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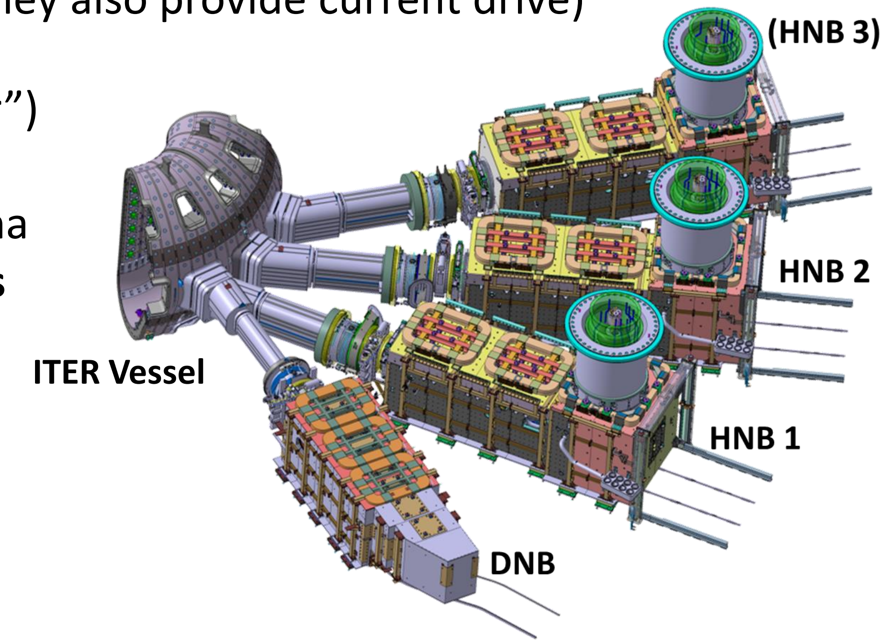
Towards low divergence beams for the ITER neutral beam injection system

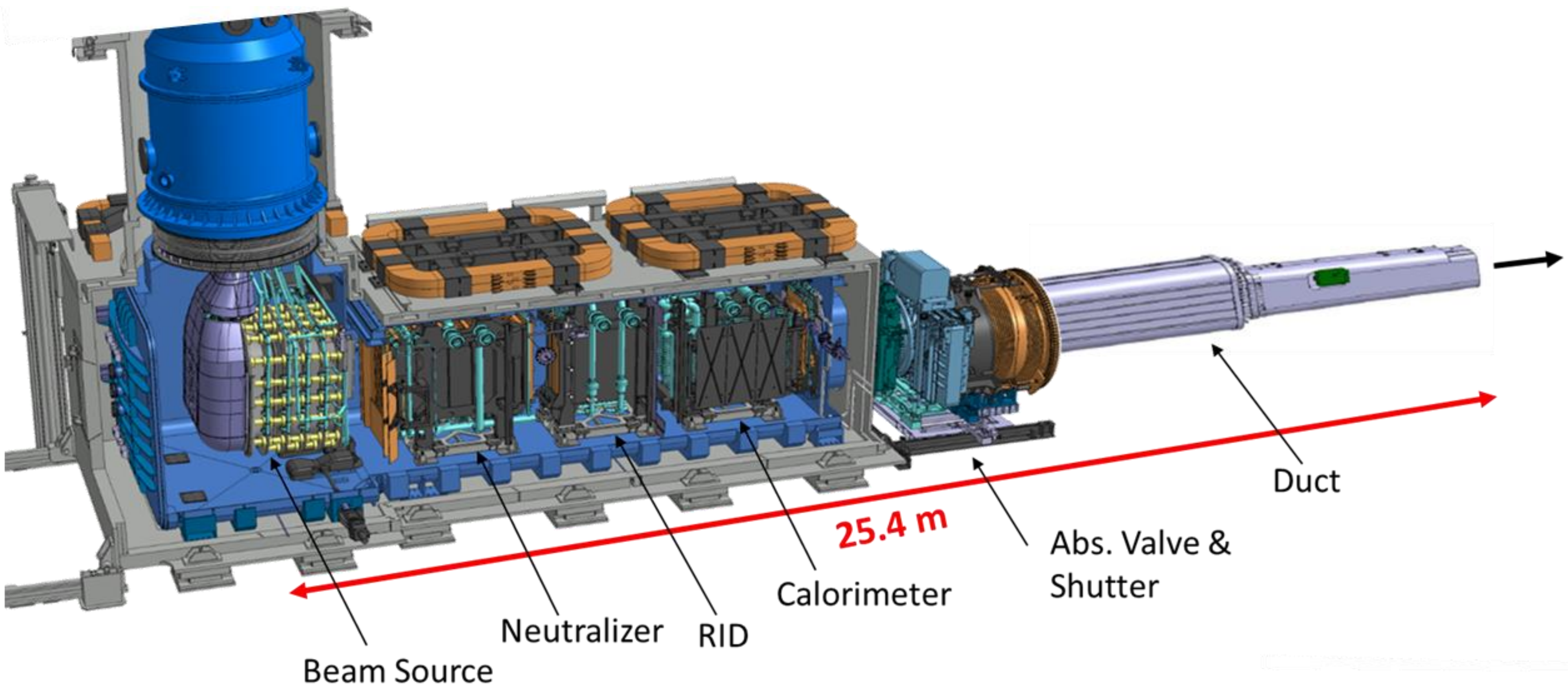
P. Veltri, N. Den Harder, U. Fantz, B. Heinemann, J. Hiratsuka, A. Hurlbatt, M. Kashiwagi, M. Kisaki, A. Pimazzoni, G. Q. Saquilayan, E. Sartori, G. Serianni, K. Tsumori, J. Zacks and Experiment Advisory Committee Contributors

Presented by P. Veltri, Neutral Beam Section
ITER Organization

Introduction: NBI Power and Losses

- Neutral are the beams main plasma heating method for present fusion device (They also provide current drive)
- Atom beam production based on the conversion of ions in a gas cell ("Neutralizer")
- For large fusion device like ITER, 1 MeV necessary to access the core of the plasma
  → **need for negative ions**
- Requirements for ITER NBI extremely demanding





2 HNBs (+1): H_2 / D_2
- I = 46 / 40 A
- V = 0.87 / 1 MV
- t_{pulse} = 1000 / 3600 s
- P_{beam} = 16.5 MW
- **divergence ≤ 7mrad**

Introduction: NBI Power and Losses

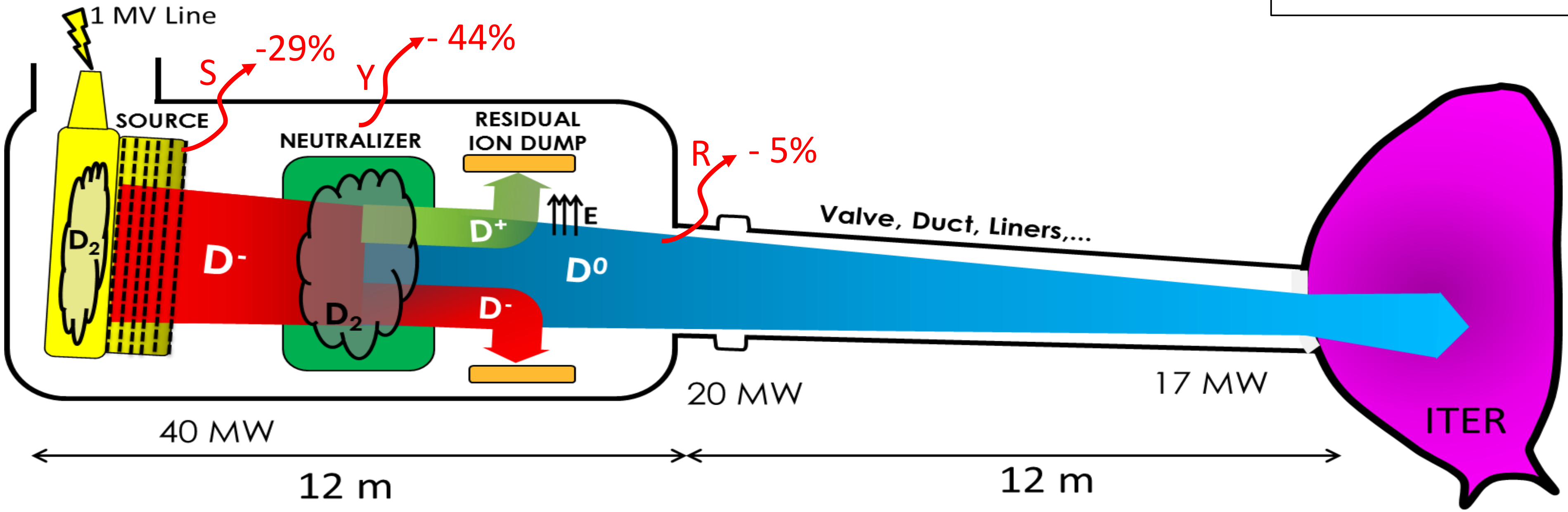
Beam Power= $j_{D-} \cdot A_{PG} \cdot V \cdot (1-S) \cdot Y_N \cdot (1-T_R) \cdot T_G$

j_{D-}= Extracted D^- current density (290 A/m2)
A_{PG}=PG aperture area=0.197m^2
V=beam Voltage= 1 MeV
S= stripping Losses=29%
Y_N=Neutraliz. Yield=56%
T_R =Re-ionization Losses=5%

T_G= Transmission= T_G (Beamline geometry, divergence, misalignment, beam tilting)

(neglecting beam losses in the accelerator by direct impact)

Beam Power ≥ 16.7 MW ⇒ **T_G ≥ 78%**



Introduction: NBI Power and Losses

- Beam current shared among 1280 beamlet arranged in lattice of 20x64 beamlets; typical radius 2-3 mm.
- Trajectories are ballistic from Neutralizer exit to ITER (22 m) → Transmission only depend on angle
- Each beamlet is aimed along a specific axis, to maximize the clearance with beamline components (channels in Neut. and RID)

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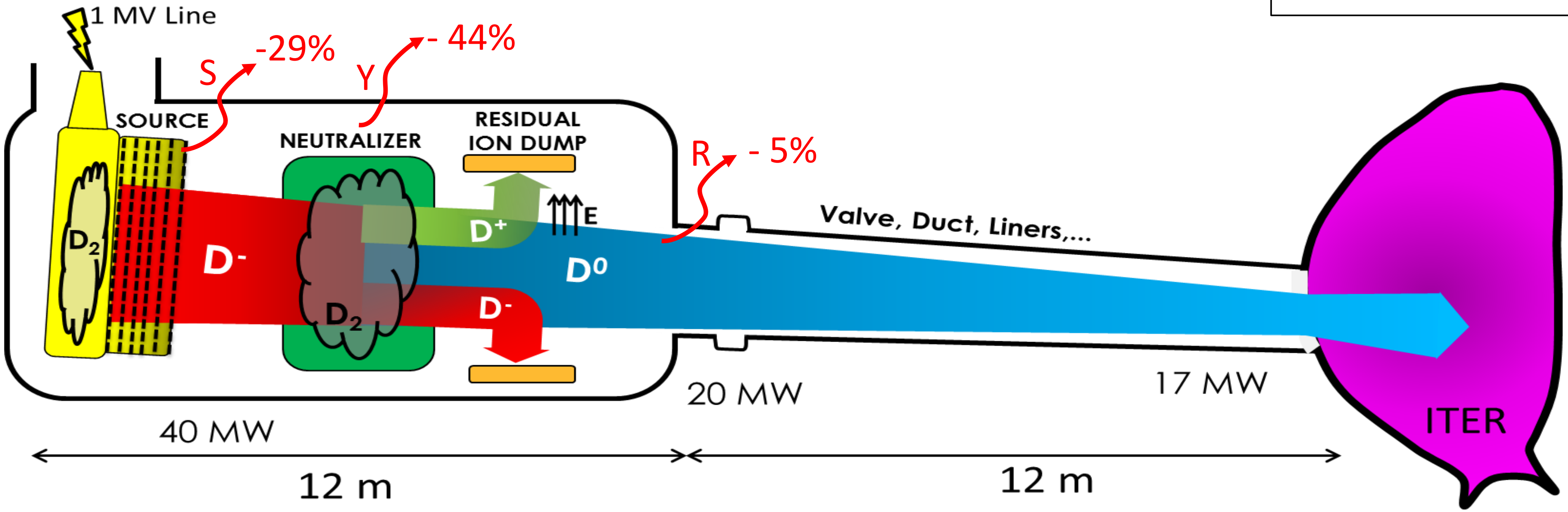

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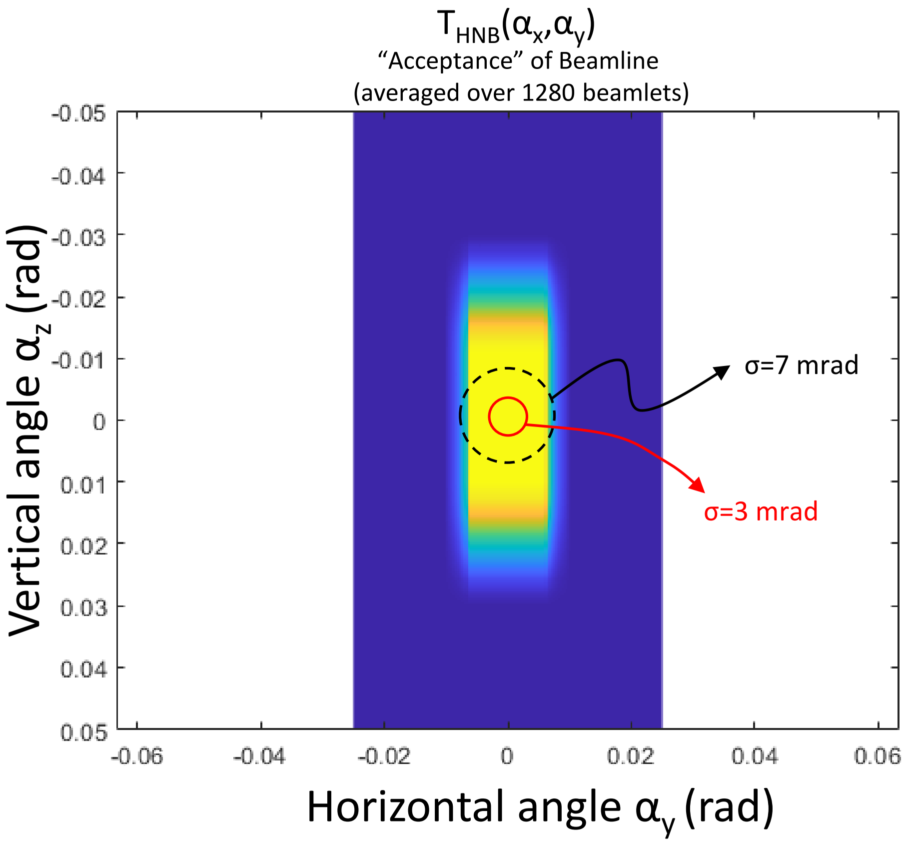

