Crab Cavities Conditions

Rama Calaga, CERN

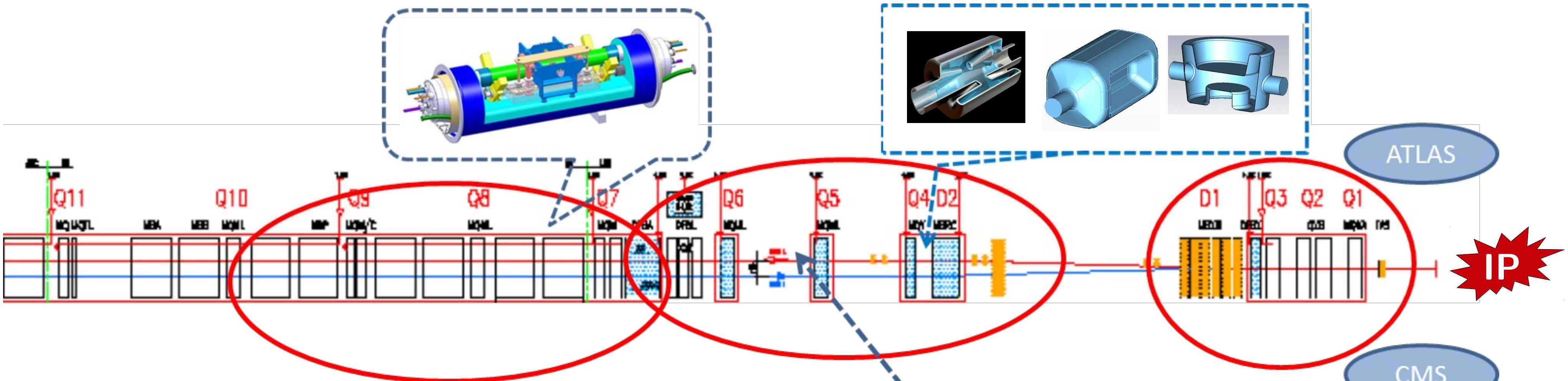
Task 2.2 Meeting, Sep 20, 2012

HL-LHC & crab cavities (why, what & how?)

Basic parameter choice

Present Status, Next Steps

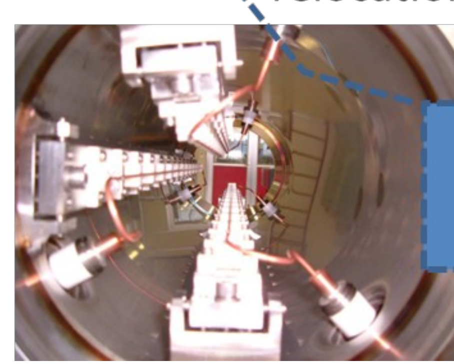
A total of 1.2 km of the LHC ring to upgraded



3. For collimation we need to change also this part, DS in the continuous cryostat

2. Deep change also matching section: Magnets, collimators and CC

1. Deep change in the IRs and interface to detectors; relocation of Power Supply

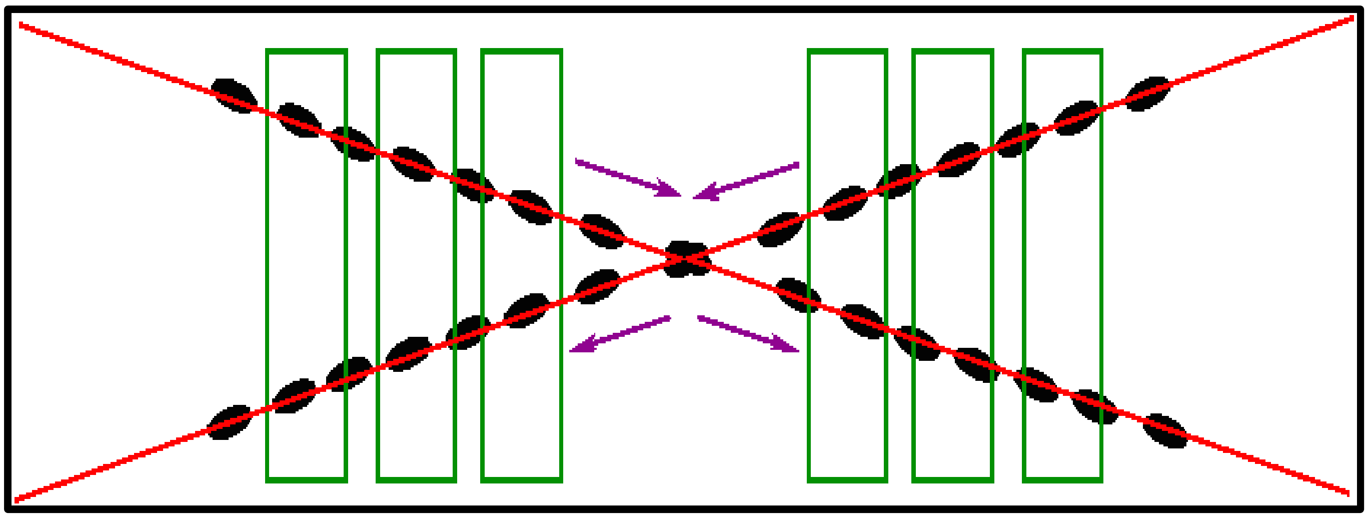


4. LR BB compensation wires

Upgrade with β* Reduction

32+ parasitic interactions/IP

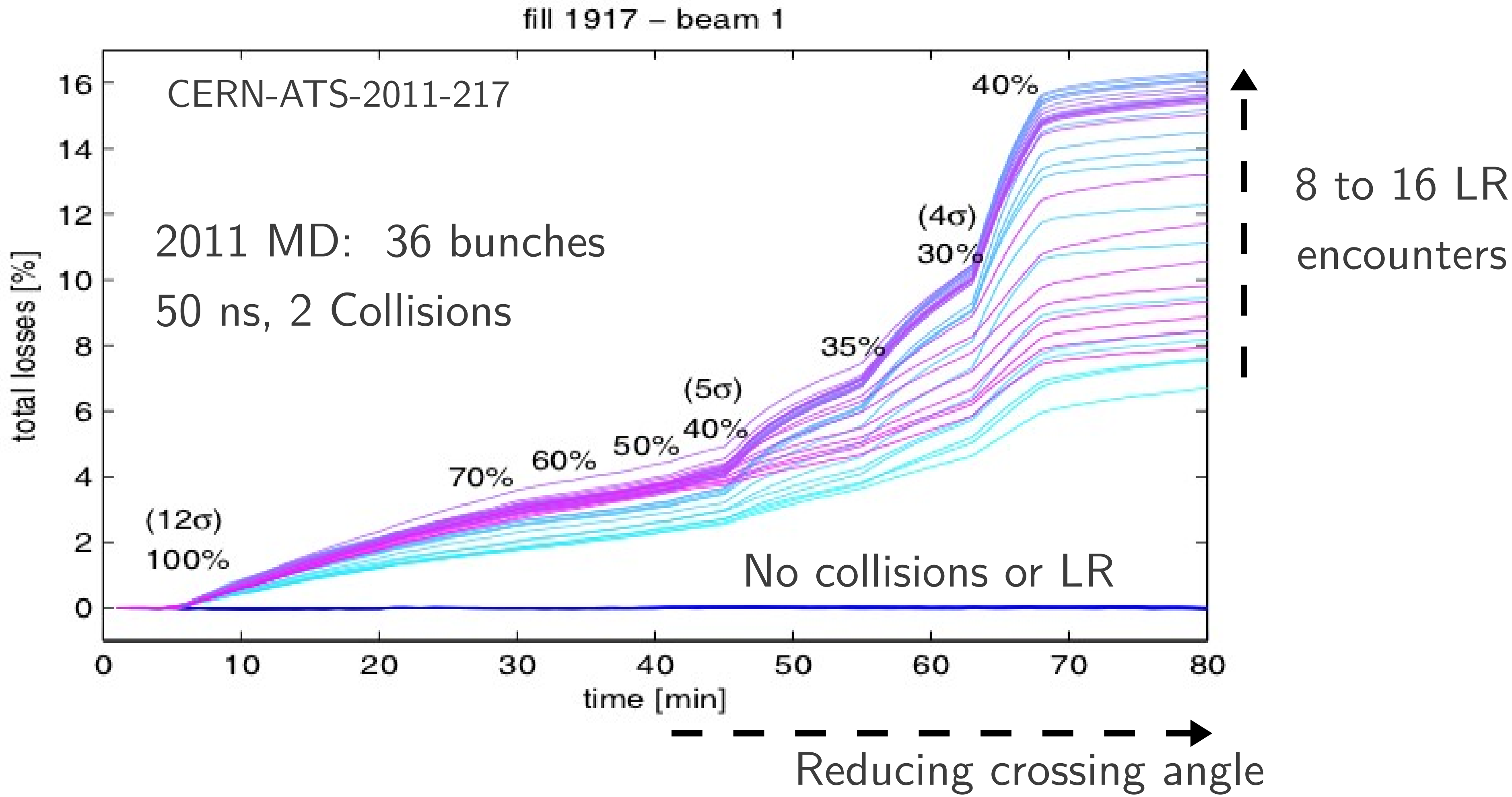
Maintain ∼10σ separation



[1]Some preliminary simulations indicate an increase in the separation ∼12σ

[1]S. White et al., LHC-CC10

For Non-Believers

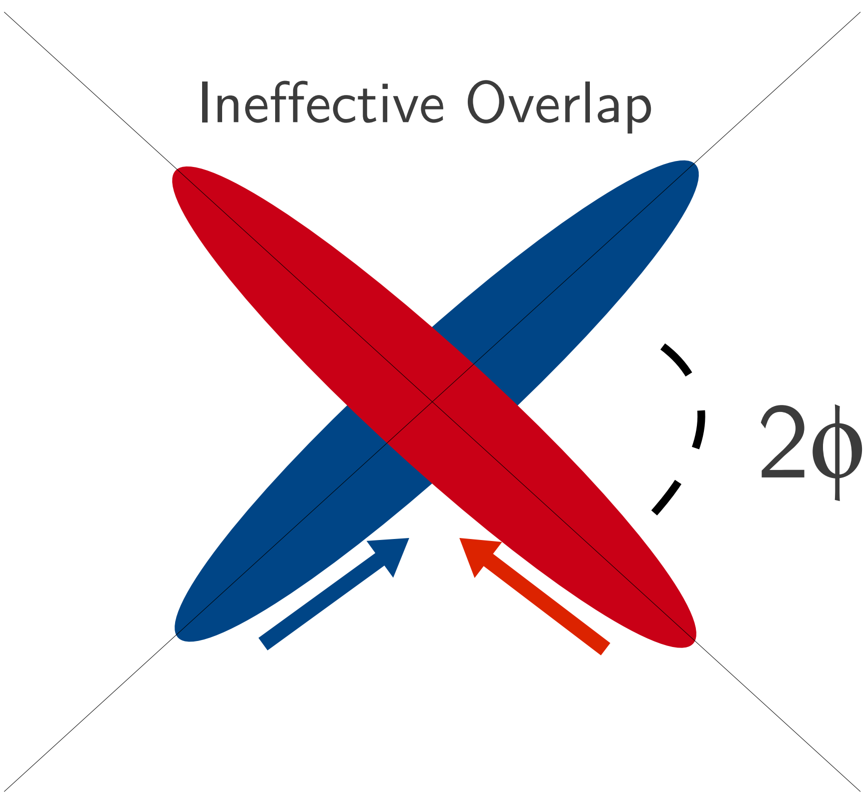


Nominal $\rightarrow$ 4 IRs, 120(+) parasitic encounters

Consequence

Upgrade: reduce β* (by factor 2-4)

Approx double the crossing angle (10σ sep)



Piwinski angle

$$\Phi = \frac{\sigma_z}{\sigma_x} \phi_c$$

$$\sigma_{eff} = \sqrt{\sigma_x^2 + \sigma_z^2 \phi_c^2}$$

Note: don't forget hour-glass effect (for β^*/σ_z)

Some Numbers

$$L = L_{HO} \cdot R_{\Phi}$$

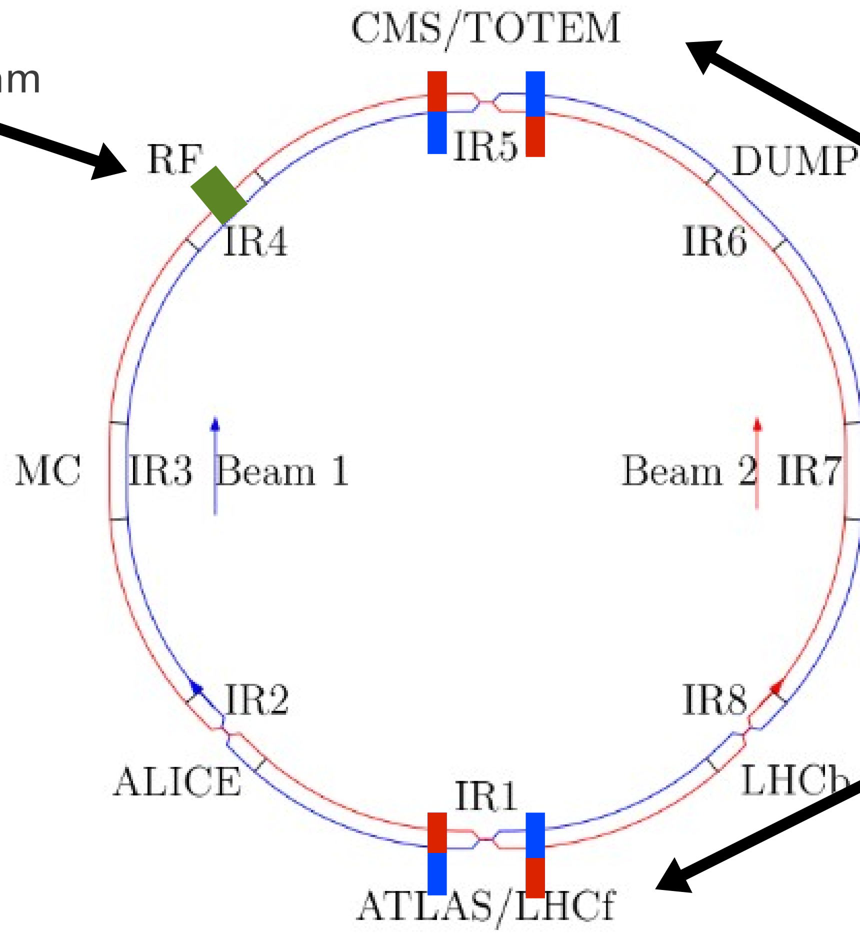
	2012	2015	2023
Energy	4 TeV	7 TeV	7 TeV
β^* [cm]	60	55?	15
2ϕ [μrad]	313	247	473

$R_{\Phi}(\sigma_z = 7.55\text{cm})$	0.85	0.82	~0.37	very inefficient
Pile-Up	~40	19	100-150	

(Assume: $2\,\phi \simeq d.\sqrt{\epsilon/\beta^{ip}}$ $\varepsilon_N = 2.5\ \mu\text{m}$, $d=10\sigma$)

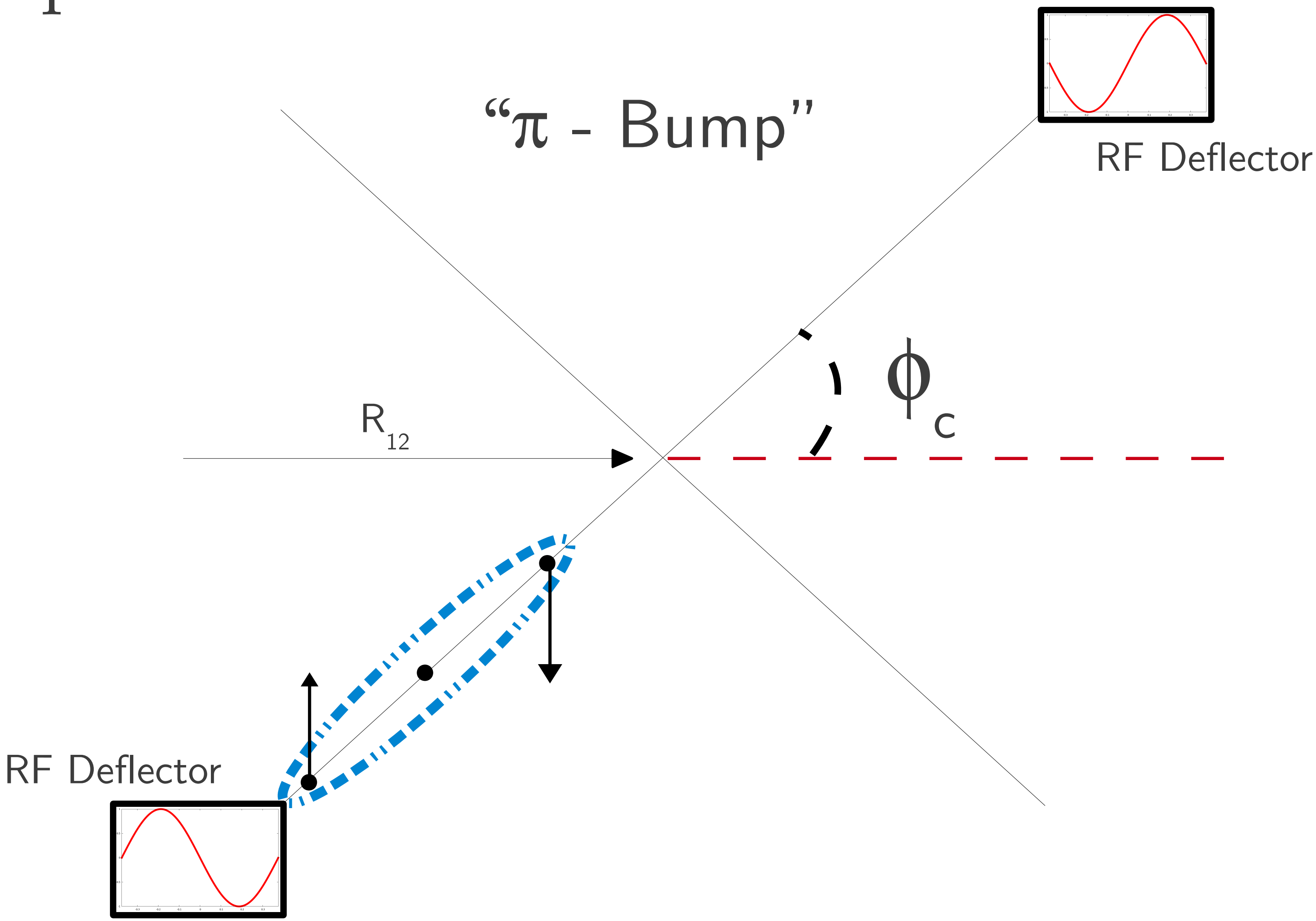
To Recover

Single test module /beam
@IR4, Global Scheme



BASELINE
4 modules per beam
@IR5/IR1, Local Scheme

Principle



$$\Delta p_x = \frac{qV}{E} . \sin(\phi_s + \omega t) \longrightarrow V_{crab} = \frac{cE \tan(\phi_c)}{\omega R_{12}} . \frac{2 \sin(\pi Q)}{\cos(\phi_{cc-ip} - \pi Q)}$$

