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Precision high voltage platform (HVP) for ion mass analysis

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1) Introduction: why HRMS may need 10^{-5} relative voltage stability

2) General and design consideration for precision HVP

3) Example of other high voltage platforms and transmission lines

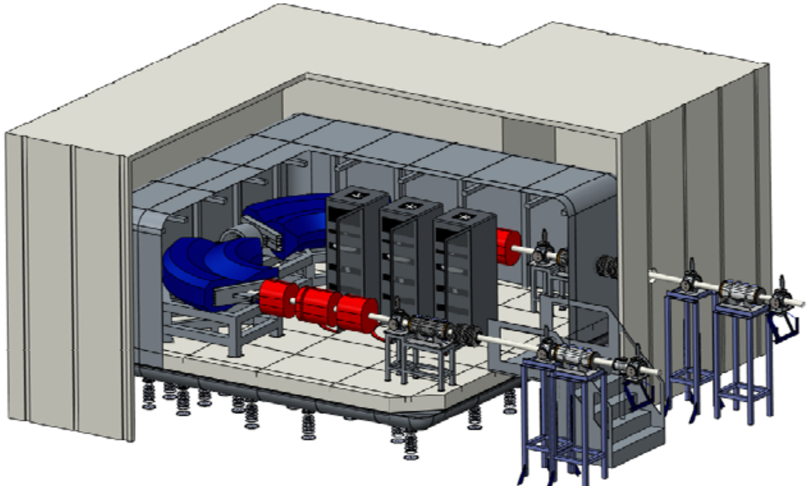
4) Summary and conclusions

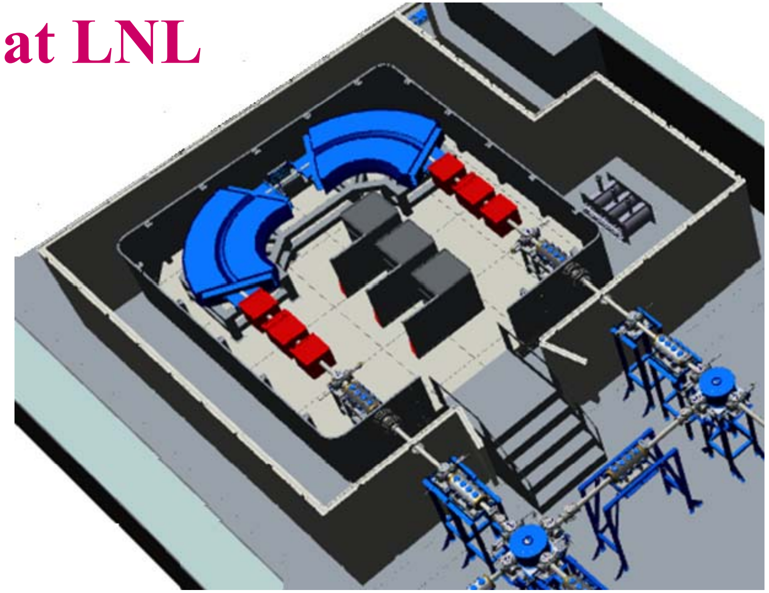
Abstract

High voltage platform are of widespread use in nuclear physics accelerator in order to provide the initial acceleration of ion. The ion source environment is particular challenging for high voltage holding, since discharge can be energized from source radiation or secondary particle generated by the ion beam.

Moreover spectrometers for charge to mass ratio of exotic nuclei requires a well defined beam energy, which poses challenging requests to high voltage design, rising the question of which electrode design rules are necessary for quiet voltage operation, with typically tolerable energy rms fluctuation in the 10^{-5} order, including contributions from all devices in a beamline (spanning a 10 m size). The need for thick plate ground, balanced transformer load and control of stray capacitances are also noted.