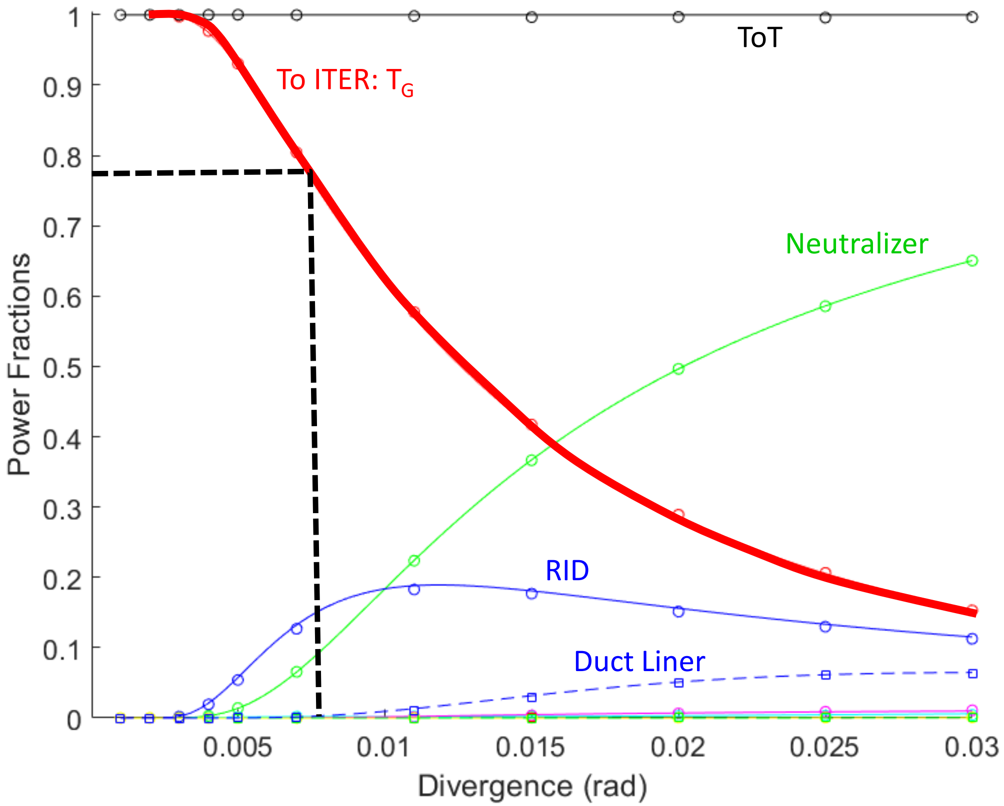

Assuming a Gaussian angular distribution, the limit of T_G =78% is reached when the distribution characterized by a 1/e width (i.e. *divergence*) of **7 mrad**

Lines: Transfer matrix approach
Symbols: BTR code

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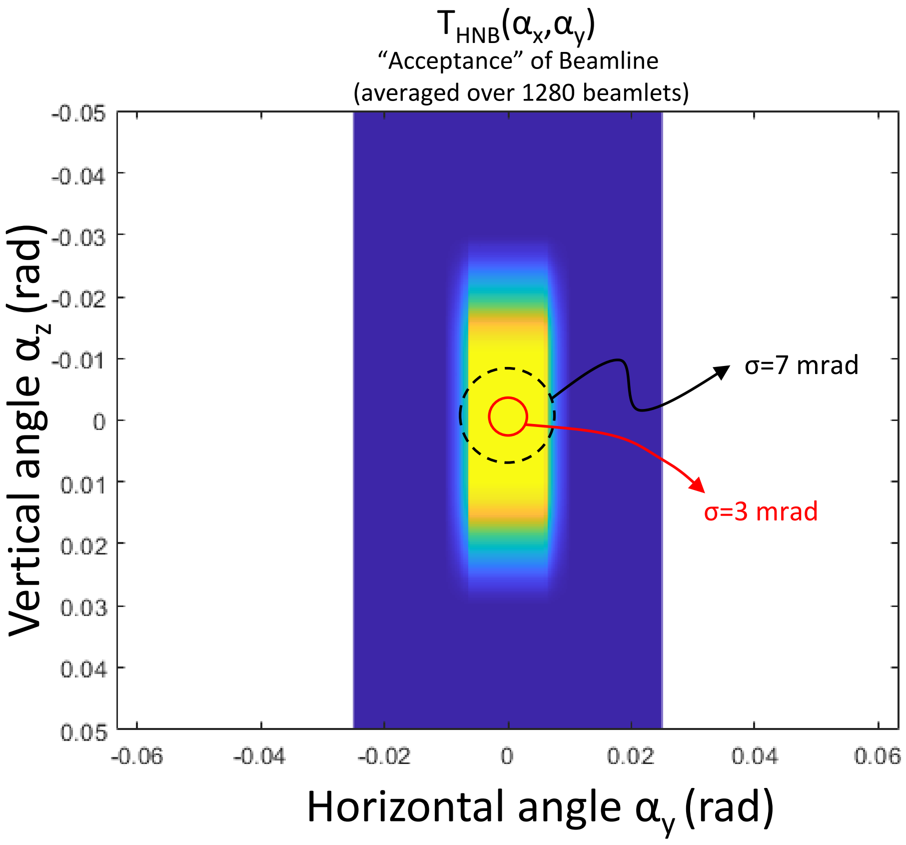

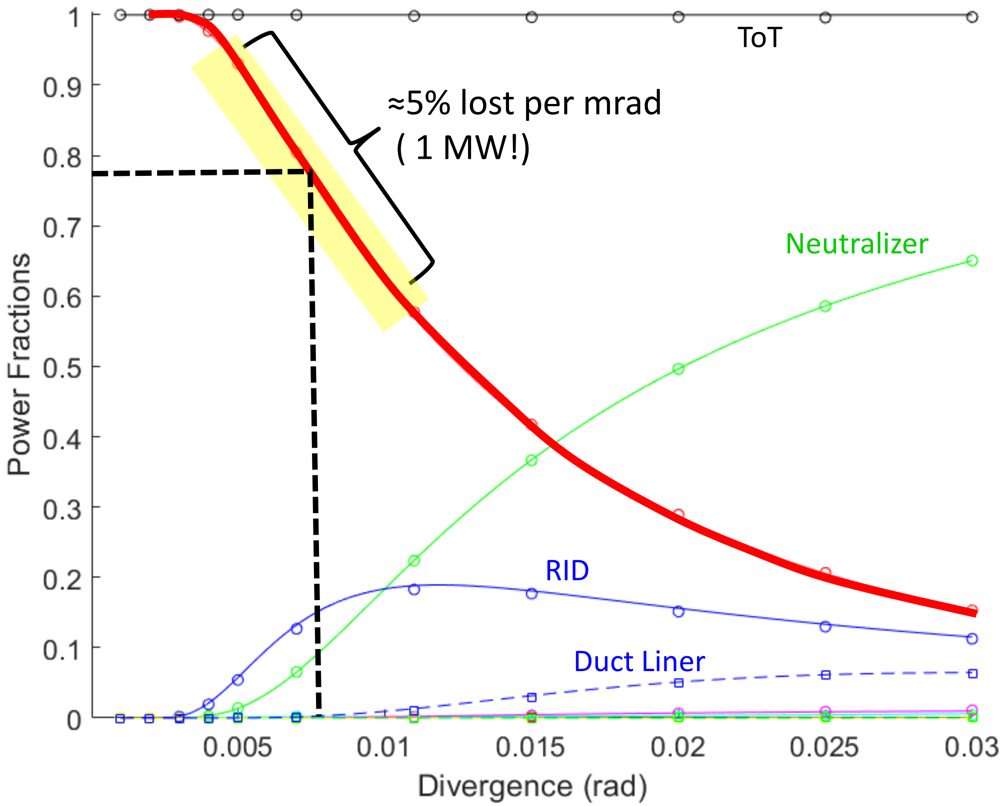

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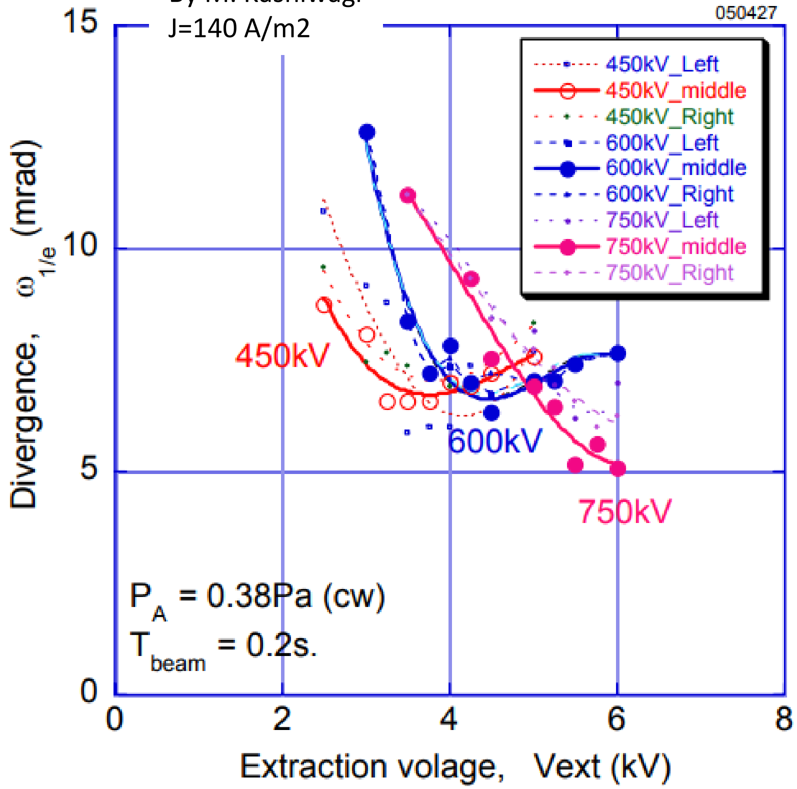
Symbols: BTR code

Beam Divergence in RF Sources

- ITER design ion source was filament driven since ~2006. Low divergence <7 mrad was routinely achieved.
- Due to filament lifetime issues, the RF concept, pioneered by IPP Garching in Germany, was later selected as baseline for ITER source
- Main Focus of research for RF sources at the time: to achieve high current densities and low co-extracted electron current.
- Today H- current density achieved at IPP close to fulfill ITER HNB requirement (330 A/m2)

By M. Kashiwagi
J=140 A/m2



T. Inoue, 4th IAEA Technical Meeting on "Negative Ion Based Neutral Beam Injectors", 2005

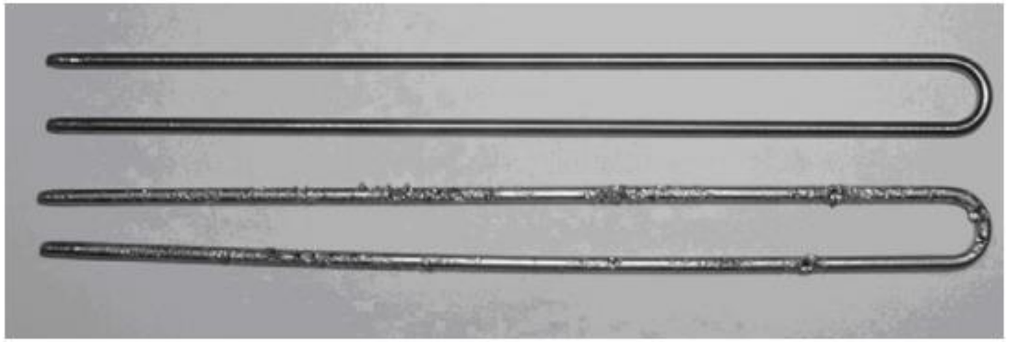


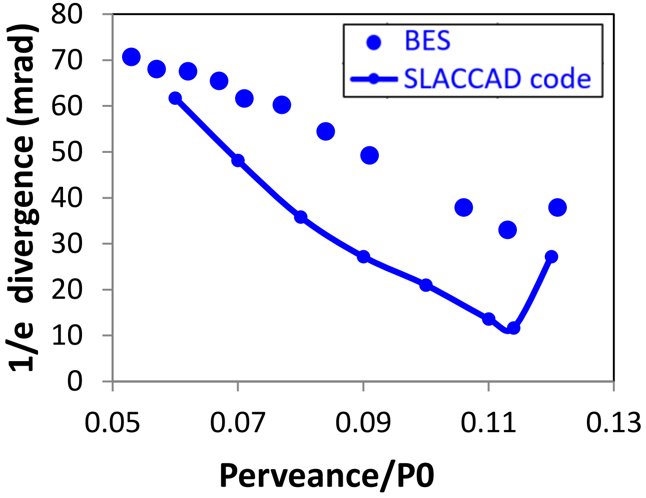
Figure 6. The MANTIS Kamaboko III tungsten filaments (1.50 mm diameter, 170 mm length): the new above, and the used after 10^4 s of plasma operation. 0.13 g of the initial 6.26 g was lost during operation.

A. Krylov et al. «Caesium and tungsten behaviour in the filamented arc driven Kamaboko-III negative ion source» Nucl. Fusion 46, 2006

Beam Divergence in RF Sources (2018)

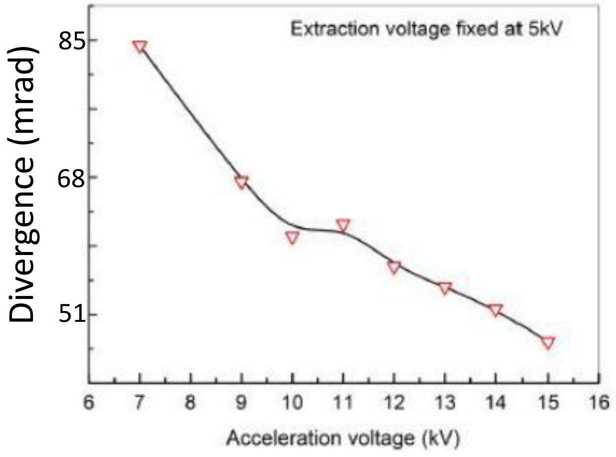
- Single beamlet divergence measured in RF sources (not only in IPP) > 25 mrad!
- Possible causes: Absence of compensation of B field, accelerator not optimized for divergence (JET/PINI-like), Low current,…
- Differences in diagnostics systems and analysis techniques
- Ray tracing codes (SLACCAD, OPERA, Ibsimu, …) gives lower divergences unless high $T_{\perp}$ assumed
- Same codes works well for positive sources and arc sources

MANITU, IPP



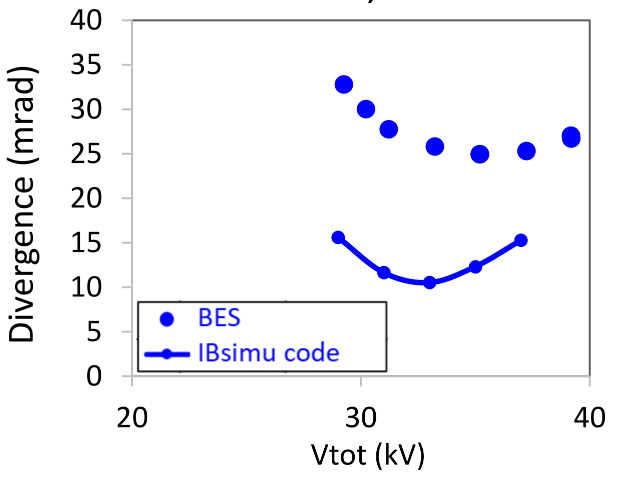
Adapted from: P. Agostinetti et al, AIP Conf. Proc. 1515 (2013)

