Detailed Design Report

1st MAX MAC Meeting
September 1-2, 2010
MAX-lab, Sweden

Chapter 2

MAX IV 3 GeV Storage Ring

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MAX IV Facility

Linear Lattice

- **Target: ultralow-emittance SR, sufficient number of IDs**
- **3 GeV, 20-fold MBA, 528 m → ε_x = 0.33 nm rad**
- **DWs further reduce emittance → ε_x ~ 0.17 nm rad**
- **MBA: simple (high periodicity), robust (relaxed optics)**
  - 7-bend achromat: 5 x 3º (UC) + 2 x 1.5º (MC)
  - 20 long straights (one reserved for injection), 4.8 m
  - 40 short straights (9-12 reserved for RF cavities), 1.3 m
- **Compact optics → strong focusing, gradient dipoles**
  - $J_x = 1.86$, $\eta_x < 8$ cm, $\alpha_c = 3\times10^{-4}$, $\alpha_2 = 1.3\times10^{-4}$

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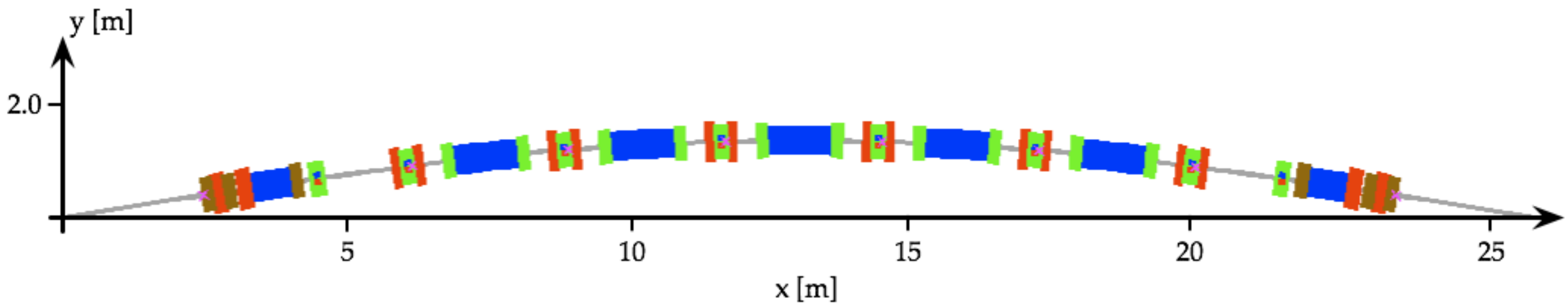

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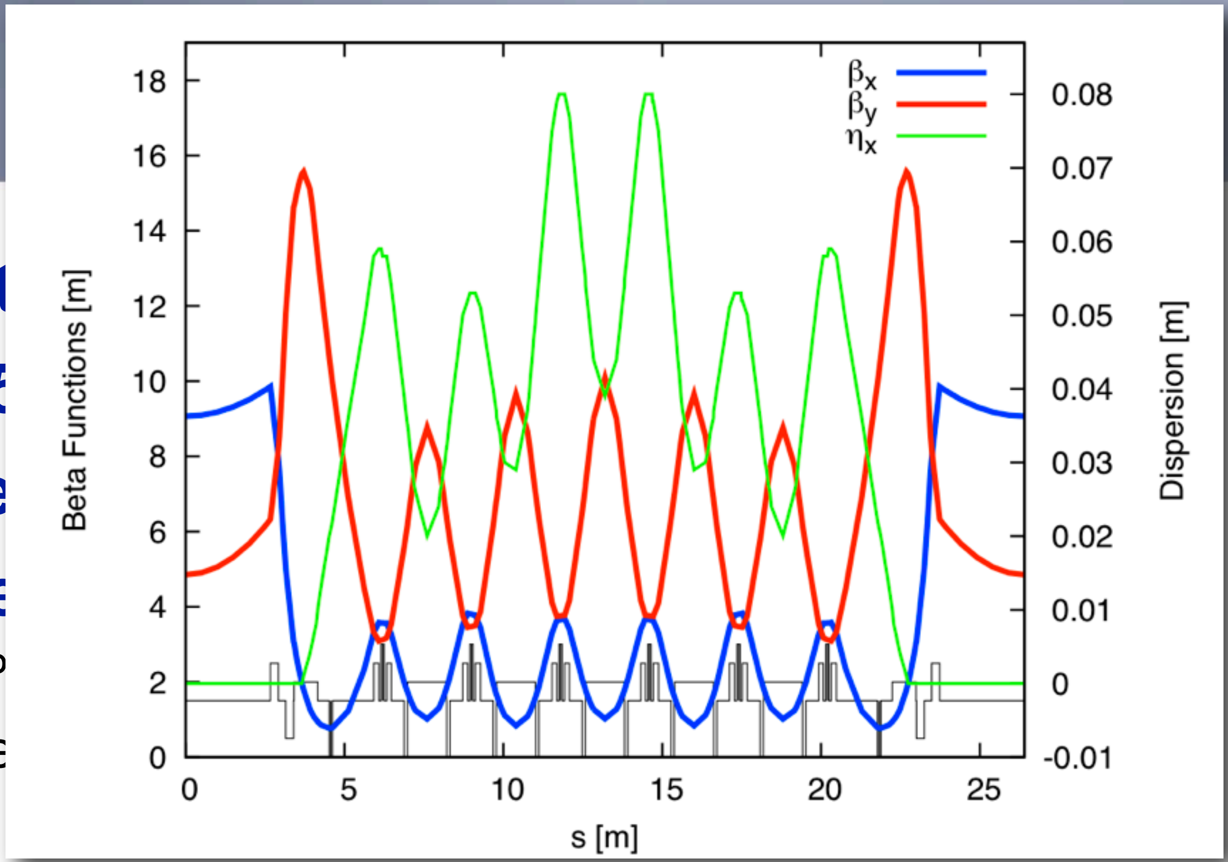

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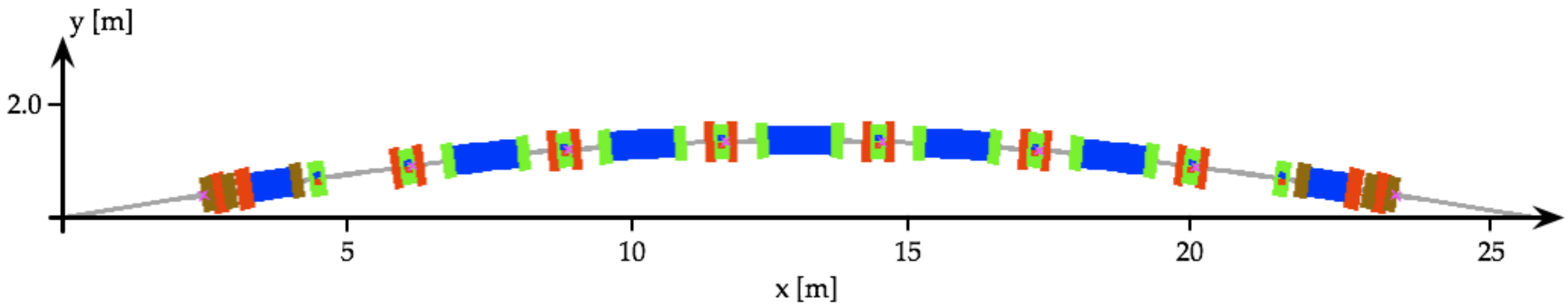
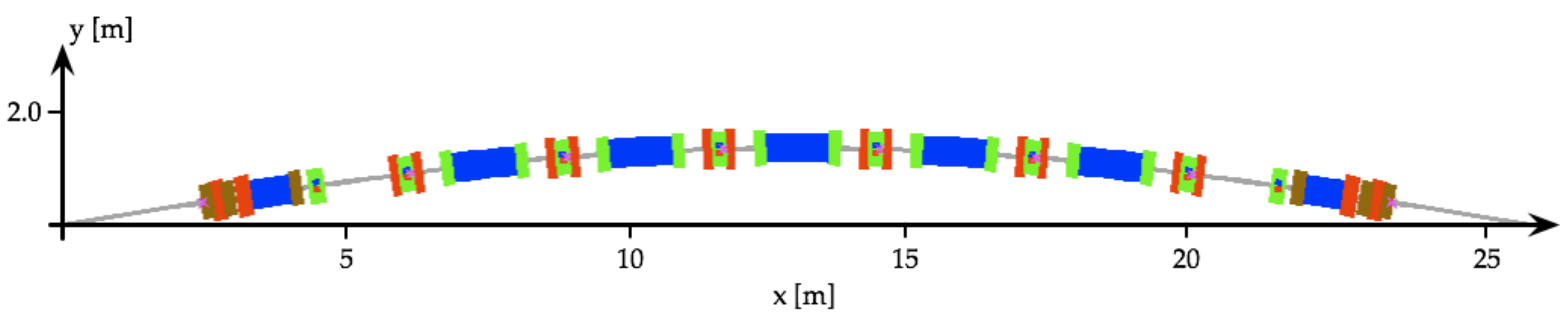


Detailed Design Report on the MAX IV Facility

Nonlinear Optics

- **Strong-focusing lattice → low dispersion → large natural chromaticity → strong sextupoles**
- **5 sextupole families (18 sextupoles per MBA)**
  - Sextupole tuning → chromaticity shaping
  - Small chromatic TS → high MA despite small chamber; lattice MA > 4.5%
  - Minimize res. driving terms within achromat → minimize ID perturbation
- **3 octupole families (6 octupoles per MBA)**
  - Minimize ADTS (first-order effect!) → small tune footprint → large DA