1.1) Introduction: the high voltage platform for precision mass spectrometry (HRMS of SPES) at LNL





Typical features of precise HVP (high voltage platform):

Heavy load (40 t) and precise alignment ⟹ rigid structure

Limited space around < 1m; magnet need water cooling and 70 kVA

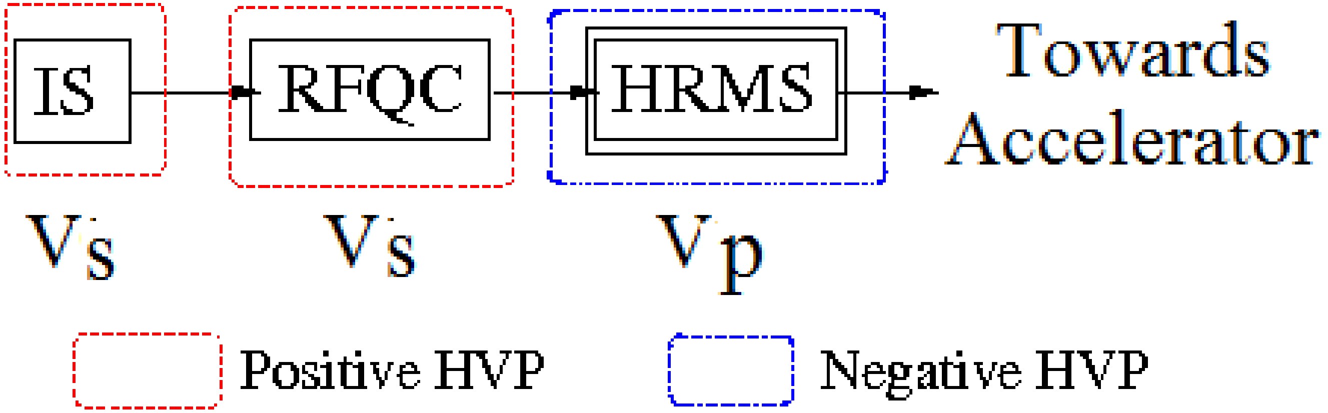
Moderate voltage (working -120 kV, rating -150 kV); a ground cage is needed.

Air is filtered inside ground cage and temperature conditioned within 1 K

But: Extreme voltage stability (see next slide) , and accuracy

Large surface (>200 m^2); installation below ground level

1.2) SPES (selective production of exotic species) considers actually a two voltage platform system



IS = ion source

RFQC= RFQ cooler

HRMS=High resolution mass spectrometer

V_s= 40 kV

V_p= -120 kV

V_a= 160 kV (acceleration voltage from source to separator magnet)

$$V_a = V_s - V_p$$

Of course V_a ripple is the combination of both power supply ripples, so the worst power supply dominate. MOREOVER any ground fluctuation between V_s and V_p power supply will add to noise

For the case of non-random fluctuation, compensation of V_s and V_p ripple is in principle possible, but hardly conceivable in practice.

1.3) Isobar separation example

M dimensionless mass ratio

$$M = \frac{m}{|q|} \Big/ \frac{m_u}{e}$$

Bending radius r_b

$$r_b = \frac{1}{B}\sqrt{\frac{2m_u}{e} M (V_a + E_i)}$$

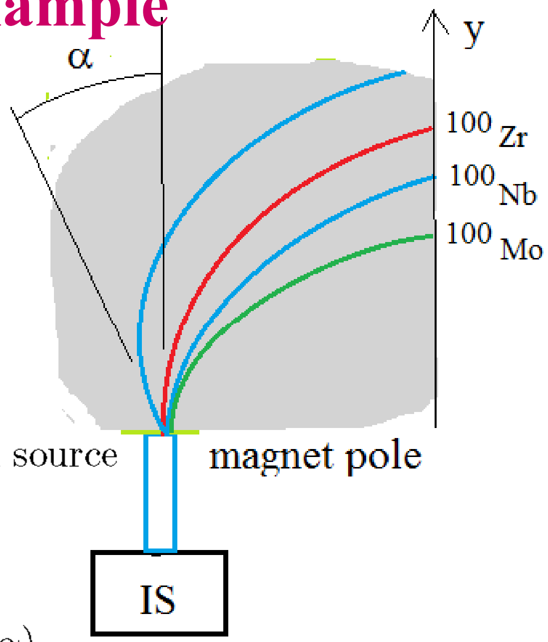
V_a acceleration voltage

E_i voltage due energy fluctuation from source

σ_{Ei} rms energy spread in eV;

Exit position $y \cong r_b + O(\epsilon^2)$

ϵ emittance (due to angle deviation α)