ROBIN, IPR



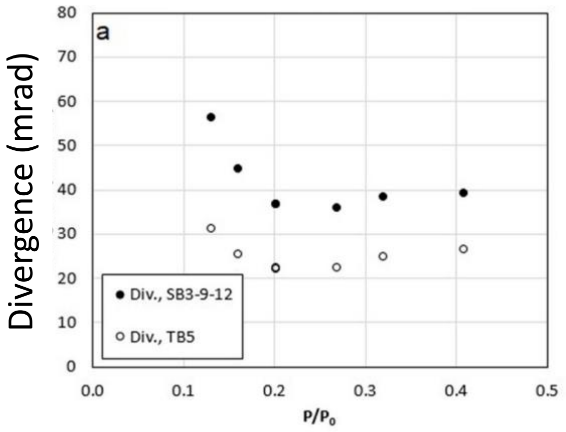
Data Courtesy of M. Singh, IPR

ELISE, IPP



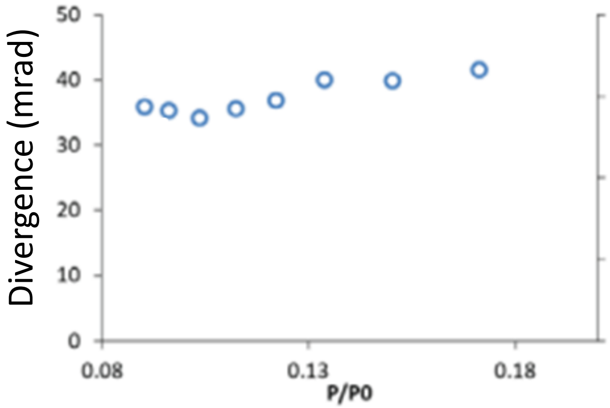
Data Courtesy of IPP, Experimental Campaign July 2017

SPIDER, NBTF



M. Barbisan et al. Plasma Phys. Control. Fusion 63 (2021) 125009

NIO1, RFX-INFN

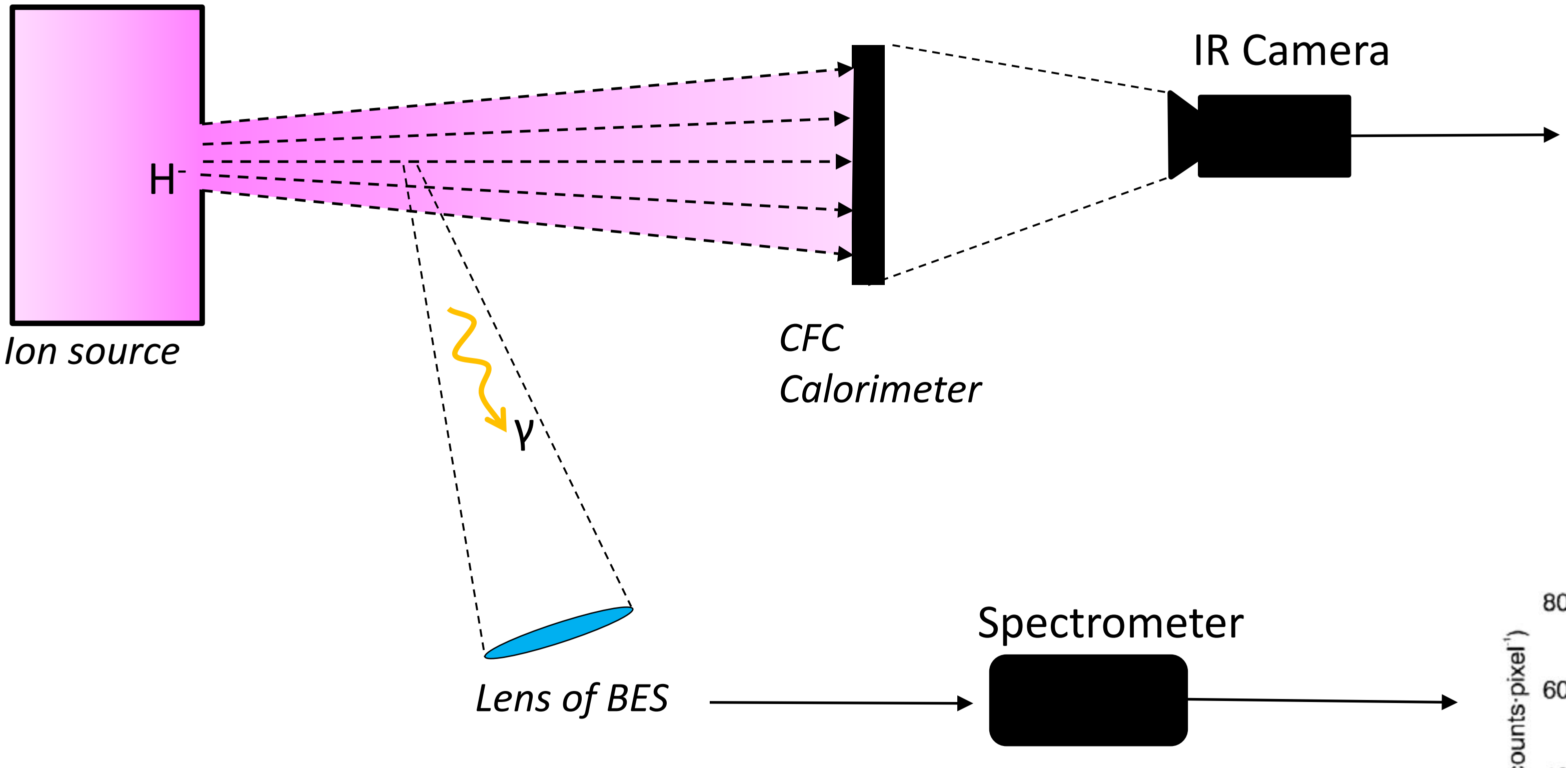


M. Barnisan et al. AIP Conf. Proc. 2011, 080012 (2018)

- Results compared and discussed within the NBTF Experiment Advisory Committee (EAC).

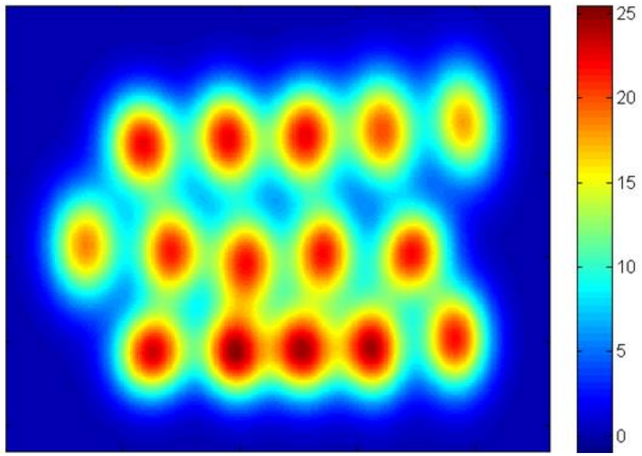
Diagnostics for beam divergence: BES and CFC

- Additional Complexity: Different diagnostics (BES vs. CFC tile) used in the RF or Arc based test beds
- Cross validation Required



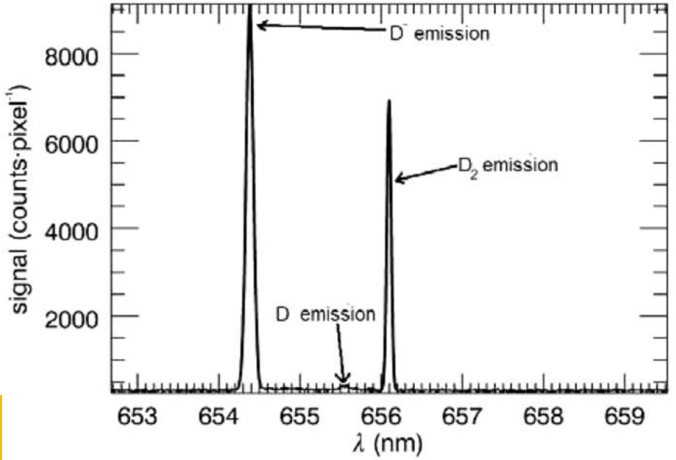
CFC–IR Calorimetry aka “beamlet Monitor”

(Standard in Arc Source)



Beam Emission Spectroscopy

(Standard in RF source)

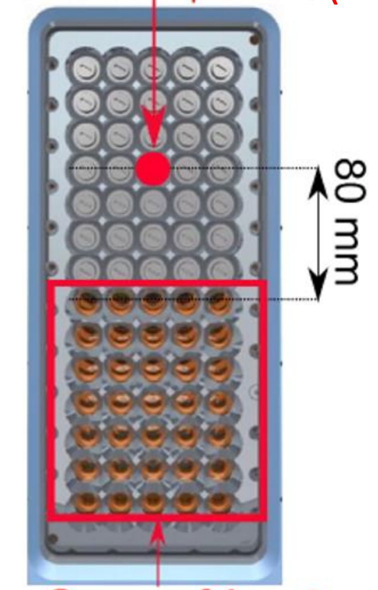


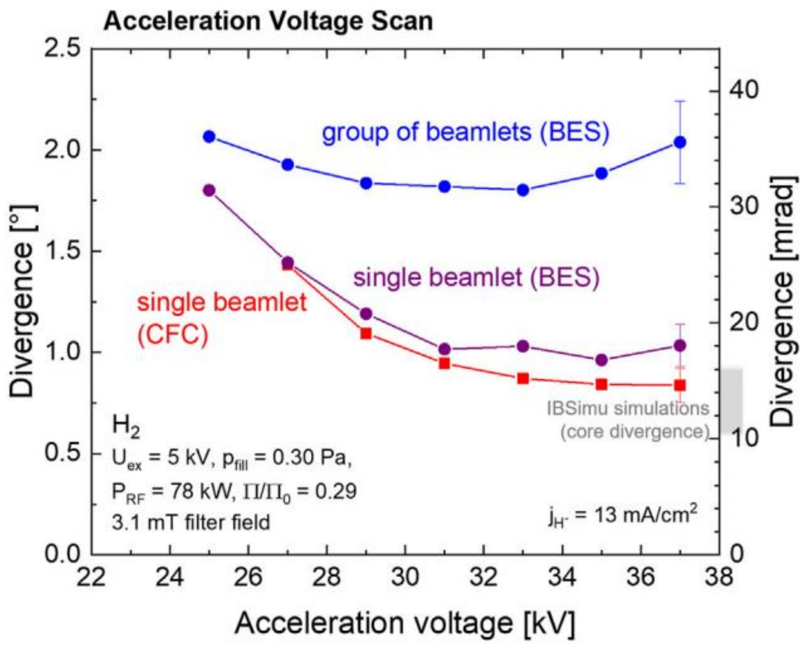
Diagnostics for beam divergence: BES vs CFC

Additional Complexity: Different diagnostics (BES vs. CFC tile) were used in the RF or Arc based test beds and a cross validation of them was therefore advisable.

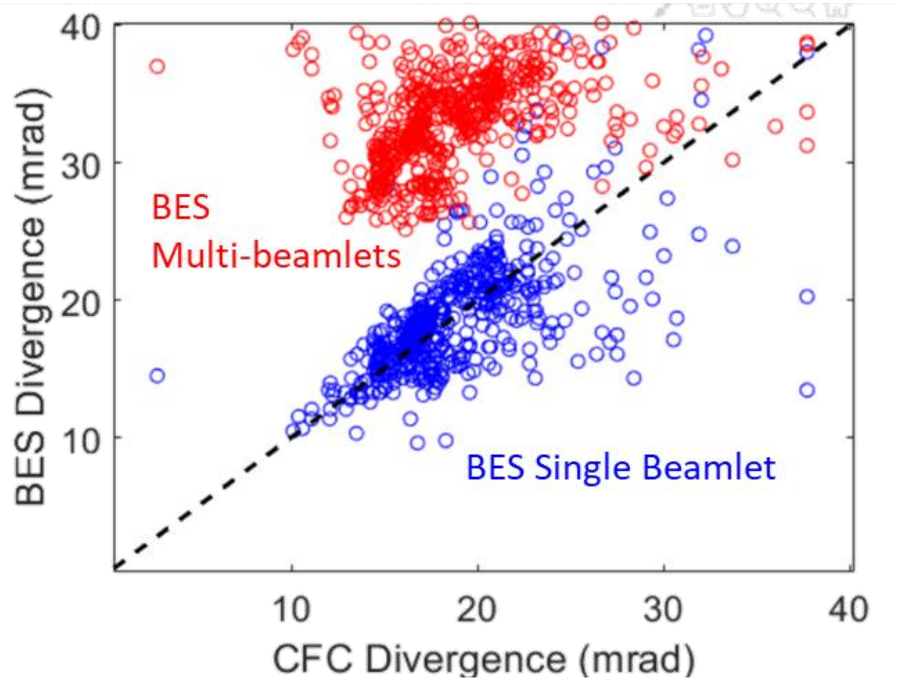
Test in BATMAN Upgrade (2019) by IPP-RFX:

- Good agreement between the two for single beamlet
- Multi-beamlet effects (zig-zag deflection, repulsion,..) → Apparent increase of BES divergence



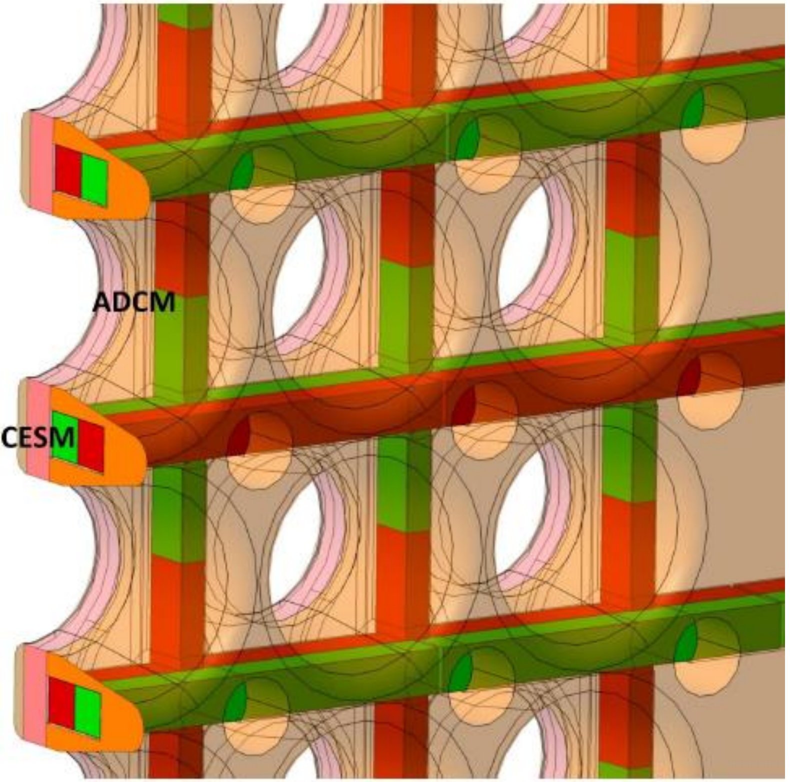


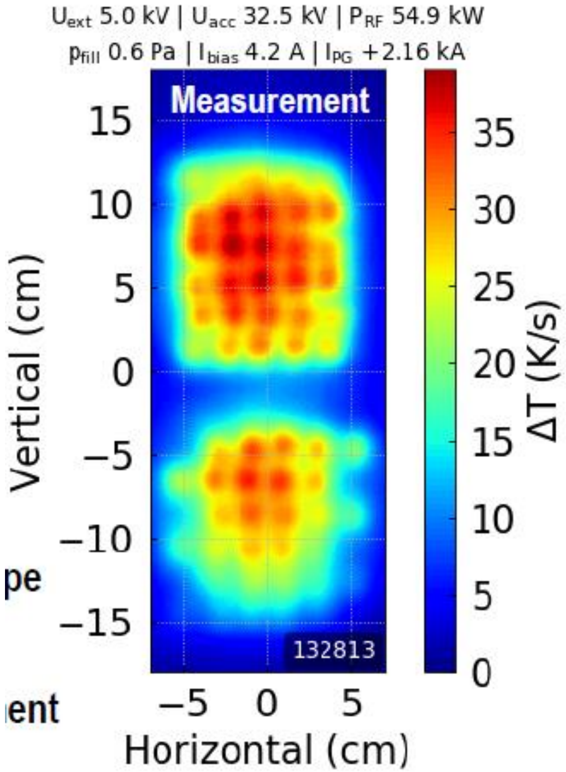
U. Fantz et al. Front. Phys. 9:709651 (2021)

