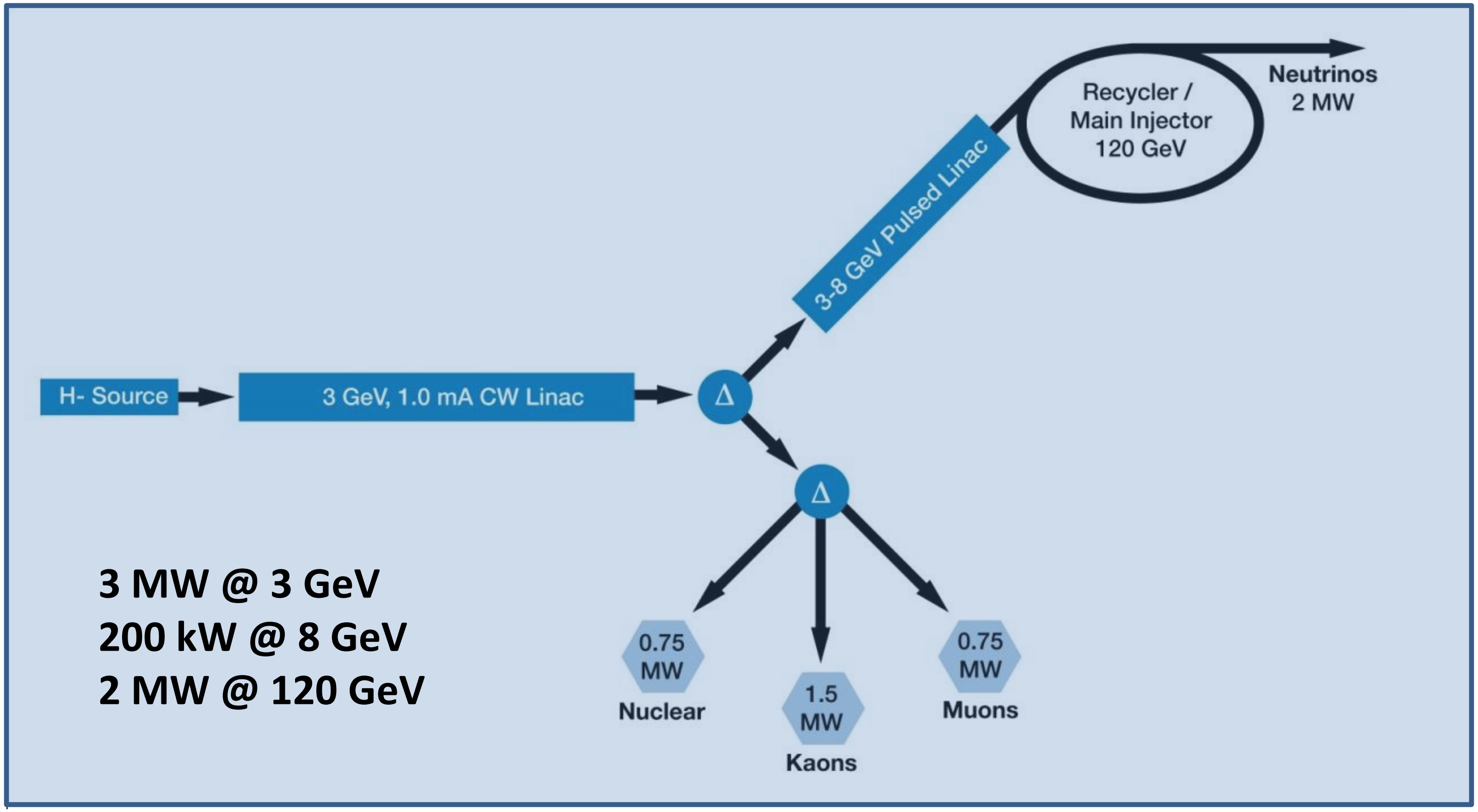
A beam splitter for the Project X

LHC Crab Cavity Meeting

11/15/2011

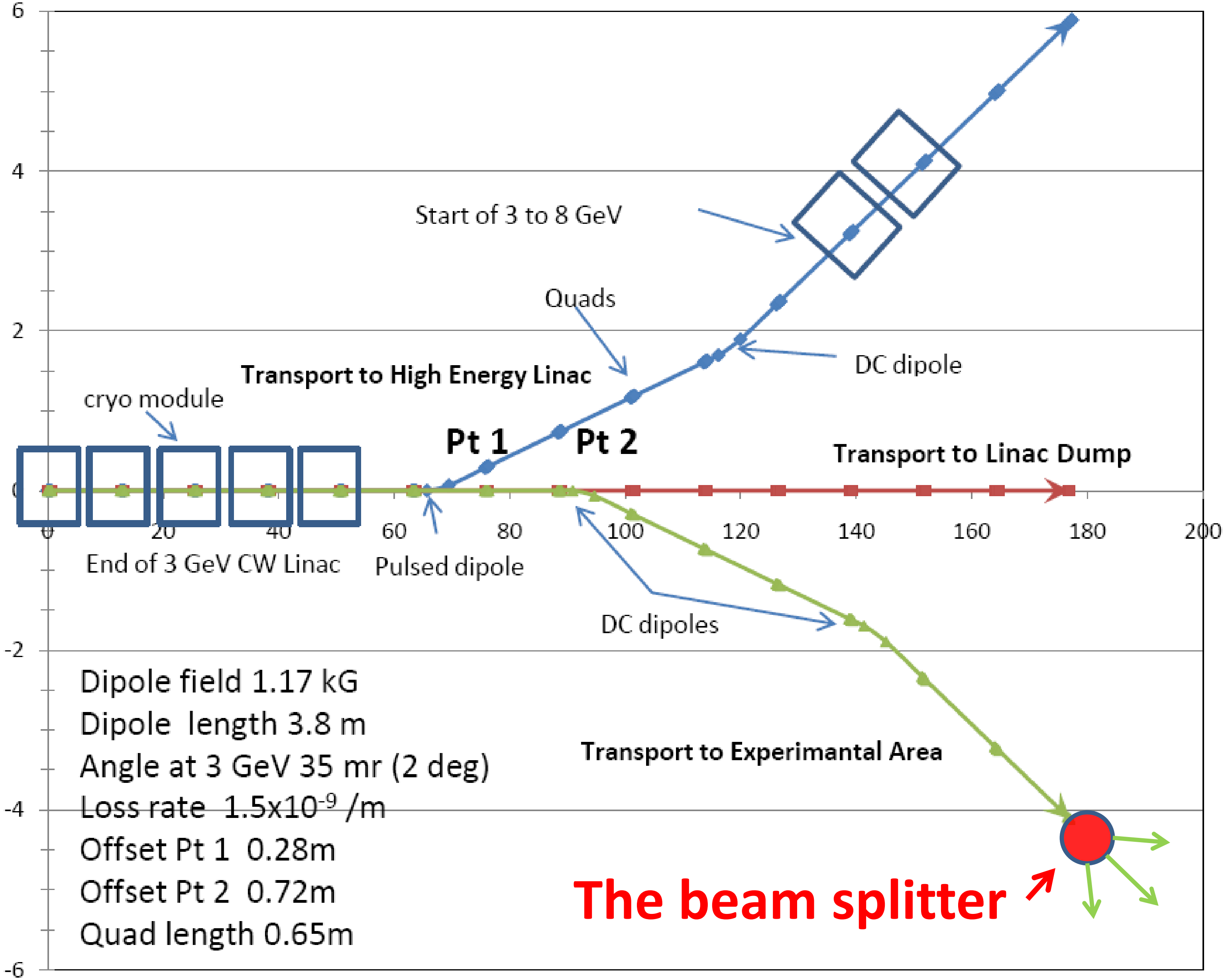
V. Yakovlev and M. Champion

Project X multi-experiment facility:



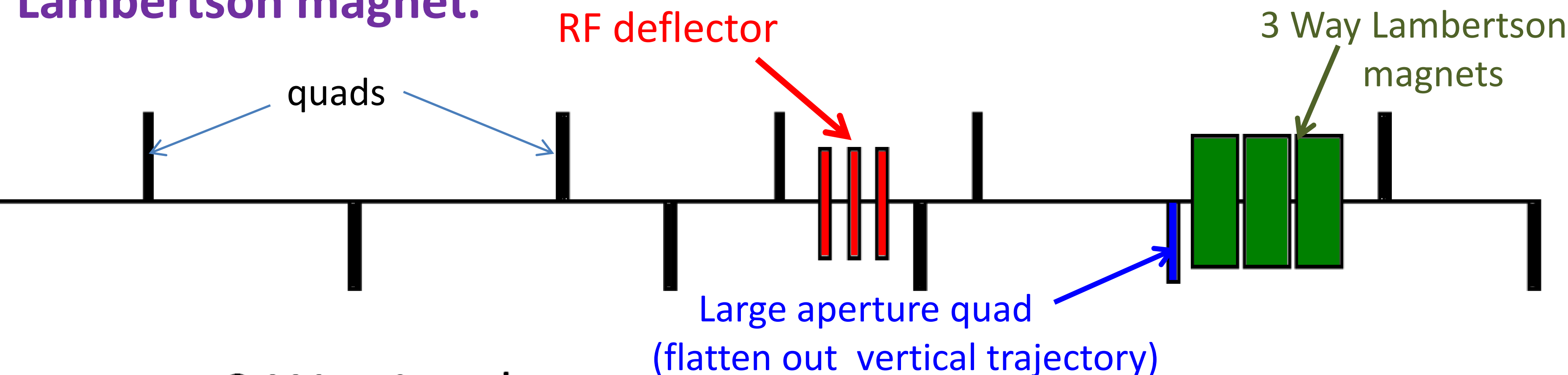
- 3-GeV, 1-mA CW linac provides beam for rare processes program ~3 MW;
- flexible provision for beam requirements supporting multiple users;
- <5% of beam is sent to the Main Injector.

