新奇加速器技術を用いた将来の加速器への夢

2016/9/7

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High energy accelerator organization (KEK)

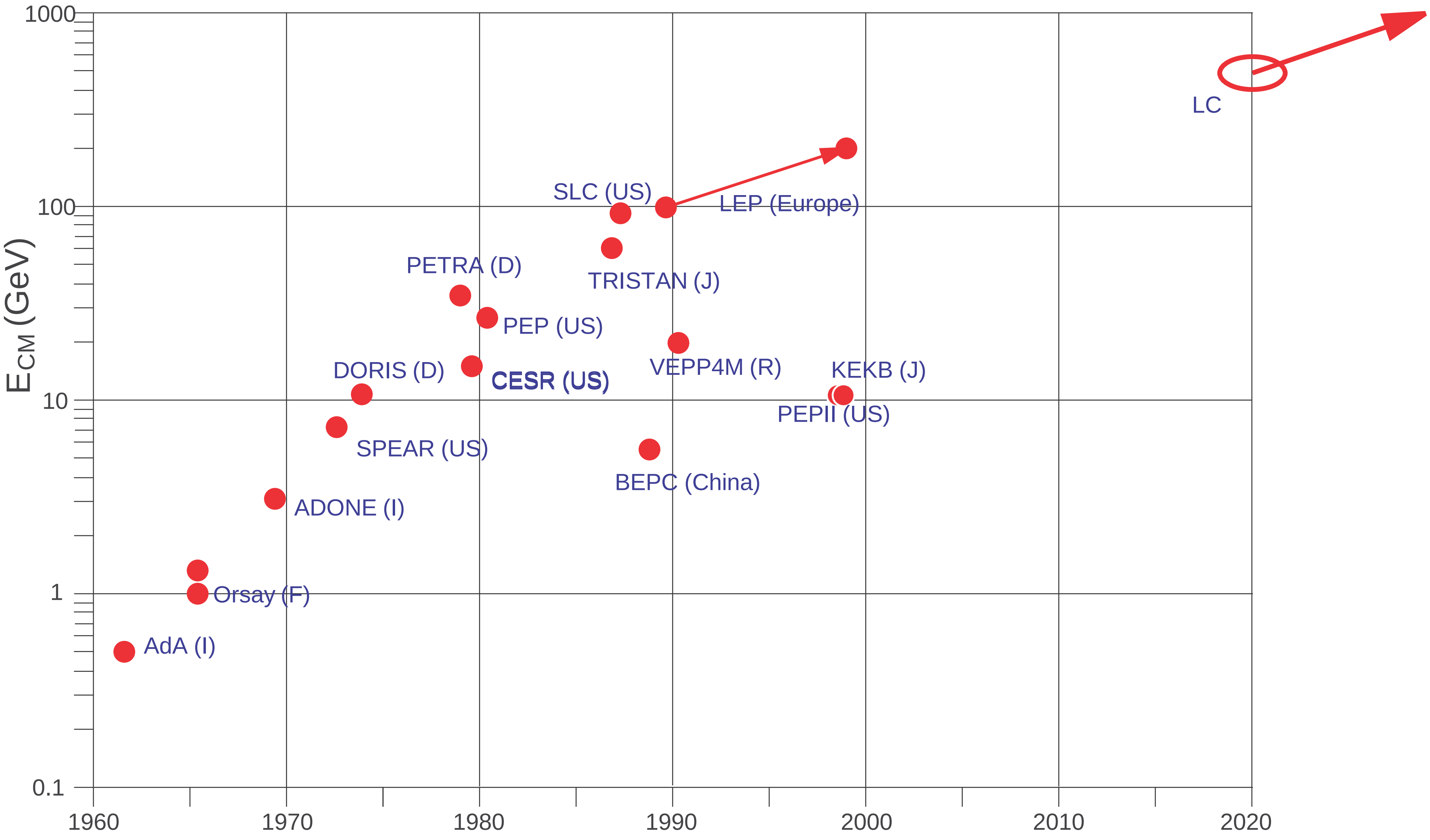
Alternative for Energy Frontier

- 電子
  - 円形加速器 : 輻射で限界？
    - いやまだ限界でない → 100 km の FCC
    - シンクロトロン放射のエネルギー回収 → ERR
  - リニアコライダー： 高電界 L = V/E と効率
    - Nb超伝導(2K運転, < 40MV/m) → 高温超伝導 薄膜超伝導
    - 誘電体 : 誘電体フォトニック DLA(Laser, THz)
    - 周波数重畳
    - プラズマ加速
      - レーザープラズマアフターバーナー
      - 陽子ビームプラズマ ← J-PARC の Energy Frontier への転用の可能性
- 陽子 : 輻射が無い
  - 強磁場 p(GeV/c)=0.3 B(T) ρ(m) LHC 7TeV=0.3x8.4Tx2804m → HE-LHC
  - スーパーフェリック
  - Crystal Accelerator
- ミュオン： 輻射が無いが冷却が問題
  - MICE(FERMI)
  - Ultra Slow Muon : μ^+のみ → μ^+e^- collider
  - 45 GeV e^+

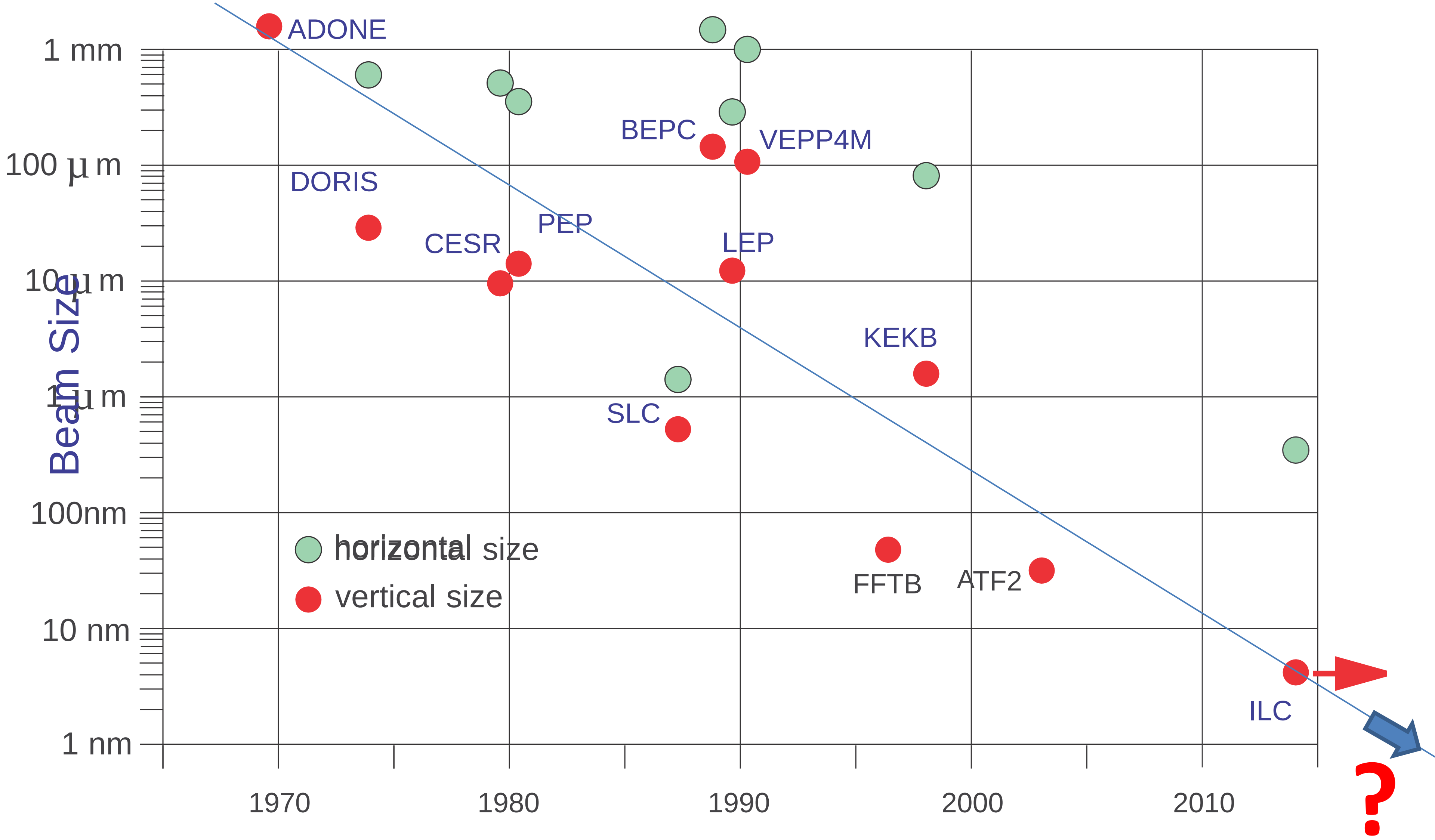
Alternative for High Intensity

- 電子陽電子コライダー
  - ビーム寿命 → エミッタンスコンバーター
  - 電力消費 → ERR
- 陽子 / イオン 大強度加速器
  - パルス磁場 → FFAG
  - インダクション → 超高速半導体スイッチ
    - **Photoconductive Semiconductor Switch (PCSS)**
    - Semiconductor Opening Switch (SOS)
- イオン蓄積リング
  - **Relic Neutrino との衝突 : 低閾値β崩壊核**
  - EC ビーム
  - 励起イオン

e^+e^- Collderの歴史



Beam Sizeの歴史



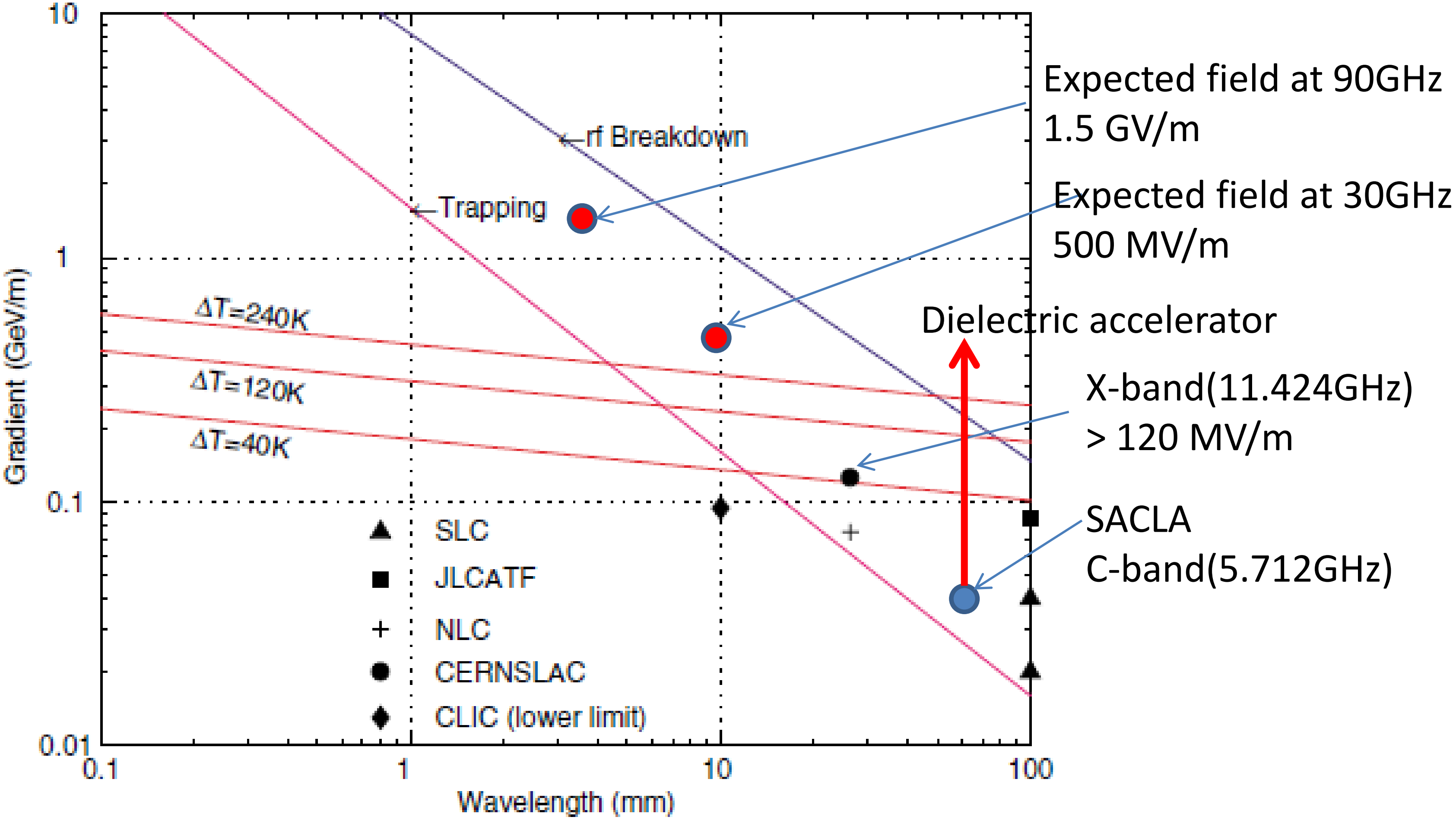
ムーアの法則に沿うには何が見込みがあるか？

- 大型化＝金/製造コスト
  →　金が指数的に増えるわけが無いので
  （バブル世代の人の問題）
  - 穴堀＋磁石、高周波加速等のコストダウン
    →　スーパーフェリック
    →　超伝導はコスト的に？？？
- 磁場　→　VLHC
- 電場＋ビームサイズ　→　リニアコライダー
- 回収効率　→ ERL / ERR

Microwave accelerator

Limit of metal wall microwave accelerator

$$E_{\mathrm{s,\ max}} \approx 195\mathrm{MV/m}[\nu(\mathrm{GHz})]^{1/2}.$$



Expected field at 90GHz
1.5 GV/m

Expected field at 30GHz
500 MV/m

Dielectric accelerator

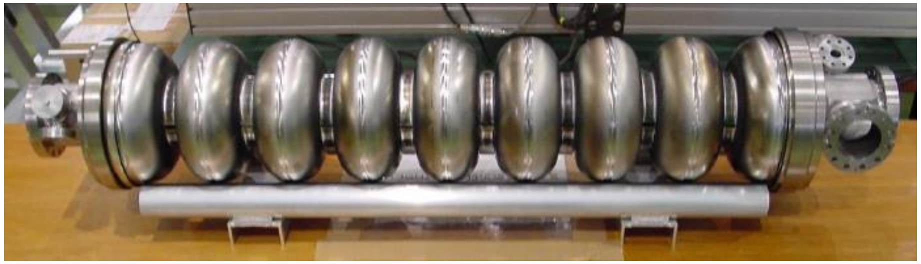
X-band(11.424GHz)
> 120 MV/m

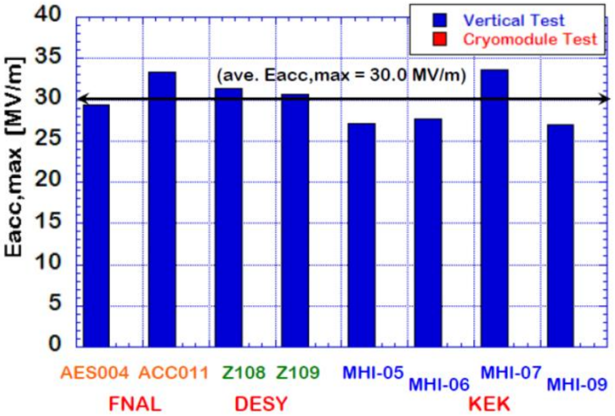
SACLA
C-band(5.712GHz)

Current limit of microwave accelerator

- RF source
  - X-band (11.424GHz) LC　　Klystron
    Failure of 100MW klystron development
    + RFvPulse compressor
  - CLIC　　Drive beam

- Quench　ILC(Superconductor)





→ High Tc material : NbN, MgB2 etc,.

加速器の電界を大幅に上げるには

- 耐圧の高い媒質

  ×金属

  ◎プラズマ

  ○誘電体

$$W(\text{蓄積エネルギー}) = \int \frac{\varepsilon E^2 + \mu H^2}{2} dV$$

$$E = \sqrt{\frac{2W}{\varepsilon V}} \sim f\sqrt{W}$$

E：電界、H：磁界
V：体積
f： 周波数

- **体積を小さくする** or 蓄積エネルギーを上げる

$$Q = \frac{\omega W}{P_{wall}}$$

周波数の高い加速器： THz

- 従来のGHz帯加速方式
  → 20GHz以上の高周波源が無い
- **100 fs 程度の超短パルスとプラズマ or 誘電体による変換**

・レーザー駆動	レーザー高強度化は著しく速い
・電子ビーム駆動	SLAC/KEK等で可能&世界最高電圧の実績
・陽子ビーム駆動	CERN/J-PARC等で可能→バンチ圧縮が問題

Q値の高い材料

- 常伝導Cu： Q～10,000
- 超伝導Nb： Q～10^{10} しかし電界<40MV/m
- **誘電体 ： Q～10^6**

私の最近の研究テーマ

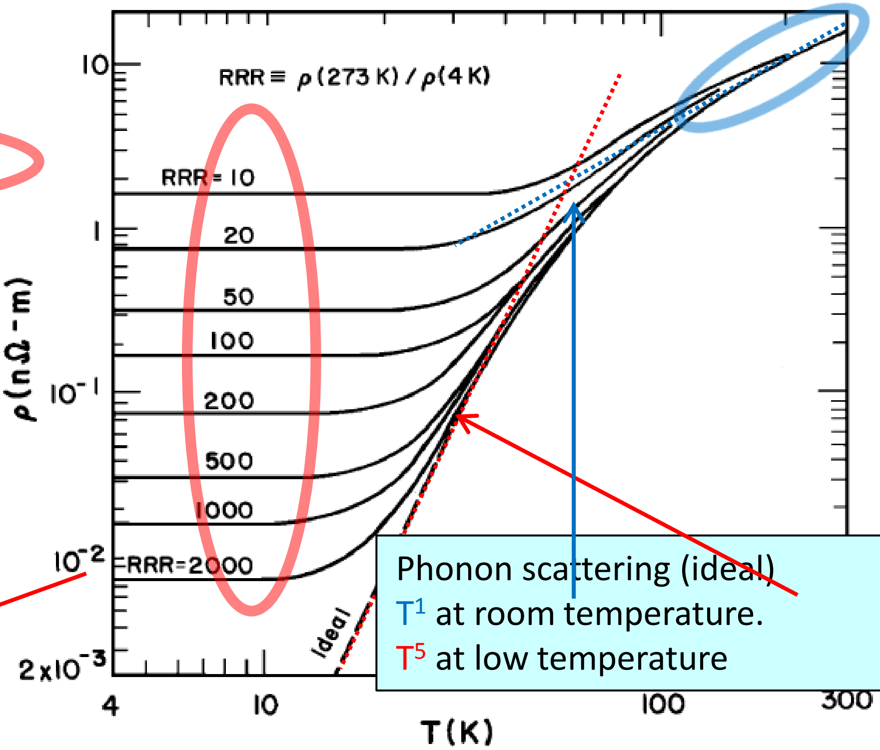
Cryogenic cavity :

Quality factor

$$Q_0 = \frac{Stored\ \ energy}{Power\ \ loss\ \ per\ 1\ RF\ cycle}$$

$$Q_0 \propto \frac{1}{\sqrt{\rho}}$$

Copper resistivity



Phonon scattering (ideal)
T^1 at room temperature.
T^5 at low temperature

Resistivity vs Temperature

$$RRR \equiv \frac{R(T=300K)}{R(T=4.2K)}$$ residual resistivity ratio : RRR

RRR=2000 at 10 K
Electric resistivity goes down to 1/1000

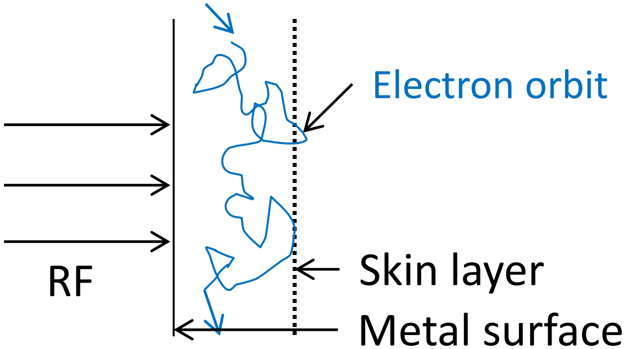
Q_0 factor expected up to 30 ??? but ....

R. L. Powell and F. R. Fickett, Cryogenic Properties of Copper, International Copper Research Association, Dec. 1979.

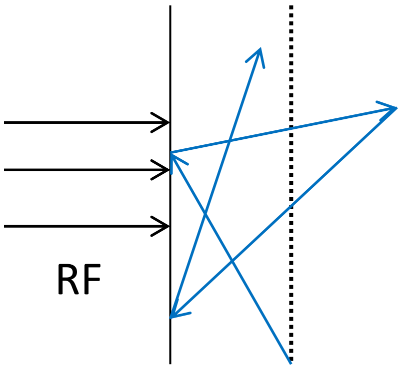
*N. Ashcroft & N. Mermin: Solid State physics, p.526 (W. B. Saunders Co., 1976).

Cryogenic cavity / Anomalous skin effect

Room temperature : *(l << δ)*



Low temperature : *(l >> δ)*



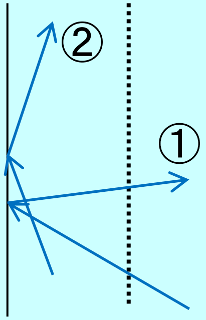
l >> δ :

Anomalous skin effect

外部電場の１周期の周期運動の間に表皮深さ内で複数回、伝導電子の散乱が起こる。

⇩

l << δ : *classical skin effect* is dominant



①表皮深さ内で散乱されず、深部に伝播するためRFの遮蔽・吸収に寄与しない。

② RFの遮蔽・吸収に寄与する。

⇩

①の分だけ、電気伝導に有効な電子数N_{eff}が減少したように見える。

$$N_{eff} = \gamma N \frac{\delta_{eff}}{l}, \quad \sigma_{eff} = \gamma \sigma_{dc} \frac{\delta_{eff}}{l}$$

$$\delta_{eff} = \sqrt{\frac{2}{\omega \mu \sigma_{eff}}}$$

$\gamma = 1$: *diffusion reflection*

$\gamma = 8/9$: *specular reflection*

$$R_{anomalous} = \frac{1}{\delta_{eff}\sigma_{eff}} = \sqrt{\frac{\omega\mu}{2\sigma_{eff}}}$$

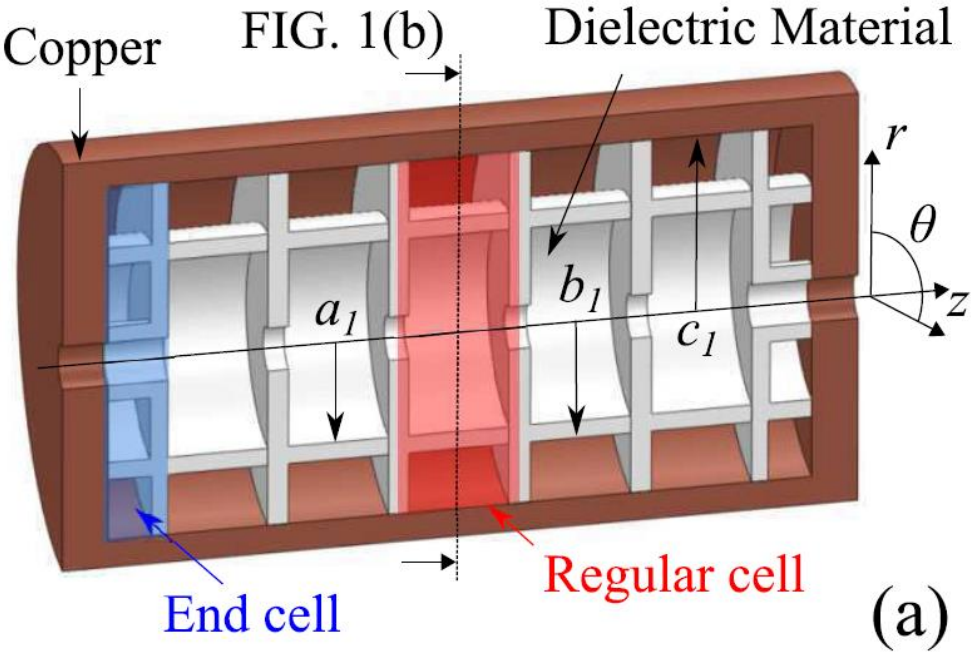
$$\frac{\delta_{eff}}{l} << 1$$

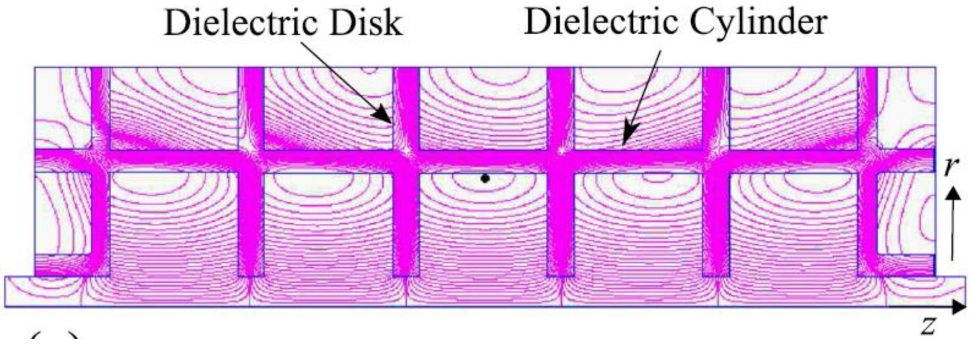
有効電気伝導率が減少するため、表面抵抗は増加する。

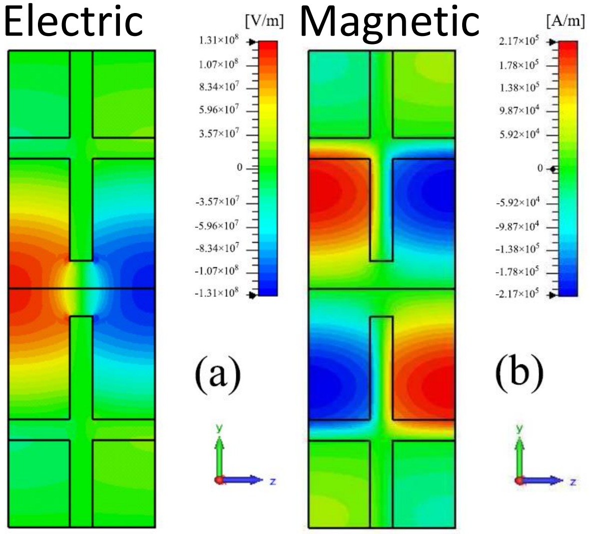
誘電体アシスト型加速管

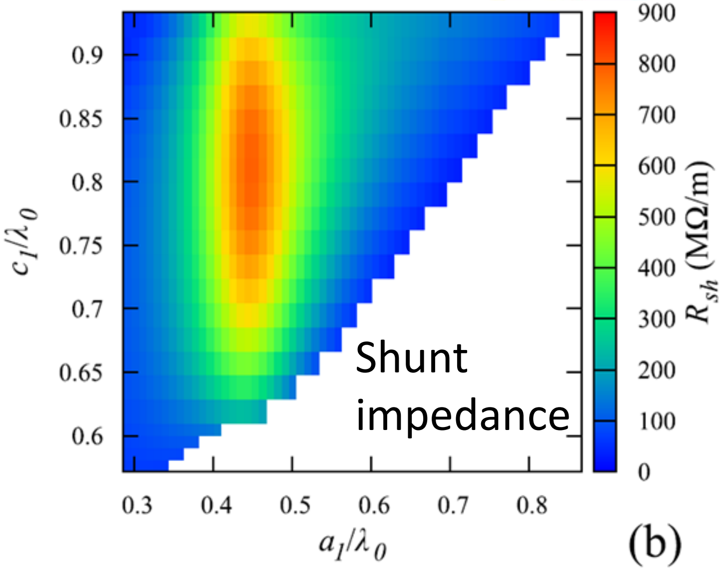
- 1 GΩ/m of Shunt Impedance

  (80MΩ/m for normal conductor accelerator)









"Dielectric assist accelerating structure"
Phys. Rev. Accel. Beams 19, 011302
Published 25 January 2016.