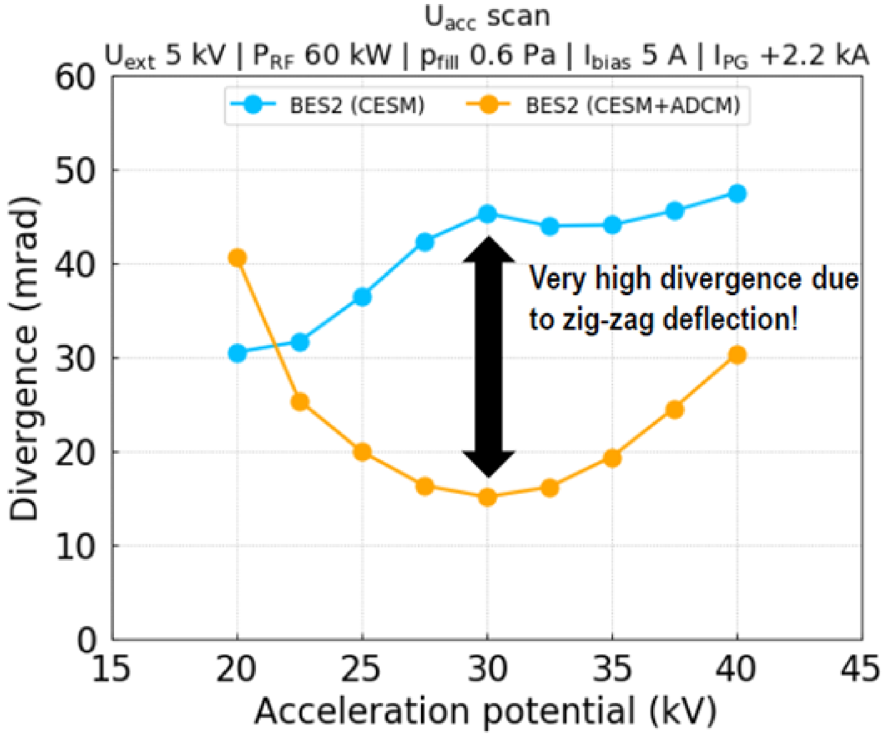


Diagnostics for beam divergence: Compensation of deflection

- Tests with MITICA-like Extractor at BUG (IO-IPP collaboration) Included a compensation system for the zig-zag deflection, based on the ADCM magnets in the EG.
- Divergence measured with BES on a group of beamlet decreases considerably, and matches the divergence from single beamlet.



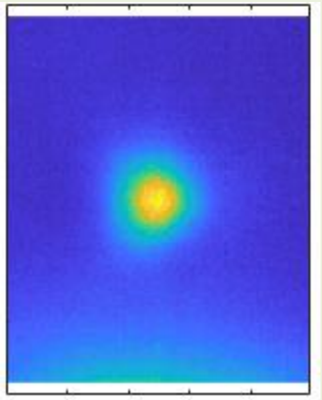
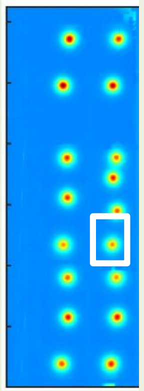
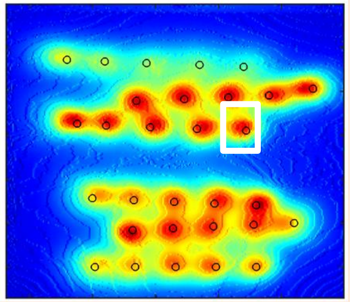
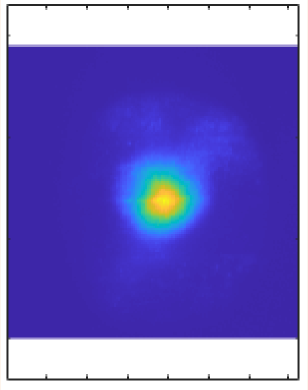
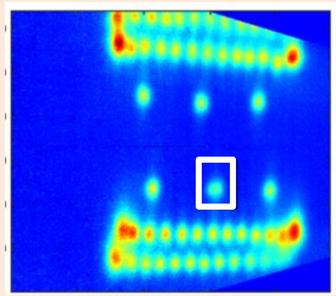




N. den Harder @ EAC Meeting #7

Beam Divergence in RF sources: Benchmark

In the course of years the CFC tile (IR calorimetry) was available in several labs→ ideal diagnostics for comparisons
Divergences from 5 test beds (2 RF, 3 Arcs) calculated independently by different labs, on the basis of common data sets

Parameter	**RF Sources**		**Arc Sources**		
	BUG (IPP)	SPIDER (NBTF)	NITS (QST)	MTF (QST)	RNIS (NIFS)
P_{is} [Pa]	0.31	0.35	0.3	0.3	0.3
RF/Arc Power [kW]	68.5	23/driver		36.6	70
U_{ex} [kV]	4.6	4	4.25	7.1	2.7
U_{acc} [kV]	**31.8**	**38**	**22.3**	**790**	**40**
d [mm]	851	500	903	2400	846
CFC thickness [mm]	20	20	10	10 (FRONT)	10
Preview Full IR data					

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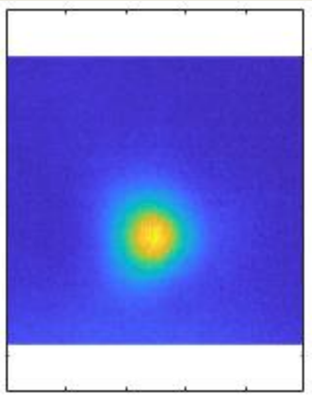
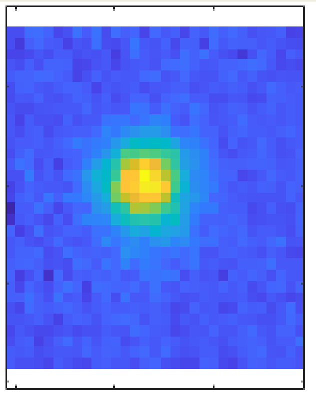
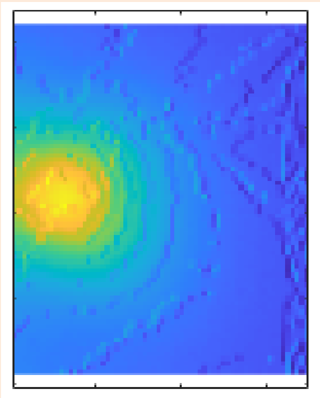
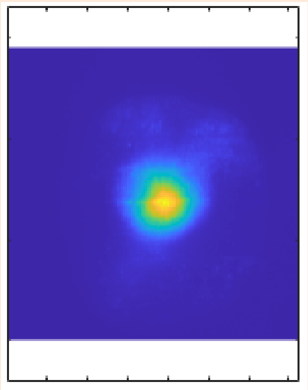
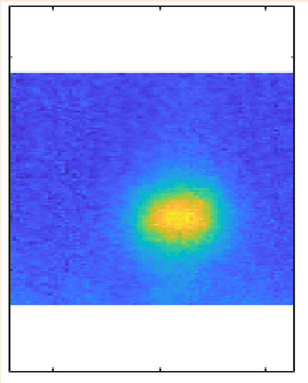
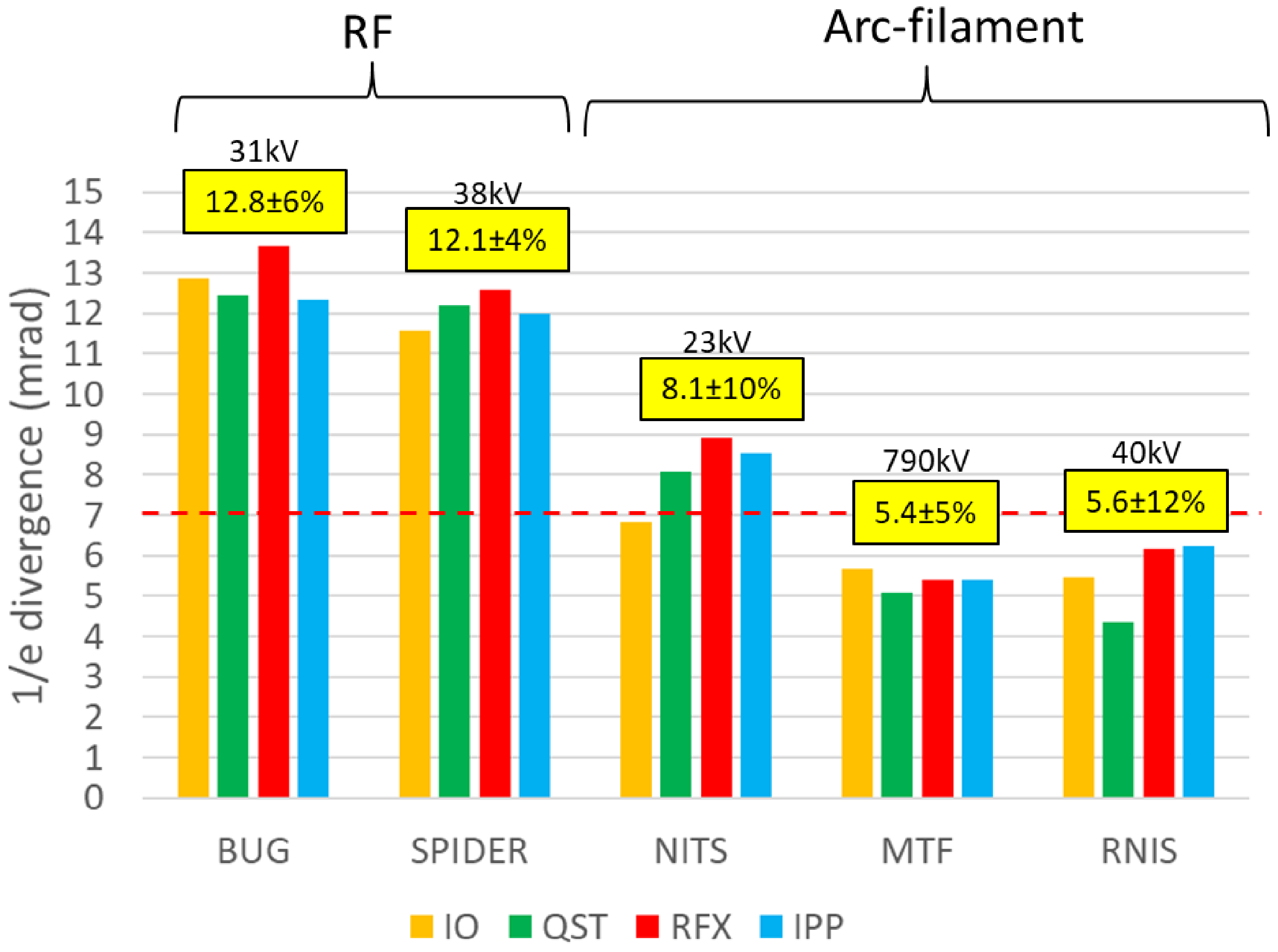
Preview **Cropping of selected beamlets**					

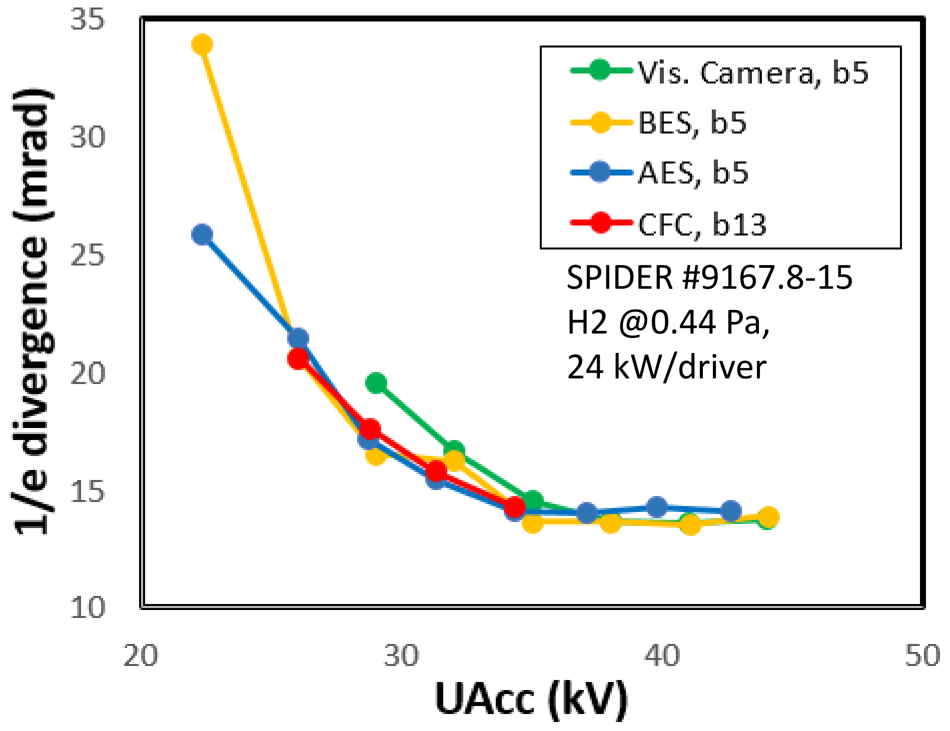
Beam Divergence in RF sources: Benchmark

- Variation due to analysis technique or operator choices cannot justify the discrepancy
- Beam Divergence of RF sources > 7 mrad
- Arc Source have divergence ≈7 mrad or below
- This information might help understanding the cause of higher divergence in RF sources
- Some common principle for CFC data analysis were shared and agreed by laboratories
- Single Gaussian + Offset enough to produce meaningful results.