3 GeV Switchyard



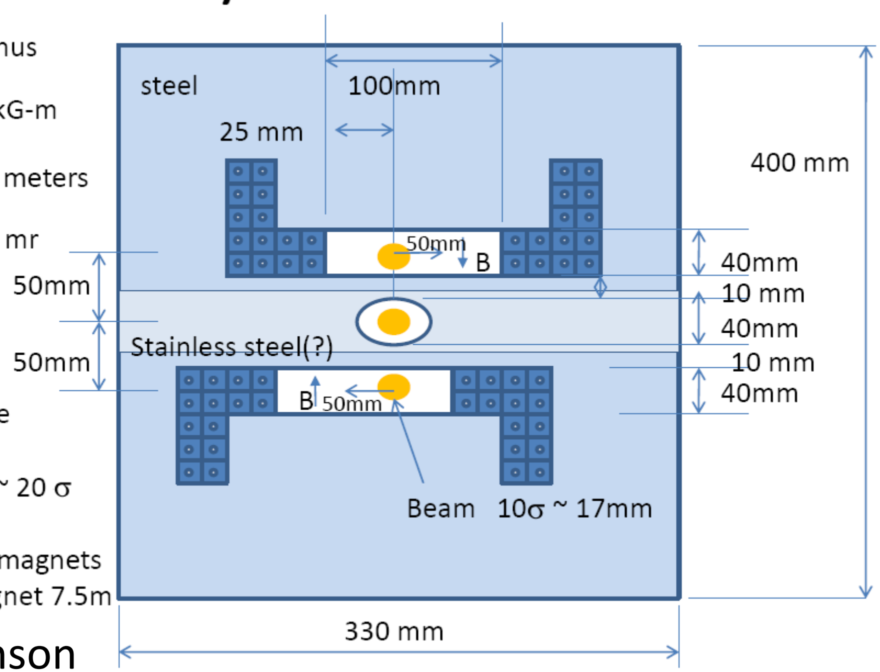
D. Johnson

The bunches are separated in vertical direction by RF cavity by 50 mm (~25 σ_t) and than deflected in horizontal direction by 3 Way Lambertson magnet.



3 Way Lambertson

Beam = Hminus
K.E. = 3 GeV
$B\rho$ = 127.58kG-m
B = 1.2kG
Length = 2.5 meters
BL = 3 kG-m
Angle = 23.5 mr



I~275A/pole

Aperture ~ 20 σ

Need 3 short magnets
Or 1 long magnet 7.5m

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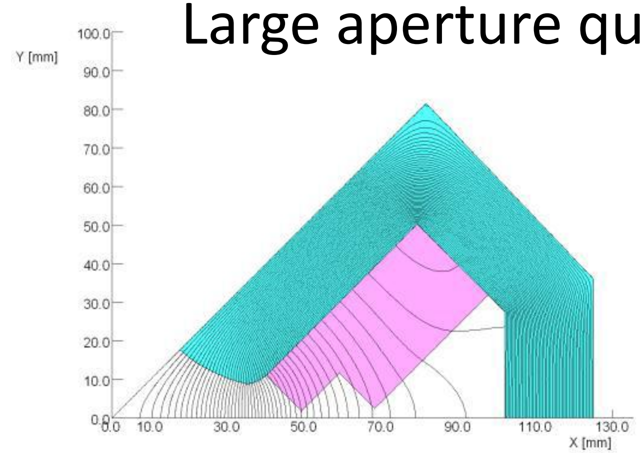
Large aperture quad



Example from RCS:
5.5T/m (inj)
17.5T/m peak (670A)
Only need:~ 2 T/m gradient

Operating scenario at the bunch sequence frequency of 162.5 MHz:

- RF separator directs

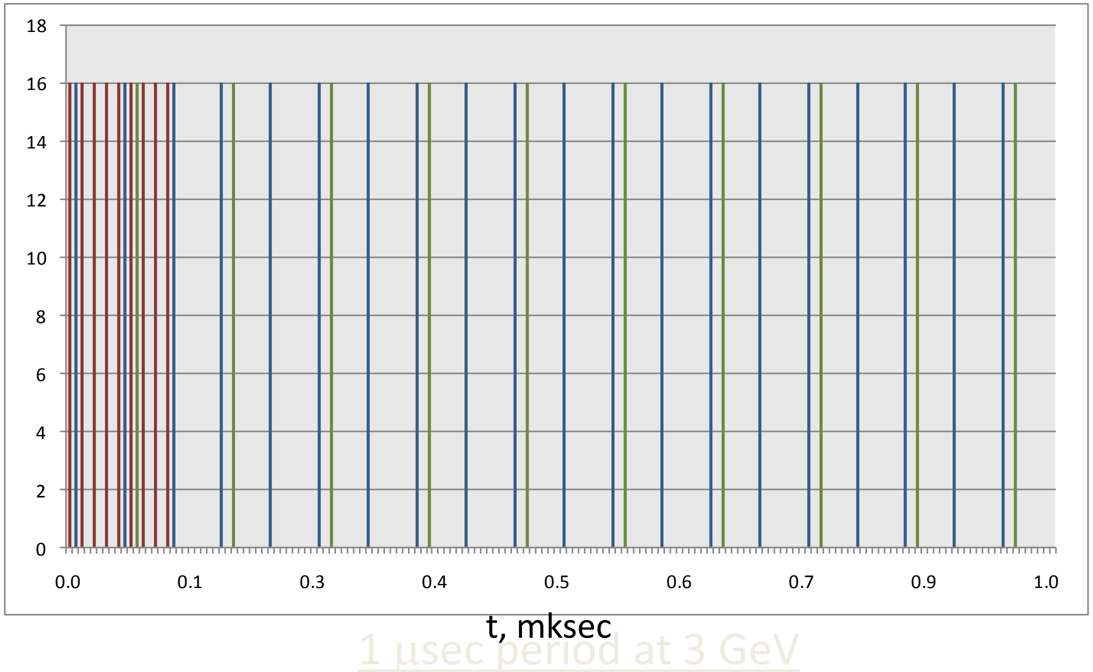
  Muon pulses (16e7) 81.25 MHz, 100 nsec at 1 MHz 700 kW;

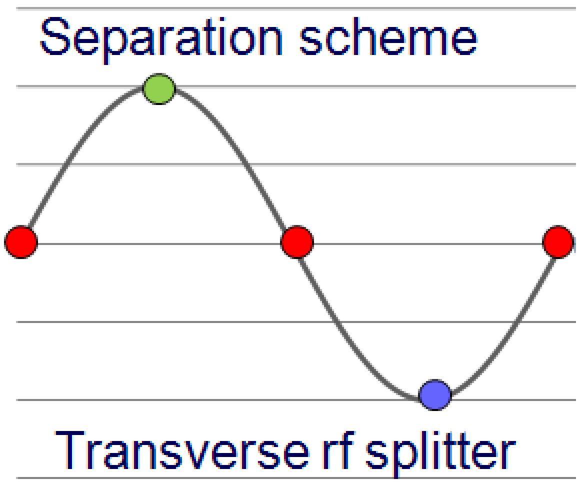
  Kaon pulses (16e7) 20.3 MHz 1540 kW

  Nuclear pulses (16e7) 10.15 MHz 770 kW

- Deflecting structure should operating at the frequency

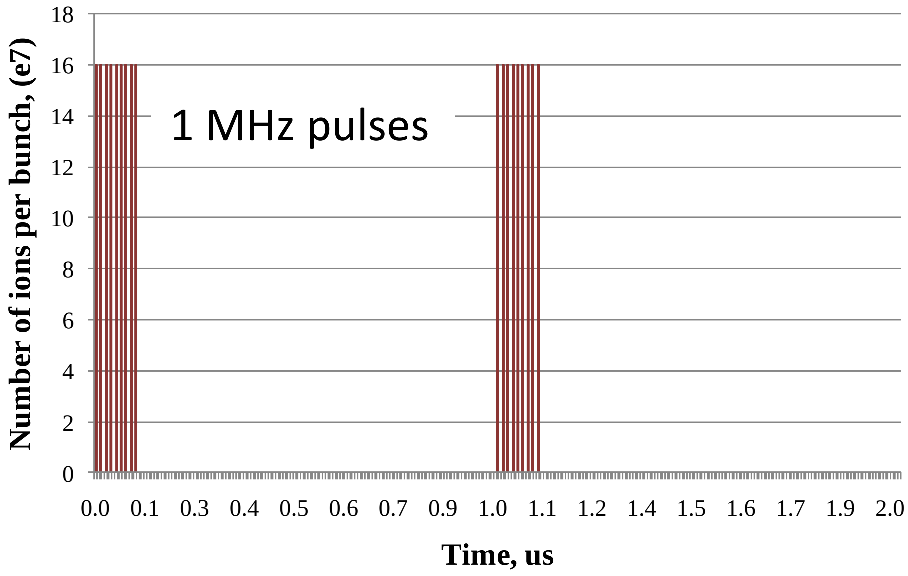
$f_0(m \pm 1/4)$,where f_0 is the bunch sequence frequency (f_0=162.5 MHz).



