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Deflecting Cavity Development for Project-X

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Project X

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Project X missions

Concurrent

- Long-Baseline
  Neutrino Experiment: 2 MW at 60-120 GeV
  - well understood beam requirements;
  - it will be supported in any configuration we select.
- Rare Processes: ≥ several 100's kW at 2.x – 8 GeV
  - well understood beam requirements for this mission. 4^{th} Project X Physics Workshop (Nov 2009)
- NF/MC Platform: upgradable to 4 MW at 5 – 15 GeV
  - MC beam requirements are (x~10) harder than NF;
  - High on our "radar screen" but is not a driver;
  - Do not need to have it on day 1 of initial program; need to demonstrate a plausible path.

Status of Project X

- Project X is currently in the R&D phase awaiting CD-0 approval
  - DOE is funding a vigorous R&D program, emphasis on SRF
- Recently we examined several possible "Initial Configurations" of the machine. Goal: Deliver the largest Physics "bang for the buck" !
- All versions provide 2 MW of beam power to LBNE
- ICD-1 was based on a pulsed 8 GeV 20 ma ILC-like H^- linac
  - Excellent choice for the neutrino mission
  - Problematic for the study of rare processes (duty factor)
- ICD-2 employs a 3 GeV 1 mA CW linac that accelerates H^- or P's
  - Provides an additional 2-3 MW to the high intensity program
    - High duty factor & flexible beam manipulation via RF separators
  - 3-8 GeV = <u>either</u> a pulsed linac or a rapid cycling synchrotron.
- ICD-2 is currently the focus of our R&D efforts

- Identified optimum energies and beam structure required for various proposed rare decay programs
- Led us to increase CW beam energy to 3 GeV (was 2 GeV)

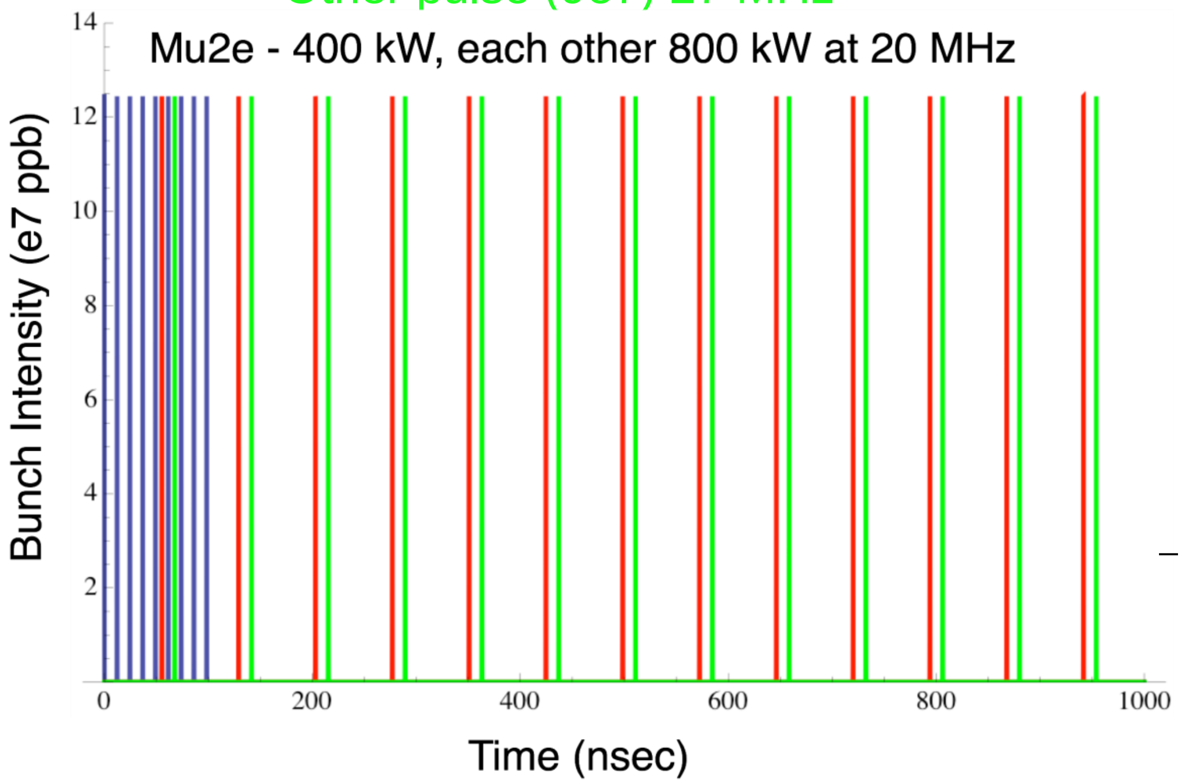
	Proton Energy (kinetic)	Beam Power	Beam Timing
Rare Muon decays	**2 – 3 GeV**	**> 500 kW**	**1 kHz – 160 MHz**
Precision K^0 studies	**2.6 – 3 GeV**	**> 200 kW**	**20 – 160 MHz (< 50 psec pings)**
Rare Kaon decays	**2.6 – 4 GeV**	**> 500 kW**	**20 – 160 MHz (< 50 psec pings)**
(g-2) measurement	**8 GeV**	**20 – 50 kW**	**30 - 100 Hz**
Neutron and exotic nuclei EDMs	**1.5 – 2.5 GeV**	**> 500 kW**	**> 100 Hz**

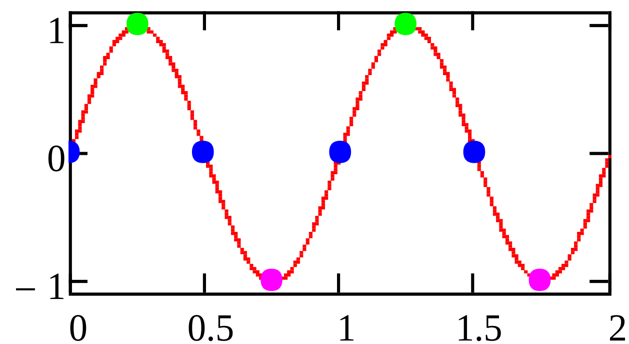
Bunch Structure

High bandwidth chopper ➔ select which RF cycle to fill with beam

1 msec period at 3 GeV

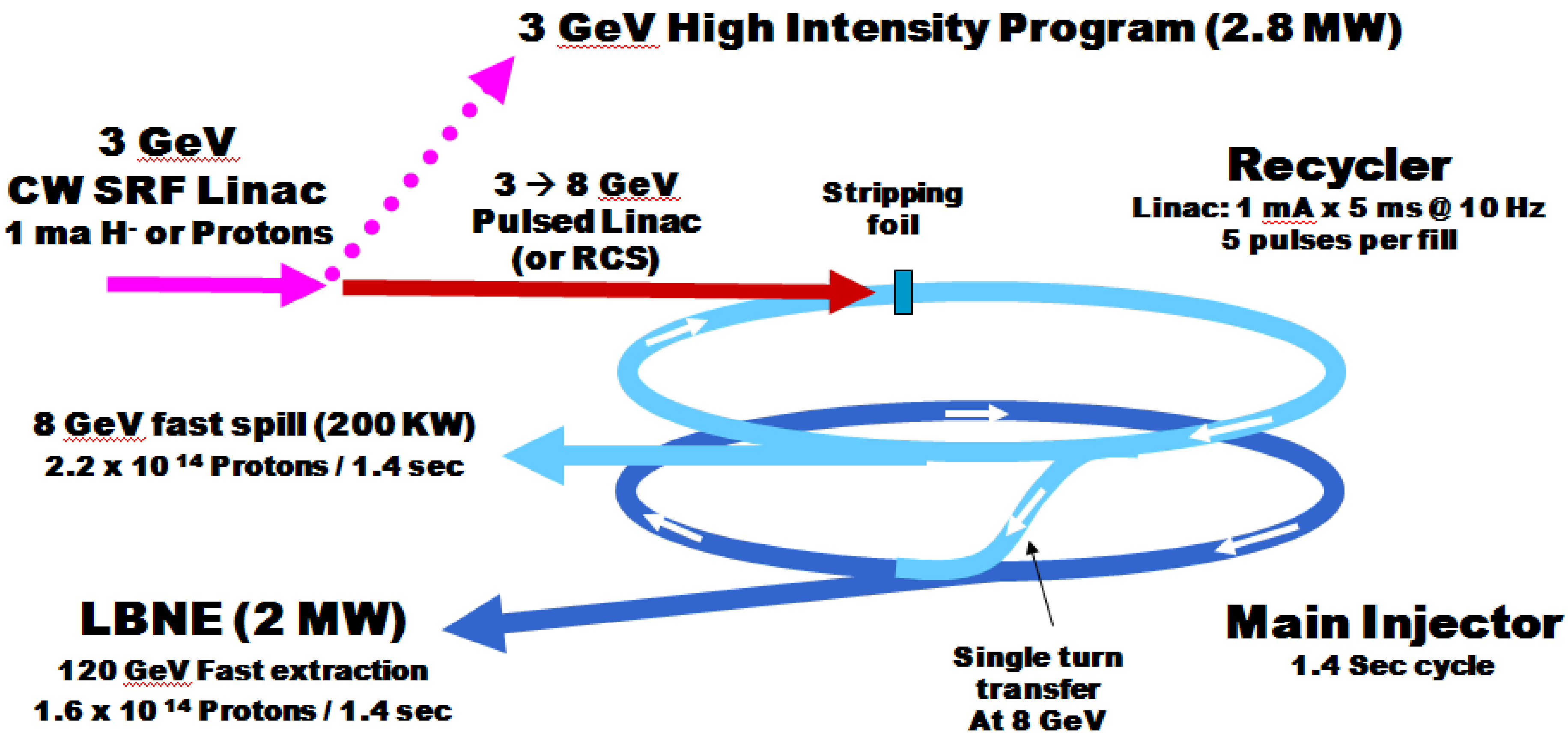
mu2e pulse (9e7) 162.5 MHz, 100 nsec	400 kW
Kaon pulse (9e7) 27 MHz	800 kW
Other pulse (9e7) 27 MHz	800 kW





