DE LA RECHERCHE À L'INDUSTRIE

LIGHT ION ECR SOURCES STATE OF THE ART FOR LINACS

LINAC2012

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www.cea.fr

OUTLINE

General assessments on light ion ECR sources

- General principle
- Several key points
- Pulsed beam and Space charge compensation

Worldwide overview

CEA involvement on IFMIF, Spiral 2 and FAIR projects

NUMEROUS HPPA-LIKE PROJECTS AROUND THE WORD

Negative ion HPPA are not listed in this table

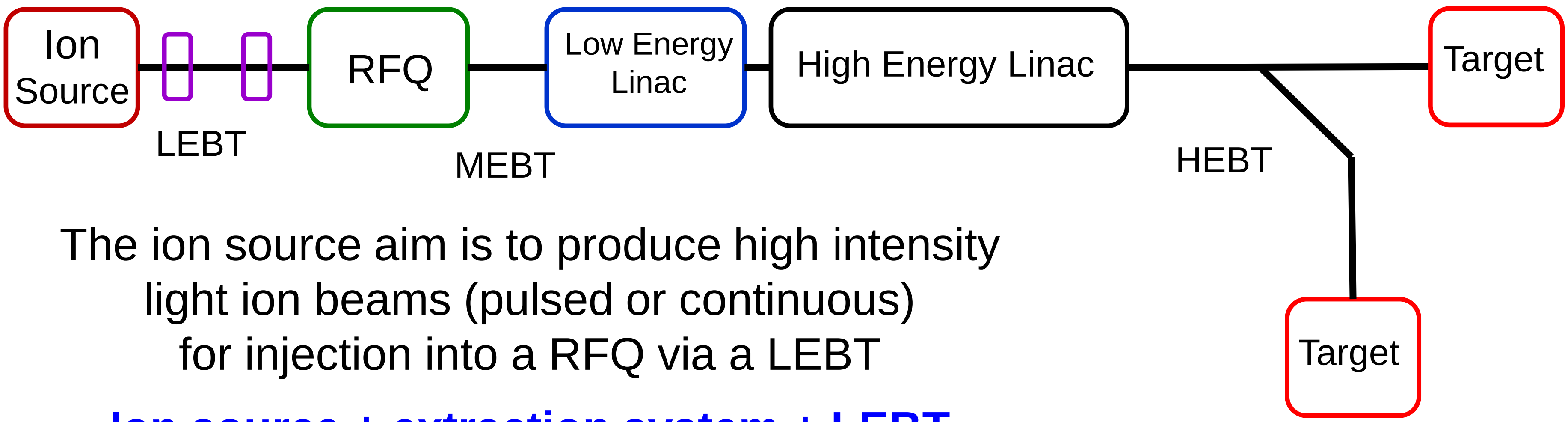
	Particles	Intensity	Pulse length	Repetition	Duty Factor	Emittance
	p/d/H^-	mA	ms	Hz	%	π mm.mad
LEDA	H^+	100	CW	-	100	0.25
IPHI*	H^+	100	CW	-	100	0.25
TRASCO	H^+	30	CW	-	100	0.2
SARAF	H^+, D^+	2	CW	-	100	0.2
IFMIF*	D^+	140	CW	-	100	0.25
Spiral2*	H^+, D^+	5	CW	-	100	0.25
PEFP	H^+	20	2		8-20	
MYRRHA	H^+	10/25	CW	-	100	0.25
Chinese ADS	H^+	10	CW	-	100	
FAIR*	H^+	100	1	4	0.4	0.3
ImPUF	H^+, D^+	5	CW	-	100	
ESS	H^+	60/90	2.9	14	4	0.3
RISP	H_2^+, D^+	1 - 5				

One of the main requests, especially for ADS is the reliability

↳ **ECR ion sources (no filament, no antenna)**

HIGH INTENSITY SOURCES

Schematic drawing of an HPPA



The ion source aim is to produce high intensity light ion beams (pulsed or continuous) for injection into a RFQ via a LEBT

Ion source + extraction system + LEBT have to be considered as a whole.

(S. Gammino at ICIS 2009)

In the 90's, CEA started the IPHI project with the SILHI source.

Goal : > 100 mA H+

and is now involved in several projects: IFMIF, SPIRAL2, FAIR, ESS, LINAC 4

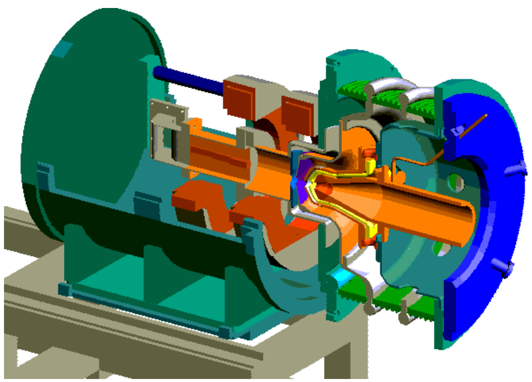
GENERAL PRINCIPLE OF THE SOURCE

ECR Source ➔ Resonance zone if $\omega = e\,B / m$

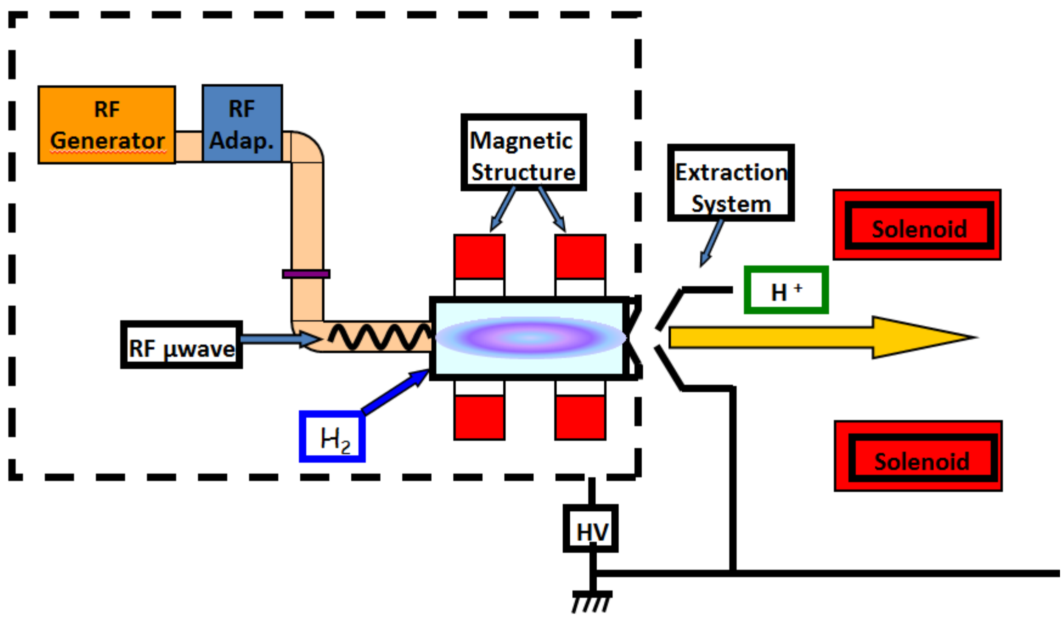
2.45 GHz ➔ 875 Gauss

ω, pulsation
e, electron charge
B, magnetic field
m, electron mass

Magnetic field provided by coils or permanent magnets
Multi-electrode extraction system



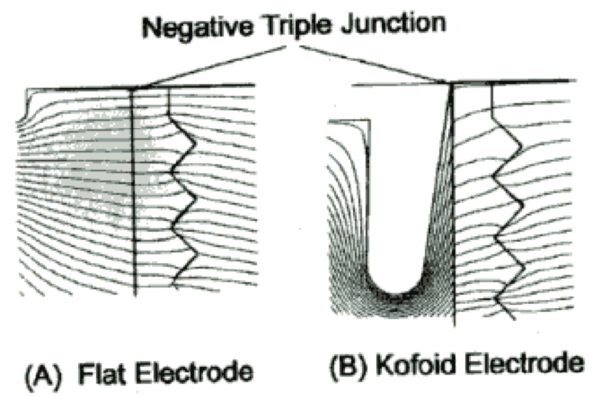

SILHI source at CEA/Saclay

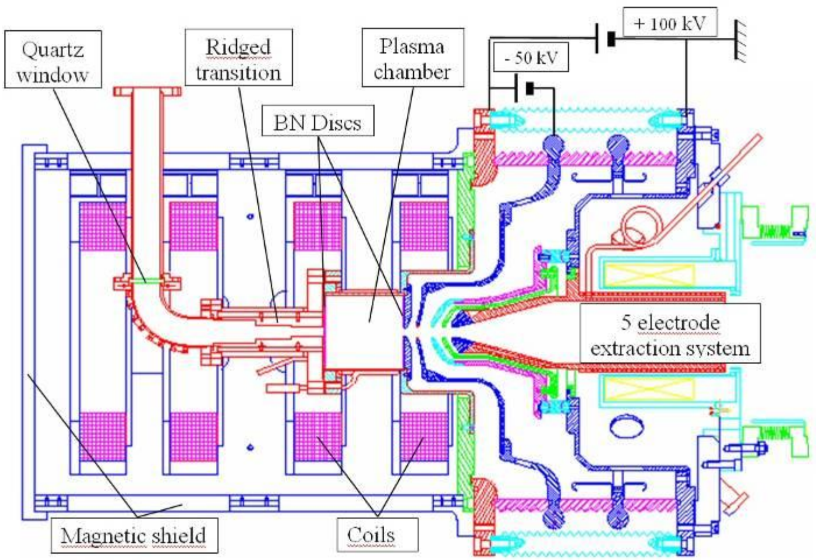


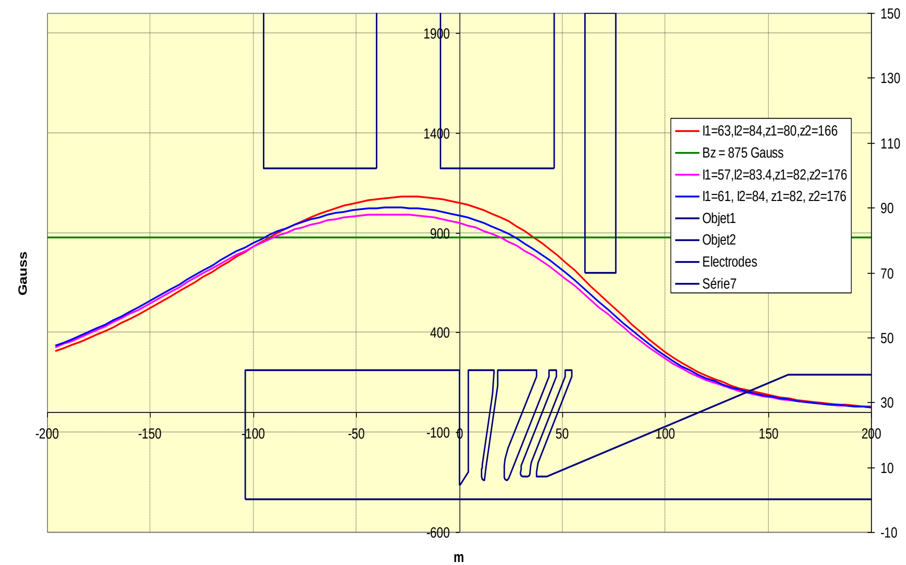
Several key points (1)

Protection of the window
Electron repeller
Ridged or tapered transition on RF chain
Ceramic disks to improve electron density
Resonance value at plasma chamber entrance
Negative Triple junction shielding

J. Sherman, RSI 69, 1998







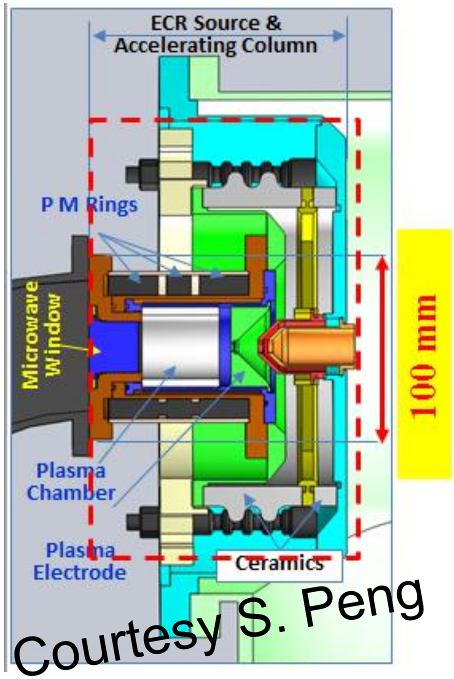
SILHI source at Saclay

Several key points (2)

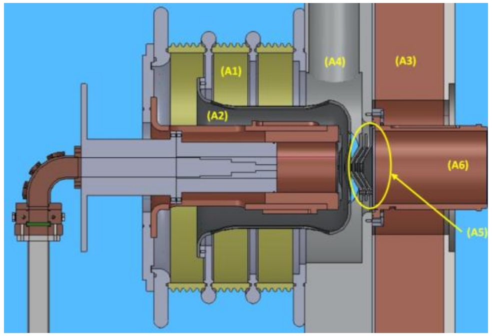
How to limit the emittance growth?

Reduce LEBT length
Small amount of heavy gas in LEBT can improve SCC

In PKU source and accel column are located into the vacuum chamber just in front of Sol1.



Courtesy S. Peng



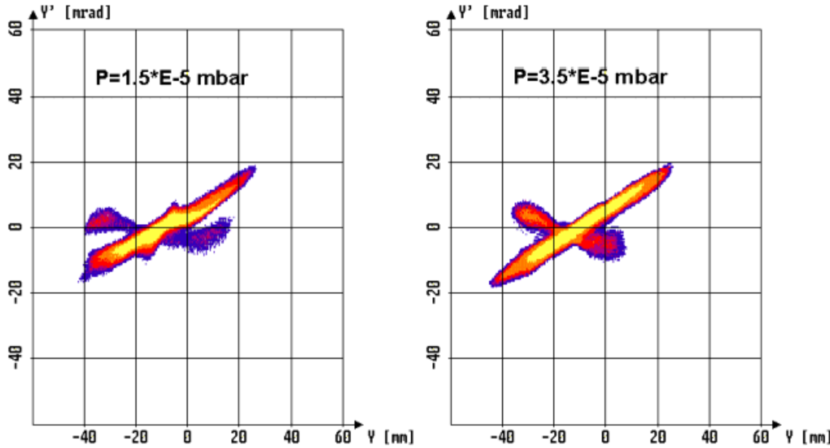
At Saclay, ALISES source developments

When HI beam interacts with residual gas, SCC occurs :

$$H^+ + H_2 \rightarrow H^+ + H_2^+ + e^-$$

Generally, electrons are confined in the beam and secondary ions are repelled towards the walls.

Space charge can reach close to 100 % but non-linearity exists (magnets, chamber size) and SCC can dramatically change.