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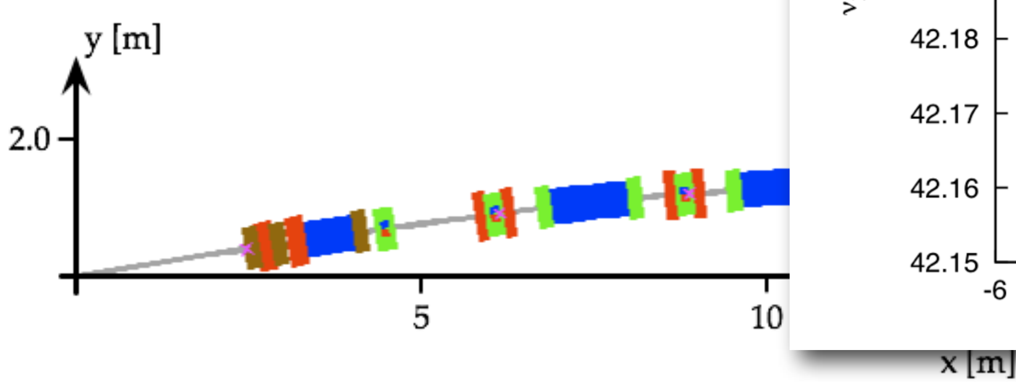

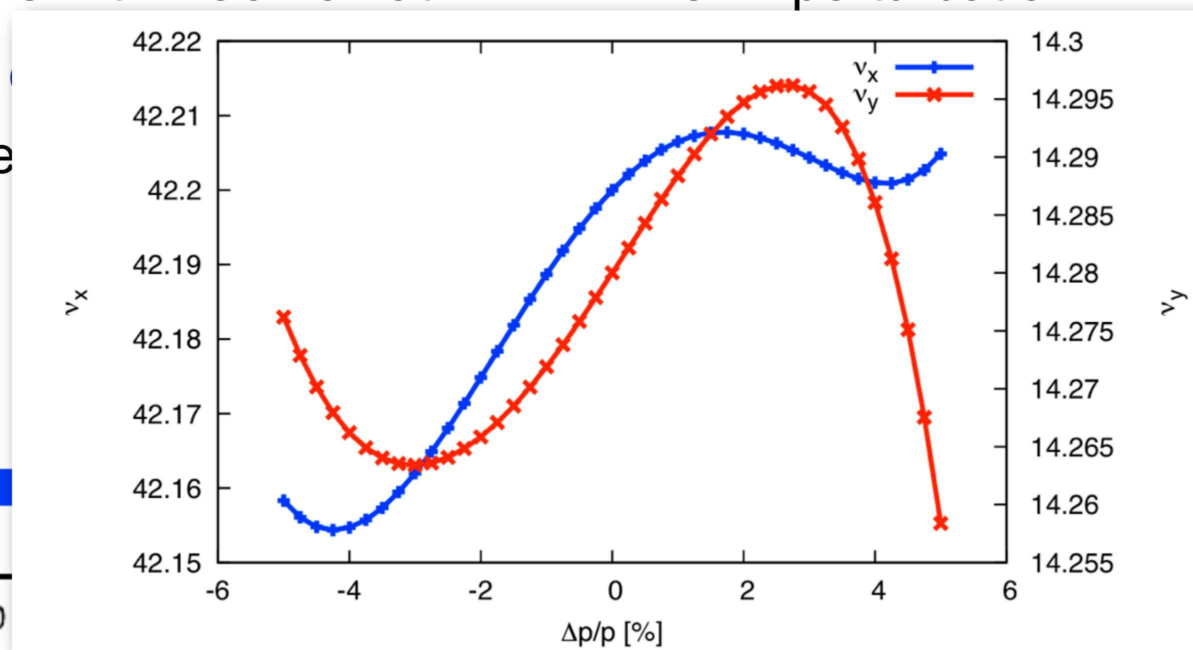

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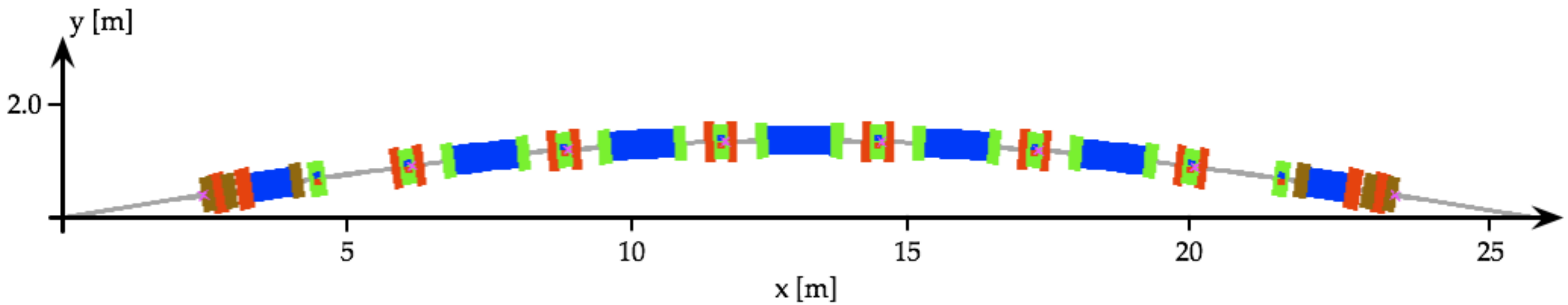

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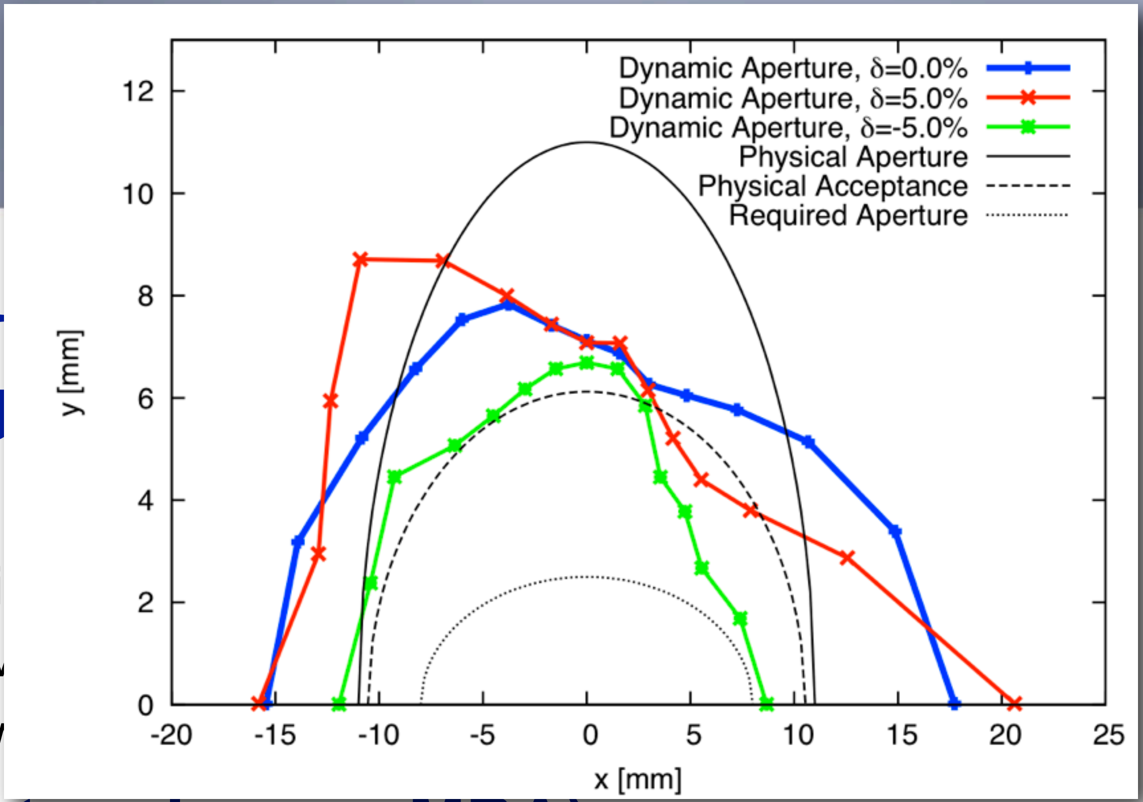

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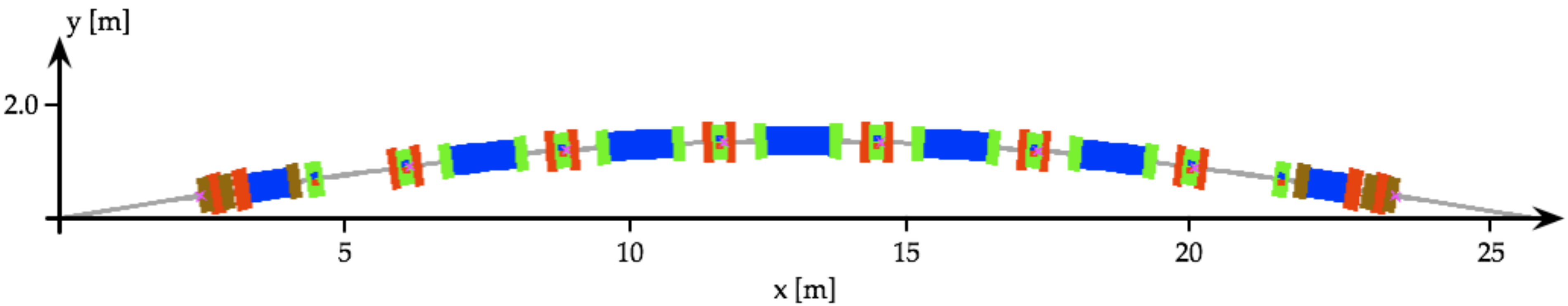

Errors & Correction

- **Shunts on dipoles and quadrupoles → reduce field errors to ~ 0.02% rms**
- **Specify tolerances for ID multipole contribution**
- **Field errors + multipole errors → sufficient DA**
- **DA dominated by misalignment errors → sufficient DA**
- **Orbit correction:**
  - 200 BPMs and dipole corrector pairs (ferrite over stainless)
  - **SOFB**: global, operate @ 10 Hz (-3dB amplification @ 0.3 Hz) → drifts
  - Phase 2: **FOFB**: global controller, local orbit control across LSs, operate @ 10 kHz (-3dB amplification @ ~ 100 Hz) → cultural noise, gap movement
  - Phase 3: Expand FOFB to global control @ 10 kHz