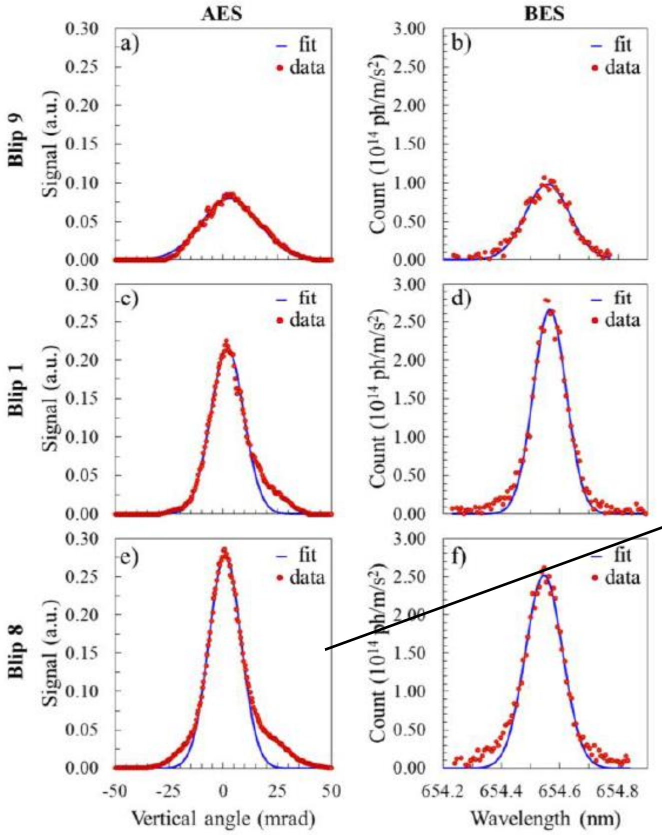


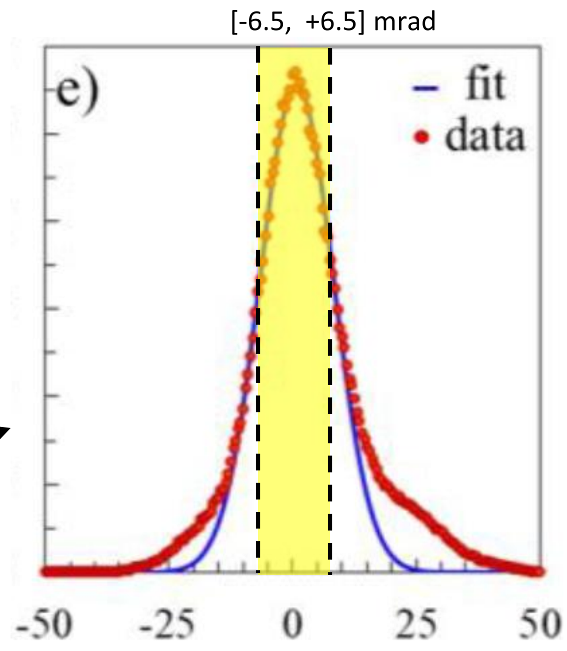
Diagnostics for beam divergence

- CFC tile can provide straightforward measure of beam quality, in 2D. Need assumption on beamlet size at GG exit
- Additional diagnostics available at SPIDER confirmed the accessible range of values in RF sources



Data Courtesy of M. Ugoletti, M. Barbisan, M. Poggi, and A. Pimazzoni (RFX)



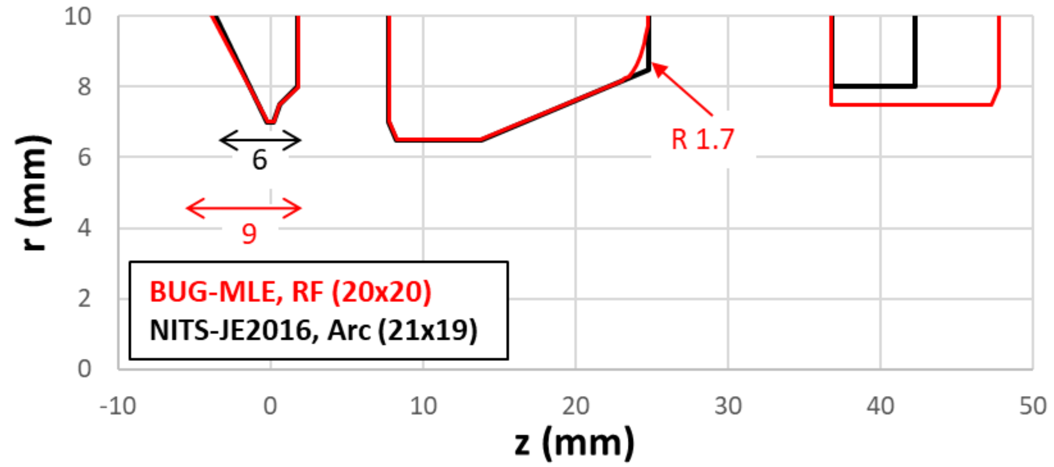


G. Serianni et al. Submitted to IEEE Transactions on Plasma Science

- Allison Emittance Scanner (AES) @ SPIDER also confirmed the existence of large lateral wings in the angular distributions (also spotted with CFC).
- This shows the limits of the (bi-) Gaussian approximation. Diagnostics for precise Angular distribution in high demand!
- 2D angular distribution would give more precise results on transmitted fraction $T_{G.}$ (Typically worse!)

PG/EG design

- The experiments with MITICA/HNB Like Extractor in QST (2017) and IPP (2021) Allowed to check the performances of the two ion sources concept with almost same extractor (PG + EG)
- GG-to-CFC distance almost same (850 vs. 900)
- Core Divergence measured in Arc source significantly lower (and not even at Perv. Match for this shot)



	BUG, IPP	QST, NITS
U_{ex} [kV]	4.6	4.25
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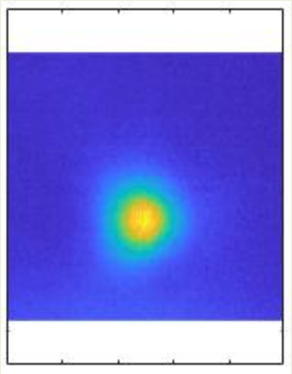
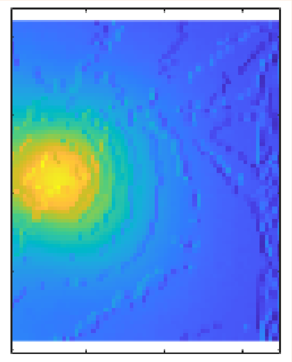
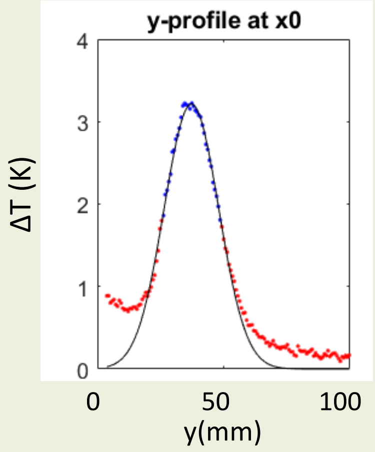
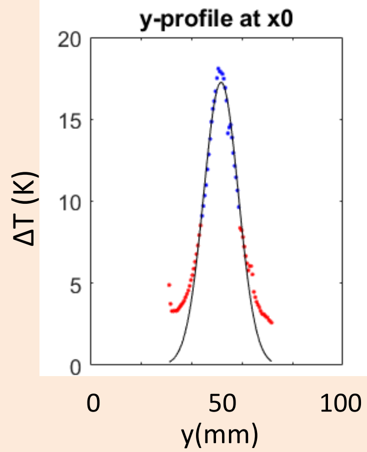
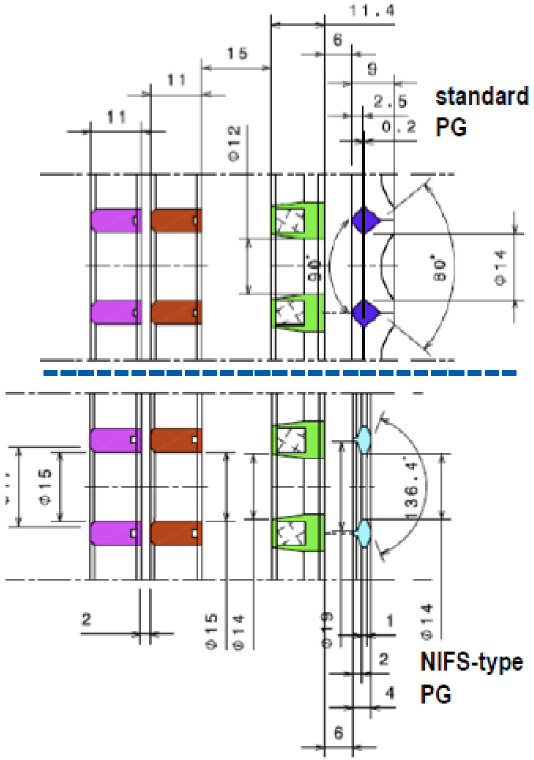
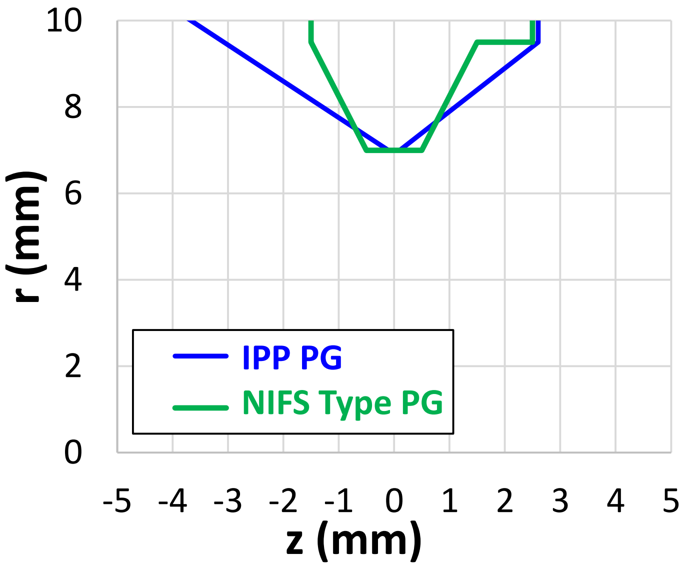
Preview Full IR data		
Fit With Threshold at 30%	 div. y≈15 mrad	 div. y≈8 mrad

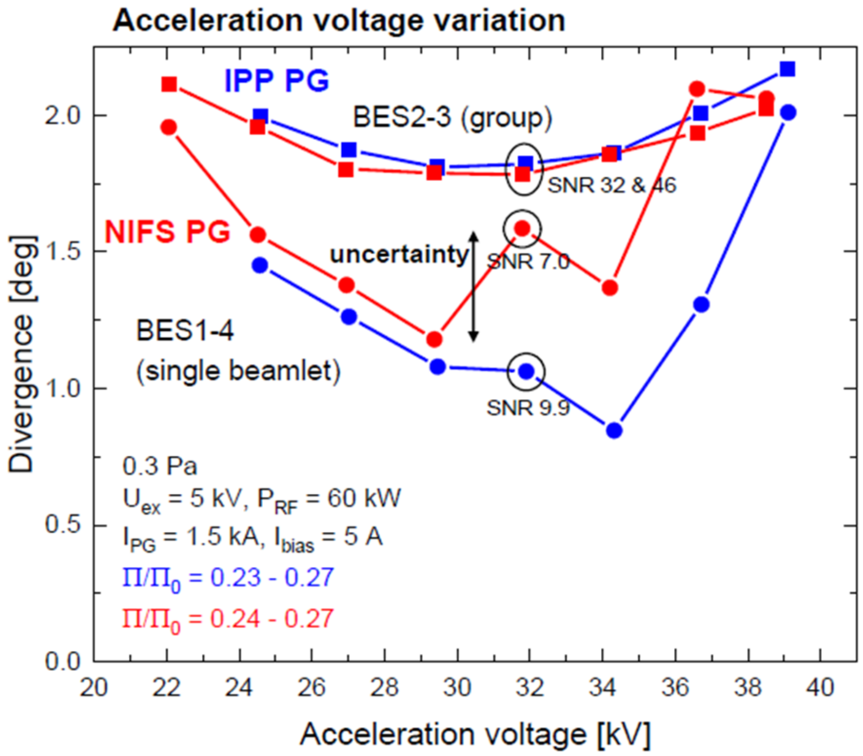
PG Chamfer /Thickness

The effect of the PG shape on beam optics was tested within a collaboration IPP-NIFS
Inner side: might affect H- transport before extraction→ Steep angle towards the plasma (+50%)
Outer side: Focusing of particle after meniscus
Thickness: distance of plasma from EG magnets

<u>No significance difference that could explain the typically lower divergence of filament ion source</u>



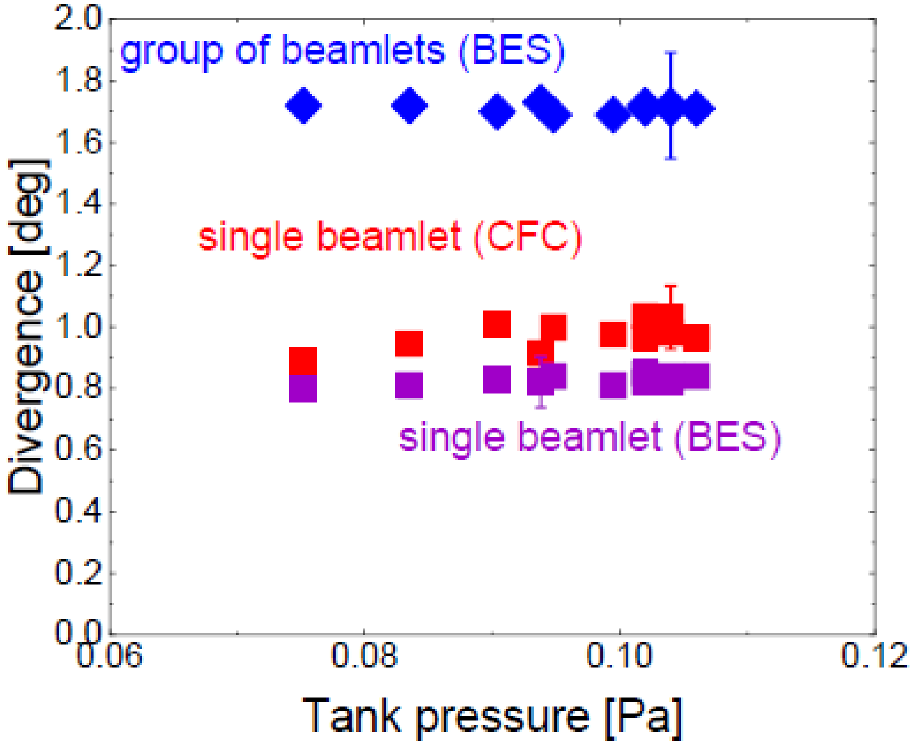




Space Charge Compensation

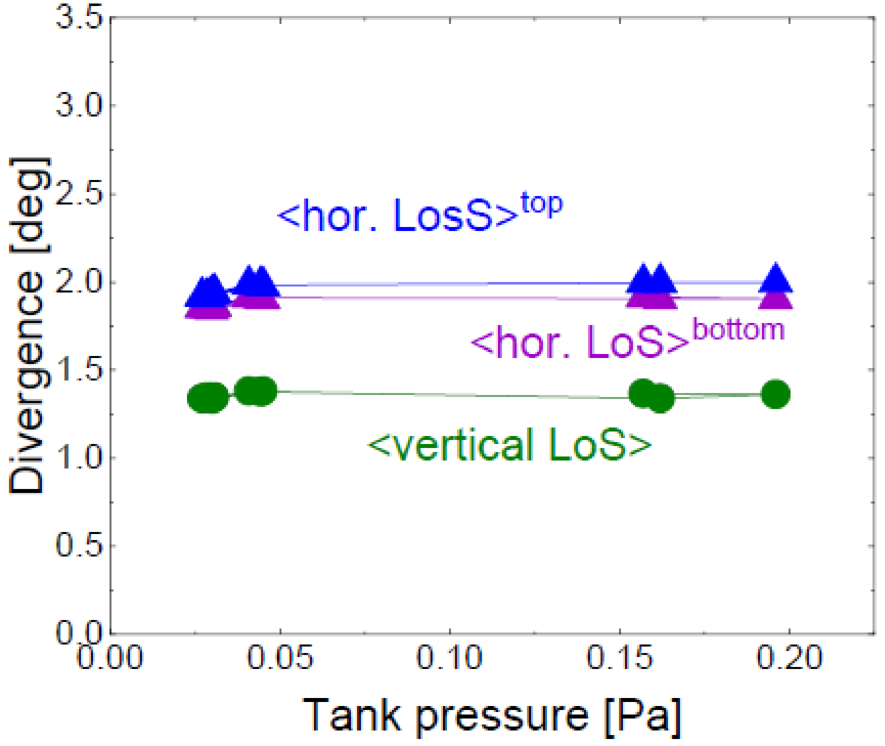
- Divergence does not depend on tank pressure (keeping P source constant)