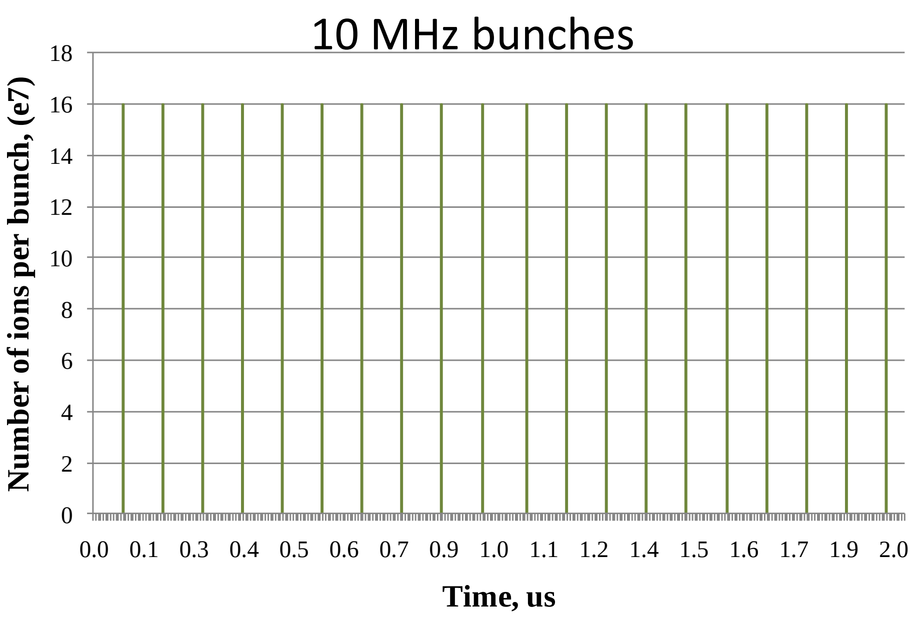


Beam after splitter

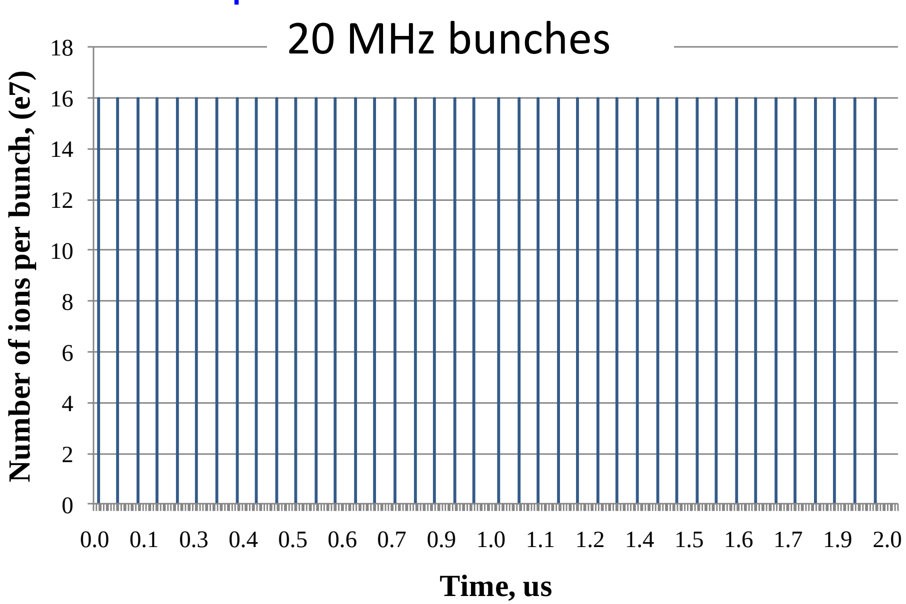
Muon pulses



Nuclear pulses



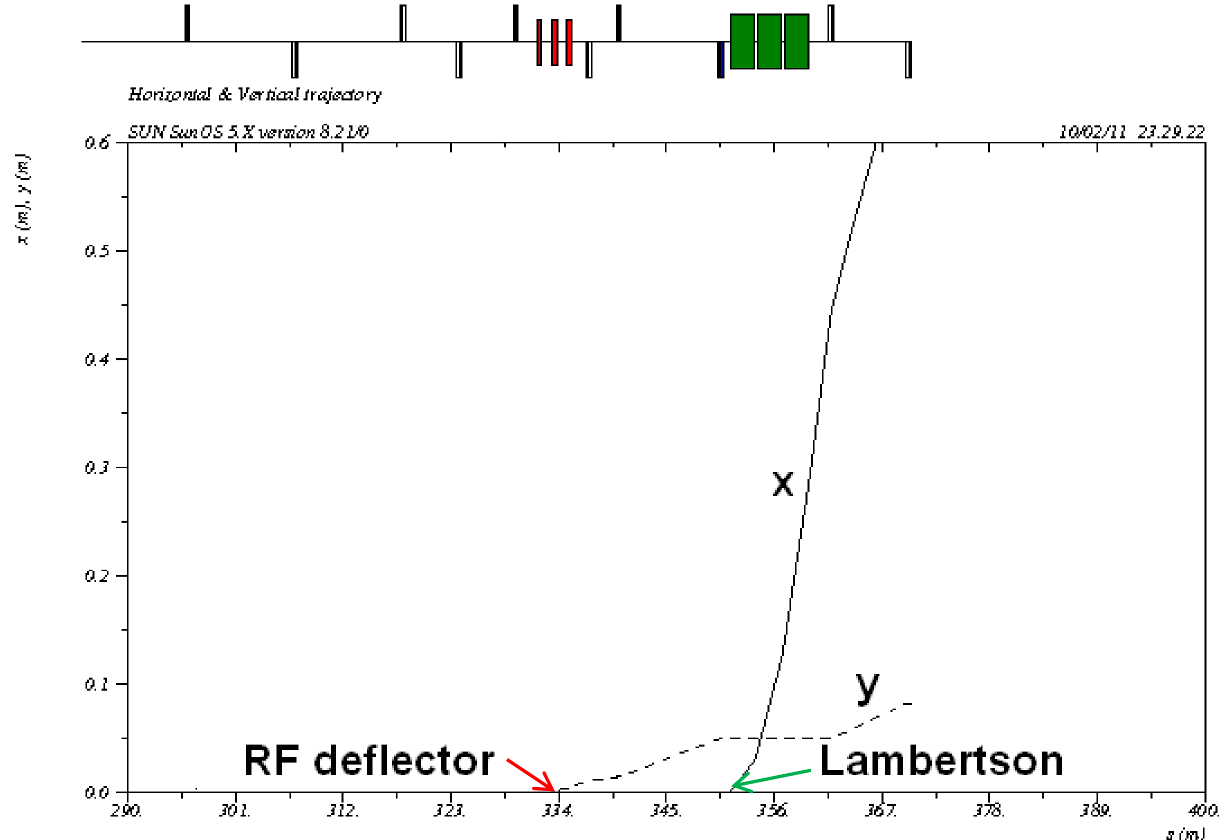
Kaon pulses



Requirements for RF kick:

Trajectory of the deflected beam in the spitting system:

- Three Lambertson magnets provide about 70 mrad bend to produce 285 mm at end of Lambertson.
- RF Separator requires total vertical kick of **+/-2.5 mrad** to match into bending aperture of 3-way Lambertson.



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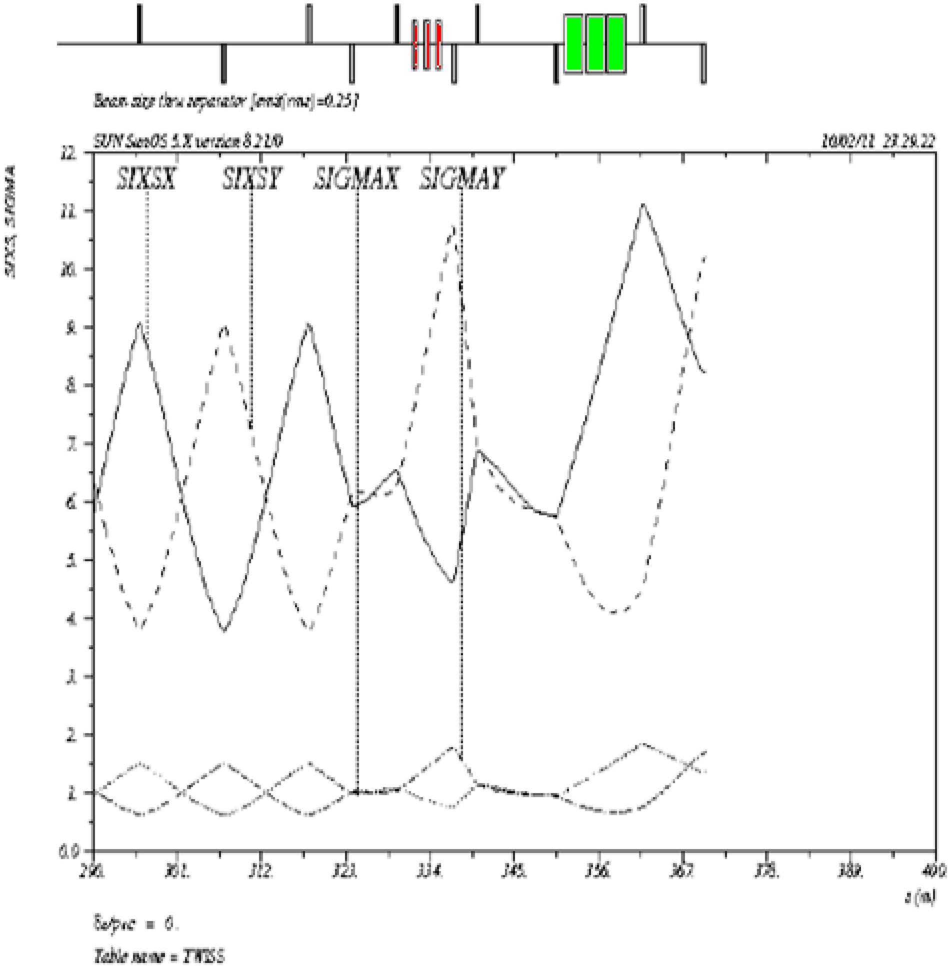
RF kick:

$\Delta p_{\perp} c = 2.5\times10^{-3} p_{||} c =$ **10 MeV**

The cavities should be superconducting because of the relatively high voltage requirement and the continuous wave operation.

Aperture requirements for deflecting RF cavity:

Beam transverse sizes in the beam splitting system.



- Beam sigma < 2 mm for ε_t (rms) 0.25 mm-mr
- Typical quad apertures ~75mm diameter
- Typical dipole gap ~ 50 mm

RF cavity aperture of 70-80 mm is OK

D. Johnson

Frequency requirements:

- Operating frequency of the deflecting RF structure is limited

  by the bunch longitudinal size - at high frequency;

  by the cavity transverse size - at low frequency.

- Deflecting structure should operate at the frequency of $f_0(m\pm1/4)$, where f_0 is the bunch sequence frequency, 162.5 MHz.

- The frequencies of

  365.625 MHz (m=2,+1/4) or

  446.875 MHz (m=3,-1/4)

  are reasonable possibilities.

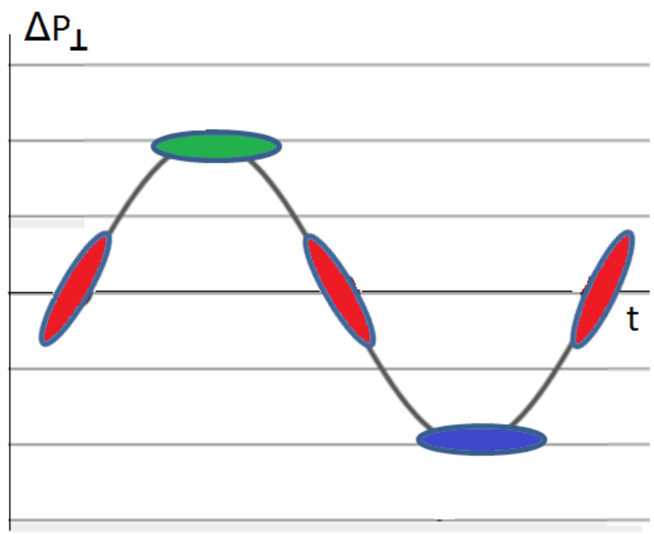
Transverse emittance dilution caused by the splitting cavity:

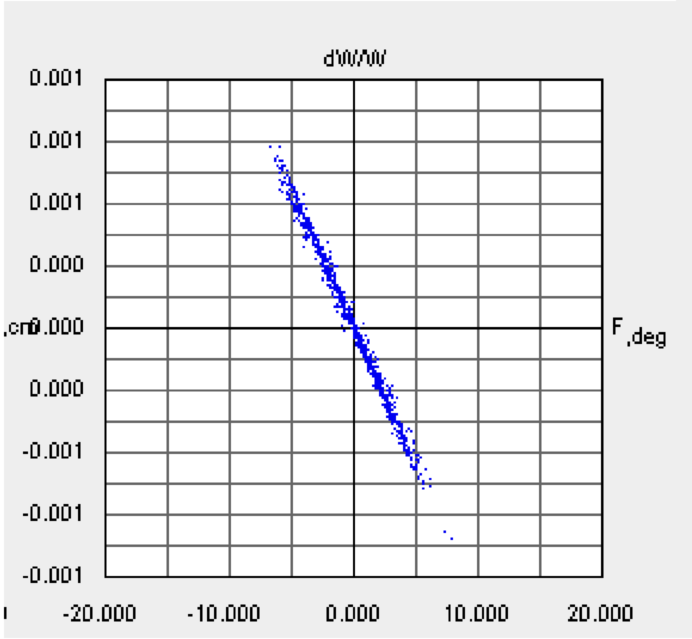
➢The magnitude of the kick spread inside the bunch depends on the bunch length;

▪For the *non-deflected* bunch $\theta_{rms} \sim 2\pi\theta_{RF} \times (\sigma_z/\lambda)$, where σ_z is the rms bunch length and λ is the RF wavelength (for 447 MHz λ = 0.67m) and θ_{RF} = 2.5 mrad is deflecting angle.

