RNB ACCELERATION IN SPES: POSSIBILITIES AND ISSUES

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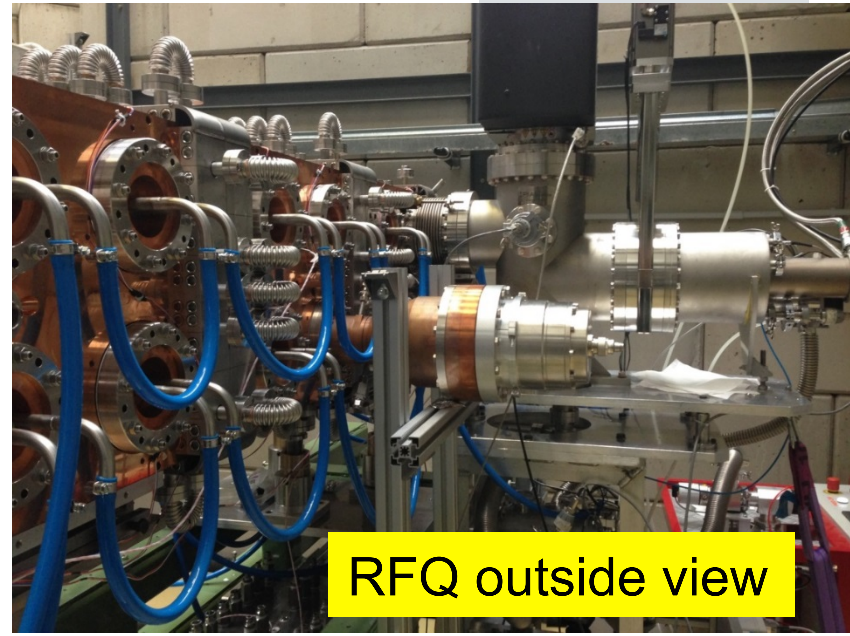
SPES, acronym of *Selective Production of Exotic Species,* is a CW radioactive ion beam facility under construction at LNL INFN in Italy.

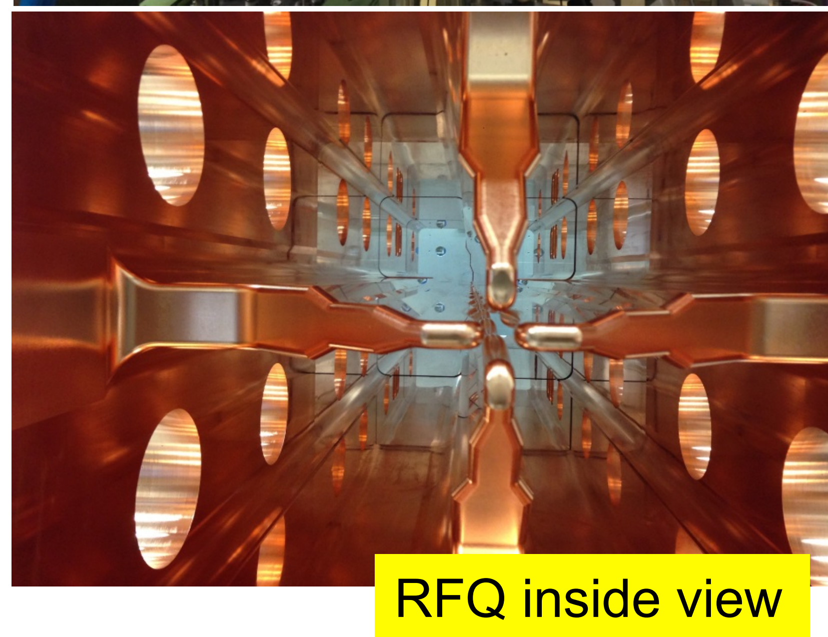
Outline

- RNB accelerator: a system strongly coupled to the experiments
- Scheme of principle.
- Main components (status of development in previous talks), separators and SRF linac
- Key features, limiting factors

Premise

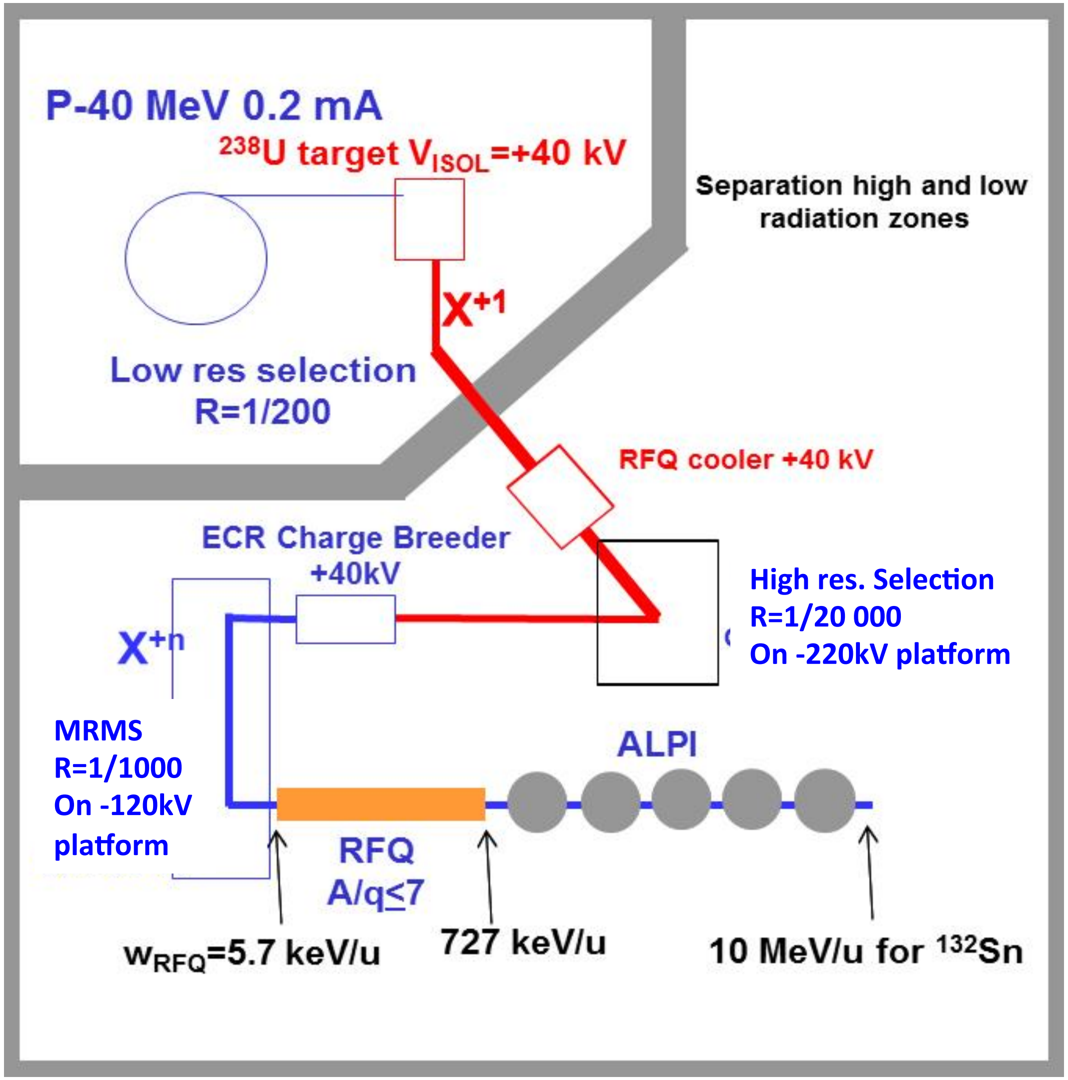
- The LNL group has designed the RFQ for IFMIF EVEDA and the DTL for ESS (main stream high intensity linacs).
- The post acceleration of SPES requires extremely good magnetic selection, high transmission (precious beam) and very good knwoledge of the position of amount and location of beam losses
- Contaminants could give similar problems for radiation protection (MPS and activation in the beam settingsteps, not much at our intensity with proper choice of ions)
- The approach computational tools (TRACEWIN, 10^5 macroparticles, accurate field maps..) are almost the same.





CW post accelerator

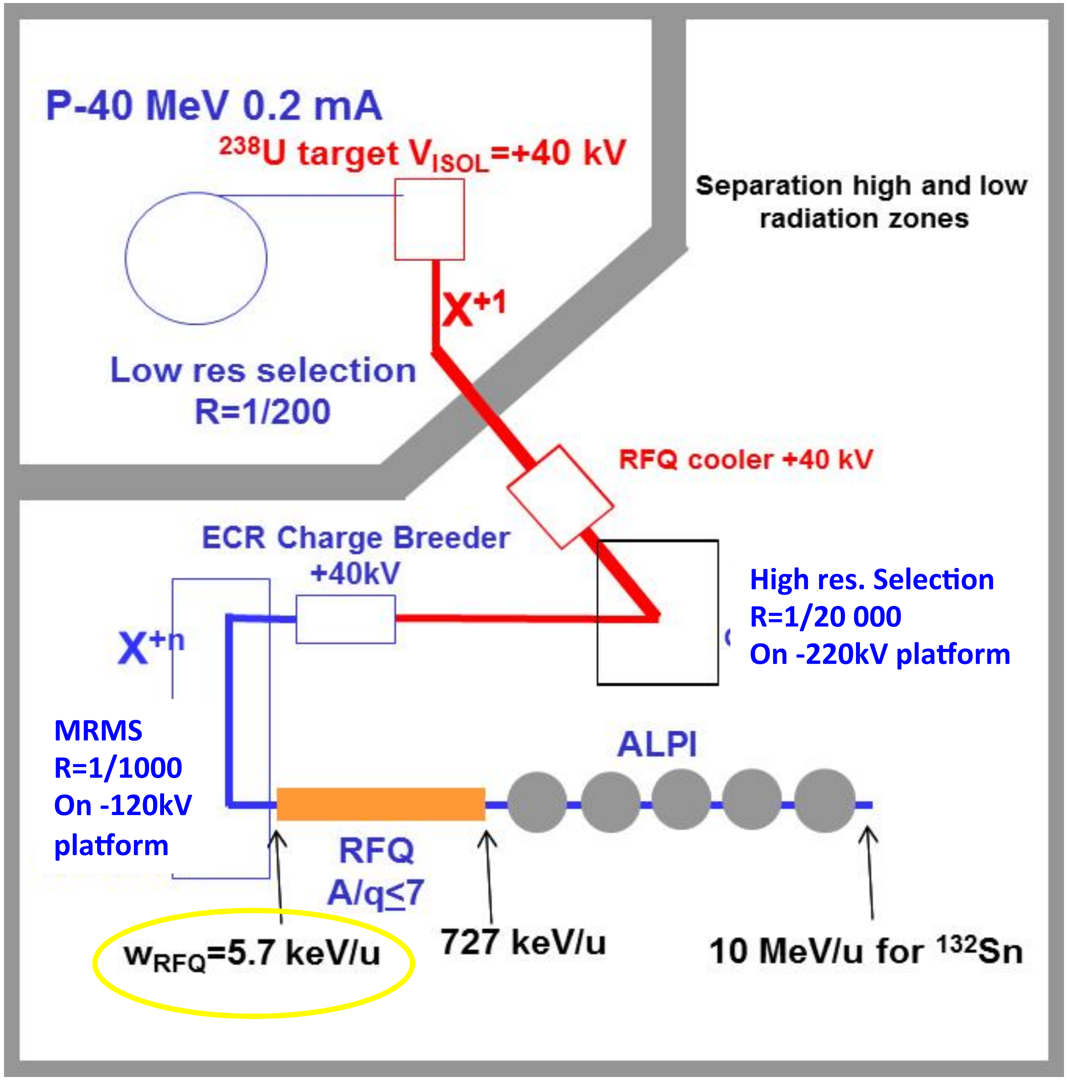
- Requirements => choices
- *High* RNB intensity
  - Direct UCx target and cw proton beam
  - cw post-accelerator
- High selectivity
  - Laser source and/or magnetic HRMS
- *High* energy
  - ALPI with a new RFQ injector



CW post accelerator

- The use of the continuous beam from the +1 source (LIS, PIS, SIS) maximizes the RNB efficiency but need a CW post accelerator (RFQ and ALPI); this layout also needs a charge breeder chosen to be an ECR that woks in continuous.
- The energy on the transfer lines are determined by the chosen RFQ input energy (w_{RFQ}=5.7 keV/u); namely, all the devices where the beam is approximately stopped (production target, charge breeder and RFQ cooler) lay at a voltage:

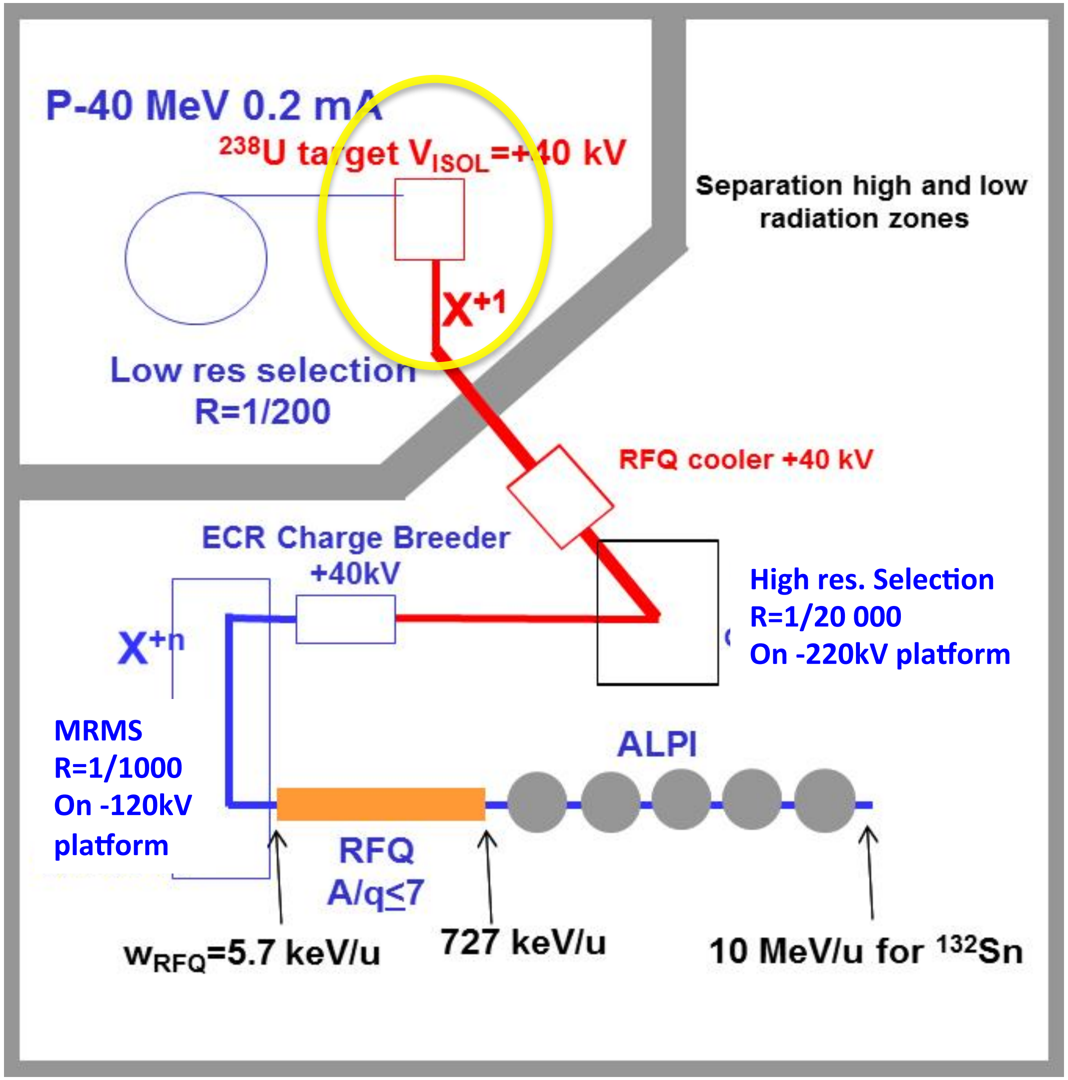
$$eV = (A/q)\,w_{RFQ}$$



CW post accelerator

- The beam preparation scheme satisfies various requirements:

1. the zone with worst radiation protection issues is reduced by means of the first isobar selection (resolution R=1/200).



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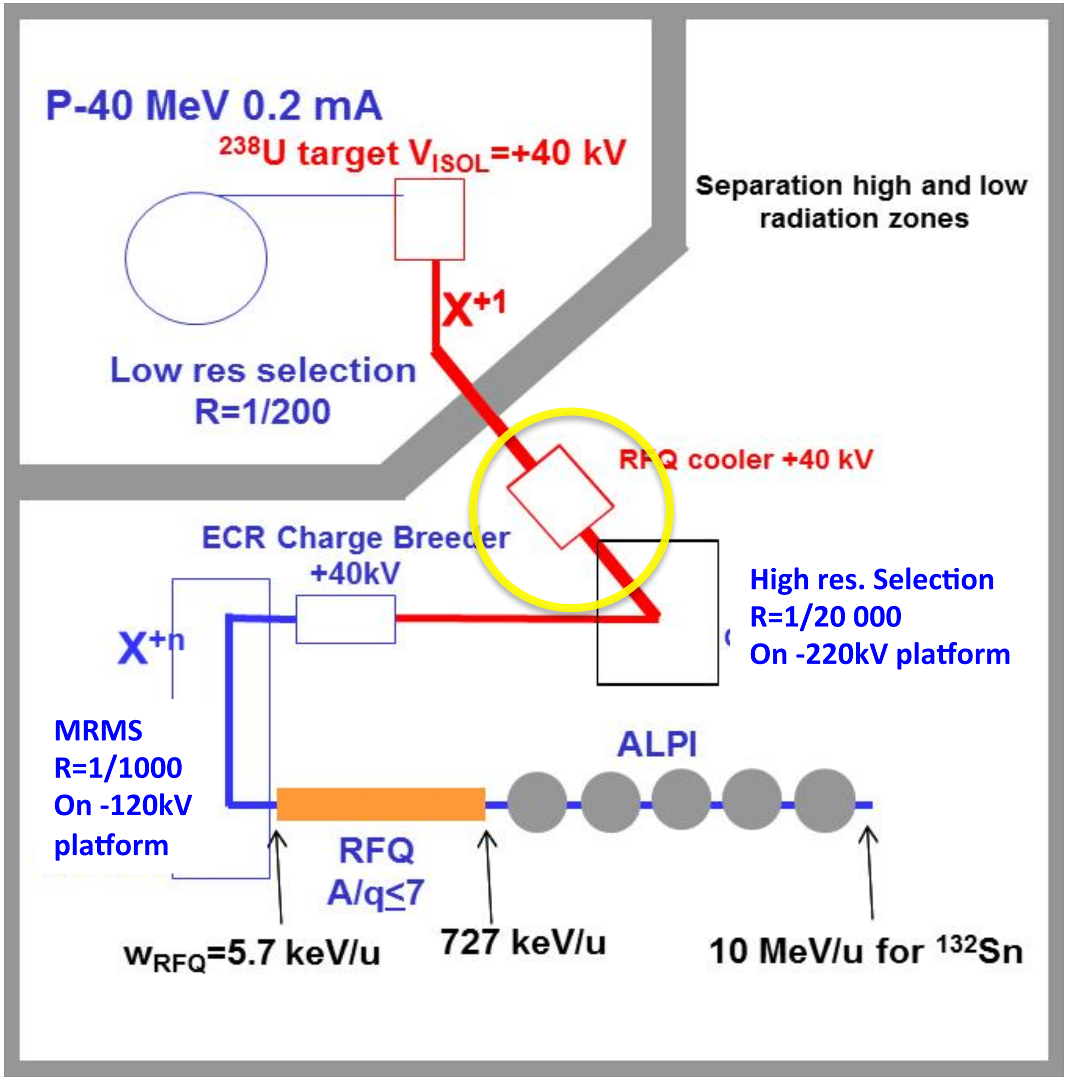