Pile up is serious for detectors & their design

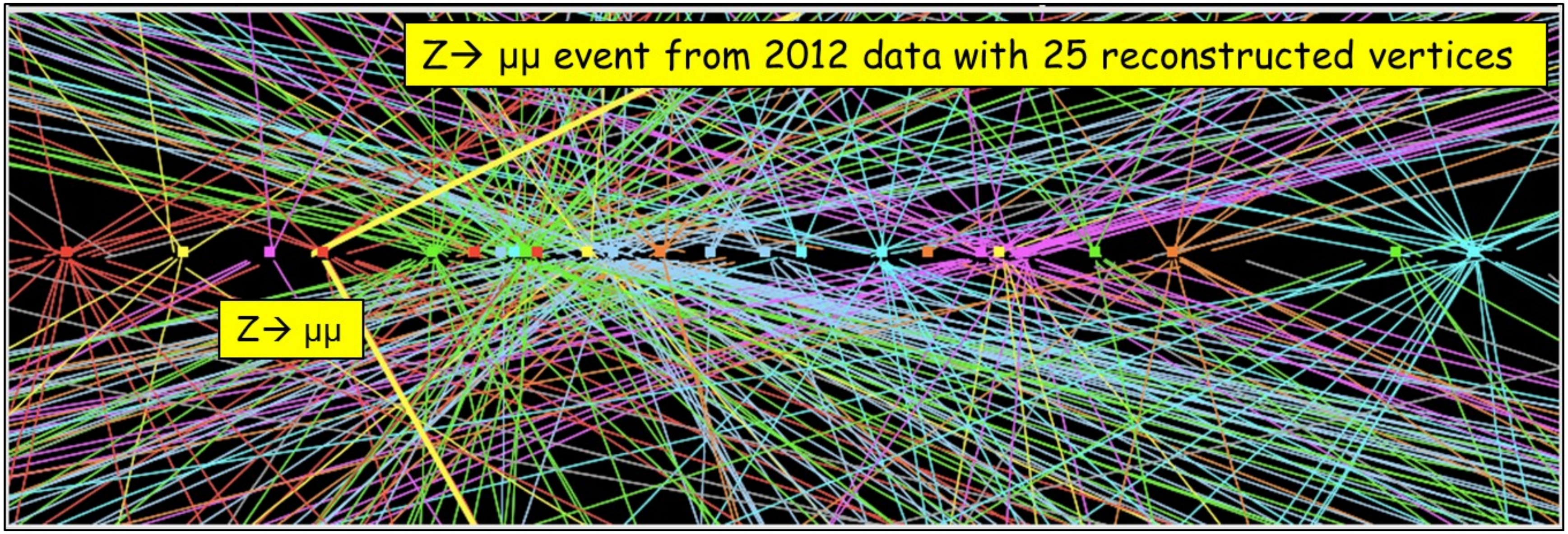
Leveling highly desired (maybe required)

Presently:

- Leveling with offsets at IP2/IP8

Upgrade:

- Leveling with crossing angle (natural with crabs)
- Leveling with β^* $\rightarrow$ constant luminous region + crabs for HO



Courtesy ATLAS

Proposed in 2005 $\rightarrow$ 5 yrs of conceptual designs $\rightarrow$ Baseline upgrade scheme

(5 dedicated workshops, Unknown number of papers/presentations)

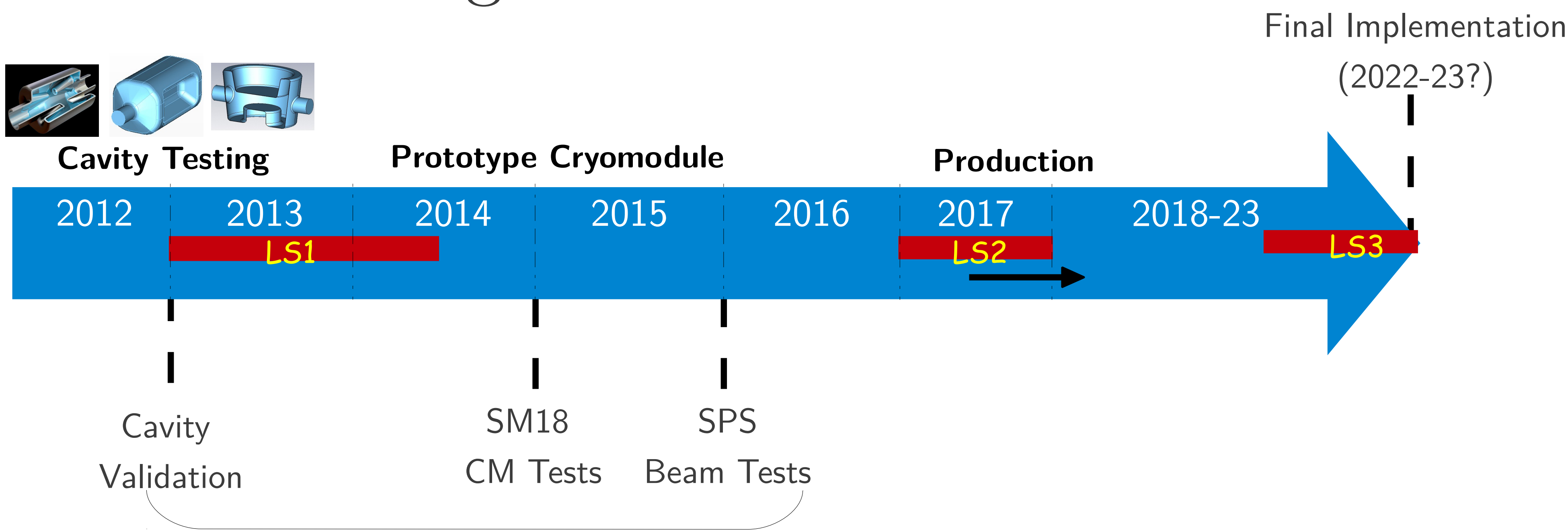
5th Workshop: LHC-CC11, Nov 2011

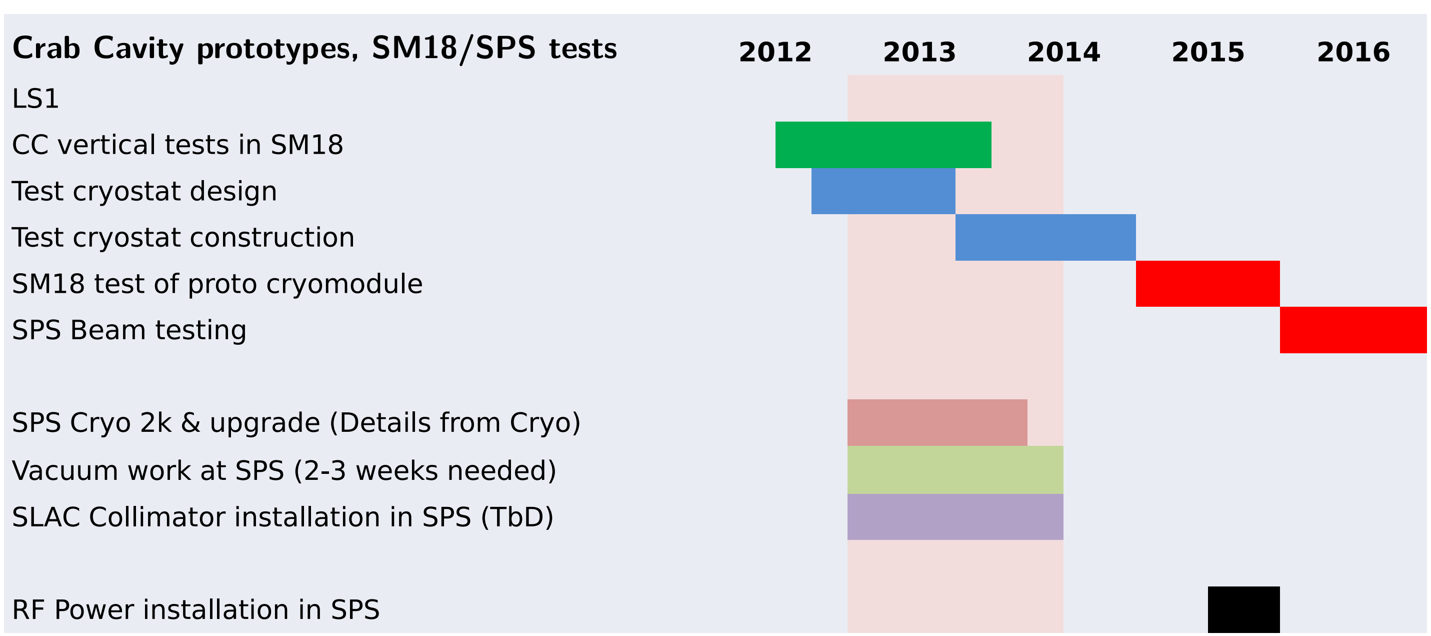
1. LHC Performance & Limitations
2. Deflecting Cavity Design
3. Fabrication of prototypes & Cryomodules
4. SPS beam tests
5. Optics & non-linear issues
6. Machine protection
7. Impedance & beam-beam issues
8. Planning & upgrade

Full Summary Report:

https://indico.cern.ch/materialDisplay.py?materialId=paper&confId=149614

Overall Planning





Basic Parameters

Frequency = 400 MHz, Transverse Diameter < 300mm

Voltage = 3 MV/cavity (2-3 cavities /module)

Operating Temp = 2 K

Qext = 10^6, R/Q ~300 Ω

RF power source = 60 kW (< 18 kW nominal)

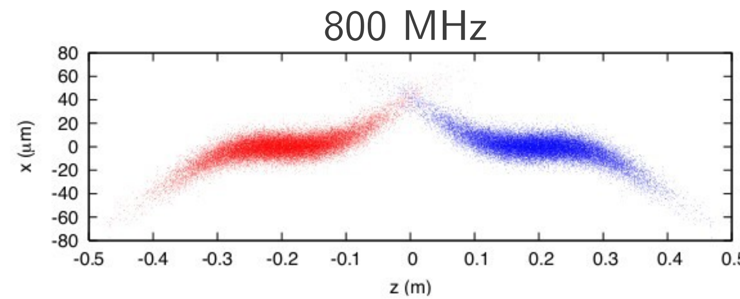
Cavity tuning/detuning ~ ± 1.5kHz (or multiples of it)

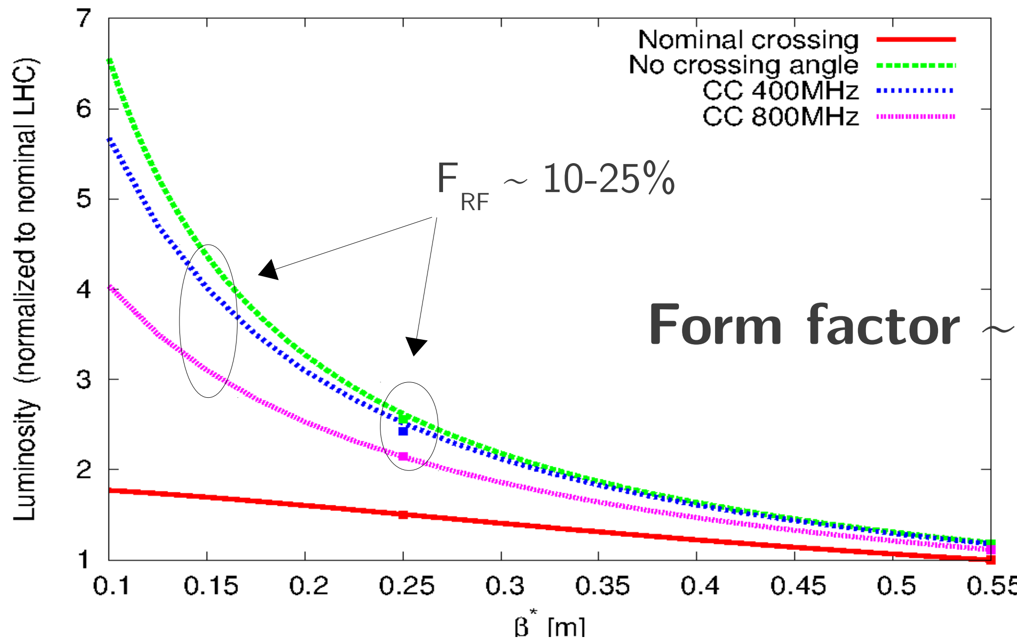
β-functions at Crab location: 3.8-4.3 km

Why 400 MHz

RF non-linearity (longitudinal)

$$L \propto \frac{N_b^2}{\sigma^2} R_\Phi F_{RF}^\Phi$$





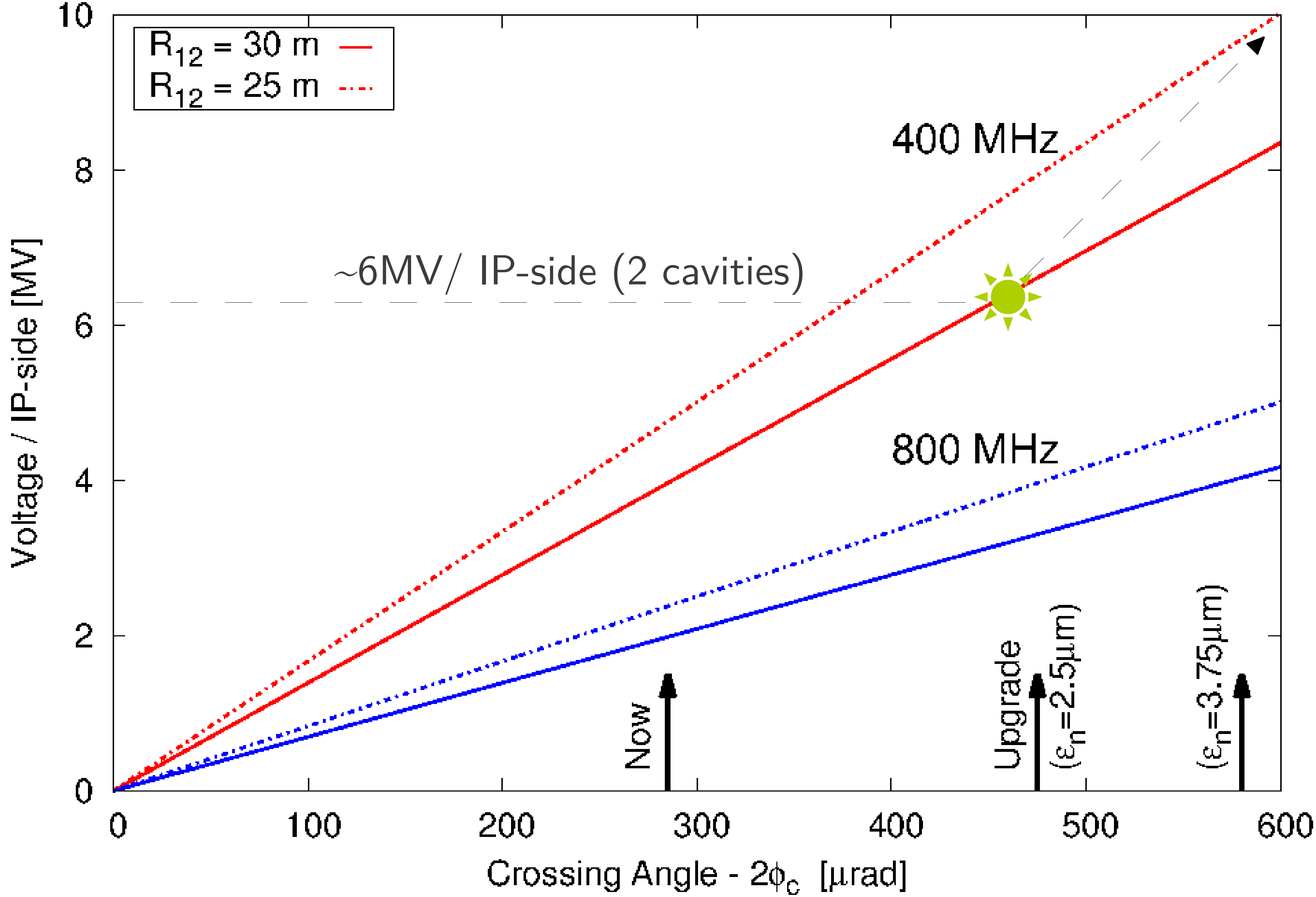
Form factor ~1 (β* 10-55 cm)

Higher frequency: smaller cavities, less voltage, phase noise

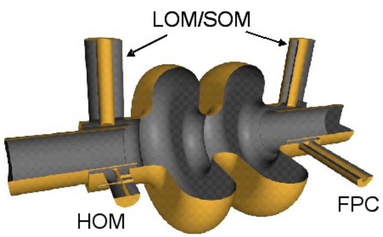
(Not all advantages are realizable)