▪For the *deflected* bunch $\theta_{rms} \sim (\sigma_z/\lambda)^2$ – negligible;

➢Due to the bunch sheering in transport to the cavity (~300m) the rms bunch length is ~ 3.5 mm, so $\theta_{rms} \sim 2\pi(2.5\text{mrad})(3.5\text{mm}/.67\text{m}) \sim 0.082$ mrad.





- The initial rms normalized emittance ε_{0y} is 0.28 mm-mrad.

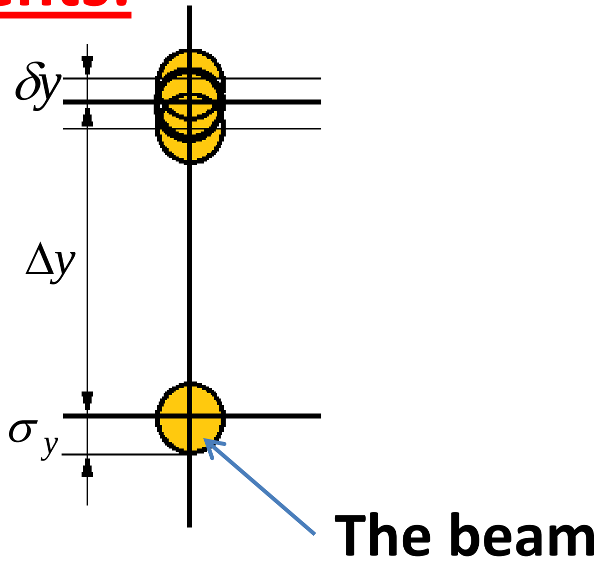
- The new emittance is given by $\varepsilon_y = [\varepsilon_{0y}{}^2 + \varepsilon_{0y} \cdot \beta\theta^2_{rms} \cdot (\gamma\beta)]^{1/2}$, where β (46m) is the lattice function at the RF cavity, and $\gamma\beta$ (~4) is the relativistic factor.

- The increase in the normalized rms emittance is determined by $\Delta\varepsilon_y = \beta\theta^2_{rms}(\gamma\beta)$ ~ 1.08 mm-mrad

This gives an emittance dilution factor of 3 for non-deflected bunches.

- **Muon experiments need small emittance. Deflected beam is to be used.**
- **For other experiments it's OK.**
- **447 MHz is OK.**
- **This problem does not exist for LHC CC, it is specific for PX.**

Amplitude and phase stability requirements:



- Amplitude stability:

$$\frac{\delta\varepsilon_\perp}{\varepsilon_\perp} = \frac{\delta y}{\sigma_y} = \frac{\delta y}{\Delta y}\cdot\frac{\Delta y}{\sigma_y} = \frac{\delta U_{kick}}{U_{kick}}\cdot\frac{\Delta y}{\sigma_y} << 1;$$

or

$$\frac{\delta U_{kick}}{U_{kick}} << \frac{\sigma_y}{\Delta y}.$$

If σ_y =2 mm, Δy=50 mm, $\delta U_{kick}/U_{kick}$ << 4%.

$\delta U_{kick}/U_{kick}$ ≤1% is OK.

- Phase stability:

$$\frac{\delta\varepsilon_z}{\varepsilon_z} \approx \frac{\delta\varphi}{\sigma_\varphi} << 1; \quad \sigma_\varphi = \frac{2\pi\sigma_z}{\lambda};$$

If σ_z =3.5 mm, λ =0.67 m, $\Delta\varphi$< <2°.

$\Delta\varphi$ ≤ 0.5° is OK.

Transverse alignment requirements:

- Energy spread is caused by transverse misalignment of the cavity;
- Energy change because transverse misalignment of the cavity;
- Input power increase in order to compensate voltage induced by the beam.
- Excitation of dipole SOM/HOMs .

- Energy spread:

$\delta E = (2\pi)^2 U_{kick} \Delta y \sigma_z / \lambda^2 << \frac{\varepsilon_z}{\sigma_z};$ (from Panofsky-Wentzel theorem)

$$\Delta y << \frac{\varepsilon_z \lambda^2}{(2\pi)^2 U_{kick} \sigma_z^2}.$$

if ε_z = 1 keV×nsec or 30 keV×cm, σ_z=3.5 mm, λ=0.67 m, U_{kick}=10 MeV,

Δy<< 3 cm – not a problem. **Δy = 2-3 mm is OK**.

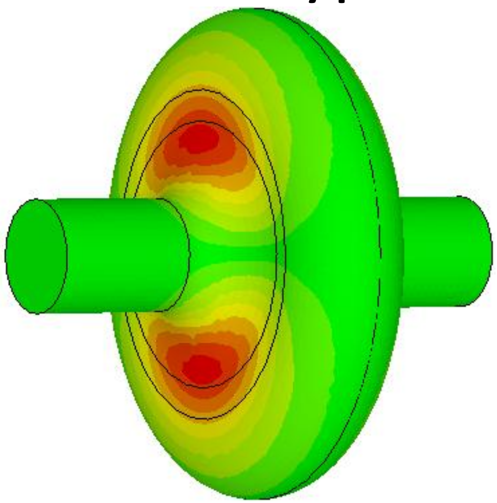
- Energy Change:

$\Delta E = 2\pi U_{kick} \Delta y / \lambda$ = 330 keV at E=3 GeV – OK for Δy ≤ 2 mm.

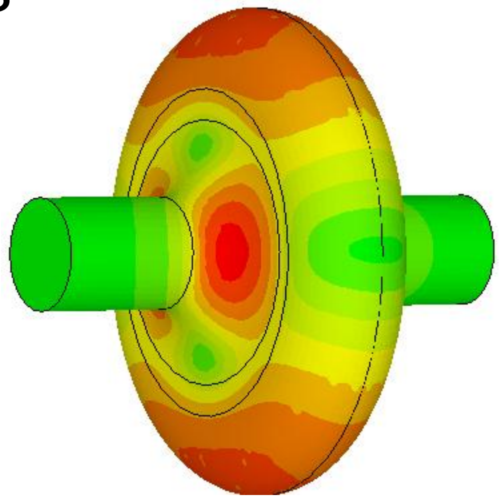
- In contrast to LHC CC, the induced voltage at operating mode is small because the operating frequency does not coincide to harmonics of the bunch sequence frequency – OK.

- Dipole SOM/HOM excitation is not a problem because of a small beam current; Δy ≤ 2 mm is OK.

Fermilab KEK-type design of 406 MHz deflecting cavity*:



Distribution of E field



Distribution of H field

Parameters		Units
R/Q	27	Ohm
G	255	Ohm
$G\times(R/Q)$	4845	Ohm^2
B_{sp}/V_{kick}	19.2	mT/MeV
E_{sp}/V_{kick}	7.8	MV/m/MeV
Longitudinal size	440	mm
Vertical size	865	mm
Horizontal size	962	mm
Aperture	220	mm

