

# The SPES charge breeder and its beamline: technological aspects

*A. Galatà, on behalf of INFN team*



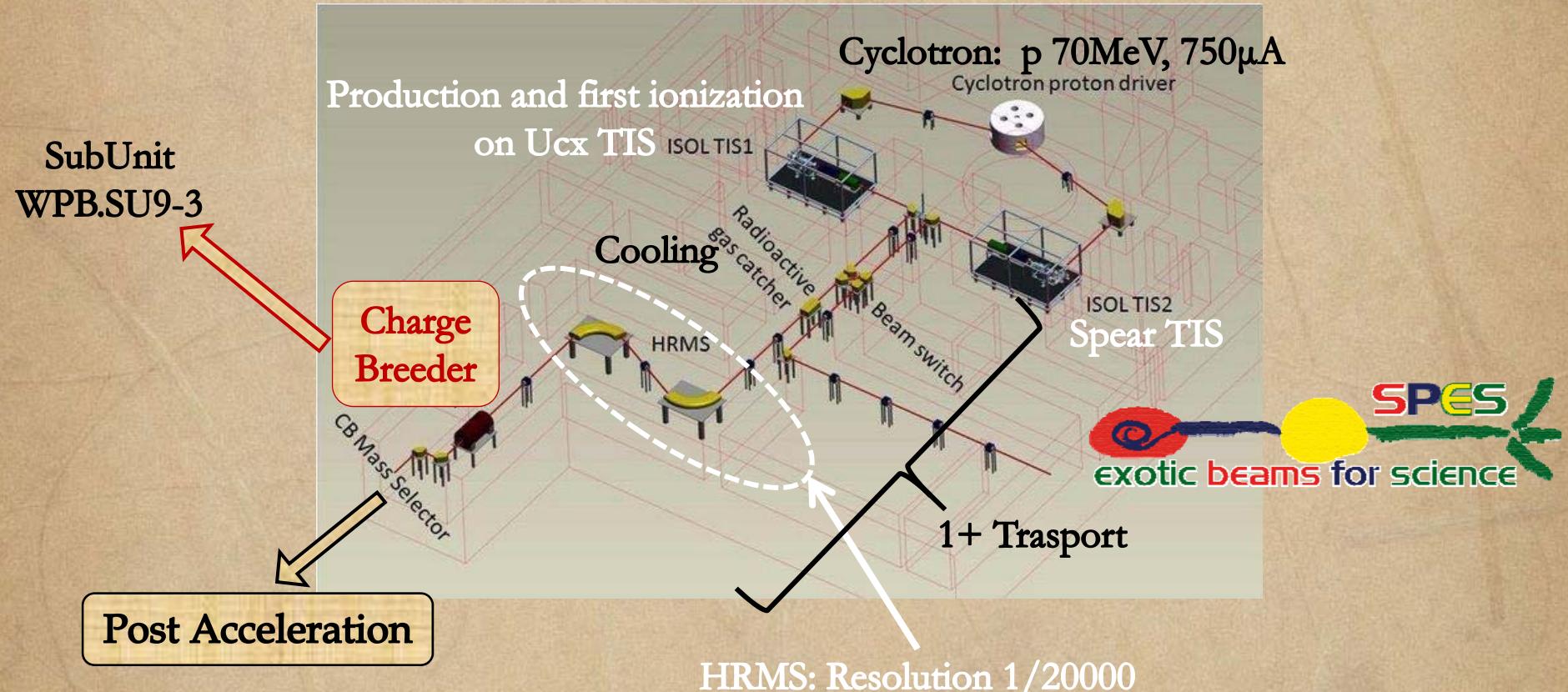
*A. Galatà, EMILIE Workshop 21-23 March 2016, GANIL*

# Outline

- The SPES Project
- The SPES-Charge Breeder and its beamline
- Acceptance tests
- Conclusions

# The SPES Project

$10^{13}$  Fissions/s; A = 80 ÷ 160



# The Cyclotron



- Construction started in 2011
- First injected beam (1MeV) in 2014 (Ottawa, CAN)
- Factory Acceptance Test completed on Nov 2014
- Shipping to Legnaro on Jan 2015
- Start installation of Cyclotron and Beamline in Legnaro Labs on May 2015
- Beam Commissioning started on Nov 2015
- First fully Acceleration without extraction on Feb 2016
- Completion of commissioning expected for July 2016

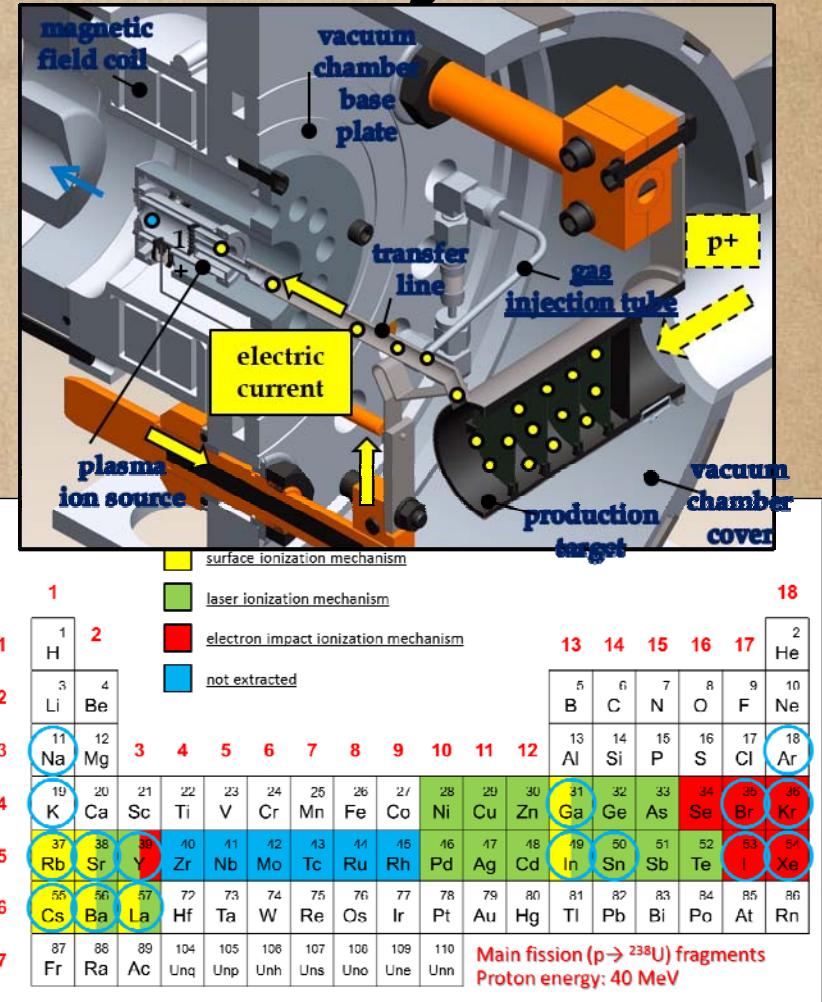
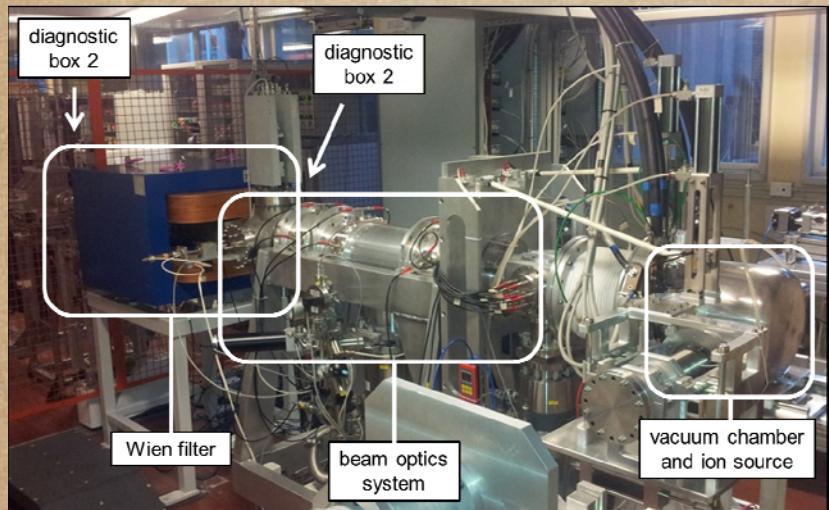
Main Parameters	
Accelerator type	Cyclotron AVF with 4 sectors, Resistive Magnet
Particle	Protons ( $H^-$ accelerated)
Energy range	35-70 MeV
Max Current Intensity	700 $\mu$ A (variable within the range 1 $\mu$ A-700 $\mu$ A)
Extraction	Dual stripping extraction
Max Magnetic Field	1.6 T ( $B_0 = 1$ T)
RF System	nr. 2 delta cavities; harmonic mode=4; $f_{RF} = 56$ MHz; 70 kV peak voltage; 50 kW RF power (2 RF amplifiers)
Ion Source	Multi-cusp volume $H^-$ source; $I_{ext} = 8$ mA; $V_{ext} = 40$ kV; axial injection
Dimensions	$\Phi=4.5$ m, $h=2$ m, $W=190$ tons