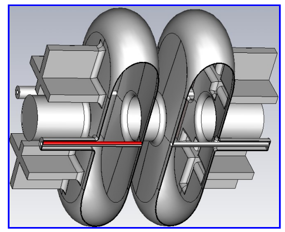
Cavity Voltage

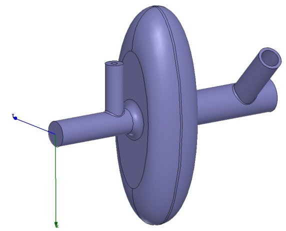
3 Cavities

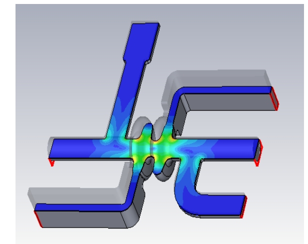


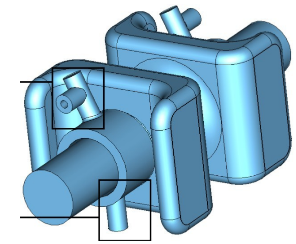
Cavity Designs Proposed for LHC

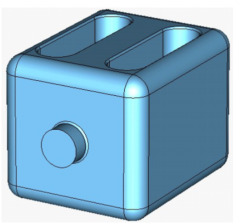


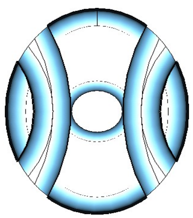


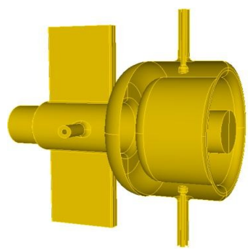


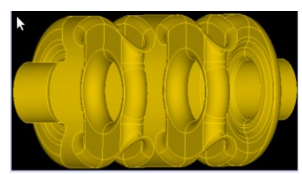


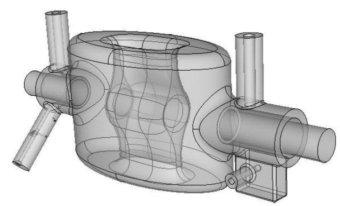


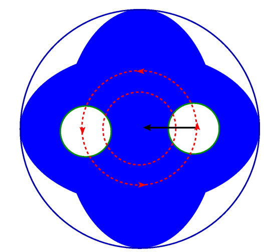


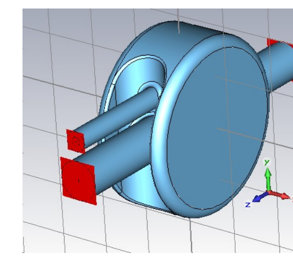


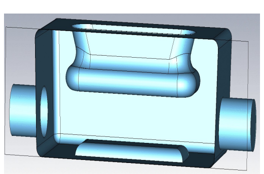


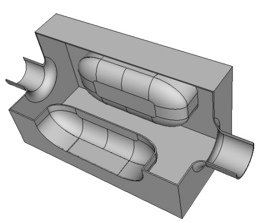


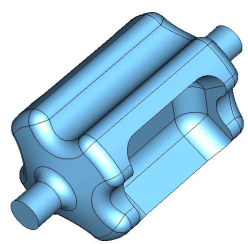


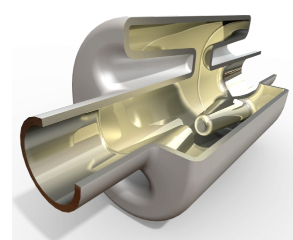


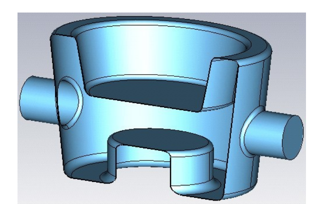


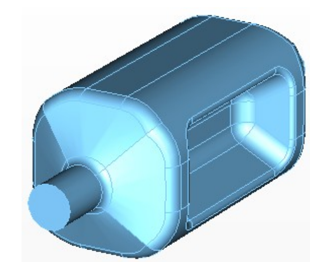










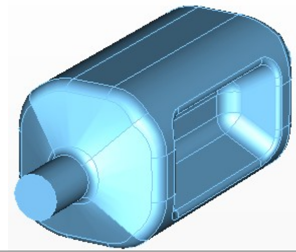
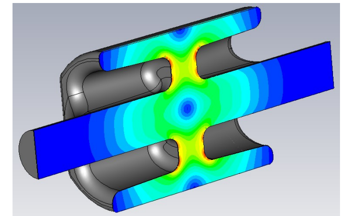
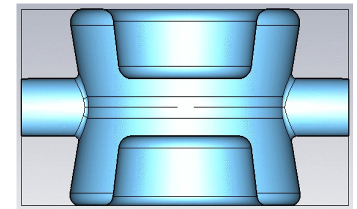


~4yr of design evolution

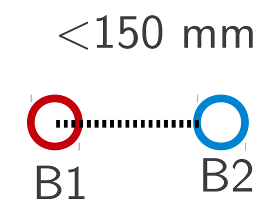
Exciting development of new concepts
(BNL, CERN, LU-CI-DL, FNAL, KEK, ODU/JLAB, SLAC)

Performance Chart

Kick Voltage: 3 MV, 400 MHz

		Double Ridge (ODU-SLAC)	4-Rod (UK)	¼ Wave (BNL)	
Geometrical	Cavity Radius [mm]	**147.5**	**143/118**	**142.5**	
	Cavity length [mm]	597	500	331	
	Beam Pipe [mm]	84	84	84	
RF	Peak E-Field [MV/m]	34	32	32	< 50 MV/m
	Peak B-Field [mT]	61	60.5	57	< 80 mT
	R_T/Q [Ω]	336	915	395	
	Nearest Mode [MHz]	584	371-378	582	



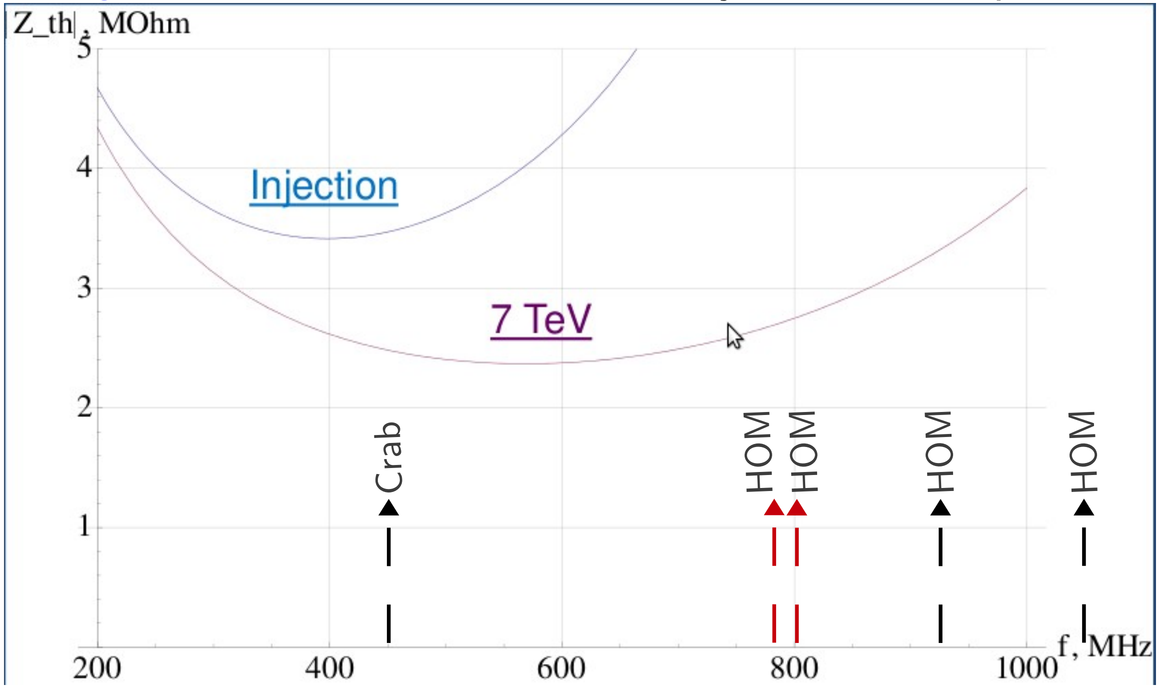
Apologies, if numbers are not latest

(Pl. correct me so I can update this table)

Impedance Thresholds

Longitudinal

Courtesy: Burov, Shaposhnikova



Longitudinal impedance

2.4 MΩ total (7 TeV)

Strongest monopole mode:

R/Q=200Ω → Qe<1x10^3

Damping → Qe < 100-500

Transverse

Energy $\gamma m_p c^2$	Beta-function $\beta_{x,y}$	Impedance $-\mathrm{Re}\, Z_{\mathrm{th}}$
450 GeV	150 m	2.7 MOhm/m
7 TeV	4 km	1.5 Mohm/m

Strongest dipole mode:

Z < 0.6 MΩ/m (0.58 GHz)

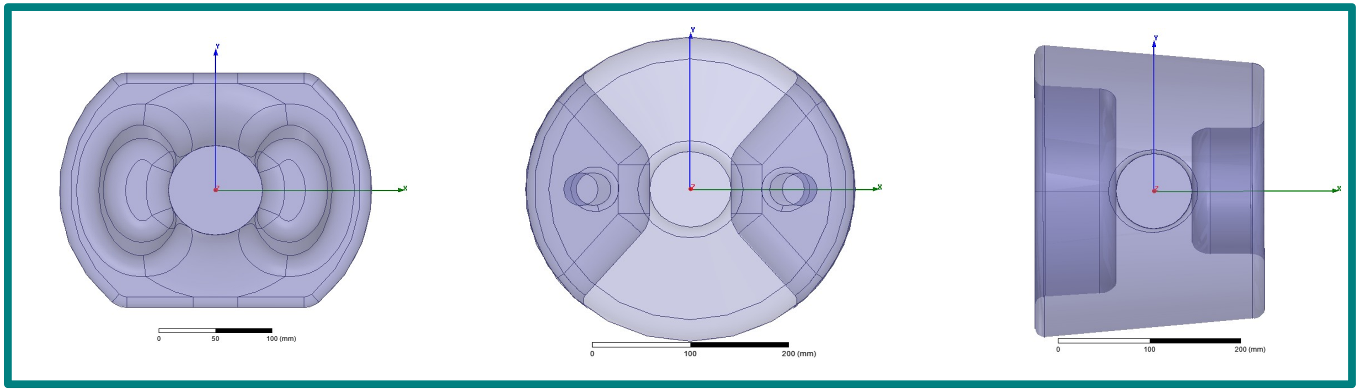
(Qext = 500)

RF Multipoles

Courtesy: A. Grudiev et. al

Like IR magnets, higher order components of the deflecting field important

Long term simulations underway to determine tolerances



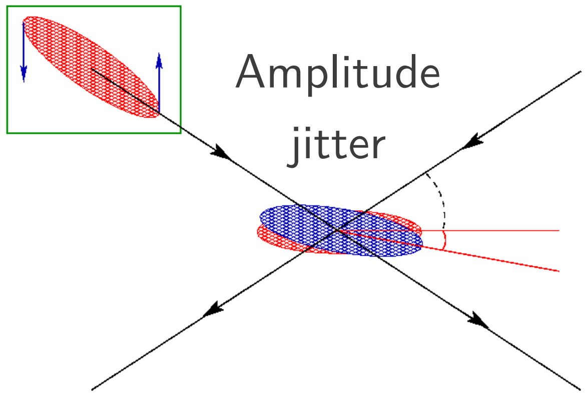
Mitigation by shaping

mTm/m^{n-1}	MBRC	4-Rod	Pbar/DRidge	¼-wave
~~b_2~~	55	0	0	114
b_3	7510	900	3200	1260
b_4	82700	0	0	1760
b_5	2.9×10^6	-2.4×10^6	-0.5×10^6	-0.2×10^6
b_6	52×10^6	0	0	-1.7×10^6
b_7	560×10^6	-650×10^6	-14×10^6	0

→ $\Delta Q \sim 10^{-3}$

→ $\Delta \xi \sim 10^{-3}$

RF Noise



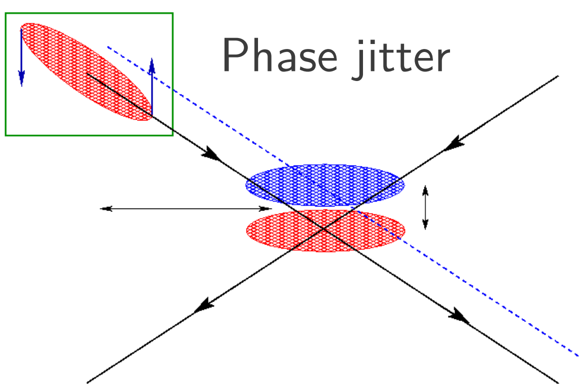
$$\frac{\Delta V_T}{V_T} \ll \frac{1}{\tan(\theta/2)} \frac{\sigma_x^*}{\sigma_z}$$

<u>For example:</u>

θc=570µrad; ΔV/V=0.4%

σ_x*=7µm, σ_x*=7.55cm

θ_{err}=1.2µrad



$$\Delta x_{IP} = \frac{\theta_c}{k_{RF}} \delta\phi$$

<u>For example:</u>

$\Delta\phi = 0.005^0$, θc=570µrad

Δx_{IP} = 0.3µm (5% of σ_x^*)

LHC Main RF, $\Delta\phi = 0.005^0$ at 400 MHz (Philippe)

(summing noise at all betatron bands from DC→300kHz)

Note: IOTs & SSAs are <u>less noisy</u> + betatron comb ($\Delta\phi \leq 0.001$)

MP: Potential Failure Scenarios

Some "slow" failures

- Power supply trips (50-300 Hz > millisec) $\rightarrow$ greater than 300 turns
- RF arcing (few μs) $\rightarrow$ Response of cavity τ_F (millisec)
- Operator mistake $\rightarrow$ Response of cavity τ_F (millsec)
- Mechanical changes $\rightarrow$ high Q SC cavity (100's of ms)

$$\tau_F = 2Q_{ext}/\omega$$

Fast failures

- Cavity quench or RF breakdown
- Sudden discharge in the cavity or couplers
- Fast orbit changes (due to what?)

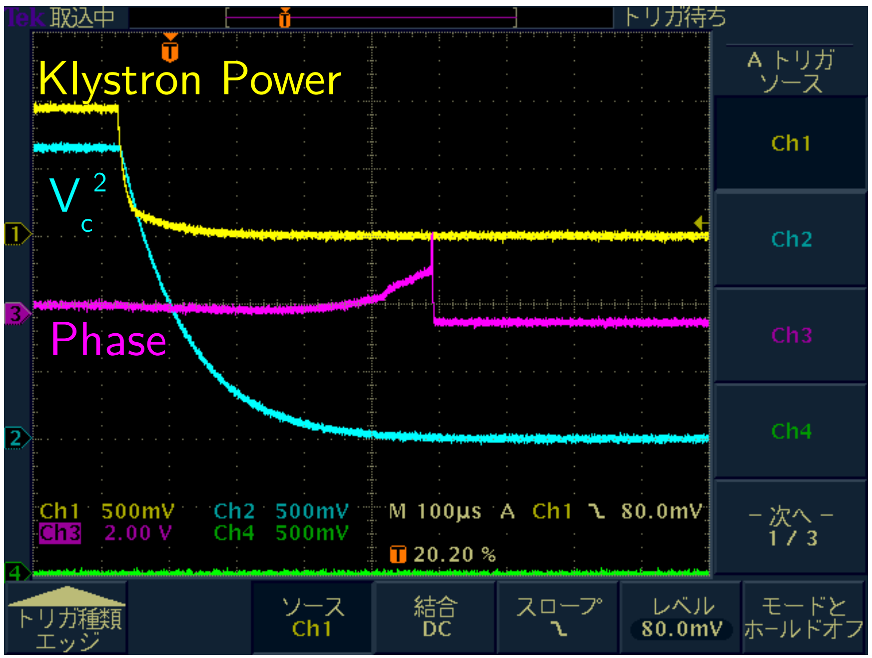
LHC Collimation, maximum allowed losses (R. Assmann, HB2010):

- Slow: 0.1% of beam per second for 10s
- Transient: 5×10^{-5} in ~ 1ms
- Fast: Upto 1 MJ in 200ns into 0.2mm^2

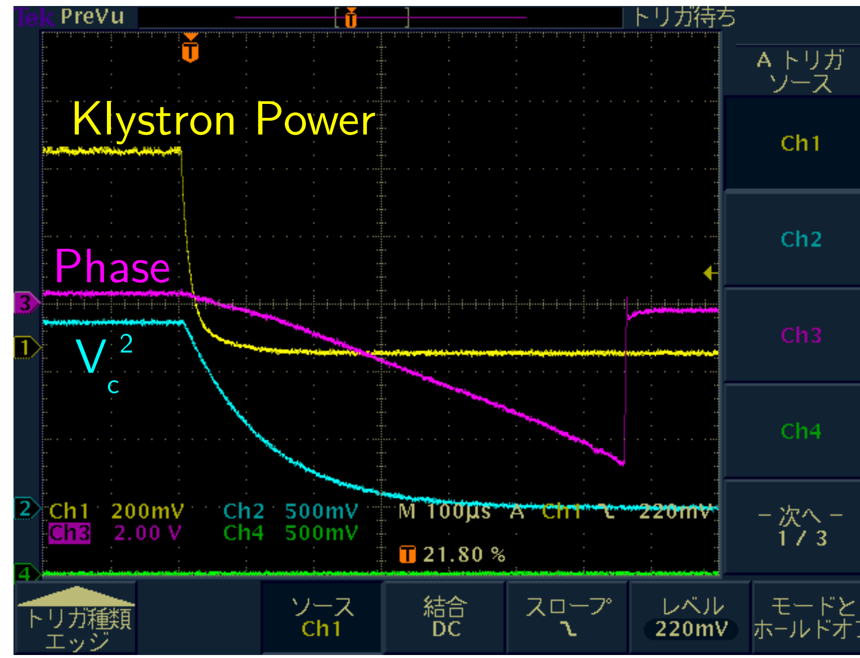
KEKB: RF Off (No Beam)

K. Nakanishi et al., LHC-CC10

HER Ring



LER Ring



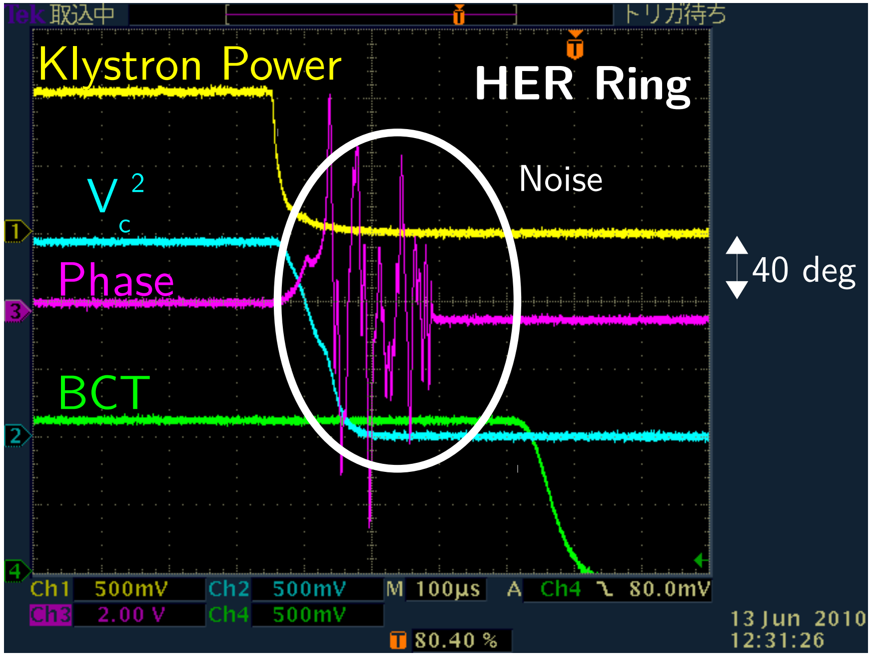
Mainly gradual changes in phase is observed

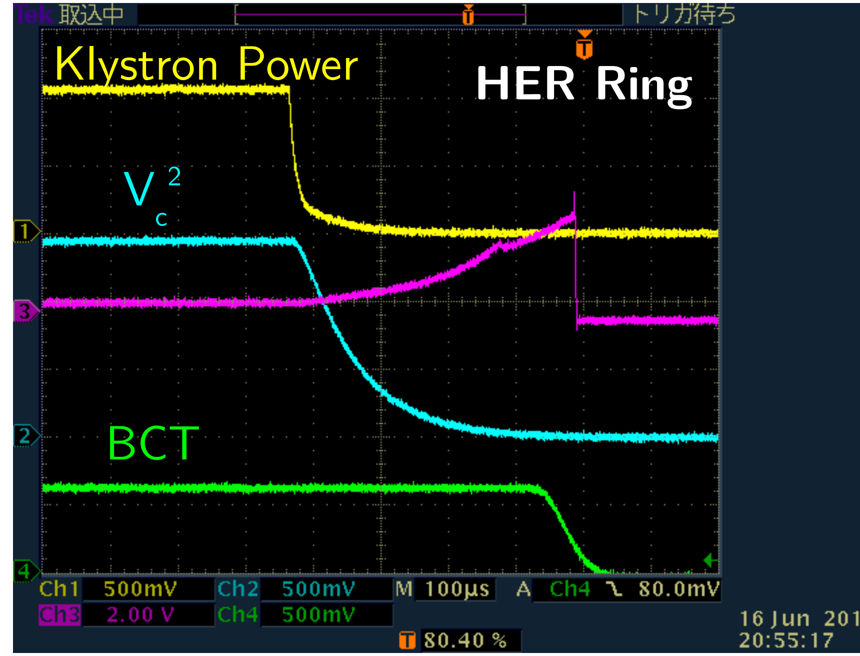
Some erratic phase behavior in HER cavity → possible input coupler discharge

