Introduction to Muon Collider & $\gamma\gamma$ Collider

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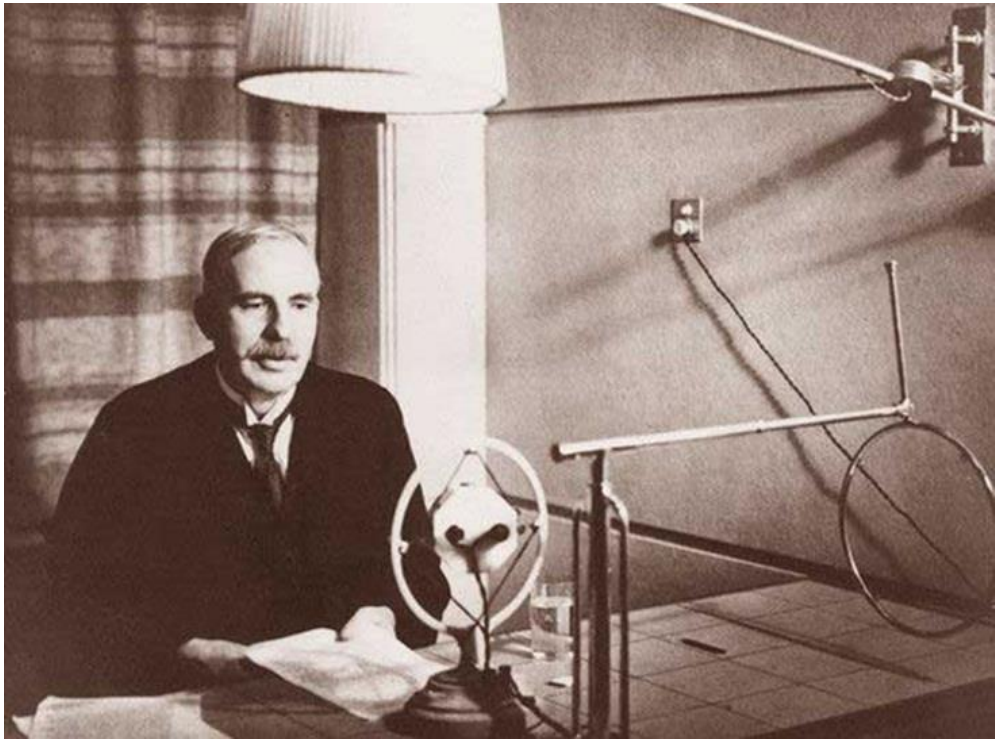
Outline

- A brief history of particle accelerators and colliders
- Muon collider
  - $\mu^+\mu^-$ collider *vs* e^+e^- collider
  - "Traditional" muon collider
  - Muon collider for Higgs factory
  - New idea for a muon collider
- $\gamma\gamma$ collider
  - Principle
  - $\gamma\gamma$ collider for Higgs factory
  - Example – How to build a low energy $\gamma\gamma$ collider

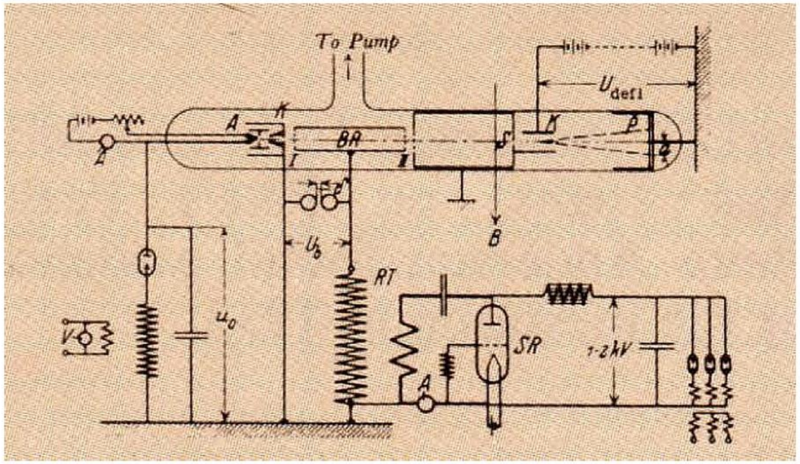
Beginning of the Particle Accelerator Era

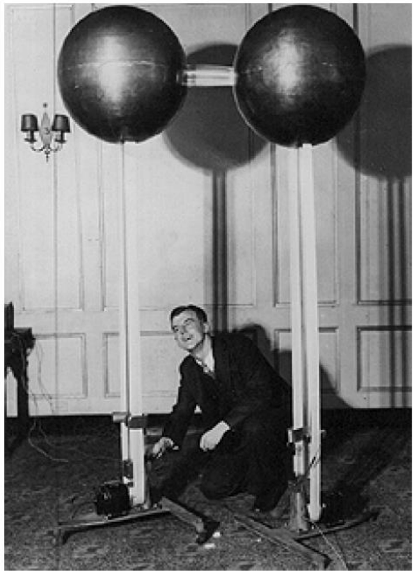


1919: Ernest Rutherford discovered the nuclear disintegration by bombarding nitrogen with alpha particles from natural radioactive substances. Later he **called for "a copious supply" of particles more energetic than those from natural sources.** The particle accelerator era was born.

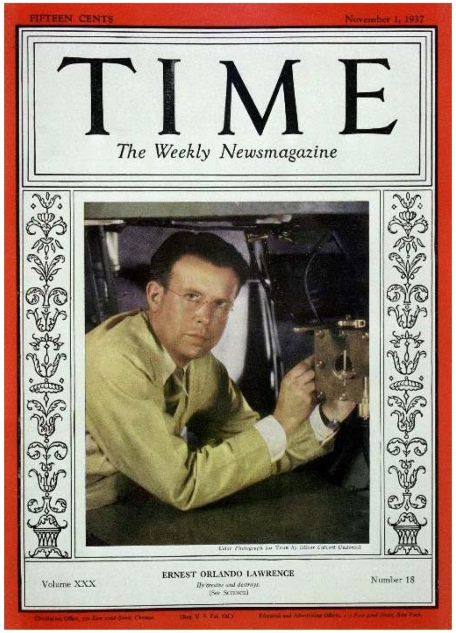
First Accelerators

1928: Rolf Wideröe, 88 cm glass tube linac

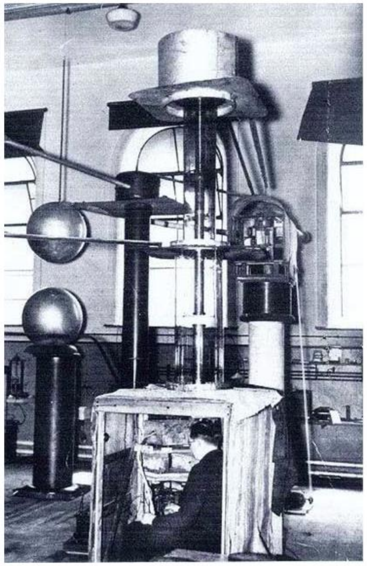




1929: Van de Graaff generator



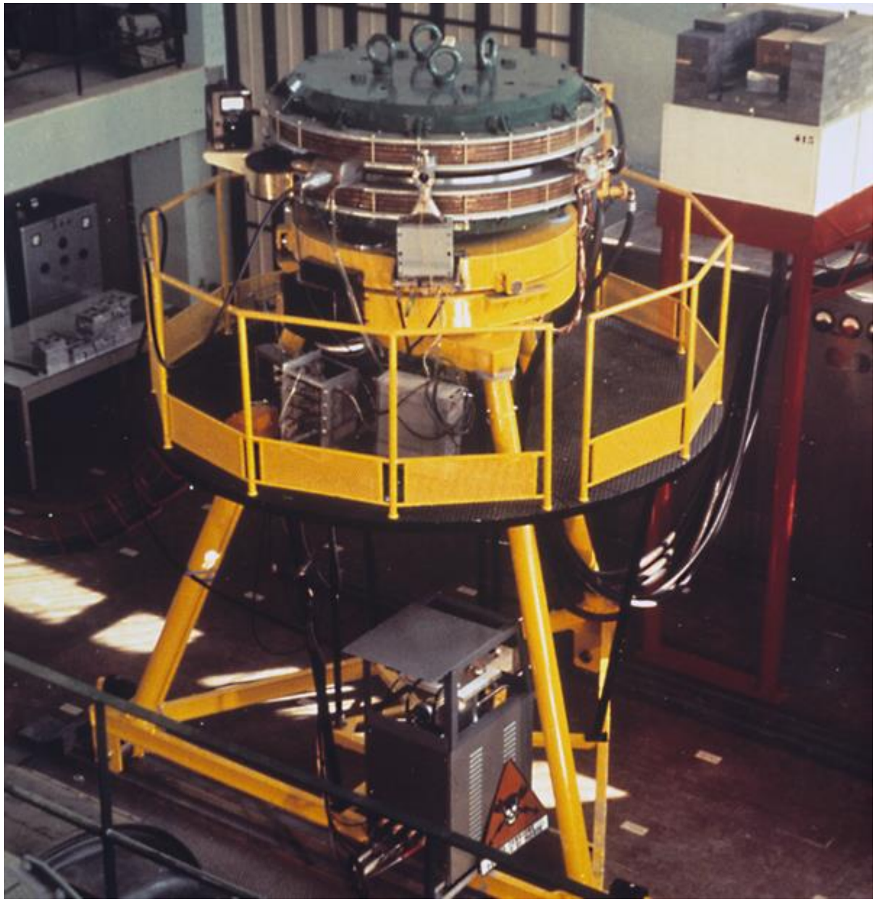
1930: Ernest Lawrence, 4” cyclotron



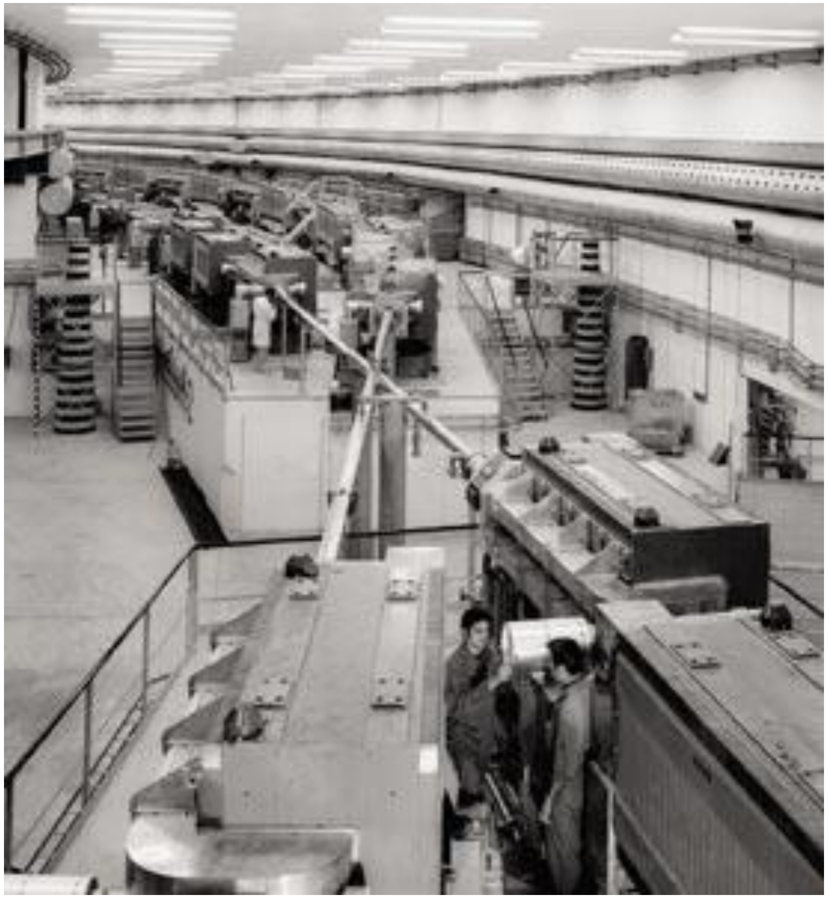
1932: Cockcroft-Walton electrostatic accelerator

First Colliders

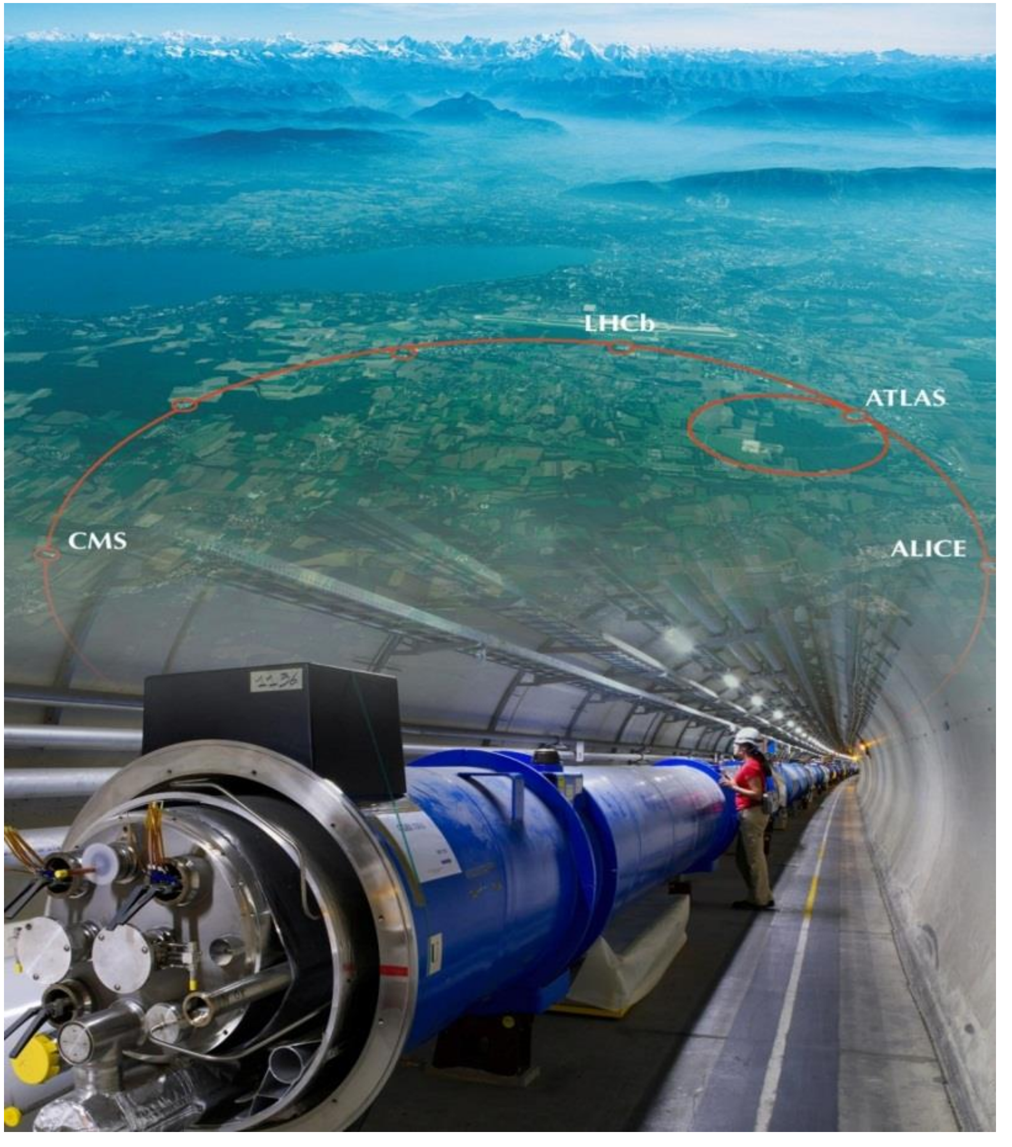
1961: AdA first lepton collider



1969: ISR first proton collider



World's Largest Collider – LHC (27 km)



Tens of Thousands Accelerators were built

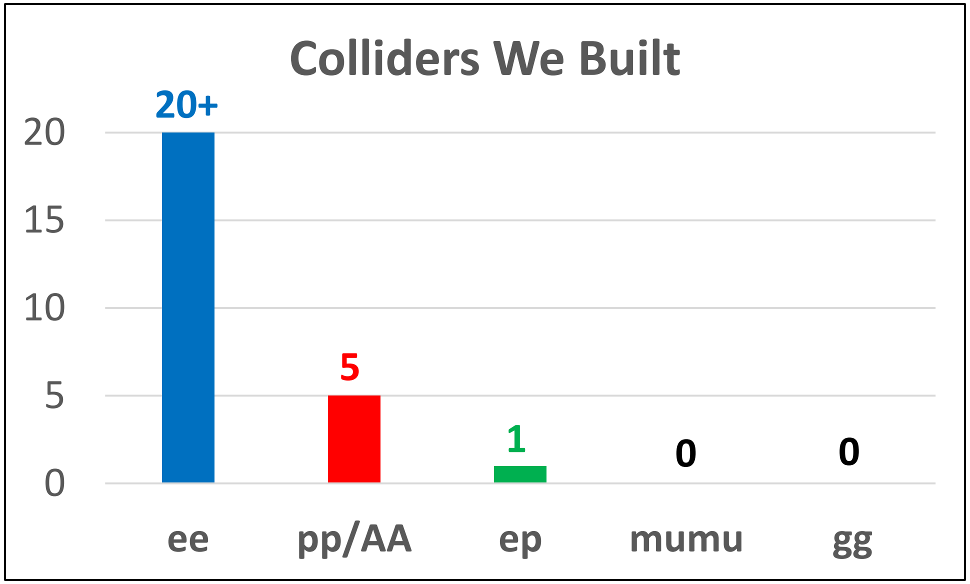
Light Sources

Neutron Sources

Medical Accelerators

Industrial Accelerators

Scores of Colliders were built



- Started in 1960s, first 3 colliders: <u>***AdA***</u> in Italy, <u>***CBX***</u> in the US and <u>***VEP-1***</u> in Russia (then Soviet Union).
- Since then, we have built more than 20 *ee* colliders.
- We have also built 5 *pp* and *ion-ion* colliders as well as one *ep* collider.
- <u>**However, we have never built a muon collider, nor a $\gamma\gamma$ collider**</u> because technically it is very difficult.
- But things are changing – there is a new idea about muon collider, and today's advanced laser technology makes $\gamma\gamma$ collider immediately possible.