*Thanks to M. Maggiore*

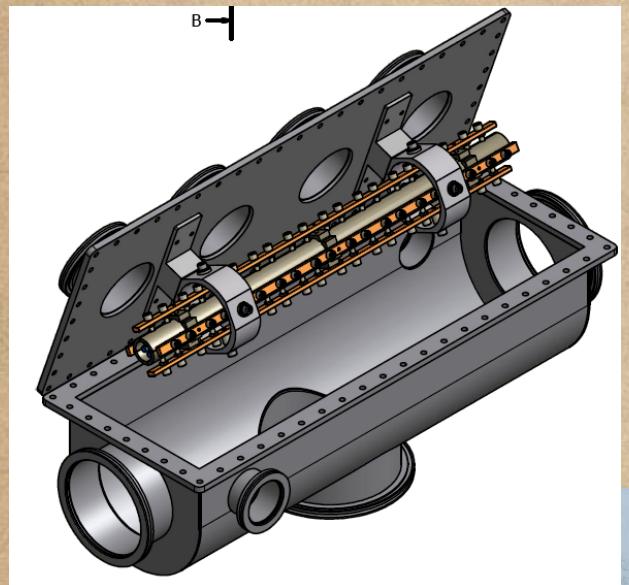
# Target Ion Source System

Surface, plasma and laser ion sources

*Based on ISOLDE design*



# Beam cooler



Mass Range	9-200 amu
Transv. Emitt. Injected beam (norm rms)	0.007 π. mm.mrad
Emittance Reduction factor	10 (max)
Buffer gas	He @ 300 K
Beam Intensity	50-100 nA → x10 <sup>11</sup> pps
Energy spread of extracted beam	~1 eV
RF Voltage range	0.5 – 2.5 kV (1 kV at q(Mathieu) <sup>*</sup> =0.25)
RF Frequency range	1 -30 MHz (3.5 – 15 MHz at q <sup>*</sup> =0.25)
RFQ gap radius ( $r_0$ )	4 mm
RFQ Length	700 mm
Pressure Buffer Gas (He) range	0.1 – 2.5 Pa
Average energy during the cooling	<10 eV
(*): max transmission efficiency (~80%)	



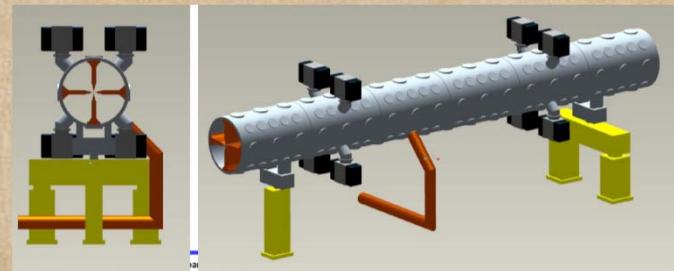
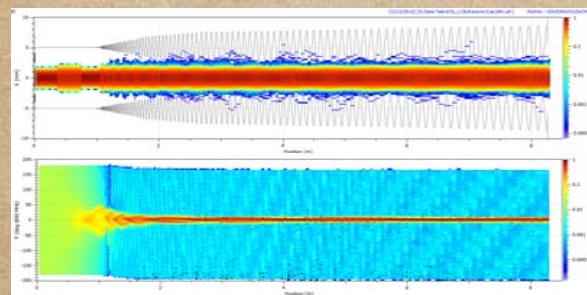
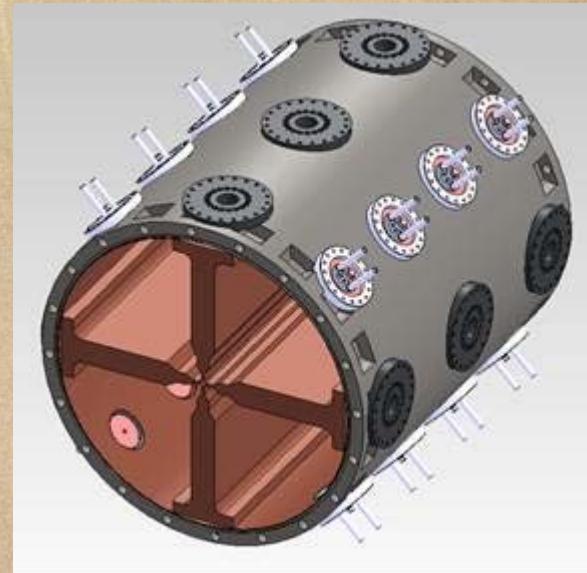
*Simulation with SIMIONS*



*A prototype has been built*

# New RFQ Injector for ALPI

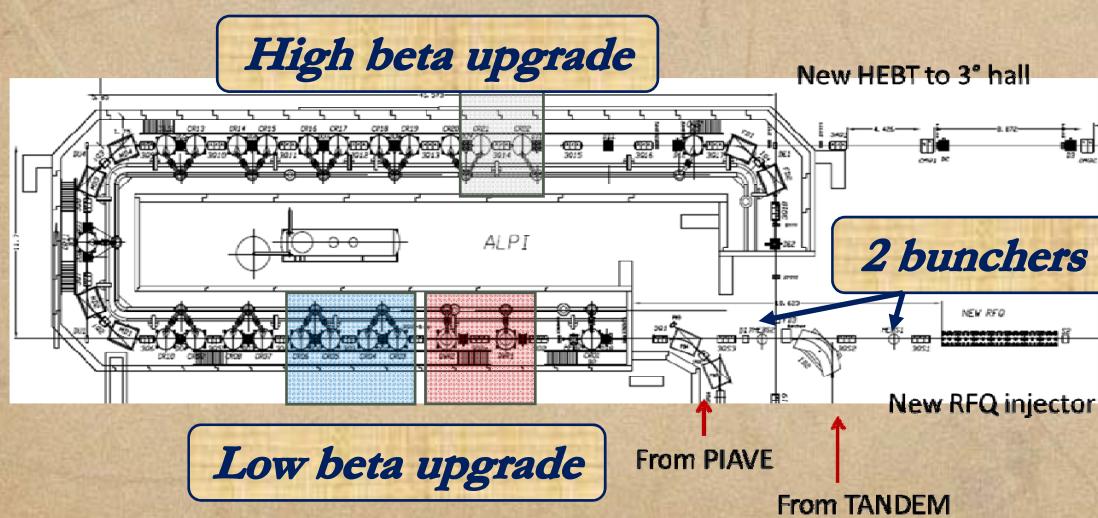
- Energy 5.7  $\rightarrow$  727.3 keV/A [ $\beta=0.0395$ ] ( $A/q=7$ )
- Beam transmission >95%
- $e_{\text{long,RMS,out}} = 0.15 \text{ ns}^*\text{keV/u}$ .
- L=695 cm (7 modules)
- Intervane voltage 63.8 – 85.8 kV
- RF power (four vanes) 100 kW.
- Mechanical design and realization, similar to the Spiral2 one, takes advantage of IFMIF experience (LNL, INFN\_Pd, Bo, To) for up to 1 mA



Mechanical layout of the RFQ tank module ( $\approx 1 \text{ m}$ )

# ALPi Upgrade

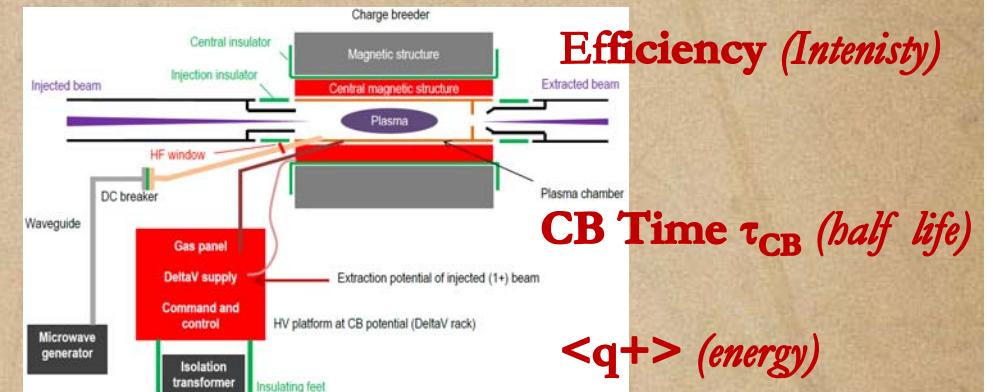
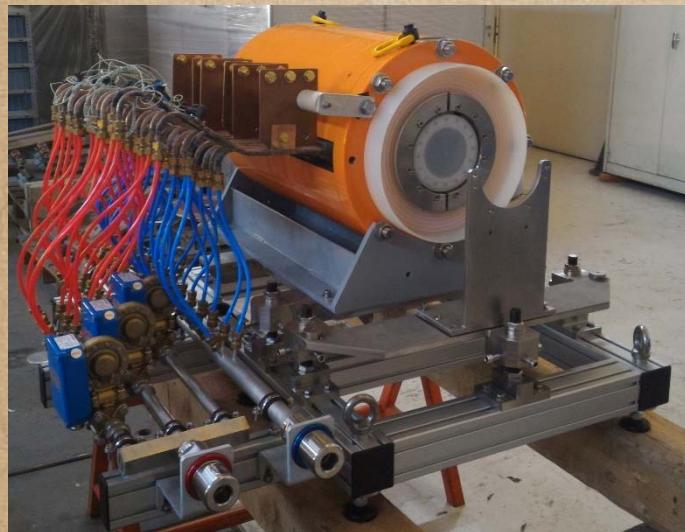
- 6 more cryostats in the low beta section
- 2 more cryostats in the high beta section
- Stronger triplets
- 2 new bunchers
- Cryogenics upgrade



# The SPES-Charge Breeder

- Focusing.
- Deceleration ( $V, B$ ).
- Interaction with the plasma.