誘電体アシスト型加速管

特徴:

- 1m 辺り 5 MW で 100 MV/m が達成可能
- ロングパルス　～100μs (⇔常伝導　数100ns)
- パルスコンプレッサー不要 ⇒ 高システム効率

開発の現状

- 高電界試験中
- 科研費　若手A　→　基盤A
- 三菱重工との共同研究締結
- 国内特許出願済、国際特許申請準備中

Energy recovery

Energy Recovery Ring (ERR)

$$P = \frac{2}{3}\frac{e^2 c}{4\pi\varepsilon_0}\frac{\beta^4\gamma^4}{\rho^2} = \frac{2}{3}\frac{e^2 r_e}{m_e^{\ 3}} E^2 B^2,\ r_e = 2.82\times 10^{-15},\ m_e = 0.511 MeV$$

$$p = eB\rho,\ E = cp$$

$$T_0 = \frac{2\pi\rho}{c}$$

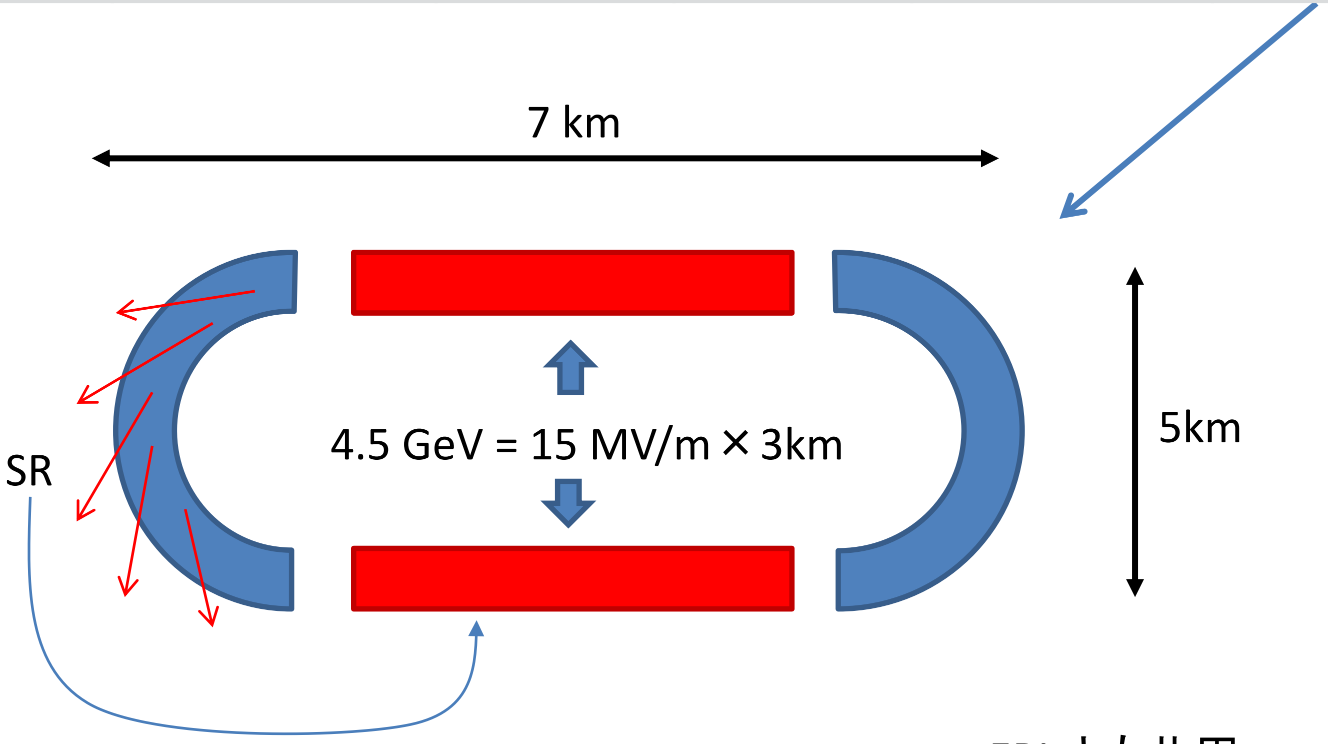
$$W_{1turn} = PT_0 = \frac{2}{3}\frac{e^2 r_e}{m_e^{\ 3}} E^2 \frac{E^2}{e^2 c^2 \rho^2}\frac{2\pi\rho}{c} = \frac{4\pi}{3}\frac{r_e}{\left(m_e c\right)^3}\frac{E^4}{\rho}$$

$$W_{1turn}[eV] = 8.85\times 10^4 \frac{E^4[GeV]}{\rho[m]} = 2.65\times 10^4 E^3[GeV]B[T]$$

$$P_{total} = \frac{W_{1turn} N_e}{T_0} = W_{1turn}[eV] I_{beam}$$

Energy Recovery Ring (ERR)

	SuperKEKB	LEPII	FCC	KEKB−Higgs	ERL−Higgs
Energy(GeV)	7	100	120	120	120
Circumference(km)	3	27	100	3	15
Bending Radius(km)	0.4	3.026	11	0.4	2
Ibeam(A)	2.6	0.008	0.03	0.03	0.03
W1turn(MeV)	0.53122125	2924.653	1668.305	45878.4	9175.68
Psynchrotron(MW)	1.38117525	23.39722	50.04916	1376.352	275.2704



7 km

4.5 GeV = 15 MV/m × 3km

5km

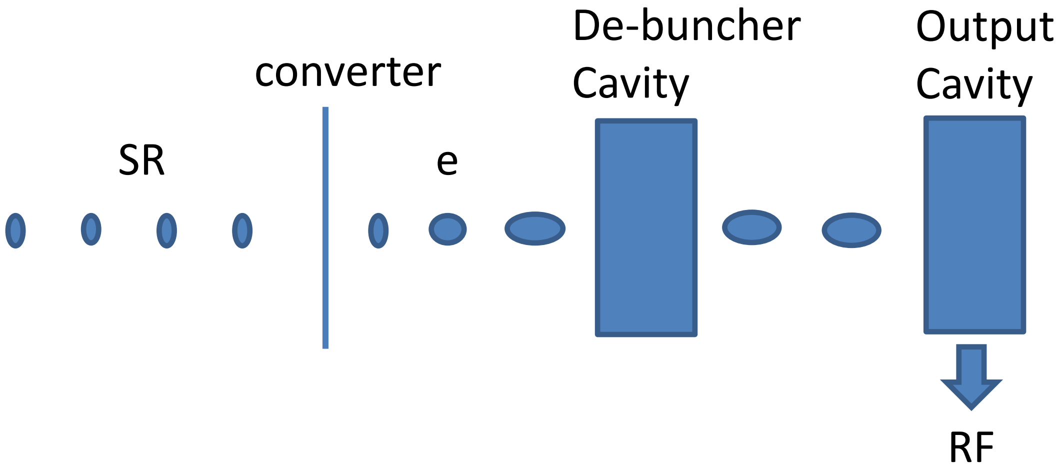
SR

80%リカバリーで両リングで 80MW

ERL とも共用

SR → RF recovery

- Klystron : DC → RF の効率で 50%
- Lasertron : Buncher e- → DC加速 → RF
- SR → Bunched e- 1keV → RF



De-buncher Cavity

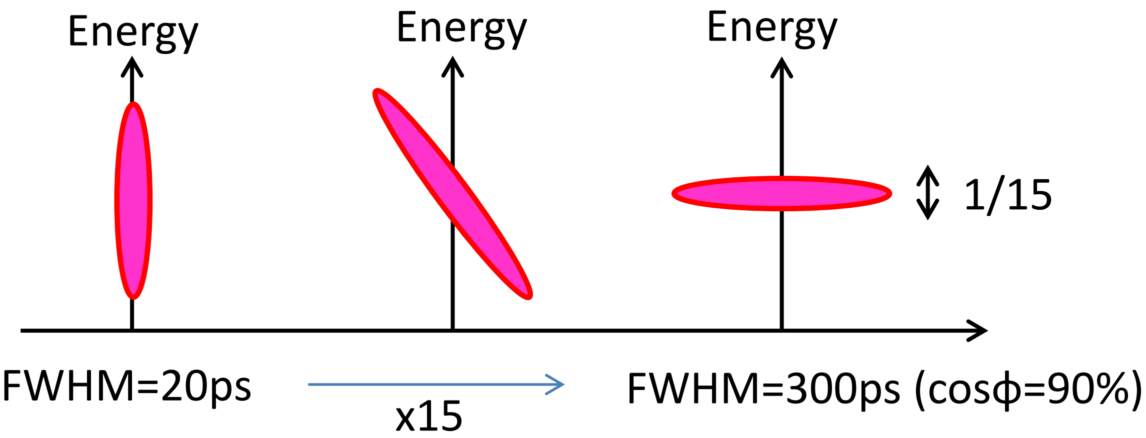
Output Cavity

converter

SR

e

RF



Energy

Energy

Energy

1/15

FWHM=20ps

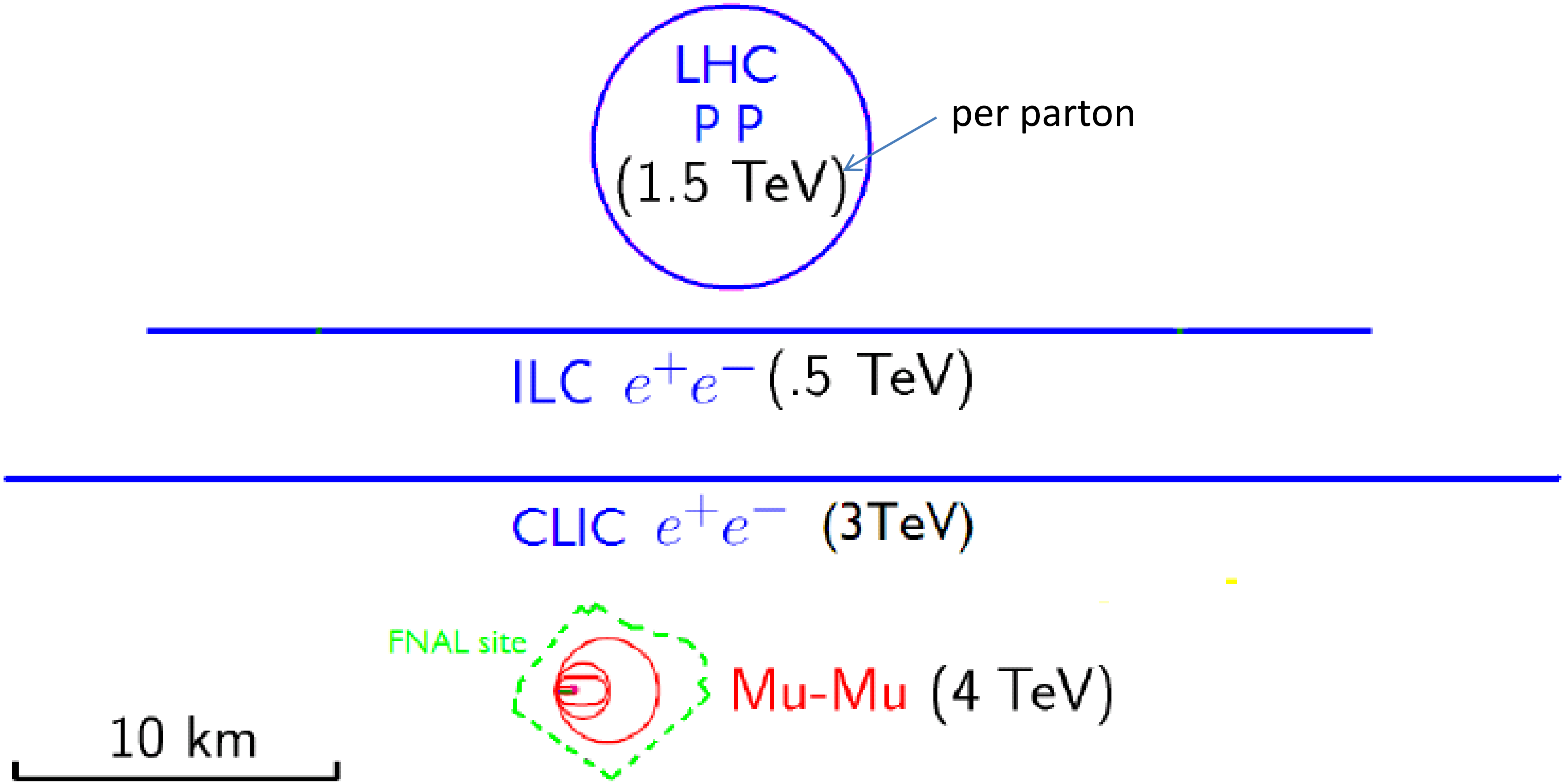
x15

FWHM=300ps (cosφ=90%)

※Abort Gap has to be considered

Muon collider

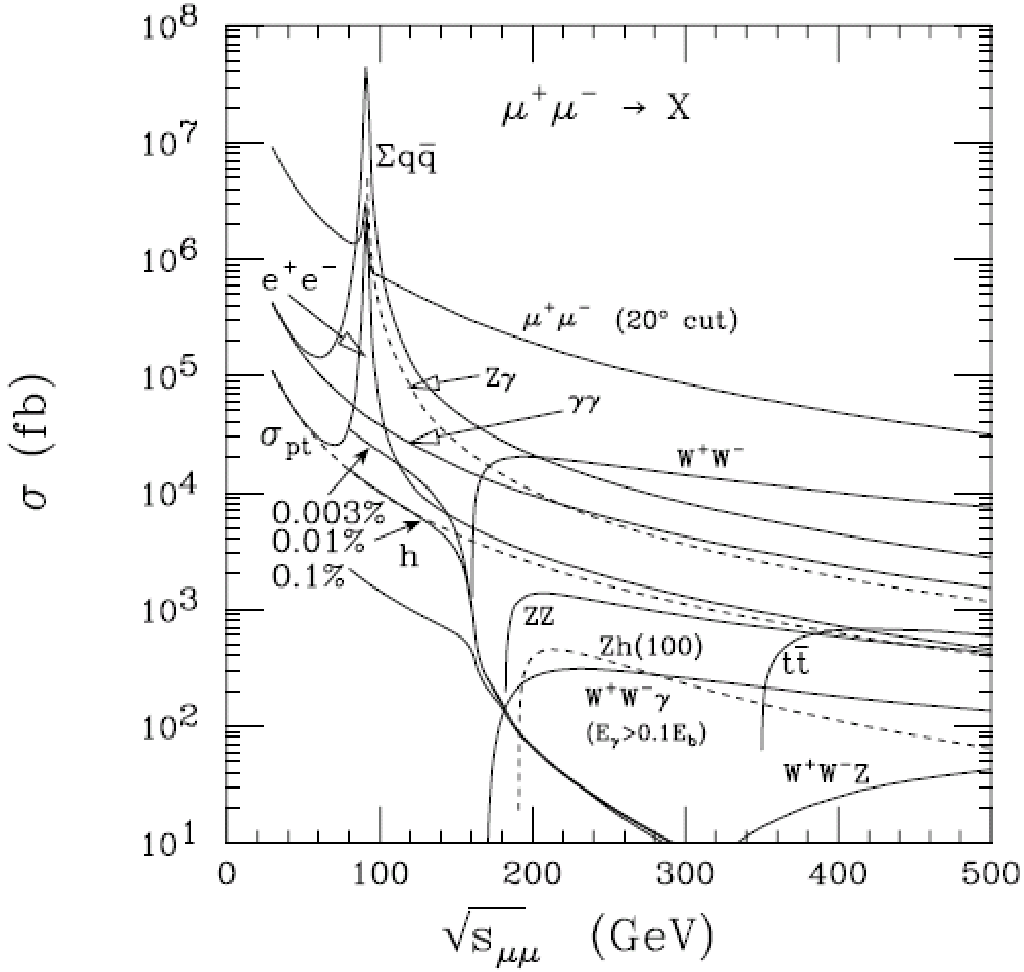
Size Comparison



- 1/10 of pp collider size
- Much smaller than ILC
- 2 TeV in KEKB ring (8.3T magnet same as LHC)

$$p = (0.3GeV / c)\ \rho(= 400m)\, B(= 8.3T) = 1TeV / c$$

Higgs Cross Section



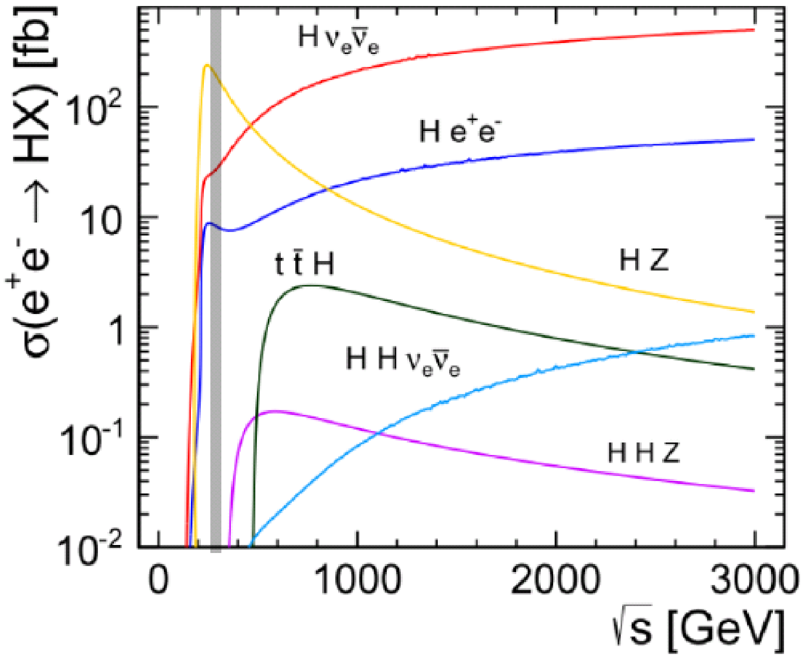
$\Delta E_{beam} / E_{beam}$	$\sigma_{eff}(\mu^+\mu^- \to H, M_H = 126\text{ GeV})$
0	35.3 pb
.01%	10.1 pb
0.1%	1.0 pb
0.4%	250 fb

$$\frac{\Gamma(h \to \mu\bar{\mu})}{\Gamma(h \to e\bar{e})} \sim \frac{M_\mu^{\ 2}}{M_e^{\ 2}} = 50,000$$

$$\sigma_h(\sqrt{s}) = \frac{4\pi\Gamma(h \to \mu\bar{\mu})\Gamma(h \to X)}{(s - m_h^{\ 2})^2 + m_h^{\ 2}(\Gamma_{tot}^t)^2}$$

$$= 35.3\,pb\ @\ M_H = 126\,GeV$$

$$\sigma(e^+e^- \to ZH) \sim 200\,fb$$



Parameter (including Higgs Factory)

CoM energy (TeV)	3	0.4		0.1	
p energy (GeV)	16	16		16	
p's/bunch	2.5×10^{13}	2.5×10^{13}		5×10^{13}	
Bunches/fill	4	4		2	
Repetition rate (Hz)	15	15		15	
p power (MW)	4	4		4	
μ/bunch	2×10^{12}	2×10^{12}		4×10^{12}	
μ power (MW)	28	4		1	
Wall power (MW)	204	120		81	
Collider circumference (m)	6000	1000		350	
Average bending field (T)	5.2	4.7		3	
rms $\Delta p/p\%$	0.16	0.14	0.12	0.01	0.003
6D $\epsilon_{6,N}$ $(\pi \mathrm{m})^3$	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}
rms ϵ_n (π mm mrad)	50	50	85	195	290
β^* (cm)	0.3	2.6	4.1	9.4	14.1
σ_z (cm)	0.3	2.6	4.1	9.4	14.1
σ_r spot (μm)	3.2	26	86	196	294
σ_θ IP (mrad)	1.1	1.0	2.1	2.1	2.1
Tune shift	0.044	0.044	0.051	0.022	0.015
n_{turns} (effective)	785	700	450	450	450
Luminosity $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	7×10^{34}	10^{33}	1.2×10^{32}	2.2×10^{31}	10^{31}
Higgs/year			1.9×10^{3}	4×10^{3}	3.9×10^{3}

$$L \sim \frac{n_b N_\mu^{\,2}}{\varepsilon_\perp \beta^*} h\left(\frac{\sigma_z}{\beta^*}\right) \sim \frac{n_b N_\mu \xi}{\beta^*} h\left(\frac{\sigma_z}{\beta^*}\right)$$

$$\xi = \frac{r_\mu N_\mu}{4\pi\varepsilon_{\perp N}}$$

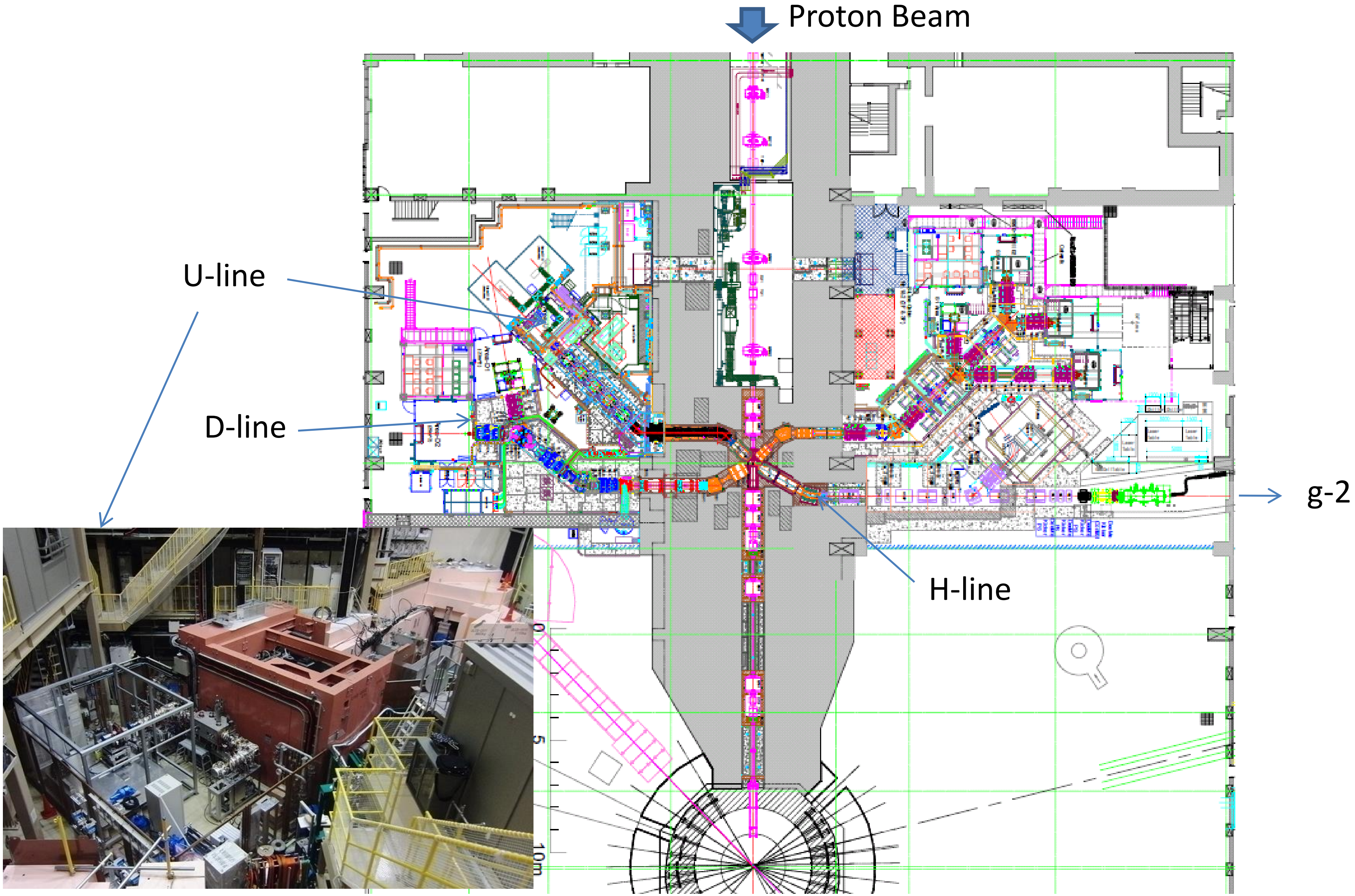
$$\sigma(\mu\mu \rightarrow H) = 5\times 10^4 \;\; fb$$