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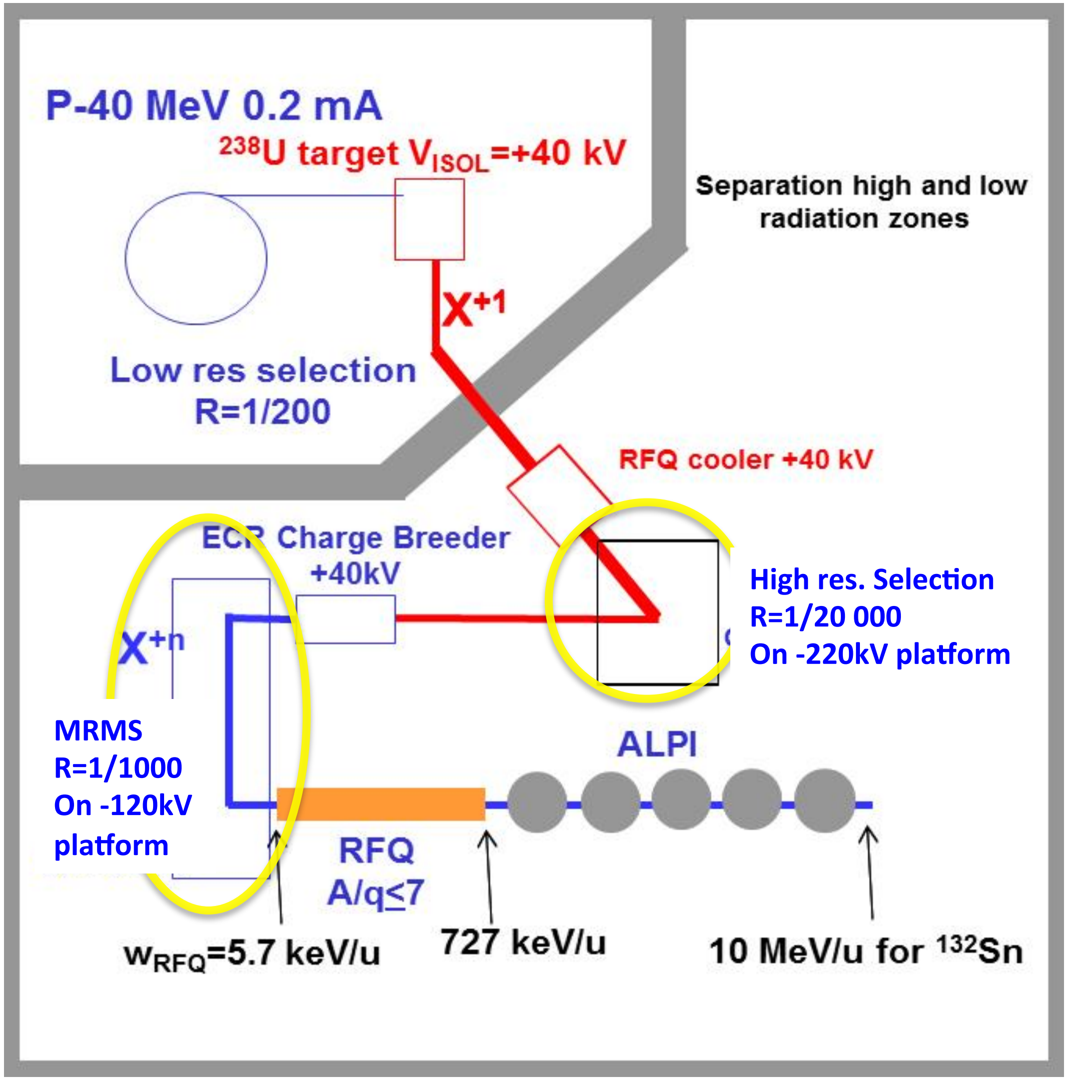

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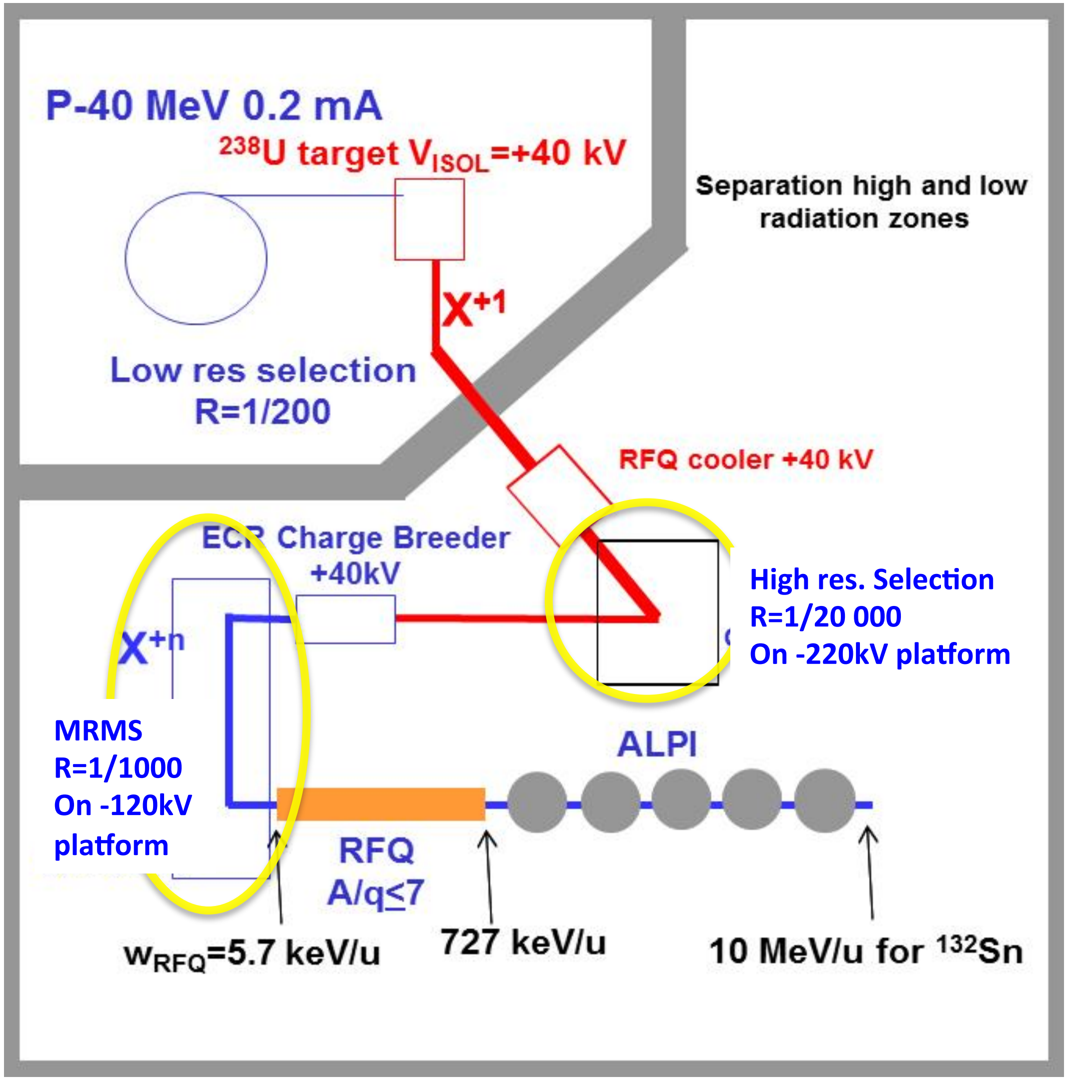

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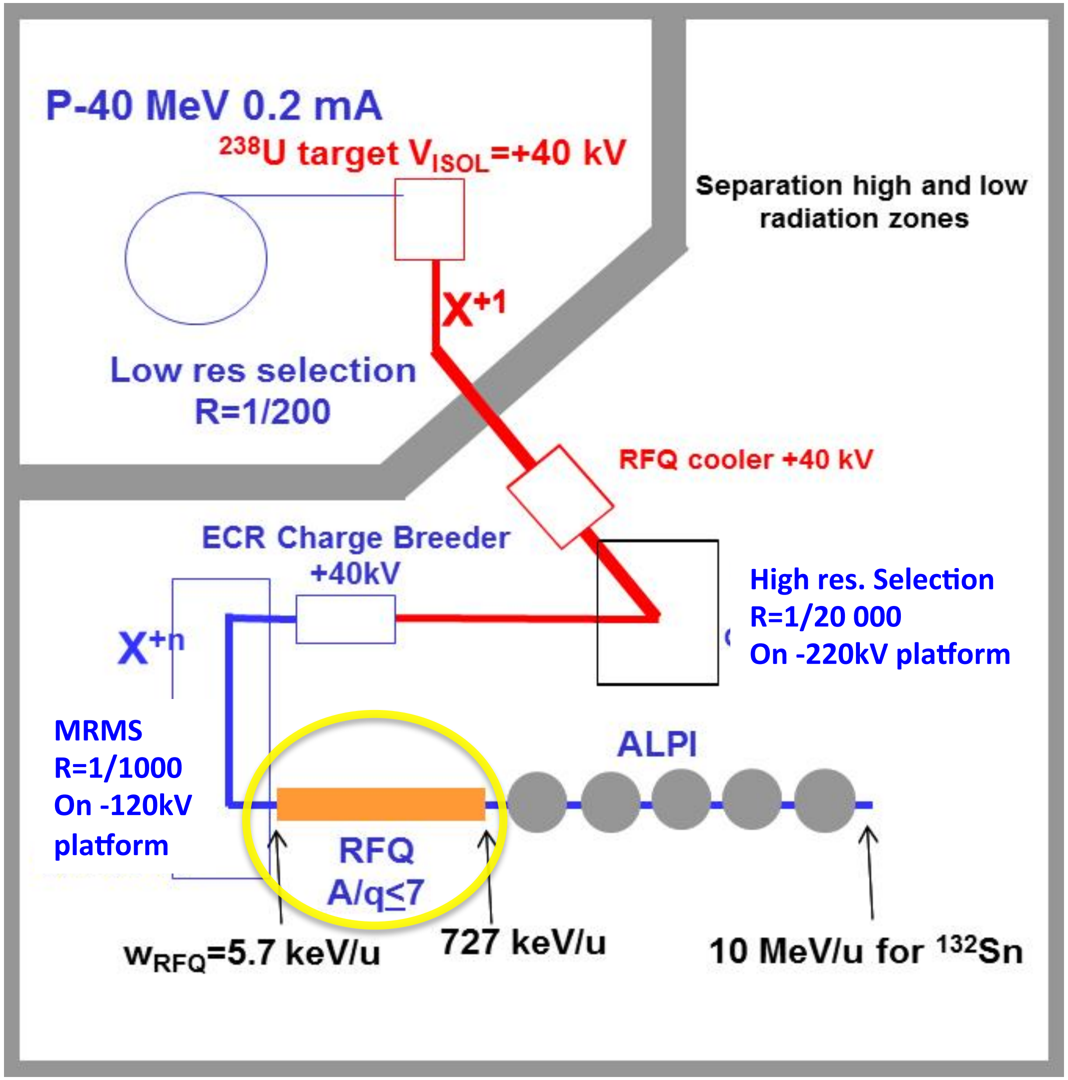

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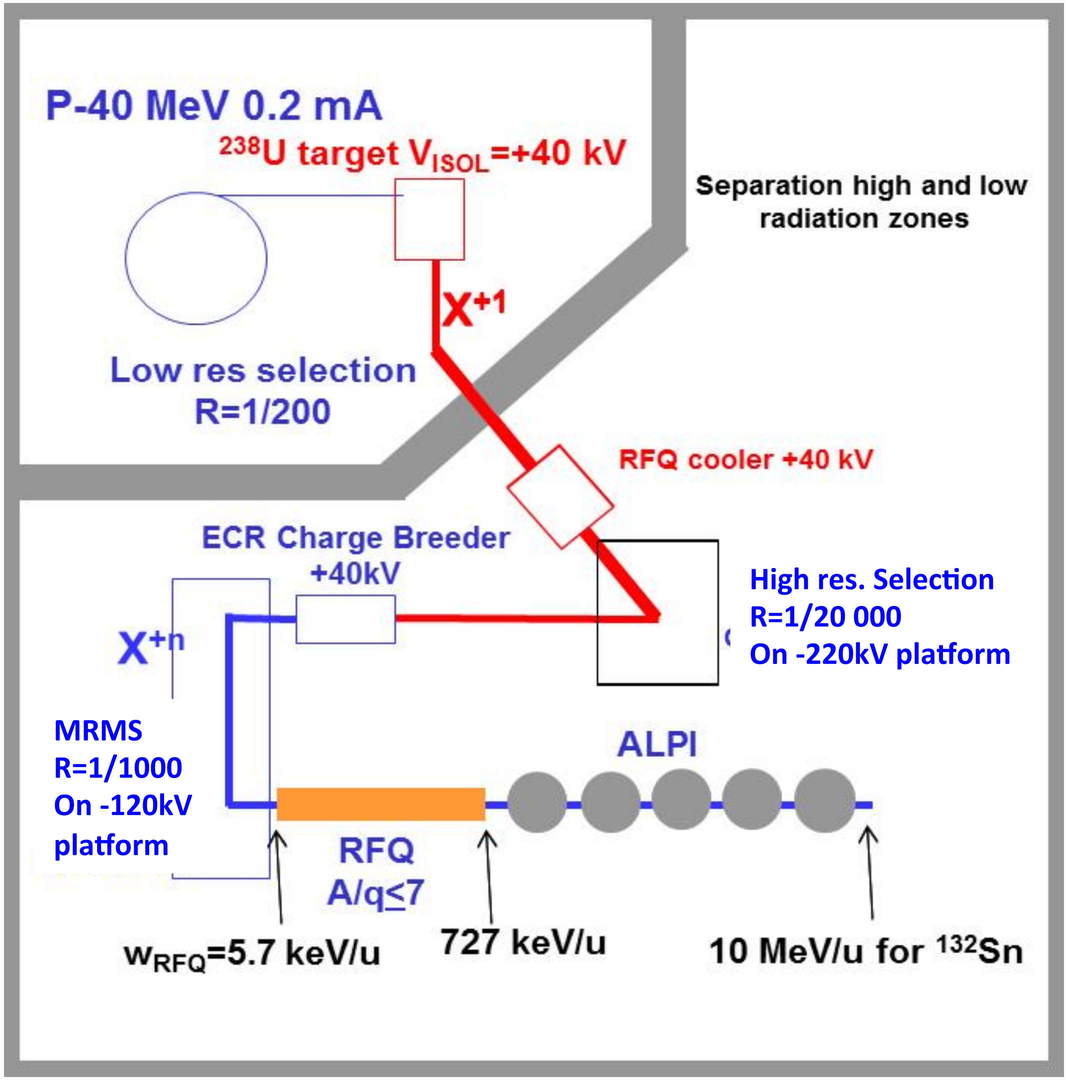
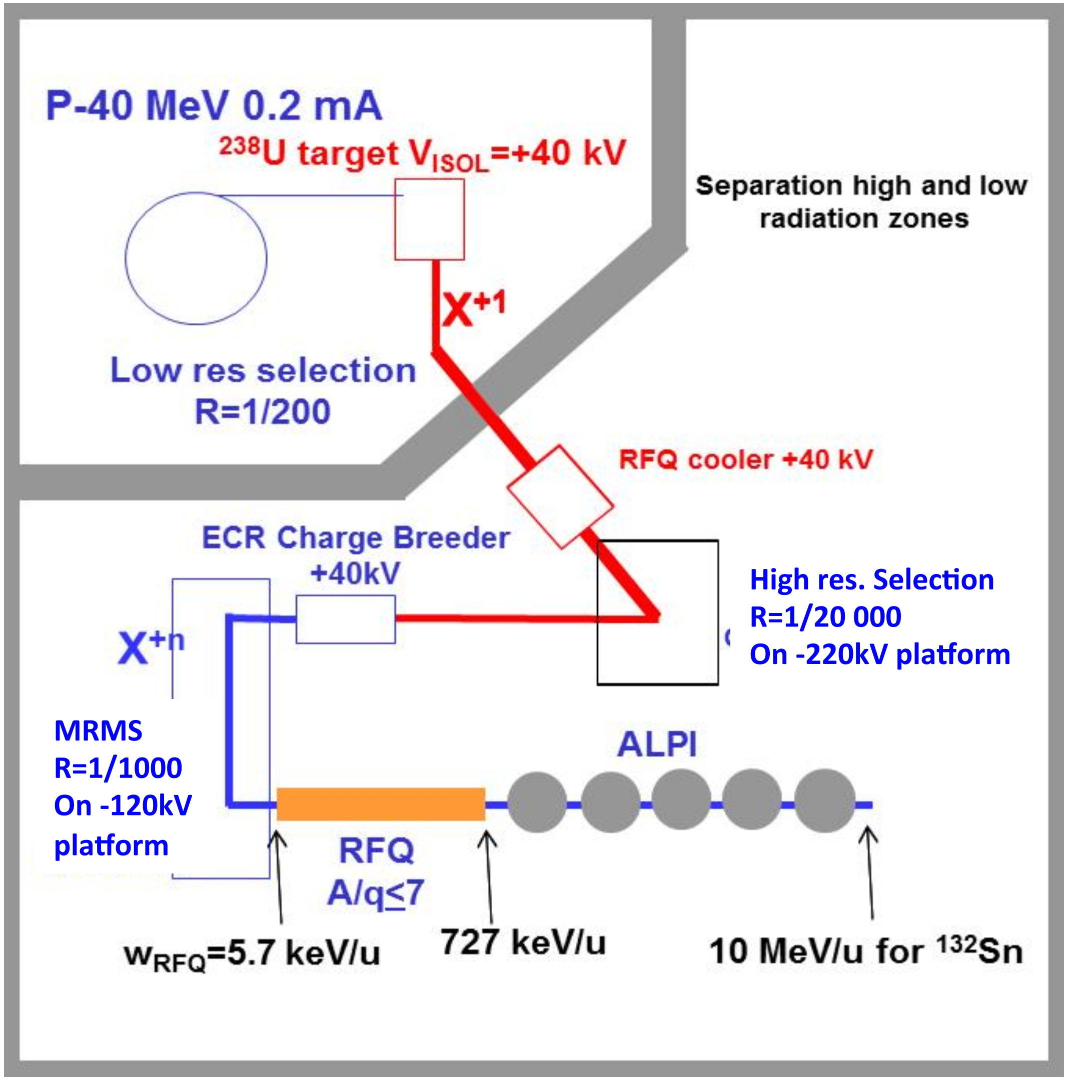
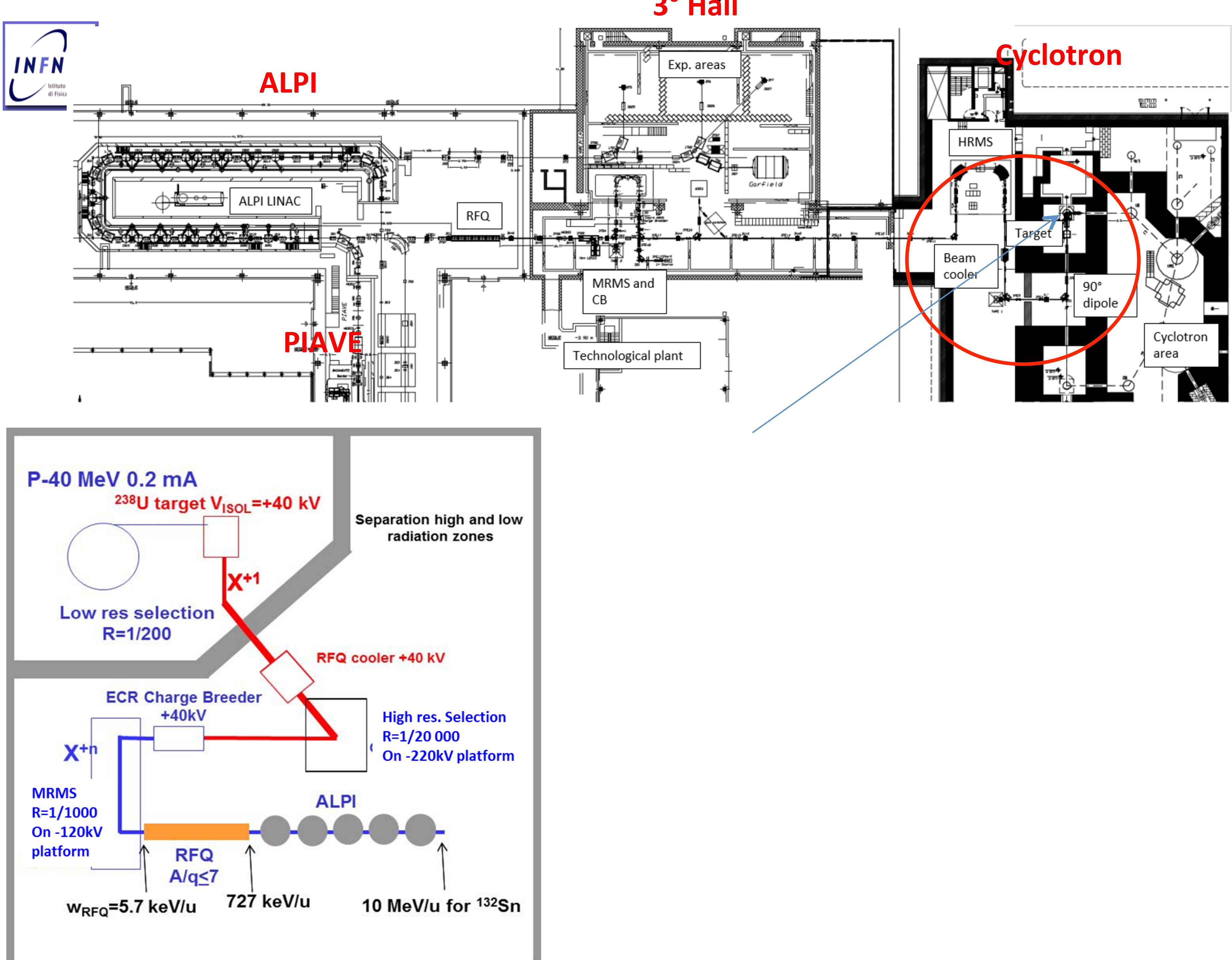
6. An external 5 MHz buncher before the RFQ will be available for specific experiments (at the price of about 50% beam transmission).
7. The dispersion function is carefully managed in the various transport lines; where possible the transport is achromatic, otherwise the dispersion is kept low (in particular at RFQ input D=0, D' is about 50 rad).