**ECR technique**



**Efficiency (Intensity)**

**CB Time  $\tau_{CB}$  (half life)**

**$\langle q+ \rangle$  (energy)**

*high charge states*

*reliability*

*high acceptance*

*cw-pulsed operation*

*limited maintenance*

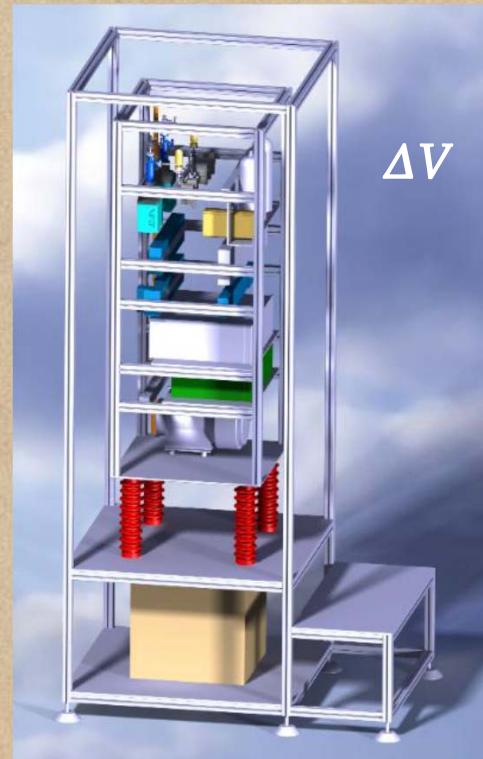
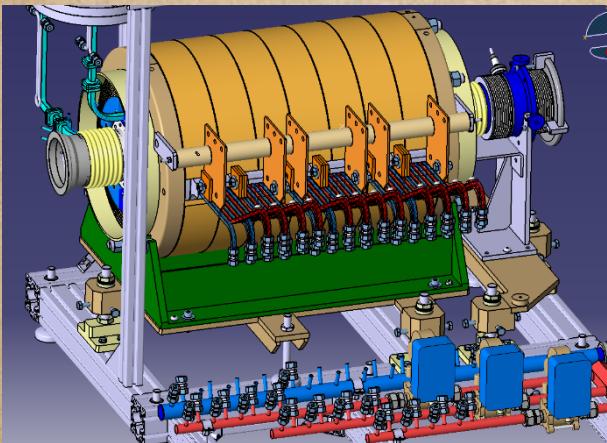
**Upgraded version of Phoenix from LPSC**

# LNL and Charge Breeding

- Collaboration with LPSC since 2010.
- 2012-2015: EMILIE Project (LNL+LNS)
  - ✓ INFN Deputy.
  - ✓ Electromagnetic study of the PHOENIX plasma chamber.
  - ✓ Numerical simulation of the charge breeding process.
- June 2014: Research Collaboration Agreement LNL-CNRS (LPSC)
  - ✓ Delivery within one year of a complete CB and ancillaries up to 500k€
- 2015: Acceptance tests and delivery @ LNL

# The SPES-Charge Breeder

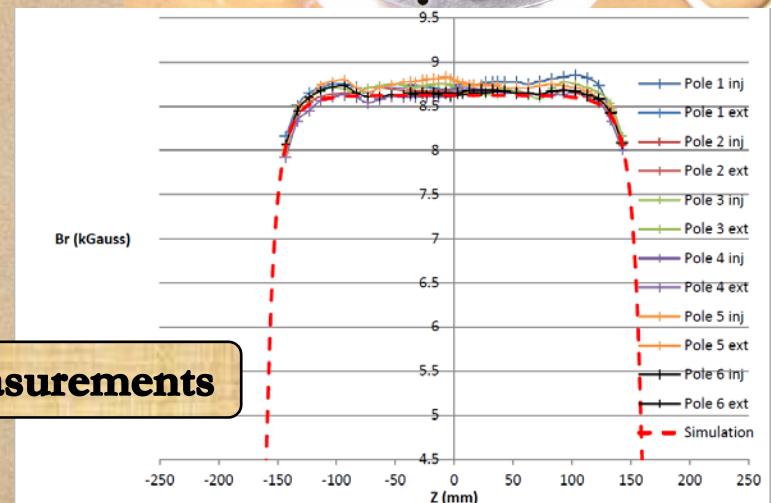
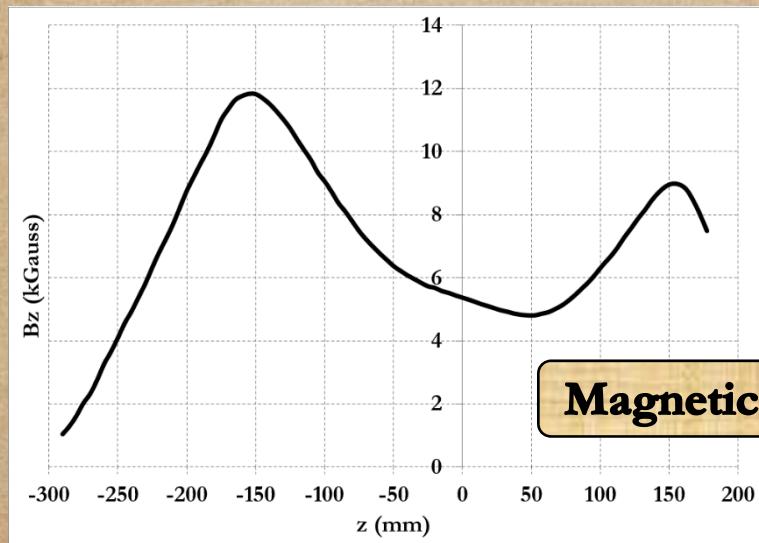
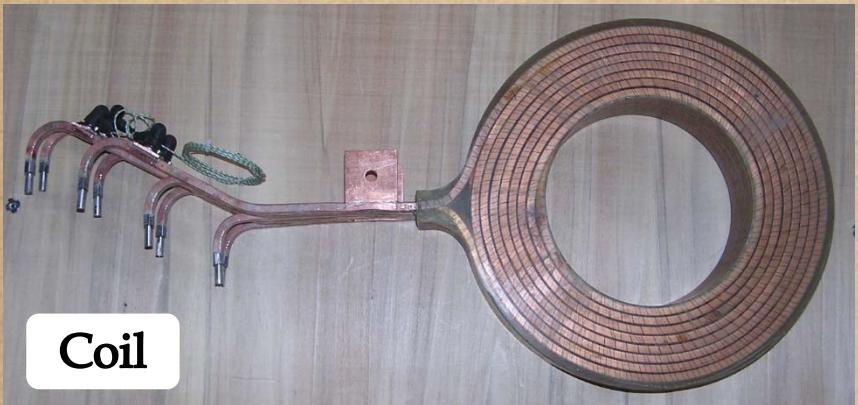
- 2<sup>nd</sup> generation ECRIS (2000)
- 3 coils
- Permanent magnet hexapole
- 2 microwave ports



CHARACTERISTICS	
f [GHz]	14.5
Max Power [kW]	2
Binj [T]	1.2
Bmin [T]	0.4
Bext [T]	0.8
Brad [T]	0.8
Chamber length [m]	0.288
Chamber radius [m]	0.036

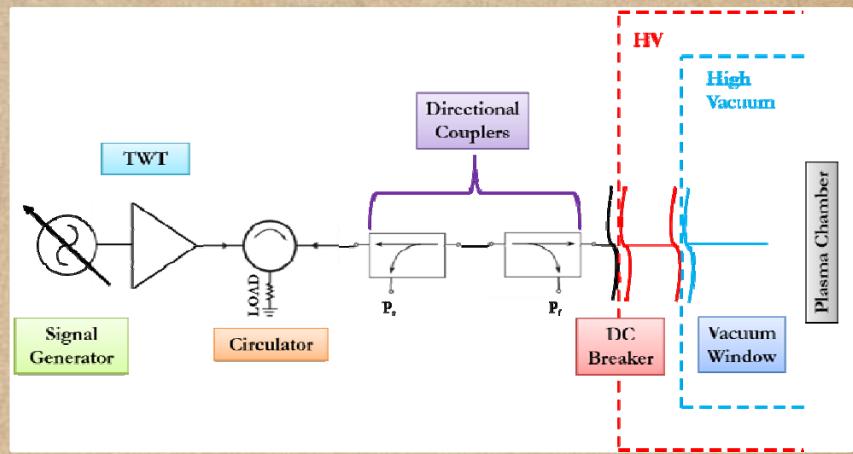
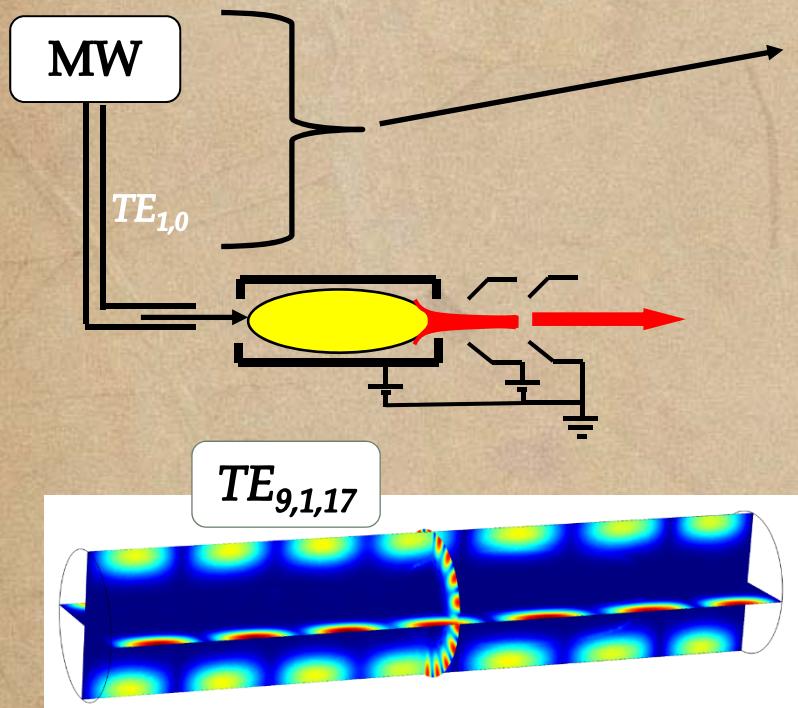
Recent upgrades + special needs from SPES