Other muon generation method

- Decay π → 6D Cooling
- Surface μ → Ultra Cold
- J/Ψ
- e^+e^- (γ) → Pair Production

Ultra Cold Muon

J-PARC / MLF / Ultra Slow Muon



Proton Beam

U-line

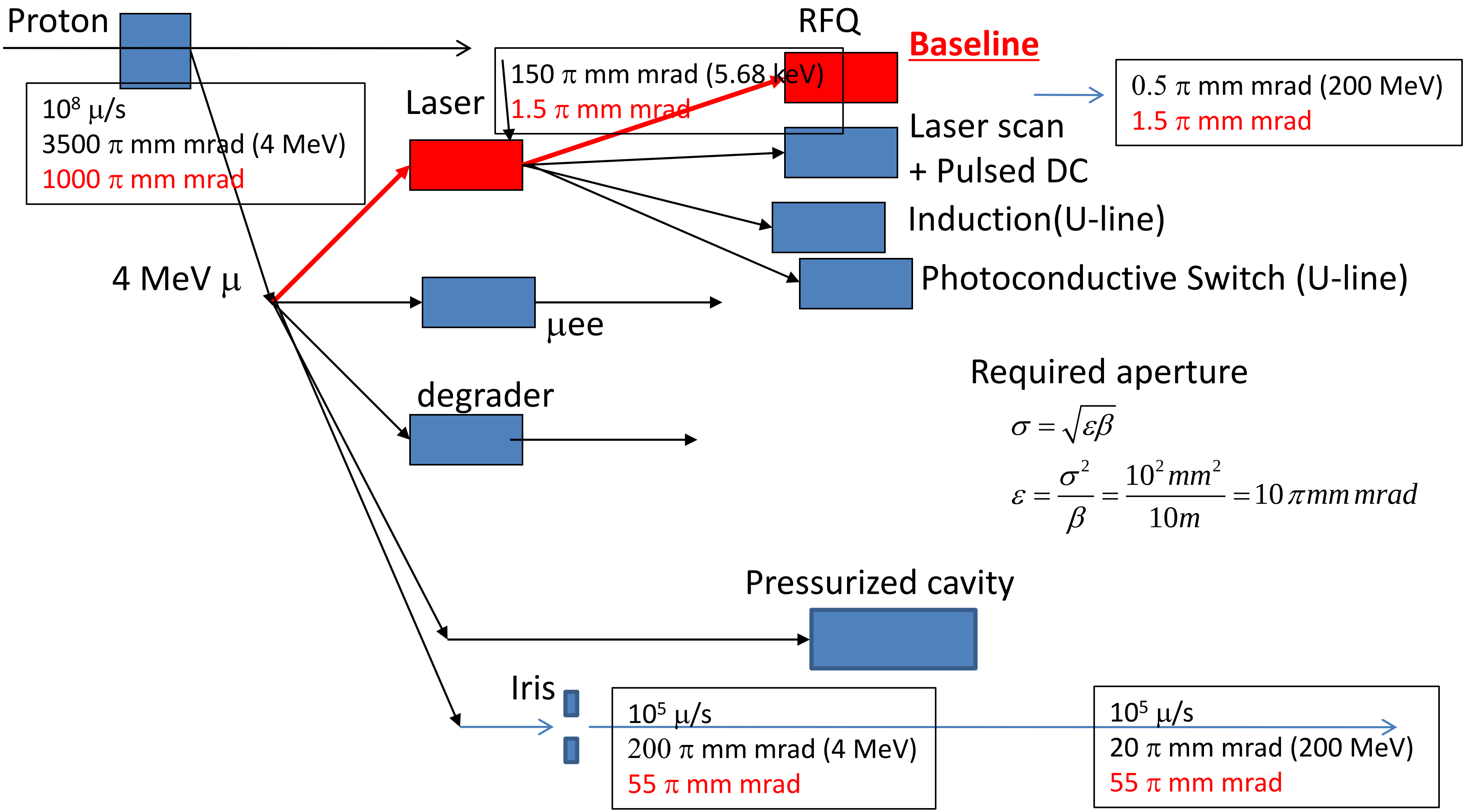
D-line

H-line

g-2

Considerable Scenario / Surface μ

- Number of μ
- Emittance
- Normalized emittance



Proton

10^8 μ/s
3500 π mm mrad (4 MeV)
1000 π mm mrad

Laser

150 π mm mrad (5.68 keV)
1.5 π mm mrad

RFQ

Baseline

0.5 π mm mrad (200 MeV)
1.5 π mm mrad

Laser scan
+ Pulsed DC

Induction(U-line)

Photoconductive Switch (U-line)

4 MeV μ

μee

degrader

Required aperture

$$\sigma = \sqrt{\varepsilon\beta}$$

$$\varepsilon = \frac{\sigma^2}{\beta} = \frac{10^2\, mm^2}{10m} = 10\,\pi mm\, mrad$$

Pressurized cavity

Iris

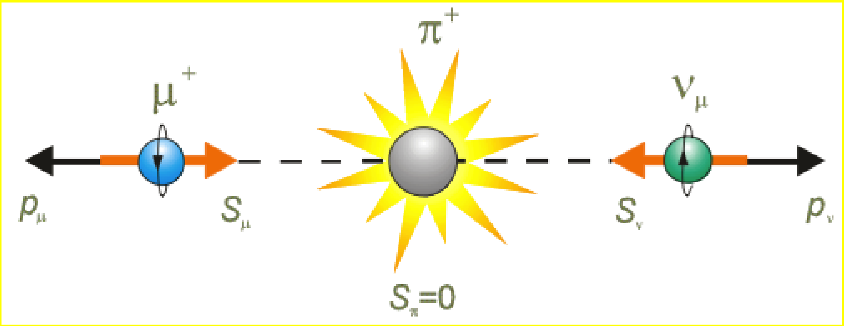
10^5 μ/s
200 π mm mrad (4 MeV)
55 π mm mrad

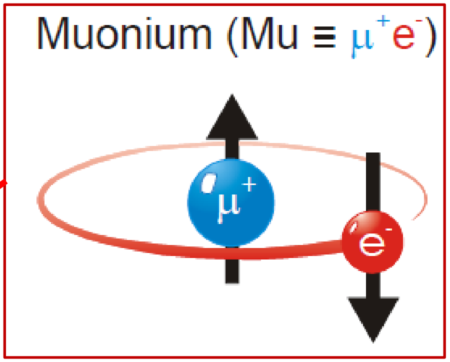
10^5 μ/s
20 π mm mrad (200 MeV)
55 π mm mrad

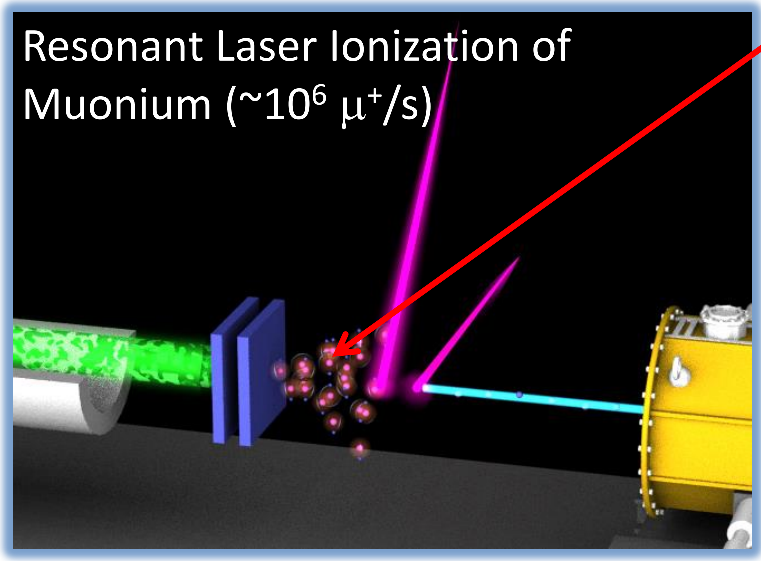
	5.7keV	30keV	340 keV	4 MeV	200 MeV
βγ =	0.01	0.024	0.08	0.278	2.71

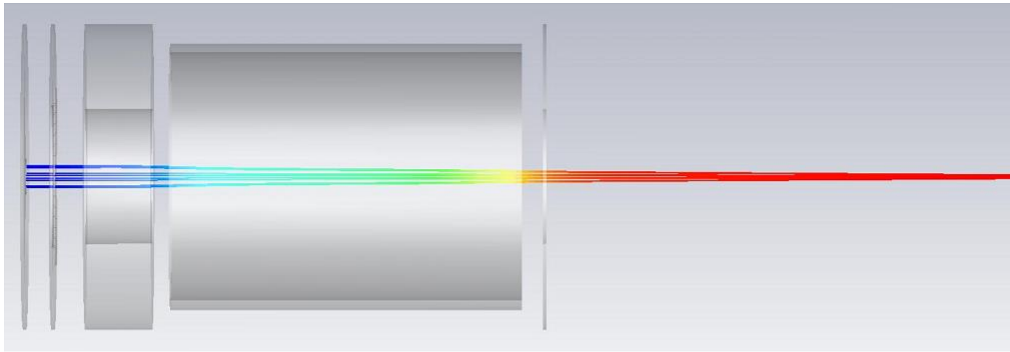
Ultra Slow Muon

- Surface μ
  - Spin Polarized
  - p_μ = 29.8 MeV/c (4MeV) Ult
- Ultra Slow Muon
  - Laser (122nm) Excitation



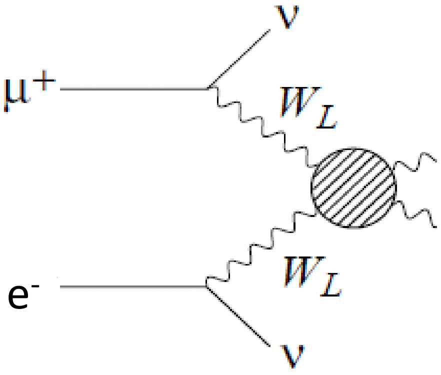



Resonant Laser Ionization of Muonium (~10^6 μ^+/s)



非対称 μ^+e^- Collider

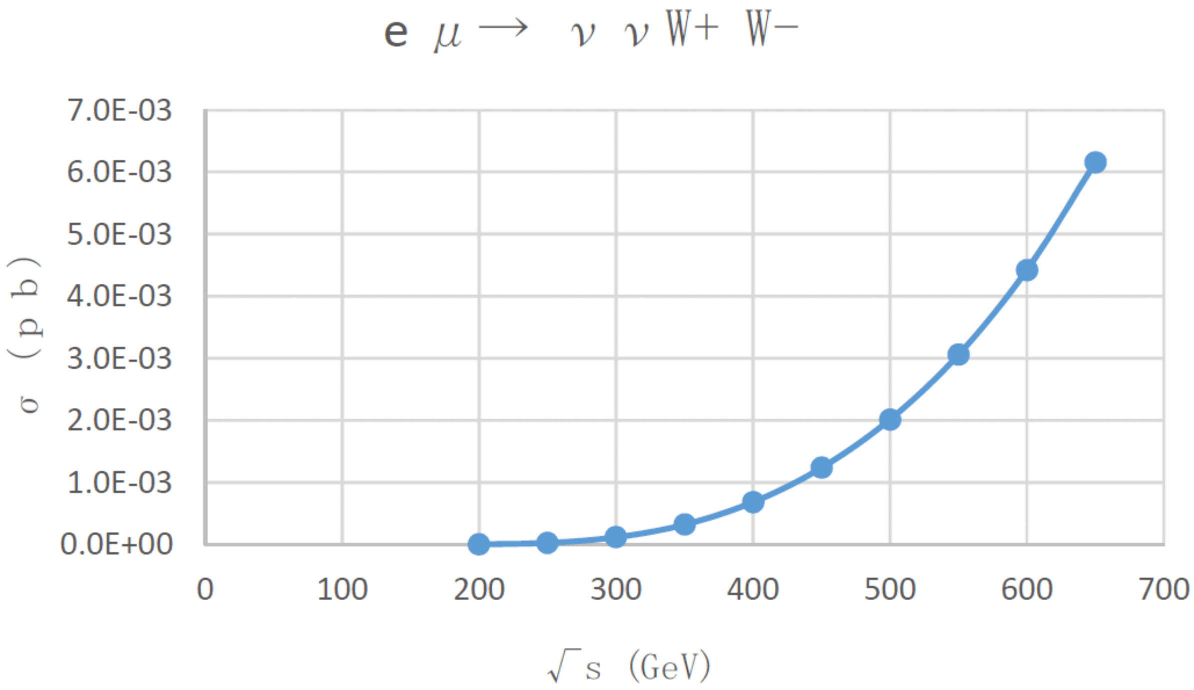
- メリット / デメリット
  - 〇Ultra Cold μ^+ 1TeV で e^- の emittance とオーダーで合う
  - 〇τ_μ が伸びる
  - 〇 e^- 側で数が稼げる
  - ×T-channel (W/Z-fusion)



- KEKB(TRISTAN) Ring : ECM ～300 GeV
  - – 1 TeV (μ^+) : γ = 10,000(τ～20ms), ρ=400m, 8.3T(LHCと同じ)
  - – 20 GeV (e^-) : γ = 40,000
- Emittance
  - – 5 nm / 150pm (μ^+) ×β=3.2 /0.3mm → σ = 4 / 0.2 μm
  - – 1 nm / 4 pm (e^-)
- Luminosity $L = \dfrac{N_+ N_-}{4\pi\sigma_x\sigma_y} f_{rep} = 10^{31} cm^{-2} s^{-1} @ 1MHz(10bunch),\ 10^8 \mu^+, 10^{10} e^-$

μe Cross Section

- T-channel の ee よりかなり小さい？



Muon Pair Creation

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

$$2m_e + T_1 + T_2 = 2m_\mu + T_3 + T_4$$

$$p_1 + p_2 = p_3 + p_4 \sim 600\ MeV/c$$

$$T_{CM} \sim 2\sqrt{T_1 T_2} = 2m_\mu$$

$$T_2 = 18.7\,MeV$$

Cross section:

$$\sigma = \frac{e^4\sqrt{|k|^2 - m^2}\left(2|k|^2 + m^2\right)}{96\pi|k|^5}$$

$$= \left(\hbar c\right)^2 \frac{4\pi\alpha^2}{3s} = 8\ \mu barn$$

$$\alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c},\ \ \left(\hbar c\right)^2 \approx 0.4\ GeV^2 mbarn$$

$\beta_{IP} = 10mm(h)/0.1mm(v)$ (ATFのFinal Focusを仮定)

$Positron\ DR(1.1GeV)$:

$$\varepsilon_{x,y} = 42.5nm(h)/3.15nm(v),\ \ \sigma_{x,y} = 20\mu m(h)\ /\ 0.5nm(v)$$

$KEK\,ATF$ $(1.54GeV)$:

$$\varepsilon_{x,y} = 1nm(h)\ /\ 0.01nm(v),\ \ \ \sigma_{x,y} = 3.4\mu m(h)\ /\ 37nm(v)$$

$$L = \frac{N_+ N_-}{4\pi\sigma_x\sigma_y} f_{rep}$$

$N_\mu = \sigma L = 6.3$個

（低エネルギーElectronは絞れない）

$$f_{rep} = 1,\ \ N_\mu = 10000$$

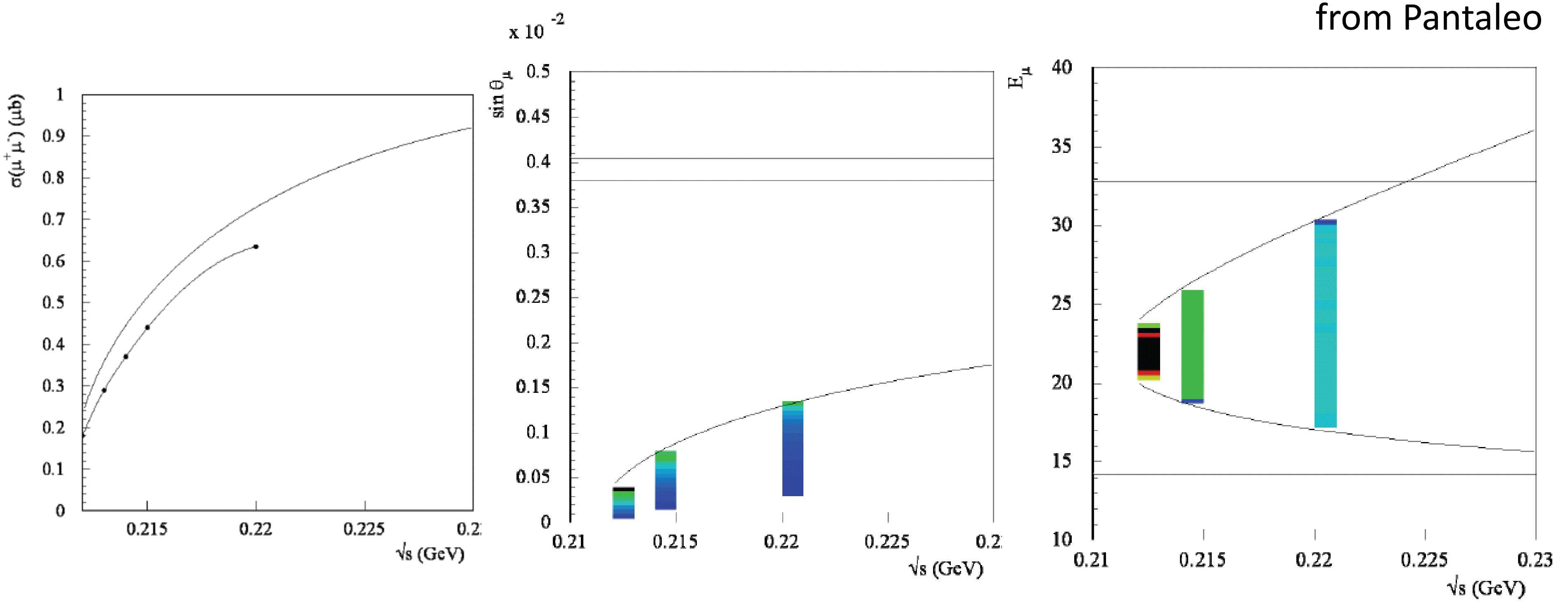
$$\sigma_{x,y} = \sqrt{\frac{N_+ N_-}{4\pi L}} = \sqrt{\frac{\sigma N_+ N_-}{4\pi N_\mu}} = 2.5nm$$

45 GeV e^+ + Plasma

45 GeV e^+

Plasma Channel ∼ 10m

from Pantaleo



@ 0.212 GeV

Nplasma = 10^{20} /cm^3, Npositron = 10^{11} /bunch => N(μ) = 10^6 / bunch

Luminosity

- 63 GeV ring : r = 25m @ 8T => C = 300m ? (1μs)
- ILCのビーム : 3.2nC (2 x 10^{10})

  x 1312 bunch (727μs/554ns) x 5Hz

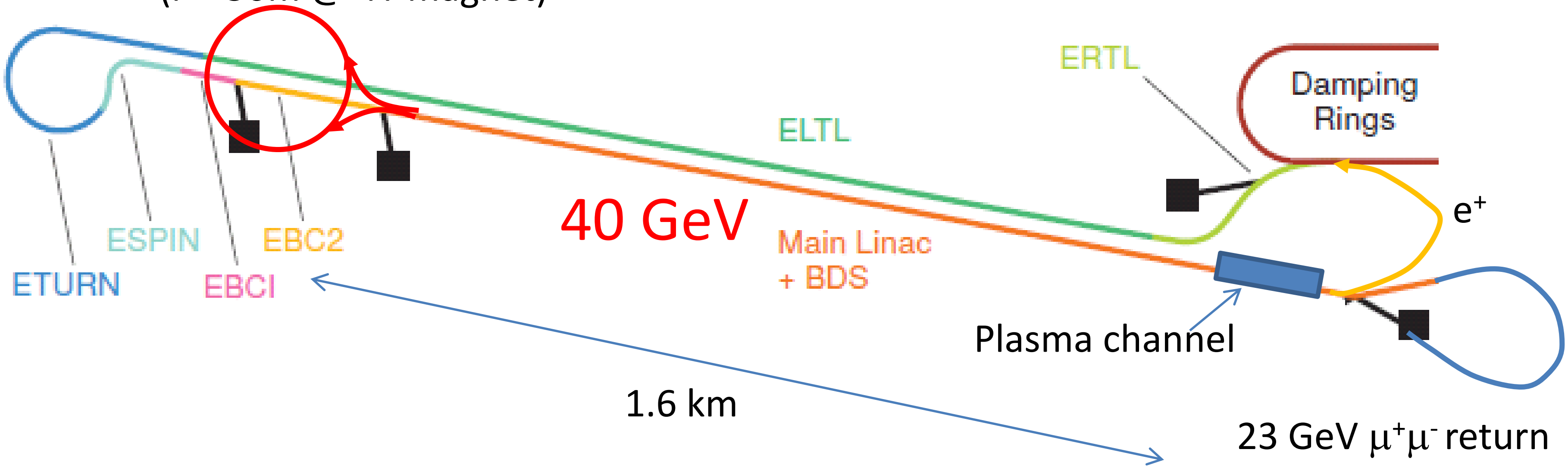
  => 2 x 10^5 μ/bunch

  => 1.3 x 10^8 μ x 2 bunch (ring)

$$L = \frac{N_+ N_-}{4\pi\sigma_x\sigma_y} f_{rep} h\left(\frac{\sigma_z}{\beta^*}\right) = \frac{{N_\mu}^2}{4\pi\varepsilon_\perp\beta^*} f_{rep} h\left(\frac{\sigma_z}{\beta^*}\right)$$

