Generation and Acceleration of Low-Emittance, High-Current Electron Beams for SuperKEKB

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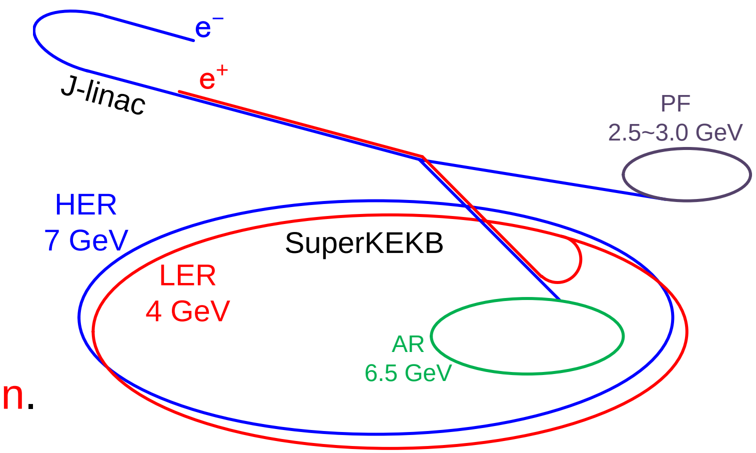
SuperKEKB Upgrade and RF gun development

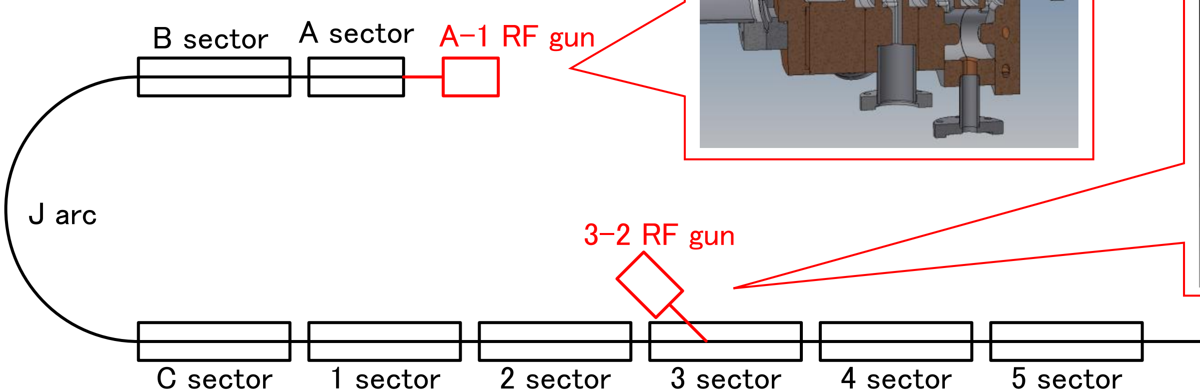
	KEKB obtained (e+ / e-)	SuperKEKB required (e+ / e-)
Energy	3.5 GeV / 8.0 GeV	4.0 GeV / 7.0 GeV
Charge	e- → e+ / e- 10 → 1.0 nC / 1.0 nC	e- → e+ / e- 10 → 4.0 nC / 5.0 nC
Emittance [mm-mrad]	2100 / 300	6 / 20

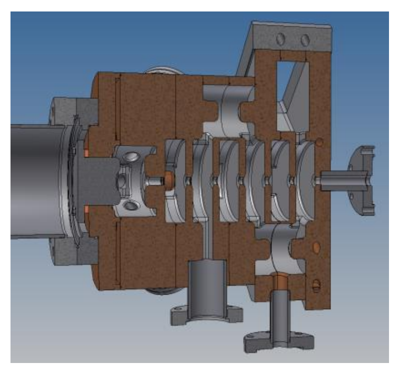


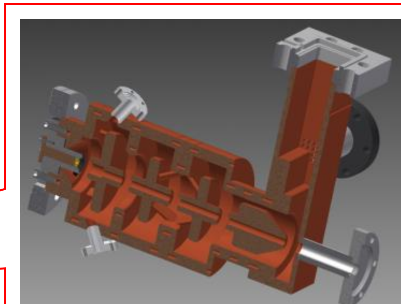
5 nC 10 mm-mrad electron beam generated by RF gun.
+ 10mm-mrad emittance preservation is required.

Quasi –travelling side couple RF-Gun with Yb laser system. (2013)

Preliminary test using DAW RF-Gun with Nd laser system due to earthquake. (2011)







RF-Gun development strategy for SuperKEKB

- Cavity : Strong electric field focusing structure
  - **Disk And Washer (DAW)** => 3-2, A-1(test)
  - **Quasi Traveling Wave Side Couple** => A-1

  => Reduce beam divergence and projected emittance dilution
- Cathode : Long term stable cathode
  - Middle QE (QE=10^{-4}～10^{-3} @266nm)
  - Solid material (no thin film) => Metal composite cathode

    => Started from LaB_6 (short life time)

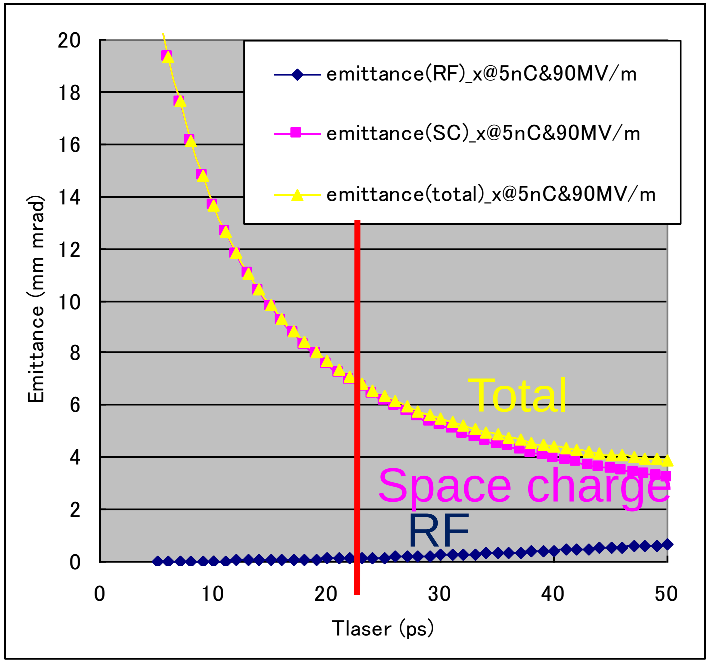
    => **Ir_5Ce has very long life time and QE>10^{-4}** @266nm
- Laser : Stable laser with temporal manipulation
  - LD pumped laser medium => Nd / Yb doped
  - Temporal manipulation => Yb doped

    => Minimum energy spread

- RF-Gun
  - **Design of RF-Gun cavity**
    - **Quasi travelling wave side couple**
  - Cathode
  - Laser
  - Test stand and schedule

RF-Gun for 5 nC

- Space charge is dominant.
  - Longer pulse length : 20 - 30 ps
- Stable operation is required.
  - Lower electric field : < 120MV/m
- Focusing field must be required.
  - Solenoid focus causes the emittance growth.
  - **Electric field focus preserve the emittance**.



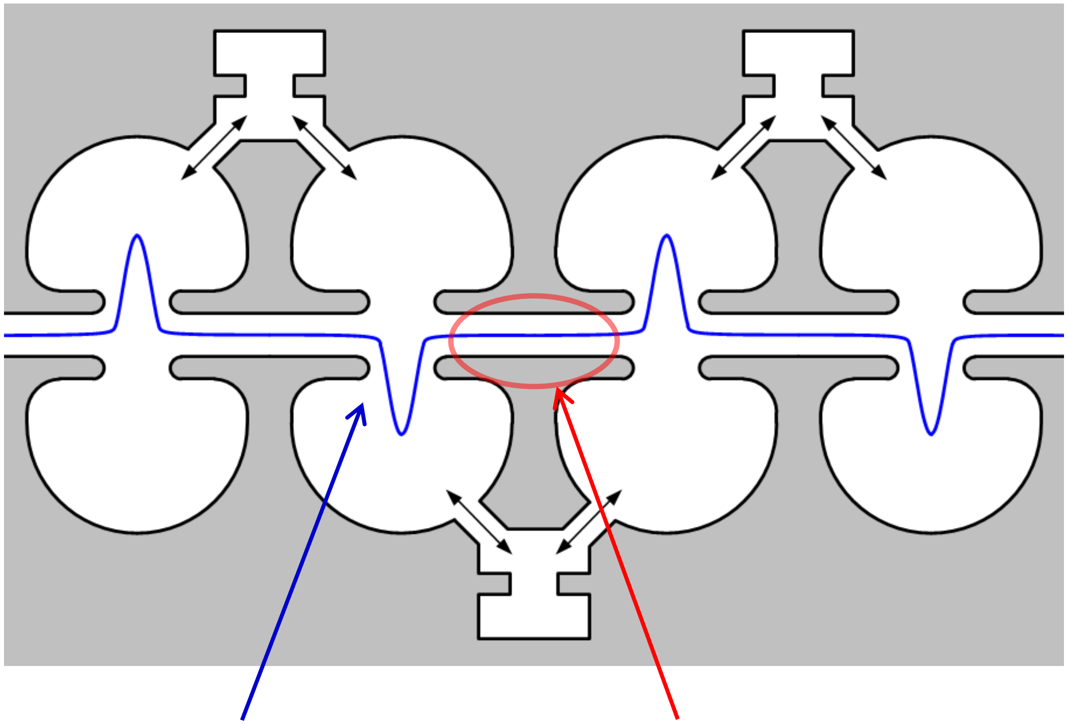
~~Epxial coupled cavity~~ : BNL

<u>Annular coupled cavity : Disk and washer or Side couple</u>

Electric focusing field by narrow gap

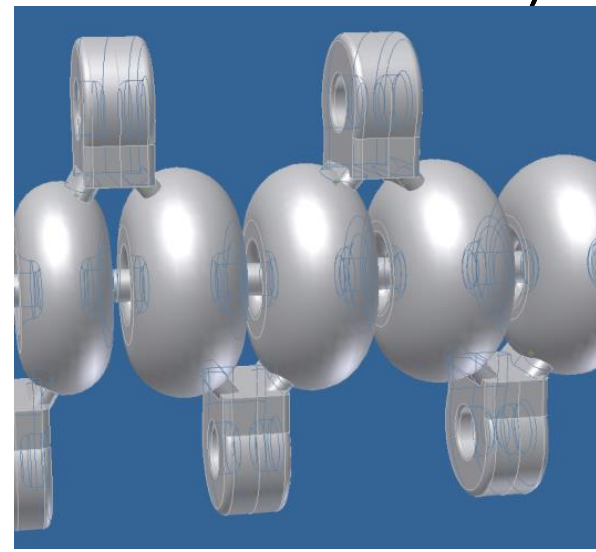
Closed gap makes focus field

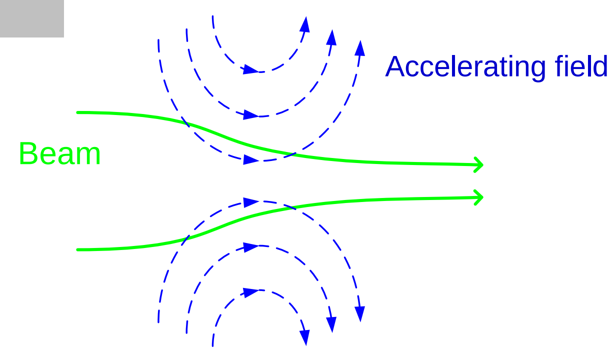
Side coupled cavity is one candidate (or DAW / ACS / CDS …)



Concentrated field has focusing effect

This structure has long drift space





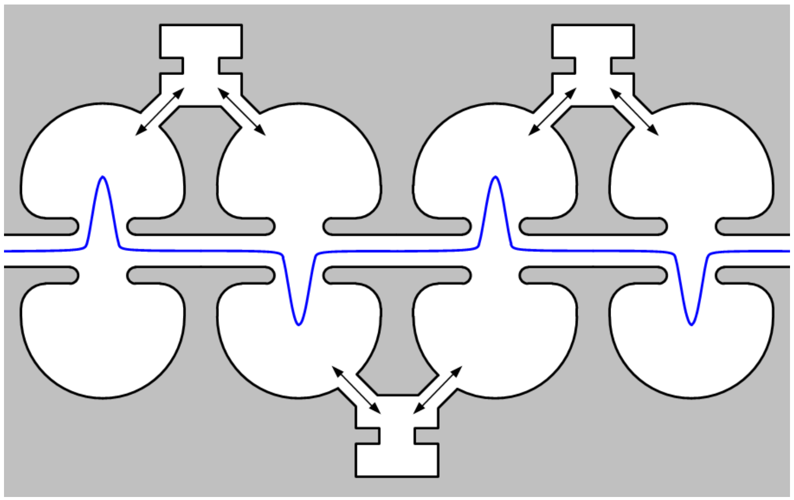
This structure has focusing field.