Comparison of Four Particles

A collider requires the following properties of particles:

- ♦ Copious supply
- ♦ Small emittance
- ♦ Stable
- ♦ Charged

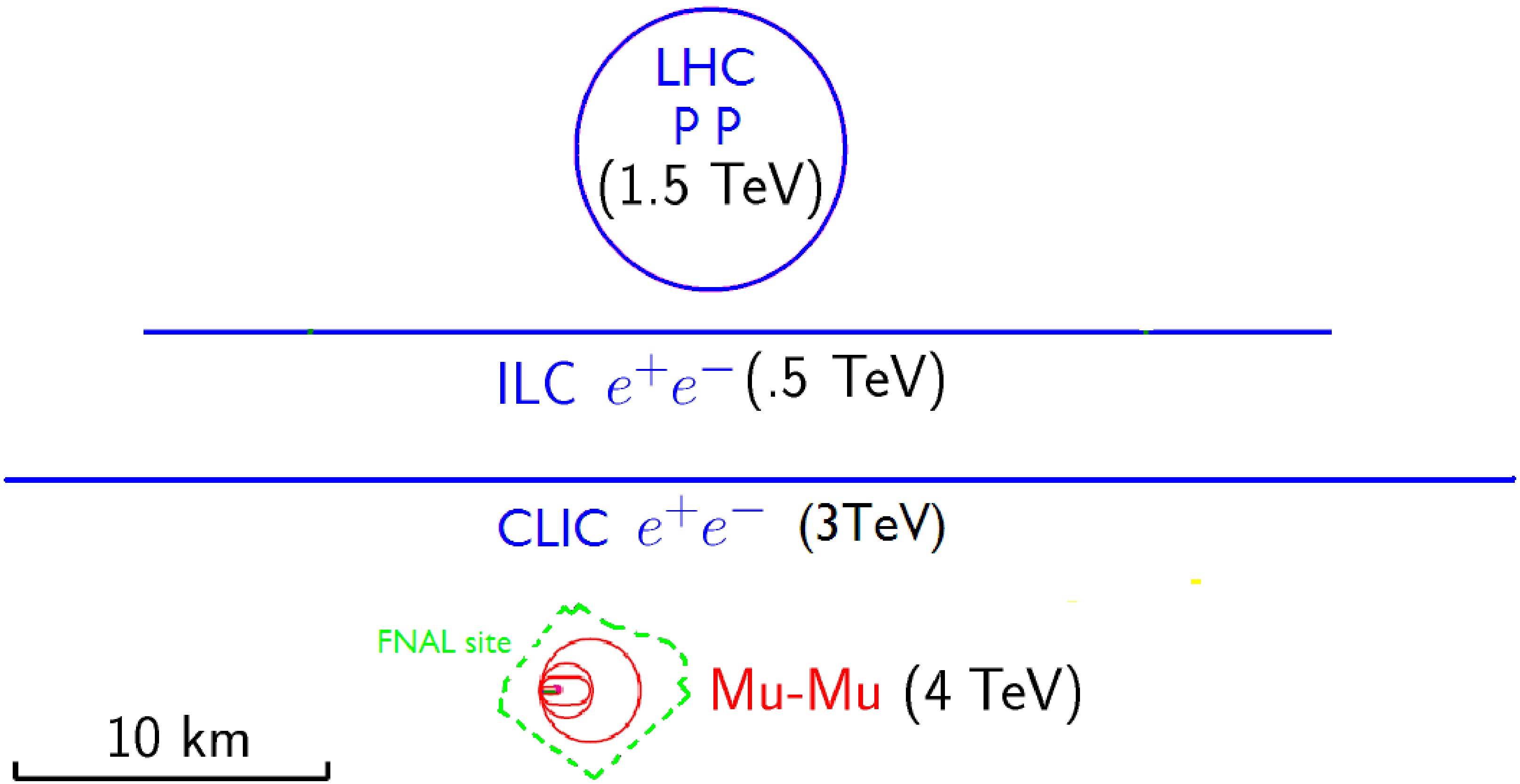
Particle	Copious supply	Small emittance	Stable	Charged
p	✓	✓	✓	✓
e	✓	✓	✓	✓
μ	✓	×	×	✓
γ	✓	✓	✓	×

$\mu^+\mu^-$ Collider *vs* e^+e^- Collider

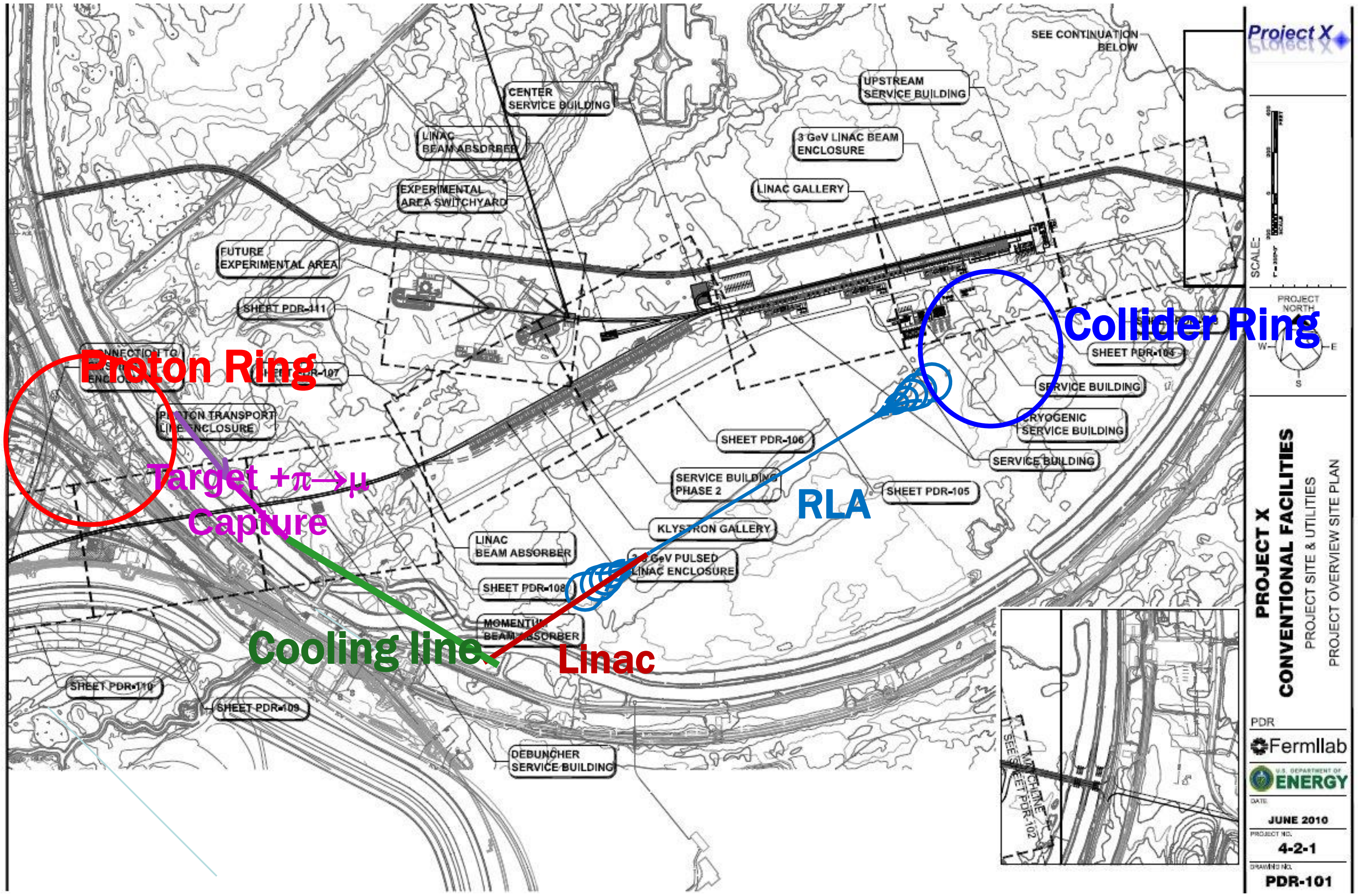
- **Advantages:**
  - Synchrotron radiation $\propto E^4/m^4$, m(μ) = 207 x m(e)
    $\Rightarrow$ high energy muon collider ring possible
  - A TeV muon collider ring is small and can fit to the size of existing labs (e.g., Fermilab)
  - Beamstrahlung (synchrotron radiation as two beams collide) also $\propto E^4/m^4$, which is suppressed in a muon collider ring
  - In a Higgs factory, the s-channel ($\mu^+\mu^- \to H$) cross section $\propto$ m^2, [m(μ)/m(e)]^2 $\cong$ 43,000

- **Disadvantages:**
  - In a "traditional" muon collider, initial muon beam has large 6D emittance and must be cooled by a factor of 10^7 (10^3 in each of the two transverse directions and 10 in longitudinal)
  - Cooling and acceleration must be fast (lifetime = 2.2 μs at rest, but increases as E/E_0)
  - Ring magnets and detector requires heavy shielding from decay electrons

Relative Size and Energy of Colliders (R. Palmer)



Fermilab Site – Scale of facility (D. Neuffer)



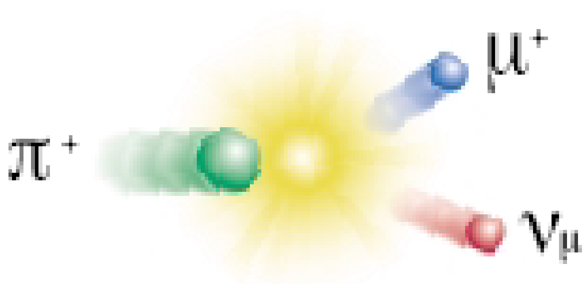
"Traditional" Muon Collider Principle

Steps:

(1) A proton driver provides high intensity (~ 4 MW) short pulse (~2 ns) proton beams on target, producing high flux pions

(2) Pion quickly decays to muon and neutrino

(3) Muon is unstable but has a relatively long mean lifetime (2.2 μs), which becomes longer at higher energy ($\propto E/E_0$). Therefore, a series of beam manipulation is possible before it decays (capture, rotation, cooling, acceleration, storage and collision)

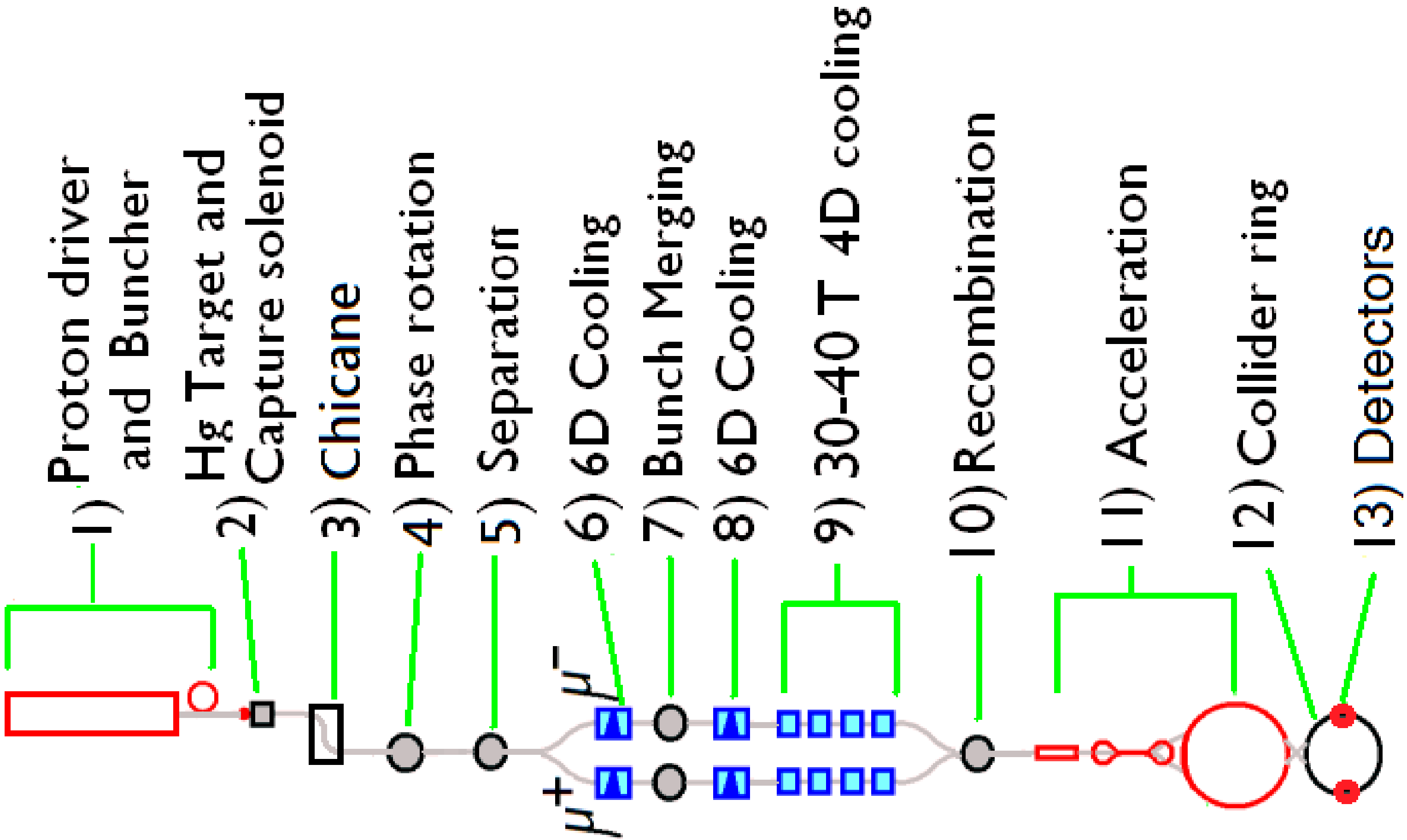


Key Technology – Ionization Cooling

- Radiation cooling (for e+, e-), electron cooling (for pbar), stochastic cooling (for pbar) – all too slow for muons

- Ionization cooling appears feasible:
  - Particles passing through an absorber, losing momentum in three coordinates. RF acceleration restores the longitudinal momentum, while transverse momentum remain reduced.
  - This method cannot be applied to protons due to strong nuclear interaction
  - It cannot be applied to electron either due to strong beamstrahlung
  - But for muons this method is ideal:
    - Muons have no strong interaction
    - Muons have negligible beamstrahlung
    - Ionization cooling is fast

Schematic of "Traditional" Muon Collider (R. Palmer)

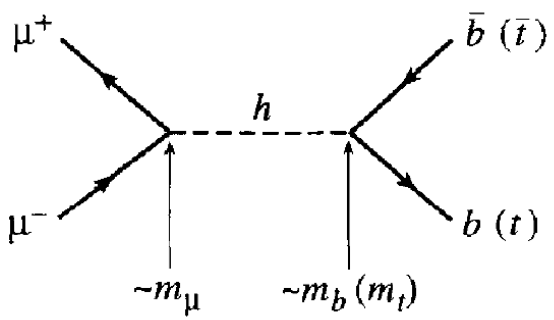


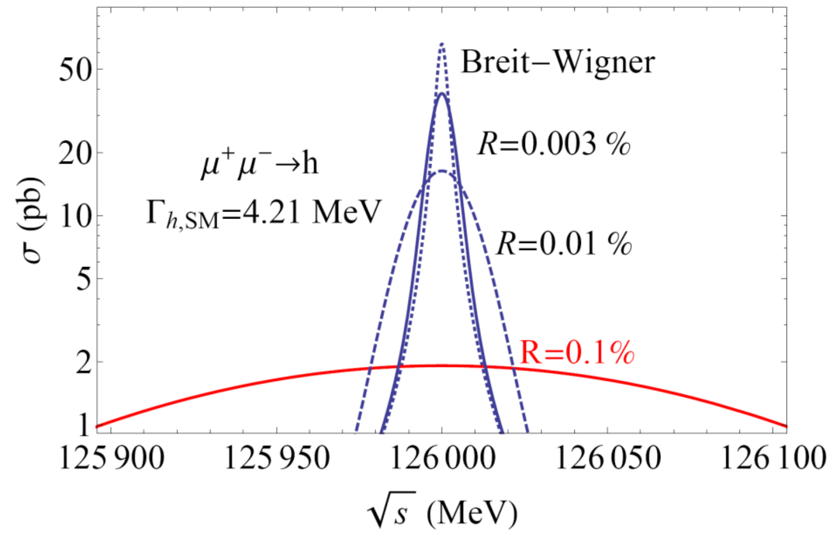
Description of Technical Systems (R. Palmer)