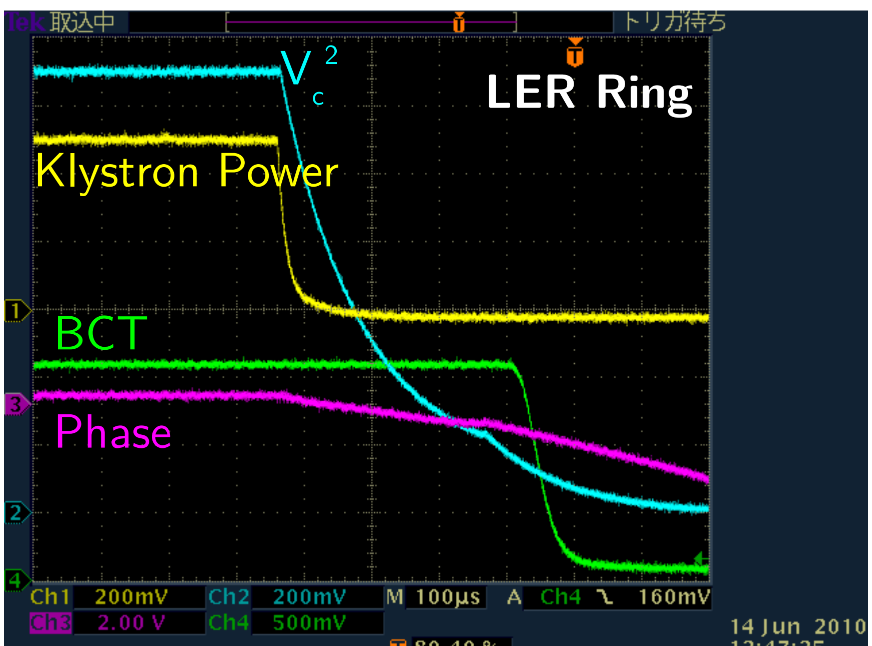
KEKB: RF Off with Beam

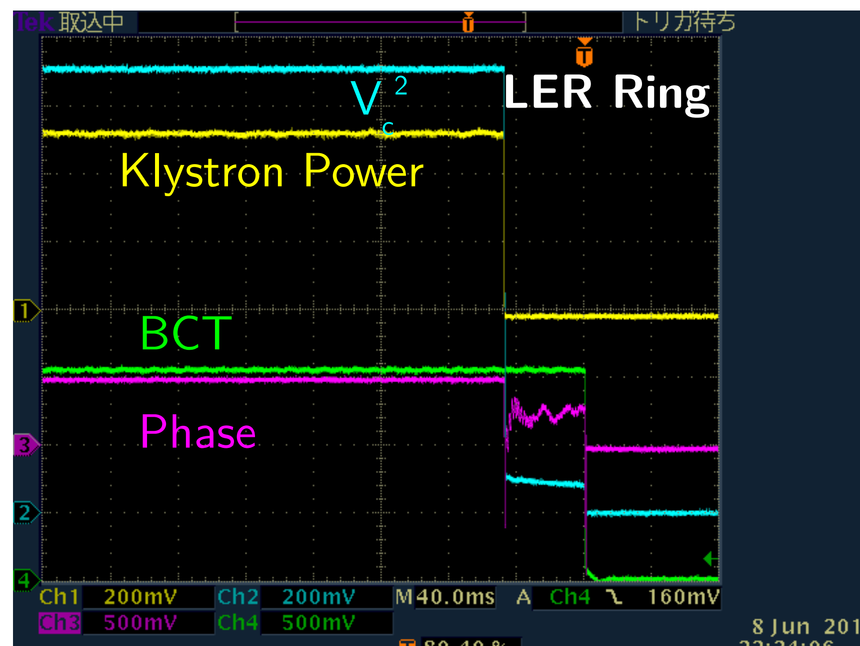
K. Nakanishi et al., LHC-CC10

Time constants agree with expectations



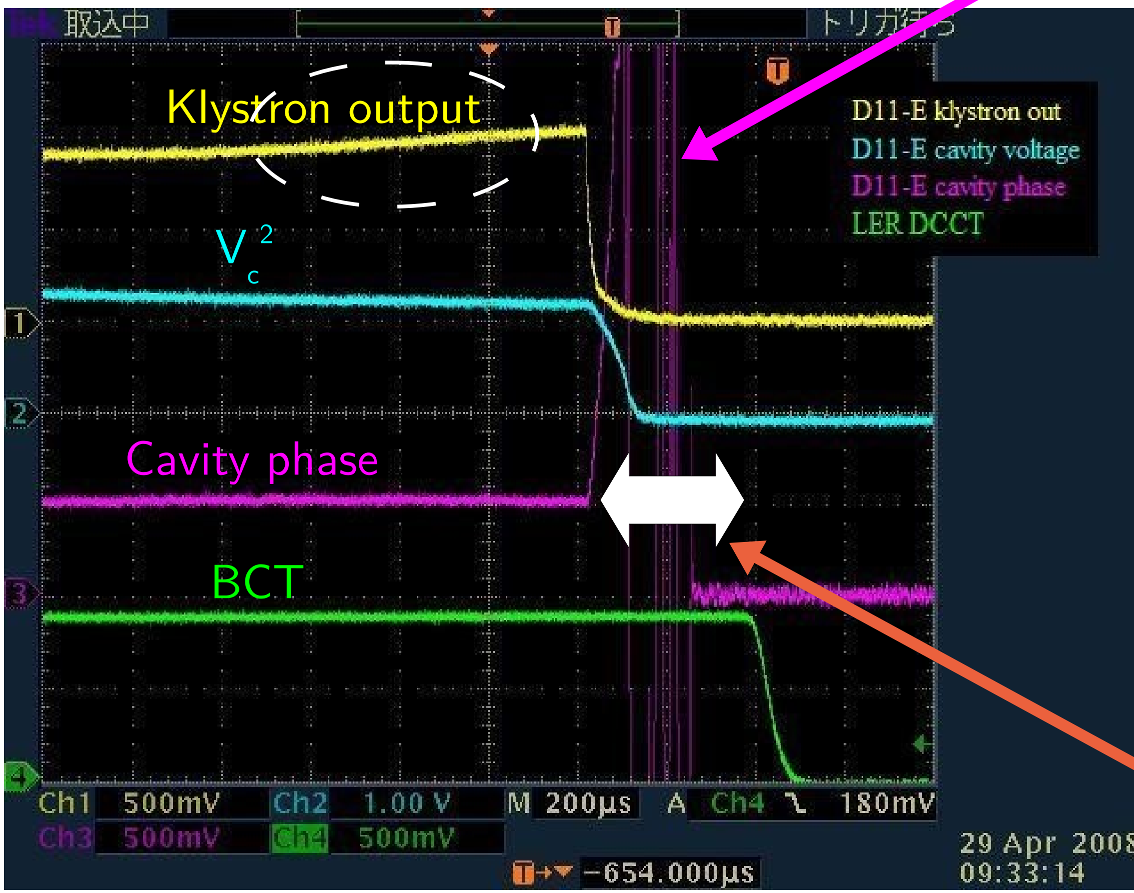


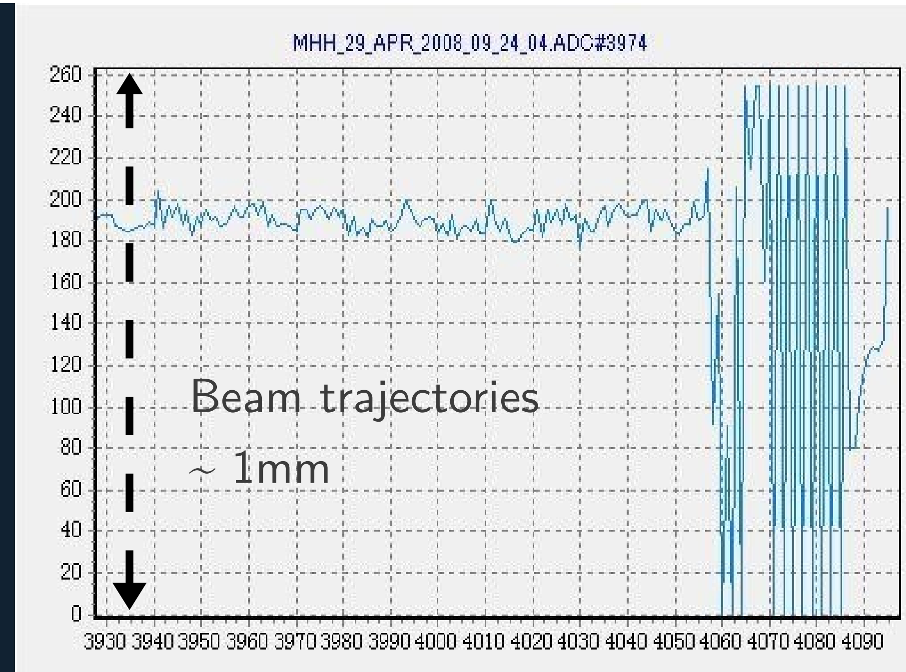




KEKB: Cavity Quench?

Could be a cavity quench
(N. Kota, IPAC10)





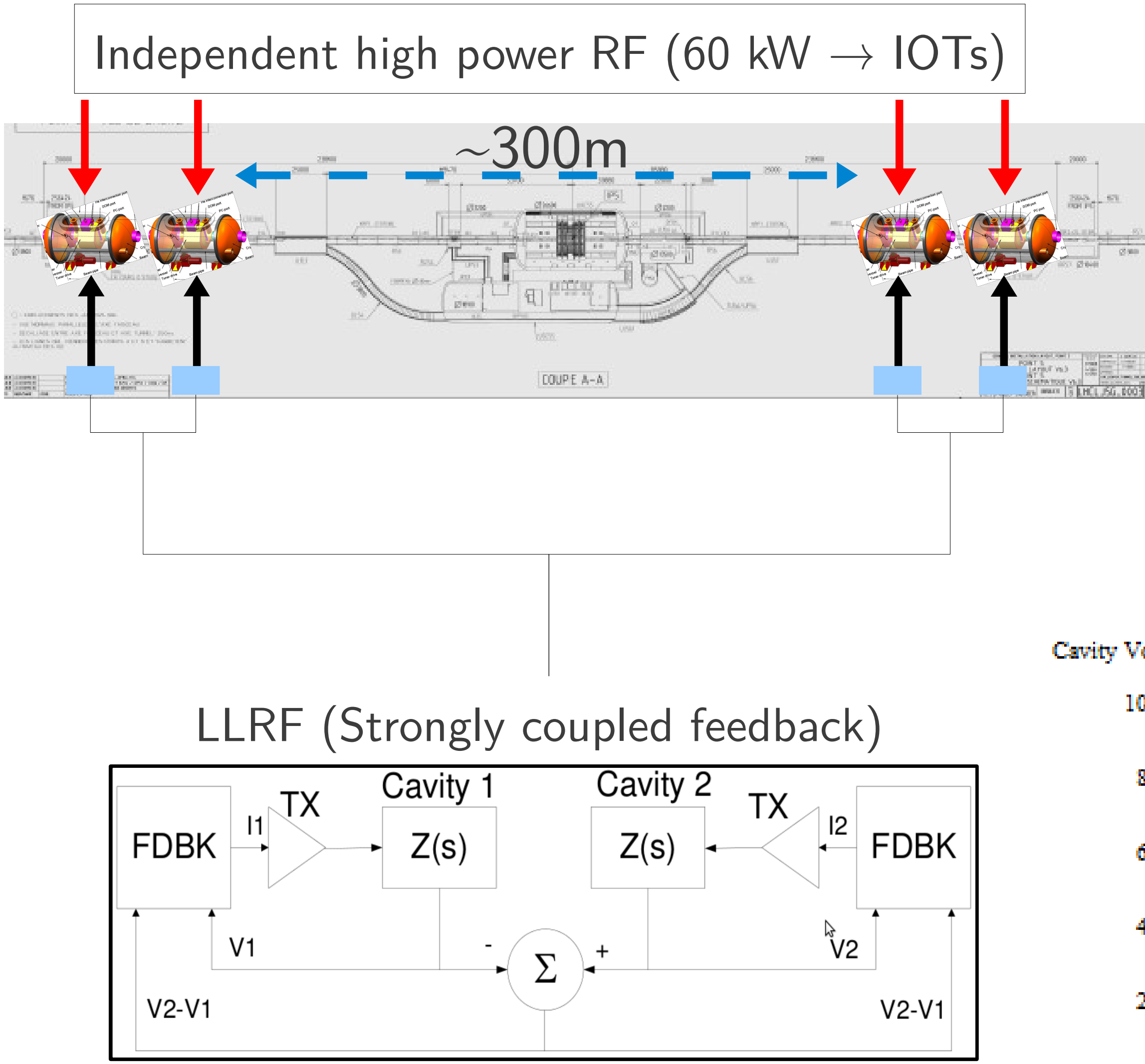
~50 deg in ~100 µs (1 LHC turn)

Initial phase change looks real, but phase behavior at "zero voltage",

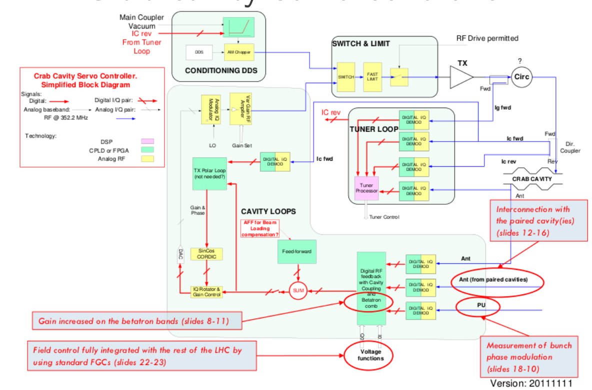
<u>what is actually measured</u> ? $\Delta x \sim$ 5mm (90 deg phase change)

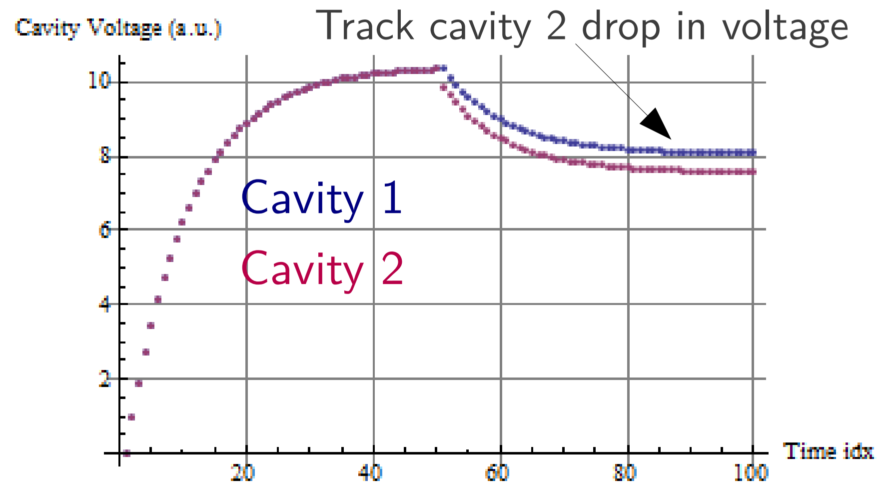
RF Distribution

P. Baudrenghien (LHC-CC11)



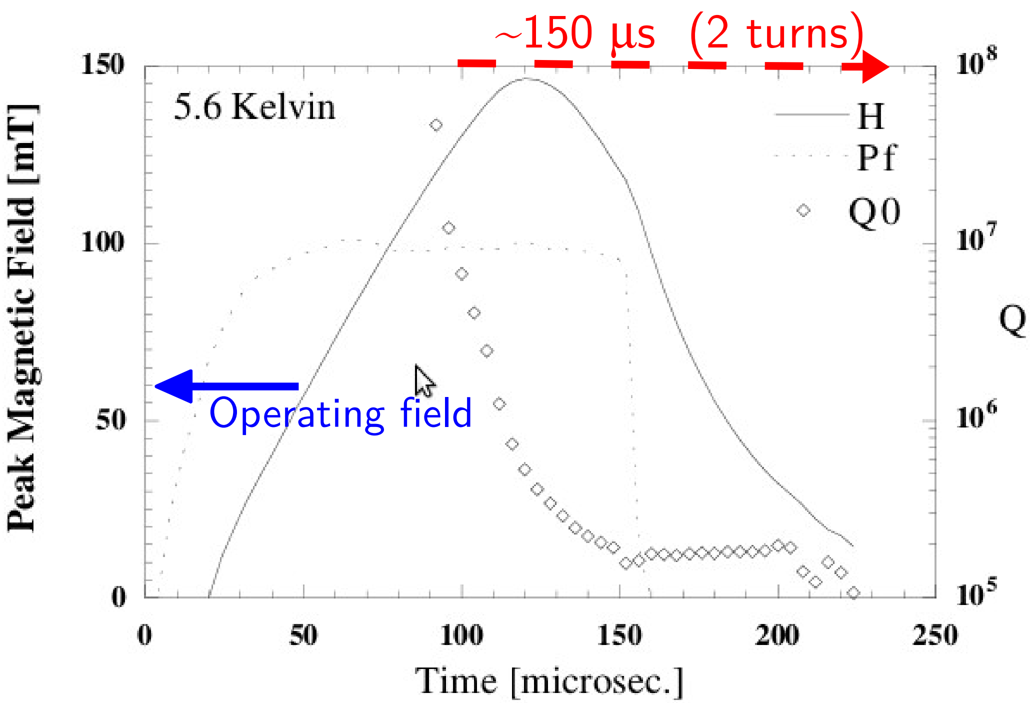
Crab cavity servo controller

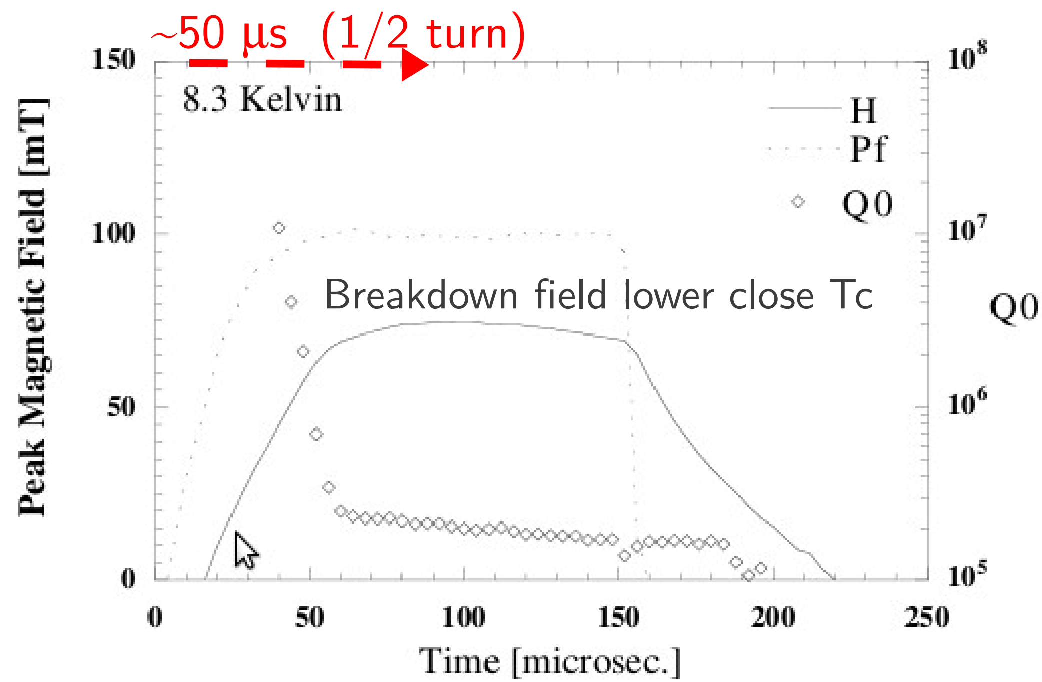




Cavity Quench

H. Padamsee et al., PAC95





Transient cavity Q meas. from high power RF pulses → thermal breakdown

- Nominally performed during cavity processing (T_{start} 2K)
- Determine the "H_c^{RF}" limit for 2K