Muon collider for Higgs factory

- 45 GeV e^+ beam x Plasma(e^-) => $\mu^+\mu^-$ pair



63 GeV Collider Ring for Higgs factory
(r = 50m @ 4T magnet)

40 GeV

e^+

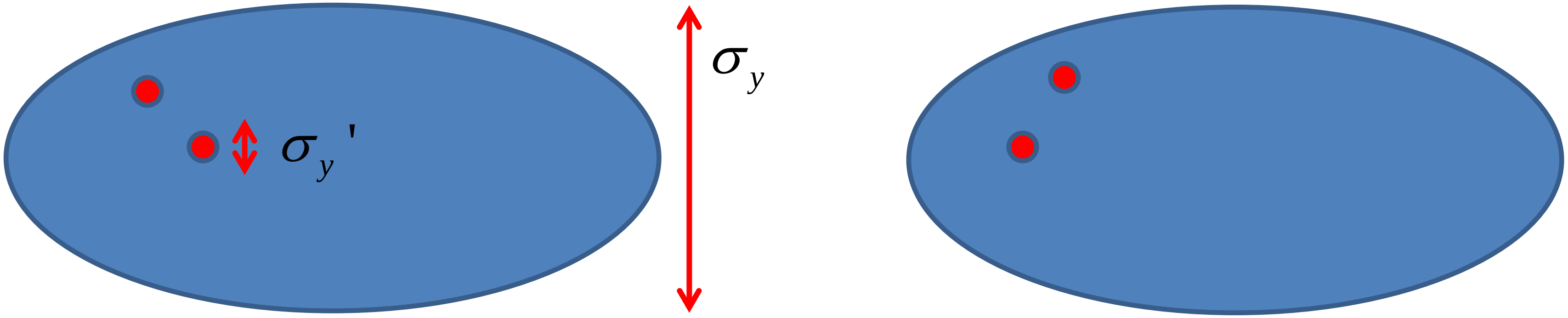
Plasma channel

1.6 km

23 GeV $\mu^+\mu^-$ return

対生成の場合の Luminosity

対生成なので、単一の Z/γ からμ+μ- が生成している
⇒ 単一粒子同士の衝突を考えられる可能性



- Macro 粒子 $$L = \frac{N_+ N_-}{4\pi\sigma_x\sigma_y} f_{rep} h\left(\frac{\sigma_z}{\beta^*}\right)$$
- 単一粒子 $$L = N \frac{1}{4\pi\sigma_x'\sigma_y'} f_{rep}$$

Novel Accelerator R&D

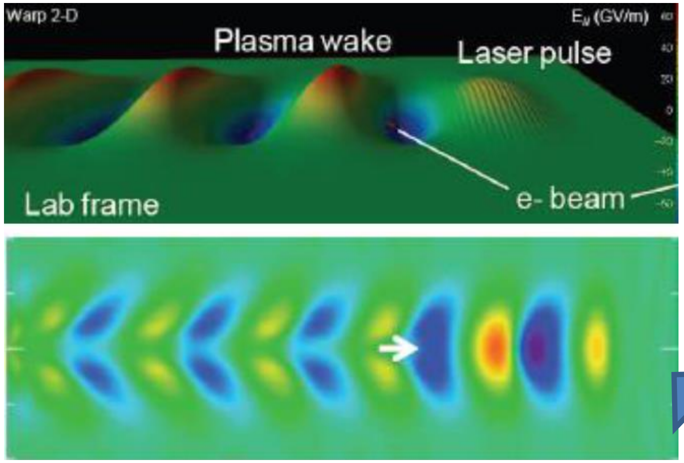
▪R&D for ultra high field accelerator (1GV/m)

- 高Q ⇔ THz
  THz : レーザー、電子ビーム、非線形光学素子
- 光伝導スイッチ

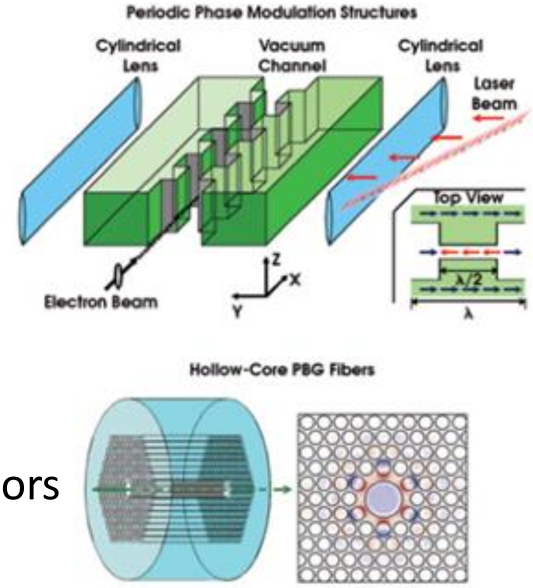
Novel accelerators

Laser driven accelerator

Laser Plasma Acceleration(LWFA)



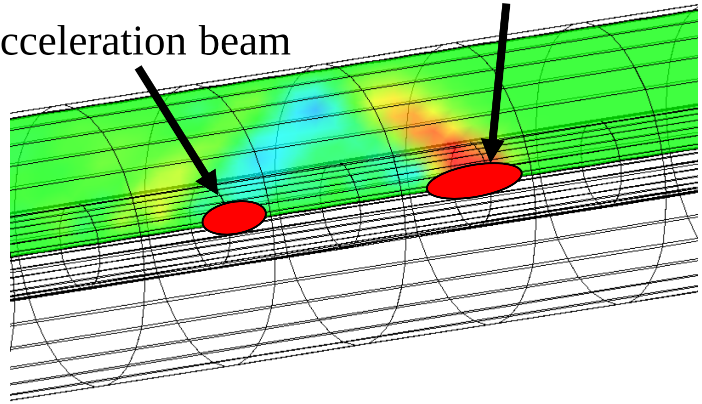
Direct Laser/THz Acceleration(DLA)



THz accelerators

Beam driven accelerator

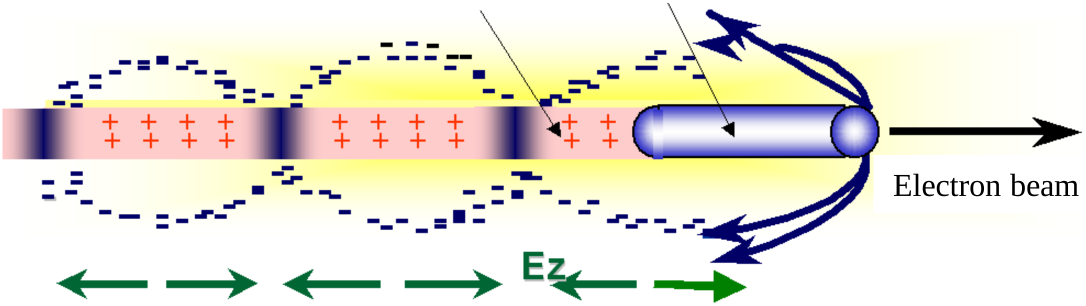
Dielectric wall accelerator(DWA)



Drive beam

Acceleration beam

Plasma wakefield acceleration (PWFA)



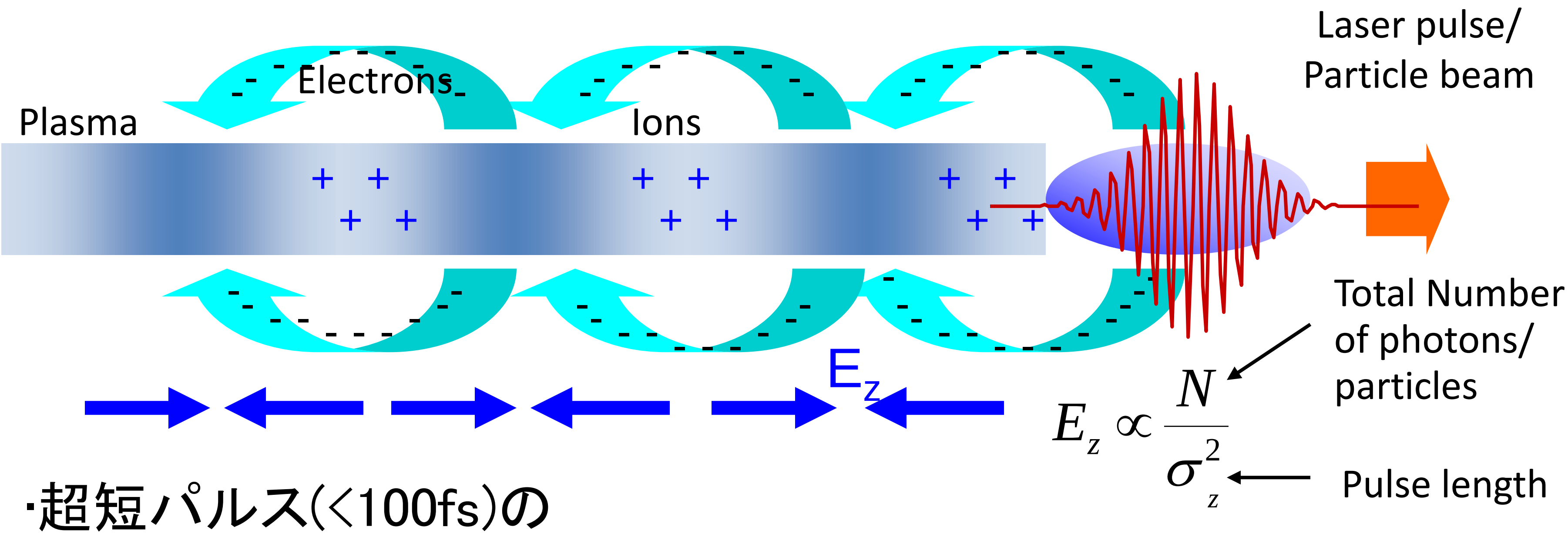
Acceleration

Deacceleration

Electron beam

THzのプラズマ振動による加速

- 何故プラズマが必要か？
  - 電磁波(レーザー)は横波なので進行方向の電界が無く加速できない
  - ビームも相対論的になると後続のビームにエネルギーを渡せない（後続のビームが駆動ビームを減速しないと変換できない）



$$E_z \propto \frac{N}{\sigma_z^2}$$

·超短パルス(<100fs)の
- レーザー場のポンデロモーティブ力
- または電子・陽子バンチのクーロン力

がプラズマ電子を排除。

·プラズマイオンの復元力で電子を引き戻す。

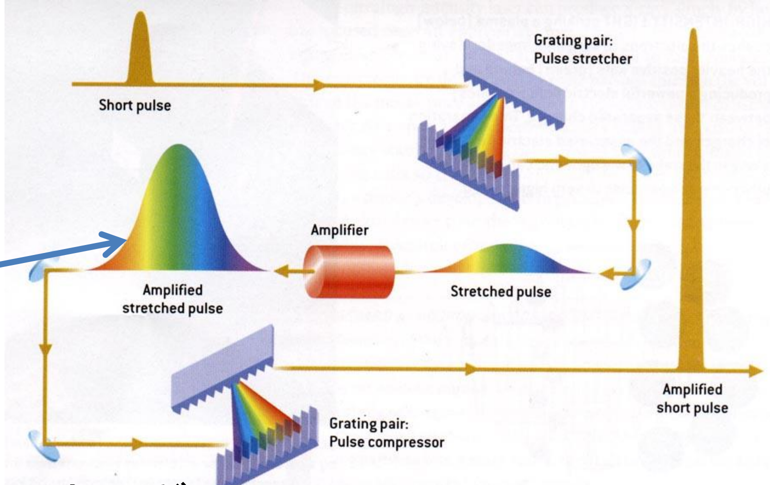
·プラズマ振動が起こる → このプラズマ振動の周波数が THz

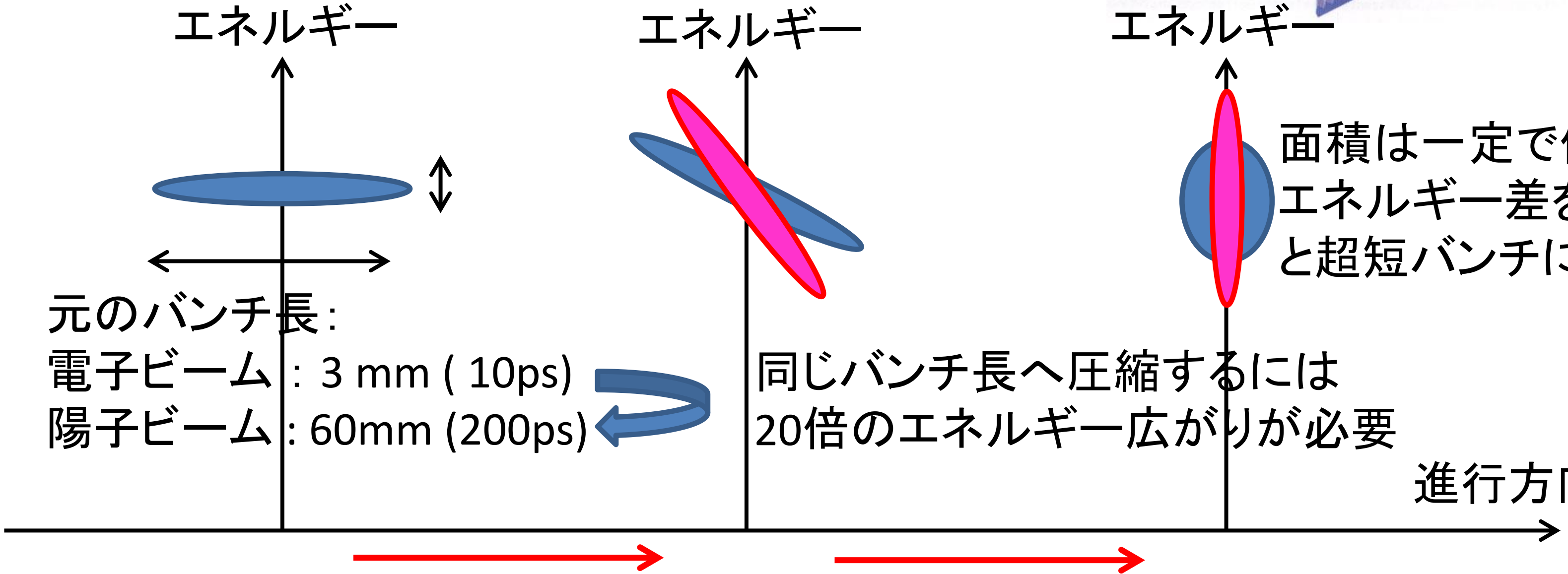
エネルギー源と電界

	常伝導	**超伝導**	**電子ビーム駆動**	**レーザー駆動**	**陽子ビーム駆動**
	6/12GHz	1.3GHz	5THz (50fs)	5THz (50fs)	? THz (後述)
駆動エネルギー	20J [/m] = 40MW ×500ns	200J [/m] = 300kW ×700μs	70J (SLAC) =23GeV×3nC 35J (KEK) =7GeV×5nC	40J (→ 1kJ)	**15kJ (SPS)** = **450GeV**×30nC 150kJ (LHC) = 7TeV×20nC 300kJ (J-PARC MR) = 40GeV×8μC
電界	40/80MV/m 放電限界	40MV/m クエンチ	20GV/m×2m = 40 GV	10 GV/m	?
繰り返し	50Hz	5Hz	50Hz	10Hz	1/18 Hz (SPS) 0.3 Hz (J-PARC MR)
ビーム電力/駆動/AC	400W / 1 kW / 8 kW (1m辺り)	10 MW / 23 MW / 150 MW (ILC)	? / 3.5 kW / 70 kW	4 W ? /400W /4kW(LD)	? / 833W/75MW (SPS) / 300kW/25MW (J-PARC)
効率	5% ?	8% ?	5%(電子生成) ×η(e→e)	現状 0.1 % ?	4 %(陽子ビーム生成) × η(p→e)

超短パルスを作るための圧縮

- バンチ圧縮には
  エネルギー差が必要
  - レーザー：CPA(チャープパルス増幅)
  - ビーム　：位相回転



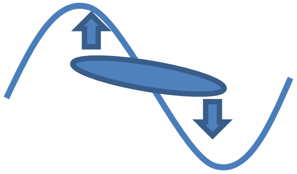


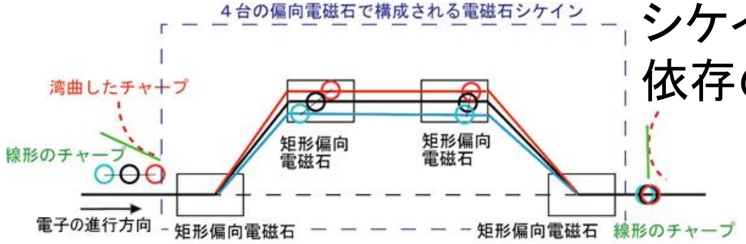
元のバンチ長：
電子ビーム：3 mm (10ps)
陽子ビーム：60mm (200ps)

同じバンチ長へ圧縮するには
20倍のエネルギー広がりが必要

面積は一定で保存するので
エネルギー差を大きくしない
と超短バンチにはならない

傾きを付けるための高周波加速



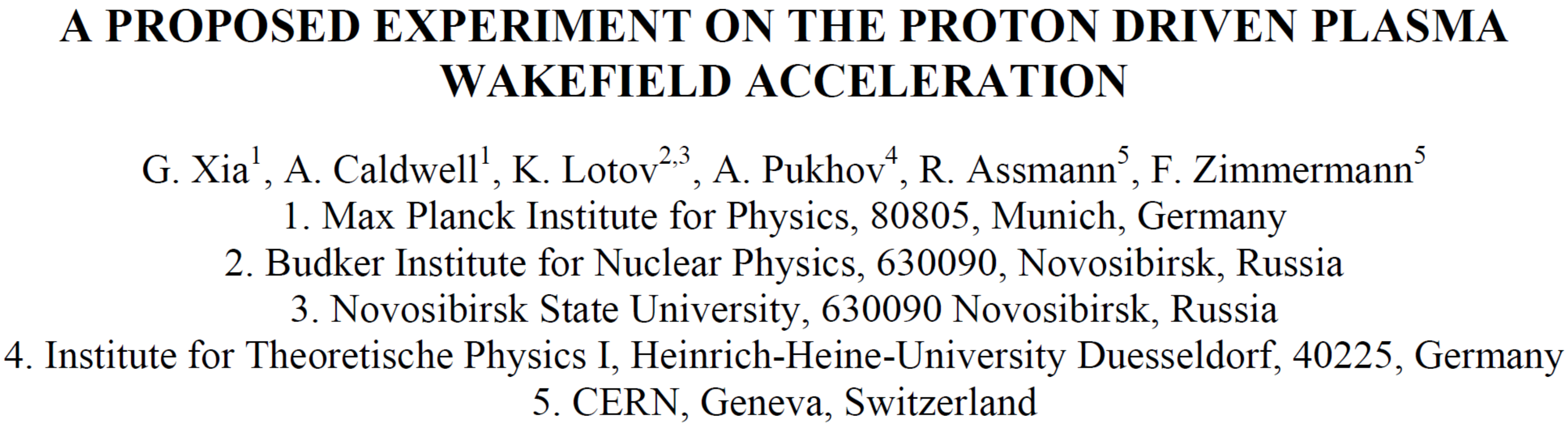


シケイン等でエネルギー
依存の経路差

Proton beam driven electron accelerator

陽子ビーム駆動電子加速

- 陽子ビーム駆動
  - ○リング加速器で放射損失が無くエネルギーが高い
  - ○粒子が重くプラズマ中の電子との衝突による損失小
  - ×バンチ圧縮が難しい
  - 独自のシミュレーションコードの開発
- Awake Collaborationとして展開
  - SPS (450GeV)での実験を計画



A PROPOSED EXPERIMENT ON THE PROTON DRIVEN PLASMA WAKEFIELD ACCELERATION

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5. CERN, Geneva, Switzerland

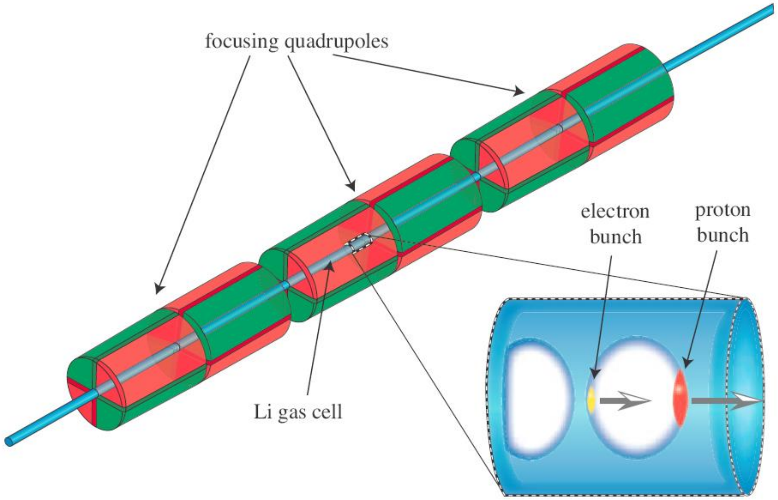
陽子ビーム駆動電子加速の最初のアイデア

プラズマ加速にはトランス比の限界がある　($DW_e < W_d$).

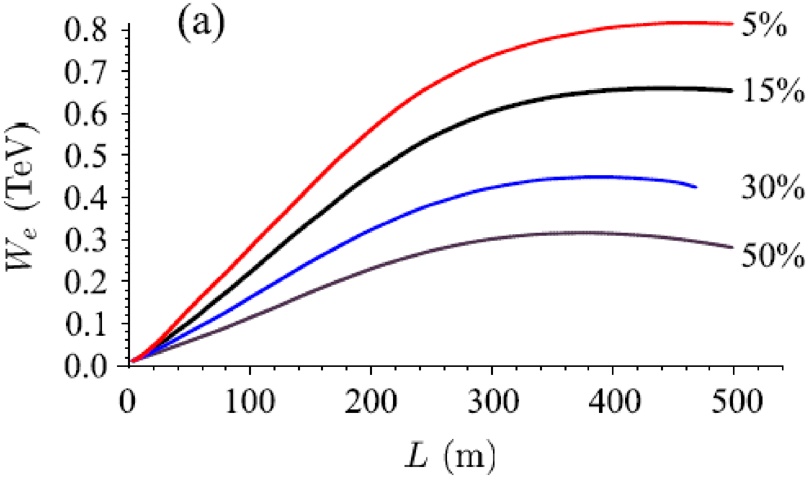
TeV に行くには
- 多段の電子ビーム駆動
- 陽子駆動

駆動エネルギーは

<40 J (laser), <120 J (electrons)
20 kJ (SPS), >150kJ (LHC)



1 TeV 陽子ビームで sub-TeV まで電子加速が可能だが・・・
プラズマ波長程度に sub-mm まで陽子ビームを圧縮できれば

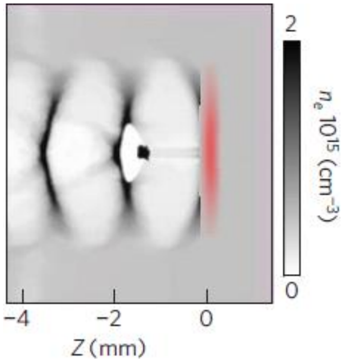


駆動ビーム: p^+
$E=1$ TeV, $N_p=10^{11}$
$\sigma_z=100\ \mu m$, $\sigma_r=0.42$ mm
$\sigma_\theta=0.024$ mrad, $\Delta E/E=10\%$

加速ビーム:e^-
$E_0=10$ GeV

Plasma: $n_p=10^{15}cm^{-3}$

マルチバンチ駆動のウェーク場を使う



① 1バンチを圧縮

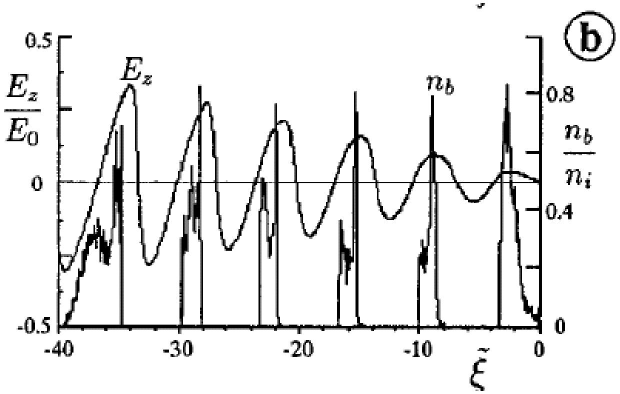
LHC beam: 7.6 cm, energy spread = 0.01%

位相空間の保存 0.1mm (300fs)に圧縮するには

→ エネルギー分散 = 7.6%

≈ 500 GeV (7 TeV ビームに対して)