BATMAN UPGRADE, IPP



H, 0.5 Pa, RF=55kW, j_{ext}=130A/m²
U_{ext}=4.6kV, U_{acc}=31kV, P/P0=0.3, 1.5mT

ELISE, IPP

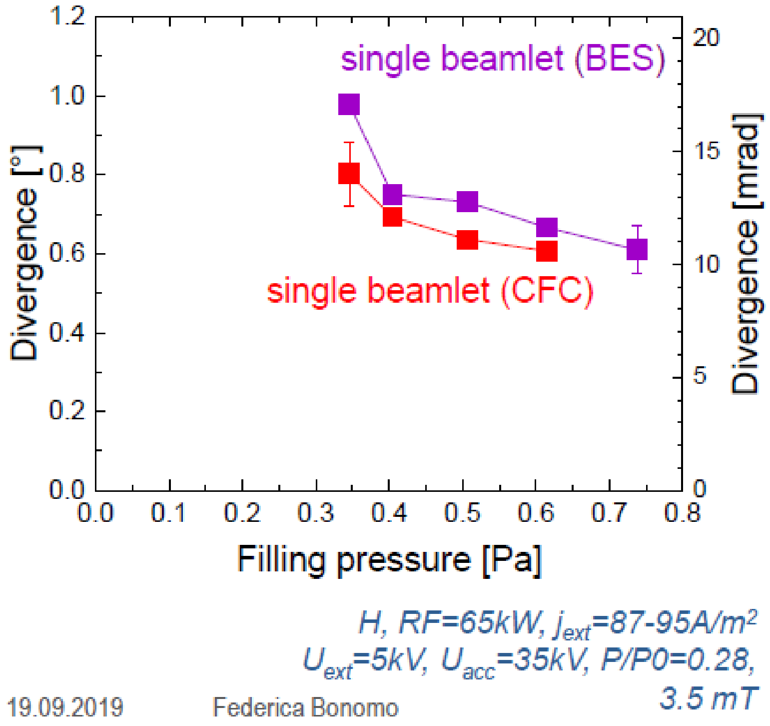


H, 0.28 Pa, 85k W/generator, $j_{ext}\approx$140A/m²
5kV+30kV, I_{PG}=1.3kA+ExtMagnets

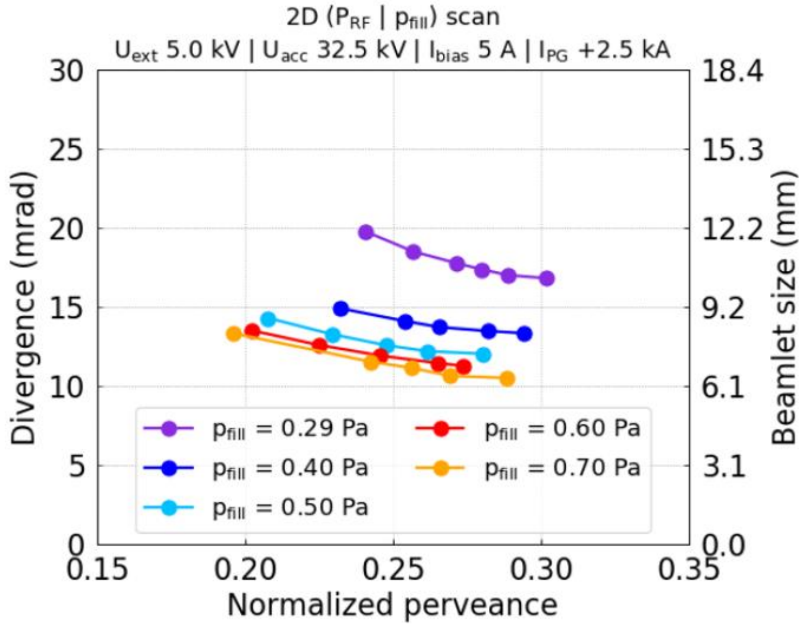
Filling Pressure Dependence

- Divergence does not depend on tank pressure (keeping P source constant)
- BUT depend strongly on ion source filling pressure

BUG, IPP 2019



BUG MITICA Like Extractor, IPP 2021



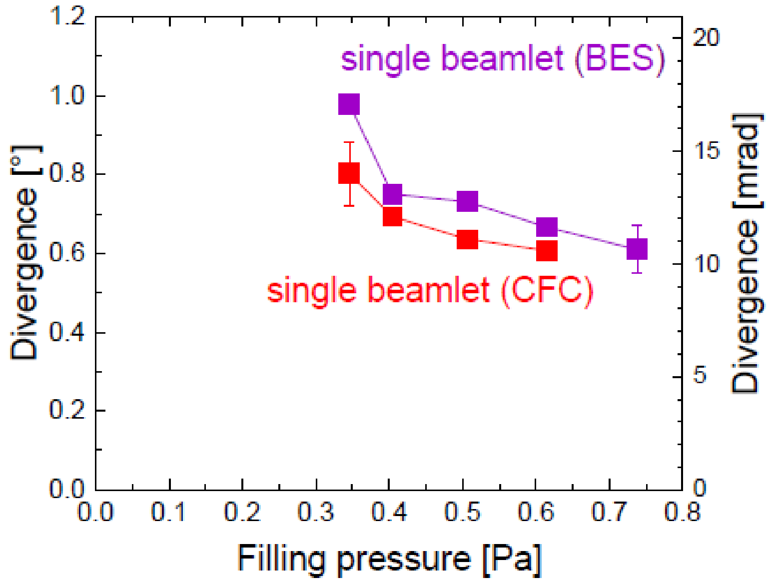
See Talk by A. Pimazzoni, Tue 4, 15:40

Same trends observed at ELISE, SPIDER, NIO1

Filling Pressure Dependence

- Divergence does not depend on tank pressure (keeping P source constant)
- BUT depend strongly on ion source filling pressure ⟶ Via H- temperature?

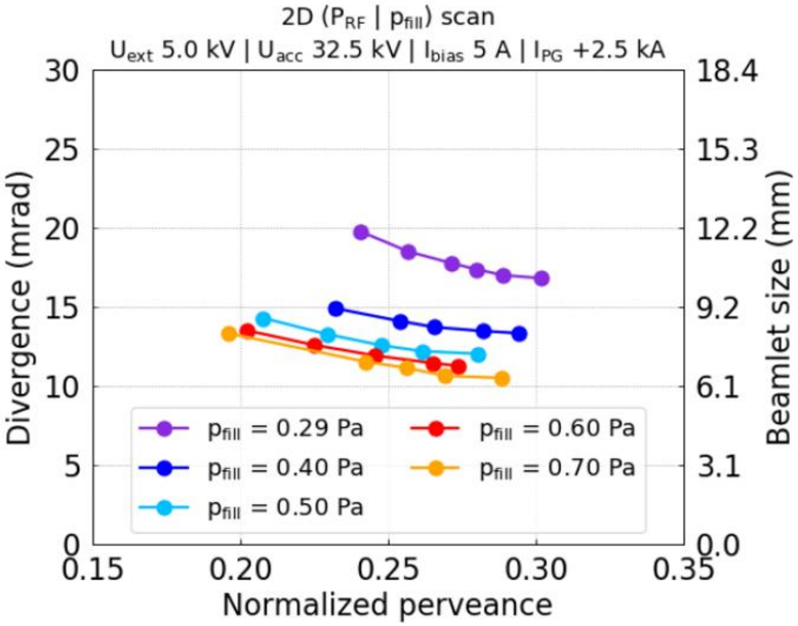
BUG, IPP 2019



H, RF=65kW, j_{ext}=87-95A/m²
U_{ext}=5kV, U_{acc}=35kV, P/P0=0.28,
3.5 mT

19.09.2019 Federica Bonomo

BUG MITICA Like Extractor, IPP 2021



See Talk by A. Pimazzoni, Tue 4, 15:40

Reproduced from: M. Bacal et al. Journal of Applied Physics ***70****, 1212 (1991);*

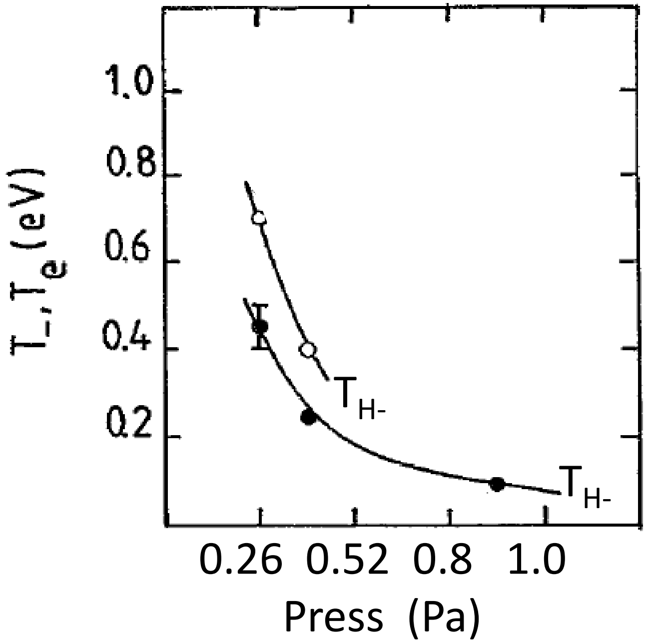


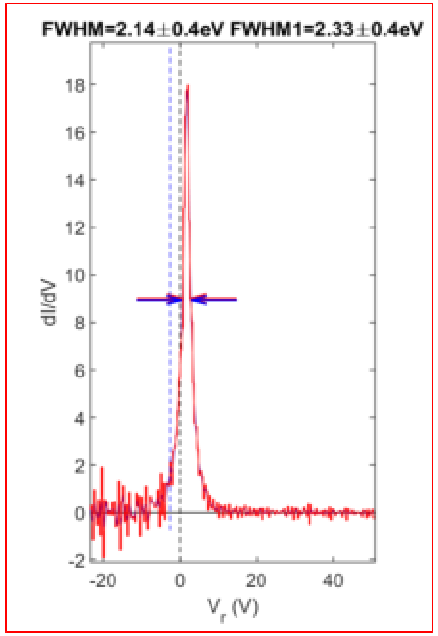
FIG. 8. Negative ion and electron temperatures vs pressure, at constant discharge current. The discharge voltage was 50 V. Open circles: 20 A; full circles: 5 A; full line: T_-; dotted line: T_e.

Same trends observed at ELISE, SPIDER, NIO1

RFEA Measurements in RF and Arc Sources

Retarding Field Energy analyzer measurements (RFX-NIFS) show very different ion energy distributions in RF and arc sources

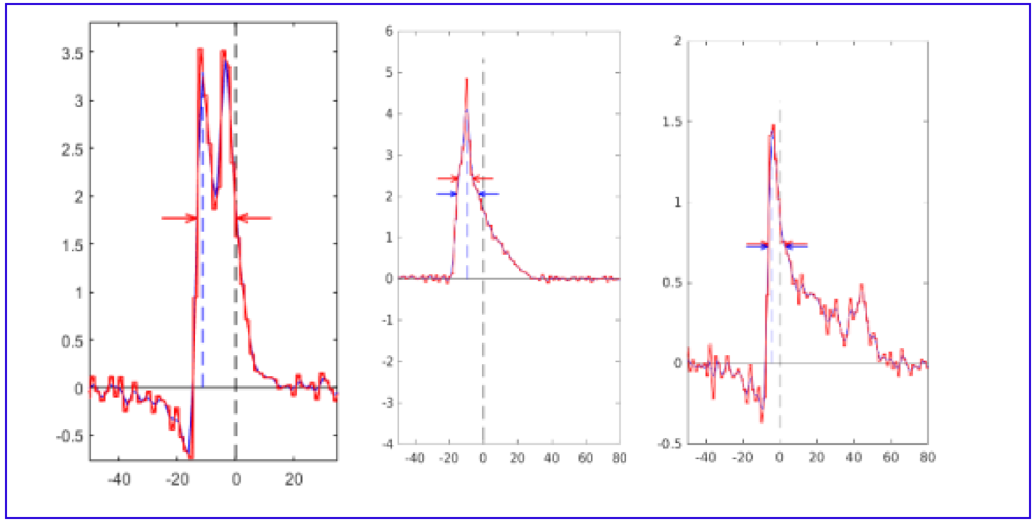
Arc Source (R-NITS, @NIFS)



Width of Distribution
1-2 eV

Source parameters do not change the width of the distribution

RF Source (SPIDER @NBTF)