P-40 MeV 0.2 mA
238U target VISOL=+40 kV
Separation high and low radiation zones
X+1
Low res selection
R=1/200
RFQ cooler +40 kV
ECR Charge Breeder
+40kV
High res. Selection
R=1/20 000
On -220kV platform
X+n
MRMS
R=1/1000
On -120kV
platform
ALPI
RFQ
A/q≤7
wRFQ=5.7 keV/u
727 keV/u
10 MeV/u for 132Sn


3° Hall
Cyclotron
ALPI
Exp. areas
HRMS
ALPI LINAC
RFQ
Target
Beam cooler
MRMS and CB
90° dipole
PIAVE
Technological plant
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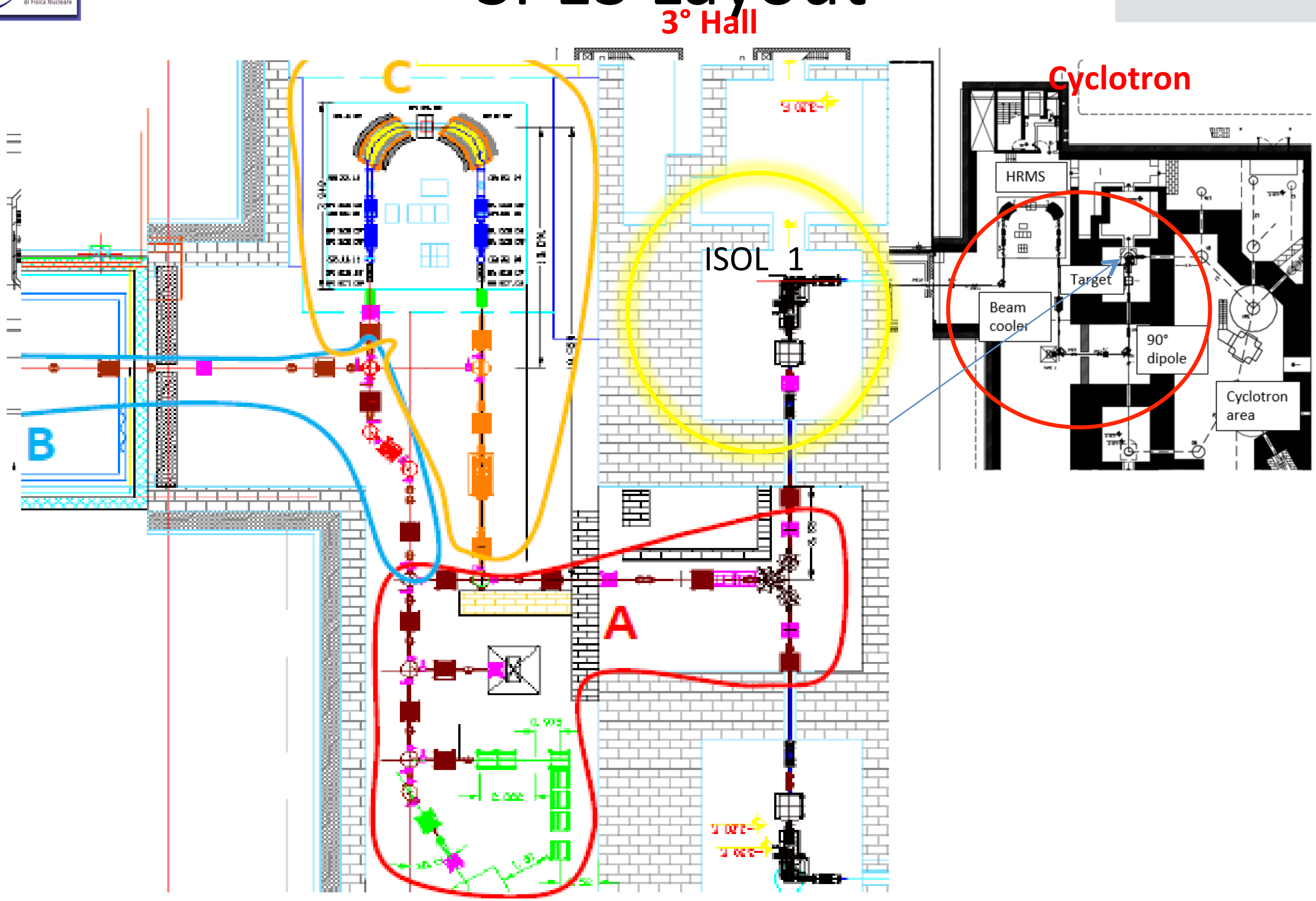
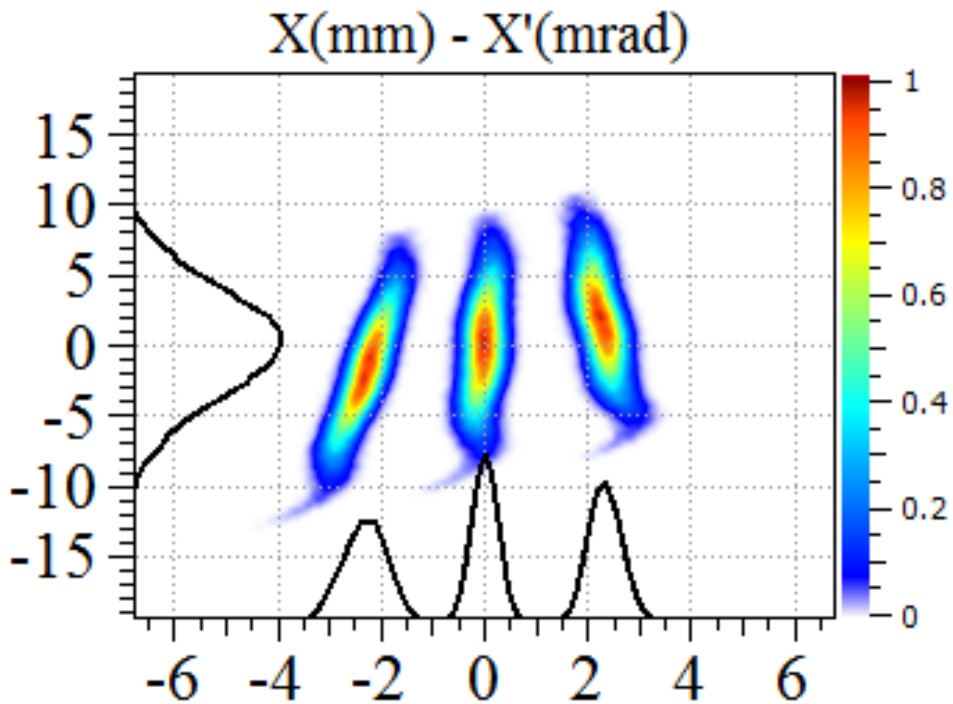
A/q≤7
wRFQ=5.7 keV/u
727 keV/u
10 MeV/u for 132Sn

SPES Layout


3° Hall
C
B
A
ISOL_1
Cyclotron
HRMS
Target
Beam cooler
90° dipole
Cyclotron area

The separators

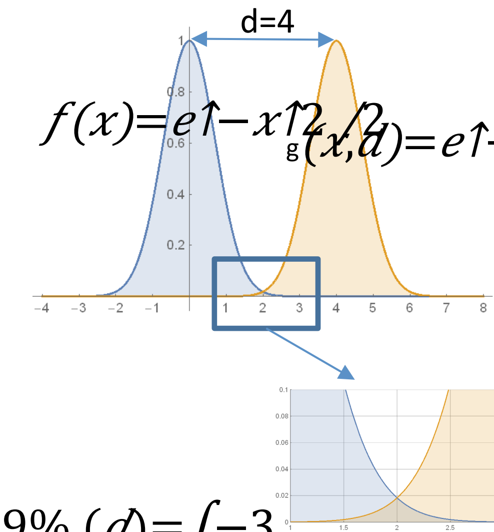
SPES HRMS
High Resolution Mass Separator



Rejectio factor in the Gaussian beam case

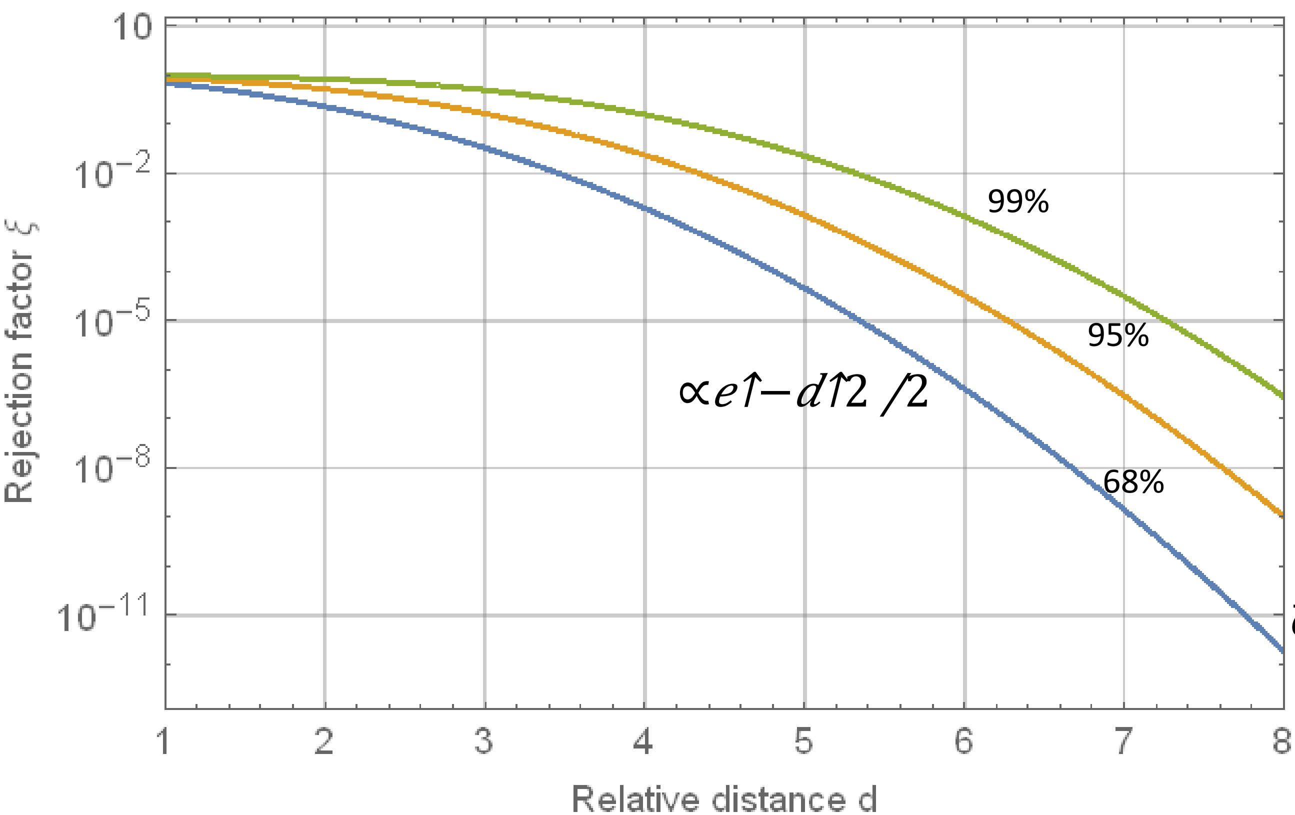
$$(I_n/I_0)_{image}=\zeta (I_n/I_0)_{object}$$

If we consider the nominal beam f(x) of amplitude I0
and a contaminants g(x) of amplitude In at a distance d,
it's possible to define a rejection factor ζ.
If the contaminants is much more than the nominal beam, the factor ζ must be very low.



$$f(x)=e^{-x^2/2}$$

$$g(x,d)=e^{-(\ldots}$$



$$\propto e^{-d^2/2}$$

$$\zeta_{99\%}(d)=\int_{-3}^{3} g(x,d)\,dx \ldots$$

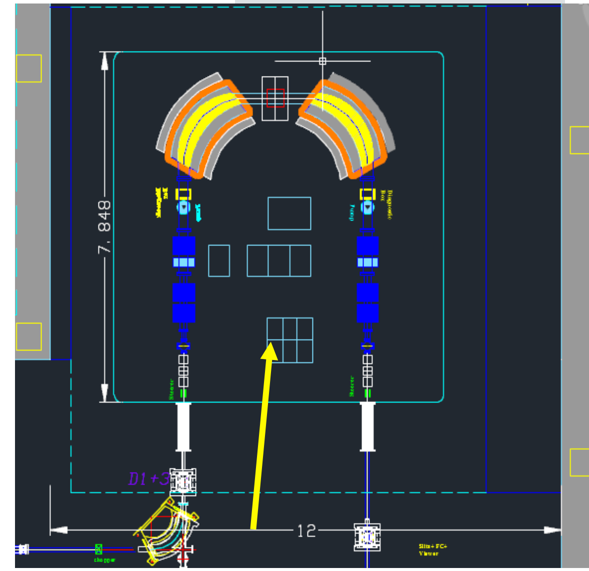
$$\zeta_{95\%}(d)=\int_{-2}^{2} g(x,d)\,dx \ldots$$

$$\zeta_{68\%}(d)=\int_{-1}^{1} g(x,d)\,dx \ldots$$

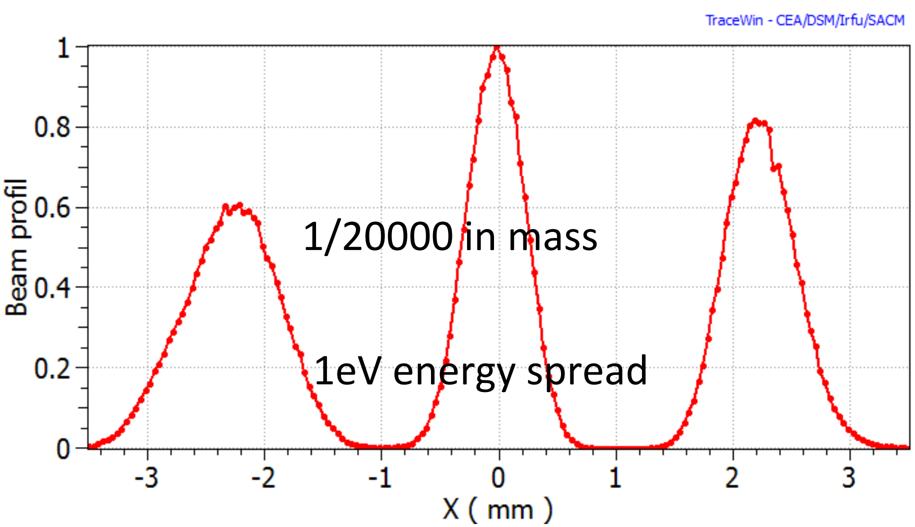
$$\int_{-s}^{s} g(x,d)\,dx \Big/ \int_{-s}^{s} \ldots$$

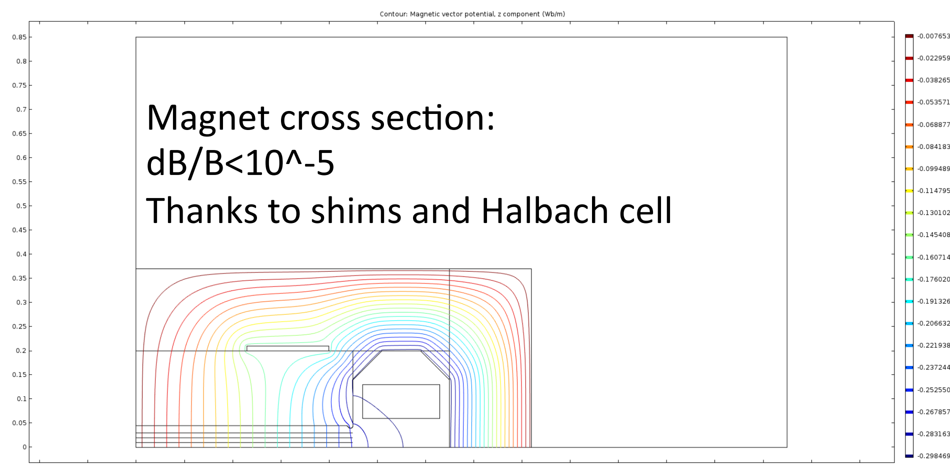
HRMS

- Physical design ready, integration with beam cooler and beam lines under way
- Preliminary dipole design and feasibility check with potential manufacturer done
- Evolution:
  - Critical Design Review in April 2018
  - Authorization to tender October 2018
  - Commissioning 2022



220 kV platform





Beam separator

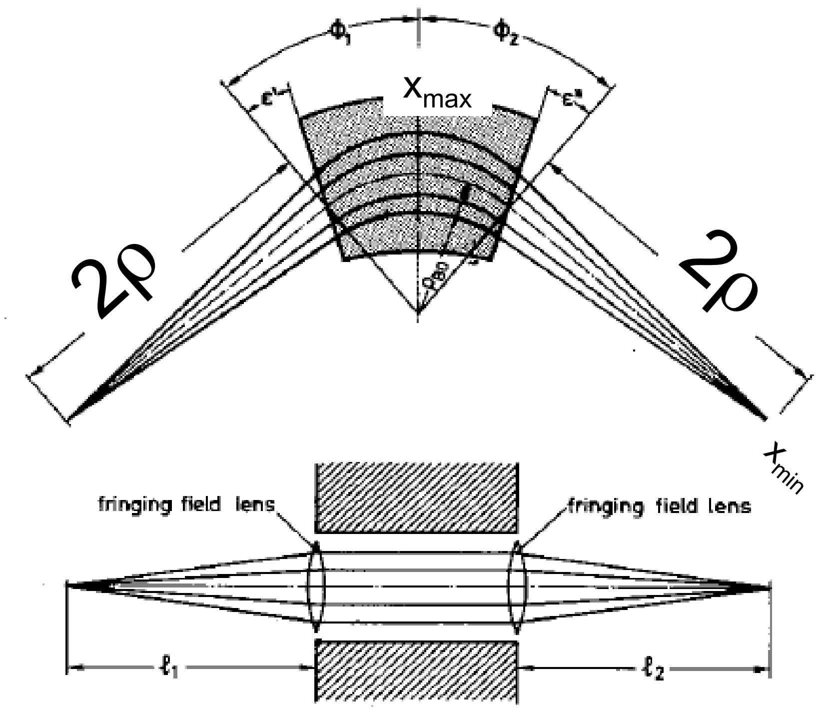


Fig. 4.8. A stigmatic focusing homogeneous sector field using the fringing field y focusing of inclined field boundaries.

