}{2}\frac{R^2}{\gamma_o{}^3 r_c}.$$

(c) with R= 6.371x10^6 m one turn is s=2πR and we have the relativistic factor of a particle loosing ½ of its energy in one turn around the Earth:

(d) $s_{1/2} = 2\pi R = \frac{7}{2}\frac{R^2}{\gamma_{cr}{}^3 r_c} \to \gamma_{cr} = \sqrt[3]{\frac{7}{4\pi}\frac{R}{r_c}}$

Results

Classical radius of the electron is 2.82E-15 m we get critical γ_{cr} = 1.08x10^7. The rest energy of electron is $m_e c^2$ =0.511x10^6 eV (0.511 MeV), it means that the dead-end energy of electron storage ring at Earth is

$$E_{cr\,e} = 2\gamma_{cr} m_e c^2 = 5.52 \cdot 10^{12} eV = 5.52 TeV$$

Rest energy of a muon is $m_\mu c^2$ =1.057 x10^8 eV (106 MeV), classical radius of 1.36E-17 m, γ_{cr} = 6.39x10^7 and

$$E_{cr\,\mu} = 2\gamma_{cr} m_\mu c^2 = 6.75 \cdot 10^{15} eV = 6{,}747\ TeV$$

For proton with $m_p c^2$ =1.057 x10^8 eV (106 MeV), classical radius of 1.53E-18 m, γ_{cr} = 1.32x10^8 and

$$E_{cr\,p} = 2\gamma_{cr} m_p c^2 = 1.24 \cdot 10^{17} eV = 1.24 \cdot 10^5\ TeV$$

Note, that the later will require average bending magnetic field of 65 T, which is not within reach of current technology.

Reality hurts…

R	6371	6371	1000	500	km
Energy	124,075	28,670	4,500	2,250	TeV
<B>	64.92	15	15	15	T
Photon energy	675.031	8.328	0.205	0.051	GeV
SR @ 1 A	6.20E+07	1.77E+05	684	85.5	GW
	1.55E+06	4,420	106	27.2	kW/m

R	250	100	50	16	km
Energy	1125.00	500.00	225.00	50	TeV
<B>	15	16.67	15	10.5 (16)	T
Photon energy	13	3	0.5	0.02	MeV
SR @ 1 A	10.69	1.04	0.09	.003	GW
	6.80	1.66	0.272	0.030	kW/m

Next step in energy will require developing in-cryo-vacuum absorbers at kW/m level

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What is new?
One more circular collider?
Onde more wheel?

"Yes, but what have you invented lately?"

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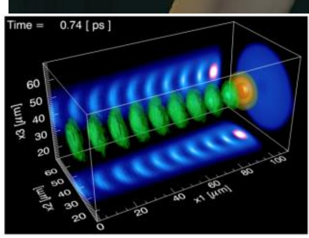
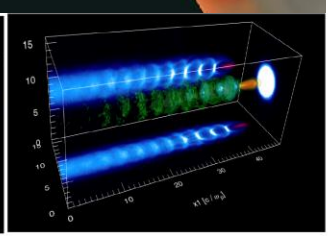
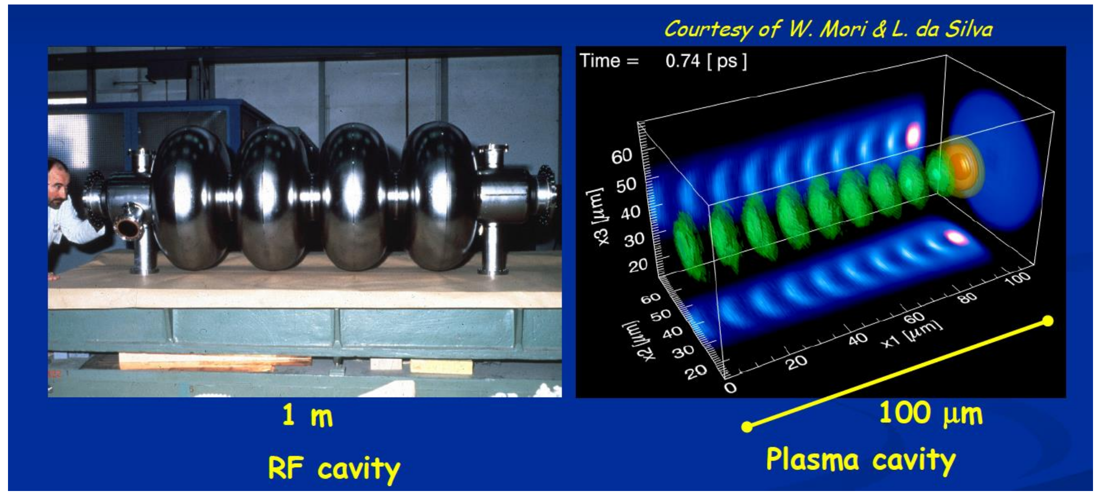
New scale: GeV/cm
-> TeV/10 m?

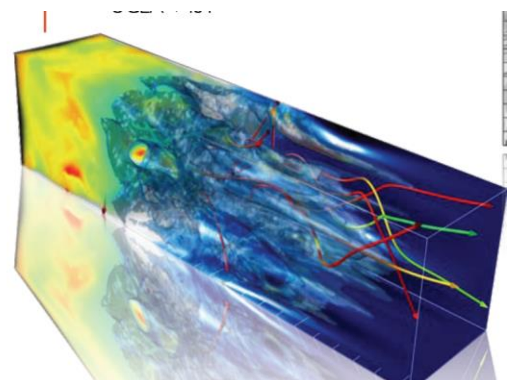


Laser Wake



Electron beam Wake





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Challenges

- High accelerating gradient – looks very good … GeV/cm
- Repeatability from shot to shot
  - Beam parameters…..
  - Direction…
  - Rebuilding the target…
- Good beam quality…
  - No '
- Staging

Unfinished list of challenges

- Energy in the proton beam is in GJ -> needs huge energy in the laser/e-beam drivers
- High rep-rate is required
- Energy in the plasma bubble is limited -> many more stages
- We will need learn how to generate proton bunches fitting into "buble" of 10s of microns
- Operation at the same luminosity will lead to huge pile-up problem in the detector
- Beam-strahglung at the very high energies
- ………… And many many more
- **Hence, a very long way to go before competing with the "wheel"**

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Conclusions

- FCC challenges are well understood and a very balanced R&D program is pursued
- FCC challenges are extension of those faced by LHC – to be exact, those but on steroids
- Advanced acceleration techniques, while progressing fast, are not around the corner. It will takes decades for them to be considered as alternative to circular hadron colliders.