Nb coated cavities on OFE-Cu could be more quench resistant

Simulations & Mitigation

Nominal LHC shows no noticeable (?) effects even with 1-turn failures

HL-LHC Upgrade (β^*~15cm, ϕ~0.6mrad) → Ongoing

- "Worst case scenario" - single cavity @10MV + 1-turn failure
- Multiplicity in cavities to reduce risks

Mitigation

- Optics → fine tune for a crab specific safe optics
- Technology limits → stick to 3MV/cavity (~60 mT Hs)
- Impedance → 2 cavities /beam/IP side preferred
- Appropriate RF and other interlocks: <u>SPS tests invaluable!!</u>

Present Cavity Status

UK 4Rod cavity

- Niobium cavities finished
- Bulk surface treatment (performed @Niowave)
- Heat treatment and testing at CERN (ongoing)

EuCARD (+CERN)

ODU-SLAC Dbl ridge cavity

- Niobium cavities finished
- BCP & testing at Niowave & Jlab (ongoing)

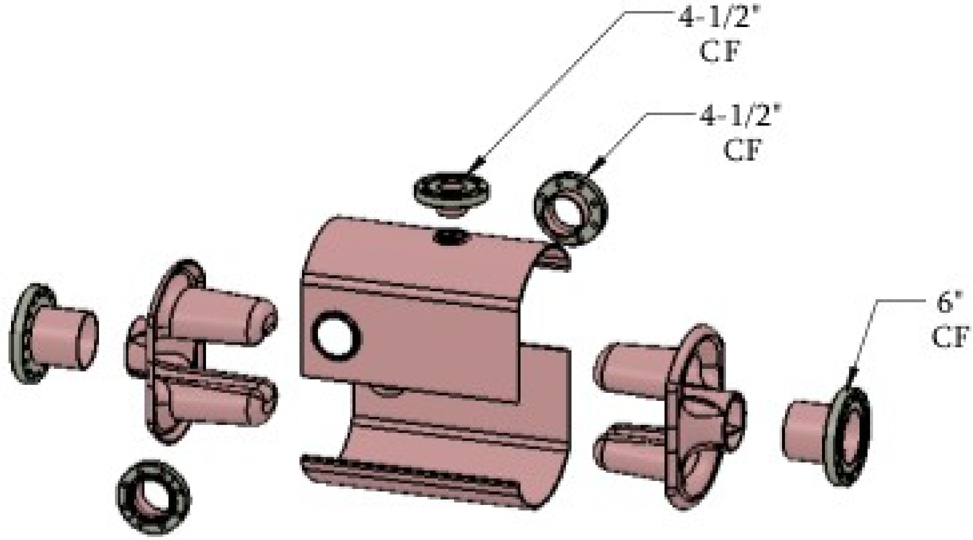
BNL Quarter Wave Cavity

- Fabrication order placed with Niowave
- Cavity expected before the end of the year

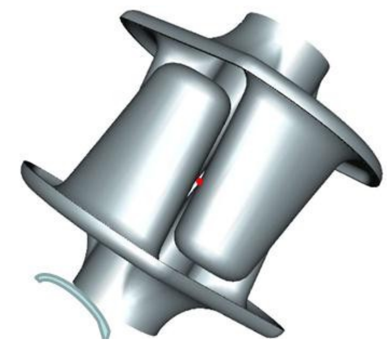
LARP + SBIR/STTR

4R Prototype

Courtesy: G. Burt, Niowave

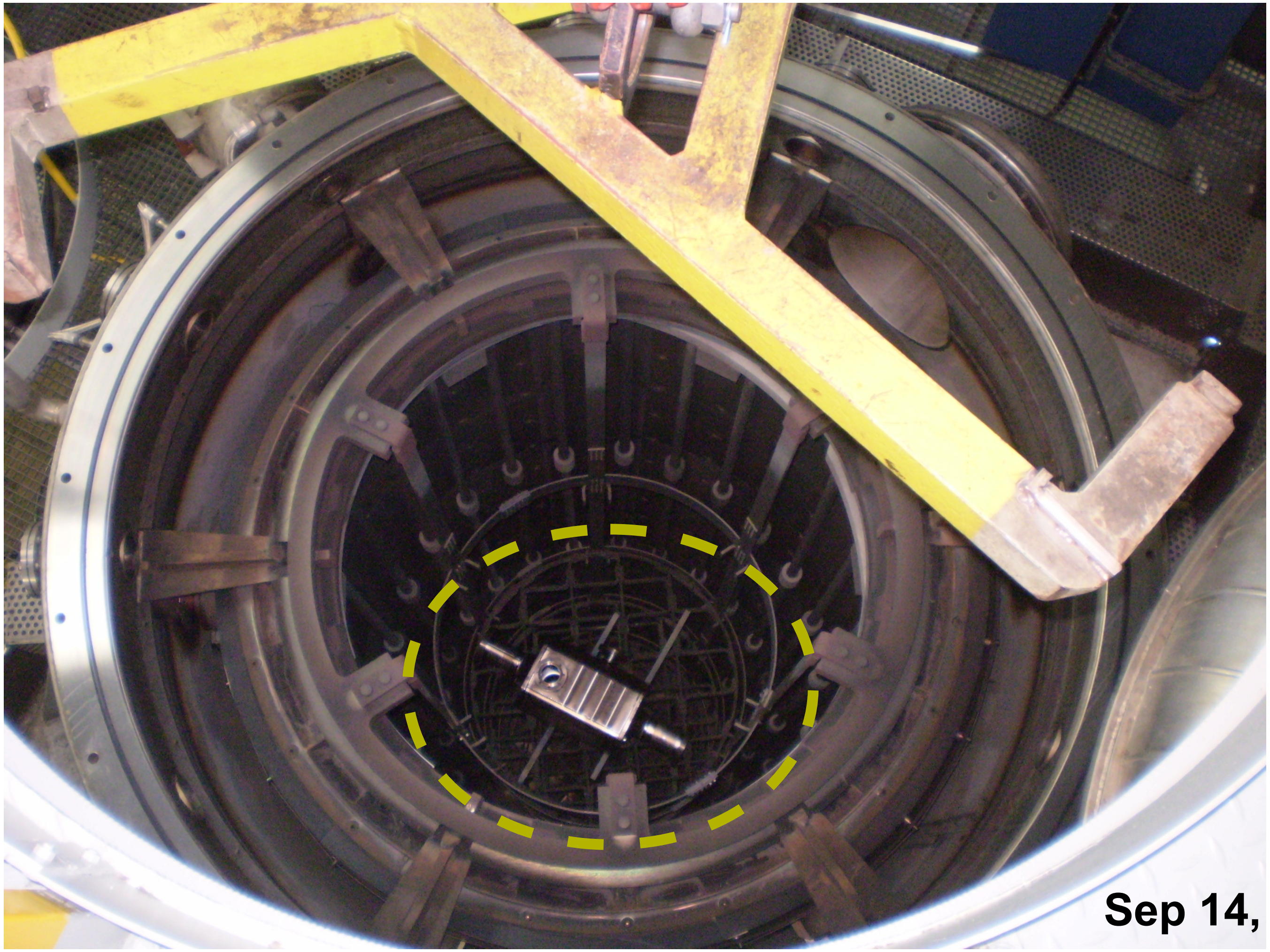


Nb rods from solid Ingot via EDM
(significant material saving)



Fabrication of the Nb cavity in US
CERN for surface treatment & testing

Cavity in the vacuum furnace in Bldg 153
(for H_2 degassing)

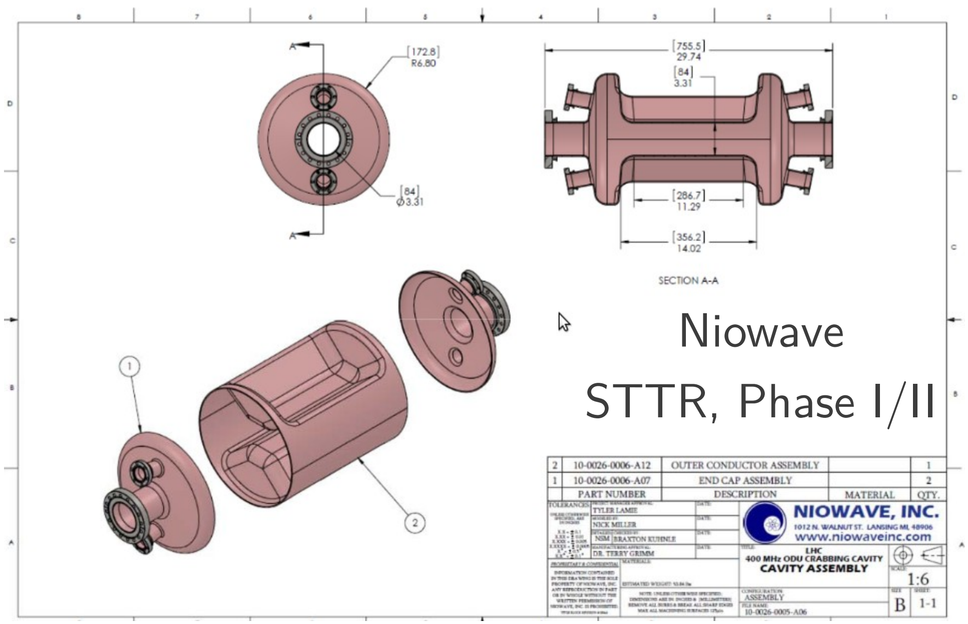


Sep 14, 2012

Light chemistry & high pressure rinsing $\rightarrow$ 2K testing in SM18 (Oct 2012)

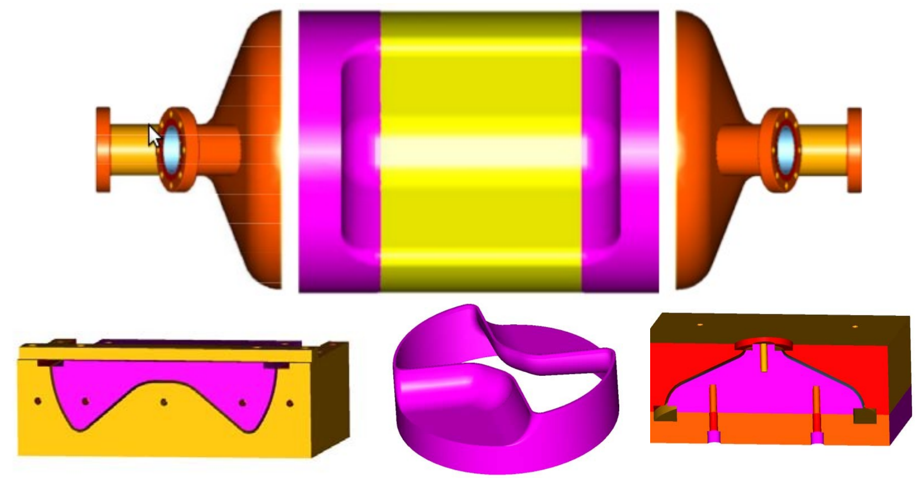
ODU-SLAC: Double Ridge

Courtesy:J. Delayan, Niowave



Niowave

STTR, Phase I/II



Jan 2012

May 2012

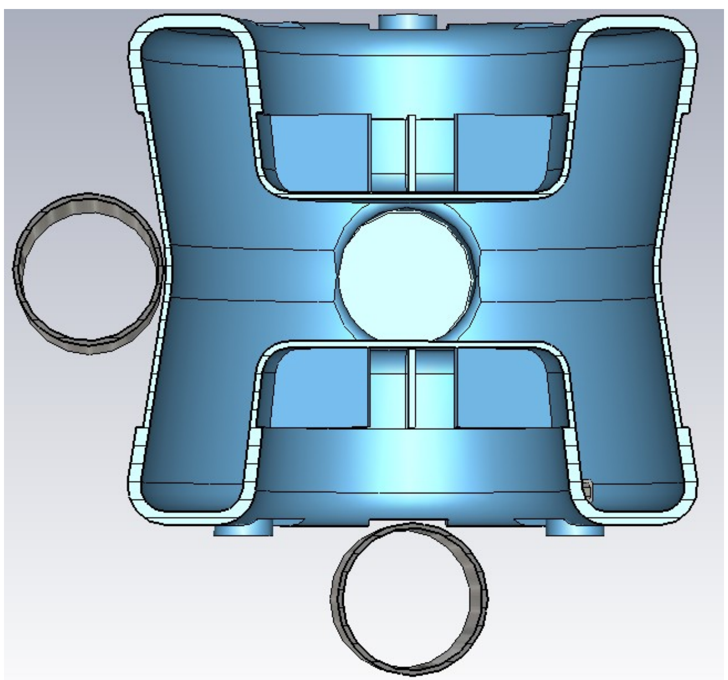
BNL: Quarter Wave

Courtesy:I. Ben-Zvi et al.

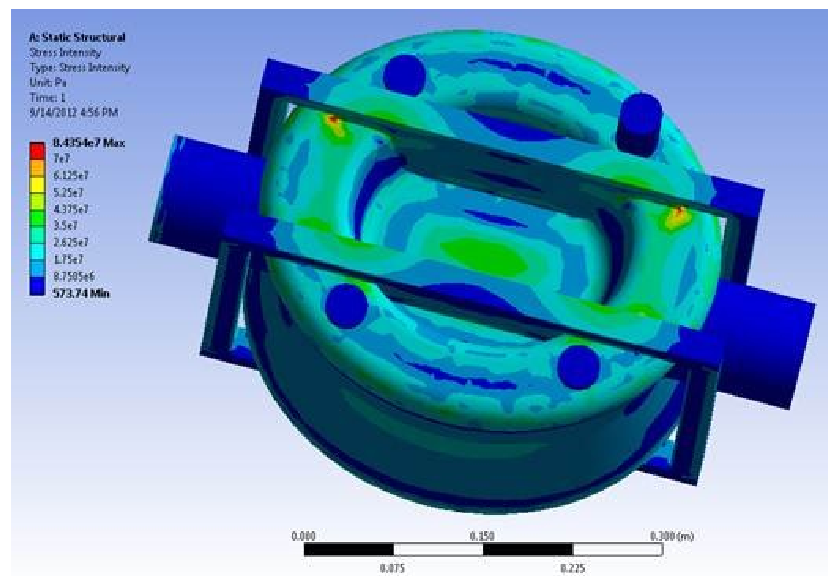
Mechanical analysis with vendor (Niowave) to finalize

- Material thickness & weld sequence with stiffeners

Cavity expected for testing end of December



Thick sheet stiffened cavity



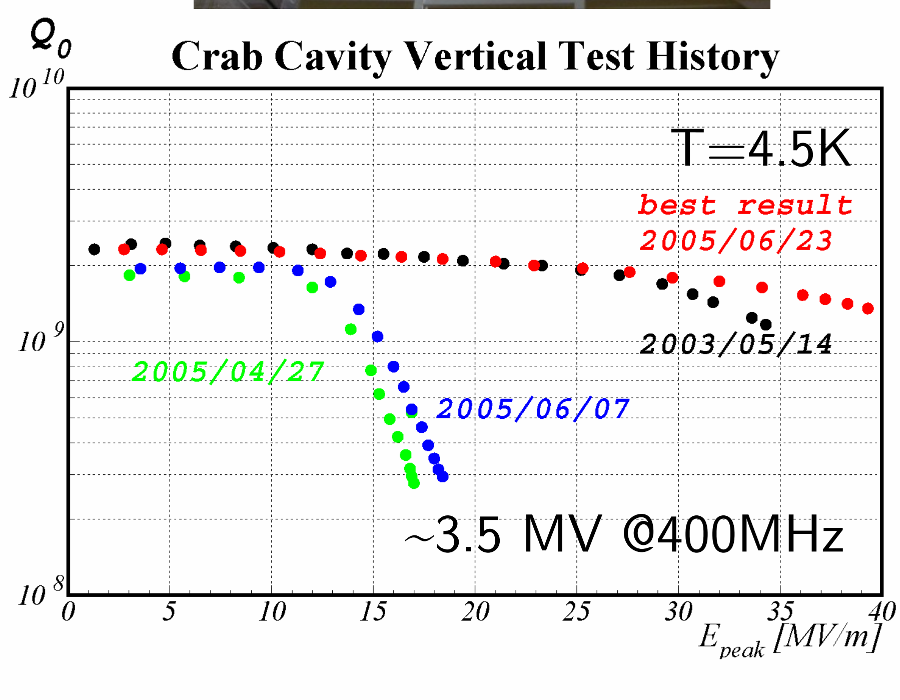
Cage structure for stiffening+Tuning

Prototype Testing, SM18

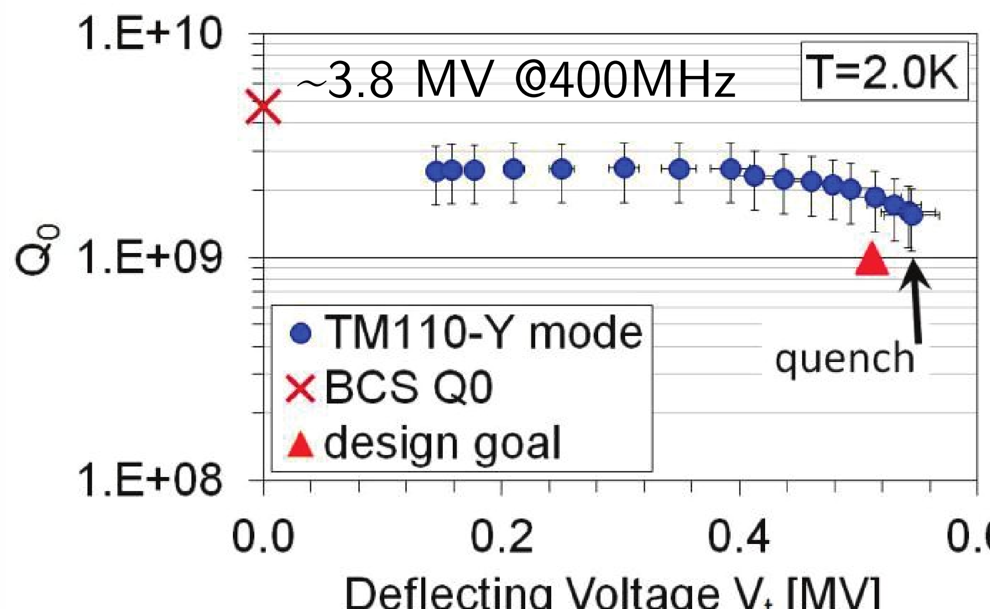
Aim:
- Field tests of all 3 cavities by summer 2013
- Characterization of surface properties
  - Multipacting, optical inspection, additional processing
- Field ramping, cycling, stability and quench margin