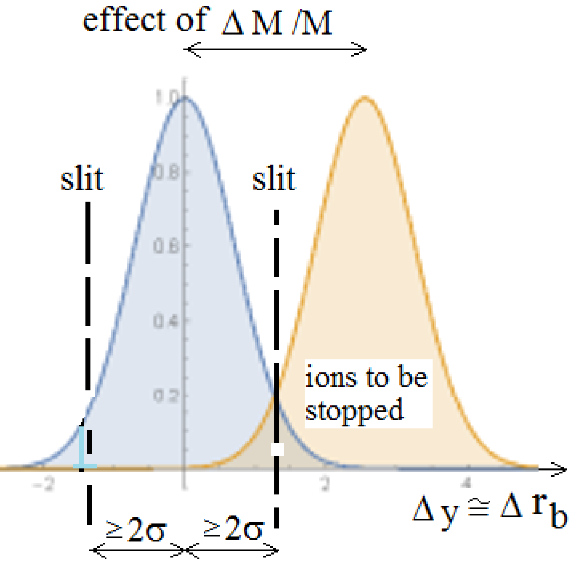
$$a_1 = M(^{100}\mathrm{Tc}) = 99.9076$$
$$b_1 = M(^{100}\mathrm{Mo}) = 99.9074$$
$$c_1 = M(^{100}\mathrm{Nb}) = 99.9143$$
$$d_1 = M(^{100}\mathrm{Zr}) = 99.9180$$

Specs for resolving power (from ^{100}Nb+Mo case)

$$M/\Delta M(c_1, b_1) = 1.45 \times 10^4 \quad \Longrightarrow \quad M/\Delta M|_{specs} = 2 \times 10^4$$

Choice of 4 σ spacing

$$\frac{\Delta M}{M} \geq 4\sigma \cong 4\sqrt{\left(\frac{\sigma_{Va}}{V_a}\right)^2 + \left(\frac{\sigma_{Ei}}{V_a}\right)^2 + 4\left(\frac{\sigma_B}{B}\right)^2 + O(\epsilon^2)}$$



Superposition of different isobar at separator exit should be minimized

The four terms above must be minimized as possible; for numerical example V_a=160 kV, we aim at $\sigma_{Va} < 1$ Vrms, $\sigma_{Ei} < 1$ Vrms, for accepting enough beam (angle α)

2.1) General considerations

In a simplified and preliminary conceptual description, each HVP platform needs two basic electronic devices:

-the high voltage generator HVg

-the main power supply, which can be a transformer (TX) or motor-generator (MG)

Accelerating voltage ripple

Ripple is due to: HVg ripple + ripple induced by TX + ripple coupled to TL (if any) ; these factor should be considered together

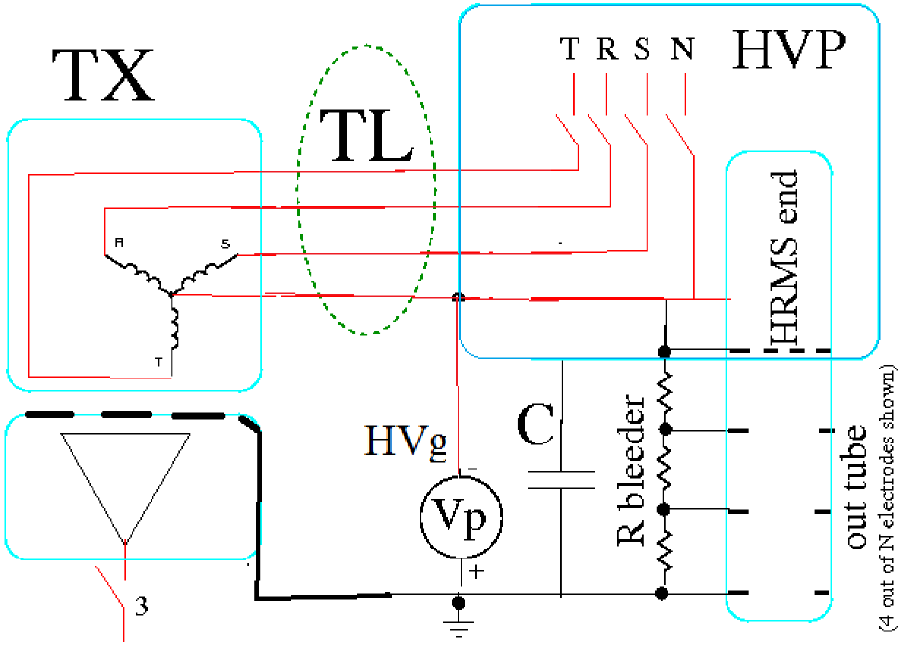
TX can be oil insulated and cooled (in that case typically placed outdoor) or resin insulated (for lower voltages). Typically: three phase with neutral provided at secondary; taps on primary.