- In the specific case of $\phi=90^0$, edge angle of 26.6^0, momentum dispersion $D=4\rho$ for stigmatic optics. Since $eB\rho=p$

$$x \qquad \frac{\Delta p}{p} = \frac{2x_{\min}}{D} = \frac{x_{\min}}{2\rho}$$

$$\frac{\Delta m}{m} - \frac{\Delta w}{w} = 2\frac{\Delta p}{p} = \frac{x_{\min}}{\rho}$$

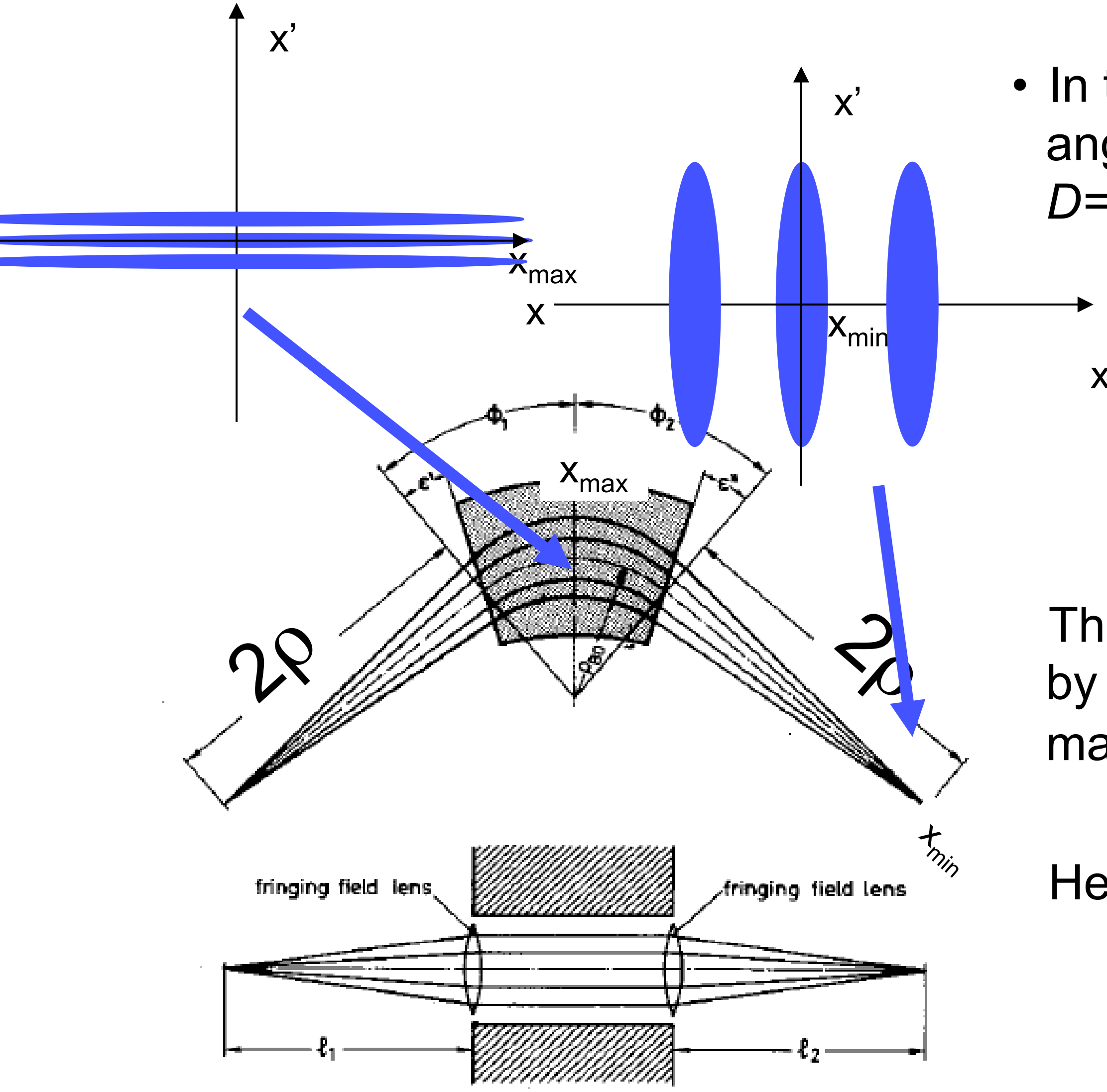
- The spot size at analysis is determined by beam maximum beam size in the magnet and beam emittance.

$$x_{\min} x_{\max} = 4\varepsilon_{geom}\rho$$

- Hence

$$\boxed{\frac{\Delta m}{m} = \frac{4\varepsilon_{geom}}{x_{\max}} - \frac{\Delta w}{w}}$$

- While geometrical aberrations depends on x_{max}/ρ



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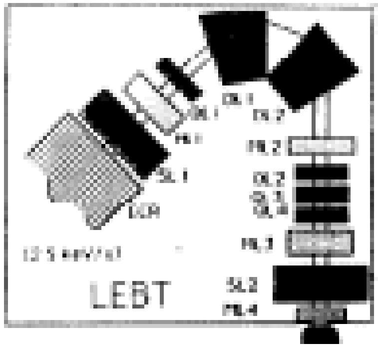
While geometrical aberrations depends on x_{max}/ρ

“Modern” separators

- Larger bending angle (135 deg CERN Linac 3, CARIBU ANL, 180^0 SPES MRMS and HRMS, DESIR ARIEL)
- Two bendings, with non linear corrections between the two dipoles at x_{max}(all)
- Optics at entrance (quadrupoles defocussing in x plane) (all)
- Optics at exit before the analysing slits, and symmetry (SPES*2, ANL, ARIEL, DESIR)
- High voltage platform, higher B field and lower energy spread and geometrical emittance (SPES*2, ARIEL)



CERN Linac3 LEBT design by AP in 1990
R=1/300 Acceptance 200 um

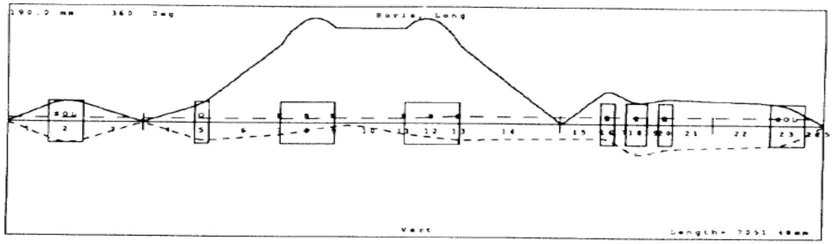
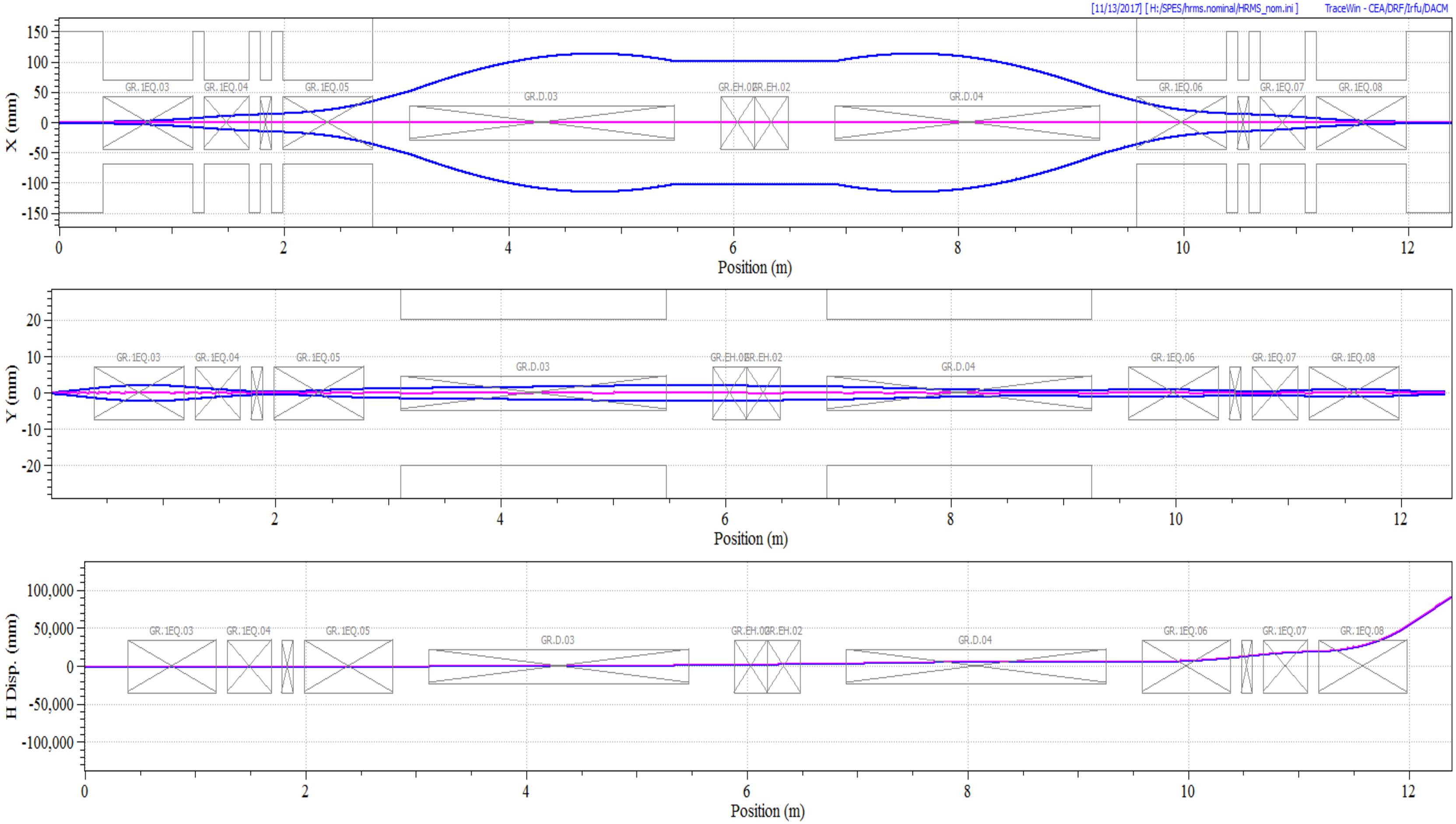


Figure 2: Beam envelopes in the LEBT

First order HRMS optics with new dipoles



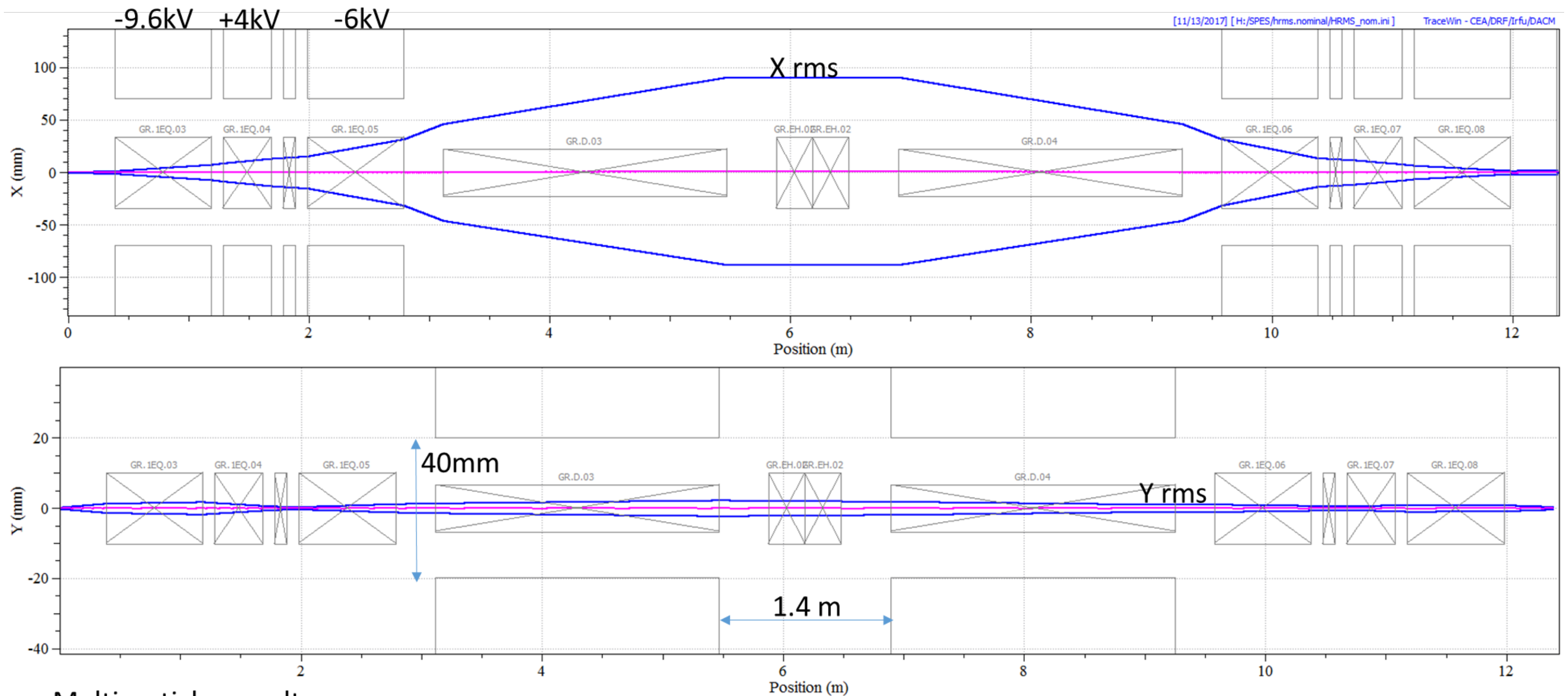
Spot radius: 0.480 mm

$\mathbf{D_x}$ **: 90 m** $\frac{D_x}{2 \cdot r_{beam}} = 93750$

No aberrations included in the calculation

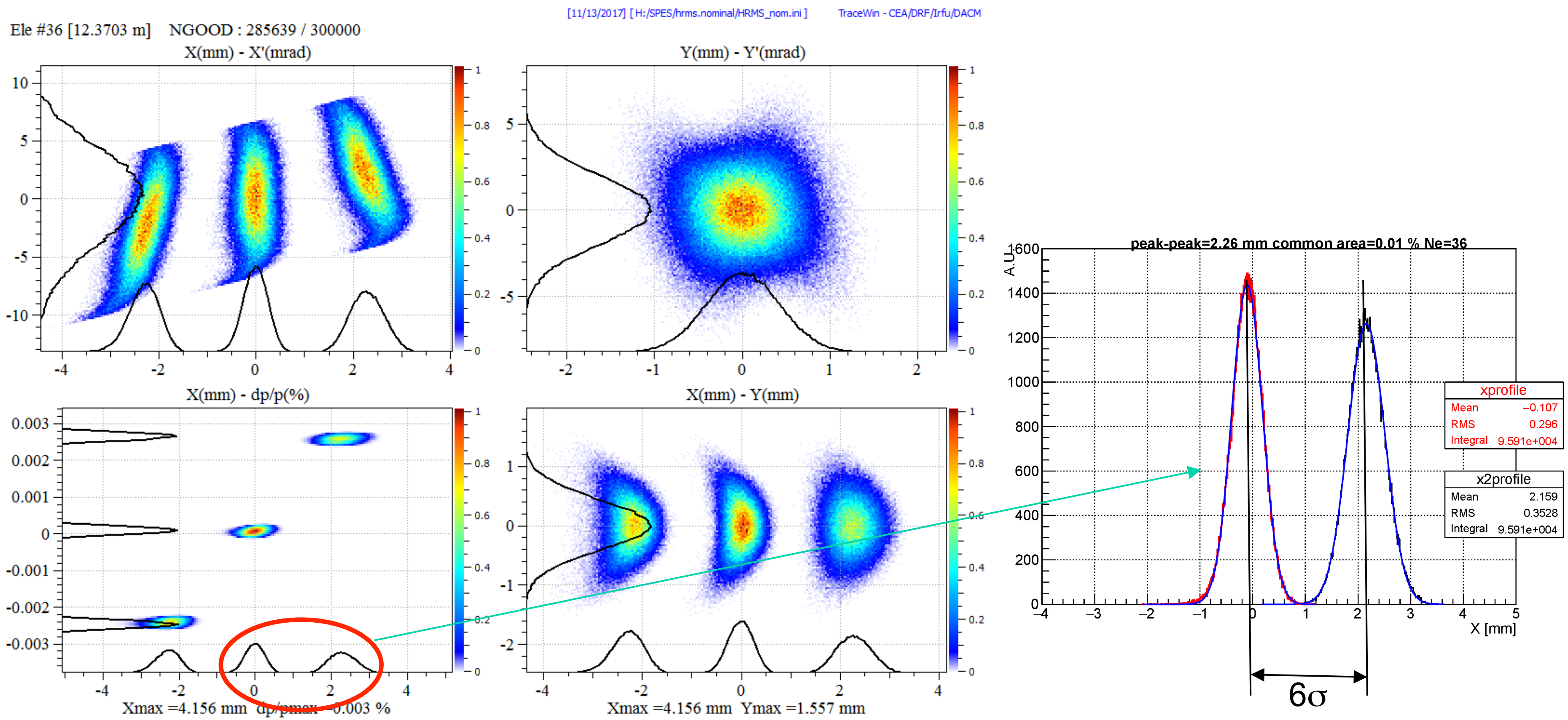
Multiparticle (higher order)

Curvatures aberrations included. Transverse Gaussian distribution in the phase spaces, truncated at 3 σ, while uniform in the longitudinal phase space (1 eV energy spread)