1) Proton driver: protons of high power (4 MW), high bunch intensity, short bunch length (2 ns)
2) Mercury jet target and capture solenoid (20 T, SC)
3) Chicane and Be proton absorber (to get rid of protons)
4) Phase rotation (to reduce energy spread by increase bunch length)
5) Charge separation (to form two beams: μ+ and μ-)
6) 6D cooling – the most critical stage, ionization cooling, using absorber (gas or liquid hydrogen, or lithium) and rf acceleration
7) Bunch merging (combining multiple bunches into a single bunch)
8) 6D cooling
9) 30-40 Tesla 4D cooling (final cooling, rf cavities inside a 3T solenoid)
10) Recombination
11) Acceleration (recirculating linac, or rapid cycling synchrotron, or FFAG)
12) Collider ring
13) Detectors

Muon Collider as Higgs Factory

s-channel production of Higgs boson (Han and Liu)





- s-channel Higgs production cross section in a muon collider is ~43,000 times larger than in an e^+e^- collider

$$\sigma(\mu^+\mu^- \to H) \cong 43{,}000 \text{ x } \sigma(e^+e^- \to H)$$

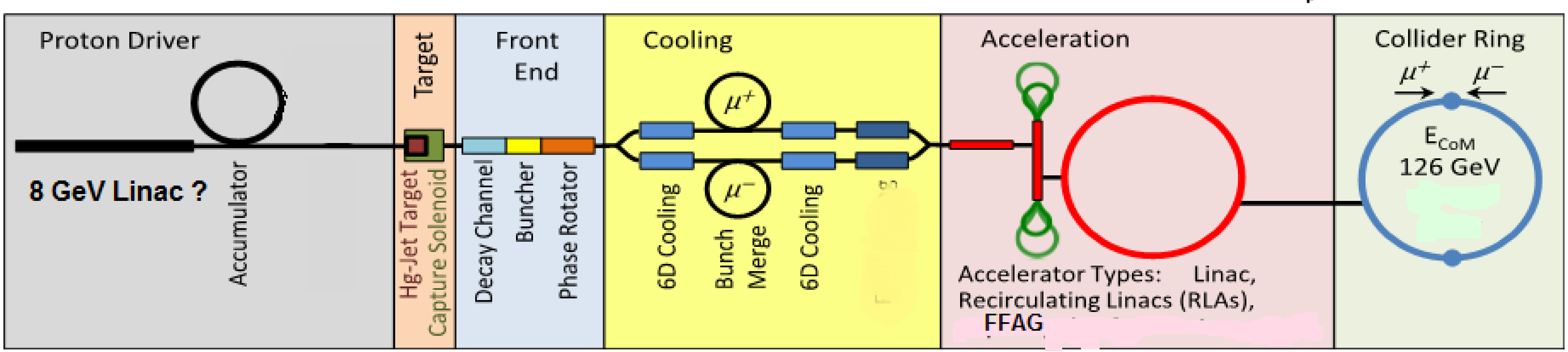
σ(peak) = 70 pb, which should be compared to $\sigma(e^+e^- \to ZH)$ = 0.2 pb

- This high cross section can compensate the low luminosity of muon collider
- Muon collider can measure the decay width Γ directly without any theoretical assumption (a unique advantage) – if the muon beam energy resolution is sufficiently high
- But the required energy resolution is very demanding

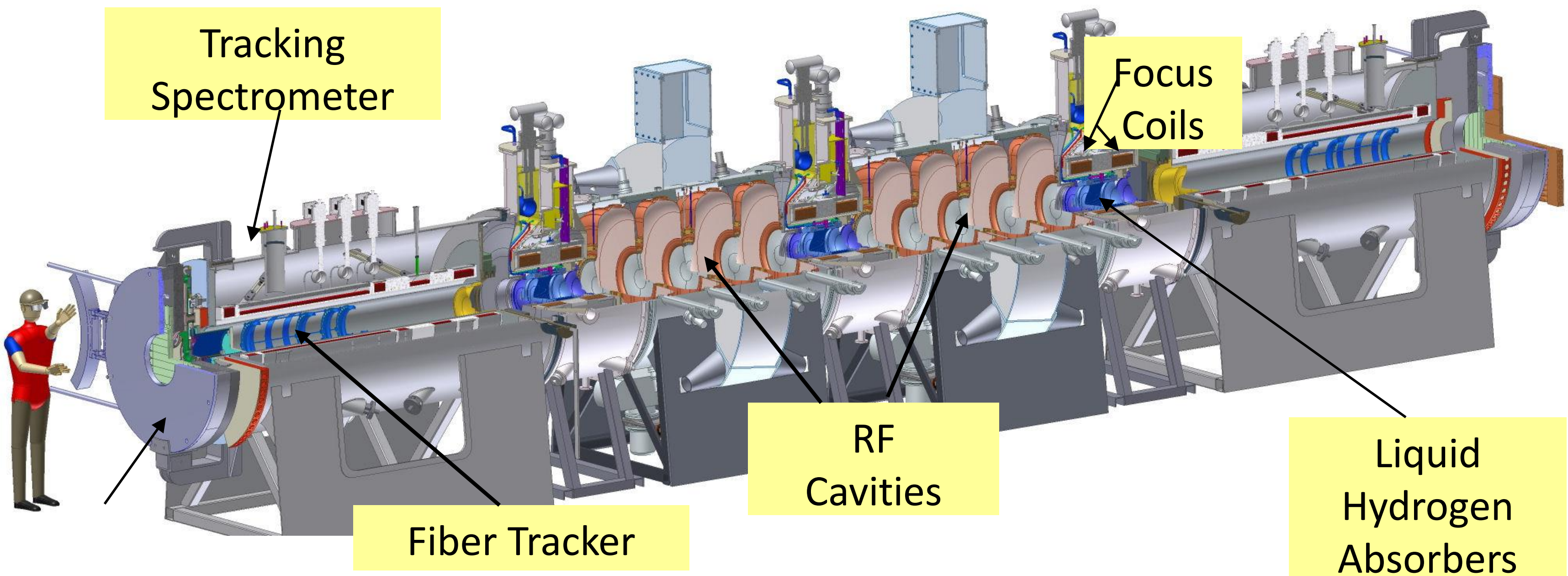
126 GeV $\mu^+\mu^-$ Collider (D. Neuffer)

- 8 GeV, 4MW Proton Source
  - 15 Hz, 4 bunches 5×10^{13}/bunch
- $\pi\rightarrow\mu$ collection, bunching, cooling
- $\varepsilon_{\perp,N}$ =400 π mm-mrad, $\varepsilon_{\parallel,N}$= 2 π mm
  - 10^{12} μ/ bunch
- Accelerate, Collider ring
  - δE = 4 MeV, C=300m
  - Detector
  - monitor polarization precession
  - for energy measurement
    - $\delta E_{error} \rightarrow$ 0.1 MeV

Parameter	Symbol	Value
Collision Beam Energy	$E_{\mu+}, E_{\mu-}$	63GeV
Luminosity	L_0	10^{31}
Number of μ bunches	n_B	1
$\mu^{+/-}$/ bunch	N_μ	10^{12}
Transverse emittance	$\varepsilon_{t,N}$	0.0004m
Longitudinal emittance	ε_{LN}	0.002m
Energy spread	δE	4MeV
Collision β^*	β^*	0.05 m
Beam size at collision	$\sigma_{x,y}$	0.02cm
Beam size (arcs)	$\sigma_{x,y}$	1.0cm
Beam size IR quad	σ_{max}	5.4cm
Storage turns	N_t	1000
Proton Beam Power	P_p	4 MW
Bunch frequency	F_p	60 Hz
Protons per bunch	N_p	5×10^{13}
Proton beam energy	E_p	8 GeV



Muon Ionization Cooling Experiment (MICE)



Under construction

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

Single particle experiment

Linda Coney, UCR

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

Status of “Traditional” Muon Collider

- The idea was first proposed by A. Skrinsky et. al and D. Neuffer in early 1980s
- A first schematic design was presented by D. Neuffer and R. Palmer in 1990s
- A complete design of neutrino factory (a facility using the same technology but less demanding) was published in 2000
- An informal collaboration on neutrino factory and muon collider was formed in 2002
- A formal, US DOE initiated and funded Muon Accelerator Program (MAP) was formed in 2012
- However, upon a recommendation of P5, DOE terminated MAP in 2014 and redirected it to a general R&D
- DOE’s support for MICE ended; MICE finished Step IV running in 2017 but will not continue.
- At this moment, “traditional” muon collider is put on the shelf without much activity

New Muon Collider Principle (M. Boscolo)

Steps:

(1) A high intensity high energy (45 GeV) e+ beam hits a thin target (0.01 radiation length), colliding with e- in the target and producing a muon pair just above the threshold ($\sqrt{s}$ = 212 MeV), which has small emittance and small energy spread; therefore, no need for cooling

(2) Muons can be accelerated and stored for collision.

$$\boxed{e^+e^- \to \mu^+\mu^-}$$

Schematic of New Muon Collider (M. Boscolo)

from e^+ SOURCE to RING:

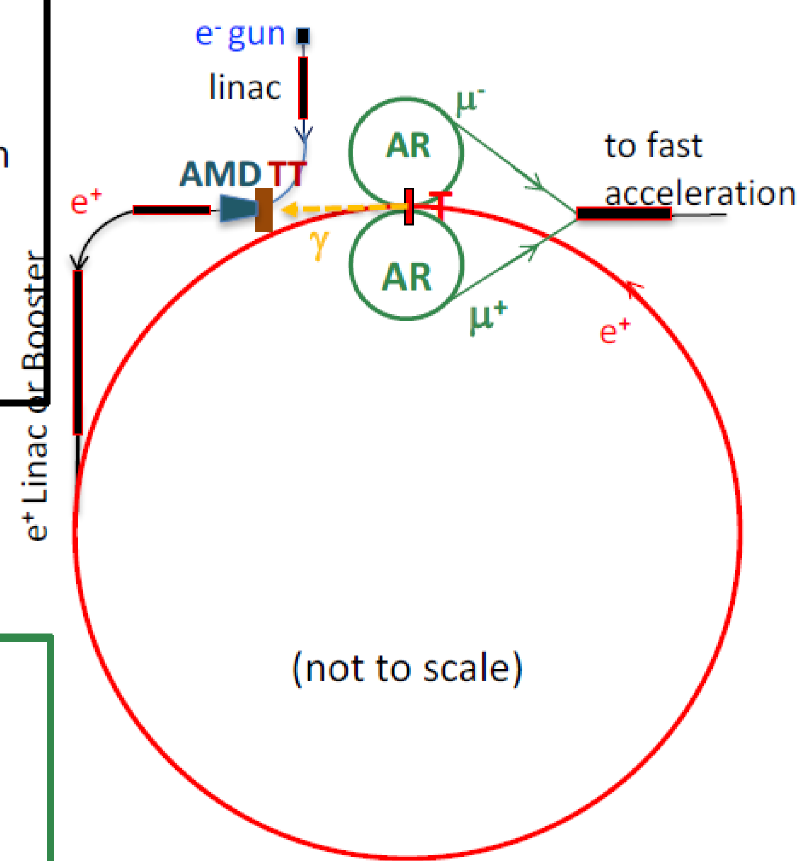
- **e^-** on conventional Heavy Thick Target (**TT**) for e^+e^- pairs production.
- possibly with γ produced by e^+ stored beam on **T** →
- Adiabatic Matching Device (**AMD**) for **e^+** collection →
- acceleration (linac / booster) , injection →

e^+ RING:

- **6.3 km 45 GeV** storage ring with target **T** for muon production

from μ^+ μ^- production to collider

- produced by the **e^+** beam on target **T** with **$E(\mu) \approx 22$ GeV**, $\gamma(\mu) \approx 200 \rightarrow \tau_{lab}(\mu) \approx 500\mu s$
- **AR**: **60 m** isochronous and high mom. acceptance rings will recombine μ bunches for ~ 1 $\tau_{\mu}^{lab} \approx 2500$ turns
- fast acceleration
- muon collider



M. Boscolo, IPAC17

Parameters (M. Boscolo)

Goal:

$@T \approx 10^{11}\ \mu/s$

Efficiency $\approx 10^{-7}$ (with Be 3mm)$\rightarrow$

$10^{18}\ e^+/s$ needed $@T \rightarrow$

e^+ stored beam with T

need the largest possible lifetime to minimize positron source rate

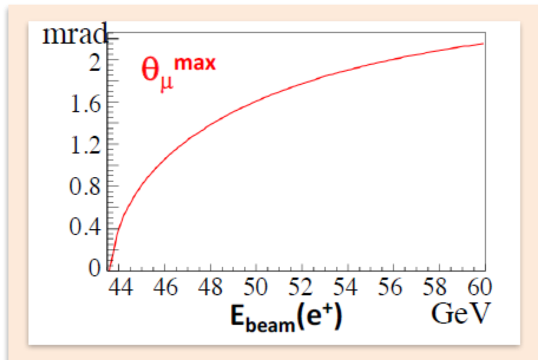
LHeC like e+ source required rate with lifetime(e+) $\approx$ 250 turns [i.e. 25% momentum aperture] $\rightarrow$ $n(\mu)/n(e^+ \text{ source}) \approx 10^{-5}$

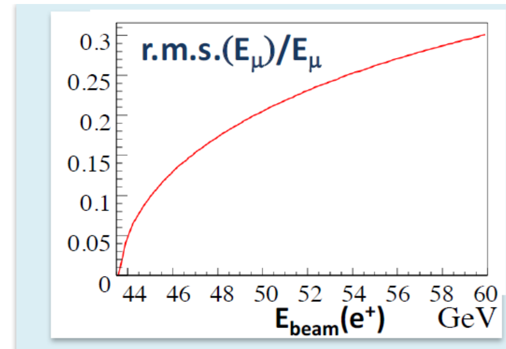
e+ ring parameter	unit	
Circumference	km	6.3
Energy	GeV	45
bunches	#	100
e^+ bunch spacing $= T_{rev}$ (AR)	ns	200
Beam current	mA	240
$N(e^+)$/bunch	#	$3 \cdot 10^{11}$
U_0	GeV	0.51
SR power	MW	120

(also 28 km foreseen to be studied as an option)

New *vs* “Traditional”

- **Advantage:**
  - No need for cooling



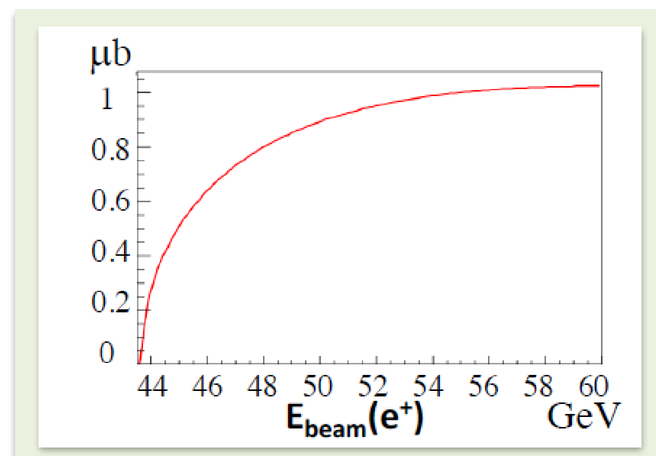


- **Disadvantage:**
  - Much smaller cross section:

    $$\sigma(e^+e^- \to \mu^+\mu^-) < 1\ \mu b$$

    about 3 orders of magnitude smaller than proton cross section (~mb)
  - Need much higher intensity of e^+ beam