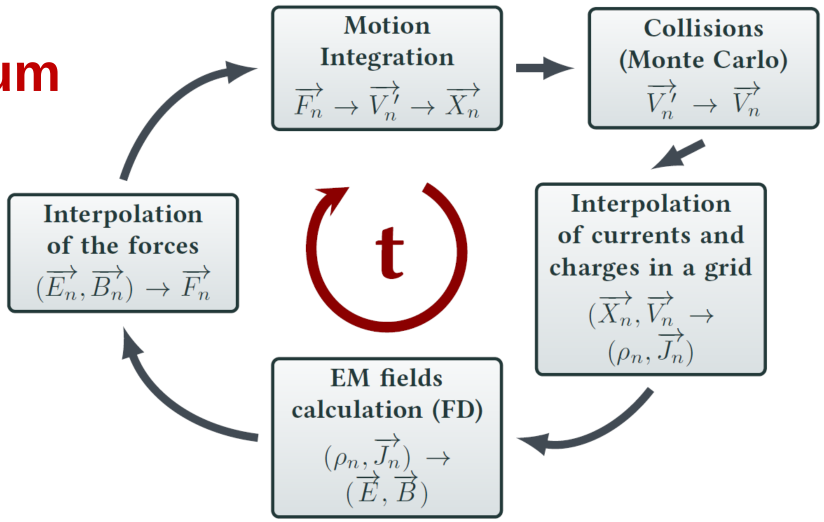


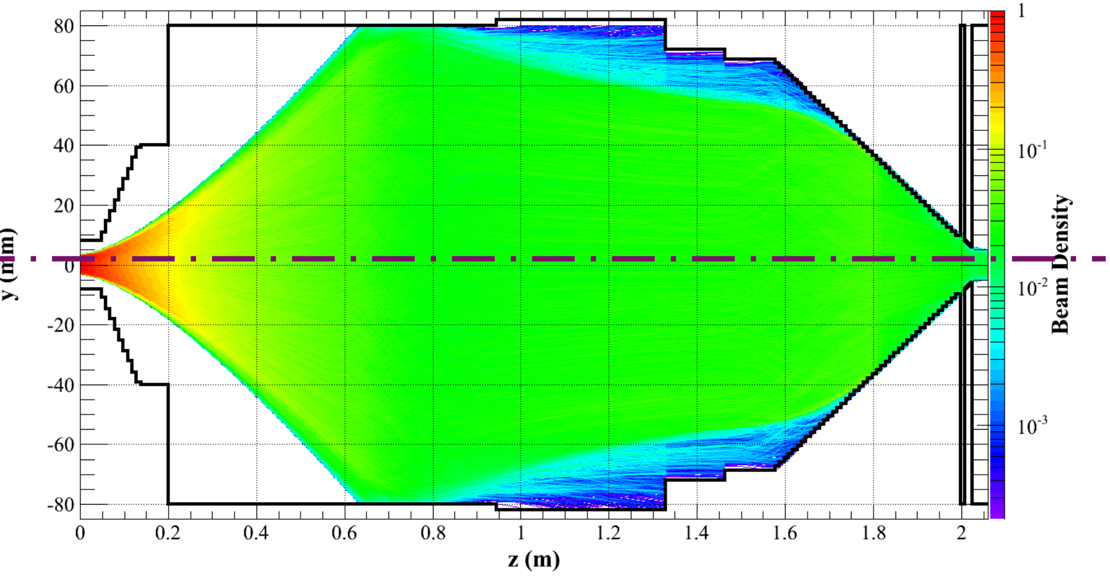
R. Hollinger, Linac2006, TU3001

Pulsed beam and Space Charge Compensation

Time is needed to reach SCC equilibrium

Dedicated code **SOLMAXP**
(R. Duperrier et al.)
has been developed at Saclay
to take into account
the space charge compensation
evolution





t = 2 µs

Pulsed beam and Space Charge Compensation

Time is needed to reach SCC equilibrium

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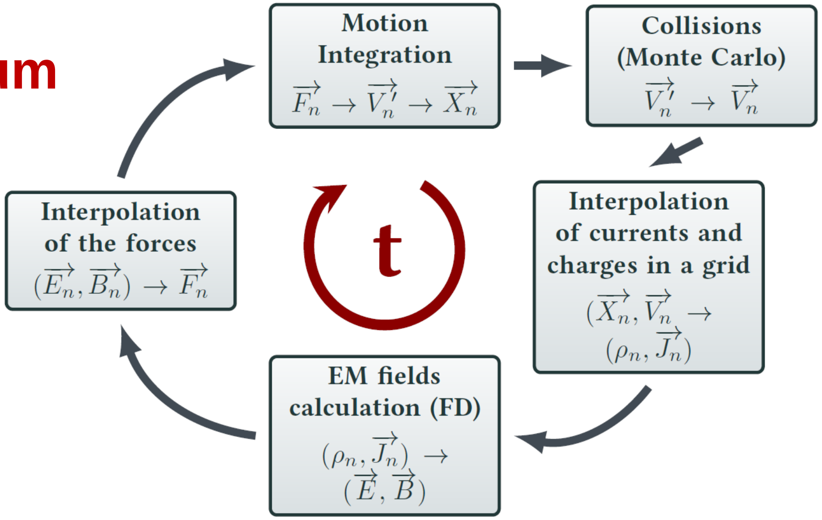

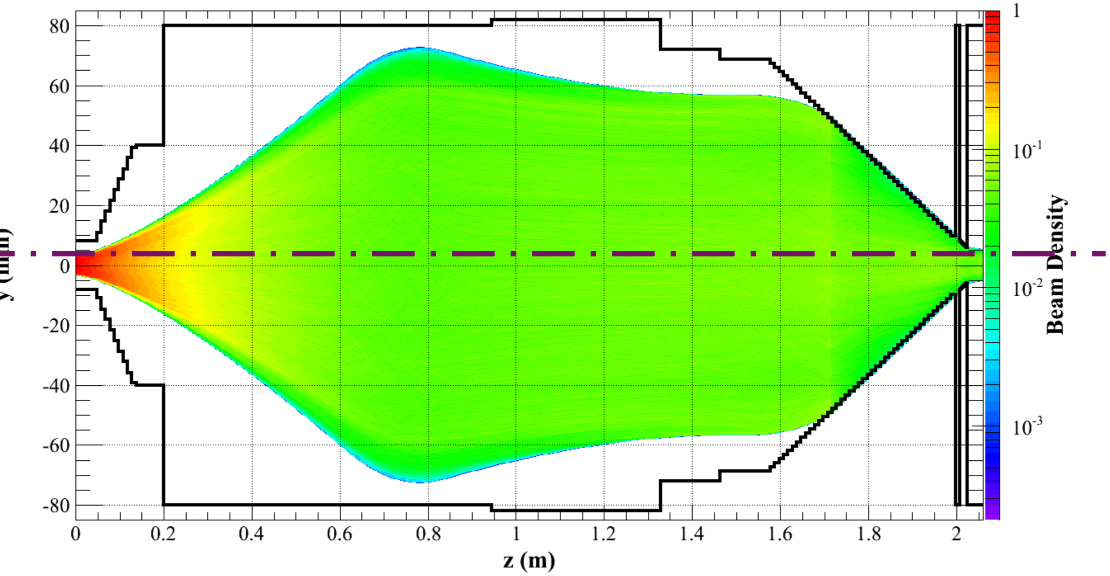

t = 4 µs

Pulsed beam and Space Charge Compensation

Time is needed to reach SCC equilibrium

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(R. Duperrier et al.)
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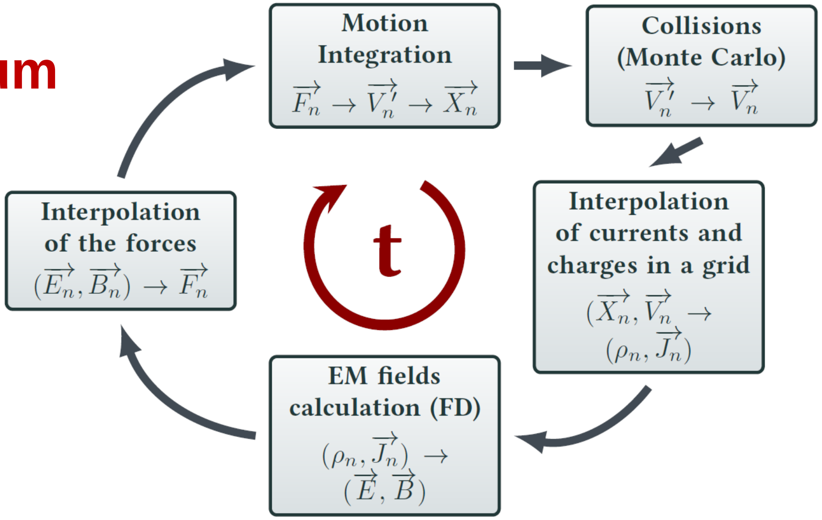

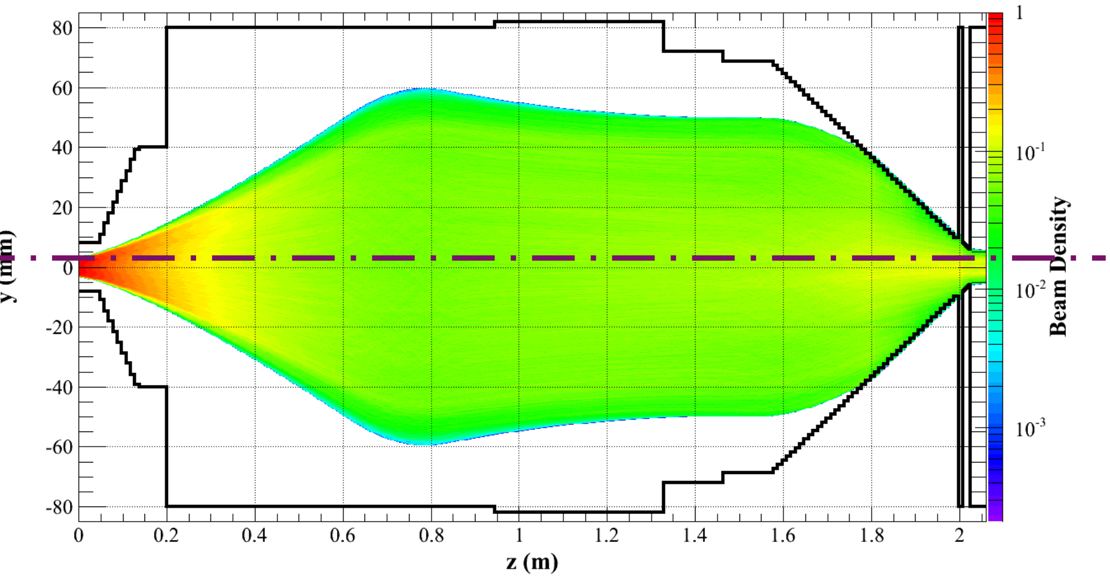

t = 6 µs

Pulsed beam and Space Charge Compensation

Time is needed to reach SCC equilibrium

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(R. Duperrier et al.)
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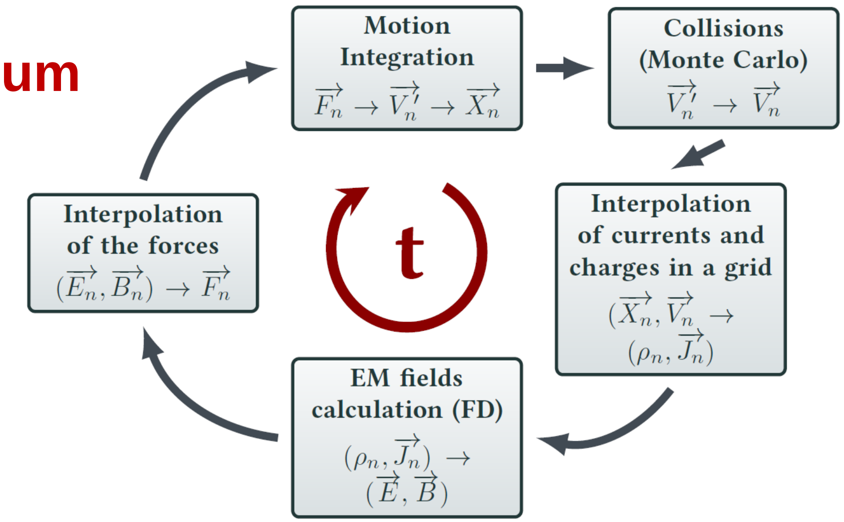
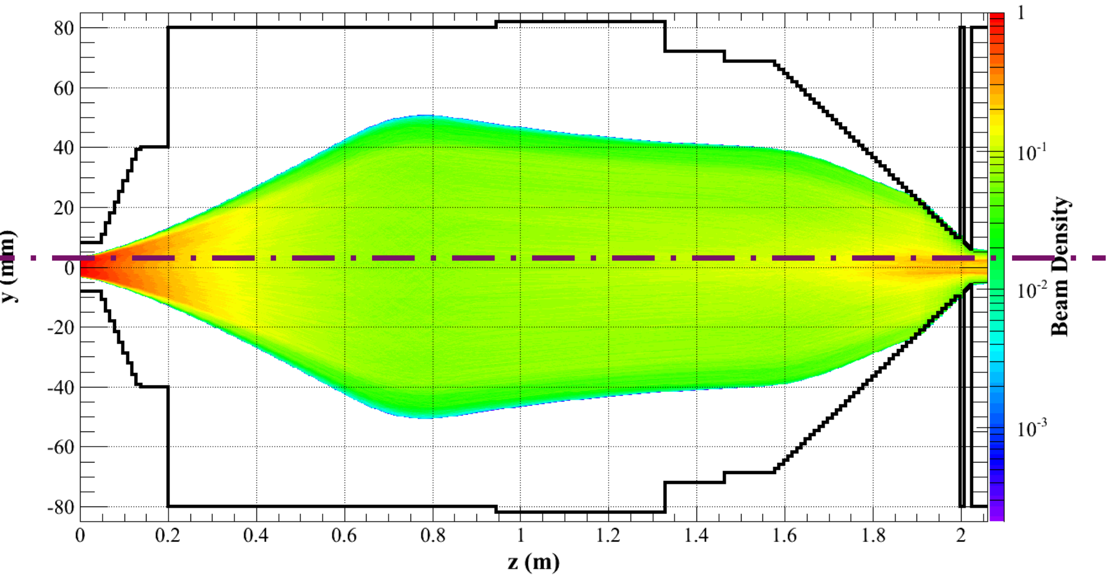
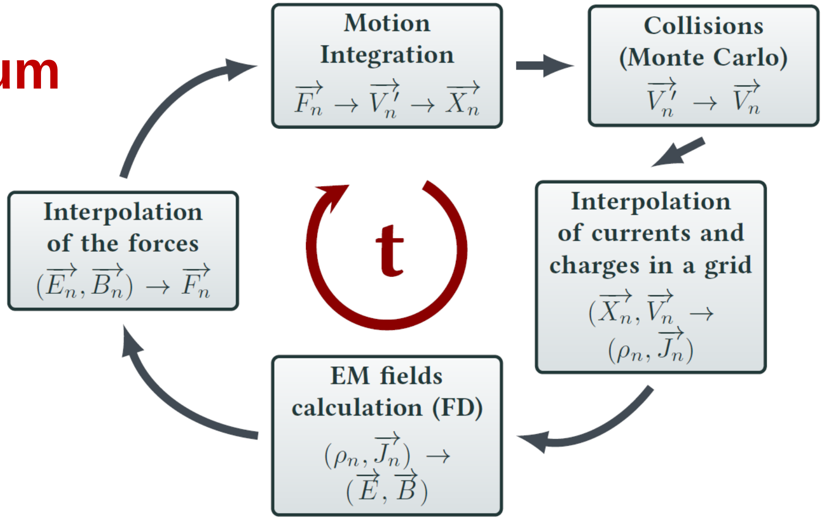




t = 8 µs

Pulsed beam and Space Charge Compensation

Time is needed to reach SCC equilibrium



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(R. Duperrier et al.)
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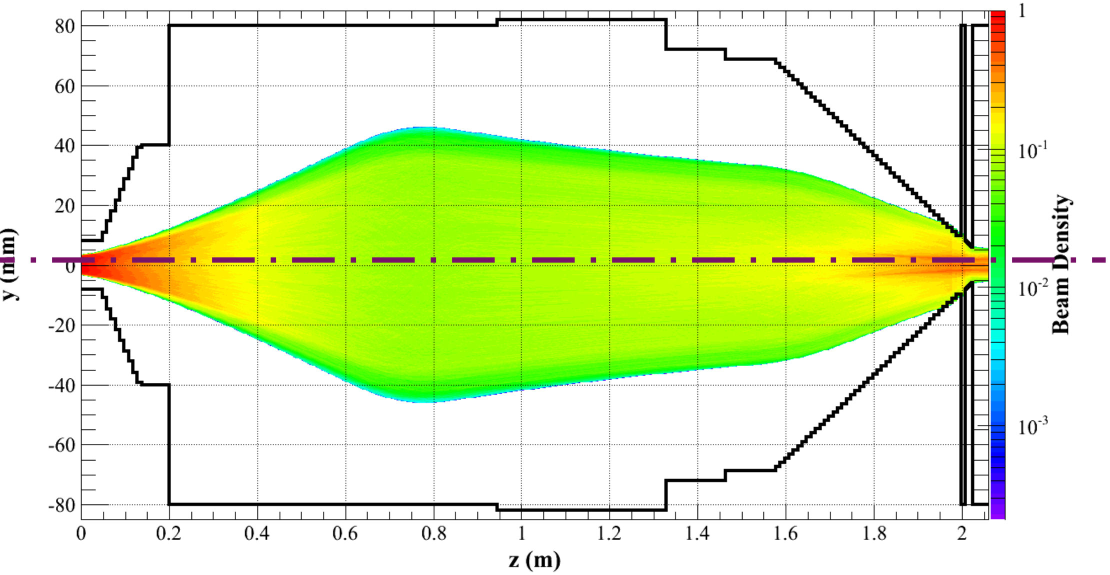