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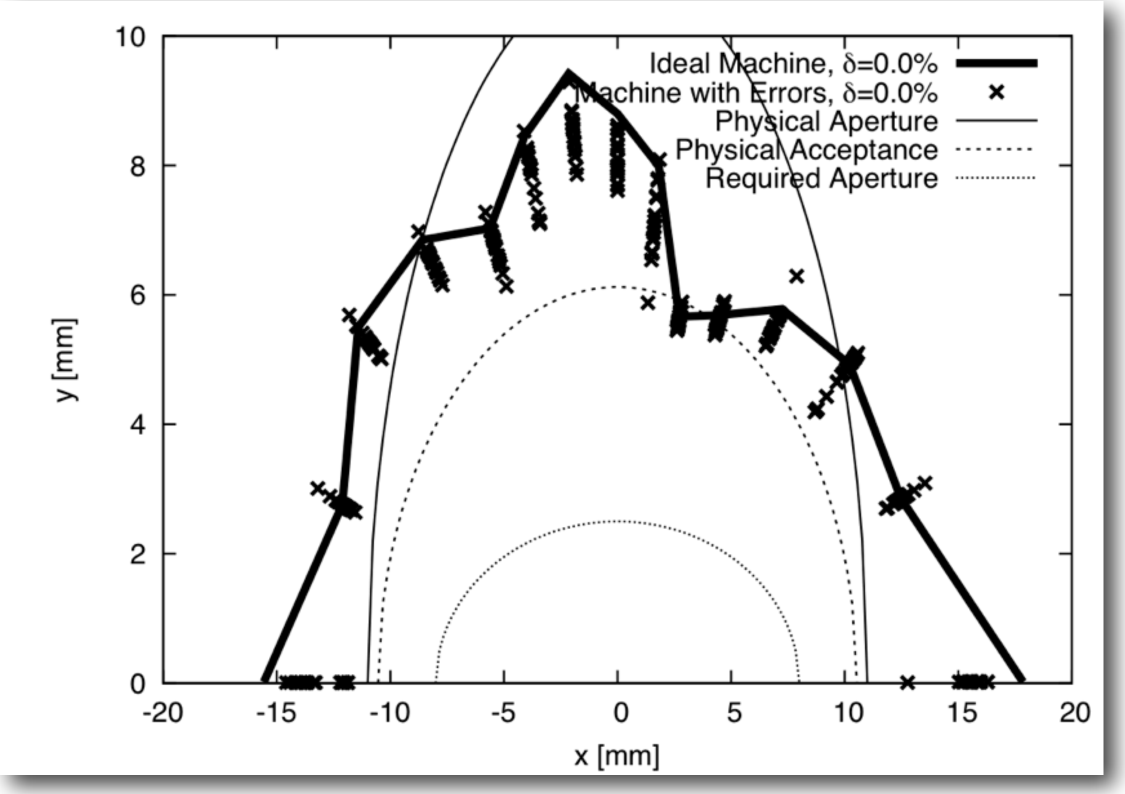

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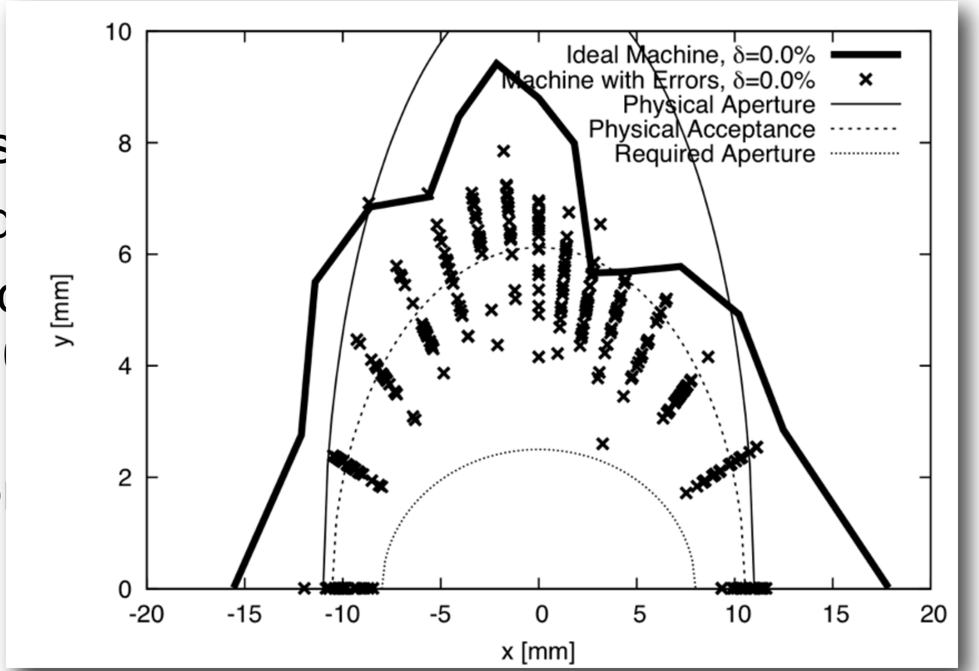

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Matching Optics to IDs

- **Optics in LS:**
  - Vertical beam size in LS: 2 µm < σ_y < 6 µm
  - 1Å diffraction limit → ε_y = 8 pm rad (~ 3% coupling)
  - Better matching to photon beam → $\varepsilon_y \approx$ 2 pm rad (~ 1% coupling)
- **DWs and strong IVUs:**
  - Local beta matching (quadrupole doublet in MC) → squeeze β_y
  - Global tune correction (pole-face strips in dipoles, QF family)
  - Nonlinear re-optimization / correction not required
- **Electron beam size in ID → coupling / ver. dispersion:**
  - BPM calibration with respect to sextupole centers → reduce betatron coupling & spurious vertical dispersion
  - Skew quadrupole windings:
    - Minimize betatron coupling & spurious vertical dispersion
    - Option: vertical dispersion bumps within achromats to regain lifetime

Magnets

- **MBA → compact optics**
  - Large number of mechanically identical magnets → inexpensive
  - Small magnet gaps → low power consumption
  - Power in families wherever possible; add floating PS where necessary
- **Dipoles**
  - Sector bends ~0.5 T with gradient
  - Soft-end dipoles in MC
  - ± 12.5 mm good field region
  - Pole-face strips → adjust gradient strength
- **Strong-focusing quadrupoles**
  - Common 2D profile (designed for max gradient), different lengths
  - 25 mm full gap
  - Roughly ± 10 mm good field region

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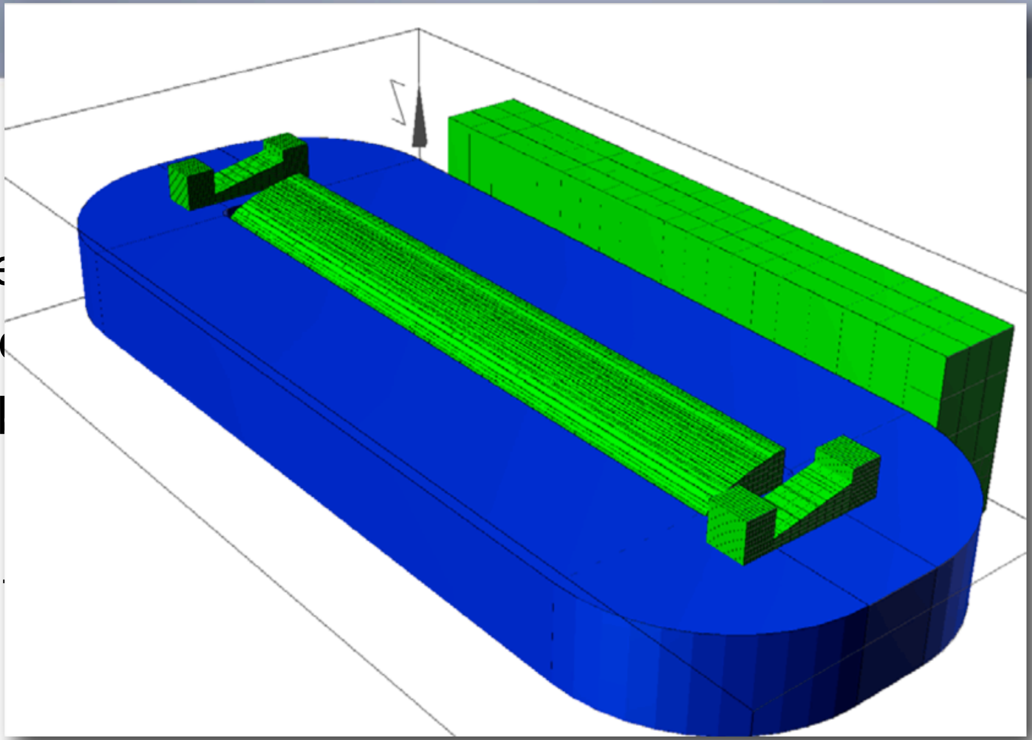