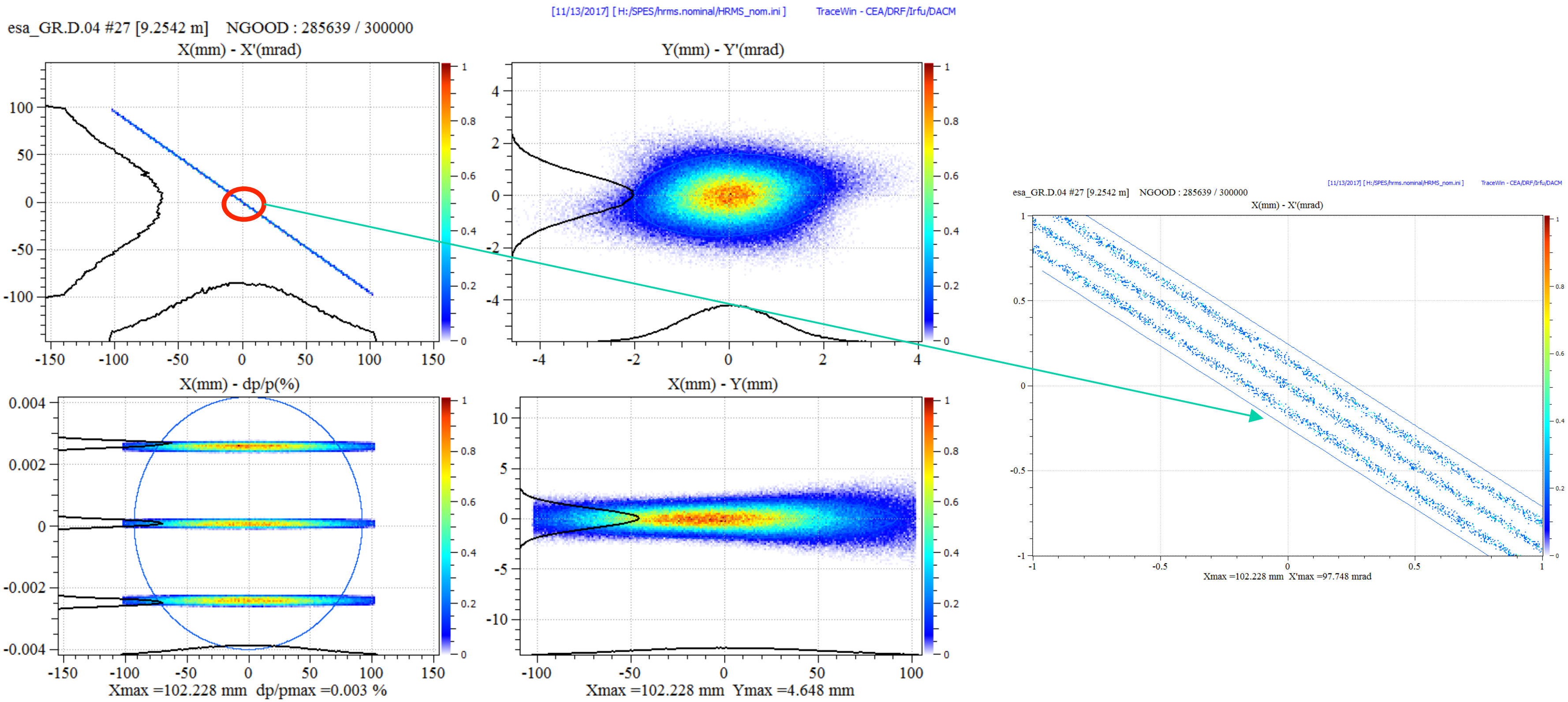


Multiparticles results

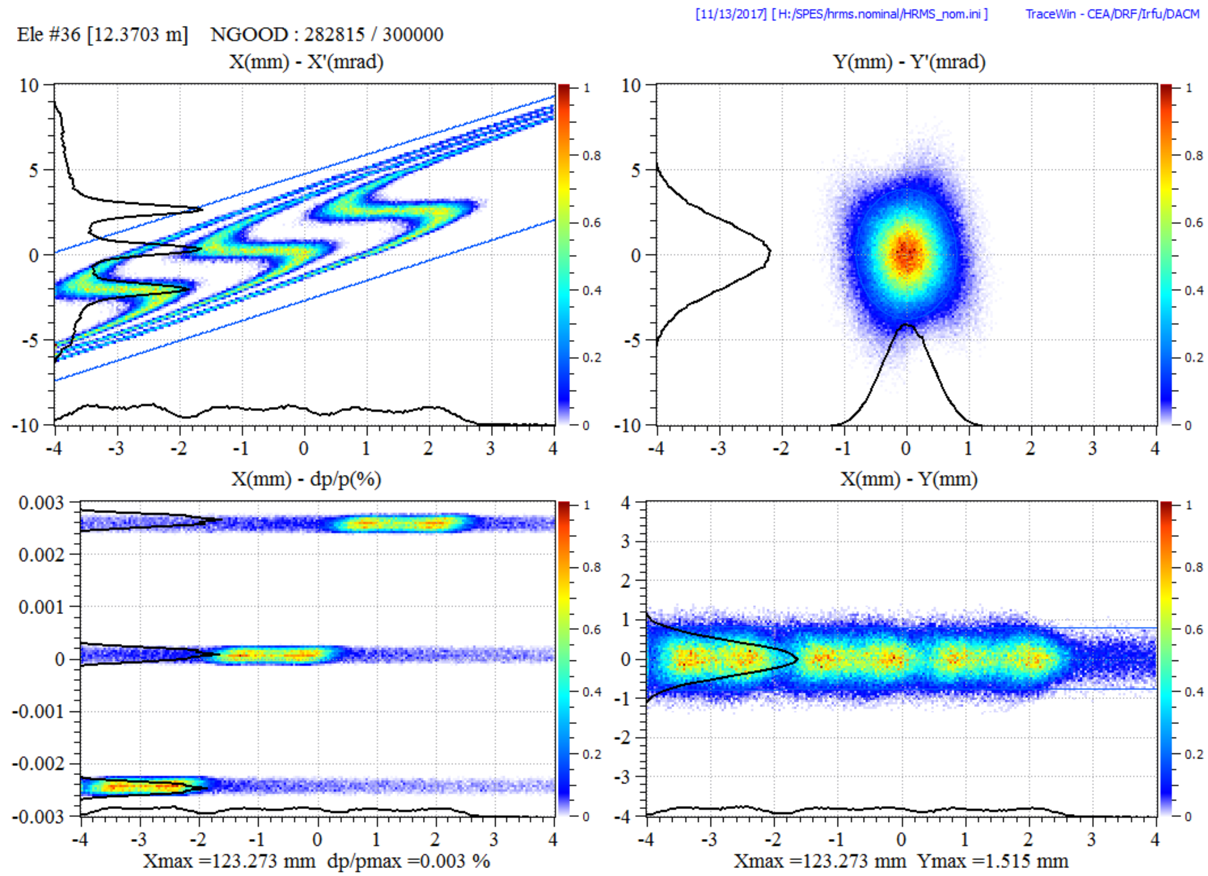
Beam at Slit position



Dipole Exit


[11/13/2017] [H:/SPES/hrms.nominal/HRMS_nom.ini]
TraceWin - CEA/DRF/Irfu/DACM
esa_GR.D.04 #27 [9.2542 m] NGOOD : 285639 / 300000
X(mm) - X'(mrad)
Y(mm) - Y'(mrad)
X(mm) - dp/p(%)
X(mm) - Y(mm)
Xmax =102.228 mm dp/pmax =0.003 %
Xmax =102.228 mm Ymax =4.648 mm
Xmax =102.228 mm X'max =97.748 mrad

Beam at Slit position without central multipole



Parameter comparison

Parameter	LEBT CERN Linac3	SPES MRMS	SPES HRMS	CARIBU	DESIR	ARIEL	
Bending radius ρ	400	750	1500	500	850	1200	mm
Bending angle	135	180	180	120	180	180	deg
gap	72	70	40	20	70	50	mm
Beam energy (extraction+plat voltage)	20	160	260	50	60	60	kV
X_{MAX}	180	180	200	200	200	200	mm
Geom emit. E (4 s)	200	56	2.8	3	1	2	um
Nominal resolution R (res. Linear)	300	1000 (2000)	20000 (80000)	20000	20000	20000	
ε/R	60000	56000	56000	60000	20000	40000	um

Large acceptance (LEBT CERN Linac3, SPES MRMS)

High resolution (SPES HRMS, CARIBU, DESIR, ARIEL)

Role of systematic errors

- For the high resolution separators is extremely important the effect of the external errors (static or dynamic)*

$$\frac{\Delta m}{m} - \left[\frac{\Delta V}{V} + 2\frac{\Delta B}{B} + 2\frac{\Delta \rho}{\rho}\right] = \underbrace{4\frac{x_{\min}}{D} + \frac{\Delta w}{w}}$$

Accelerator voltage stability
Required 10^{-5}

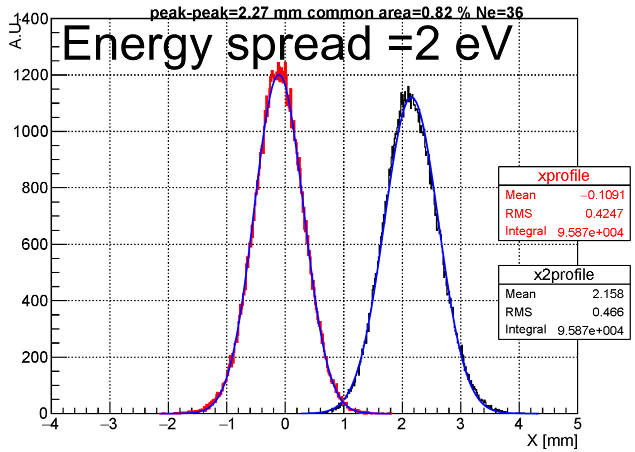
Dipole homogeneity and
Power supply stability
Required 10^{-5}

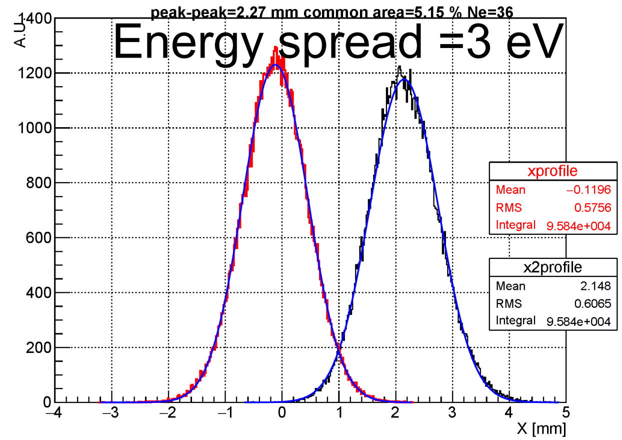
Geometrical precision and stability (vibration)
Required 10^{-5}

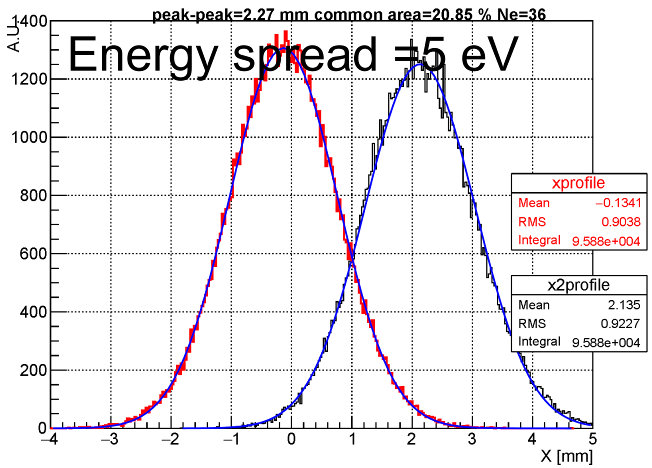
Resolution with energy spread
Required 5 10^{-5}

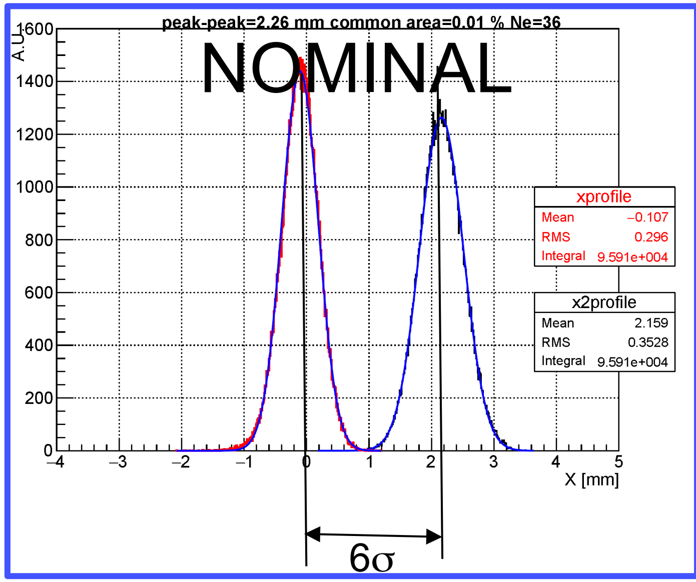
*from $\frac{\Delta m}{m} - \frac{\Delta w}{w} = 2\frac{\Delta B\rho}{B\rho}$

Impact of energy spread (or voltage stability)

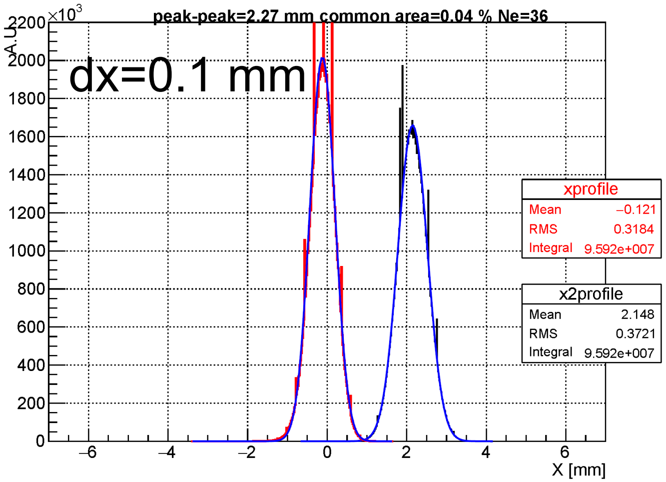


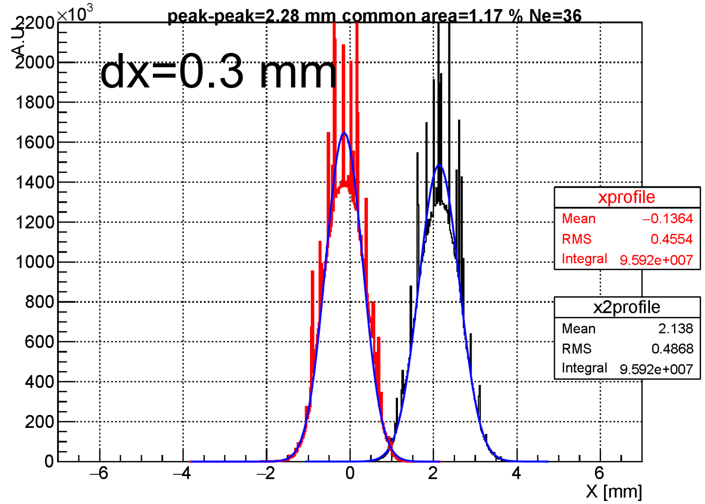


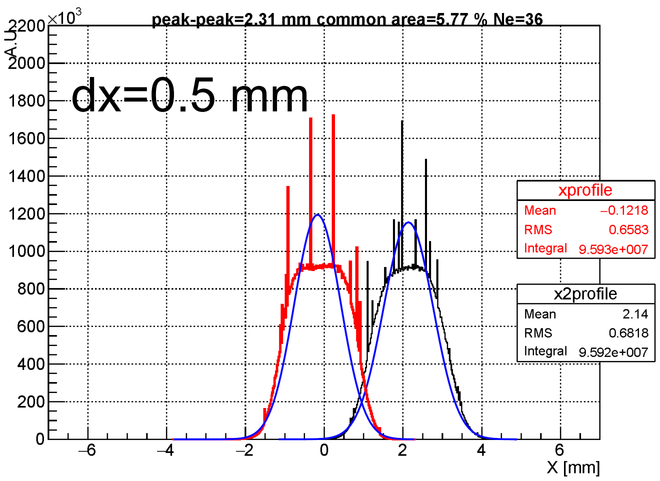


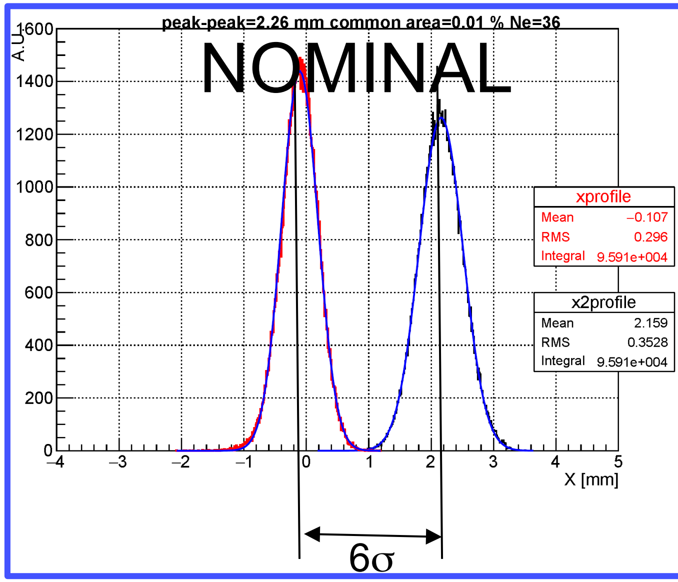


Impact of electrostatic triples disalignments

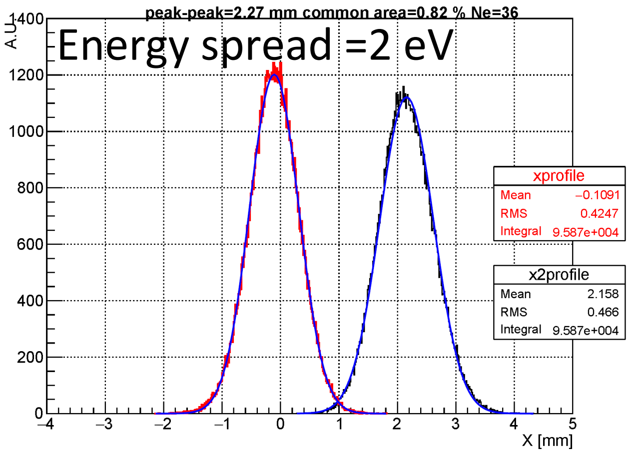


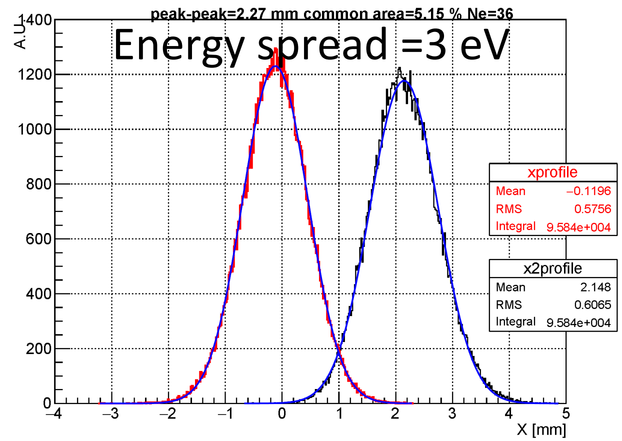


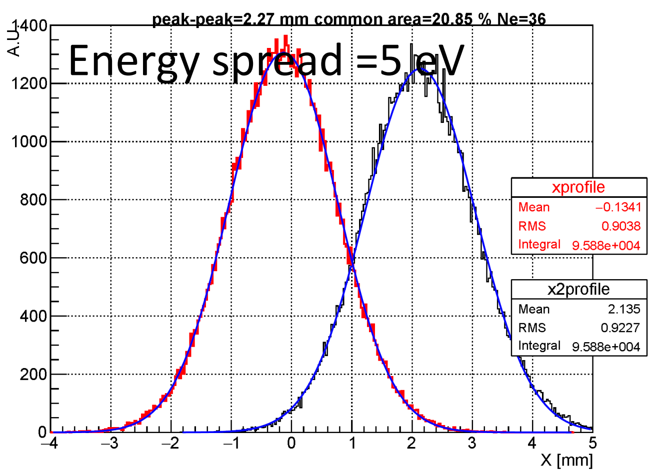


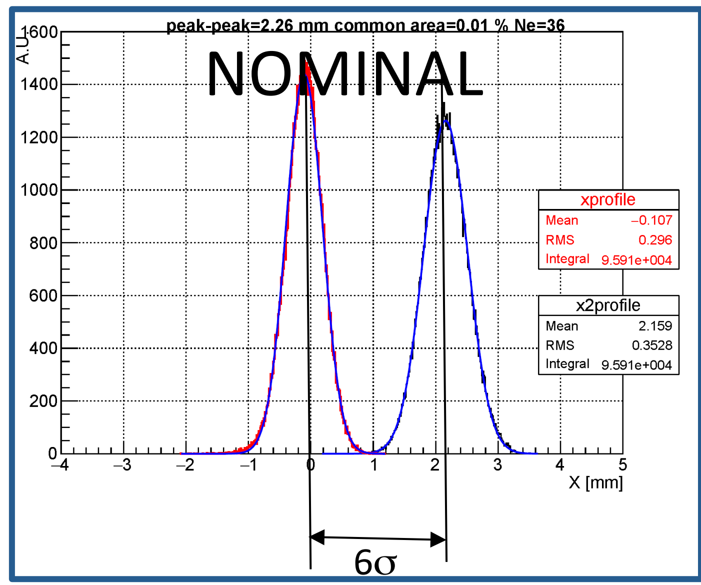


Impact of energy spread (or voltage stability)