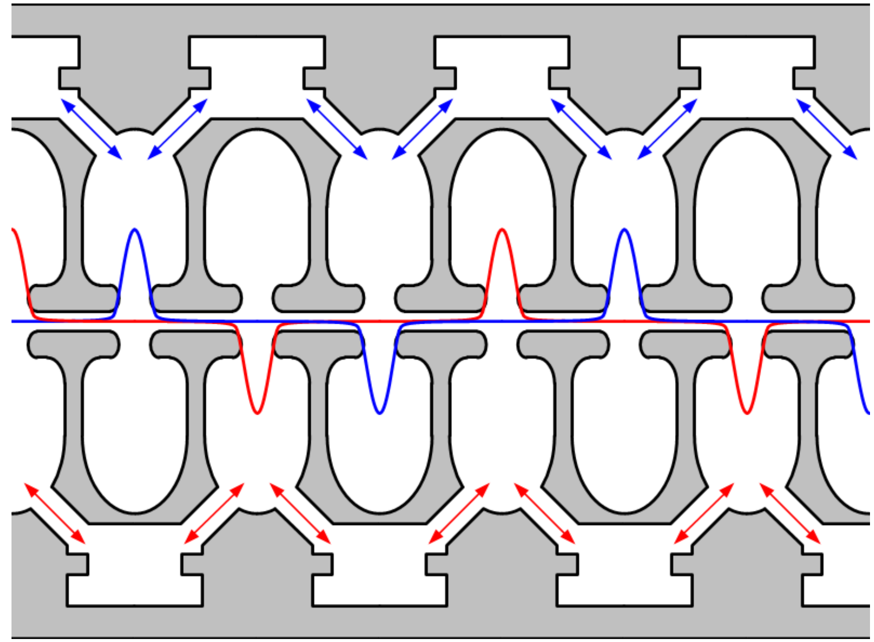
Long drift space is problem.

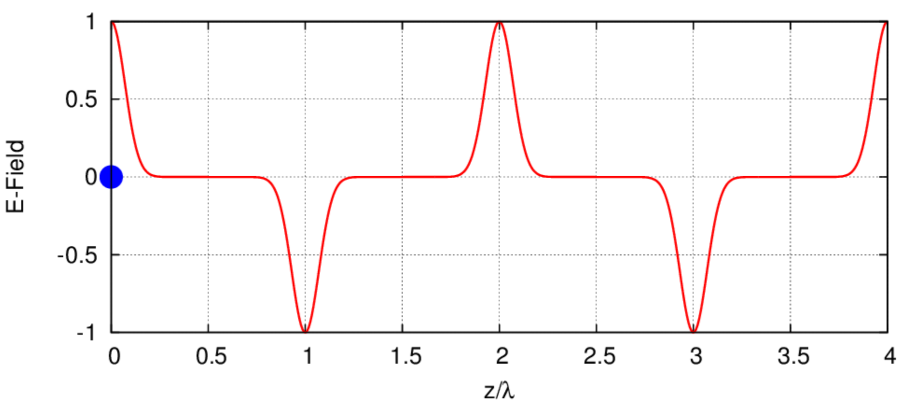
Design of a quasi traveling wave side couple RF gun

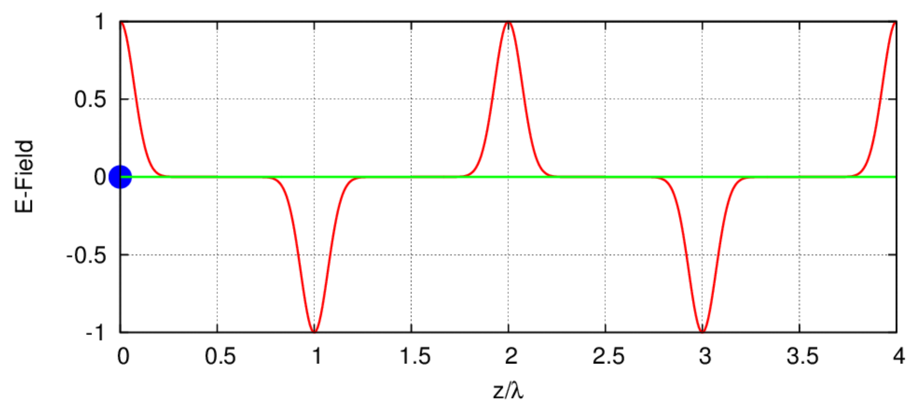
Normal side couple structure

Quasi traveling wave sidecouple structure





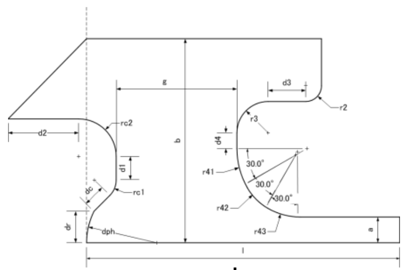




Quasi traveling wave side couple has stronger focusing field

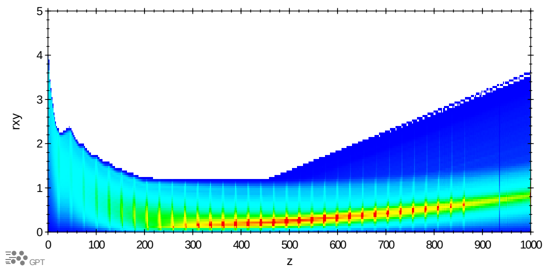
Quasi traveling wave side couple RF gun

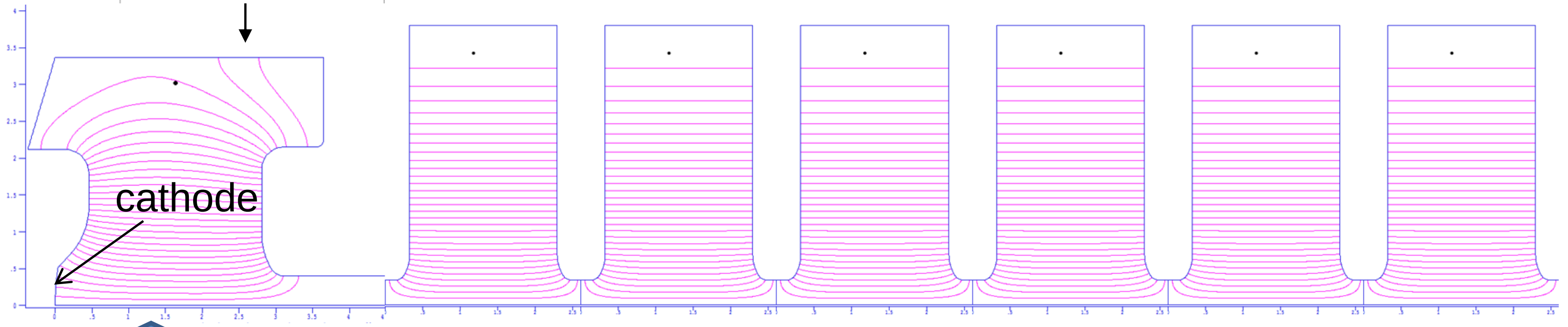
This RF gun has total of seven acceleration cavities. These are divided into two standing wave structure of 3 and 4 side coupled cavities respectively.



Cathode cell

To avoid beam defocusing, emittance growth and field concentration, a lot of parameters were searched for design.