t = 10 µs

Pulsed beam and Space Charge Compensation

Time is needed to reach SCC equilibrium

Dedicated code **SOLMAXP**
(R. Duperrier et al.)
has been developed at Saclay
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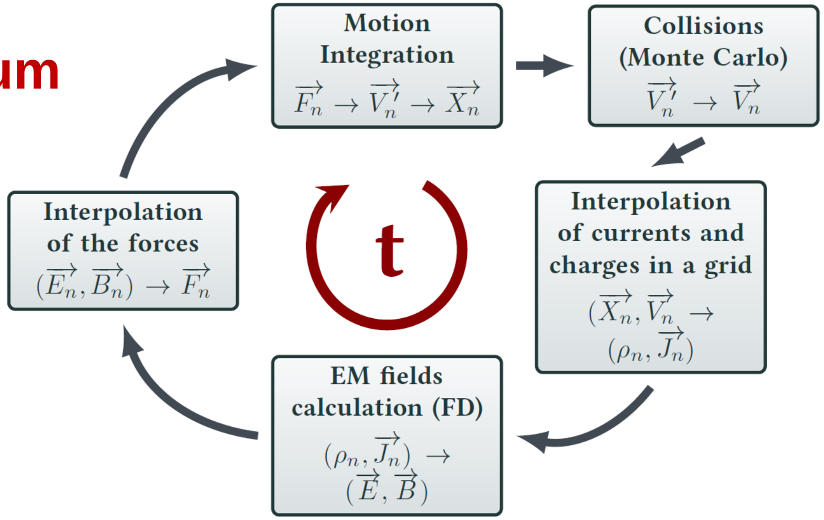
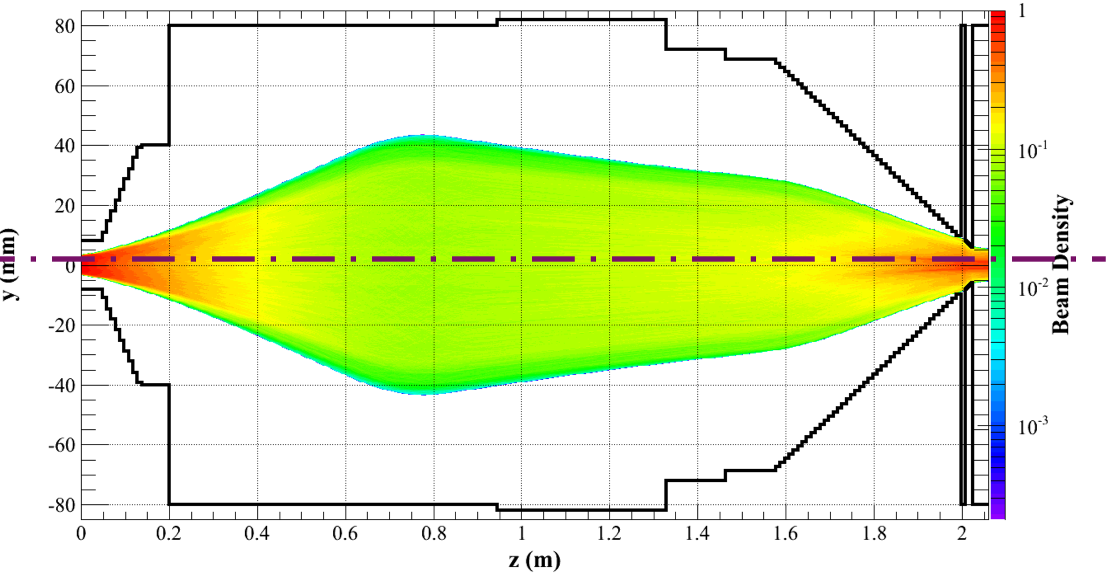
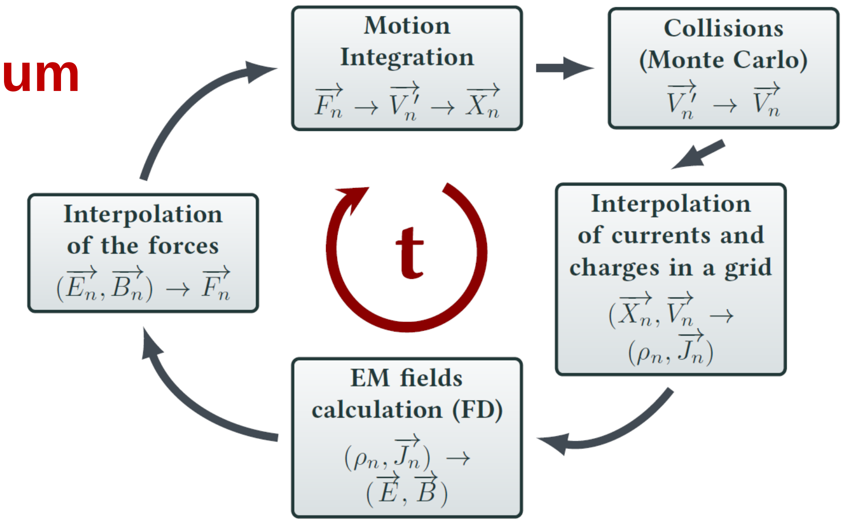




t = 12 µs

Pulsed beam and Space Charge Compensation

Time is needed to reach SCC equilibrium



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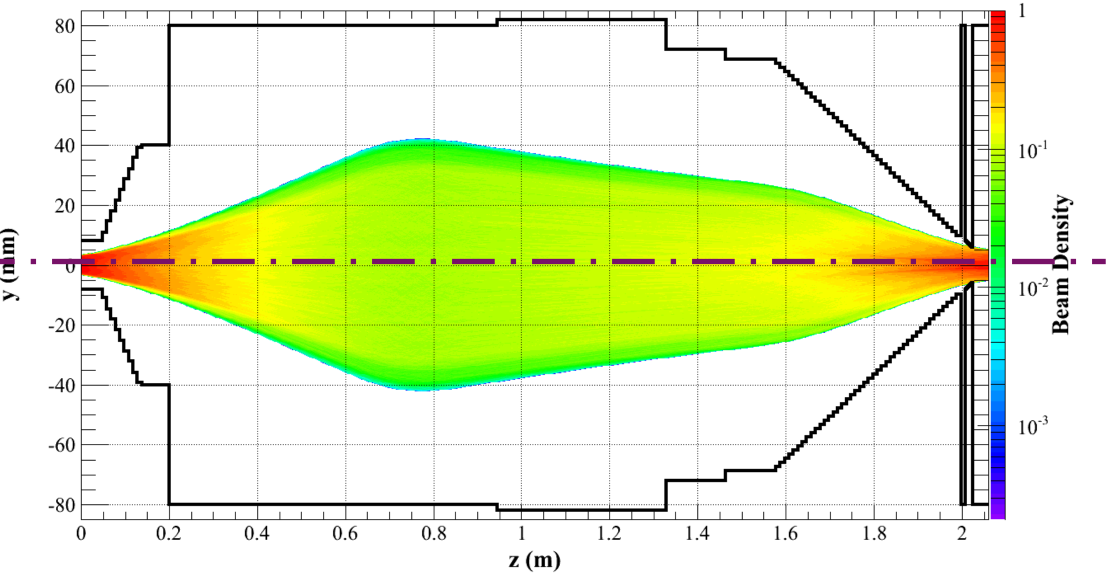
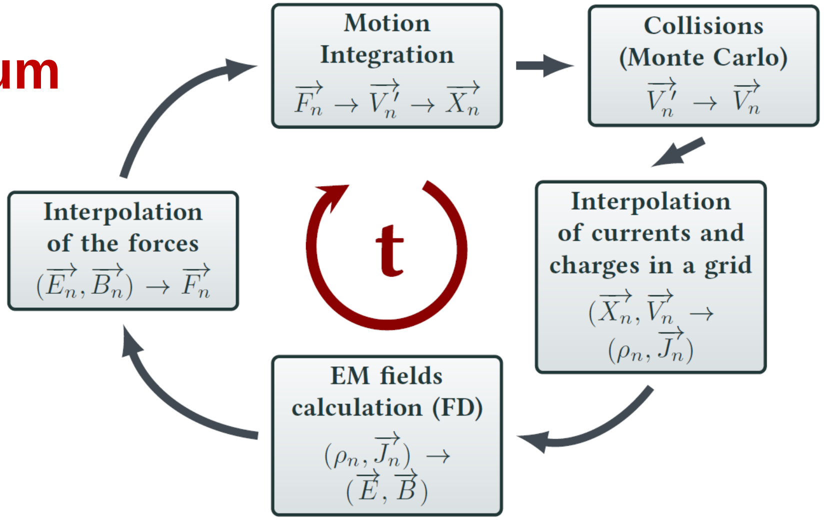


t = 14 µs

Pulsed beam and Space Charge Compensation

Time is needed to reach SCC equilibrium



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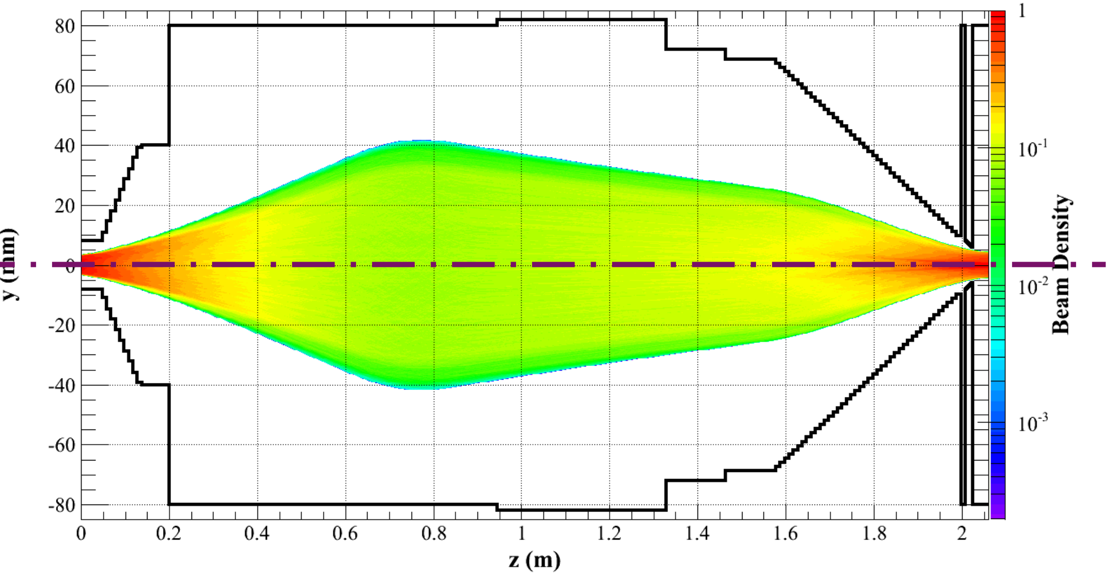

t = 16 µs

Pulsed beam and Space Charge Compensation

Time is needed to reach SCC equilibrium

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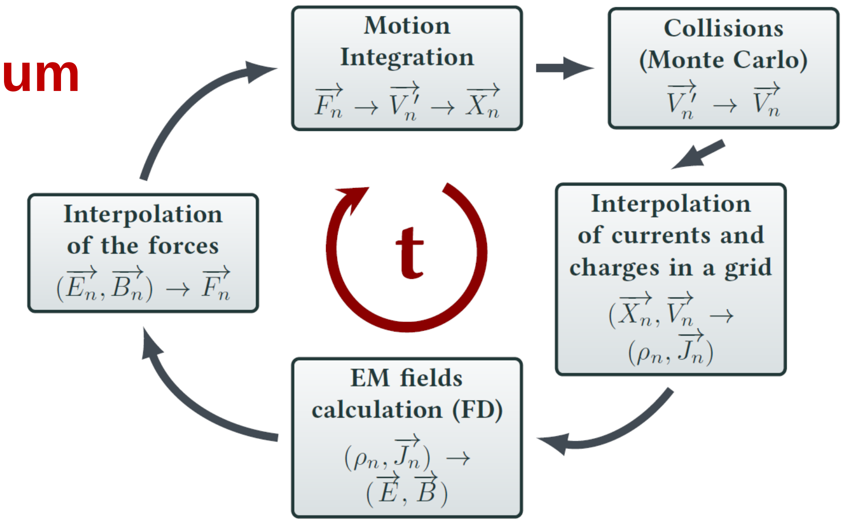

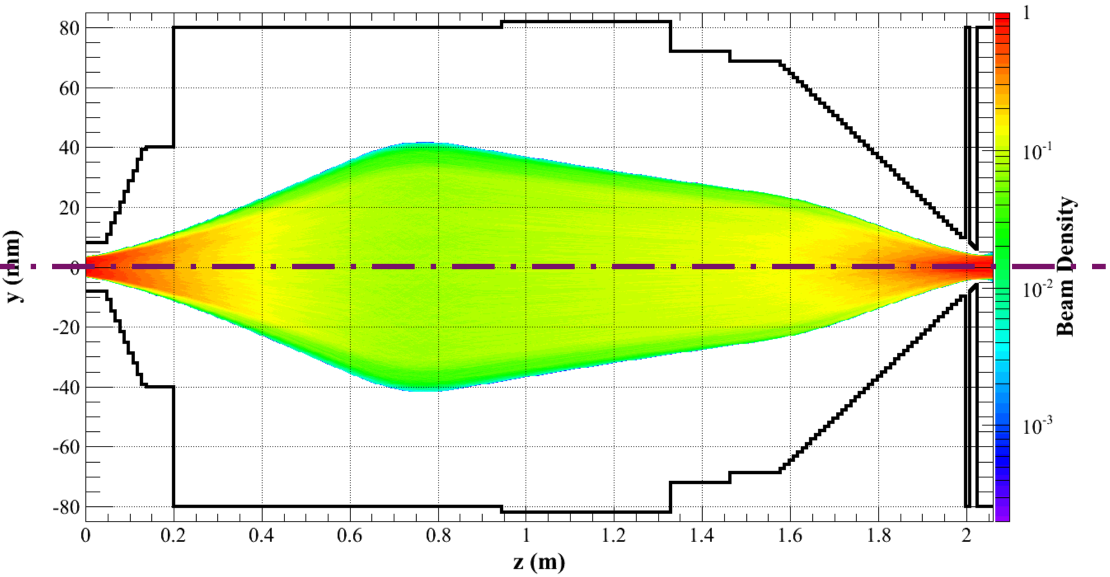

t = 18 µs

Pulsed beam and Space Charge Compensation

Time is needed to reach SCC equilibrium

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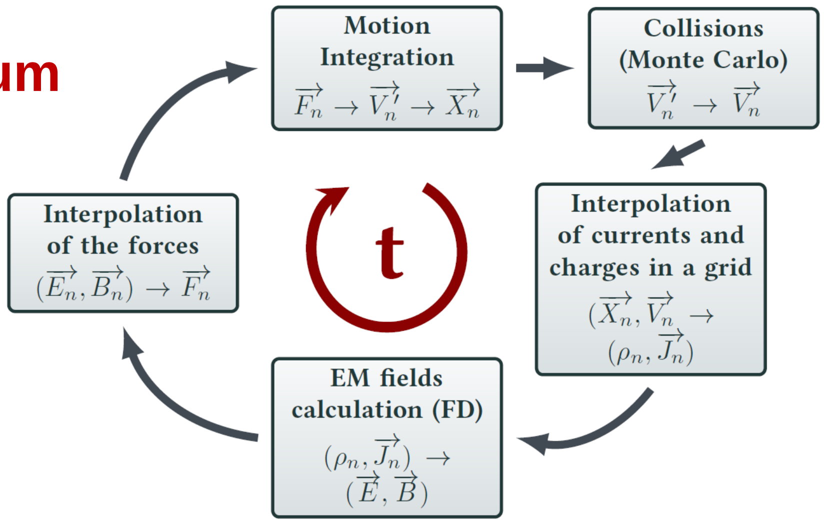
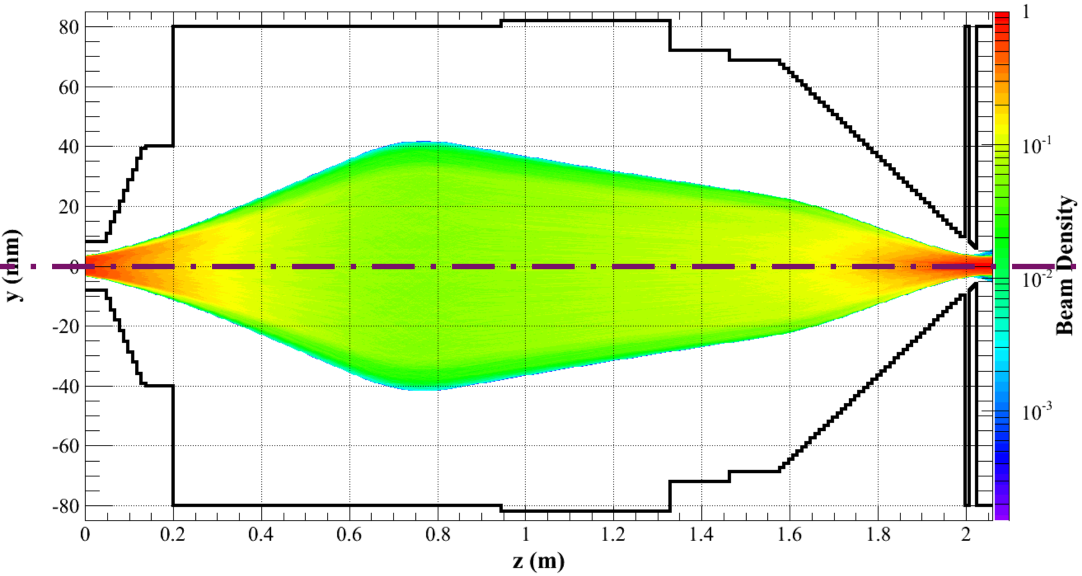
evolution