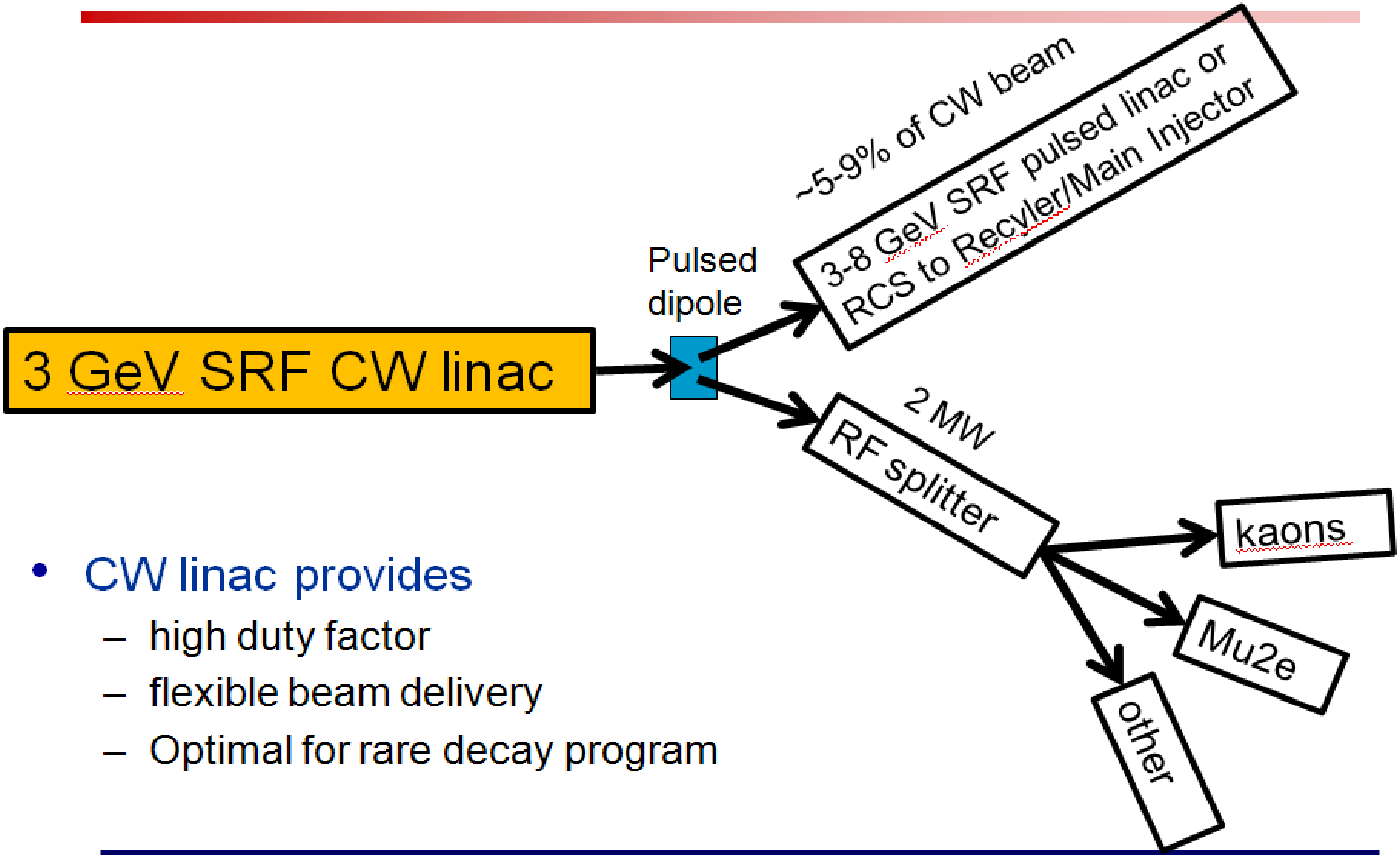
ICD-2 Layout

Project X



3-8 GeV linac would be 1300 MHz pulsed → retains synergy with ILC R&D but long pulse R&D needed

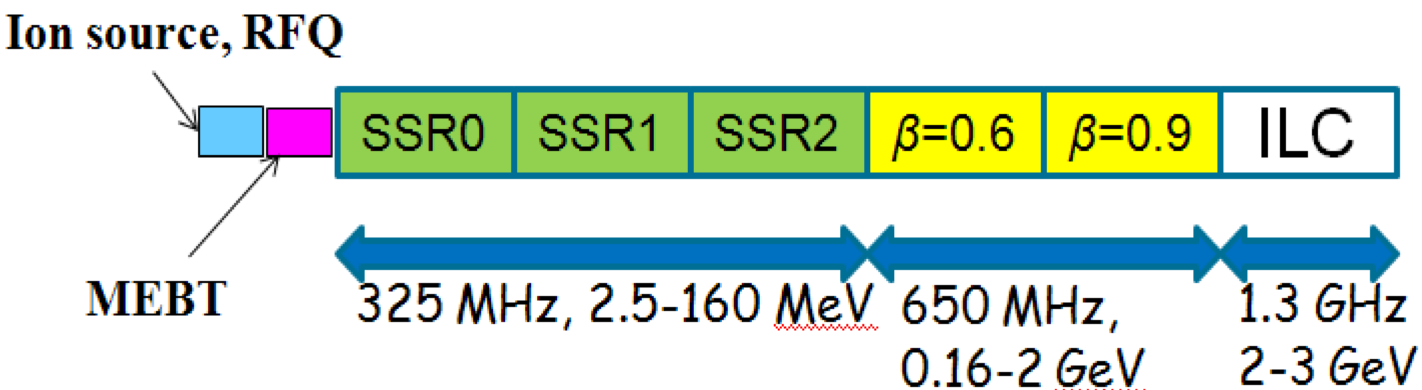
3 GeV SRF CW linac



- CW linac provides
  - high duty factor
  - flexible beam delivery
  - Optimal for rare decay program

3 GeV CW Linac

- Design based on 3 families of 325 MHz Spoke resonators, two families of 650 MHz elliptical cavities, then 1300 MHz ILC cavities



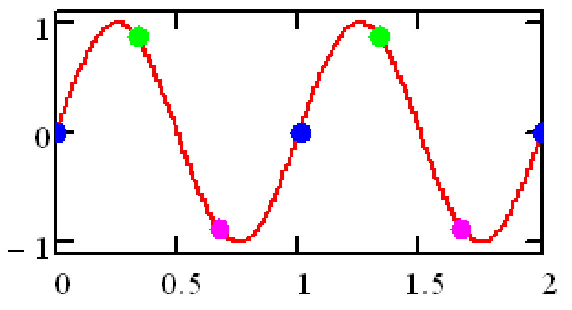
Note: 650 MHz, β=0.9, 5-cell cavities are same physical length as 1300 MHz, β=1.0, 9-cell cavities