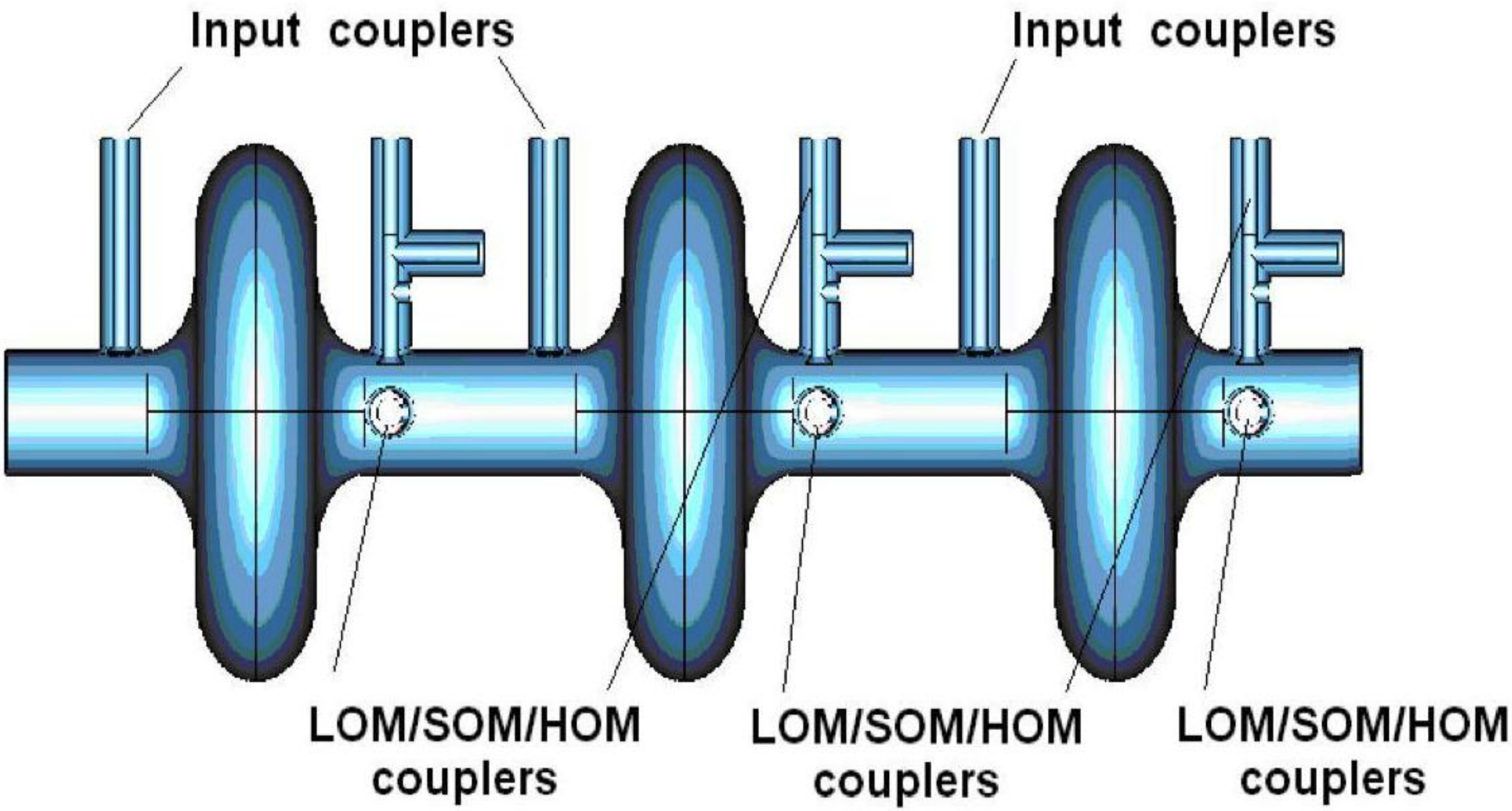
$*R/Q=V_{kick}^2/(2\omega W)$

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

High order modes

*Design developed for previous variant with 325 MHz bunch sequence frequency

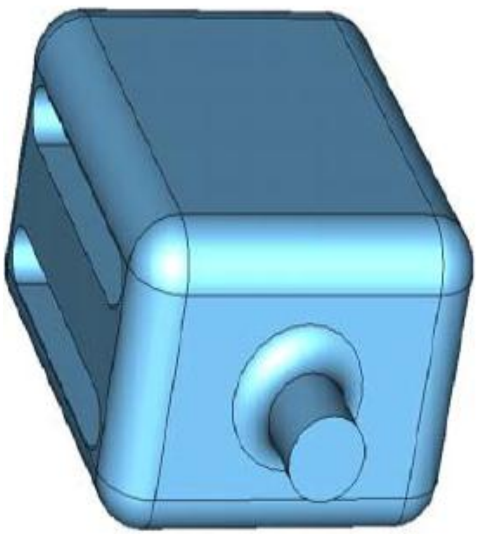
- In order to achieve the kick of 10 MeV one needs 3 cavities.
- The kick per cavity is 3.3 MeV.
- The surface magnetic field is 63 mT, that is OK for this frequency.
- **The length of the cavity+power coupler +HOM couplers is about 1 m.**
- **The total length of the deflecting RF structure is ~3.5 m.**
- **Transverse size is about ~1 m.**

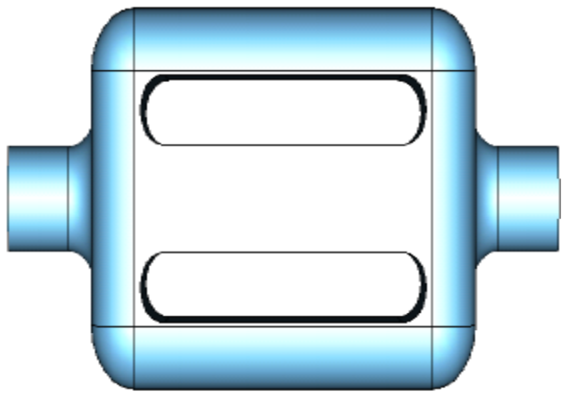


Most probably, LOM/SOM/HOM couplers are not necessary because of small beam current.

Alternative deflecting cavity version: TEM rectangular parallel-bar cavity (PBC)

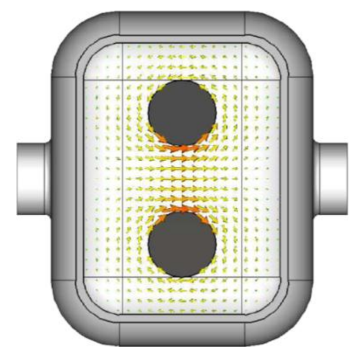
(**Jean Delayen**, Center for Accelerator Science, Old Dominion University)





Parameters		**Units**
R/Q	206.7	Ohm
G	74.1	Ohm
$G\times(R/Q)$	15316	Ohm^2
B_{sp}/V_{kick}	21.0	mT/MeV
E_{sp}/V_{kick}	5.9	MV/m/MeV
Longitudinal size	445	mm
Vertical size	383	mm
Horizontal size	300	mm
Aperture	84	mm

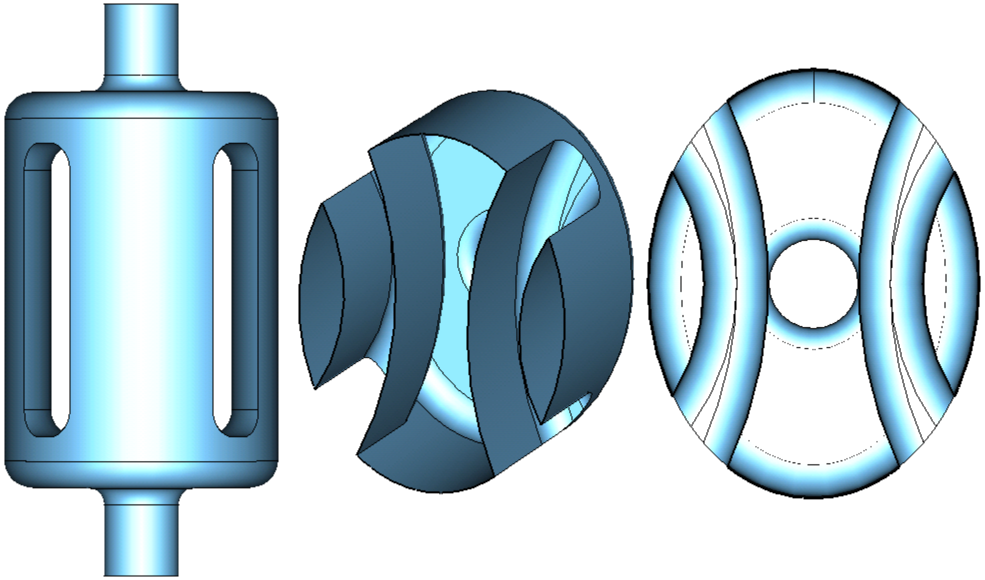
- Much lower cryo losses (~3 times);
- Much smaller transverse dimensions;
- Surface fields are about the same as for KEK-type cavity;
- The concept is not tested yet.



TEM field in the BPC with round bars

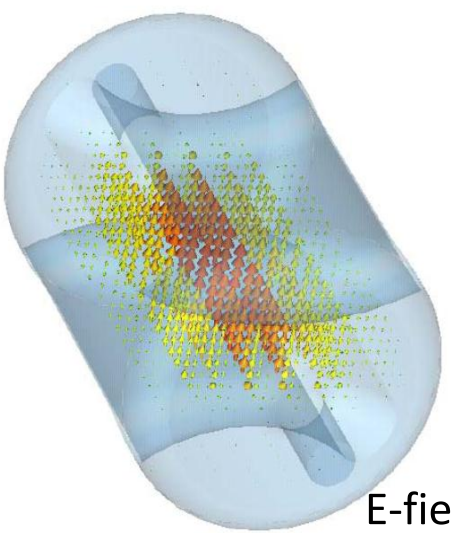
Niowave Inc. submitted Phase I SBIR proposal to DoE

Parallel - bar ellipsoidal cavity (J. Delayen, ODU)

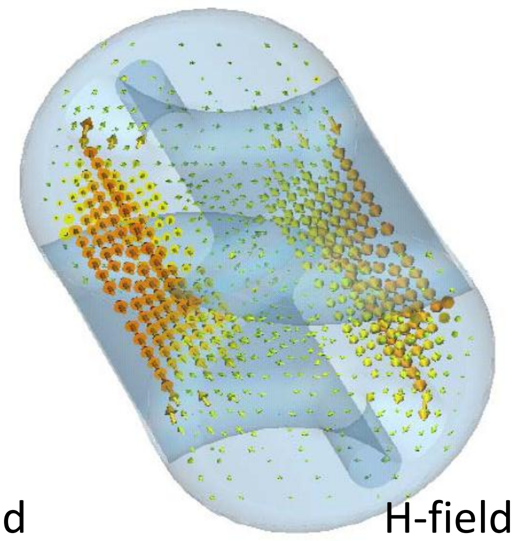


Parameters		Units
R/Q	132	Ohm
G	108	Ohm
$G \times (R/Q)$	14256	Ohm^2
B_{sp}/V_{kick}	16.0	mT/MeV
E_{sp}/V_{kick}	7.2	MV/m/MeV
Longitudinal size	445	mm
Vertical size	406	mm
Horizontal size	295	mm
Aperture	84	mm