CERN Preparations for SM18 tests
- Surface chemistry of complex geometries (already done)
- High temp vacuum baking + HPR
- RF Power: Recuperating 400 MHz tetrodes used for LHC-RF
- Cryo: Existing (2-4K) + a new dedicated 2K cryostat in 2013
- Instrumentation: RF, second sound, T-mapping & optical
- LLRF & services: Mostly exist from present testing

KEKB 500 MHz Cavities



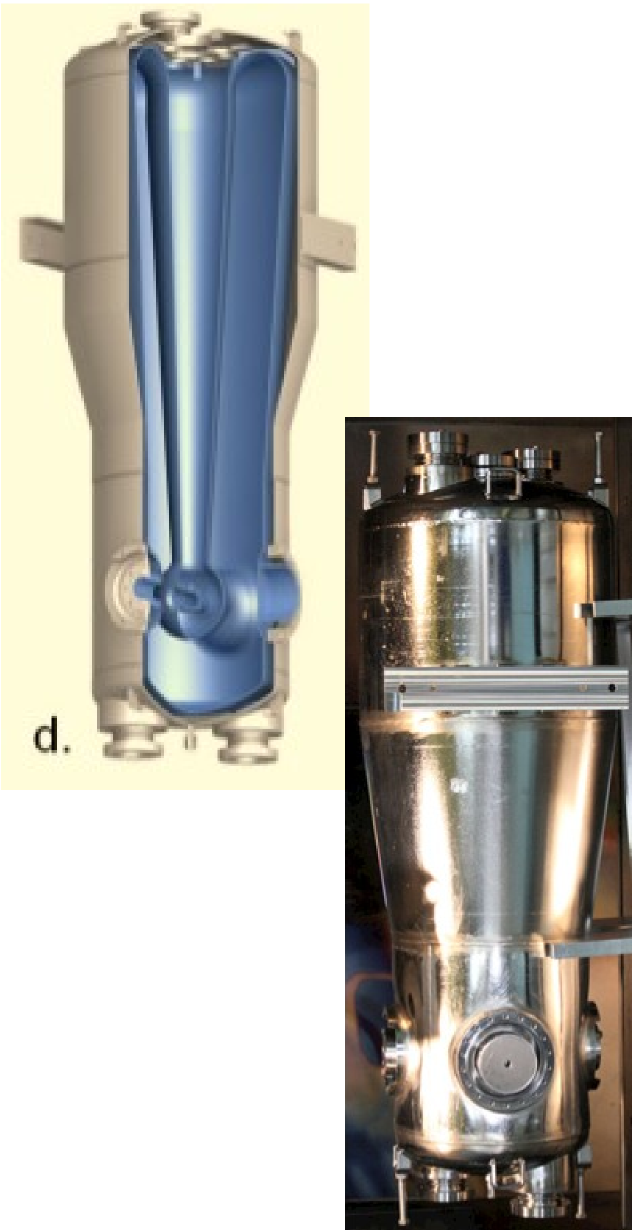
Argonne 2.8 GHz Cavities

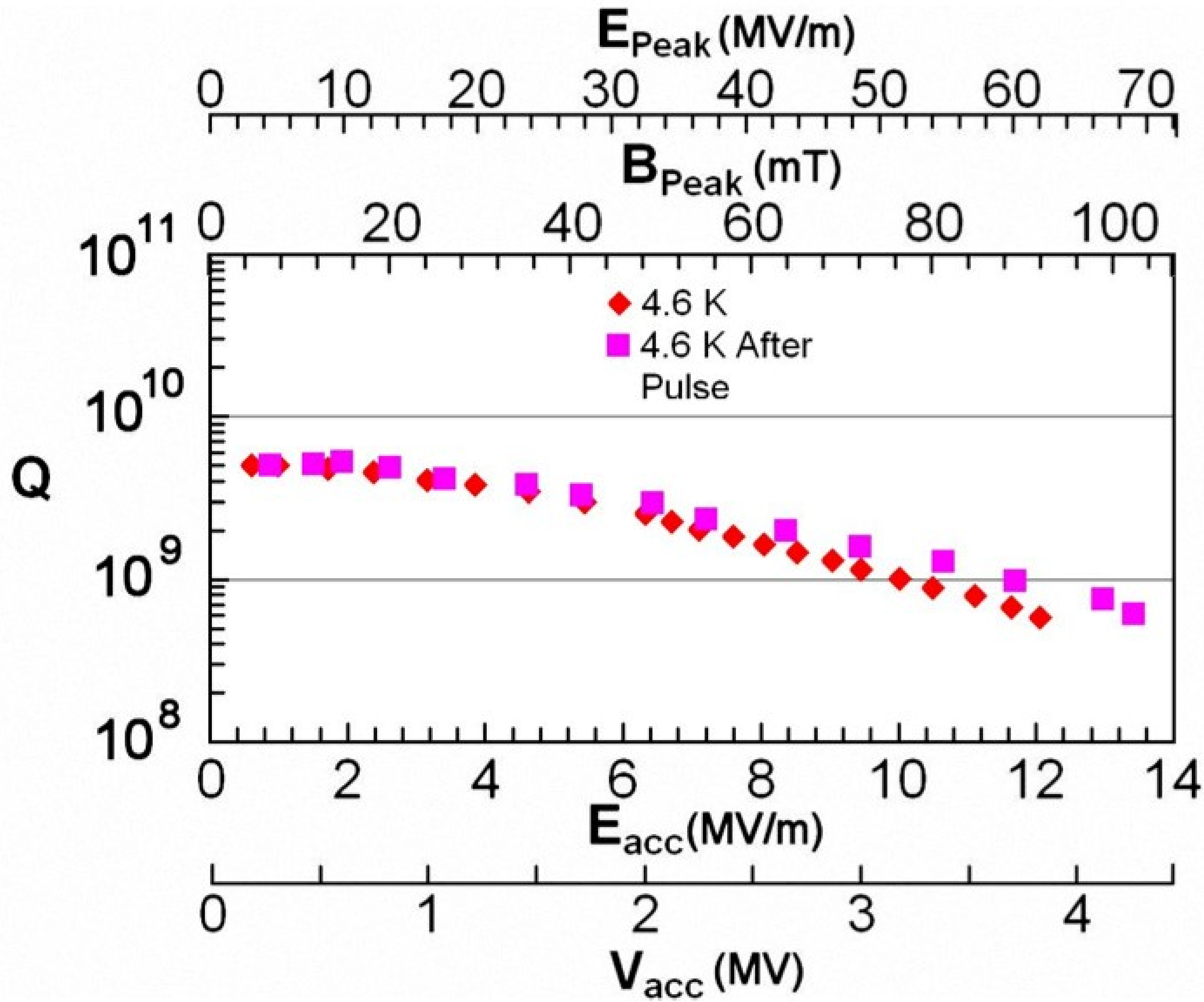


ANL Quarter Wave 72 MHz

Ep=70 MV/m, Bp=100 mT

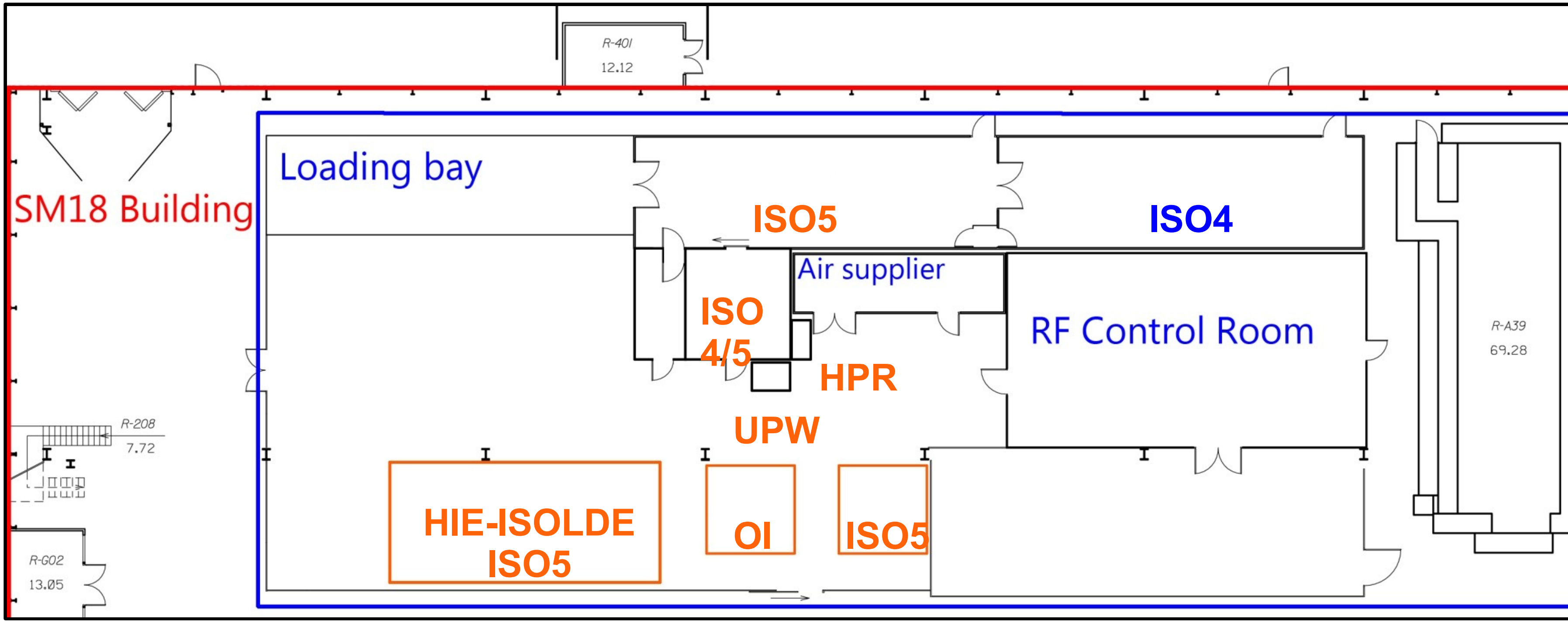
Q0 = 1 x 10^9 at 4.6 K (IPAC10)



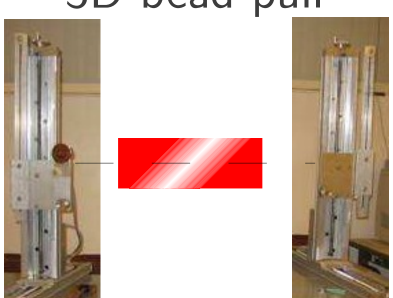


CERN SM18 Facility & Upgrade

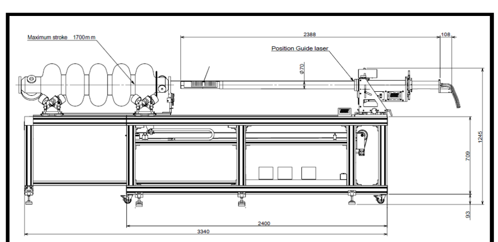
Courtesy: J. Chambrillon, K-M. Schirm



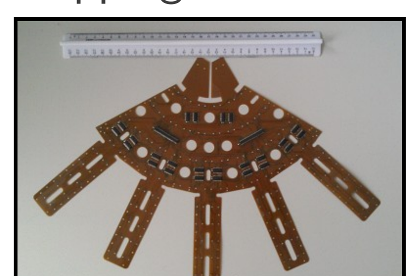
3D bead-pull



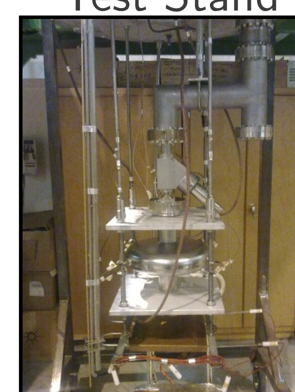
Optical Telescope



T-Mapping + 2^{nd} Sound



Test Stand

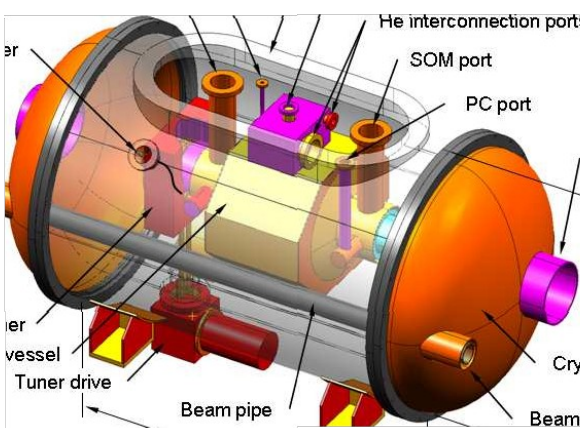


Cryomodule Development

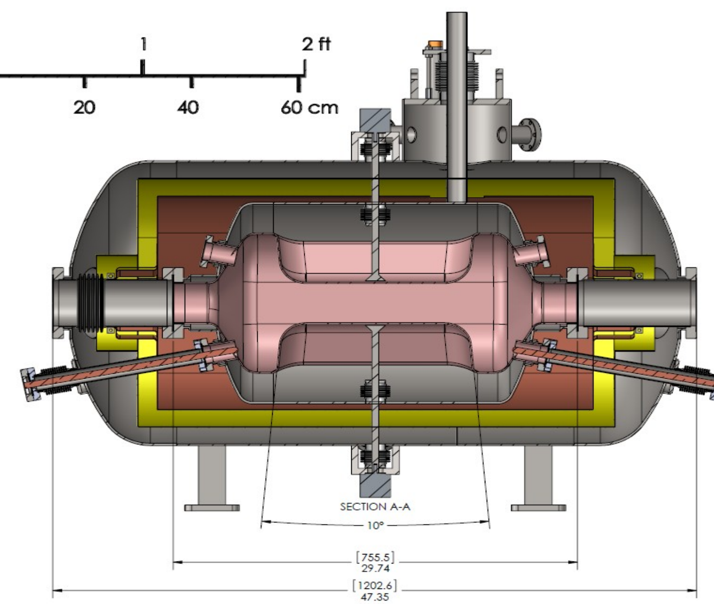
Initiating a joint effort with US and European partners

Next Steps

- Initial concepts in 6-8 months (FNAL, SBIR, Triumph, CEA-CNRS)
- Immediate task to identify constraints (environmental & RF)
- Engineering meeting at the end of 2012 for conceptual review

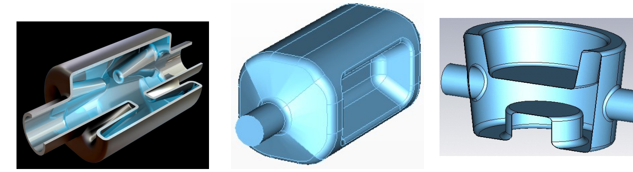


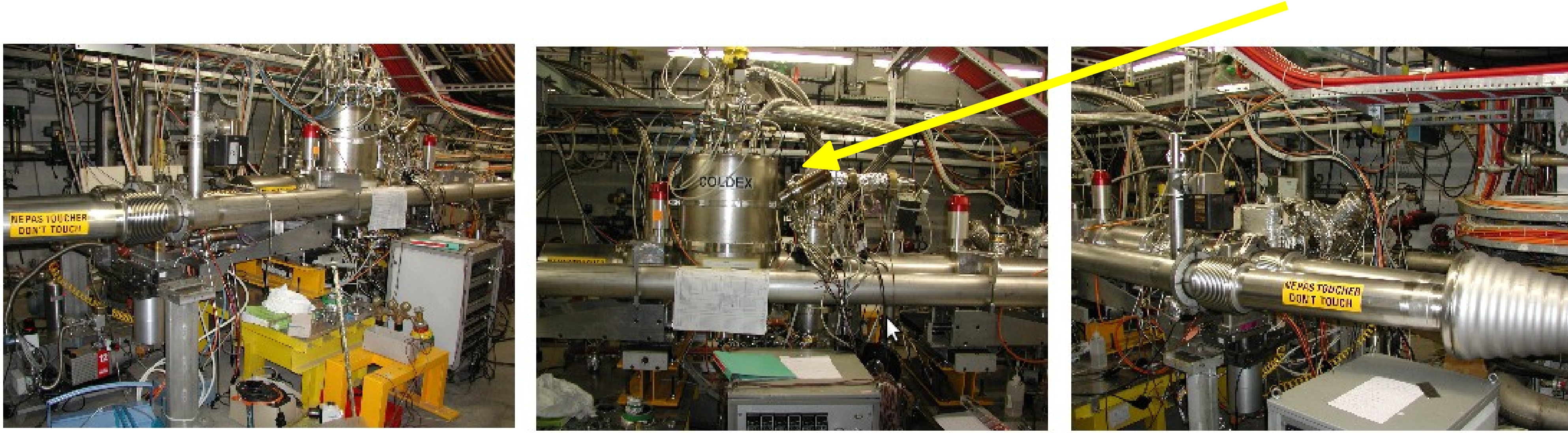
Some initial work done for elliptical cavities
FNAL (Y. Yakovlev et. al), 2010



ODU-Niowave: SBIR, Phase I

BA4 SPS Tests





Milestone 3: SPS Tests foreseen 2016

New working group in place (A. MacPherson)

Cavity validation with beam (field, ramping, RF controls, impedance)
Collimation, machine protection, cavity transparency, RF noise,
emittance growth, non-linearities,

Cryogenics, RF power, cabling and installation services (some during LS1)

Next Steps

Cavities, end of 2012

- Two prototypes at hand and 3rd to come soon
- Cavity testing is the immediate focus $\rightarrow$ 1st milestone (ongoing)

Cryomodule, end of 2014

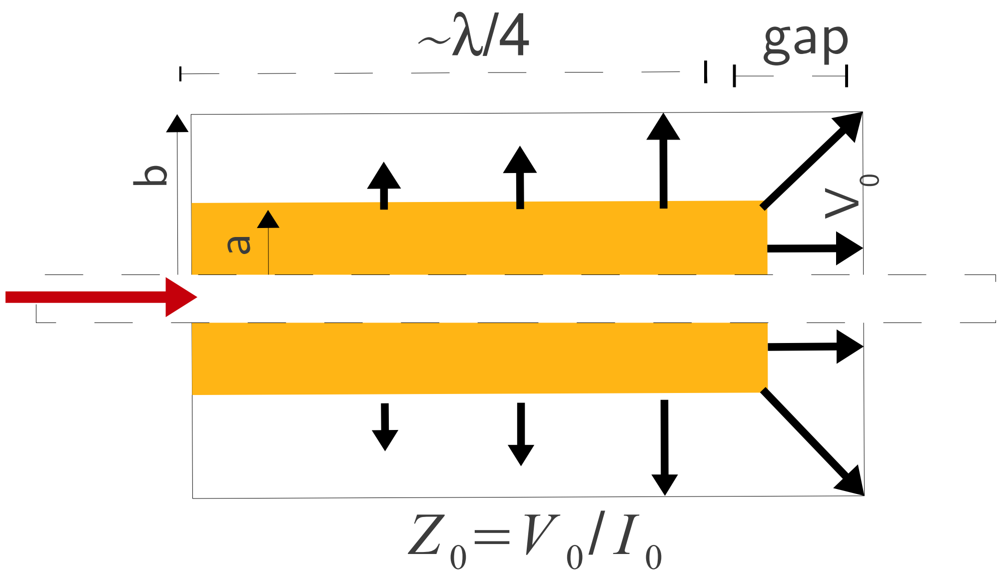
- Establishing joint collaborations with N.A. (FNAL, Triumph) & Euorpe (CEA-CNRS/IN2P3)
- Next step to review conceptual designs (Dec 13-14, 2012)

SPS/LHC Tests, end of 2016-17

- Preparation (cabling, RF, cryo etc..) in SPS will start 2013

$\lambda/4$ TEM Resonator

BNL: I. Ben-Zvi et al.