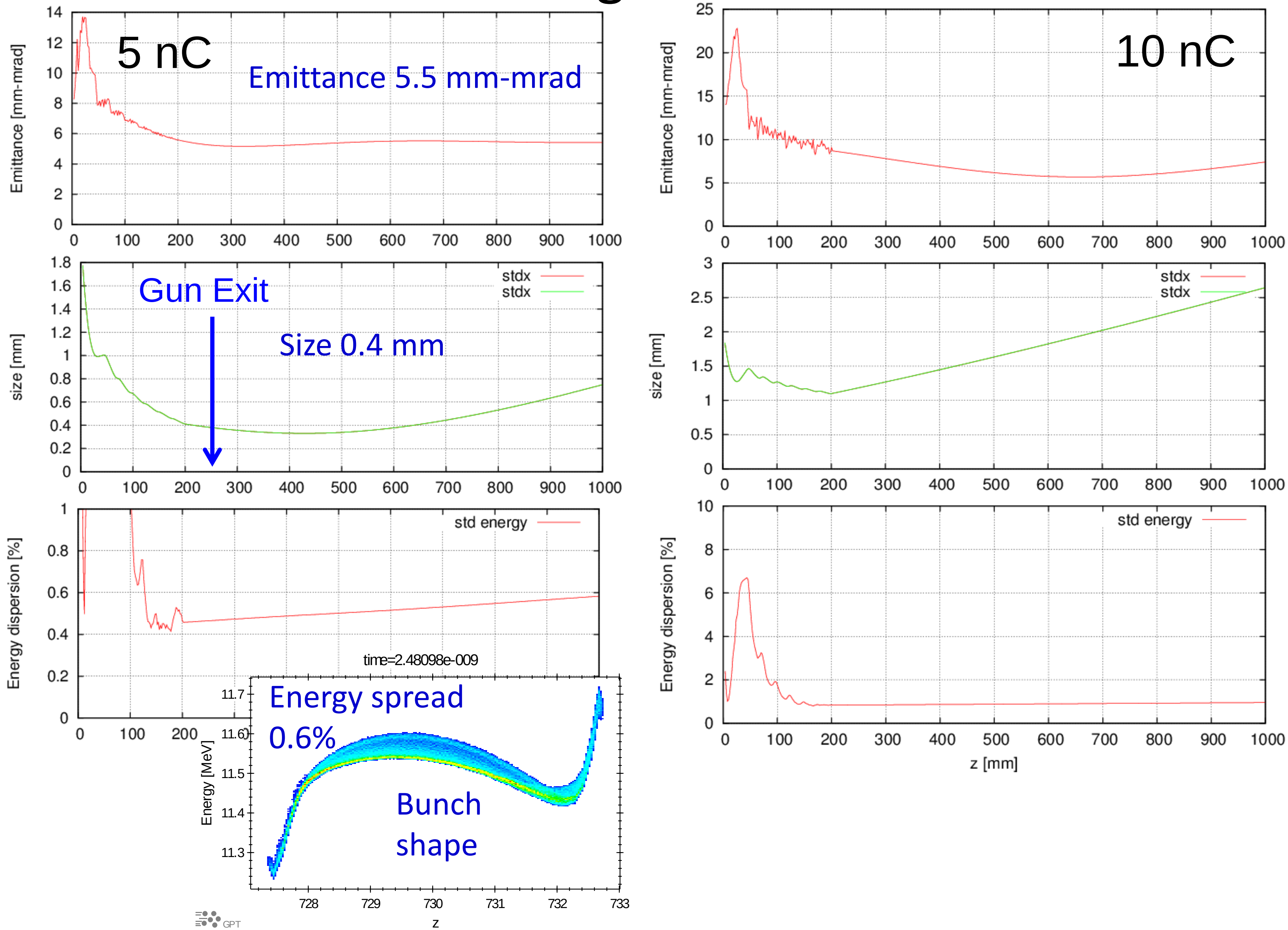
Maximum E-field at surface: 120 MV/m

Maximum E-field at surface: 100 MV/m

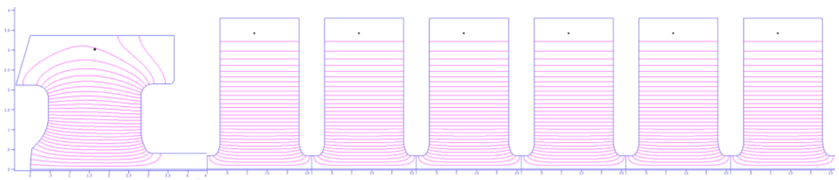
Emittance: 5.5 mm-mrad @ 5 nC

This RF gun can generate 10 nC beam

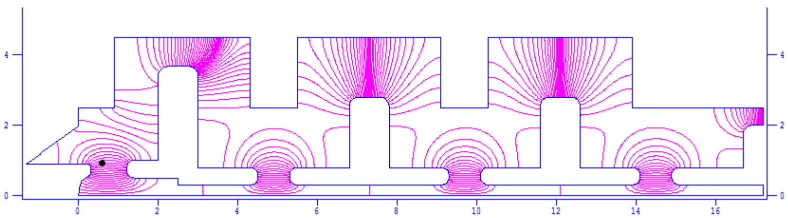
Beam tracking simulation result



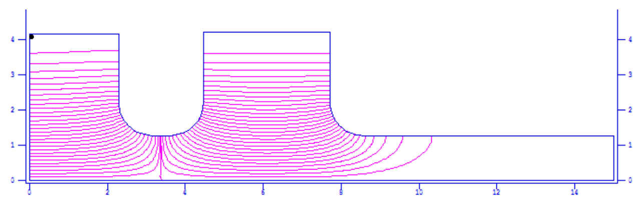
RF-Gun comparison



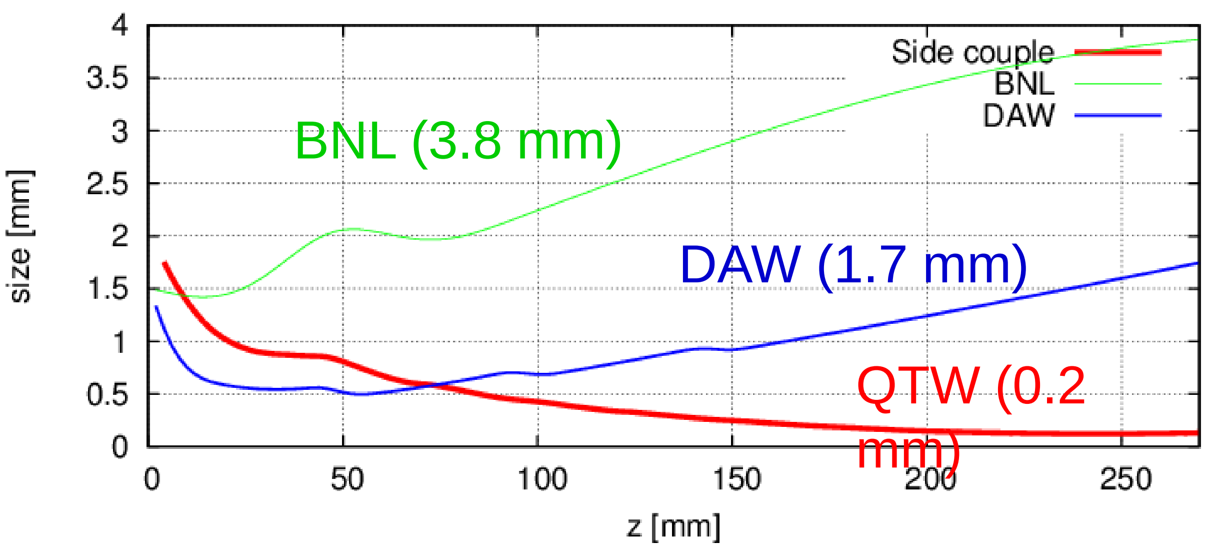
Quasi traveling wave side couple RF gun
(100 MV/m, 6mm-mrad, 13.5 MeV)



DAW-type RF gun
(90 MV/m, 5 mm-mrad, 3.2 MeV)

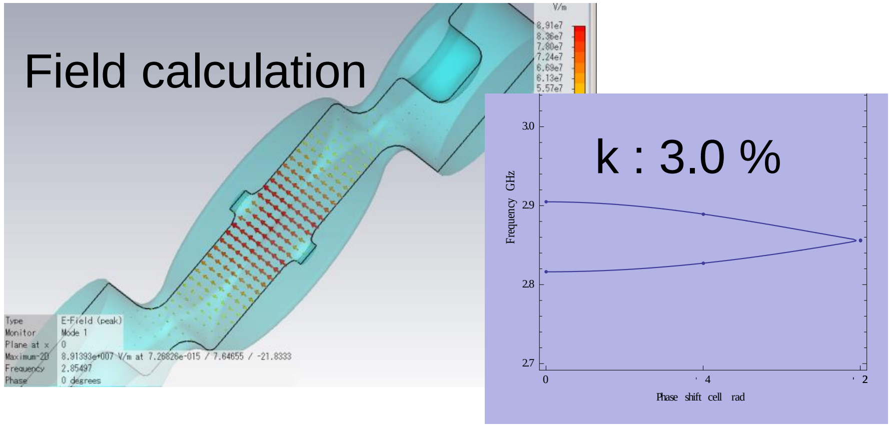


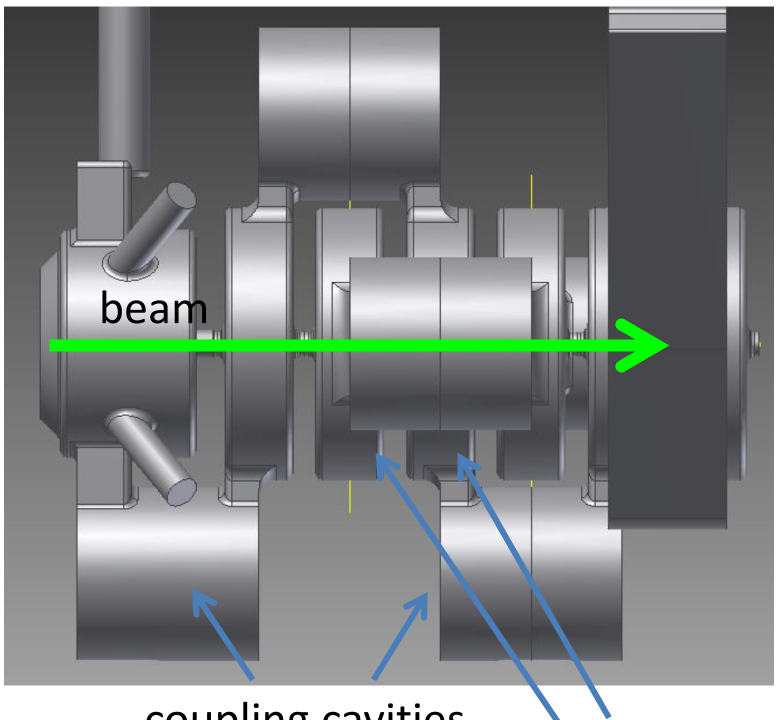
BNL-type RF gun
(120 MV/m, 11.0 mm-mrad, 5.5 MeV)