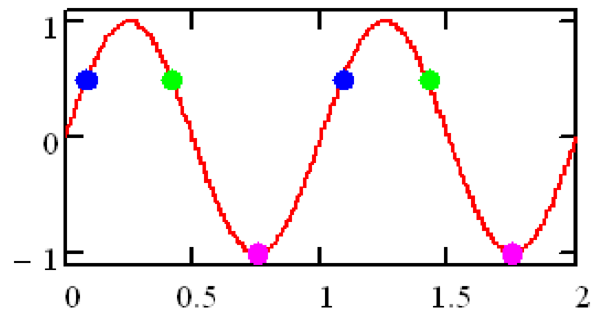
RF separation

- One RF separator can split linac beam into 2 or 3 beams
  - 3-rd sub-harmonic splitter - splits beam in 3 equal beams (CEBAF like)

    $f_b = 162.5$ MHz

    $f_{exp} = f_b/3 \approx 54$ MHz



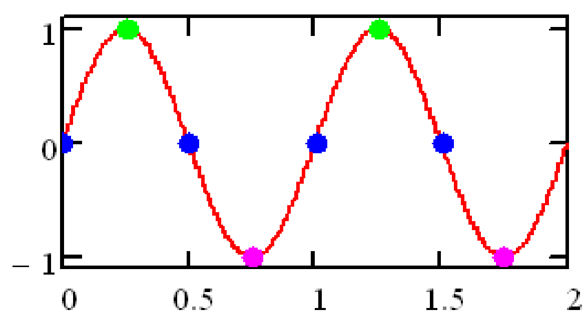


  - 4-th sub-harmonic splitter – one of 3 beams has twice larger intensity

    $f_b = 162.5$ MHz

    $f_{exp} = f_b/2 \approx 81$ MHz

    $= f_b/4 \approx 40.5$ MHz



- The beam is delivered to a target at 3 GeV.
- 4th harmonic RF separator directs
  - two quarters of the buckets to one user (Mu2e),
  - one quarter to another user (Kaon), and
  - one quarter to the third (unidentified) user.
- The natural way is to use a SC structure with the deflecting TM_{110} mode operating at the frequency $f_0(m \pm 1/4)$,where f_0 is the bunch sequence frequency determined by RFQ (f_0=162.5 or 325 MHz).

Parameters Choice

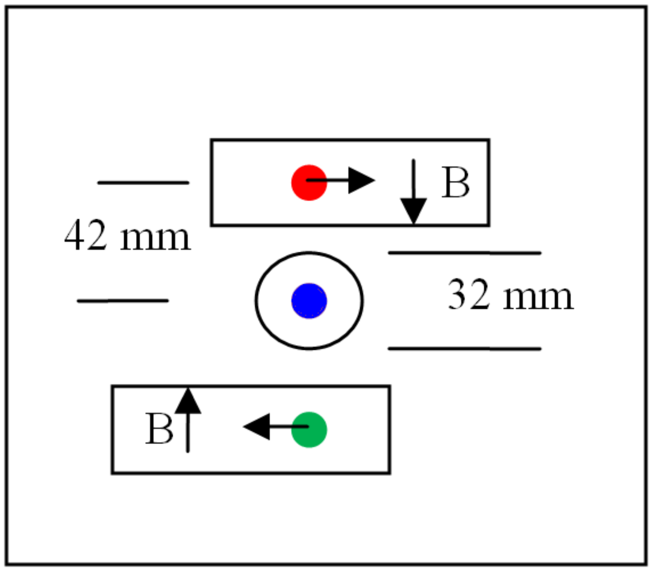
- Operating frequency of the deflecting RF structure is limited
  by the beam longitudinal size - at high frequency;
  by the cavity transverse size - at low frequency.

- The frequency of
  356.625 MHz (f_0=162.5 MHz) or
  406.25 MHz (f_0=325 MHz)
  for *m*=2 is a compromise. f_0 - RFQ frequency.

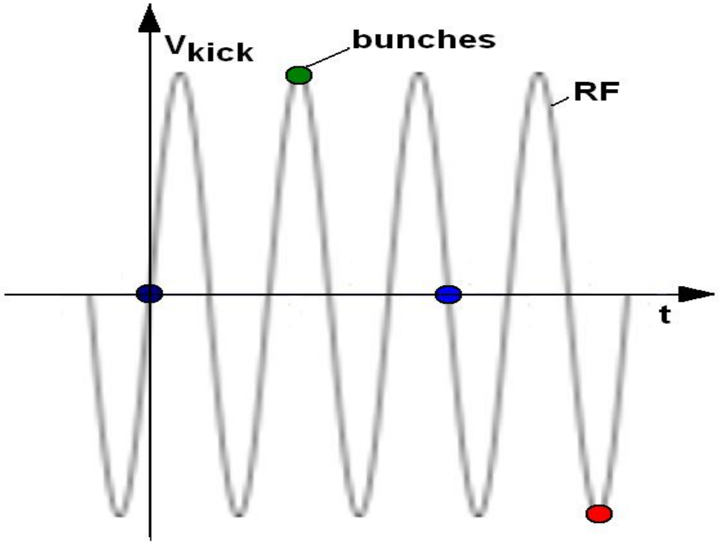
- The cavity should have a reasonable aperture (compromise between deflecting properties on one hand, and requirements for LOM/SOM/HOM dumping and possible current intercepting on the other hand). Aperture *2a* of 220 mm is chosen.

Parameters Choice

- To minimize the required deflection angle, the separation scheme will utilize the RF separator to select the aperture of a downstream 3-way horizontal bending Lambertson.
- The RF separator imparts a small vertical angle based upon the phase of the beam with respect to the RF separator phase.



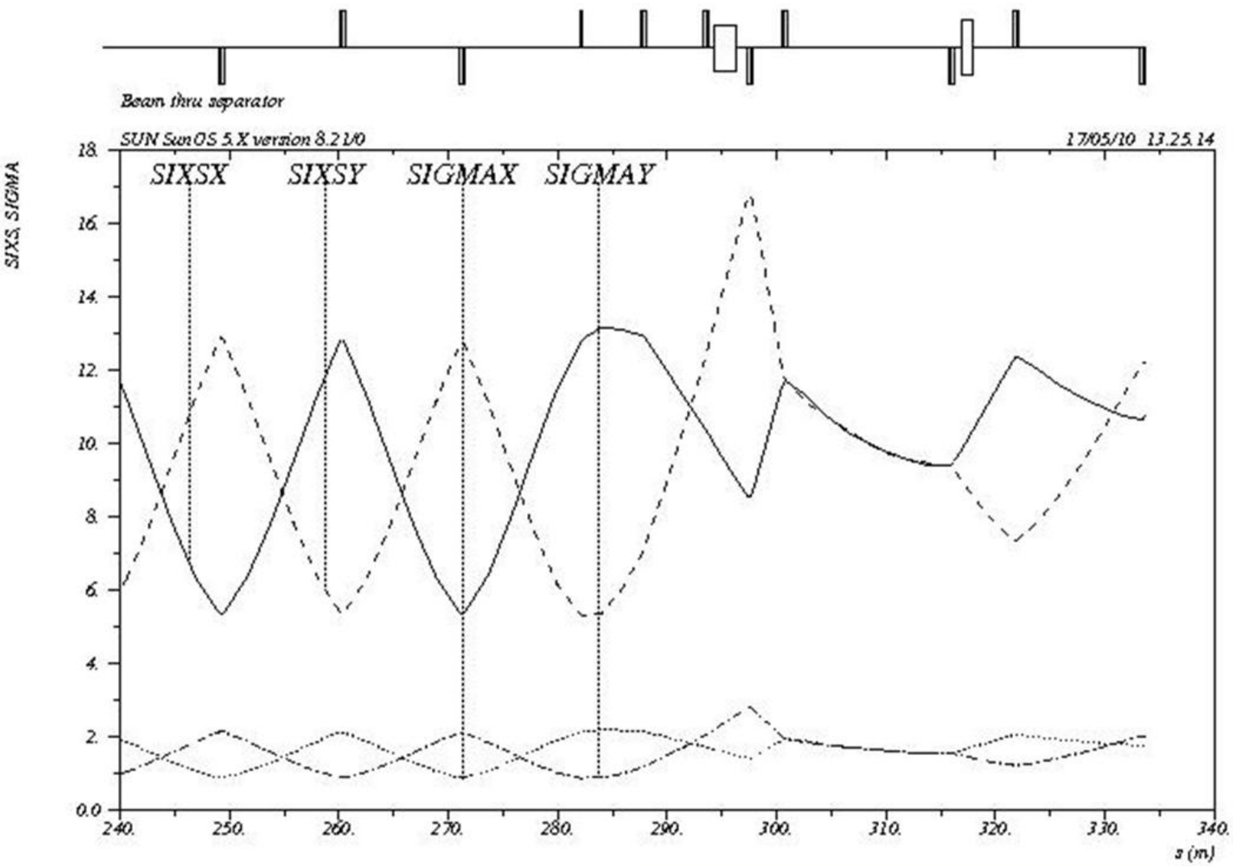
- Mu2e (blue),
- Kaon (red),
- Other experiment (green).