ILCスケールの加速器が圧縮のために必要！



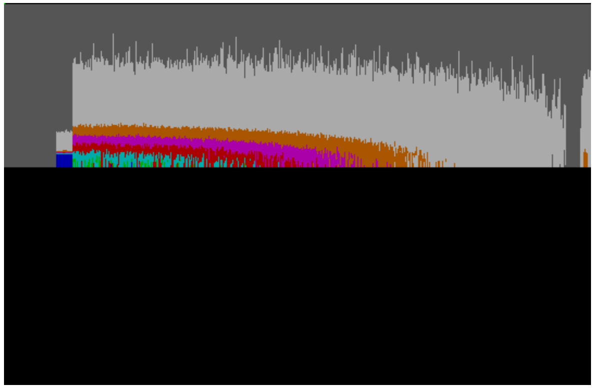
② バンチトレイン

10バンチにするにはエネルギー分散も 1/10 で良くなる

バンチ長 : 10mm

エネルギー分散: 0.076% * 2 * 4 (for bunching) = 0.6% = 42 GeV

できない事は無いが依然大変



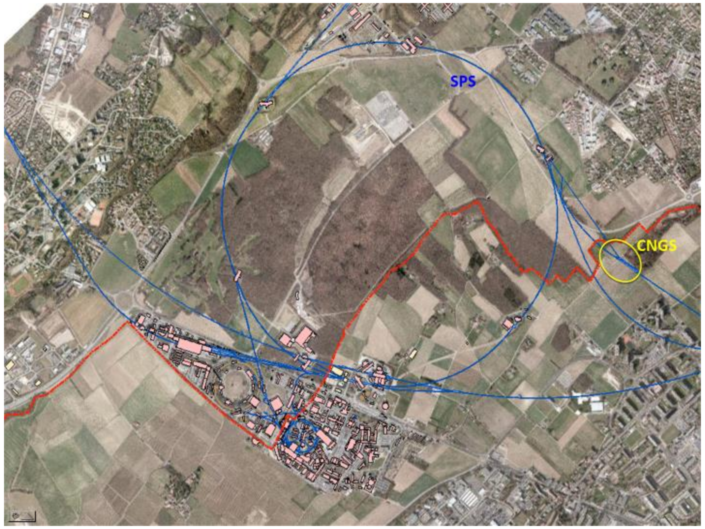
<u>③ 自己バンチング</u>

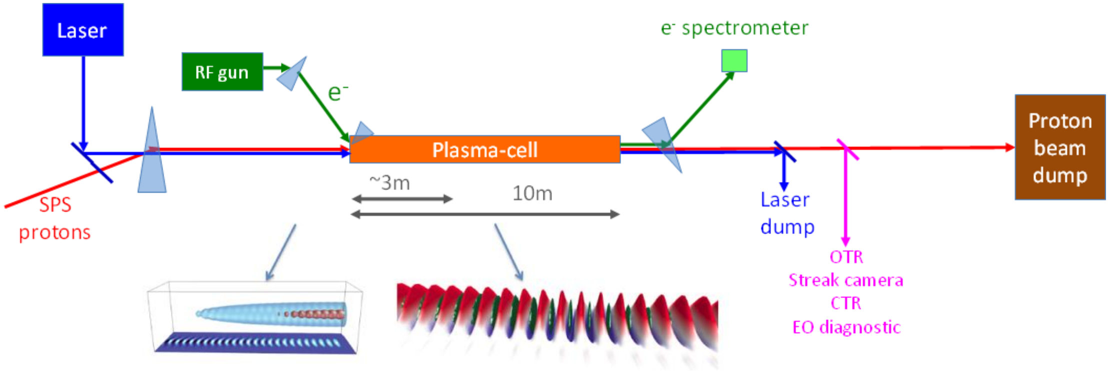
圧縮器無、チョッパー無

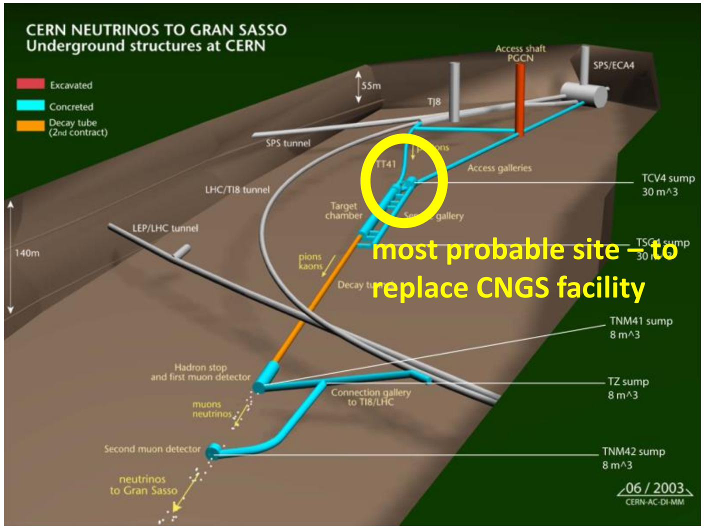
外部モジュレーションによるプラズマの自己モジュレーション

AWAKE Collaboration

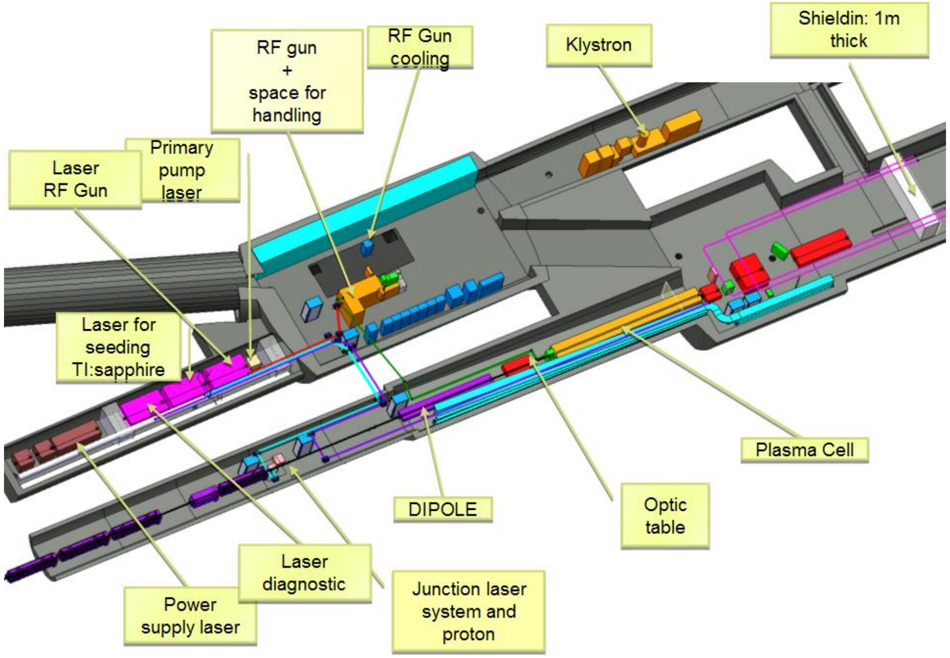
AWAKE collaboration (>60 物理屋、~25 機関)
SPS からの 450GeV 陽子ビームを利用した実験を行う



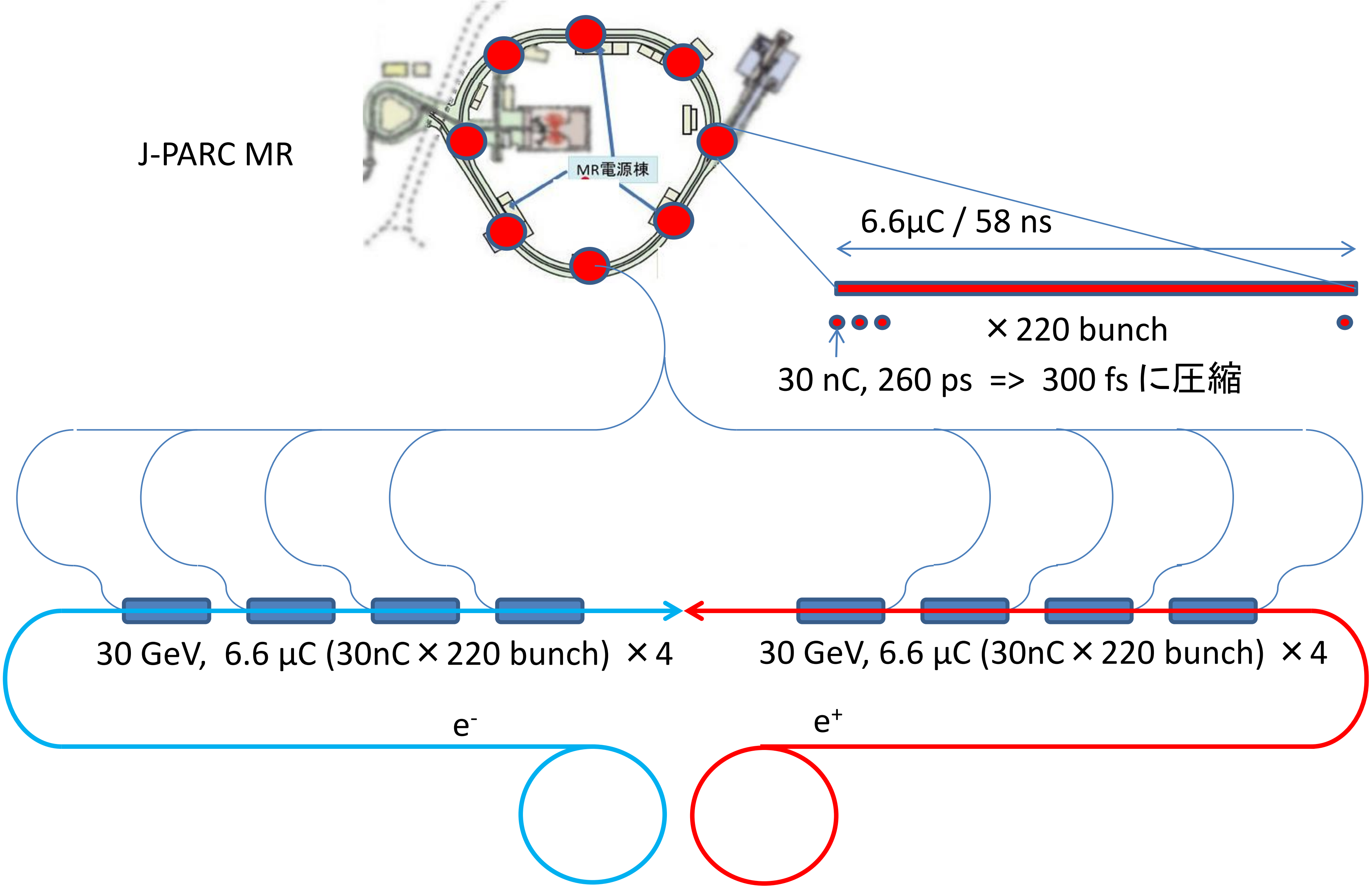




most probable site – to replace CNGS facility



J-PARC の Energy Frontier への転用は？



J-PARC MR

6.6μC / 58 ns

×220 bunch

30 nC, 260 ps => 300 fs に圧縮

30 GeV, 6.6 μC (30nC×220 bunch) ×4

30 GeV, 6.6 μC (30nC×220 bunch) ×4

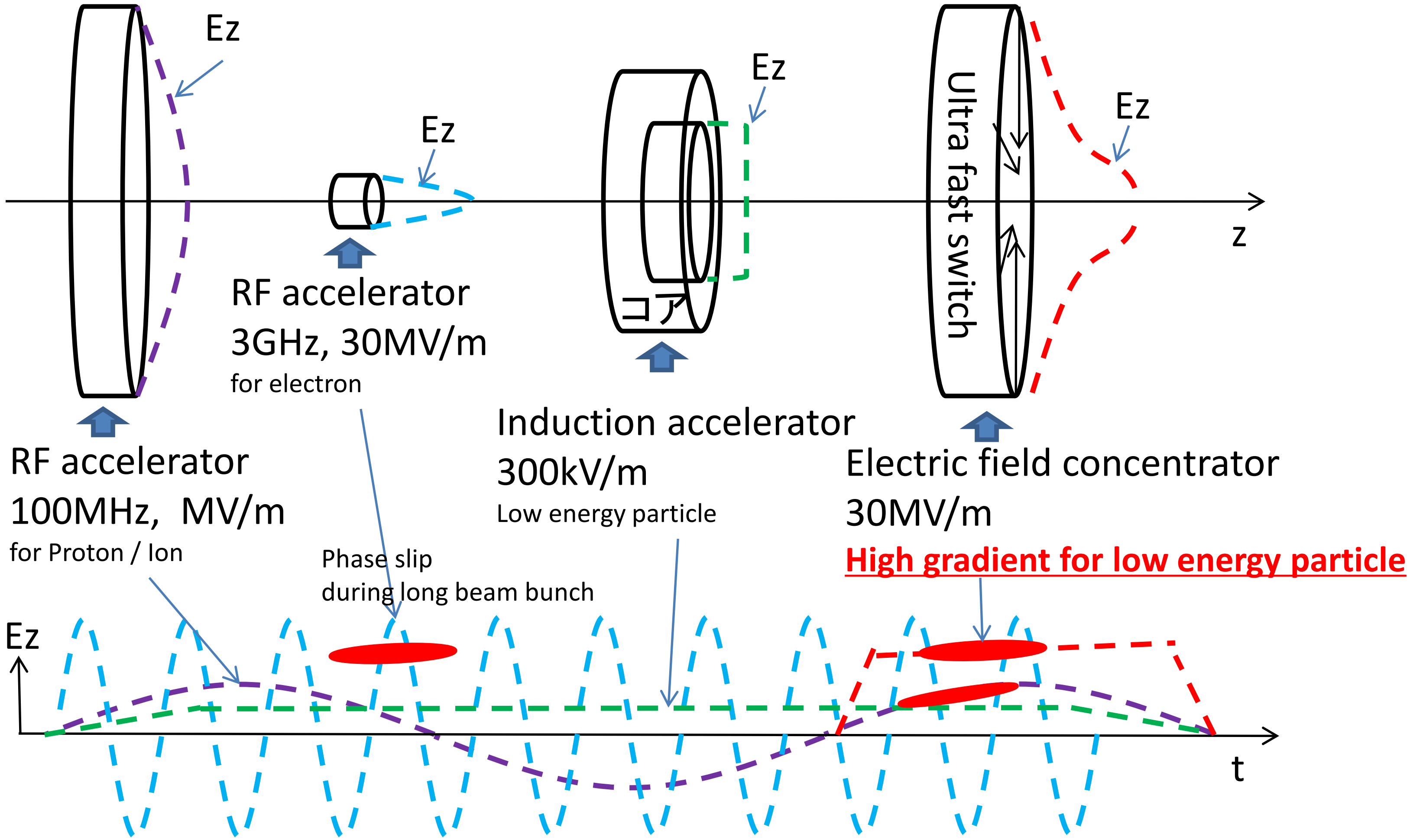
e^-

e^+

問題： エミッタンス、バースト、etc ,...

Photoconductive switch accelerator

Electric field concentrator using ultra fast switch



RF accelerator
3GHz, 30MV/m
for electron

RF accelerator
100MHz, MV/m
for Proton / Ion

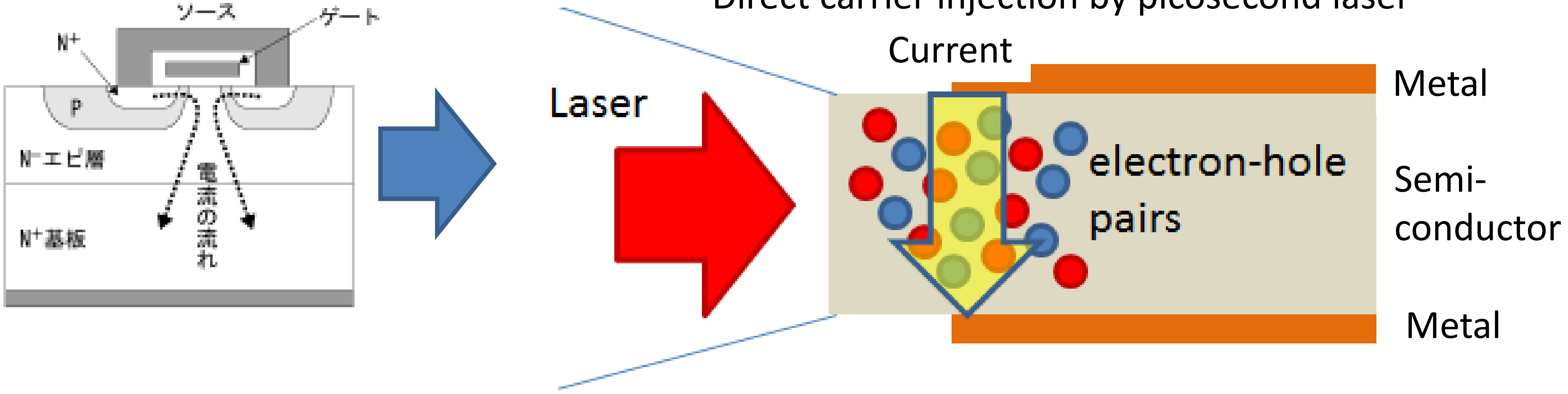
Induction accelerator
300kV/m
Low energy particle

Electric field concentrator
30MV/m
High gradient for low energy particle

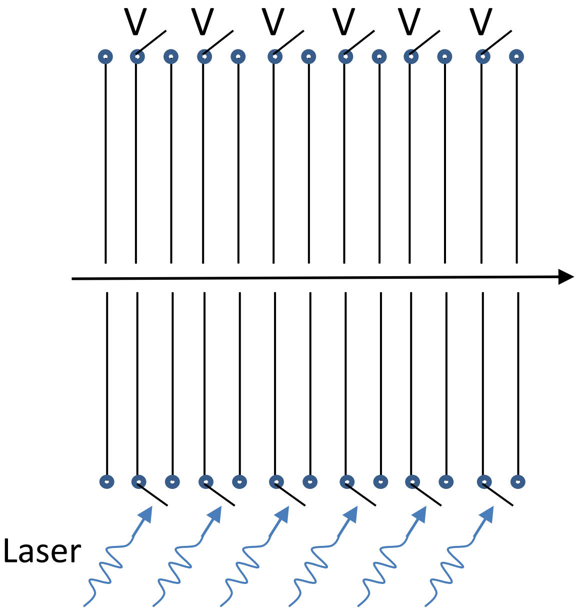
Phase slip
during long beam bunch

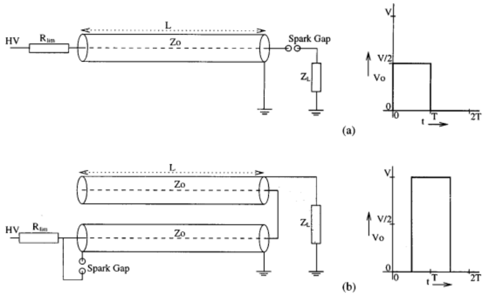
Dielectric accelerator using photo conductive switch

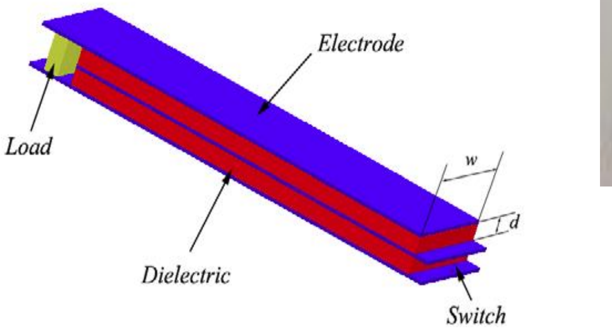
Photoconductive switch :
Direct carrier injection by picosecond laser

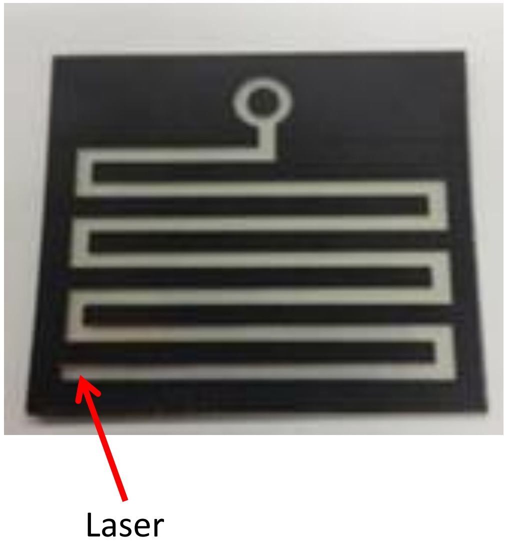


Blumlein accelerator by inverting the voltage of transmission line using phyoconductive switch









Semiconductor for photoconductive switch

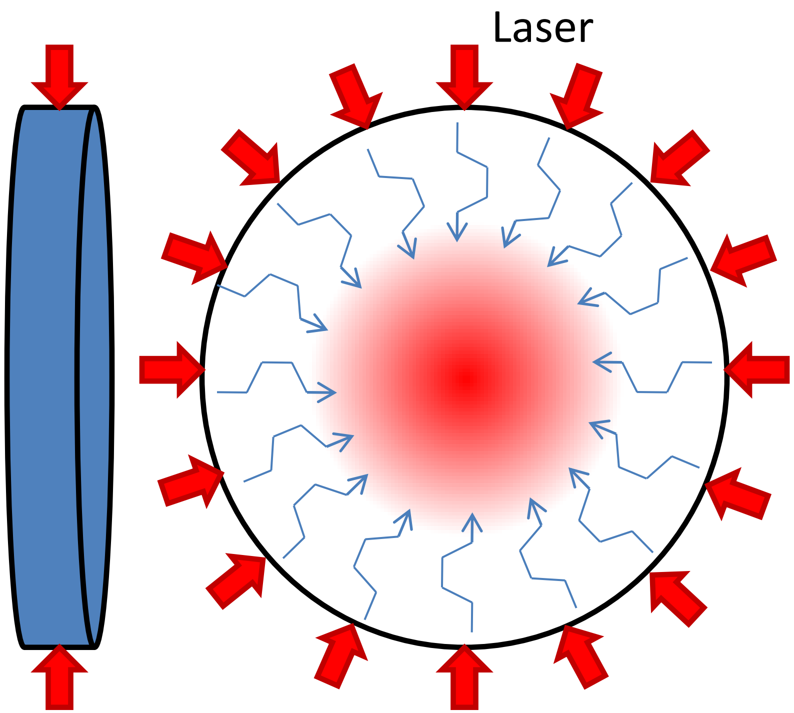
300 MV/m

	Si	**GaAs**	**InP**	**4H-SiC**	**GaN**	**GaP**
Bandgap(eV)	1.11	1.424	1.34	3.23	3.37	2.26
Wavelength(nm)	1116.06306	869.964888	924.5	383.5387	367.605341	548.154867
Insulation voltage(kV/cm)	300	250(600?)	200	3000	3300	
Relative permittivity	11.8	12.8		10	9.5	
Dark registance(Ωcm)	2×10^3	2×10^7	3.6×10^7	$>10^{11}$		
Electron mobility(cm^2/Vs)	1500	8500	6500	1000	1200	200
Hole movility(cm^2/Vs)	600	420		115	10	
Saturation electron velocity(10^7cm/s)	1	2		2	2.5	
Thermal conductivity(W/cm/K)	1.4	0.55	0.7	4.9	2.1	1.1
Expansion coefficient(10^{-5}/K)	2.4	6	4.5	4.2/4.68	5.58/3.17	5.3～5.81
Lattice constant(Å)	5.43	5.6535	5.45	3.073/10.05	3.189/5.178	5.45

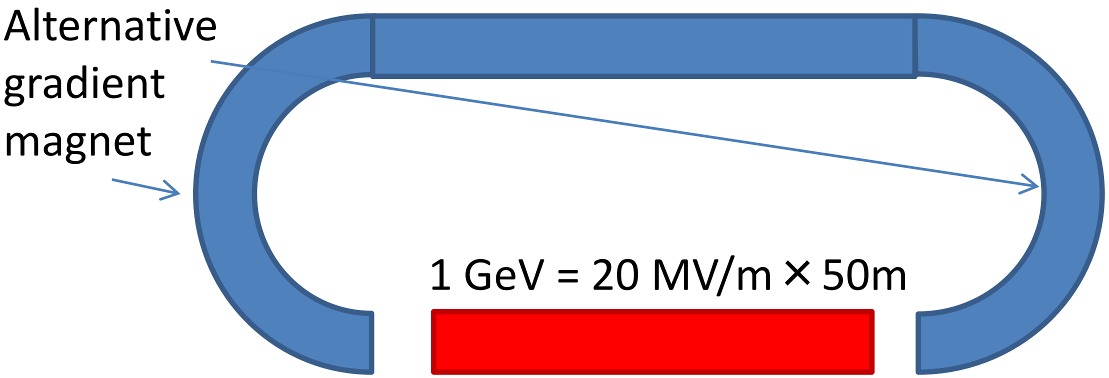
Ideal material for photoconductive switch

- High mobility / High withstanding voltage
- Small dielectric loss
- Cost of wafer

Field Concentrator Microtron



58ns = 8.7m / n=3 (Al2O3)



Alternative
gradient
magnet

1 GeV = 20 MV/m × 50m

Muon phase rotaion is
possible in last turn.