Width of Distribution
10-40 eV

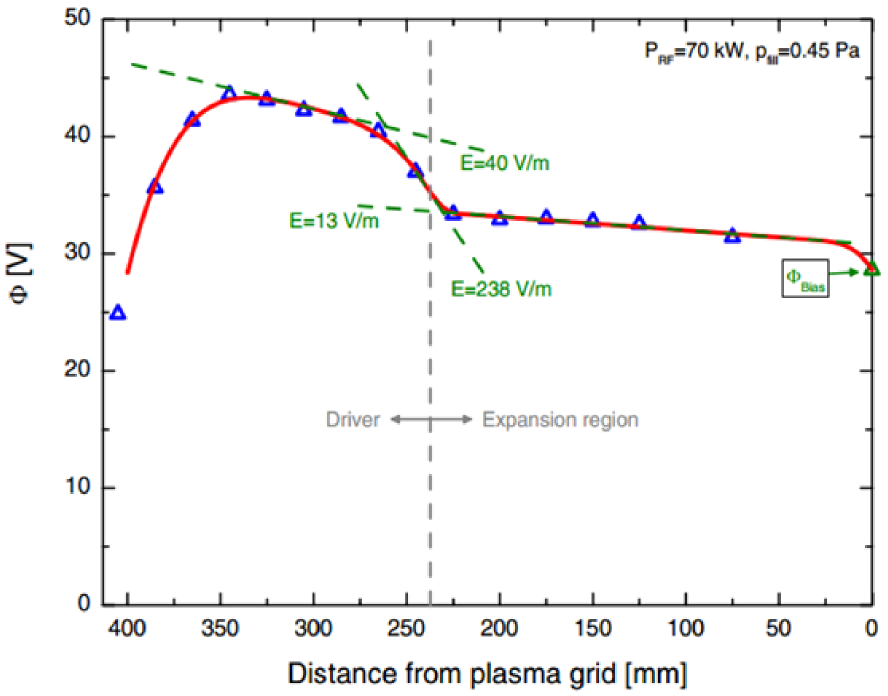
E. Sartori et al., Fusion Engineering and Design Volume 169, (2021)

Source parameters change a lot the width and shape of the distribution

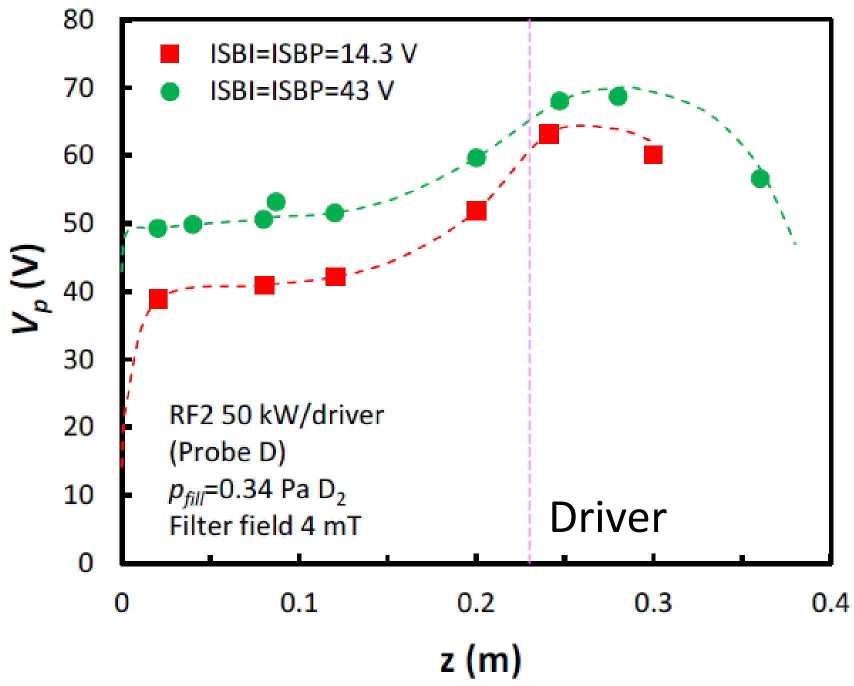
RFEA Measurements in RF and Arc Sources

- Arc sources: plasma potential is 2-3 V and almost flat inside the source
- In RF sources there is a high plasma potential difference (10-20V) between driver and expansion regions

  → acceleration of H^+/ H_2^+ that may exchange charge and momentum with H^0 and H^- in PG area: In both cases the extracted H^- would have a high transverse energy



Wunderlich et al., Plasma Physics and Controlled Fusion 54, 125002 (2012)



E. Sartori et al., Fusion Engineering and Design Volume 169, (2021)

- This hypothesis is debated and needs experimental confirmations. Modelling with test a particle model supports it.

See Talk by A. Pimazzoni, Tue 4, 15:40

Activities Ongoing / under Discussion

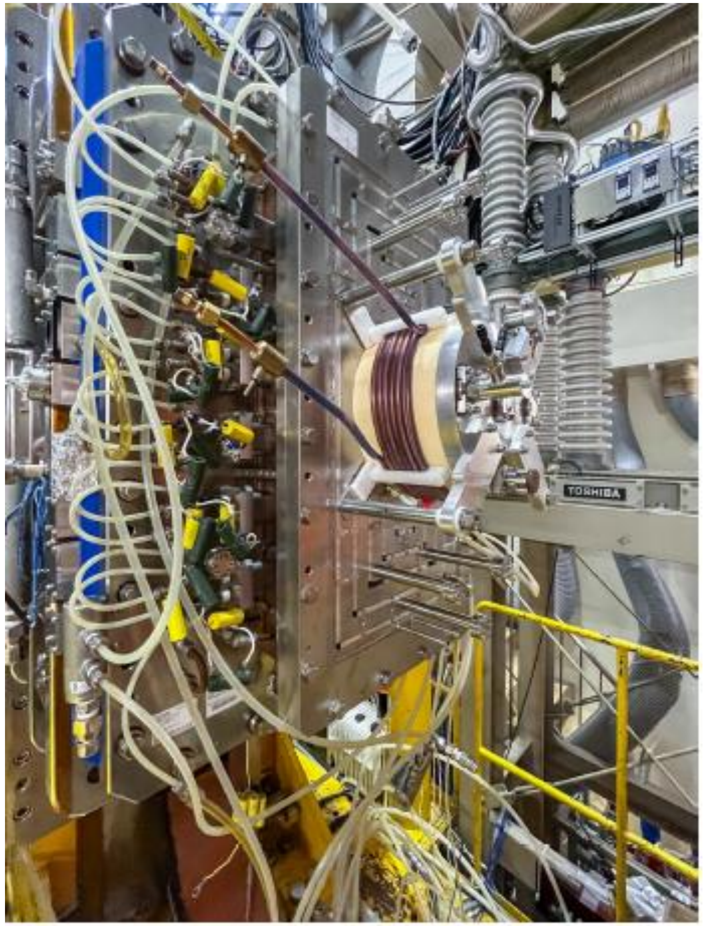
- Upgrade of SPIDER, with extensive diagnostic set (fixed RFEA + probes, Improved Emittance scanner, ….)

See Talk by E. Sartori, Wed 5, 9:20

- Joint Experiments RFX-IPP to characterize beam vs plasma properties RFEA, Emittance Scanner

- Joint Experiments RFX-QST to test MTICA accelerator at 1 MeV

- Tri-lateral collaboration IO-IPP-NIFS (2021-2025)
  - ➢ Use of on IPP facility MANITU (plasma driver, coil, RF power supplies, transformer…)→ Hybrid Source RF/ARC
  - ➢ Extensive set of source and beam diagnostics available at NIFS
  - ➢ Scope: Characterizing RF Plasma against beam divergence
  - ➢ Commissioning Ongoing



See Talk by K. Tsumori, Tue 4, 12:20

Conclusions and Outlook

- Following Observations of highly divergent beams in different fusion labs, in the last 3-4 years the beam divergence became one of the main research topics

- Several activities started to characterize /quantify the problem. Only a selection was given here.
  - ➢ Specific Investigations of the particle properties inside the plasma
  - ➢ Modelling and improvements in the diagnostics systems
  - ➢ Upgrades of existing ion sources / accelerators

- Results of benchmark activities involving several labs, allowed to quantify the divergence measured in RF source into about **12 mrad (at 0.3 Pa).**

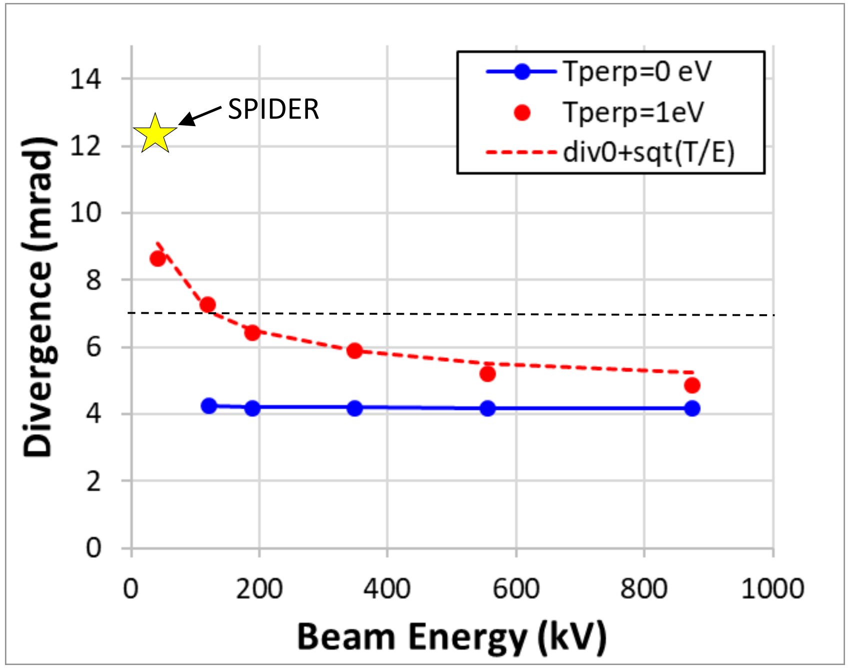
- A possible explanation is given by the large potential difference between driver and PG areas and consequent acceleration of positive ions. To be confirmed by experiments.

- Divergence scaling with energy suggest that divergence < 7 mrad is achievable at 1 MeV.

<u>But:</u>

- Beam-grid interaction along the 0.6 m long accelerator
- Diagnostic Neutral Beam (DNB) need to be operated at 100 keV

→ Mitigations/Solution still under investigation. To be continued…



Modelling results, H- beam, 870 keV, IBsimu

Thank you!

Spare Slides

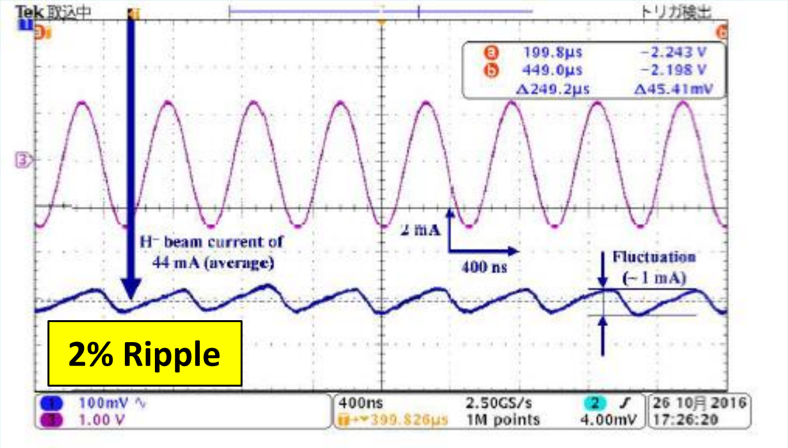
Density/Current ripple

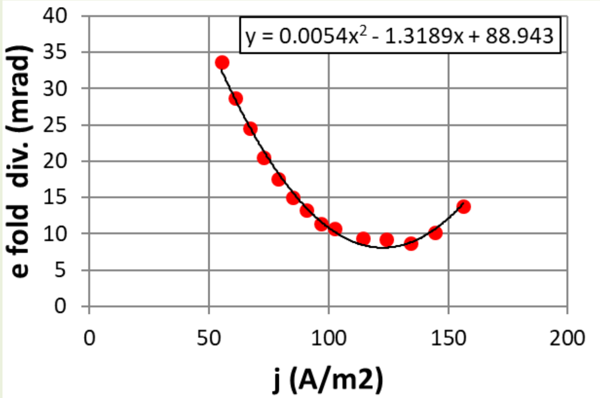
- Oscillation of Plasma light [1] or beam current [2] observed in small RF sources.
- At constant voltage divergence change over an RF cycle: The RMS divergence might be higher than the optimal one

H- current oscillates at the RF frequency (2 MHz)[2]

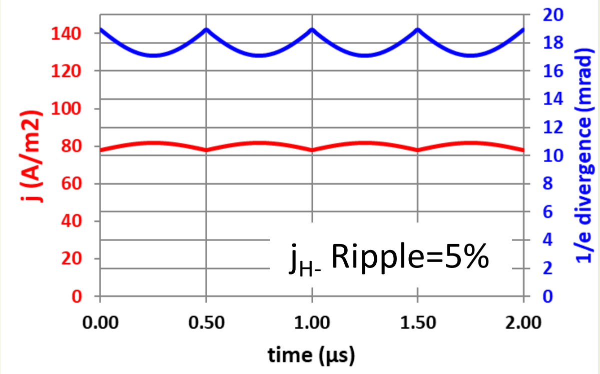
Nonetheless, divergence dependence on current relatively flat around optimum

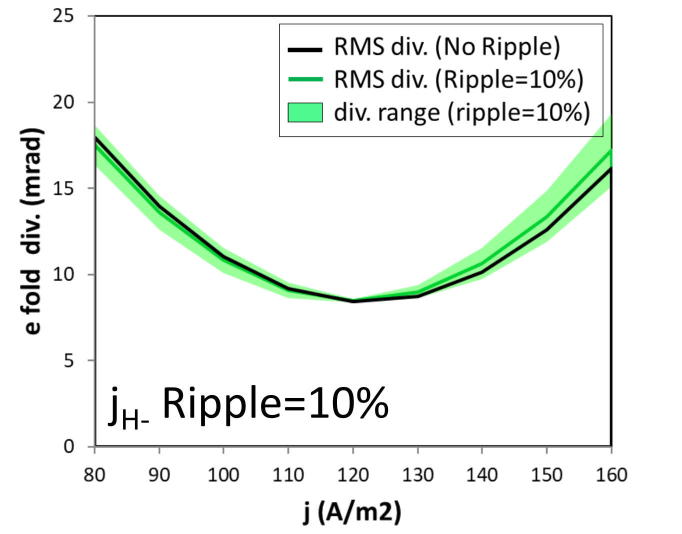
Minimum divergence should not be affected





Fit of Ibsimu code results Div. vs. j





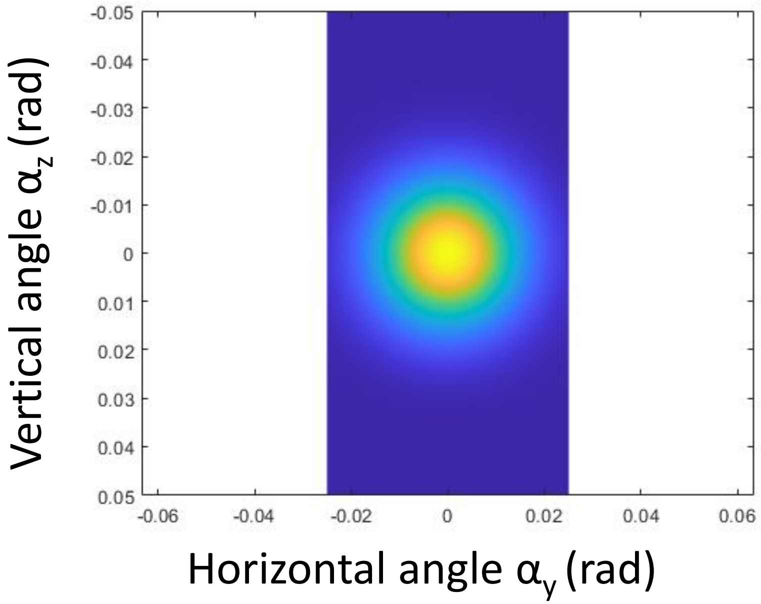
[1] T. Shibata et al., *Observation of plasma density oscillation with doubled value of RF frequency in J-PARC RF ion source*, AIP Conference Proceedings 2011, 020008 (2018);