- An initial estimate for the required separation at the Lambertson is approximately 40 to 50 mm.

Parameters Choice

The Lambertson is placed approximately 20 meters downstream of the RF separator with a vertical deflection of 2.5 mrad from the RF separator, or about 10 MeV of transverse kick.

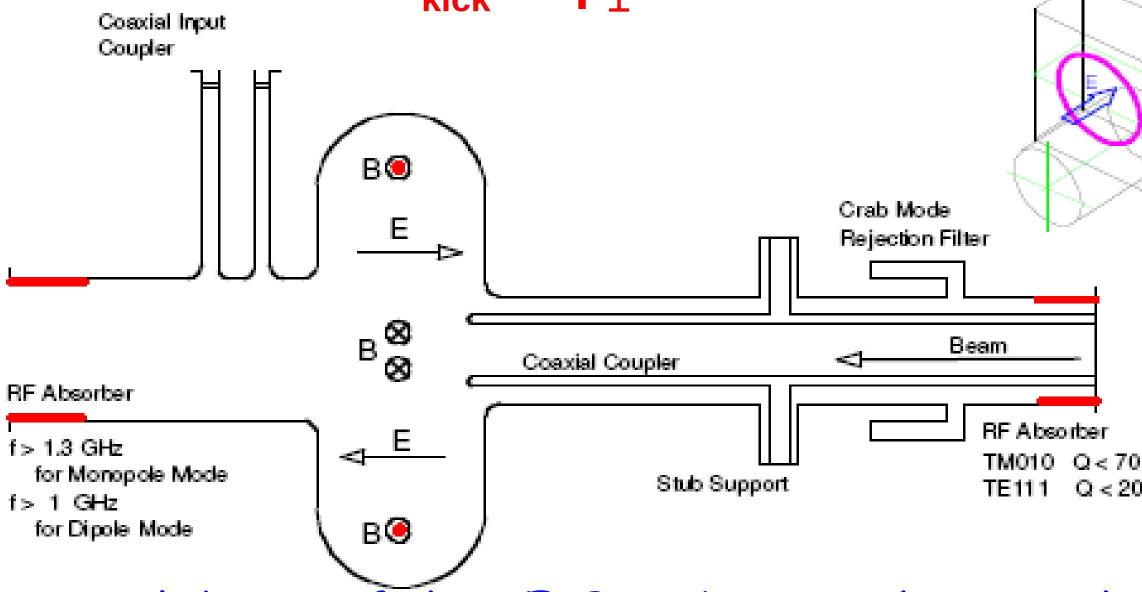


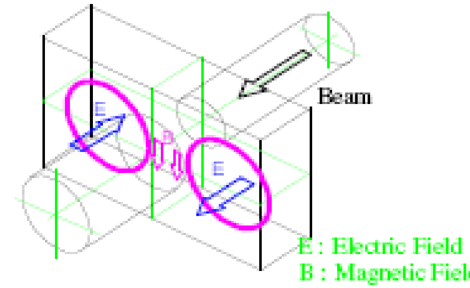
- A large aperture defocusing quad is used upstream of the Lambertson to compensate the vertical kick from the RF separator.
- All fields and gradients are consistent with minimum H^- field stripping.
- The field in the Lambertson produces 100 mrad bend to allow sufficient separation for installation of the downstream quad in each line.

Beam size (in mm) at RF separator and 3 way Lambertson.

500 MHz Crab Cavity of the KEK B-factory

$V_{kick} = \Delta p_{\perp} c/e = 1.44$ MV





Conceptual design of the KEKB crab cavity (Top view) and schematic drawing of squashed cell shape cavity is shown upper right.

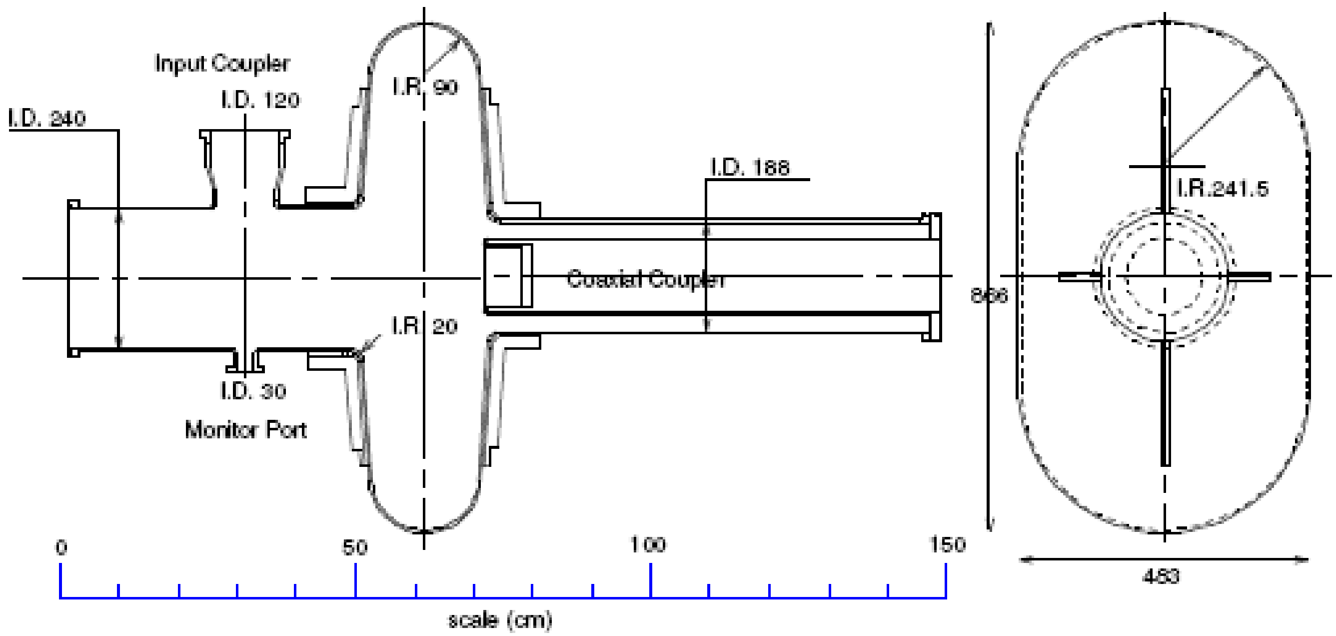
Table 1: Main parameters of KEKB.

	Beam Energy	Beam Current
LER (positron)	3.5 GeV	1.8 A
HER (electron)	8.0 GeV	1.3 A
RF frequency	508.9 MHz	
Crossing Angle	11 m rad. x 2	

RF properties of 508 MHz KEKB crab cavity

R / Qo	48.9 [Ω]
Γ	227
Esp/Vkick	14.4 [MV/m/MV]
Hsp/Vkick	415 [Oe/MV]