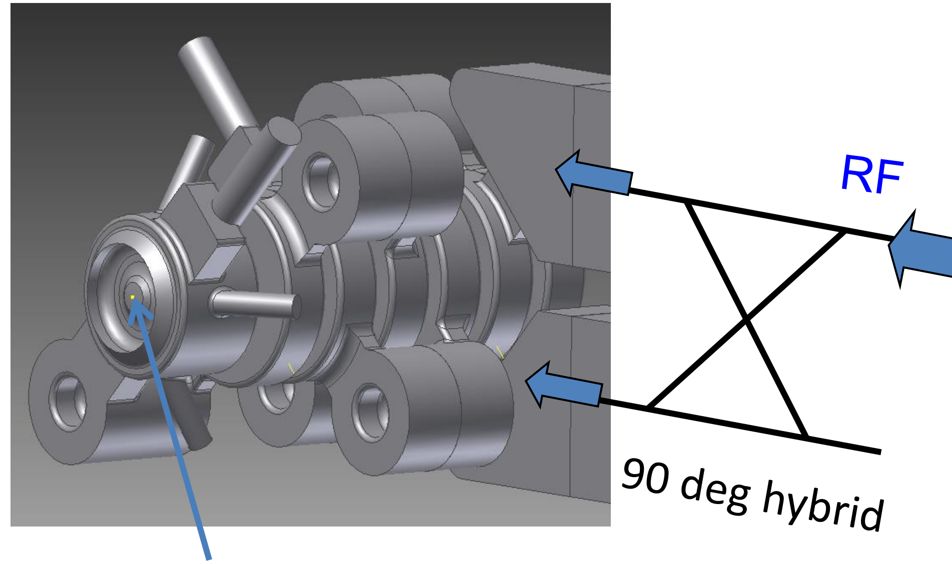


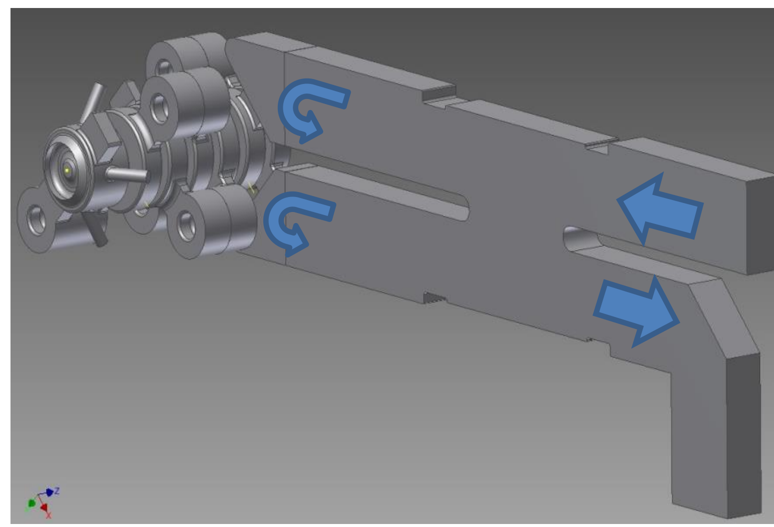
Beam Size

Cavity design



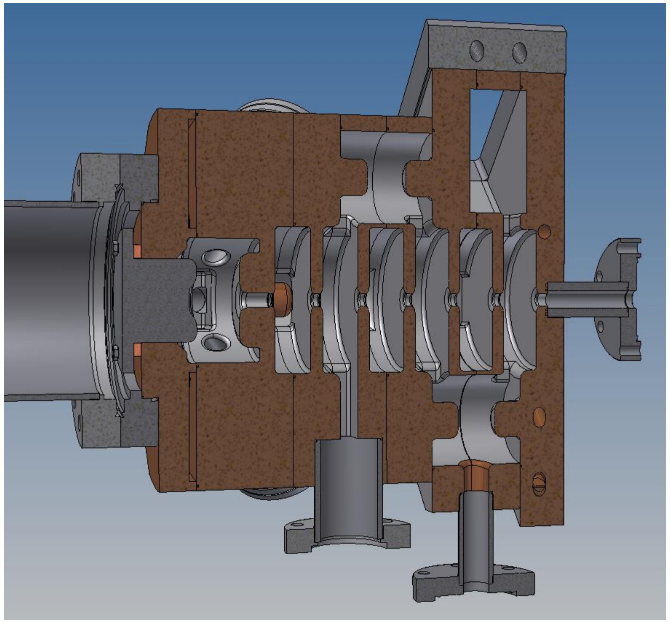


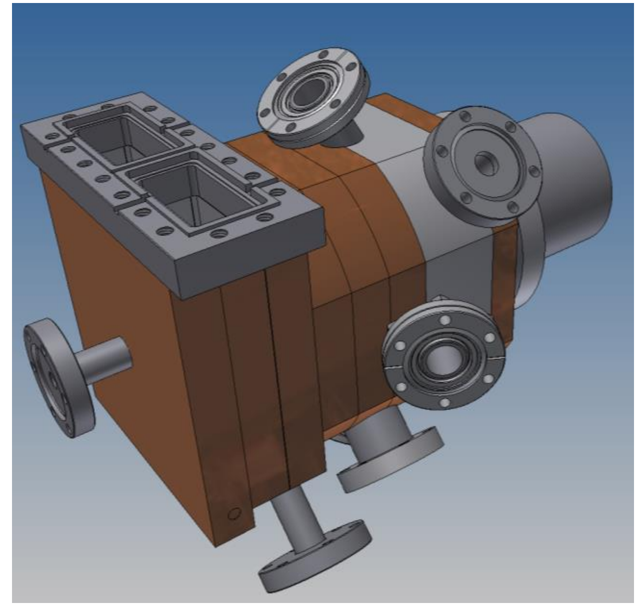


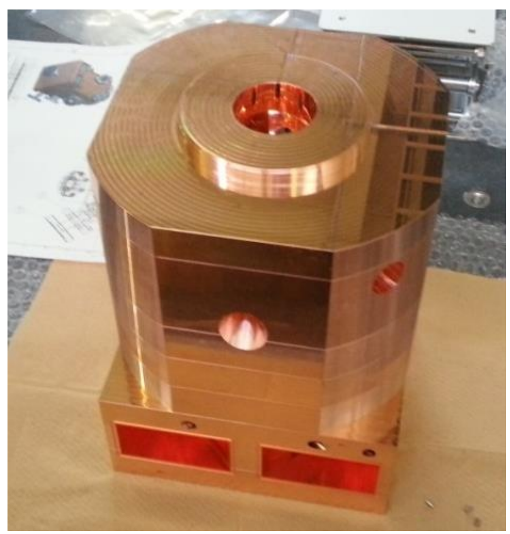


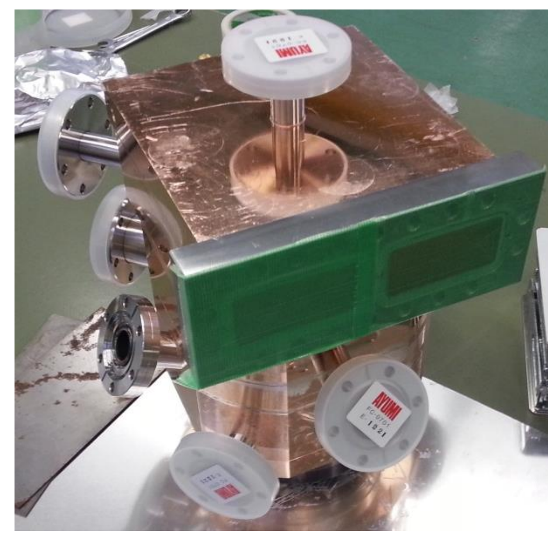
No reflection to klystron

Mechanical design and manufacturing



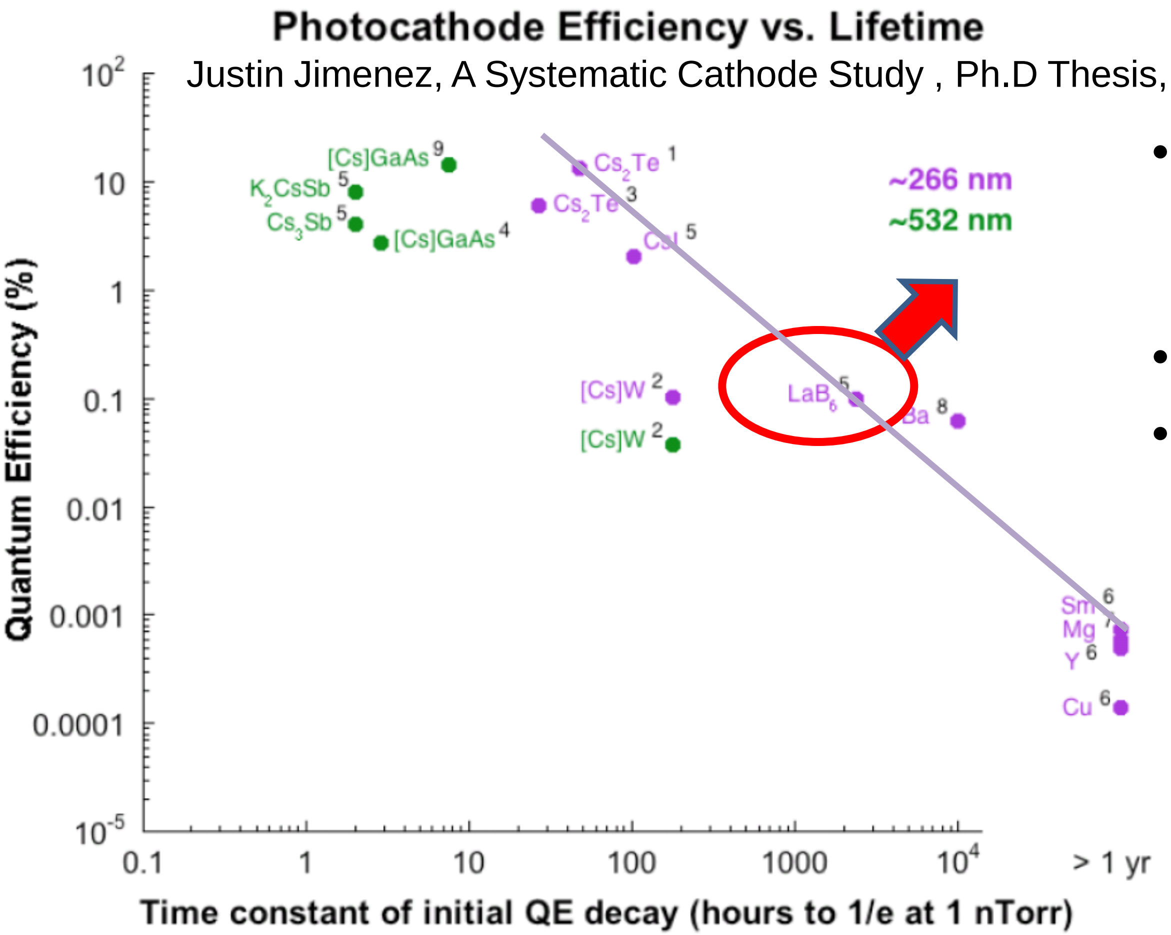






- RF-Gun
  - Design of RF-Gun cavity
  - **Cathode**
    - **Advantage of LaB6**
    - **Measurement equipment of quantum efficiency**
    - **Laser cleaning & Heat treatment**
  - Laser
  - Test stand and schedule

Cathode : Advantage of LaB_6 or Ir_5Ce



- Low Workfunction (2.8 eV) and enough QE (10^{-4}) at room temperature.
- Inactive in air
- Recover by heating or laser cleaning

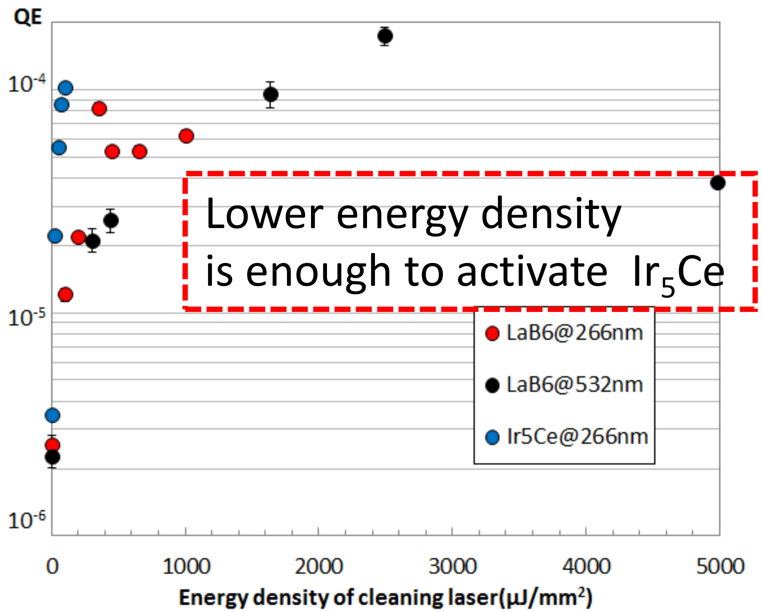
Best choice
for SuperKEKB 5 nC
long time operation

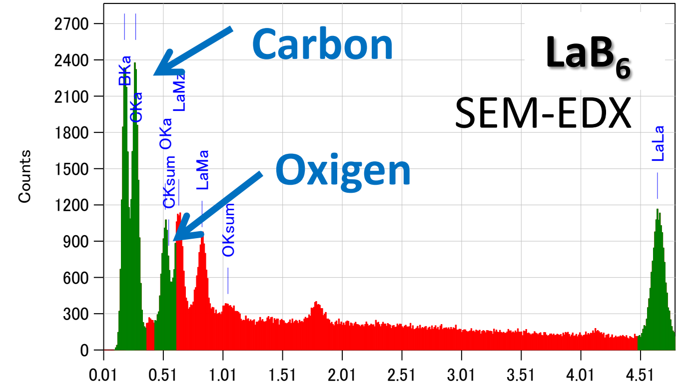
The thermocathodes can also be used as photoemitters [13]. LaB_6 should be noted as a promising photoemitter [14], which has a quantum yield of about 10^{-3} at a laser wavelength of 266 nm and $4 \cdot 10^{-4}$ at 532 nm for face (100).