$\sigma(e^+e^- \to \mu^+\mu^-)$



Status of New Muon Collider

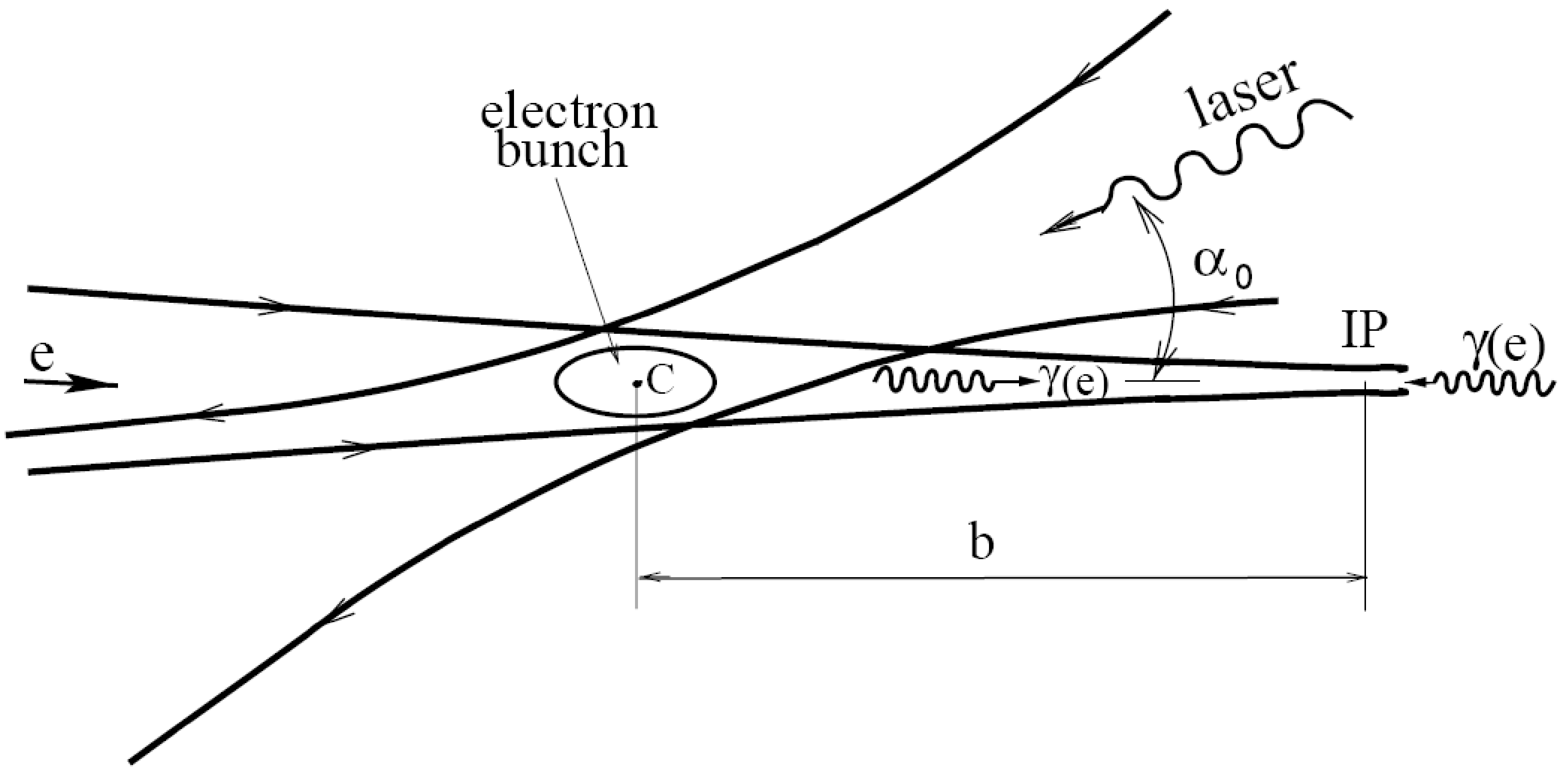
- The idea was first proposed by M. Boscolo et. al at IPAC2017
- A collaboration team on Low Emittance Muon Accelerator has been formed
- Study is at an early stage
- Tests with e+ beam was recently performed at CERN
- Being actively pursued right now

$\gamma\gamma$ Collider Principle

Two steps:

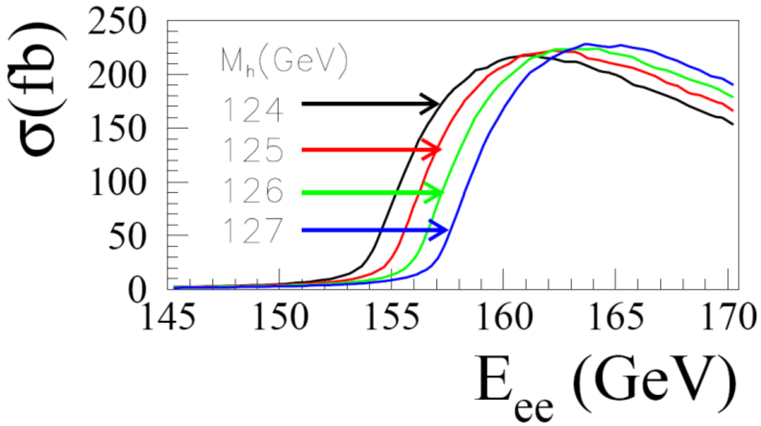
(1) Inverse Compton Scattering (ICS) $\rightarrow$ high energy γ

(2) $\gamma\gamma \rightarrow$ *H (bb, cc, $\tau\tau$, $\gamma\gamma$, e+e-)*



γγ Collider as Higgs Factory

γγ → *H* cross section



Comparable to 240 GeV e+e- → *ZH* but only need 160 GeV

Dependence of photon spectrum on polarization

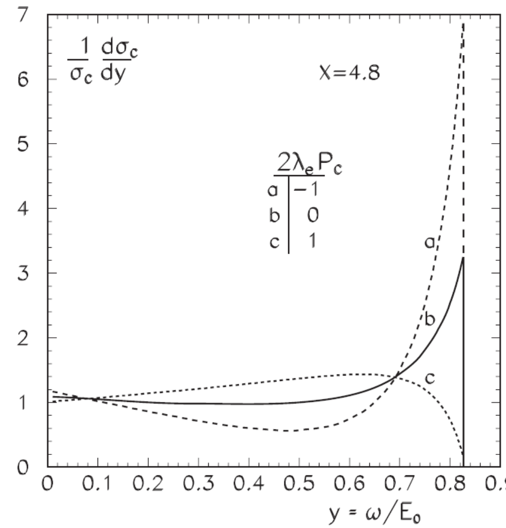
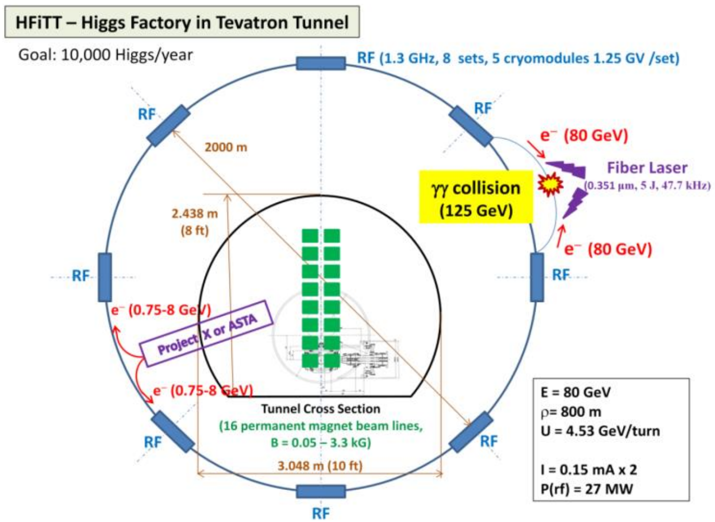


Figure 1.3.1: *Spectrum of the Compton scattered photons for different polarisations of the laser and electron beams.*

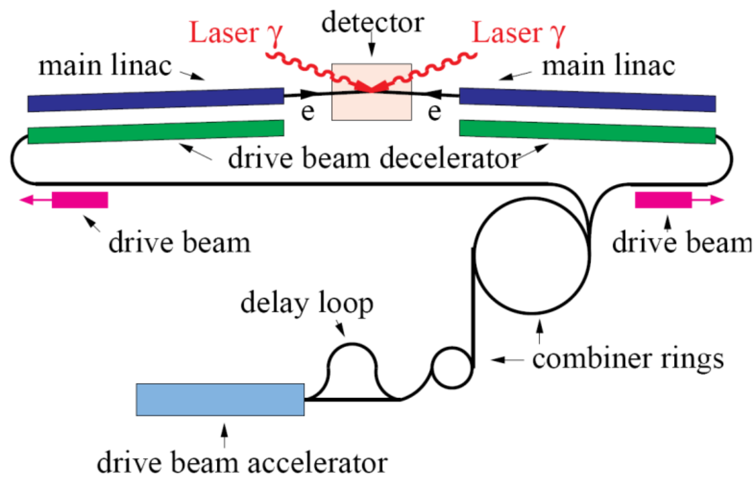
$$\omega_m = \frac{x}{x+1}E_0; \quad x \approx \frac{4E_0\omega_0}{m^2c^4} \simeq 15.3\left[\frac{E_0}{\mathrm{TeV}}\right]\left[\frac{\omega_0}{eV}\right],$$

Various Proposals for Photon Collider

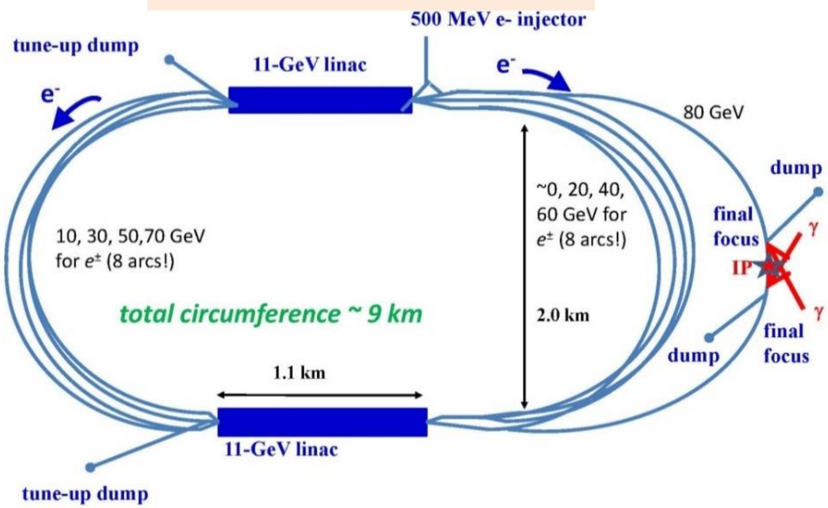
HFiTT



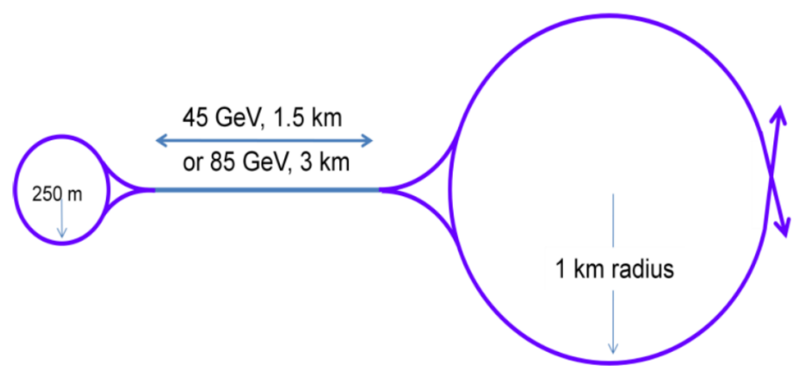
CLIC-based



SAPPHiRE



SLC-type



Key Technology – Laser

- Laser can provide very high peak power (TW or even PW), or very high energy (several MJ) at a very low frequency (one shot in several hours).

- But for $\gamma\gamma$ collider, the laser must have:
  - High average power (from hundreds watts to tens of kW)
  - High single pulse energy (J)
  - Short pulse length (ps)
  - High repetition rate (tens Hz to kHz)

ICFA-ICUIL Collaboration

"Marriage": Steel meets Glass

ICFA

International Committee for Future Accelerators

Sponsored by the Particles and Fields Commission of IUPAP

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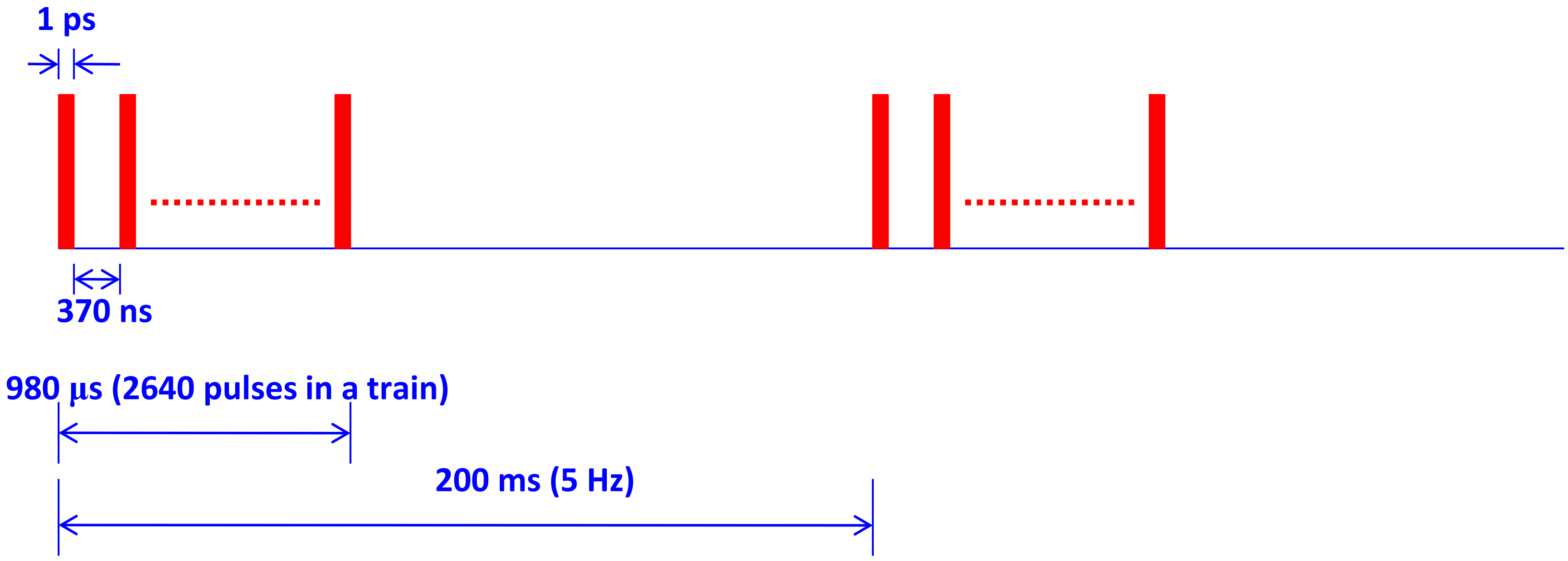
ILC-based $\gamma\gamma$ Collider

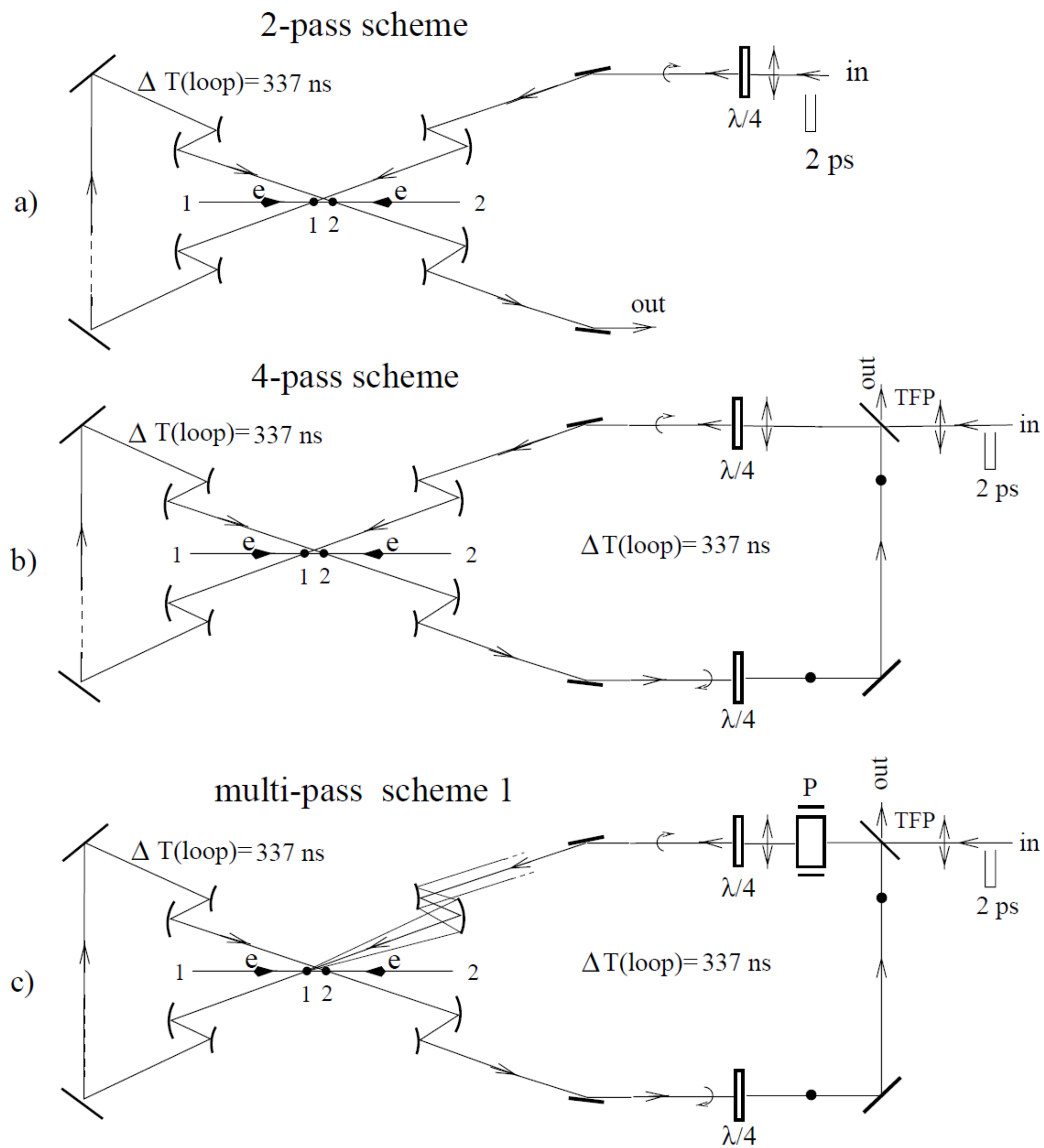


Laser Requirements

Pulse width	Pulse energy	Pulse spacing	No. pulses in a train	Laser power in a train	Laser average power	Rep rate	Wavelength	Spot size	Crossing angle
1 ps	10 J /Q	370 ns	2640	25 MW /Q	150 kW /Q	5 Hz	1 μm	120 nm x 2.3 nm	25 mrad