# SPES-CB: magnetic field



# Microwave system

Two complete microwave circuits

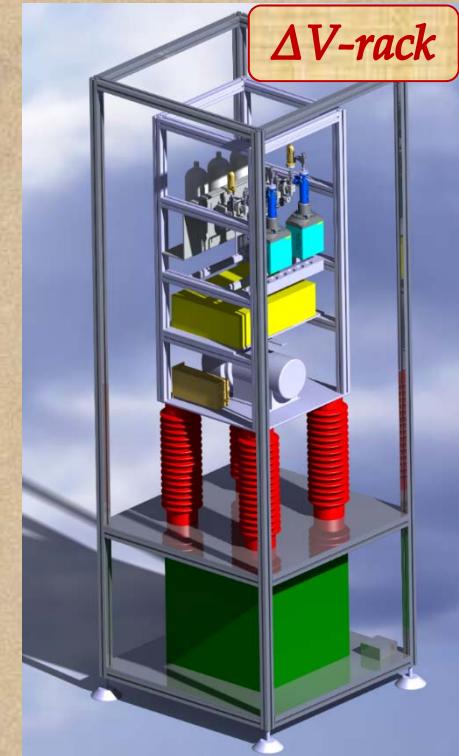
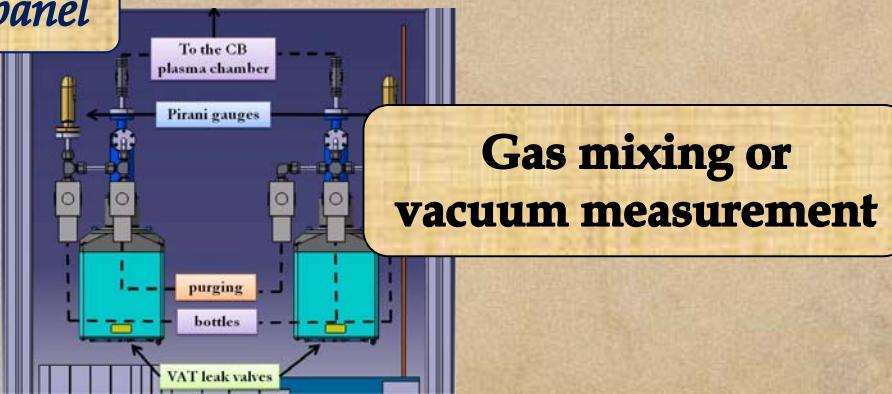


Both frequency tuning  
and TFH will be explored

# $\Delta V$ -rack e gas panel

- Injecction energy optimization
- Complete gas panel with purging pum
- Very precise leak valves
- Fully remotely controlled

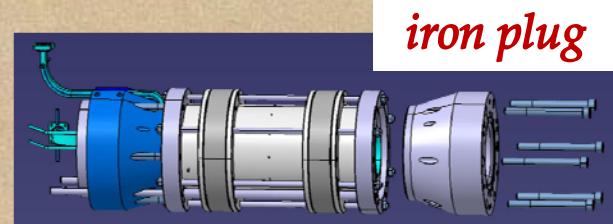
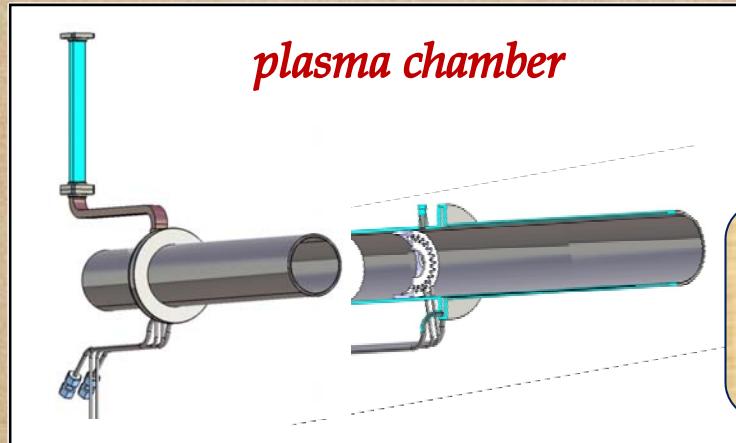
*Gas panel*



# Cleanliness

- Treatments on extraction iron plug
- Treatments on plasma chamber
- Almost all metal sealings

*Reduction of contaminants*

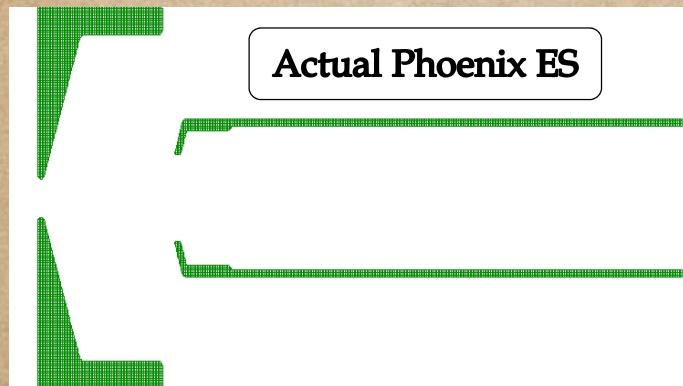
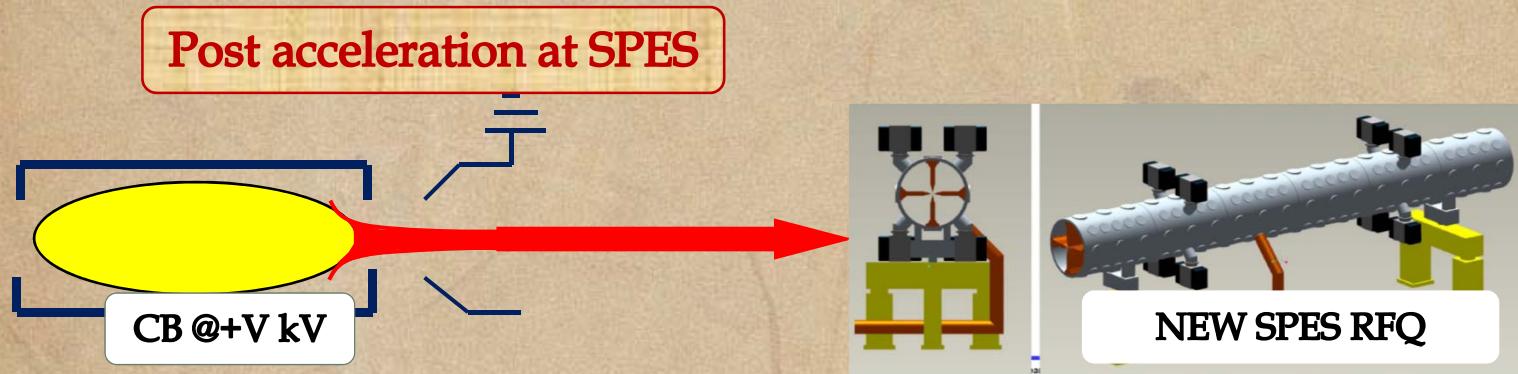


Normalizing  
Final Annealing  
Better magnetic permeability

*Thanks to C. Roncolato*

2 heat treatments during machining  
Limit outgassing  
Risks of deformations: AISI 316 LN

# The extraction system



*Good beam quality, not enough flexible*

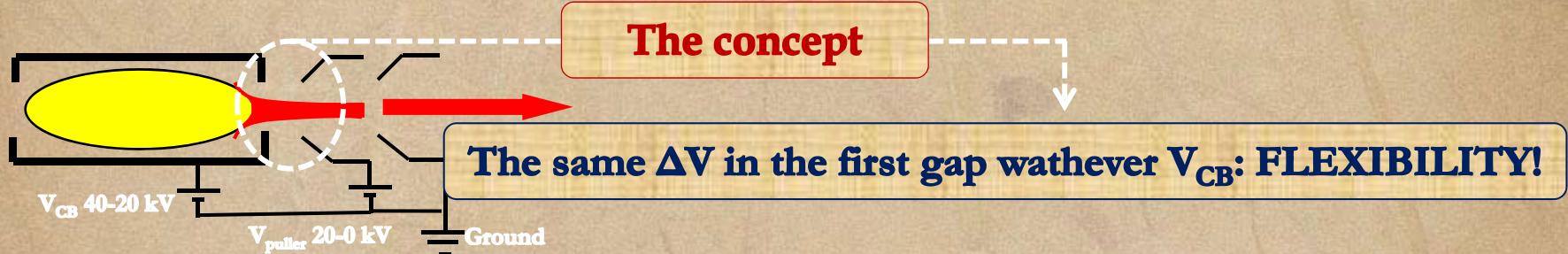
RFQ: fixed  $v$

CB: variable  $A/q$

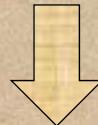
Variable CB extraction voltage  
( $V=20\text{--}40\text{ kV}$ )

SPES req.:  $\epsilon_{norm, rms} < 0.1 \pi^* \text{mm}^* \text{mrad}$

# The extraction system

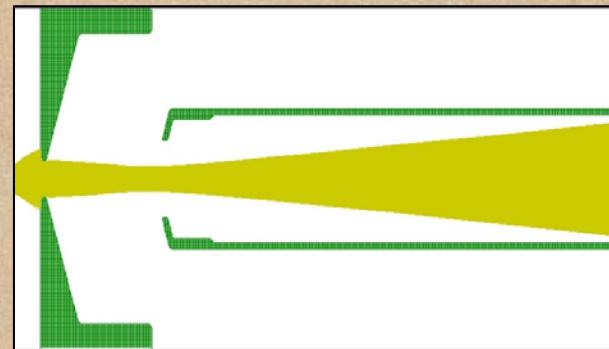


**Optimization of the extraction system: by numerical simulations**



- 3D Geometry with potentials
- Boundary conditions
- 3D magnetic map
- $V_p$  (20V)
- $KT_e$  (10 eV)
- Ions initial pos and v ( $KT_i$  0.5 eV; Bohm criterion)

*First step: validation of starting conditions!*



*Possible losses!*

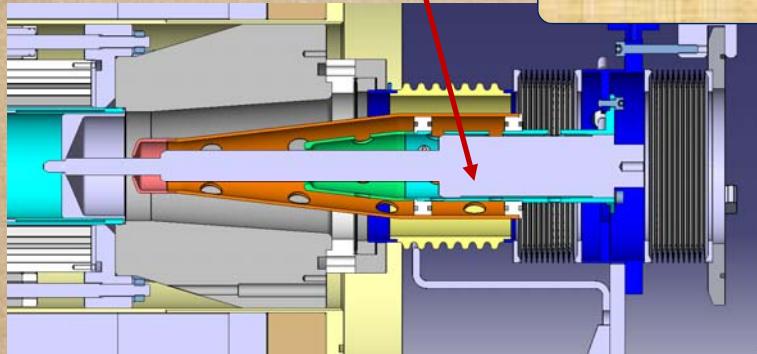
$\epsilon_{\text{norm, rms}}$ [ $\pi^* \text{mm}^* \text{mrad}$ ]	
Measured	Simulated
0.0486	0.0532