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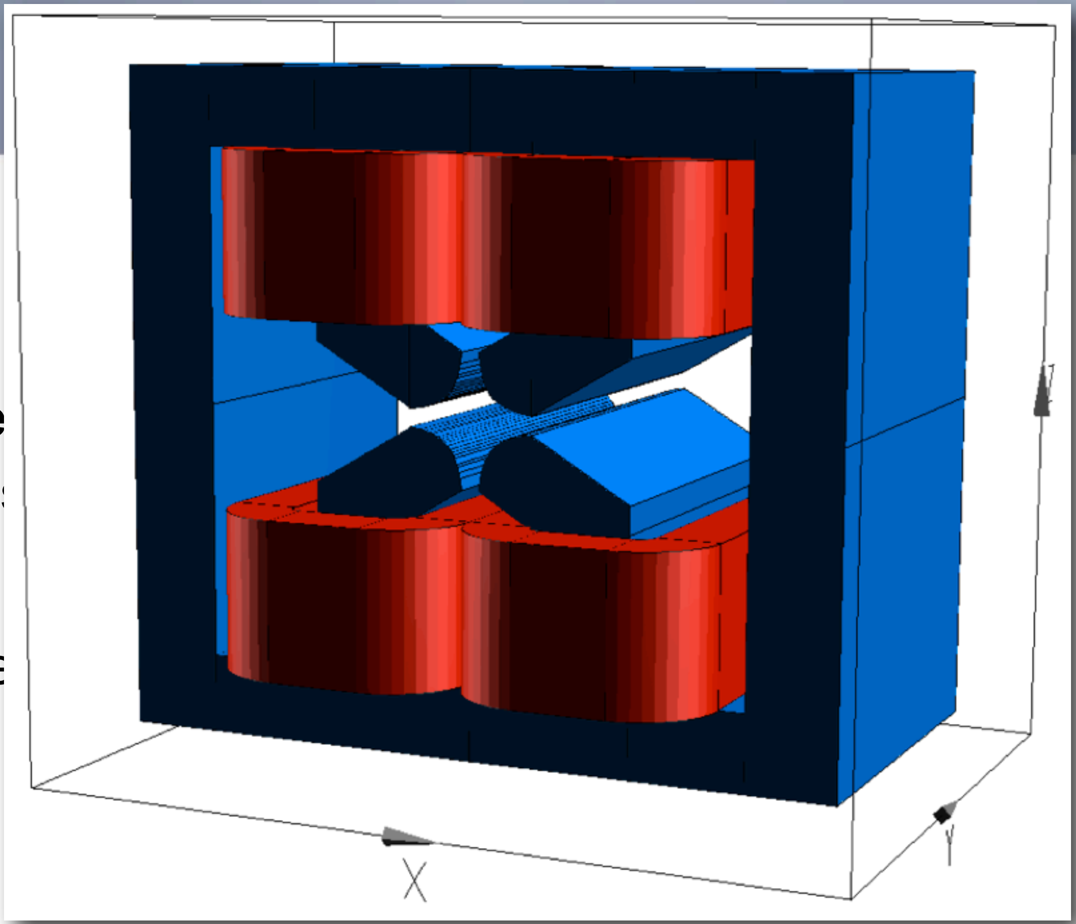

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Magnets (cont.)

- **Sextupoles**
  - One design for defocusing, one for focusing
  - 25 mm full gap
  - ± 10-11 mm good field region
- **Octupoles**
  - Two designs (25 mm and 30 mm gap)
  - Roughly ±10 mm good field region
  - Twice as strong as required → ADTS tuning → DA shaping
- **Extra windings on sextupoles & octupoles**
  - Upright quadrupole → beam-based BPM calibration
  - Skew quadrupole (dispersive & non-dispersive)
  - Auxiliary sextupoles
  - Remote switching of powering where required

Magnets (cont.)

- **Dipole correctors**
  - Ferrite magnets
  - Install over stainless steel chamber sections → fast
  - No extra dedicated FOFB correctors required

- **Integrated magnet design**
  - Excellent alignment
  - Reduces amplification factor (correlated misalignments)
  - Solid iron magnet blocks = girders → simple concrete supports
  - Vibrational EF pushed beyond 100 Hz → minimize displacement

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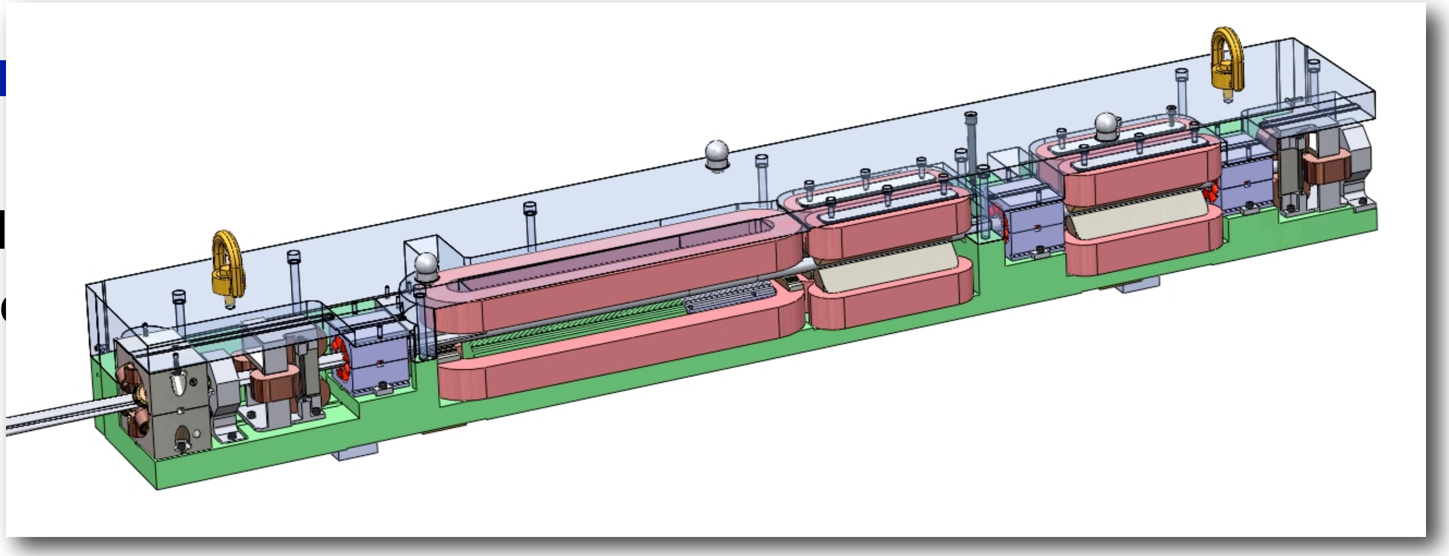

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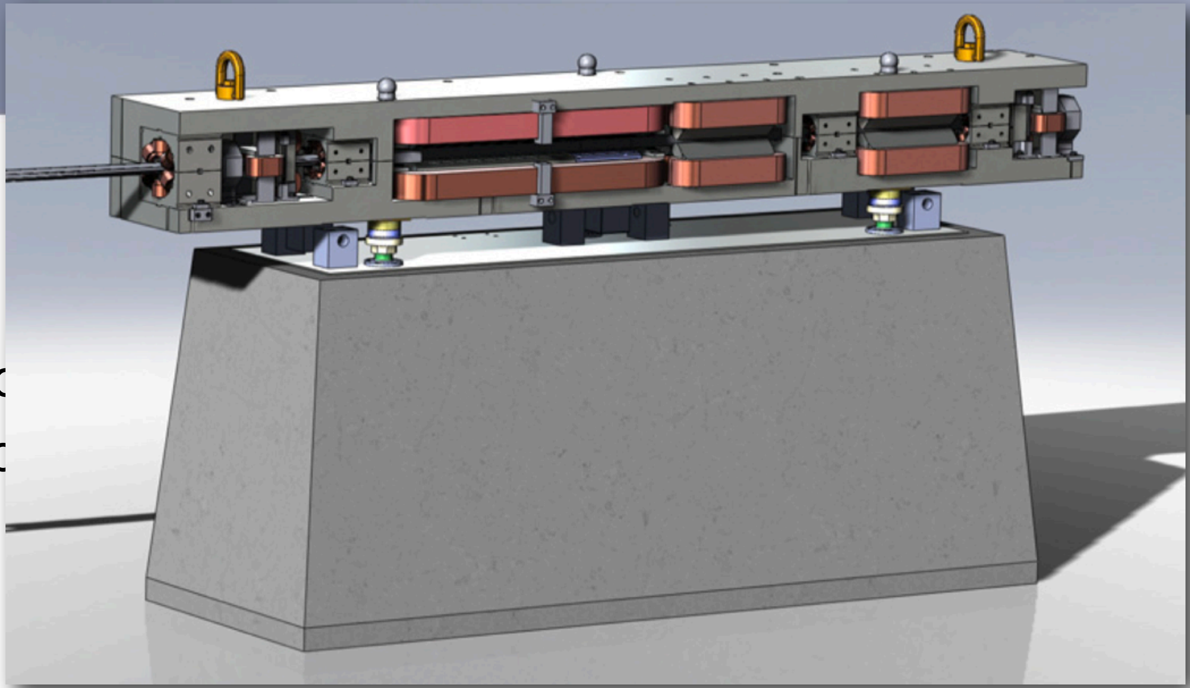

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RF System

- **All cavities installed in short straights**
- **100 MHz main RF system**
  - Improved MAX II/III capacity-loaded cavity design
  - 300 kV maximum gap voltage (30 kW Cu losses)
  - 6 cavities ensure RF acceptance beyond 4.5% for ID-equipped ring
  - Mechanical tuning → elastic deformation
  - Low frequency advantages:
    - Achieve high RF acceptance at lower voltages
    - Lower voltage and high coupling of cavities to transmission lines → 60% of electrical power to transmitters is converted to SR
  - Higher-order modes:
    - Lowest HOM at 406 MHz, four measured modes can drive CBMI
    - Suppression with damping couplers (capacitive damping from antennas, inductive coupling loops)