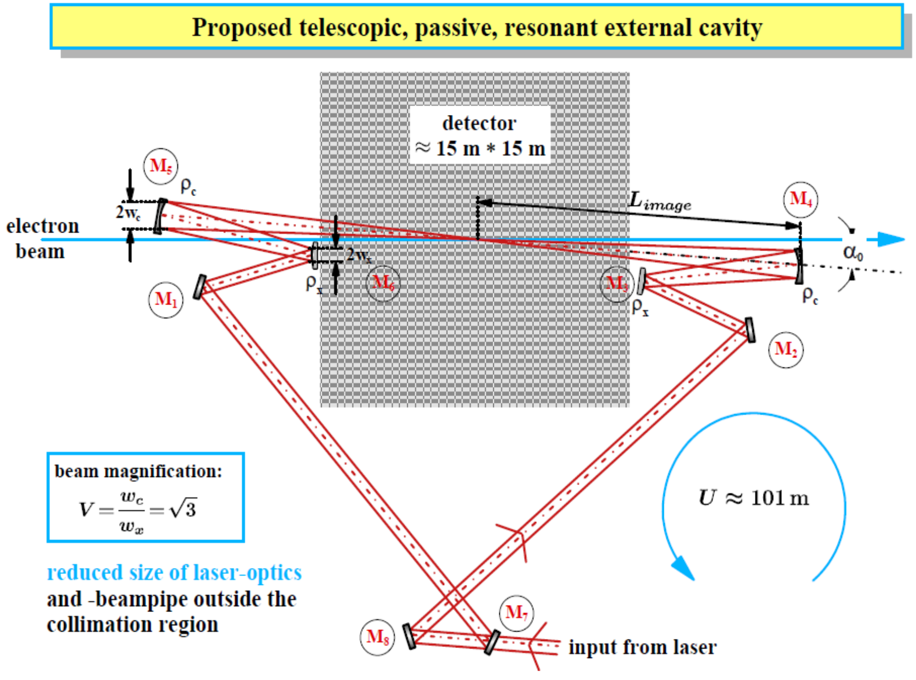
Need an optical cavity with Q ~ 300

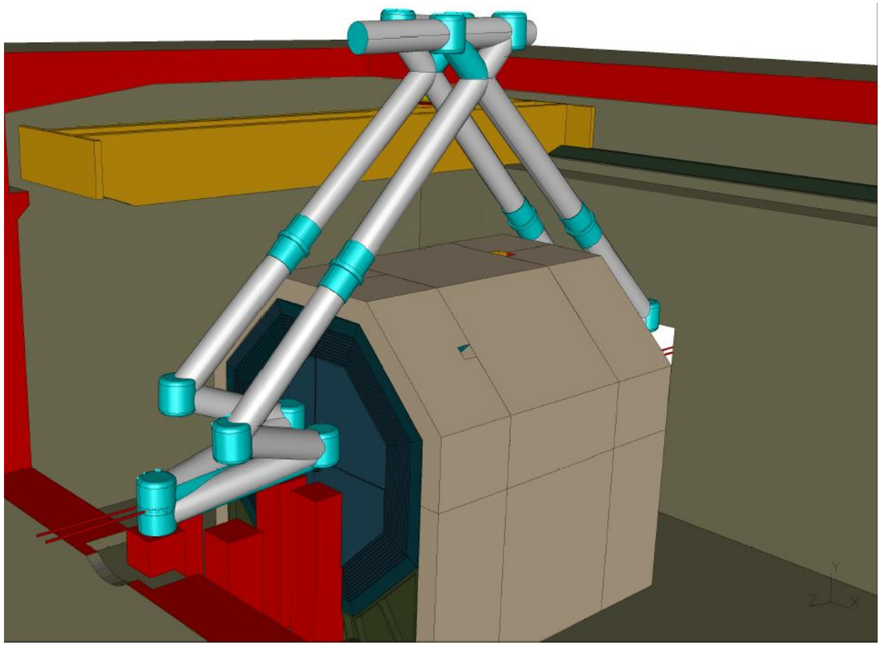
Multi-Pass Optics (from the DESY TESLA Design)



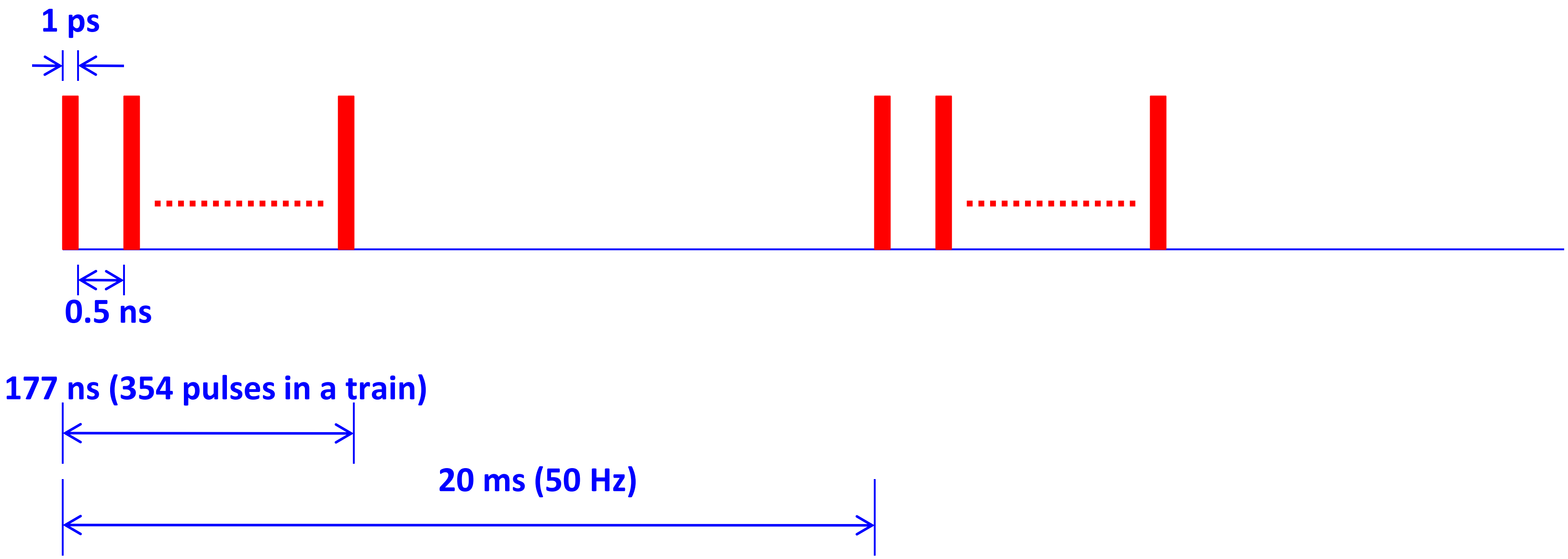
Pulse Stacking Laser Cavity for ILC (T. Takahashi)

- total length ~100m
- power enhancement ~100





CLIC-based and X band-based $\gamma\gamma$ Collider

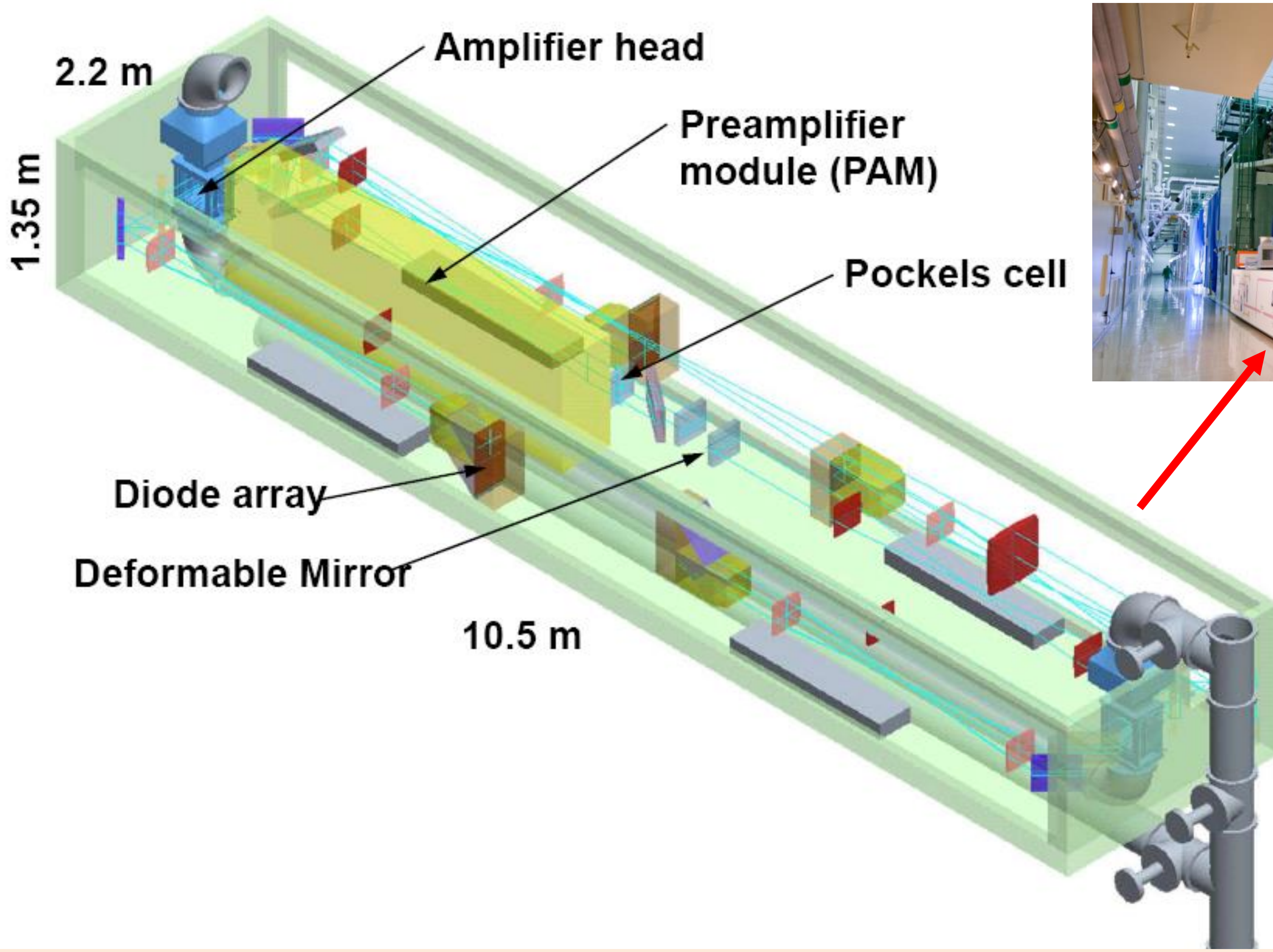


Laser Requirements

Pulse width	Pulse energy	Pulse spacing	No. pulses in a train	Laser power in a train	Laser average power	Rep rate	Wavelength	Spot size	Crossing angle
1 ps	5 J	0.5 ns	354 (5 x 354 = 1770 J per train)	10 GW	88.5 kW	50 Hz	1 μm	120 nm x 2.3 nm	25 mrad

Livermore LIFE fusion project laser beam: 130 kW average power, 8100 J /pulse, 16 Hz (LIFE would have 384 such beams)

The entire 1ω beamline can be packaged into a box which is 31 m³ while providing 130 kW average power



Livermore fusion project LIFE will have 384 laser boxes
One would be enough for γγ collider

Nature Photonics (G, Mourou et al., v. 7, p. 258, April 2013)

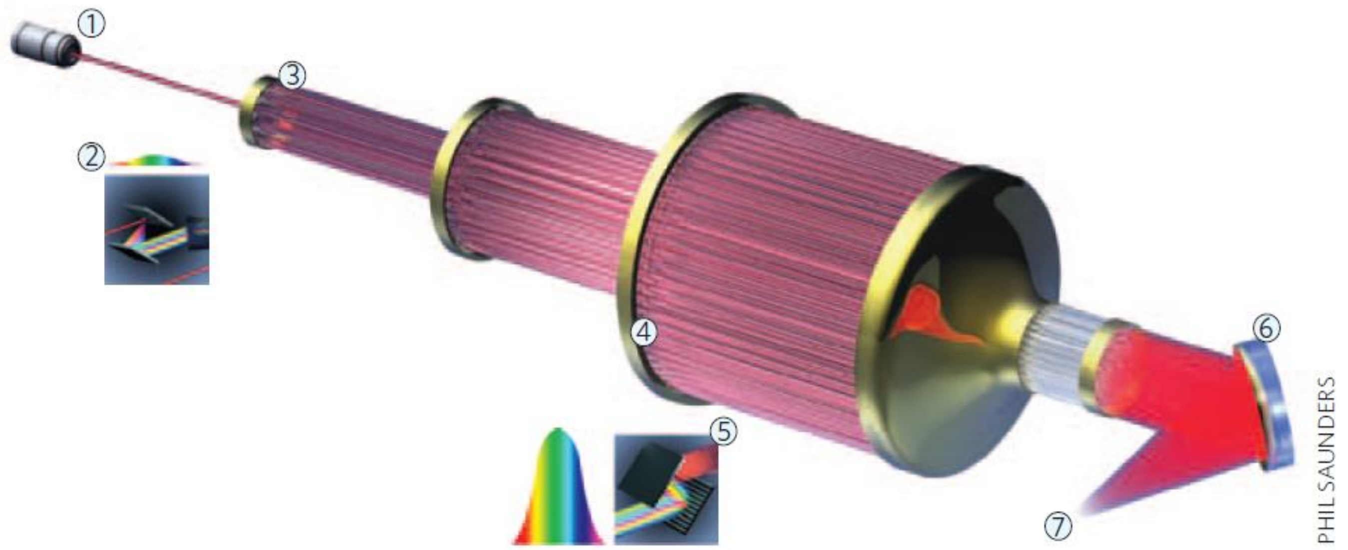
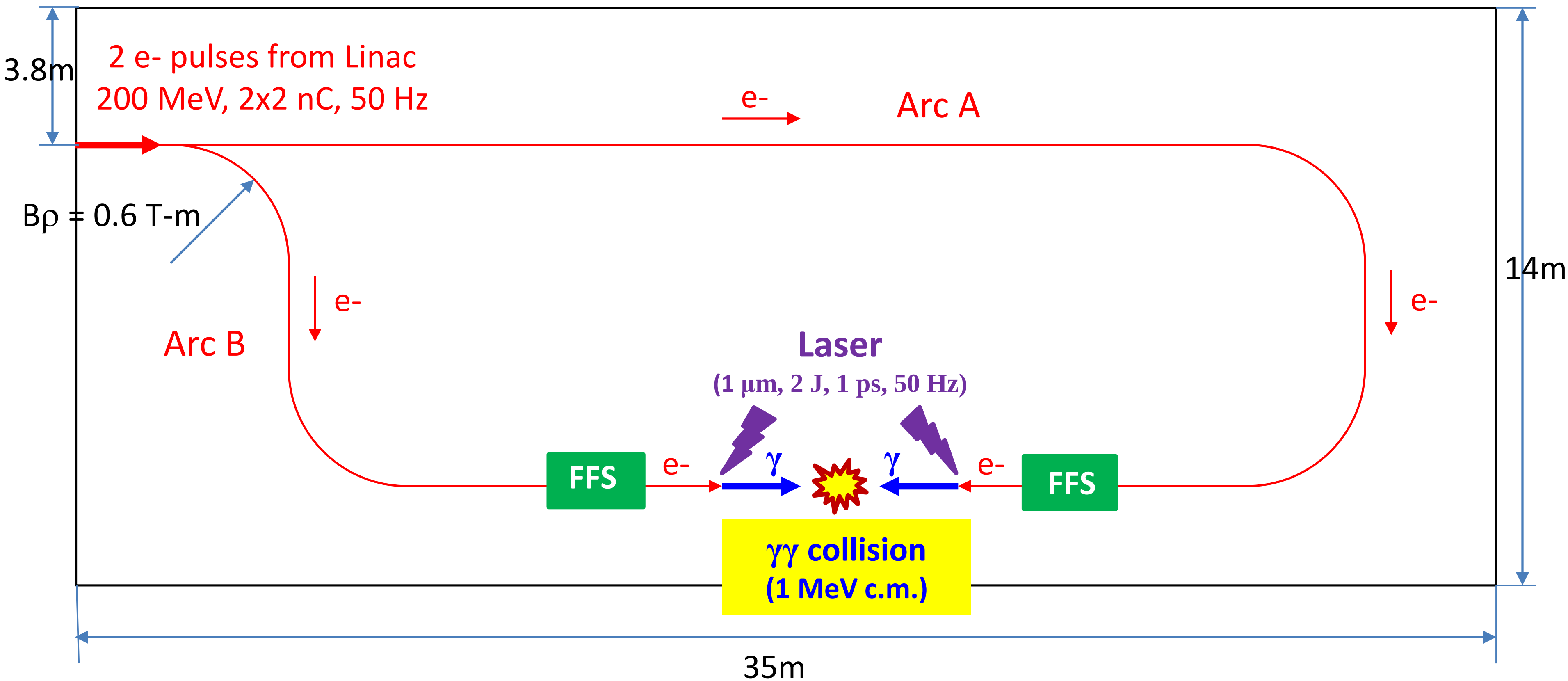