- Parameters are about the same as for rectangular PBC

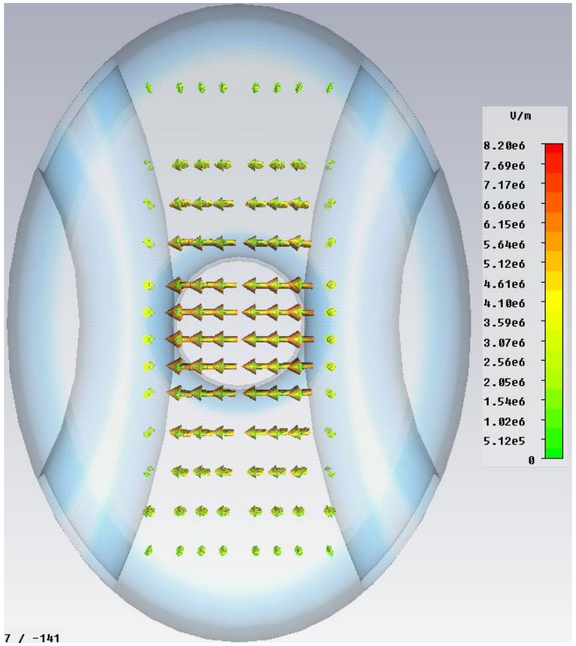


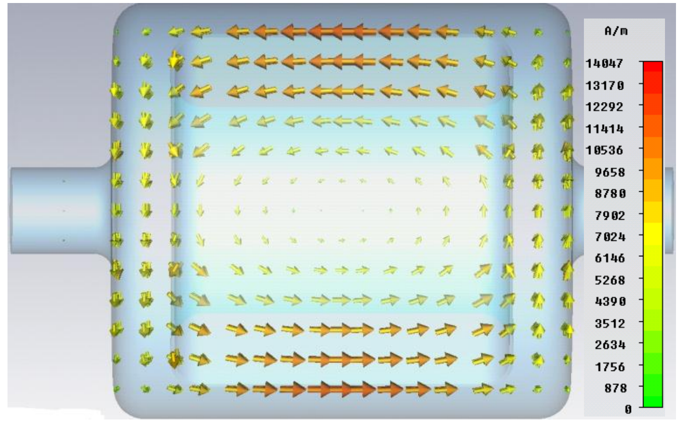
E-field

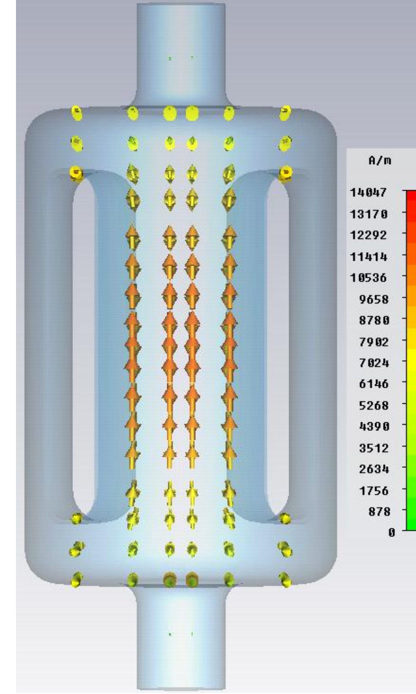


H-field

ORIGINAL ODU VARIANT



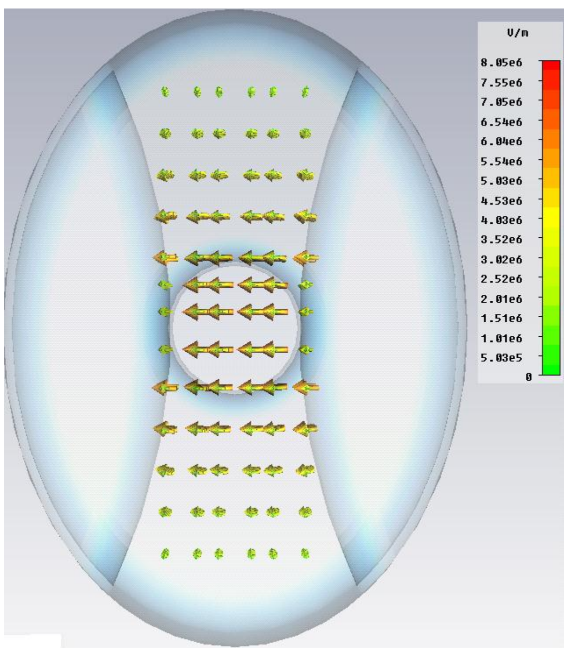


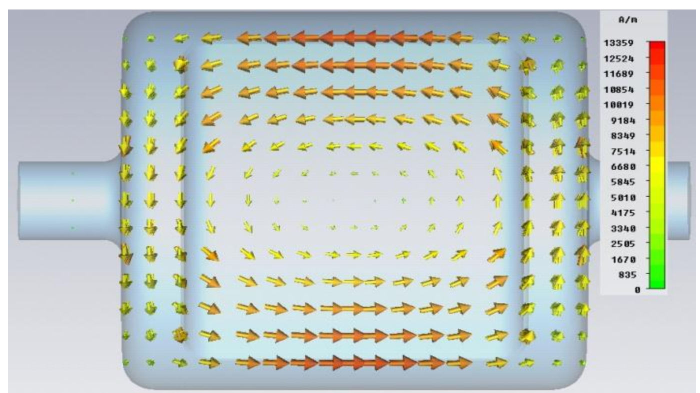


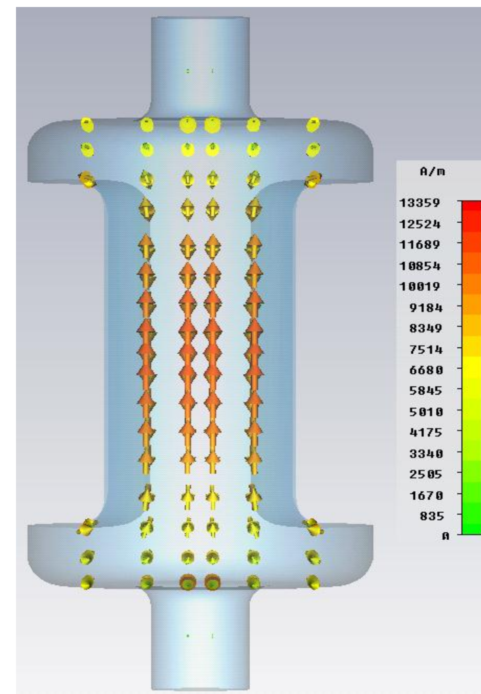
H-Field

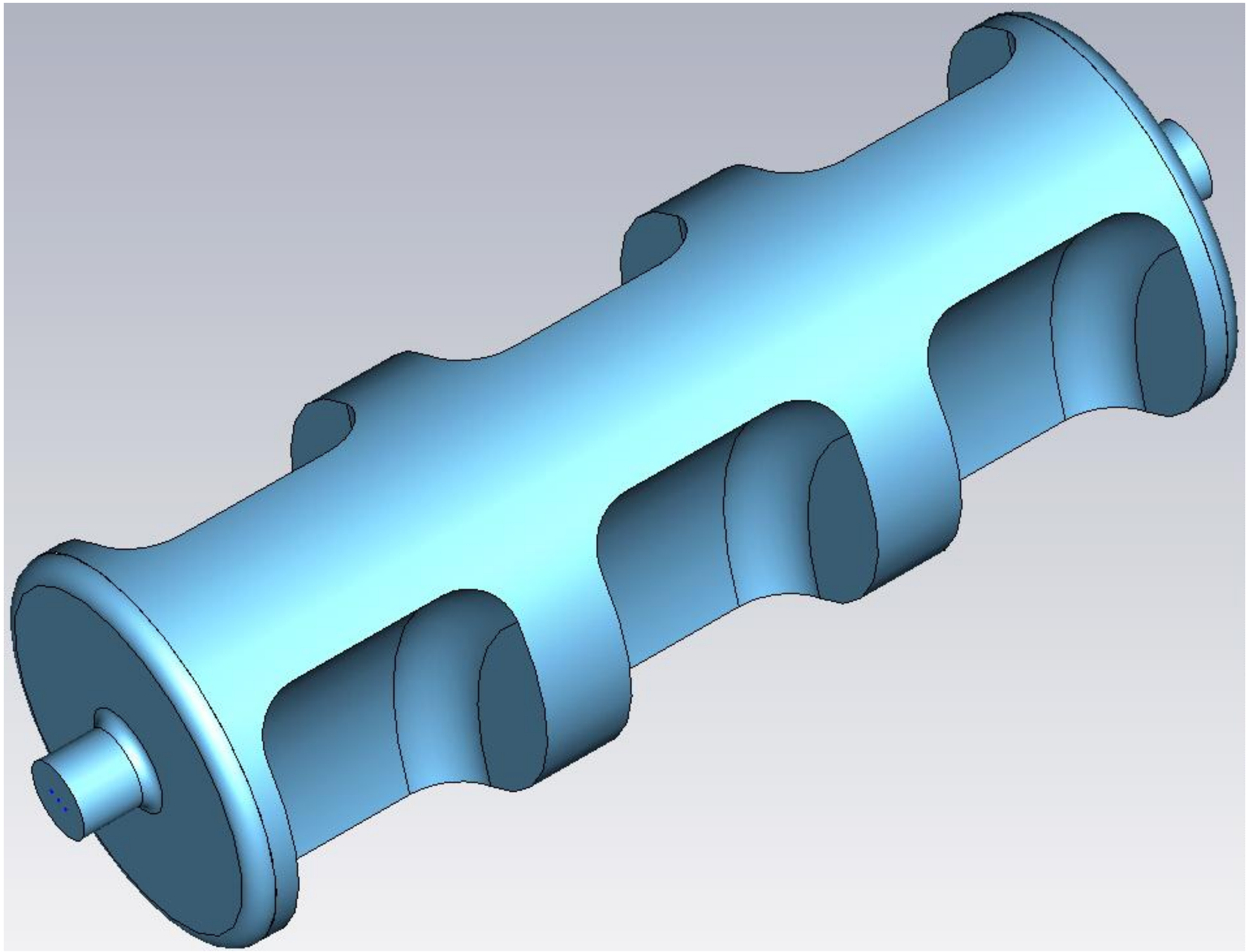
E-Field

VARIANT WITHOUT BARS



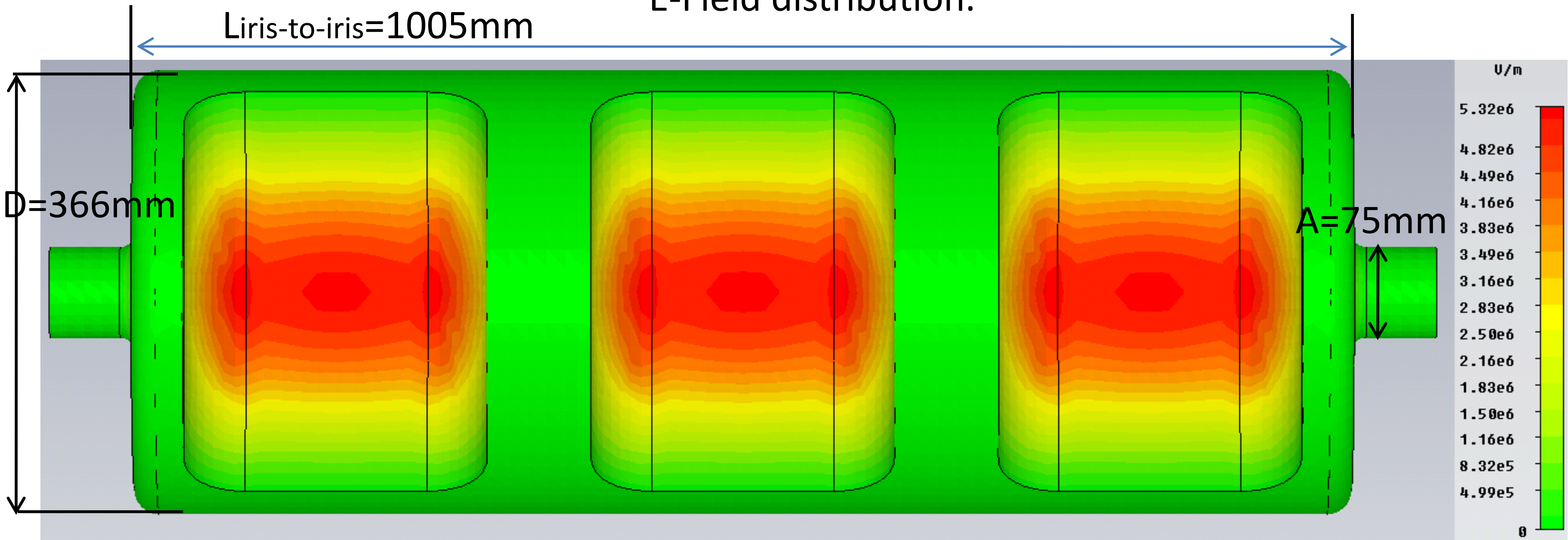




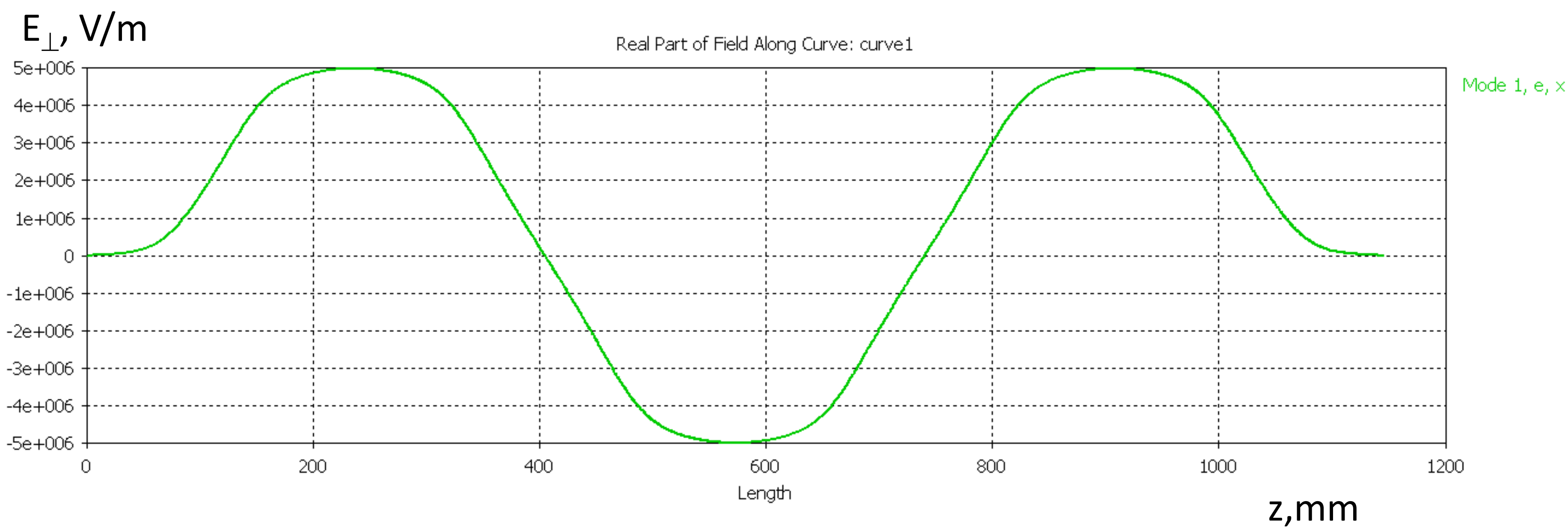


Further development of the ODU TE cavity: FNAL Squashed TE_{113} deflecting cavity for Project X.