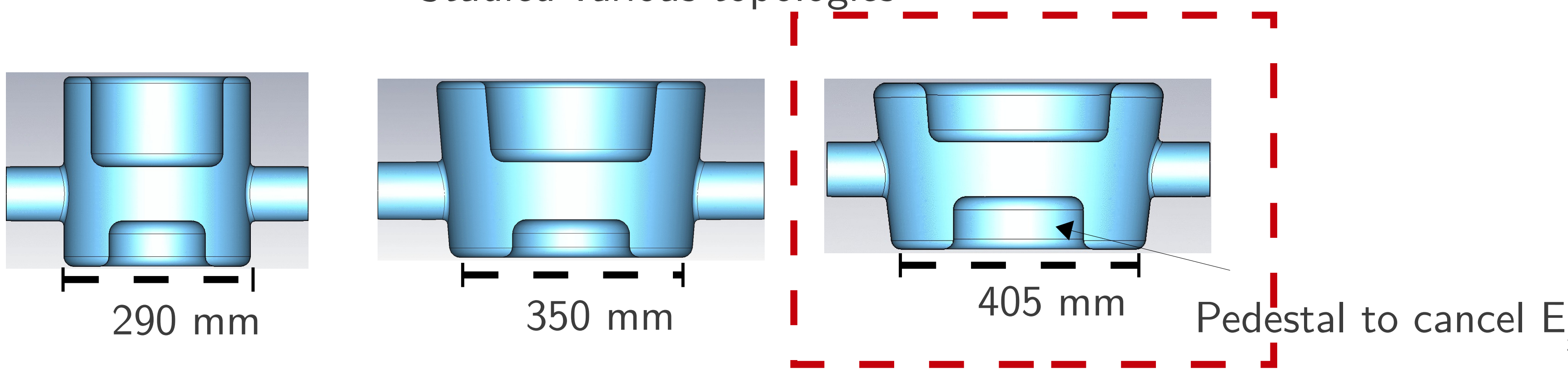


Frequency µ resonator length

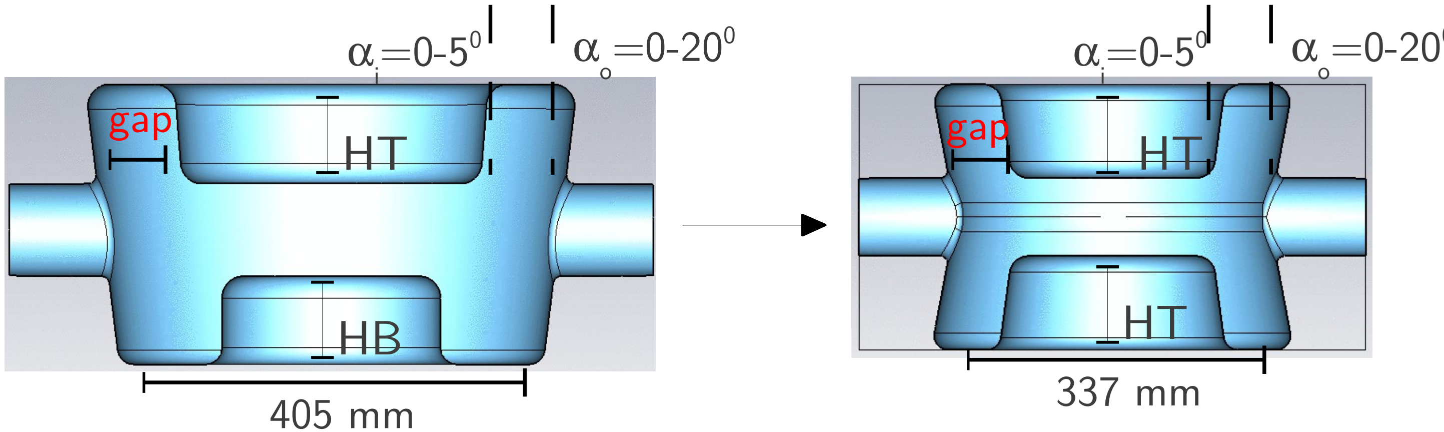
HOMs widely spaced

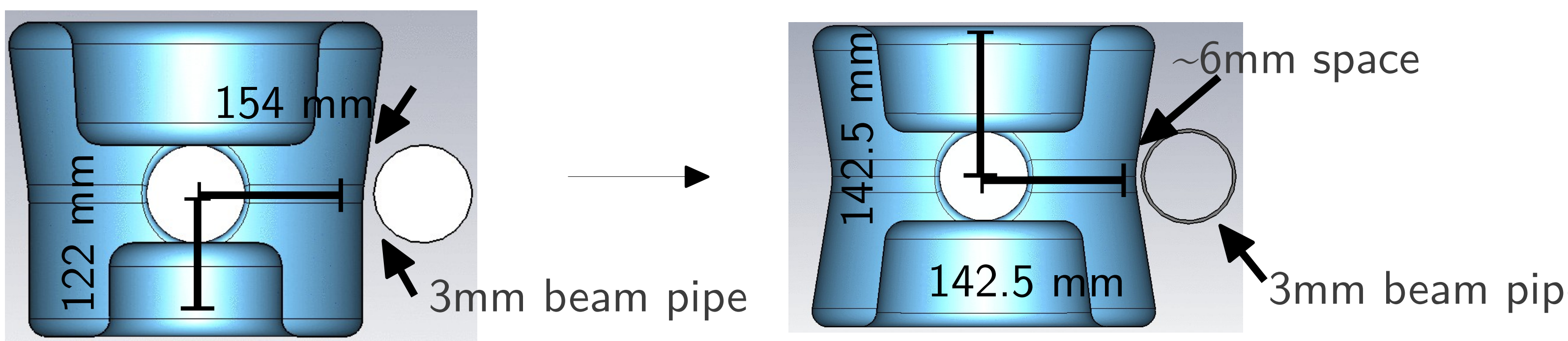
$$Z_0 \tan(\beta l) = \frac{1}{\omega C_{gap}}$$

Studied various topologies



Asym Vs Sym ¼Wave





	Type III, Asym	Type II, Sym
Epk	43 MV/m	32.3 MV/m
Bpk	61 mT	57.3 mT
Vacc	120 kV	0.0 V
1st HOM	657 MHz	582 MHz

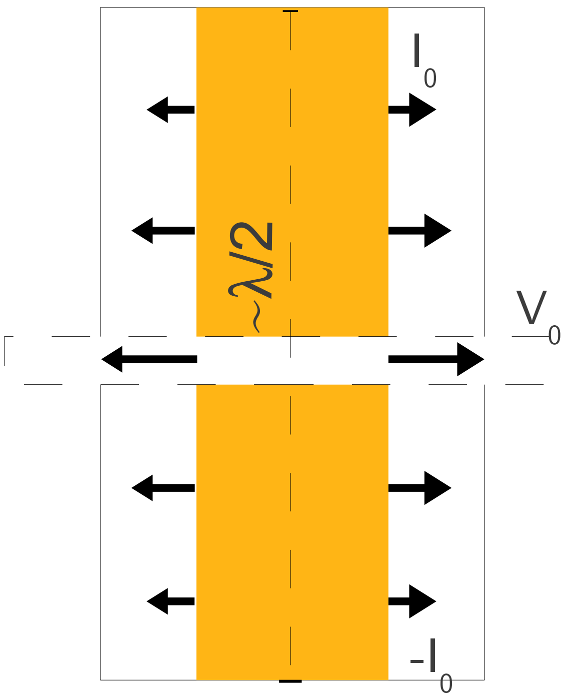
Prototype symmetric structure:

- Long. voltage is zero
- Better for non-linearity

But loss of mode separation & compactness vertically

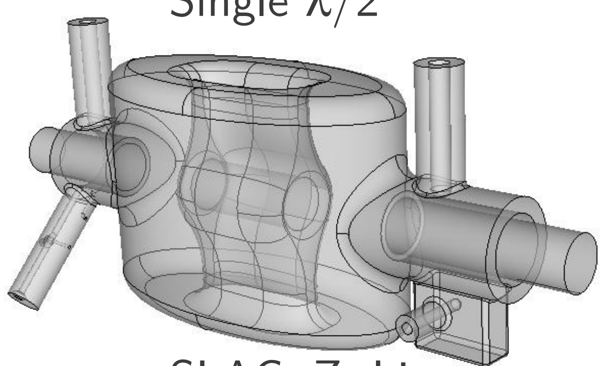
$\lambda/2$ TEM Resonator

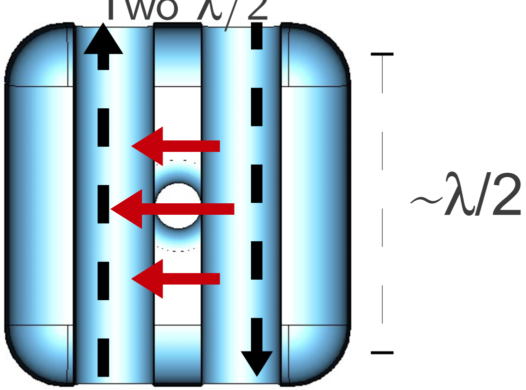
Z. Li, J. Delayen et al.



Two $\lambda/4$ resonators $\rightarrow$ $\lambda/2$

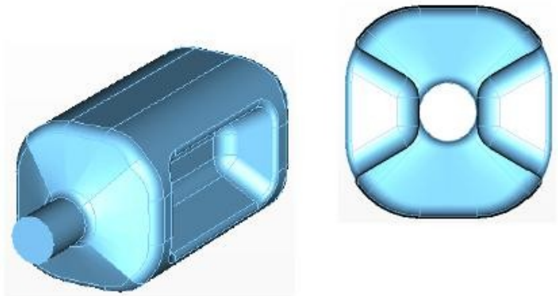
- Downside HOM (TE_{11} like) for deflection
- More elegant is to use two $\lambda/2$ resonators





Now evolved into <u>symmetric ridge waveguide</u>

For compactness in both transverse directions



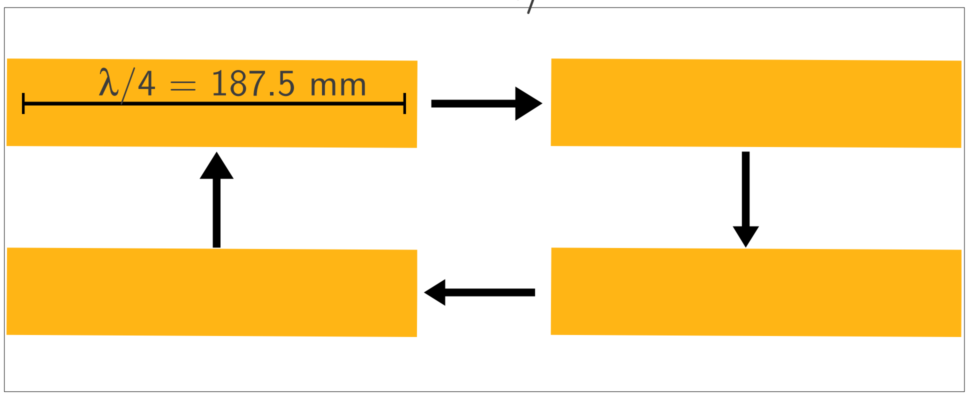
ODU-SLAC

Also, Initially proposed by
F. Caspers (Crab WS 2008)

4Rod $\lambda/4$ Resonator

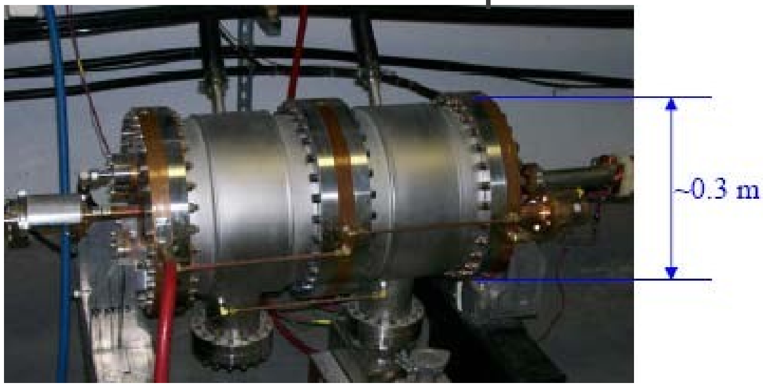
Courtesy G. Burt, B. Hall

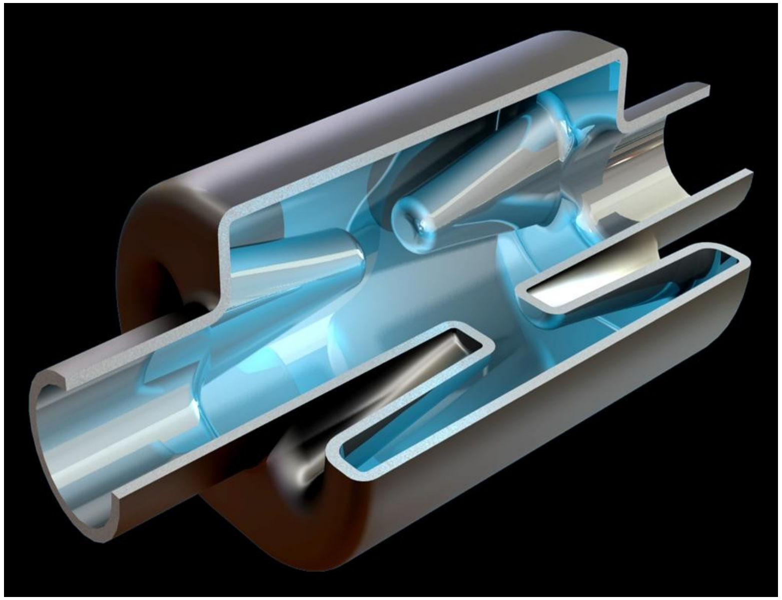
Four co-linear $\lambda/4$ resonators



4 eigenmodes, mode 2 is our crab mode

500 MHz CEBAF Separator



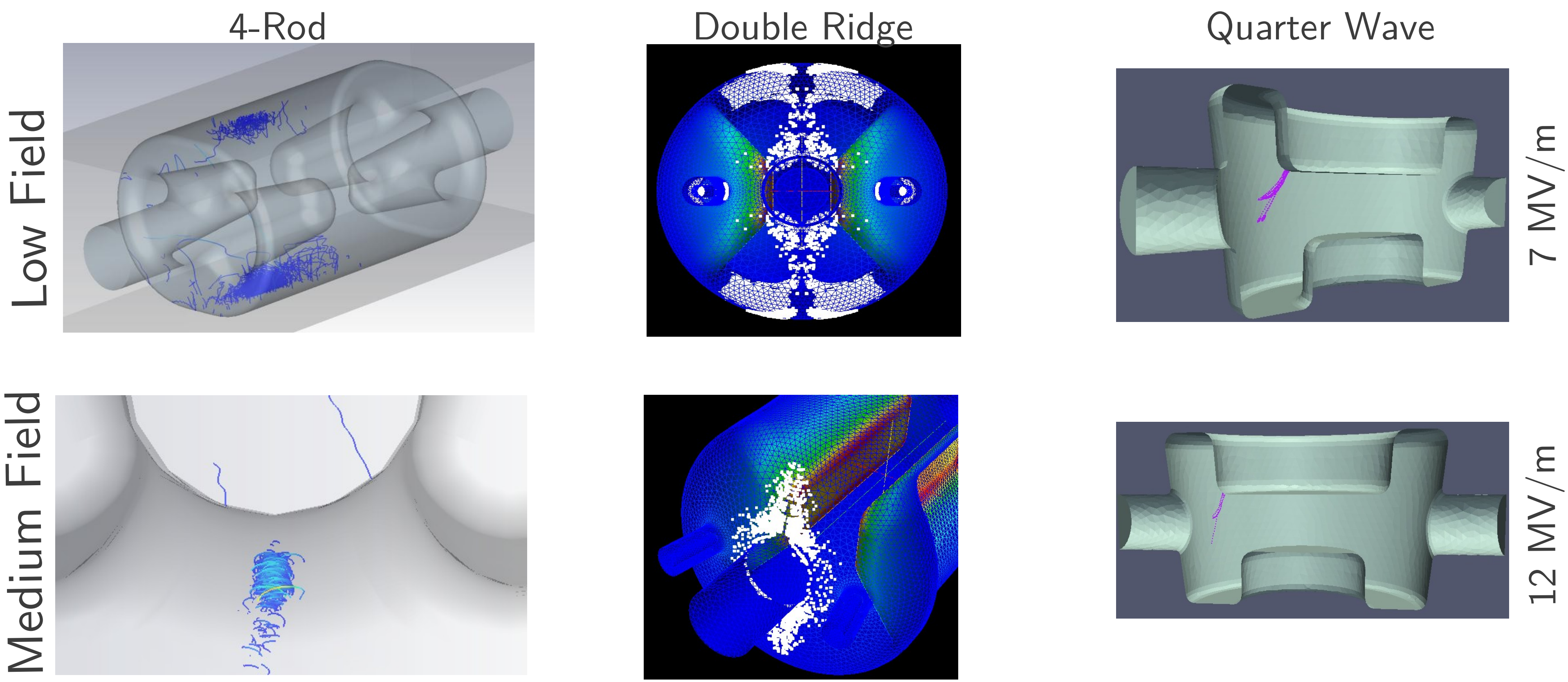


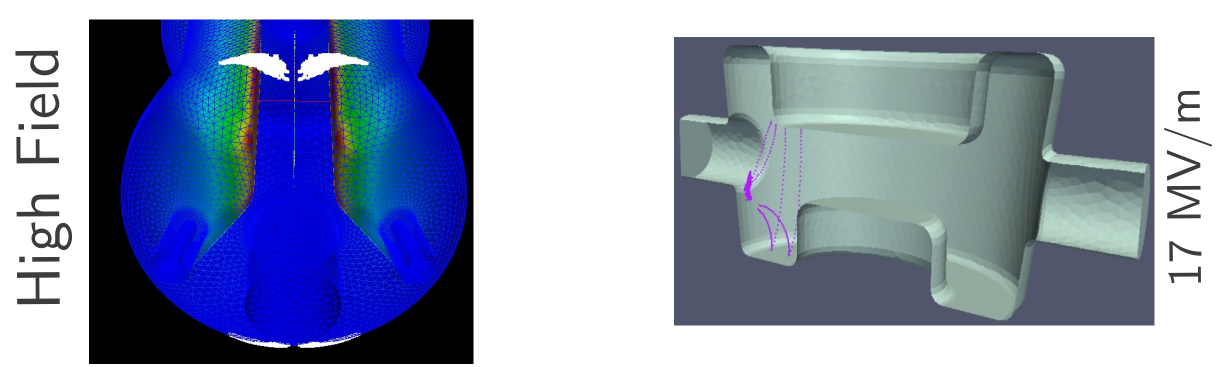
LU-DI-JLab

Ultra compact, conical resonators for mechanical stability

Downside is the deflecting mode is not the lowest order mode

Multipacting



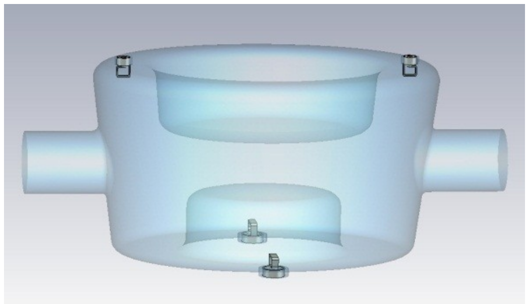


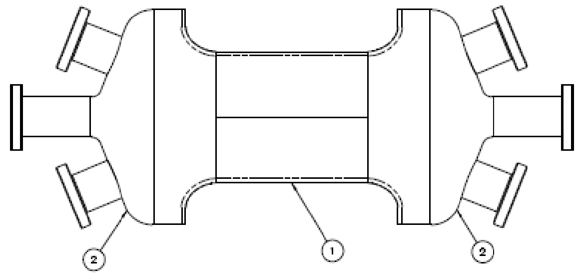
SLAC codes to compare three cavities (Z. Li)