t = 20 µs

Pulsed beam and Space Charge Compensation

Time is needed to reach SCC equilibrium

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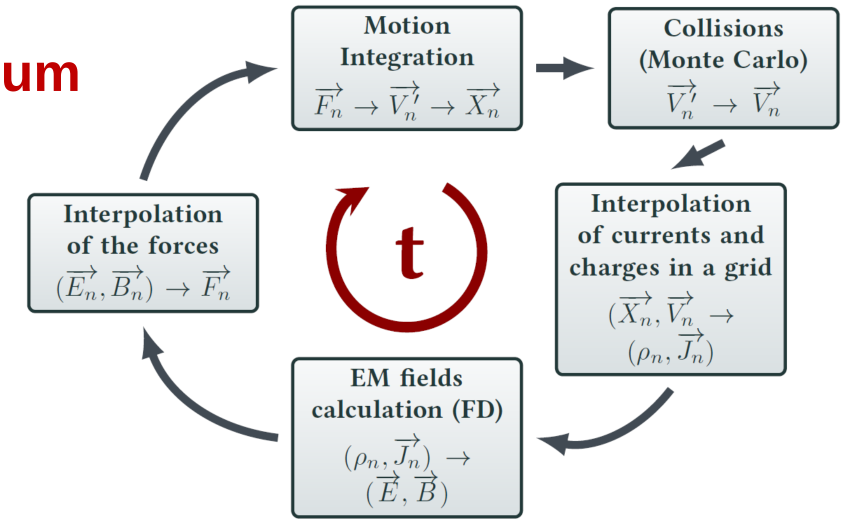
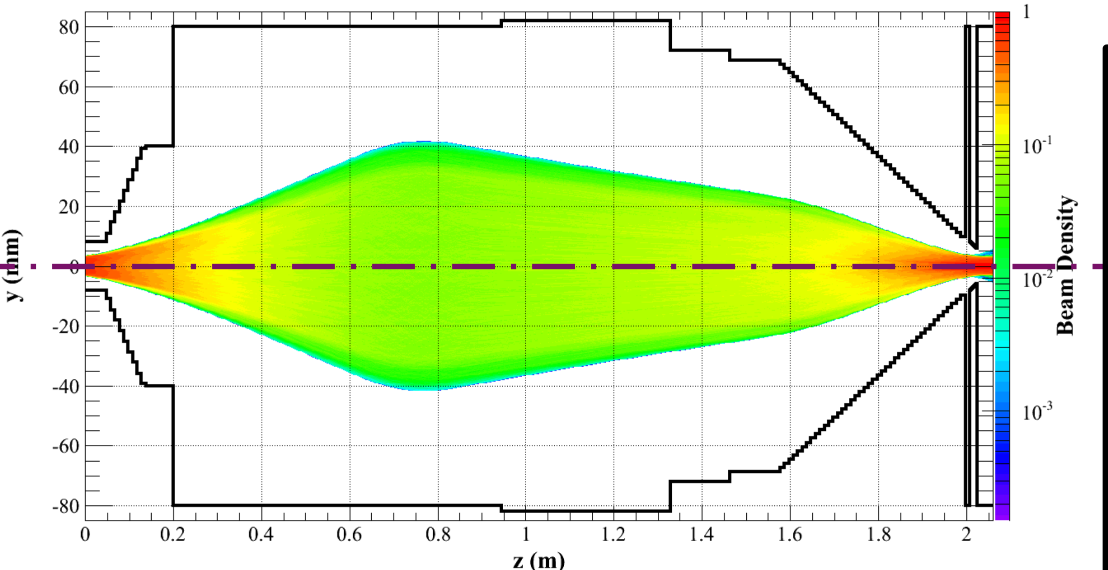
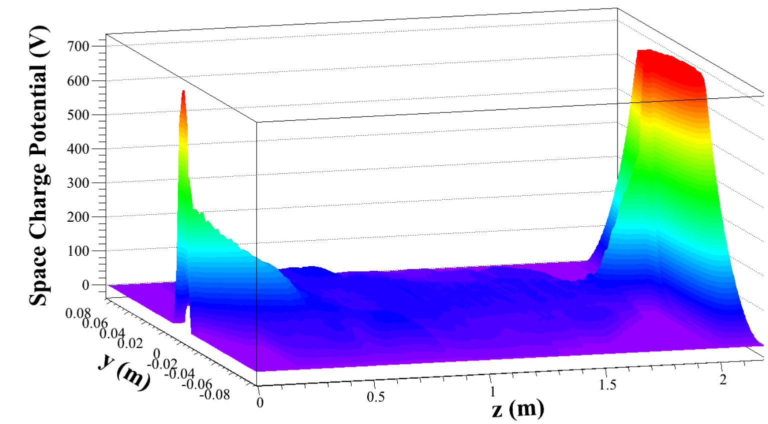
evolution





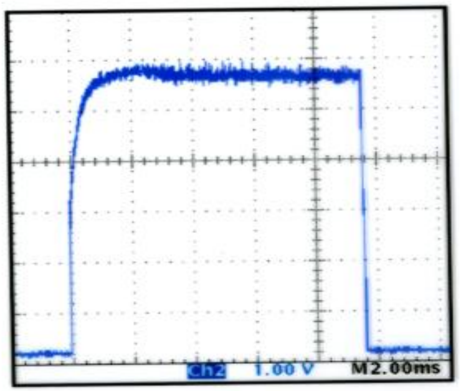
t = 20 µs

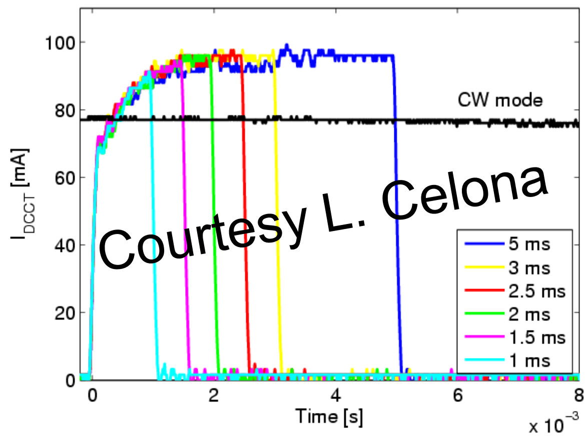
SOLMAXP gives the SC potential map allowing calculation of SC electric field map

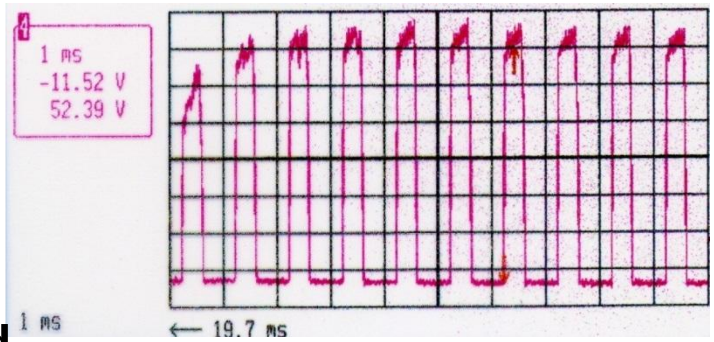


Pulsed beam and Space Charge Compensation

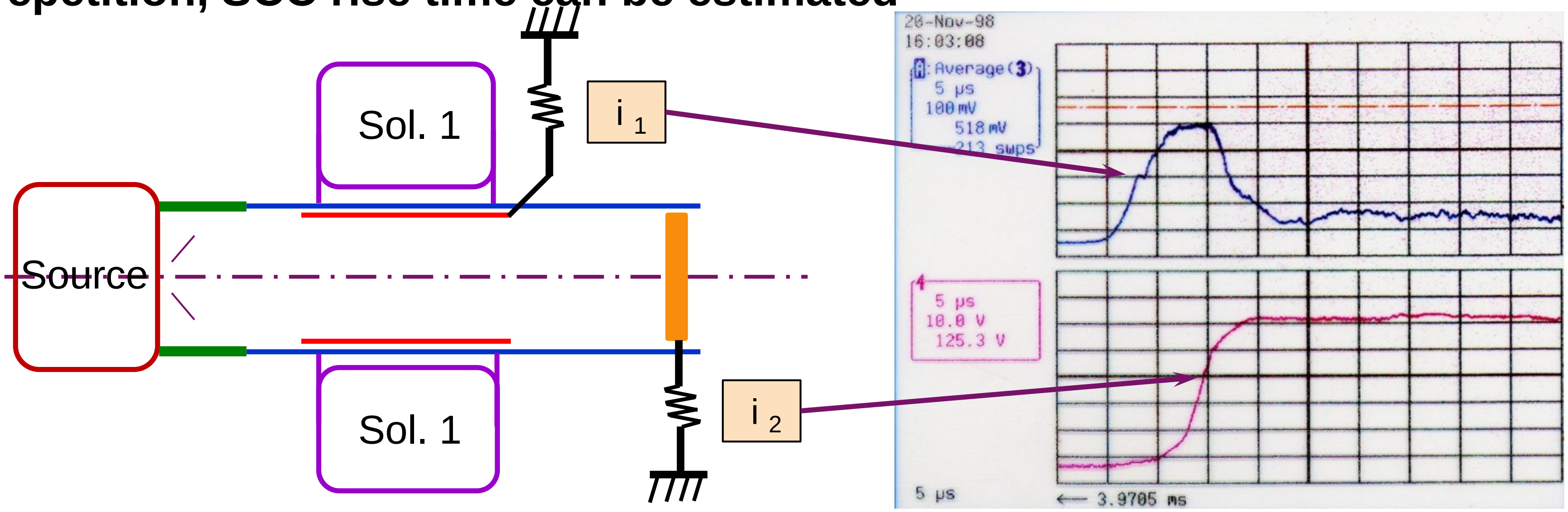
Pulse rise time depends on repetition rate and can reach 1 - 2 ms





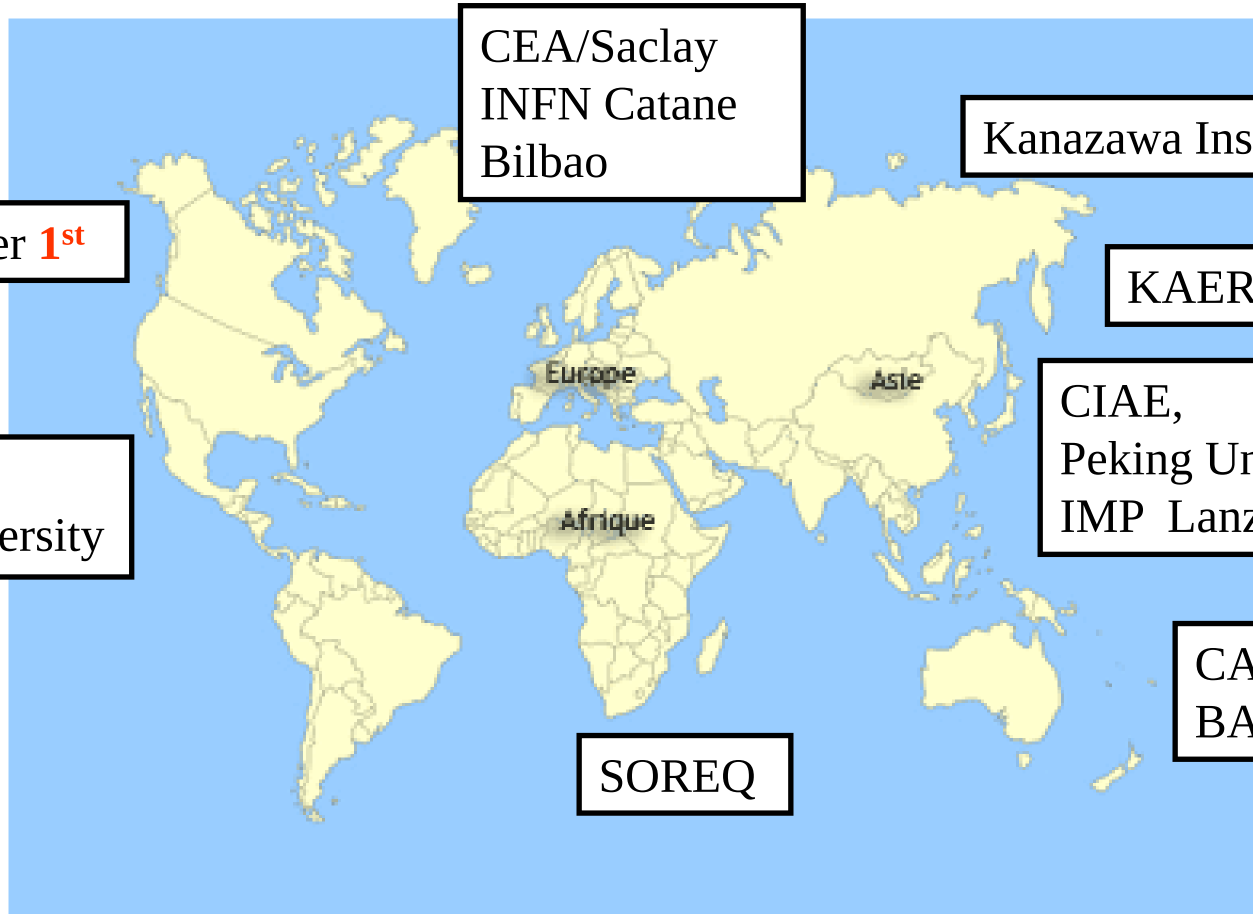


With fast repetition, SCC rise time can be estimated



HPPA worldwide ion source activity

Several groups develop ECR sources to produce high intensity light ion beams



CEA/Saclay
INFN Catane
Bilbao

Kanazawa Inst. Techn.

Chalk River 1st

KAERI

CIAE,
Peking University
IMP Lanzhou

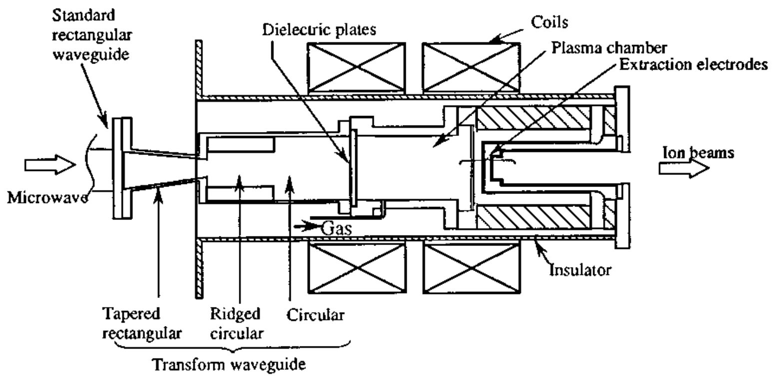
Los Alamos
Indiana University

CAT
BARC

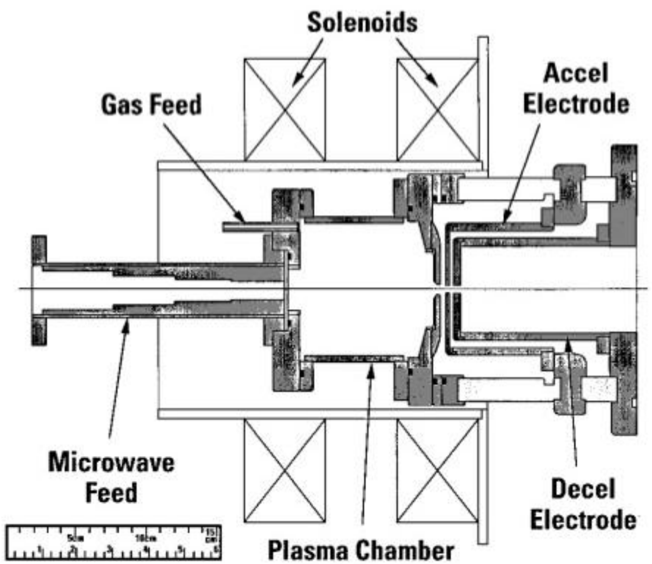
SOREQ

And several companies in Europe, USA, Japan, …

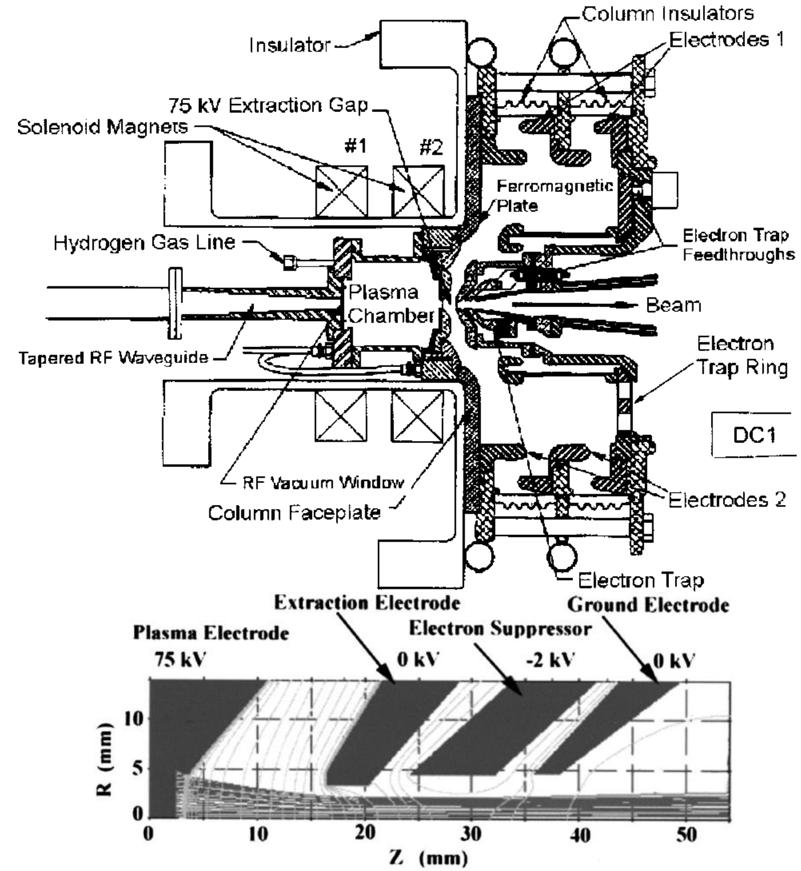
Pioneers…



Ion source developed by N. Sakudo for implanters



Chalk River source with triode extr. system
(T. Taylor, J-F. Mouris)