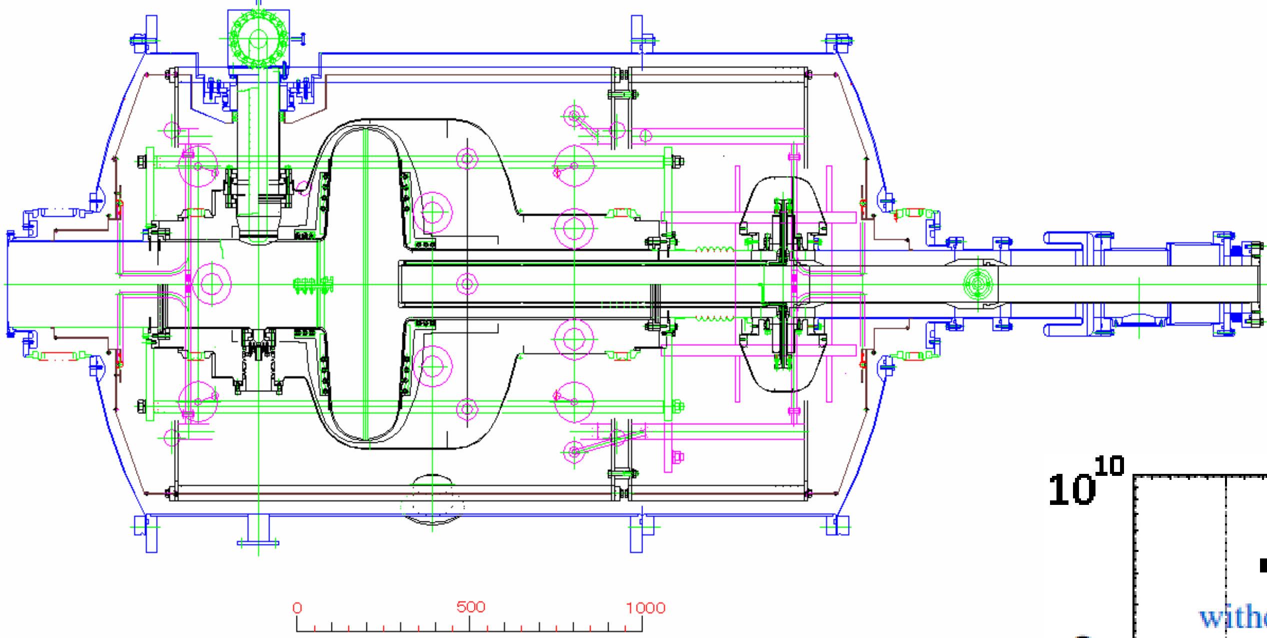
KEKB crab cavity with a coaxial coupler

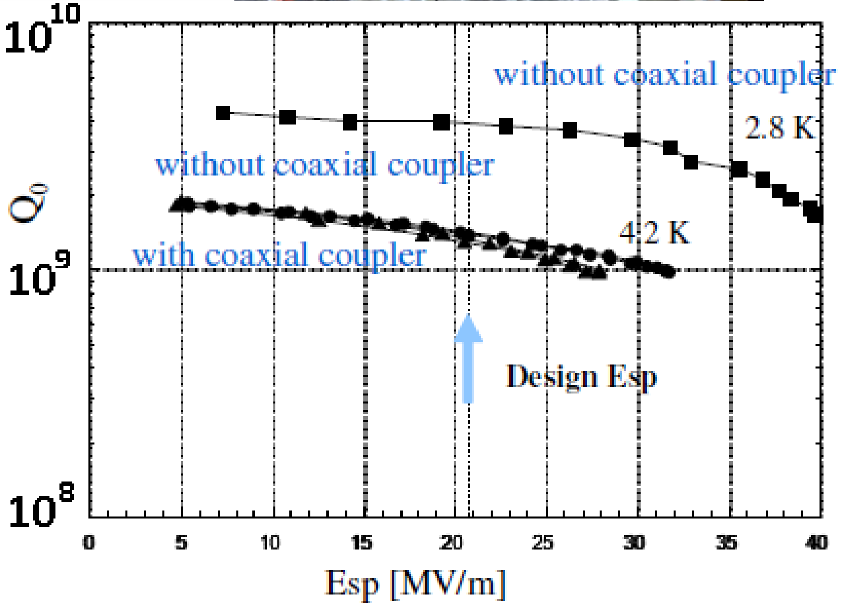


- The cavity is not axially symmetric (squashed-cell shape cavity), with racetrack shape to push up the resonance frequency of unwanted degenerate TM_{110} mode to 700MHz.
- A coaxial coupler inserted into the cavity cell is used to extract the lowest 430MHz TM_{010} acceleration mode and the higher TE mode outside the cavity.

Cavity Performance

Design of the KEKB crab cavity (Top view).





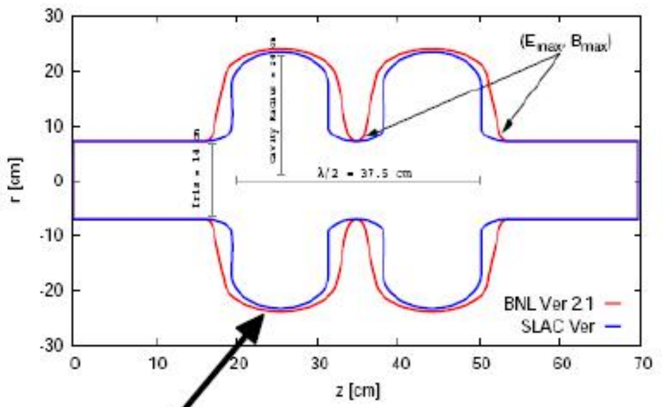
E_{sp} reached to 30MV/m (V_{kick}=2.1 MV) keeping Q_0 values higher than 10^9 at 4.2 K. Operating value is *E_{sp} = 21MV/m*, or *V_{kic}=1.44 MV.*

- KEKB Crab Cavity shape is optimized in order to accommodate the HOM absorbers necessary to suppress parasitic modes excited by ~2 A beam.
- It gives high ratio of B_{sp}/V_{kick}, that is 41.5 mT/MV.
- For ILC1 cavity at the gradient of 18 MeV/m one has surface magnetic field of 76 mT.
- For KEKB crab cavity it corresponds to the kick of ~2 MeV/cavity.

LHC Crab cavity design (R&D)

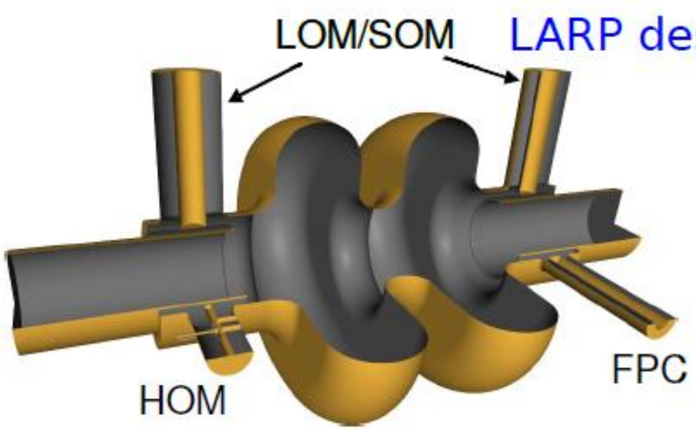
Prototype Cavity/Couplers

Frequency = 800 MHz

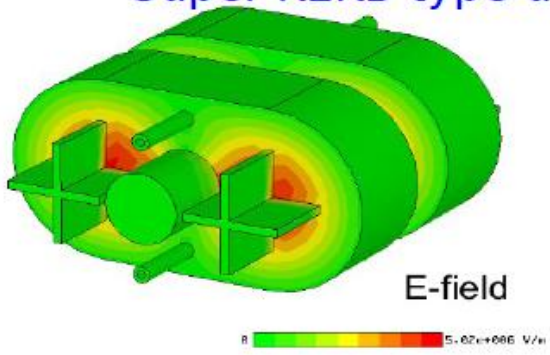


Note the cavity radius ~ 23 cm

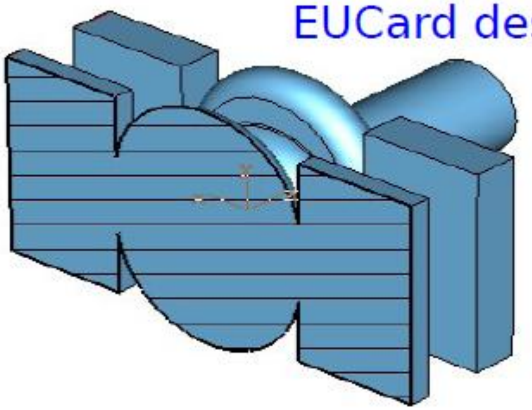
LARP design



Super-KEKB type design



EUCard design

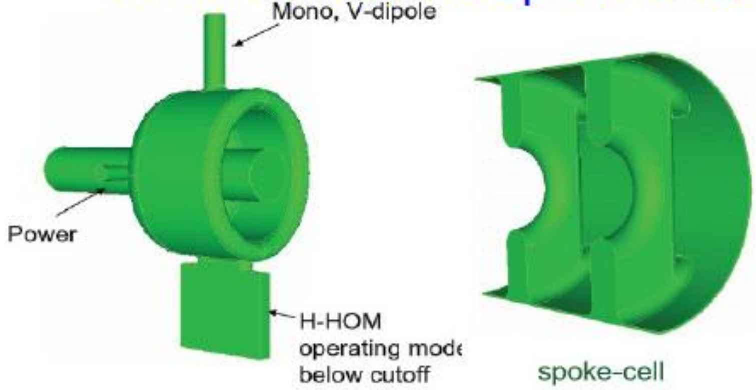


Proposals for compact design (exotic)