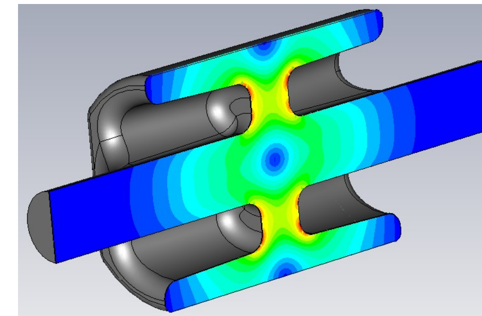
Benchmark with measurements

HOM Damping

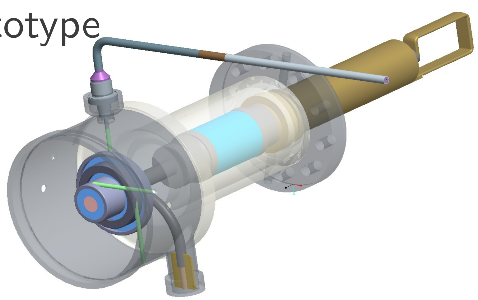
Approx: $R/Q=200\Omega \rightarrow Qe<1x10^3$



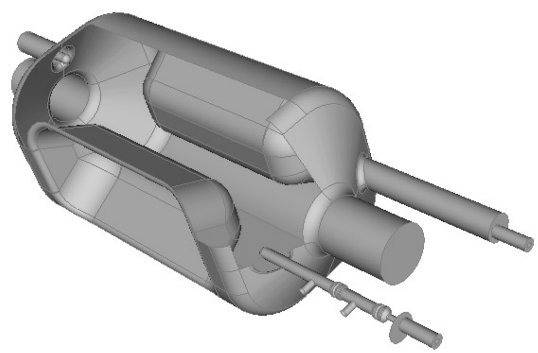




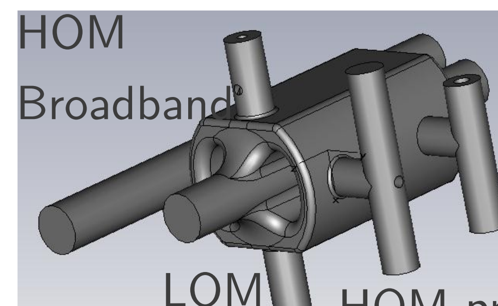
56 MHz RHIC Prototype



3-5 stage Chebyshev
High pass filter loops



4 Symmetric couplers
on the end caps
(2-stage high pass)

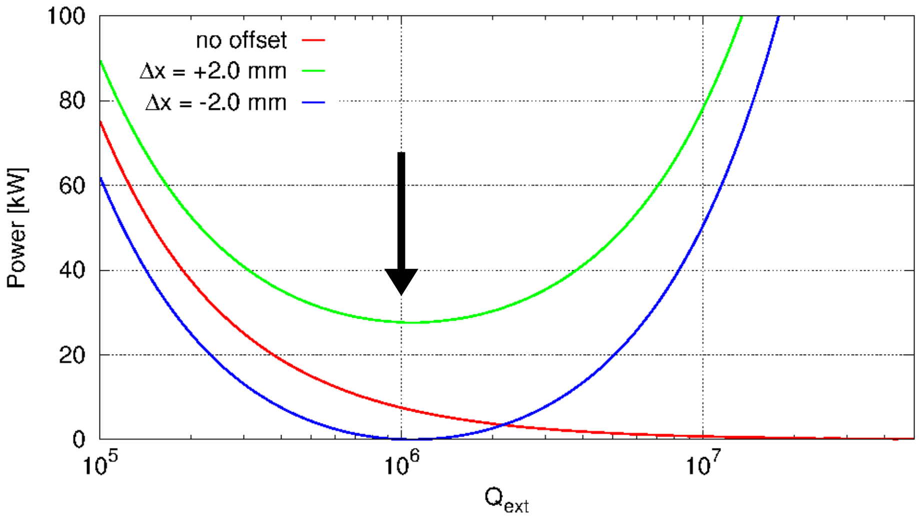


Symmetric HOM/LOM
couplers on cavity body

Power Couplers

Power requirement ~60 kW (only ~18kW in operation)

- Peak power handling up to 250 kW
- Inner conductor to >20 mm (50 Ω)
- Air cooling with disc/cylindrical windows



RF system development

- Common power coupler platform for all cavities
- 50 kW tetrodes at 400 MHz already available for SM18 tests
- Investigate IOTs for the SPS tests

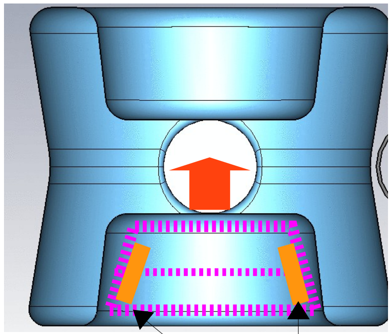
Tetrode (SPS)
400 MHz, ~50kW

IOTs (TV Transmitter)
Light Sources

Cavity Tuning

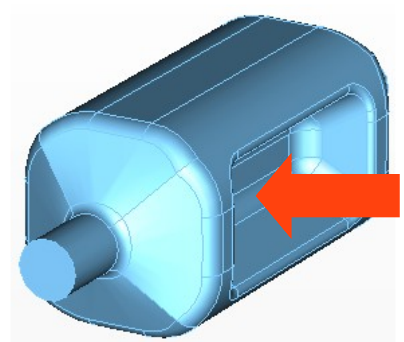
In operation $\pm$ 3kHz

Static: ~100 kHz



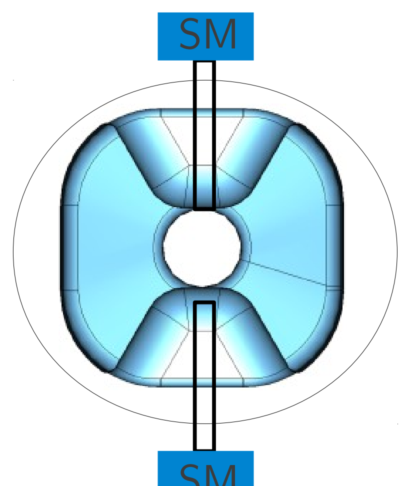
Push/pull

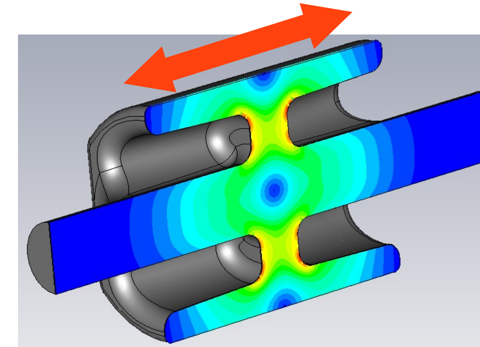
Blade like tuner



Push/pull on

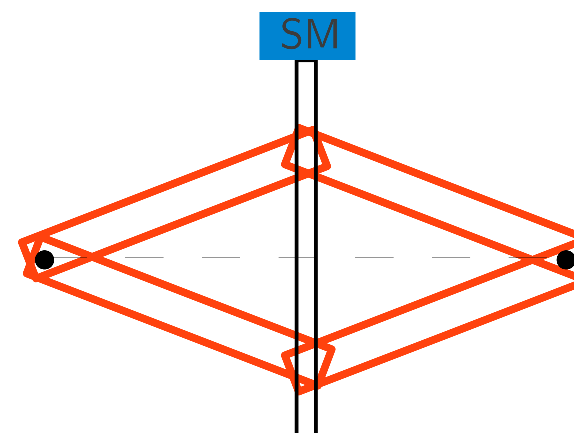
cavity ridges





Scissor jack type

mechanism

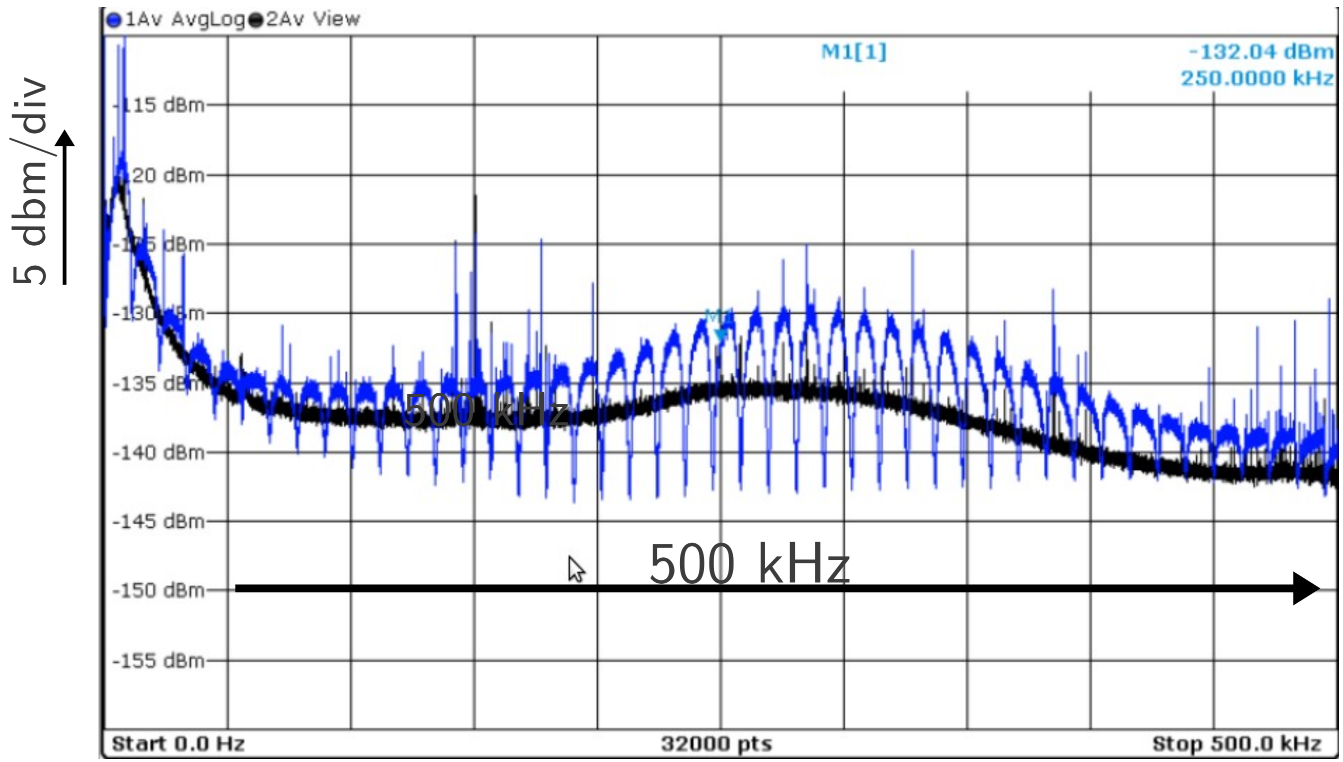


CEBAF Tuner

RF Noise, LHC

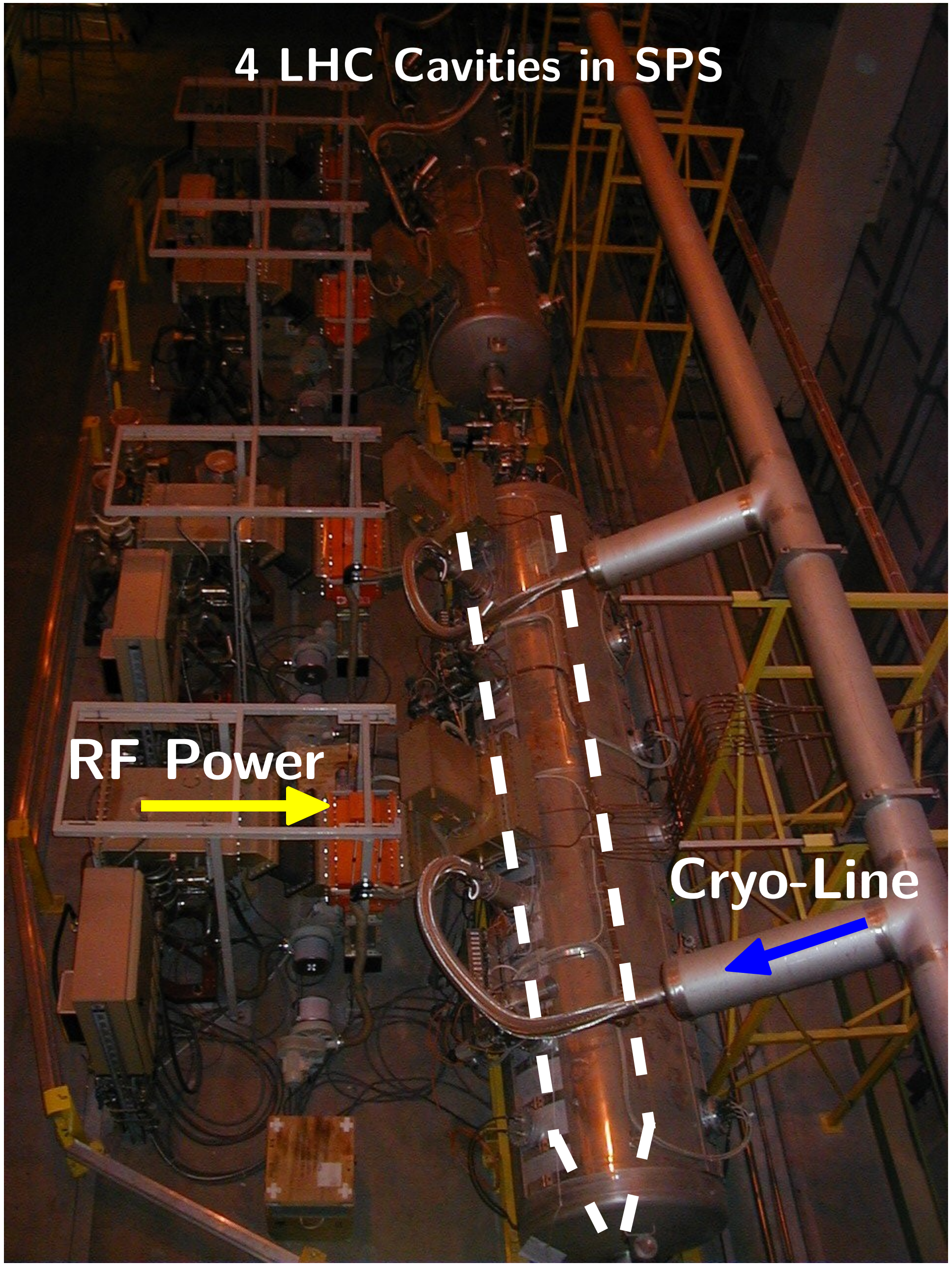
with 1-T feedback

P. Baudrenghien



- Selective reduction at all f_{rev} lines (V=1.5MV, Q_L=60k)
- Using a betatron comb, we can expect ~16dB reduction at selective frequencies

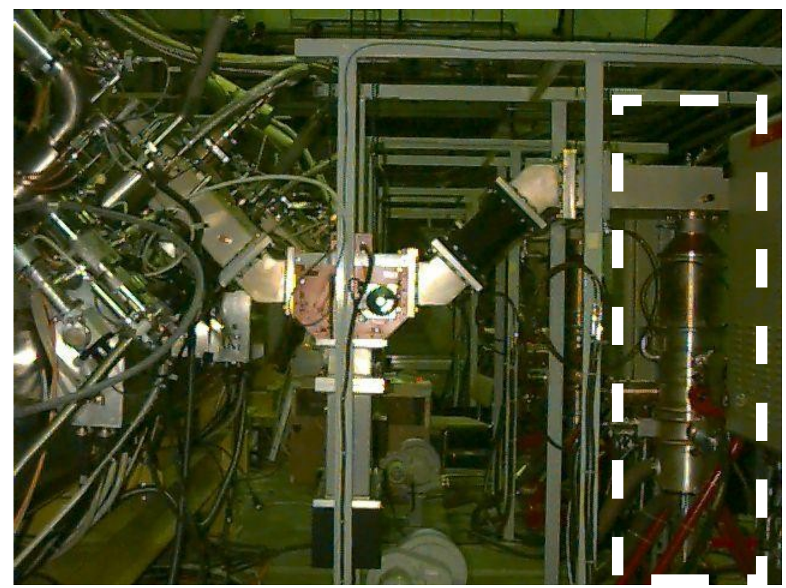
SPS, BA4 Setup (1998)



Y-Chamber like, similar to present COLDEX

Crab cavity test setup in SPS
will look similar

50 kW Tetrode



Courtesy E. Montesinos