When TX and HVP are placed in different room, considerable effort in devoted to transmission line TL construction, which can be

Cables (Alice's HVP, max from 300 to 350 kV)

Air Insulated (SPIDER, 100 kV)

SF6 Insulated (MITICA, 1 MV)



3 phase TX, transmission line TL, HVg, total capacitance C, and bleeder resistance R

Resin insulated transformers

In our case, the TX is to be placed near the HVP. Thus: no problem with transmission line; but only resin insulation is allowed (and the 150 kV rating needs special acceptance tests)

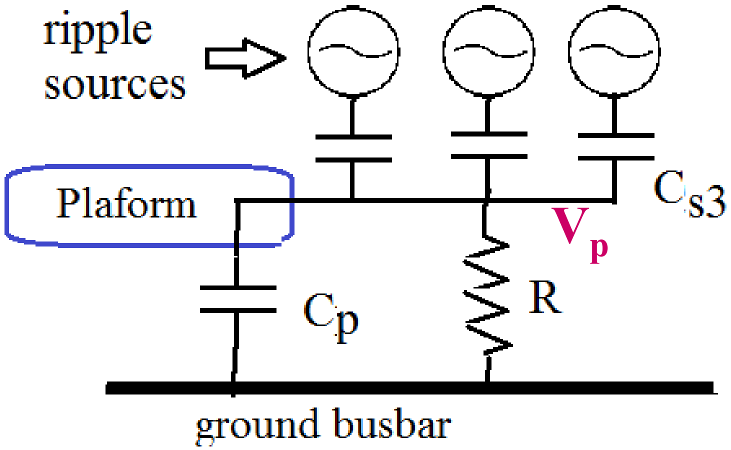
NIO1 resin transformer (courtesy M. Bigi and G. Serianni) rated 70 kV, tested 100 kV (NIO1 stays for Negative Ion Optimization phase 1, and its design voltage is 60 kV)

2.2) Design considerations

1) It was believed that the bleeder impedance (resistor R) must be much smaller of the impedances Z_c of stray capacitance Cs1, Cs2, C_{s3} , which couples noise into platform. For example: max bleeder current 2.5 mA → R= 60 Mohm, $Cs \leq 30$ pF, so $Zc \geq 110$ Mohm; dissipated power 0.4 kW (to be adequately cooled. Anyway Cp seems much more effective (see later Alice example)

1bis) and/or Add a earth shield between TX winding

1ter) and/or Distribute load equally on the three phases (most equipments do this; can single-phase devices be powered by auxiliary three phase TX2 in platform?)



2) Round the HVP envelope to keep stably more voltage (not so necessary for Vp=-120 kV) with radius re=20 or 30 cm (note that re=10 cm should be sufficient to avoid corona, anyway the larger the safety margin the better). The corona free operation is important , corona* may be intermittent and change load to HV power supply, giving V_p fluctuation and this condition need monitoring

*[D. Faircloth, private communication at ICIS2019]

3) Air gaps: Electrostatic discharge is complicate multiphysics problem, so practical design needs large margin rule of thumbs (and space around and caution)

So many designs use 2 kVDC/ cm as reference value for major air gaps (that is 1.4kV[ACrms]/cm)

$\Longrightarrow$ HRMS: Distance wall/cage $d = V_p / [2\ \mathrm{kV/cm}]$ about 75 cm (real distance 90 cm).