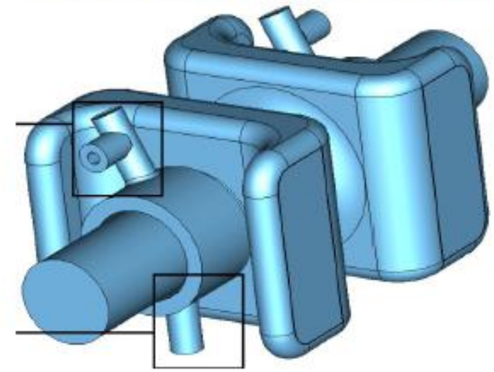
Compact Structure, Phase II

Frequency = 800 MHz

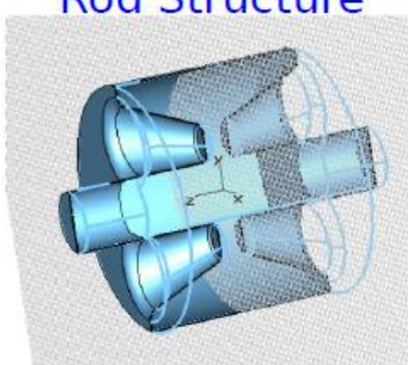
SLAC ½ Wave & Spoke Structures



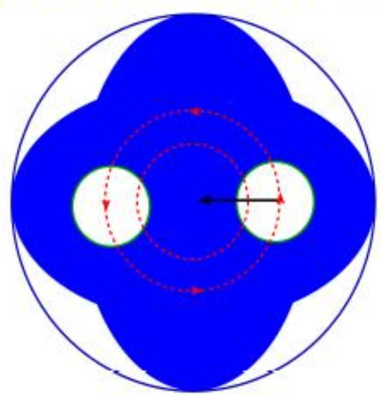
FNAL Mushroom Cavity



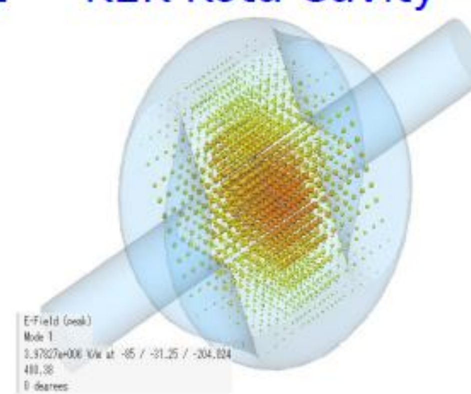
EUCard,UK-JLAb Rod Structure



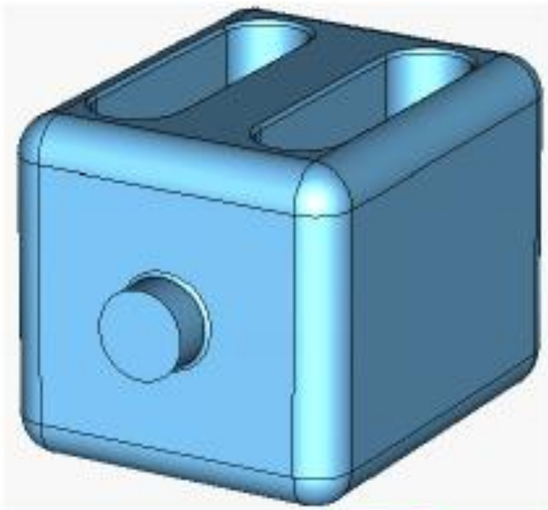
BNL TM010, BP Offset

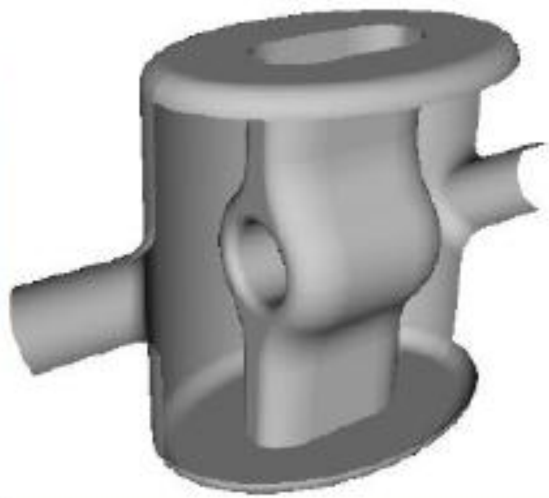


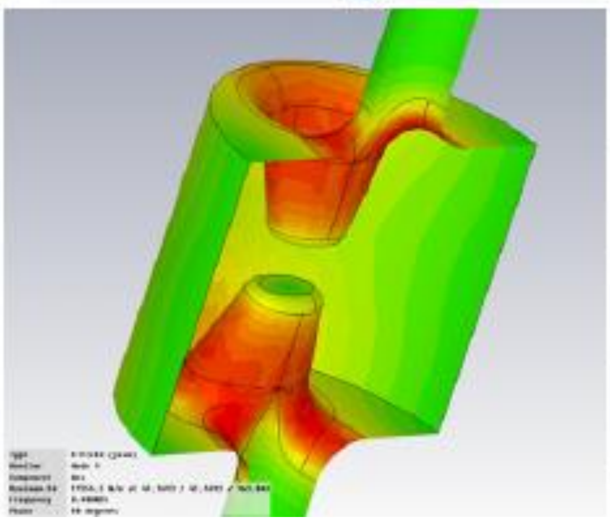
KEK Kota Cavity

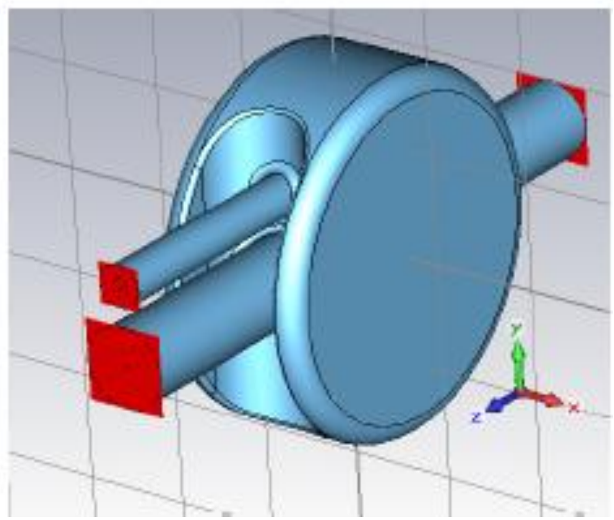


More designs









Frequency = 800 MHz

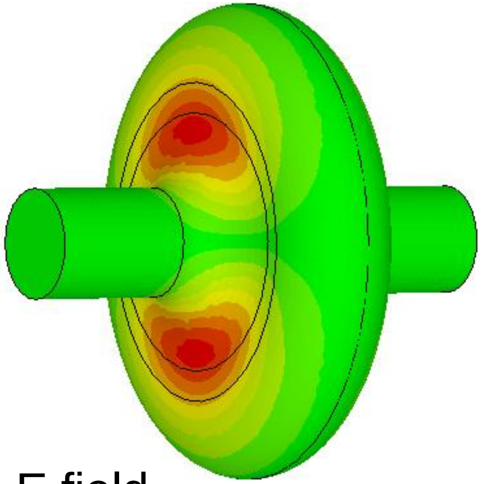
Top left: Half wave double rod cavity.

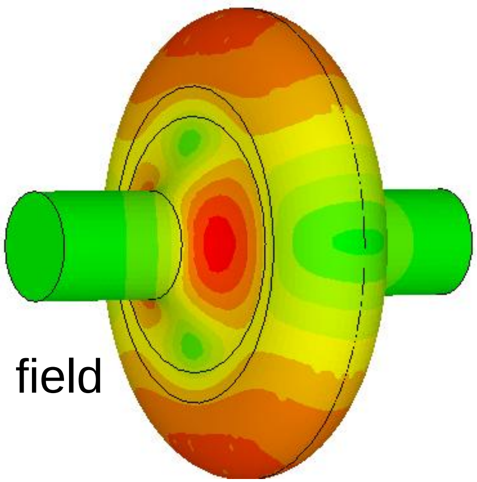
Top right: Half wave single rod cavity.

Bottom left: Double rod loaded cavity.

Bottom right: Rotated pill-box Kota cavity

Project X deflecting cavity design


E field


H field

Features:

Simple single-cell cavity with elliptical transverse cross-section

Parameters of operating mode

Frequency, [MHz]	406.25
V_{kick} , (MeV)	3.3
E_{sp}/V_{kick} , [(MV/m)/MeV]	7.8
B_{sp}/V_{kick} , [mT/MeV]	19.2**
R/Q* [Ohm]	27
Longitudinal size [mm]	440
Vert/Horiz. size (mm)	865/962

High order modes

MONOPOLE		DIPOLE1		DIPOLE2	
F,MHz	R/Q,Ω	F,MHz	R/Q,Ω	F,MHz	R/Q,Ω
289.2	118	406.25	27.3	427.9	25.2
557.1	1.5	529.1	6.2	528.3	6.1
635.7	6	691.4	0.16	695.7	0.04
692.6	0.001	726.7	0.03	743.6	0.14
730.1	16	759.5	2.8	759.4	2.5
825.2	0.002	797.6	0.08	797.8	0.12

$^*R/Q=V_{kick}^2/(2\omega W)$

****compared to 41.5 mT/MeV for KEKB CC**

Some Requirements

- In order to achieve the kick of ~10 MeV one needs 3 cavities.
- The kick per cavity is 3.3 MeV.
- The surface magnetic field is 64 mT, (less than for 650 MHz and 1300 MHz cavities in SC Linac).
- The length of the cavity + power coupler + HOM couplers is ~ 1 m.
- The total length of the deflecting RF structure is ~3.5 m.
- Transverse size is ~1 m.