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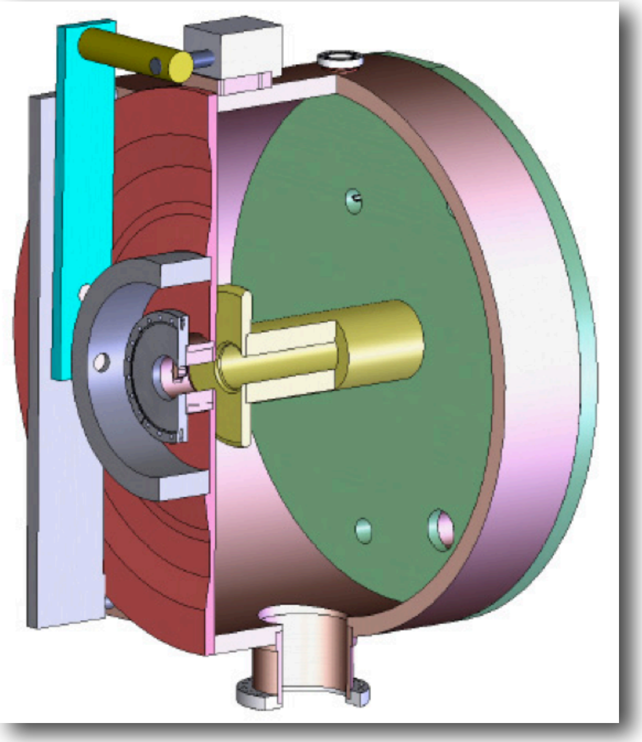

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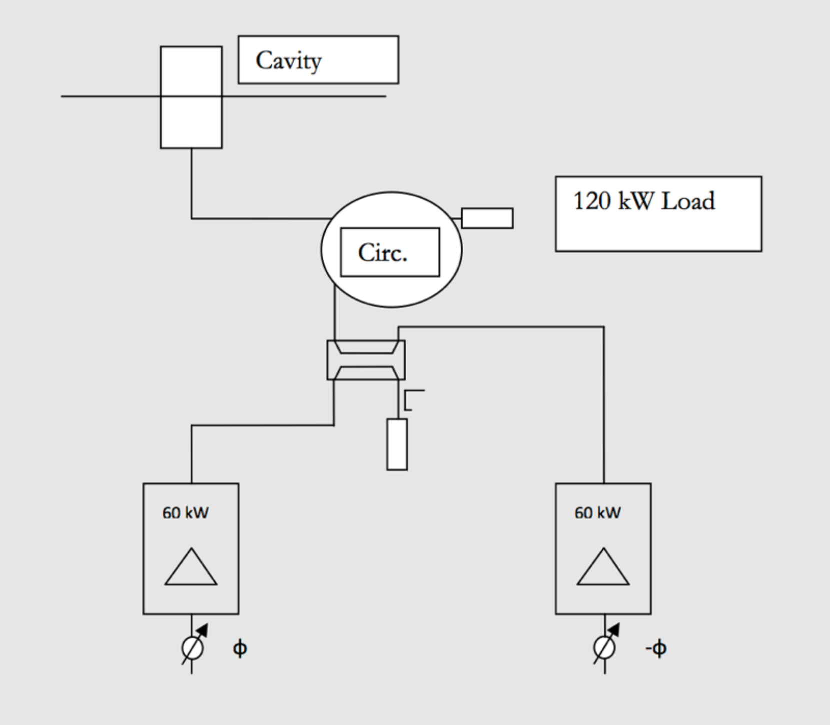
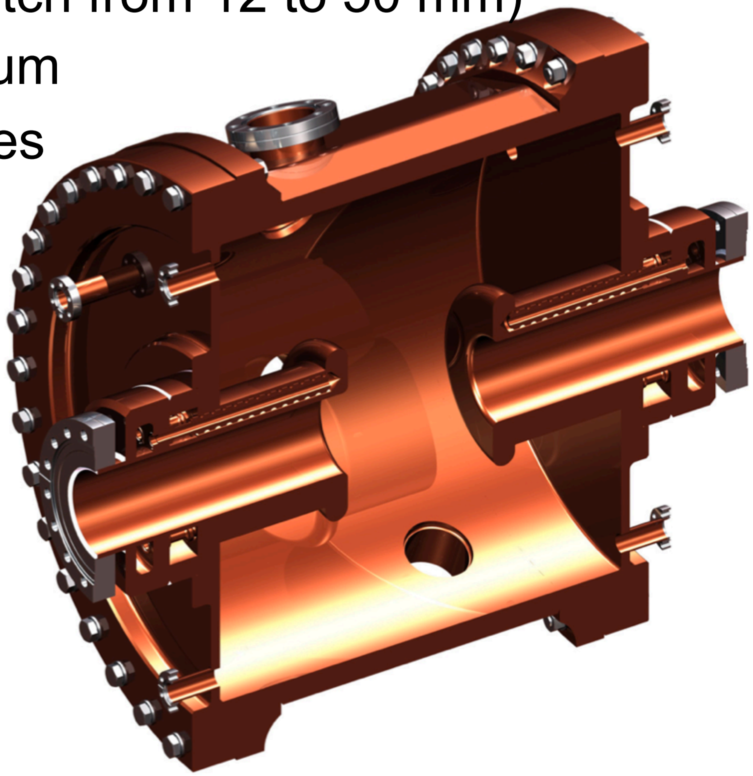
RF System (cont.)

- **RF stations**
  - 2x 60 kW transmitter
    - Tetrode amplifiers → low power consumption (70% efficiency)
  - 3dB hybrid with dummy load
    - Regulate cavity power by phasing → transmitters run at const. power
  - 120 kW transmission line with circulator
  - High degree of modularity → high reliability



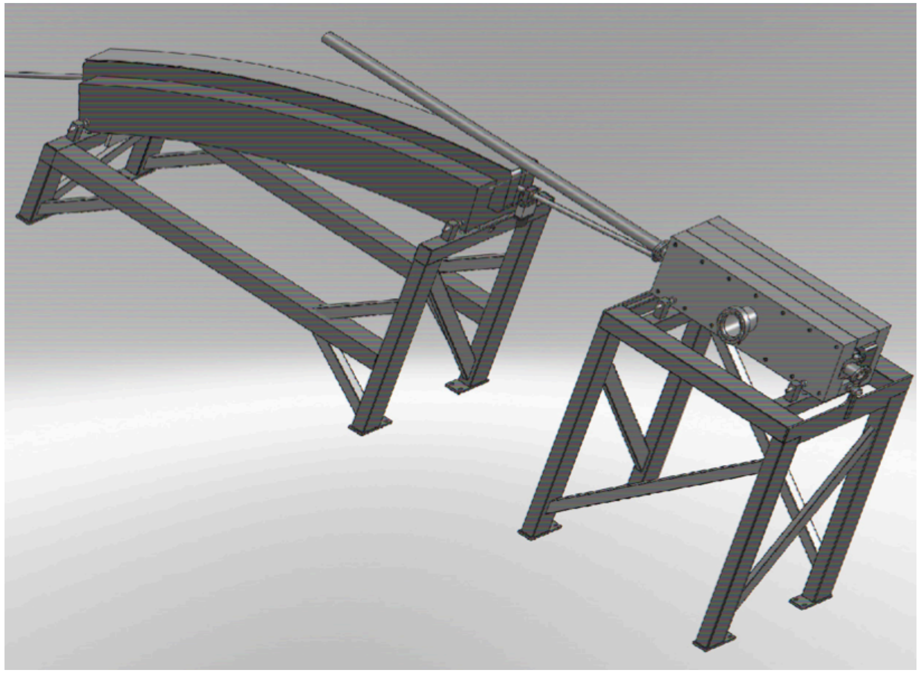
RF System (cont.)

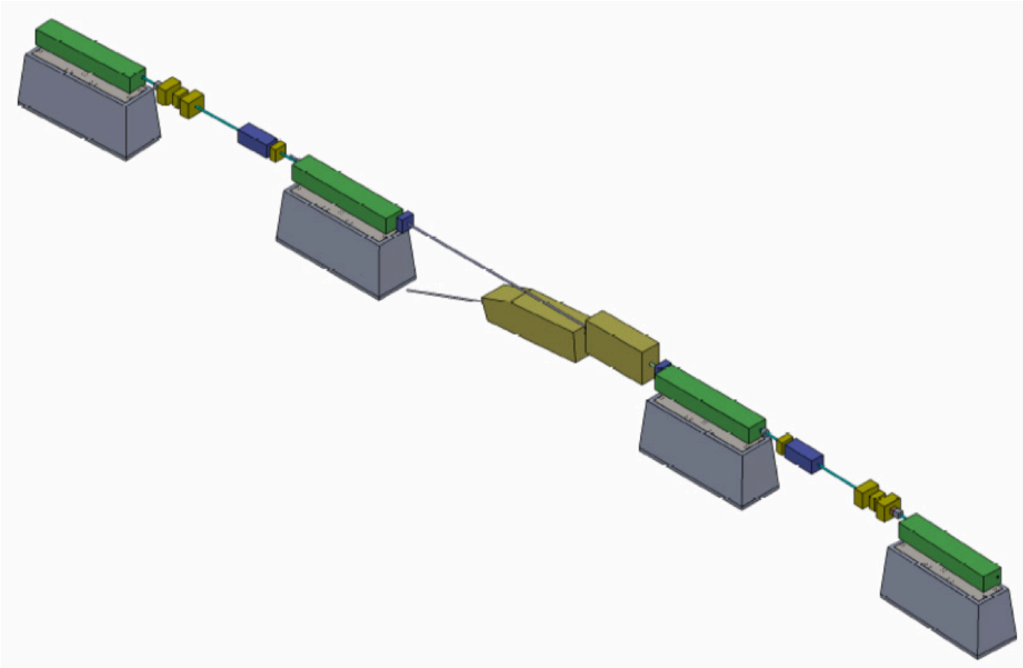
- **300 MHz harmonic RF system**
  - Low RF voltage → warm harmonic cavities
  - Capacity-loaded design similar to main cavity → push HOMs to high freq.
  - Require ~ 500 kV → three passive LCs
  - LCs can stretch ~ by factor 5 (we plan to stretch from 12 to 50 mm)
  - Long bunches → reduce bunch power spectrum
    - ring more tolerant against HOM instabilities
    - positive effect on RWI