Insulator height > d say 1 m

Creepage insulator distance > 3 d that is 4 m at least

4) Last but not least; a rapid passive discharge time $\tau = C_p\, R \le$ few seconds;

first example $C_p \le 5$ nF , R= 60 Mohm $\Longrightarrow$ $\tau = C_p\, R \le 0.3$ s

2nd example $C_p = 6$ nF , R= 166 Mohm $\Longrightarrow$ $\tau = C_p\, R = 1$ s

Any further advice or idea to avoid causes of voltage fluctuation (at 10^{-5} level) is welcomed

5) DISCLAIMER: these notes are just for initial information, any real design should be carefully revised for compliance to existing safety rules and laws. Please expect painful work before system performs according to specifications.

3) Example of other high voltage platforms and transmission lines

3.1) Alice’s HVP output acceleration tube (test 450 kV). Note also: rounding of platform edges (40 cm radius), connection to HVP, water pipes.

D = wall to HVP min distance=175 cm

Insulator creepage distance 6 m

Voltage divider resistance 4 Gohm

Total bleeder resistance (include water) R= 1 Gohm

TX capacitance 2 nF, total capacitance about 4 nF

In Alice’s HVP (at INFN-LNL) the ripple redundant specification $V_r/V_p < 10^{-4}$ was satisfied, but this required:

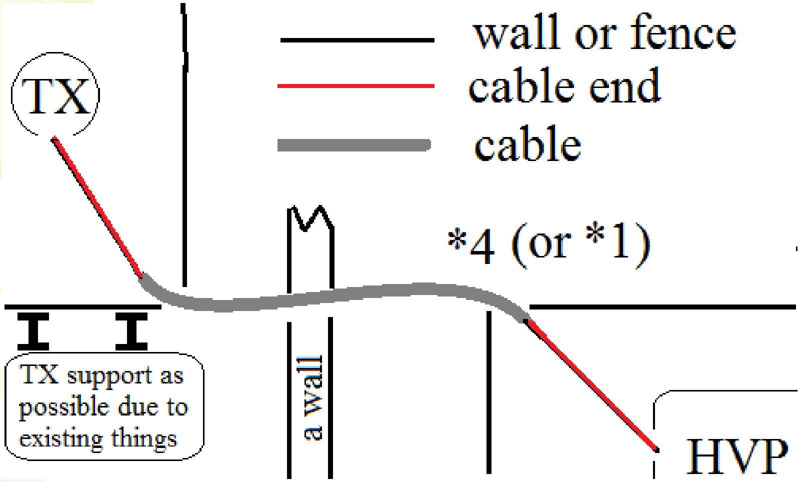
-a 18 bit DAC to set voltage (with filters);

-a suitable HV generator (rated ripple 25 Vpp);

-a balanced TX (and loads of phases)

Even better $V_r = 17$ Vpp was once measured at V_p about 300 kV; so $\sigma_{Vp} = 6$ Vrms and $\sigma_{Vp} / V_p = 2*10^{-5}$ which is a very promising step towards HRMS specs, especially considering that Alice’s budget limits.

Alice transmission line



Notes on caps and cables: 1) avoid shorts when charged. 2) Typical cap. Ct= 70-100 pF/m, bending radius 2 or 3 m; Alice used S-design for thermal dilation compensation. Shield length Lc= 3 m, end 2 m each.

C (cable) = 4 * Lc * Ct = about 1 nF

If suitable three-phase cable is available, factor 4 can be dropped.

Oil transformer (test 400 kV) output bushing and line towards Alice's HVP

+350 kV

135 kVA (used up to 75 kW)

3.2) MMRS Legnaro

In this case, that (as in SPES last design) the transmission line is avoided since conduit