75keV LANL source with tetrode extr. system
(J. Sherman)

This source designed for LEDA allowed
75 mA accelerated beam behind 6.7 MeV RFQ

PKUNIFTY deuteron injector

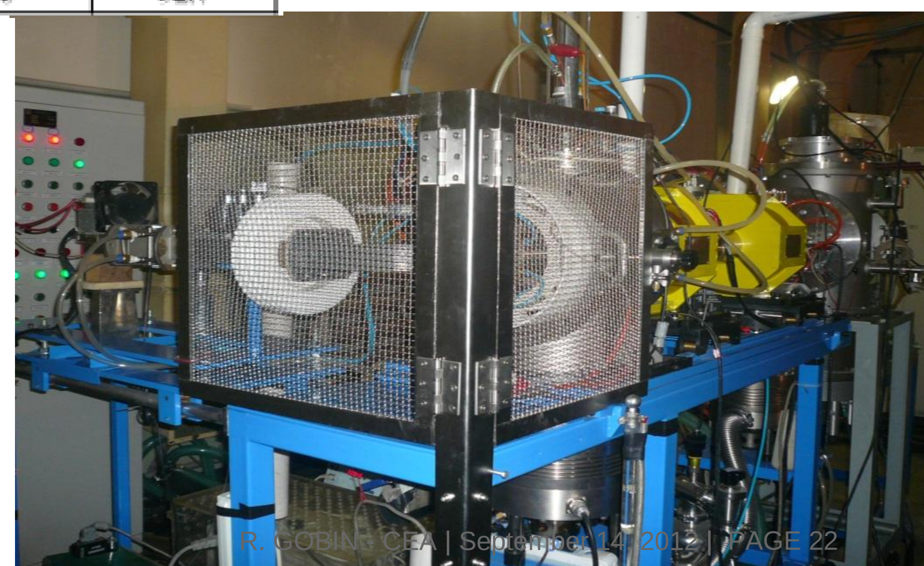
Courtesy S. Peng

Particles		Deuteron		Proton
Parameter	Unit	Request	Status	Status
Particle Energy	keV	50	50	50
Macro-pulse Frequency	Hz	100	100	100
Pulse width	mS	1.0	0.1~1.0	0.1~1.0
LEBT input current (I max)	mA	-	77 (83)	100 (120)
LEBT output current	mA	50	56	-
Ion fraction of source (LEBT)	%	>80 (90)	81.0 (99.5)	89.7
$\varepsilon_{RMS,x,y}$	π.mm.mrad	< 0.2	0.12~0.16	< 0.2
Transmission	%	-	90	92.7

ImPUF is a new project in Peking University to produce fast neutrons dedicated to material research.

- CW accelerator
- H_2^+ beam operation for commissioning
- D^+ ~ 5 mA @ 3 - 40 MeV
- H^+ ~ 5 mA @ 3 - 33 MeV

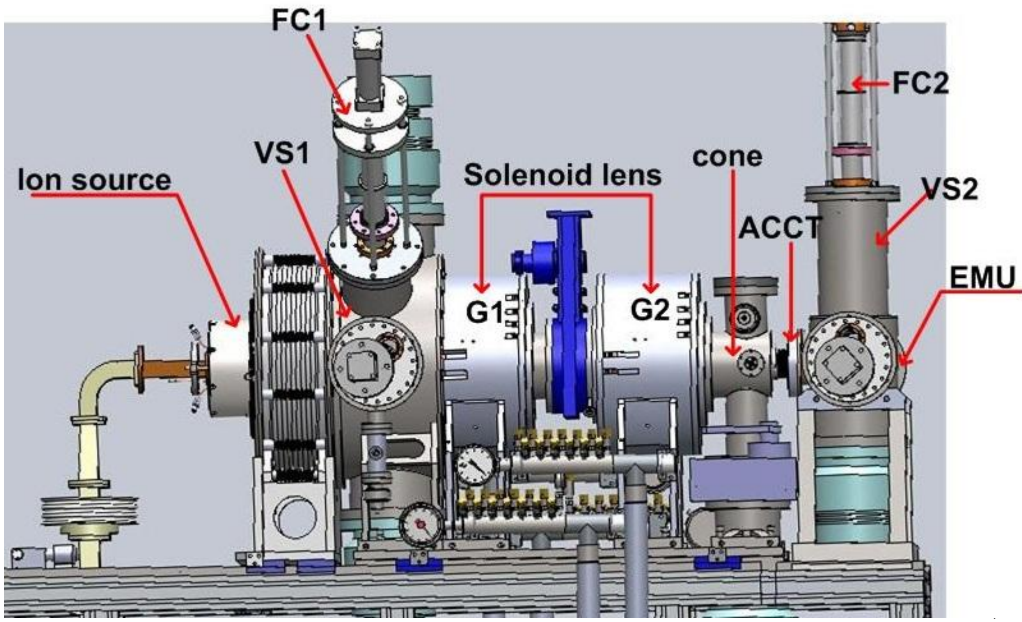
Very compact permanent magnet ion source



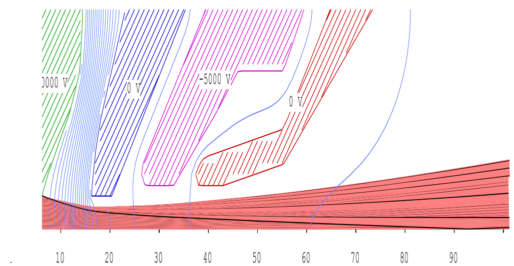
IMP Lanzhou

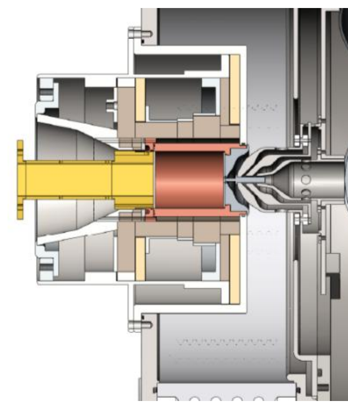
Courtesy Z. Zhang, Z. Zhao

IMP Lanzhou is involved in Tsinghua University irradiation tool (CPHS) project and Chinese ADS

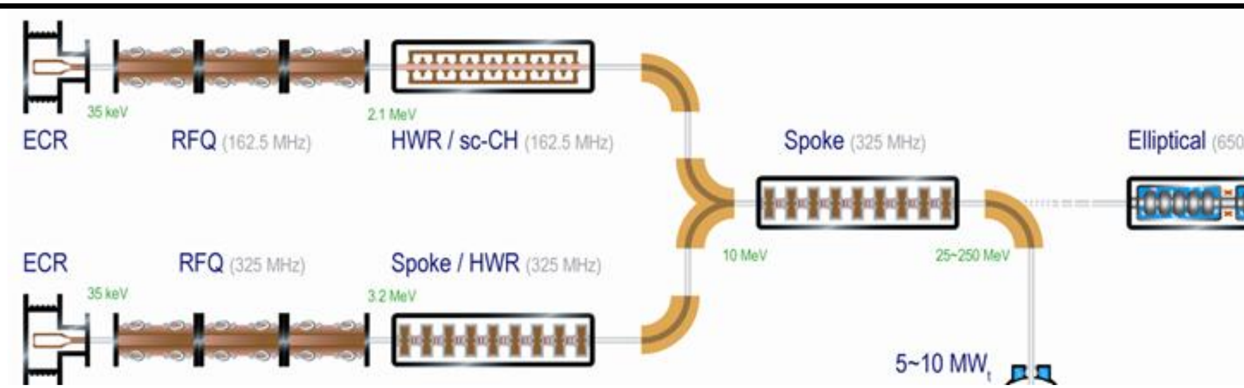


For CPHS, to limit spark rate in extraction system, a 4th electrode (grounded) has been added between plasma electrode and repeller.





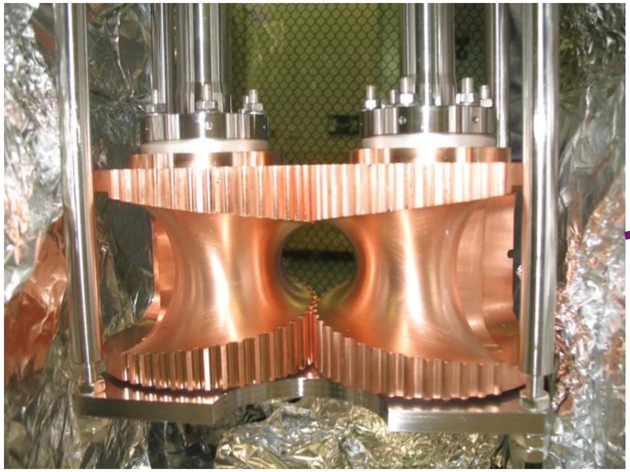
For CADS, IMP is in charge of the design, construction and studies **for both 35 keV injectors**.



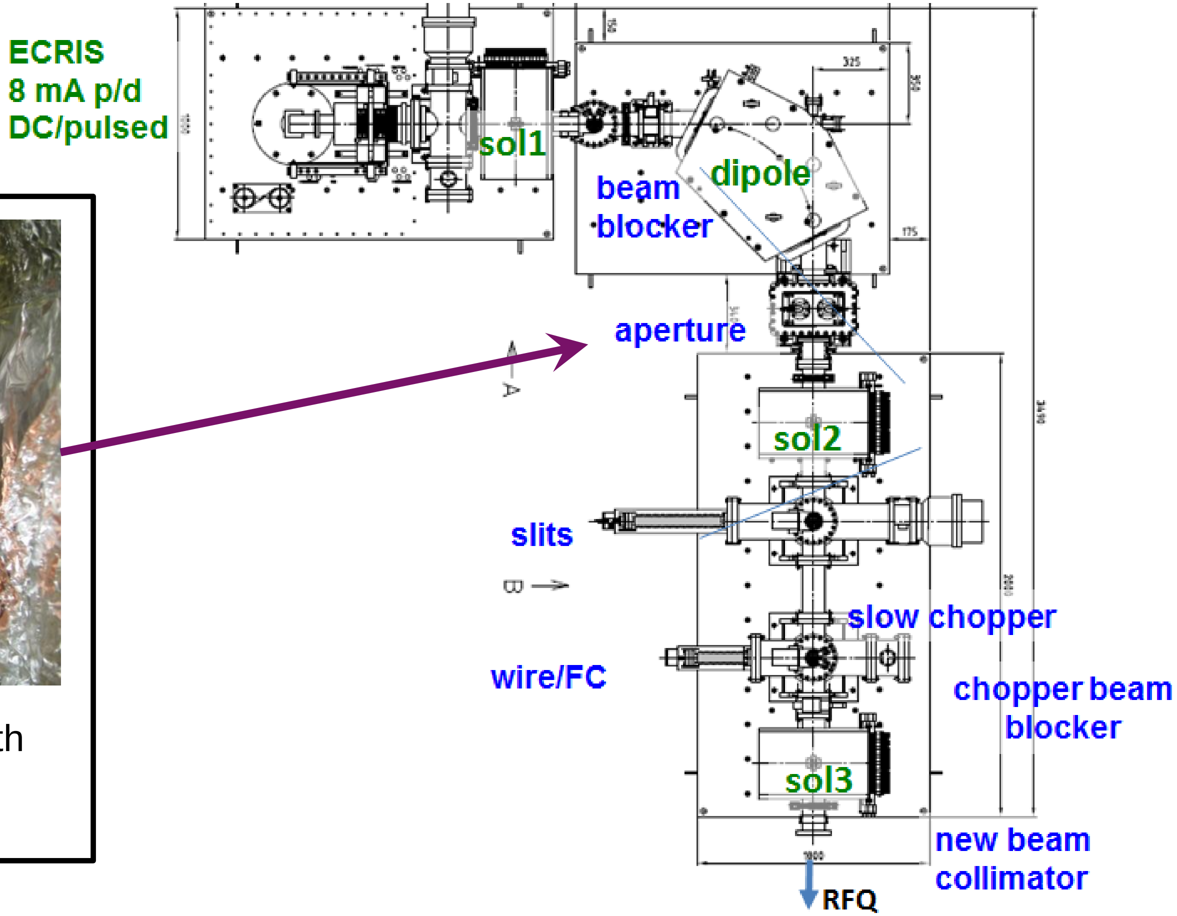
SARAF source in Israel

Courtesy L. Weissman

Source and LEBT designed and built by RI (former ACCEL).
Pulsed or continuous mode.
High reliability.
High molecular ion fraction.
Ingenious variable aperture is placed after the dipole.

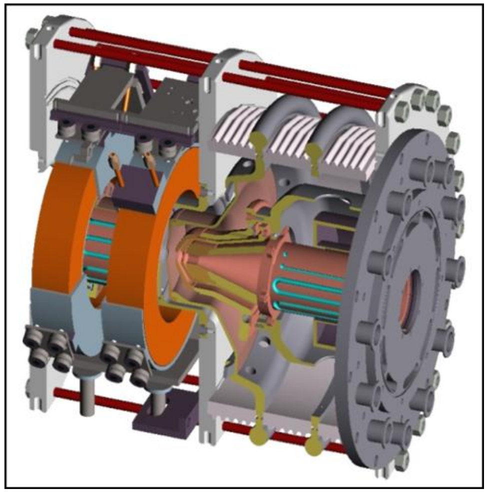


Varying the aperture together with Sol1 allows changing the beam intensity by almost factor 100.

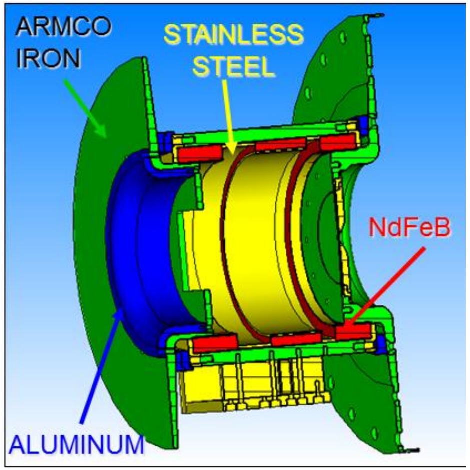


TRIPS, VIS and ESS source in Catania
Courtesy L. Celona & S. Gammino

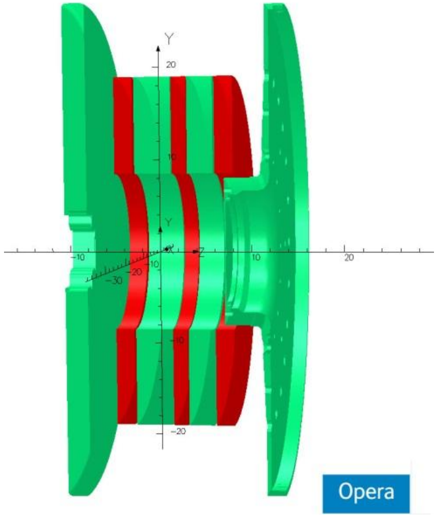
Important work is done at INFN/LNS on magnetic configuration



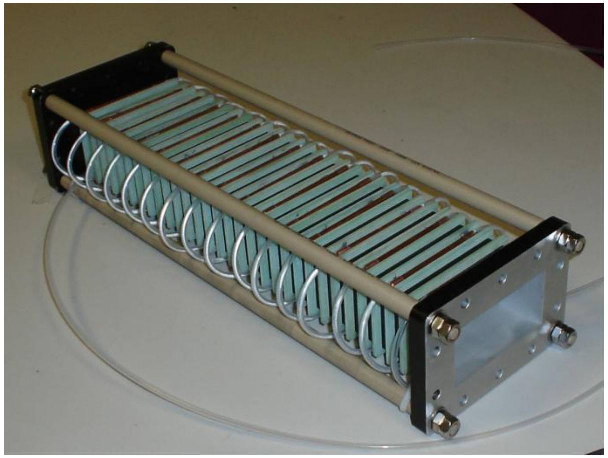
TRIPS with 2 coils
and 80 kV DC break



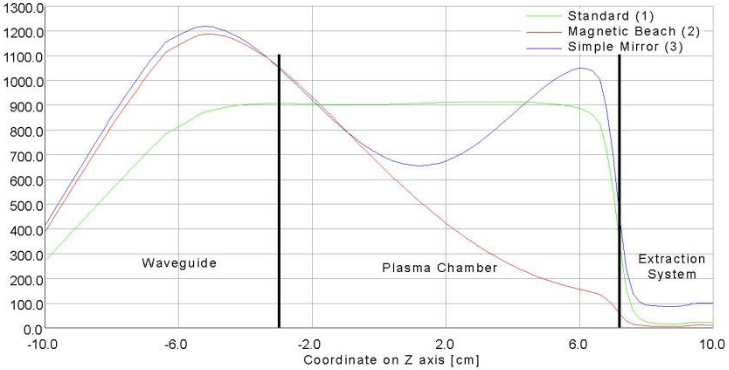
VIS with permanent
magnets + iron



ESS source
with 2 + 1 coils.