Transfer Line & Injection

- TL is vertical achromatic bend
- 1 m concrete floor between linac tunnel and SR hall
  - quadrupoles, cooling, and cabling installed on slanted girder
- 5º septa plus 20º bends, 6 quads, symmetric layout
  - Flexible optics to accommodate to linac optics and injection matching





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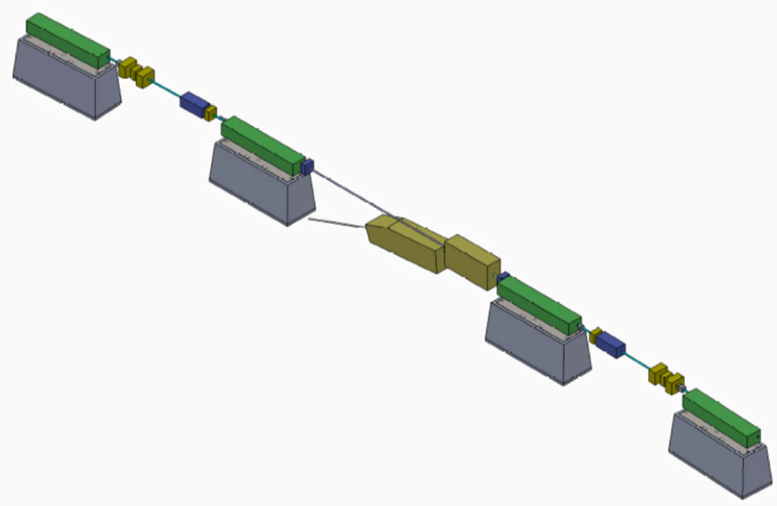
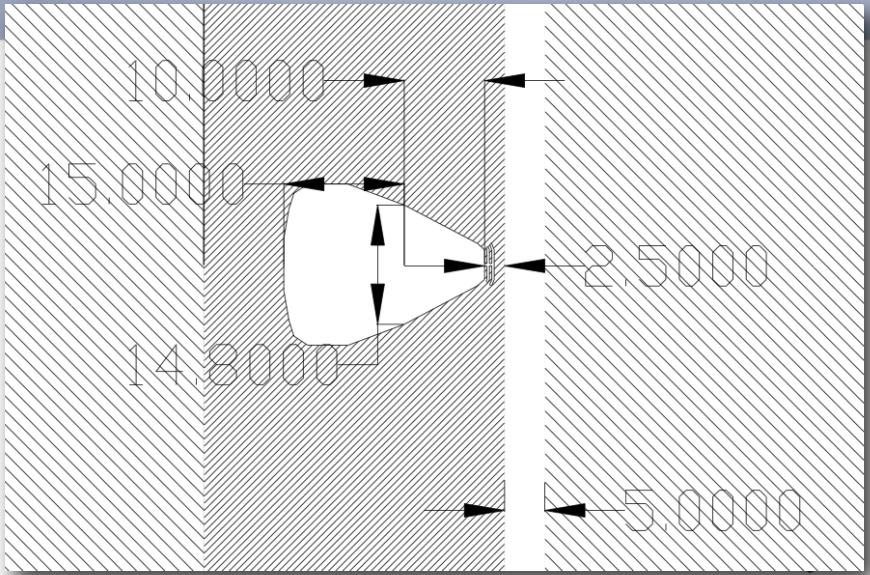


- **4-kicker injection bump → -8 mm**
  - 2x 500 mm, -2.7 mrad before/after DIPm
  - 2x 100 mm, +0.2 mrad in long straight
- **Lambertson septum**
  - derived from MAX I/III design
  - 5º, 0.85 T, 2.5 mm blade @ -10 mm
  - Septum filter → minimize (and linearize) leak field onto stored beam
- **Injected beam @ -13.5 mm → < 6 mm oscillation ampl.**
- **Alternative: pulsed sextupole magnet**
  - Does not require balancing 4-kicker bump
  - Retain injection point & position/angle of injected beam
  - PSM one achromat length downstream, $l \approx 300$ mm, $b_2 \approx 92\ m^{-2}$, $\tau \approx 3 \mu s$
  - Oscillation amplitude < 6.3 mm
  - 2-turn option: $\tau = 7\ \mu s$, reduced field strength, < 7.3 mm amplitude

Transfer Line & Injection (cont.)



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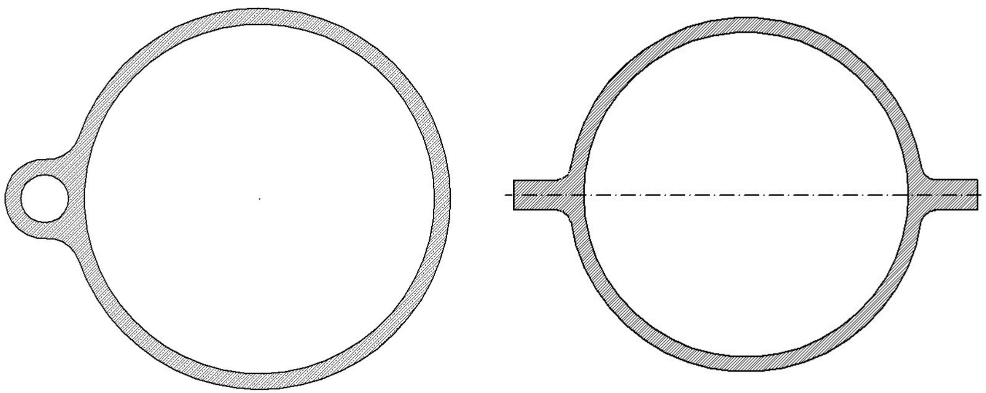
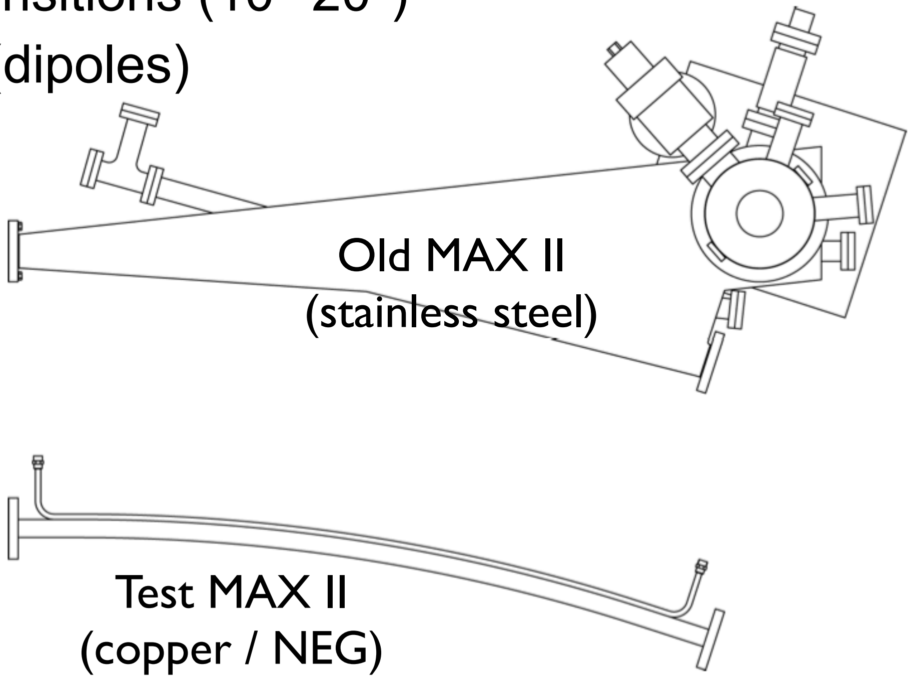
Vacuum System

- **Challenge:**
  - Narrow magnet apertures
  - Compact lattice leaves little space
- **Solution: NEG-coated OFHC Cu vacuum chamber**
  - Narrow chamber, no lumped absorbers, reduce no. of required pumps
  - Inner tube diameter 22 mm, conical transitions (10º-20º)
  - Outer diameter 24 mm + cooling tube (dipoles)





Vacuum System (cont.)

- **Flanges & bellows around LSs and RF cavities**
- **BPM case is rigid steel body with CF40 flanges**
- **Bellow and gate valves are RF-shielded**
- **Baking**
  - NEG activation @ ~200 C, 24 h
  - In-situ bake: remove upper magnet block half, raise chamber into oven

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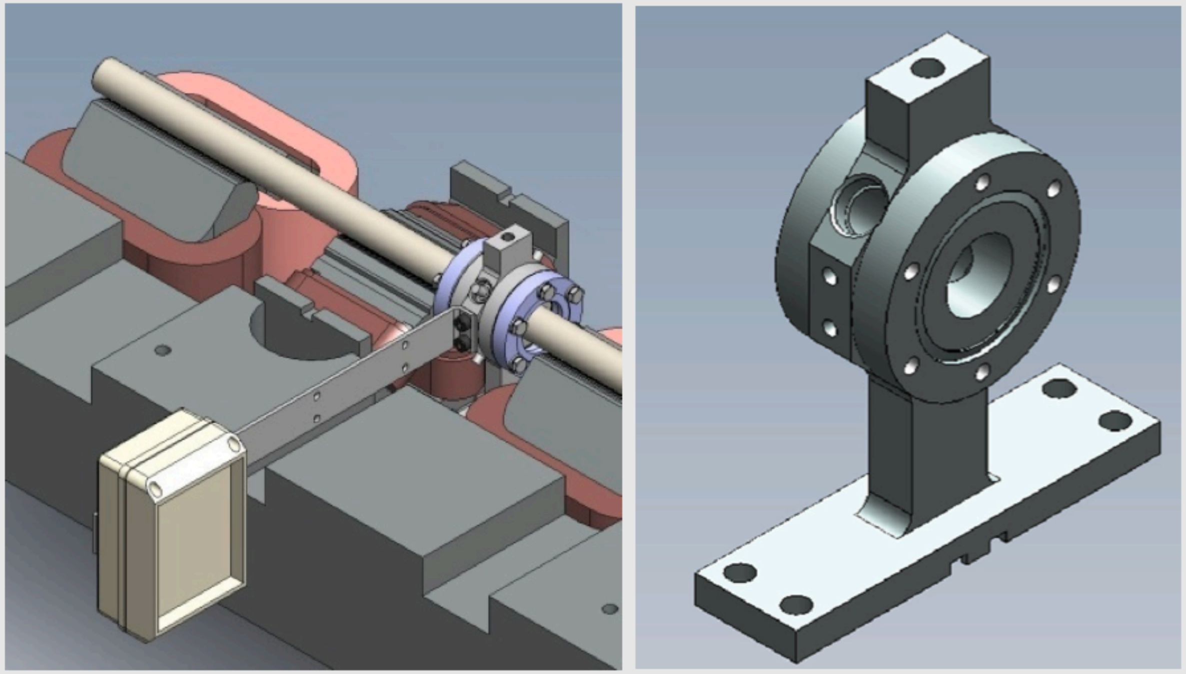