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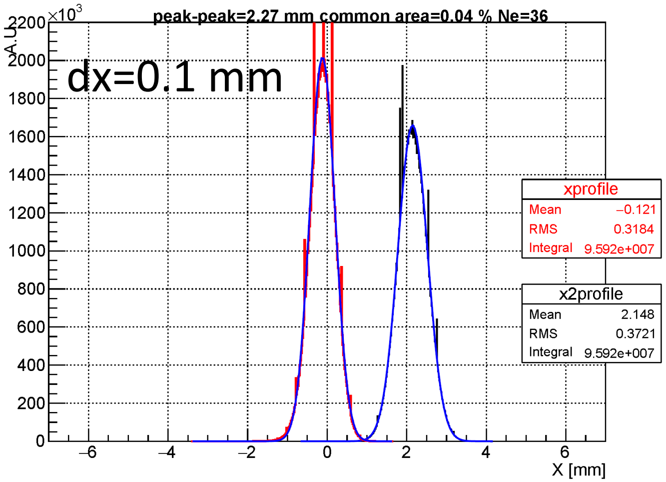
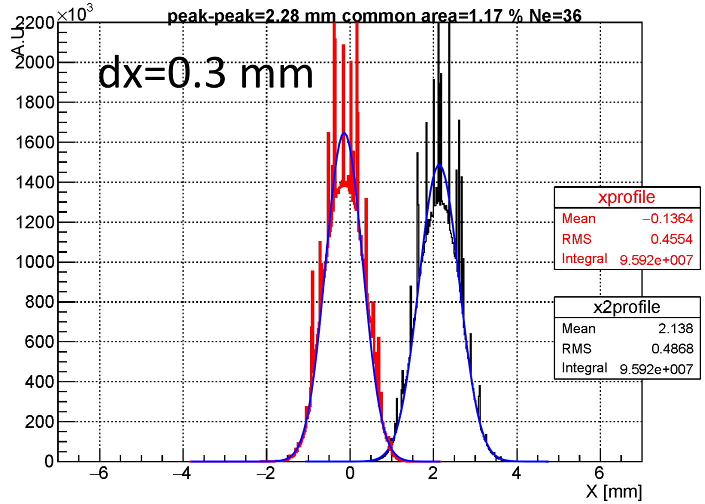
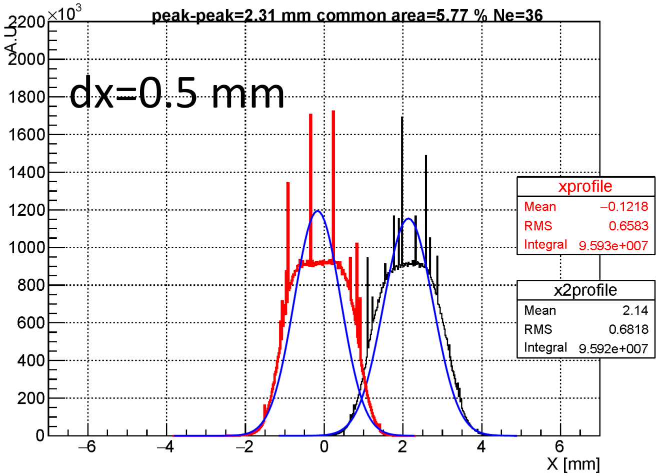
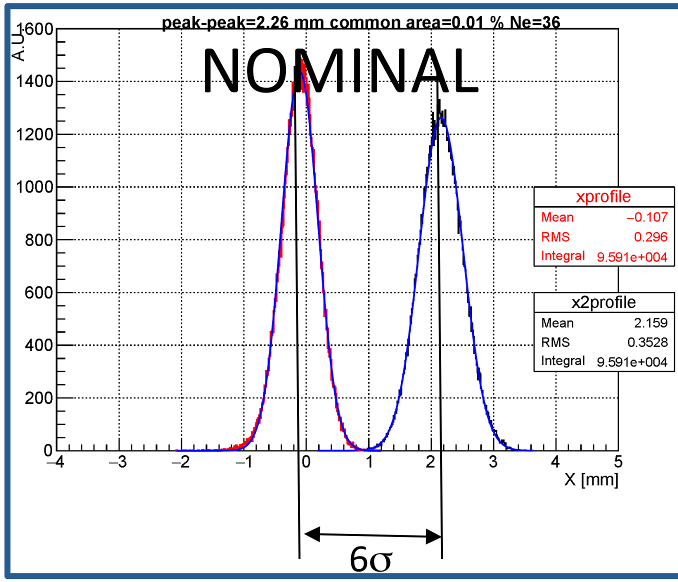


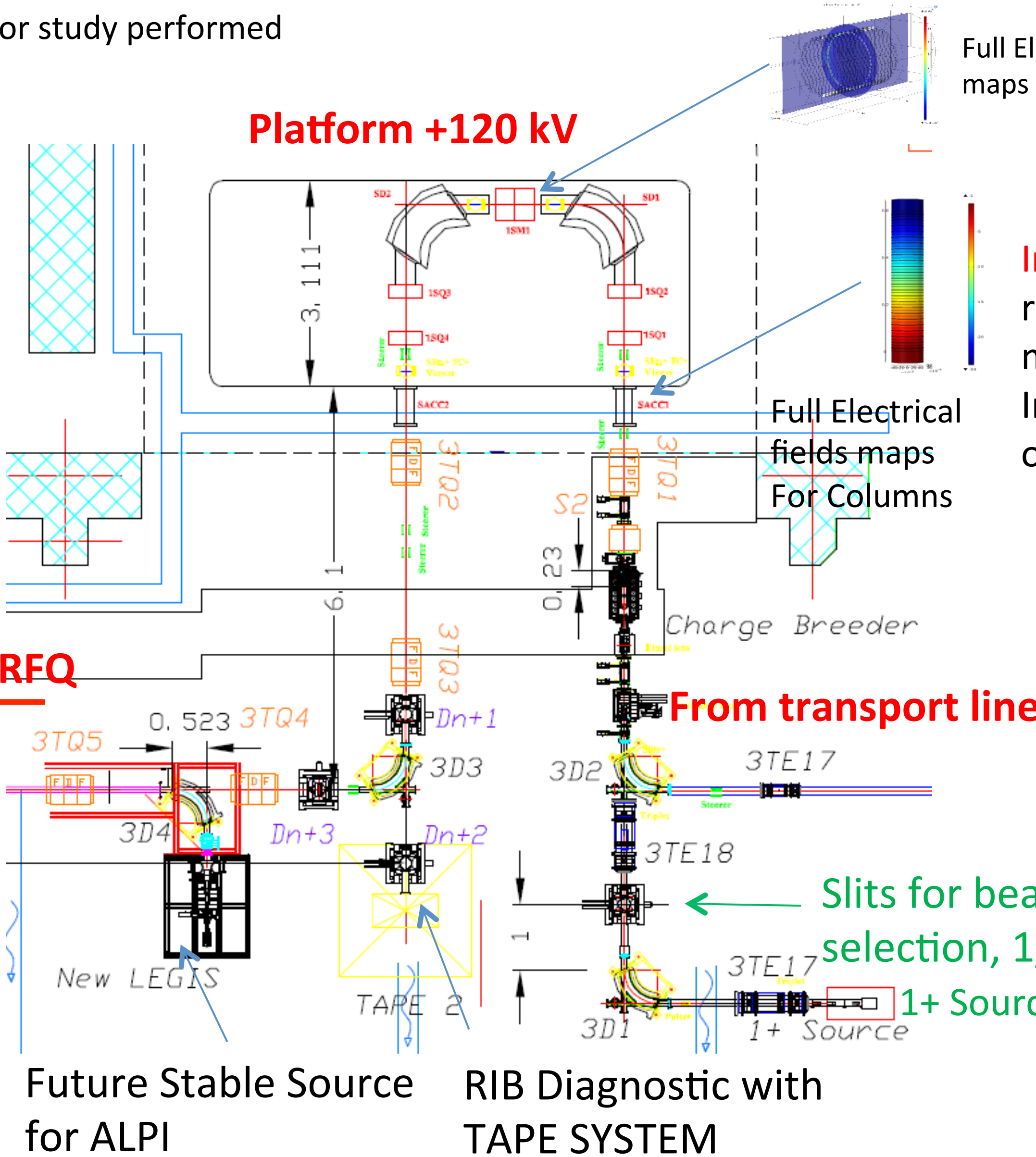






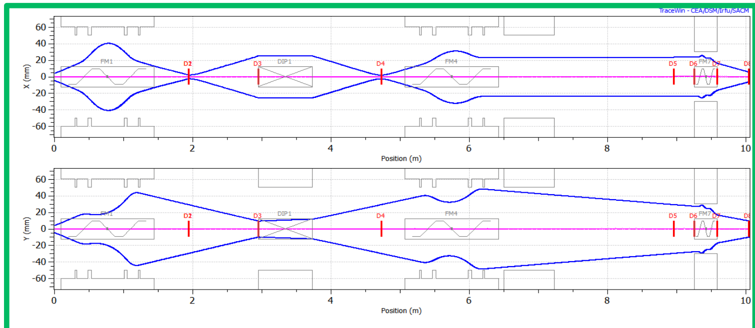
CB and Medium Resolution Mass Spectrometer

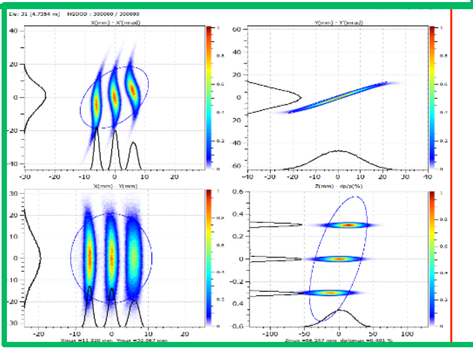
Error study performed



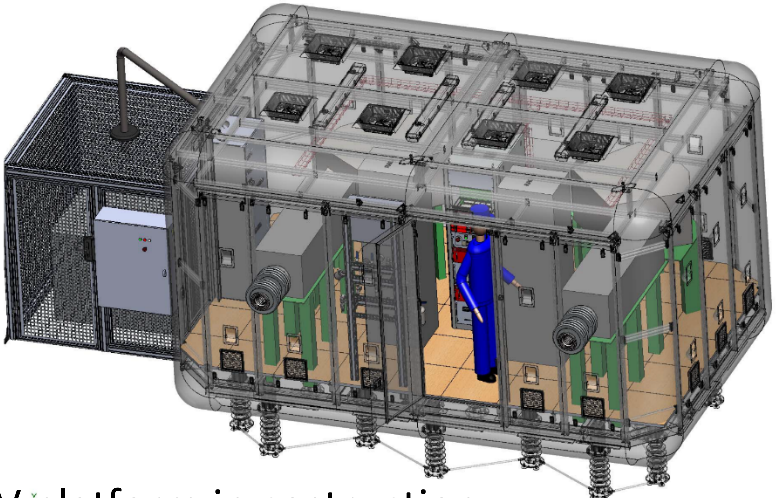
Input: 0.1 rms transverse norm., 28.44 rms geo. Tot geo emittance 222.7 pi mm mrad.

Input Twiss parameters from simulation of CB. Spread of 5 eV.. Brho = 0.076 Tm



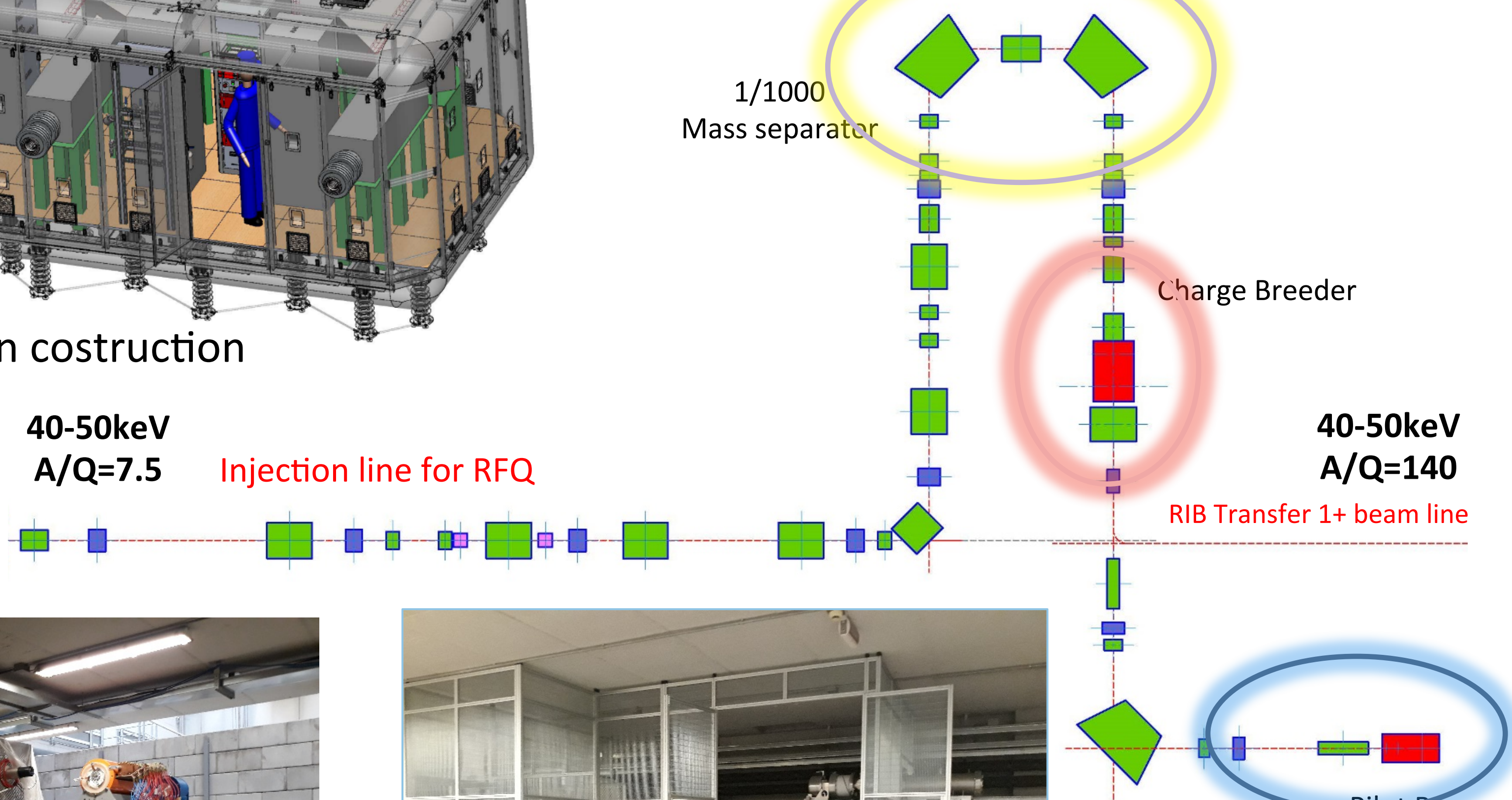


Phase 2A: Installation of Charge Breeder and n+ beam line



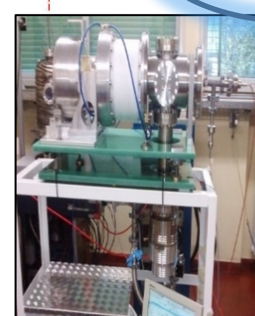
HV platform in costruction

MRMS and HV platform



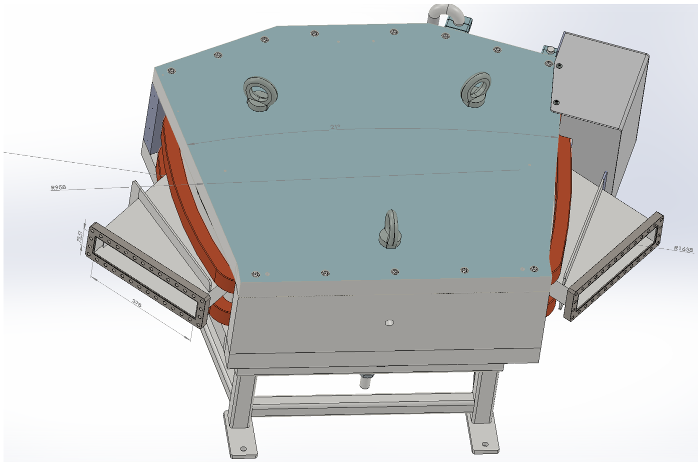
Charge Breeder
Installation Status on 17th/01/2018

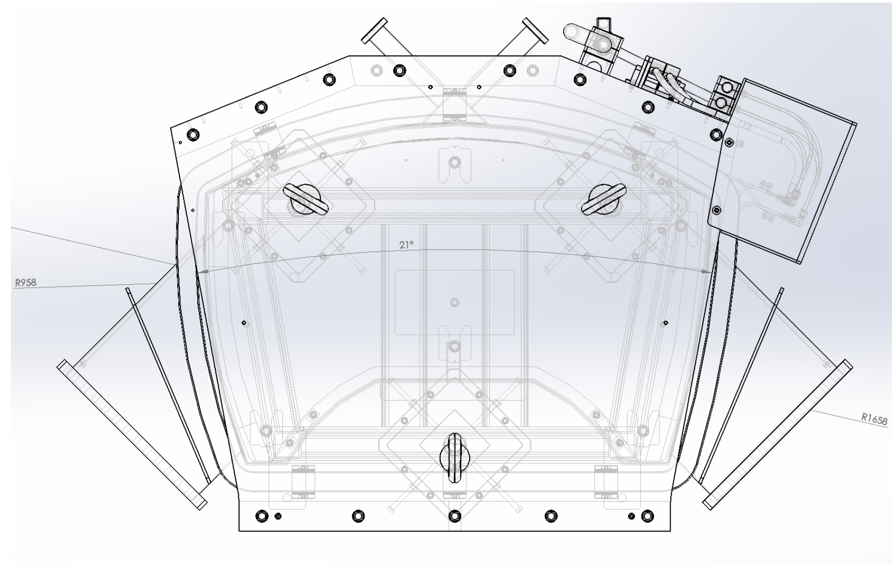
Pilot beam Ion Source
Installation Status on 17th/01/2018

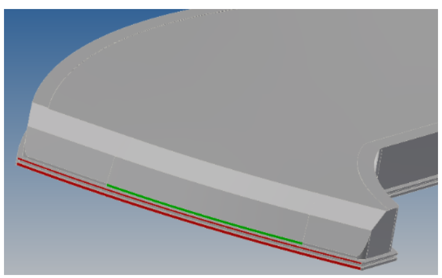


C.Roncolato

SD1 Dipole DF design



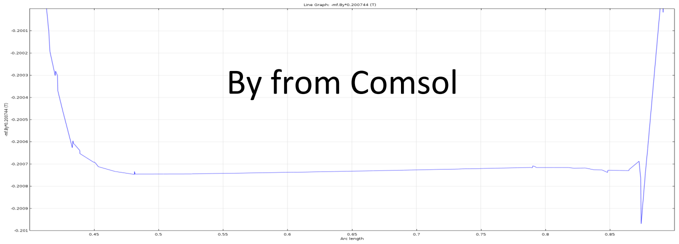




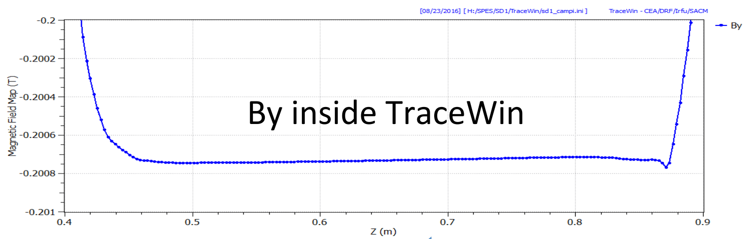
Green line measured for in/out radius

Parameter	Contract Request	DF design
Edge angle	33.35 °	(90-21)/2=34.5 °
Input Radius	1474 mm	1658 mm
Output Radius	828 mm	958 mm
Overall size rs. beam axe	<350 mm	460 mm
Coils ext.	<200 mm	70 mm