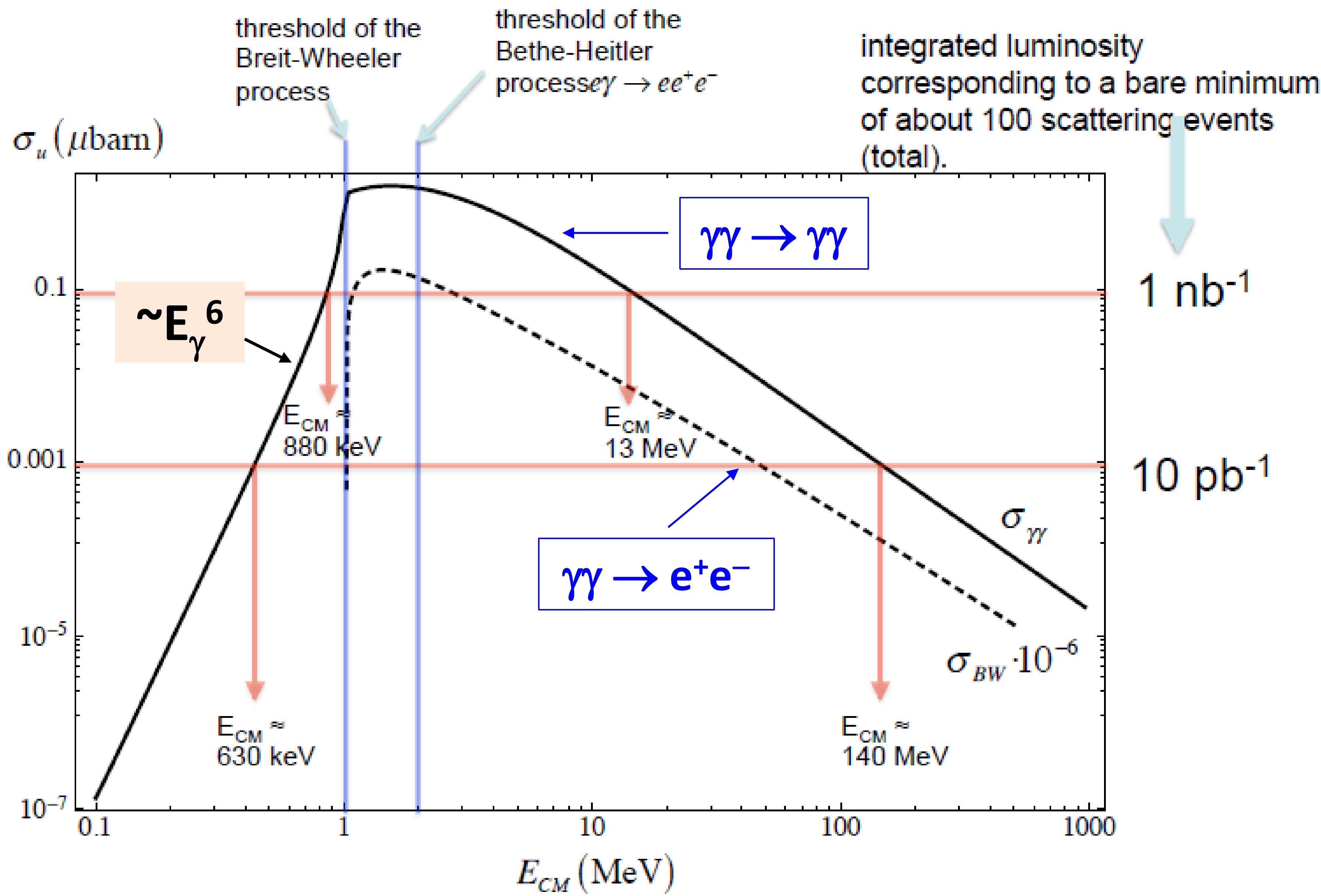
Figure 2: Principle of a coherent amplifier network (CAN) based on fiber laser technology. An initial pulse from a seed laser (1) is stretched (2), and split into many fibre channels (3). Each channel is amplified in several stages, with the final stages producing pulses of ~1 mJ at a high repetition rate (4). All the channels are combined coherently, compressed (5) and focused (6) to produce a pulse with an energy of **>10 J** at a repetition rate of **10 kHz** (7). [5]

Example – How to build a $\gamma\gamma$ Collider



Two unique experiments:

- $\gamma\gamma \rightarrow \gamma\gamma$ scattering: predicted (Halpern) but never observed in the laboratory
- $\gamma\gamma \rightarrow e^+e^-$: predicted (Breit-Wheeler) but never observed in the laboratory



Edoardo Milotti - LNF/IRIDE

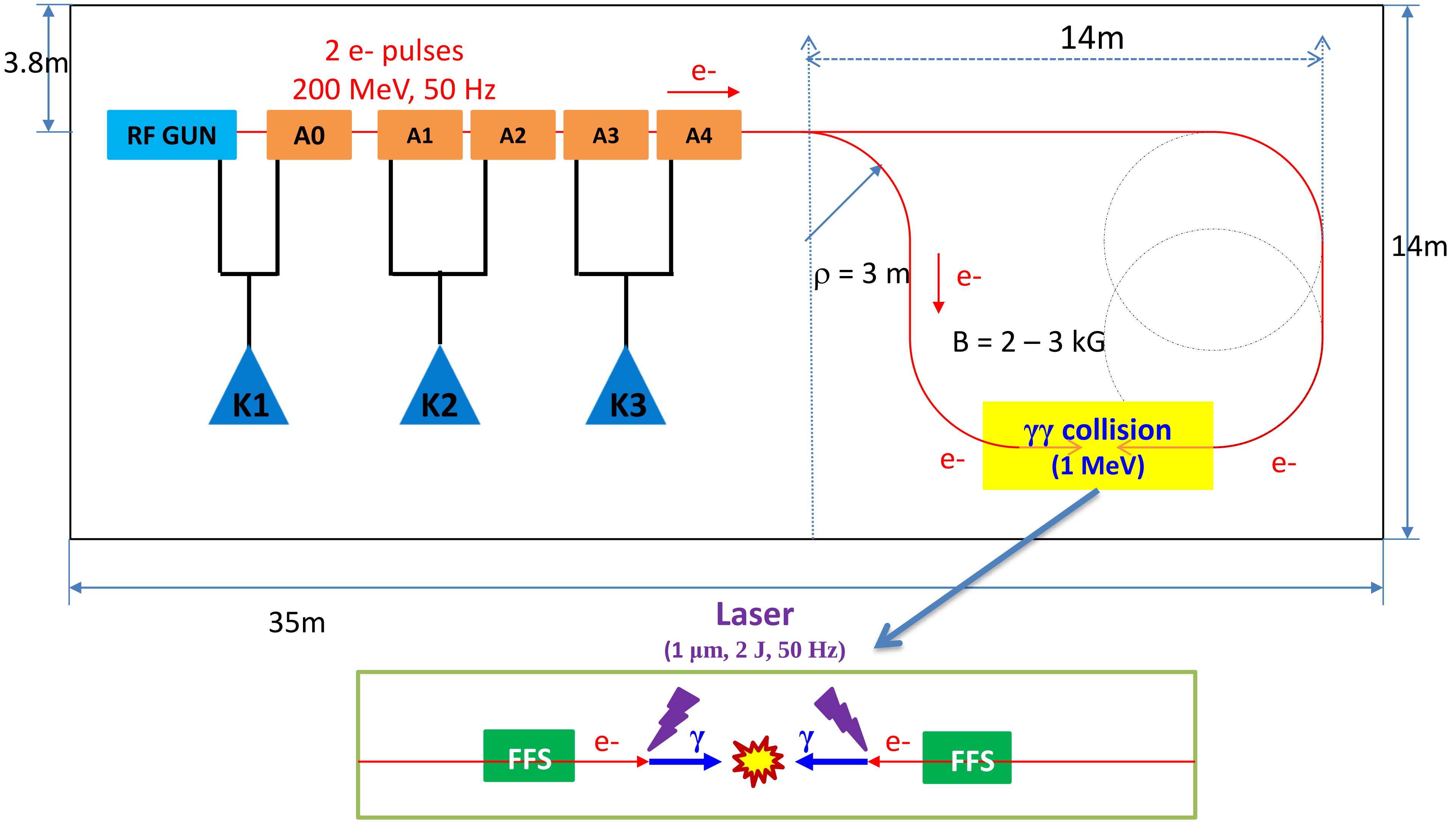
$\gamma\gamma$ Collider Parameters (11/01/2018)

Electron beam		Laser beam		γ Beam / $\gamma\gamma \to \gamma\gamma$ collision	
E	200 MeV	λ	1.054 μm	E(c.m., peak)	**1 MeV** (2 x 0.5)
Charge	**2 nC**	Waist	5 μm	N (total)	**2 x 10^{11} /s**
σ(x,y)	2 μm	Rayleigh	298 μm	Rep rate	50 Hz
ε	**6.4 nm**	Pulse energy	**2 J**	σ(x,y)	2 μm
β^*	626 μm	Pulse length	**1 ps**	*L*	**1 x 10^{27} $cm^{-2}s^{-1}$**
σ(z)	2 ps	Rep rate	**50 Hz**	$\int L$	10 nb^{-1} /year
Rep rate	50 Hz	Crossing θ	167 mrad	Cross section	3 μb
Crossing θ	0 mrad	d (IP-CP)	313 μm	Event rate	7 /hr
L (geometric)	1.6 x 10^{28}	Nonlinear a_0	0.45		30,000 /year

Event rate:

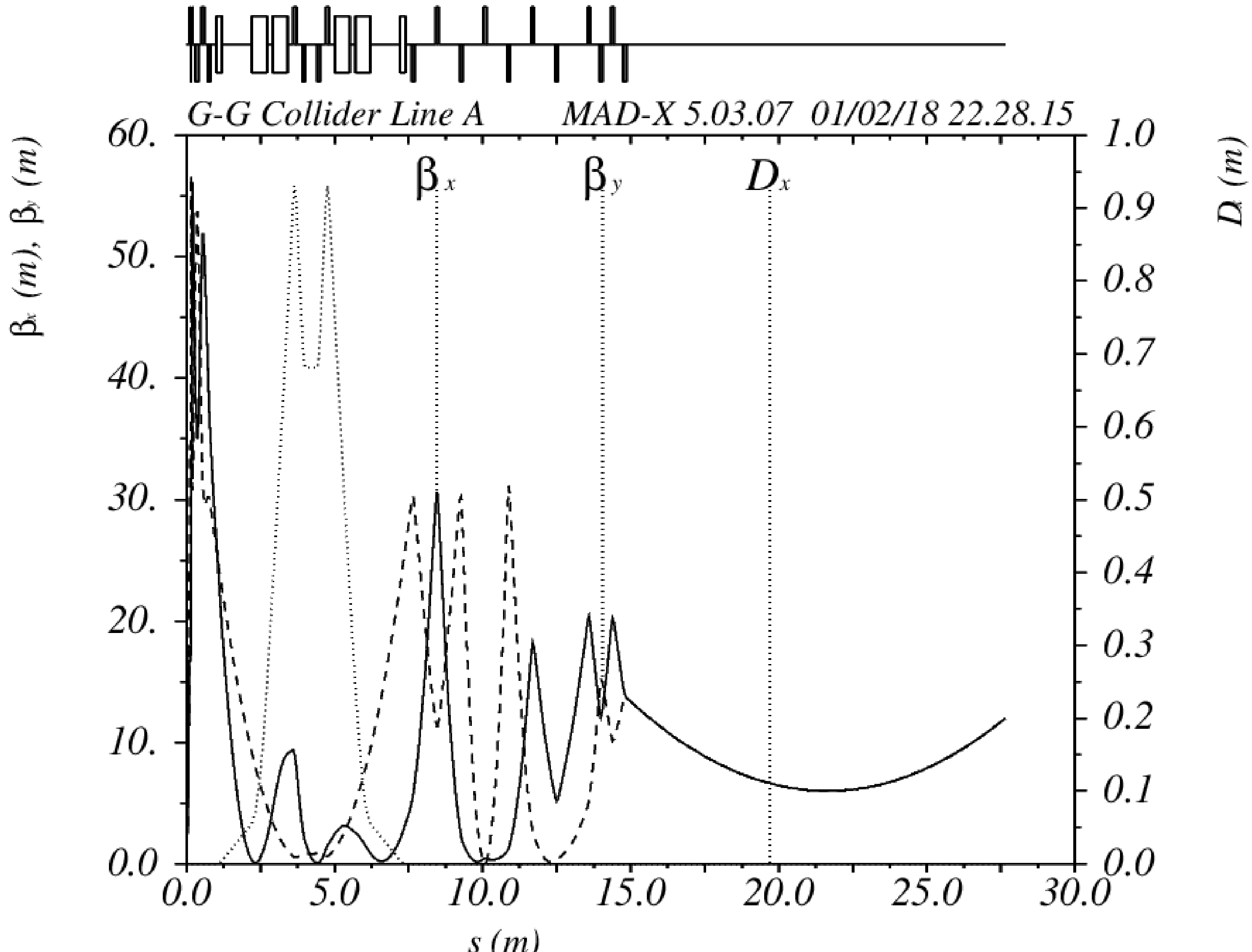
- $\gamma\gamma \to \gamma\gamma$: L = 1 x 10^{27}, σ = 3 μb $\Rightarrow$ several events per hour (30,000 events/ year) (*Comparable to the Higgs rate in CEPC, in which the luminosity is higher by 7 orders of magnitude, but cross section is smaller by 7 orders of magnitude*)
- $\gamma\gamma \to e^+e^-$: L = 1 x 10^{27}, σ = 100 mb $\Rightarrow$ 100 events per second

Electron Linac for γγ Collider



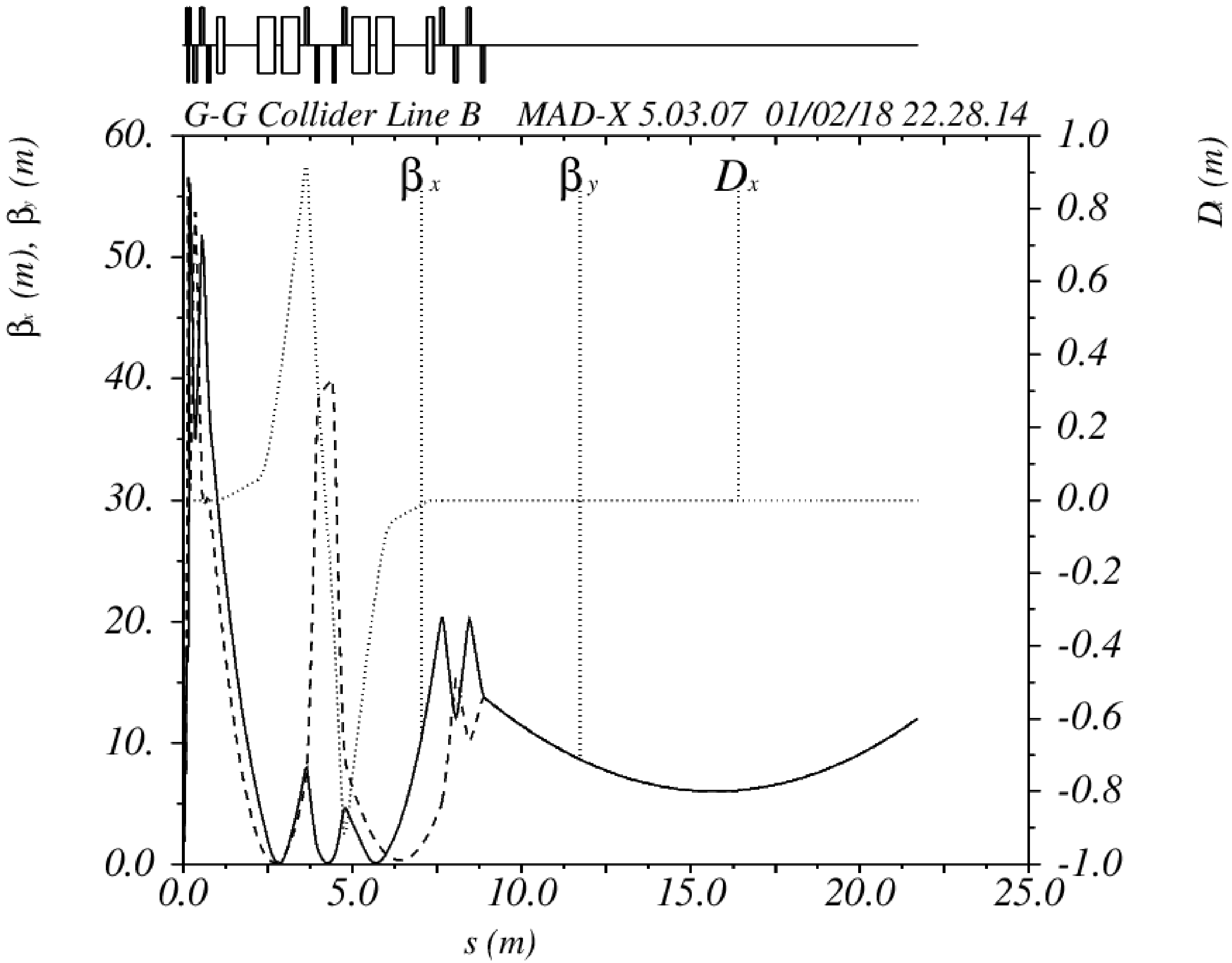
W.B. Liu

1 sigma beam size of BEAM Line A (beam energy dispersion effect is not included)