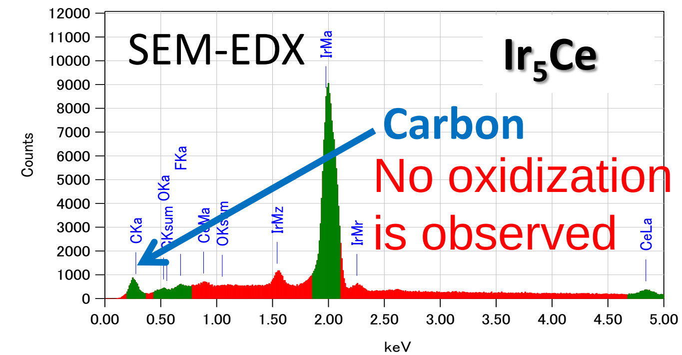
Physica Scripta. Vol. T71, 39-45, 1997.
Cathodes for Electron Guns
G. I. Kuznetsov

Ir_5Ce Cathode

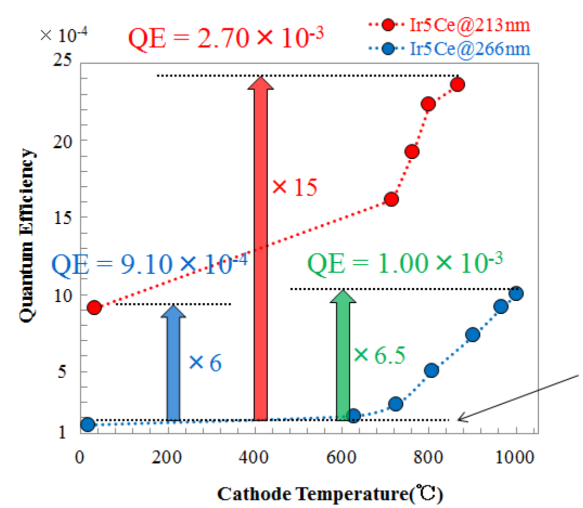
Quantum efficiency improvement by Laser cleaning



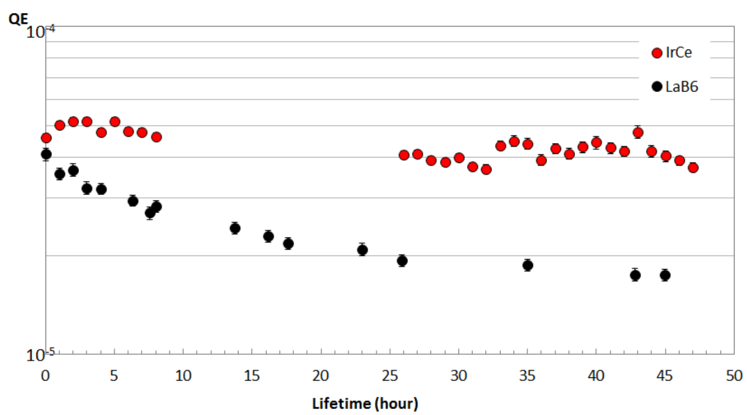




QE Enhancement of IrCe cathode



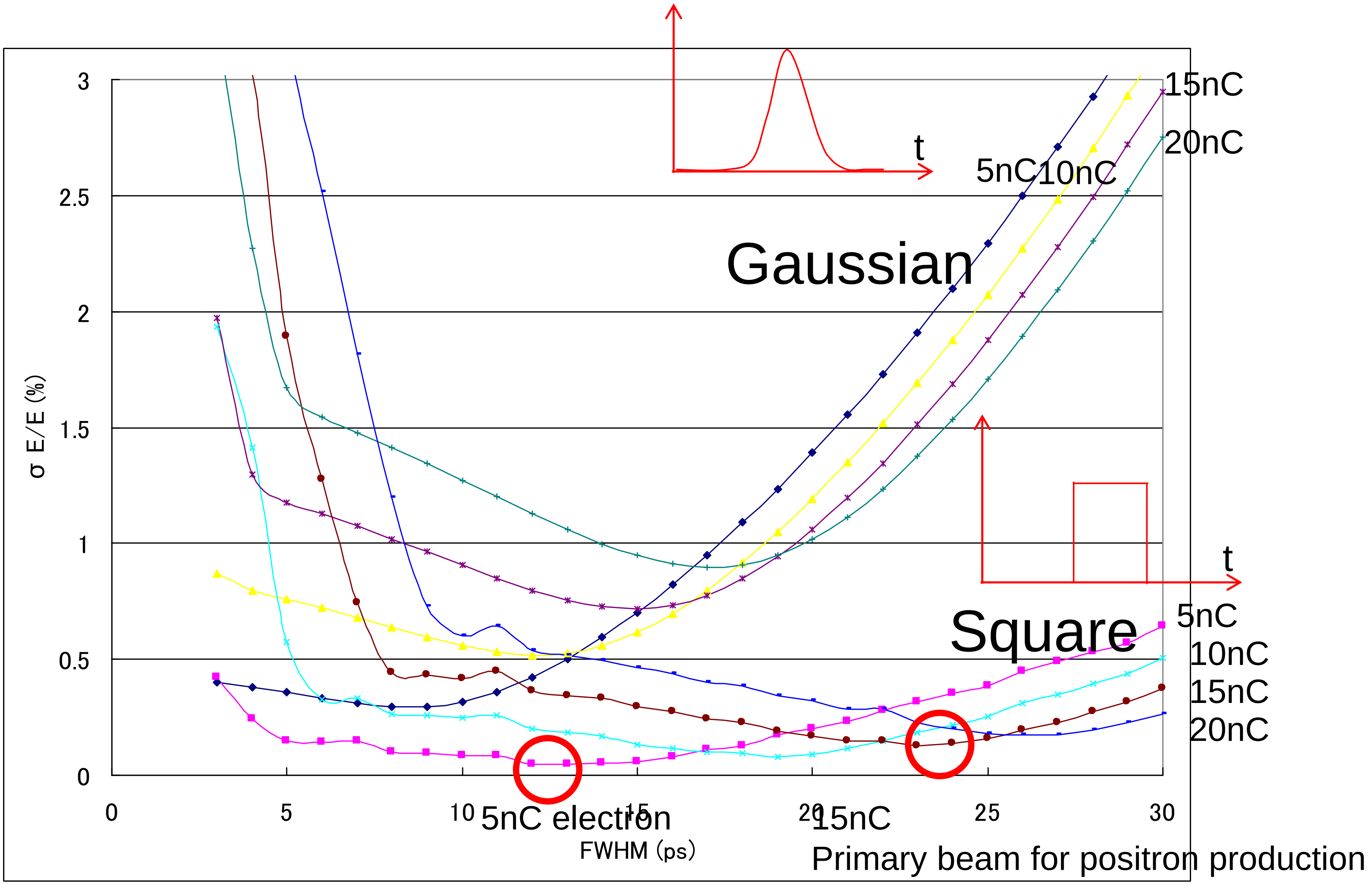
QE lifetime



- RF-Gun
  - Design of RF-Gun cavity
  - Cathode
  - **Yb Laser for spatial & temporal manipulation.**
  - Test stand and schedule

Energy spread reduction using temporal manipulation

Energy spread of 0.1% is required for SuperKEKB synchrotron injection.



Properties of laser medium

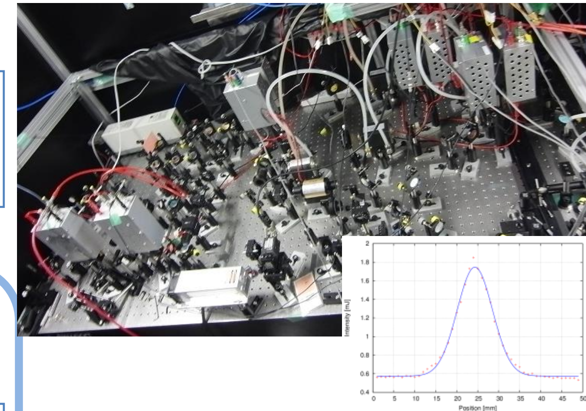
Nd-doped

○ 4-state laser is easy to operate.
○ High power pump LD is available.
○ Large crystal is available
× Pulse width is determined by SESAM. (Gaussian)

τ～200μs, 40%

LD Pump (808nm) → 808nm → Nd:YVO4 / Nd:YAG → 1064nm → SHG(532nm) 40%, FHG(266nm) 20%, 5HG(213nm) 3%

Nd laser system for 3-2 RF-Gun



Yb-doped

○ Wide bandwidth => pulse shaping
○ Long fluorescent time => High power
○ Fiber laser oscillator => Stable
○ Small state difference
× ASE
× Absorption

τ～900μs, 40%

LD Pump (941/976nm) → 941/976nm → Yb-glass / Yb:YAG / Yb:BOYS → 1040nm → SHG(520nm) 40%, FHG(260nm) 20%, 5HG(208nm) 3%

→ Best for RF-Gun

Ti-doped

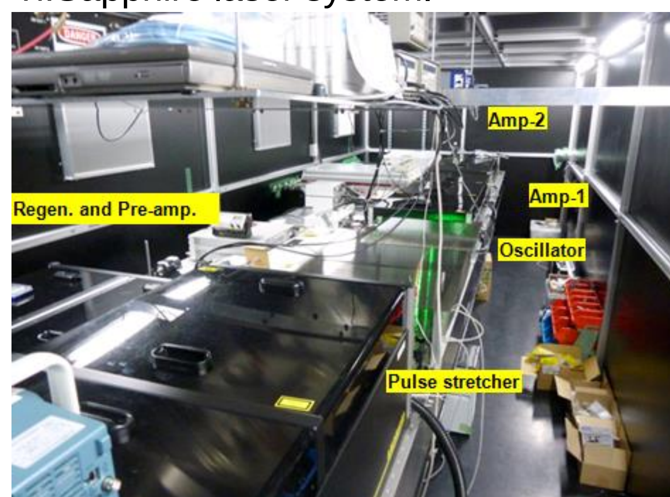
Pump: **τ=200μs, 40%**

Pump (808nm) → 808nm → Nd:YAG → 1064nm → SHG **40%** → 532nm → Ti:Sapphire (**τ～3μs, 40%**) → 800nm → SHG(400nm) 40%, THG(266nm) 20%, FHG(200nm) 10%

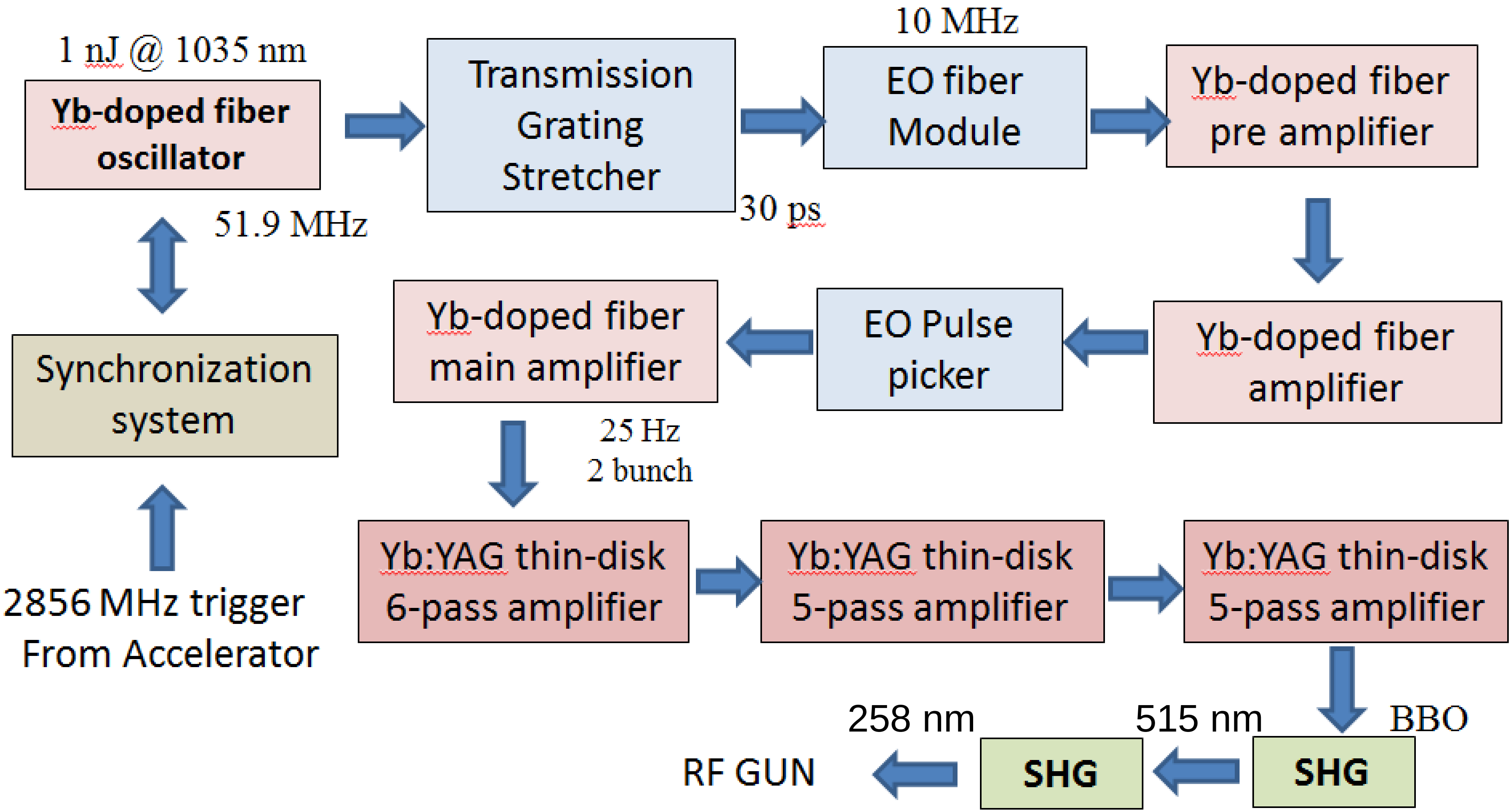
○ Very wide bandwidth
○ High breakdown threshold } TW laser is based on Ti-Sapphire
× Low cross section }
× Short fluorescent time => Q-switched laser is required for pumping

	Material	Nd:YAG	Yb:YAG	Ti:Sapphire
Fluorescence	Wavelength	1064nm	1030nm	660−1100nm
	Fluorescent time	230μs	960μs	3.2μs
	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%

Ti:Sapphire laser system.