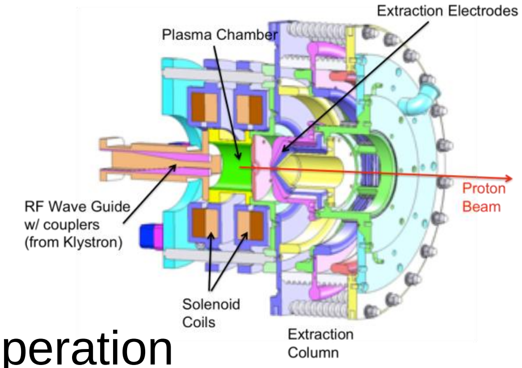


3rd coil to obtain
minimum B field
in Plasma Chamber

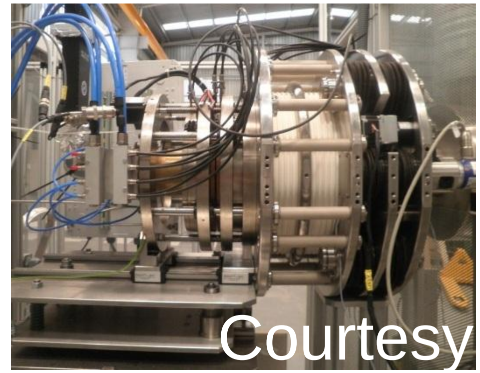


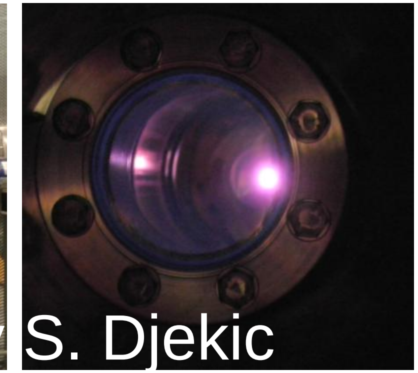
Others…

In Bilbao
1st proton beam
has been extracted
July 2012 at 15 keV
with 25 mm gap.



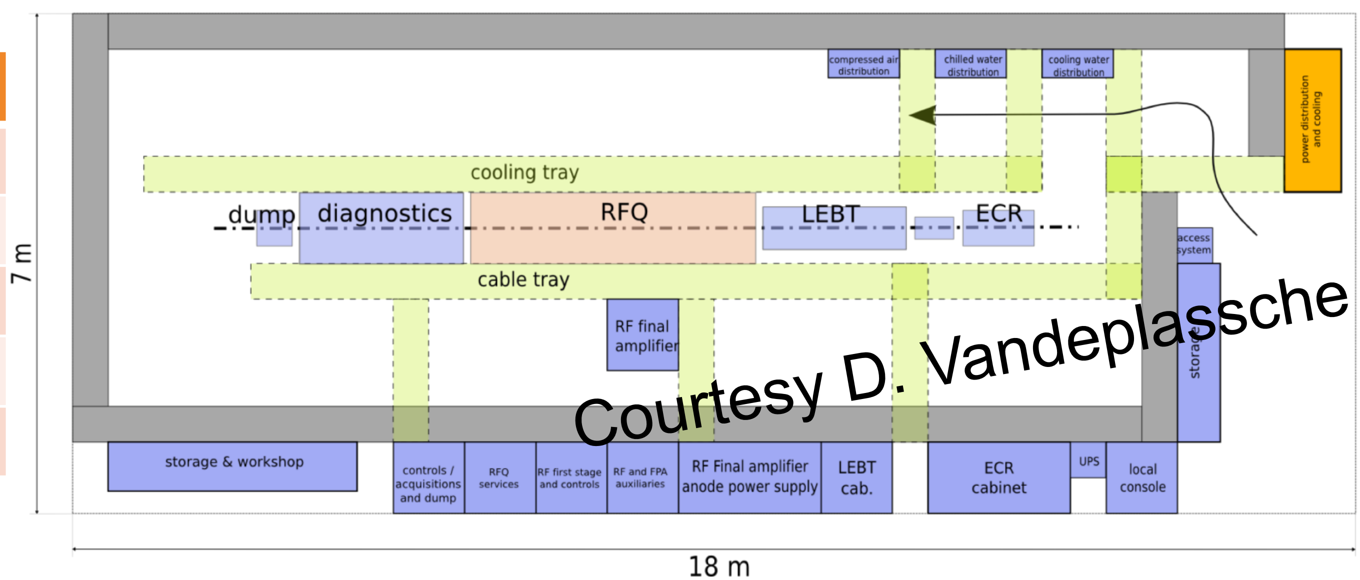
2.7 GHz klystron operation





In Belgium, Myrrha project is preparing a front end test stand in UCL with an ECR ion source from Pantechnik.

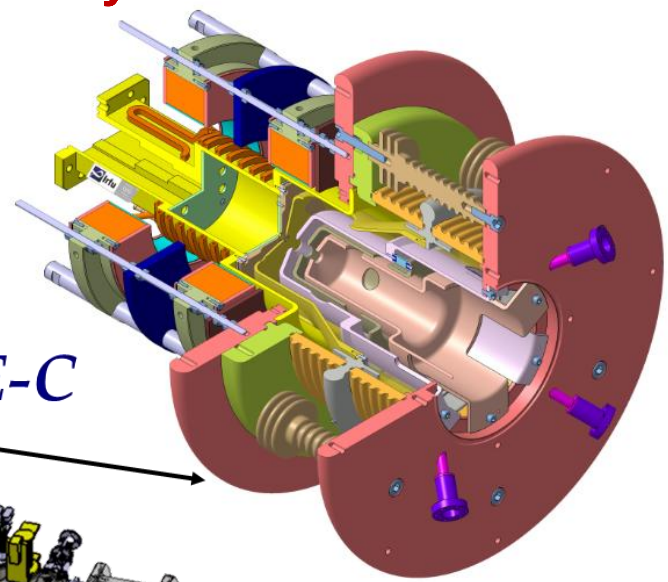
Parameters	
particle	p
Energy	600 MeV
Current	4 mA
mode	CW
MTBF	> 250 h

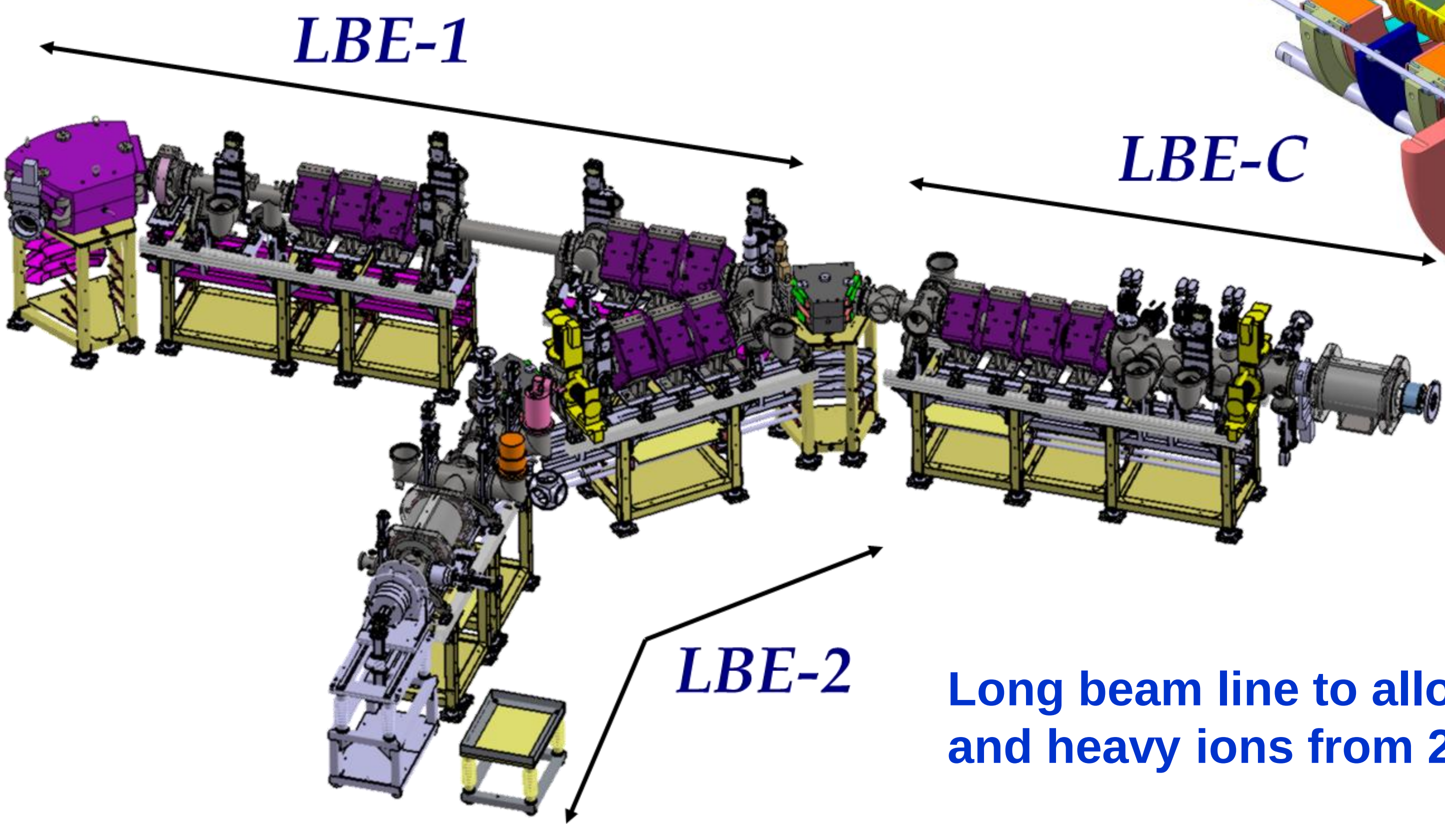


Spiral 2 in GANIL (France)

Ions	Energy	Current
H^+	20keV	8mA
D^+	40keV	6mA

Permanent magnet source
5 electrode extraction system
Small HV platform
DC break

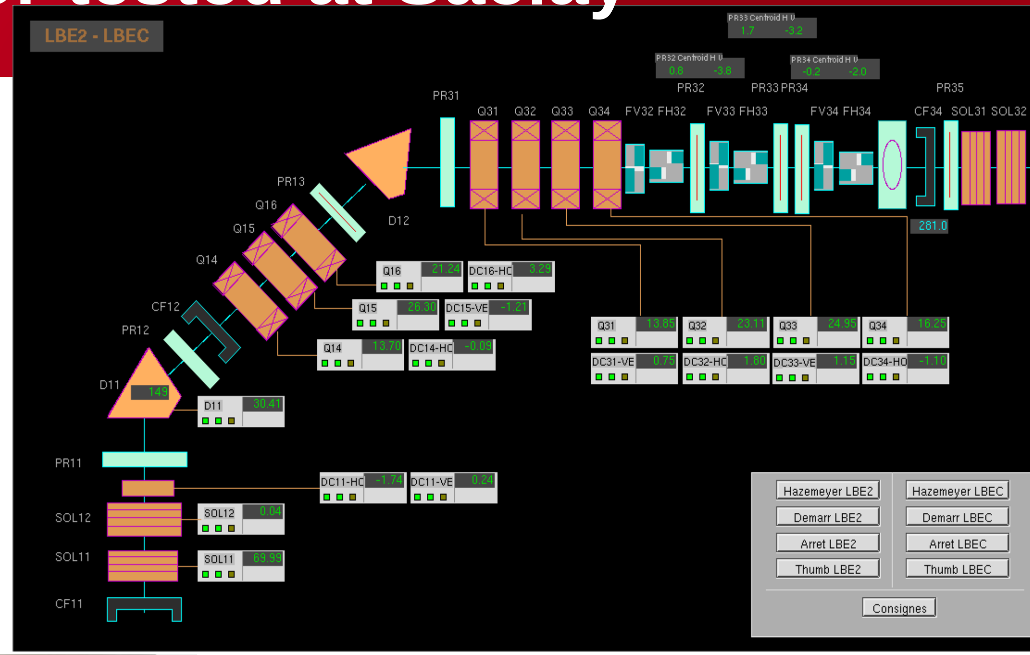


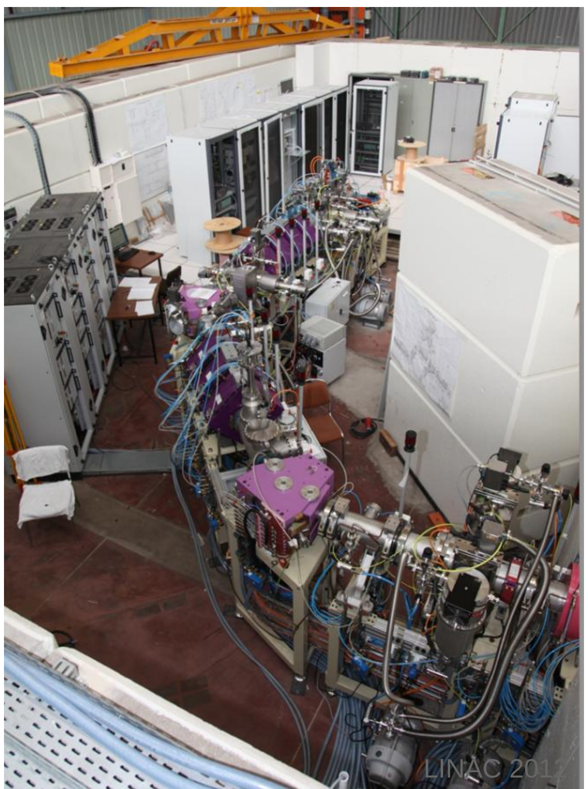


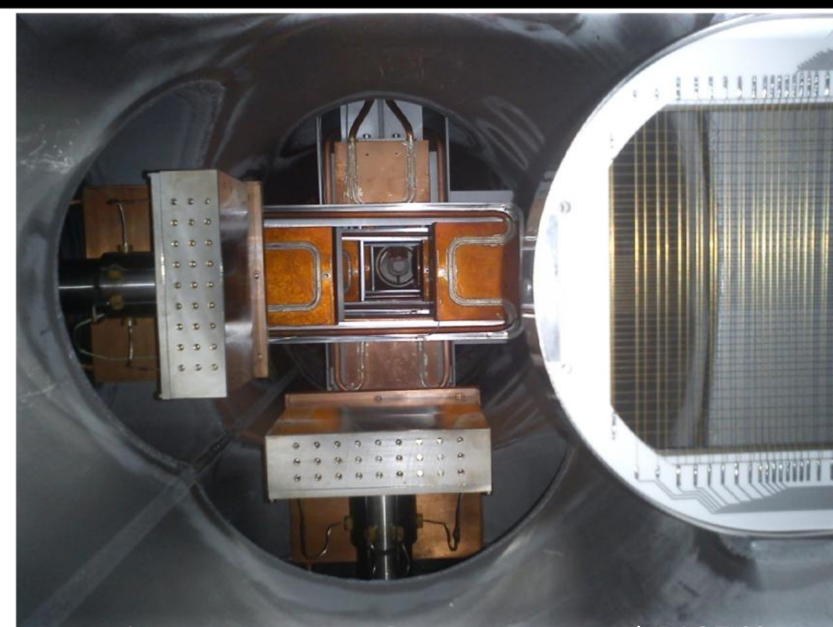
Long beam line to allow injecting light and heavy ions from 2 different sources

Spiral 2 Injector tested at Saclay

The whole Sp 2 injector has been built and tested at Saclay before transfer to GANIL in Caen