Blumlein DWA Microtron

	放医研	群馬大	Blumlein Microtron	J-PARC RCS	J-PARC MR	Blumlein Microtron
Energy (MeV/iu)	430	400	400	3000	50000	50000
Injection Energy(MeV/u)			0	400	3000	3000
Particle per bunch				4.15E+13	4.13E+13	4.15E+13
Particle per spill	1.15E+08	2.40E+09		8.30E+13	3.30E+14	4.15E+13
Particle per second	2.30E+08	1.20E+09		2.08E+15	9.90E+13	2.08E+14
Repetition	2	0.5		25	0.3	5
Numer of Bunch				2	8	1
Bunch Length(ns)				58	58	58
Bunch Spacing(ns)					598	
Charge per bunch(nC)				6.65E+03	6.61E+03	6.65E+03
Charge per spill (nC)	1.84E-02	3.84E-01	0.00E+00	1.33E+04	5.29E+04	6.65E+03
Current (nA)	3.68E-02	1.92E-01	0.00E+00	3.32E+05	1.59E+04	3.32E+04
Peak Current(A)				1.15E+02	1.14E+02	1.15E+02
Revolution (MHz)	1.697	4.761905		0.833333333	0.188679245	
Revolution (us)	0.589275	0.21		1.2	5.3	
Circumference(m)	176.7826	63		348.333	1567.5	
Bending Radius(m)					89.381	
Bending Magnetic Field(T)					1.9	
Injection(s)				0.0005	0.17	
Acceleration(s)				0.02	1.96	
Acceleration Gradient(MV/m)			20		0.03	20
Accelerator Length(m)			0.5		1.846	1
Number of Acceleration Unit			1		6	50
Acceleration Voltage(MV)			10		0.28	1000
Q value					20	
Number of Turns			40		167857.1429	47
Real Acceleration(s)					0.889642857	
Delay Line Length(m)						17.4
Injection Emittance(π mm・mrad)				4	54	
Painting Emittance(π mm・mrad)				216		
Extraction Emittance(π mm・mrad)				54		
Power Consumption(W)						
Beam Power (W)	1.58E-02	7.69E-02	0.00E+00	9.97E+05	7.93E+05	1.66E+06

Experimental plan for **stageing** laser plasma acceleration at KEK

LWFA (linear region)

$$E=-\frac{\partial A}{\partial t}-\nabla\phi,\quad B=\nabla\times A,\ \ \nabla\cdot A=0\ (coulomb\,gauge)$$

$$\frac{1}{\mu}\nabla\times\nabla\times A= j+\varepsilon\frac{\partial}{\partial t}\left(-\frac{\partial A}{\partial t}-\nabla\phi\right)$$

$$\frac{\partial\rho}{\partial t}+\nabla\cdot j=0,\ \ j=\rho v,\ \ \rho=\rho_0+\delta\rho\ \rightarrow\ \nabla\cdot v=-\frac{1}{\rho_0}\frac{\partial\delta\rho}{\partial t}$$

$$\frac{dp}{dt}=m\left(\frac{\partial v}{\partial t}+\left(v\cdot\nabla\right)v\right)=-e\left(E+v\times B\right)=e\left(\frac{\partial A}{\partial t}+\nabla\phi+v\times\left(\nabla\times A\right)\right)$$

$$v_0=\frac{e}{m}A=ca,\ \ F_p=m\frac{\partial\delta v}{\partial t}=-mc^2\left(\left(a\cdot\nabla\right)a+a\times\left(\nabla\times a\right)\right)=-mc^2\nabla\left(\frac{a^2}{2}\right)$$

$$A=A_0e^{jk(z-ct)}$$

$$S=\left(-jkcA_0\right)\left(-jkA_0\right)$$

$$I=\frac{E^2}{c}=ck^2\left|A\right|^2$$

$$a_0=\frac{eA_0}{m_ec}=\frac{e}{m_eck}\sqrt{\frac{I}{c}}$$

div

$$m\frac{\partial\nabla\cdot v}{\partial t}+mc^2\Delta\left(\frac{a^2}{2}\right)=-e\nabla\cdot E=\frac{e}{\varepsilon}\delta\rho$$

$$\left(\frac{\partial^2}{\partial t^2}+\frac{e\rho_0}{m\varepsilon}\right)\frac{\delta\rho}{\rho_0}=c^2\Delta\left(\frac{a^2}{2}\right)\quad\rightarrow\quad\omega_p=\sqrt{\frac{e\rho_0}{m\varepsilon}}$$

$$\left(\frac{\partial^2}{\partial t^2}+\omega_p{}^2\right)\phi=\frac{\rho_0c^2a^2}{2\varepsilon}=\omega_p{}^2\frac{mc^2a^2}{2e}\quad\leftarrow\quad\Delta\phi=\frac{\delta\rho}{\varepsilon}$$

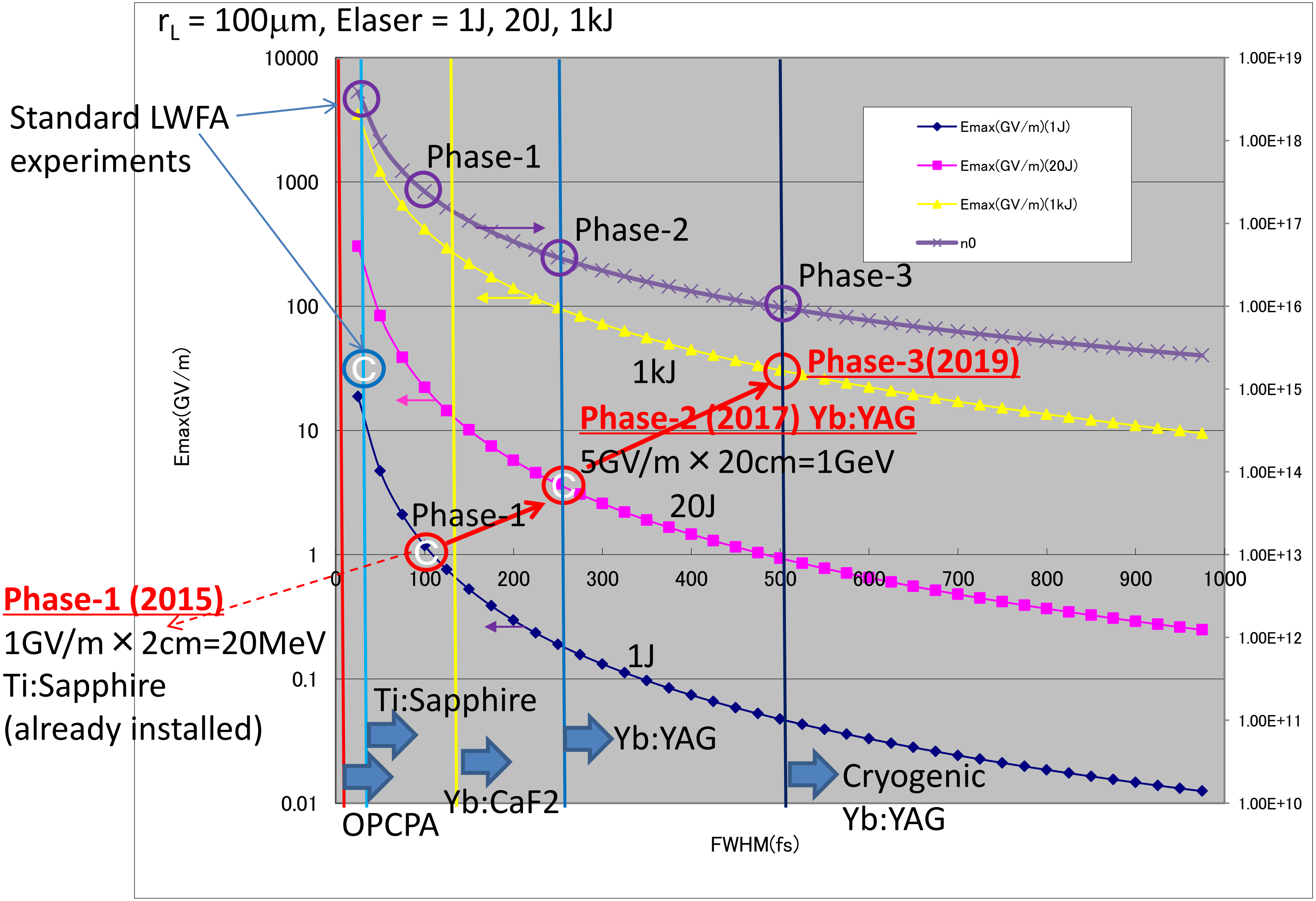
$$\left(\frac{\partial^2}{\partial\varsigma^2}+k_p{}^2\right)\phi=k_p{}^2\frac{mc^2a^2}{2e}\quad\leftarrow\quad\varsigma=z-ct$$

$$\phi=-\frac{mc^2k_p}{2e}\int_\varsigma^\infty d\varsigma'\sin\left(\varsigma-\varsigma'\right)a^2\left(r,\varsigma'\right)$$

$$E_z=-\frac{\partial\phi}{\partial\varsigma},\ a=a_0e^{-\frac{r^2}{r_0{}^2}-\frac{\varsigma^2}{2\sigma_z{}^2}}$$

$$eE_z=$$

Possible experimental region for LWFA



r_L = 100μm, Elaser = 1J, 20J, 1kJ

Standard LWFA experiments

Phase-1 (2015)

1GV/m × 2cm=20MeV

Ti:Sapphire

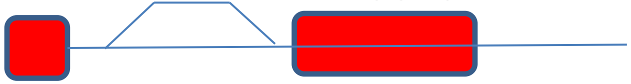
(already installed)

Phase-2 (2017) Yb:YAG

5GV/m × 20cm=1GeV

Phase-3(2019)

Stageing laser plasma acceleration



LWFA
< 50fs

LWFA
> 100 fs

Re-bunching

RF-Gun

Bunch Compressor

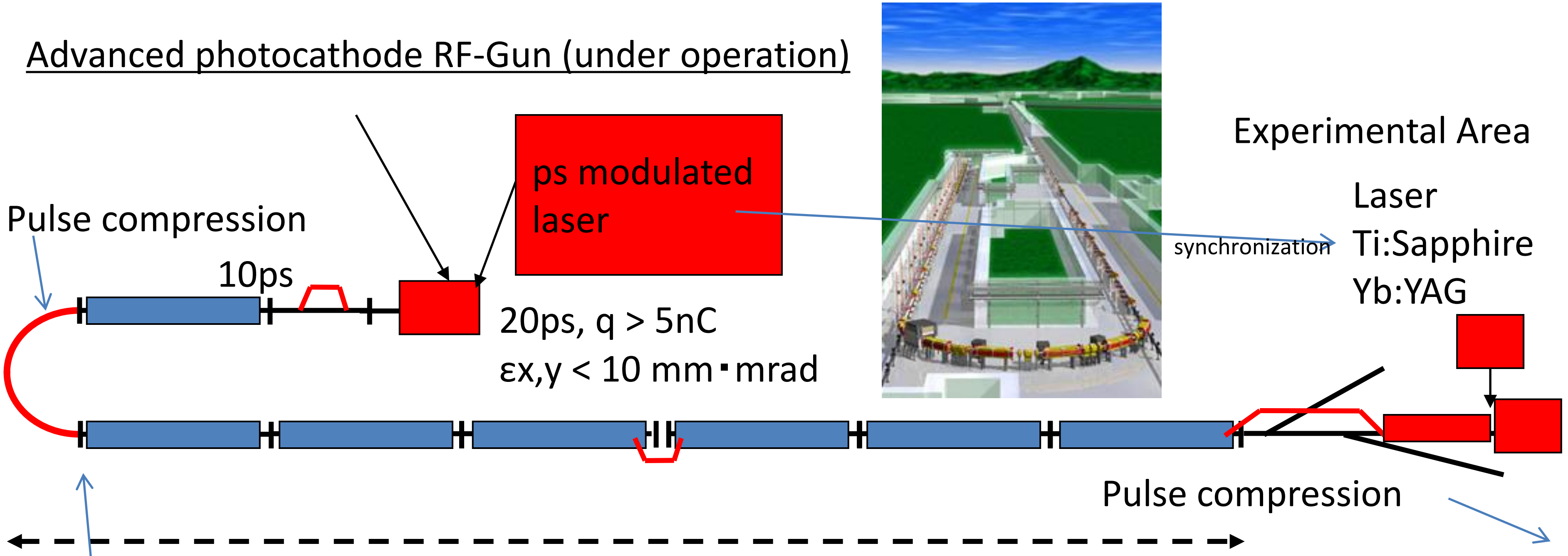
Bunch Compressor

LWFA
> 100 fs

Conventional accelerator

KEK / DESY等

Facility concept of Ultra High Intense Beam-Laser Complex using existing7 GeV KEK LINAC



Advanced photocathode RF-Gun (under operation)

ps modulated laser

Experimental Area

Laser
Ti:Sapphire
Yb:YAG

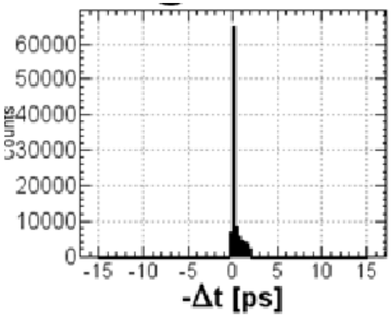
Pulse compression

20ps, q > 5nC
εx,y < 10 mm･mrad

Pulse compression

Total length ~400m => 7 GeV

～a few 100 fs



e- 7 GeV, 7nC
σx,y = 35μm (β～1m)
/ 50fs = **1 PW**

Future target : 1 PW beam x 10 J laser

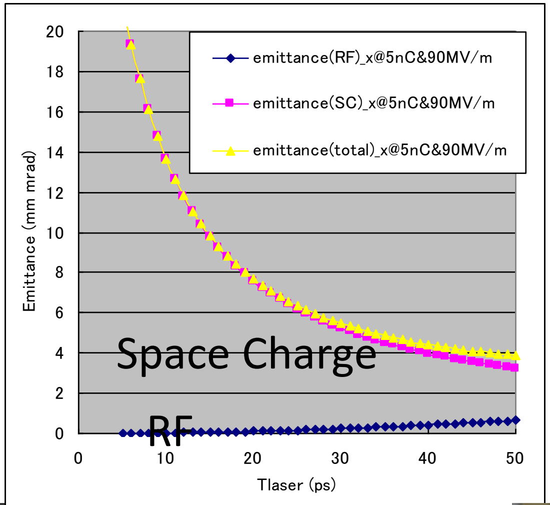
(upgrade to 100J in the future)

Beam Quality

Transverse

High Charge & Low emittance RF-Gun

Logitudinal

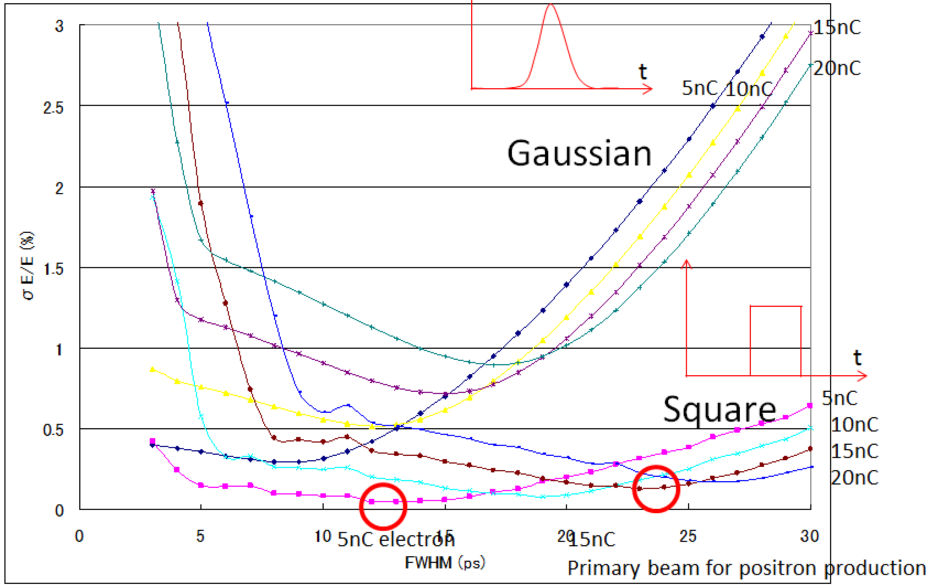


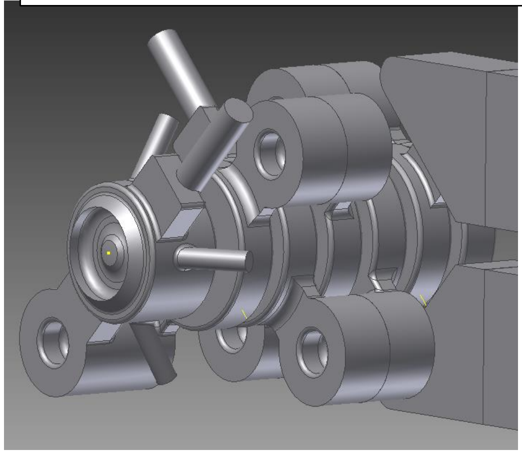
8 GeV で

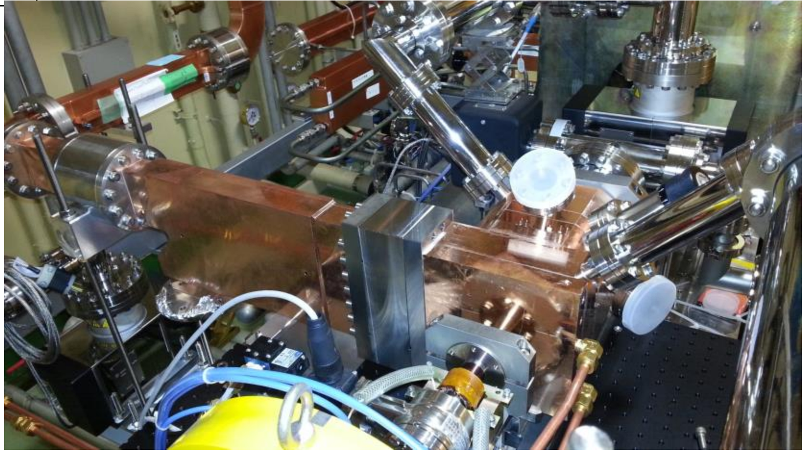
γ = 16,000

↓

ε = 0.6 nm・mrad





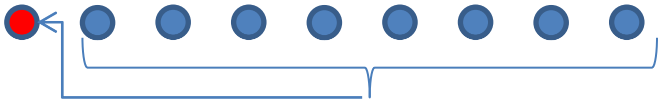


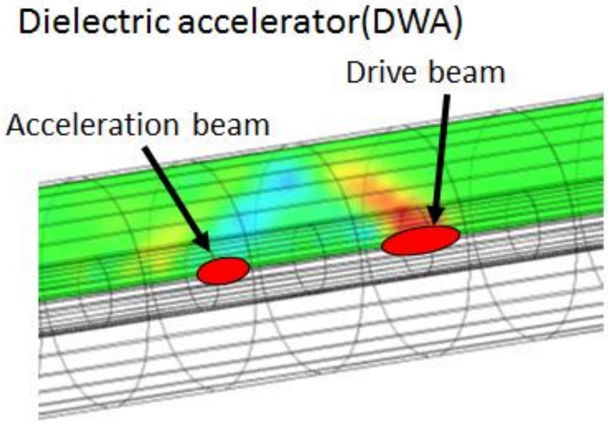
0.1 % energy spread
at 5 nC x 12 ps
⇒ 30 fs / 5nC / 40%
= 1.2 PW

Maximum Current : 5 nC × 200bunch × 50Hz = 50 μA

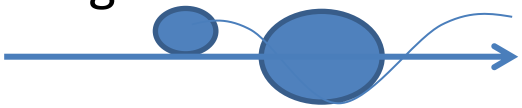
Beam-Laser complex at KEK

- Beam driven accelerator
  - Stable PW beam 7 GeV x 7 nC/50fs
  - Reliable path to MW average power (FLAST Forward is on going.)
  - Resonant DWA for the energy multiplification



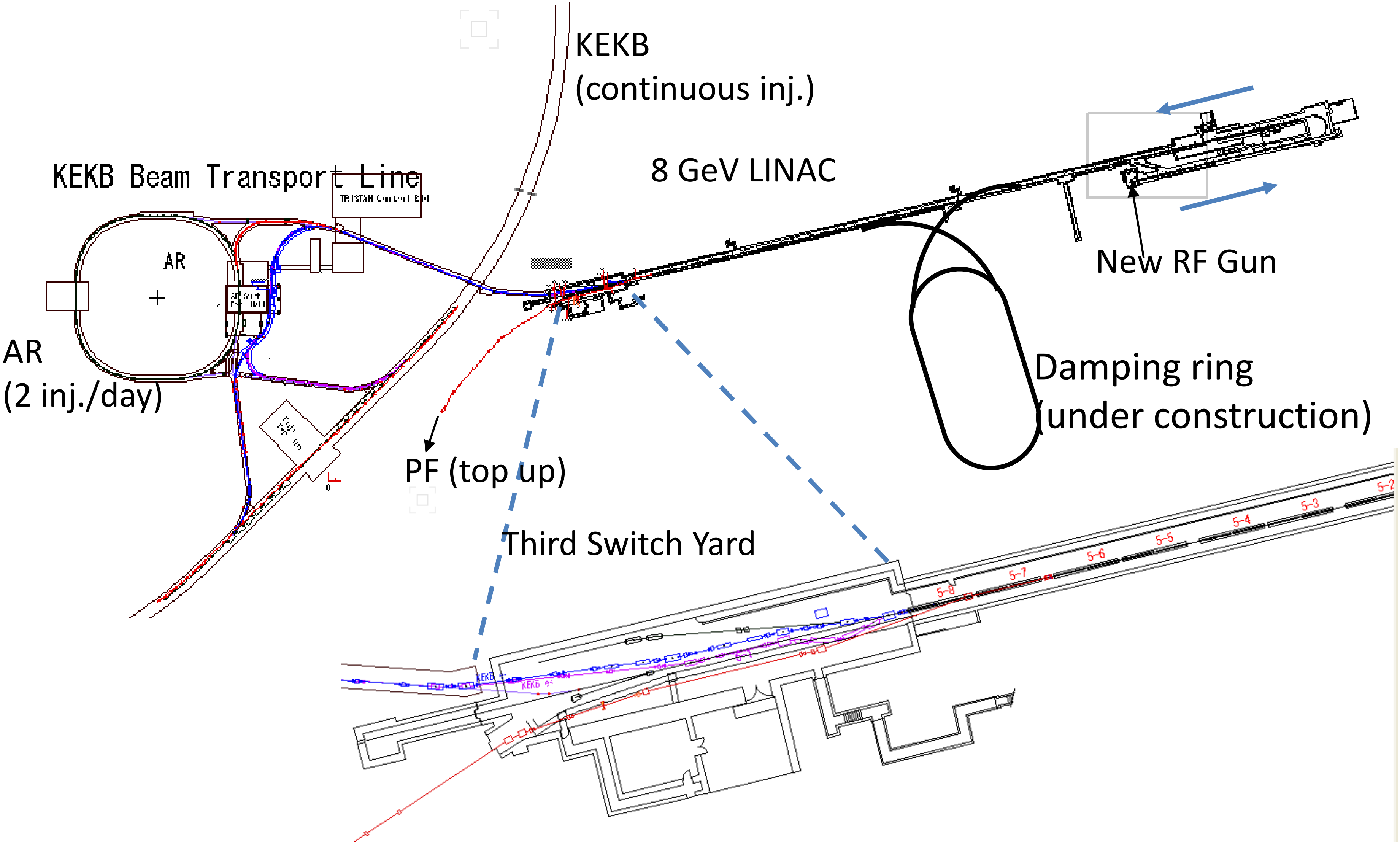


  - PWFA for High brilliance X-ray source
    Betatron oscillation with offset witness bunch injection
    Beta matching using Laser Plasma Focussing



- Laser plasma after burner
  - Synchronization : PLL between photocathode drive laser and LWFA laser.
  - **Focus to Linear regime** (no LWFA injection)
  - **Precise beam diagnostics** with beam optics
    ε = **1.5nm** , β = 1m => σ = 40μm , η = 100 mm
    < 1 MeV / 7 GeV resolution is possible
- Direct Laser / THz acceleration
  - 1 GV/m

8 GeV LINAC Third Switch Yard



KEKB
(continuous inj.)