[2] K. Shinto, T. Shibata, A. Miura, T. Miyao and M. Wada, *Observation of Beam Current Fluctuation Extracted from an RF-driven H- Ion Source*, AIP Conference Proceedings 2011, 080016 (2018);

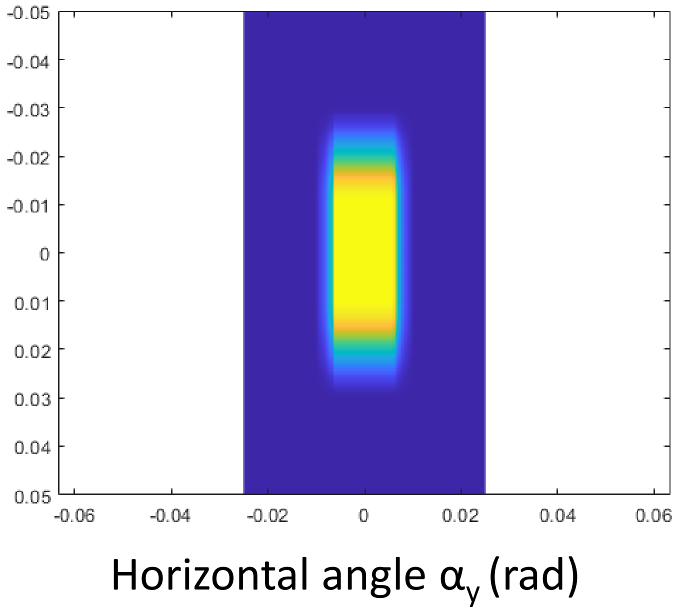
Owing to the symmetry of the system, (and for ideal alignment and uniform divergence along extraction area) one can obtain the acceptance of the beamline can be averaged

Horizontally: Sharp cutoff at about 6.5 mrad → Neutralizer channels
Vertically: Wider acceptance to accommodate the need for source tilting

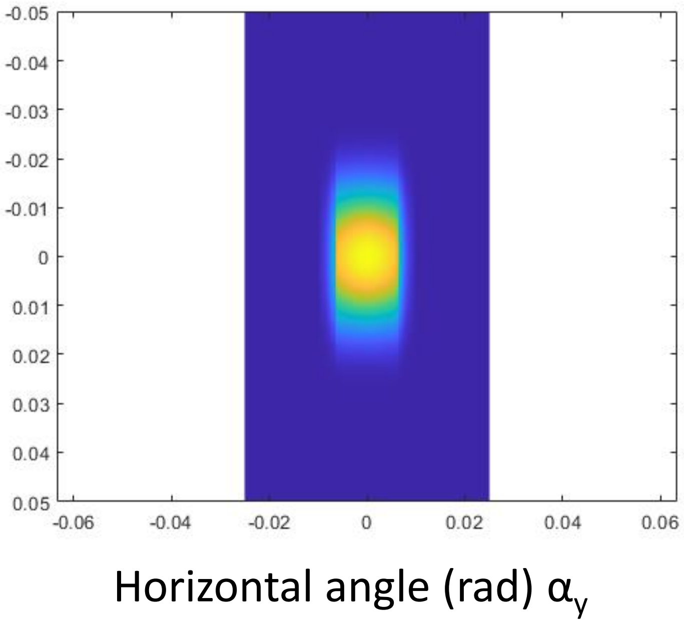
$G(\alpha_x, \alpha_y)$
Angular Particle Distribution
(here Gaussian with divergence 5 mrad, no halo)



$T_{HNB}(\alpha_x,\alpha_y)$
"Acceptance" of Beamline
(averaged over 1280 beamlets)

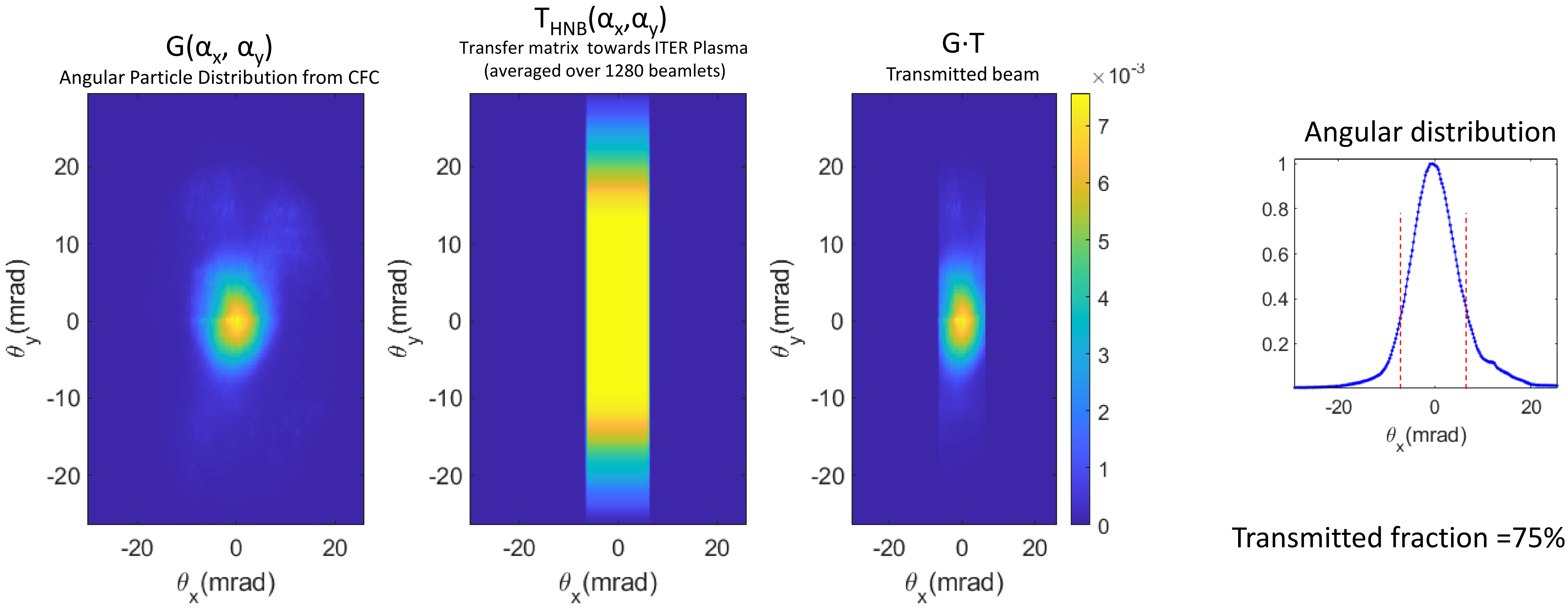


G·T
Transmitted beam



$\iint(G(\alpha_x, \alpha_y).*T(\alpha_x,\alpha_y)\, d\alpha_y\, d\alpha_z$= Transmitted fraction

In the case of MTF the beamlet is well isolated and the CFC is very far from the source (>2.5 m) therefore the measured spatial profile is a good approximation of angular distribution: we can apply our Transfer matrix

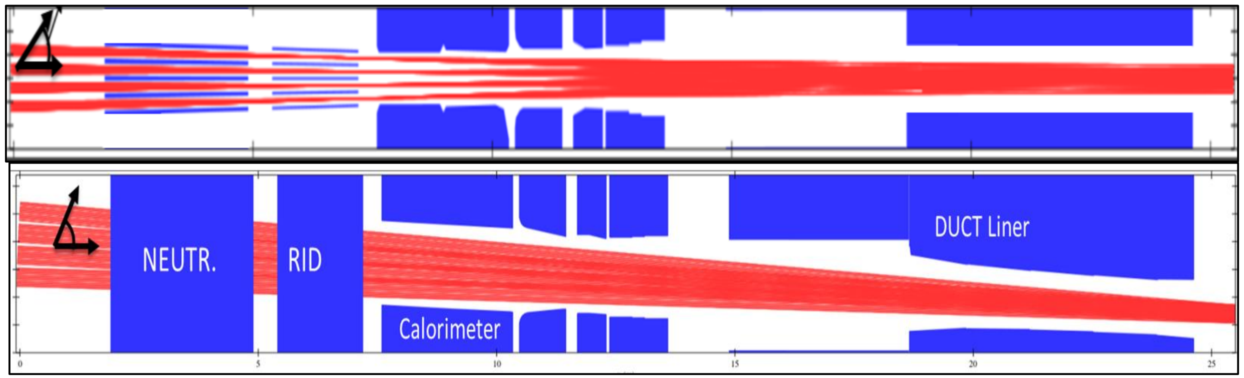


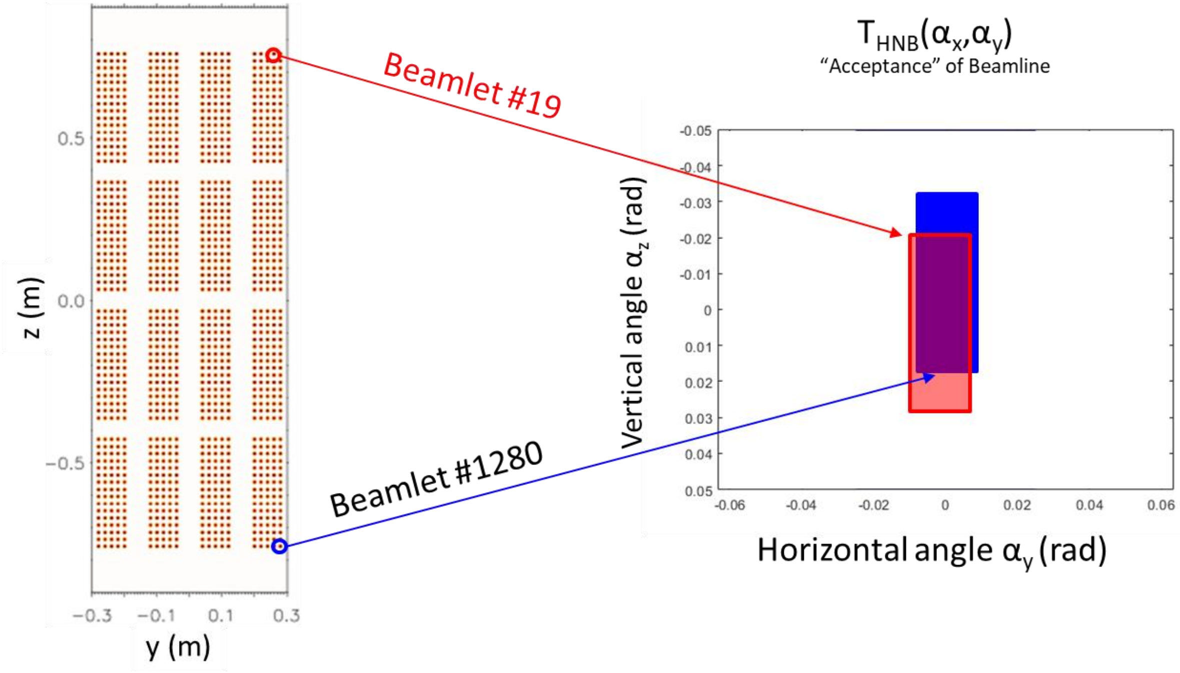
Transmitted fraction =75%!

Reminder: Core Divergence given by a Gaussian fit was 5.6 mrad

Introduction: Beam Transmission and divergence

- Beam current shared among 1280 beamlet arranged in lattice of 20x64 beamlets; typical radius 2-3 mm.
- Ions are neutralized soon after accelerator: Trajectories are ballistic along the following 22 m.
- Each beamlet is aimed along a specific axis, to maximize the clearance with beamline components (channels in Neut. and RID)





- Specific "acceptance" for each beamlet, depending mainly on his 2D angular distribution: starting positions of particles within a beamlet are negligible.

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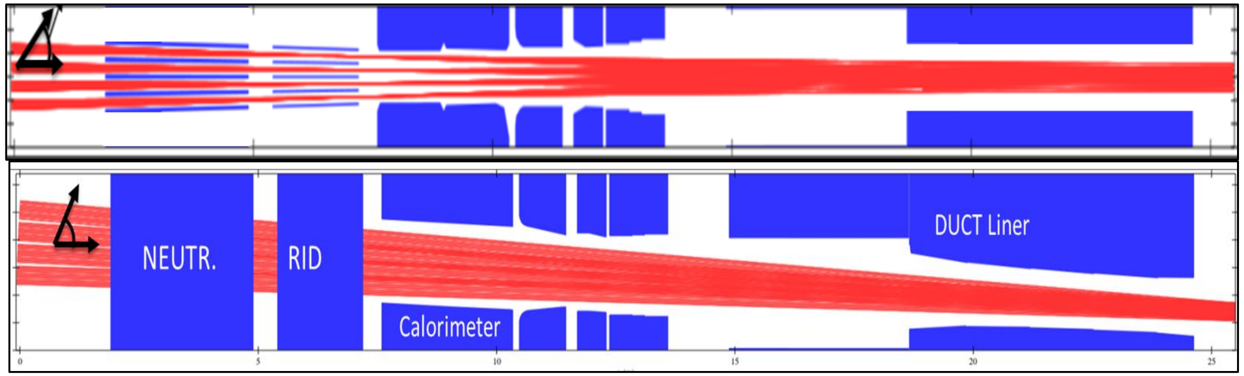
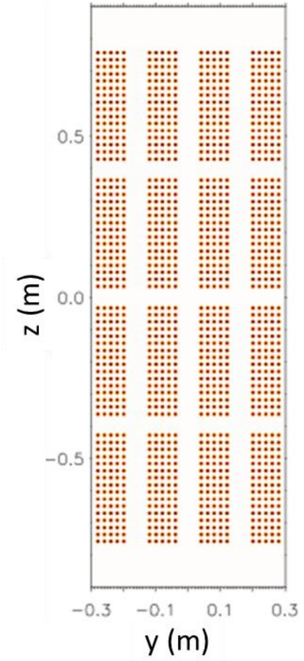
Top View



Lateral View



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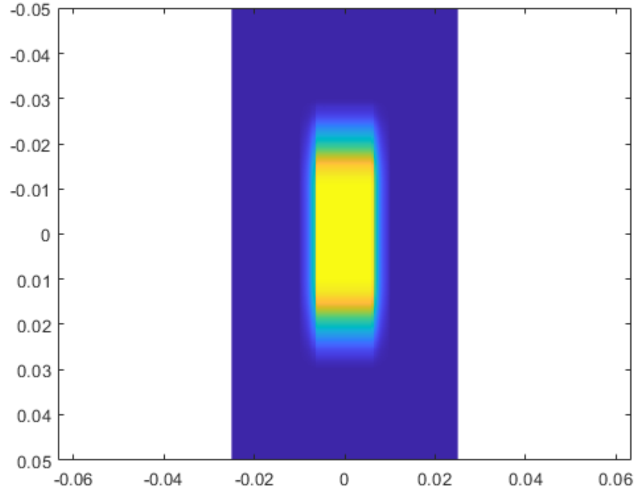

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