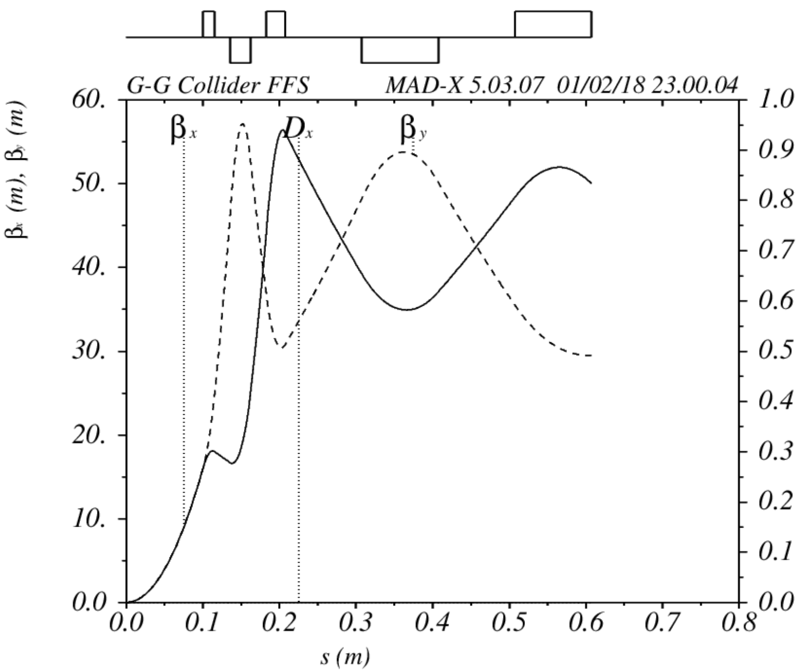


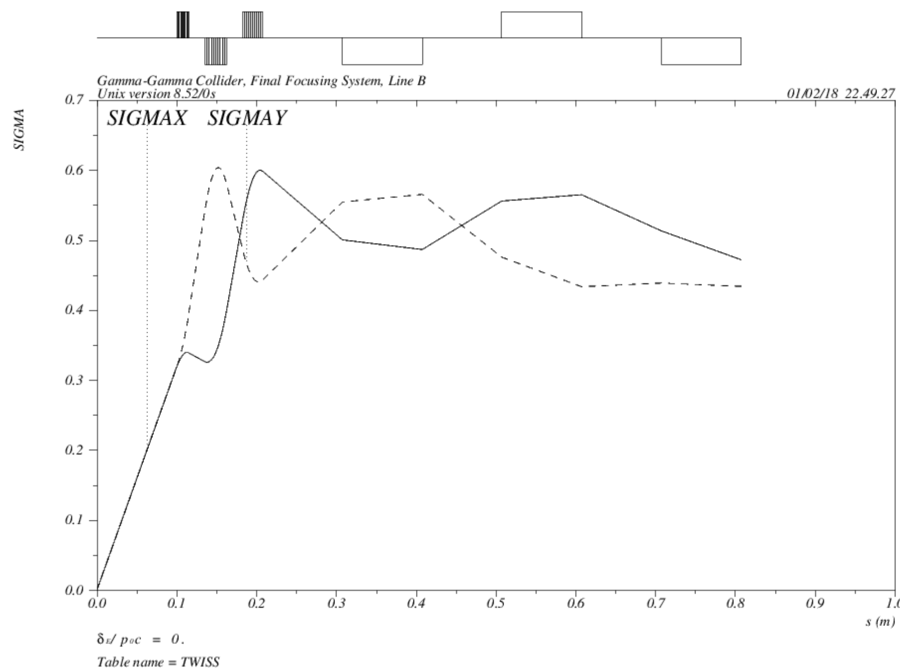
W.B. Liu

1 sigma beam size of BEAM Line B (beam energy dispersion effect is not included)



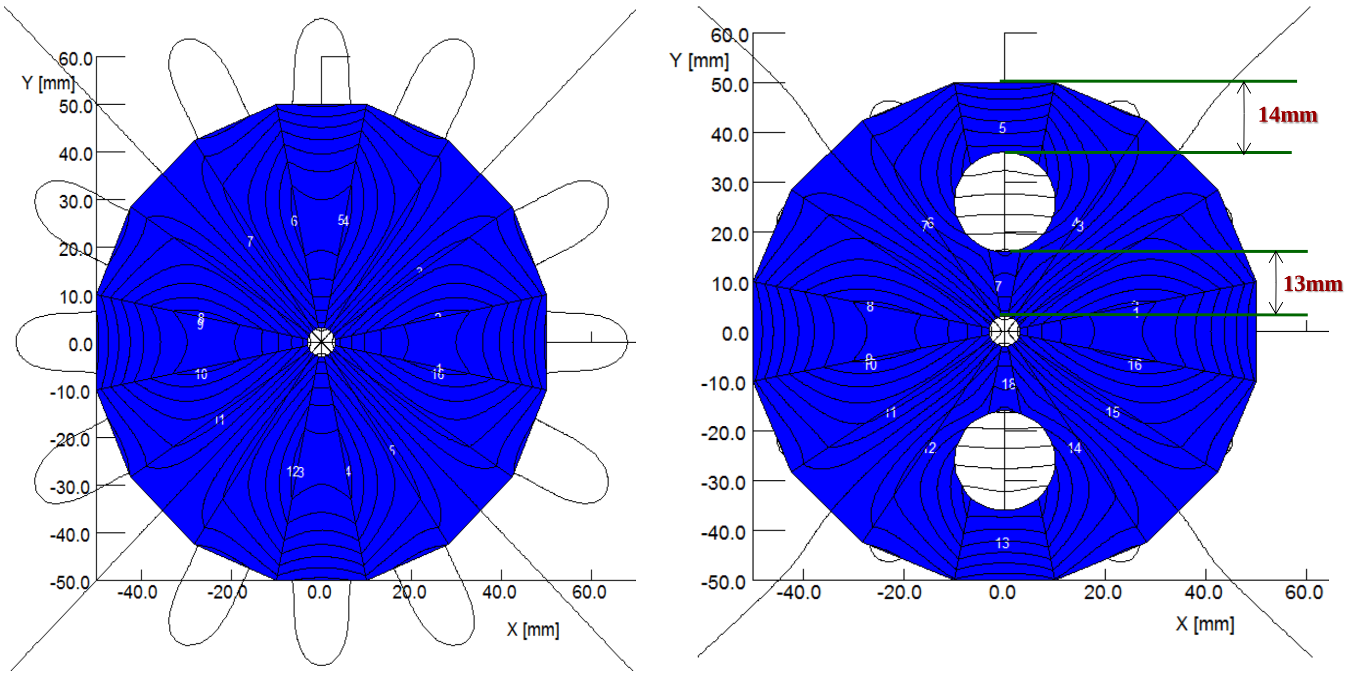
W.B. Liu



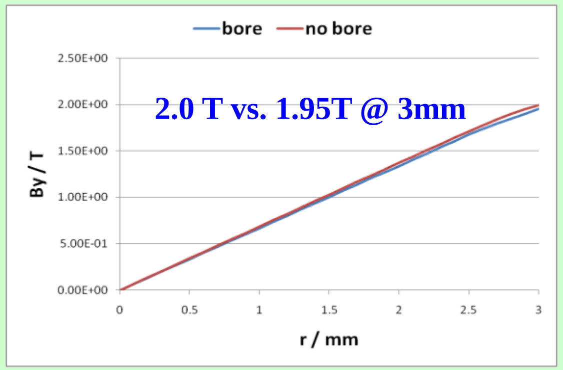


Beta fuction and 1 sigma beam size near the IP.

16-piece Permanent Quadrupole (Y. Chen)



	d（mm）	*G*（T/m）	*L*（mm）
1#	6	590	9.1
2#	6	590	15
3#	6	590	25

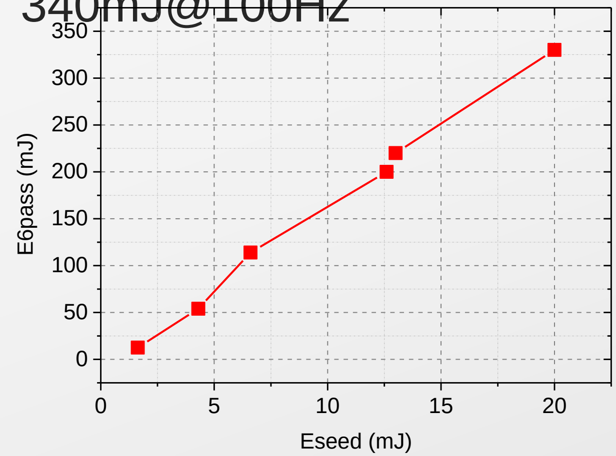


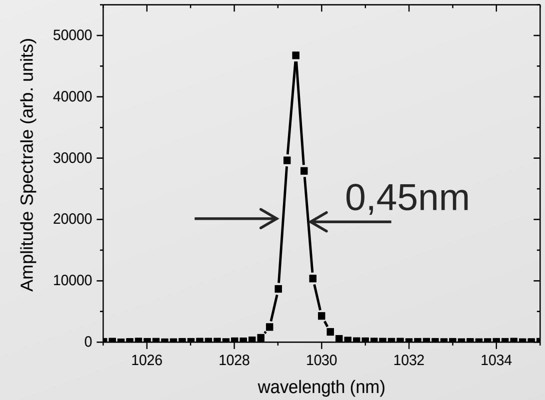
Narrowband power amplifier

	Magma 300
Pulse duration	< 5 ps
Average power	30 W
Pulse energy	300 mJ
Repetition rate	100Hz
Wavelength	1030 nm
Beam quality	$M^2 < 1.3$ - TEM_{00}
Footprint	75 x 50 cm
Cooling	Cryo

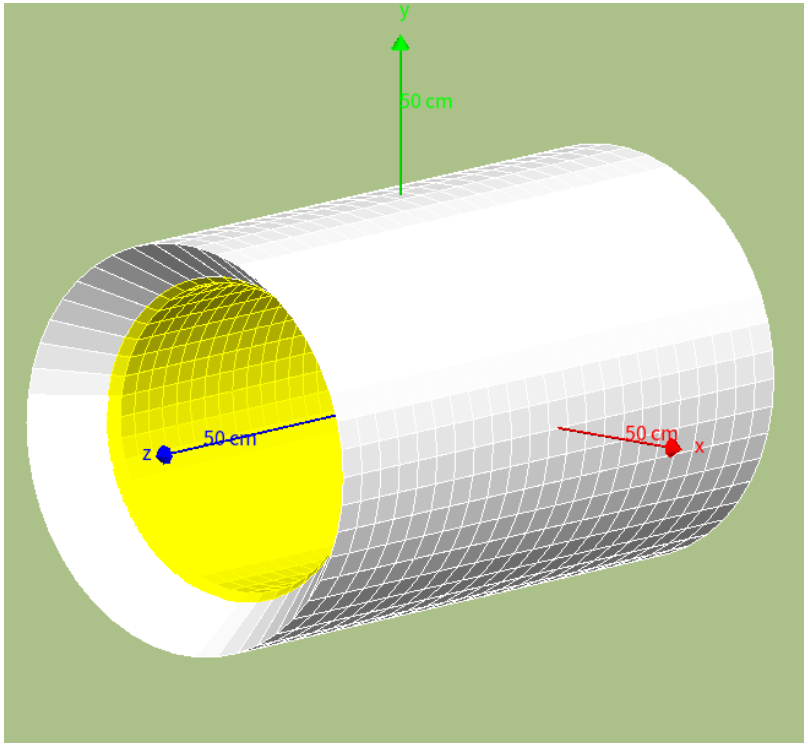
- Extracted energy :

340mJ@100Hz





Detector (Y. Huang, C. Zhang, J. Lu)



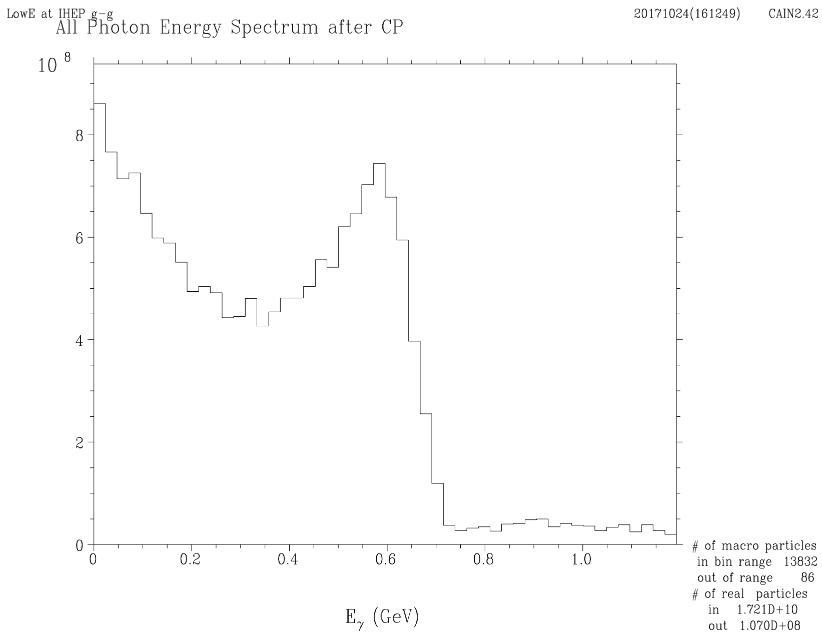
- **Detector dimension**
  - **Length =76cm**
  - **Inner diameter = 40cm**
  - **Thickness = 6cm**

- **PS detector**
  - **Attached in front and inner side of the crystal**
  - **Thickness = 1cm .**

- **CsI crystal**
  - **46 Lines,**
  - **23 crystals per line**
  - **966 crystals**

Photon Spectrum

Unpolarized Electron



Polarized Electron

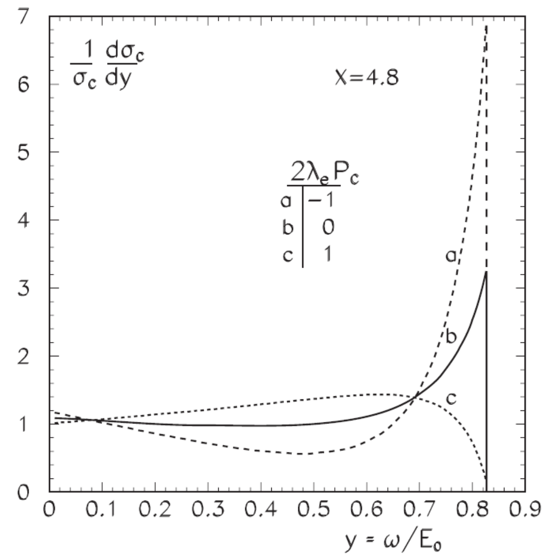
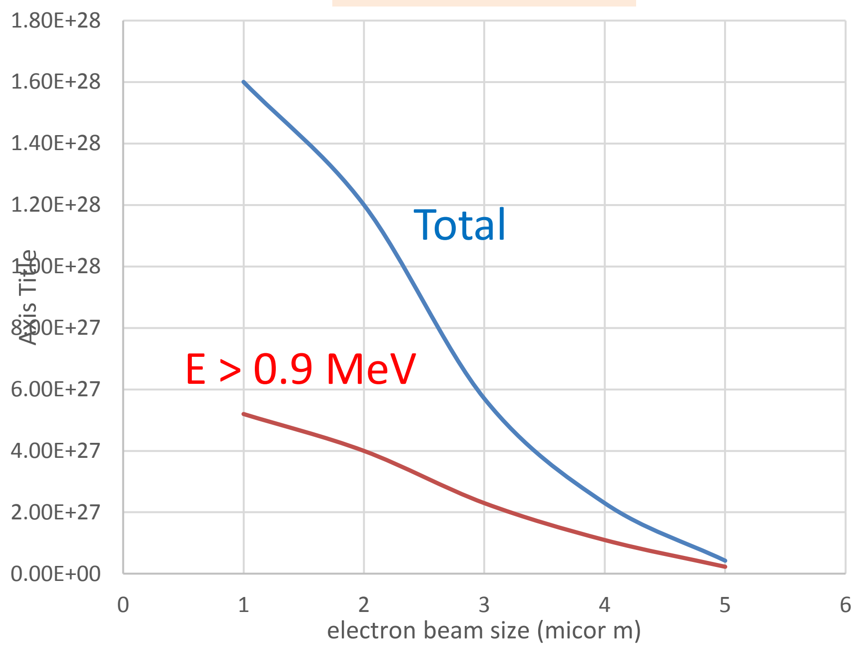
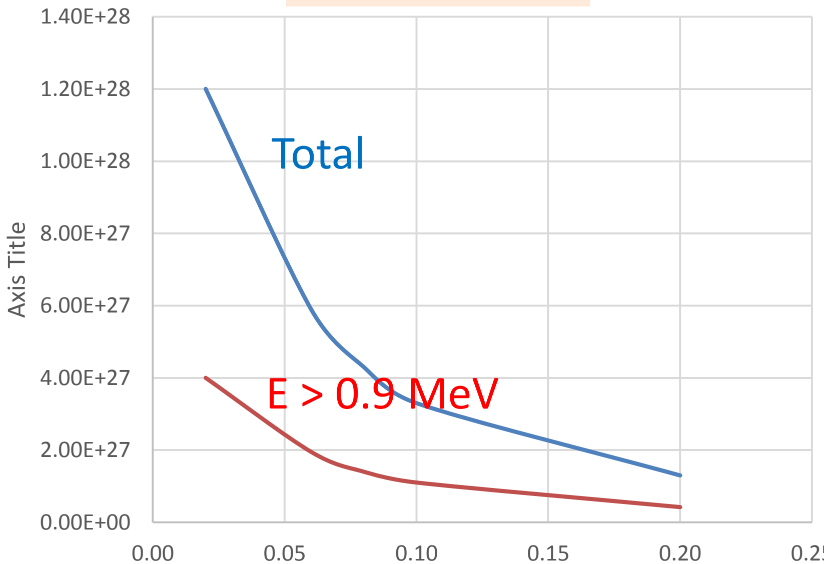