*Good agreement*

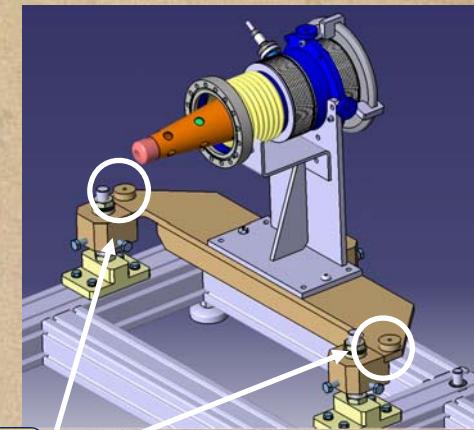
# The new extraction system

*LPSC design optimized by numerical simulation*

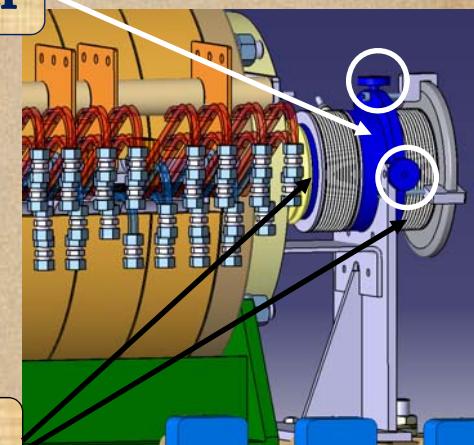
**Special tool for electrodes alignment**



**Possibility to align by laser**



**Two bellows for independent regulation**

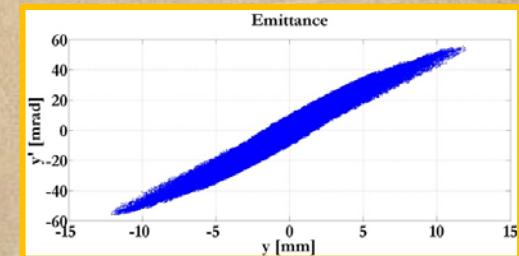
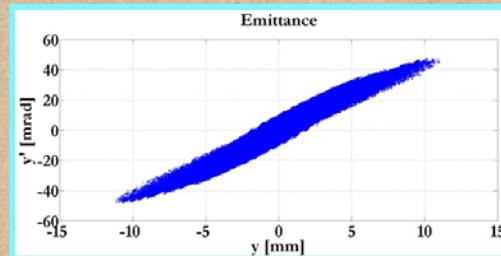
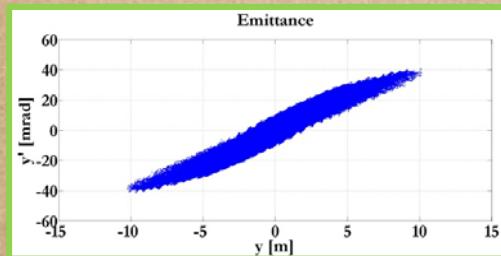
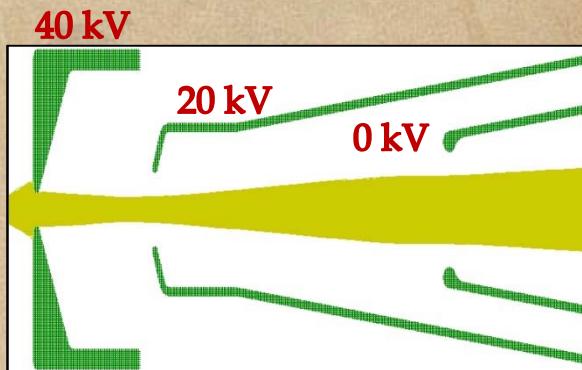


# The new extraction system

Emittance verified in  
different configurations



Setting	$\epsilon_{\text{norm, rms}}$
40-20 [kV]	0.0449
34-14 [kV]	0.0448
28-8 [kV]	0.0449



Desired flexibility obtained

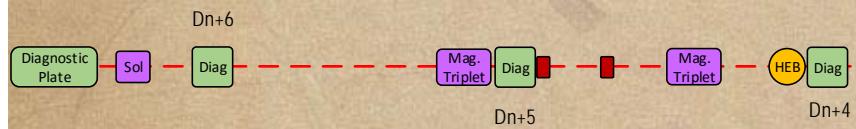
# SPES-CB beamline

## Main Elements:

- Stable Beam Source
- Chopper
- Charge Breeder
- MRMS
- Buncher
- Diagnostic Plate

## Magnetic Elements:

- 1+ Selector Dipole
- Solenoids (x3)
- MRMS Dipole (x2)
- Triplets (x6)
- Steerers (x10)

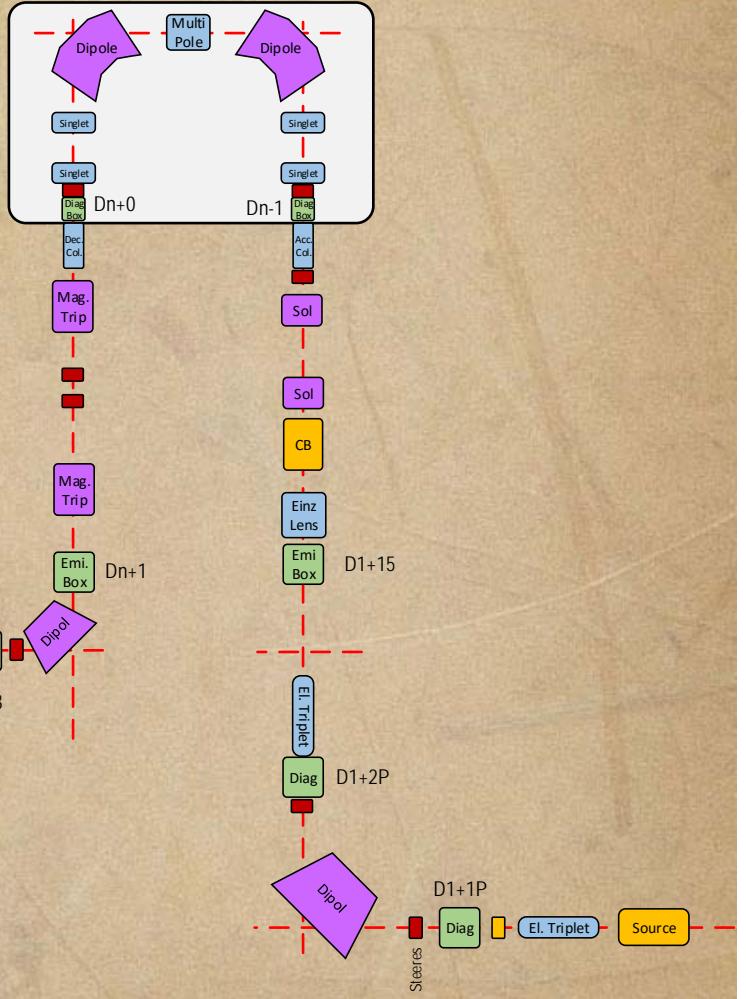


## Diagnostic Elements:

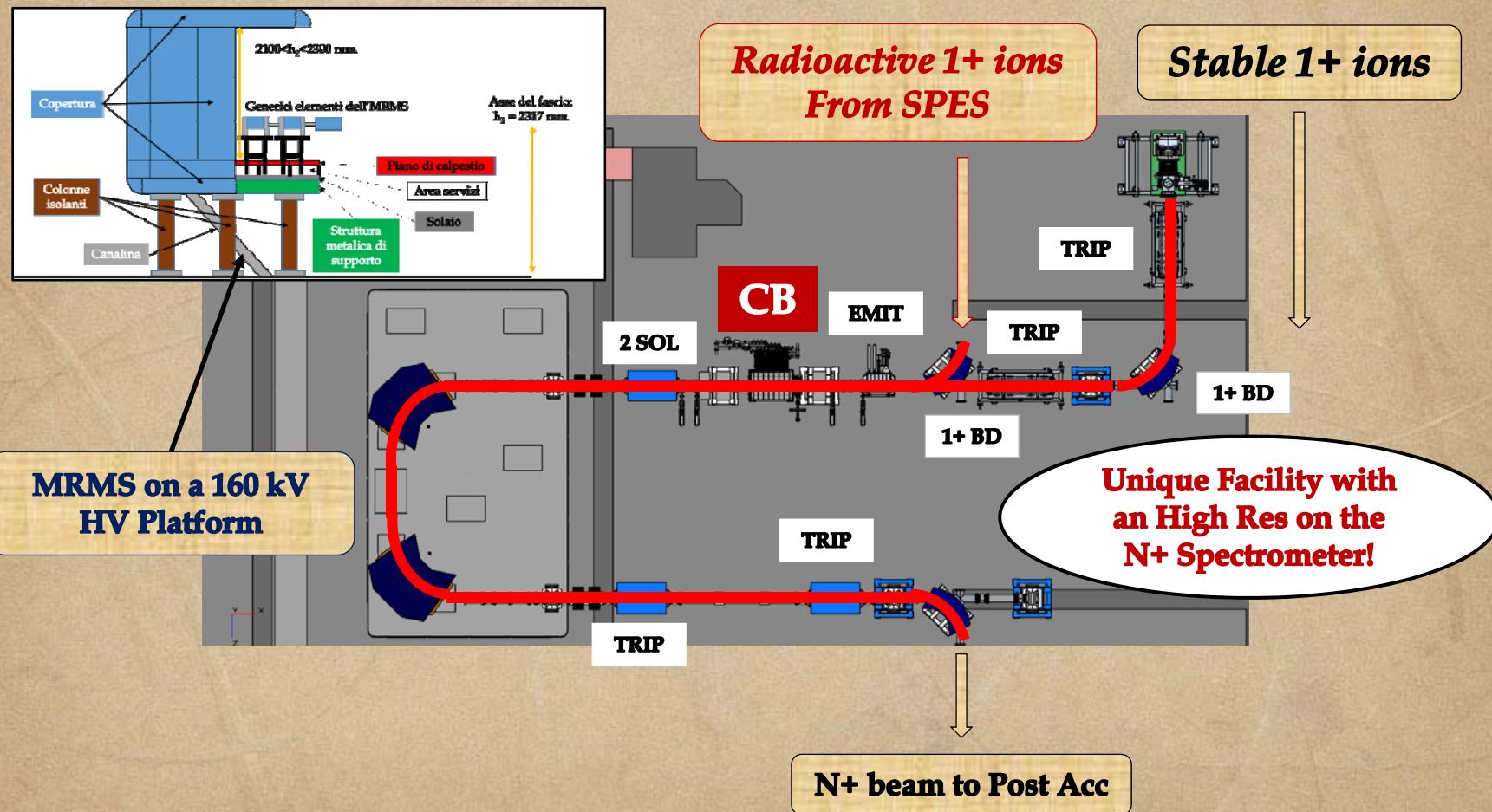
- Diagnostic Boxes (x6)
- Emittance Boxes (x2)
- Slits Boxes