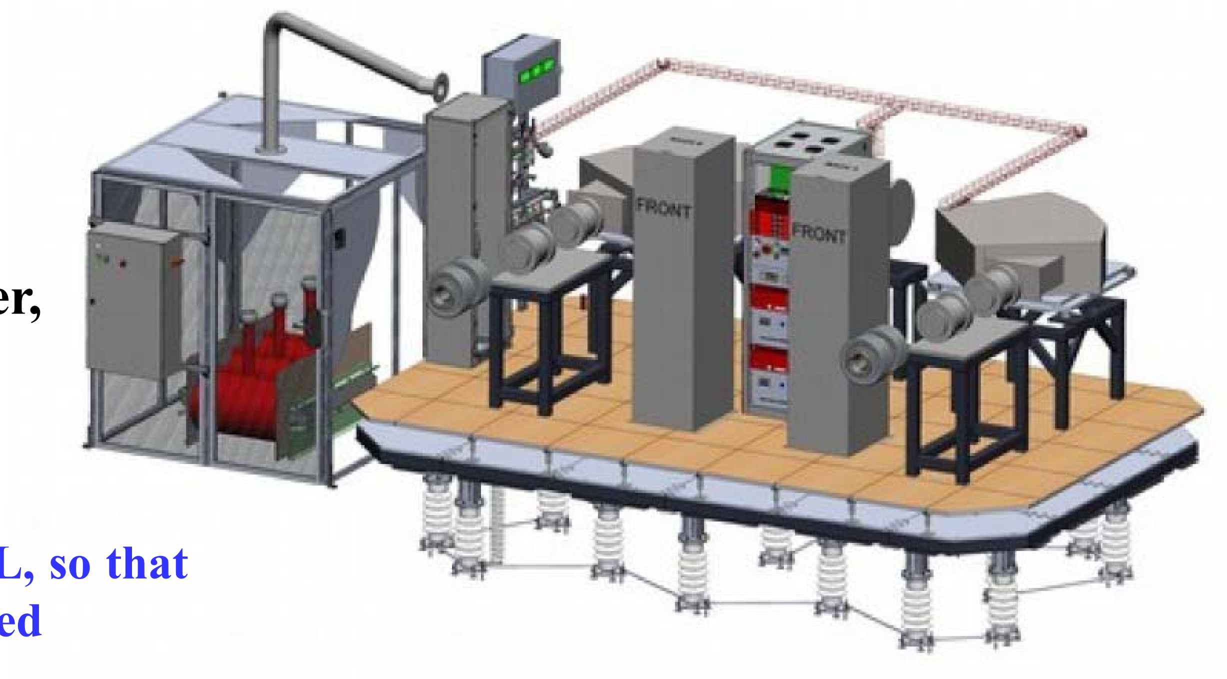
Vp = -130 kV (operation)

|Vp|=150 kV (nominal max)

Power 50kVA

For this spectrometer, required resolving power is $\Delta M / M = 10^{-3}$

MMRS is now installed at LNL, so that further experience can be gained



MMRS (medium mass resolution spectrometer) 150 kV platform drawing (maker Pantechnik). Note TX conduit to HVP and TX location; HVP covers are hidden to shown inside components. Courtesy A. Galatà