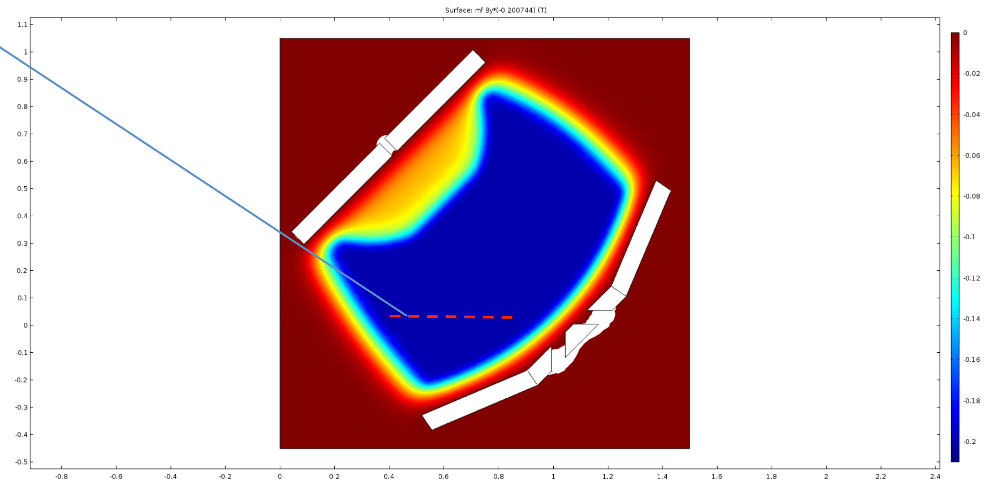
By from Comsol



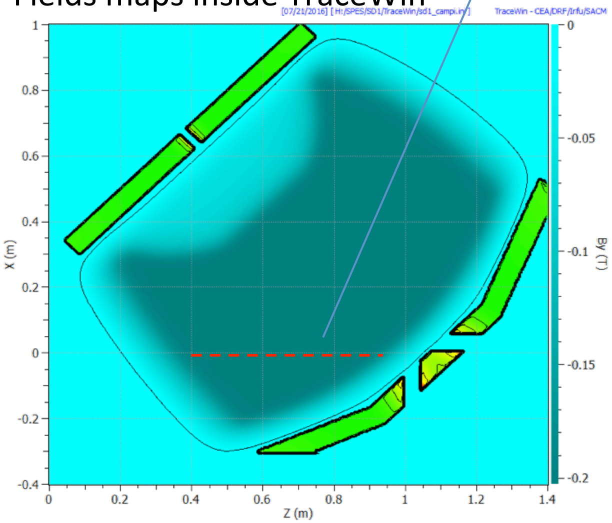
By inside TraceWin



Model simulated with Comsol



Fields maps inside TraceWin

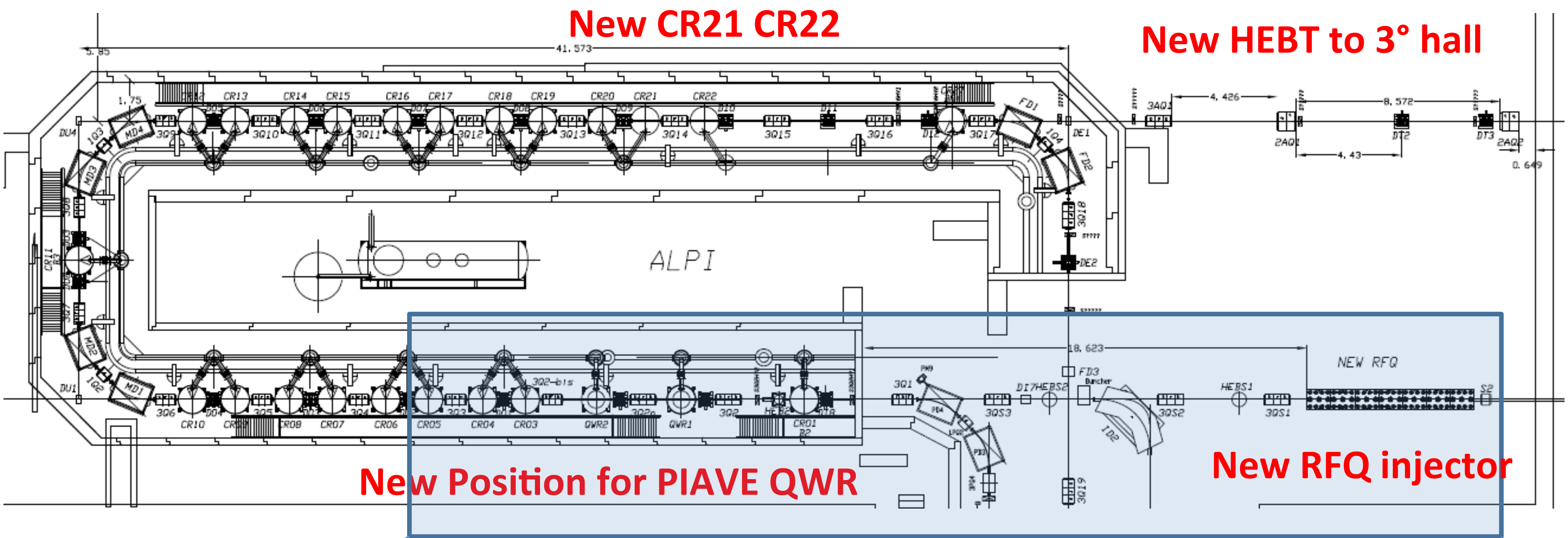


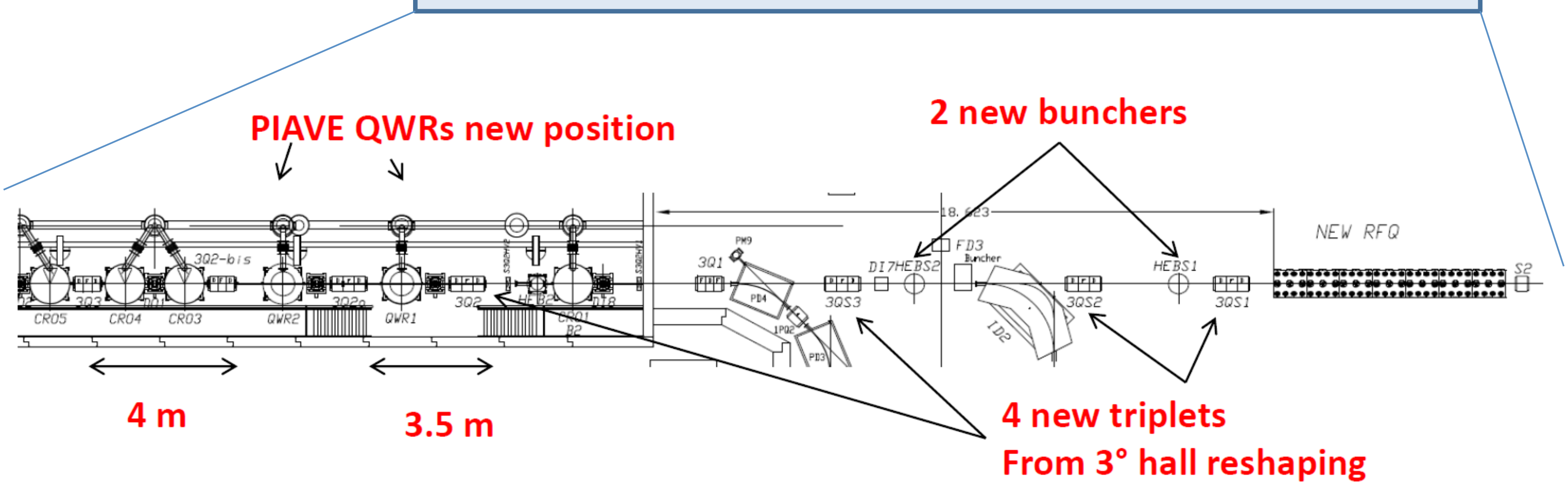
Fields imported inside TraceWin with a full 3D (Bx,By,Bz) maps:
300 points along X and Z, 20 points along y.

Points to evaluate in:	Grid	
Data format:	Spreadsheet	
x:	range(-0.3,1.4/300,1.1)	m
y:	range(-0.05,0.1/20,0.05)	m
z:	range(0,1.4/300,1.4)	m

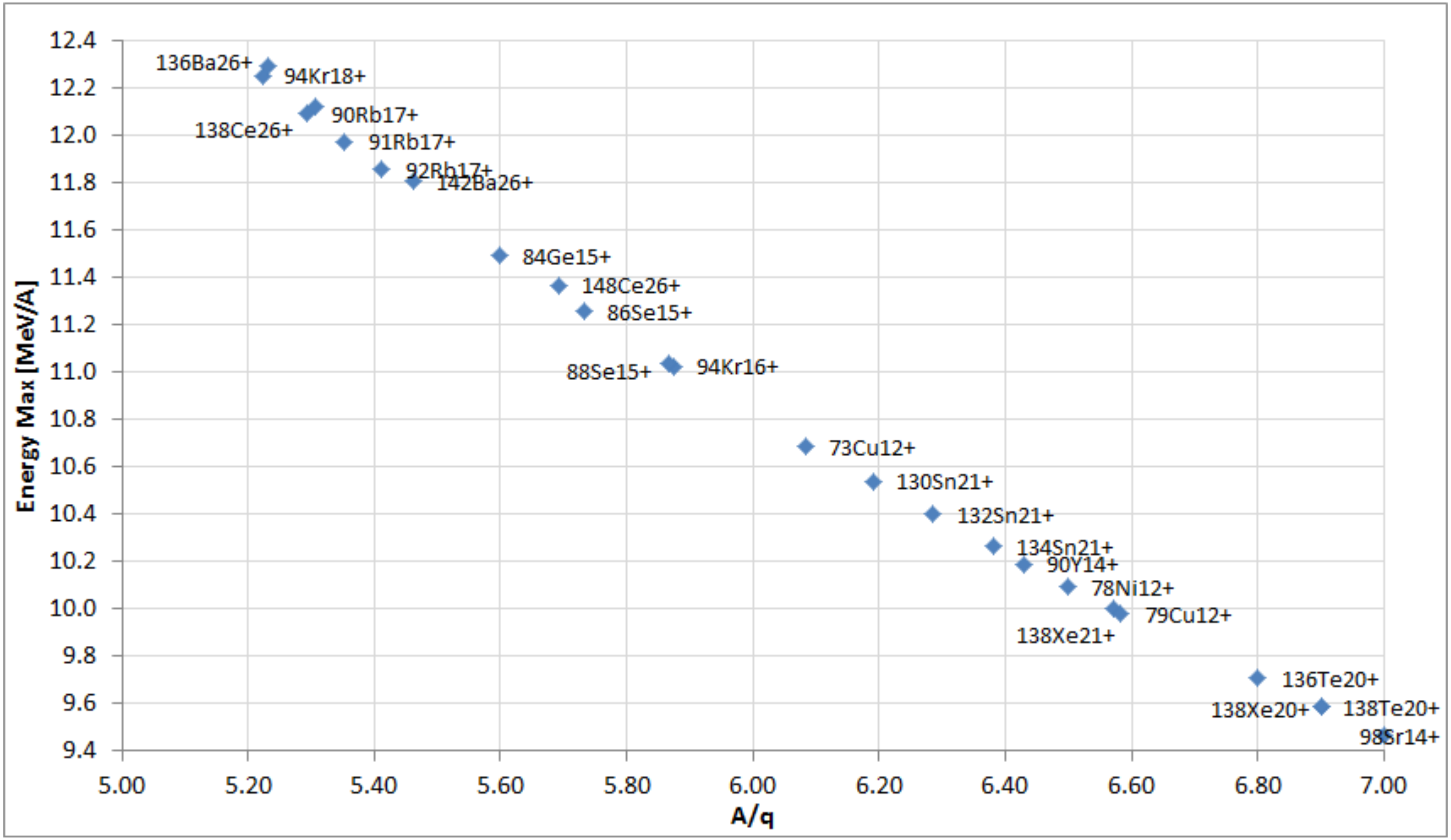
ALPI and the new RFQ

SPES Layout: zoom on ALPI LINAC





Energy from SPES Post-Accelerator as function of A/q

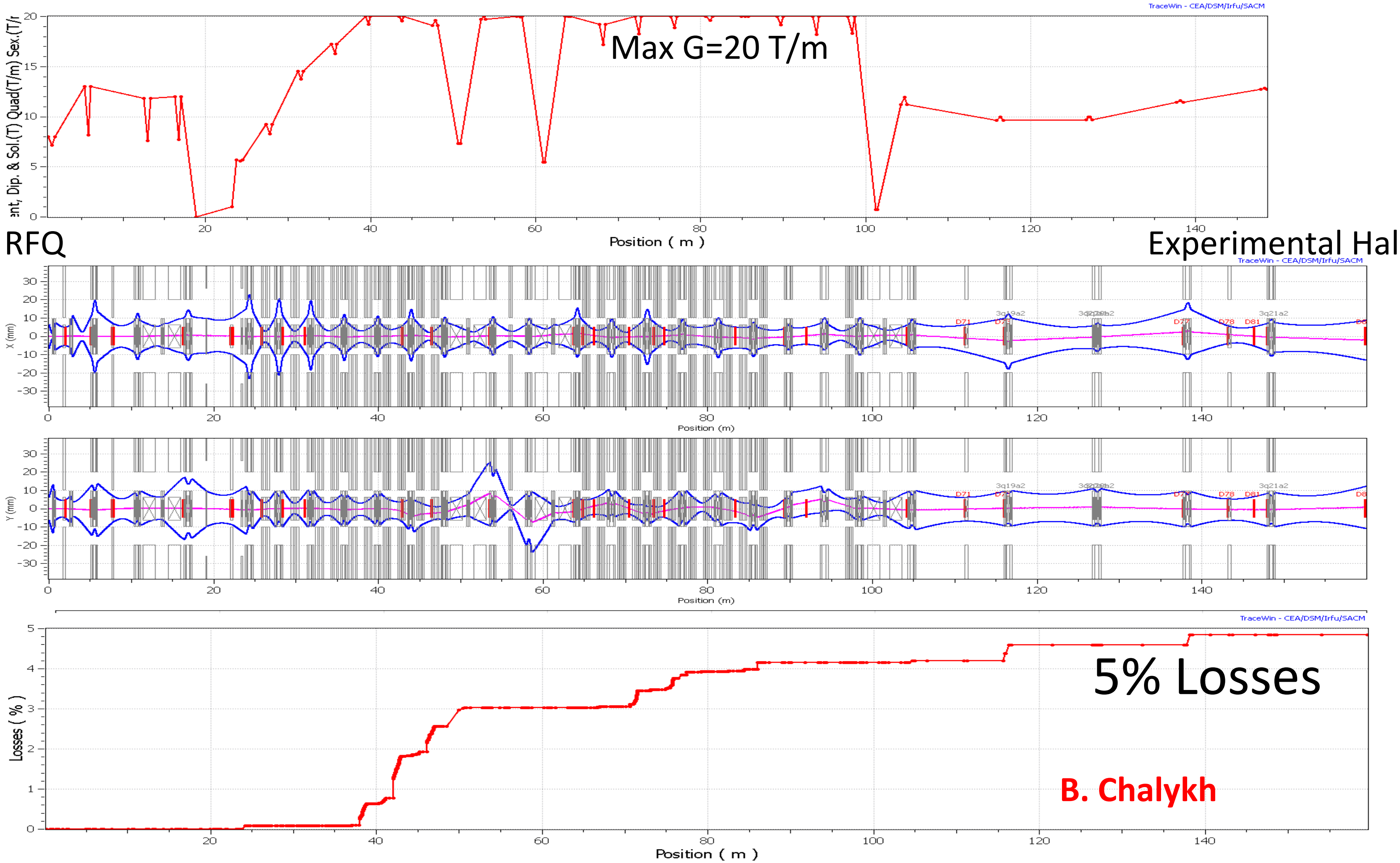


Preliminary results from ALPI performances with 2 cavities off (margin), Low Beta=5 MV/m, Medium Beta=4.3 MV/m, High Beta=5.5 MV/m

ALPI: main improvements needed

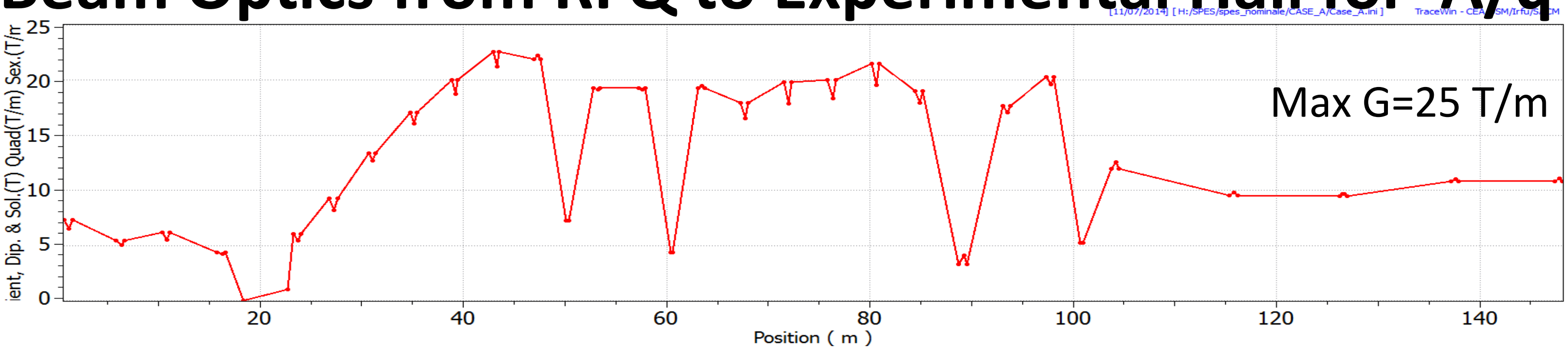
1. **New quadrupoles** for the low energy section (30T/m instead of 20 T/m) ➔delivered at LNL, to be installed.
2. Establishment of GPS network and constant survey of the **alignment** with laser tracker➔done.
3. New LLRF **digital controllers** (.1 deg .01% field resolution) necessary for linac paramenters scaling➔tested, to be gradually installed.
4. Improved **beam instrumentation** for pilot beams (grids, FC, slits, MCP) and new for RNB (MCP and tape systems) ➔being done
5. New (**EPICS**) control system for systematic control of all the machine parameters➔90% done
6. General survey of all the parameters (**PLC**)➔to be done
7. **Machine development shifts are under way with ALPI to improve the knowledge and operation of the accelerator**