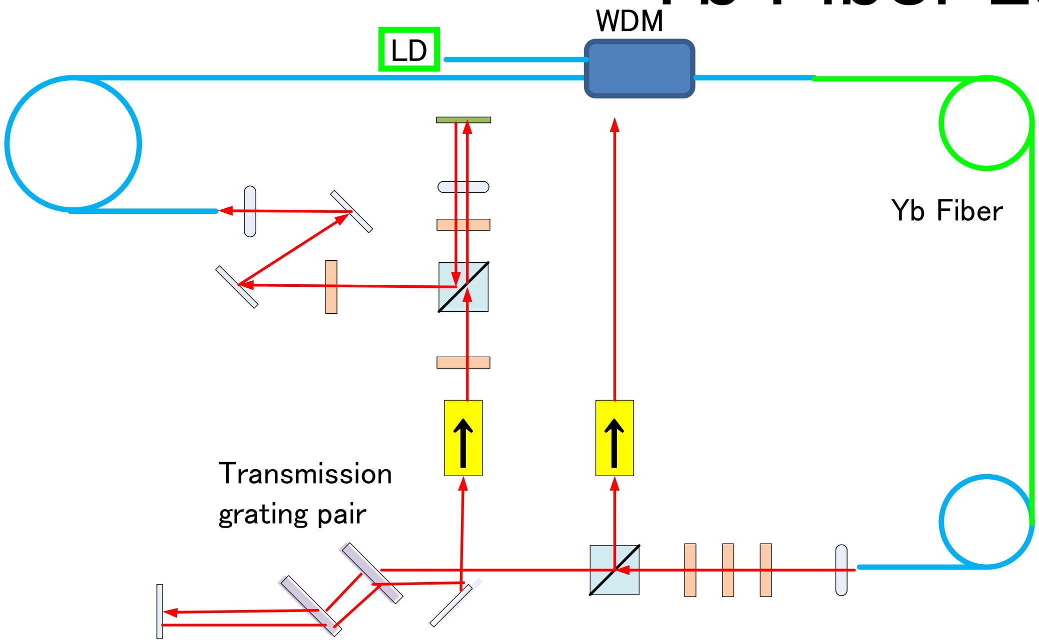


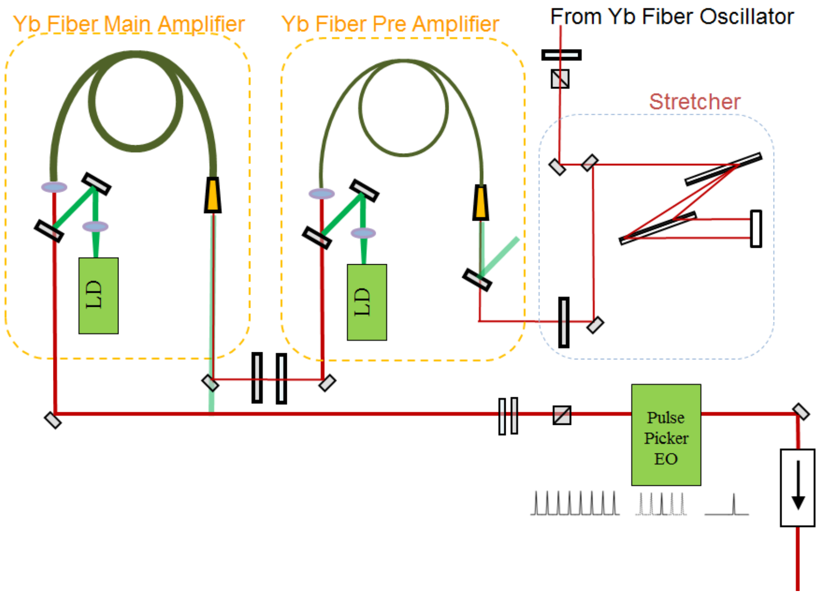
Yb fiber & thin disk hybrid laser system

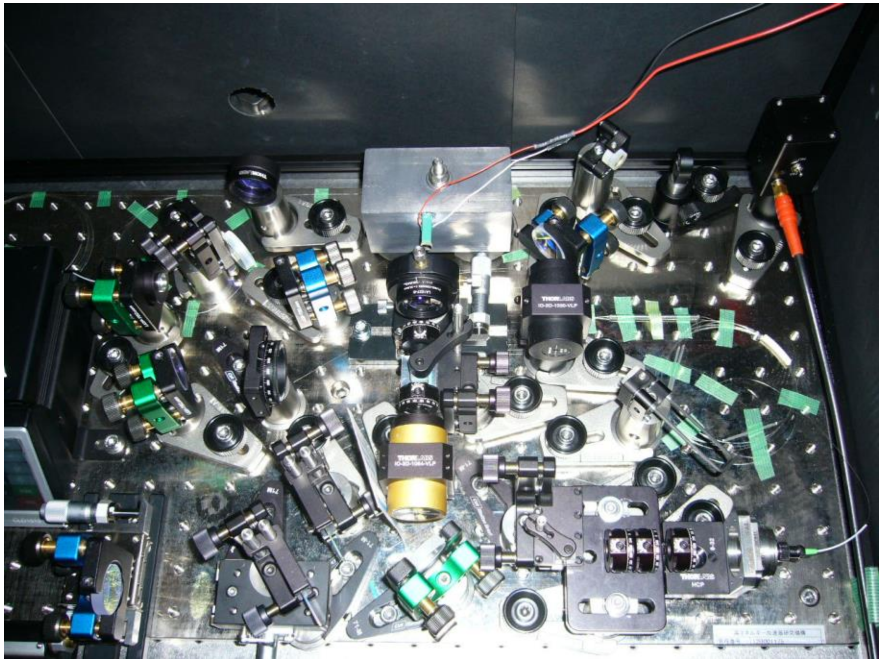


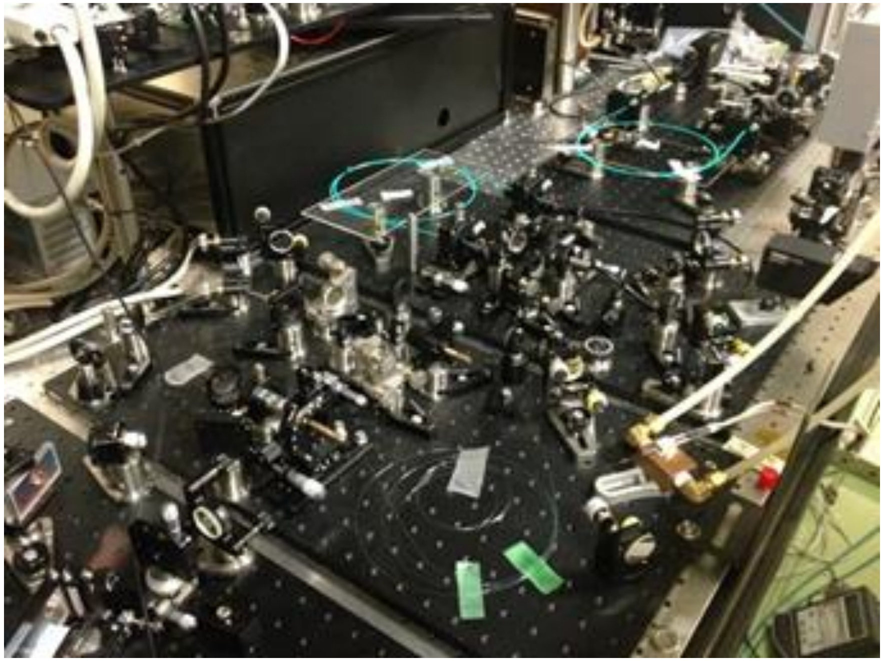
QE = 10^{-4} ➡ A few mJ @ 258nm, 50Hz is required.