Figure 1.3.1: *Spectrum of the Compton scattered photons for different polarisations of the laser and electron beams.*

Luminosity Calculation (code CAIN)

(T. Takahashi)

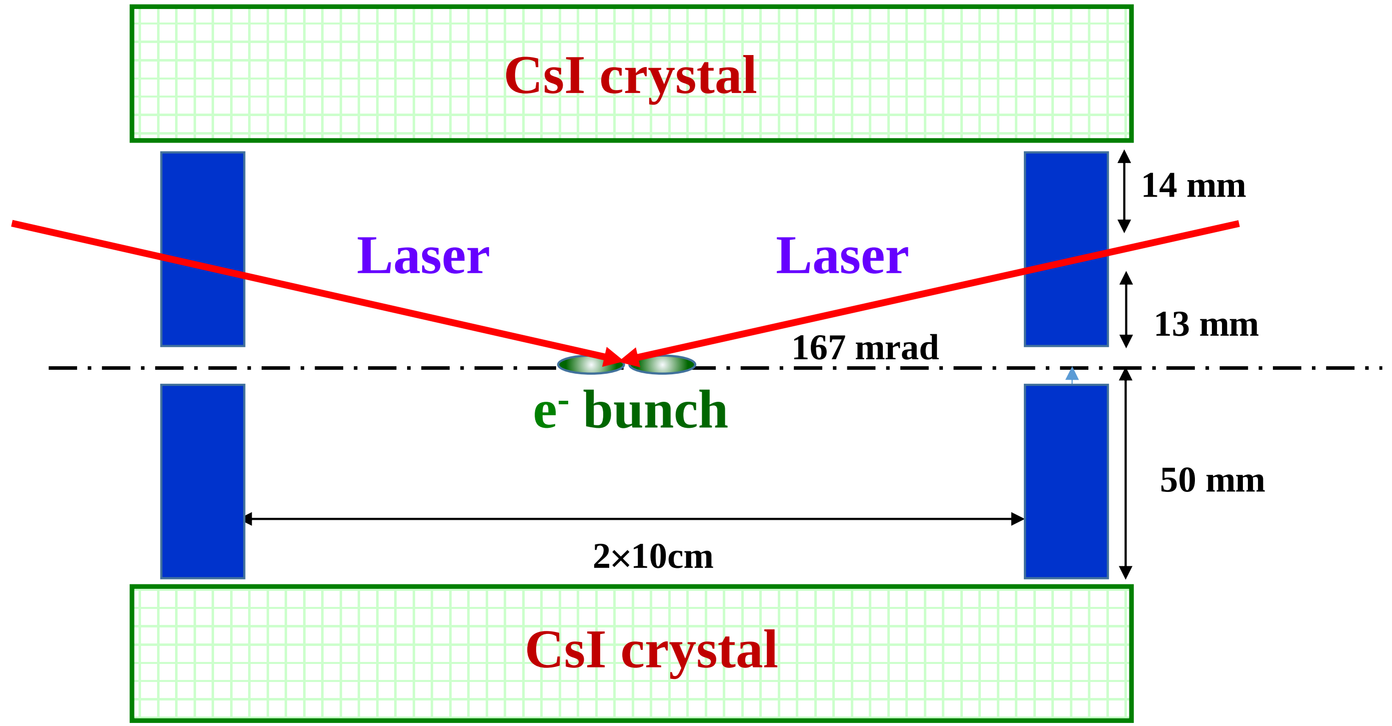




$L = 1.1\times 10^{27} cm^{-2} s^{-1}$ for 0.9MeV < W

$L = 3.3\times 10^{27} cm^{-2} s^{-1}$ for all energy

Detector Simulation (T. Takahashi, B.H. Sun)

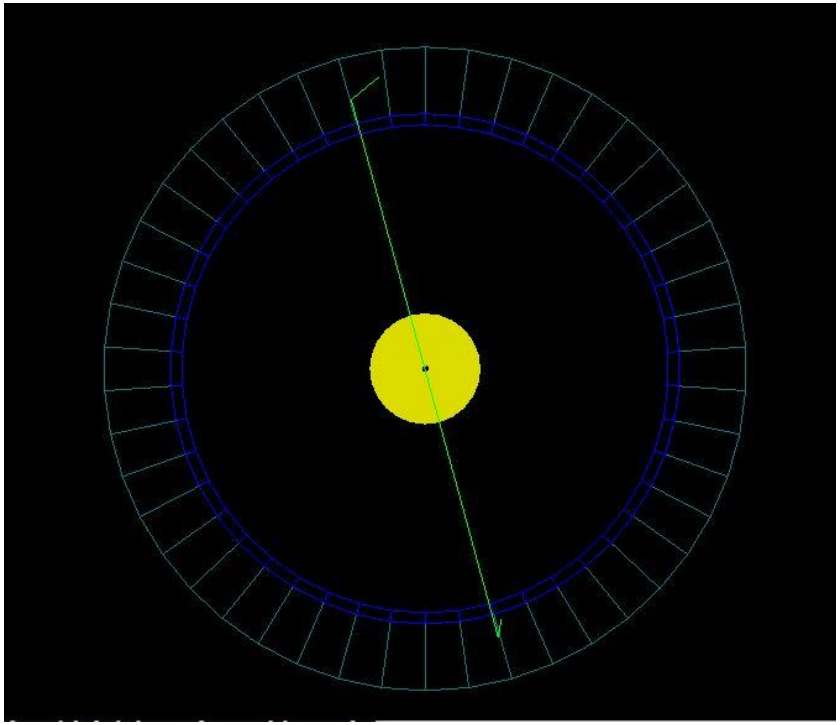
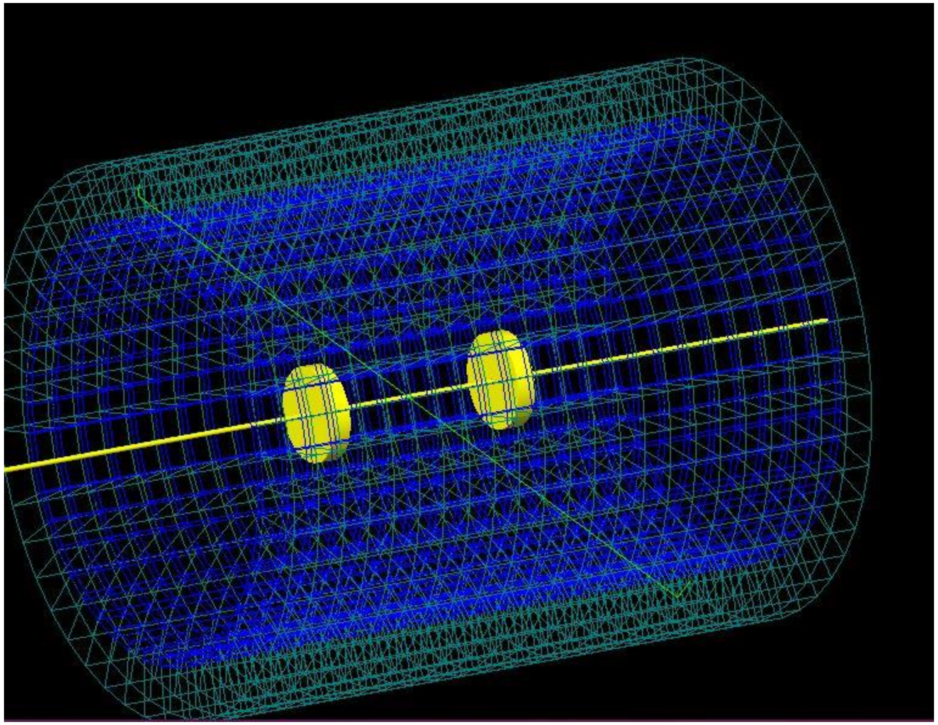


- **Detection simulations** **design, resolution, efficiency, background …**
- **Physics simulation** $\gamma\gamma \rightarrow \gamma\gamma$, $\gamma\gamma \rightarrow e^+e^-$, $\gamma e^- \rightarrow \gamma e^-$ …
- **Shielding design and simulation** **beam Scattering, collimation design…**

The study gets under way

Detector Simulation (T. Takahashi, B.H. Sun)

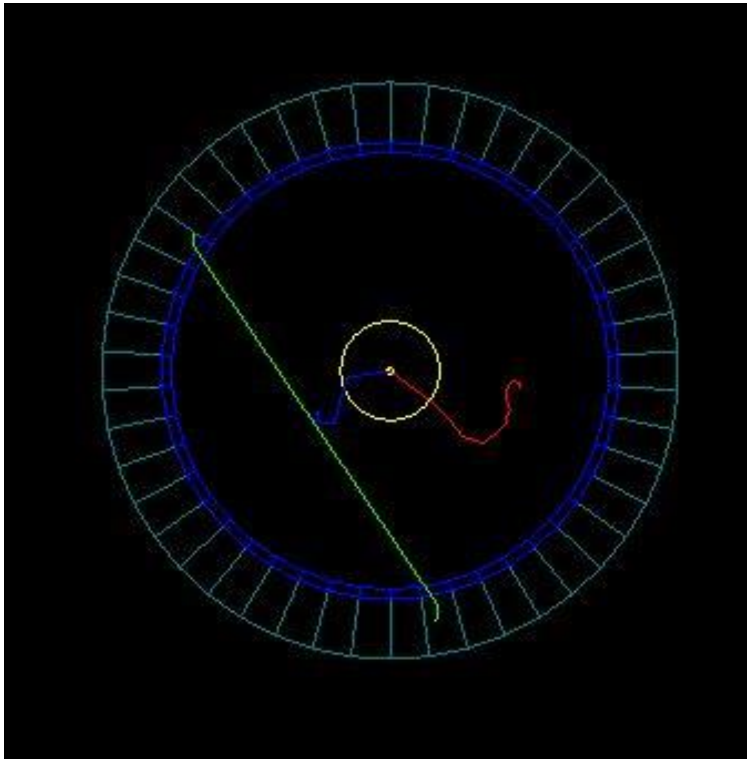
$$\gamma\gamma \to \gamma\gamma \quad \sqrt{s} = 1.41 MeV$$

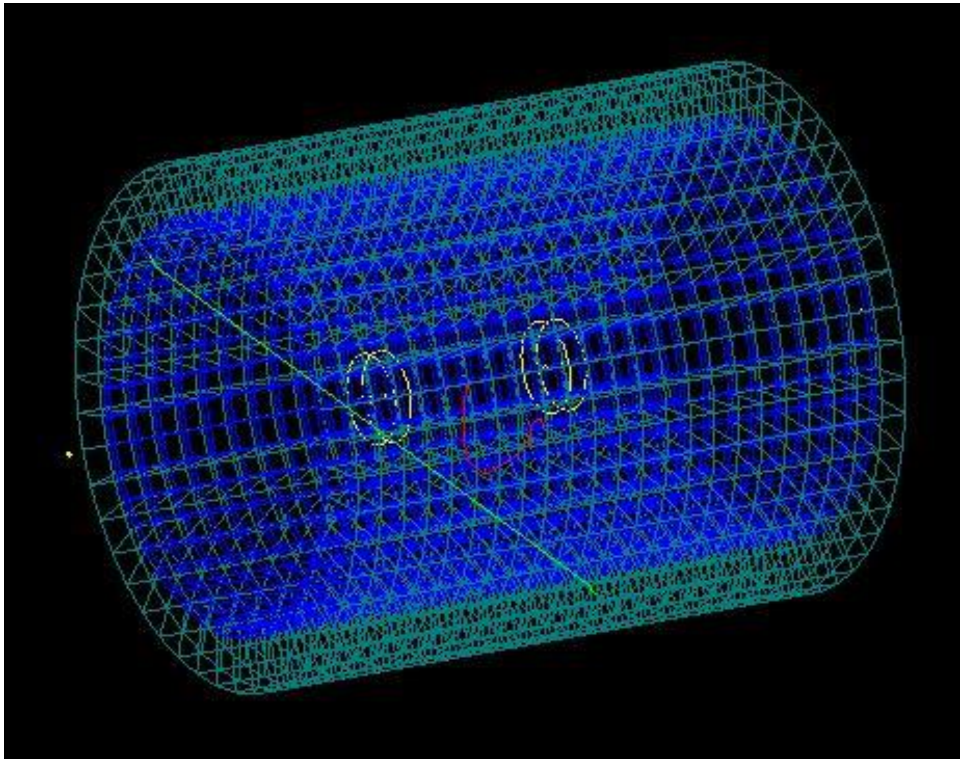



Back to back photons 0.0019 events/s

Detector Simulation (T. Takahashi, B.H. Sun)

$$\gamma\gamma \rightarrow e^+e^- \;\; \sqrt{s} = 1.41 MeV \;\; \Rightarrow \;\; p_{e^\pm} \approx 0.48 MeV$$





Low momentum e^+ e^- not back to back 64 events/s

Challenges

- **<u>Electron beam</u>**:
  - ∗ high charge (2 nC)
  - ∗ low emittance (6 nm at 200 MeV)
- **<u>Laser beam</u>**:
  - ∗ high average power (100 W)
  - ∗ high repetition rate (50 Hz)
  - ∗ high intensity (2 J)
  - ∗ short pulse (1 ps)
- **<u>FFS</u>**:
  - ∗ small size, high gradient PMQ (600 T/m)
- **<u>Detector</u>**:
  - ∗ to select $\gamma\gamma$ signal from e+e- signal
  - ∗ strong background from eγ and e-e- collisions
- **<u>Timing</u>**:
  - ∗ Jitter requirement: <100 fs
  - ∗ between e-beam and laser
  - ∗ between two laser beams

Status of $\gamma\gamma$ Collider

- High energy $\gamma\gamma$ collider for Higgs factory:
  There are a number of proposals. However, the timeline to construct a real one appears to be very long – it has to wait until a high energy e+e- collier is built (e.g., ILC, CLIC)

- Low energy $\gamma\gamma$ collider:
  Being actively pursued in China, Italy and Japan (part of ELI-NP). The construction of at least one of them is likely to happen soon.

- Medium energy $\gamma\gamma$ collider:
  If a low energy $\gamma\gamma$ collider is successfully built, a medium energy one may quickly follow suit, because it can use existing electron accelerators and also because there are a lot of interesting physics in several GeV range.

Summary

- Both muon collider and $\gamma\gamma$ collider were proposed in 1980s but have never been built because of technical difficulties.
- The “traditional” muon collider had been pursued for more than 20 years but the activity is stalled due to lack of technology breakthrough (e.g., how to solve the problem of RF breakdown in a strong magnetic field) and other reasons.
- A new idea about muon collider was recently proposed and appears to gain momentum, because it has no need for muon cooling. But it must find a solution for how to produce a high intensity e+ beam.
- From early on, $\gamma\gamma$ collider had been considered as an afterburner of a high energy linear collider and, thus, a remote possibility.
- However, interest in a low energy $\gamma\gamma$ collider together with today’s advanced laser technology has changed the game plan. A first $\gamma\gamma$ collider can be built in just a few years.
- This field is very challenging and will attract young and talented people who love challenges.
- But this field also contains high risk. ROI (return on investment) is uncertain – it could be enormous (success will crown you “world no. 1”), but it might also go nowhere.

Questions?