Connectors in a box   Housing

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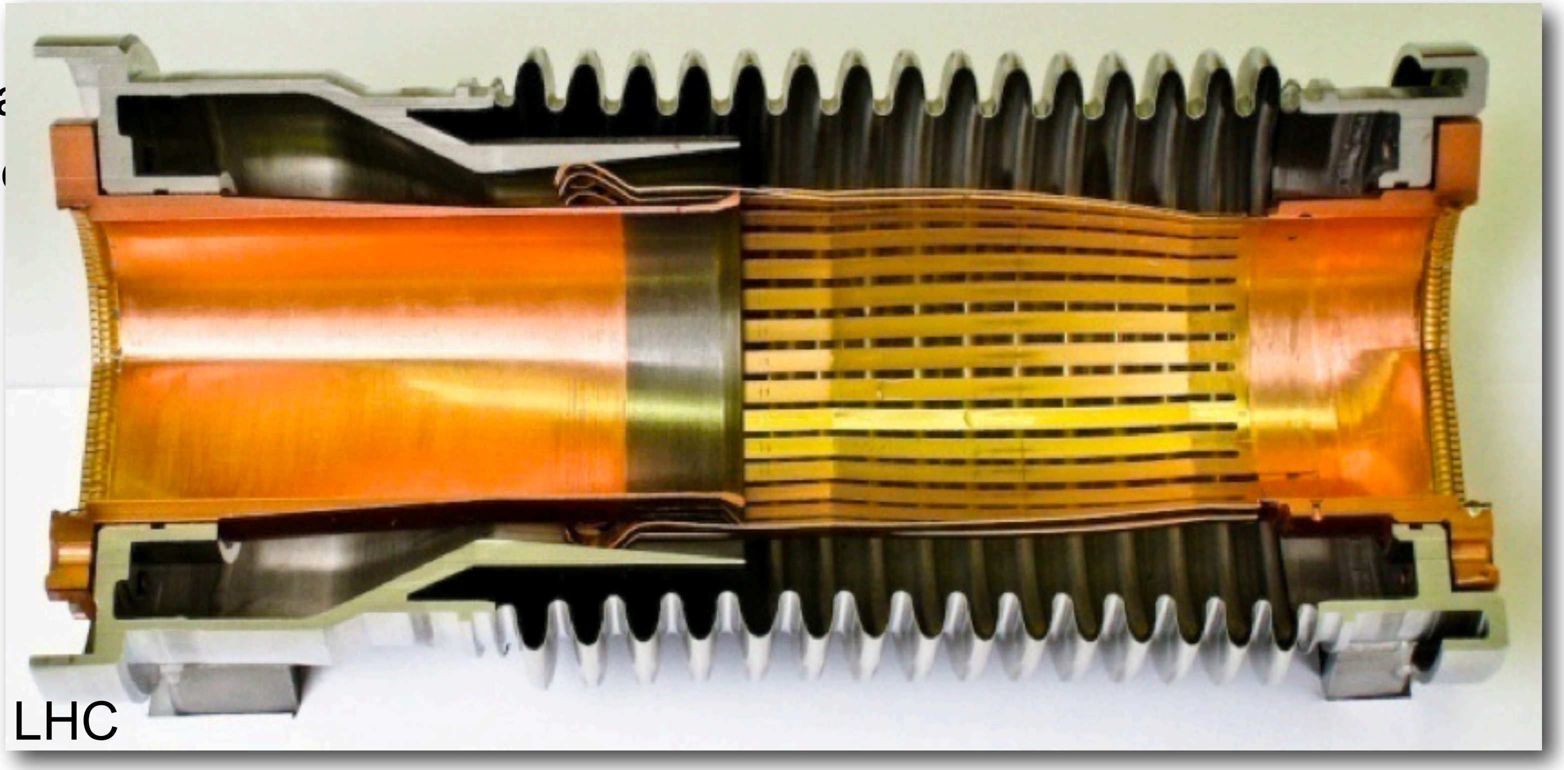

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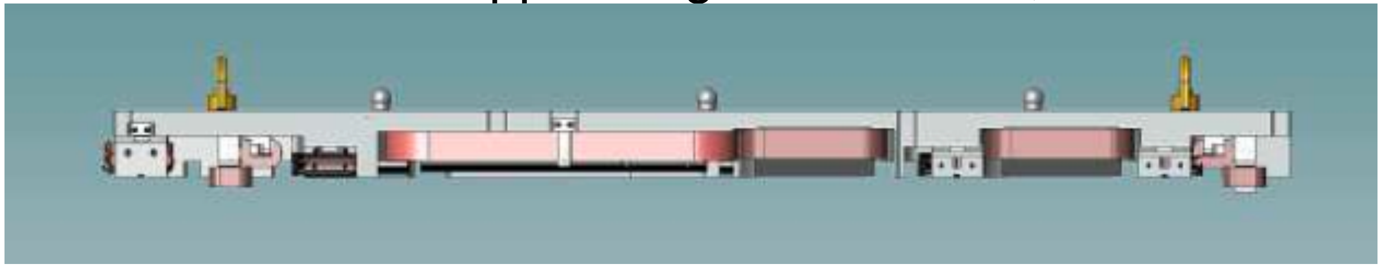
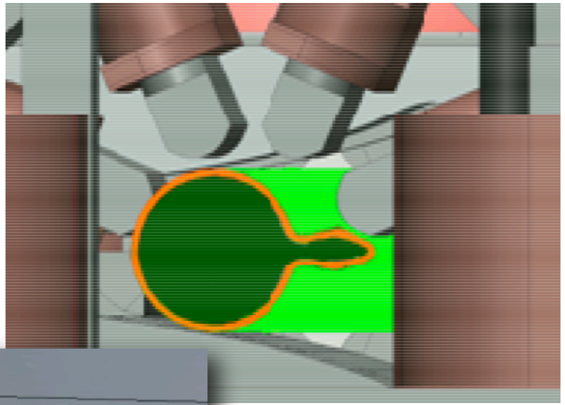
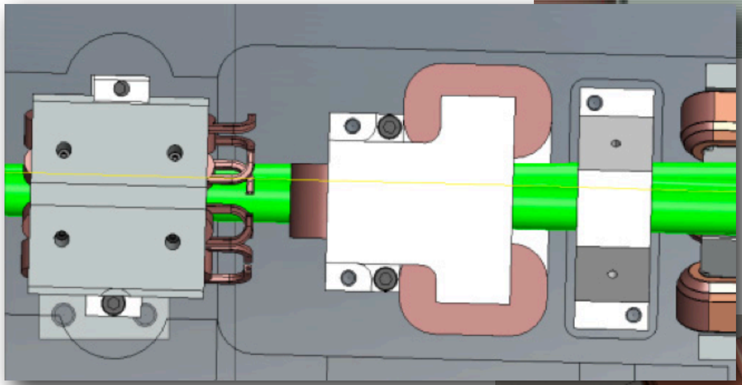
- **Baking**
  - NEG activation @ ~200 C, 24 h
  - In-situ bake: remove upper magnet block half, raise chamber into oven

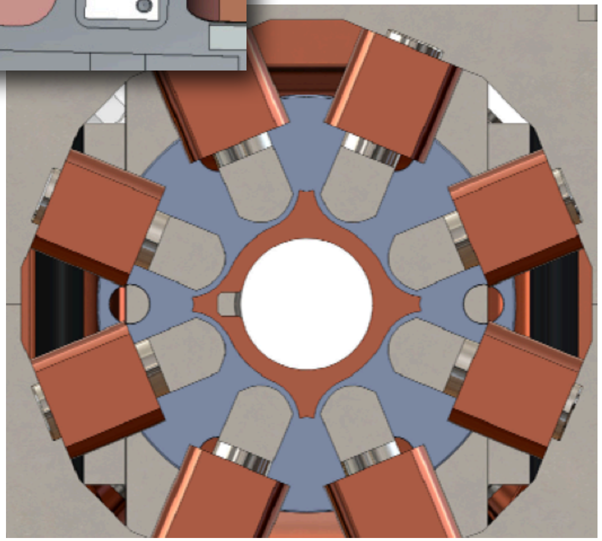


Vacuum System (cont.)

- **Special geometry**
  - Keyhole chambers for photon extraction
  - Crotch chamber in short straights
  - Kicker and septum chambers
  - Stripline and scraper chambers
  - Tapering to RF cavities
  - Diagnostic beamlines
  - ID chambers
- **Photon beamlines**
  - Absorbers, gate valves, cooled apertures
- **Vacuum diagnostics**
  - Gamma detectors, radiation monitors
  - Ion pump currents
  - RGA (as part of the turbo pump stand)







Beam Diagnostics

- **Beam position**
  - Resolve ~ 0.2 µm @ 500 mA for ~ 10 ms sampling time
  - Need also: “commissioning mode”
    - short, weak pulse (~ 300 pC, 1 ns)
    - TxT measurement, however with relaxed accuracy
  - Further requirements: time stamping (synchronized to machine clock), post mortem input, interlock output, support for Tango CS
  - State of the art (commercial) digital BPM solutions fulfill requirements
  - Hybrid solution possible:
    - Fast digital BPMs flanking straight sections
    - Inexpensive slower BPM electronics within the achromats
    - Spare fast units can be used for commissioning
- **Tune measurement**
  - Stripline pair + spectrum analyzer (parasitic measurement possible)
  - Button BPM signal + Fourier analysis (larger perturbation)

Beam Diagnostics (cont.)