Yb Fiber Laser



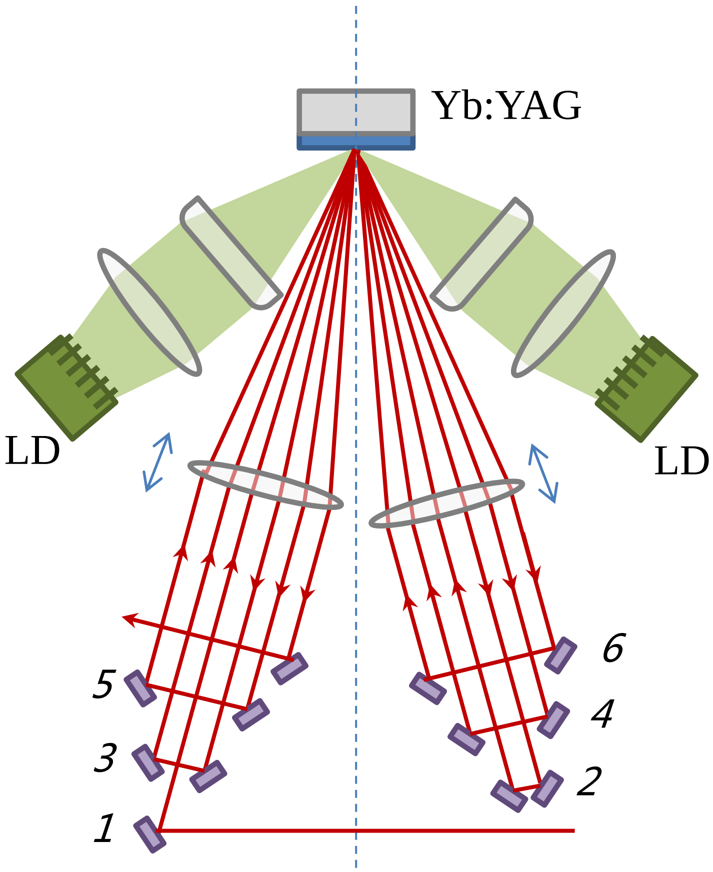






Thin-disk multi-pass amplifier

- 0.5 mmt Yb:YAG thin-disk
- 3-stage 4-6 multi-pass amplifier



SHG+FHG → A few mJ @ 258nm

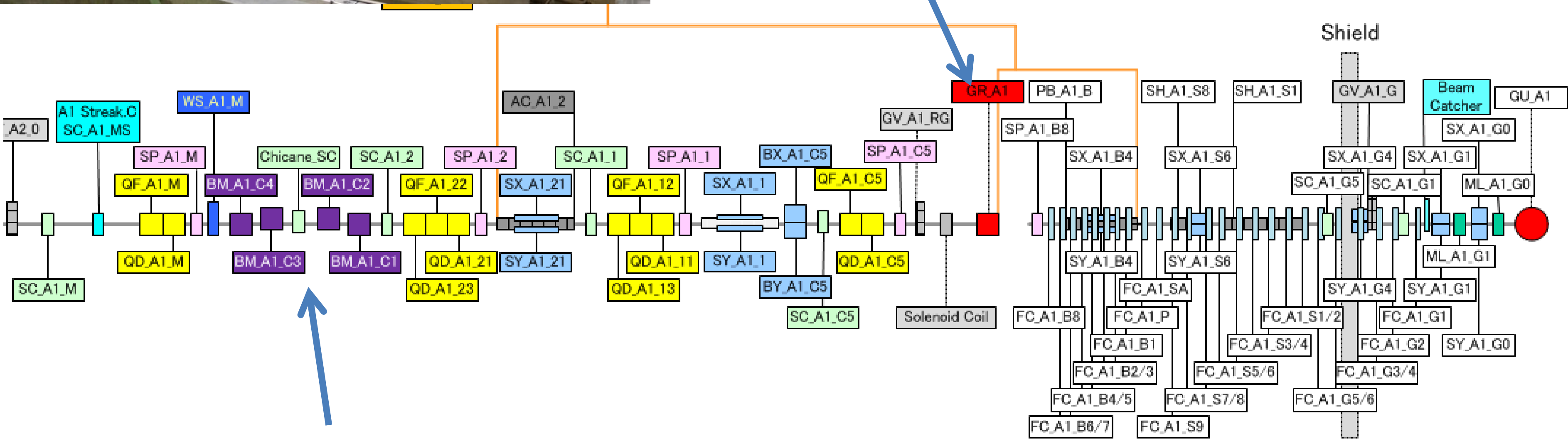
- RF-Gun
  - Design of RF-Gun cavity
  - Cathode
  - Laser
  - **Test stand and schedule**
    - **3-2 RF-Gun for preliminary test & PF injection**
    - **A-1 RF-Gun**

A-1 RF gun

- Quasi-travelling wave side couple RF-Gun
- Yb based laser system

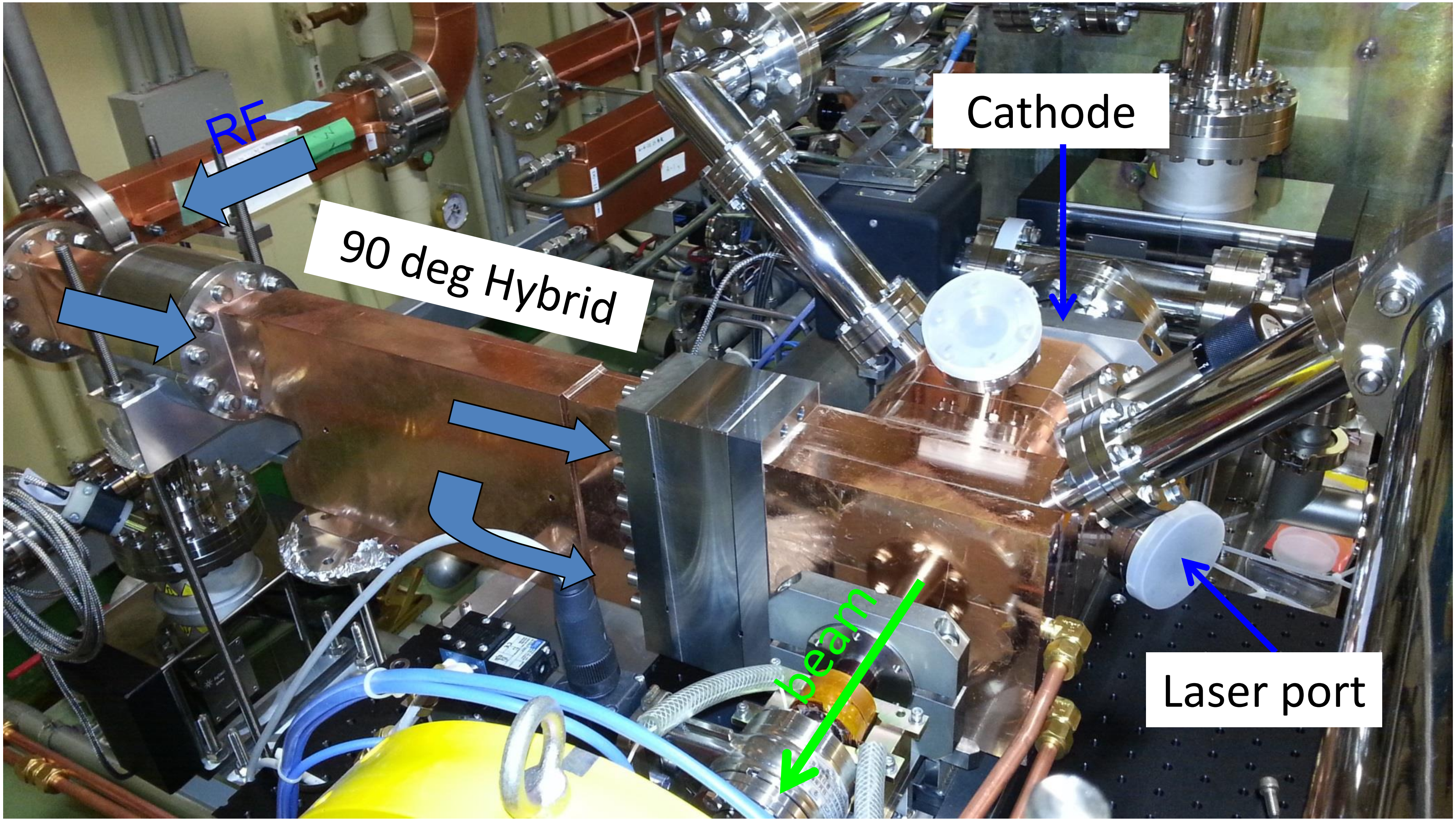
Existing DC-Gun & pre-bunche

Installed RF-Gun



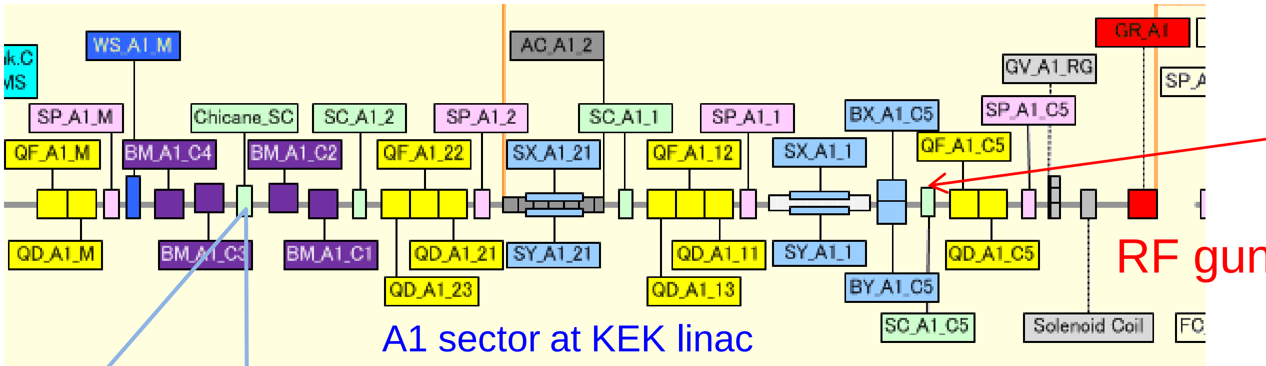
Chicane for bunch compression
30ps => 10ps

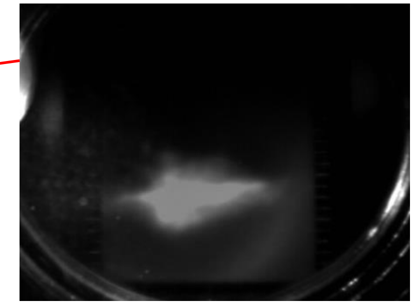
Installed RF gun

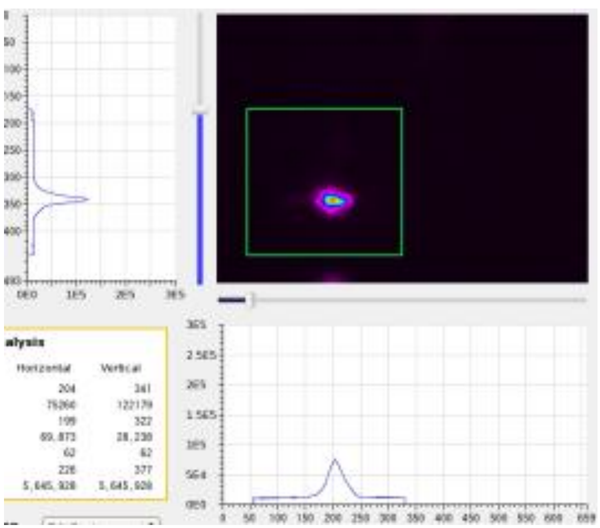


A-1 RF gun results

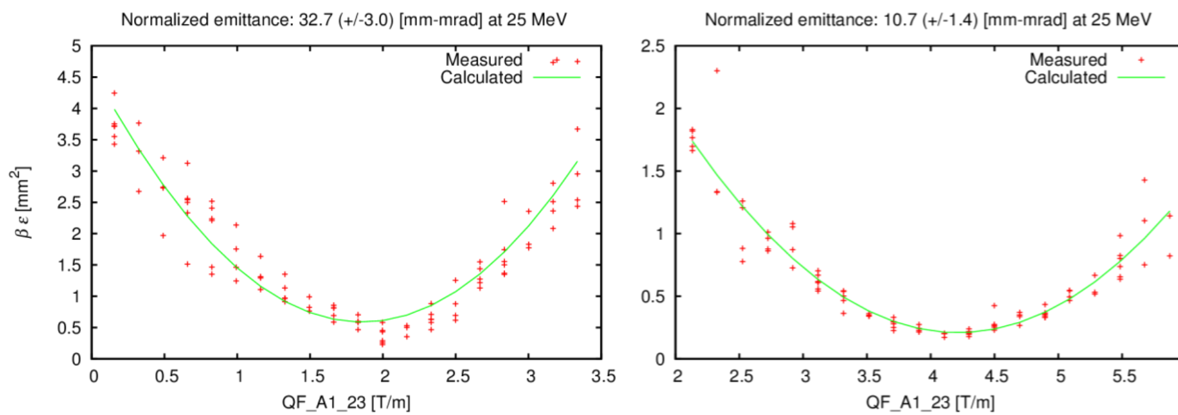
5.6 nC bunch charge was observed.