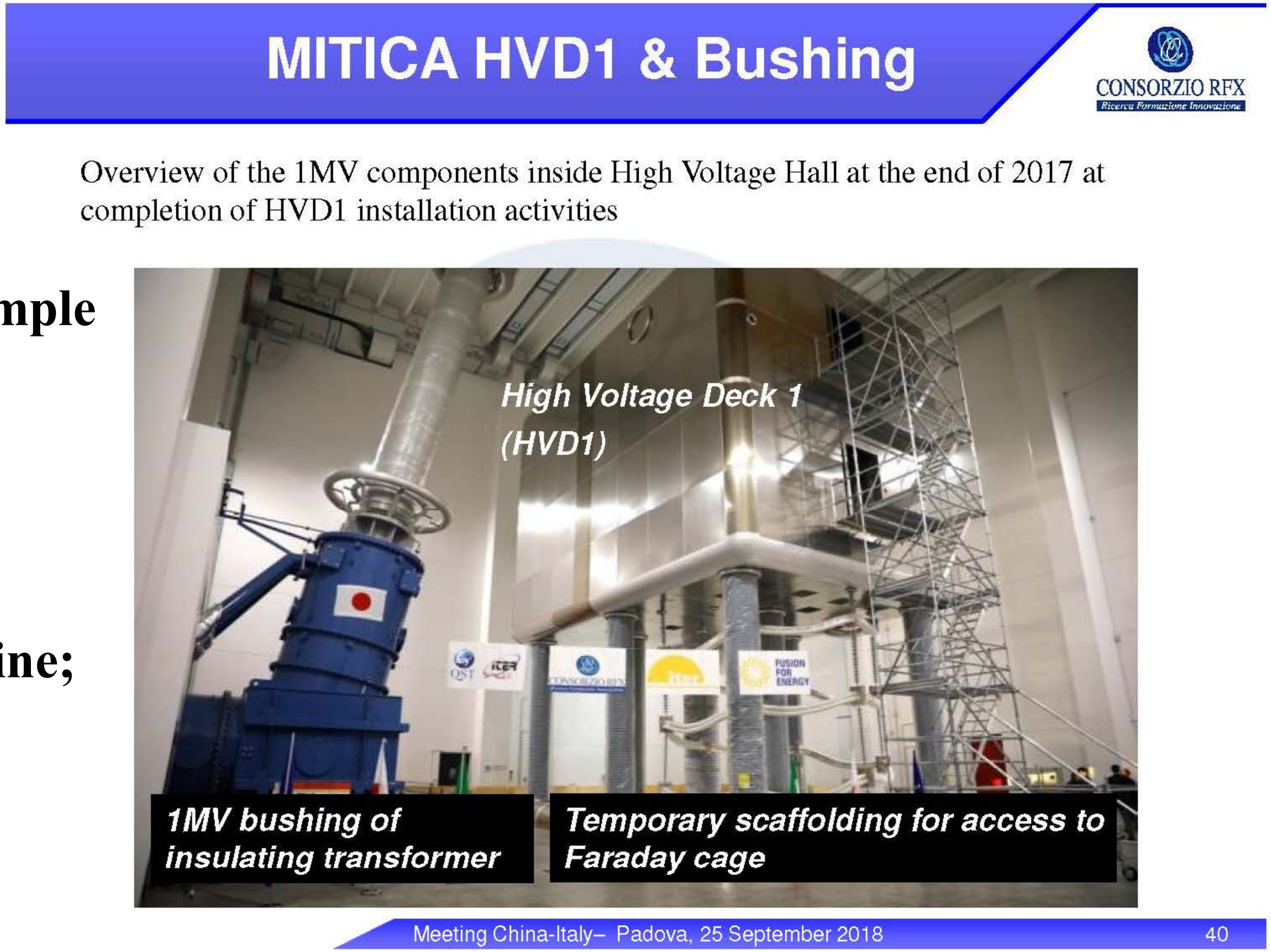
3.3)

We finish with an example of the largest HVP, at Consorzio RFX

Vp=-1MV

Air gap 6 m

Double transmission line; length in 10^2 m order



MITICA HVD1 & Bushing

CONSORZIO RFX
Ricerca Formazione Innovazione

Overview of the 1MV components inside High Voltage Hall at the end of 2017 at completion of HVD1 installation activities

High Voltage Deck 1 (HVD1)

1MV bushing of insulating transformer

Temporary scaffolding for access to Faraday cage

Meeting China-Italy– Padova, 25 September 2018 40

Courtesy of V. Toigo (slide 40 in V. Toigo, Spider and Mitica Project, meeting Italy China, 26/9/18)