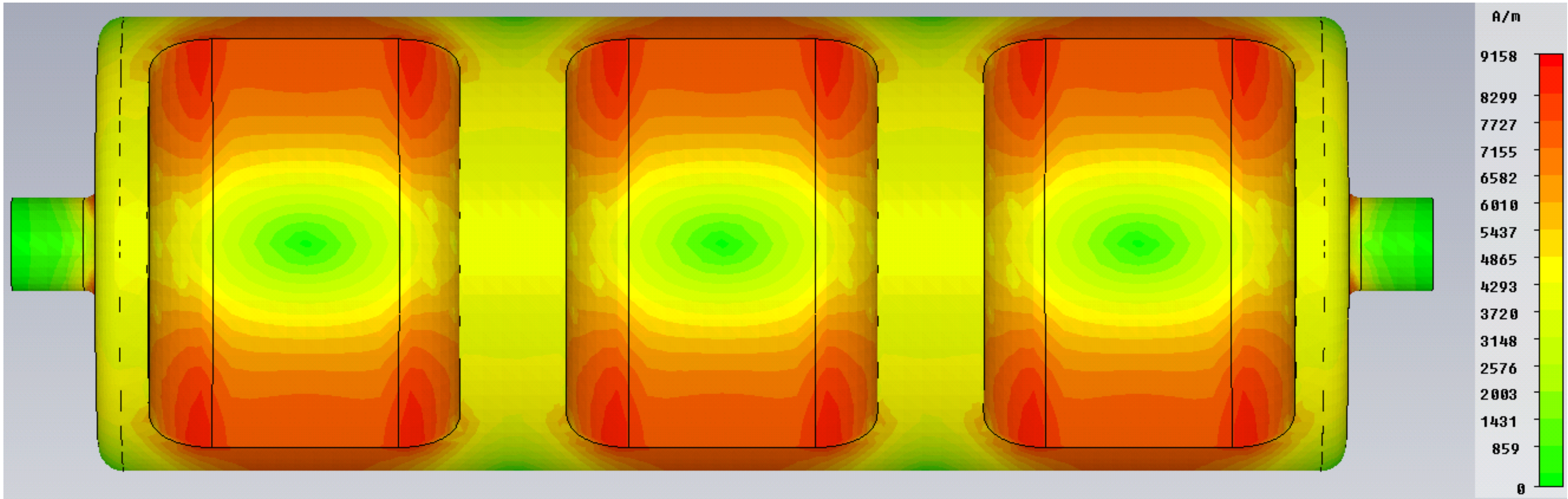
E-Field distribution.



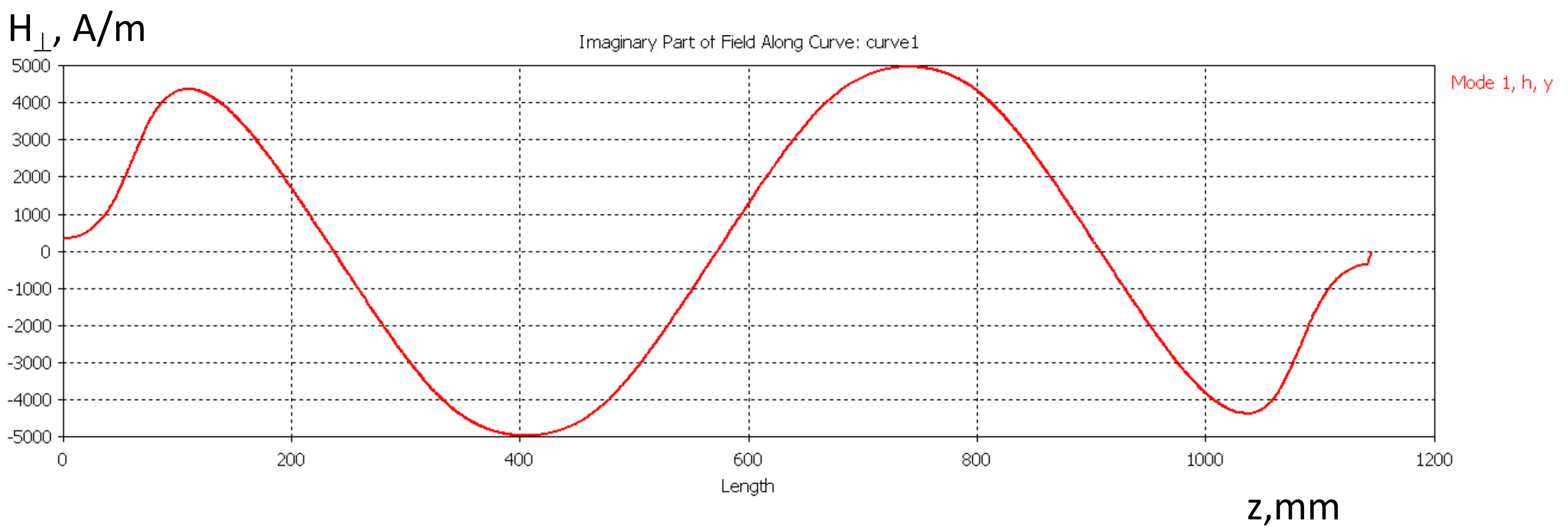
Transverse electric field $E_\perp$ distribution along the axis. Stored energy is 1 J.



H-Field distribution.



Transverse magnetic field $H_\perp$ distribution along the axis. Stored energy is 1 J.



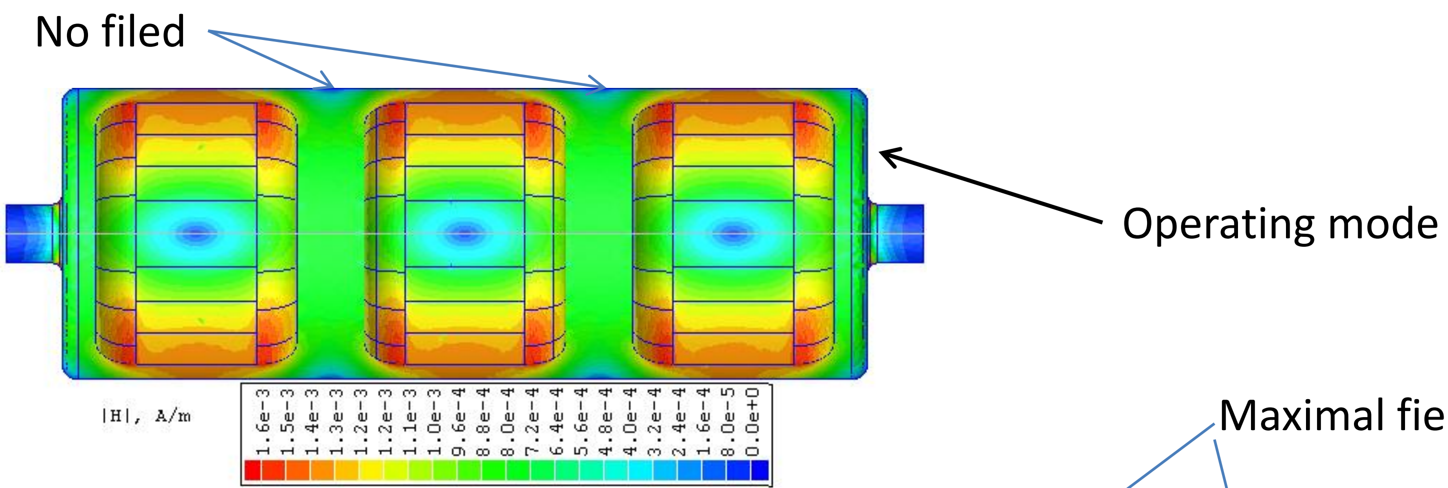
F , MHz	447
Mode	TE_{113}
R/Q*, Ω	500
G, Ω	117
Vkick, MeV	10
Epeak, MV/m	34
Bpeak, mT	74
Cavity Diameter, mm	366
Aperture, mm	75
Cavity Length, mm	1005
Electric Field Kick, MeV	15.87
Magnetic Field Kick, MeV	-5.87