## Electrostatic Elements:

- Triplets (x2)
- Einzel Lens
- Singolets (x2)
- Multipoles



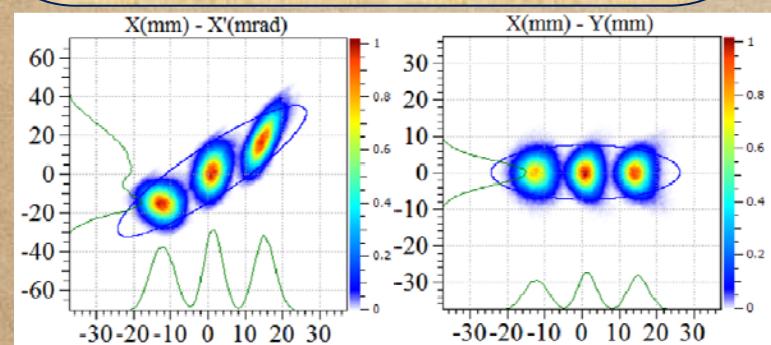
# The SPES-CB beamline



# The MRMS

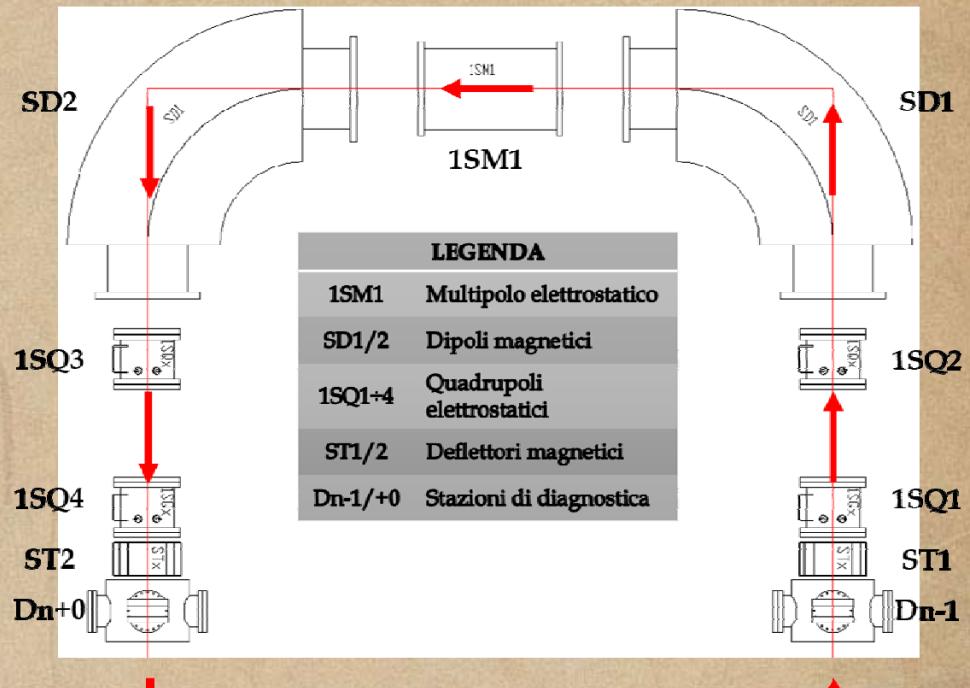
## Dipoles:

- $R=750$  mm
- $\Phi=90^\circ$
- Edge=33.35 °
- $B=0.2$  T
- Gap= $\pm 35$  mm
- $R_{\text{sex}}=1474$  and 828 mm
- Field homogeneity  $10^{-4}$   
( $\pm 180$  mm hor,  $\pm 35$  mm ver)



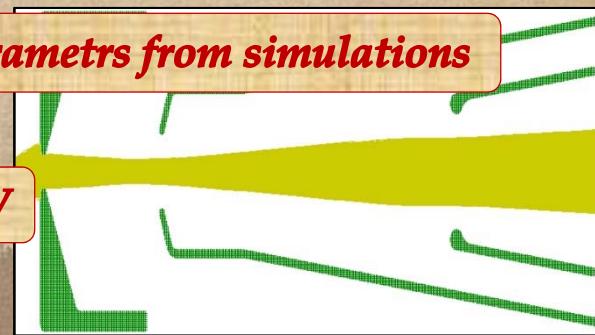
Thanks to L. Bellan

$$\epsilon_{\text{norm, rms}} = 0.1 \pi^* \text{mm} * \text{mrad}, \Delta E = 15 \text{ eV}$$



Beam direction

*Twiss parameters from simulations*



# Acceptance Tests

# SPES-CB Requirements

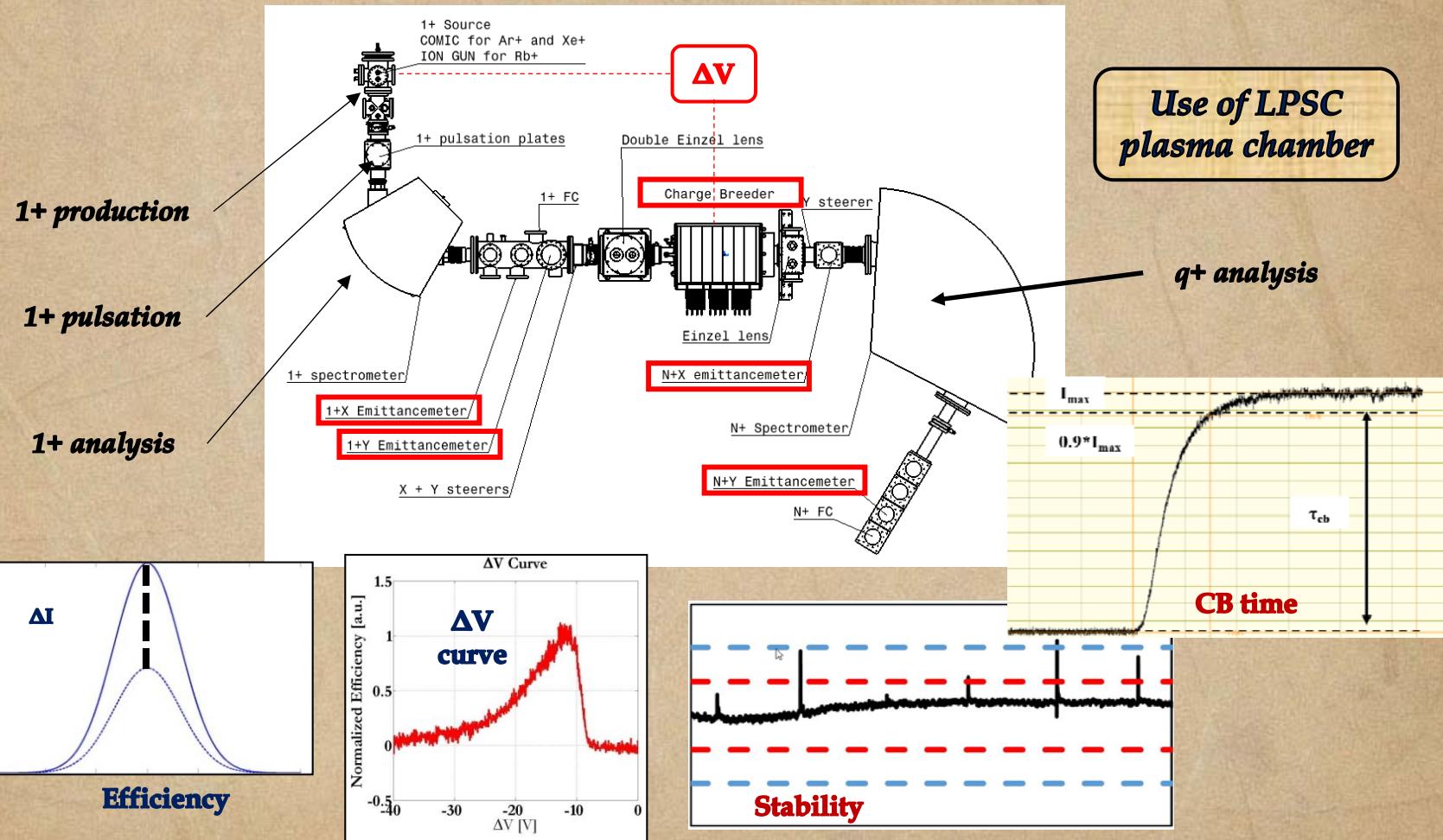
- **Efficiency**
- **Charge Breeding Time**  $\tau_{CB} \leq 15\text{ms} * q$
- **Emittance:**  $\epsilon_{norm,rms} < 0.1 * \pi * \text{mm} * \text{mrad}$
- **Stability**

- ✓ Higher than 5% for condensable (**Rb**) with  $A/q < 7$ ;
- ✓ Higher than 10% for gaseous (**Ar, Xe**) with  $A/q < 7$ ;
- ✓ Two injected intensities: 0.5 and 1  $\mu\text{A}$

*To be verified on the  
LPSC test bench*

- ✓ Within  $\pm 5\%$  from the reference value for the  $1^+$  beam
- ✓ Within  $\pm 5\%$  from the reference value for the charge breeder itself
- ✓ Overall stability within  $\pm 10\%$