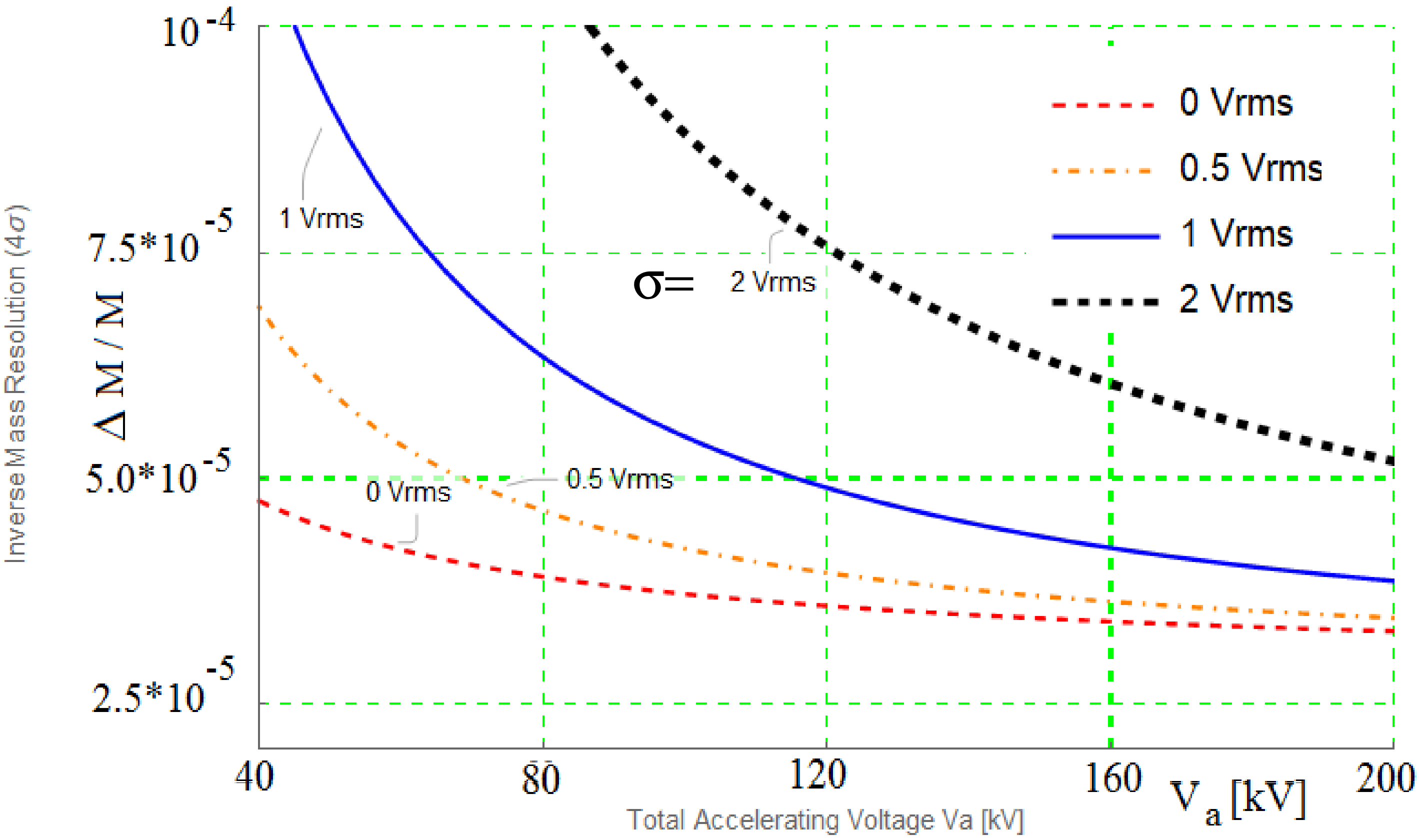
4.1) Final optics simulation and summary

$$\sigma^2 = \sigma_{Ei}{}^2 + \sigma_{Va}{}^2$$

Beam resolution as a function of spread (r.m.s.) σ

compared with results of multiparticle simulations (TraceWin), which include a rms geometrical emittance of

3.2 π mm mrad.



A careful design of HRMS magnet allows to reduce emittance effects, so that σ_{Ei} or σ_{Va} spec can be relaxed somewhat

4.2) HRMS HVP summary

Hrms platform 6.4x 6.85 m2, with 1.5 m bending radius magnet design)

Nominal voltage -150 kV (operation -120 kV with current beam optics)

Power needed 70 kVA, water cooling provided for equipments, air temperature conditioned

Power supply current rating 2 to 5-10 mA (total bleeder R= 60 Mohm to 200 Mohm, with bleeder cooling tbd, goal for total capacitance 5 to 6 nF, voltage decay time from 0.4 s to 1.2 s)

The relatively moderate voltage facilitate construction. Anyway it is wise to overdesign insulation and corona relief, since the required voltage stability is worldwide challenging, even if LNL has some experience in preliminary steps.

Even more challenging is the combination with the RFQC equipment (equivalent to a +40 kV platform and externally supplied), especially on ground bus bar efficacy, to be verified experimentally.

The beam optic design (see M. Comunian et al.) provides some flexibility to obtain requested resolving power (M/ΔM=20000) up to input energy spread σ_{Ei} =2 Vrms

Thank you for attention

Disclaimer: **for standard and safety aspects (which request careful training) please refer to qualified experts and literature elsewhere.**