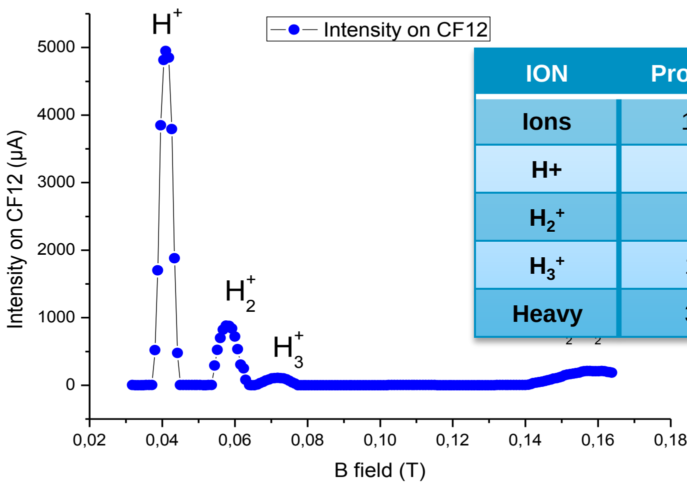






Spiral 2 beam characterization

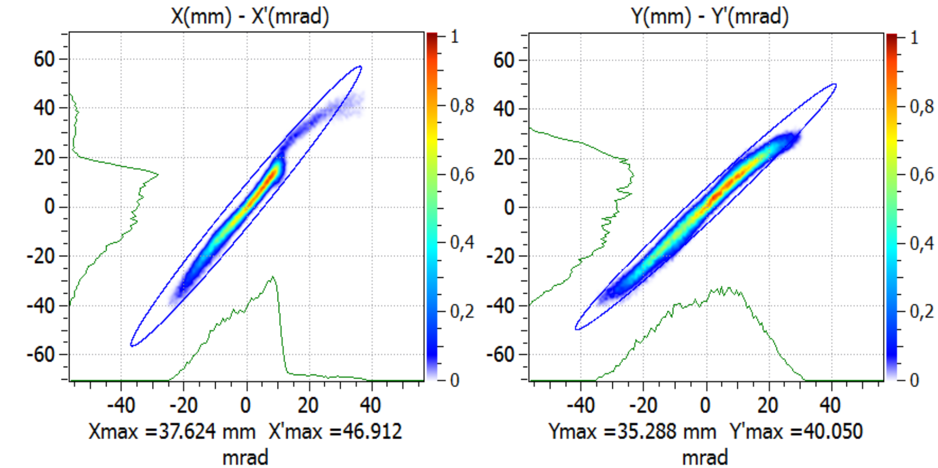
CW PROTON BEAM



ION	Proportion
Ions	100%
H+	81%
H_2^+	14%
H_3^+	1,7%
Heavy	3,4%

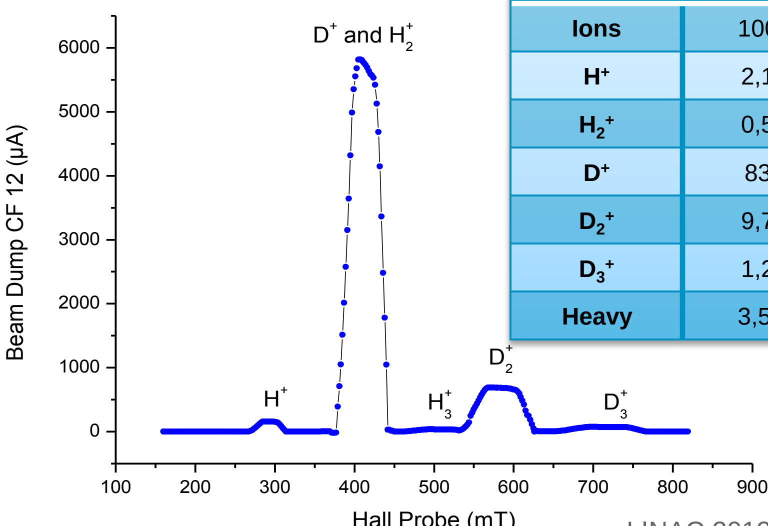
Species measured after 1st dipole

- Nominal tuning : ~0.22 π.mm.mrad



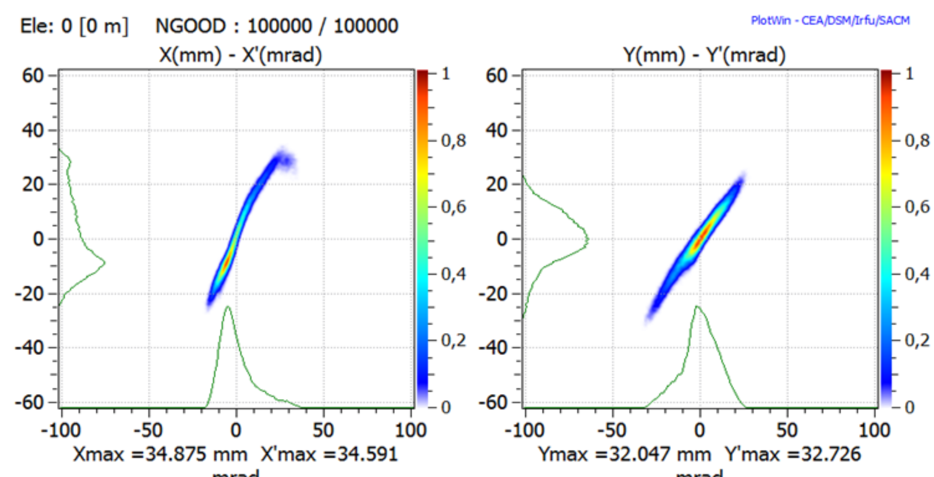
Emittances measured right after second dipole

CW DEUTERON BEAM



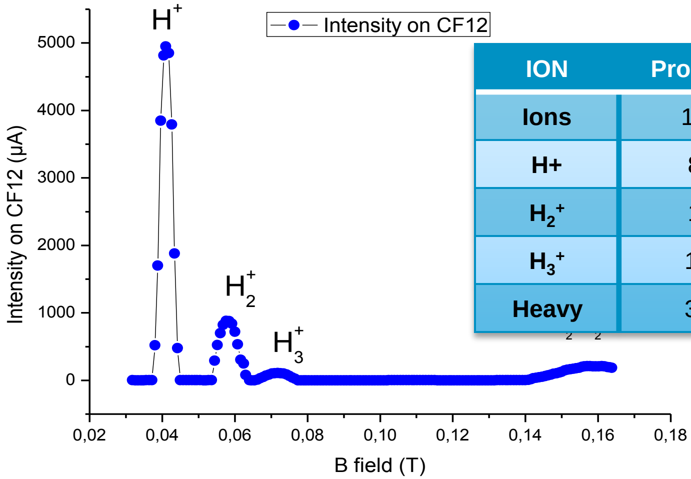
ION	Proportion
Ions	100%
H+	2,1%
H_2^+	0,5%
D+	83%
D_2^+	9,7%
D_3^+	1,2%
Heavy	3,5 %

Measurements ~0.18 π .mm.mrad



Spiral 2 beam characterization

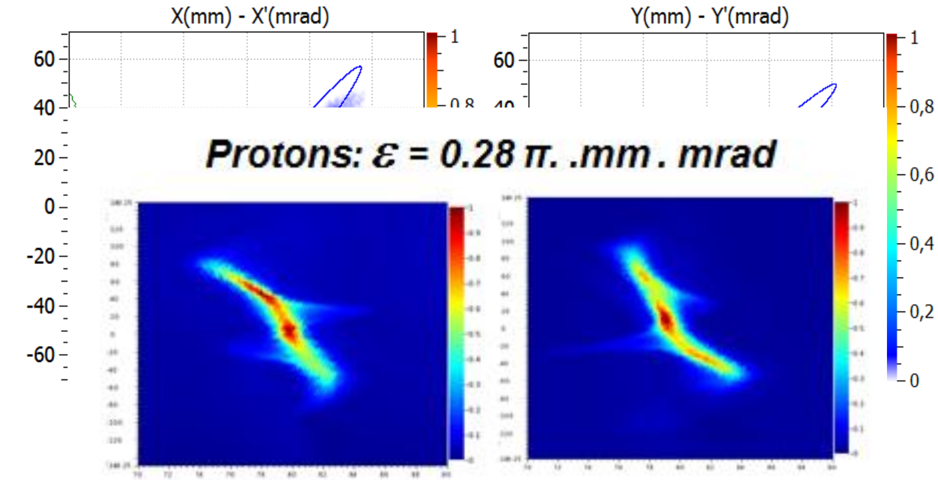
CW PROTON BEAM



ION	Proportion
Ions	100%
H+	81%
H_2^+	14%
H_3^+	1,7%
Heavy	3,4%

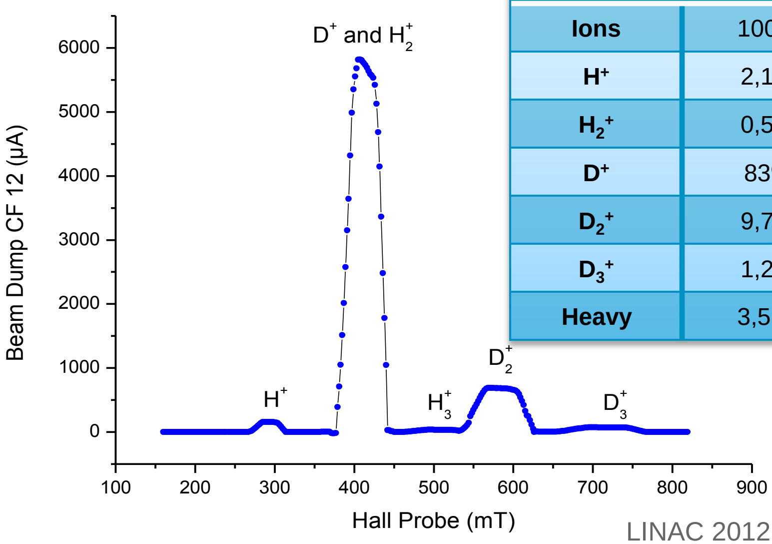
Species measured after 1st dipole

- Nominal tuning : ~0.22 π.mm.mrad

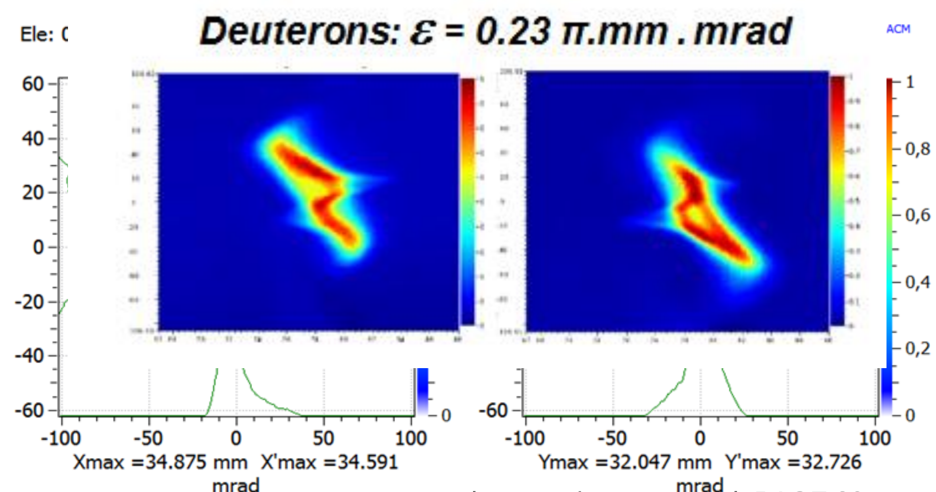


Emittances measured at the RFQ entrance flange

CW DEUTERON BEAM



ION	Proportion
Ions	100%
H⁺	2,1%
H_2^+	0,5%
D⁺	83%
D_2^+	9,7%
D_3^+	1,2%
Heavy	3,5 %

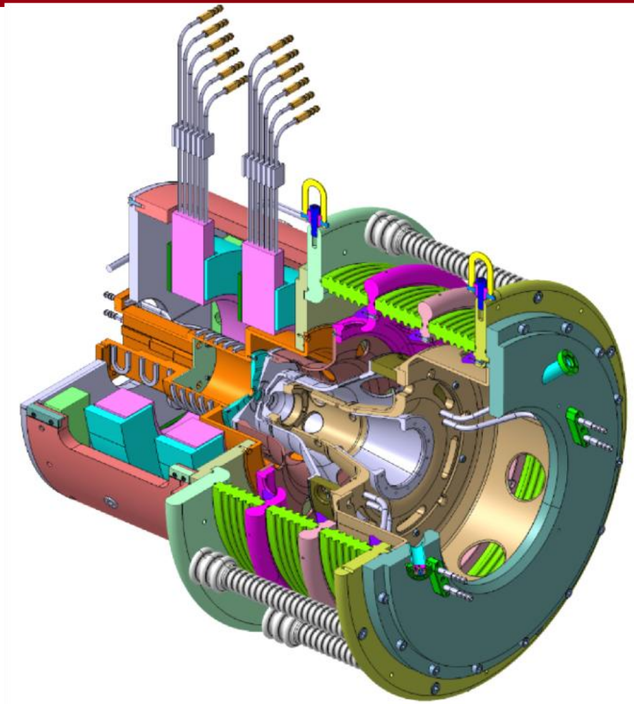


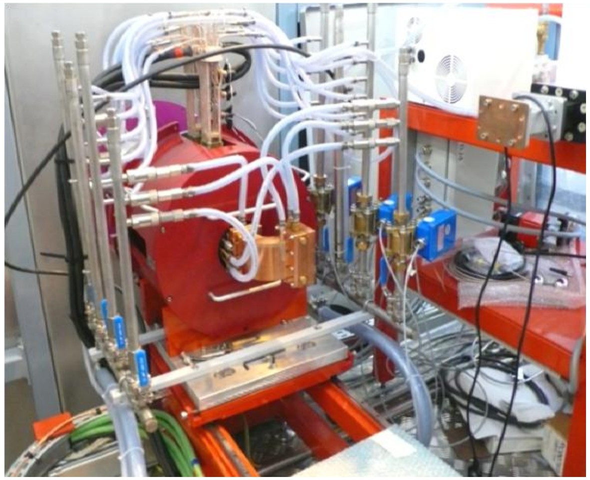
IFMIF Injector

As shown on Tuesday, IFMIF is the machine
of all the challenges…
as soon as the exit of the source.

Requirements	**Acceptance criteria**	Comment
Particle type	**D^+**	H^+ for injector conditioning
Output energy **Energy stability**	**100 keV** **± 100 eV**	Fixed by the RFQ acceptance
Output D^+ current	**140 mA**	RFQ transmission $\geq$ 90%
Species fraction D^+	**$\geq$ 95 %**	At the output of the LEBT
Beam current noise	**$\leq$ 2 % rms**	At frequencies below ~1 MHz
rms norm. emittance	**$\leq$ 0.30 π mm mrad**	At the output of the LEBT
Duty factor	**CW**	Possibility of pulsed operation.
Modulation capability	**1 ms – CW** **@ 1-20 Hz**	Typically

IFMIF Injector has been designed, built and under test
at Saclay before shipment to Rokkasho site in Japan





IFMIF Extraction System

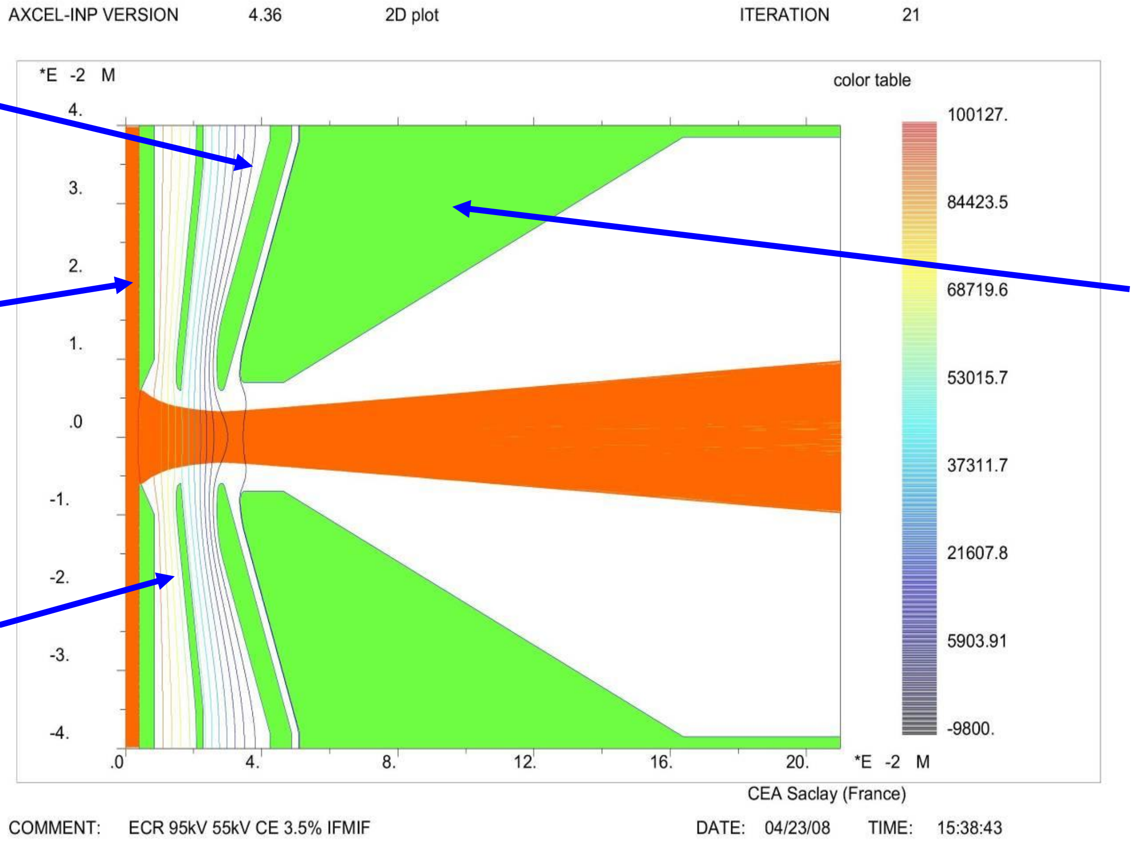
100 KeV, 175 mA total beam current, 1560 A/m² (Φ 12mm)