Power requirements:

- V_{kick} = 3.3 MeV per cavity, Total Kick = 10 MeV;
- Power necessary to maintain RF field (Q_0=1.e9, 4.2 K):
  $P = V_{kick}^2/[2(R/Q) \times Q_0]$ = 200 W/cavity – cryogenic losses
- Compensation of the beam loading caused by misalignment (I_0 = 1mA; $\Delta x=\sigma_x$=0.5 mm; $U_{ind}<0.01\times V_{kick}$):
  $U_{ind}= I_0 \times(R/Q) \times(k\,\Delta x)Q_{load} < 0.01\times V_{kick}$; → $Q_{load} < 3\cdot 10^8$ and
  $P = V_{kick}^2/[2(R/Q) \times Q_{load}]$ = 700 W / cavity
- Microphonics: Q_{load}~1.3e7 ($\Delta f \sim 6\sigma_f$ =30 Hz for σ_f = 5 Hz)
  $P=V_{kick}^2/[2(R/Q) \times Q_{load}]$=16 kW/cavity (for KEKB it is 100 kW to tolerate offset of 1 mm); $U_{ind}=0.004\times V_{kick}$
  $P_{total} = P \times 3 <50$ kW.
  Note that power required for microponics may be significantly reduced by fast piezo-tuner.
- Compensation of the beam loading caused by the beam deflection:
  $Q_{beam_load} \sim Z_{beam}/Z_0 \sim$1.e10, not an issue ($Z_{beam}=p_{||}c/e/I_0$).
- Total cryogenic losses: ~0.6 kW at 4.2 K.

LOM/SOM/HOM damping

- **Monopole mode (LOM):**

  $P = I_0^2 \cdot [(R/Q)Q_{load}]/2 < 0.1\ P_{cryo} = 26$ W,

  $Q_{load} < 4.10^5$ for (R/Q)=118 Ω.

- **Dipole modes (SOM):**

  $V_{kick\_SOM} < 0.01 \cdot V_{kick} = 33$ keV for Δy=0.5 mm.

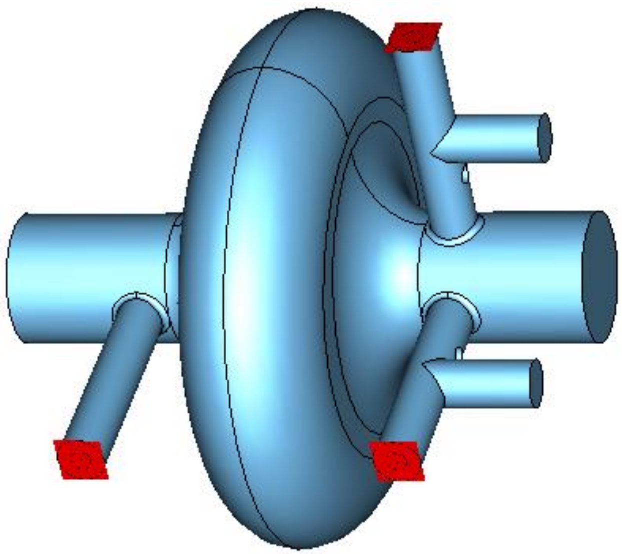
  $Q_{load} < 10^8$.

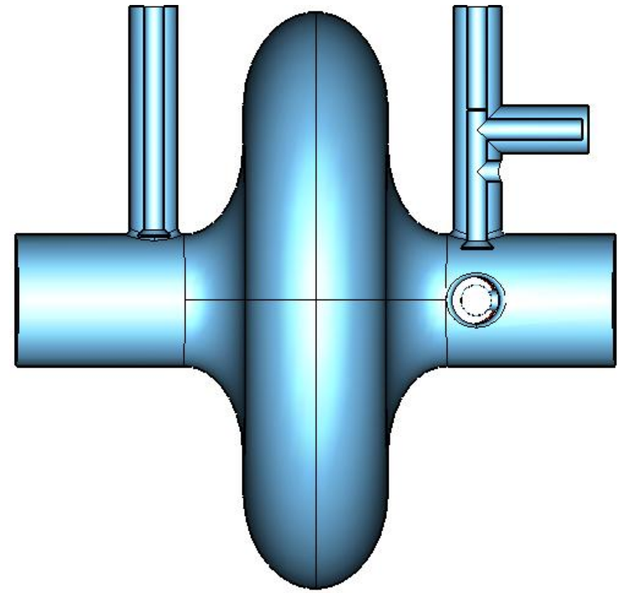
- **Dipole modes (HOM):**

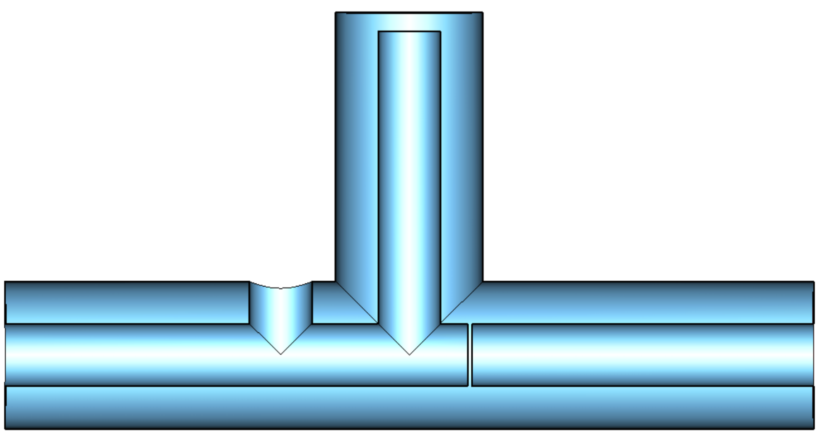
  $Q_{load} < 1.10^8$ for $(R/Q) = 6\ \Omega$