Beam Optics from RFQ to Experimental Hall for A/q=7

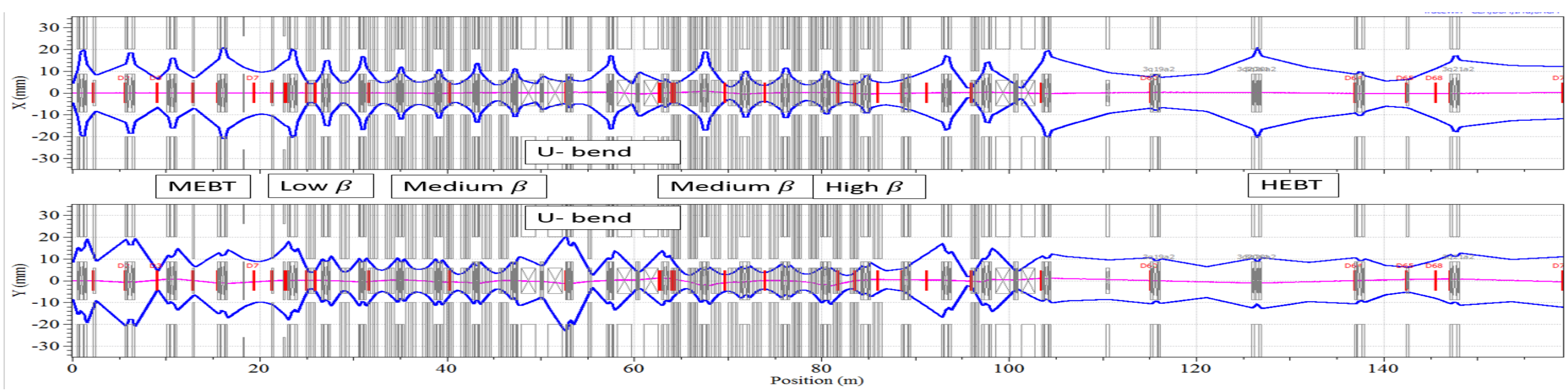


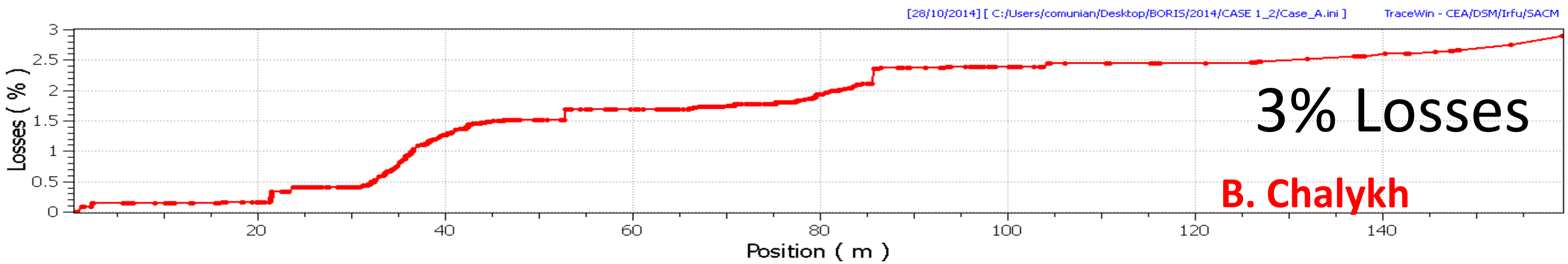
B. Chalykh

Beam Optics from RFQ to Experimental Hall for A/q=7

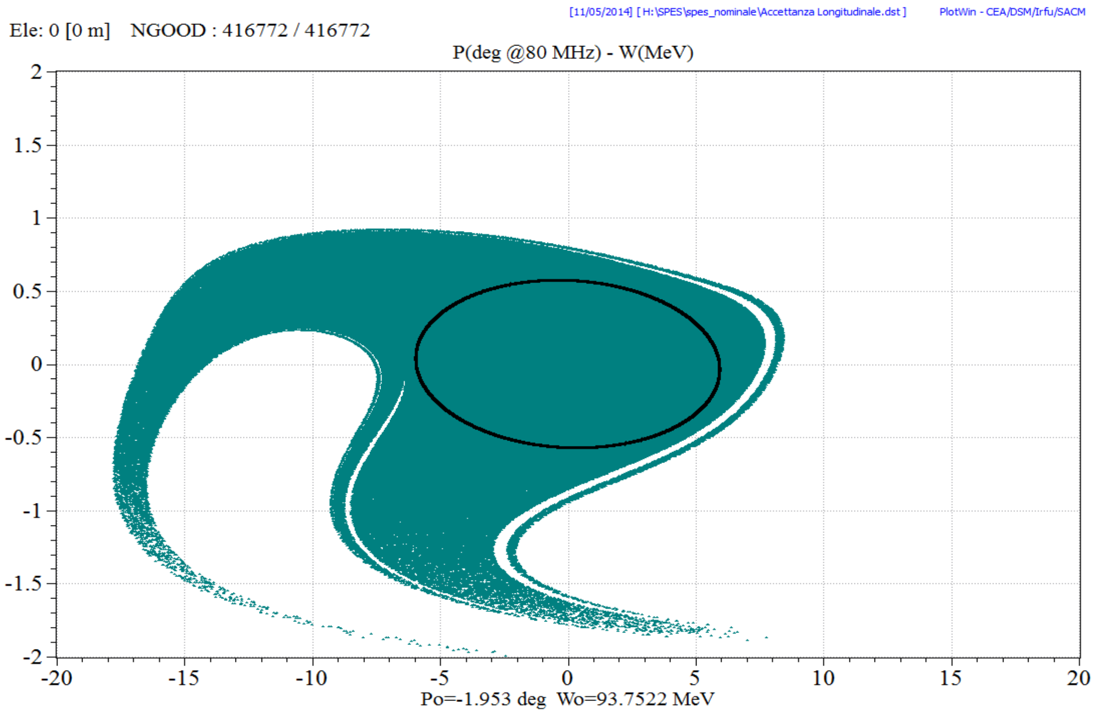


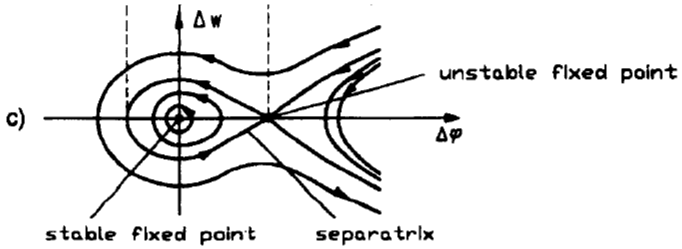
RFQ Experimental Hall





ALPI long acceptance plot

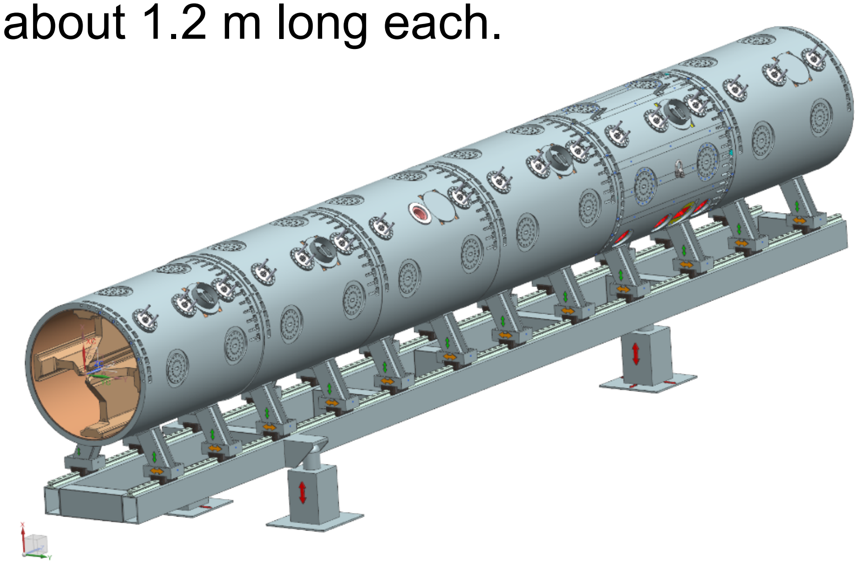




SPES RFQ Essentials: Main parameters

Paramater [units]	Design value
Frequency [MHz]	80
In/out. Energy [keV/u]	5.7-727 (β=0.0035-0.0359)
V_{iv}[kV]	63.76-85.85
Beam current [μA]	100
Vane Length [m]	6.95
R_0[mm]	5.29-7.58
ρ/R_0	0.76
Synchronous phase (deg.)	-90 ÷ -20
Focusing Strength B	4.7 ÷ 4
Shunt impedance [kΩ*m]	419-438 (30% margin)
Stored Energy [J]	2.87
RF Power [kW]	115 (with 30 %margin for 3D details and RF joint, and 20% margin for LLRF regulation)
Q_0 value (SF)	16100 (30% margin)
Max power density [W/cm^2]	0.31 (2D), 13 (3D)
max $\delta V_{iv}/V_{iv}$ [%]	±3
Transmission [%]	94
Output Long RMS Emit [keV deg / u]	4.35

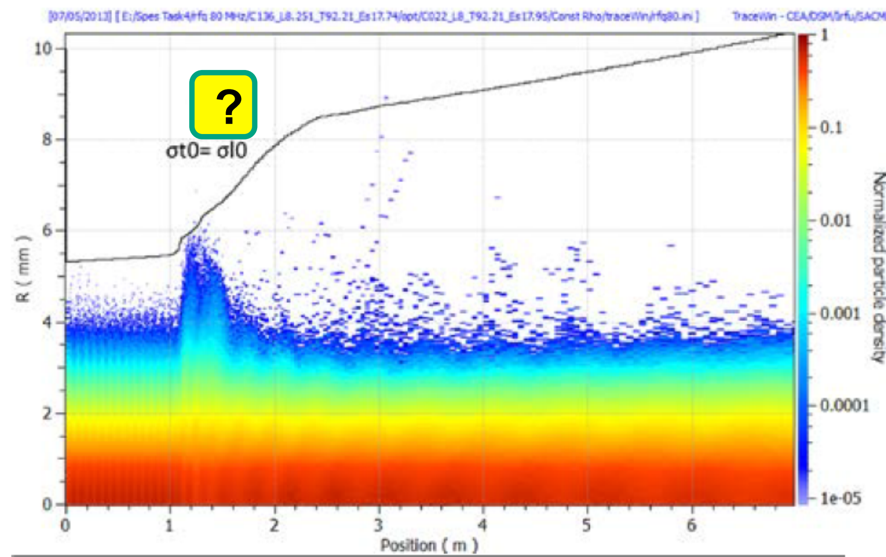
The SPES RFQ is designed in order to accelerate beams in CW with A/q ratios from 3 to 7. The RFQ is composed of 6 modules about 1.2 m long each.

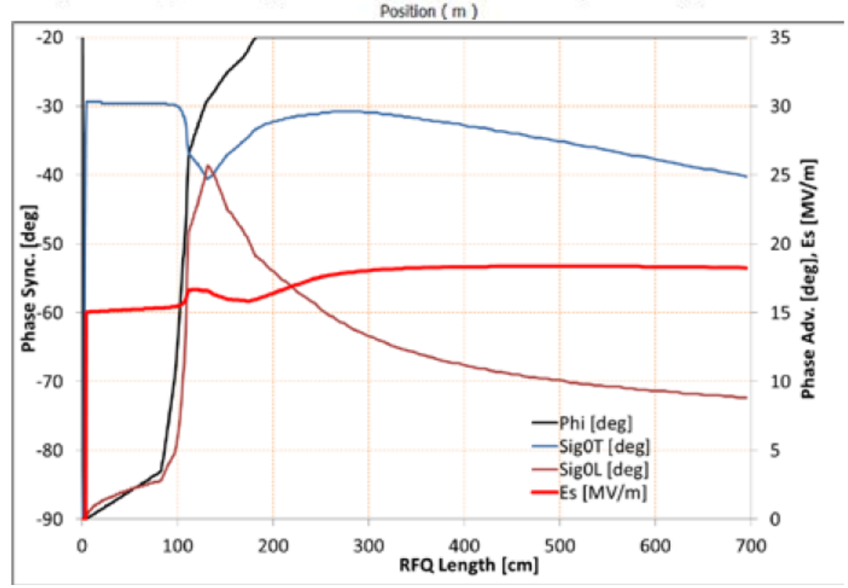


SPES RFQ

Table 2: RFQ design parameters

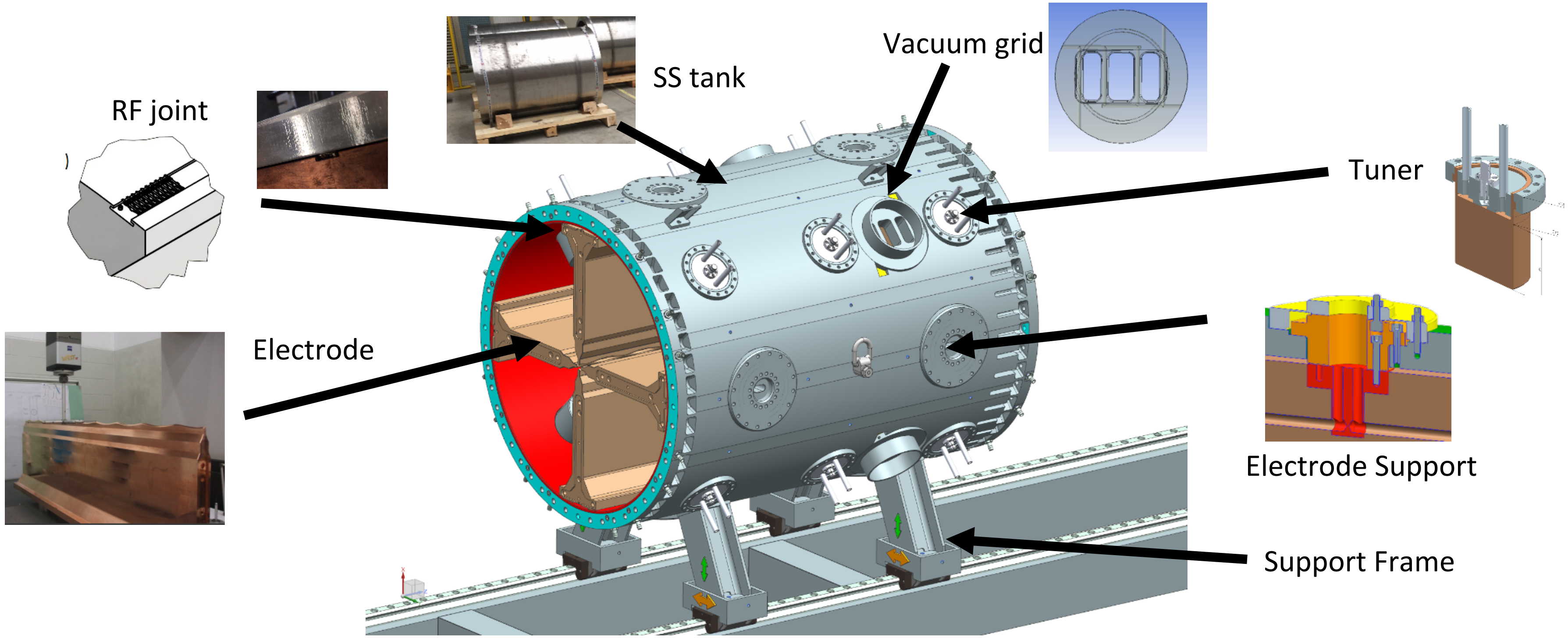
Parameter (units)	Design
Inter-vane voltage V (kV, A/q=7)	63.8 – 85.84
Vane length L (m)	6.95
Average radius R_0 (mm)	5.33 – 6.788
Vane radius ρ to average radius ratio	0.76
Modulation factor m	1.0 – 3.18
Min small aperture a (mm)	2.45
Total number of cells	321
Synchronous phase (deg.)	-90 – -20
Focusing strength B	4.7 – 4
Peak field (Kilpatrick units)	1.74
Transmission (%)	95
Input Tr. RMS emittance (mmmrad)	0.1
Output Long. RMS emittance (mmmrad) / (keVns/u)/(keVdeg/u)	0.055 / 0.15 / 4.35



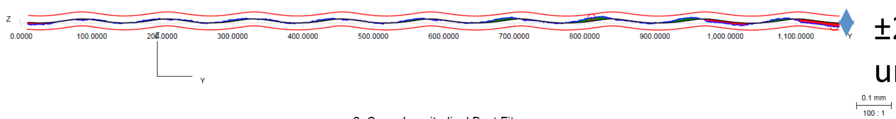


SPES RFQ essentials (2): building blocks

Each module is basically composed of a Stainless Steel Tank (AISI LN 304) and four OFE Copper Electrodes. A copper layer thickness is plated on the tank inner surface and a spring joint between tank and electrode is used in order to seal the RF

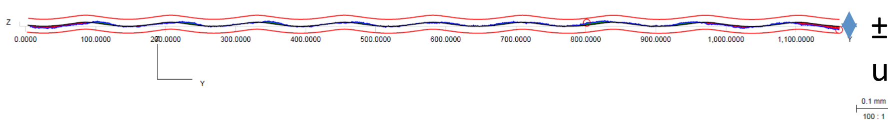


Consegnati e accettati 16 elettrodi/24, ne aspettiamo gli ultimi 8 in marzo '18



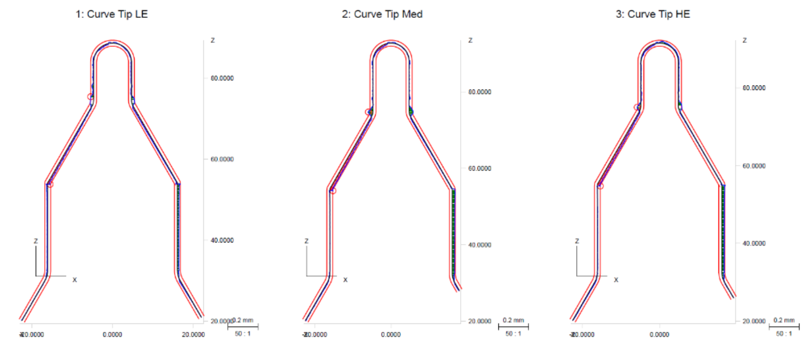
±20 um

2: Curve Longitudinal Best Fit

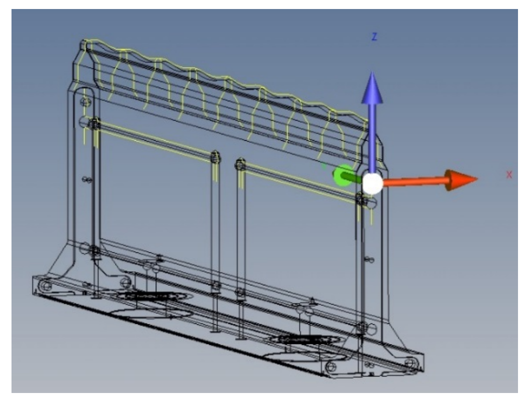


±20 um

No	Identifier	Sigma [mm]	Form [mm]	Number of Points	Lower Tol. [mm]	Upper Tol. [mm]	MinInd	Min Dev. [mm]	MaxInd	Max Dev. [mm]	Best Fit	X [mm]	Y [mm]	Z [mm]		X	Y	Z
1	Curve Longitudinal	0.0042	0.0244	1163	-0.0200	0.0200	1163	-0.0141	354	0.0102	Translation	0.0000	0.0000	0.0000	Rotation	0.0000	0.0000	0.0000
2	Curve Longitudinal Best Fit	0.0033	0.0172	1162	-0.0200	0.0200	1	-0.0101	363	0.0071	Translation	0.0000	-0.0255	0.0008	Rotation	-0.0001	-0.0000	-0.0010



No	Identifier	Sigma [mm]	Form [mm]	Number of Points	Lower Tol. [mm]	Upper Tol. [mm]	MinInd	Min Dev. [mm]	MaxInd	Max Dev. [mm]
1	Curve Tip LE	0.0067	0.0384	498	-0.0200	0.0200	120	-0.0186	195	0.0198
2	Curve Tip Med	0.0101	0.0620	522	-0.0200	0.0200	121	-0.0245	522	0.0375
3	Curve Tip HE	0.0086	0.0465	523	-0.0200	0.0200	123	-0.0225	199	0.0239



Ok!

Almost all scanned profiles of each electrodes are in compliance with tolerance on best fitted curve profiles (0.04mm) except for some small spot (Outliers <1 % of measured points)

Pilot beam, futuristic beams

- The MRMS resolves beams with D(q/A)>0.1%.
- The ALPI acceptance (for a given setting) <0.3%
- Hence the **pilot beam** needs a (delicate and moderate) resetting of the field and possible phases in ALPI.
- We need to gain experience (once the new controllers and beam instrumentation will be available.

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- We need to gain experience (once the new controllers and beam instrumentation will be available.

- Giacomo asked us about to capabilities of SPES for heavy beams (**A>220, like Rn, Ra, Pa…),**
- Production is not programmed, but it is in interesting perturbative method to test the solidity of our design of the post accelerator.
- The main difficulty is the CB, to get A/q=7 we need high charge states (34-36) so a different **ECR** source (**superconducting**?).
- The Breeder and the ISOL source is at 40 kV (electrostatic transport lines are ok), but the Bρ is higher HRMS, and Wien filter, that can work at lower resolution (changing the voltage) but a **stronger LRMS magnetic dipole** is needed.

Conclusions

- SPES post accelerator beam design has involved the study of many critical devices, and the overall optimization to distribute the criticality.
- The beam transport lines from are designed, partially under construction; main elements, including the 7m long RFQ are in construction or installation (like the CB).
- The HRMS design will be reviewed in the April (CDR) and the procurement will start afterwards.
- An agreement with CNRS for the development of RFQ cooler is under preparation.

Thanks to SPES Team: G. Prete, L. Bellan, C. Baltador, D. Bortolato, E. Fagotti, A. Galatà G. Bisoffi, P. Favaron, A. Andrighetto, A. Pisent, M. Comunian, A. Palmieri, D. Zafiropoulos, L. Sarchiapone, J. Esposito, C. Roncolato, L. Ferrari, M. Rossignoli, M. Calderolla, M. Poggi, M. Manzolaro, M. Monetti, L. Calabretta, M. Guerzoni…………..