(80% D^+, 15% D_2^+,5% D_3^+) ⇔ (140mA D^+, 26 mA D_2^+,9 mA D_3^+)

e- screening electrode
Φ12mm
-9.8 kV

Plasma electrode
Φ12mm
45° angle
100 kV

Intermediate electrode
Φ12mm
Adjustable
57 kV

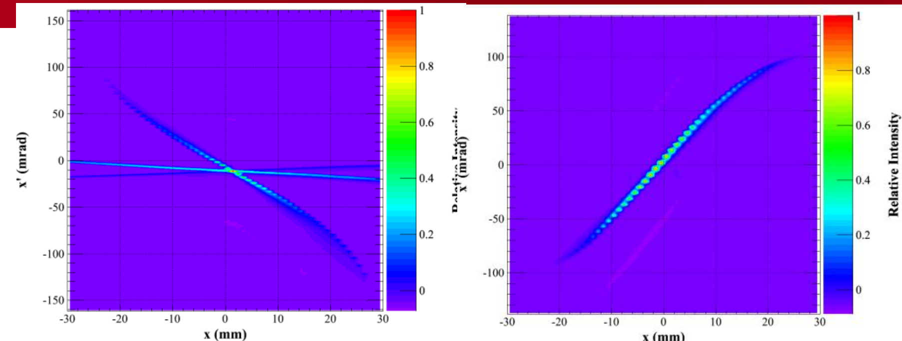


Grounded electrode
Φ14mm
0 kV

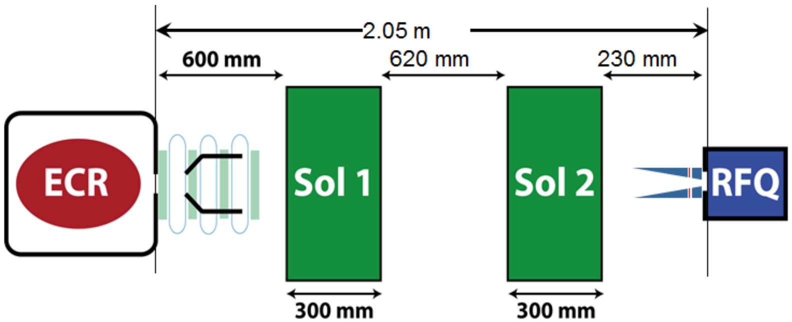
Preliminary tests at high energy showed high spark rate.
The installation of a 2nd grounded electrode (between puller and repeller) is underway.

IFMIF beam analysis

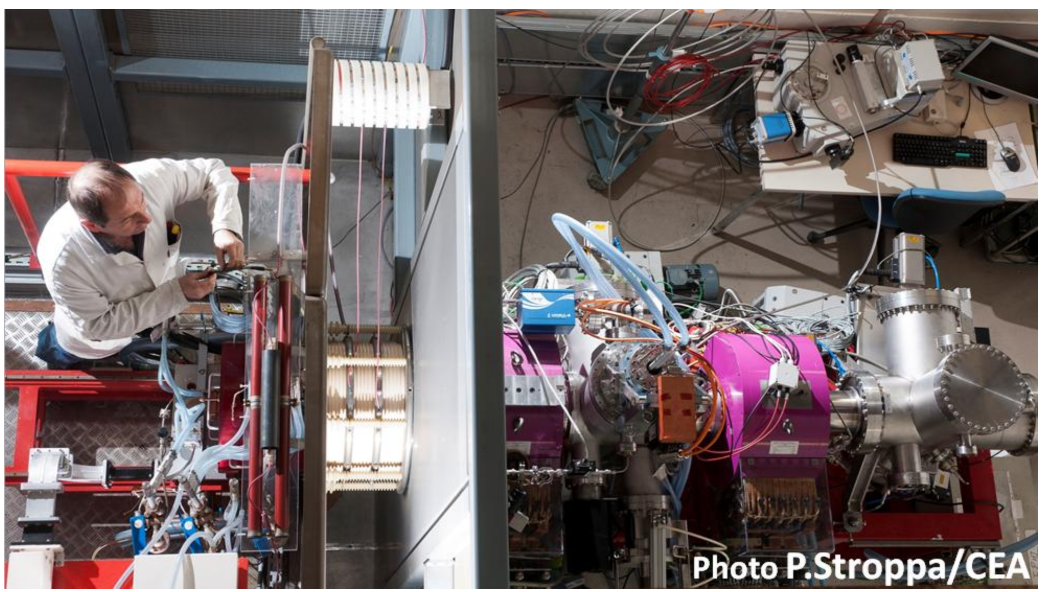
Electrode plasma Φ 10
$I_{ext.}$ = 81 mA
I_{BS} = 42 mA (with cone)

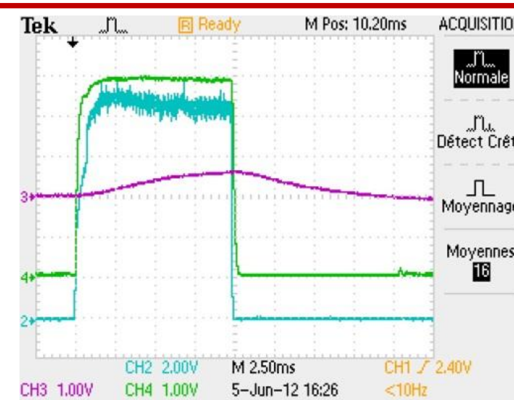


CW 50 keV H+ beam.
Emittance:
- After Sol1, 81 mA, 0. 46 π.mm.mrad
- After cone, 42 mA, 0.29 π.mm.mrad



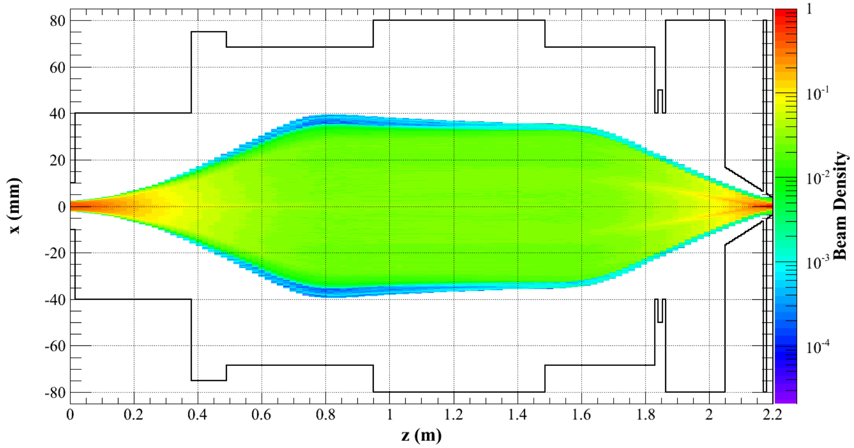
1st D+ beam: 100keV, I ext. 125 mA 1% dc





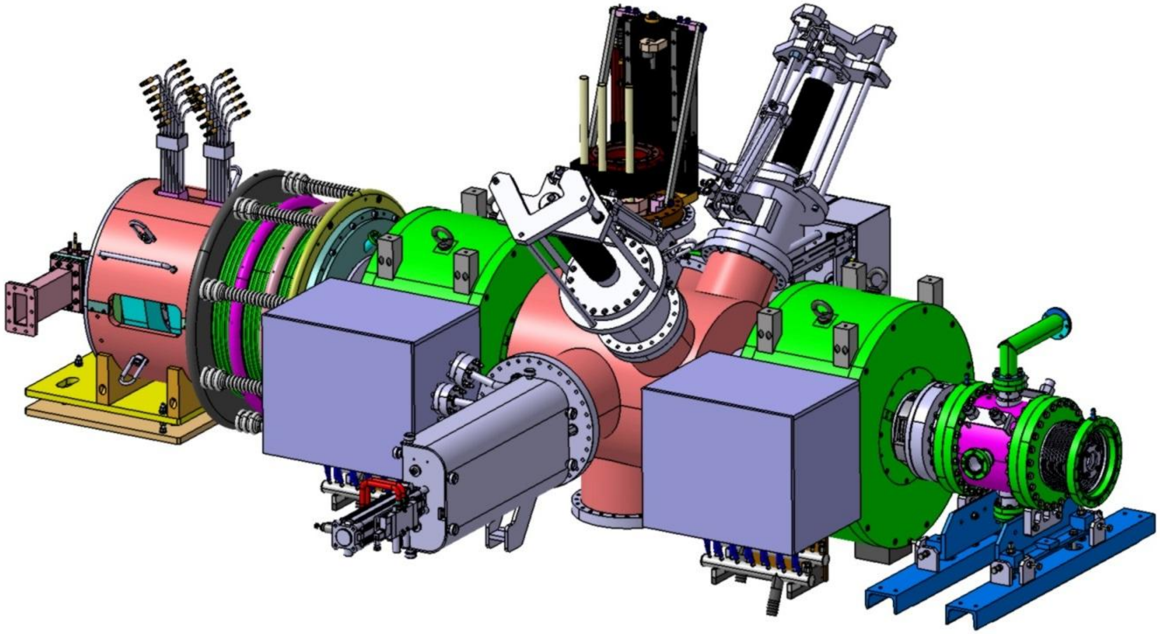
Green: current from HVPS
Blue: current on Beam Stop (w/o cone)

FAIR proton linac injector



FAIR p-linac injector

- SILHI-type ion source.
- The ion source is operating in pulsed mode.
- 5 electrode extraction system.
- LEBT with a 2 solenoids focusing scheme.
- LEBT design is based on IFMIF LEBT.
- Chopper system after the second solenoid.



- Pulsed beam (36µs-4Hz)
- Energy: 95 keV
- H^+ : 100 mA at RFQ entrance

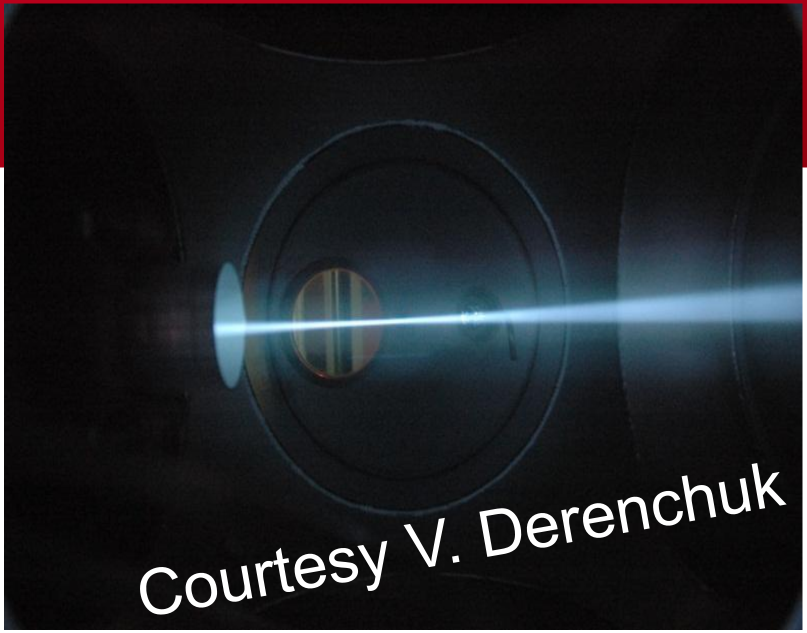
Diagnostics:

- Allison scanner.
- Wien Filter
- Wire scanner
- Iris
- 2 ACCTs

First beam in CEA-Saclay: Mid-2013

CONCLUSION

Several words from Bloomington:
“For the proton therapy system we have been the ion source (20 keV – few mA into CW RFQ).
6 months servicing for changing BN disks
Between 2006 and 2012 there have been no failures of the ion source.”

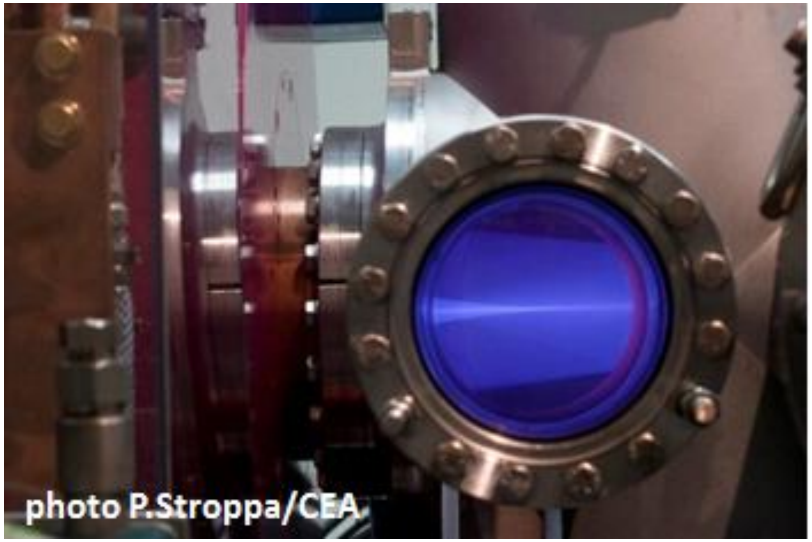


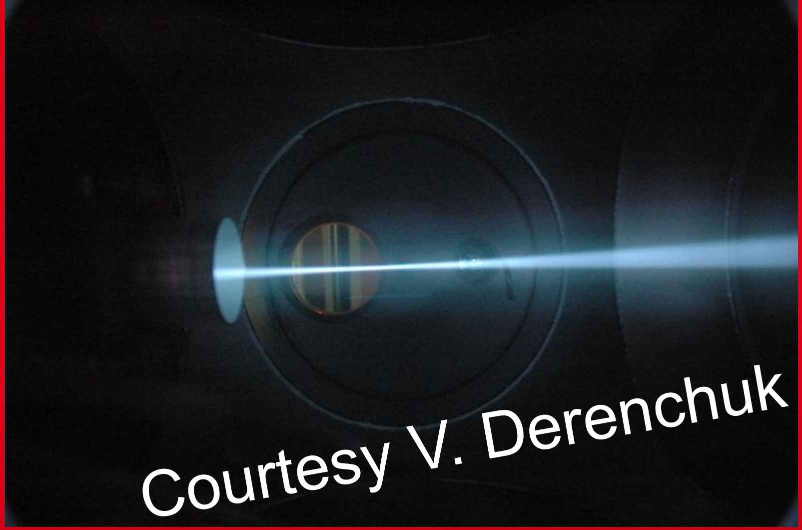
In conclusion, such sources are very well adapted for HPPAs

Special thanks to:

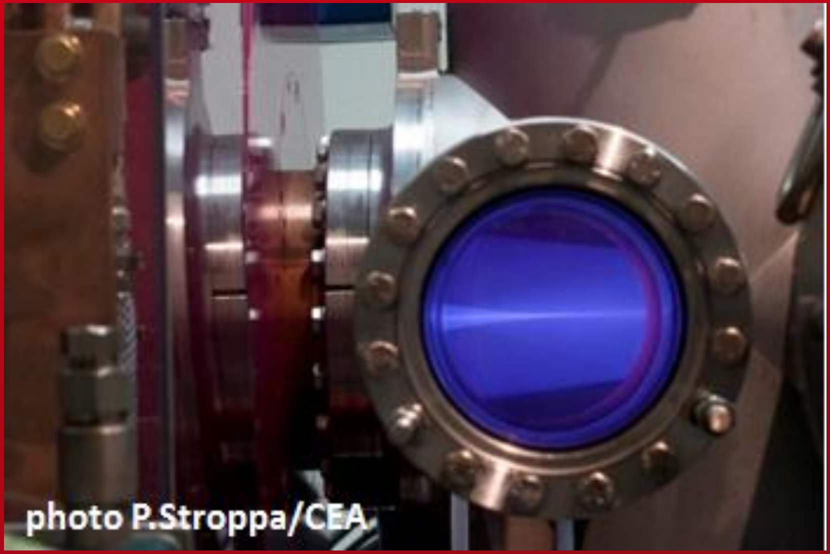
- **L. Celona**
- **V. Derenchuk**
- **S. Djekic,**
- **S. Gammino,**
- **S. Peng,**
- **D. Vandeplassche,**
- **L. Weissman**
- **Z. Zhang**
- **H. Zhao**

and to SPIRAL 2, IFMIF and FAIR injector groups.





Thank you for your attention



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