- **Current measurement**
  - DCCT delivers 10^{-4} accuracy
  - BPM sum signal can be used to determine lifetime (if calibrated by DCCT, can also be used for current measurement)
- **Emittance monitor**
  - 2D beam image available online at all times
  - Vertical beam size from π-polarization method (UV-vis. ver. polar. SR)
  - System is already operational @ SLS
  - Install two monitors: dispersive monitor → energy spread
- **Bunch length monitor**
  - Streak camera or fast photodiode (expected rms ~ 170 ps)
- **Filling pattern monitor → homogeneous filling (top-up)**
  - BPM front-end → sub-µm stability
  - IBS → transverse distribution, lifetime

Beam Diagnostics (cont.)

- **Scrapers**
  - Gas lifetime calibration (→ Touschek lifetime measurement)
  - Vertical acceptance measurement
  - ID protection + loss concentrator
  - Determine overall dynamic MA with horizontal scraper
- **Pinger magnets**
  - Strong single-turn kickers synchronized with TxT BPM read-out
  - Tune measurement
  - Nonlinear characterization (demonstrated e.g. Diamond)
- **Beam loss monitors**
  - Global fiber optic system (@ MAX-FEL) → beam loss location along SR
  - Local measurement methods:
    - PIN diode detectors
    - Scintillator setup (coincidence measurement → resonant spin depolarization → energy calibration)

Beam Diagnostics (cont.)

- **Temperature sensors (absorber-free vacuum system)**
- **Beam dynamics characterization**
  - MATLAB Middle Layer (with interface to Tango CS)
  - Accelerator Toolbox → modeling, simulation
  - LOCO (through MML) → response matrix , BPM offset calibration, beta functions, dispersion
  - Chromaticity from tune measurements at E+ΔE
- **Nonlinear optics characterization**
  - Spectral analysis of TxT BPM data after pinger excitation
  - Analogous to LOCO-approach: calibrate nonlinear machine model

Intrabeam Scattering & Lifetime

- **MAX IV 3 GeV SR is IBS-limited**
- **Reduce IBS emittance blowup → ultralow emittance**
  - LCs → stretch bunches → dilute charge density → reduce IBS blowup
  - DWs → increase bunch energy spread → reduce IBS blowup

- **“Paradox”: Touschek lifetime large despite ultralow emittance and high stored current**
- **Emittance reduction → lifetime improvement**
  - DWs and LCs pay off twice (direct effect & indirect effect via IBS)

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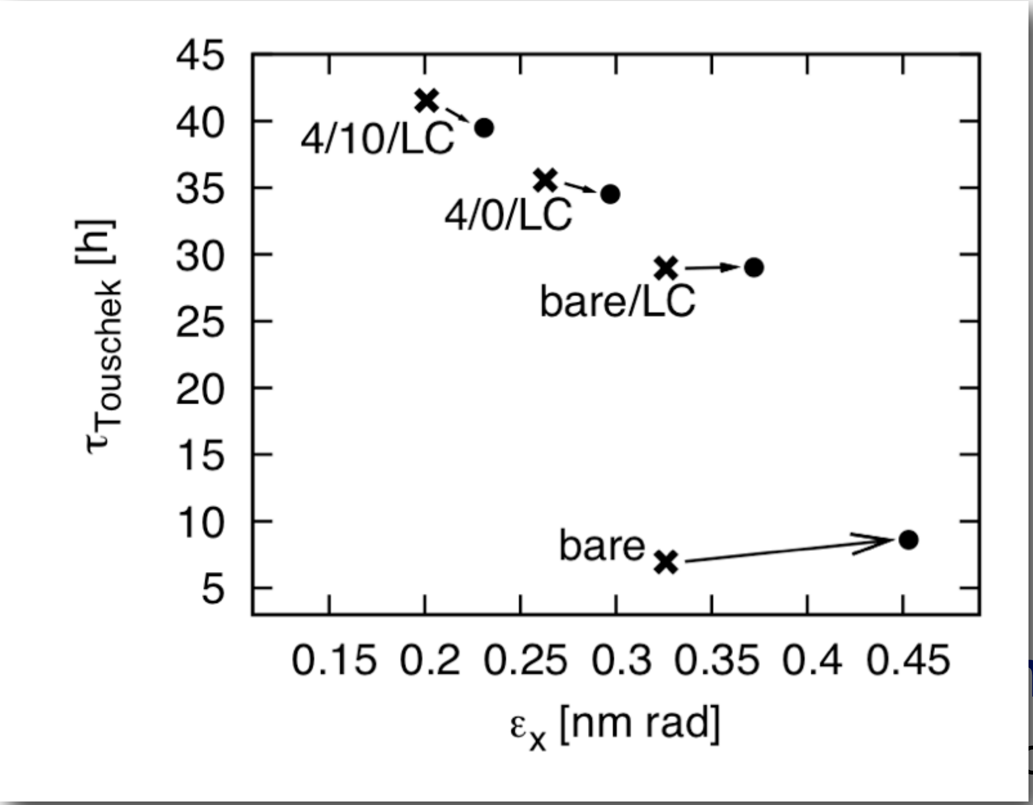

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Detailed Design Report on the MAX IV Facility

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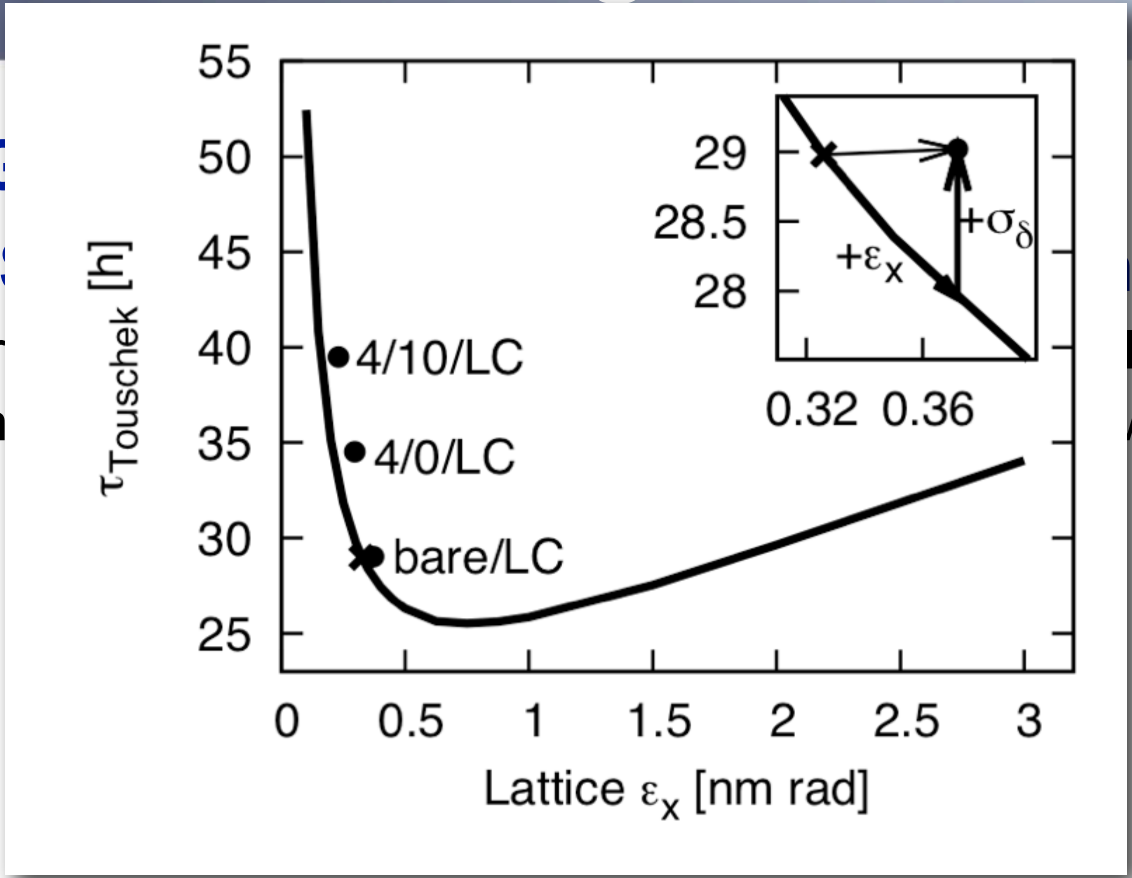

- **MAX IV 3 G**
- **Reduce IB**… **ittance**
  - LCs → str… IBS blowup
  - DWs → in… up
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Intrabeam Scattering & Lifetime (cont.)

- **Gas lifetimes**
  - Assume 2 pb CO rest gas; vertical aperture limitation from strong IVU
  - Elastic scattering: 25.4 h
  - Bremsstrahlung: 56.1 h (weak dependence on MA; here 4.5%)
- **Touschek lifetime**
  - 500 mA, 176 bunches, realistic vacuum chamber
  - 6D Tracking in Tracy-3 including IBS, set ε_y = 8 pm rad
  - Tracking studies for various configurations:
    - Different ID configurations and U_{cav}, but δ_{RF} > 4% always
    - "Worst case": 4 PMDW + 10 IVU, 4% RF MA
      τ_{ts} = 25.5 h → τ_{tot} = 10.3 h
    - Typical: τ_{ts} = 39.5 h → **τ_{tot} = 12.1 h**
  - Top-up: 5 mA deadband (1%) → 8.8 nC top-up shot every 7 min