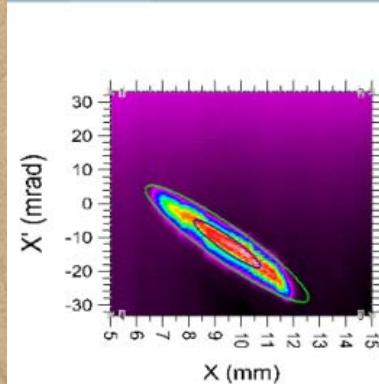
# Acceptance tests at LPSC



# Acc. tests: Ar<sup>1+</sup> → Ar<sup>8+</sup>

## 1+ beam:

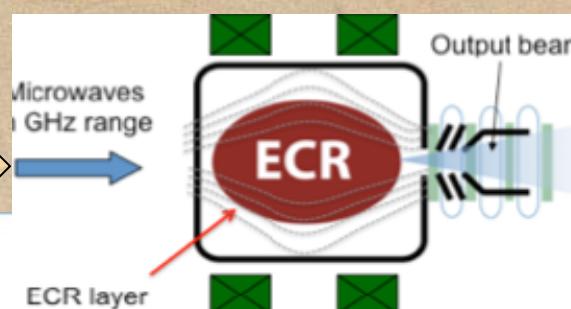
- ✓  $\varepsilon_{\text{norm,rms}} = 0.034 \pi \text{mm}^2 \text{mrad}$
- ✓ 1.2  $\mu\text{A}$  of Ar<sup>1+</sup>
- ✓  $V_{\text{ext}} = 20 \text{ kV}$
- ✓  $E_1/E_2 = 11.3/7 \text{ kV}$



COMIC

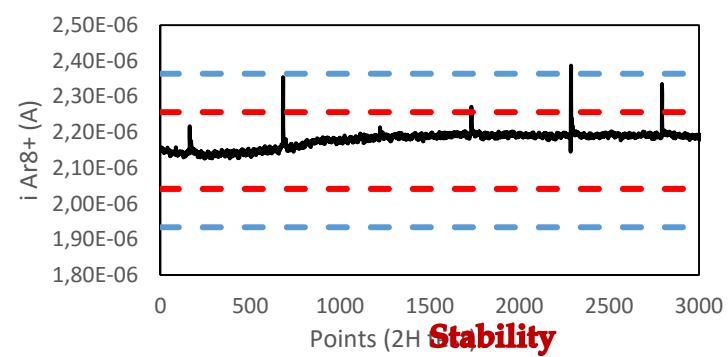
## Charge Breeder:

- ✓  $\Delta V = 45 \text{ V}$
- ✓ Coils: 1160/242/622 A
- ✓  $P = 200 \text{ W}$



Thanks to J. Angot

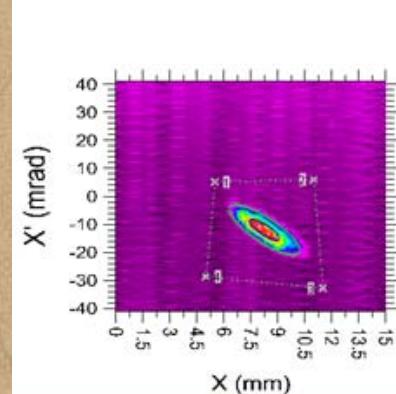
	Req	Exp
Efficiency [%]	>10	15
Emittance	<0.1	full 0.04 Ar <sup>8+</sup> 0.03
CB time [ms*q]	≤ 15	10
Global capture	-	> 60% (no 1+)



# Acc. tests: $Xe^{1+} \rightarrow Xe^{20+}$ (I)

## 1+ beam:

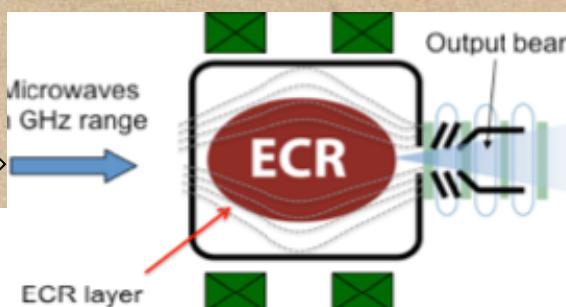
- ✓  $\epsilon_{\text{norm,rms}} < 0.01 * \pi * \text{mm} * \text{mrad}$
- ✓ 0.5  $\mu\text{A}$  of  $Xe^{1+}$
- ✓  $V_{\text{ext}} = 16.1 \text{ kV}$
- ✓  $E_1/E_2 = 9.6/6 \text{ kV}$



*COMIC*

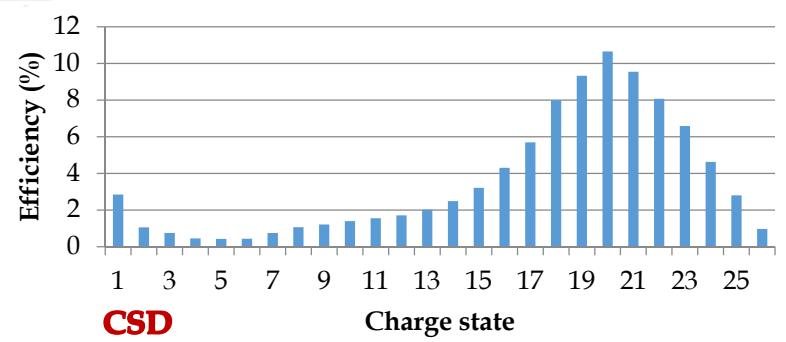
## Charge Breeder:

- ✓  $\Delta V = -27 \text{ V}$
- ✓ Coils: 1158/165/740 A
- ✓  $P = 330 \text{ W}$



*Thanks to J. Angot*

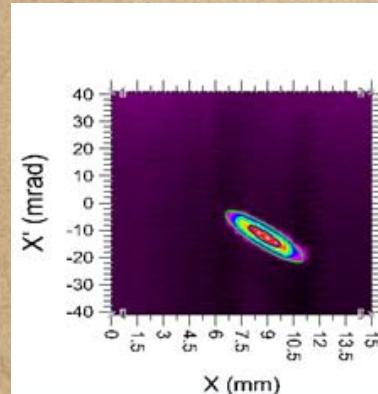
	Req	Exp
Efficiency [%]	>10	11.2
Emittance	<0.1	full 0.03 $Xe^{20+}$ 0.01
CB time [ms*q]	$\leq 15$	17
Global capture	-	$\sim 90\%$ (no 1+)



# Acc. tests: Xe<sup>1+</sup> → Xe<sup>20+</sup> (II)

## 1+ beam:

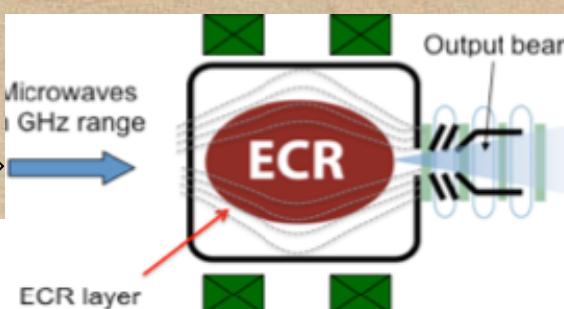
- ✓  $\epsilon_{\text{norm,rms}} < 0.01 \pi \text{ mm}^2 \text{ mrad}$
- ✓ 0.9  $\mu\text{A}$  of Xe<sup>1+</sup>
- ✓  $V_{\text{ext}} = 16.1 \text{ kV}$
- ✓  $E_1/E_2 = 9.6/6 \text{ kV}$



*COMIC*

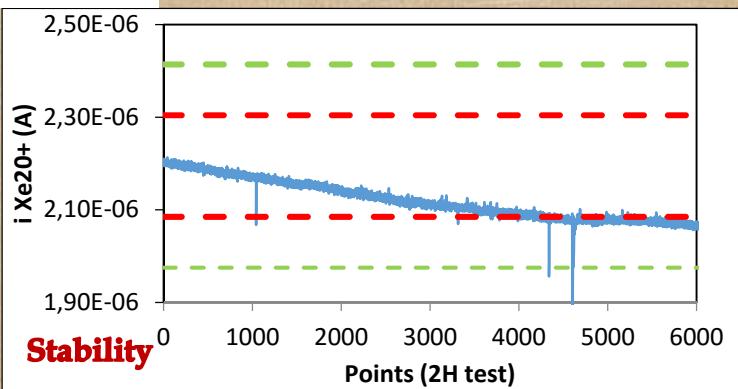
## Charge Breeder:

- ✓  $\Delta V = -27 \text{ V}$
- ✓ Coils: 1158/165/677 A
- ✓  $P = 330 \text{ W}$



*Thanks to J. Angot*

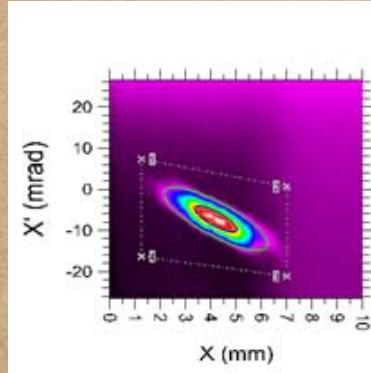
	Req	Exp
Efficiency [%]	>10	10.5
Emittance	<0.1	full 0.03 Xe <sup>20+</sup> 0.02
CB time [ms*q]	≤ 15	15
Global capture	-	> 90% (no 1+)



# Acc. tests: Rb<sup>1+</sup> → Rb<sup>19+</sup> (I)

## 1+ beam:

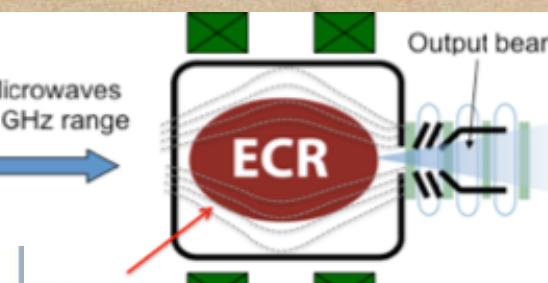
- ✓  $\epsilon_{\text{norm,rms}} = 0.01 \pi \text{ mm}^2 \text{ mrad}$
- ✓ 0.96  $\mu\text{A}$  of Xe<sup>1+</sup>
- ✓  $V_{\text{ext}} = 20 \text{ kV}$
- ✓  $E_1/E_2 = 10.25/11 \text{ kV}$