KEKB Beam Transport Line

8 GeV LINAC

AR
(2 inj./day)

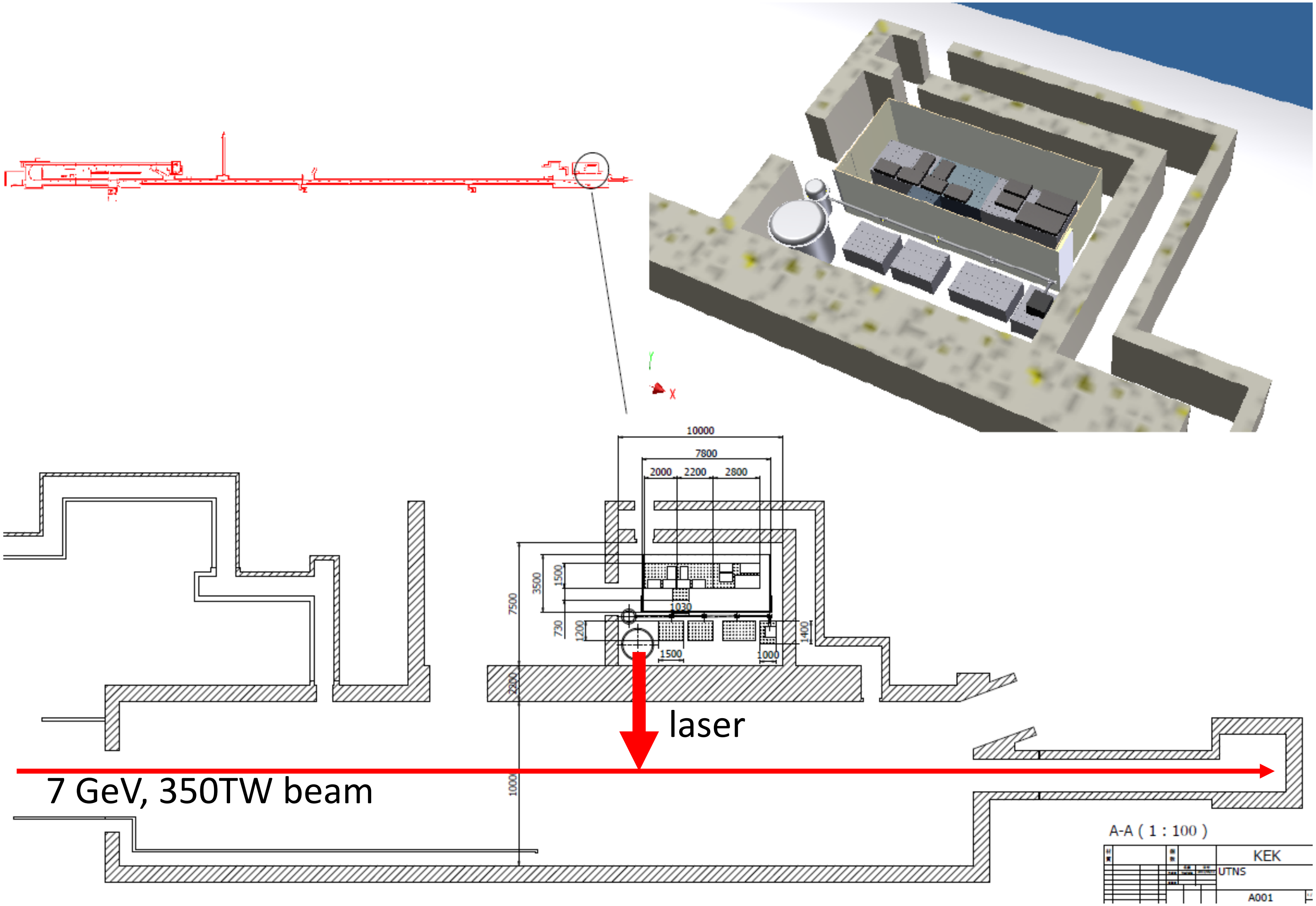
PF (top up)

New RF Gun

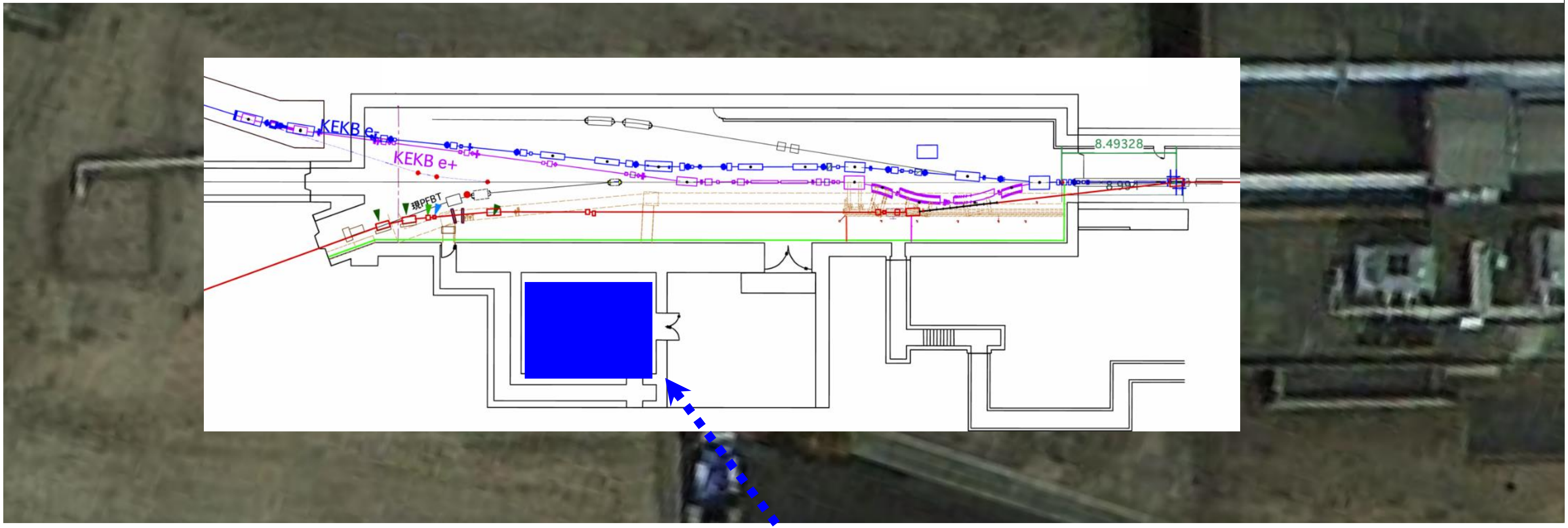
Damping ring
(under construction)

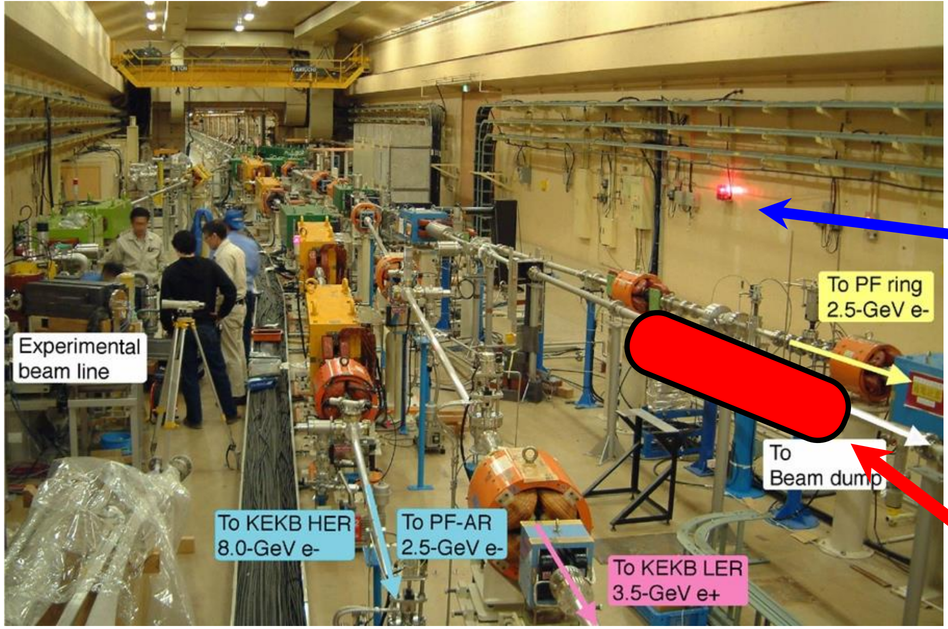
Third Switch Yard

Experimental area for laser plasma after burner



Experimental area for laser plasma after burner





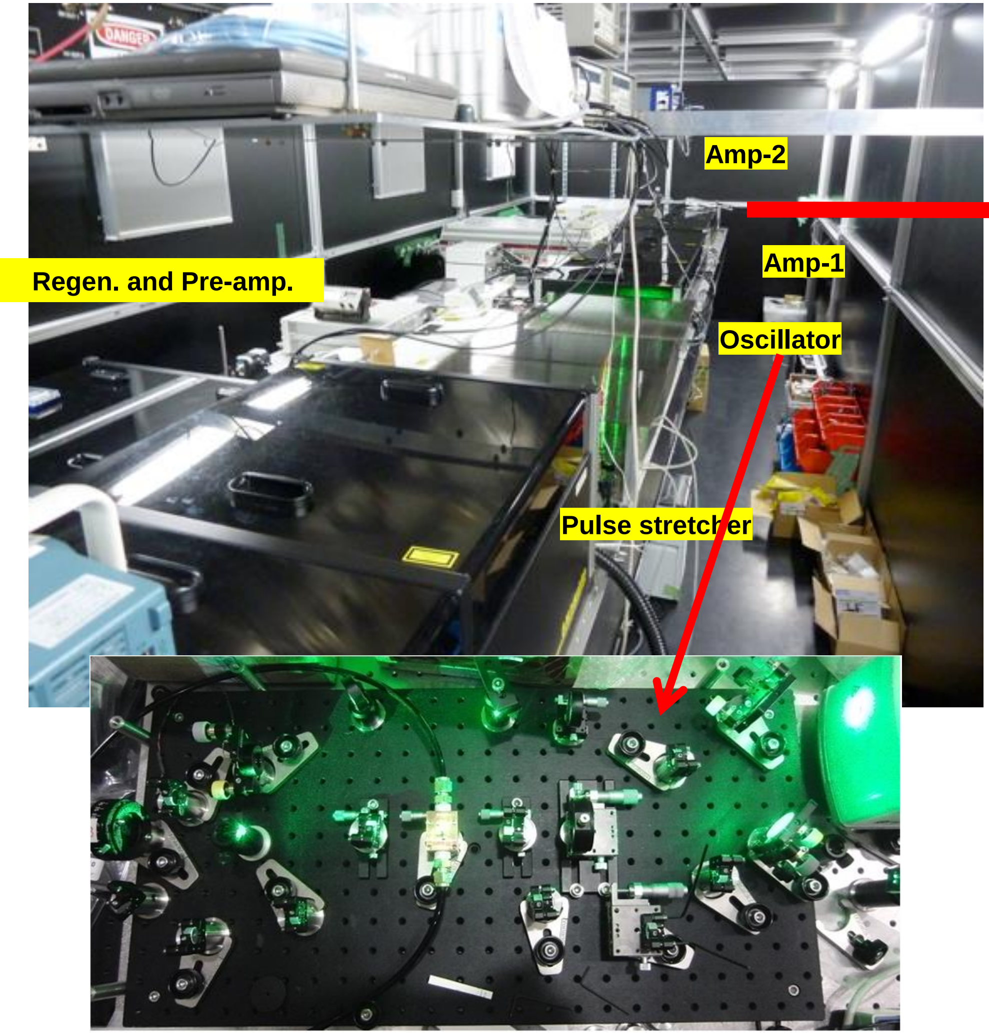
Ti:Sapphire Laser
7 TW => 100TW(future)

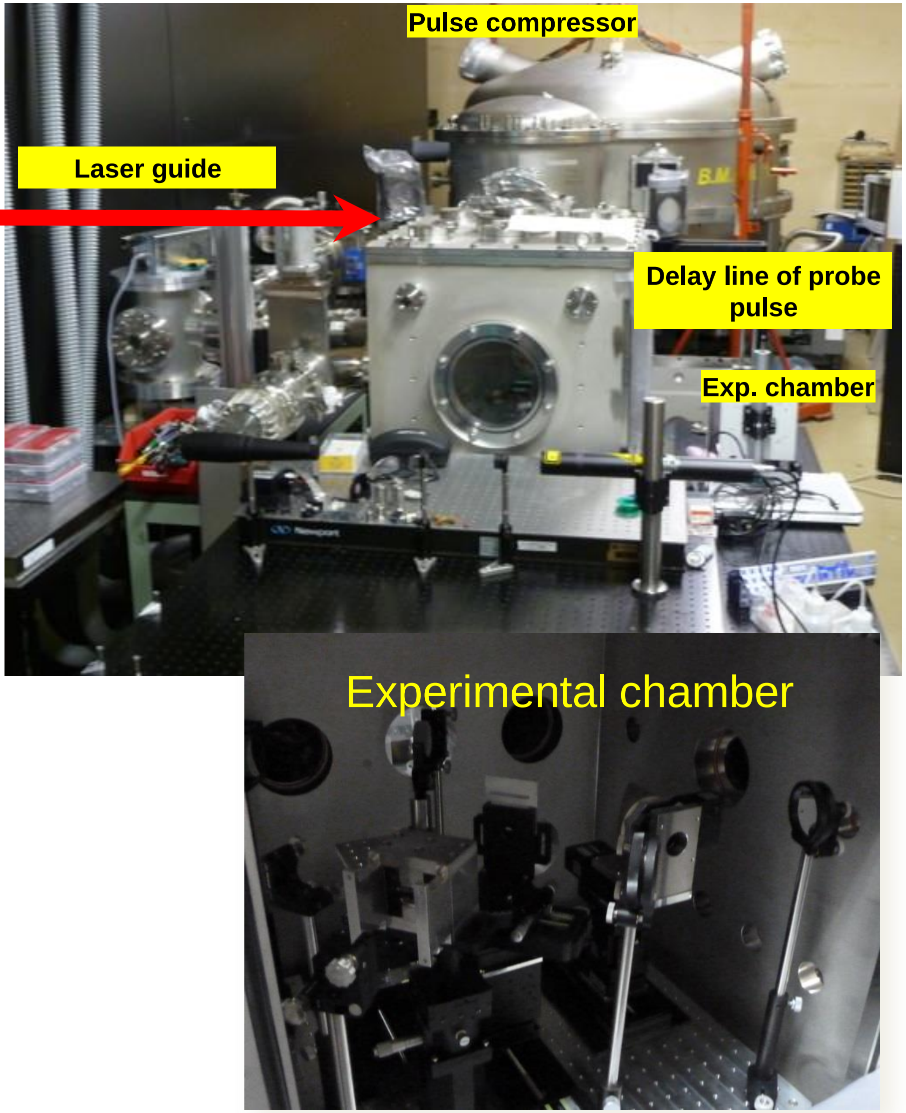
Compressor
Vacuum chamber

under installation

Ti:Sapphire Laser from U-Tokyo Uesaka-lab

THALES α-10 + Oscillator



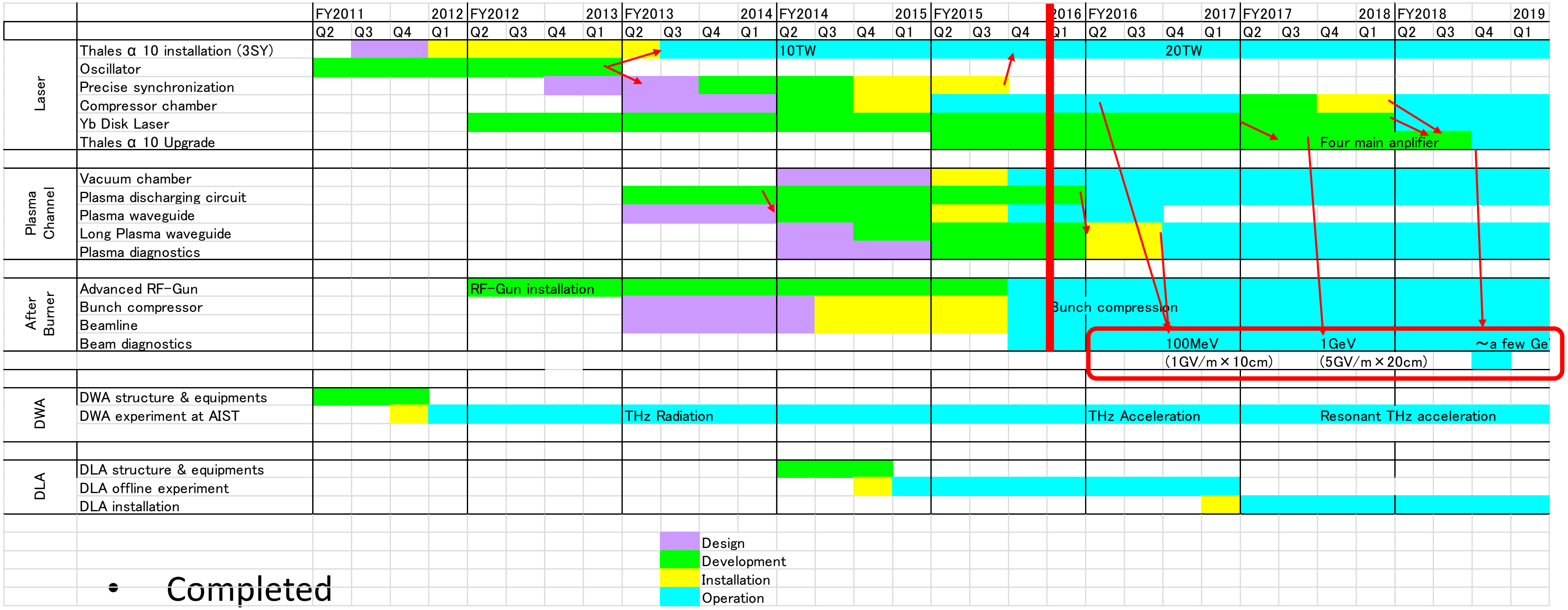


300mJ/40fs = 7 TW at present

=> 25 TW (upgrade compressor and Nd:YAG pump) in FY2013

=> ??? TW (Yb:YAG pump)

Schedule (FY2011-2019)

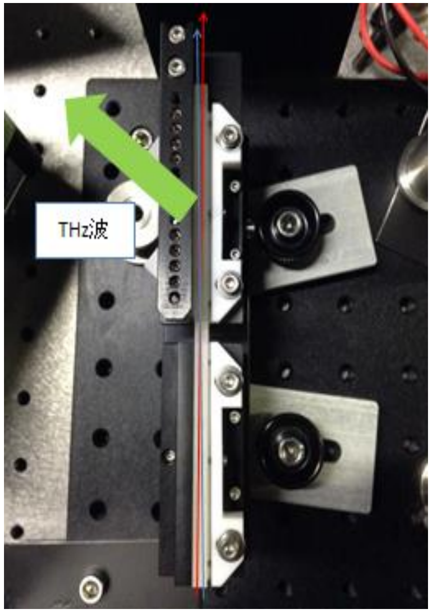


- Completed
  - Oscillator and synchronization
  - Ti:Sapphire laser already installed
  - High charge & low emittance RF gun installed
  - 4-stage bunch compressor
- Under development
  - Laser upgrade
    - Transmission grating compressor
    - High energy Yb:YAG disk laser
  - Long plasma waveguide
  - Beam diagnostics

Direct Laser / THz acceleration

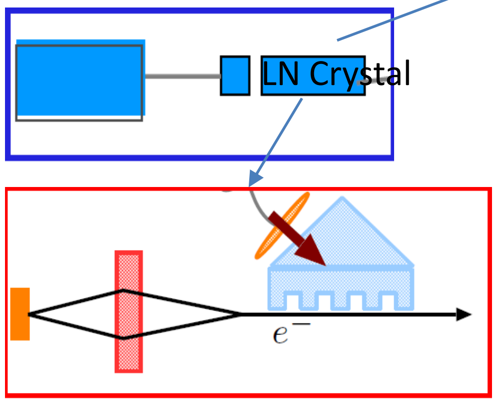
Direct Laser / THz acceleration

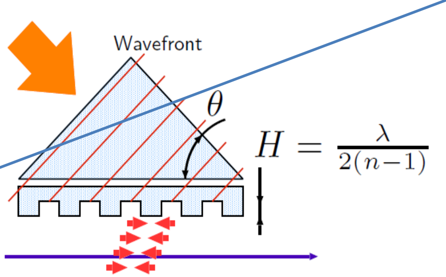
- Direct Laser Acceleration
  - Test Structure is fabricated in NIMS process
- Direct THz Acceleration
  - Same gradient at 10mJ (1.2THz) ⇔ 100J (12GHz)
  - High Intense THz is single cycle or a few cycle
    → Normal injection is ineffective
    => Prism Injection Schme