beam size measurement for Q-scan



Q-scan emittance measurement

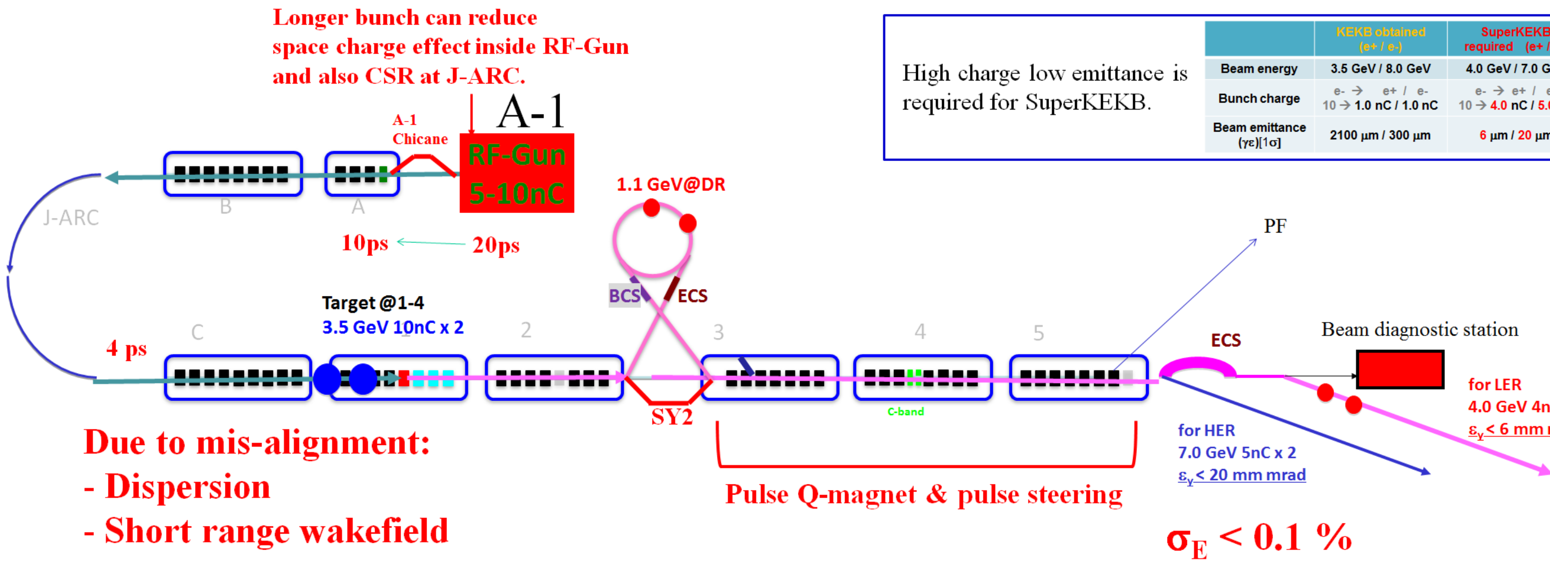
x	y
32.7 ±3.1 mm-mrad	10.7 ±1.4 mm-mrad

Emittance preservation

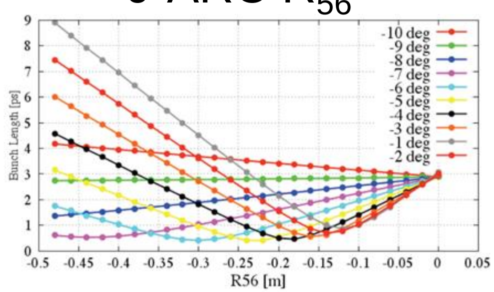
Emittance preservation

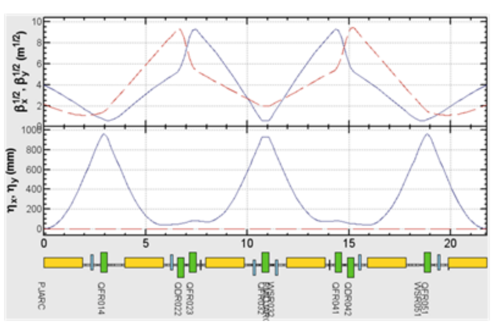
High charge low emittance is required for SuperKEKB.

	KEKB obtained (e+ / e-)	SuperKEKB required (e+ / e-)
Beam energy	3.5 GeV / 8.0 GeV	4.0 GeV / 7.0 GeV
Bunch charge	e- → e+ / e- 10 → 1.0 nC / 1.0 nC	e- → e+ / e- 10 → 4.0 nC / 5.0 nC
Beam emittance (γε)[1σ]	2100 μm / 300 μm	6 μm / 20 μm

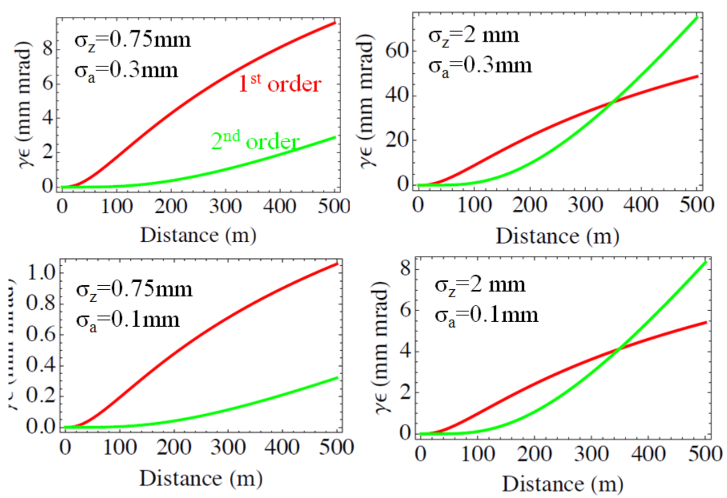


J-ARC R_{56}

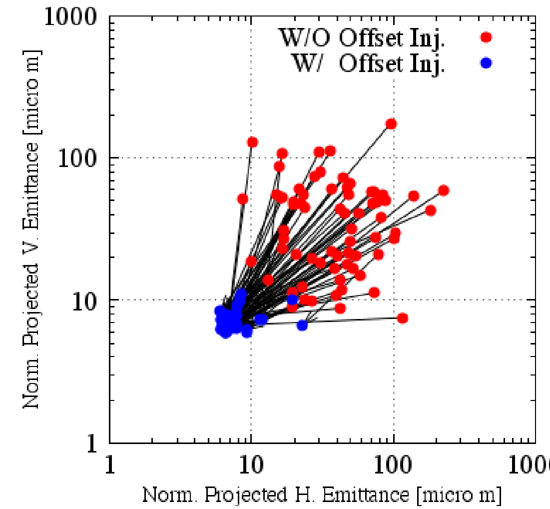




Emittance growth after 500 m

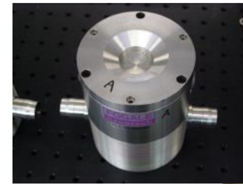


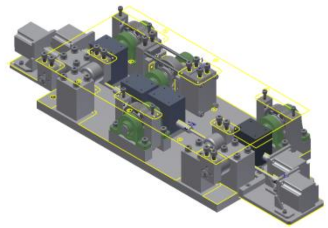
Initial offset

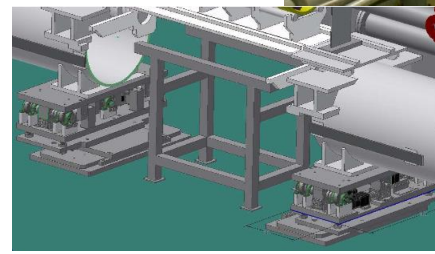


Hardware for emittance preservation

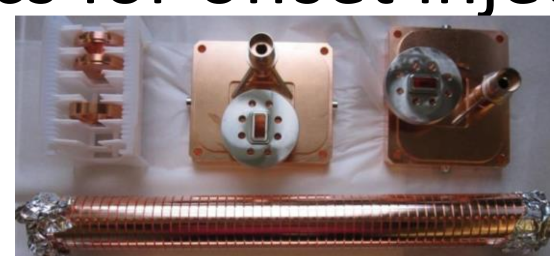
- Alignment
  - Continuous monitor (HLS, Wire)
    + Active mover





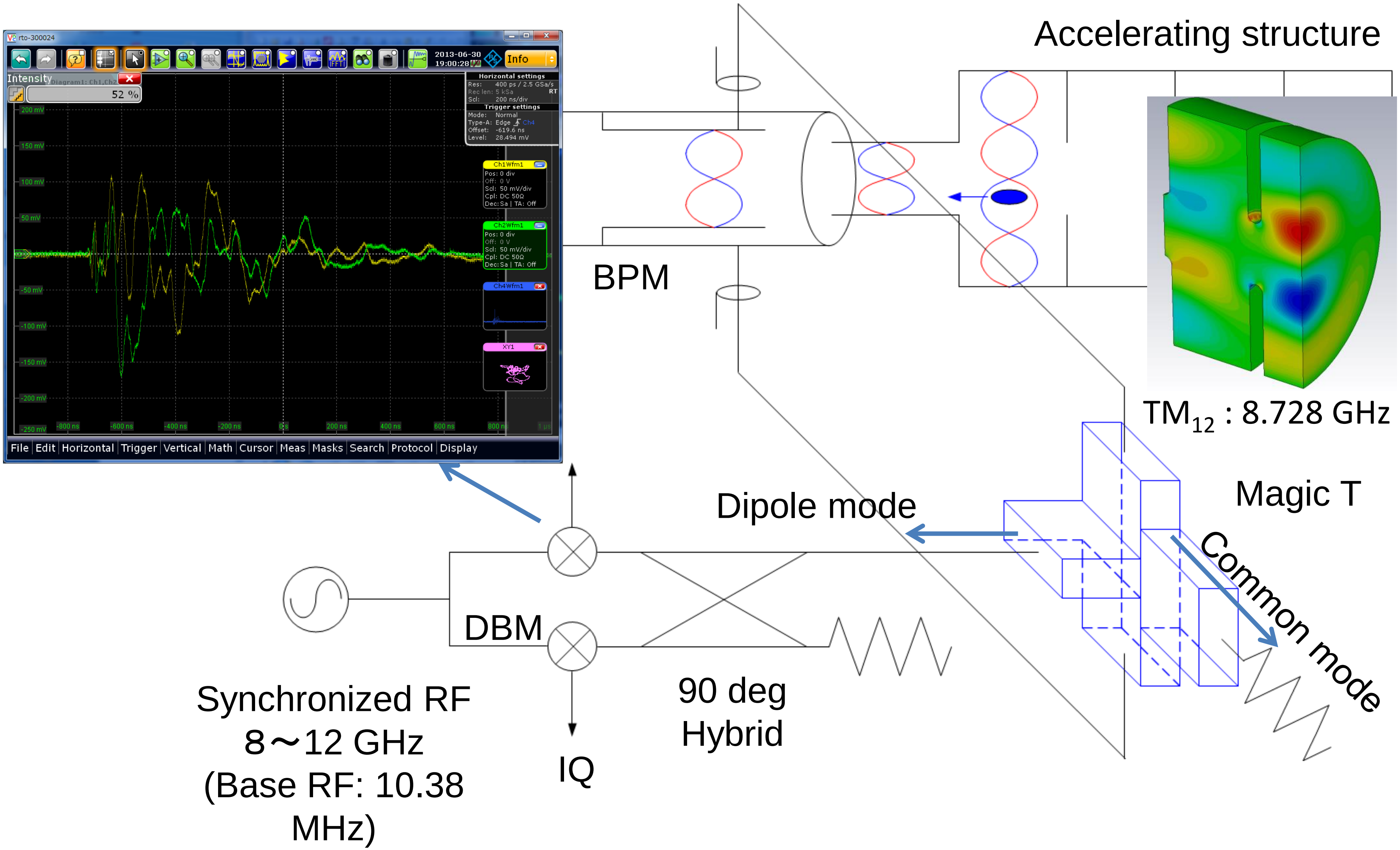


  - Beam based alignment
    (Higher mode measurement)
- Temporal manipulation
  - Laser pulse shaping
  - Bunch compression
- Beam diagnostics for offset injection
  - RF Deflector



Developed by SLAC

Preliminary test for higher order transverse wakefield from accelerating structure.



Summary

- RF-Gun cavity
  - **Quasi travelling wave side couple structure**.
- Cathode
  - Room temperature **Ir_5Ce** cathode has enough QE.
  - Laser cleaning & laser injection angle is effective.
  - R&D for the QE improvement.
- Laser & control
  - **Yb based laser system : A-1 RF-Gun**
    - **Yb-fiber :** Precise RF synchronization.
    - Yb-disk amplifier: High power output.
    - Temporal manipulation Under experiment.
  - Stability / Control: Improved but not enough.
- RF gun comissioning
  - 5.6 nC bunch charge was generated by this RF gun.
- Emittance Preservation
  - Alignment / Bunch compression / Monitor etc.