*HeatWave Labs*

## Charge Breeder:

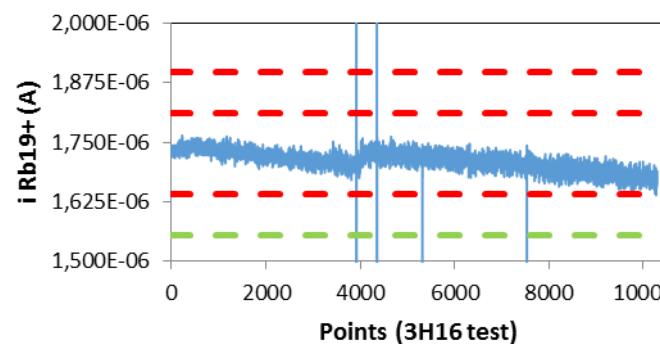
- ✓  $\Delta V = 7.3 \text{ V}$
- ✓ Coils: 1160/256/750 A
- ✓  $P = 487 \text{ W}$



> 3h Stability

*Thanks to J. Angot*

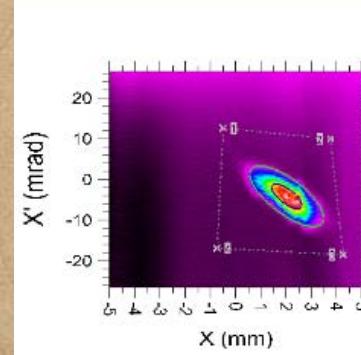
	Req	Exp
Efficiency [%]	>10	7.8
Emittance	<0.1	full 0.04 Rb <sup>19+</sup> 0.02
CB time [ms*q]	≤ 15	28
Global capture	-	> 50%



# Acc. tests: Rb<sup>1+</sup> → Rb<sup>19+</sup> (II)

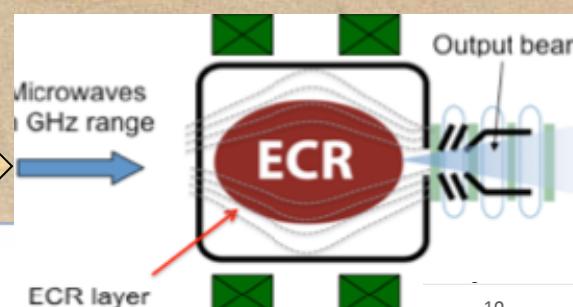
## 1+ beam:

- ✓  $\epsilon_{\text{norm,rms}} < 0.008 \pi \text{mm}^2 \text{mrad}$
- ✓ 0.5  $\mu\text{A}$  of Xe<sup>1+</sup>
- ✓  $V_{\text{ext}} = 20 \text{ kV}$
- ✓  $E_1/E_2 = 10.3/11.5 \text{ kV}$



## Charge Breeder:

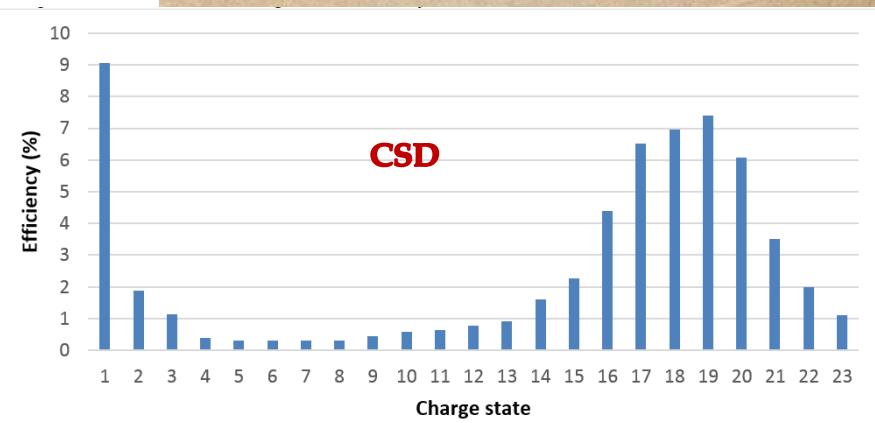
- ✓  $\Delta V = -6.7 \text{ V}$
- ✓ Coils: 1156/259/750 A
- ✓  $P = 425 \text{ W}$



Thanks to J. Angot

	Req	Exp
Efficiency [%]	>10	7.8
Emittance	<0.1	full 0.04 Rb <sup>19+</sup> 0.01
CB time [ms*q]	≤ 15	28.5
Global capture	-	50 %

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# Frequency tuning with Cs

## 1+ beam:

- ✓  $\varepsilon_{\text{norm,rms}} = 0.0011 \pi \text{mm}^2 \text{mrad}$
- ✓ 0.27  $\mu\text{A}$  of  $\text{Cs}^{1+}$
- ✓  $V_{\text{ext}} = 15.5 \text{kV}$
- ✓  $E_1/E_2 = 7/10 \text{kV}$

## Charge Breeder:

- ✓  $\Delta V = -4.3 \text{ V}$
- ✓ Coils: 1180/268/760 A
- ✓  $P = 415 \text{ W}$

**f= 14.521**

- ✓ Full beam:  $\varepsilon_{\text{norm,rms}} = 0.04 \pi \text{mm}^2 \text{mrad}$  (96%); GC **61%**
- ✓  $\text{Cs}^{26+}$ : **10.2%**;  $\varepsilon_{\text{norm,rms}} \sim 0.01 \pi \text{mm}^2 \text{mrad}$  (96%);  $\tau_{\text{CB}} = 541 \text{ ms} \sim 21 \text{ ms} * q$

## 1+ beam:

- ✓  $\varepsilon_{\text{norm,rms}} = 0.01 \pi \text{mm}^2 \text{mrad}$
- ✓ 0.96  $\mu\text{A}$  of  $\text{Xe}^{1+}$
- ✓  $V_{\text{ext}} = 20 \text{kV}$
- ✓  $E_1/E_2 = 10.25/11 \text{kV}$

## Charge Breeder:

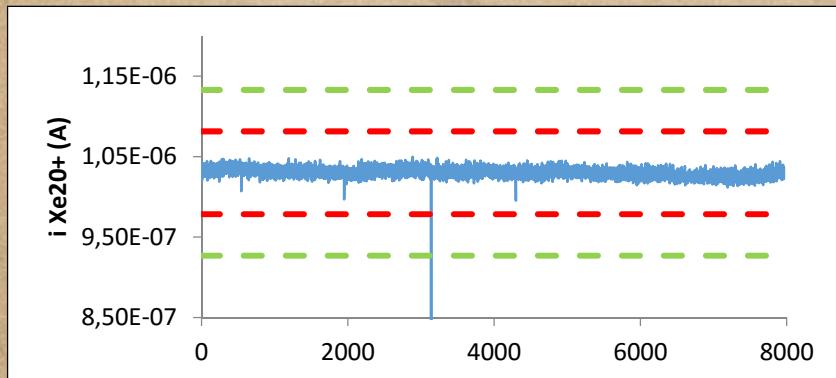
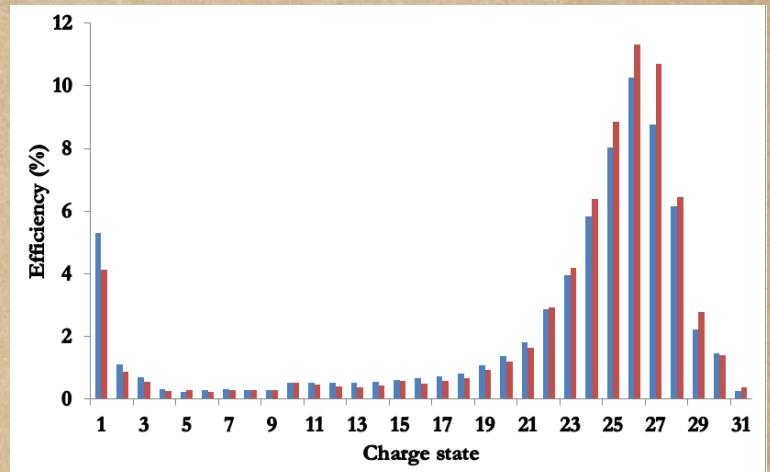
- ✓  $\Delta V = -7.3 \text{ V}$
- ✓ Coils: 1160/256/750 A
- ✓  $P = 487 \text{ W}$

**f= 14.324**

- ✓ Full beam:  $\varepsilon_{\text{norm,rms}} = 0.044 \pi \text{mm}^2 \text{mrad}$  (96%); GC **65%**
- ✓  $\text{Cs}^{26+}$ : **11.3%**;  $\varepsilon_{\text{norm,rms}} \sim 0.02 \pi \text{mm}^2 \text{mrad}$  (96%);  $\tau_{\text{CB}} = 460 \text{ ms} \sim 18 \text{ ms} * q$

# Frequency tuning with Cs

*The effect of the frequency is evident*



*Excellent long term stability*

# Acceptance tests: remarks

- Requirements fulfilled without any problem.
- «Best ever» for almost all beams.
- Very low emittance of the **n+** beam.
- Good stability.
- Very low emittance of the 1+ beam **injected**
- **Injection optic is critical.**
- **UHV base vacuum** and **precise gas** regulation are **mandatory**.
- $\tau_{CB}$  changes by changing the tuning parameters.
- **Frequency tuning is effective.**

		Efficiency* [%]		
Ion	M/q	SPES req	Best LPSC	SPES-CB
Cs <sup>26+</sup>	5.1	> 5	8.6	11.3
Xe <sup>20+</sup>	6.6	> 10	10.5	11.2
Rb <sup>19+</sup>	4.5	> 5	6.5	7.8
Ar <sup>8+</sup>	5	> 10	16.2	15.2

\*results obtained for the same 1+ injected current

All issues considered  
for the SPES-CB

An intense  
experimental activity  
will be necessary



# Conclusions

- The SPES-CB has been built following LNL specs
- Flexibility and purity have been addressed
- Confidence on good results with the MRMS
- Promising results from acc. Tests
- Installation in late 2016, beginning 2017

# Thank you for your attention