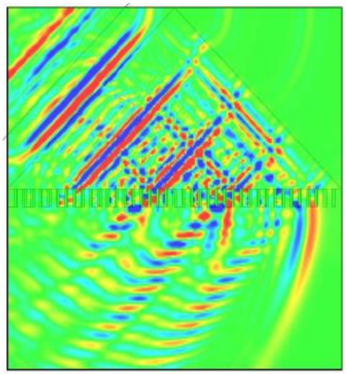
Microchip Laser

Parametric THz

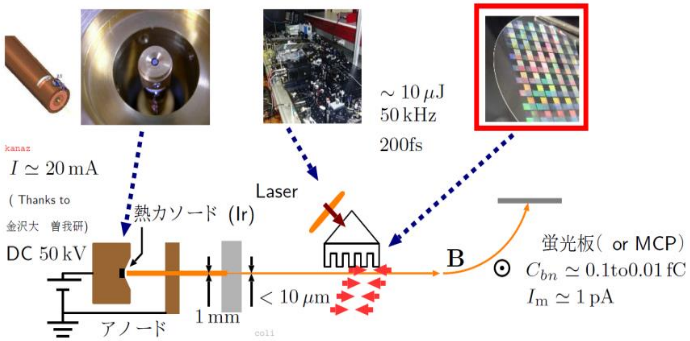




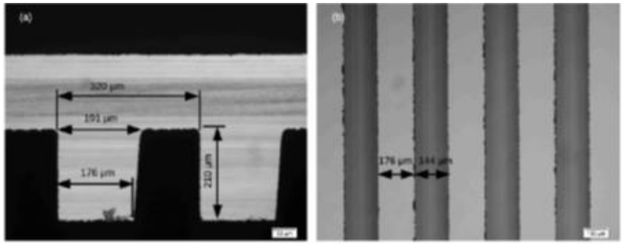
$$H = \frac{\lambda}{2(n-1)}$$



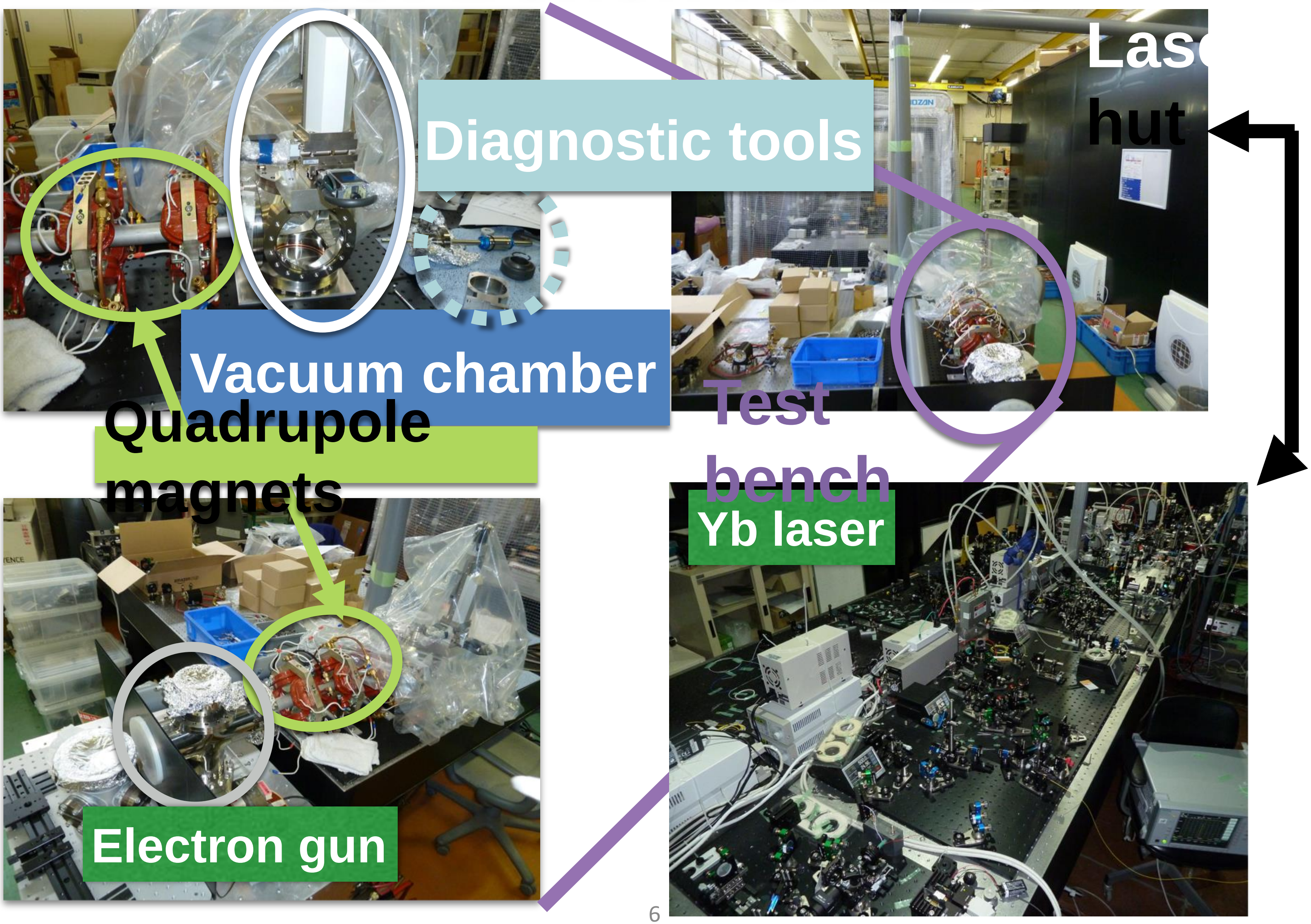
Grating : $(n-1)H = \frac{\lambda}{2}$



THz DLA structure



Test Bench for DLA



Diagnostic tools

Vacuum chamber

Quadrupole magnets

Electron gun

Las hut

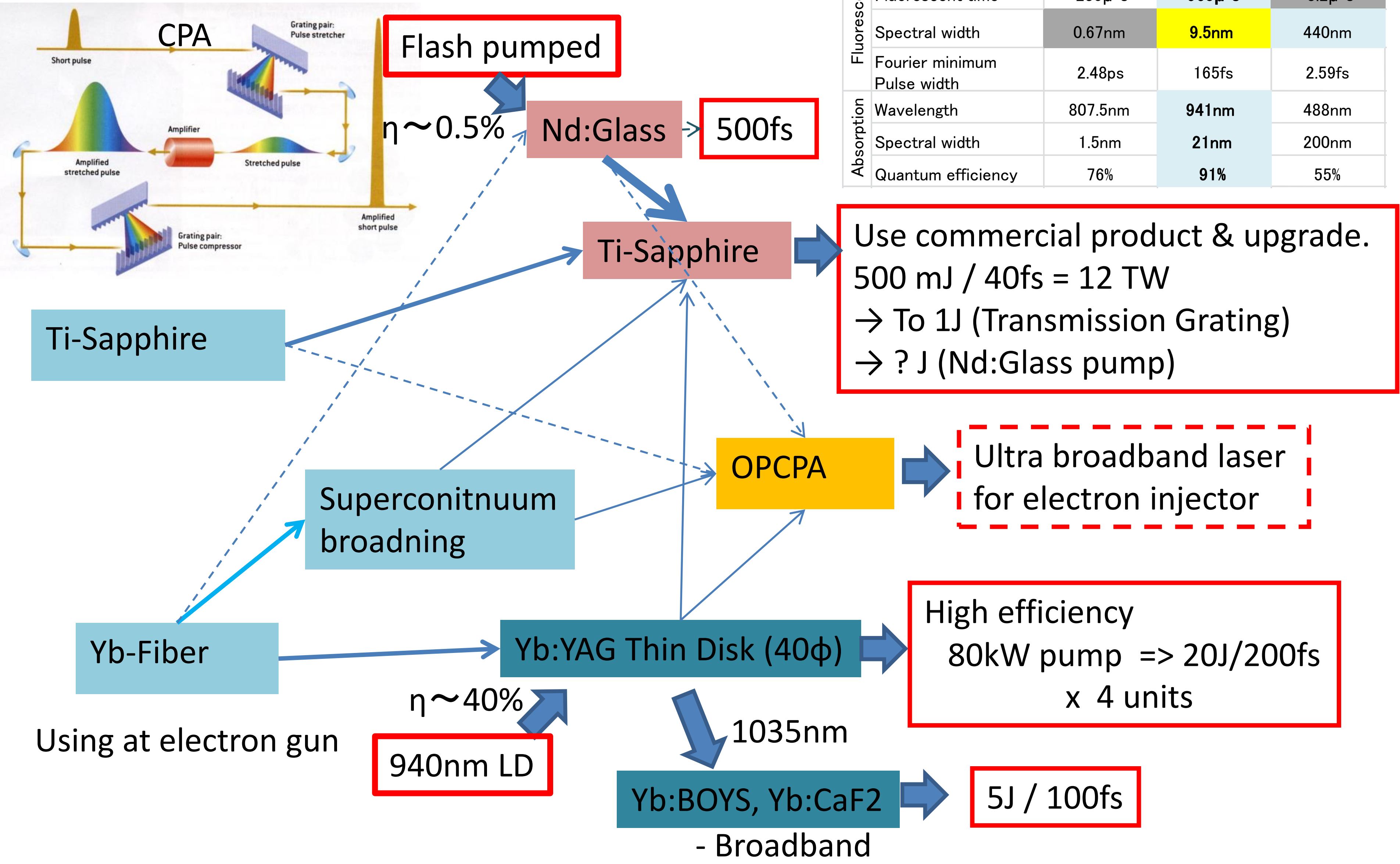
Test bench

Yb laser

Laser development toward high energy sub-picosecond LWFA afterburner experiment

Laser development in KEK

	Material	Nd:YAG	Yb:YAG	Ti:Sapphire
	Wavelength	1064nm	1030nm	660–1100nm
Fluorescence	Fluorescent time	230μ s	**960μ s**	3.2μ s
	Spectral width	0.67nm	**9.5nm**	440nm
	Fourier minimum Pulse width	2.48ps	165fs	2.59fs
Absorption	Wavelength	807.5nm	**941nm**	488nm
	Spectral width	1.5nm	**21nm**	200nm
	Quantum efficiency	76%	**91%**	55%



Flash pumped

η～0.5%

Nd:Glass

500fs

Ti-Sapphire

Use commercial product & upgrade.
500 mJ / 40fs = 12 TW
→ To 1J (Transmission Grating)
→ ? J (Nd:Glass pump)

Ti-Sapphire

OPCPA

Ultra broadband laser
for electron injector

Superconitnuum
broadning

Yb-Fiber

Yb:YAG Thin Disk (40ϕ)

High efficiency
80kW pump => 20J/200fs
x 4 units

η～40%

Using at electron gun

940nm LD

1035nm

Yb:BOYS, Yb:CaF2
- Broadband

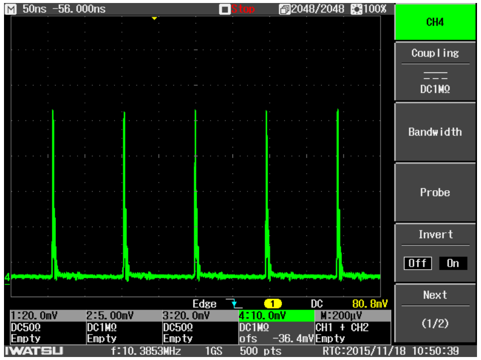
5J / 100fs

Oscillator

Pump

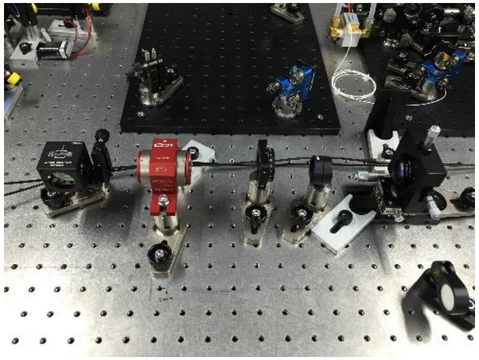
Amplifier

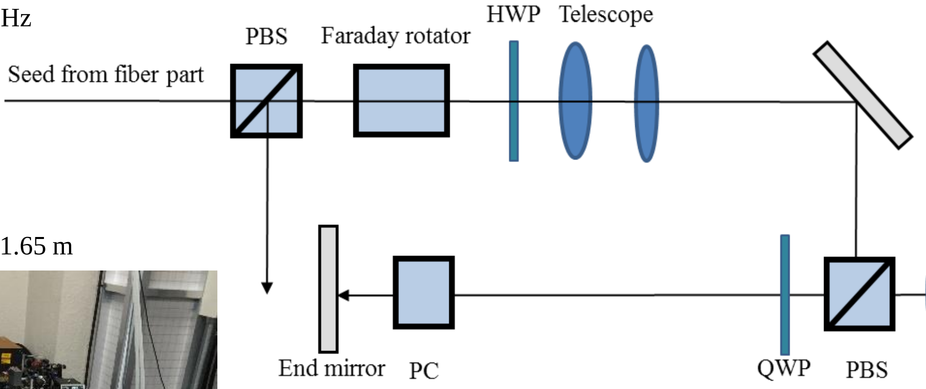
Yb:YAG regenerative amplifier: Experimental setup

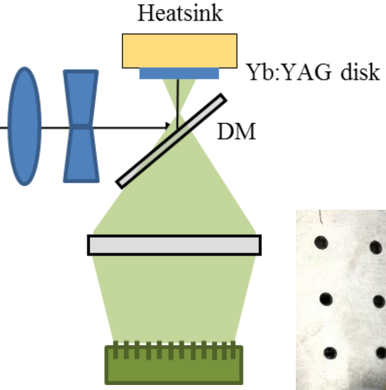


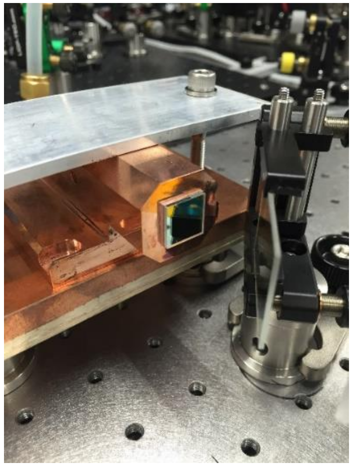
```
M 50ns -56.000ns        Stop   2048/2048  100%
Edge  1  DC  80.8mV
1:20.0mV   2:5.00mV   3:20.0mV   4:10.0mV         M:200µV
DC50Ω      DC1MΩ      DC50Ω      DC1MΩ            CH1 + CH2
Empty      Empty      Empty      ofs   -36.4mV    Empty
IWATSU   f:10.3853MHz   1GS   500 pts   RTC:2015/11/18 10:50:39
```

- Repetition rate: 10 MHz
- Power: 160 mW
- Pulse width: 30 ps





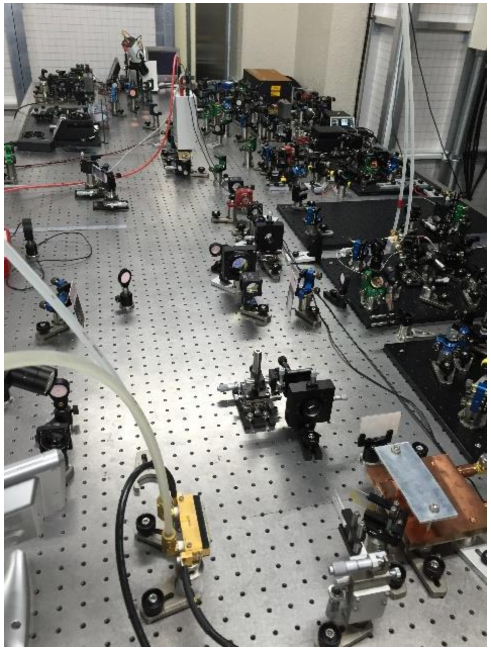


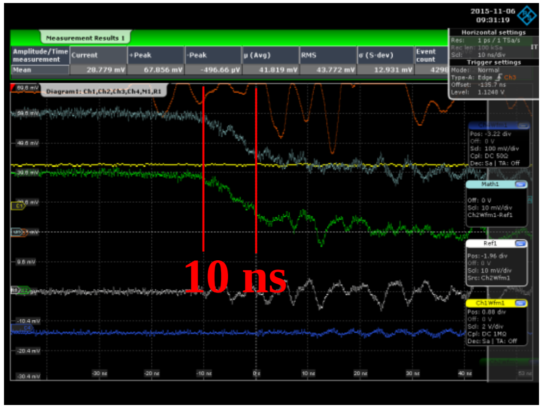


- Thickness of Yb:YAG disk: 1.0 mm
- Size: 12.7 x 12.7 mm
- Doping concentration: 10 a.t.%

- High quality copper heatsink by water cooling
- Cooling temperature: 16 Centigrade

Cavity length: 1.65 m





2015-11-06 09:31:19

Measurement Results 1

Amplitude/Time measurement	Current	+Peak	-Peak	μ (Avg)	RMS	σ (S-dev)	Event count
Mean	28.779 mV	67.856 mV	-496.66 μV	41.819 mV	43.772 mV	12.931 mV	4298

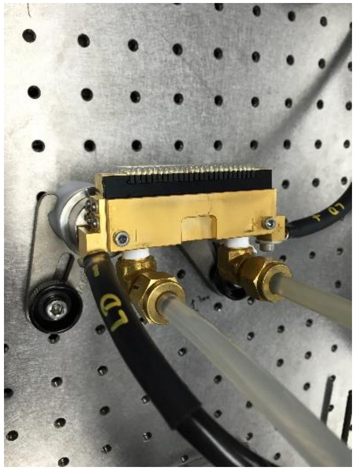
Horizontal settings
Res: 1 ps / 1 TSa/s
Rec len: 100 kSa
Scl: 10 ns/div

Trigger settings
Mode: Normal
Type-A: Edge Ch3
Offset: -135.7 ns
Level: 1.1248 V

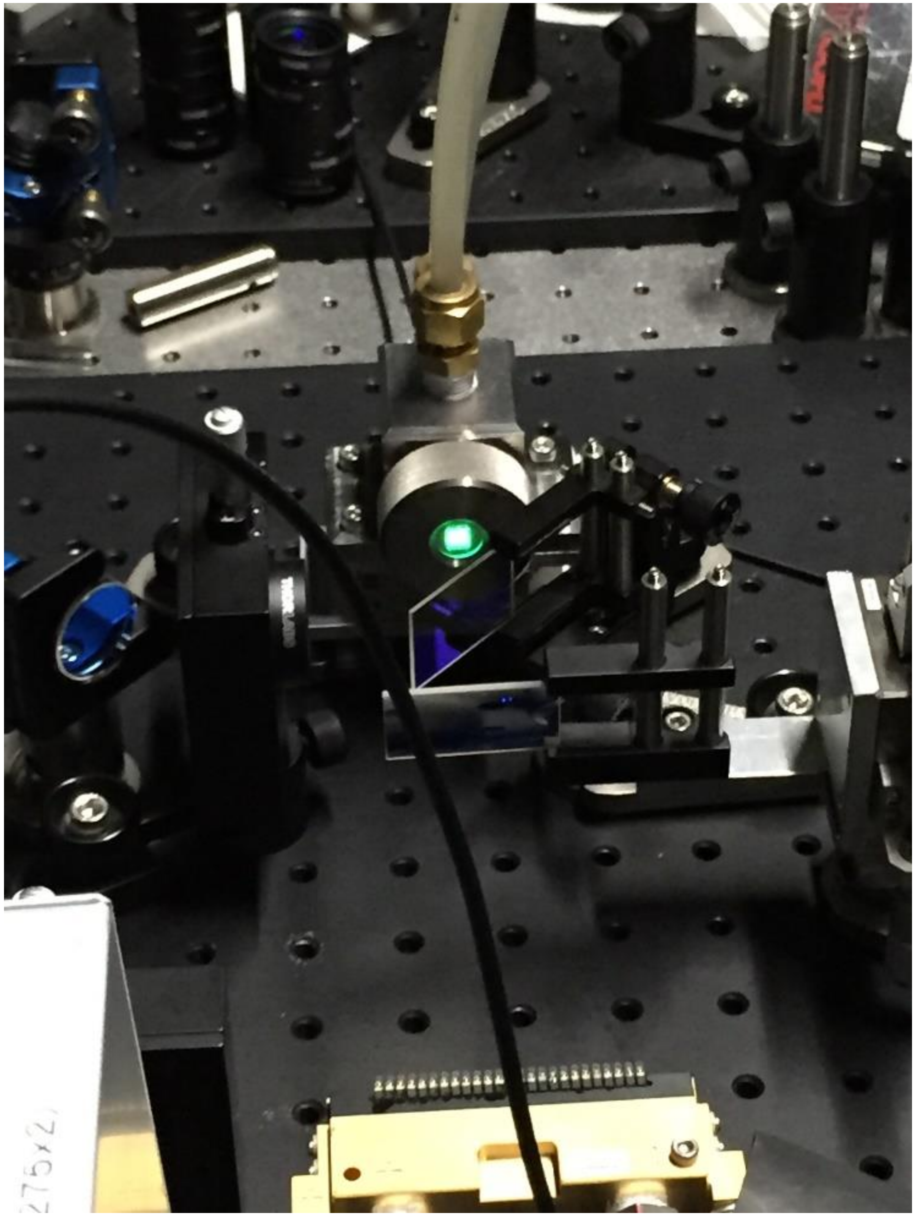
Diagram1: Ch1,Ch2,Ch3,Ch4,M1,R1

Pockels cell rise time: 10-15 ns

- Repetition rate: 1-50 Hz
- Peak power: 10 kW
- Pulse width: 600 μs
- Small divergence along the fast axis direction



10kW = 6J LD pump 50 pps



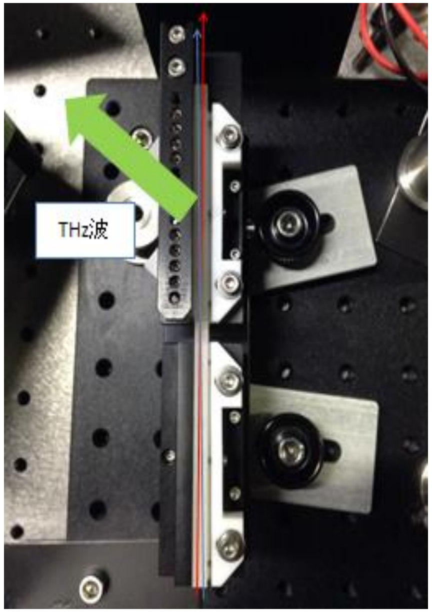
➡ 2J output

→ 38ϕ Yb:YAG Disk
+ 10kW x 8

Novel Accelerator / THz-DLA

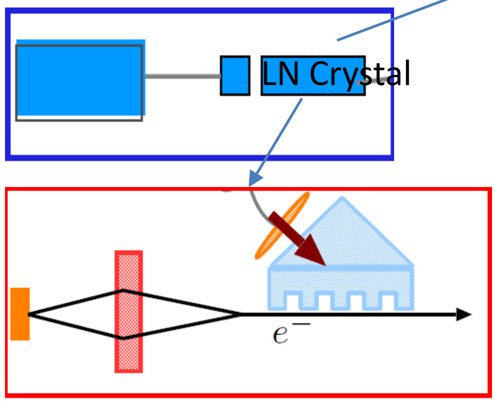
Direct Laser / THz acceleration

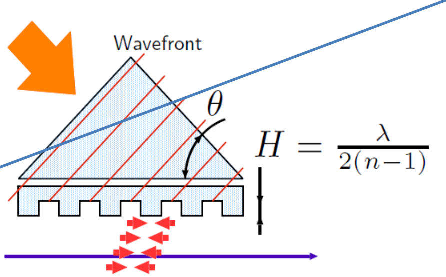
- Direct Laser Acceleration
  - Test Structure is fabricated in NIMS process
- Direct THz Acceleration
  - Same gradient at
    10mJ (1.2THz) ⇔ 100J (12GHz)
  - High Intense THz is single cycle or a few cycle
    → Normal injection is ineffective
    => Prism Injection Schme



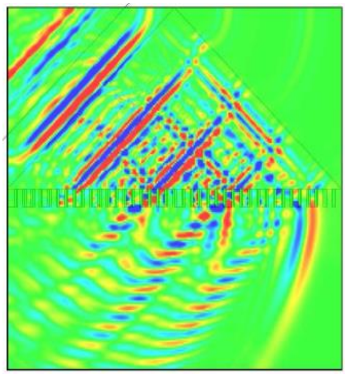
Microchip Laser

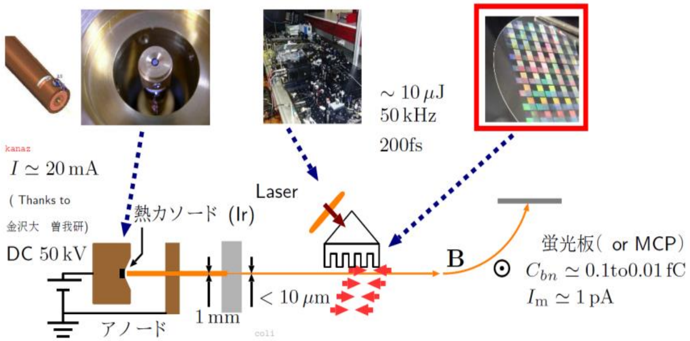
Parametric THz



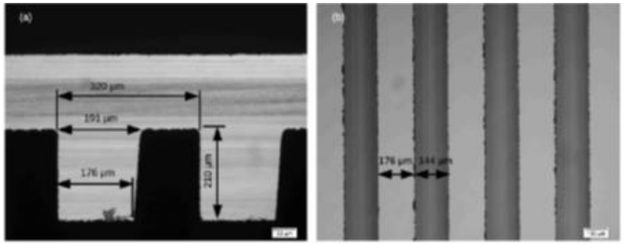


Grating : $(n-1)H = \dfrac{\lambda}{2}$

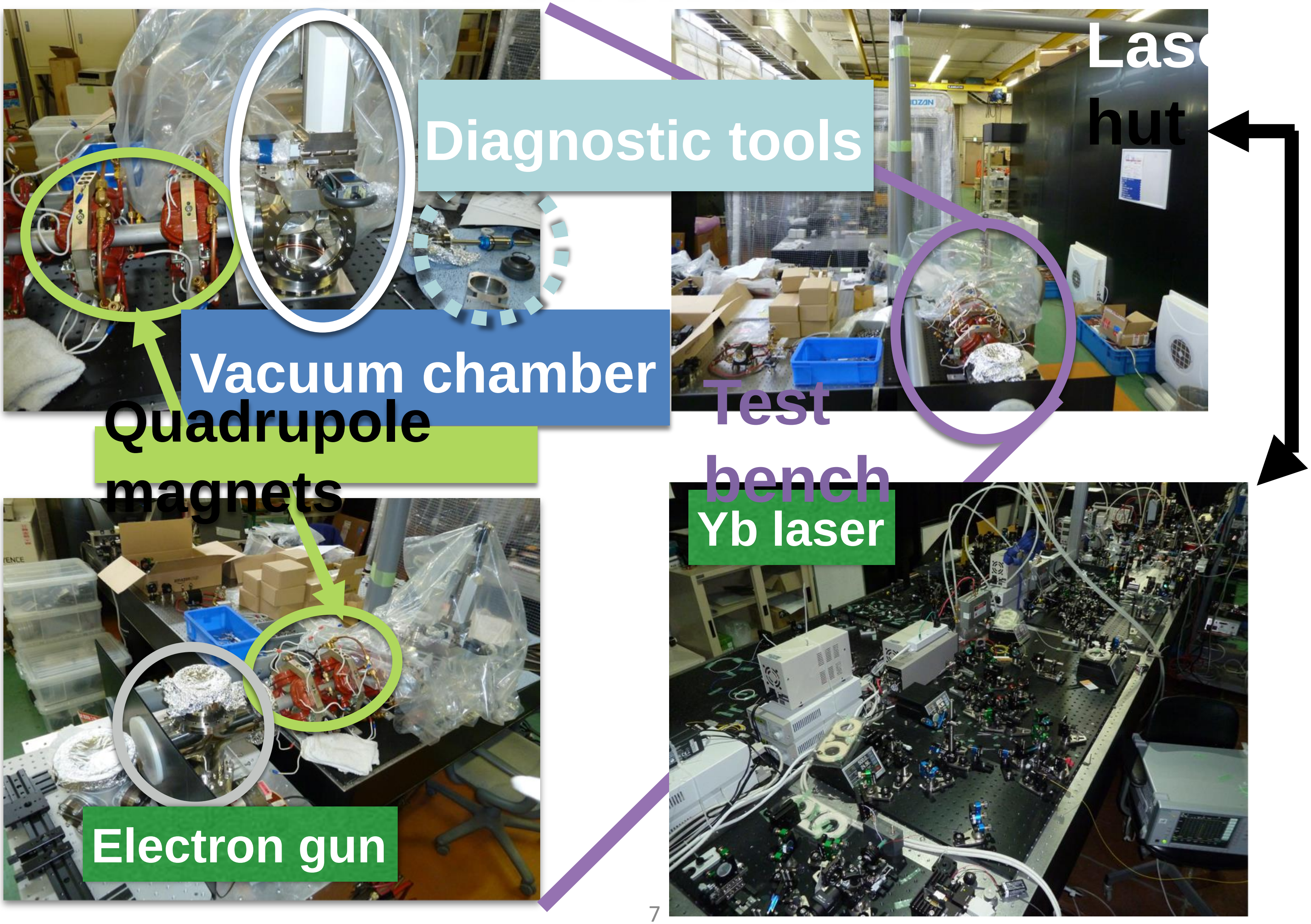




THz DLA structure



Test Bench for DLA



Diagnostic tools

Vacuum chamber

Quadrupole magnets

Electron gun

Las
hut

Test bench

Yb laser

Alternative for Energy Frontier

- 電子
  - 円形加速器 : 輻射で限界？
    - いやまだ限界でない → 100 km の FCC
    - シンクロトロン放射のエネルギー回収 → ERR
  - リニアコライダー： 高電界 L = V/E と効率
    - Nb超伝導(2K運転, < 40MV/m) → 高温超伝導 薄膜超伝導
    - 誘電体 : 誘電体フォトニック DLA(Laser, THz)
    - 周波数重畳
    - プラズマ加速
      - レーザープラズマアフターバーナー
      - 陽子ビームプラズマ ← J-PARC の Energy Frontier への転用の可能性
- 陽子 : 輻射が無い
  - 強磁場 p(GeV/c)=0.3 B(T) ρ(m) LHC 7TeV=0.3x8.4Tx2804m → HE-LHC
  - スーパーフェリック
  - Crystal Accelerator
- ミュオン： 輻射が無いが冷却が問題
  - MICE(FERMI)
  - Ultra Slow Muon ：μ^+のみ → μ^+e^- collider
  - 45 GeV e^+