$*R/Q = Vkick^2/2\omega W$

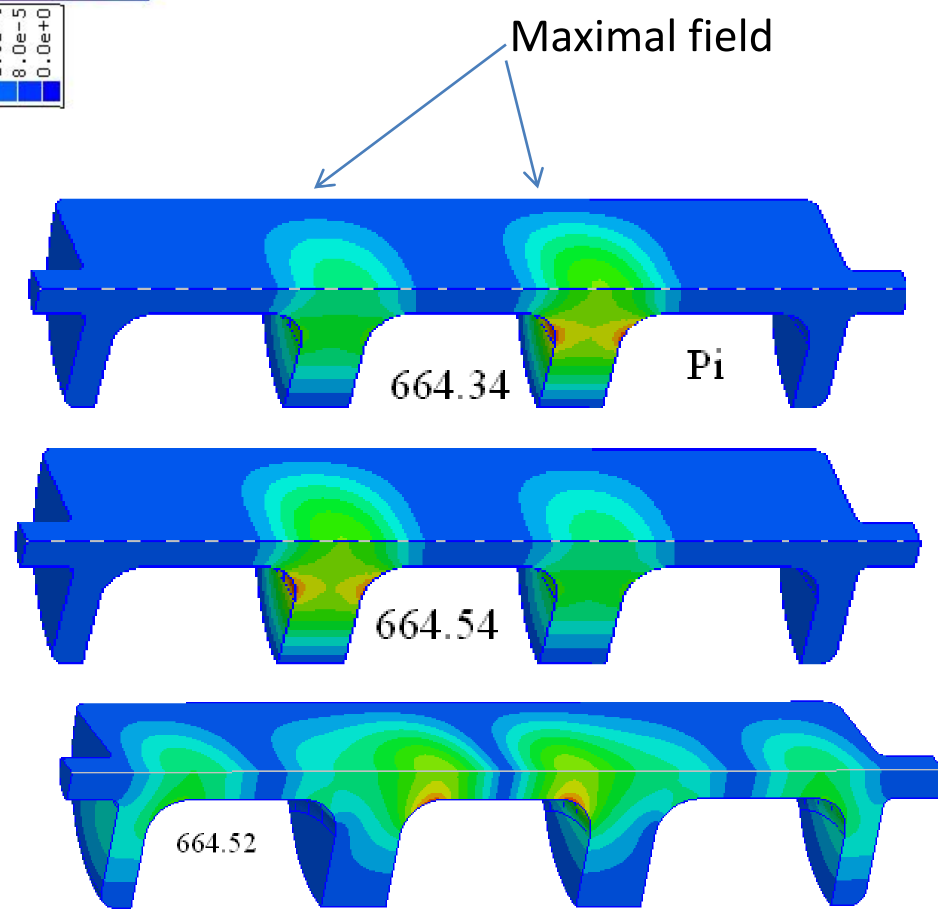
Main parameters of the TE_{113} squashed-wall cavity

HOMs:

Dipole and monopole modes F<1 GHz



F, MHz	Vkick^2/2ωW	Vacc^2/2ωW
376.59	1.5	
419.74	7.6	
447.30	500	
664.34		128.9
664.54		121.3
664.52	41.7	
677.85		82.5
678.28		82.5
705.28	72.1	
719.70	25.7	
922.79	6.2	
937.63	5.8	
982.18	0.0	



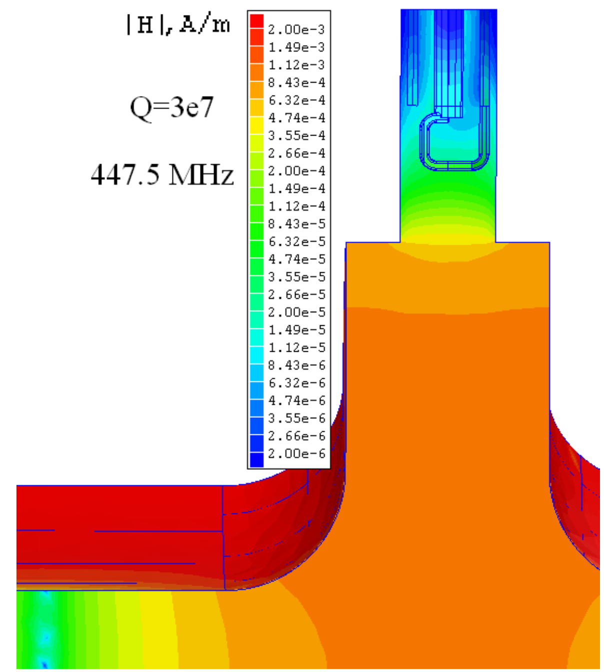
Power losses on a coupler loop.

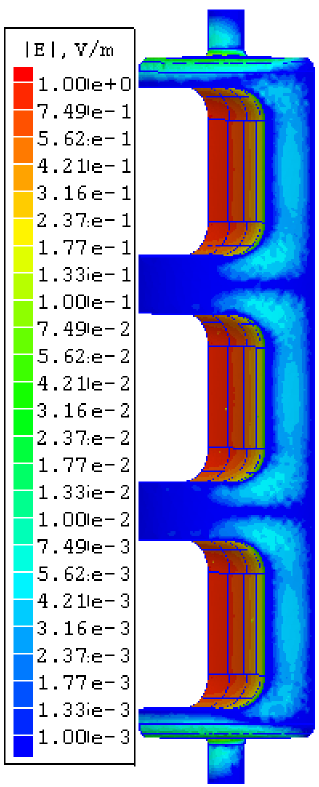
447 MHz deflector cavity. Coupler losses at Vkick=10 MV.

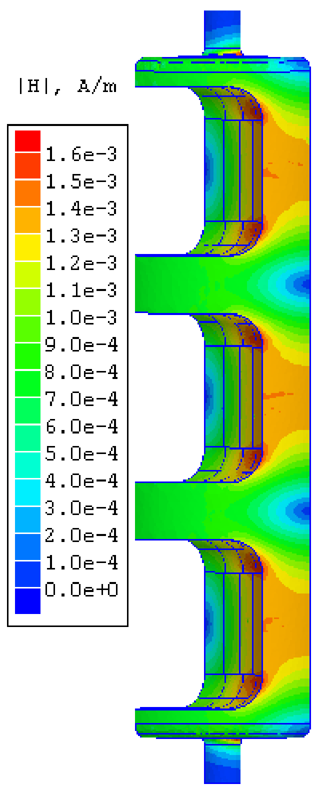
F, MHz	L*, mm	Qext	Rs,Ohm	Pcav, W	Ploop, W
447.3	193	7.6e5	1E-08	8.77	107.60
447.3	203	4.8e6	1E-08	8.77	17.24
447.3	**213**	**3.1e7**	**1E-08**	**8.77**	**2.62**

2K

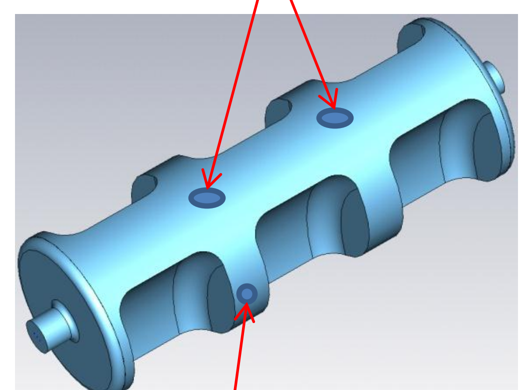
Bandwidth: 15 Hz; Input power in this case is 3.25 kW







HOM damper



Main coupler

L* is the distance of the loop to the beam axis

- The splitting RF cavity is ~300 m far of the CW linac;
- A separate cryo system is preferable*;
- Operating temperature ~3.5 K* (He pressure fluctuations ~0.2 mbar);
- Input power requirements are determined mainly by amplitude of microphonics δf: $P_{inp} \approx U_{kick}^2/[(R/Q)_{\perp}\cdot(f/2\delta f)]$.
  For squashed-wall cavity for δf=15 Hz P_{inp} = 3.25 kW.
- Microphonics amplitude is determined by
  - Expected He pressure fluctuations ;
  - Cavity mechanical properties, namely, df/dP
- Means necessary to fight microphonics:
  - Minimizing of the He pressure fluctuation;
  - Minimizing of df/dP;
  - Minimizing the acoustic energy transmitted to the cavity by external vibration sources;
  - Active piezo control;
  - Cavity over-coupling.

* A. Klebaner

- A modification of the ODU cavity – a squashed-wall TE_{113} one - for the beam splitting system of the Project X is simple and compact .
- One such a cavity provides all the necessary kick of 10 MeV.
- The cavity has the length of 1 m and diameter of 0.37 m instead of 4.5 meter-long, 1 m in transverse size 3-cavity KEK-type RF system.
- The new cavity sizes are close to FNAL 650 MHz cavity. Thus, all the same surface processing and test facilities may be used.
- This cavity may be used for 1 GeV extraction, which is also considered for ADS experiments.

CONCLUSION:

❖Beam splitting cavity for PX should have the following requirements:

- RF kick – 10 MeV CW;
- Frequency - 447 MHz (or 366 MHz).

❖Beam splitting cavity for PX has the following features/issues:

- Small beam loading (operating frequency is not harmonic of the bunch sequence frequency);
- Most probably, no problem with HOMs (small beam current);
- No size limitations.

But:

- Microphonics;
- Emittance dilution for non-deflected bunches.

❖Our baseline:

- 3-gap squashed-wall cavity (version of ODU parallel – bar cavity) .

Synergy with the LHC crab cavity CM:

	Project X	LHC CC	
The kick, MeV	10	5	
Frequency, MHz	447	400	close
Transverse size	about the same		
Longitudinal size	about the same		
	(taking into account HOM dampers for LHC CC)		
Operating temperature	about the same		
HOM issues and dampers	no	yes	
Microphonics issues	yes	no	
Emittance dilution	yes	no	
Environment limitations (including the second beam pipe)	no	yes	

CMs for PX deflecting cavity and LHC CC may contain many common elements