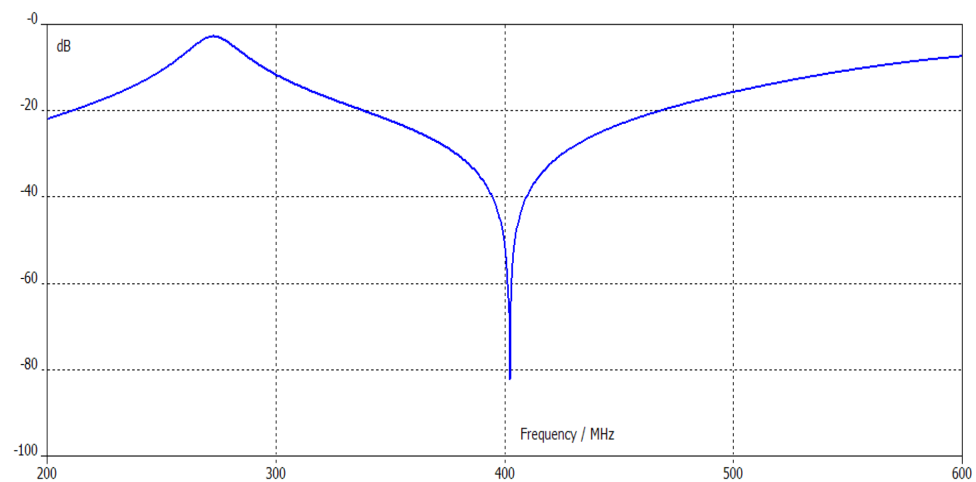
Project X

LOM/SOM/HOM dampers and notch filters

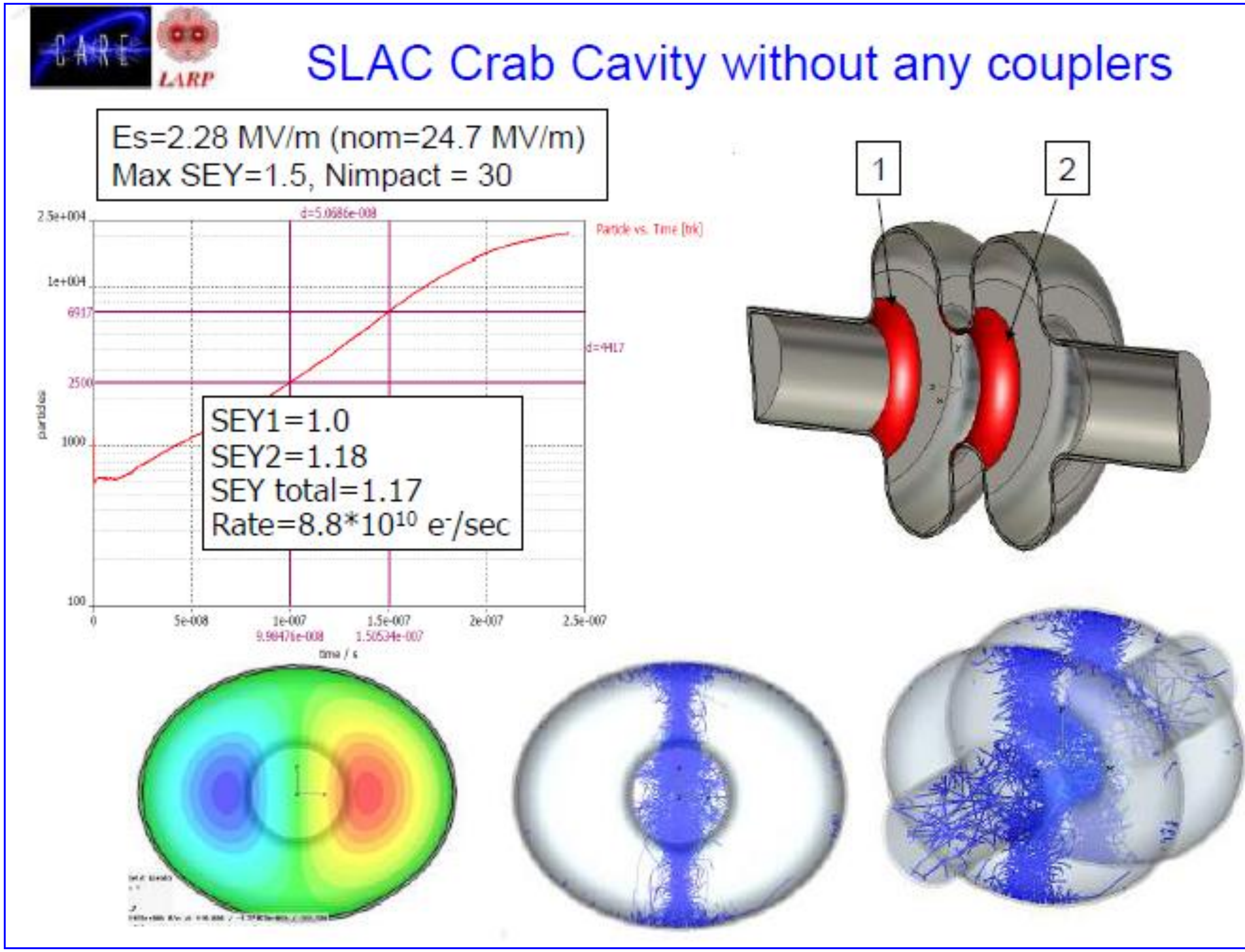






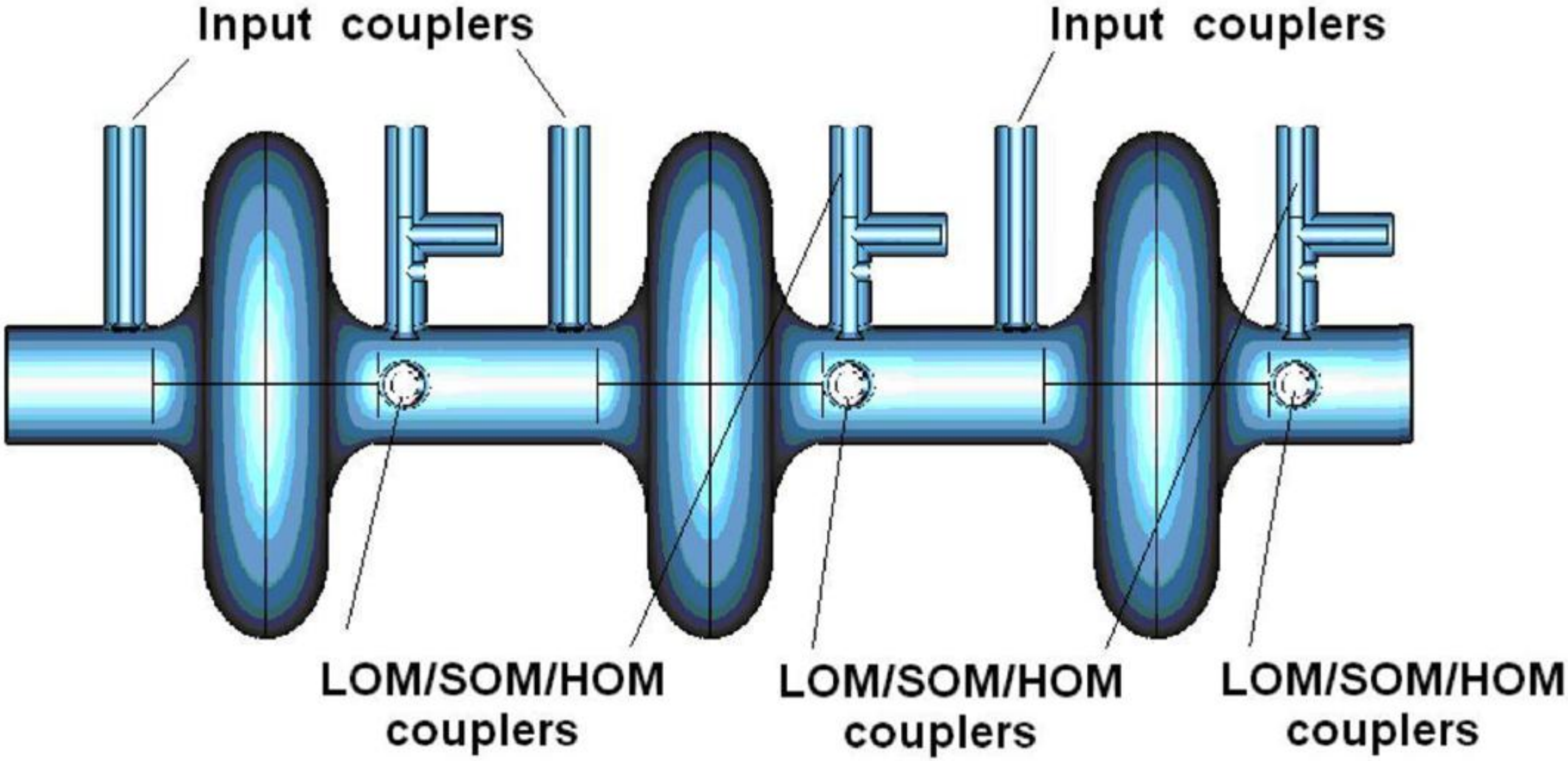


Multipactoring

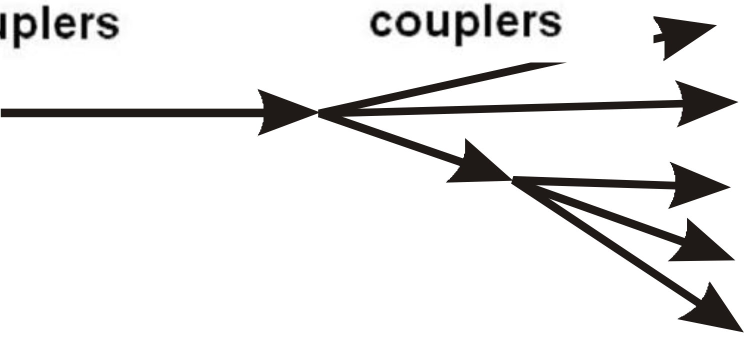


- MP is an issue?
- Need simulations and better understanding
- Typical picture of MP is shown on the left, simulated for LHC crab cavity (800 MHz)
- Similar simulations shows MP zones for KEK cavity (500 MHz) and coaxial line
- Fortunately MP is soft and can be processed out.

Project X Deflecting section



Additional RF separators allow simultaneous operation for more than 3 users



Summary

1. SC deflection cavity is discussed for the Project X for 3 GeV beam distribution for different experiments.

2. Operating frequency and parameters are discussed;

3. The cavity concept is suggested.

4. Design in progress (MP, couplers, etc…)